2. MODELING OF A POWER SYSTEM FOR STABILITY STUDIES

2.1 Introduction

In order to study the steady state and transient stability of a power system, it is essential that the power system components included in a study be properly modeled. As power systems have expanded and modern excitation systems introduced into large synchronous machines, it may be inappropriate to utilize simplified machine models in investigating the transient stability beyond the first swing. Adequate machine modeling, including that of AVR and AGC, is an important part in carrying out a stability study.

A synchronous machine can be modeled with varying complexity. It has been justified that a fifth order representation of the synchronous machine under disturbances can satisfy the requirement that the subtransient phenomena of the machine be properly modeled while its mathematical representation is still fairly simple [4]. Further detailed modeling is not worthwhile as the computation effort increases rapidly while the gains in terms of accuracy are very little. Three machine representations used in this study are discussed in this chapter.

Generally, an excitation system includes two major parts: a voltage regulator and an exciter. According to the type of power source utilized by the exciter, excitation systems can be classified as [5]:

1. type DC system which utilizes a DC generator with a commutator as the power source of the excitation system;

2. type AC system which utilizes an alternator and either stationary or rotating rectifiers to produce the direct current for the exciter; and

3. type ST system which utilizes transformers and rectifiers to provide the direct current.

Modeling details of the excitation systems used in this project will be presented in this chapter.

The speed governing and turbine system for hydro power generators can be modeled either by detailed or by simplified representation [6]. Both the detailed and the simplified equivalent models are discussed here. Then, the modeling of two specific power system stabilizers (PSSs) utilized in the studies reported in this thesis, and one IEEE standard PSS model utilized in designing the new PSSs are discussed. Lastly, the modeling of disturbances, loads, transformers and network is briefly presented.

2.2 Synchronous Machine Models

The coordinate system utilized for synchronous machine modeling in this thesis is the original coordinate system employed by Park [7].

1. Two - Axis Model with Subtransient

With the effects of rotor damping being represented by two short circuited damper windings on the rotor in this model, the following derived differential equations are utilized to describe the subtransient behavior of a synchronous machine (see Appendix D for detailed derivation):

$$\dot{E}_q^{'} = \frac{1}{\tau_{do}^{'}}\left\{kE_{fd} - E_q^{'} - \left(x_d - x_d^{'}\right)i_d\right\} \quad (2.1)$$

$$\dot{E}_{sum} = \frac{1}{\tau_{do}^{"}}\left\{-E_{sum} - \left(x_d^{'} - x_d^{"}\right)i_d\right\} \quad (2.2)$$

$$\dot{E}_d^{"} = \frac{1}{\tau_{qo}^{"}}\left\{-E_d^{"} + \left(x_q - x_q^{"}\right)i_q\right\} \quad (2.3)$$

where

$$E_{sum} = E_q^{"} - E_q^{'}$$

A block diagram of this model is shown in Figure 2.1.

The differential equation describing machine motion is given by

$$\Delta\ddot{\delta} = (\mathrm{P_m} - \mathrm{P_e} - \mathrm{P_l} - \mathrm{D}\Delta\omega)/2\mathrm{H} \quad (2.4)$$

$$\Delta\dot{\delta} = \omega_o\left(\Delta\omega\right) \quad (2.5)$$

where H is the machine inertia constant in second and ω_o is the synchronous speed of the machine in radian per second.

The block diagram shown in Figure 2.2 depicts the relationship of the various variables in Equations (2.4) and (2.5).

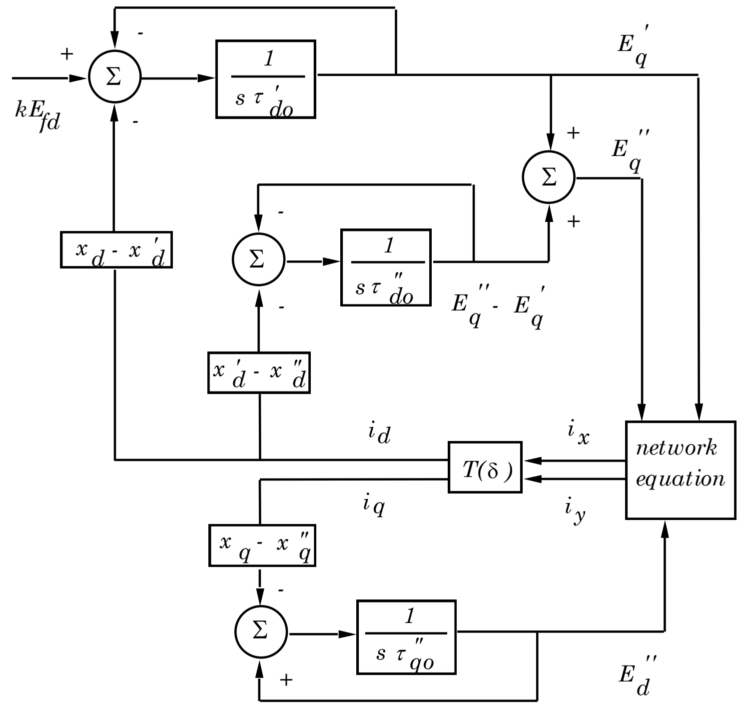

Figure 2.1: Block diagram of E" synchronous generator model.

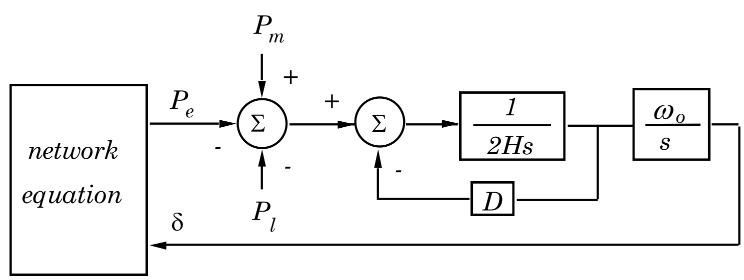

Figure 2.2: Block diagram for computation of speed and rotor angle.

Generation saturation can be taken into account by modifying the reactances x_{ad} and x_{aq} according to machine saturation at 1.0 pu and 1.2 pu terminal voltage that usually are known from the manufacturer. There are several algorithms to realize this modification [4,8]. An iterative procedure was employed in the studies reported in this thesis. At the same time, the corresponding time constants must also be modified. Detailed derivation of their expressions is given in Appendix D of the thesis. They are quoted here as part of the mathematical model of the synchronous machine modeled by the two-axis representation with subtransient.

Saturated time constants are

$$\tau'_{do} = \tau'^{(0)}_{do}\left\{k + (1-k)\frac{x'_d - x_\ell}{x_d^{(0)} - x_\ell}\right\} \tag{2.6}$$

$$\tau''_{do} = \tau''^{(0)}_{do}\left\{k + (1-k)\frac{x''_d - x_\ell}{x_d^{(0)} - x_\ell}\right\} \tag{2.7}$$

$$\tau''_{qo} = \tau''^{(0)}_{qo}\left\{k + (1-k)\frac{x''_q - x_\ell}{x_q^{(0)} - x_\ell}\right\} \tag{2.8}$$

where the superscript (0) indicates unsaturated values, and k is the saturation factor. Other symbols are conventional.

2. Two-Axis Model with Transient

This model is similar to the one presented previously. The subtransient effects are totally ignored, however, the transient effects are taken into account. There are two rotor windings, one is the field winding in the d-axis and the other is the equivalent damper winding in the q-axis formed by the solid rotor.

The basic equations of this model are given by:

$$\mathrm{v_q} = \mathrm{E'_q} - \mathrm{x'_d}\,\mathrm{i_d} - \mathrm{r_a}\,\mathrm{i_q} \tag{2.9}$$

$$\mathrm{v_d} = \mathrm{E'_d} + \mathrm{x'_q}\,\mathrm{i_q} - \mathrm{r_a}\,\mathrm{i_d} \tag{2.10}$$

$$\dot{E}'_q = \frac{1}{\tau'_{do}}\left\{kE_{fd} - E'_q - \left(x_d - x'_d\right)i_d\right\} \tag{2.11}$$

$$\dot{E}'_d = \frac{1}{\tau'_{qo}}\left\{-E'_d + \left(x_q - x'_q\right)i_q\right\} \tag{2.12}$$

where τ'_{do} is modified according to (2.6); and

$$\tau'_{qo} = \tau'^{(0)}_{qo}\left\{k + (1-k)\frac{x'_q - x_\ell}{x^{(0)}_q - x_\ell}\right\} \tag{2.13}$$

3. One-Axis Model with Transient

In this model, the amortisser effects are totally neglected. There is only one rotor winding present in the model, i.e., the field winding. Its differential equation is the same as (2.11). Saturation is treated in the same manner as explained previously. The difference between this model and the two-axis transient model is that as no damper windings are modeled, the differential equation for E'_d is, therefore, eliminated.

Voltage behind transient reactance model can be achieved by assuming that the time constant τ'_{do} is very large.

2.3 Controller Modeling

There are three kinds of controllers that directly affect the operation of a synchronous generator, and thus the stability of a power system. They are excitation system, speed governing and turbine system, and power system stabilizer. One of the most influential of the three is the excitation system. This section presents their modeling in the form of block diagrams.

2.3.1 Excitation Systems

Throughout this thesis, the IEEE standard excitation representation will be adopted and the universally accepted convention will be used. As power components and controllers are simulated by programming their block diagrams, mathematical expressions for their modeling may not be necessary. Therefore, only the block diagrams are presented.

Two solid state excitation systems, i.e., SCRX and SCRXIL, the latter having a maximum field current limit, and one modified DC type 2 excitation system are used in the research reported in this thesis. As these three models are non-standard IEEE models, they will be discussed here in more detail.

1. Modified DC type 2 excitation system — EXDC2B

A modified version of the DC type 2 excitation system, as shown in Figure 2.3, is utilized to model the rotating DC excitation system in this thesis.

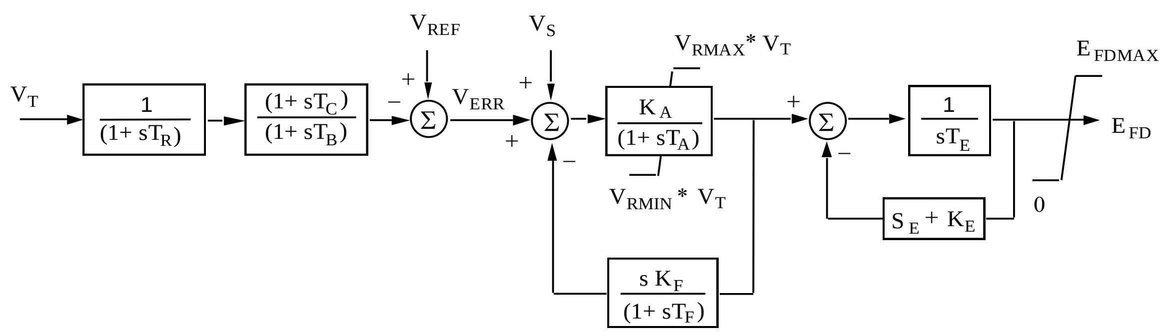

Figure 2.3: Modified IEEE DC type 2 exciter.

2. Solid state excitation systems — SCRX, and SCRXIL

The SCRX exciter is a solid state exciter fed by either bus terminal voltage or independent supply (solid). The block diagram of the system is shown in Figure 2.4. The switch SW is set to terminal voltage V_T if the exciter is fed by bus. Otherwise it is set to 1.0. If the exciter accepts negative current, the negative current logic is bypassed. However, if I_{fd} is negative, the output voltage E_{fd} of the excitation system is reversed.

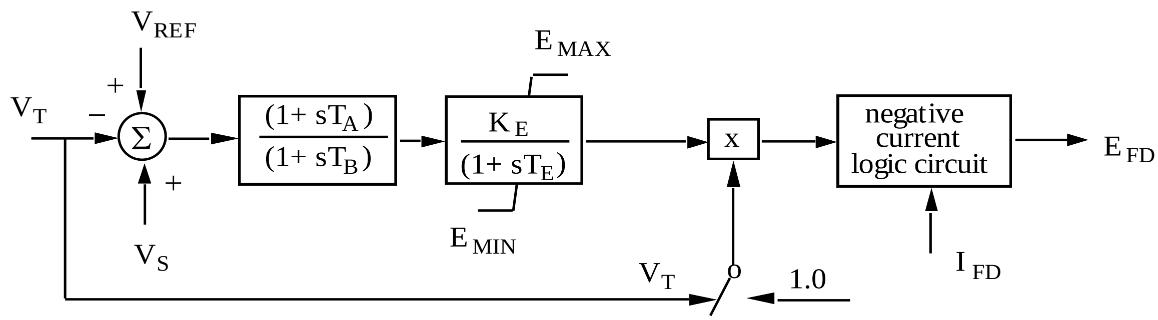

Figure 2.4: SCRX excitation system fed either by bus or by solid.

A variant of the SCRX type exciter is SCRXIL and is used in this project. The structure is the same as that of SCRX as shown in Figure 2.4, except that a maximum field current limitation is introduced. This maximum current limit protects the exciter and the generator rotor.

2.3.2 Speed Governing and Turbine Systems

The modeling of speed governing and turbine systems for both steam and hydro generators is quite standard [6]. As steam generators are not present in the system studied in this thesis, the modeling of their speed governing and turbine system will not be discussed here. The detailed model of a hydro generator's speed governing and turbine system is given in Figure 2.5. Its equivalent representation is also shown in Figure 2.6.

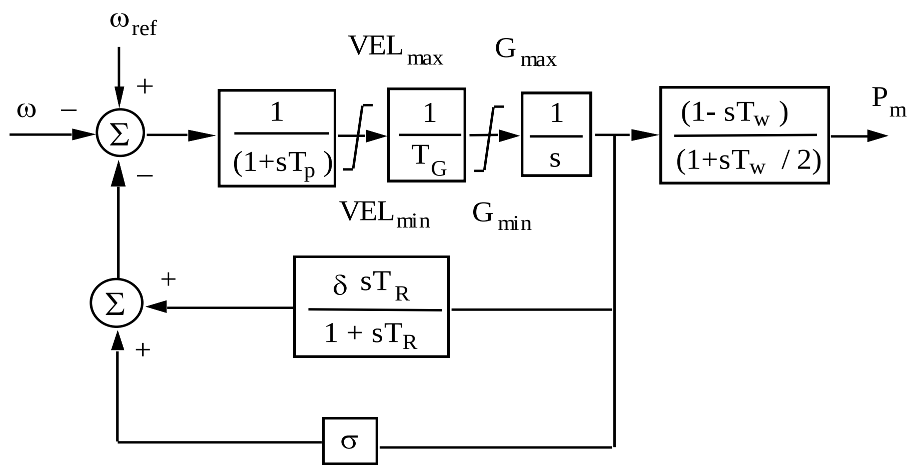

Figure 2.5: Detailed representation of hydrogovernor turbine system.

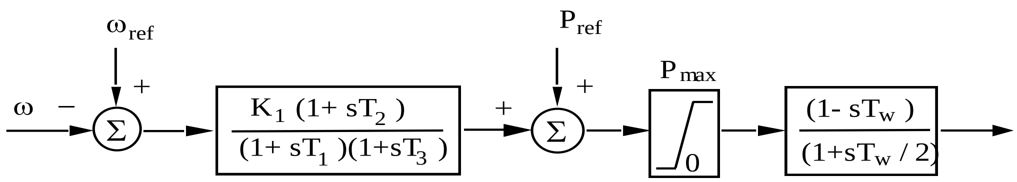

Figure 2.6: Equivalent representation of hydrogovernor turbine system.

2.3.3 Supplementary Excitation Controllers

In order to suppress the low frequency electromechanical oscillations in a power system, supplementary excitation controllers well known as power system stabilizers are often installed to provide positive damping [9].

The input signal to a PSS can be arbitrary [9]. Generally, any one or a combination of the following can be utilized as input signal:

(a) deviation of machine shaft speed

(b) deviation of terminal frequency

(c) net accelerating power

(d) deviation of terminal voltage

The input signals must be in per unit. A PSS with a different input signal will have a different transfer function.

Two PSS models are used in the studies reported in this thesis. Their input signals are generator electrical power and net accelerating power, respectively. The former is identified as IEEESN and the latter as IEEEST. Their block diagrams are shown in Figure 2.7 and Figure 2.8, respectively.

Note that only a single time constant A_1 is present in the filter transfer function, this is because of the inherently low level of torsional interaction when net accelerating power is used as stabilizer input.

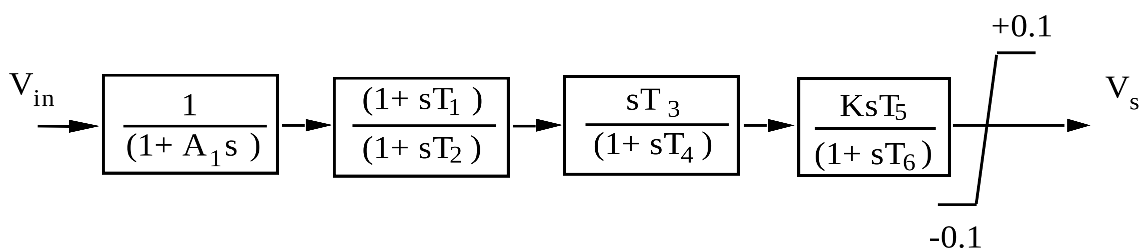

Figure 2.7: IEEESN PSS using generator electrical power as input.

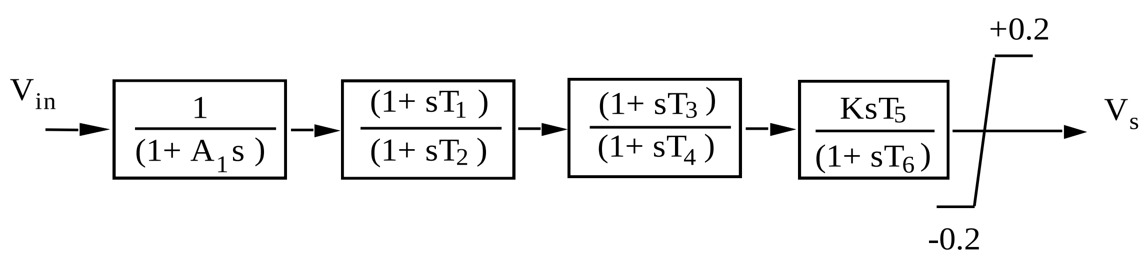

Figure 2.8: IEEEST PSS using net accelerating power as input.

As an example, the settings of the two PSSs used in this project are listed in Table 2.1. Their effects on the system stability will be discussed in subsequent chapters.

Table 2.1: PSS settings in APNS

PSS	Input	K	A_1	T_1	T_2	T_3	T_4	T_5	T_6	Limits
IEEESN	g.e.p.	-.05	.014	.000	.025	4.4	4.4	5.0	5.0	±0.1
IEEEST	n.a.p.	10.	.000	.400	1.00	.08	.50	2.0	2.0	±0.2

where g.e.p. is generator electrical power; and n.a.p. is net accelerating power.

The IEEE standard PSS model [5] is utilized to design new PSSs described in Chapter 6. The block diagram of the model is shown in Figure 2.8. The transfer function of the filter in the diagram can be expressed by:

$$\frac{(1 + A_5 s + A_6 s^2)}{(1 + A_1 s + A_2 s^2)(1 + A_3 s + A_4 s^2)} \tag{2.13}$$

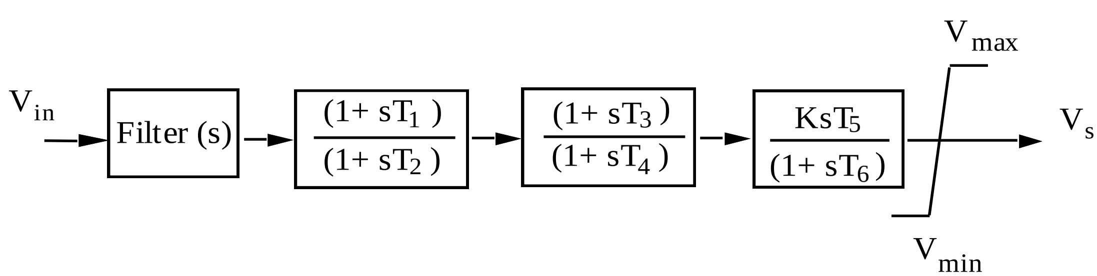

Figure 2.9: IEEE standard PSS model.

2.4 Modeling of SVC

A static var compensator (SVC) may function to meet any or all of the following objectives by fast and continuous control of reactive power flow in the system.

(a) Voltage regulation

(b) Enhancement of steady state and transient stability

(c) Compensation of reactive power flow, minimizing losses

(d) Damping of subsynchronous oscillations

A transient model of the SVC can be modeled by the block diagram as shown in Figure 2.10.

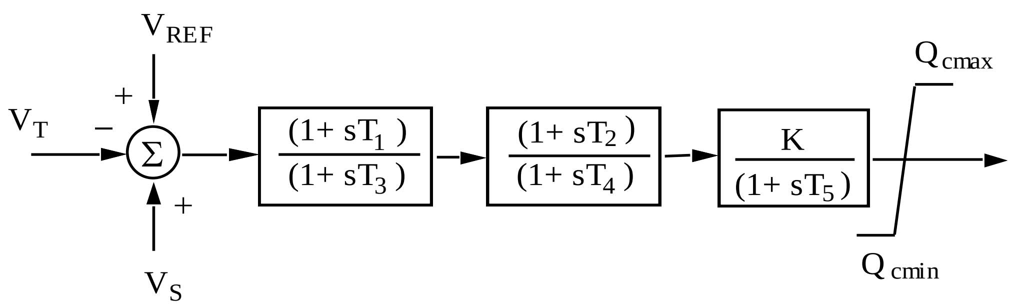

Figure 2.10: Transient study model of SVC.

In Figure 2.10, K is the gain setting, $T_1 \sim T_5$ are time constants, $Q_{c\,min}$ and $Q_{c\,max}$ is minimum and maximum generated reactive power (in Mvar), respectively, injected into the network.

2.5 Modeling of Disturbances

The modeling of disturbances is an important aspect in simulating the dynamic behavior of a power system with acceptable accuracy. Both symmetrical and asymmetrical disturbances should be modeled. A symmetrical disturbance can be easily modeled as the system will remain symmetrical under such a disturbance. Under asymmetrical disturbance, the solution of a stability problem of the disturbed three-phase network can be carried out by a three-phase stability program, where the symmetrical component method is employed to resolve the system into three symmetrical three-phase systems. Thus the total computations will increase up to three times. On the other hand, it has been found [10] that the average braking torque produced by the reaction of the two magnetic fields, one produced by the negative sequence current and the other by the rotor winding current, is approximately zero, and that zero sequence currents yield a zero component torque as the three-phase zero sequence currents are electrically in phase and have 120 degree displacement in space. Hence, only the positive sequence quantities are needed to be taken into account during a transient process. However, the negative and zero sequence networks have to be incorporated into the positive sequence network at the fault point.

Each disturbance can be described and modeled as a sequence of four events. They are pre-fault, fault, post-fault and line restoration ,i.e., autoreclosure if any. The admittance matrix of the network is modified each time there is a change in the configuration of the network during the disturbance.

As most faults in a practical power system are asymmetrical in nature, it is important that engineers know what behavior a system would exhibit under such disturbances and what measures should be taken to maintain system stability while maximizing the availability of power supply to customers.

2.6 Load Modeling

Loads can be modeled by any characteristics as long as their representations are known. Specifically, a large induction motor can be simulated by its transient model [11]. Other load representations are [12]:

1. Constant impedance model

   In this model, the power varies directly with the square of the voltage magnitude.

2. Constant current model

   The power varies directly with the voltage magnitude in this model.

3. Constant power (MVA) model

   In this model, the power does not vary with the changes in voltage magnitude.

4. Polynomial load model

   This model expresses the relationship between power and voltage magnitude as:

$$P = P_o \left\{ a_1 \left(\frac{V}{V_o} \right)^2 + a_2 \left(\frac{V}{V_o} \right) + a_3 \right\} \tag{2.14}$$

$$Q = Q_o \left\{ a_4 \left(\frac{V}{V_o} \right)^2 + a_5 \left(\frac{V}{V_o} \right) + a_6 \right\} \tag{2.15}$$

where V_O should be the rated voltage, and P_O and Q_O should be the power consumed at rated voltage. However, they are normally taken as the values at the initial system operating condition for the study. The coefficients in the model satisfy the following equations:

$$a_1 + a_2 + a_3 = 1 \tag{2.16}$$

$$a_4 + a_5 + a_6 = 1 \tag{2.17}$$

Exact simulation of loads requires that at each time step, a load flow study be carried out in order to obtain the accurate bus voltage. This will increase the computation effort to an unacceptable extent. However, an alternative is to calculate new operating point by the fast decoupled load flow program only at instant when an event of a disturbance happens. At other times, the bus voltage is held constant as computed in the latest load flow study when used in load representations. Load modeling itself is a very difficult task as meaningful data are simply unavailable and collecting and processing load data is expensive. Therefore, the constant impedance model is employed in the studies reported in this thesis.

2.7 Modeling of Network and Transformers

Transmission lines of a power system are represented by lumped parameters, as used in a load flow program. Positive, negative and zero sequence impedances of power apparatus are needed to assemble the three sequence admittance matrices. Algebraic equations are utilized to describe the relationship of the electrical quantities in the network during both steady state and transient process.

Transformers are modeled by their steady state equivalent circuits that consist of branches that are treated similar to transmission lines. The sequence impedances of transformers are also needed in assembling the admittance matrices of the network.

2.8 Summary

This chapter has outlined the basic models utilized in the studies reported in this thesis.

Firstly, the modeling of synchronous machines and their three controllers was presented. Several synchronous generator models were discussed. However, more attention is given to the two-axis model in which the subtransient voltages of the two axes (d, q) were defined and, thereafter, the mathematical representation was given. Three excitation system models, which are not IEEE standard models; were presented. The detailed and simplified equivalent models of the speed governing and turbine system for hydro generators were given. PSS models and the modeling of a SVC were also introduced.

Then, the modeling of symmetrical and asymmetrical disturbances, which plays an important role in stability simulation studies, was discussed. Finally, various load models were given and the modeling of transformers by their steady state equivalent circuits was presented.