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Stability of Hydro Power Plants in Island Operation

Peining Wu

Master of Science in Electric Power Engineering
Submission date: July 2016
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Summary

In this thesis, the stability of hydro power plant in island operation is studied. The thesis is conducted in three prospective.

First, the hydro power plant power system model is built. hydraulic turbine and governing system, exciting system and synchronous generator are studied in a theoretical way. There are two types of hydraulic turbine introducing in the thesis.One is simple linear turbine and the other is nonlinear turbine. The comparison between these two turbine is made. The results shows that nonlinear turbine has better performance.

Further the mechanical-hydraulic governor and PID governor are presented in the thesis.The working principle of automatic voltage regulator and IEEE PSS2A stabilizer is illustrated.

Second order generator model and third order generator model are shown in the thesis and the detailed derivation process is presented.

Based on the theory above, hydro power plant power system model is built in PowerFactory and simulink. There are four types of hydro power plant model: simple hydraulic power plant model in simulink, complex hydraulic power plant model in simulink, single generation power system in PowerFactory, two generation power system in PowerFactory.

Through comparison between the simulink models and PowerFactory model, the simulink model is validated. It proves that simple hydraulic power plant model is not suitable applying in island operation. The complex hydraulic power plant model predicts much precise dynamics than simple hydraulic power plant model.

Second, characteristics of hydraulic governor are analysed in the island operation. Sensitivity analysis regarding the temporary droop, reset time and permanent droop is executed. It concludes that increment of the temporary droop and reset time will eliminate the oscillations, however, the response time of the system will be slow. In addition, the governor characteristics in both transient state and steady state are explored. The results shows that the governor characteristic are both linear in terms of the island operation.

Third, the effect of power system stabilizer on power system stability are studied. In order to explore the influence of the PSS, a three-phase short circuit at a bus which is close to the load is defined. First, a three phase short circuit test is applied in grid-connected operation, which aims to illustrates that power system stabilizer has positive effect on the generator in response to the disturbances. After validation, a three phase short circuit is made at the same bus with the grid-connected operation in island operation. There are ten cases being analyzed in this thesis.

By analysing the power system stabilizer in different cases, it is concluded that the power system stabilizer has positive effect on both grid-connected mode and island mode. Furthermore, the parameters of the PSS has huge impact on the behaviour of the power system. Inappropriate parameters could worsen the performance of the power system regarding to the small disturbances.

Preface

It is my master thesis in the Electric Power Engineering department, Norwegian University of Technology and Science.

I would like to thank my supervisor Kjetil Uhlen who has been constructing me all the way along and always gives me good suggestions and helps me solve the problems in terms of the master thesis. Besides, I would also like to thank Trond Toftevaag who is willing to listen to me and provides me a lot of good materials and books.

Last but not least, this thesis is dedicated to my beloved family.

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Symbols and Abbreviations

Symbols

G	gate position
H	hydraulic head at gate
K_u	water velocity constant
L	length of conduit
A	pipe area
ρ	mass density
a_g	acceleration due to gravity
t	time in seconds
M	Coefficient of inertia
P_e	Electrical power
P_m	Mechanical power
R_p	Permanent droop
T_r	Transient droop
T'_{d0}, T''_{d0}	d-axis open circuit transient and subtransient time constant
T'_{q0}, T''_{q0}	q-axis open circuit transient and subtransient time constant
T_w	water starting time
X_d, X'_d, X''_d	d-axis synchronous, transient and subtransient reactance
X_q, X'_q, X''_q	q-axis synchronous, transient and subtransient reactance
ω	rotor speed

Abbreviations

AVR	Automatic voltage regulator
PID	Proportional-integral-derivative controller
PI	Proportional-integral controller
$d-axis$	Direct axis of generator
$q-axis$	Quadrature axis of generator
HPP	Hydraulic power plant
PSS	Power system stabilizers

Chapter 1

Introduction

1.1 Background

Hydro power is a sustainable and renewable energy. Comparing with coal, solar and wind energy, hydro power has advantages of efficiency, cheap and environmentally friendly. In the world wide, hydro power plant has been implemented in many countries.

Particularly, the primary electricity in Norway is generated by hydro power plants. As a result, hydro power plant plays an important role in Norway power generation. Therefore, stability of hydro power plant is a critical topic in power system stability studies.

Nowadays, there are some small hydro power plants operates in a intentional island operation[6]. Besides, unintentional island is one of serious contingencies in power systems. When power system meets island operation, the generator faces large load changes. There will be a power imbalance between the mechanical power that provided by the turbine and the electrical power consumed by the loads.

Consequently, the frequency will deviates significantly if the power imbalance is enormous. The system can be exposed to hazards and risks[13], which has negatively effect on power quality, even worse, the power system will be unstable.

Turbine governing system is used to control power and frequency in the hydro power plant system[7], which is capable to maintain the acceptable frequency range during transient condition.

1.2 Objectives

In the thesis, different types of hydro power plant model in terms of the island operation is built. Furthermore, comparison between simple hydro power plant model and complex hydro power plant model in island operation. The main challenges of modelling the hydro power plant model is investigated.

An analytical approach is applied to analysis the requirements for governing system control in hydro power plants and, and through modeling and simulation studies identify the main challenges in governor tuning and design in the transition between grid connected and island operation.

The effect of power system stabilizers is studied. To explore whether the power system stabilizer has positive effect on the stability of power system after island operation.

1.3 Structure of the Report

The structure of the report is as following Chapter 1 introduced the background information of the project.

Chapter 2 introduces both physical part of turbine and the working principle of the hydro turbine. In addition, hydro turbine is illustrated in a mathematical way. In terms of the mathematical explanation, the turbine can be presented in a linear turbine and nonlinear turbine. Through a step change test in both turbine models, a comparison is made between linear turbine and nonlinear turbine, which shows that nonlinear turbine is capable of showing more detailed dynamic response than linear turbine. On the other hand, two types of governor are depicted in the chapter 2. One Is mechanical governor and the other is a PID governor. These two governors are illustrated in a theory prospective.

Chapter 3 mainly presents the excitation system in generators. Excitation system includes automatic voltage regulators and power system stabilizers. The relationship between excitation system and generator and the working approach of the excitation system are explained. In particular, the power system stabilizer- IEEE PSS2A, which is used in this thesis, is specifically illustrated in a mathematical prospective.

Chapter 4 explains the theory of synchronous machine model, and present the specific mathematical equations of the second order generator model and third order generator model. Besides, the excitation control is considered in the third order generator model

Chapter 5 presents the hydro power system models which are used in this thesis. It illustrates the measurement of building a mathematical hydro power plant simulink model. Since in this thesis, synchronous generator is used, the hydro power plant model is based on the synchronous generator. There are two kinds of hydro power plant model in the chapter 4. One is a simple hydro power plant model, which only takes governor and turbine into account. And it is a second generator model. The other is a complex hydro power plant model, which not only considers the effect of frequency but also takes field voltage into account.

Chapter 6 shows the results of hydraulic power system when it faces the island operation. There are two situations of island operation. One is power deficit condition and the other is power oversupply condition. The analysis based on the response of the system is given in chapter 5. It shows the stability requirements of the power system, and the meaning of doing the research of stability of hydro power plant in island operation.

Chapter 7 depicts the governor control analysis in terms of the island operation. Through simulation in the powerfactory model, the effect parameters of the governor is analysed.Through tuning of the governor parameter, the performance of the governor is better than before. The relationship between the changes of frequency and changes of load is explored as well.

Chapter 8 studies the effect of power system stabilizer in the two types of power system model in the PowerFactory. By using the linear analysis and time domain analysis, the response of the power system can be measured.

Chapter 9 is the discussion of the thesis.

Chapter 10 is the conclusion and further work of the thesis

Chapter 2

Hydraulic Turbines and governoring system

Hydraulic turbine is a critical component in hydro power plant. Understanding the hydraulic turbine characteristic is benefit to understand the behavior of hydro power plant in disturbances. The categories of the hydraulic turbine and the work principle is introduced in this chapter. Further, the turbine was analysed in mathematical perspective. Two different types of hydraulic turbines are presented specifically, and the differences between these two models are studied. In addition, the hydraulic governor is studied. Mechanical hydraulic governor and PID governor are presented and also explained in a mathematical way.

2.1 Hydraulic turbines

2.1.1 Introductions of hydraulic turbine

The hydraulic turbine is a mechanical device that converts the potential energy exerted by the water as it falls from an upper to lower reservoir, into rotational mechanical energy.

Basically, hydraulic turbine can be divided into two types: one is the impulse type turbine, the other is reaction turbine. Impulse turbine also called Pelton Wheel, which is used in high-head hydro electric power plants. It consisted of needle, jet deflector torand runner with bowl-shaped bucket. The structure of the Pelton wheel is shown in figure2.1. The size of the jet can be

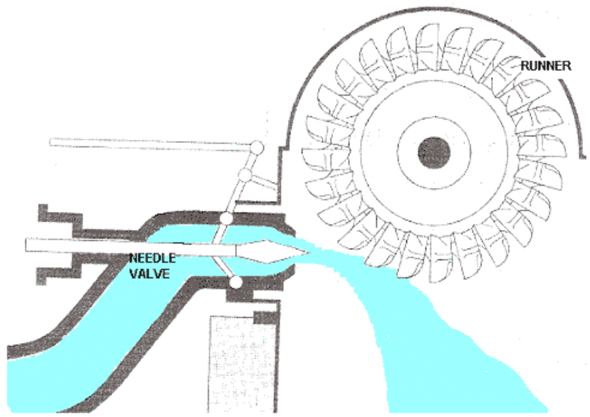


Figure 2.1: The structures of pelton turbine turbine[1]

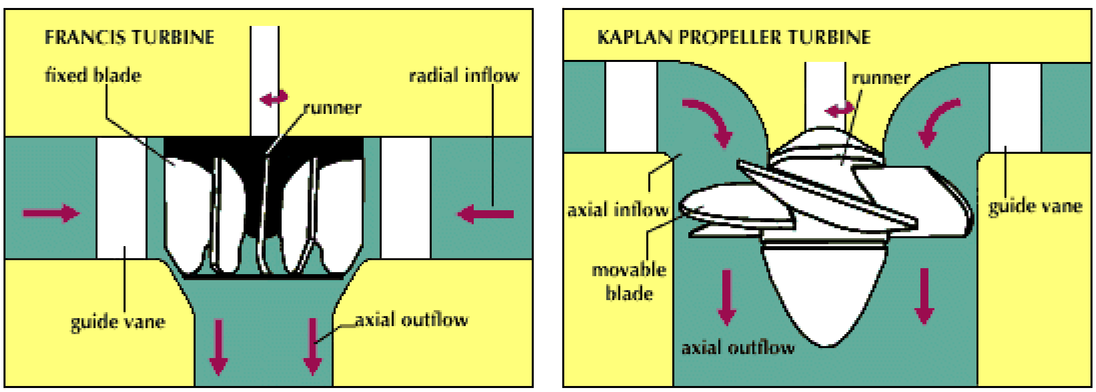


Figure 2.2: Francis turbine and Kaplan turbine[2]

controlled, so that the output rotational mechanical energy can be controlled correspondingly by the governing system.

Unlike the impulse turbine, the reaction turbine is used inn low and medium head hydro power plant. It equipped with blades inside, wicket gates, runner, as shown in figure2.2. When the water flows through the blades the runner starts to run. Normally the water flow is controlled by the wicket gates. The reaction turbine has two categories: Francis turbine and propeller turbine, which also called Kaplan turbine.

No matter what kind of turbine it is, the general working principal of turbine is that the water flow motivates the runner moves. The wicket gate is used to control the water flow so that the speed of the runner can be adjusted. Normally, the effects of water inertia, water compressibility, and pipe elasticity would affect on the performance of hydraulic turbine[7]. Therefore, when modelling hydraulic turbine, it is important to take those factors into account.

However, when it comes to turbine mathematical expression, three assumptions are normally made in terms of simplicity. The assumptions are as following:

- The hydraulic resistance is neglected
- The penstock pipe is inelastic
- The water is incompressible

Based on those assumptions, the basic turbine mathematical equations can be built. The simple strucutre of hydro power plant is shown in figure2.3. The penstock water velocity U, turbine mechanical power P_m and the acceleration of the water column $\frac{d\Delta U}{dt}$ depict the primary characteristics of the hydraulic turbine[7]. Their mathematical expressions are shown in Equation(2.1),(2.2),(2.3) respectively.

$$U = K_u G\sqrt{H} \tag{2.1}$$

$$P_m = K_p HU \tag{2.2}$$

$$\frac{d\Delta U}{dt} = \frac{-A(\rho a_g)\Delta H}{\rho LA} \tag{2.3}$$

Where G represents the gate position, H refers to hydraulic head, A stands for the area of the pipe, ρ is the mass density, a_g means acceleration of gravity, K_u and K_p are the proportional coefficients.

2.1.2 Simple linearized turbine model

Since the three principal equations of the hydraulic turbine are introduced in the previous section, the simple linearized turbine model can be deduced. Linearizing Equation(2.1),(2.2), the

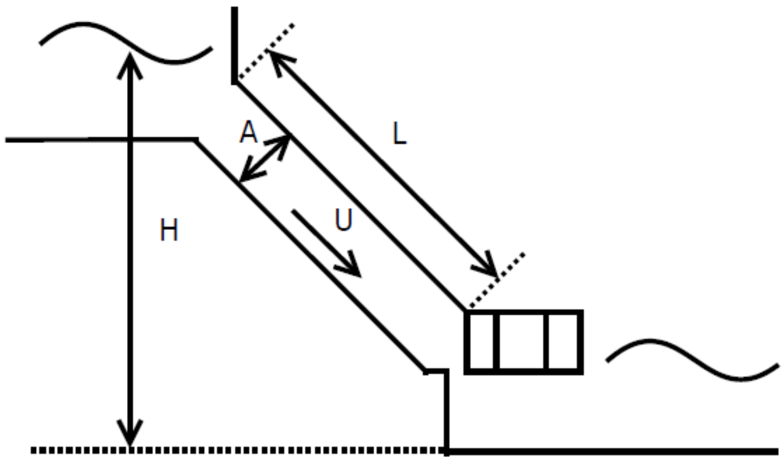


Figure 2.3: The layout of the hydro power plant

linearized form of turbine characteristic equations can be shown as

$$\Delta U = \frac{\partial U}{\partial H}\Delta H + \frac{\partial U}{\partial G}\Delta G \tag{2.4}$$

$$\Delta P = \frac{\partial P}{\partial H}\Delta H + \frac{\partial P}{\partial U}\Delta U \tag{2.5}$$

$$(\rho L A)\frac{d\Delta U}{dt} = -A(\rho a_g)\Delta H \tag{2.6}$$

in which

$$\frac{\partial U}{\partial H} = K_u G_0 \frac{1}{2\sqrt{H_0}}$$

$$\frac{\partial U}{\partial G} = K_u \sqrt{H_0}$$

$$\frac{\partial P}{\partial H} = K_p U_0$$

$$\frac{\partial P}{\partial U} = K_p H_0$$

Normalize these three equations:

$$\Delta\bar{U} = 0.5\Delta\bar{H} + \Delta\bar{G} \tag{2.7}$$

$$\Delta\bar{P_m} = \Delta\bar{H} + \Delta\bar{U} \tag{2.8}$$

$$\frac{LU_0}{a_g H_0}\frac{d\Delta\bar{U}}{dt} = -\Delta\bar{H} \tag{2.9}$$

where the superbar represents the normalized value.

In general, Equation(2.9) can also be written as

$$T_\omega \frac{d\Delta\bar{U}}{dt} = -\Delta\bar{H} \tag{2.10}$$

In which

$$T_w = \frac{LU_r}{a_g H_r} \tag{2.11}$$

T_ω represents the water starting time. Water starting time means the time required for a head H_0 to accelerate the water in the penstock from standstill to the velocity U_0[7]

Substituting ΔH into equation(2.7) yields

$$\Delta\bar{P_m} = 3\Delta\bar{U} - 2\Delta\bar{G} \tag{2.12}$$

From the equation(2.8), we have

$$\Delta\bar{H} = \Delta\bar{P_m} - \Delta\bar{U} \tag{2.13}$$

Substituting equation(2.13) into equation(2.10),yields

$$T_\omega \frac{d\Delta\bar{U}}{dt} = \Delta\bar{U} - \Delta\bar{P_m} \tag{2.14}$$

Therefore,the relationship between change in speed and change in gate position is

$$T_{\omega}\frac{d\Delta\bar{U}}{dt} = 2(\Delta\bar{G} - \Delta\bar{U}) \tag{2.15}$$

Rewrite the equation in the Laplace expression, the water speed can be expressed by

$$\Delta\bar{U} = \frac{1}{1+0.5T_{\omega}s}\Delta\bar{G} \tag{2.16}$$

Substituting the equation(2.16) into the equation(2.12). The transfer function between mechanical power and gate position is

$$\frac{\Delta\bar{P_m}}{\Delta\bar{G}} = \frac{1-T_{\omega}s}{1+0.5T_{\omega}s} \tag{2.17}$$

Therefore the simple linear turbine model can be built according to the transfer equation.The block diagram of the turbine model is shown as follows

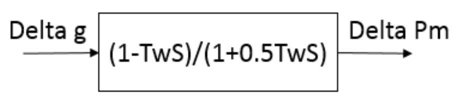


Figure 2.4: The block diagram of classical turbine model

2.1.3 Nonlinear hydraulic turbine model[4]

The nonlinear hydraulic turbine model is In Simple linear model, the hydraulic head H times water velocity U produces the mechanical power, however, hydraulic turbine mechanical output power is also affected by the speed deviation damping effect in reality[5].

Therefore, the mechanical power can be given as

$$\bar{P_m} = A_t\bar{H}(\bar{U} - U_{nl})\eta - K_D\Delta\omega\bar{G} \tag{2.18}$$

Where η is the turbine efficiency, K_d is proportional constant factor and A_t is also a constant factor which can be represented as

$$A_t = \frac{1}{\bar{H}(U - U_{nl})} \frac{turbinepower(MW)}{generatorMVArating} \tag{2.19}$$

In general, η is neglected, therefore the mechanical power can be expressed by

$$P_m = A_t H(U - U_{nl}) - K_D \Delta\omega g \tag{2.20}$$

The equations which are considered in the nonlinear turbine modelling are show as following

$$\bar{U} = \bar{G}\sqrt{\bar{H}} \tag{2.21}$$

$$\bar{P_m} = A_t \bar{H}(\bar{U} - U_{nl}) - K_D \Delta\omega \bar{G} \tag{2.22}$$

$$\frac{d\Delta\bar{U}}{dt} = \frac{\bar{H} - H_0}{T_\omega} \tag{2.23}$$

In order to make all the variables in the same base, so the variables are all in normalized form.From equation(2.23),we can write it in Laplace form

$$\frac{\bar{U}}{\bar{H} - \bar{H}_0} = \frac{-1}{T_\omega s} \tag{2.24}$$

Therefore, based on the mathematical relationship among the equations(2.21),(2.22), (2.24), the nonlinear turbine model can be made, which can be represented by the block diagram as shown in Figure2.5

2.1.4 Comparison of hydraulic turbines

In order to exam the characteristics of the simple linear turbine model and nonlinear turbine model. Two different step changes as a input signal was made. One situation is that gate signal grows from 0.9 to 1, the other situation is gate signal drops from 0.2 to 0.1. With those two

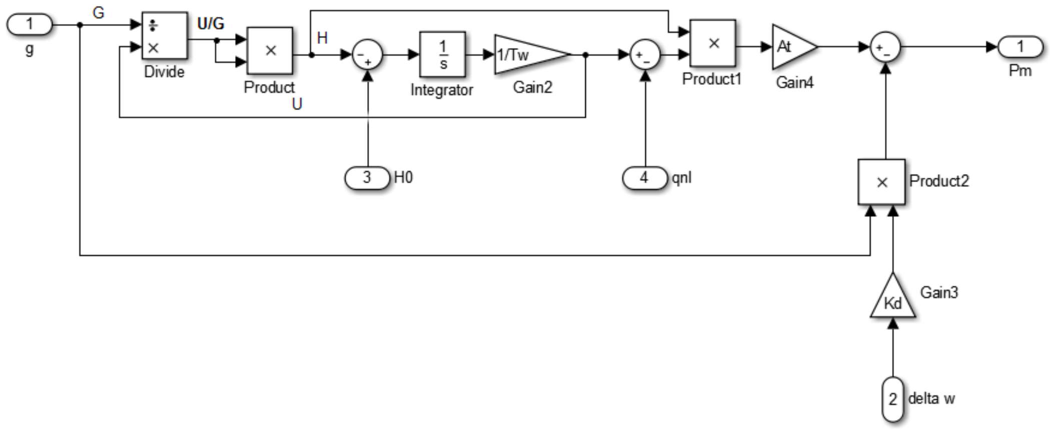


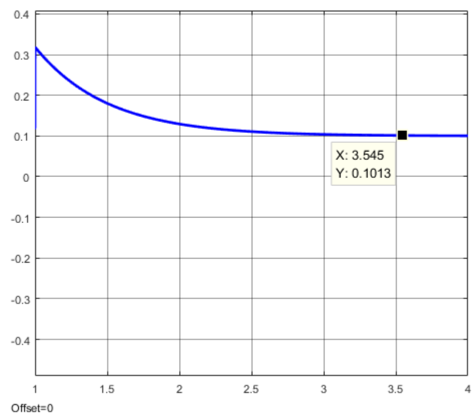
Figure 2.5: The block diagram of Nonlinear turbine model with inelastic water column

different step change test, the mechanical power, which is the output signal of the linear and nonlinear turbine, are shown in the figure2.6 and figure2.7 respectively.

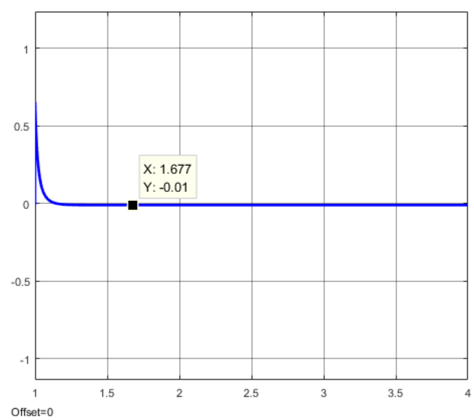
Figure2.6 represents the step response of gate signal changing from 0.2 to 0.1. We can see that the mechanical power both rises after a step change, however, the nonlinear turbine reacts faster than the linear turbine. In nonlinear turbine model, the mechanical power turns to stability at 1.677s, however, the linear turbine model takes 3.545s. Further, the mechanical power in the nonlinear turbine rises to approximately 0.6 after the step change, and the mechanical power increases by 0.2.

Figure2.7 shows the mechanical power change in response of gate signal decreases from 1 to 0.9.

Thus, linear turbine model is very simple, which is suitable for small signal studies. A nonlinear turbine model assuming inelastic water column is suited for transient stability studies.

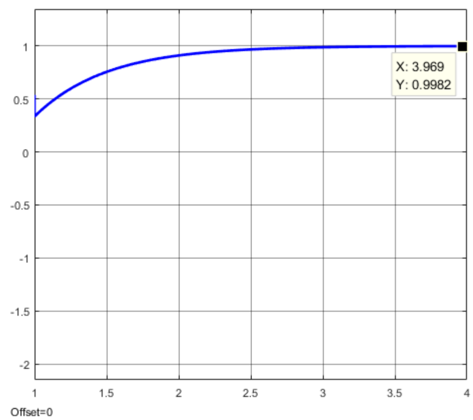


(a) Step response of linear turbine model

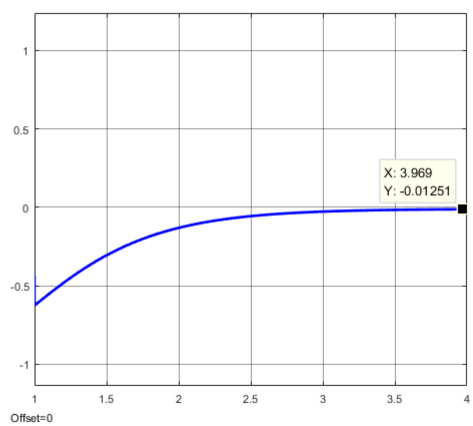


(b) Step response of nonlinear turbine model

Figure 2.6: Step change test in different turbine model



(a) Step response of linear turbine model



(b) Step response of nonlinear turbine model

Figure 2.7: Step change test in different turbine model

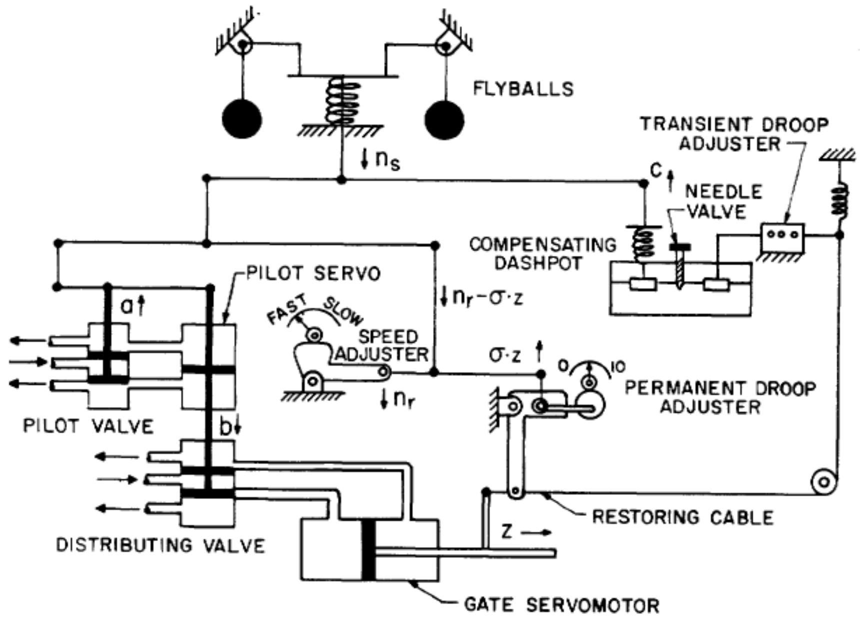


Figure 2.8: layout of the mechanical-hydraulic governor[14]

2.2 Hydraulic governing system

2.2.1 Introduction of hydraulic governing system

There are two primary types of governing control system, one is mechanical-hydraulic type, the other is electro-hydraulic type. Mechanical-hydraulic type is a old type, and nowadays it is replaced by the electro-hydraulic governing system.

The principal of the turbine control is that when mechanical torque equals to the electrical torque, the speed of the turbine-generator will not change. When electrical torque is greater than mechanical torque, the speed of the turbine reduces, making the turbine valve open and the power of the turbine increases. Basically,governing system has two control loops. One is the speed loop, the other is valve position loop. Those two loops ensure that when torques increases, the power decreases.

2.2.2 Mechanical-hydraulic Governor

Figure2.9 shows the layout of the mechanical-hydraulic governor. When the measured rotor speed is different with the reference speed, the transient droop adjuster would develop a signal to impede the fast change of gate position. The permanent droop is used to adjust the difference between measured rotor speed and reference speed in steady state.

Block diagram of the mechanical-hydraulic governor is presented in figure2.9.A high force is required to move the control gate so that it could overcome high water pressure and high friction forces[7]. Because of this,in hydraulic governing system, there are two servomotors, which are pilot servomotor and gate servomotor respectively.

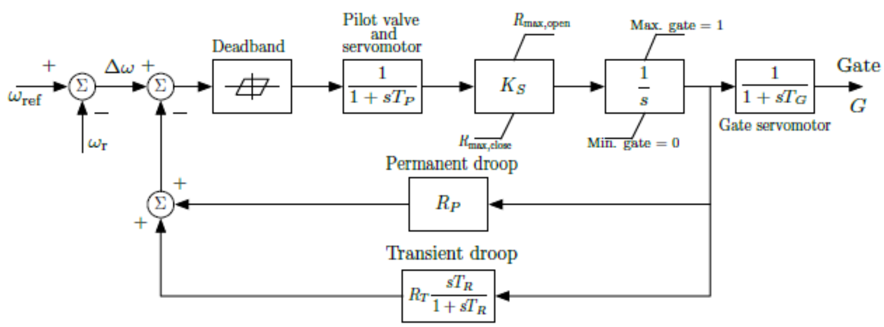


Figure 2.9: The block diagram of the mechanical-hydraulic governor[7]

The transfer function of the relay valve and gate servomotor is

$$\frac{g}{a} = \frac{K_1}{s} \tag{2.25}$$

Besides, the transfer function of the pilot valve and pilot servomotor is

$$\frac{b}{a} = \frac{K_2}{1 + T_p s} \tag{2.26}$$

Combining the equations(2.25)and(2.26), the transfer function of relay valve and pilot valve is

$$\frac{g}{b} = \frac{K_1 K_2}{s(1 + T_p s)} \tag{2.27}$$

2.2.3 Electro-hydraulic Governor

Unlike mechanical-hydraulic governor, in the electro-hydraulic governing system, the speed of the turbine is measured electronically, which could reduce the deadband and increase the accuracy[10].

Electro-hydraulic governor consist of a PID controller, permanent droop R_p, pilot servomotor, gate servomotor.The block diagram of electro-hydraulic governor is presented in Figure2.10

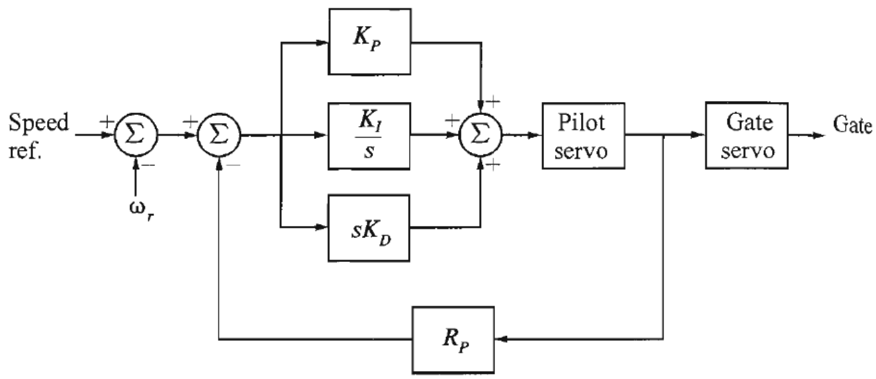


Figure 2.10: Block diagram of electro-hydraulic governor[7]

If set the derivative value to be zero, the PID governor becomes PI governor, which is equivalent with mechanical-hydraulic governor. The mathematical relations is as follows

$$K_p = \frac{1}{r} \tag{2.28}$$

$$K_i = \frac{1}{rT_r} \tag{2.29}$$

Chapter 3

Excitation system

In this chapter, automatic voltage regulator and power system stabilizer are presented. Particularly, the PSS2A model is explained in a mathematical way The working principle is shown in this chapter. Moreover, the effects of these two controller is studied.

3.1 Introduction of excitation system

3.2 Automatic voltage regulator

Excitation system consists of an exciter and an automatic voltage regulator(AVR). Excitation system control the voltage and reactive power flow.The excitation system performs control and protective functions essential to the satisfactory performance of the power system by controlling the field voltage and thereby the field current.

Figure3.2 shows the elements of a synchronous generator excitation system. Exciter provides dc power to the synchronous machine field winding, constituting the power stage of the excitation system.Regulator processes and amplifies input control signals to a level and form appropriate for control of the exciter.

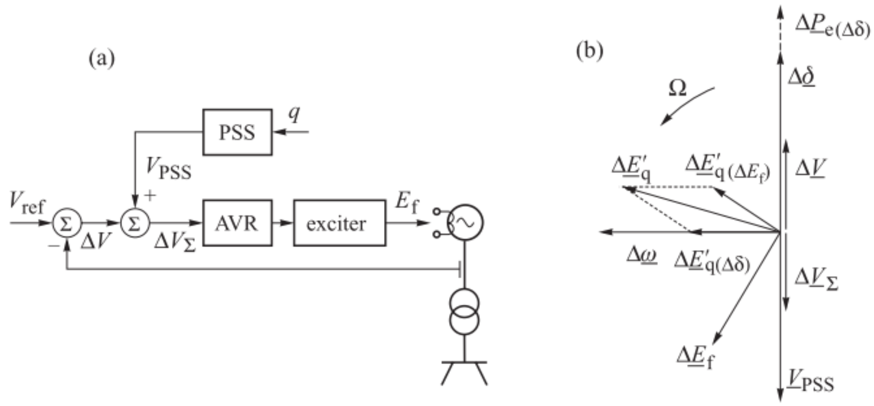


Figure 3.1: Block diagram of excitation system[8]

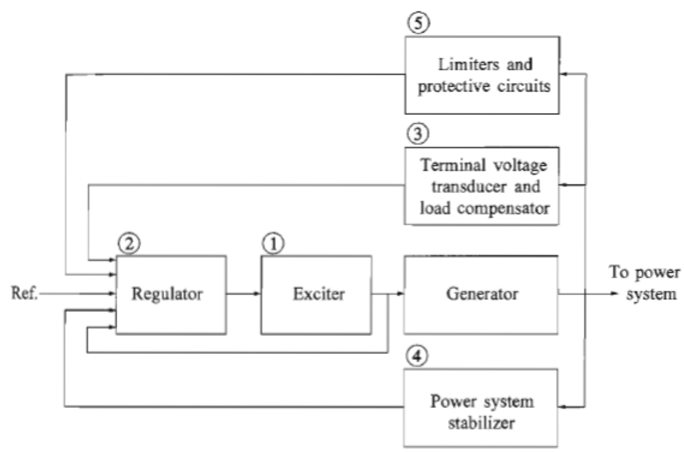


Figure 3.2: functional diagram blocks of a synchronous generator excitation system

3.2.1 Excitation system Modelling

There are many types of excitation systems, in this project, the excitation system shown in Figure3.3 is used, according to the excitation controller avr_SEXS type in the powerfactory model library.

3.3 Power system stabilizers

Power system stabilizer is a additional control loop to the AVR or governing system, which helps damp in the system in low frequency oscillations situation. The basic function of a PSS is to add

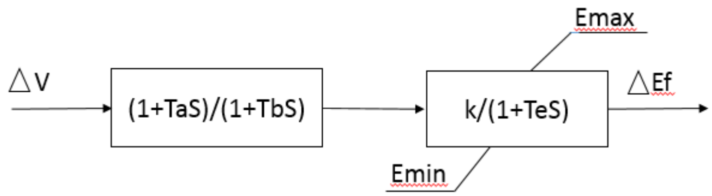


Figure 3.3: The block diagram of excitation system

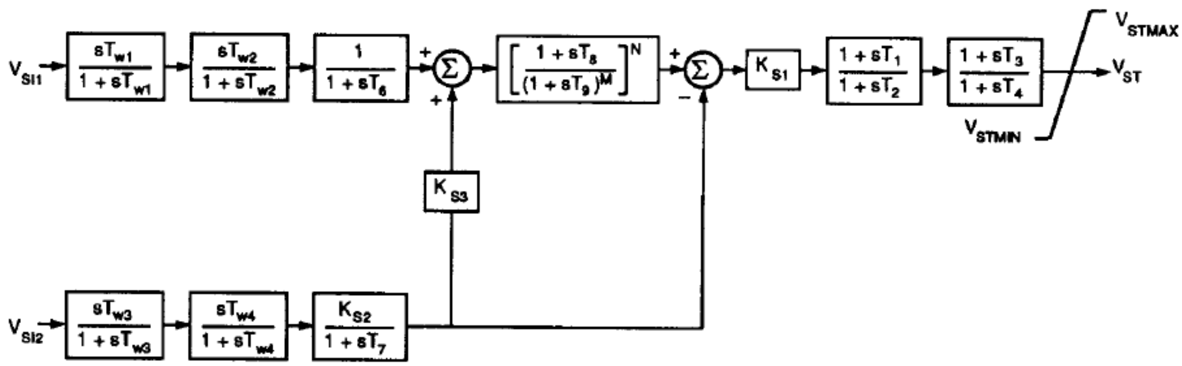


Figure 3.4: Block diagram of PSS2A[8]

damping to the generator rotor oscillation. In the hydro power plant model in this thesis, IEEE PSS2A is applied.

3.3.1 IEEE PSS2A Stabilizer

IEEE PSS2A is a dual input stabilizer. The input signals are electric power and shaft speed respectively. The structure of the PSS2A is shown in figure3.4.

In the block diagram, V_{sl1} refers to rotor speed ω, and V_{sl2} presents the electrical power P_e. T_{w1},T_{w2},T_{w3},and T_{w4} are time constant of the washout circuit. K_{s1},K_{s2},and K_{s3} are proportional coefficients. T_8 and T_9 is the time constant of the ramp track filter. M and N are the filter coefficients. $T_1 \sim T_6$ are the lead-lag time constant[9].

The mechanical power and the electrical power, and the rotor speed has following relationship

$$M\frac{d\omega}{dt} = P_m - P_e \tag{3.1}$$

Based on the above equation, we can rewrite as

$$\Delta P_m = Ms\Delta\omega + \Delta P_e \tag{3.2}$$

When the signal ΔP_m passes through the ramp track filter, it becomes

$$\Delta P_m G(s) = (Ms\Delta\omega + \Delta P_e)G(s) \tag{3.3}$$

where $G(s)$ is

$$G(s) = [\frac{1 + sT_8}{(1 + sT_9)^M}]^N$$

Accelerating power signal can be obtained by

$$\Delta P_a = \Delta P_m - \Delta P_e \tag{3.4}$$

In which the mechanical power can be represented by $\Delta P_m G(s)$

therefore the accelerating power can be presented as

$$\Delta P_a = (Ms\Delta\omega + \Delta P_e)G(s) - \Delta P_e \tag{3.5}$$

As a result, the two input signals become one signal in the end, and the rest of the $PSS2A$ is the same as single input PSS.

Chapter 4

Synchronous generator

Two types of synchronous generator are presented. One is simple linearized synchronous generator model, and the other one is third-order nonlinear synchronous generator model. Those two models are explained in a mathematical way. The nonlinear synchronous generator model consists of a automatic voltage regulator.

4.1 Synchronous generator connected to strong grid

A synchronous salient pole generator is used in this thesis. In order to simulate the system in transient studies, a power system that a synchronous generator connected to the infinite busbar through the setup transformer is built.

The diagram of the power system is shown in Figure4.1, where V_s represents the voltage source on the infinite busbar side, R is load, V_g is the generator terminal voltage, x_t is the impedance of the transformer, and $R_l + jx_l$ is the impedance of the transmission line.

According to the diagram of the power system, the equivalent circuit of the power system could be derived, the equivalent circuit is presented in Figure4.2

The parameters of the power system is given in the appendix.With the given parameters, the power angle δ_0, the infinite busbar voltage V_s, generator terminal voltage V_g, and line current I

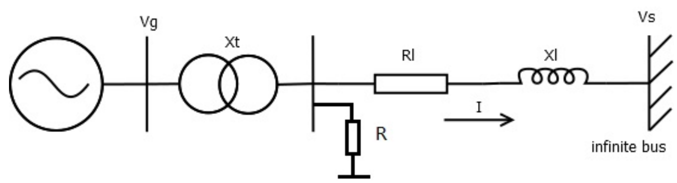


Figure 4.1: Single line to bus system

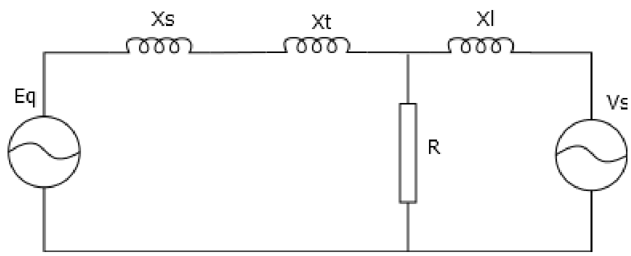


Figure 4.2: The equivalent circuit of the single line power system

can be calculated. The process of the calculation is given in the appendix. The phasor diagram of the power system is as follows

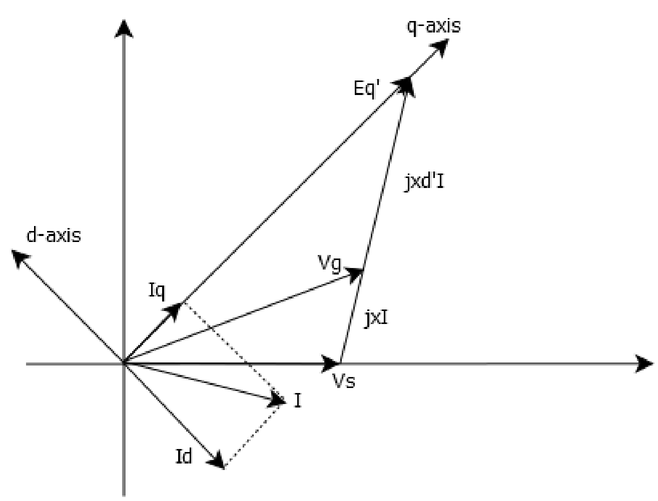


Figure 4.3: Phasor diagram of the system

From the phasor diagram, the relationship between V_g and V_s can be derived as

$$V_g = V_s + jx_d I \tag{4.1}$$

Similarly, the relationship between E'_q and V_s can be written as

$$E'_q = V_s + jx'_d I \tag{4.2}$$

The swing equation of the generator is

$$M\frac{d\Delta\omega}{dt} = P_m - P_e - P_D \tag{4.3}$$

Where P_m is the mechanical turbine power, P_e is the air-gap electrical power, M is inertia coefficient. Moreover, M and P_D can be represented by

$$M = 2H, P_D = D\Delta\omega \tag{4.4}$$

The relationship of rotor angle δ and rotor speed ω is given by

$$\frac{\delta}{dt} = \Delta\omega \tag{4.5}$$

4.1.1 Synchronous generator connected to strong grid simplified model

The second-order model of synchronous generator model is also referred as the classical synchronous generator model, which is used widely in the simplified analysis of power system dynamics.

In second order model, there are several simplifications being made. The changes of internal emf E_f and the armature current I_d are assumed to be very small so that E'_q can be regard as constant value[10]. Moreover, the effect of the damper windings is also neglected, which means E'_d is constant value as well.Therefore, the generator model can be represented by

$$M\frac{d\Delta\omega}{dt} = P_m - P_e - D\Delta\omega$$
$$\frac{d\delta}{dt} = \Delta\omega$$

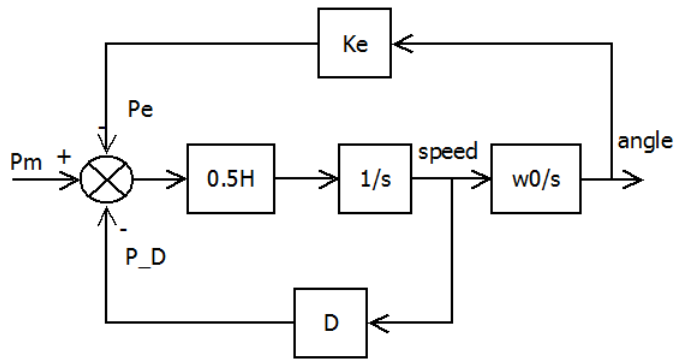


Figure 4.4: Block diagram of Synchronous generator connected to strong grid simplified model

For synchronous salient-pole generators, $x_d > x_q$, therefore, neglecting the losses, the electrical power can be represented by

$$P_e = \frac{E_q V_s}{x_d}\sin\delta + \frac{V_s^2}{2}\frac{x_d - x_q}{x_q x_d}\sin 2\delta \tag{4.6}$$

Linearizing equation(4.6), since E'_q is constant, we can get

$$\frac{\partial P_{E'_q}}{\partial \delta} = \frac{E'_q V_s}{x'_d}\cos\delta - {V_s}^2 \frac{x_q - x'_d}{x_q - x'_d}\cos 2\delta \tag{4.7}$$

Based on the equations (4.3),(4.5),(4.7),the Power plant connected to strong grid simplified model can be represented as Figure4.4

4.1.2 Third-order nonlinear synchronous generator model

In third order model, the effect of E_f is considered, so the equation of quadrature-axis transient emf E'_q is included in the model. The E_d is still considered as constant in third order model. Rotor winding equations

$$T'_{d0}\frac{dE'_q}{dt} = E_f - E'_q + i_d(x_d - x'_d) \tag{4.8}$$

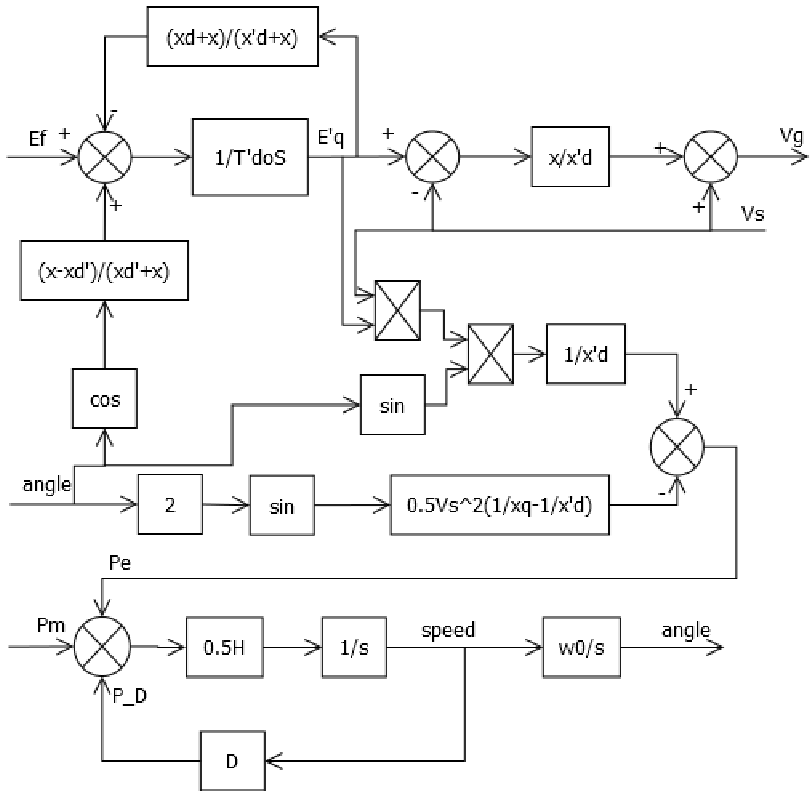


Figure 4.5: Block diagram of synchronous generator connected to strong grid nonlinear model

where T'_{d0} is the d-axis open circuit transient time constant, E_f is the field voltage. Therefore, the third-order generator model is represented by the following equations

$$M\frac{d\Delta\omega}{dt} = P_m - P_e - D\Delta\omega$$
$$\frac{d\delta}{dt} = \Delta\omega$$
$$T'_{d0}\frac{dE'_q}{dt} = E_f - E'_q + i_d(x_d - x'_d)$$

Based on the equivalent circuit of the power system, the equation of E'_q can be derived as

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}}[-\frac{xd+x}{x'_d+x}E'_q + \frac{x-x'_d}{x'_d+x}V_s\cos\delta + E_f] \tag{4.9}$$

According to the equations(4.1)(4.2)(4.3)(4.5)(4.9), the block diagram of synchronous generator connected to strong grid nonlinear model can be yield, which is shown in Figure4.5

Chapter 5

Hydro Power Plant Model

Based on the mathematical models of the Chapter2 and the block diagram of hydro power plant as shown in the figure5.1, hydro power plant model could be built. The simple hydro power plant model and hydro power plant model include voltage control is modeled in the simulink. Simple hydro power plant model consist of governor, turbine, and generator. In hydro power plant model include voltage control, excitation system was added. In this chapter, the response of the generator in these two models are presented respectively. Besides, comparison between simulink model and powerfactory model is made. Simulink and DIgSILENT PowerFactory are good tool in analysis dynamic behaviour of the HPP.

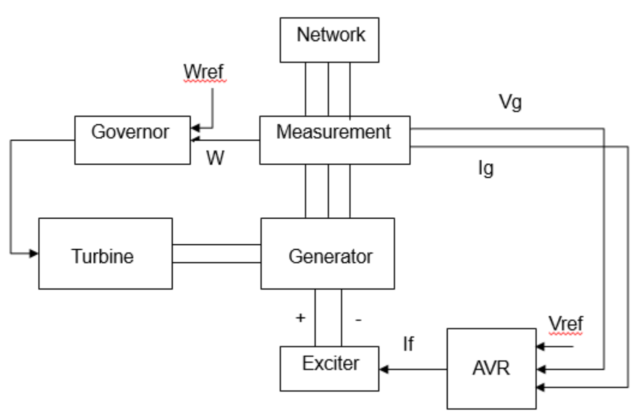


Figure 5.1: Block diagram of hydro power plant

5.1 HPP models in powerfactory

There are two types of hydro power plant in powerfactory, one is single generation power system, and the other one is two parallel generations power system. PowerFactory offers large various of grid devices. Besides, the parameters of these devices can be customized to suits the specific requirements. In the PowerFactory model, it consists of synchronous machine, Y-N transformer, voltage independent load, a stiff network, buses, and transmission lines. The parameters of those devices are presented in the appendix A.

The generator control system included three types of controller: governor, automatic voltage regulator(AVR) and power system stabilizer(PSS). Governor type in this model is gov_HYGOV. It is a typical mechanical-hydraulic nonlinear governor model with a simple hydraulic representation of the penstock with unrestricted head race and tail race, and no surge tank[12]. AVR model type is the avr_SEXS. It is no specific type of excitation system, but rather the general characteristics of a wide variety of properly-tuned excitation systems[12]. PSS model type is pss_PSS2A, which is a dual input power system stabilizer.

The detailed presentation of the three controllers are shown in the chapter 2 and chapter 4. The structure of the gov_HYGOV,avr_SEXS and pss_PSS2A are presented in the appendix C.

5.1.1 Single generation power system model

As shown in Figure5.2, a three phase synchronous salient pole generator is connected to a stiff network. The rated active power of the generator is 40MW, and the load is 25MW.

5.1.2 Two generators power system model

In the two generators power system model, two generators connected in parallel. The rated power of each generator is 40MW, which is the same with the one generators power system model. The local load is 50MW, which is the double of the load in the one generator power system model. The parameters of the other components, such as governor, AVR and PSS are the

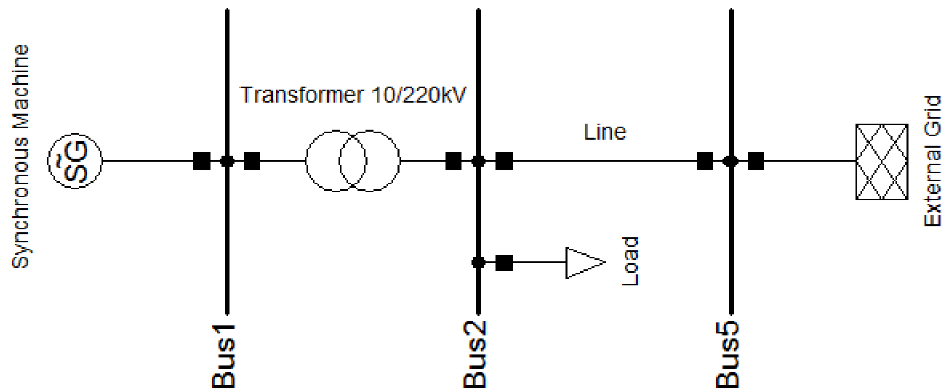


Figure 5.2: Single generator power system model

same with the single generator system model.The line 2 in the figure5.3 disconnect at 1s to form a island situation.

5.2 HPP models in Matlab/Simulink

5.2.1 Simple hydro power plant model

Figure5.5 presents the structure of the model.Simple hydro power plant model consist of a classical turbine linear model and PI controller governor. For the purpose of comparing the response between the HPP model and PowerFactory model, the parameters of these models should be the same.

The reference[3] yields that PI governor controller is equivalent to the mechanical-hydraulic governor model.Therefore, the parameters of the mechanical-hydraulic governor in the PowerFactory model can be implemented in the PI governor controller.

The second-order synchronous model and the classical turbine model are illustrated in chapter4 and chapter 2 are used to built the generator and turbine in this model respectively. Figure5.4 shows the governor subsystem.

In the model we set the electrical power to be constant value in respect to the island operation, and the value of electrical power is based on the powerfactory plot of the electrical torque.

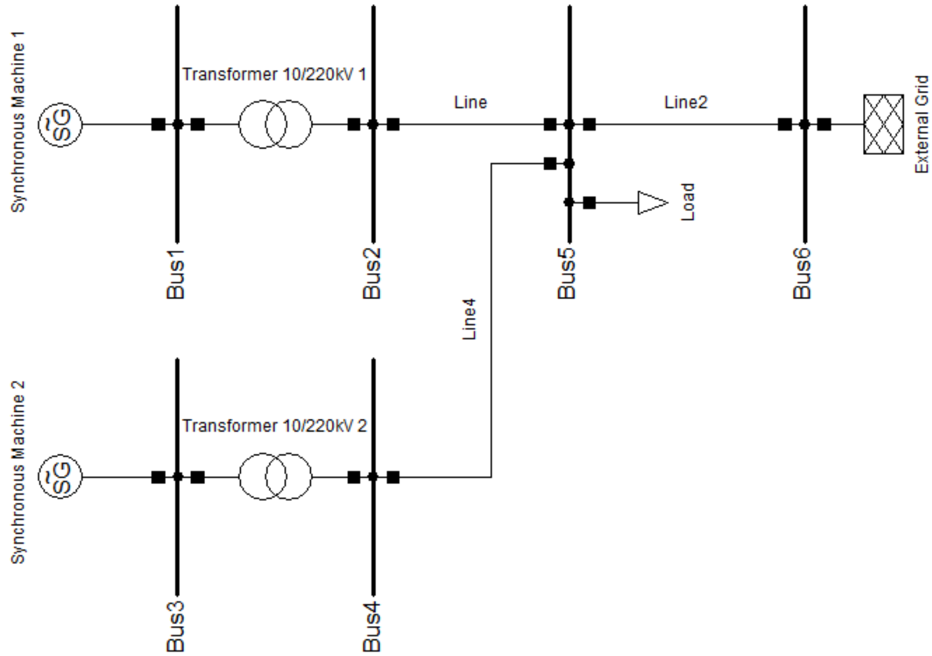


Figure 5.3: Two generators power system model

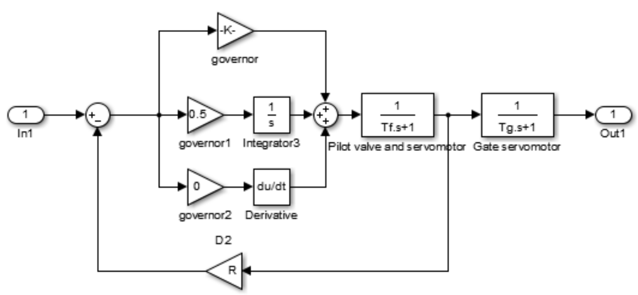


Figure 5.4: PID governor model

It is found that in island operation the electrical power is equal to 0.63. Before disturbance, the electrical torque is 0.375. The system switches to island operation at 200s. The block diagram of generator is shown in figure5.6.

5.2.2 Complex hydro power plant model

In this model, excitation system is included in the hydro power plant.Except excitation system, the rest part of the complex hydro power plant model is the same as the simple hydro power plant model. At 200s, the model switches to island operation, and the electrical power changes

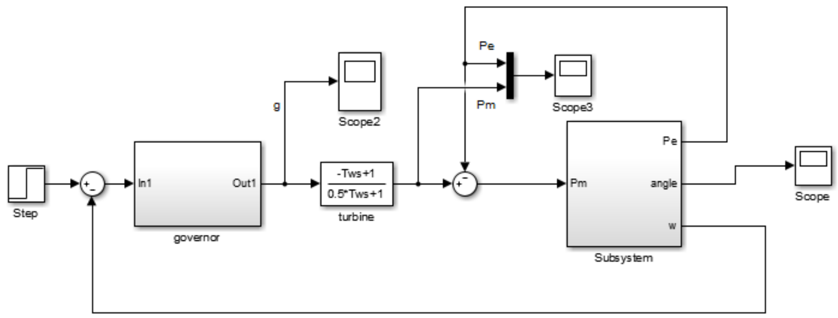


Figure 5.5: Simple hydro power plant model

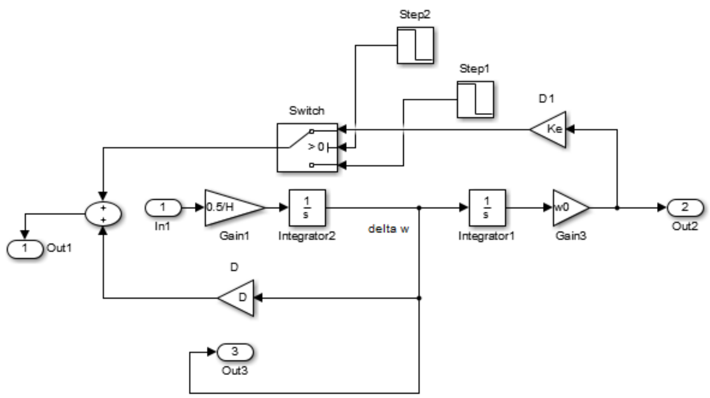


Figure 5.6: Block diagram of generator

from 0.375 to 0.63. The whole system is shown in Figure5.7

The subsystem blocks in the figure5.7 are shown in the following figures. Last but not least, the whole hydro power plant model with complete connection details are presented in the appendix c.

5.3 Validation of the two HPP matlab models

The synchronous machine in the PowerFactory is a sixth order model[11], which is capable of reflecting the precise dynamics of the power system facing the large disturbances, for instance:islanding. Therefore, the single generation model in the PowerFactory can be treated as a reference in the validation of the HPP models. Through comparing the changes of the electrical power and mechanical power between matlab model and PowerFactory model, the validation

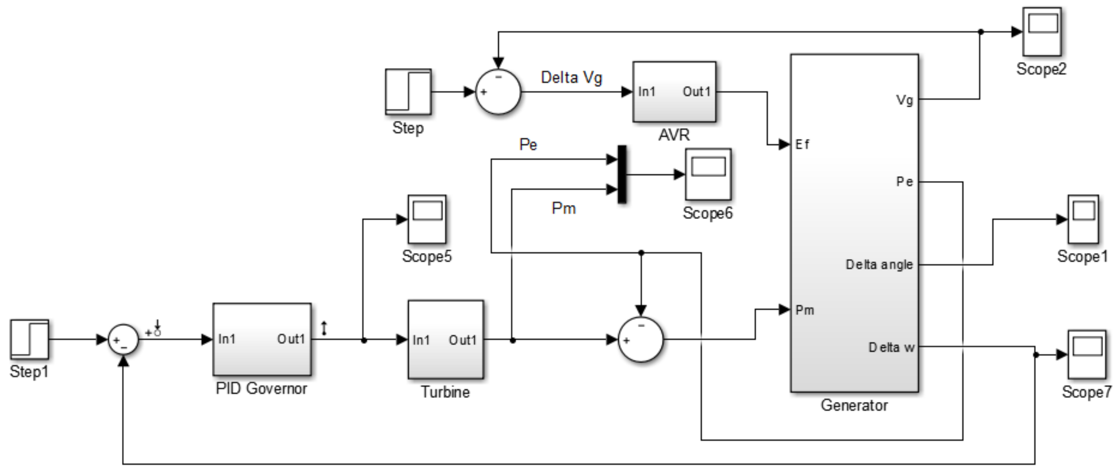


Figure 5.7: Block diagram of complex hydro power plant

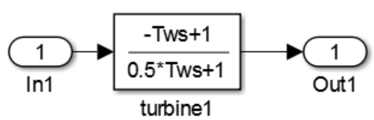


Figure 5.8: Block diagram of turbine

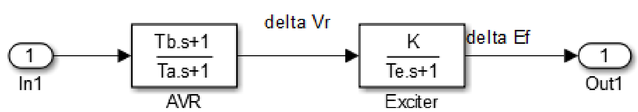


Figure 5.9: Block diagram of AVR

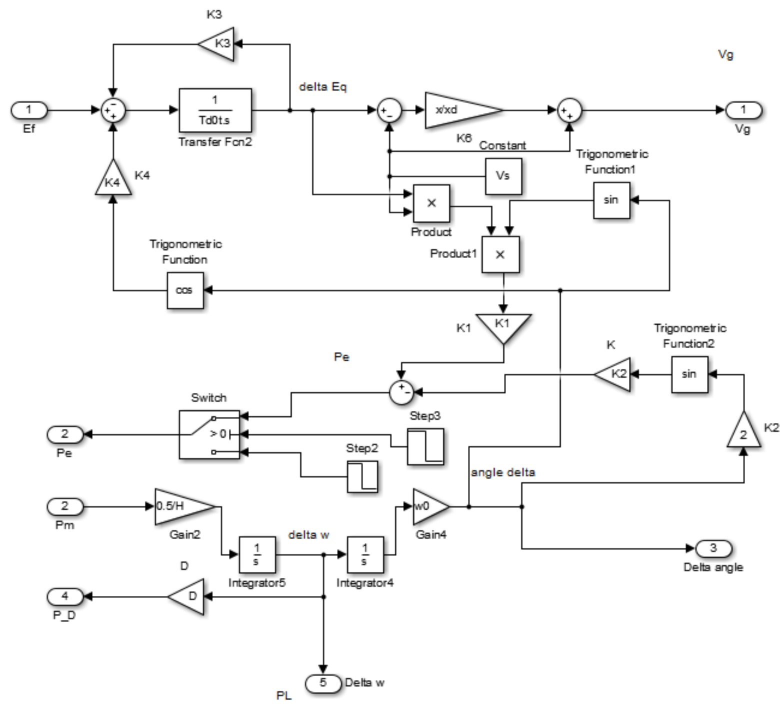


Figure 5.10: Block diagram of generator

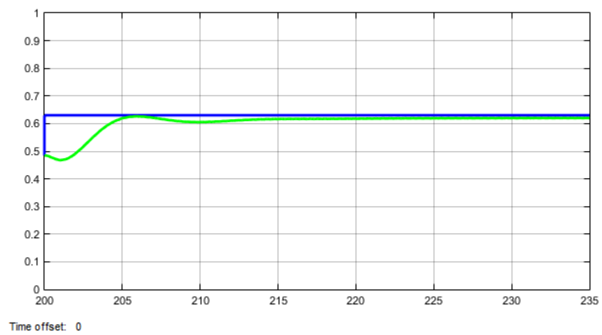
can be accomplished.

Case A: Comparison between simple HPP model and PowerFactory model

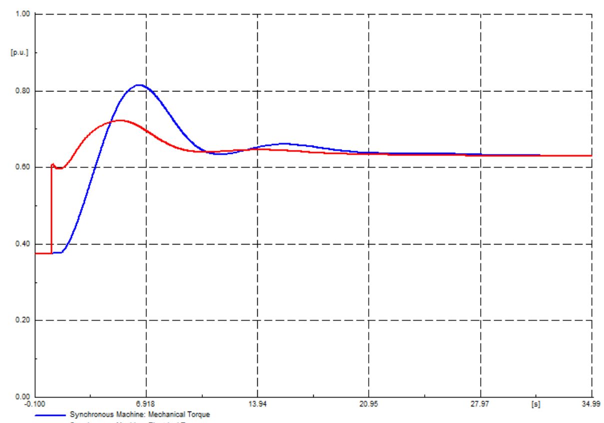
Figure 5.11 shows the electrical power and mechanical power in PowerFactory model and simple HPP model. Clearly, since the changes of the electrical power is manually defined, the electrical power in the figure 5.11(a) is constant during the transient time. On the contrary, the changes of the electrical power in the figure 5.11(b) is a dynamic response.

Further, there are obvious differences regarding the mechanical power. The maximum value of the mechanical power in the simple HPP model is $0.6pu$, however it is $0.8pu$ in the PowerFactory model. Consequently, mechanical power has relatively greater changes in PowerFactory model. In addition, the PowerFactory model takes longer time to turn into stable than the simple HPP model.

Comparing with the results of these two models, it demonstrates that the simple HPP model does not have qualification dealing with the islanding simulations.

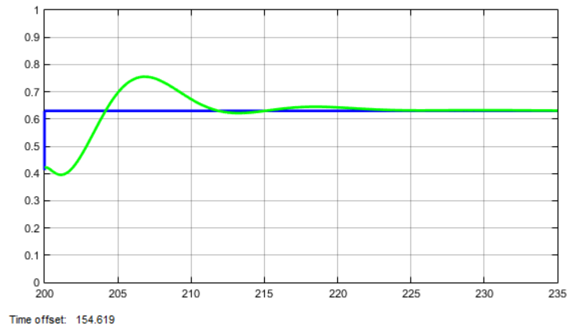


(a) Electric power and mechanical power of the simple generator model

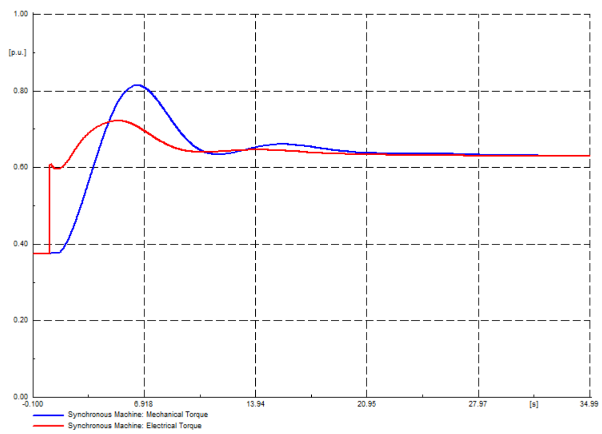


(b) Electrical power and Mechanical power of the power-factory model

Figure 5.11: Electrical power and Mechanical power of the generator in different models



(a) Electric power and Mechanical power of the complex hydro power plant



(b) Electrical power and Mechanical power of the power-factory model

Figure 5.12: Electrical power and Mechanical power of the generator in different models

Case B: Comparison between complex HPP model and PowerFactory model

Figure 5.12 reveals that the maximum mechanical power is approximately $0.75pu$. There is $0.05pu$ difference in comparison with the maximum mechanical power in PowerFactory. Apart from this, the complex HPP model spends around $22s$ returning to the stable situation, which is very close to the time in PowerFactory model.

The findings illustrates that the complex HPP model has much more satisfactory performance than the simple HPP model in island operation simulations. If the system are not required very precise response, the complex HPP model could be utilized.

Chapter 6

Island operation in hydro power plant model

There are basically two types of situation with island operation. One is generation deficit and the other is surplus generation. These two kinds of operations are simulated in the single generator power system and two generators power system. In this section time domain analysis is applied. The dynamic response of the generator variables are presented.

6.1 Single generator power system

The switch on the transmission line operates at $1s$, as a result, the generator and the load become an island area. In this case, assume the stiff network is frequency independent, therefore, there is no influence on the stiff network.

6.1.1 Generation deficit in island

Generation deficit in island means the load is greater than the production power of the generator. In this case, generator produces 15MW power and the load consumes 25 MW power. Before separation, the external grid offers 10MW power to the load. The system splits into two

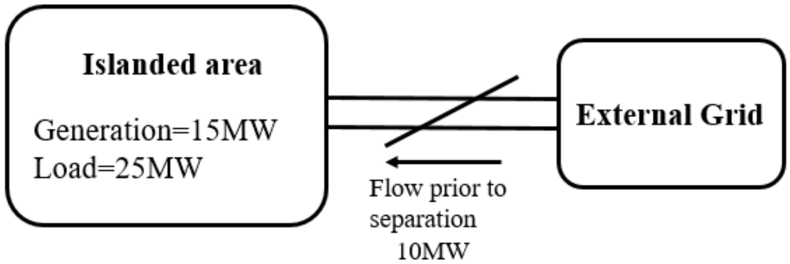


Figure 6.1: Schematic diagram of the under-generated island

independent areas after disconnection, as shown in Figure6.1. As the result, there is only one generation left in the island area. The generator needs to supply the load independently.

From the power flow calculations in the powerfactory, there is 0.1MW loading shedding. The generator produces 24.9MW active power to supply the load. The time domain results are shown in the figure6.2.

The electrical power rises from instantly at 1s and the rotor speed drops immediately after the line disconnection, and reaching its minimum value $0.903pu$ at $0.242s$. As the active power rises after the disturbance, the torque increases therefore the rotor speed decreases correspondingly.

In the plot the speed drops from $1pu$ to 0.903 pu, which indicates that the frequency of the system drops from 50HZ to 45.15HZ. According to the standards, the frequency variations should not exceeds 1Hz during the disturbances. Therefore, the system is not stable when it turns to island operation.

6.1.2 Surplus generation in island

Over-generated island refers to the conditions that generation of the power plant is bigger than the load. In terms of the over-generated island mode, the production power of the local generator is 35MW, and the load remains to be 25MW. Prior to the division, the external grid consumes 10MW.

Figure6.4 presents the responses of the rotor speed, electrical torque and mechanical torque.

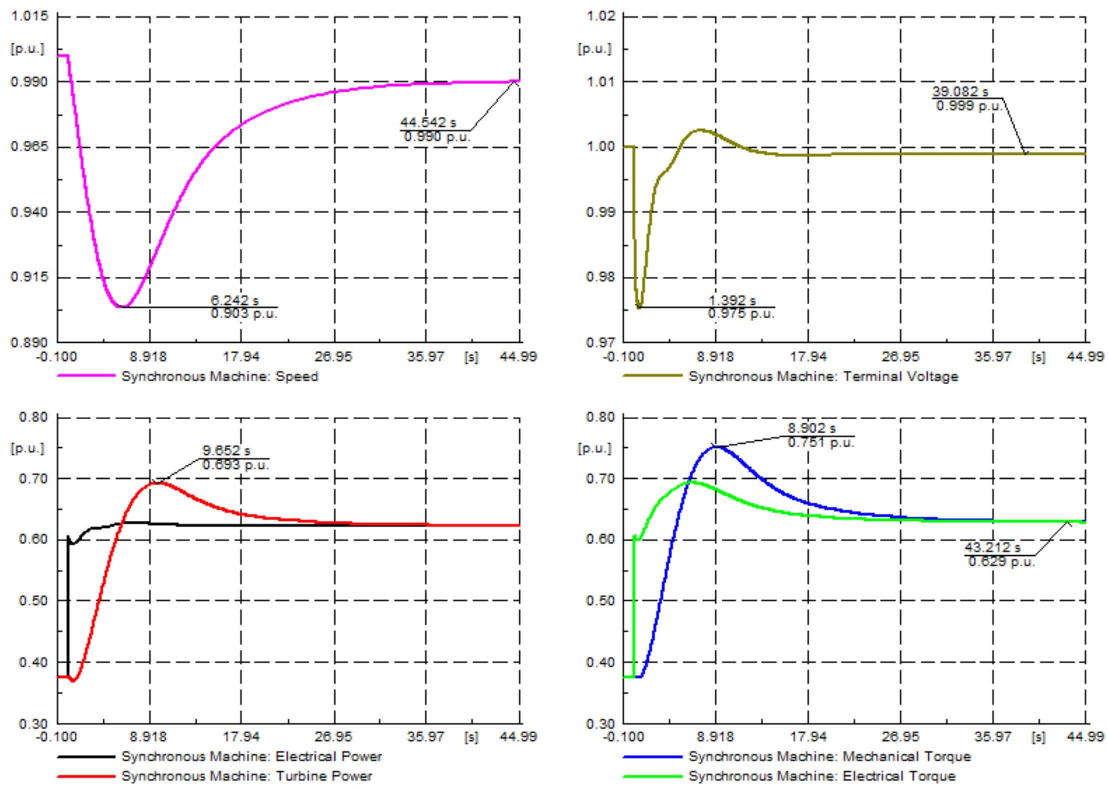


Figure 6.2: Dynamic response of the model in under-generated island operation

As a consequence of islanding,the terminal voltage gets back to the steady state quickly than the speed. The active power decreases rapidly, so the turbine power goes down matching the fluctuation. From the figure, the speed increases by around 9.8%, which implies that the frequency in the system rises from 50Hz to 54.9Hz.

It shows that when generator output power is bigger than the load, there is increment for speed and frequency after island operation. Besides, the island operation causing the instability in the system in this case.

6.2 Two generations power system in island operation

In this section, the load defined as 150MW. Except this, the rest parameters are all the same. The system operates in a island mode at 1s. The reaction of the system is presented in the figure6.5.

Due to the enormous increment of the load demand, which is far above the sum of the rated

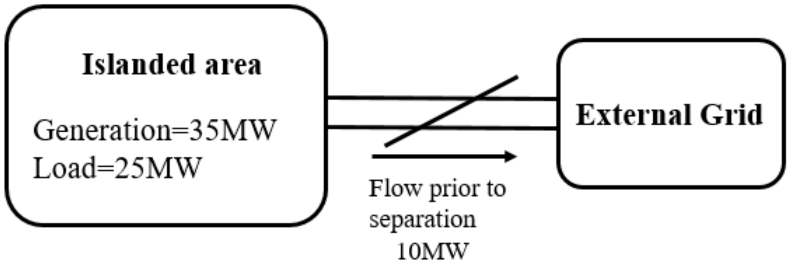


Figure 6.3: Schematic diagram of the over-generated island

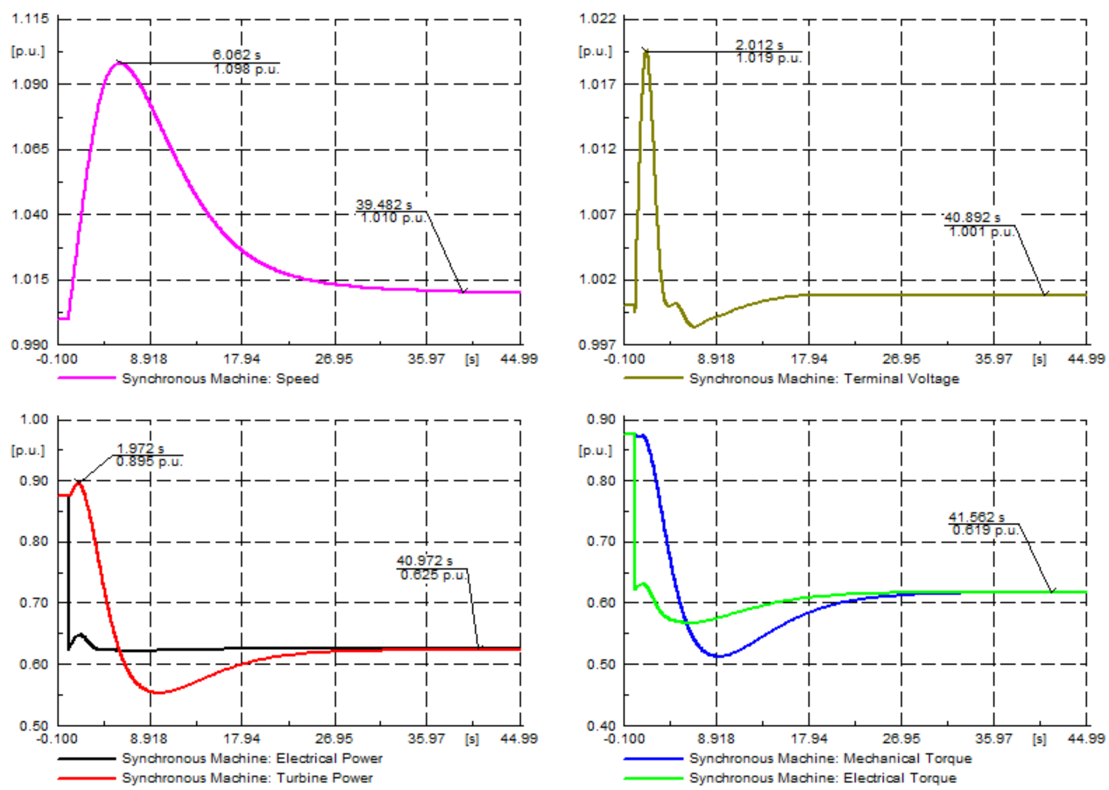


Figure 6.4: Dynamic response of the model in over-generated island operation

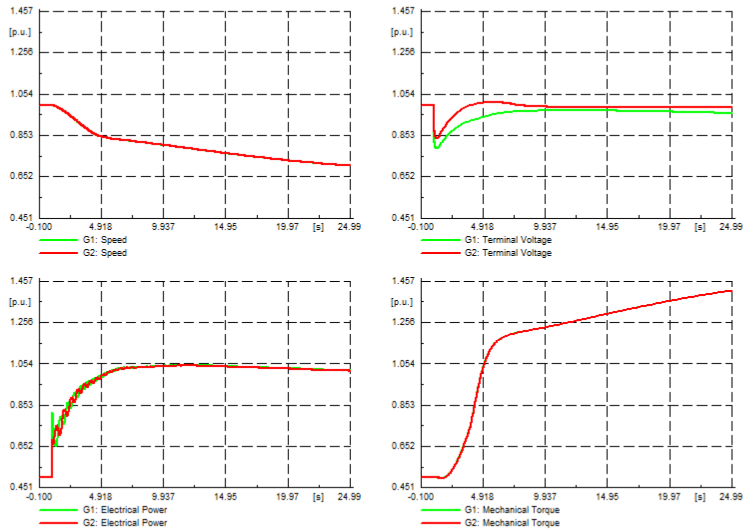


Figure 6.5: Dynamic response of the model in two generators model

power of the two generators. The figure 6.5 shows that the system is crushing down. The speed declines remarkably to $0.67pu$, which is a unacceptable value.

Chapter 7

Governor Analysis in island opeation

As the reference[7] said, in isalnd opeation of hydro power plant, the parameters of the governor plays a critical role in island stability. In order to analysis the dynamic response of the generator in island operation, single generator power system model and two generator power system model are built in powerfactory.

7.1 Governor parameters analysis

As load varies, the stability of the islanded areas depends largely on the control system provided by the governor and on the action of the over frequency and under frequency protection schemes. Therefore understanding the governor settings effects on the island operation is critical.

According to the reference[7], temporary droop, reset time and permanent droop have significant impact on the behavior of the governing control, so we mainly focus on analysing of these three parameters.Moreover, eigenvalue analysis is applied to see the trends of damping. Besides, comparison of speed response are made.

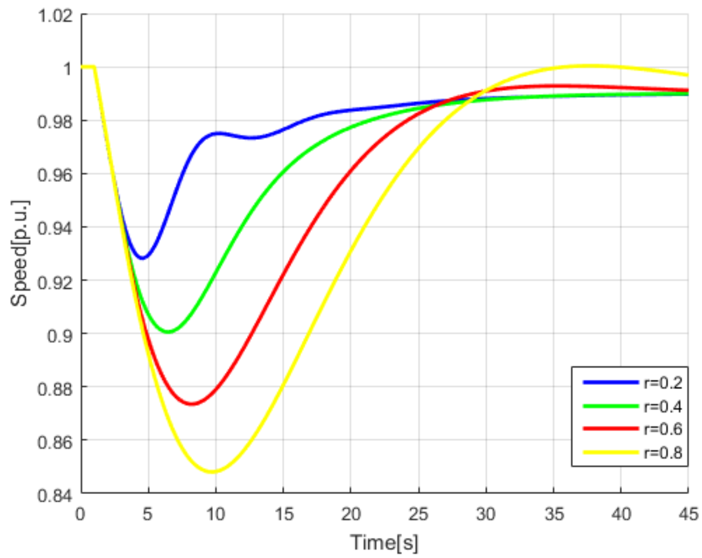


Figure 7.1: Comparison of speed response between different values of temporary droop

7.1.1 Temporary Droop

The values of temporary droop varies from 0.2 to 0.8. Table7.1 illustrates that when increasing the value of temporary droop(from 0.2 to 0.6), the damping ratio of the mode 9 and mode 11 goes up.

However, when temporary droop exceeds 0.6, there is decrement of damping ratio. It represents that increasing temporary droop improves the damping in island operation, but the value should not be higher than 0.6.

Except the eigenvalue comparison, the dynamic response of the speed with different temporary droop r is presented in figure7.1. Comparing with the speed response, there is oscillation reduction from $r = 0.2$ to $r = 0.6$, which proves the inference of the eigenvalues analysis. Further the response time gets longer and the drop of the speed becomes bigger and bigger along with the increment of the temporary droop.

Table 7.1: Results of sensitivity analysis on temporary droop

Temporary Droop	Mode 9		Mode 11	
	Eigenvalues	Damping ratio	Eigenvalues	Damping ratio
0.2	-0.8176±j2.0113	0.3766	-0.2901±j0.6799	0.3925
0.4	-0.8322±j2.0005	0.3841	-0.3611±j0.2156	0.8586
0.6	-0.8366±j1.9963	0.3865	-0.1302±j0.1202	0.7347
0.8	-0.8376±j1.9994	0.3841	-0.0860±j0.1131	0.6054

Table 7.2: Results of sensitivity analysis on reset time

Reset time	Mode 9		Mode 11	
	Eigenvalues	Damping ratio	Eigenvalues	Damping ratio
3	-0.8300±j2.0011	0.383118	-0.0977±j0.3883	0.2441
5	-0.8309±j2.0005	0.383588	-0.1758±j0.3050	0.2994
8	-0.8313±j2.0013	0.383594	-0.3095±j0.2340	0.7977
13	-0.8318±j1.9998	0.384046	-0.4107±j0.2926	0.8145
20	-0.8334±j1.9915	0.386043	-0.4370±j0.3338	0.7964

7.1.2 Reset time

The reset time T_r changes from 3 to 20. The eigenvalues is presented in the table7.2 and dynamic response of the speed is demonstrated in the figure7.2. In terms of the eigenvalues, the damping ratio and damped frequency grows with the increasing of the reset time from 3 to 13. But when reset time grows from 13 to 20, the damping ratio reduces slightly.

From the speed response point of view, there is increment of damping of the speed curves with increasing values of reset time. Besides, the response time becomes longer when the value reset time rises. Last but not least, there is alteration in minimum point of the speed, but the change is not enormous.

It indicates that, in the range of 3-13, the bigger value of reset time will reduce the oscillation. Nonetheless the reset time should not be too large. Otherwise, oscillation will increase and the response time of the speed lengthen causing instability.

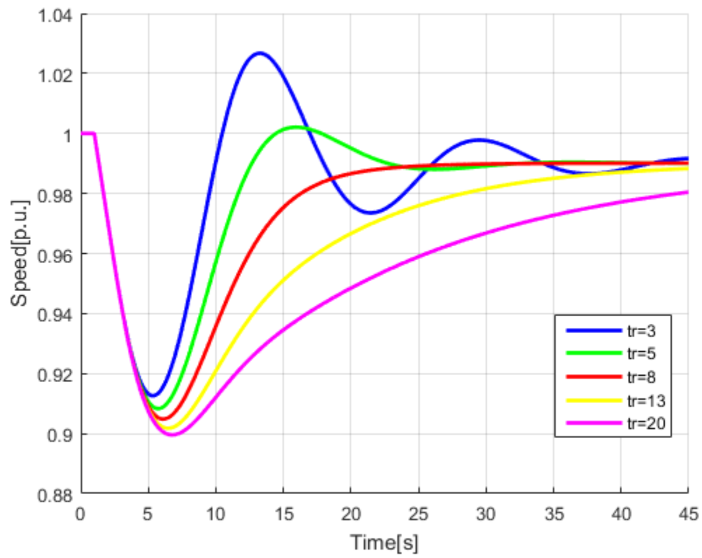


Figure 7.2: Comparison of speed response between different values of reset time

7.1.3 Permanent droop

The permanent droop changes from 0.02 to 0.08. Table7.3 and figure7.3 present the eigenvalues results and rotor speed in response to the permanent droop value variation respectively.

It is found that the damping ratio of mode 9 and mode 11 rise slightly along with the growing value of permanent droop, which shows that the damping is improved a little. In addition, the plot illustrates that the response time increases and minimum transient frequency reduces slightly when permanent droop raises. Besides, the steady state speed value decreases enormously.

According to the findings, permanent droop does have positive effect on the damping improvement, however the impact is not as significant as reset time. Furthermore, it has relatively great influence on the frequency value in the steady state. [1]

[1] In this case, the steady state means system becomes stable again after the disturbance

Table 7.3: Results of sensitivity analysis on permanent droop

Permanent droop	Mode 9		Mode 11	
	Eigenvalues	Damping ratio	Eigenvalues	Damping ratio
0.02	-0.8293±j2.0072	0.3819	-0.3733±j0.2967	0.7829
0.05	-0.8324±j1.9983	0.3845	-0.3723±j0.2431	0.8374
0.08	-0.8354±j1.9893	0.3872	-0.3648±j0.1940	0.8830

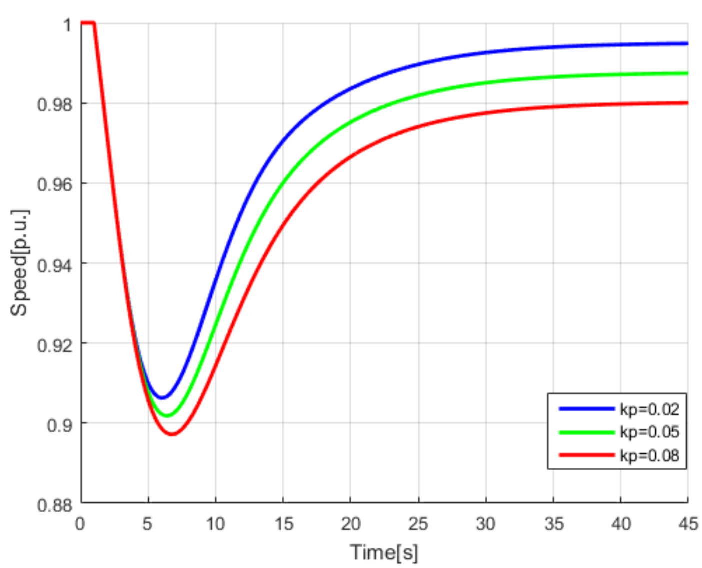


Figure 7.3: Comparison of speed response between different values of permanent droop

Table 7.4: The old and new settings of the governor

Parameters	Old values	New values
Temporary droop	0.38	0.2588
Reset time	10	8.233
Permanent droop	0.04	0.01

7.2 Optimal setting of the governor

As shown in the previous simulation, the default parameters of governor does not have good performance in island operation. The system is unstable when it turns into island mode. Therefore, tuning of the governor settings is a critical work in order to make the system stable in the island operation. Except that, the objective of tuning governor is to ensure the system have quicker response as well.

The default governor parameters are shown in table7.4. Based on the analysis of the parameters of governor in island situation, there are three principle guiding the tuning.

First, the temporary droop should not be big as the large value of temporary droop will enlarge the transient frequency. Second, the reset time have good performance in the ranges of 8 to 13. Third, the permanent droop should be as small as possible on the premise of the stable of the power system.

According to the three tuning principle, by the means of trial and error, a new settings of governor is concluded. Table7.4 shows the old and new parameters of the governor. In addition, the comparison of the performance between the new settings and old settings is presented in the figure7.4.

It can be clearly seen that the speed response of new setting has better performance than the old setting's. the minumm value of speed of the new setting is $0.97pu$ in undergenerated island, and the minmum value of the old setting is around 0.9. Response time of new setting is shorter than the olding setting's. Last but not least, the steady state speed value of new setting is close to $1pu$.

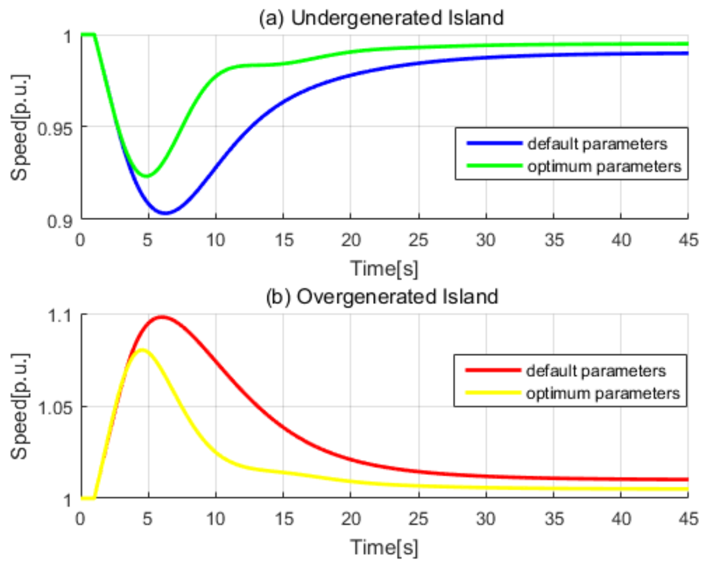


Figure 7.4: Comparison of speed response between different values of permanent droop

7.3 Governor characteristic analysis

governor characteristic analysis in single generation system

The figure7.4 shows that even though the new settings improves the performance of the generator, the system is still unstable. This is because there is working range of the governor. If the difference between the load power and output power of the generator is big, the governor can not help to make the system stable as it beyonds the working range of the governor. Therefore, the governor characteristic should be analysed in island operation. In this section, the transient state and steady state are studied.

Transient state analysis

The turbine is regulated by the $HY - Gov$ in the one generator system. Through changing the output power of the generator, the power-frequency characteristic can be obtained. The output power ranges from 0MW to 40MW (the maximum output power according to the generator's settings).

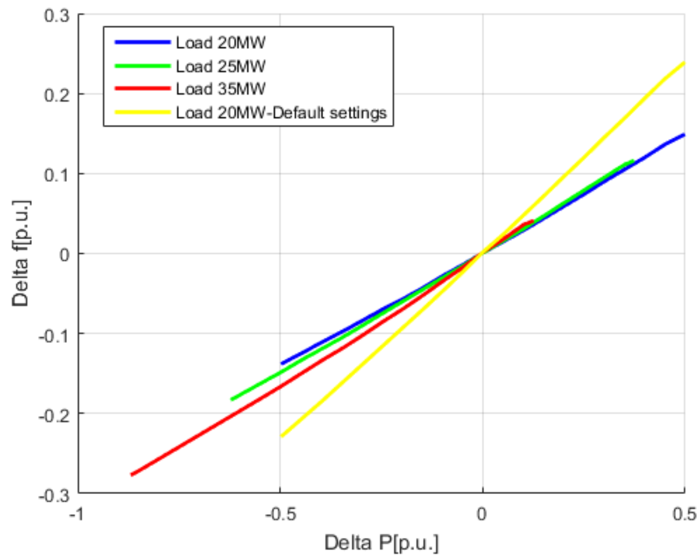


Figure 7.5: Governor characteristic in transient state

Figure7.5 shows the Power-frequency characteristic for different load and different governor settings. Moreover, the slope of the curves in the plot are different according to the different load. In the same governor settings condition, the bigger the load, the bigger the slope. It shows the load has impact on the governor performance. on the other hand, the slope of the load20MW with default governor settings is the biggest among the curves, which indicates that the parameters of the governor has more influence than the load on the power-frequency characteristic.

Steady state analysis

Except the transient state analysis, the steady state is analyzed as well. In this case, the steady state means the system recover to the stable situation in the island operation. By changing the output power of the generator, the function of the delta power and delta f is obtained, which is shown in figure7.6.

The slope of the load 20MW, Load 25MW, and load 35MW are all the same. The slope of the load20MW with the default governor settings is approximately 4%, and the slope of the The other three load are around 1%. Those value of the slope is the same as permanent droop in the

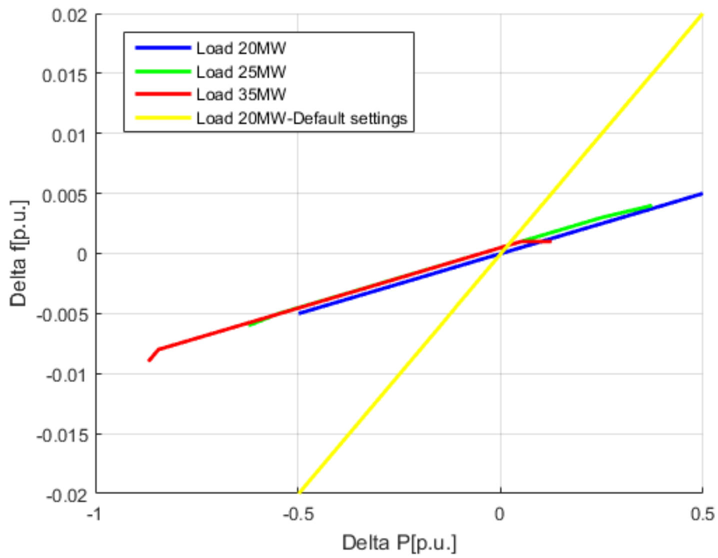


Figure 7.6: Governor characteristic in steady state

governor settings. Therefore, the permanent droop is the slope of the function of delta p and delta f in this case. Permanent droop has critical impact on the steady state frequency in the island operation.

governor characteristic analysis in two generation system

In the two generators power system, the governor settings of the two generators are the same. Applying the same method as in the one generators system, the power-frequency characteristic is acquired.

Figure7.7 shows the power-frequency characteristic of the load 20MW for one generators and Load 40MW for two generators. The output power of the two generators are the same. So each generator produces 20MW active power. The plot shows the power-characteristic are the same and the performance of the generator in the two generator system is linear. Therefore, the power-frequency characteristic has no difference between one generators and two generator power system, when the output power is the same between generators.

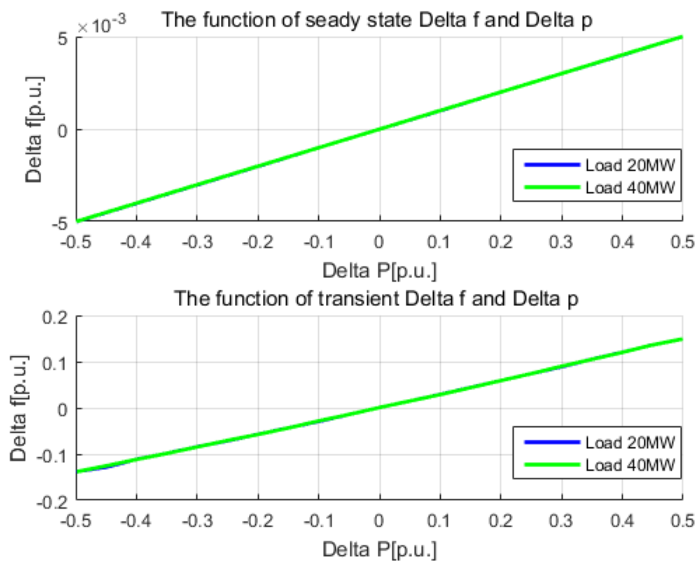


Figure 7.7: Governor characteristic in two generators model

Chapter 8

Power system stabilizers analysis in island operation

In this section, the power system stabilizer will firstly be studied in the grid-connected operation concerning the validation of the positive effect of PSS in terms of disturbances. After the validation, the PSS will be studied in the island operation to see if the PSS has positive effect on the stability of power system after island operation.

Linear analysis and time domain analysis are both used to investigate the effect of PSS. Through comparison of dynamic response of the generator state variables and damping ratio changes of electromechanical mode, the effect of PSS can be induced.

8.1 Power system stabilizer effect on one generator system

In normal operation, which means the system connect with the main grid, three phase symmetrical short circuit event is defined on bus 2 at 50s, and the fault is cleared at 50.05s.

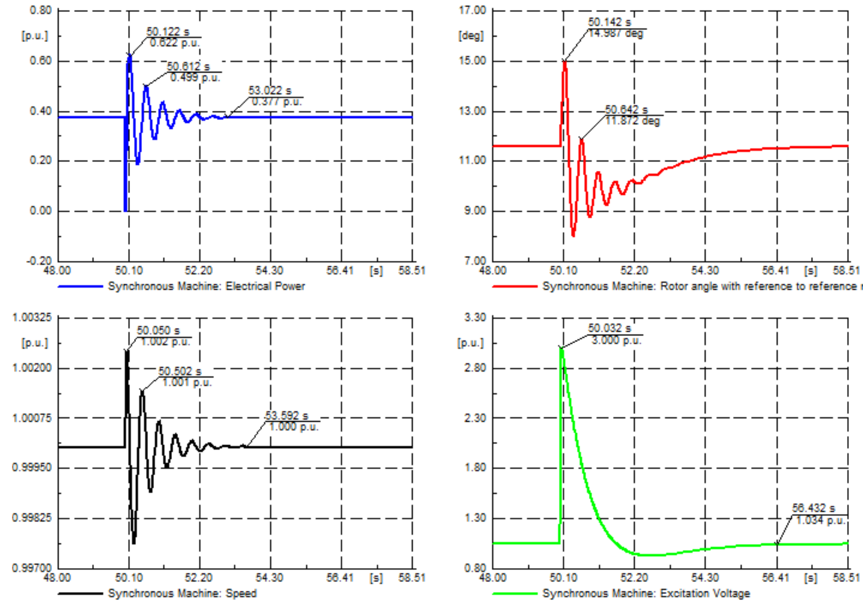


Figure 8.1: Dynamic response of case 1

Table 8.1: Eigenvalues in response to the short circuit in normal operation

Mode	Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
Mode 07	-1.67302	±12.31527	1.960037	0.134613
Mode14	-0.35052	±0.216328	0.03443	0.850979

8.1.1 Case 1: Single power system in grid-connected operation without PSS

First, the generator doesn't equipped with PSS. The response of the speed and electrical power are shown in the following plot. From the figure8.1, it can be seen that electrical power decreases sharply to 0 pu, whereas the rotor speed goes back to the initial value after clearing the fault.

There are two pairs of complex conjugate eigenvalues, as shown in table8.1. As the 0.2-2Hz is the electro-mechanical mode, the mode 06 is a critical mode. Its damped frequency is 1.960037 Hz, which corresponds the frequency of the oscillations.

Electrical power, rotor angle, speed and excitation voltage are illustrated in the figure8.1. It can be seen that the electrcial power goes down vertically when the fault occurs and it starts to oscillate, then it reaches stable at 53.022s. Unlike electrical power, speed, rotor angle, and excitation voltage rises after disturbance. Speed goes back to stable at 53.592s after oscillations.

From the Table in the appendix C, it shows that Synchronous Machine phi is the main element to determines the mode 06, as observability magnitude and participation magnitude for mode 7 are both 1. In the same way, SEXS:xb mainly determines the mode 14. Therefore it can be induced that mode06 is related with the rotor angle.

8.1.2 Case 2:Power system in grid-connected operation with default parameters PSS

In this case the power system stabilizers was applied to the generator, a three phase short circuit fault,which is as the same as the no pss condition, applied on the bus 2. Figure8.2 illustrates the electrical power and rotor speed response, and the eigenvalues are shown in the table8.2.

From the figure and the table, it shows that the damped frequency of the electro-mechanical mode has increased to 1.962626Hz, and the damping ratio decreases slightly to 0.134049, which means the stability of the system is slightly improved.

From the table in the appendix we can see that mode 8 observability factor pss2A :x8 participation factor is SEXS:xb. mode 20 observability factor SEXS:xe, participation factor SEXS:xb, mode 11 observability factor pss2A:x8, participation factor pss2A:x9,pss2A:x10,pss2A:x11. Mode 13 observability factor pss2A:x8, participation factor HYGOV:xf, Mode25 observability factor SEXS:xe, participation factor: PSS2A:xm.

From those eigenvalues we can see that the damping ratio of mode 20, mode 11, mode 13 and mode25 are nearly close to 1, which means those mode are fairly stable. However, mode 08 has damping ratio of 0.134049. Comparing with its damping ratio in no pss situation, the damping ratio of mode 8 decreases. It is not good for the stability of the power system.

When the power system stabilizer is applied into the generator control system, the damping ratio of mode 8 becomes smaller, which indicates that the behavior of the system turns into bad side. The parameters of the power system stabilizer determine the response of the power system stabilizers in a large degree[15], Therefore the parameters of the power system stabilizer should be tuned.

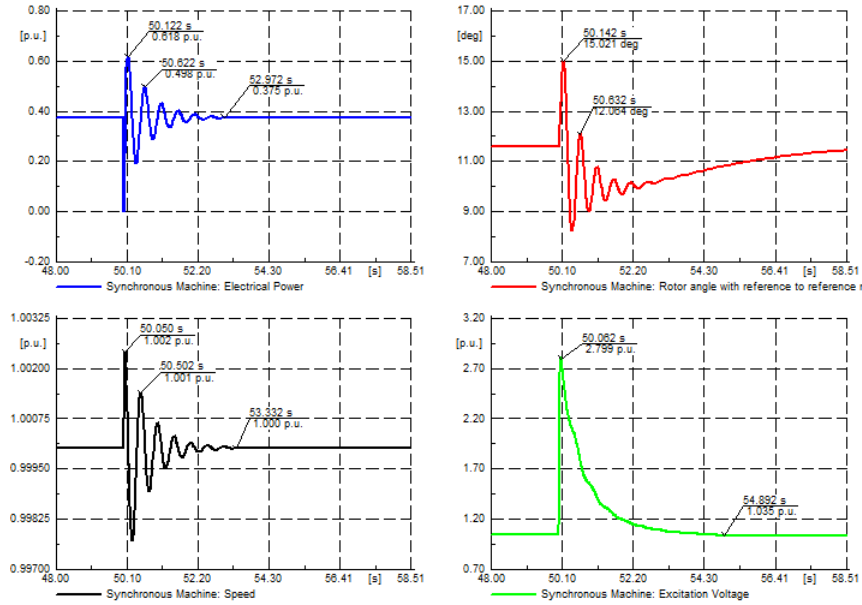


Figure 8.2: Dynamic response in case 2

Table 8.2: Eigenvalues in response to the short circuit in normal operation with PSS

Mode	Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
Mode 08	-1.66808	±12.33154	1.962626	0.134049
Mode 20	-0.35082	±0.21745	0.261846	0.0849969
Mode 11	11.5115	± 1.645227	0.261846	0.989941
Mode 13	-9.06197	±1.35272	0.164769	0.993537
Mode 25	-0.6793	±0.063738	0.010144	0.995627

Table 8.3: Eigenvalues changes due to change of T_b

T_b	T_a	Mode 7			
		Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
10	2	-1.67302	12.31527	1.960037	0.1346127
8	2	-1.673072	12.31521	1.960027	0.1346175
6	2	-1.673158	12.3151	1.960009	0.1346255
4	2	-1.67333	12.31489	1.959975	0.1346414
2	2	-1.673836	12.31422	1.959868	0.1346885
T_b	T_a	Mode 14			
		Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
10	2	-0.402997	0.2445949	0.03892849	0.8548645
8	2	-0.402997	0.2445949	0.03892849	0.8548645
6	2	-0.5075037	0.2677551	0.04261455	0.8844524
4	2	-0.9973919	0.4666785	0.07427419	0.905755
2	2	-1.178945	1.269209	0.2020009	0.6805732

Tuning parameters of excitation system

Since the default parameters of the power system stabilizer doesn't give a good performance during the disturbances, the parameters of the power system stabilizer should be tuned.

As the parameters of automatic voltage regulator is a default value in the powerfactory. In order to make system behaviour better during the disturbances, the parameters of the AVR are firstly tuned. The T_b and T_a are the T_b changes from 10 to 2, T_a remains to be the same.

From the table8.3, we can see that when decreases the value of T_b from 10 to 4, the damping ratio of mode 7 and mode 14 rise. Specifically, mode 14 increases more obviously. This is because the participation factor of mode 14 is SEXS:xs. However, when it continuously decreases to 2, the damping ration of mode 14 goes down significantly. Therefore, $T_b = 4$ has the best performance among those options.

As we determine the value of T_b, we need to investigate the effect of T_a as well. Table8.4 presents the eigenvalues changes in response to the changes of T_a. The value of T_a ranges from 1 to 3, and T_b remains to be 4. It can be seen that when Ta is 2, the overall response of the system is the best. Therefore, parameters of automatic voltage regulator can be redefined as $T_a = 2$ and

Table 8.4: Eigenvalues changes due to change of T_a

		Mode 7			
T_b	T_a	Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
4	1	-1.673081	12.31522	1.960028	0.1346181
4	2	-1.67333	12.31489	1.959975	0.1346414
4	3	-1.673582	12.31455	1.959922	0.1346649
		Mode 14			
T_b	T_a	Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
4	1	-0.4038412	0.501087	0.07975047	0.6275064
4	2	-0.9973919	0.4666785	0.07427419	0.905755
4	3	-1.139505	0.9814248	0.1561986	0.7577083

Table 8.5: Default parameters of PSS

K_{s1} PSS gain[pu]	4
T_{s1} 1st Lead-lag Derivative Time Constant [s]	0.18
T_{s2} 1st Lead-lag Delay Time Constant [s]	0.02
T_{s3} 2nd Lead-lag Derivative Time Constant [s]	2
T_{s4} 2nd Lead-lag Delay Time Constant [s]	5

$T_b = 4$.

Since the parameters of the automatic voltage regulator are determined, the parameters of power system stabilizer can be tuned. As the filters of the power system stabilizers are aim to filter the harmonics, they don't have much influence on the behavior of the power system stabilizers. PSS gain K_{s1}, 1st lead-lag derivative time constant T_{s1}, 1st lead-lag delay time constant T_{s2}, 2nd lead-lag derivative time constant T_{s3}, and 2nd lead-lag delay time constant T_{s4} are important value to be tuned. The default value of K_{s1}, T_{s1}, T_{s2},T_{s3},and T_{s4} are shown in the table8.5

Figure8.3 shows bode diagram of the default settings of the parameter. It shows that the maximum phase is around 55deg, which is in the first phasor. It didn't add damping to the rotor speed. Further, we can see that the curve is not symmetrical, the left side of phase curve should be moved toward to the right direction.

T_{s1}, T_{s2},T_{s3},and T_{s4} are critical values to determine the shape of the phase curve. Therefore, we need to tune the these parameter to make the phase in the second phasor, which can add

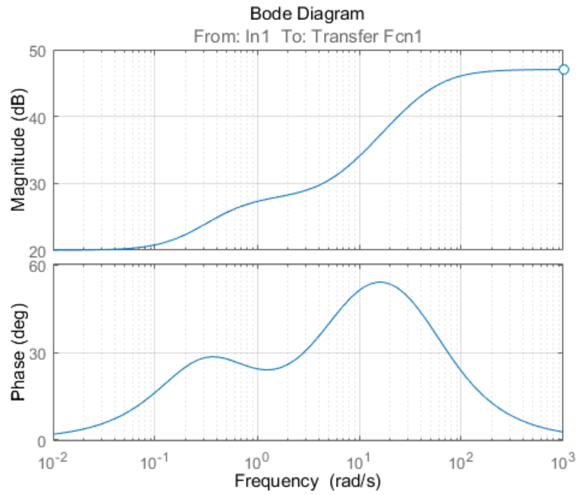


Figure 8.3: Bode diagram of the default value

Table 8.6: Tuning parameters of PSS

K_{s1}	T_{s1}	T_{s2}	T_{s3}	T_{s4}	Mode 9 Damping ratio	Mode 21 Damping ratio
3	0.2	0.02	0.2	0.01	0.1520071	0.8551003
3	0.2	0.02	0.3	0.01	0.16302462	0.8575531
3	0.2	0.02	0.4	0.01	0.1741089	0.8596493
3	0.2	0.01	0.4	0.01	0.1779428	0.8599231
3	0.2	0.03	0.4	0.01	0.1691912	0.8593754
3	0.33	0.01	0.4	0.01	0.2115257	0.8240683
4	0.33	0.01	0.4	0.01	0.23774	0.7788467
5	0.33	0.01	0.4	0.01	0.0.2627252	0.7347924

more damping on the rotor speed. On the other hand, the value of T_{s4} and T_{s3} should be less than 1 so that the phase curve can be symmetric.

Based on the analysis of the default parameter bode plot, various values of T_{s1}, T_{s2},T_{s3},and T_{s4} are chosen to test the response of the power system. These variables are presented in the table8.6.

From the table8.6, it can be seen that when K_{s1}=3, T_{s1}=0.33, T_{s2}=0.01,T_{s3}=0.4,and T_{s4}=0.01 has the best performance among these parameters, as the damping ratio of mode 09 reaches around 0.2 and damping ratio of mode 21 is still 0.824.

The bode diagram of new parameters are shown in the figure8.4. It shows that at frequency

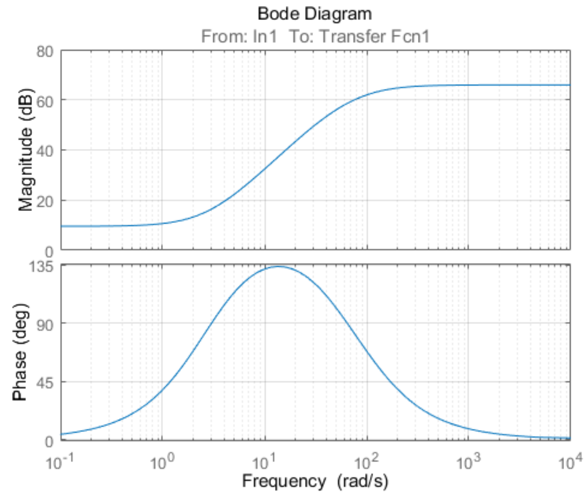


Figure 8.4: Bode diagram of new parameters

Table 8.7: Eigenvalues in response to the short circuit in different cases

Case	Mode	Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
case 4	Mode 09	-0.8194	2.0163	0.320903	0.376488
	Mode 11	-0.29551	58256	0.092717	0.452388
case 5	Mode 16	-0.33699	1.95229	0.30717	0.170097
	Mode 21	-0.12864	0.399446	0.063574	0.306551
case 6	Mode 15	-0.83757	1.801666	0.286744	0.421557
	Mode 20	-0.26991	0.370883	0.059028	0.588421

12.3 rad/s, it has the maximum phase shift, which can add damping to the system.

8.1.3 Case 3: Power system in grid-connected operation with new parameters PSS

From the figure8.5, it can be seen that the electrical power reaches stable at 52.302s, and speed reaches stable at 52.992s. Those are faster settled than without pss. The damping ratio of the case 3 is much bigger than case 1 and case 2. It illustrates that the new parameters PSS improve the damping of the system.

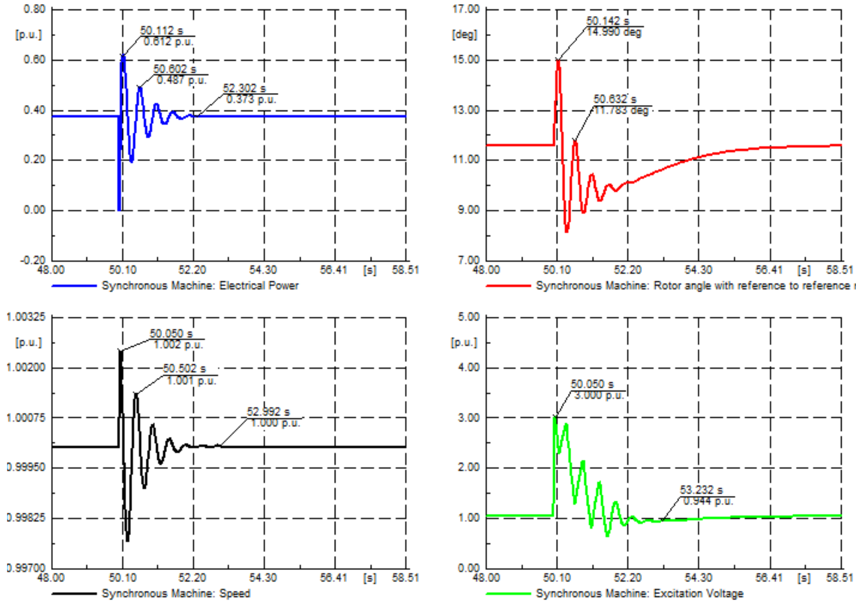


Figure 8.5: Dynamic response in case 3

8.1.4 Case 4: Power system in island operation without PSS

As the power system stabilizer function is validated in the section 7.1.1, so that power system stabilizers effect in island operation can be explored.

Firstly, when there is no power system stabilizer in the generator control system, the reaction of electrical power and rotor speed in response to the three phase short circuit are studied. figure8.6 illustrates the changes of electrical power and rotor speed, which are greatly different with the grid-connected case. The rotor speed falls down to 0.991 pu in island case, however, it decreases to 0.998 pu in grid-connected case, which various much bigger than the grid-connected case. It also indicates that the system is weaker than the grid-connected mode. Further, the rotor angle is zero in this case, it is because that the generator and the load disconnect from the main grid, the rotor angle becomes the reference.

8.1.5 Case 5: Power system in island operation with new parameters PSS

In case 5, the parameters of power system stabilizers are default value. After island operation, the system meets the three phase fault disturbance. The response of the system are shown in

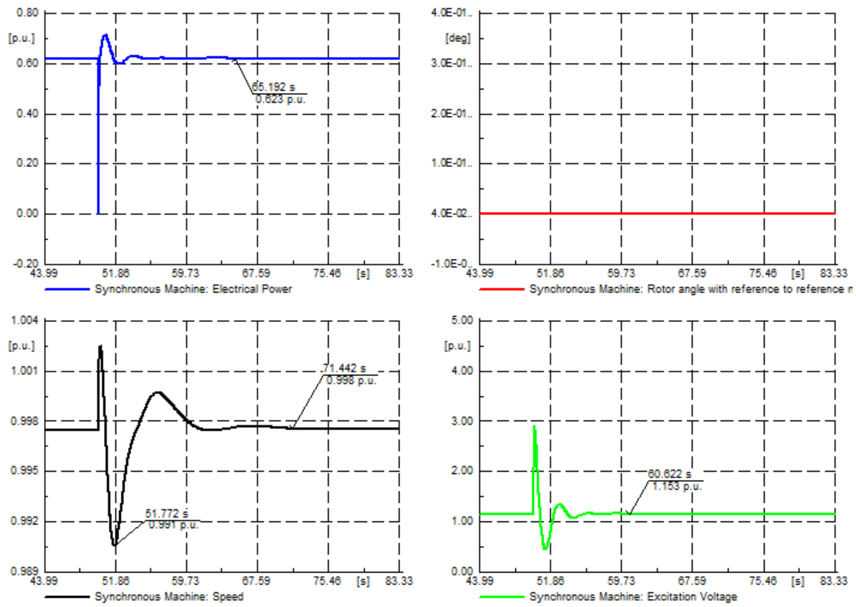


Figure 8.6: Results of the dynamic response

the figure8.7. From the table8.7, we can see that the damping ratio in case 4 is improved, which indicate that the old parameter PSS has positive effect in case 5.

8.1.6 Case 6: Power system in island operation with old parameter PSS

When the generator with new parameter PSS faces the island operation, the figure8.8 shows the response. It shows that the speed and electrical power are in very bad response, which are more serious than case 5. Consequently, the new parameters of PSS is not suitable in island operation. In addition, the eigenvalue is shown in the table8.7, it shows that the damping ratio of the case 6

8.2 Power system stabilizer effect on two generators system

8.2.1 Case 7: Two power system in grid-connected operation without PSS

As the same with one generator system cases, a three phase symmetrical short circuit event is made at bus 5.

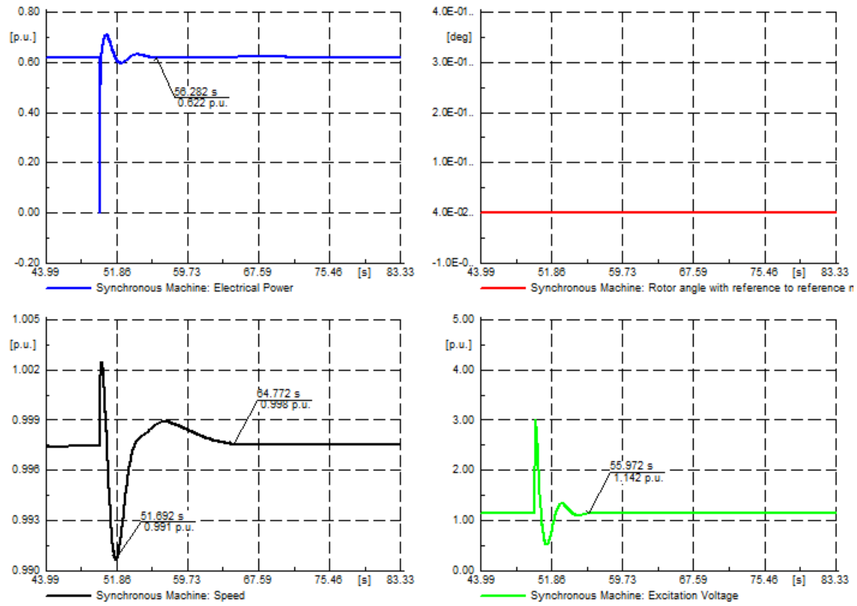


Figure 8.7: Results of the dynamic response in case 5

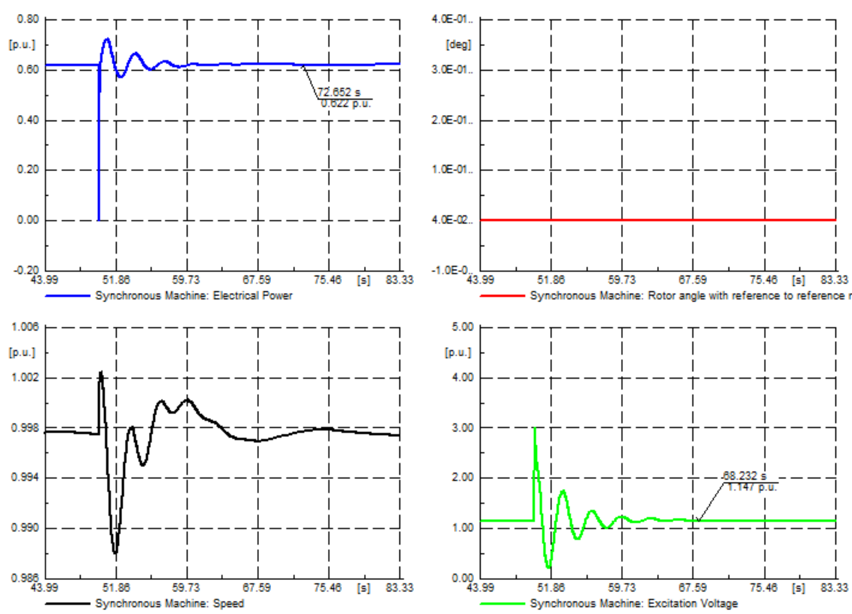


Figure 8.8: Results of the dynamic response in case 6

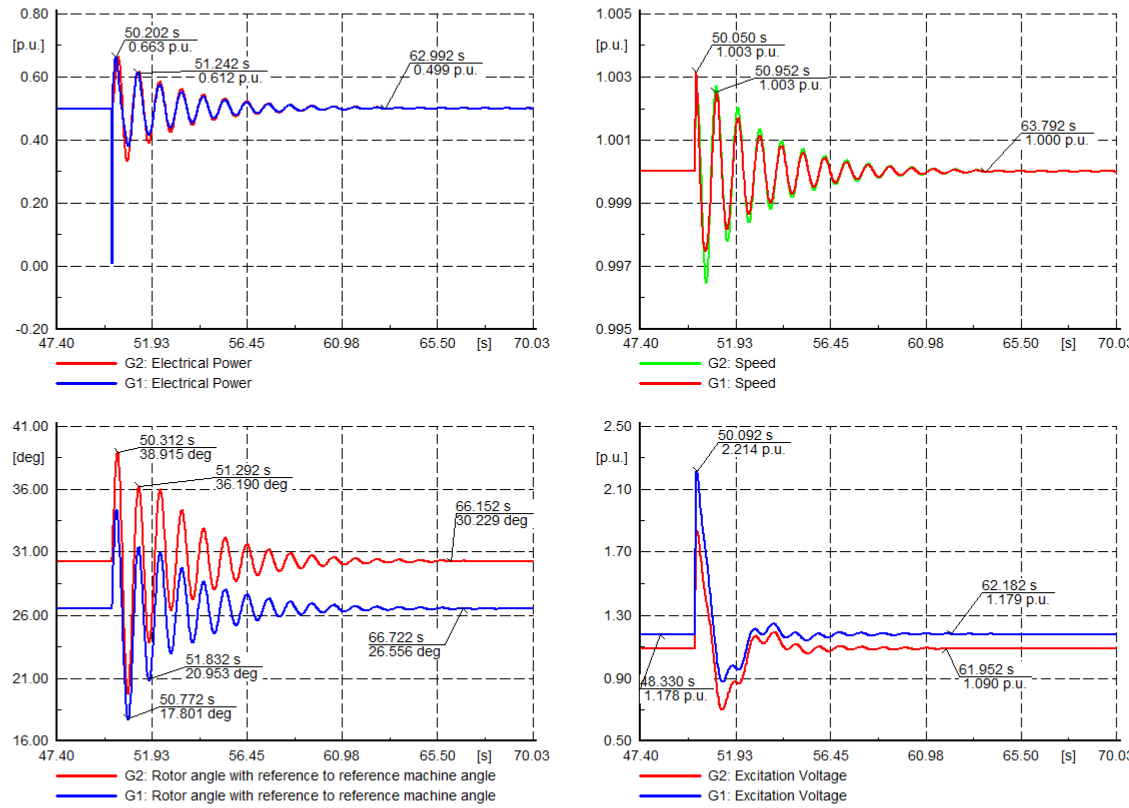


Figure 8.9: Results of the dynamic response in case 7

Figure8.9 shows the electrical power and rotor speed in response to the disturbances in without PSS case. It can be seen that the electrical power and the rotor speed of the two generators oscillates in the same direction, and comparing it with one generation system, the oscillations lasts longer. Electrical power and rotor speed restored to stable at approximately 63.14s.Besides, table8.8 presents the result of the eigenvalues analysis in without pss case.

There are two pairs of electromechanical mode in this case, as shown in the table8.8. The damping ratio of mode 06 and mode 15 are much lower than grid-connected situation.

8.2.2 Case 8: Two power system in grid-connected operation with new parameters PSS

Figure8.10 presents the electrical power and rotor speed in with pss case. It shows that electrical power and rotor speed get back to normal value at around 63s, which is slightly shorter than

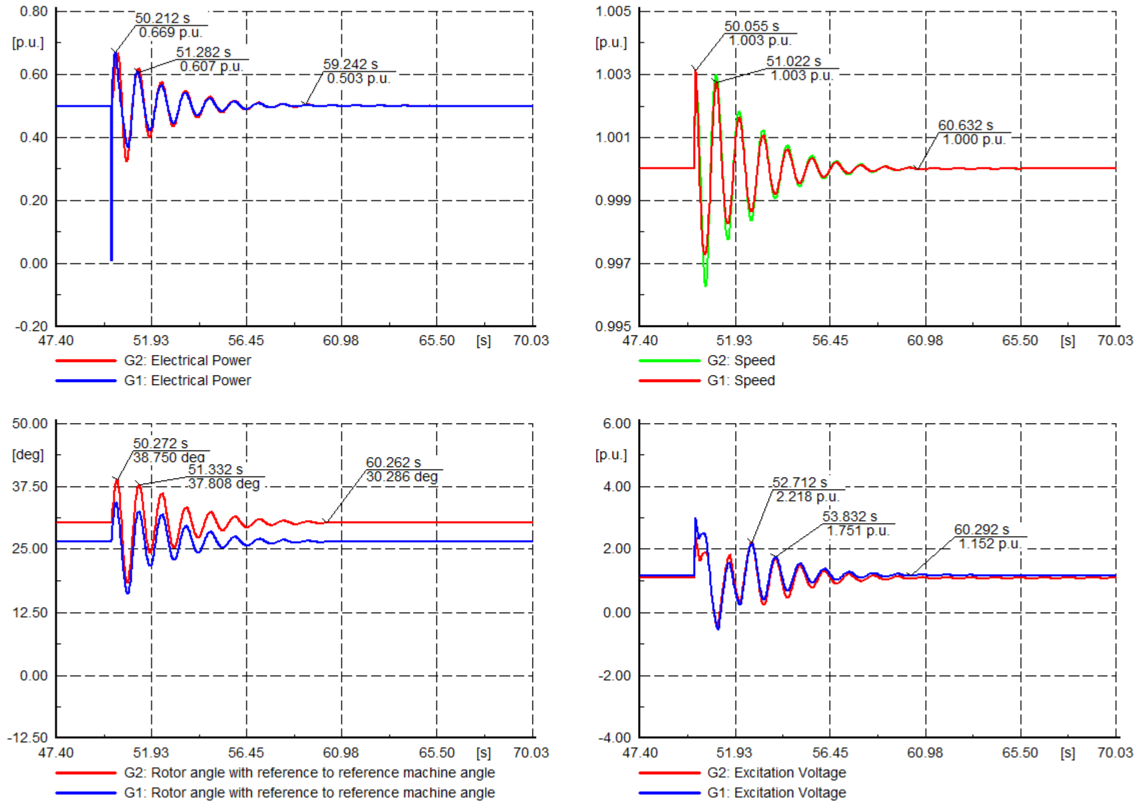


Figure 8.10: Results of the dynamic response in case 8

in the without pss case. The eigenvalue results in with pss case are shown in the table8.8. By comparing the eigenvalues in table8.8, it shows that the damping ratio of all the three mode rise. The damped frequency of mode 12, and mode 20 are decreases. The damped frequency of mode 6 increases.

It indicates that the power system stabilizer can be used in the grid-connected operation, and it has positive effects on the power system when the system comes to the disturbances.

8.2.3 Case 9: Two power system in island operation without PSS

In case 9 the power system firstly meet the island operation, after island operation, a three phase short circuit fault defined at 50s, and the fault is cleared at 50.05s. The eigenvalues results are shown in the table8.9

The figure8.11shows the dynamic response in this case. As the G1 is the reference of the

Table 8.8: Eigenvalues in response to the short circuit in different cases

Case	Mode	Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
case 7	Mode 12	-0.3013996	6.066792	0.96556	0.04961902
	Mode 6	-1.377937	11.42846	1.818896	0.1197037
	Mode 14	-0.8496491	2.312998	0.368125	0.344809
case 8	Mode 22	-0.4368153	5.437607	0.865422	0.08007431
	Mode 16	-2.563664	11.49333	1.82922	0.2177066
	Mode 28	-0.9425134	2.250817	0.3582287	0.3862465

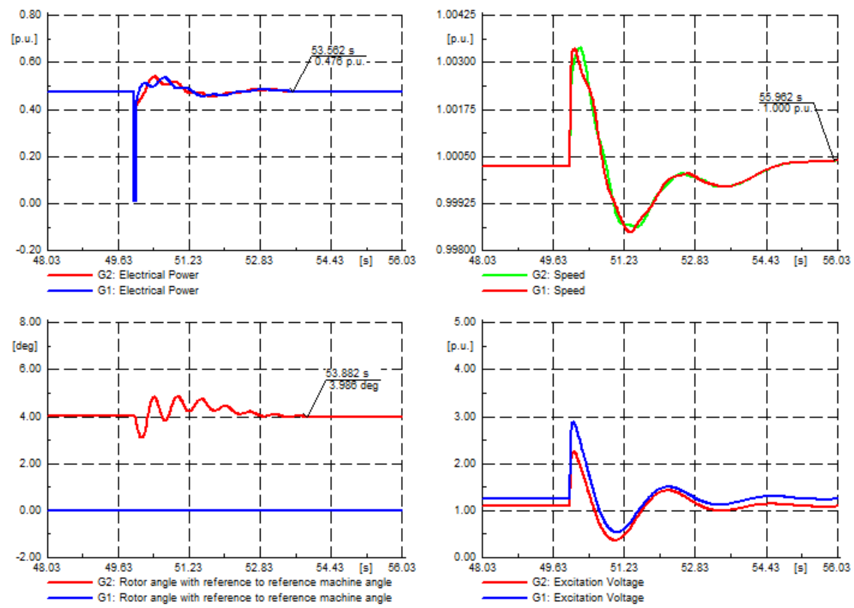


Figure 8.11: Results of the dynamic response in case 9

isolated area, it shows that G_1 is 0 pu. Electrical power suffers instant drop and then it oscillates. In respect to the speed and excitation voltage, they rises rapidly after the disturbance. They go back to stable at around 55.902 s.

8.2.4 Case 10: Two power system in island operation with old parameters PSS

Since the old parameters of PSS has good performance in single generation in island operation, the old parameters of PSS is applied in the case 10. The time domain results are shown in the fig-

Table 8.9: Eigenvalues in response to the short circuit in different cases

Case	Mode	Real part[1/s]	Imaginary part[1/s]	Damped frequency[Hz]	Damping ratio
case 9	Mode 9	-0.8194	2.01629	0.320904	0.3764883
	Mode 12	-0.29551	0.58256	0.092717	0.4523884
case 10	Mode 16	-0.83757	1.801666	0.286744	0.4215573
	Mode 20	-0.26991	0.370883	0.059028	0.5884214

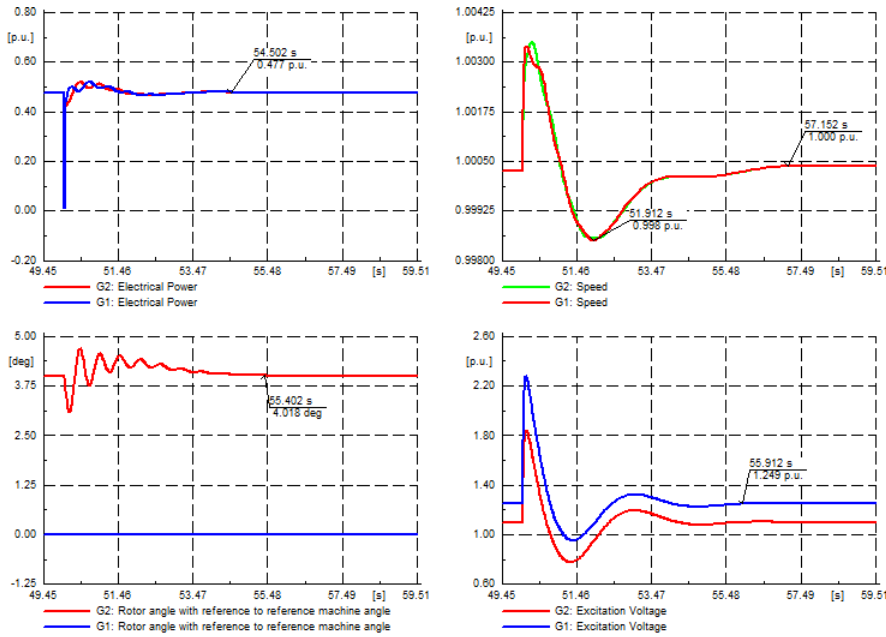


Figure 8.12: Results of the dynamic response in case 10

ure, and the eigenvalues results are shown in the table8.9.Comparing with the according mode, the damping ratio 0.3764883 of mode 9 in the case 9 increases to 0.4215573 of mode 16 in the case 10. Further the damped frequency 0.320904 HZ of mode 9 decreases to 0.286744 HZ.It is the same trend for mode 12 and mode 20

The dynamic response is presented in the figure8.12. It is obvious that the oscillation time in the case 10 is shorter than in the case 9.

From the results of eigenvalue analysis and time domain analysis, it is can be concluded that the default value of PSS is suitable for the island operation. The PSS could help the power system behaves better in island operation.

Chapter 9

Discussion

9.1 Hydro Power Plant Model

There are two kinds of hydro power plant model in the thesis. One is a simple hydro power plant model, which only takes governor and turbine into account. And it is a second generator model. The other is a complex hydro power plant model, which not only considers the effect of frequency but also takes field voltage into account.

The approach of establishing the hydro power plant is illustrated in detail in this thesis. Further a comparison is made between simple hydro power plant model and complex hydro power plant model. On the other hand, hydro power plant power system is built in PowerFactory, which are single generation power system and two generations power system respectively. The characteristics of all the elements that are used in the models are presented.

The validation of the linear hydro power plant is made by comparing the dynamic response with the nonlinear model in powerfactory. Through the comparison, nonlinear hydro power plant model shows more dynamic details than linear hydro power plant model.

Moreover, an nonlinear turbine model is presented in the thesis. When the nonlinear turbine model applied in the hydro power plant model, the simulink can't calculate the results. Therefore, turbine which used in the hydro power plant model is a linear model. The complex hydro power plant model does not contain the nonlinear turbine is a drawback.

9.2 Governor analysis

Governor is a critical part of control generators. When it faces island operation, the normal governor value is not suitable anymore. There is necessary to adjust the governor parameters. By analysing the three main parameters in the governor: reset time, temporary droop, and permanent droop, the governor can significantly improve the stability of the power system in primary control.

However, in this thesis, a algorithm optimal for governor parameters is not achieved. The new parameters in this thesis is a relative optimal parameters, but it can not say that the new parameters mentioned are the absolute optimal parameters for the governor in island operation.

9.3 Power system stabilizers analysis

The impact of power system stabilizers in island operation is studied. Through modal analysis in powerfactory, the damping ratio and damped frequency are calculated. Comparing the changes of damped frequency and damping ratio, it appears that in island operation, PSS improves the stability in terms of some electro-mechanical mode, but not entirely. It shows that the default parameters of the PSS is not suitable for the island operation. Therefore PSS should be tuned. Applying the tuned parameters to the PSS, there is increment of damping ratio, which proves that the tuned PSS helps the stability of the system.

Selection of power system stabilizers has huge influences on the performance of the power system stabilizers.

The probably designed power system stabilizers has the ability to ensure that the oscillations are very well damping. In contrast, if the power system stabilizers have not suitable parameters, it will decrease the damping making the system unstable.

In this thesis, the effect of power system stabilizers is specially studied in two kinds of power system. One is single generation power system, and the other is two parallel generations power system. The type of the power system stabilizer is IEEE2A, which is a dual input power system stabilizers.

In the single generation power system, the PSS with the default parameters in the PowerFactory is firstly tested in the grid-connected operation. Eigenvalue analysis and time domain analysis are used in the simulation, in order to measure the response of the power system in terms of different situations. From the eigenvalue analysis of case 2, it is found that the damping ratio of the critical mode goes down, which indicates that the system becomes less stable than case 1. Therefore, the default settings of the power system stabilizers are not suitable for the single generation power system in grid-connected power system. The parameters of the PSS should be tuned.

The tuning method is mainly focus on the phase shift of the PSS. The main objective of the tuning is that make the maximum phase of the power system stabilizers are various from the 90-135 degree, which means that the power system stabilizers could add damping to the rotor speed. The lead-lag time constants T_{s1}, T_{s2}, T_{s3} and T_{s4} are firstly be tuned.

Various parameters are chosen to tune the parameters of the PSS, selecting the best performance parameters to determine the new parameters of the PSS.

Chapter 10

Conclusions and Further work

10.1 Conclusions

Through modelling and comparing between the hydro power plant models, the simple HPP model cannot reflect the precise response regarding to the island mode. Therefore, simple HPP model should not be utilized when simulating the large disturbances.

On the other hand, the complex HPP model could used in a large disturbance simulation analysis, however, it cannot response as precise as the model in PowerFactory.

From the simulation in terms of governor in this thesis, it is clear that the governor has the ability to maintain the hydro power system stable when the plants face the island operation, as long as the deviations of the load is not big. The time-domain analysis reveals that the parameter in the grid connected operation is not suitable in the island operation.

The sensitivity analysis of temporary droop, reset time and permanent droop are conducted. The results indicate that the increment of temporary droop helps the system improves the damping when it turns into island operation, however it should not be bigger than 0.6 s, otherwise the system will response very slow and the maximum drop of the speed will becomes bigger and bigger.

Further, the reset time should not be too small, otherwise it will cause oscillations largely.Besides, the increases of the reset time also benefits to the damping of the system and it should not be too great. Permanent droop is related with the value of stable frequency after island operation. The small it is, the close to the original stabled frequency.

Additionally, the governor characteristics in transient state is linear in island operation.Besides, it shows that different load value has impact on the governor characteristic in island operation. The bigger the load, the bigger the slope. In other words, if the load is small, the deviation of the frequency is small in island operation. The governor can easily maintain the stability of the frequency.

Governor characteristics in steady state is also linear curve. The difference with the governor characteristic in transient state is that the load deviation does not influence characteristic significantly. However, the governor parameters influences the governor characteristic in steady state mainly.

Last but not least, when the system meets a huge change of load, for example: the increment of load demand is bigger than the rated power of the generator, governor cannot maintain the constant frequency. In other words, the ability of governor to maintain the stability of the power system is limited.

By analysing the power system stabilizer in different cases, it concluded that the power system stabilizer has positive effect on both grid-connected mode and island mode. Furthermore, the parameters of the PSS has huge impact on the behaviour of the power system. Inappropriate parameters could worse the performance of the power system regarding to the small disturbances.

In addition, the parameters of PSS in the grid connected mode is not suitable in the island mode, and it could damage the response of the power system in the island mode.

10.2 Further Work

Nonlinear turbine model can be implemented into the complex HPP model. Comparison could be made between the new complex HPP model and the PowerFactory model. To see if the new complex HPP model can predict precise response of the hydro power plant in island operation.

In addition, the algorithm of optimum parameters of the governor in island operation could be studied. Further, the algorithm optimum parameters of the PSS in island operation could also be studied.

Appendix A

Parameters

A.1 Power system model in PowerFactory

Table A.1: Synchronous generator parameters

Parameter	Value
Generator type	Salient pole
Nominal apparent power S_{gN}	50 MVA
Nominal voltage U_{gN}	10 KV
Inertial time constant H	3.1 s
Power Factor	0.8
Stator leakage reactance X_l	0.1 p.u.
Stator resistance R_a	0 p.u.
Direct-axis synchronous reactance X_d	1.05 p.u.
Quadrature-axis synchronous reactance X_q	0.66 p.u.
Direct-axis transient reactance X'_d	0.328 p.u.
Direct-axis subtransient reactance X''_d	0.254 p.u.
Quadrature-axis subtransient reactance X''_q	0.273 p.u.
Direct-axis transient time constant T'_{d0}	2.49 s
Direct-axis subtransient time constant T''_{d0}	0.06 s
Quadrature-axis subtransient time constant T''_{q0}	0.15 s

Table A.2: Transformer parameters

Parameter	Value
Nominal power S_{tN}	55MVA
Nominal frequency	50 Hz
HV-side rated voltage	220KV
LV-side rated voltage	3%

Table A.3: Transmission line parameters

Parameter	Value
Rated voltage	220KV
Rated current	1 KA (in ground)
Positive sequence resistance	0.025 Ω
Positive sequence reactance	0.5 Ω

Table A.4: Load parameters

Parameter	Value
Active power	25 MW
Reactive power	1.5205 Mvar
Voltage	1 p.u.
Positive sequence reactance	0.5 Ω

Table A.5: Governor parameters

Parameter	Value
Temporary droop r	0.04 p.u.
Governor time constant T_r	10 s
Filter time constant T_f	0.1 s
Servo time constant T_g	0.5 s
Water time constant T_w	1 s
Turbine gain A_t	1 s
Dturb frictional losses factor	0.01 p.u.
No load flow qnl	0.01 p.u.
Permanent droop R	0.04 p.u.
Turbine rated power P_N	0 p.u.
Gmin minimum limit	0
Velm gate velocity limit	0.15 p.u.
Gmax maximum gate limit	1 p.u.

Table A.6: AVR parameters

Parameter	Value
Filter delay time constant T_b	10 s
Filter derivative time constant T_a	2 s
Exciter time constant T_e	0.5 s
Emini controller minimum output	-3 p.u.
Emax controller maximum output	3 p.u.

Table A.7: IEEE2A PSS parameters

Parameter	Value
1st Washout 1th time constant T_{w1}	1.5 s
1st washout 2th time constant T_{w2}	1.5 s
1st signal transducer time constant T_6	0.015 s
2nd washout 1th time constant T_{w3}	1.5 p.u.
2nd washout 2th time constant T_{w4}	1.5 p.u.
2nd signal transducer factor K_{s2}	0.5
2nd signal transducer time constant T_7	1.5 p.u.
washout coupling factor K_{s3}	1.5 p.u.
PSS gain K_{s1}	3 p.u.
1st lead-lag derivative time constant T_{s1}	0.18 s
1st lead-lag delay time constant T_{s2}	0.02 s
2nd lead-lag derivative time constant T_{s3}	2 s
2nd lead-lag delay time constant T_{s2}	5 s
Ramp tracking filter derivative time constants T_8	0.4
Ramp tracking filter delay time constants T_9	0.1
Ramp tracking filter N	1
Ramp tracking filter M	4
1st input selector I_{c1} [1-6]	1
2nd input selector I_{c2} [1-6]	3
Derivative factor K_d	0.01 p.u.
PSS base selector (1=gen MVA, 0=gen MV) IPB	1
Vstmin controller minimum output	-0.05
Vstmin controller maximum output	0.05

A.2 Parameters of the hydro power plant model in matlab

Table A.8: Governor parameters

Parameter	Value
T_f	0.1 s
R	2 s
T_g	0.5 s
r	0.38 p.u.
T_r	10 p.u.
rT_r	$r * T_r$
K_d	0.01 s
K_s	0.1 s

Table A.9: Turbine governing system diagram parameters

Parameter	Value
T_w	1 s
A_t	1 s
H_0	1 s
q_{nl}	0.01 p.u.

Table A.10: Generator diagram parameters

Parameter	Value
H	3.1 s
D	2 s
K_e	1 .27
w_0	100*π p.u.

Table A.11: Generator diagram parameters in complex HPP model

Parameter	Value
H	3.1 s
D	2 s
K_e	1 .27
w_0	100*π p.u.

Table A.12: AVR parameters in complex HPP model

Parameter	Value
K	900 s
T_e	0.5 s
T_a	2
T_b	10

Table A.13: Turbine governing system parameters in complex HPP model

Parameter	Value
T_w	1 s
A_t	1 s
H_0	1 s
q_{nl}	0.01 p.u.

Table A.14: Generator diagram parameters in complex HPP model

Parameter	Value
H	3.1 s
D	2 s
K_e	1 .27
w_0	100*π p.u.
X	0.6
X_d 1.05	
X_{dt}	0.328
V_s	0.898
K_2	0.6184
K_3	1.778
K_1	$1/x_{dt}$
T_{d0t}	2.49
K_4	0.2632

Appendix B

Calculations of synchronous generator parameters

The voltgae base value and apparent power base value are $V_B = 245KV$ and $S_B = 50$ respectively
The impedance base value can be calculated by

$$Z_B = \frac{{V_B}^2}{S_B} = \frac{245^2}{50} = 1200.5\Omega$$

the per unit value of the transmission line impedance x_l, V_s and load R are shown as follows

$$x_{lpu} = \frac{x_l}{Z_B} = \frac{j0.4 \times 250}{1200.5} = j0.0833$$
$$V_{spu} = \frac{V_s}{V_B} = \frac{220}{245} = 0.898\angle 0$$
$$R_{pu} = \frac{R}{Z_B} = \frac{2000}{1200.5} = 1.67$$

The per unit value of active power P_s and reactive power Q_s is calculated by

$$P_{spu} = \frac{P_s}{S_B} = \frac{15}{50} = 0.3$$

$$Q_{spu} = P_s \tan\phi = 0.3 \tan\cos 0.9 = 0.145$$

So, the line current can be calculated by

$$I_l = \frac{s^*}{V_s} = \frac{P_s + jQ_S}{V_s} = 0.371\angle{-25.78}$$

The drop voltage then can be calculated by

$$\Delta V_l = x_l I_l = 0.0309\angle 64.2$$

Consequently,the voltage across the load V_l is

$$V_l = V_s + \Delta V_l = 0.912\angle 1.75$$

so, the current of the load I_R is

$$I_l = \frac{V_l}{R_{pu}} = 0.547\angle 1.75$$

and the generator current I_g is

$$I_g = I_l + I_R = 0.893\angle{-9.33}$$

The drop voltage across the transformer is

$$\Delta V_t = x_t I_g = 0.0893\angle 80.7$$

Therefore, the generator voltage is

$$V_g = V_l + \Delta V_t = 0.933\angle 7.14$$

The voltage E_Q, which is in phase with E_q, can be calculated by

$$E_Q = V_g + I_g x_q = 1.24\angle 34.3$$

As a result, the external power angle $\delta = 34.3$, the angle between I_g and E_q is

$$\beta = \delta - arg(I_g) = 43.6$$

the current I_g on the q-axis and d-axis are

$$I_{gd} = |I_g| \sin\beta \angle(\delta - 90) = 0.616\angle -55.7$$
$$I_{gq} = |I_g| \cos\beta \angle\delta = 0.647\angle 34.3$$

The drop voltages across the q-axis and d-axis are

$$\Delta V_{xd} = x_d I_{gd} = 0.647\angle 34.3$$
$$\Delta V_{xq} = x_q I_{gq} = 0.427\angle 124$$

Therefore, the external voltage E_q is

$$E_q = V_g + \Delta V_{xd} + \Delta V_{xq} = 1.47\angle 34.3$$

Appendix C

Synchronous generators

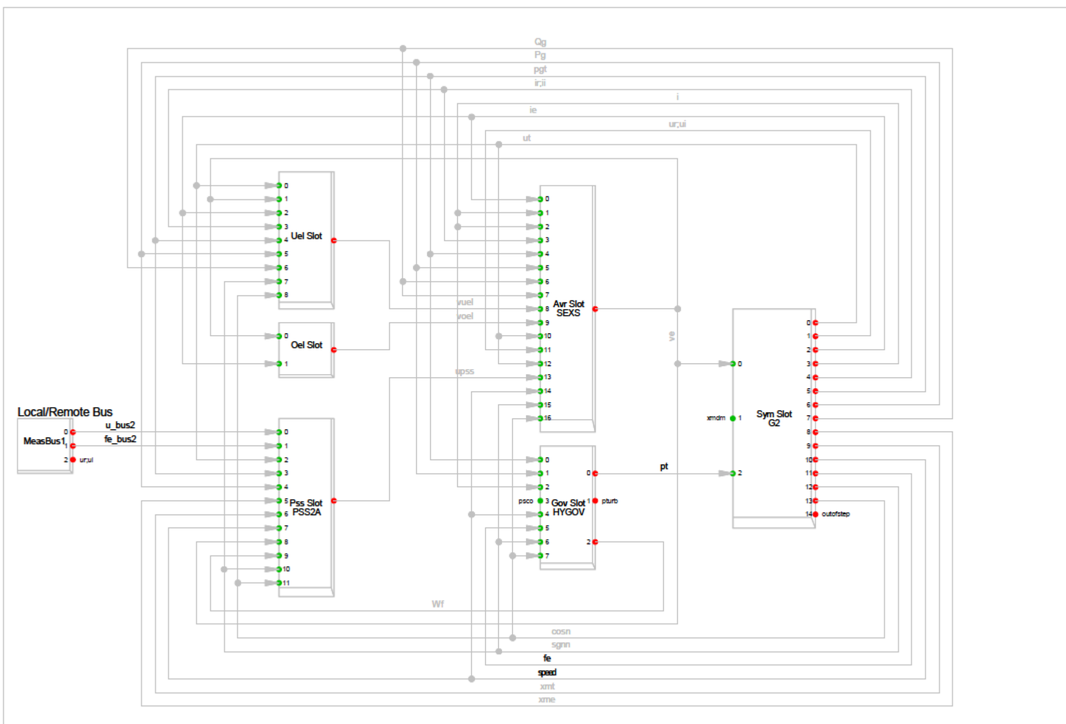


Figure C.1: Synchronous machine signal interconnections[12]

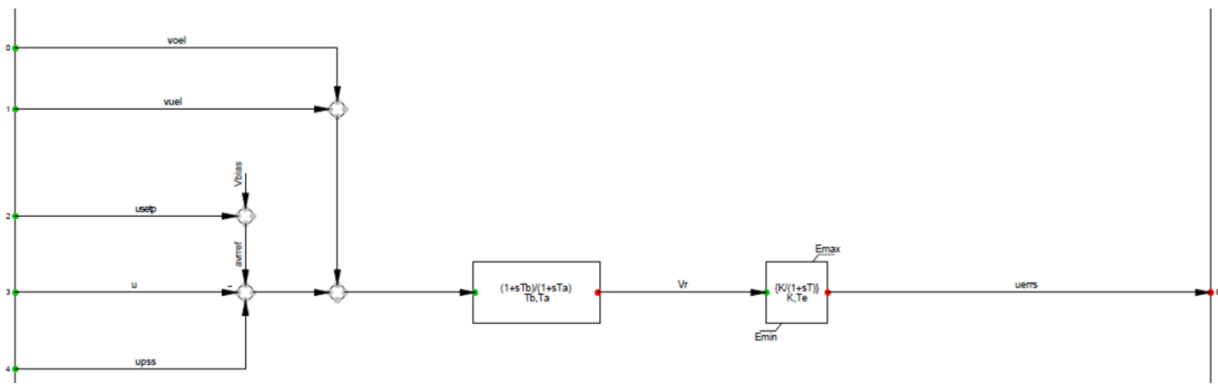


Figure C.2: The structure of the automatic voltage regulator[12]

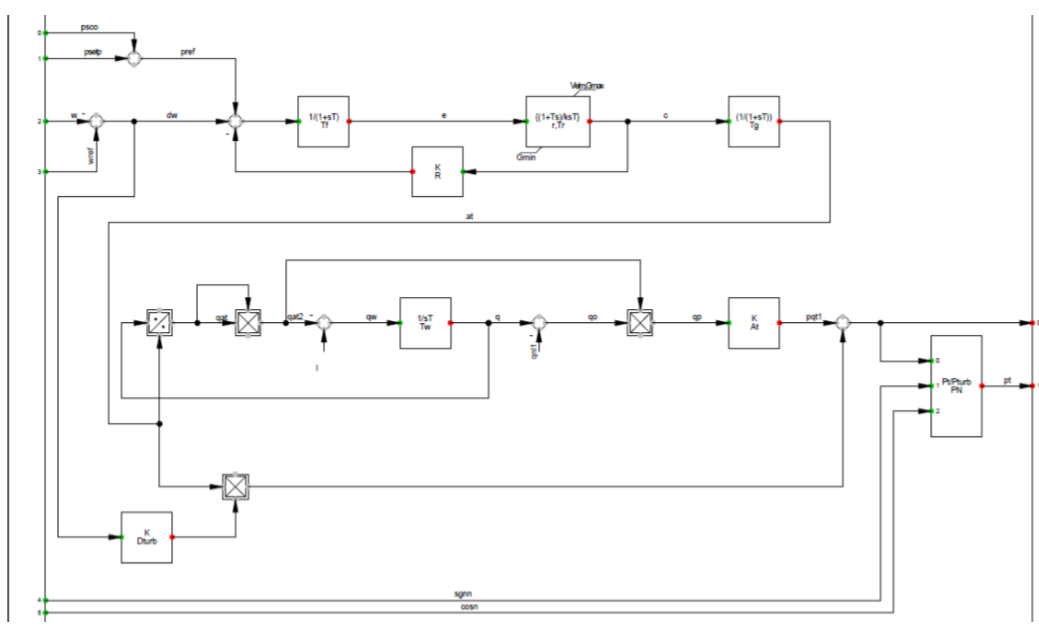


Figure C.3: The structure of the HY_Gov[12]

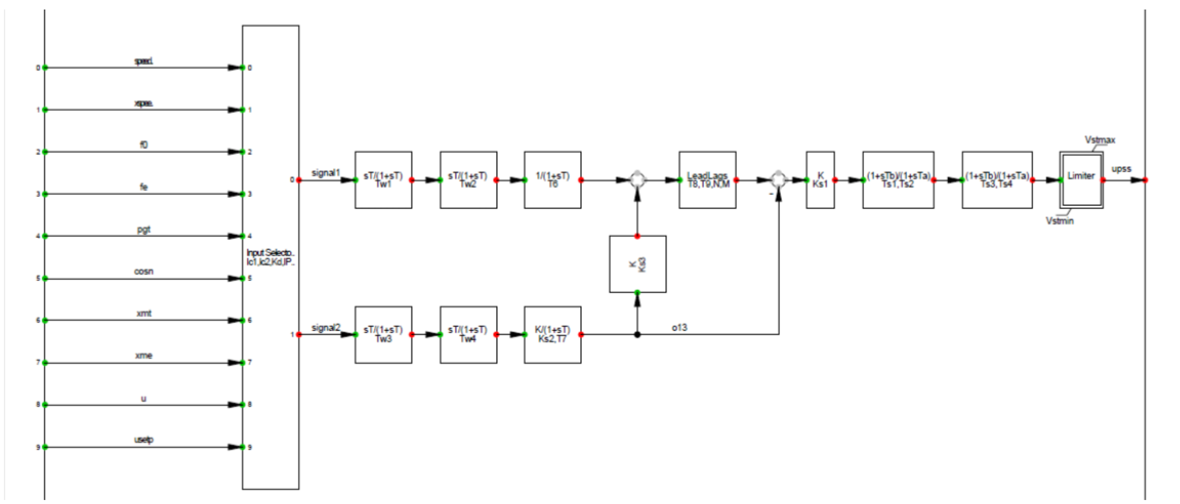


Figure C.4: The structure of the IEEE PSS2A[12]

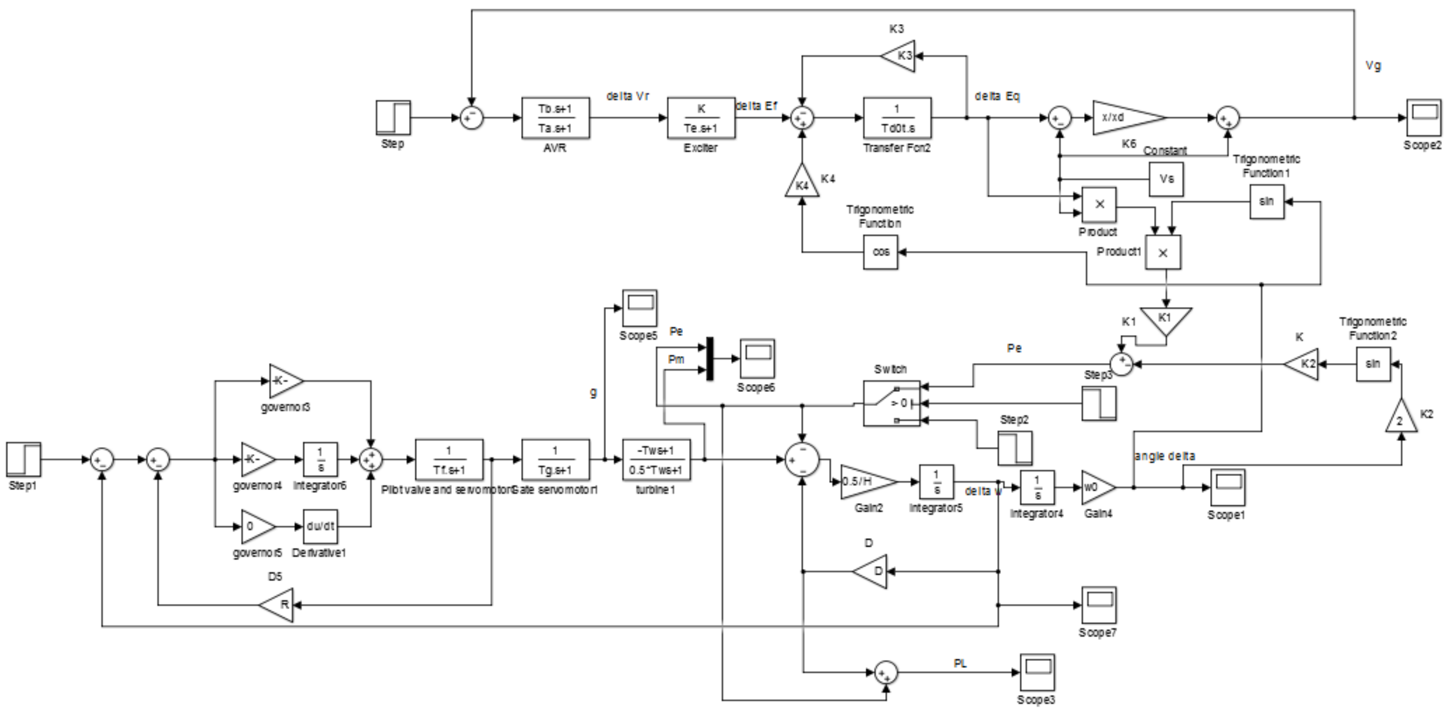


Figure C.5: Hydro power plant with voltage control

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