Evaluating the Dynamic Stability of Power System Using UPFC based on Indirect Matrix Converter

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***Abstract*—In this paper, the affects of the newly presented structures of unified power flow controller (UPFC) on power system dynamic stability are investigated. The newly presented UPFC structure is based on indirect matrix converter (IMC) controlled by the space vector method (SVM). A non-linear modeling is accomplished for a sample power system possessing UPFC-IMC in order to investigate the affects of it on the dynamic stability. The linear model of the power system is then mentioned in state equations form defining system elements and linearizing the non-linear model around the operation point. A Heffron-Philips model is presented according to the mentioned state equations for the sample power system possesses UPFC-IMC. The accuracy of the mentioned theoretical cases is reconfirmed through the simulation results in MATLAB/Simulink.**

***Index Terms*—UPFC-IMC, FACTS device, low frequency oscillations, modified Heffron-Philips model**

I. Introduction

The generator electromechanical oscillations are one of the most important problems propounded in power systems, which occurs during the large distortions as the input mechanical power and the output electric power balance is obviated and the damping torque is decreased [1]. The conventional technique of generator electromechanical oscillations damping in power system is to add a power system stabilizer (PSS) to the generator exciting system [2-3]. Installing PSS in power system increases the stability margin of the power system against the electromechanical oscillations in addition to the system ability enhancement in electromechanical oscillations damping. Recent progresses in power electronics field and high power semiconductors manufacturing magnificently change the compensation and power transmission fields in power systems. The main idea supports the FACTS concept is to improve the ability of transmission system activating its several elements at components. UPFC is a member of the FACTS family [4]. Prevalent UPFC structure introduced by Gyugyi in 1991 [5], consists of two two-level three-phase series and shunt converters connected to each other through a back-to-back dc link. Increasing the converter weight, cost, size, and power losses are some of the most important disadvantageous of prevalent UPFC. Therefore, several new structures are presented to overcome such disadvantageous [6-8]. One of the best-presented structures is the matrix converter based UPFC [9]. The matrix converter structure is based on 9 bidirectional switches contain two IGBTs accompanied by two parallel-reverse diodes, which can be switched in high frequencies and directly transmit the energy in ac/ac mode applying no electrolyte capacitor. The matrix converter structure has the advantageous such as adjustable power factor, high qualitative input and output currents, high operation speed, and lower size, in addition to possessing no electrolyte capacitor in dc link. It also possesses disadvantageous such as restricted voltage transfer ratio by 0.86 and requiring numerous high power semiconductor devices capable of high frequency switching. According to the considerable advantageous of matrix converter structure, in compare with its disadvantageous, it quickly supersedes ac/dc/ac converters in scientific researches. The most distinctive restriction of utilizing UPFC-IMC falls in its switching pattern, which just holds 27 permitted modes out of $2^9 = 512$ possible modes. This refers to the nature of matrix converter structure, which is due to impossibility of short circuiting input phases and impossibility of open circuiting output phases during each switching period. Two common Venturini [10] and SVM [11] are presented to control 27 permitted switching modes of UPFC-IMC. The SVM algorithm is based on three-phase input current of line and three-phase output voltage. Each output is connected to a single input according to the switching modes. In [12], the UPFC-IMC switching is carried out by indirect technique. The operation of UPFC-IMC is modeled in two voltage source rectifier (VSR) and voltage source inverter (VSI) sides by switching through ISVM technique.

In [13], a dynamic modeling of UPFC-IMC was presented. In this paper, the impacts of UPFC-IMC presented in [12] are evaluated on the power system dynamic stability and on the electromechanical oscillations damping. In order to achieve such aim, it is assumed that the UPFC-IMC presented in [12] is connected to the sample power system. The analyses begin by deriving non-linear equations of the investigated power system. The linear equations are obtained linearizing the non-linear equations around the operating

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point and the modified Heffron-Philips model is proposed in continuous. The system is then simulated in MATLAB/Simulink and the most effective signal is introduced to optimum control of UPFC-IMC in power system and attenuates rotor oscillations of synchronous generator.

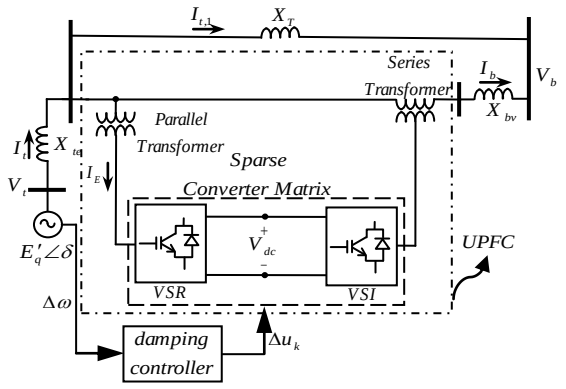

Figure 1. Single line diagram of investigated system

II. Investigated System

In this paper, the IEEE-St1A sample power system is used to investigate dynamic stability. The evaluated power system structure is shown in Fig. 1. It is assumed that the buses are ideal and R_E and R_B are neglected against X_E and X_B. In this paper, E and B subscripts are used for VSR side and VSI side, respectively, and subscript g refers to the side of converter (E and B). In Fig. 1, X_{bv}, X_{tE}, and X_T are transmission line, Equivalent transformer, and transmission line 1 reactance, respectively. Also, V_t, V_{dc}, and V_b are generator terminal, artificial dc link, and infinite bus voltages, and I_t, $I_{t,1\&2}$, I_b and I_g show terminal output, transmission line 1 & 2, infinite bus, and passing on g side currents. So, δ is system load angle.

III. Dynamic Modeling of Power System

A. Non-linear Dynamic Model

All components of the investigated power system such as all reactances and resistances of generator, transformer, transmission line, series and parallel transformers, along with transient states of transmission line and UPFC-IMC transformer are under consider in non-linear modeling process. The following non-linear equations are obtained for investigated system:

$$\dot{\delta} = \omega_0(\omega - 1). \tag{1}$$

$$\dot{\omega} = \frac{P_m - P_e - D_m\Delta\omega}{M}. \tag{2}$$

$$\dot{E}'_q = \frac{-E_q + E_{fd}}{T'_{do}}. \tag{3}$$

$$\dot{E}_{fd} = \frac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a}. \tag{4}$$

where the follows are valid in (1)-(4):

$$P_e = V_{t,d}I_{t,d} + V_{t,q}I_{t,q},\ E_q = E'_q + (X_d - X'_d)I_{t,d}$$

$$V_t = V_{t,d} + jV_{t,q},\ V_{t,d} = X_qI_{t,q},\ V_{t,q} = E'_q - X'_dI_{t,d}$$

$$I_{t,d} = I_{t,1,d} + I_{E,d} + I_{B,d},\ I_{t,q} = I_{t,1,q} + I_{E,q} + I_{B,q}$$

$$I_{t,1,d} = \frac{X_E}{X_T}I_{E,d} + \frac{1}{X_T}\frac{m_EV_{dc}}{2}\cos\delta_E - \frac{1}{X_T}V_b\cos\delta$$

$$I_{t,1,q} = \frac{X_E}{X_T}I_{E,q} + \frac{1}{X_T}\frac{m_EV_{dc}}{2}\sin\delta_E - \frac{1}{X_T}V_b\sin\delta$$

$$I_{E,d} = \frac{(X_{dT} + X_{BB}X_{b,3})V_b\cos\delta}{X_{d,E}} - \frac{(X_{dT} + X_{BB}X_{b,2})}{X_{d,E}}\frac{m_EV_{dc}}{2}\cos\delta_E + \frac{X_{BB}}{X_{d,E}}E'_q - \frac{X_{dT}}{X_{d,E}}\frac{m_BV_{dc}}{2}\cos\delta_B$$

$$I_{E,q} = \frac{(X_{qT} + X_{BB}X_{a,3})}{X_{q,E}}V_b\sin\delta - \frac{(X_{qT} + X_{BB}X_{a,2})}{X_{q,E}}\frac{m_EV_{dc}}{2}\sin\delta_E - \frac{X_{qT}}{X_{q,B}}\frac{m_BV_{dc}}{2}\sin\delta_B$$

$$I_{B,d} = \frac{1}{X_{d,E}}\left[X_EE'_q + (X_{b,1} - X_EX_{b,2})\left(\frac{m_EV_{dc}}{2}\cos\delta_E\right) + (X_{b,3}X_E - X_{b,1})V_b\cos\delta + X_{b,1}\left(\frac{m_BV_{dc}}{2}\cos\delta_B\right)\right]$$

$$I_{B,q} = \frac{1}{X_{q,E}}\left[(X_{a,1} - X_BX_{a,2})\left(\frac{m_BV_{dc}}{2}\sin\delta_B\right) + (X_{a,3}X_B - X_{a,1})V_b\sin\delta + X_{a,1}\left(\frac{m_BV_{dc}}{2}\sin\delta_B\right)\right]$$

$$X_{dT} = X_{tE} + X'_d,\ X_{qT} = X_{tE} + X_q,\ X_{d,E} = X_{tE} + X'_d + X_E$$

$$X_{q,E} = X_{tE} + X_q + X_E,\ X_{BB} = X_{bv} + X_B$$

$$X_{a,1} = \frac{(X_{q,E}X_T + X_{qT}X_E)}{X_T},\ X_{a,2} = 1 + \frac{X_{qT}}{X_T},\ X_{a,3} = -\frac{X_{qT}}{X_T}$$

$$X_{b,1} = \frac{(X_{d,E}X_T + X_{dT}X_E)}{X_T},\ X_{b,2} = 1 + \frac{X_{dT}}{X_T},\ X_{b,3} = -\frac{X_{dT}}{X_T}$$

In the aforementioned equations, M, X_d, X_q, and X'_d show inertia constant, generator reactance on d axis, generator reactance on q axis, generator transient

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reactance on d axis, respectively, and $I_{t,w}$, $I_{t,1,w}$, $I_{t,2,w}$, and $V_{t,w}$ ($w=d,q,0$) define terminal output current, current in transmission line 1, current in transmission line 2, generator terminal voltage on w axis, respectively. Also, P_m, P_e, δ_g, and m_g ($g=E,B$) mechanical power of generator, electric power of generator, phase angle on g side, and modulation index on g side, respectively.

B. Linear Dynamic Model

The linear dynamic model is obtained from the non-linear dynamic model of the system determined by (1)-(4) [1]. In order to achieve such aim, the non-linear equations (1)-(4) are linearized around the operation point of the investigated system and consequently, the system linear equations are derived. The obtained linear equations are as follows:

$$\Delta\dot{\delta} = \omega_0 \Delta\omega . \tag{5}$$

$$\Delta\dot{\omega} = \frac{\Delta P_m - \Delta P_e - D_m \Delta\omega}{M} . \tag{6}$$

$$\Delta\dot{E}'_q = \frac{-\Delta E_q + \Delta E_{fd}}{T'_{do}} . \tag{7}$$

$$\Delta\dot{E}_{fd} = \frac{-\Delta E_{fd} + K_a(\Delta V_{ref} - \Delta V_t)}{T_a} . \tag{8}$$

where the followings are valid in (5)-(8):

$$\begin{aligned}\Delta P_e = {} & K_1\Delta\delta + K_2\Delta E'_q + K_{p,E}\Delta m_E \\ & + K_{p,\delta E}\Delta\delta_E + K_{p,B}\Delta m_B + K_{p,\delta B}\Delta\delta_B\end{aligned} . \tag{9}$$

$$\begin{aligned}\Delta E_q = {} & K_4\Delta\delta + K_3\Delta E'_q + K_{q,E}\Delta m_E \\ & + K_{q,\delta E}\Delta\delta_E + K_{q,B}\Delta m_B + K_{q,\delta B}\Delta\delta_B\end{aligned} . \tag{10}$$

$$\begin{aligned}\Delta V_t = {} & K_5\Delta\delta + K_6\Delta E'_q + K_{v,E}\Delta m_E \\ & + K_{v,\delta E}\Delta\delta_E + K_{v,B}\Delta m_B + K_{v,\delta B}\Delta\delta_B\end{aligned} . \tag{11}$$

The constant values are defined in details in appendix A.

C. The Proposed Modified Heffron-Philips Model

The modified Heffron-Philips model could be proposed for the investigated system considering (5)-(8) linear equations. Fig. 2 shows the proposed modified Heffron-Philips block diagram, in which the operation of UPFC-IMC is controlled by the linearized Δm_E, Δm_B, $\Delta\delta_E$, and $\Delta\delta_B$ control signals. The block diagram of the proposed modified Heffron-Philips model shown in Fig. 2, holds 18 constants. These constants can be considered as the row input vectors to decrease the calculations complexity. The input row vectors are defined as follows:

$$K_{p,uk} = [K_{p,E} \quad K_{p,\delta E} \quad K_{p,B} \quad K_{p,\delta B}] . \tag{12}$$

$$K_{q,uk} = [K_{q,E} \quad K_{q,\delta E} \quad K_{q,B} \quad K_{q,\delta B}] . \tag{13}$$

$$K_{v,uk} = [K_{v,E} \quad K_{v,\delta E} \quad K_{v,B} \quad K_{v,\delta B}] . \tag{14}$$

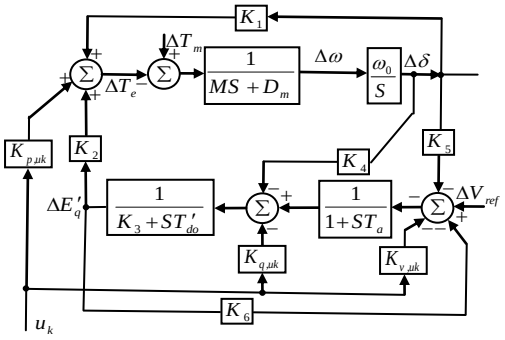

Figure 2. The proposed modified Heffron-Philips model

The row vectors of (12)-(14) are applied on the proposed modified Heffron-Philips system as the following input vector according to the UPFC-IMC input signal:

$$U = [\Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B]^T . \tag{15}$$

TABLE I. SYETEM OPERATION CONDITION IN $\Psi(\mu)$

Operation conditions	V_t	V_b	P_e
μ_1	$1.0\,pu$	$1.0\,pu$	$0.1\,pu$
μ_2	$1.0\,pu$	$1.0\,pu$	$1.0\,pu$

D. The State Equations of the Investigated System

The dynamic model of the investigated system can be defined on (5)-(8) bases and in state space equations form as follows:

$$\dot{X} = AX + BU . \tag{16}$$

A and B matrices of (16) can be defined as follows:

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 \\ -\frac{K_4}{T'_{d0}} & 0 & -\frac{K_3}{T'_{d0}} & \frac{1}{T'_{d0}} \\ -\frac{K_a K_5}{T_a} & 0 & -\frac{K_a K_6}{T_a} & -\frac{1}{T_a} \end{bmatrix} . \tag{17}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{K_{p,E}}{M} & -\frac{K_{p,\delta E}}{M} & -\frac{K_{p,B}}{M} & -\frac{K_{p,\delta B}}{M} \\ -\frac{K_{q,E}}{T'_{d0}} & -\frac{K_{q,\delta E}}{T'_{d0}} & -\frac{K_{q,B}}{T'_{d0}} & -\frac{K_{q,\delta B}}{T'_{d0}} \\ -\frac{K_a K_{v,E}}{T_a} & -\frac{K_a K_{v,\delta E}}{T_a} & -\frac{K_a K_{v,B}}{T_a} & -\frac{K_a K_{v,\delta B}}{T_a} \end{bmatrix} . \tag{18}$$

In addition, X and U matrices of (16) are considered as follows:

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$$X = [\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd}]^T . \tag{19}$$

$$U = [\Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B]^T . \tag{20}$$

IV. Simulation Results

As shown in Fig. 1, the probable oscillation states are recognized by UPFC-IMC using $\Delta\omega$ error signal. The non-linear analysis of the investigated system is accomplished using non-linear equations (1)-(4). It is assumed in simulations that a three-phase to ground fault is occurred in $t = 1\text{sec}$ on transmission line 1. This fault is occurred under $\Psi(\mu)$ system operation region shown in Table I, considering other power system parameters presented in appendix B. Fig. 3(a) shows the simulation results under μ_1 operation condition. The stability of the investigated system faces with drawbacks as the oscillation occurs. Under μ_1 operation condition, the system responds to the oscillations with $u_k = \delta_E$ fast. However, the system attenuates the electromechanical oscillations with lower speed considering $u_k = \delta_B$. Fig. 3(b) illustrates the simulation results under μ_2 operation condition. Based on the simulation results shown in Fig. 3(b), the system is able to maintain the stability and to attenuate the oscillations with $u_k = m_E$ and maintain the stability of the investigated system with $u_k = \delta_E$ and it might undamaged the protective systems and other power system connected devices.

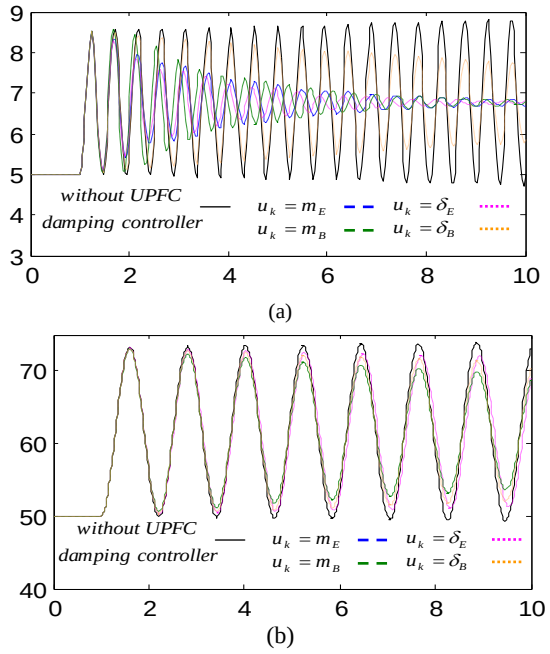

Figure 3. Simulation results, (a) under μ_1 operation condition, (b) under μ_2 operation condition

V. Conclusion

In this paper, non-linear and linear modeling is presented for UPFC-IMC, and the modified Heffron-Philips model is proposed. According to results, under μ_1 and μ_2 operation condition, $u_k = \delta_E$ and $u_k = m_E$ improve dynamic stability. It can be claimed that the selected signal is persistent if it has a uniform performance in total $\Psi(\mu)$ region and is able to attenuate the electromechanical oscillations of the power system. The control signal persistence against the electromechanical oscillations in total $\Psi(\mu)$ region causes optimum control and maximum system capacity utilization. Therefore, the persistent signal selection is particularly important. Also, according to simulation results, with $u_k = \delta_E$ improve dynamic stability in all $\Psi(\mu)$.

Appendix A

$$K_1 = s_1\left[b_2 + d_2 + (s_4 - 1)b_2 + s_5 \sin\delta\right] + \left[b_1 s_4 + d_1\right] \times\left[(g_1 V_b \cos\delta) + s_4 (e_1 V_b \cos\delta) + s_5 \cos\delta)\right]$$

$$K_2 = I_{t,q} + s_1(b_1 s_4 + d_1),\ K_3 = 1 - s_3(b_1 s_4 + d_1)$$

$$K_4 = s_3(b_2 s_4 + d_2 + s_5 \sin\delta)$$

$$K_5 = X_q V_b s_6\left(g_1 \cos\delta + s_4(e_1 \cos\delta) + s_8 \cos\delta\right) - s_7 X'_d\left(b_2 s_4 + d_2 + s_5 \sin\delta\right)$$

$$K_6 = s_7[1 - X'_d(b_1 s_4 + d_1)]$$

$$K_{p,E} = s_1(b_3 s_4 + d_3 - 0.5 V_{dc} s_8 \cos\delta_E) + s_2\left\{\left(0.5 V_{dc} \sin\delta_E\right)(e_2 + g_2) + V_b \sin\delta[(s_4 - 1)e_2 + s_8]\right\}$$

$$K_{p,\delta E} = s_1(b_4 s_4 + d_4 - 0.5 m_E V_{dc} s_8 \sin\delta_E) + s_2(0.5 e_2 m_E V_{dc} s_4 \times\cos\delta_E + 0.5 g_2 m_E V_{dc} \cos\delta_E - 0.5 m_E V_{dc} s_8 \cos\delta_E)$$

$$K_{p,B} = s_1(b_5 s_4 + d_5) + s_2 \times\left\{\left[\left(0.5 V_{dc} \sin\delta_B\right)(e_3 + g_3) + V_b \cos\delta(s_4 - 1)e_1 + s_8\right\}\right.$$

$$K_{p,\delta B} = s_1(b_6 s_4 + d_6) + 0.5 s_2 m_B V_{dc}(s_4 e_3 \cos\delta_B + g_3 \cos\delta_B)$$

$$K_{q,E} = s_3(b_3 s_4 + d_3 + 0.5 V_{dc} s_8 \cos\delta_E)$$

$$K_{q,\delta E} = s_3(b_4 s_4 + d_4 - 0.5 m_E V_{dc} s_8 \sin\delta_E)$$

$$K_{q,B} = s_3(b_5 s_4 + d_5),\ K_{q,\delta B} = s_1(b_6 s_4 + d_6)$$

$$K_{v,E} = 0.5 X_q V_{dc} s_6(s_4 e_2 \sin\delta_E + g_2 \sin\delta_E - s_8 \sin\delta_E) - s_7 X'_d(b_3 s_4 + d_3 + 0.5 s_8 V_{dc} \cos\delta_E)$$

$$K_{v,\delta E} = 0.5 X_q m_E V_{dc} s_6(e_2 s_4 + g_2 \cos\delta_E - s_8 \cos\delta_E) - s_7 X'_d\left(b_4 s_4 + d_4 - 0.5 m_E V_{dc} s_8 \sin\delta_E\right)$$

$$K_{v,B} = 0.5 X_q V_{dc} s_6\left(e_3 s_4 + g_3 \sin\delta_B\right) - s_7 X'_d\left(b_5 s_4 + d_5\right)$$

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$$K_{v,\delta B} = 0.5X_q s_6 \left(e_3 s_4 + g_3 \cos\delta_B\right) - s_7 X'_d (b_6 s_4 + d_6)$$

$$a_1 = \frac{X_{bv} + X_B}{X_{tE} + X'_d + X_E}, a_4 = -\frac{(X_{tE} + X'_d)}{(X_{tE} + X'_d + X_E)}$$

$$a_2 = \frac{X_T (X_{tE} + X'_d + X_E) + (X_{bv} + X_B)(X_{tE} + X'_d)}{(X_{tE} + X'_d + X_E)}$$

$$a_3 = -\frac{X_T (X_{tE} + X'_d) + (X_{bv} + X_B)(X_T + X_{tE} + X'_d)}{X_T (X_{tE} + X'_d + X_E)}$$

$$b_1 = a_1, b_2 = -a_2 V_b \cos(\delta), b_3 = 0.5 a_3 V_{dc} \cos(\delta_E)$$

$$b_5 = 0.5 a_4 V_{dc} \cos(\delta_E), b_6 = -0.5 a_4 m_B V_{dc} \sin(\delta_B)$$

$$c_1 = \frac{X_E}{X_{tE} + X'_d + X_E}, c_2 = \frac{X'_d + X_E}{X_{tE} + X'_d + X_E}$$

$$c_3 = \frac{X_T + X_{tE} + X'_d + X_E X_T (X_{tE} + X'_d + X_E) + X_E{}^2 (X_{tE} + X'_d)}{X_T (X_{tE} + X'_d + X_E)}$$

$$c_4 = \frac{X_T (X_{tE} + X'_d + X_E) + X_E (X_{tE} + X'_d)}{X_T (X_{tE} + X'_d + X_E)}$$

$$d_1 = c_1, d_2 = -c_2 V_b \sin(\delta), d_3 = 0.5 c_3 V_{dc} \cos(\delta_E)$$

$$d_4 = -0.5 c_3 m_E V_{dc} \sin(\delta_E), d_5 = 0.5 c_4 V_{dc} \cos(\delta_B)$$

$$d_6 = -0.5 c_4 m_B V_{dc} \sin(\delta_B)$$

$$e_1 = -\frac{X_{tE} + X_q - (X_{tE} + X_q)(X_{bv} + X_B)}{X_T (X_{tE} + X_q + X_E)}$$

$$e_2 = -\frac{X_{tE} + X_q + (X_T + X_{tE} + X_q)(X_{bv} + X_B)}{X_T (X_{tE} + X_q + X_E)}$$

$$e_3 = \frac{X_{tE} + X_q}{X_{tE} + X_q + X_E}$$

$$g_1 = \frac{-X_E X_{tE} + X_q - X_T (X_{tE} + X_q + X_E) - X_E (X_{tE} + X_q)}{X_T (X_{tE} + X_q + X_E)}$$

$$g_2 = \frac{X_T (X_{tE} + X_q + X_E) + X_E (X_{tE} + X_q) + X_E (X_T + X_{tE} + X_q)}{X_T (X_{tE} + X_q + X_E)}$$

$$g_3 = \frac{X_T (X_{tE} + X_q + X_E) + X_E (X_{tE} + X_q)}{X_T (X_{tE} + X_q + X_E)}$$

$$s_1 = V_{t,d} - X'_d I_{t,q}, \; s_2 = V_{t,q} + X_q I_{t,d}, s_3 = X'_d - X_d$$

$$s_4 = \frac{X_E}{X_T} + 1, s_5 = \frac{V_b}{X_T}, \; s_6 = \frac{V_{t,d}}{V_t}, s_7 = \frac{V_{t,q}}{V_t}, s_8 = \frac{1}{X_T}$$

APPENDIX B

Other details of the investigated power system used in simulations are as follows:

$$\delta_E = 30^\circ, \delta_B = 25^\circ, X_E = X_B = X_{tE} = X_{bv} = X_d = 0.1pu$$

$$X_T = 1.3pu, X_q = 2X'_d = 0.6, V_{dc} = E'_q = 0.5V_b = 2.0pu$$

$$m_E = m_B = 1, M = 8.0s, f_{s,E} = f_{s,B} = 50Hz, T'_{do} = 5.044s$$

$$T_a = 0.05s, K_a = 50, D_m = 0$$

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