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AN ARTIFICIAL NEURAL NETWORK BASED POWER SYSTEM STATIC VAR REGULATOR

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ABSTRACT

An Artificial Neural Network (*ANN*) based power system static VAR controller is developed. The Static *VAR* Compensator (*SVC*) (Thyristor Controlled -Fixed Capacitor (*TCRFC*) type) is used for voltage regulation and enhancing power system stability. The *ANN* is trained off-line using the Variable Structure control system data at different operating conditions and various external disturbances. Moreover, the trained *ANN* parameters are tuned and updated on-line using the synchronous machine speed deviation state as *ANN* output error. A sample digital simulation results of the power system speed deviation state responses are obtained when reference terminal voltage, speed state, and input torque disturbances take place. The digital simulation results prove the effectiveness and robustness of the present Adaptive Neural Network in terms of high performance power system and fast damping response of the power system electromechanical mode oscillations.

KEY WORDS : Computer Applications

1- INTRODUCTION

It is well known that the power system operates as a highly nonlinear dynamic system. The power system stability depends upon operating point condition. An additional signal to the excitation system of synchronous machine has been developed to enhance power system stability[1-3]. Different control techniques have been applied to design a controller called power system stabilizer (PSS) to generate the additional signal [4-6]. The non-linear model of the power system is linearized to employ linear control methods that is used to develop *PSS*.

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Recently a Variable Structure sliding control technique has been implemented to establish the *PSS*. However, the mathematics of the variable structure controller is complicated that prohibits its real time implementation . Moreover, the controlled plant using variable structure control system is an oscillatory and requires plant of large inertia. With advent of Artificial Neural Network (*ANN*) computational model , an open field to system identification and system control has been appeared [7],[8] . The present paper utilizes the *ANN* to emulate the variable structure sliding mode controller to design a Static *VAR* power system stabilizer.

2- POWER SYSTEM REPRESENTATION

The simulated power system consists of a synchronous machine with excitation control system connected to Infinite Bus Bar through double circuit transmission lines as shown in fig.(1). Furthermore, a *SVC* (Fixed Capacitor-Thyristor Controlled Reactor (*FCTCR)* type) is connected to machine terminal. As known,the power system is non linear dynamic system and the linearized mathematical model at nominal operating points(P=0.8 p.u.,power factor=0.8 lag, Voltage=1.0 p.u.) is obtained and is listed in appendix.

3- STATIC VAR COMPENSATOR MODEL

With advent of power electronic switches, the controlled static reactive devices have been designed instead of mechanical switches . Moreover, the *SVC* has advantages in sense of fast response with less maintenance requirement compared with mechanical ones. The electrical engineers first utilizes the *SVC* to regulate the voltage and improve the power factor. Recently the *SVC* is applied to enhance the power system stability and increase the transmission long line capability. The *SVC* includes mainly Thyristor-controlled reactor (*TCR)*,Thyristor-switched capacitor (*TSC)* , Fixed capacitor,Thyristor controlled reactor *(FCTCR)* and Thyristor-switched capacitor, Thyristor controlled reactor (*TSCTCR)*. The *FCTCR* type is used in this work as shown in fig.(1) . The essential feature of the *SVC* is that the equivalent susceptance ($B_c - B_L$) changes with thyirstor firing delay angle control and in turns the reactive current injected or absorbed from power system is regulated [9-11]. The main work is that how to control and generate the control signal of the electron switch. The present work uses the *SVC* to enhance and restore the power system stability after different disturbances applied upon power system. The *SVC* control model is shown in fig.(2). The input signal to *SVC* control circuit is the terminal voltage error compensated by adjusting the firing delay angle of the *SVC* thyristors. An additional signal is generated by variable structure control system to restore the power system stability due to different disturbances. That the above additional signal is added to terminal voltage error($V_{ref} - V_t$) to change the firing delay angle of the *SVC* thyristors and therefore the SVC equivalent susceptance changes as shown in fig (2) . However, the variable structure control system is complicated and it is difficult to work on line. The Artificial Neural Network approach is employed in the present work to design controller to stabilize the power system in fast time and it is possible to apply on-line.

4- VARIABLE STRUCTURE CONTROL SYSTEM

The adaptive model reference control (*AMRC*) system is designed to make the controlled plant tracks the predefined model reference response . Moreover, The *AMRC* is insensitive to the variation of the controlled plant parameters . However, the *AMRC* is complicated and difficult to implement on line. The Variable structure sliding mode control technique is basically *MRAC* but is easier to implement than the conventional *MRAC* [12]. The present paper uses the Variable Structure sliding mode control system to design a Static *VAR* power system stabilizer. The Variable Structure sliding mode control technique construction is shown in fig.(3).

The control action of the above Variable Structure controller is given by:

- $U = -\Psi_1 \Delta\omega - \Psi_2 \Delta\delta$ (1)

where

$$\Psi_i = \begin{cases} \alpha_{.i} \text{ if } X_{.i}\, S > 0.0 \\ . \\ \alpha_i \text{ if } X_{.i}\, S < .0.0 \end{cases} \qquad i = 1,2 \qquad (2).$$

U is controller output signal sent to the control circuit of the *SVC*' s thyristors used for power system stabilizer.

$X_{.1}$, X_2 are $\Delta\omega$ and , $\Delta\delta$ respectively

and S is the switching hyperplane and equals

$$S = C\,X = 0.0 \qquad (3)$$

and C is calculated using pole assignment technique as follows:

The controlled plant state-space model is given by:

$$\dot{X} = A\,X + b\,U \tag{4}$$

and.

choosing the coordinate transformation M

$$Z = M.X \tag{5}$$

in order that

$$M.b = \begin{bmatrix} 0 \\ b_2 \end{bmatrix} \tag{6}$$

by substituting $X = M^{-1} Z$ in equation (4) results

$$Z = M\,A\,M^{-1}\,Z + M\,b\,U \tag{7}$$

by partitioning Z such that $Z = [Z^T_1 \quad Z^T_2]$ such that

Z^T_2 to be scalar Then equation (7) yields

$$\begin{bmatrix} \dot{Z}_1 \\ \dot{Z}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b_2 \end{bmatrix} U \tag{8}$$

$A_{11}, A_{12}, A_{21}, A_{22}$ are the submatrices making the MAM^{-1} matrix

from equation (8)

$$\dot{Z}_1 = A_{11}\,Z_1 + A_{12}\,Z_2 \tag{9}$$

$$\dot{Z}_2 = A_{21}\,Z_1 + A_{22}\,Z_2 + b_2 U \tag{10}$$

equation (9) describes the dynamic response of the open – loop control system with state vector Z_1 and control signal Z_2.

Since the pair (A, b) is assumed to be controllable, the pair (A_{11}, A_{12}) is also controllable[12]

By substituting $X = M^{-1} Z$ in equation (3)

$$\sigma = C^T M^{-1} Z = 0.0 \tag{11}$$

writing $C^T M^{-1} = [C^T_1\ C_2]$ where C_1 is a $(n-1)$ columan vector and C_2 a scalar, then equation (11) may be written by

$$C^T_1\,Z_1 + C_2\,Z_2 = 0.0 \tag{12}$$

assuming $C_2 = 1$, results

$$Z_2 = -C^T_1\,Z_1 \tag{13}$$

the equations of the sliding mode in closed loop form can be expressed as

$$\dot{Z}_1 = (A_{11} - A_{12}\,C^T_1)\,Z_1 = A_c\,Z_1 \tag{14}$$

The eignvalues of matrix A_c may be placed arbitrarily in the complex plane

The algorithm for determine S can be summarized as follows

(1) select the transformation matrix M

(2) calculate the vector C_1 such that the eigenvalues.

$\lambda_1, \ldots, \lambda_{n-1}$ of the matrix A_c describing the dynamic behaviour in sliding mode.

(3) choose the equation of the hyperplane to be of the form.

$$S = [C^T_1 \quad 1]\,M\,X = 0.0 \tag{15}$$

Using the above controller to stabilize the power system due to different disturbances (speed state deviations disturbance, operating point changes, reference terminal voltage disturbance, input power disturbance) ,the power system speed deviation state responses are stored and used with control signals to train the Artificial Neural Network to emulate the Variable structure control system with less calculating time and less computer memory and to interpolate the control signal at points not used in the training stage.

5- ADAPTIVE ARTIFICIAL NEURAL NETWORK APPROACH

The Artificial Neural Network (*ANN*) has the ability to learn and emulate any object or plant which can not be represented in a mathematical form. The power system engineers utilize the *ANN* in system identification and design of controller . The present paper employs the *ANN* approach to design a Static *VAR* power system stabilizer. However, the *ANN* should be trained off-line using benchmark data . The power system response due to different disturbances using the above mentioned variable structure controller is used for off-line training of the *ANN* . The *ANN* structure as shown in fig.(4) consists of input layer, hidden layer, and output layer. The hidden layer has three neurons. The input states which are used for training the *ANN* are the speed deviation state responses at time sample (k), (k-1), (k-2), torque angle deviation state responses at time sample (k), (k-1) , (k-2), and feedback output control signal at time sample (k-1) , (k-2). While the *ANN* output state represents the control signal to controlled plant of Static *VAR* power system stabilizer , U at time sample (k). . All above states responses are obtained and collected when different disturbances such as operating point changes, reference terminal voltage disturbances, and input mechanical power disturbance reapplied . The MATLAB Neural Network package is used for training *ANN* . The following statistical results of *ANN* are obtained and given by:

Momentum constant = .95
learning factor =.001
No_ of iterations = 2000
No_of data = 1500
sum squared error =.0001
transfer function of hidden and output nodes are tansigmoid function.

After training stage completed , the trained *ANN* parameters (link weights and node biases) are obtained. The power system responses using the trained *ANN* power system stabilizer due to different disturbances not used in learning stage data are obtained.To enhance the power system stability using the

trained *ANN* , the *ANN* parameters are updated and tuned on line using the speed deviation state signal.

The following steps describe the on-line *ANN* connection weights and node thresholds tune approach :

step 1 : compute the input to hidden layer nodes
step 2 :compute the output of hidden layer nodes
step 3 : compute the output of output layer node
step 4 : update the weights from hidden to output layer
step 5 : update the weights from input to hidden layer
step 6 : update the biases of output nodes
step 7 : update the biases of hidden nodes

6- RESULTS AND DISCUSSIONS

Fig. (5) shows the power system with Static *VAR* power system stabilizer. The power system speed deviation state response due to speed deviation disturbance (.05 p.u.) at different operating point conditions were not used in the *ANN* training stage given by (P=.8p.u.,Q=.62 p.u).,(P=.65p.u,Q=.62p.u.,),(P=.8p.u,Q=.5p.u),and (P= .8p.u,Q=-.5p.u) are shown in figs (6),(7),(8),(9) respectively using The proposed *ANN* and Variable structure control system. While fig (10) depicts the speed deviation response due to input power disturbance (torque disturbance =.15 p.u) was not used in the *ANN* training data at operating point (P=.8p.u.,Q=.62 p.u.). when reference terminal voltage disturbances (.15 p.u.) the power system speed deviation response at (P=.8p.u,Q=.62p.u.) is shown in fig.(11). The above digital results prove the effectiveness and robustness the *ANN* Static *VAR* power system stabilizer in terms of fast response and high performance power system compared to the Variable structure control system. Furthermore, The *ANN* controller is simple and has fast action over the complicated variable structure controller.

7- CONCLUSIONS

This paper aims at developing power system Static *VAR* Stabilizer based on Artificial Neural Network *ANN* approach . The proposed *ANN* Static *VAR* Stabilizer is used to emulate the Variable structure control system . The *ANN* is trained off-line using the Variable Structure sliding mode controller data . The trained *ANN* parameters (Weights and biases) are tuned and updated on-line using the synchronous machine speed deviation state as *ANN* output error signal. The valildation of the present *ANN* controller is tested by making different disturbances such as speed state, reference terminal voltage, and input torque disturbances in the investigated power system . The power system speed deviation responses due to the

above mentioned disturbances are obtained . The digital simulation results show the effectiveness and powerful of the proposed *ANN* controller in sense of fast damping electromechanical mode oscillations of power system and high performance power system.

8- REFERENCES

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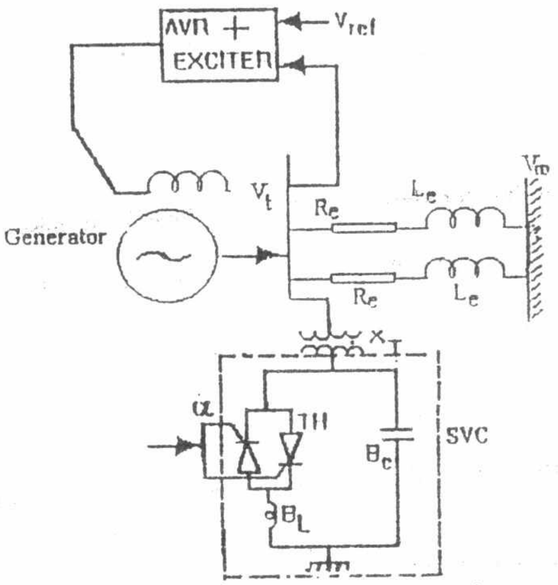
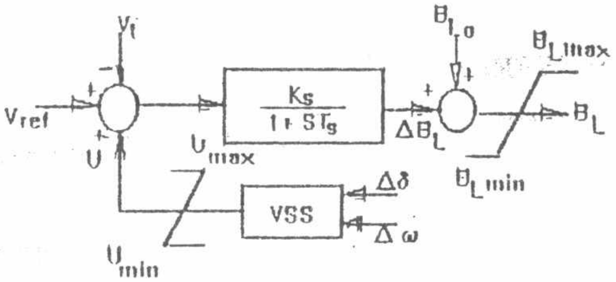
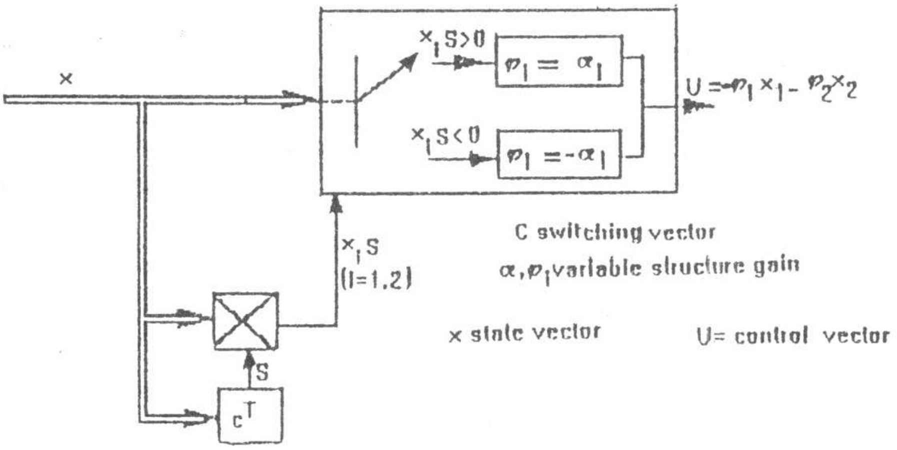


Fig(1)Investigated power systemdiagram



Fig(2) Control model of the Variable Structure SVC system



Fig(3) Variable Structure Control System(VSCS)

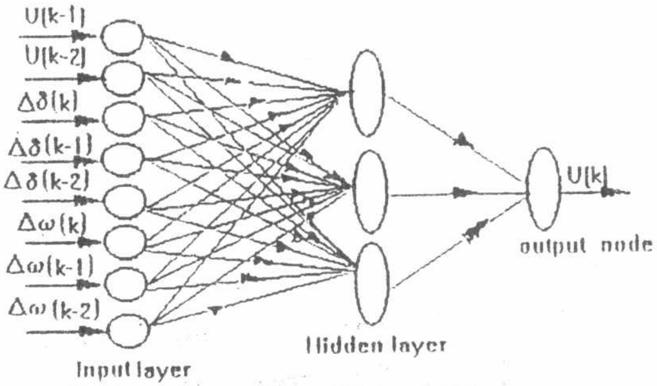
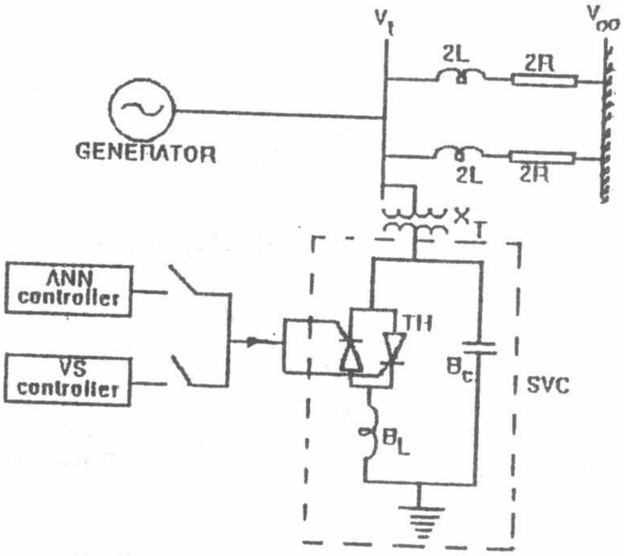


Fig (4) Proposed Neural Network Structure



Fig(5) Power system diagram with controllers

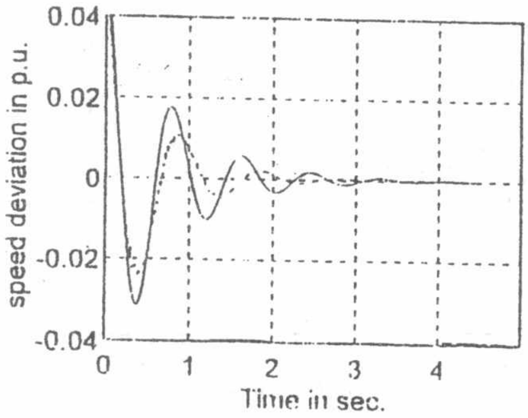
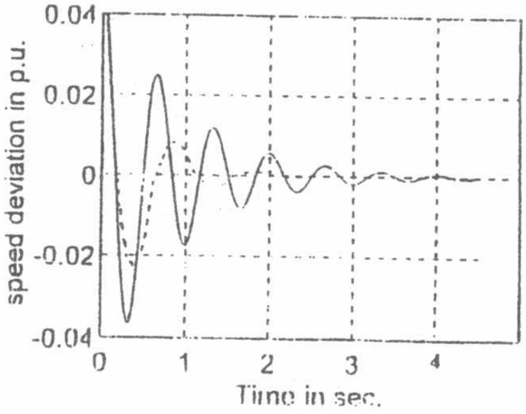
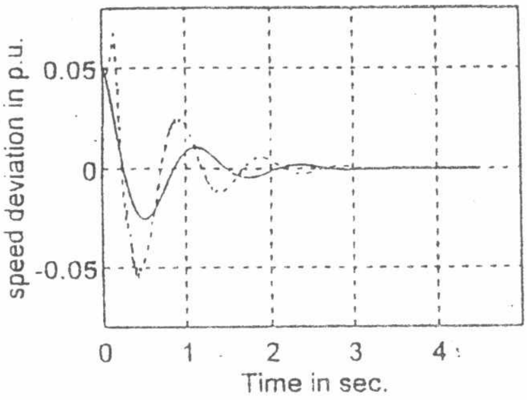


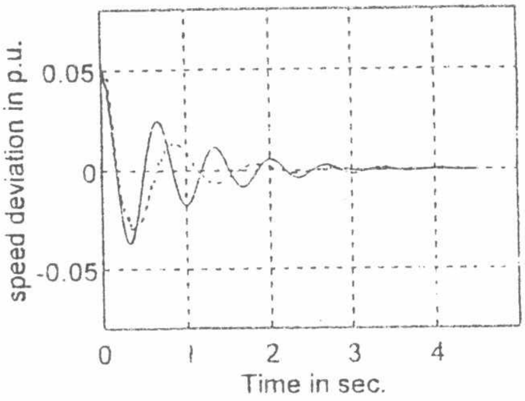
Fig (6) Power system speed deviation response for speed deviation distrubance 0.05 P.U (P=0.8 P.U ,Q=0.62 P.U)
______ ANN
.... Variable structure control system



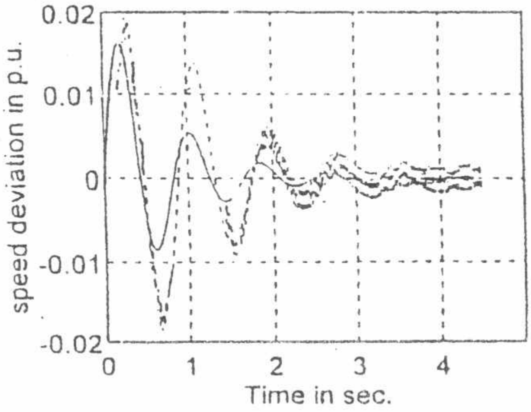
Fig(7) Power system speed deviation response for speed deviation distrubance 0.05 p.u. (P=0.62 p.u Q=0.62 p.u.)
______ ANN
.... variable structure control system



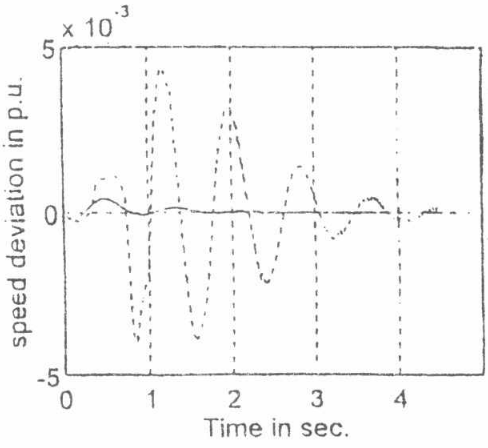
Fig(8) Power system speed deviation response
for speed deviation distrubance 0.05 p.u.
(P=0.8 p.u Q=0.50 p.u.)
______ ANN
……………… variable structure control system



Fig(9) Power system speed deviation response
for speed deviation distrubance 0.05 p.u.
(P=0.8 p.u Q=0.5 p.u.)
______ ANN
……………… variable structure control system



Fig(10) Power system speed deviation response
for Torque distrubance 0.15 p.u.
(P=0.8 p.u Q=0.62 p.u.)
______ ANN
……………… variable structure control system



Fig(11) Power system speed deviation response
for reference terminal voltage distrubance 0.15 p.u.
(P=0.8 p.u Q=0.62 p.u.)
______ ANN
……………… variable structure control system

APPENDIX

The power system data:

1-Synchronous generator

$\omega_b .. = 377..\text{rad / sec} .... L_F .. = 1.651\text{p.u.}$

$L_{d.} . = 1.7\text{p.u.} .... L_D .. = 1.605\text{p.u.}$

$L_q . = 1.64\text{p.u.} .... L_Q .. = 1.526\text{p.u.}$

$KM_F .. = KM_D .. = M_R .. = 1.55\text{p.u.} .... KM_Q .. = 1.49\text{p.u.}$

$r .. = 0.001096\text{p.u.} .... r_e ..... = 0.02\text{p.u.}$

$r_F .. = 0.000742\text{p.u.} .... L_e ..... = 0.4\text{p.u.}$

$r_D .. = 0.0131\text{p.u.} .... r_Q .... = .054\text{p.u.}$

$H ... = 2.37\text{s} .... D ...... = 0.0$

$I_d ... = I_q ... = ..0.15\text{p.u.}$

$2 - \text{voltage..regulator..and...exciter}$

$K_A .. = 50 .... E_{FD\max} ... = 7.3\text{p.u.}$

$T_A ... = 0.01\text{s} .... E_{FD\min} .... = -7.3\text{p.u}$

$T_E ... = 0.002\text{s}$

$3 - \text{static..Var...compensator}$

$K_V .. = 10 .... T_V ... = 0.15\text{s}$

$B_c ... = 0.5\text{p.u.} .... X_T .. = 0.08\text{p.u.}$

$B_{Lo..} . = \text{steady.state.value..of..} B_L .. = -0.6\text{p.u.}$

$B_{L\max} .. = -0.3\text{p.u} .... B_{L\min} .. = -0.85\text{p.u.}$

$U_{s\max} .. = 0.1 .... U_{s\min} .. = -0.1\text{p.u.}$

$4 - .\text{initial..operating..condition}$

$P_G .. = 1.0\text{p.u.} ..... V_t .. = 1.0\text{p.u.} ..... PF .. = 0.85.(\text{lagging})$

The matrices of the linearized system are

$A = M^{-1}K$

$B = M^{-1}B'$

where M, K, B' are as follows.

$$K = \begin{bmatrix} -D & 0 & k_{13} & \frac{-kM_F i_{q0}}{3} & \frac{-kM_D i_{q0}}{3} & k_{16} & \frac{kM_Q i_{d0}}{3} & 0 & 0 & 0 & 0 & 0 \\ \omega_b & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ k_{31} & -\sqrt{3}V_\infty \cos\delta_0 & r + r_e & 0 & 0 & L_q + L_e & kM_Q & 0 & 0 & -r_e & -L_e & 0 \\ 0 & 0 & 0 & r_F & 0 & 0 & 0 & \frac{-\sqrt{3}r_F}{kM_F} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_D & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ k_{61} & -\sqrt{3}V_\infty \sin\delta_0 & -L_d - L_e & -kM_F & -kM_D & r + r_e & 0 & 0 & 0 & L_e & -r_e & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & r_Q & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ k_{91} & 0 & k_{93} & k_{94} & k_{95} & k_{96} & k_{97} & 0 & -1 & 0 & 0 & 0 \\ k_{101} & 0 & -r & 0 & 0 & -L_q & -kM_Q & 0 & 0 & 0 & -L_{m0} & \frac{-i_{nq0}}{B_n^2} \\ k_{111} & 0 & L_d & kM_F & kM_D & -r & 0 & 0 & 0 & L_{m0} & 0 & \frac{i_{nd0}}{B_n^2} \\ k_{121} & 0 & k_{123} & k_{124} & k_{125} & k_{126} & k_{127} & 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

$$M = \begin{bmatrix} 2H & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-(L_d + L_e)}{\omega_b} & \frac{-kM_F}{\omega_b} & \frac{-kM_D}{\omega_b} & 0 & 0 & 0 & 0 & \frac{L_e}{\omega_b} & 0 & 0 \\ 0 & 0 & \frac{-kM_F}{\omega_b} & \frac{-L_F}{\omega_b} & \frac{-M_R}{\omega_b} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-kM_D}{\omega_b} & \frac{-M_R}{\omega_b} & \frac{-L_D}{\omega_b} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-(L_q + L_e)}{\omega_b} & \frac{-kM_Q}{\omega_b} & 0 & 0 & 0 & \frac{L_e}{\omega_b} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-kM_Q}{\omega_b} & \frac{-L_Q}{\omega_b} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_E & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{93} & m_{94} & m_{95} & m_{96} & m_{97} & 0 & T_A & 0 & 0 & 0 \\ 0 & 0 & \frac{L_d}{\omega_b} & \frac{kM_F}{\omega_b} & \frac{kM_D}{\omega_b} & 0 & 0 & 0 & 0 & \frac{L_{m0}}{\omega_b} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{L_q}{\omega_b} & \frac{kM_Q}{\omega_b} & 0 & 0 & 0 & \frac{L_{m0}}{\omega_b} & 0 \\ 0 & 0 & m_{123} & m_{124} & m_{125} & m_{126} & m_{127} & 0 & 0 & 0 & 0 & T_V \end{bmatrix}$$

$$B' = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad K_V]^t$$

and

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The unknown elements in the matrices M and K are given as follows.

$m_{93} = -K_A v_{d0} L_d/(3V_{t0}\omega_b)$
$m_{94} = -K_A v_{d0} kM_F/(3V_{t0}\omega_b)$
$m_{95} = -K_A v_{d0} kM_D/(3V_{t0}\omega_b)$
$m_{96} = -K_A v_{q0} L_q/(3V_{t0}\omega_b)$
$m_{97} = -K_A v_{q0} kM_Q/(3V_{t0}\omega_b)$
$m_{123} = -K_V v_{d0} L_d/(3V_{t0}\omega_b)$
$m_{124} = -K_V v_{d0} kM_F/(3V_{t0}\omega_b)$
$m_{125} = -K_V v_{d0} kM_D/(3V_{t0}\omega_b)$
$m_{126} = -K_V v_{q0} L_q/(3V_{t0}\omega_b)$
$m_{127} = -K_V v_{q0} kM_Q/(3V_{t0}\omega_b)$
$k_{13} = (L_q - L_d) i_{q0}/3$
$k_{16} = -(L_d i_{d0} + kM_F i_{F0} - L_q i_{d0})/3$
$k_{31} = L_q i_{q0} + L_e(i_{q0} - i_{nq0})$
$k_{61} = -L_d i_{d0} - L_e(i_{d0} - i_{nd0}) - kM_F i_{F0}$
$k_{91} = K_A[v_{d0} L_q i_{q0} - v_{q0}(L_d i_{d0} + kM_F i_{F0})]/(3V_{t0})$
$k_{93} = (v_{d0} K_A r - v_{q0} K_A L_d)/(3V_{t0})$
$k_{94} = -v_{q0} K_A kM_F/(3V_{t0})$
$k_{95} = -v_{q0} K_A kM_D/(3V_{t0})$
$k_{96} = (v_{d0} K_A L_q + v_{q0} K_A r)/(3V_{t0})$
$k_{97} = v_{d0} K_A kM_Q/(3V_{t0})$
$k_{101} = -L_{n0} i_{nq0} - L_q i_{q0}$
$k_{111} = L_{n0} i_{nd0} + L_d i_{d0} + kM_F i_{F0}$
$k_{121} = K_V[v_{d0} L_q i_{q0} - v_{q0}(L_d i_{d0} + kM_F i_{F0})]/(3V_{t0})$
$k_{123} = (v_{d0} K_V r - v_{q0} K_V L_d)/(3V_{t0})$
$k_{124} = -v_{q0} K_V kM_F/(3V_{t0})$
$k_{125} = -v_{q0} K_V kM_D/(3V_{t0})$
$k_{126} = (v_{d0} K_V L_q + v_{q0} K_V r)/(3V_{t0})$
$k_{127} = v_{d0} K_V kM_Q/(3V_{t0})$
$V_{t0} = [(v_{d0}{}^2 + v_{q0}{}^2)/3]^{1/2}$
$B_n = B_C + B_{T0}$
$L_{n0} = X_T - 1/B_n$