CHAPTER 3

DYNAMIC AGGREGATION OF GENERATING UNIT MODELS

3.1 Introduction

This chapter presents the method for grouping generating units that are coherent into an equivalent generating unit model. Actually, groups of coherent generating unit models are available for various types of synchronous machines, governor and turbine systems, excitation systems, and power system stabilizers. When the generating unit models for a group of coherent generators are to be replaced by an equivalent unit model, data for this unit model must be calculated from the unit model data for the group of coherent generators. This is generally known as **dynamic aggregation.**

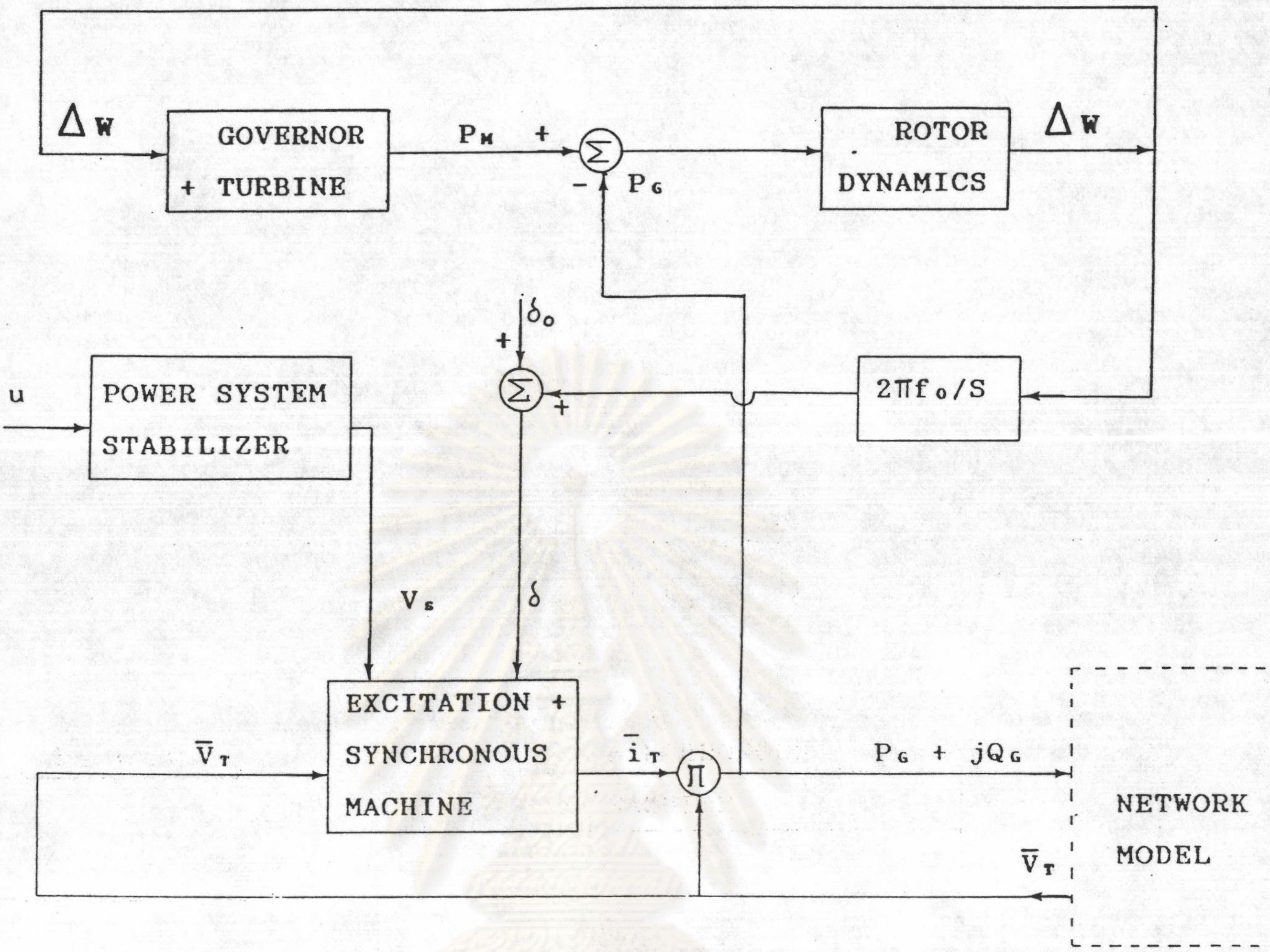
Available methods for calculating the parameters of the equivalent generating unit model can be divided into two methods:

- Weighting of the transfer functions of the various individaul unit models[5].
- Aggregated of the transfer functions of the various individual unit models [2,6].

The first method is used in this thesis. The unit model parameters of the equivalent machine are calculated as weighted mean values of the parameters of the machines include in the coherent group.

By the definition of coherency, coherent generating units have the same speed w, and the same terminal voltage V_T, since they are attached to a common bus as a result of generator buses reduction.

The block diagram of Figure 3.1 represents the functional relations between the mechanical input power and electrical output power of an individual generating unit and its speed w, and the terminal voltage V_T , these being considered as input variables.



Definition of Variable:

ΔW = p.u. frequency deviation

P_M = total mechanical power in p.u.

P_G = total active power output in p.u.

Q_G = total reactive power output in p.u.

V_T = terminal voltage

i_T = terminal current

u = power system stabilizer input signal

V_s = power system stabilizer output

δ = angle of machine internal voltage

S = Laplace operator

Figure 3.1 Generating Unit Model

A similar block diagram is used to model an equivalent generating unit, with the individual mechanical power replaced by the sum of individual mechanical power in the coherent group and the electrical power replaced by the sum of individual electrical power in the coherent group.

The method for identifying the parameters of the equivalent generating unit models can be done by considering separately the rotor dynamics, the governor and turbine systems, the electric-magnetic circuits of synchronous machine, the excitation systems and the power system stabilizing systems.

3.2 Rotor dynamics

The mechanical equation for one machine is described by:

$$2.H_j.[d\Delta W_j/dt] = P_{Mj} - P_{Gj} - D_j.\Delta W_j \qquad (3.1)$$

where ΔW = frequency deviation in per-unit values

H = inertia constant of rotor and turbine in MWs/MVA

P_M = mechanical power in per-unit values

P_G = electrical power in per-unit vaules

D = damping constant in per-unit values

j = machine subscript

As all machines in a coherent group have the same frequency deviation, the equation of motion of the equivalent machine can be arrived at by adding up the equation of motion of all machines in the coherent group:

$$[\sum_{j=1}^{n} 2.H_j].[d\Delta W_j/dt] = \sum_{j=1}^{n} P_{Mj} - \sum_{j=1}^{n} P_{Gj} - \sum_{j=1}^{n} D_j.\Delta W_j \qquad (3.2)$$

This assumes that all parameters being referred to the same base MVA. If, however, the parameters being referred to the rated outputs of the individual machine as base MVA, we obtain:

$$H_e = \sum_{j=1}^{n} [\, S_{nj}/S_{ne} \,].H_j \tag{3.3}$$

$$D_e = \sum_{j=1}^{n} [\, S_{nj}/S_{ne} \,].D_j \tag{3.4}$$

where H_e = inertia constant of the equivalent machine

D_e = damping constant of the equivalent machine

S_{nj} = rated power output of machine no. j

S_{ne} = rated power output of the equivalent machine

$j = 1,2,.......,n$

3.3 Magnetic circuits of the synchronous machine

Seven different types of the synchronous machine are used in this thesis:

Type 1: Model with one field winding, one damper winding in d-axis and two damper winding in q-axis. Saturation included.

Type 1A: As type 1 but saturation excluded.

Type 2: Model with one field winding, one damper winding in d-axis and one damper winding in q-axis. Saturation included.

Type 2A: As type 2 but saturation excluded.

Type 3: Model with one field winding and no damper windings. Saturation included.

Type 3A: As 3 but saturation excluded.

Type 4: The machine is modelled with a constant voltage behind the transient reactance.

3.3.1 Equivalent machine time constants

Time constants of the equivalent machine T'_{do}, T''_{do}, T'_{qo} and T''_{qo} are calculated by using the first method, weighted by the rated output power of the coherent machine, the following formulars are obtained:

$$T'_{doe} = [\ 1/S_{ne}\ ].\ \sum_{j=1}^{n} S_{nj}.T'_{doj} \qquad (3.5)$$

$$T''_{doe} = [\ 1/S_{ne}\ ].\ \sum_{j=1}^{n} S_{nj}.T''_{doj} \qquad (3.6)$$

$$T'_{qoe} = [\ 1/S_{ne}\ ].\ \sum_{j=1}^{n} S_{nj}.T'_{qoj} \qquad (3.7)$$

$$T''_{qoe} = [\ 1/S_{ne}\ ].\ \sum_{j=1}^{n} S_{nj}.T''_{qoj} \qquad (3.8)$$

where T'_{doj} = d-axis transient open circuit time constant of machine no. j

T''_{doj} = d-axis subtransient open circuit time constant of machine no. j

T'_{qoj} = q-axis transient open circuit time constant of machine no. j

T''_{qoj} = q-axis subtransient open circuit time constant of machine no. j

T'_{doe} = d-axis transient open circuit time constant of equivalent machine

T''_{doe} = d-axis subtransient open circuit time constant of equivalent machine

T'_{qoe} = q-axis transient open circuit time constant of equivalent machine

T''_{qoe} = q-axis subtransient open circuit time constant of equivalent machine

j = 1,2,.....,n

3.3.2 Equivalent machine reactances

The reactances of the equivalent machines X_d, X_q, X'_d, X'_q, X''_d, X''_q and X_l are calculated by connecting the relevant reactances of the coherent machines in parallel. As the reactances are expressed in per-unit values, referred to rated output and rated voltages of the machines, the following formulars are obtained:

$$X_{de} = [S_{ne}/U^2_{ne}]/[\sum_{j=1}^{n} S_{nj}/(X_{dj}.U^2_{nj})] \tag{3.9}$$

$$X_{qe} = [S_{ne}/U^2_{ne}]/[\sum_{j=1}^{n} S_{nj}/(X_{qj}.U^2_{nj})] \tag{3.10}$$

$$X'_{de} = [S_{ne}/U^2_{ne}]/[\sum_{j=1}^{n} S_{nj}/(X'_{dj}.U^2_{nj})] \tag{3.11}$$

$$X'_{qe} = [S_{ne}/U^2_{ne}]/[\sum_{j=1}^{n} S_{nj}/(X'_{qj}.U^2_{nj})] \tag{3.12}$$

$$X''_{de} = [S_{ne}/U^2_{ne}]/[\sum_{j=1}^{n} S_{nj}/(X''_{dj}.U^2_{nj})] \tag{3.13}$$

$$X''_{qe} = [S_{ne}/U^2_{ne}]/[\sum_{j=1}^{n} S_{nj}/(X''_{qj}.U^2_{nj})] \tag{3.14}$$

$$X_{le} = [S_{ne}/U^2_{ne}]/[\sum_{j=1}^{n} S_{nj}/(X_{lj}.U^2_{nj})] \tag{3.15}$$

where X_{dj} = d-axis reactance of machine no. j
X_{qj} = q-axis reactance of machine no. j
X'_{dj} = d-axis transient reactance of machine no. j
X'_{qj} = q-axis transient reactance of machine no. j
X''_{dj} = d-axis subtransient reactance of machine no. j
X''_{qj} = q-axis subtransient reactance of machine no. j
X_{lj} = leakage reactance of machine no. j
X_{de} = d-axis reactance of equivalent machine

X_{qe} = q-axis reactance of equivalent machine
X'_{de} = d-axis transient reactance of equivalent machine
X'_{qe} = q-axis transient reactance of equivalent machine
X''_{de} = d-axis subtransient reactance of equivalent machine
X''_{qe} = q-axis subtransient reactance of equivalent machine
X_{le} = leakage reactance of equivalent machine
U_{nj} = rated voltage of machine no. j
U_{ne} = rated voltage of equivalent machine
j = 1,2,......,n

3.3.3 Saturation of the magnetic circuits of equivalent machine

The saturation of the magnetic circuits of the synchronous machine depends on parameters S(1.0) and S(1.2) of the individual machine in the coherent group which are defined in eq(3.16) and eq(3.17).

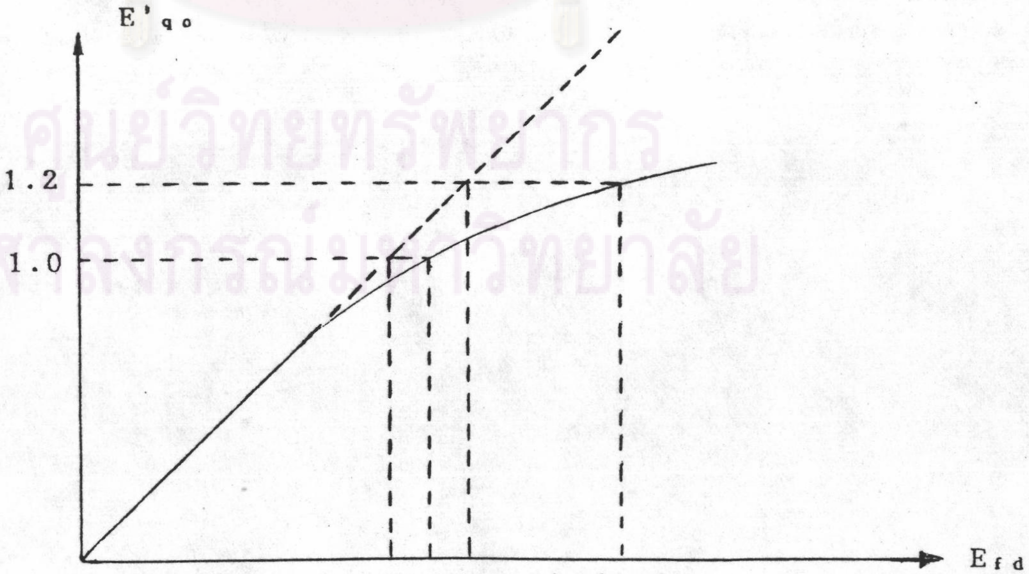


Figure 3.2 The saturation of magnetic circuits

Form the Figure 3.2

$$S(1.0) = [\ A(1.0) - B(1.0)\ ]/\ B(1.0) \qquad (3.16)$$

$$S(1.2) = [\ A(1.2) - B(1.2)\ ]/\ B(1.2) \qquad (3.17)$$

Then the parameters of saturation for the equivalent machine are obtained:

$$S(1.0)_e = [\ 1/\ S_{ne}\ ].\ \sum_{j=1}^{n} S_{nj}.S(1.0)_j \qquad (3.18)$$

$$S(1.2)_e = [\ 1/\ S_{ne}\ ].\ \sum_{j=1}^{n} S_{nj}.S(1.2)_j \qquad (3.19)$$

These values are calculated in the form of weighted mean values in the same way as the time constants.

3.4 Turbine and governing systems

Six types of turbine and three types of governor are used in the thesis.

The types of turbine:

Type 21: Mechanical torque consists of a constant part and a superimposed sinusodial variation as a function of time.

Type 22: Mechanical torque varies with an arbitrary function of time.

Type 3: Mechanical torque consists of a constant part and a part which varies with the speed of the mechine.

Type ST1: Approximate model of steam turbine with single
reheat. (See appendix 2)

Type ST2: General model for steam turbine system.
(See appendix 2)

Type HT1: Classical penstock turbine model 1. (See appendix 2)

The types of governor:

Type SG1: General speed-governing model. (See appendix 2)

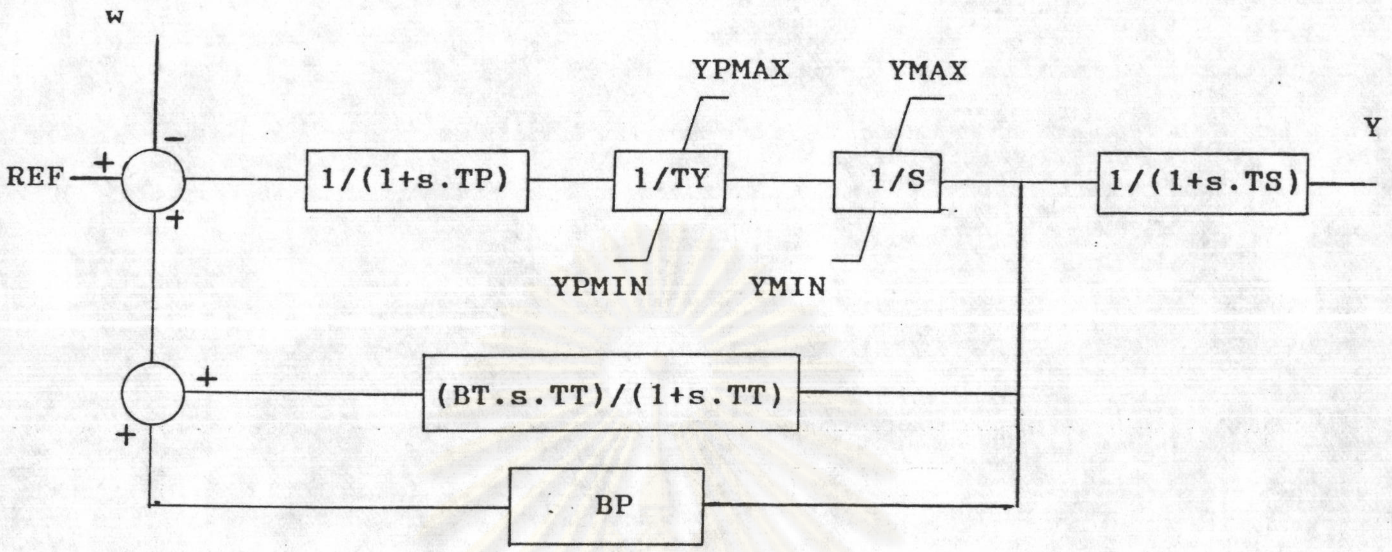
Type SG2: Approximate speed-governing model (steam turbine).
(See appendix 2)

Type SG3: Approximate speed-governig model (hydro-turbine).
(See appendix 2)

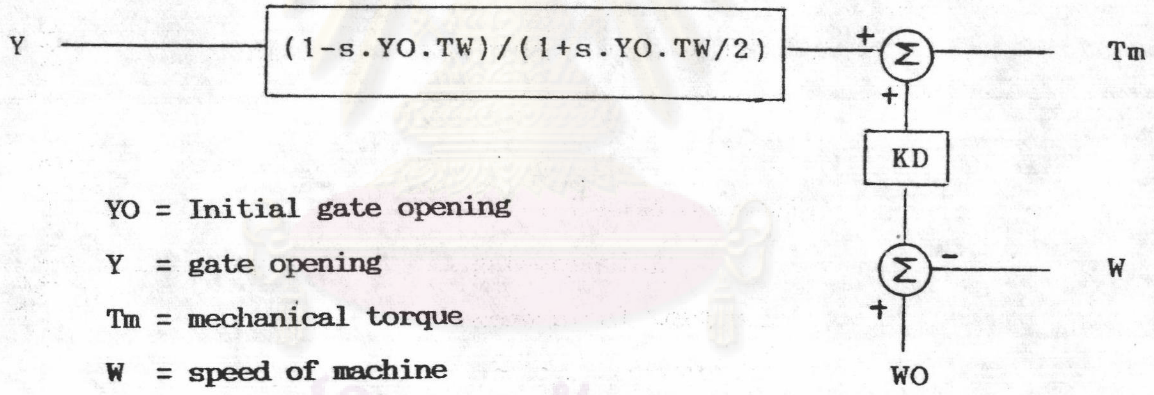
The parameters of turbines and governors for equivalent machines must be calculated as weighted mean values of the parameters of the turbines and governors in the coherent group.

One type of governor-turbine (type SG1 + type HT1) is considered. The extension to more types of governor turbine is straightforward. In the following formular, index i indicates that the parameter belongs to governor turbine no. i and index e indicates that the parameter belongs to the equivalent machine.

Hydro governor-turbine (type SG1 + type HT1) are represented by the following model in the Figure 3.3.



Governor of type SG1



YO = Initial gate opening

Y = gate opening

Tm = mechanical torque

W = speed of machine

W_o = nominal speed

Turbine of type HT1

Figure 3.3 The model of governor-turbine
(type SG3 + type HT1)

where TP = pilot value time constant. Seconds.
TY = response time; pilot or main servo-motor. Seconds.
TS = main servo-motor time constant. Seconds.
TT = transient droop time constant. Seconds.
TW = water starting time.
KD = turbine damping constant.
BT = transient droop constant.
BP = permanent droop constant.
YPMAX = max servo rate limit.
YPMIN = min servo rate limit.
YMAX = max servo position limit.
YMIN = min servo position limit.

The following designation are used in the formular below;

S_{ni} = rated power of machine no. i
S_{nr} = governor power of the coherent group
S_{ntot} = total power of the coherent group

Governor droop 1/BP and 1/BT, together with KD, YPMAX, YPMIN, YMAX and YMIN of equivalent machine are weighted by S_{nr};

$$1/BP_e = (1/S_{nr})\sum_{i=1}^{n}(S_{ni}/BP_i) \tag{3.20}$$

$$1/BT_e = (1/S_{nr})\sum_{i=1}^{n}(S_{ni}/BT_i) \tag{3.21}$$

$$KD_e = (1/S_{nr})\sum_{i=1}^{n}(S_{ni}.KD_i) \tag{3.22}$$

$$YPMIN_e = (1/S_{nr})\sum_{i=1}^{n}(S_{ni}.YPMIN_i) \tag{3.23}$$

$$YPMAX_e = (1/S_{nr})\sum_{i=1}^{n}(S_{ni}.YPMAX_i) \tag{3.24}$$

$$YMAX_e = (1/S_{nr})\sum_{i=1}^{n}(S_{ni}.YMAX_i) \tag{3.25}$$

$$YMIN_e = (1/S_{nr})\sum_{i=1}^{n} (S_{ni}.YMIN_i) \qquad (3.26)$$

Time constants TP, TY, TS and TW are weighted by S_{nr}/BT_e ;

$$TP_e = (BT_e/S_{nr})\sum_{i=1}^{n} (S_{ni}/BT_i).TP_i \qquad (3.27)$$

$$TY_e = (BT_e/S_{nr})\sum_{i=1}^{n} (S_{ni}/BT_i).TY_i \qquad (3.28)$$

$$TS_e = (BT_e/S_{nr})\sum_{i=1}^{n} (S_{ni}/BT_i).TS_i \qquad (3.29)$$

$$TW_e = (BT_e/S_{nr})\sum_{i=1}^{n} (S_{ni}/BT_i).TW_i \qquad (3.30)$$

Time constant TT is weighted by $S_{nr}.BP_e$

$$TT_e = (1/S_{nr}.BT_e)\sum_{i=1}^{n} S_{ni}.BT_i.TT_i \qquad (3.31)$$

Finally, governor droop $1/BP_e$ and $1/BT_e$ are multiplied by a factor which depends on how great a proportion of the machine in the coherent group is fitted with turbine governing

$$1/BP_e = (1/BP_e).(S_{nr}/S_{ntot}) \qquad (3.32)$$

$$1/BT_e = (1/BT_e).(S_{nr}/S_{ntot}) \qquad (3.33)$$

3.5 Excitation systems

Seven types of the excitation systems are used:

Type 1: Excitation system with DC Generator-Comutator Exciter (See appendix 2)

Type 12: Excitation system with Alternator-Rectifier Exciter (See appendix 2)

Type 15: The ASEA Excitation system with Potential Source-Rectifier Exciter (See appendix 2)

Type 4: Excitation system with DC Genertor-Comutator Exciter and Non-Continuously Acting Regulator (See appendix 2)

Type BBC: Static voltage exciter (See appendix 2)

Type ST2: Excitation system with DC Generator-Comutator Exciter (See appendix 2)

Type ST3: Excitation system with DC Generator-Comutator Exciter (See appendix 2)

One type of the excitation system (type 12) is considered. The extension to more type of excitation system is straightforward. In the following formular, index i indicates that the parameter belongs to the excitation no. i and index e indicates that the parameter belongs to the excitation for an equivalent machine.

The excitation system type 12 is represented by the following model in the Figure 3.4.

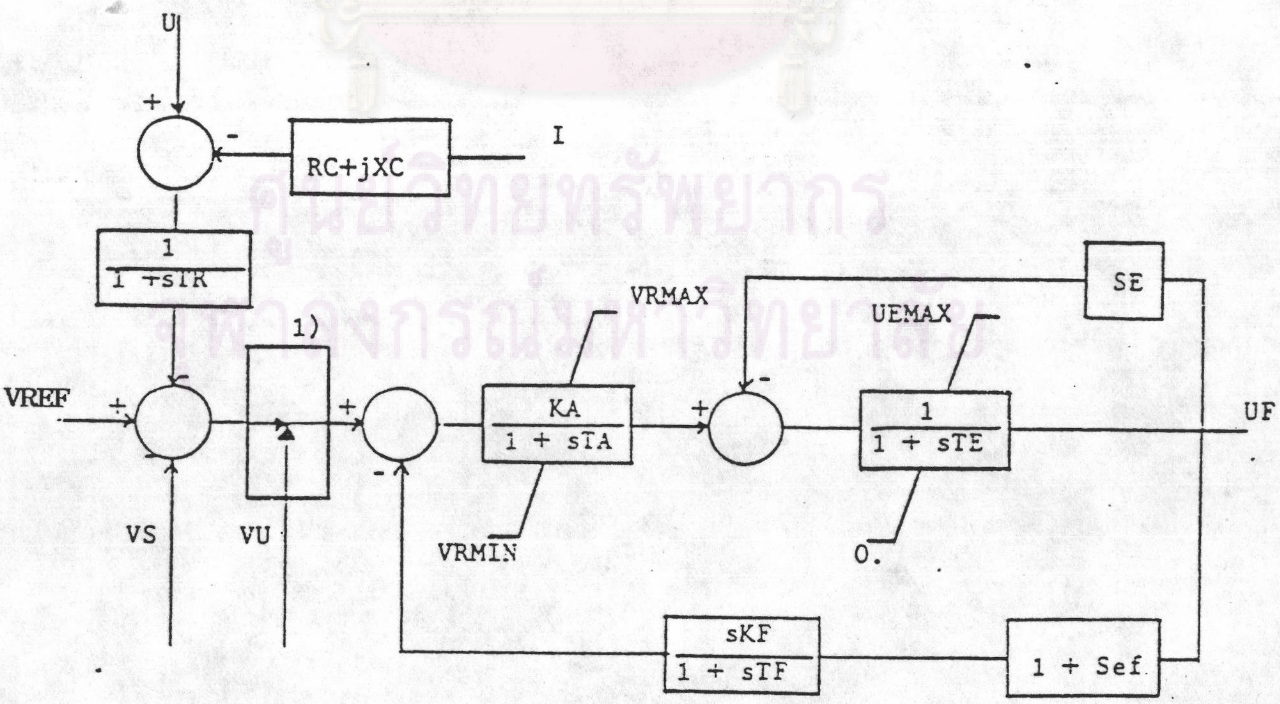


Figure 3.4: The model of the excitation system type 12

where KA = regulator gain

KF = regulator stabilizing circuit gain

TA = regulator time constant

TE = exciter time constant

TF = regulator stabilizing circuit time constant

TR = voltage transducer filter time constant

VRMAX = maximum value of voltage regulator

VRMIN = minimum value of voltage regulator

i = 1,2,......,n

All parameters of the excitation system of an equivalent machine are calculated, as mean values, weighted by the rated output power of individaul machine in the coherent group:

$$KA_e = (1/S_{ne}) \sum_{i=1}^{n} (S_{ni}.KA_i) \tag{3.34}$$

$$KF_e = (1/S_{ne}) \sum_{i=1}^{n} (S_{ni}.KF_i) \tag{3.35}$$

$$TA_e = (1/S_{ne}) \sum_{i=1}^{n} (S_{ni}.TA_i) \tag{3.36}$$

$$TF_e = (1/S_{ne}) \sum_{i=1}^{n} (S_{ni}.TF_i) \tag{3.37}$$

$$TE_e = (1/S_{ne}) \sum_{i=1}^{n} (S_{ni}.TE_i) \tag{3.38}$$

$$TR_e = (1/S_{ne}) \sum_{i=1}^{n} (S_{ni}.TR_i) \tag{3.39}$$

$$VRMAX_e = (1/S_{ne}) \sum_{i=1}^{n} (S_{ni}.VRMAX_i) \tag{3.40}$$

$$VRMIN_e = (1/S_{ne}) \sum_{i=1}^{n} (S_{ni}.VRMIN_i) \tag{3.41}$$

3.6 Other control equipments

For this purpose other control equipments to include, other types of turbine, other types of governor, other types of excitation system and all types of power system stabilizers . Model data for this control equipment is selected so that the equivalent generating unit model has the same control characteristics as the "largest" generating unit model in the coherent group.