Dynamic Stability and Optimal Control of a Multi-machine Power Networks Modeling and Simulation

N. Abu-Tabak, J.Y. Auloge, P. Auriol

Abstract-- In electrical power networks small oscillations appear from time to time. These oscillations concern the quantities determining the equilibrium point of the system, and following which, system stability and system behaviors are influenced. To improve system behaviors and dynamic stability it is necessary to minimize these transient states. The objective of our study is, first, showing the importance of good choice of state variables of a multimachine power system because controllability and observability of the system depend on this choice. On the other hand, we want to increase the damping of the small oscillation by adding of additional signals on excitation systems. The results of simulation approve the utility of the method used in this paper to choice the weighting matrices. These matrices are used to obtain the optimal control which minimizes a quadratic index. The problem of immeasurable states is noted but not discussed in detail.

Keywords: Damping of small oscillations, linear optimal control, and dynamic stability.

I. INTRODUCTION

In this paper, the problem of small signal stability will be treated. The linear modeling in the state space of an electrical multimachine power system will be discussed. The optimal control method will be applied to improve the dynamic responses of the power system under small disturbances. The problem of the state observer will briefly be noted in the last section.

II. SMALL OSCILLATION AND STABILITY PROBLEM

Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism. The stability problem involves the study of the electromechanical oscillations inherent in power systems. Small-signal stability is the ability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purpose of analysis.

In the literature, the authors interest in finding new approaches of control to improve the small-signal (dynamic) stability of power system. In this paper we will use the classical optimal control method but we will focalize on the problem of choice of the state vector for good representation of power system. This is a small idea but it is very important because it influences the observability and the controllability of the system.

Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

III. LINEAR MODELING OF MULTIMACHINE POWER SYSTEM

An electrical multimachine network is composed of several synchronous generators, transmission lines and loads. All elements and interactions between synchronous machines are taken into account in the state space linearized model. The operating point may be obtained by Newton-Raphson method for load flow study.

A. Load model

Load is a passive admittance, and given by:

$$\overrightarrow{y_{Li}} = \frac{P_{Li} - jQ_{Li}}{|V_i|^2} \tag{1}$$

where P_{Li}, Q_{Li} are the active and reactive load powers. $|V_i|$ is the voltage magnitude at the load node (i).

B. Transmission line model

Transmission line is considered as constant series impedance

C. Synchronous generator model

Synchronous machine is considered as a voltage behind a transient reactance.

$$\overrightarrow{E'_{qi}} = \overrightarrow{V_i} + jX'_{di} \cdot \overrightarrow{I_{Gi}} \tag{2}$$

where: $\overrightarrow{V_i}$ is the complex voltage at generator nodes, $\overrightarrow{E'_{qi}}$ is the voltage behind transient reactance jX'_{di}, and $\overrightarrow{I_{Gi}}$ is the injected current at generator node (i).

Each synchronous machine is described by Park's equations with neglect the resistance of the stator winding and the following from the voltage equations of stator

- The transformer voltage terms, $\dot{\psi}_q = \dot{\psi}_d = 0$.
- The effect of speed variation.

In rotor equation damping winding effect is neglected.

The reasons of the two first simplifications are discussed in [12]. Hence, Park's model of synchronous machine becomes.

$$v_d = -\omega \cdot \psi_q \qquad v_q = +\omega \cdot \psi_d \qquad v_F = r_F(i_F) + \frac{\dot{\psi}_F}{\omega_b} \tag{3}$$

D. Network model

The network is represented by constant admittances and reduced by eliminating all buses without generator. $\vec{Y}_{red} = \vec{Y}_1 - \vec{Y}_2 \cdot \vec{Y}_4^{-1} \cdot \vec{Y}_3$ where: $\begin{bmatrix} \vec{Y}_1 & \vec{Y}_2 \\ \vec{Y}_3 & \vec{Y}_4 \end{bmatrix}$ is the reorganized admittance matrix of the network. It is the same matrix of $(\vec{Y}_{BUS} + \vec{Y}_L)$ but after reorganization of its columns and rows.

The final admittance matrix is $\vec{Y}_f = \left(\vec{Y}_{red}^{-1} + jX'_d\right)^{-1}$ (4)

where X'_d is the diagonal matrix of transient reactance of the machines.

The objective, here, is obtaining the network under the following form (5).

$$\begin{bmatrix} [\vec{I}_G] \\ [\vec{I}_L] \end{bmatrix} = \begin{bmatrix} \vec{Y}_1 & \vec{Y}_2 \\ \vec{Y}_3 & \vec{Y}_4 \end{bmatrix} \cdot \begin{bmatrix} [\vec{V}_G] \\ [\vec{V}_L] \end{bmatrix} \quad \text{where:} \quad \begin{matrix} [\vec{I}_G] = [\vec{Y}_{red}] \cdot [\vec{V}_G] \\ [\vec{I}_G] = [\vec{Y}_f] \cdot [\vec{E}'_q] \end{matrix} \tag{5}$$

The indices (G, L) represent the generator and load nodes.

The diagram, shown below in Fig. 1, represents the relationships between voltages and currents in a network. From Fig. 1 equation (6) can be written

$$\vec{V}_i = \vec{E}'_{qi} - jX'_{di} \cdot \vec{I}_i - j(X_{qi} - X'_{di}) \cdot \vec{I}_{qi} \tag{6}$$

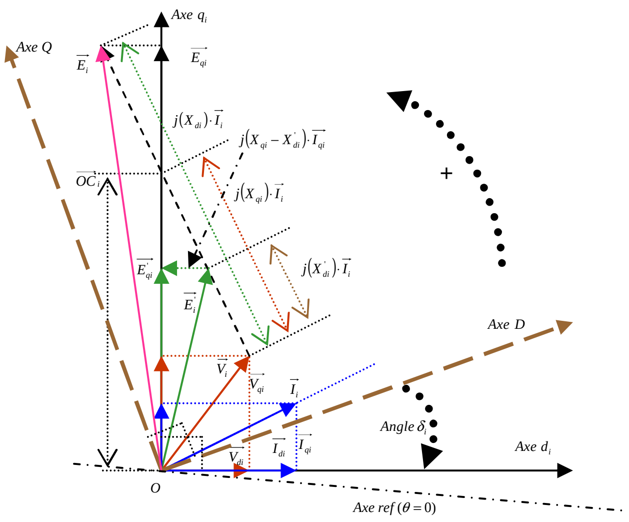

Fig. 1. Voltages and currents diagram of a network

To determine rotor angles of machines three reference axes may be used. Axis $(\theta = 0)$ is the reference axis to calculate the equilibrium state. (D,Q) is the common reference axis, it can be (d_1, q_1) or other axis. (d_i, q_i) is the individual reference axis of the machine (i).

E. Excitation system Model

The *IEEE* type 1 excitation system model is chosen and illustrated in Fig. 2.

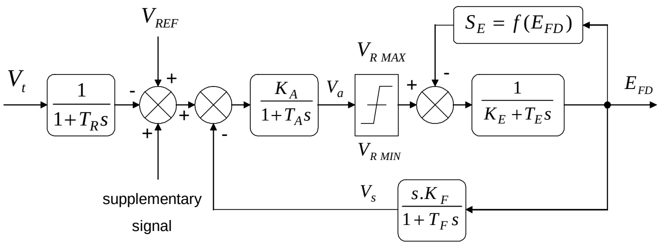

Fig.2. Excitation system

The saturation effect is neglected. T_R is very small, so $\frac{1}{1+T_R s}$ can be neglected. $sV_s = sV_a = 0$ because these voltages vary quickly compared to the other terms [1], [2], [3], [17]. Thus, after simplification discussed in [17] we have:

$$sE_{FD} = -\frac{K_E}{T_E + K_A K_F} E_{FD} + \frac{K_A}{T_E + K_A K_F}(V_{REF} - V_t) \tag{7}$$

F. Equation of motion.

The swing equation for the machine (i) is given by:

$$\dot{\omega}_i = \frac{1}{M_i}(T_{mi} - T_{ei} - D_i \cdot \omega_i) \text{ in } (pu/s) \tag{8}$$

$$\dot{\delta}_i = \omega_b(\omega_i - 1) \text{ in } (elec.rad/s) \tag{9}$$

where T_{mi}, T_{ei} are the mechanical and electrical torque, D_i is the damping coefficient, M_i is the mechanical starting time. δ_i is the torque angle, ω_i is the angular speed and ω_b is its value of base. For the electrical part, the effect of the salience is taken into account as shown in the following equations:

$$T_{ei} \cong \mathrm{Re}(\vec{I}_i \cdot \vec{V}_i) = I_{qi} \cdot E'_{qi} + I_{qi}\left(X_{qi} - X'_{di}\right) \cdot I_{di} \tag{10}$$

$$\dot{E}'_{qi} = \frac{1}{T'_{d0i}}\left(E_{FDi} - E'_{qi} - \left(X_{di} - X'_{di}\right) \cdot I_{di}\right) \tag{11}$$

Terminal voltage equations of the *i*th machine:

$$V_{di} = X_{qi} \cdot I_{qi} \qquad V_{qi} = E'_{qi} - X'_{di} \cdot I_{di} \tag{12}$$

G. Complete model of the ith machine in a multi-machine power system

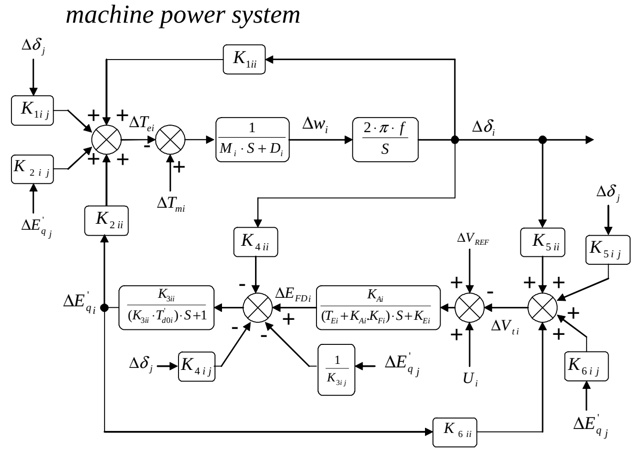

Fig. 3. One machine model in multimachine network

Fig. 3. represents the *i*th machine model in the power system of m machines. The deviation of the mechanical torque is neglected, thus $\Delta T_{mi} = 0$ [4], [10], [11], [12].

From Fig. 3 we can write the state space model of our system in the following form.

$$\left[\overset{\bullet}{\Delta X}\right]=[A]\cdot[\Delta X]+[B]\cdot[U]+[B]\cdot[\Delta V_{ref}] \qquad (13)$$

In (13) the state variables are the deviations of equilibrium point. The principle of linearization is discussed in detail in [12]. The detailed linear modeling is discussed in [1] to [4].

$$[\Delta X]=[\Delta(\delta_2-\delta_1),\ \Delta(\delta_3-\delta_1),\cdots\Delta(\delta_m-\delta_1),\ \Delta\omega_1,\ \Delta\omega_2,\cdots\Delta\omega_m$$
$$\Delta E'_{q1},\ \Delta E'_{q2},\cdots\Delta E'_{qm},\ \Delta E_{FD1},\ \Delta E_{FD2},\cdots\Delta E_{FDm}]^T \qquad (14)$$

$[U]=[U_1,U_2,\cdots,U_m]^T$ is the control vector. If the system is uncontrolled then this vector is zero. [1], [2], [3], and [18] based on [19] used the deviation of individual rotor angle $\Delta\delta_i$ as a state variable. Because the reference axis turns in synchronism with the rotor of an arbitrary chosen machine, they considered that the angle deviation of this machine $\Delta\delta_C$ is zero. Hence, (13) must be modified by eliminating of the state $\Delta\delta_C$ from the left and right hand sides. We will not follow this approach for the following reasons:

(i) By linearization we are interested in the deviation around the equilibrium point and not in the deviation with respect to the common reference of the system. Hence, $\Delta\delta_C$ can not be zero.

(ii) If we follow the same approach of [19], this means that a perturbation on the speed of the machine considered as reference does not have an effect on other state variables. This is not physically logical!

Taking into account $\Delta\delta_C$ results in one of the eigenvalues equaling zero. This is natural because the relationship between speed and angle deviations. If one of eigenvalues of system is zero full system is uncontrollable and unobservable. To avoid this problem, we have chosen the deviation of the relative angle between all machines and the first machine as shown in (14).

IV. STABILIZER DESIGN BASED ON LQR APPROACH

Using optimal control, from [1] to [4] and [13], displaces eigenvalues of system towards the left of the imaginary axis in (real-imaginary) plan. This displacement increases the damping of system. Feedback gain is calculated to be realizable and to give a control respecting the capacities of machines. For a system $x^\bullet(t)=A\cdot x(t)+B\cdot u(t)$, the optimal control is based on minimization of a performance index of quadratic form:

$$J=\frac{1}{2}\int_0^\infty\left[x^T(t)\cdot Q\cdot x(t)+u^T(t)\cdot R\cdot u(t)\right]\cdot dt \qquad (15)$$

where $(Q\geq 0, R>0)$ are diagonal matrices, the weighting matrix of state variable deviations and that of the control effort respectively. To find feedback gain we must calculate (P) where (P) is the solution of Riccati's equation (16).

$$-A^T\cdot P-P\cdot A+P\cdot B\cdot R^{-1}\cdot B^T\cdot P-Q=0 \qquad (16)$$

Feedback gain is given by $K=R^{-1}\cdot B^T\cdot P$ and the control vector becomes $u=-K\cdot x$. This control is added to the excitation system as supplementary signal. The closed loop is a new system and described by $x^\bullet(t)=[A-B\cdot K]\cdot x(t)$. For our study, the equation of the closed loop is given by (17).

$$\Delta X^\bullet(t)=[A-B\cdot K]\cdot\Delta X(t)+[B]\cdot[\Delta V_{ref}] \qquad (17)$$

The question arises of how to decide the weighting matrix Q and R of the performance function (15). In [14] a method is developed to determine Q in conjunction with a left shift of the eigenvalues as far as the practical controller permit. In [15] it is possible to determine Q and R matrices as follows.

A. Choosing the Q matrix

The importance of each state variable of a linear dynamic system may be related to its combined measure of controllability and observability, determined by transforming the system into an ordered balanced form [16], through the following transformation: $x(t)=T^{-1}x_b(t)$

where T is balanced transformation matrix and x_b is the state vector of the balanced form

$$\overset{\bullet}{x}_b(t)=A_b x_b(t)+B_b u(t)$$
$$y_b(t)=C_b x_b(t) \qquad (18)$$

where $A_b=TAT^{-1},\quad B_b=TB,\quad C_b=CT^{-1}$ (19)

The controllability and observability gramians, denoted by W_c and W_o respectively, of the system are defined as follows:

$$W_c=\int_0^\infty e^{At}BB^{-1}e^{A^Tt}dt \quad , \quad W_o=\int_0^\infty e^{A^Tt}C^TC\,e^{At}dt \qquad (20)$$

For open loop stable system, these gramians satisfy the following Lyapunov equations:

$$AW_c+W_cA^T+BB^T=0 \text{ and } A^TW_o+W_oA+C^TC=0 \qquad (21)$$

when the system is in a balanced form, its controllability W_c and observability W_o gramians are equal and diagonal, *i.e.*

$$W_c=W_o=\Sigma=\mathrm{diag}(\sigma_1,\cdots,\sigma_m,\sigma_{m+1},\cdots\sigma_n) \qquad (22)$$

where $\sigma_i\geq\sigma_{i+1}\geq 0;\quad (i=1,\cdots,n-1)$ are called the *Hankel* singular values (HSVs), or second order modes of the system, and m is a number of most dominant (most controllable and observable) modes. Based in the above analysis, the choice of the Q matrix is made as follows:

(i) The first m states of the balanced system are those states which are deemed to contribute most to the dynamical behavior of the system. Thus they should be weighted according to their contribution.

(ii) Ignore the last $n-m$ states by placing zero weighting on term. This is because these states are poorly controllable and/or observable, and therefore play a minor role in the dynamical behavior of the system. Thus it is impractical and useless to expend energy, which has to be very high, on these states. For calculate the Q matrix:

$$Q_b=\mathrm{diag}(1,\sigma_1/\sigma_2,\cdots,\sigma_1/\sigma_m,0,0,\cdots 0) \text{ and } Q=T^*Q_bT \qquad (23)$$

where T^* is the conjugate transpose of T.

B. Choosing the R matrix

The choice of the control weighting matrix R is accomplished by using the following procedure.

(i) Partition the system as follows:

$$\dot{x}(t) = A\,x(t) + \sum_{i=1}^{r} b_r u_r(t), \qquad y(t) = I_n\, x(t) \tag{24}$$

where I_n is the identity matrix of order n.

(ii) Consider the ith single input multioutput systems:

$$\dot{x}(t) = A\,x(t) + b_r u_r(t), \quad y(t) = I_n\, x(t), \quad i = 1, 2, \cdots, r \tag{25}$$

(iii) Transform the ith single input multioutput systems into its respective balanced form.

(iv) Calculate the contribution of the ith control input ω_i as:

$\omega_i = tr(\Sigma_i)$, where $\Sigma_i = W_{ci} = W_{oi}$, W_c and W_o are the controllability and observability gramians corresponding to the ith control input.

(v) From the R matrix as

$$R = \gamma(1, \omega_2/\omega_1, \omega_3/\omega_1, \cdots, \omega_r/\omega_1) \tag{26}$$

where γ is a positive scalar constant that determines the tightness of the control action. Normally, this should be set to $\gamma = \omega_1/\sigma_1$.

If, however, there are practical limitations which restrict the amount of control energy to be injected into the system, then γ should be chosen as $\gamma > \omega_1/\sigma_1$. On other hand, if more emphasis is to be placed on the closed loop state performance, then γ should be chosen as $\gamma < \omega_1/\sigma_1$.

V. NUMERICAL APPLICATION

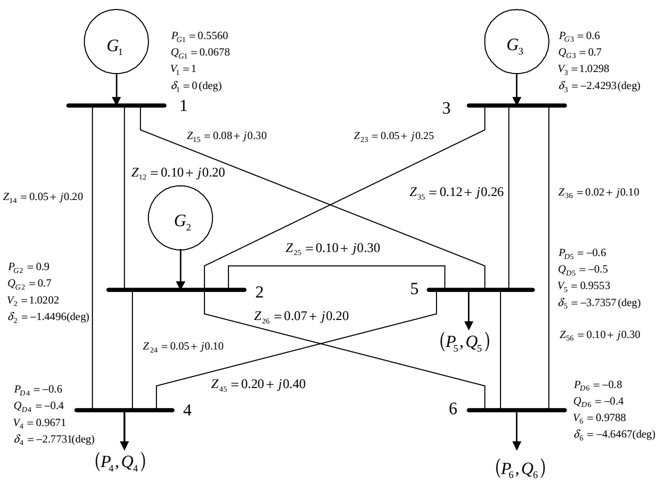

Fig.4. Simple network

TABLE I

DATA OF MACHINES AND EXCITATION SYSTEMS

	M (s)	D	X_q (pu)	X_d' (pu)	X_d (pu)
G1	9.26	2.5	0.57	0.2	1.02
G2	4.61	6	1.66	0.32	1.68
G3	4.61	6	1.66	0.32	1.68

K_F	T_F (s)	K_E	T_E (s)	T_{d0}' (s)	K_A	T_A (s)
0.05	0	1	0	7.76	50	0.02
0.05	0	1	0	4	50	0.02
0.05	0	1	0	4	50	0.02

VI. RESULTS OF SIMULATION

A. Without control

After having the state space model of this system as shown in (13), the eigenvalues of the state matrix A are calculated without control. We also have calculated the eigenvalues of the system with optimal control from (17).

TABLE II

SYSTEM EIGENVALUES

$-0.6956 \pm j11.1046$	$-0.4776 \pm j8.9554$	$-0.3899 \pm j1.8842$
0.0000	-0.6803	$-0.4989 \pm j0.8577$
$-0.5568 \pm j0.6217$	×	×

TABLE III

SYSTEM EIGENVALUES

-0.2700	$-0.7150 \pm j11.0446$	$-0.6946 \pm j6.4763$
$-0.3547 \pm j1.8532$	$-0.5068 \pm j0.8473$	$-0.5548 \pm j0.6206$

TABLE IV

SYSTEM EIGENVALUES

$-0.6956 \pm j11.1046$	$-0.4776 \pm j8.9554$	$-0.3899 \pm j1.8842$
-0.6803	$-0.5568 \pm j0.6217$	$-0.4989 \pm j0.8577$

TABLE V

SYSTEM EIGENVALUES

$-2.0042 \pm j11.6142$	$-2.0975 \pm j9.7554$	$-3.3794 \pm j4.2340$
$-6.3994 \pm j3.9303$	$-5.6818 \pm j3.4038$	-5.5338

Tables II, III, and IV show the eigenvalues of the system without control. Table V shows those of the system with optimal control. The system in case II has $\Delta\delta_i$ as state variables as detailed in [4]. We remark the existence of zero as pole of the system. The system in this representation is partially controllable and observable. In case III, we follow the approach discussed in [19] deleting the first row and column in the state matrix. The eigenvalues have changed, hence, the dynamic responses of the state variables of the system change. In case IV, we take $\Delta(\delta_i - \delta_1)$ as state variables as in (14), the eigenvalues of the initial system did not change but the zero disappeared. With this representation, the system is autonomous from the common reference. It is controllable and observable.

B. With optimal control

The system in case V is controlled. With optimal control the eigenvalues have displaced as shown in table V. Thus, the controlled system has become less oscillating, and the return to the equilibrium point is faster than the case without control. The values of weighting matrices according (23) and (26) are calculated and taken as follows:

$Q = \text{diag}\,[200, 170, 157600, 161310, 150720, 50, 200, 120, 0, 0, 0]$

$R = \text{diag}\,[2.2465, 2.1199, 2.1016]$.

To show the dynamic responses of the state variables, we have simulated at moment 0 (s) a disturbance of amplitude -0.1 (pu) for 200 (ms) in the reference voltage ΔV_{REF} of the 2th machine.

The following figures from 5 to 12 show that the system is stable, the state variables return to their initial states after 10 (s). With optimal control this time is reduced at 3 (s), and the state amplitudes are considerably smaller than those without control. In addition, the high frequency components of transient responses are filtered, and the curves are smoothed. Consequently, these figures and the Table V confirm the efficacy of the approach discussed in section IV based on [15], and concerning the choice of weighting matrices Q and R .

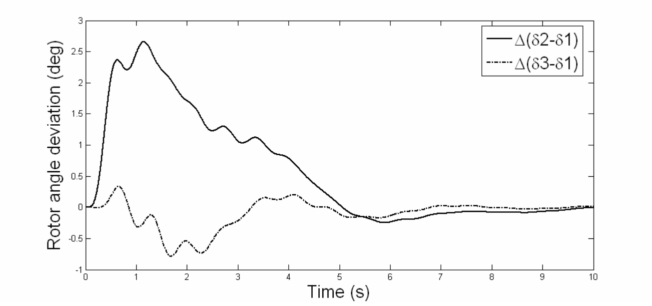

Fig. 5. Rotor angle deviation without control

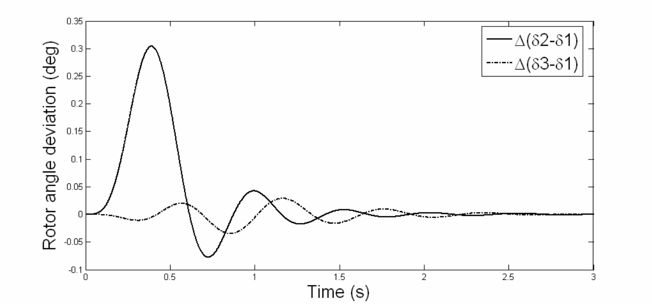

Fig. 6. Rotor angle deviation with optimal control

For the angular speed deviations, we note that all machines have the same curves. It is physically logical because if one machine accelerates or decelerates the other machines also must accelerate or decelerate to remain in synchronism.

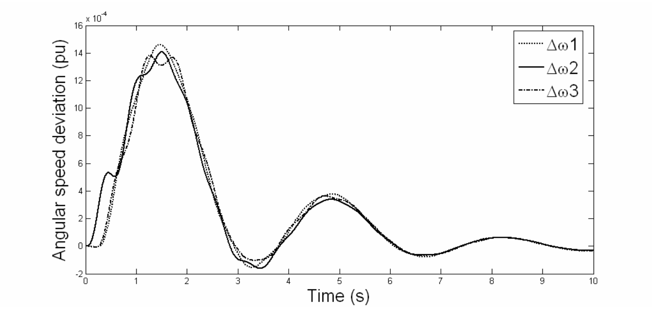

Fig. 7. Angular speed deviation without control

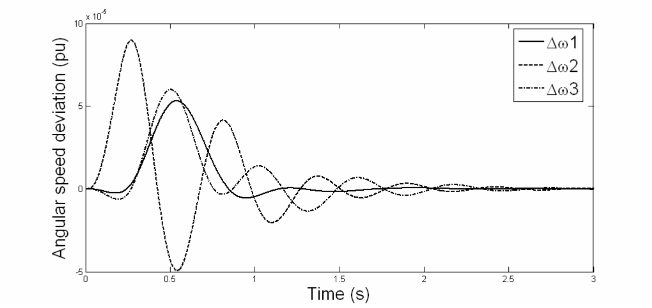

Fig. 8. Angular speed deviation with optimal control

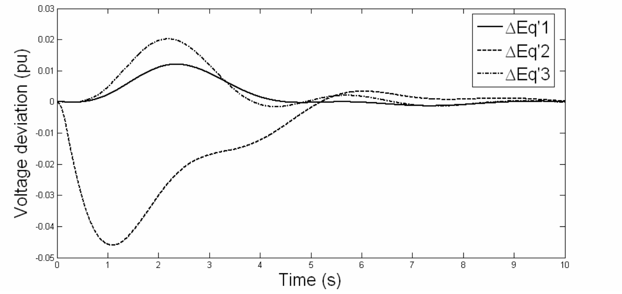

Fig. 9. Voltage deviation without control

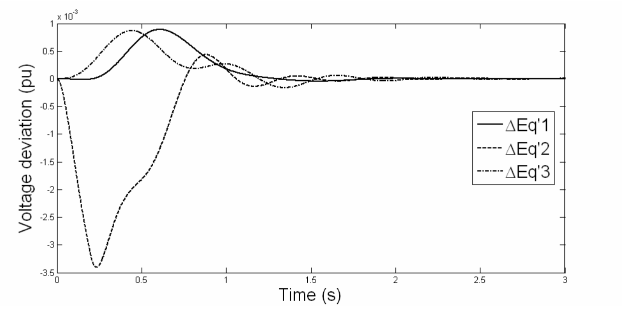

Fig. 10. Voltage deviation with optimal control

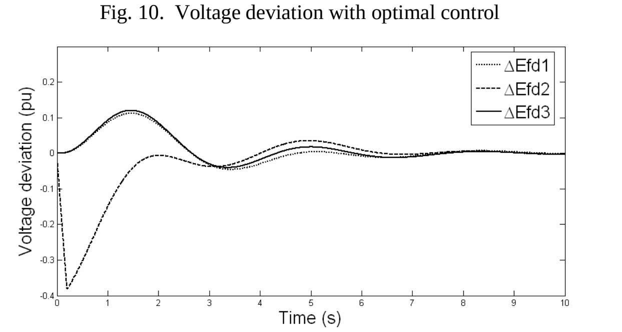

Fig. 11. Voltage deviation without control

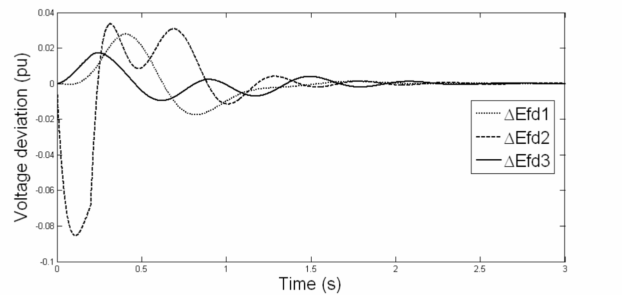

Fig. 12. Voltage deviation with optimal control

In this paper we suppose that all state variables are accessible or measurable, but, this is not correct because the rotor angle and the internal voltage behind the transient reactance are not accessible. Hence, it is necessary to use a state observer to obtain the lacking state variables. In addition, it is possible to estimate the control signal if we have the feedback gain of the closed loop of the system. Fig. 13. shows the block diagram of *Luenberger* observer of reduced order. It estimates a linear function as the control signal produced by optimal control method. The observer is a dynamical system, thus, it will modify the initial system dynamic. On other hand, the observer dynamic is influenced by the choice of its gain. This gain fixes the eigenvalues of the observer. They are those of matrix D .

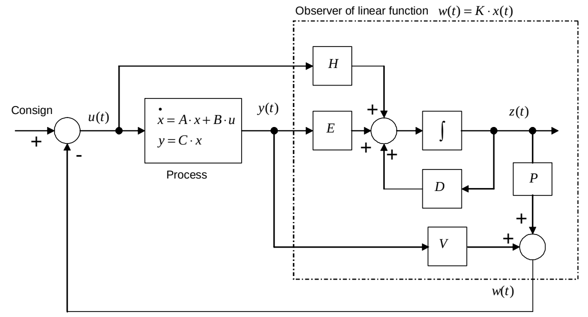

Fig. 13. State observer

$$\dot{z}(t) = D \cdot z(t) + H \cdot u(t) + E \cdot y(t) \text{ and } w(t) = P \cdot z(t) + V \cdot y(t)$$

To have a good operation of the complete system, we must find a compromise between the choice of the gain of the observer and that of the optimal control. It may be one of perspectives of the work presented in this paper.

VII. CONCLUSION

In this paper the linear modeling of multimachine power system briefly was discussed. The comparison between two models of multimachine power system based on the different choices of state variables showed a difference in the eigenvalues of these models. To improve the dynamic stability of power system, acting on the excitation systems of the synchronous machines by an optimal control was efficient. The optimal control was based on the minimization of quadratic function. The choice of weighting matrices was simple and practical following the discussed approach in section IV. A state variables observer is indispensable to estimate the immeasurable state variables. This problem was noted but not detailed here; and this may be a perspective for our study.

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