

CHAPTER 3

POWER SYSTEM DYNAMIC MODEL

3.1 Structure of the Power System Model

The overall power system representation in this thesis includes models for the following components :

- Synchronous generator and the associated excitation systems
- AC transmission network including static fixed-impedance, loads
- HVDC link

For system stability studies concerning electromechanical oscillation, it is appropriate to neglect the transmission network and the machine stator transients. The dynamics of synchronous generator rotor circuits, excitation systems and HVDC controls are represented by the sets of differential equations. The result is that the complete system model consists of a large number of non-linear ordinary differential and algebraic equations.

We can describe complex power system as our plant which consists of generators, transmission network, and HVDC links as depicted in Fig. 3.1. It is noted that there can be a number of generators and HVDC links included in the system.

For Thailand's system, there is only one HVDC link connected between the bus in Southern part of Thailand (Khlung Ngae) and the Northern part of Malaysia (Gurun). Power can be imported or exported through HVDC. When the Thailand system is under generation, it will import power from Malaysia so that the converter in Khlung Ngae bus will act as an inverter. On the other hand, when Thailand system has surplus of power, it will export power to Malaysia so the converter in Khlung Ngae bus will act as a rectifier.

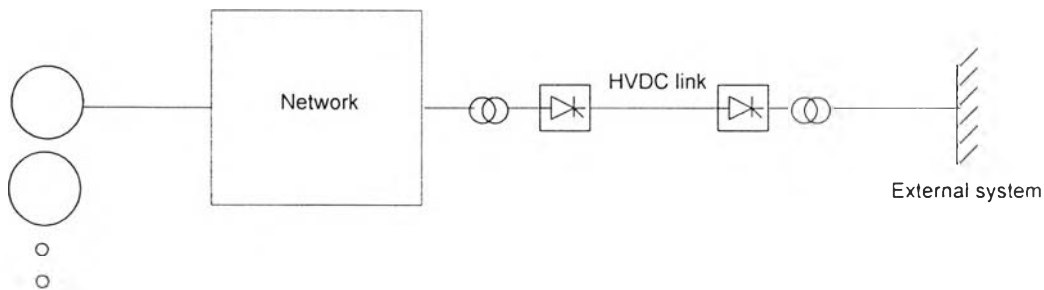


Figure 3.1 AC-DC power systems.

Optimal design and operation of HVDC system require detailed understanding of the various phenomena that result from interaction between the DC system and the AC system in which the DC link is embedded. The modeling of the various components of the AC/DC system needs to be applicable to the analysis and simulation under steady state and transient conditions. We have already presented the converter, the C/DC interface, and the HVDC link, and its basic control in previous chapter.

Now, we will present model of the AC system model which basically consists of generating units and the network. Each generating unit comprises of synchronous generator and its excitation.

3.2 Synchronous Generator Model

We will use a simplified generator model with two axes adopted from [14] as show in Fig. 3.2.

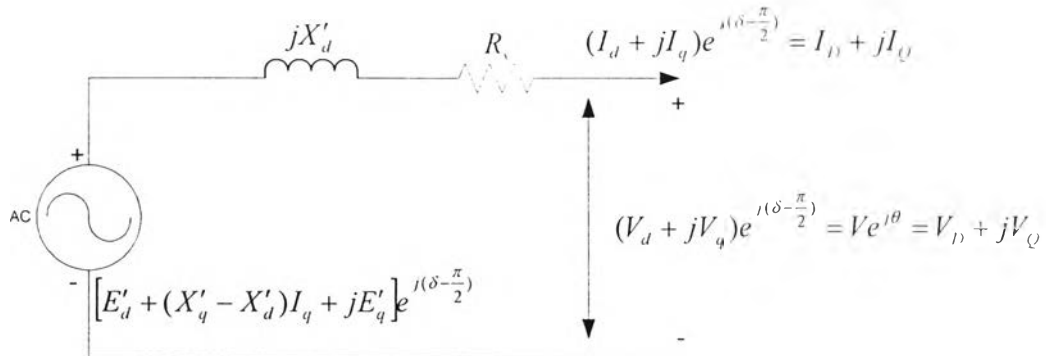


Figure 3.2 Two-axis synchronous machine model.

Defines :

- X'_d is the d-axis transient synchronous reactance
- X'_q is the q-axis transient synchronous reactance
- R_s is the armature resistance
- I_d is the d-axis current referred to the machine reference frame
- I_q is the q-axis current referred to the machine reference frame
- I_D is the d-axis current referred to the network reference frame
- I_Q is the q-axis current referred to the network reference frame
- τ'_{q0} is the q-axis transient open circuit time constant
- τ'_{d0} is the d-axis transient open circuit time constant
- X_d is the d-axis synchronous reactance
- X_q is the q-axis synchronous reactance
- δ is the angular position of the rotor with respect to a synchronously rotating reference
- ω is the angular velocity of rotor
- E'_q is the q-axis transient voltage
- E'_d is the d-axis transient voltage
- E_{fd} is the DC field voltage
- ω_s is the rated value of an angular velocity of rotor in electrical radian
- T_M is the mechanical torque applied
- T_e is the electromagnetic torque developed
- T_D is the damping torque component
- D is the damping factor
- H is the inertia constant

From the above figure, the stator algebraic equation can be written as :

$$Ve^{j\theta} + (R_s + jX'_d)(I_d + jI_q)e^{j(\delta - \frac{\pi}{2})} - [E'_d + (X'_q - X'_d)I_q + jE'_q]e^{j(\delta - \frac{\pi}{2})} = 0 \quad (3.1)$$

Multiplying eq. (3.1) by $e^{-j(\delta - \frac{\pi}{2})}$ and equating the real and the imaginary parts, we obtain :

$$E'_d - V \sin(\delta - \theta) - R_s I_d + X'_q I_q = 0 \quad (3.2)$$

$$E'_q - V \cos(\delta - \theta) - R_s I_q + X'_d I_d = 0 \quad (3.3)$$

In addition, the dynamic behaviors of the rotor motion and the rotor circuits can be describing using the following differential equations [14]:

$$\dot{\delta} = \omega - \omega_s \quad (3.4)$$

$$\dot{\omega} = \frac{(T_M - T_e - T_D)}{M} \quad (3.5)$$

$$\dot{E}'_q = \frac{(E_{fd} - (X'_d - X'_q)I_d - E'_q)}{\tau'_{d0}} \quad (3.6)$$

$$\dot{E}'_d = \frac{((X'_q - X'_d)I_q - E'_d)}{\tau'_{q0}} \quad (3.7)$$

where

$$M = \frac{2H}{\omega_s} \quad (3.8)$$

$$T_e = (E'_q I_q + E'_d I_d + (X'_q - X'_d)I_q I_d) \quad (3.9)$$

$$T_D = D(\omega - \omega_s) \quad (3.10)$$

The equations of importance in studying power system stability are the rotational inertia equations describing the effect of an imbalance between the electromagnetic torque and the mechanical torque of the individual machines. The equation of motion of a synchronous machine is commonly referred to as the *swing equation* because it represents swings in rotor angle δ due to disturbances. These swing equations are represented by eq. (3.4) and (3.5).

3.3 Excitation System

In order to improve the damping characteristics of the synchronous generator, supplementary excitation controls have been widely employed. In this study, we use the IEEE type I exciter as shown in Fig. 3.3 [14, 15].

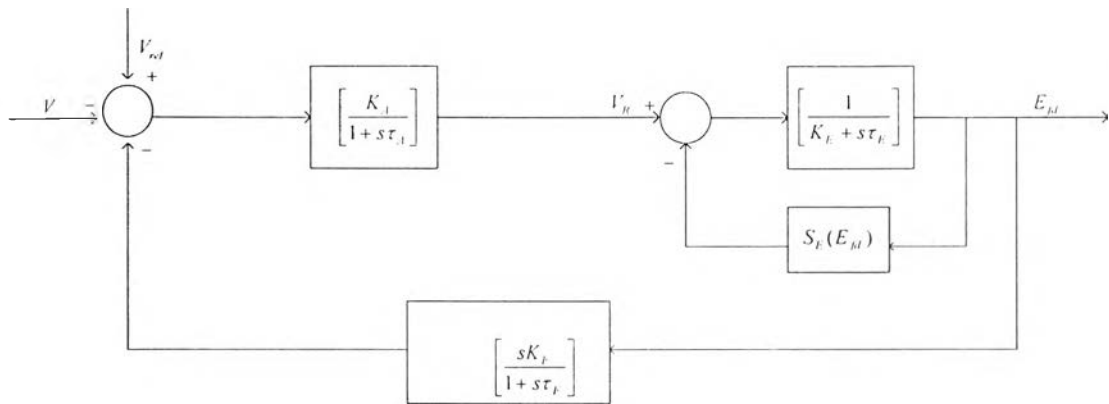


Figure 3.3 Block diagram of the IEEE type I excitation control.

From the block diagram above, we have three following equations :

$$\dot{E}_{fd} = \frac{K_E + S_E(E_{fd})}{\tau_E} E_{fd} + \frac{V_R}{T_E} \quad (3.11)$$

$$\dot{V}_R = -\frac{V_R}{\tau_A} + \frac{K_A}{\tau_A} R_f - \frac{K_A K_f}{\tau_A \tau_f} E_{fd} + \frac{K_A}{\tau_A} (V_{ref} - V) \quad (3.12)$$

$$\dot{R}_f = -\frac{R_f \hat{f}}{\tau_f i} + \frac{K_{fi}}{(\tau_{fi})^2} E_{fd} \quad (3.13)$$

$$S_E = A_{EX} \cdot e^{B_{EX} \times E_{fd}}$$

where

- E_{fd} is the exciter voltage
- V_R is the regulator voltage
- R_f is the stabilizer voltage
- K_A is the voltage regulator gain
- τ_A is the voltage regulator time constant
- K_E is the exciter gain
- τ_E is the exciter time constant
- K_f is the regulator stabilizing circuit gain
- τ_f is the regulator stabilizing circuit time constant
- S_{EX} is the rotating exciter saturation at ceiling voltage
- A_{EX} is the saturation constant for rotating exciters
- B_{EX} is the saturation constant for rotating exciters

3.4 Network Characteristic Equations

The network characteristics can be described in the form of power balance. From Fig. 3.1, we see that the network is connected to generating units and HVDC links. The network also interfaces dynamic interactions between generators and HVDC links.

The network can consist of many electrical buses and branches depending on the system of interest. Some of the buses connect to the generators, and others of buses

connect to HVDC. The rest of the buses which are not connected to generating units or HVDC can be an open-circuit bus or a load bus. Equations below describe steady-state performance of each bus with regard to the type of such bus.

It is assumed that the ordering of the buses here starts from generator buses, HVDC buses, and lastly the load buses. The numbering of the buses is as follows :

$$\begin{aligned} t = 1, 2, \dots, m & \quad \text{are a group of generator buses} \\ h = m + 1, \dots, m + d & \quad \text{are a group of HVDC buses} \\ l = m + d + 1, \dots, m + d + p & \quad \text{are a group of load buses} \\ n = m + d + p & \end{aligned}$$

where

$$\begin{aligned} m & \text{ is the number of generators} \\ d & \text{ is the number of HVDC} \\ p & \text{ is the number of loads} \\ n & \text{ is the number of buses} \end{aligned}$$

3.4.1 Generator Buses

The two equations representing real and reactive power balance for each generator bus are given below.

For real power balance,

$$I_{dt} V_t \sin(\delta_t - \theta_t) + I_{qt} V_t \cos(\delta_t - \theta_t) - \sum_{k=1}^n V_t V_k Y_{tk} \cos(\theta_t - \theta_k - \alpha_{tk}) = 0 \quad (3.14)$$

For reactive power balance,

$$I_{dt} V_t \cos(\delta_t - \theta_t) - I_{qt} V_t \sin(\delta_t - \theta_t) - \sum_{k=1}^n V_t V_k Y_{tk} \sin(\theta_t - \theta_k - \alpha_{tk}) = 0 \quad (3.15)$$

for $t = 1, 2, \dots, m$

3.4.2 HVDC Buses

Similarly, the two equations which are represented real and reactive power balance in HVDC bus. Reactive power is needed for AC-DC conversion. The real power flowing through the HVDC link can be in either direction. When the power is exported to another system, we have these following equations :

For real power balance,

$$E_{drh} I_{dch} - \sum_{k=1}^n V_h V_k Y_{hk} \cos(\theta_h - \theta_k - \alpha_{hk}) = 0 \quad (3.16)$$

For reactive power balance,

$$E_{drh} I_{dch} \tan(\phi_{rh}) - \sum_{k=1}^n V_h V_k Y_{hk} \sin(\theta_h - \theta_k - \alpha_{hk}) = 0 \quad (3.17)$$

for $h = m + 1, \dots, m + d$

On the contrary, when the power is imported to the system of interest we have these following equations :

For real power balance,

$$E_{dih} I_{dch} - \sum_{k=1}^n V_h V_k Y_{hk} \cos(\theta_h - \theta_k - \alpha_{hk}) = 0 \quad (3.18)$$

For reactive power balance.

$$E_{dch} I_{dch} \tan(\phi_{ih}) - \sum_{k=1}^n V_h V_k Y_{hk} \sin(\theta_h - \theta_k - \alpha_{hk}) = 0 \quad (3.19)$$

for $h = m + 1, \dots, m + d$

3.4.3 Load Buses

For the load buses, we have equations for both real and reactive power also.

$$P_{Ll}(V_l) - \sum_{k=1}^n V_l V_k Y_{lk} \cos(\theta_l - \theta_k - \alpha_{lk}) = 0 \quad (3.20)$$

$$Q_{Ll}(V_l) - \sum_{k=1}^n V_l V_k Y_{lk} \sin(\theta_l - \theta_k - \alpha_{lk}) = 0 \quad (3.21)$$

for $l = m + d + 1, \dots, m + d + p$

P_{Ll} and Q_{Ll} are voltage dependence loads. In this thesis, loads are assumed as constant power type.

3.5 Load Flow Analysis

Load flow analysis is an essential tool for planning, design and operation of the power systems. It is basically to determine the operating point of the system in steady state condition, which in here will be used for initializing variables for dynamic study.

3.5.1 AC Load Flow

Under normal condition, power systems operate in their steady state mode. The basic calculation to determine the characteristic of this state is called load flow (or power flow).

The objective of load flow calculation is to determine the steady state operating characteristic of the power generation/ transmission system for a given set of loads. Loads are normally specified by their constant active and reactive power requirement.

The solution is expected to provide information of voltage magnitudes and angles, active and reactive power flows in the lines, power losses, and the reactive power generated or absorbed at the voltage-controlled buses.

The complete definitions of power flow require knowledge of four variables at each bus k in the system, which are :

P_k : the injected real or reactive power

Q_k : the injected reactive power

V_k : the voltage magnitude

θ_k : the voltage phase angle

Generally, only two variables are known for each bus, and the aim of the load flow analysis is to solve for the remaining two variables of that bus.

We define three different types of buses on the steady-state assumption as follows

:

1. Nonvoltage-controlled bus.

The total injected power $P_k + jQ_k$, is specified at this type of bus. Both P_k and Q_k are assumed to be unaffected by small variations in voltage magnitude of the bus.

2. Voltage-controlled bus.

The total injected active power P_k is specified, and the voltage magnitude V_k is maintained at specified value by reactive power injection. This type of bus generally corresponds to a generator where P_k is fixed by turbine governor setting and V_k is fixed by automatic voltage regulators acting on the machine excitation, or reactive power supply from static shunt capacitors or rotating synchronous compensator.

3. Slack (swing) bus.

This bus arises because the system losses are not known precisely in advance of the load flow calculation. Therefore the total injected power cannot be specified at every single bus. It is usual to choose one of the available voltage controlled buses as slack, and to regard its active and reactive power as an unknown. Phase angle of the slack bus is usually assigned as the system phase reference. Hence, for this bus its complex voltage $V_s \angle \theta_s$ is completely specified.

The load flow program solves a set of simultaneous nonlinear algebraic equations for the two unknown variables at each bus in a system normally using numerical techniques such as the Newton-Raphson method.

3.5.2 DC Load Flow

Incorporation of the HVDC transmission system into the AC networks has been a major challenge programs during the last few years. It requires some modification in the load flow and stability programs.

The objective of power flow calculation of the AC-DC interconnected system is to find equilibrium states which satisfy operating conditions of both AC and DC systems, and also satisfy a set of relation between AC and DC quantities.

In performing AC power flow calculation, two variables are specified while the remaining two are solved iteratively. In case of AC-DC interconnected system, a set of equations for DC system and several relations between AC and DC quantities must be simultaneously solved, as well. The iterative procedure is repeated until all the relations between the AC and DC quantities are satisfied with sufficiently small errors.

The magnitude of the AC voltages and the complex power of the AC-DC interconnecting equations must be coincident at the interconnecting point of the AC-DC system, of which it implies that three variables must coincide at the interconnecting point [16].

In AC power flow calculation of AC systems, three variables cannot be specified at a single bus. Therefore two specified variables are used to obtain an equilibrium state of the AC system, while the remaining one variable, in general, can be different from that determined by DC power flow calculation. The DC quantities are then recalculate on the basis of the new solutions of AC load flow.

The -iterative calculation above is repeated until the three variables at the interconnecting point (HVDC bus) become coincident in both AC and DC systems. First, the active and reactive power and the bus voltages to be supplied from the AC system are calculated using the specified values and the initial conditions of the DC system. After that the bus voltage will be evaluated by the AC power-flow calculations. Then we will compare the bus voltage from DC and AC calculation. This comparison will be used to select proper tap position of the power transformer of HVDC. The AC and DC

calculations are performed iteratively until the voltage difference due to the tap position becomes sufficiently small.

3.6 Initial Condition Calculations

It is necessary to compute the initial values of all dynamic states under the given inputs. In power system dynamic analysis, the fixed inputs and initial conditions are normally found from a base case load flow solution, assuming that such load-flow solution exists.

3.6.1 Initial Conditions of HVDC

To do the computation, it is assumed that E_{di} , I_{dc} , α and γ are given. Also the parameters in the HVDC such as R_{dc} , R_{cr} , R_{ci} are given. After running load flow which also involves DC calculation as described above, initial conditions of HVDC can be calculated by following steps below. Here subscript r denotes rectifier, and i for inverter.

1. Compute E_{dr}

From Fig. 2.5 we can get this following relationship :

$$E_{dr} = E_{di} + I_{dc} R_{dc} \quad (3.22)$$

2. Compute E_{dr0}

$$E_{dr0} = \frac{\left(E_{dr} + \frac{3}{\pi} X_r I_{dc} \right)}{\cos(\alpha)} \quad (3.23)$$

3. Compute E_{di0}

$$E_{di0} = \frac{\left(E_{di} + \frac{3}{\pi} X_i I_{dc} \right)}{\cos(\gamma)} \quad (3.24)$$

4. Compute AC voltage at interface bus

$$V_i = \frac{E_{di0}}{k}$$

$$V_r = \frac{E_{dr0}}{k}$$

$$\text{where } k = \frac{3\sqrt{2}}{\pi}$$

5. Compute ϕ using eqs. 2.7 and 2.10

$$\phi_r = \cos^{-1} \left(\frac{E_{dr}}{E_{dr0}} \right)$$

$$\phi_i = \cos^{-1} \left(\frac{E_{di}}{E_{di0}} \right)$$

6. Compute P using eqs. 2.5 and 2.8

$$P_r = E_{dr} I_{dc}$$

$$P_i = E_{di} I_{dc}$$

7. Compute Q using eqs. 2.6 and 2.9

$$Q_r = P_r \tan(\phi_r)$$

$$Q_i = P_i \tan(\phi_i)$$

8. Compute I_{dcr}

Using eq. 2.15 by setting derivative equal to zero :

$$I_{dcr} = \frac{\left(\frac{\gamma}{K_i} + I_{dc} \right)}{0.9} \quad (3.25)$$

9. Compute Δu

Using eq. 2.13 by setting derivative equal to zero :

$$\Delta u = \frac{\alpha}{K_r} + I_{dc} - I_{dcr} \quad (3.26)$$

Finally, we obtain P and Q of HVDC to be used for AC load flow calculation.

3.6.2 Initial Conditions of Generating Unit

To do the computation, it is assumed that P , Q , V and θ at the generator buses are given from load flow results. Also the parameters in the generator and exciter are given. Initial conditions of generating unit can be calculated by following steps below :

1. Compute current in the generator bus.

$$I_G = \left(\frac{P + jQ}{Ve^{j\theta}} \right)^* \quad (3.27)$$

This current is in the network reference frame and is equal to $(I_d + jI_q)e^{j(\delta - \frac{\pi}{2})}$.

To make clear, assign I_G to be I_{DQ} . Note that subscribe DQ ($_{DQ}$) is for network reference frame and subscribe dq ($_{dq}$) is for machine reference frame.

We can use transformation (T) to transform the value in network reference frame to machine reference frame and vice versa. The machine - network transformation is given by

$$F_{dq} = T * F_{DQ} \quad (3.28)$$

$$\text{where } T = \begin{bmatrix} \sin \delta & -\cos \delta \\ \cos \delta & \sin \delta \end{bmatrix} \quad (3.29)$$

Also note that,

$$F_{DQ} = T^{-1} * F_{dq} \quad (3.30)$$

$$\text{where } T^{-1} = \begin{bmatrix} \sin \delta & \cos \delta \\ -\cos \delta & \sin \delta \end{bmatrix} \quad (3.31)$$

The variable F above can be either I or V .

2. Compute δ (delta).

$$\delta = \text{angle on } (V_{DQ} + (R_s + jX_q)I_{DQ}) \quad (3.32)$$

3. Compute I_d, I_q, V_d, V_q for the machine.

From eq. 3.28 we can obtain the values of I_d', I_q', V_d', V_q' by multiply I_{DQ} and V_{DQ} with T. I_{DQ} is from calculation no 1, and V_{DQ} is come from the load flow solution. V_{DQ} is the voltage at the generator buses.

$$\begin{bmatrix} I_d' \\ I_q' \end{bmatrix} = \begin{bmatrix} \sin \delta & -\cos \delta \\ \cos \delta & \sin \delta \end{bmatrix} \begin{bmatrix} I_D \\ I_Q \end{bmatrix} \quad (3.33)$$

$$\begin{bmatrix} V_d' \\ V_q' \end{bmatrix} = \begin{bmatrix} \sin \delta & -\cos \delta \\ \cos \delta & \sin \delta \end{bmatrix} \begin{bmatrix} V_D \\ V_Q \end{bmatrix} \quad (3.34)$$

4. Compute E_d' using eq. 3.2.

$$E_d' = V \sin(\delta - \theta) + R_s I_d - X_q' I_q$$

5. Compute E_q' using eq. 3.3.

$$E_q' = -V \cos(\delta - \theta) + R_s I_q + X_d' I_d$$

6. Compute E_{fd} using eq. 3.6 by setting the derivative term equal to zero :

$$E_{fd} = E_q' + (X_d - X_d') I_d \quad (2.35)$$

7. Compute $R_f, V_R, V_{ref}, \omega, T_M$

With the field voltage E_{fd} known, the other variables R_f, V_R and V_{ref} can be found using eqs. 3.11-3.13 by setting relevant derivative terms equal to zero :

$$V_R = (K_E + S_E(E_{fd})) E_{fd} \quad (3.36)$$

$$R_f = \frac{K_F}{T_F} E_{fd} \quad (3.37)$$

$$V_{ref} = V + \left(\frac{V_R}{K_A} \right) \quad (3.38)$$

The mechanical states ω and T_M are found using eqs. 3.4 and 3.5 by setting the associated derivative terms equal to zero :

$$\omega = \omega_s \quad (3.39)$$

$$T_M = E_d' I_d + E_q' I_q + (X_q' - X_d') I_d I_q \quad (3.40)$$

This completes all the computations required for determining initial conditions of the states variables and necessary inputs to be used for linearization process which will be the topic of discussion in the next chapter.