A METHOD OF CONSTRUCTING FUZZY CONTROL RULES FOR ELECTRIC POWER SYSTEMS

Tomoyuki Ueda, Atsushi Ishigame, Shunji Kawamoto, and Tsuneo Taniguchi

Department of Electrical Engineering
University of Osaka Prefecture, Sakai, Osaka 591, Japan

ABSTRACT: The paper presents a method of constructing simple fuzzy control rules for the determination of stabilizing signals of automatic voltage regulator and governor, which are controllers of electric power systems. Fuzzy control rules are simplified by considering a coordinate transformation with the rotation angle θ on the phase plane, and by expanding the range of membership functions. Also, two rotation angles θ_1 and θ_2 are selected for the linearizable region and the nonlinear one of the system, respectively. Here, θ_1 is chosen by the pole assignment method, and θ_2 by a performance index. Fuzzy inference is applied to the connection of two rotation angles θ_1 and θ_2 by regarding the distance from the desired equilibrium point as a variable of condition parts. The control effect is demonstrated by an application of the proposed method to one-machine infinite-bus power system.

1. INTRODUCTION

Due to the large scale and complexity of electric power systems, the stabilization has become an important problem. Recently, fuzzy control[1] has been studied for the stabilizing control[2],[3] of electric power systems. The authors have considered an application of fuzzy inference to the determination of stabilizing signals ue and ug of AVR (automatic voltage regulator) and GOV (governor), respectively, which are controllers of electric power systems[4]-[6]. Membership functions of fuzzy control play an important role, but they are chosen by way of trial and error. Therefore, constructing fuzzy control rules with many membership functions is complicated. Thus, it is desirable to construct fuzzy control rules for power systems analytically.

The purpose of this paper is to propose a method of constructing fuzzy control rules for electric power systems analytically, by simplifying variables of condition parts and rules, and minimizing the number of membership functions. In the method I [5], variables of condition parts and rules are simplified by a coordinate transformation with the rotation angle θ on the phase plane and by expanding the range of membership functions. ue and ug can be respectively determined by a rotation angle θ and one membership function which are suitable for each controller. In the method II, two rotation angles θ_1 and θ_2 are selected for the linearizable region of the system, which is the neighborhood of the desired equilibrium point, and for the nonlinear one, respectively. Here, θ_1 is chosen by the pole assignment method, and θ_2 by a performance index. Furthermore, fuzzy inference is applied to the connection of θ_1 and θ_2, by regarding the distance from the desired equilibrium point as a variable of condition parts. To demonstrate the control effect of the methods I and II, simulations are performed by using one-machine infinite-bus system. As the result, rules for AVR and GOV are simplified, the number of membership functions is minimized, and a good control effect is obtained.

2. MODEL SYSTEM

The model system used in this paper is one-machine infinite-bus system, which is shown in Fig.1. Constants of the model system are indicated in Table 1. Block diagrams of AVR and

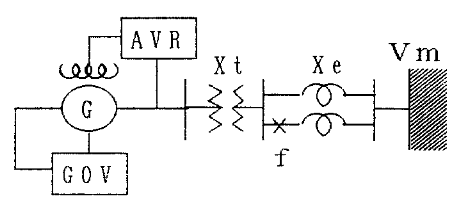


Fig.1 One-machine infinite-bus system.

Table 1 System constants.

$M=5.2_{(s)}$, $D=5.2_{(p.u.)}$, $xd'=0.4_{(p.u.)}$, $xd=1_{(p.u.)}$,	
$xq=0.6_{(p.u.)}$, $Td_0'=2_{(s)}$, $Ta=0.1_{(s)}$, $Ka=5$,	
$Tg=0.3_{(s)}$, $Kg=5$, $xt=0.1_{(p.u.)}$, $xe=0.9_{(p.u.)}$.	

Table 2 The equilibrium point.

$\delta_0=0.775_{(rad)}$, $\omega_0=120\pi_{(rad/sec)}$,	
$eq'_0=1.203_{(p.u.)}$, $ef_0=1.413_{(p.u.)}$,	
$Pm_0=0.557_{(p.u.)}$, $Vt_0=1.1_{(p.u.)}$, $Vm=1.0_{(p.u.)}$.	

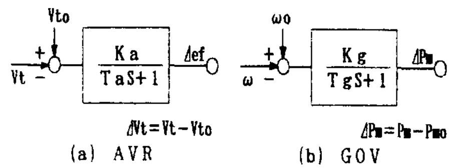


Fig.2 Block diagrams of controllers.

GOV, which are approximated to the first order lag system, are shown in Fig.2. ue and ug are added to the controllers to advance the control effect. Swing equations of the model system are given as follows;

$$d\delta/dt = \Delta\omega, \tag{1}$$

$$d\Delta\omega/dt = (Pm-Pe-D\Delta\omega)/M, \tag{2}$$

$$deq'/dt = (ef-eq'-(xd-xd')id))/Td_0', \tag{3}$$

$$d\Delta ef/dt = (-\Delta ef-Ka\Delta Vt)/Ta+ue/Ta, \tag{4}$$

$$d\Delta Pm/dt = (-\Delta Pm-Kg\Delta\omega/\omega_0)/Tg+ug/Tg, \tag{5}$$

where

$\Delta\delta = \delta-\delta_0$,
$\Delta\omega = \omega-\omega_0$,
$\Delta ef=ef-ef_0$,
$\Delta Pm=Pm-Pm_0$,
$\Delta Vt=Vt-Vt_0$,
δ :rotor phase angle of generator,
ω :rotor speed of generator,
eq':transient induced voltage,
ef :excitation voltage,
Pm :mechanical power input,
Pe :electrical power output,
Vt :terminal voltage,
id :d-axis components of armature current,
M :inertia constant,
D :damping coefficient,
Td_0':time constant of d-axis circuit,
xd :d-axis synchronous reactance,
xd':d-axis transient reactance,
Ka :AVR gain,
Ta :AVR time constant,
Kg :GOV gain,
Tg :GOV time constant,
xt :transformer reactance,
xe :line reactance,
Vm :infinite bus voltage.

Here, "$_0$" denotes the value of variables on the desired equilibrium point. These values for simulations are indicated in Table 2. Also, ue and ug are restricted by

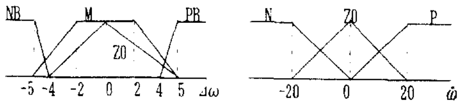
$$-3ef_0 \leq ue-Ka\Delta Vt \leq 3ef_0, \tag{6}$$

$$-0.2Pm_0 \leq ug-Kg\Delta\omega/\omega_0 \leq 0.2Pm_0. \tag{7}$$

3. Fuzzy control

Fuzzy control rules express a relation between the state variable x and the control quantity u such as "if x is Negative Big then u is Positive Big", and are constructed under knowledge and experience of an expert. To determine ue and ug, fuzzy control rules are constructed under the equal area method on the phase plane of $\Delta\delta$-$\Delta\omega$ or $\Delta\omega$-$\dot{\omega}$ ($\dot{\omega}$:the rotor acceleration of generator). For constructing rules, the sign of ue and ug is much related to that of $\Delta\omega$ than others. That is to say, for AVR, if $\Delta\omega$ is positive (negative), the excitation must be increased (decreased), that is, $ue>0$ ($ue<0$). For GOV, if $\Delta\omega$ is positive (negative), the valve must be closed (opened), $ug<0$ ($ug>0$). However, in practice, applying control rules earlier as a preceding control is necessary because of the delay time in the system. Therefore, $\Delta\delta$ or $\dot{\omega}$ should be added to variables of the condition parts.

One example of the previous fuzzy control rules[4] constructed for the model system (Fig.1) is shown in Fig.3. In the rules, $\Delta\omega$ and $\dot{\omega}$ are used as variables of the condition parts. Membership functions are used only in the condition parts. In the operation parts, constants instead of fuzzy sets are used, and ue and ug are obtained as eqs.(8) and (9) in Fig.3 by the weighted average method. However ue and ug must not exceed the restriction of eqs.(6) and (7). In rules of AVR and GOV, Rule1 and Rule2 are rules based on the knowledge that the sign of ue and ug is much related to that of $\Delta\omega$ than others, Rule3 and Rule4 are preceding control rules, and Rule5 is a rule for the neighborhood of the desired equilibrium point. It is difficult to construct such five rules for each controller by way of trial and error. Especially, procedures for constructing the preceding control rules, *AVR



Rule1 if ⊿ω is PB then ue1=uemax

Rule2 if ⊿ω is NB then ue2=uemin

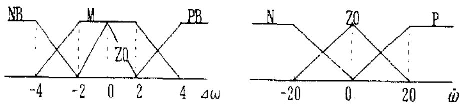
Rule3 if ⊿ω is M and $\dot{\omega}$ is N then ue3=uemin/2

Rule4 if ⊿ω is M and $\dot{\omega}$ is P then ue4=uemax/2

Rule5 if ⊿ω is ZO and $\dot{\omega}$ is ZO then ue5=0

$$ue=\frac{\Sigma\ \lambda_i\, uei}{\Sigma\ \lambda_i} \qquad (i=1\sim5) \qquad (8)$$

*GOV



Rule1 if ⊿ω is PB then ug1=ugmax

Rule2 if ⊿ω is NB then ug2=ugmin

Rule3 if ⊿ω is M and $\dot{\omega}$ is N then ug3=ugmin/2

Rule4 if ⊿ω is M and $\dot{\omega}$ is P then ug4=ugmax/2

Rule5 if ⊿ω is ZO and $\dot{\omega}$ is ZO then ug5=0

$$ug=\frac{\Sigma\ \mu_i\, ugi}{\Sigma\ \mu_i} \qquad (i=1\sim5) \qquad (9)$$

where PB:Positive Big , NB:Negative Big , M:Medium , P:Positive, N:Negative , ZO:Zero , λ_i, μ_i:grades of the condition parts, uemax=3ef$_0$, uemin=-3ef$_0$, ugmax=0.2Pm$_0$, ugmin=-0.2Pm$_0$.

Fig.3 The previous fuzzy control rules[4].

which combine membership functions of ⊿ω and $\dot{\omega}$, are too complicated.

4. A simplification of constructing membership functions (The method I [5])

The method I proposed in this chapter has two aims, that is, simplifying variables of the condition parts and rules , and minimizing the number of membership functions. In the method I , rules are constructed on the ⊿ω-$\dot{\omega}_1$ phase plane ($\dot{\omega}_1$=k$\dot{\omega}$, k:positive constant). For the first aim, instead of constructing the preceding control rules, the rotation angle θ of a coordinate transformation on the phase plane is introduced as shown in Fig.4. The choice of θ is much easier than constructing the preceding control rules such as Rule3 or Rule4 in Fig.3. Therefore, variables of the condition parts come to be only ⊿$\tilde{\omega}$ (=⊿ω cosθ + $\dot{\omega}_1$ sinθ). For the second, since ue and ug seem to have the symmetry with respect to the sign of ⊿$\tilde{\omega}$, the number of rules can be decreased by expanding the range of membership functions from [0,1] to [-1,1]. Consequently, the number of membership functions for each controller are decreased to only one. Here, the membership function for AVR is

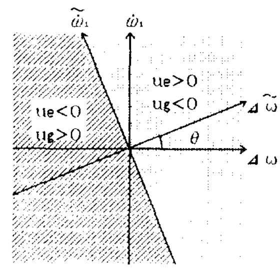


Fig.4 Coordinate transformation.

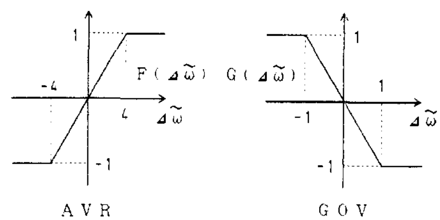


Fig.5 Membership functions.

represented as F(⊿$\tilde{\omega}$), and that for GOV is as G(⊿$\tilde{\omega}$). Examples of F(⊿$\tilde{\omega}$) and G(⊿$\tilde{\omega}$) are shown in Fig.5. For the construction of F(⊿$\tilde{\omega}$) and G(⊿$\tilde{\omega}$), it is necessary to consider the inertia constant M because ⊿ω receives its influence. Then, ue and ug are given by

$$ue=aF(⊿\tilde{\omega}) \ , \quad ug=bG(⊿\tilde{\omega}) \ , \qquad (10)$$

where a,b: the greatest values of ue and ug.

Thus, by the method I , five rules in the previous fuzzy control for each controller can be represented by the rotation angle θ and one membership function.

To demonstrate the control effect of the method I , simulations are performed under the three-phase short circuit fault for 0.22(sec) at the point f of one-machine infinite-bus system (Fig.1). As soon as the fault is cleared, the transmission of electricity by two lines is switched to that by one line, and AVR and GOV are operated. Constants k, θ, a, and b are given as

$$k=0.25, \quad \theta_{AVR}=35^\circ \ , \quad \theta_{GOV}=30^\circ \ ,$$

$$a=3ef_0, \quad b=0.2Pm_0,$$

and F(⊿$\tilde{\omega}$) and G(⊿$\tilde{\omega}$) are shown in Fig.5. Time responses of ⊿δ and ⊿ω are illustrated in Figs.6 and 7 with the result of No-control and the previous fuzzy control. In Fig.6, for the first swing, the method I is inferior to the

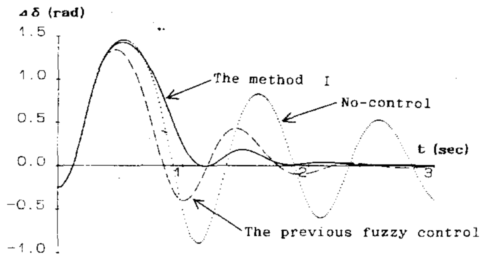


Fig.6 Time responses of $\Delta\delta$.

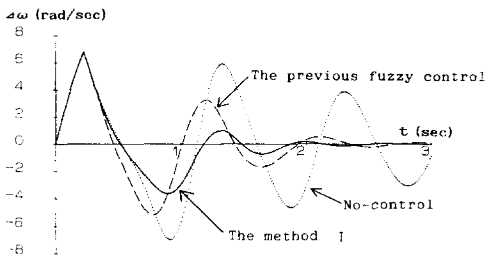


Fig.7 Time responses of $\Delta\omega$.

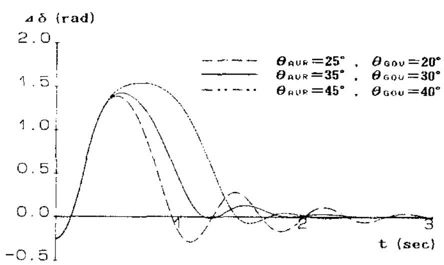


Fig.8 Time responses of $\Delta\delta$ with the parameter θ.

previous fuzzy control, but for swings on and after the second one, the former is superior to the latter. In Fig.7, time response of $\Delta\omega$ by the method I converge to the desired equilibrium point faster than that by the previous fuzzy control, and the method I gives an improvement in transient stability.

In the method I, the rotation angle θ is chosen by way of trial and error. Time responses of $\Delta\delta$ with the parameter θ is shown in Fig.8. If θ is set larger (smaller), the control effect for the first swing becomes better(worse), but that for swings on and after the second one becomes worse (better).

5. An application of fuzzy inference to the rotation angle θ (The method II)

In the method I, the rotation angle θ, which corresponds to the delay time, is chosen by way of trial and error. The method II proposed in this chapter presents an approach to obtain θ analytically.

In the method II, the electric power system is divided into two regions. One is a linearizable region which can be approximated the electric power system as a linear system in the neighborhood of the desired equilibrium point. Another is a nonlinear region. First, in the linearizable region, membership functions $F(\Delta\tilde{\omega})$ and $G(\Delta\tilde{\omega})$ shown in Fig.5 can be obtained as

$$F(\Delta\tilde{\omega}) = \frac{1}{4}\Delta\tilde{\omega} = \frac{1}{4}(\Delta\omega\cos\theta_{AVR} + k\dot{\omega}\sin\theta_{AVR}), \quad (11)$$

$$G(\Delta\tilde{\omega}) = -\Delta\tilde{\omega} = -(\Delta\omega\cos\theta_{GOV} + k\dot{\omega}\sin\theta_{GOV}). \quad (12)$$

By substituting eqs. (11) and (12) into eq.(10), ue and ug are given by

$$ue = \frac{a}{4}(\Delta\omega\cos\theta_{AVR} + k\dot{\omega}\sin\theta_{AVR}), \quad (13)$$

$$Ug = -b(\Delta\omega\cos\theta_{GOV} + k\dot{\omega}\sin\theta_{GOV}). \quad (14)$$

Substituting eq.(2) into $\dot{\omega}$ of eqs.(13) and (14), eq.(13) into eq.(4), and eq.(14) into eq.(5), gives

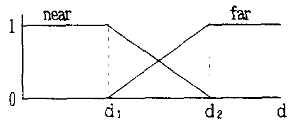
$$\frac{d\Delta ef}{dt} = \frac{1}{Ta}(-\Delta ef - Ka\Delta Vt) + \frac{a}{4Ta}\{\Delta\omega\cos\theta_{AVR} + \frac{k}{M}(Pm-Pe-D\Delta\omega)\sin\theta_{AVR}\}, \quad (15)$$

$$\frac{d\Delta Pm}{dt} = \frac{1}{Tg}(-\Delta Pm - Kg\frac{\Delta\omega}{\omega_0}) - \frac{b}{Tg}\{\Delta\omega\cos\theta_{GOV} + \frac{k}{M}(Pm-Pe-D\Delta\omega)\sin\theta_{GOV}\}. \quad (16)$$

At the desired equilibrium point, eqs.(1), (2), (3), (15), and (16) can be linearized as

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}. \quad (17)$$

By the pole assignment method[7], θ_{AVR1} and θ_{GOV1} are chosen to give the greatest absolute value of the real part in the dominant roots of $\mathbf{A}$ depending on θ_{AVR} and θ_{GOV} (see Appendix for $\mathbf{A}$). Then, the rotation angle θ_1 in the linearizable region can be given by θ_{AVR1} and θ_{GOV1}. Secondly, in the nonlinear region, θ_{AVR2}



*AVR

Rule1 if d is near then $\theta_{AVR}=\theta_{AVR1}$ and $ue1=aF(\Delta\tilde{\omega}_1)$

Rule2 if d is far then $\theta_{AVR}=\theta_{AVR2}$ and $ue2=aF(\Delta\tilde{\omega}_2)$

*GOV

Rule1 if d is near then $\theta_{GOV}=\theta_{GOV1}$ and $ug1=bG(\Delta\tilde{\omega}_1)$

Rule2 if d is far then $\theta_{GOV}=\theta_{GOV2}$ and $ug2=bG(\Delta\tilde{\omega}_2)$

$$ue=\frac{\varepsilon_1 ue1+\varepsilon_2 ue2}{\varepsilon_1+\varepsilon_2} \qquad ug=\frac{\eta_1 ug1+\eta_2 ug2}{\eta_1+\eta_2} \tag{19}$$

where $d=(\Delta\omega^2+\dot{\omega}_1^2)^{1/2}$, $\varepsilon_1, \varepsilon_2, \eta_1, \eta_2$:grades of the condition parts.

Fig.9 Rules for fuzzy inference.

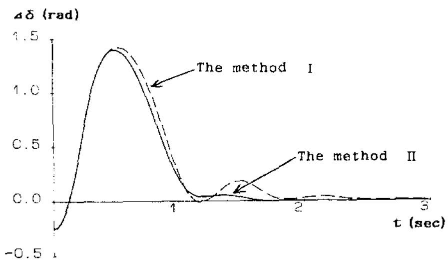


Fig.10 Time responses of $\Delta\delta$.

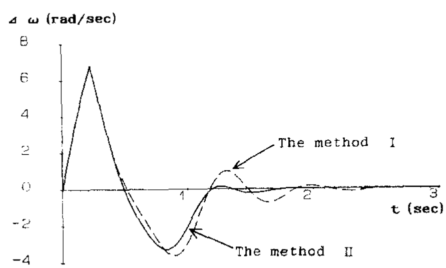


Fig.11 Time responses of $\Delta\omega$.

and θ_{GOV2} as θ_2 are chosen by the following performance index ;

$$J=\int_0^T t\,|\Delta\delta|\,dt \ , \tag{18}$$

where T: simulation time.

This index is related to the speed of response and the stability. Also, fuzzy inference is applied to the connection of two rotation angles θ_1 and θ_2 by regarding the distance d from the desired equilibrium point as a variable of the condition parts. The rules are shown in Fig.9. Rule1 indicates a rule for the linearizable region, and Rule2 for the nonlinear region.

To demonstrate the control effect of the method II, simulations are performed. The fault condition, k, a, b, $F(\Delta\tilde{\omega})$, and $G(\Delta\tilde{\omega})$ are the same as those of the method I in chapter4. θ_{AVR1}, θ_{AVR2}, θ_{GOV1}, θ_{GOV2}, d_1, and d_2 in Fig.9 are given as

$$\theta_{AVR1}=48^\circ \ , \ \theta_{AVR2}=33^\circ \ , \ \theta_{GOV1}=47^\circ \ ,$$

$$\theta_{GOV2}=12^\circ \ , \ d_1=3, \quad d_2=7.$$

Time responses of $\Delta\delta$ and $\Delta\omega$ are illustrated in Figs.10 and 11 with the result of the method I. In Figs.10 and 11, it turns out that time responses of $\Delta\delta$ and $\Delta\omega$ by the method II converge to the desired equilibrium point faster than those by the method I.

6.CONCLUSION

A method of constructing fuzzy control rules for electric power systems has been proposed in this paper. By the coordinate transformation and expanding the range of membership functions, variables of the condition parts and fuzzy control rules are simplified, and the number of membership functions is minimized. By considering the rotation angles θ_1 for the linearizable region and θ_2 for the nonlinear region, the control effect can be improved. However, membership functions $F(\Delta\tilde{\omega})$ and $G(\Delta\tilde{\omega})$ are constructed by way of trial and error. An analytical construction of $F(\Delta\tilde{\omega})$ and $G(\Delta\tilde{\omega})$, and an application to multi-machine electric power systems are presently being investigated.

The authors would like to thank Mr. T.Imoto and Mr. A.Tanaka for simulations. This work is partly supported by Grant-in-Aid for Scientific Research of Ministry of Education, Japan, under Grant No.02750193.

7.REFERENCES

[1] M.Sugeno, "Fuzzy control," Nikkankogyo-shinbun Publ.Co., 1988. (in Japanese)

[2] T.Hiyama, "Application of rule-based stabilising controller to electric power system," IEE Proc., Vol.136, Pt.C, No.3, pp.175-181, 1989.

[3] T.Hiyama, and T.Nakano, "Application of fuzzy logic stabilizer to electric power system," '88 KIEE ANNUAL CONFERENCE International Sessions 88.11., pp.33-37, 1988.

[4] T.Imoto, T.Ueda, A.Ishigame, and T.Taniguchi, "Fuzzy control for stabilizing electric power systems," IEE of Japan, Spring Meeting, Vol.8, No.1055, pp.224, 1989. (in Japanese)

[5] T.Ueda, A.Ishigame, S.Kawamoto, and T.Taniguchi, "Simplification of constructing membership functions of fuzzy control for power systems," IEE of Japan, Vol.110B, No.5, pp.445-446, 1990. (in Japanese)

[6] A.Ishigame, T.Imoto, S.Kawamoto, and T.Taniguchi," Combination of fuzzy and optimal controls for stabilizing power systems," IEE of Japan, Vol.110B, No.10, 1990 (to be published, in Japanese)

[7] M.Ito, "Automatic control," Maruzen Publ.Co., 1981. (in Japanese)

8.APPENDIX

$\mathbf{x}$ and $\mathbf{A}$ in eq.(17) are given as follows;

$$\mathbf{x} = \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta eq' \\ \Delta ef \\ \Delta Pm \end{bmatrix} = \begin{bmatrix} \delta - \delta_o \\ \omega - \omega_o \\ eq' - eq'_o \\ ef - ef_o \\ Pm - Pm_o \end{bmatrix}, \qquad (A.1)$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ A_{21} & -D/M & A_{23} & 0 & 1/M \\ A_{31} & 0 & A_{33} & 1/Td_o' & 0 \\ A_{41} & A_{42} & A_{43} & -1/Ta & A_{45} \\ A_{51} & A_{52} & A_{53} & 0 & A_{55} \end{bmatrix}, \qquad (A.2)$$

where

$$A_{21} = \frac{1}{M}\left\{-\frac{eq'_o Vm\cos\delta_o}{xe+xd'} + \frac{(xq-xd')Vm^2\cos(2\delta_o)}{(xe+xd')(xe+xq)}\right\},$$

$$A_{22} = -\frac{Vm\sin\delta_o}{M(xe+xd')},$$

$$A_{31} = -\frac{(xd-xd')Vm\sin\delta_o}{Td_o'(xe+xd')},$$

$$A_{33} = -\frac{(xe+xd)}{Td_o'(xe+xd')},$$

$$A_{41} = -\frac{Ka\{(P^2-R^2)\sin\delta_o\cos\delta_o - QReq'_o\sin\delta_o\}}{Ta\{P^2\sin^2\delta_o+(Qeq'_o+R\cos\delta_o)^2\}^{1/2}} + \frac{ak\sin\theta_{AVR}}{4MTa}\left\{-\frac{eq'_o Vm\cos\delta_o}{xe+xd'} + \frac{(xq-xd')Vm^2\cos(2\delta_o)}{(xe+xd')(xe+xq)}\right\},$$

$$A_{42} = \frac{a\cos\theta_{AVR}}{4Ta} - \frac{aDk\sin\theta_{AVR}}{4MTa},$$

$$A_{43} = -\frac{Ka(Q^2eq'_o+QR\cos\delta_o)}{Ta\{P^2\sin^2\delta_o+(Qeq'_o+R\cos\delta_o)^2\}^{1/2}} - \frac{akVm\sin\delta_o\sin\theta_{AVR}}{4MTa(xe+xd')},$$

$$A_{45} = \frac{ak\sin\theta_{AVR}}{4MTa},$$

$$A_{51} = -\frac{bk\sin\theta_{GOV}}{MTg}\left\{-\frac{eq'_o Vm\cos\delta_o}{xe+xd'} + \frac{(xq-xd')Vm^2\cos(2\delta_o)}{(xe+xd')(xe+xq)}\right\},$$

$$A_{52} = -\frac{1}{Tg}\left(\frac{Kg}{\omega_o} + b\cos\theta_{GOV} - \frac{D}{M}bk\sin\theta_{GOV}\right),$$

$$A_{53} = \frac{bkVm\sin\delta_o\sin\theta_{GOV}}{MTg(xe+xd')},$$

$$A_{55} = -\frac{1}{Tg} - \frac{bk\sin\theta_{GOV}}{MTg},$$

$$P = \frac{xqVm}{xe+xq}, \quad Q = \frac{xe}{xe+xd'}, \quad R = \frac{xd'Vm}{xe+xd'}.$$