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A NOVEL ON LINE ADAPTIVE BASED STABILIZER FOR DYNAMIC STABILITY IMPROVEMENT WITH UPFC

N.M. Tabatabaei [1] A. Hashemi [2] N. Taheri [2] F.M. Sadikoglu [3]

1. *Electrical Engineering Department, Seraj Higher Education Institute, Tabriz, Iran, n.m.tabatabaei@gmail.com*
2. *Electrical Engineering Department, Sama Technical and Vocational Training School, Islamic Azad University, Kermanshah Branch, Iran, n.taheri.1362@gmail.com, ahmad.hashemi.v@gmail.com*
3. *Near East University, Lefkosa, Northern Cyprus, fahri@neu.edu.tr*

Abstract- In this paper, a linearized model of a power system installed with a UPFC has been presented UPFC has four control loops that, by adding an extra signal to one of them, increases dynamic stability and load angle oscillations are damped. To increase stability a novel on-line adaptive controllers, has been used analytically to identify power system parameters. Suitable operation of adaptive controllers to decrease rotor speed oscillations against input mechanical torque disturbances is confirmed by the simulation results.

Keywords: Dynamic Stability Improvement, Adaptive Controller.

I. INTRODUCTION

A unified power flow controller (UPFC) is one the FACTS devices which can control power system parameters such as terminal voltage, line impedance and phase angle [1] and [2]. Recently, researchers have presented dynamic UPFC models in order to design a suitable controller for power flow, voltage and damping controls [9]-[13]. Wang has presented a modified linearized Heffron-Phillips model of a power system installed with a UPFC [1], [3], [7] and [11]. Wang has not presented a systematic approach to design the damping controllers. Furthermore, no effort seems to have been made to identify the most suitable UPFC control parameters, in order to arrive at a robust damping controller and has not used the deviation of active and reactive powers, ΔP_e and ΔQ_e as the input control signals. Abido has used the PSO control to design a controller and this manner not only is an off-line procedure, but also depends strongly on the selection of the primary conditions of control systems [4] and [6].

An adaptive controller is able to control a nonlinear system with fast changing dynamics, like the power system better, since the dynamics of a power system are continually identified by a model. Advantages of on-line adaptive controllers over conventional controllers are that they are able to adapt to changes in system operating conditions automatically, unlike conventional controllers whose performance is degraded by such changes and require re-tuning in order to provide the desired performance [9]. In [14], an adaptive based controller for STATCOM has been provided and has been used as a VAR compensator in [15].

II. THE POWER SYSTEM CASE STUDY

Figure 1 shows a single-machine-infinite-bus (SMIB) system installed with UPFC. The static excitation system model type IEEE-ST1A has been considered. The UPFC considered here is assumed to be based on pulse width modulation (PWM) converters. The UPFC is a combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) which is coupled via a common dc link.

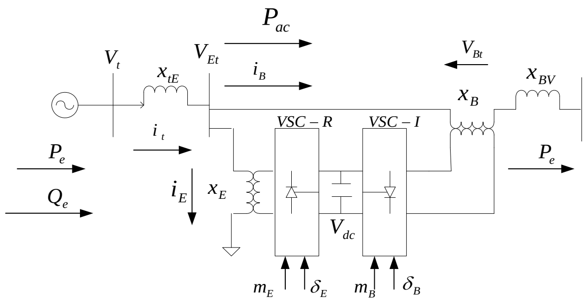

Figure 1. UPFC installed in a SMIB system

III. STATE SPACE EQUATIONS OF POWER SYSTEM

If the general pulse width modulation (PWM) is adopted for GTO-based VSCs, the three-phase dynamic differential equations of the UPFC are [6]:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \ , \ \Delta\dot{\omega} = \frac{\Delta P_m - \Delta P_e - D\Delta\omega}{M}$$

$$\Delta\dot{E}'_q = \frac{-\Delta E_q + \Delta E_{fd} + (x_d - x'_d)\Delta i_d}{T'_{do}}$$

$$\Delta\dot{E}_{fd} = \frac{-\Delta E_{fd} + K_A(\Delta V_{ref} - \Delta v + \Delta u_{pss})}{T_A} \quad (1)$$

$$\Delta\dot{V}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta V_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B$$

The equations below can be obtained with a line arising from Equation (1).

$$\Delta P_e = K_1 \Delta\delta + K_2 \Delta E'_q + K_{qd} \Delta V_{dc} + K_{qe}\Delta m_E + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B \quad (2)$$

$$\Delta E'_q = K_4 \Delta\delta + K_3 \Delta E'_q + K_{qd} \Delta V_{dc} + K_{qe}\Delta m_E + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B \quad (3)$$

$$\Delta V_t = K_5 \Delta\delta + K_6 \Delta E'_q + K_{vd} \Delta V_{dc} + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \quad (4)$$

$$\Delta V_{dc} = K_7 \Delta\delta + K_8 \Delta E'_q - K_9 \Delta V_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \quad (5)$$

The state-space equations of the system can be calculate d by combination of Equations (2) to (5) with Equation (1):

$$\dot{x} = Ax + Bu$$

$$x = [\Delta\delta, \Delta\omega, \Delta E'_q, \Delta E_{fd}, \Delta V_{dc}]^T \quad (6)$$

$$u = [\Delta u_{pss}, \Delta m_E, \Delta\delta_E, \Delta m_B, \Delta\delta_B]^T$$

where Δm_E, Δm_B, $\Delta\delta_E$ and $\Delta\delta_B$ are a linearization of the input control signal of the UPFC and the equations related to the K parameters have been presented in Appendix 3. The linearized dynamic model of Equations (2) to (5) can be seen in Figure 2, where there is only one input control signal for u. Figure 2 includes the UPFC relating the pertinent variables of electric torque, speed, angle, terminal voltage, field voltage, flux linkages, UPFC control parameters and dc link voltage.

$$A=\begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{M} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{K_{qd}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{pd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \quad (7)$$

$$B=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{p\delta b}}{M} \\ 0 & -\frac{K_{qe}}{T'_{do}} & -\frac{K_{q\delta e}}{T'_{do}} & -\frac{K_{qb}}{T'_{do}} & -\frac{K_{q\delta b}}{T'_{do}} \\ \frac{K_A}{T_A} & -\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{v\delta b}}{T_A} \\ 0 & K_{ce} & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix}$$

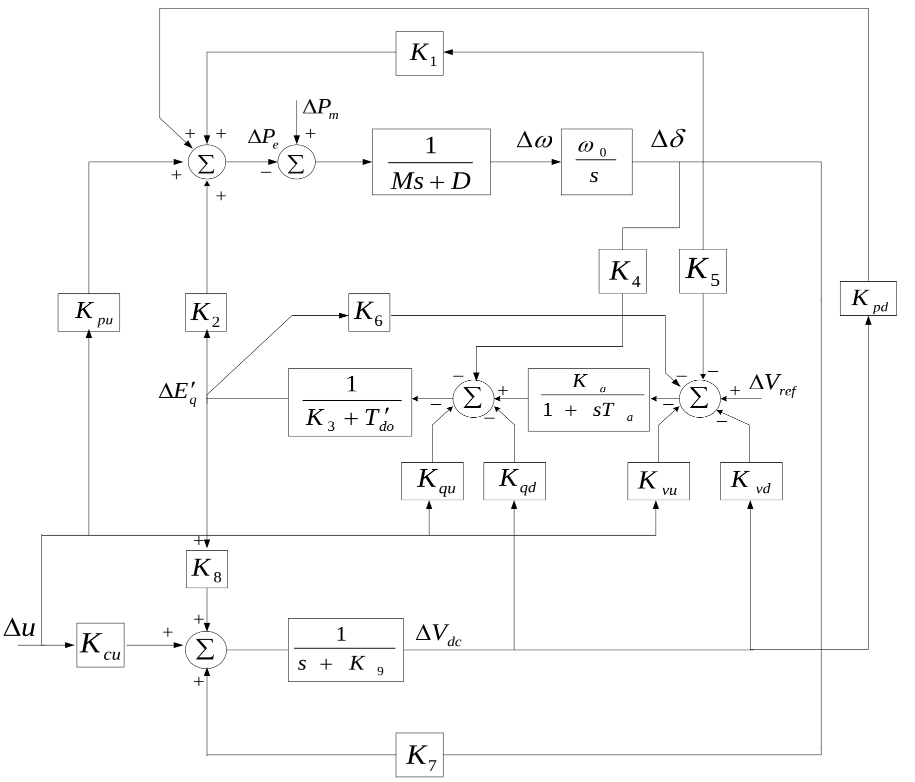

Figure 2. Modified Heffron-Phillips model of SMIB system with UPFC

A. Adaptive Controller

Figure 3 shows a block diagram of a process with a self-tuning regulator (STR). The parameters of the power system transfer function are estimated by estimation block with samples taken from input $\Delta\delta_E$ and output $\Delta\omega$ with a specified sampling time [15], [16]. It has been shown as the discrete mod of the state equation of the power system (7) as follows:

$$H(q) = \frac{\Delta\omega(q)}{\Delta\delta_E} = \frac{B(q)}{A(q)} = \frac{b_0 q^4 + b_1 q^3 + b_2 q^2 + b_3 q + b_4}{q^5 + a_1 q^4 + a_2 q^3 + a_3 q^2 + a_4 q + a_5} \quad (8)$$

The block labeled controller design contains the computation's Diophantine equation required to perform a design of a controller with a specified method and few design parameters that can be chosen externally. The recursive least-square method (RLS) will be used for parameter estimation and the design method is a deterministic pole placement (MDPP). A general linear controller can be described by

$$Ru(t) = Tu_c(t) - Sy(t) \quad (9)$$

where R, S and T are polynomials. A block diagram of the closed-loop system is shown in Figure 3. General equations of R, S and T are polynomials and have been calculated by MDPP as follows:

$$\begin{aligned} R(q) &= q^4 + r_1q^3 + r_2q^2 + r_3q + r_4 \\ S(q) &= s_0q^4 + s_1q^3 + s_2q^2 + s_3q + s_4 \\ T(q) &= t_0q^4 + t_1q^3 + t_2q^2 + t_3q + t_4 \end{aligned} \quad (10)$$

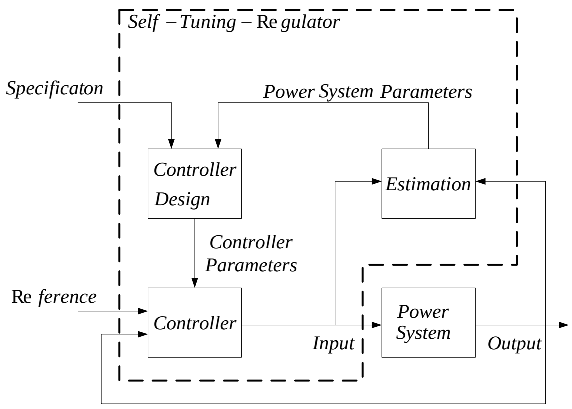

Figure 3. Block diagram of Self Tuning Regulator

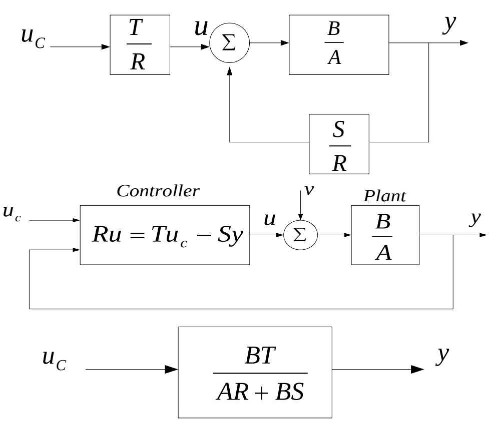

Figure 4. A general linear controller with 2 degrees of freedom

The closed-loop characteristic polynomial is thus:

$$AR + BS = A_C \quad (11)$$

The key idea of the design method is to specify the desired closed-loop characteristic polynomial A_C. The polynomial R and S can then be solved from Equation (11). In the design procedure we consider polynomial A_C to be a design parameter that is chosen to give desired properties to the closed-loop system. Equation (11), which plays a fundamental role in algebra, is called the Diophantine equation. The equation always has solutions if polynomials A and B do not have common factors. The solution may be poorly conditioned if the polynomials have factors that are closed. The solution can be obtained by introducing polynomials with unknown coefficients and solving the linear equations obtained.

In fact, in an off-line state, the adaptive controller parameters are as according to Figure 5.

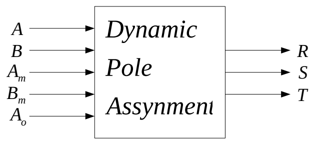

Figure 5. Block diagram of off-line adaptive controller inputs and outputs

$\frac{B_m}{A_m}$ is the desired transfer function of power system. B_m and A_m polynomials must be chosen in the way that the adaptive controller can omit the perturbation in input mechanical torque with suitable speed. The desired transfer function used in this paper according to Equation (8) offers as below:

$$\frac{y(q)}{u(q)} = \frac{B_m(q)}{A_m(q)} = \frac{q^4}{q^5 + a_1q^4 + a_2q^3 + a_3q^2 + a_4q + a_5} \quad (12)$$

According to Figure 4, designing an adaptive off-line controller (MDPP technique) consists of the three following steps:

1. Selection polynomials of A_m, B_m and A_o as below:

$$\deg A_m = \deg A = n \quad (13)$$

$$\deg B_m = \deg B = m \quad (14)$$

$$\deg A_o = \deg A - \deg B^+ - 1 \quad (15)$$

$$B_m = B^+B^- \quad (16)$$

That B^+ and B^- are strongly and poorly damped roots polynomials.

2. The Diophantine equation is formed as below and will be solved for finding R' and S polynomials:

$$AR' + B^-S = A_oA_m \quad (17)$$

3. Calculating R and T control as below:

$$R = R'B^+ \quad (18)$$

$$T = A_oB'_m \quad (19)$$

But the on-line control design consists of the three following steps:

1. Selection polynomials of A_m, B_m and A_o.

2. Calculation of $\hat{\theta}$ matrix with RLS as in the equations:

$$y(q) = \frac{B}{A}u(q) \quad (20)$$

$$A(q)y(q) = B(q)u(q) \quad (21)$$

$$\begin{aligned} &y(q) + a_1y(q-1) + a_2y(q-2) + ... + a_ny(q-n) = \\ &= b_1u(q+m-n-1) + ... + b_mu(q-m) \end{aligned} \quad (22)$$

$$\begin{aligned} y(q) = &[-y(q-1)\ ...\ y(q-n)\ u(q+m-n-1) \\ &...\ u(q-m)].[a_1\ ...\ a_n\ b_1\ ...\ b_m]^T \end{aligned} \quad (23)$$

$$y(q) = \phi^T(q-1)\theta \quad (24)$$

$$K(q) = P(q)\phi(q) = P(q-1)\phi(q)[I + \phi^T(q)P(q-1)\phi(q)]^{-1} \quad (25)$$

$$P(q) = P(q-1) - P(q-1)\phi(q)[I + \phi^T(q)P(q-1)\phi(q)]^{-1} \times$$
$$\times\phi^T(q)P(q-1) = [I - K(q)\phi^T(q)]P(q-1) \quad (26)$$

$$\hat{\theta}(q) = \hat{\theta}(q-1) + K(q)[y(q) - \phi^T(q)\hat{\theta}(q-1)] \quad (27)$$

3. Calculation of R, S and T polynomials with MDPP.

IV. SIMULATION RESULTS

The linearized model of the case study system in Figure 1 with parameters is shown in Appendix 1 and has been simulated with MATLAB/ SIMULINK. In order to examine the robustness of the damping controllers to a step load perturbation, it has been applied a step duration in mechanical power (i.e., $\Delta P_m = 0.01\text{pu}$) to the system seen in Figure 2. Figure 6 is related to an estimation of the control reference system in the on-line adaptive controller at nominal condition calculated by RLS technique. Some of the coefficients of the transfer function of the power system in Equation (10) and their estimation by RLS technique have been shown in Figure 6. It can be seen that the estimation of transfer function coefficients have been converged to the polynomials of the reference power system model at less than 20 iterations.

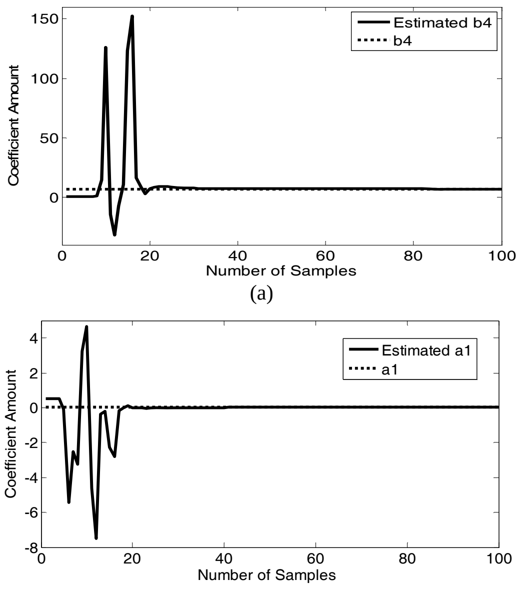

Figure 6. Adaptive controller polynomial coefficients of RLS estimated plant at nominal operating condition, (a) b_4, (b) a_1

After estimation of the transfer function of the reference control model, in order to calculate the on-line adaptive controller polynomial coefficients, the Diophantine equation must be solved. In the following, it has been shown some of the parameters R and S in Figure 7 at a nominal condition. It can be considered that the coefficients have been converged at less than 20 iterations samples have been taken from the input and output of the transfer function of the case study with sampling time $T_s = 0.01\text{s}$ for adaptive control designing. The desired transfer function of Equation (12) has been presented in Appendix 2. Figure 8 shows the dynamic responses of $\Delta\omega$ with adaptive controller at nominal operating loads due to $\Delta P_m = 0.01\text{pu}$ perturbation. , it can be seen that the dynamic response of the system equipped with an adaptive controller (Figure 8) has adequate quality because short settling time as 0.1 seconds. Also, the dynamic response of the system equipped with the adaptive controller (Figure 8) has an agreeable small peek amplitude amount.

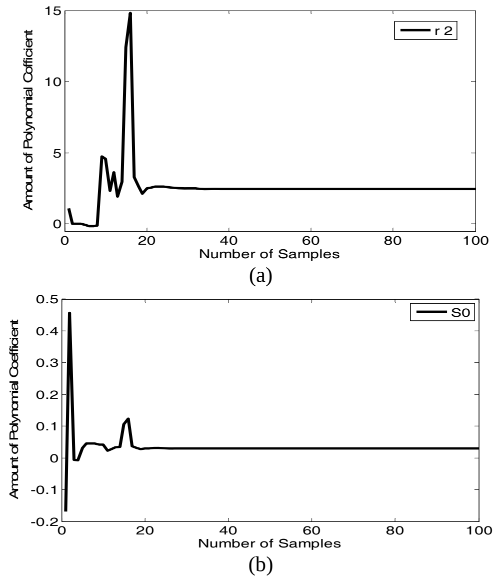

Figure 7. Adaptive controller parameters calculated with Diophantine equation at nominal operating condition, (a) r_2, (b) s_0

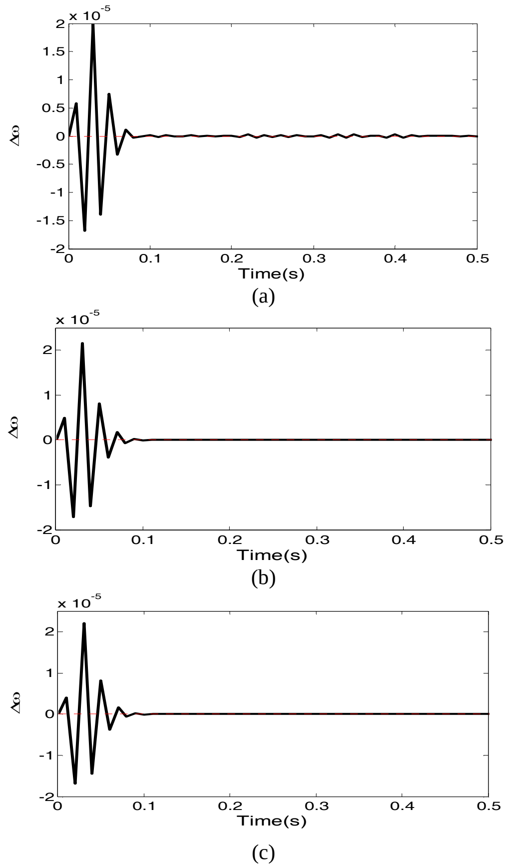

Figure 8. Dynamic responses of $\Delta\omega$ with adaptive controller at different operating conditions due to $\Delta P_m = 0.01\text{pu}$, (a) Light, (b) Nominal, (c) Heavy

V. CONCLUSIONS

In this paper, a UPFC has been used for dynamic stability improvement and a state-space equation has been applied for the design of damping controllers. Simulation results operated by MATLAB/SIMULINK show that using an input speed deviation signal decreases speed oscillations effectively. According to the simulation results, the designed adaptive controller for the system has the perfect effect in oscillation damping and dynamic stability improvement.

APPENDICES

Appendix 1. The Parameters of Test System

Generator:

$M = 2H = 8.0$ MJ/MVA

$D = 0.0$

$T'_{do} = 5.044$ s

$X_d = 1.0$ pu

$X_q = 0.6$ pu

$X'_d = 0.3$ pu

Excitation System:

$K_a = 100$

$T_a = 0.01$ s

Transformer:

$X_{tE} = 0.1$ pu

$X_E = X_B = 0.1$ pu

$X_E = X_B = 0.1$ pu

Transmission Line:

$X_{BV} = 0.3$pu

$X_e = X_{BV} + X_B + X_{tE} = 0.5$ pu

Operating Condition:

$V_t = 1.0$ pu

$P_e = 0.8$ pu

$V_b = 1.0$ pu

$f = 60$ Hz

Parameters of DC Link:

$V_{dc} = 2$ pu

$C_{dc} = 1$ pu

Appendix 2. Adaptive Controller Parameters

$A_m = (q-0.01)(q-0.03)(q-0.02)(q-0.1)(q+0.1)$

$B_m = q^4$

$A_o = 1$

$\deg B_m = \deg B = m = 4$

$\deg A_m = \deg A = n = 5$

Appendix 3. *K* Parameters for UPFC HVDC Network

$$K_1 = \frac{(V_{td} - I_{tq}x'_d)(x_{dE} - x_{dt})V_b \sin\delta}{x_{d\Sigma}} + \frac{(x_q I_{td} + V_{tq})(x_{qt} - x_{qE})V_b \cos\delta}{x_{q\Sigma}}$$

$$K_2 = \frac{-(x_{BB} + x_E)V_{td}}{x_{d\Sigma}x_d} + \frac{(x_{BB} + x_E)x'_d I_{tq}}{x_{d\Sigma}}$$

$$K_3 = 1 + \frac{(x'_d - x_d)(x_{BB} + x_E)}{x_{d\Sigma}}$$

$$K_4 = -\frac{(x'_d - x_d)(x_{dE} - x_{dt})V_b \sin\delta}{x_{d\Sigma}}$$

$$K_5 = \frac{V_{td}x_q(x_{qt} - x_{qE})V_b \cos\delta}{V_t x_{q\Sigma}} - \frac{V_{tq}x'_d(x_{dtE} - x_{dt})V_b \sin\delta}{V_t x_{d\Sigma}}$$

$$K_6 = \frac{V_{tq}(x_{d\Sigma} + x'_d(x_{BB} + x_E))}{V_t x_{d\Sigma}}$$

$$K_7 = 0.25C_{dc}(V_b \sin\delta(m_E \cos\delta_E x_{dE} - m_B \cos\delta_B x_{dt})) - \frac{m_B \cos\delta_B x_{dt}}{x_{d\Sigma}} +$$

$$V_b \cos\delta(m_B \sin\delta_B x_{qt} - m_E \sin\delta_E x_{qe}$$

$$K_8 = -0.25\frac{m_B \cos\delta_B x_E + m_E \cos\delta_E x_{BB}}{x_{d\Sigma}}$$

$$K_9 = 0.25Cdc(\frac{m_B \sin\delta_B(m_B \cos\delta_B x_{dt} - m_E \cos\delta_E x_{dE})}{2x_{d\Sigma}} + \frac{m_E \sin\delta_E(m_E \cos\delta_E x_{Bd} - m_B \cos\delta_B x_{dt})}{2x_{d\Sigma}}$$

$$\frac{m_B \cos\delta_B(m_B \sin\delta_B x_{qt} - m_E \sin\delta_E x_{qE})}{2x_{q\Sigma}} + \frac{m_E \cos\delta_E(-m_B \sin\delta_B x_{qE} + m_E \sin\delta_E x_{Bq})}{2x_{q\Sigma}})$$

$$K_{pe} = \frac{(V_{td} - I_{tq}x'_d)(x_{Bd} - x_{dE})V_{dc} \sin\delta_E}{2x_{d\Sigma}} + \frac{(x_q I_{td} + V_{tq})(x_{Bq} - x_{qE})V_{dc} \cos\delta_E}{2x_{q\Sigma}}$$

$$K_{p\delta E} = \frac{(V_{td} - I_{tq}x'_d)(x_{Bd} - x_{dE})V_{dc}m_E \cos\delta_E}{2x_{d\Sigma}} + \frac{(x_q I_{td} + V_{tq})(-x_{Bq} + x_{qE})V_{dc}m_E \sin\delta_E}{2x_{q\Sigma}}$$

$$K_{pb} = \frac{(V_{td} - I_{tq}x'_d)(x_{dt} - x_{dE})x_{dc} \sin\delta_B}{2x_{d\Sigma}} + \frac{(x_q I_{td} + V_{tq})(x_{qt} - x_{qE})V_{dc} \cos\delta_B}{2x_{q\Sigma}}$$

$$K_{p\delta B} = \frac{(V_{td} - I_{tq}x'_d)(x_{dE} + x_{dt})V_{dc}m_B \cos\delta_B}{2x_{d\Sigma}} + \frac{(x_q I_{td} + V_{tq})(-x_{qt} + x_{qE})V_{dc}m_B \sin\delta_B}{2x_{q\Sigma}}$$

$$K_{qe} = -\frac{(x'_d - x_d)(x_{Bd} - x_{dE})V_{dc} \sin\delta_E}{2x_{d\Sigma}}$$

$$K_{q\delta e} = -\frac{(x'_d - x_d)(x_{Bd} - x_{dE})m_E V_{dc} \cos\delta_E}{2x_{d\Sigma}}$$

$$K_{qb} = -\frac{(x'_d - x_d)(x_{dt} - x_{dE})V_{dc} \sin\delta_B}{2x_{d\Sigma}}$$

$$K_{pd} = (V_{td} - I_{tq}x'_d)(\frac{(x_{dt} - x_{dE})m_B \sin\delta_B}{2x_{d\Sigma}} + \frac{(x_{Bd} - x_{dE})m_E \sin\delta_E}{2x_{d\Sigma}}) + (x_q I_{td} + V_{tq})(\frac{(x_{qt} - x_{qE})m_B \cos\delta_B}{2x_{q\Sigma}} + \frac{(x_{Bq} - x_{qE})m_E \cos\delta_E}{2x_{q\Sigma}}$$

$$K_{q\delta B} = -\frac{(x'_d - x_d)(x_{dE} - x_{dt})m_B V_{dc}\cos\delta_B}{2x_\Sigma}$$

$$K_{qe} = -(x'_d - x_d)(\frac{(x_{Bd} - x_{dE})m_E \sin\delta_E}{2x_{d\Sigma}} + \frac{(x_{dt} - x_{dE})m_B \sin\delta_B}{2x_{d\Sigma}})$$

$$K_{ve} = \frac{V_{td}(x_{Bq} - x_{qE})V_{dc}\cos\delta_E}{2V_t x_{q\Sigma}} - \frac{V_{tq}(x_{Bd} - x_{dE})V_{dc}\sin\delta_E}{2V_t x_{d\Sigma}}$$

$$K_{v\delta E} = \frac{V_{td}x_q(x_{qE} - x_{Bq})m_E V_{dc}\sin\delta_E}{2V_t x_{q\Sigma}} - \frac{V_{tq}x'_d(x_{Bd} - x_{dE})m_E V_{dc}\cos\delta_E}{2V_t x_{q\Sigma}}$$

$$K_{vb} = \frac{V_{td}x_q(x_{qt} - x_{qE})V_{dc}\cos\delta_E}{2V_t x_{q\Sigma}} - \frac{V_{tq}x'_d(x_{dt} - x_{dE})V_{dc}\sin\delta_E}{2V_t x_{d\Sigma}}$$

$$K_{v\delta B} = \frac{V_{td}x_q(x_{qE} - x_{qt})m_B V_{dc}\sin\delta_E}{2V_t x_{q\Sigma}} + \frac{V_{tq}m_B x'_d(x_{dE} + x_{dt})V_{dc}\cos\delta_E}{2V_t x_{d\Sigma}}$$

$$K_{vd} = \frac{V_{td}x_q(x_{Bq} - x_{qE})m_E\cos\delta_E}{2V_t x_{q\Sigma}} + \frac{(x_{qt} - x_{qE})m_B\cos\delta_B}{2x_{q\Sigma}} - \frac{V_{tq}m_E x'_d(x_{Bd} - x_{dE})\sin\delta_E}{2V_t x_{d\Sigma}} + \frac{m_B(x_{dt} - x_{qE})\sin\delta_E}{2x_{d\Sigma}}$$

$$K_{ce} = 0.25C_{dc}\frac{V_{dc}\sin\delta_E(m_E\cos\delta_E x_{Bd} - m_B\cos\delta_B x_{dE})}{2x_{d\Sigma}} + \frac{V_{dc}\cos\delta_E(m_E\sin\delta_E x_{Bq} - m_B\sin\delta_B x_{qE})}{2x_{q\Sigma}}$$

$$K_{c\delta e} = \frac{0.25m_E}{C_{dc}}(\cos\delta_E I_{Eq} - \sin\delta_E I_{Ed}) + \frac{0.25}{C_{dc}}(m_E V_{dc}\cos\delta_E\frac{(m_E\cos\delta_E x_{Bd} - m_B\cos\delta_B x_{dE})}{2x_{d\Sigma}} + m_E V_{dc}\sin\delta_E\frac{(m_B\sin\delta_B x_{qE} + m_E\sin\delta_E x_{Bq})}{2x_{q\Sigma}})$$

$$K_{cb} = 0.25C_{dc}\frac{V_{dc}\sin\delta_B(-m_E\cos\delta_E x_{dE} + m_B\cos\delta_B x_{dt})}{2x_{d\Sigma}} + \frac{V_{dc}\cos\delta_B(m_B\sin\delta_E x_{qt} - m_E\sin\delta_E x_{qE})}{2x_{q\Sigma}}$$

$$K_{c\delta B} = \frac{0.25m_B}{C_{dc}}(\cos\delta_B I_{Bq} - \sin\delta_B I_{Bd}) + \frac{0.25}{C_{dc}}(m_B V_{dc}\cos\delta_B\frac{(m_E\cos\delta_E x_{dE} + m_B\cos\delta_B x_{dt})}{2x_{d\Sigma}} + m_B V_{dc}\sin\delta_B\frac{(-m_B\sin\delta_E x_{qt} + m_E\sin\delta_E x_{qE})}{2x_{q\Sigma}})$$

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BIOGRAPHIES

Naser Mahdavi Tabatabaei was born in Tehran, Iran, 1967. He received the B.Sc. and the M.Sc. degrees from University of Tabriz (Tabriz, Iran) and the Ph.D. degree from Iran University of Science and Technology (Tehran, Iran), all in Power Electrical Engineering, in 1989, 1992, and 1997, respectively. Currently, he is a Professor of Power Electrical Engineering at International Ecoenergy Academy, International Science and Education Center and International Organization on TPE (IOTPE). He is also an academic member of Power Electrical Engineering at Seraj Higher Education Institute and teaches Power System Analysis, Power System Operation, and Reactive Power Control. He is the secretary of International Conference on TPE (ICTPE), editor-in-chief of International Journal on TPE (IJTPE) and chairman of International Enterprise on TPE (IETPE) all supported by IOTPE. His research interests are in the area of Power Quality, Energy Management Systems, ICT in Power Engineering and Virtual E-learning Educational Systems. He is a member of the Iranian Association of Electrical and Electronic Engineers (IAEEE).

Ahmad Hashemi was born in Kermanshah, Iran, 1984. He received his B.Sc. degree in power electrical engineering from K.N. Toosi University of Technology (Tehran, Iran) in 2006 and M.Sc. degree from Azarbaijan University of Tarbiat Moallem (Tabriz, Iran) in 2009. His main research interests are FACTS devices modeling, adaptive control and Neural Network optimizations, System Operation, and Reactive Power control and Neural Network optimizations.

Naser Taheri received the B.Sc. from University of Guilan, (Rasht, Iran) in Electronic Engineering, 2007 and M.Sc degree from Azarbaijan University of Tarbiat Moallem (Tabriz, Iran) in Power Electrical Engineering, 2009. He is currently researching on Power System Control, Flexible AC Transmission Systems (FACTS) and power systems dynamic modeling.

Fahreddin M. Sadikoglu received his M.S. and Ph.D. degrees in Measurement and Computer Technology from Azerbaijan State Oil Academy (Baku, Azerbaijan). After holding of position of Assistant and Associate Professor at Academy until 1988 and working industrial company he transfered to the Algeria University where he served as director of "Signals and Systems" reseach laboratory and professor of the Faculty of Electrical and Electronic Engineering. He has published more than 70 papers, 5 books and holds 5 patents. Currently, he is Vice-Rector and Dean of Engineering Faculty of the Near East University (Lefkosa, Notrhern Cyprus).