Proceedings of the 8th IEEE Mediterranean Conference
on Control and Automation (MED 2000)
Rio, Patras, GREECE 17-19 July, 2000

OBSERVER-BASED SLIDING MODE CONTROL OF SYNCHRONOUS GENERATOR [1]

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Abstract. This paper describes an application of the block control and variable structure control techniques to form a stabilizing controller for an synchronous generator. This combined approach enables the inherent nonlinearities of the generator to be compensated and high level external disturbances to be rejected. Also, the control system utilizes a nonlinear observer for estimation of the mechanical torque and rotor fluxes.

Keywords. Synchronous generator, stability, variable structure control, observers.

1. INTRODUCTION

A fundamental problem in the design of feedback controllers is that of stabilizing and achieving a specified transient performance in the presence of disturbances. This paper deals with excitation control of a single synchronous machine connected to an infinite bus, Fig. 1.

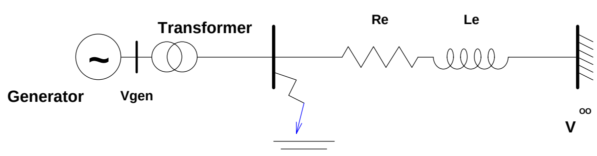

Fig1. Single machine-infinite bus system

The control schemes of synchronous machines are commonly based on reduced order linearized model and classical control algorithms that ensure asymptotic stability of the equilibrium point under small perturbations. Recently, to overcome the limitation of linear control, attention has been focused on implementation of the feedback linearization (FL) technique to provide larger stability margins.

Originally FL was applied to the reduced third order plant model [1-4]. In [5], it has been shown however that the effects of unmodeled stator and rotor electrical dynamics cannot be neglected since they affect the electromechanical dynamics. The detailed 7-th order model of synchronous machine has been considered, and a nonlinear controller using this model has been designed in [6]. The proposed nonlinear control law is a function of all plant parameters and disturbances. In practice some of these parameters are subjected to variations as a result of a change in the system loading and/or in the system configuration. Since the detailed model is so involved a direct use of the FL technique results in a computationally expensive control algorithm.

In this paper we shall resort to the block control [7] and variable structure control techniques [8] which overcome most of these problems: they are simple, computationally low demanding, and take into account structural constraints of the controller. The main feature of the proposed control are robustness to disturbances and plant parameter variations.

[1] Work supported by Conacyt, Mexico, under grant 32047-A.

The paper is organized as follows. Section 2 reviews the model of the synchronous machine. In Section 3 the block control technique is applied to design a nonlinear sliding surface, and a variable structure control strategy ensuring stability of the sliding mode is proposed. Section 4 presents a nonlinear observer design. Section 5 discusses simulation results.

2. GENERATOR MODEL

We are going to consider the single machine infinite-bus system taking into account a three-phase synchronous machine including both field and damper windings effects introduced by three rotor circuits. The complete mathematical description includes also the swing equation given by [5],

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{1}$$

$$\frac{d\omega}{dt} = \frac{\omega_s}{2H}(T_m - T_e) \tag{2}$$

where δ is the power angle of the generator; ω_s is the rated synchronous speed, H is the inertia constant; T_m is the mechanical torque applied to the shaft; and T_e is the electrical torque. After Park's transformation, the electrical dynamic using currents as the state variables, can be expressed as follows:

$$\mathbf{L}\frac{d\mathbf{i}}{dt} = -\mathbf{G}\mathbf{i} + \mathbf{V} \tag{3}$$

where

$$\mathbf{i} = (i_d, i_q, i_f, i_g, i_{kd}, i_{kq})^T, \quad \mathbf{V} = (V_d, V_q, V_f, 0, 0, 0)^T,$$

$$\mathbf{L} = \begin{bmatrix} -L_d & 0 & L_{md} & 0 & L_{md} & 0 \\ 0 & -L_q & 0 & L_{mq} & 0 & L_{mq} \\ -L_{md} & 0 & L_f & 0 & L_{md} & 0 \\ 0 & -L_{mq} & 0 & L_g & 0 & L_{mq} \\ -L_{md} & 0 & L_{md} & 0 & L_{kd} & 0 \\ 0 & -L_{mq} & 0 & L_{mq} & 0 & L_{kq} \end{bmatrix},$$

$$\mathbf{G} = \begin{bmatrix} -R_s & \omega L_q & 0 & -\omega L_{mq} & 0 & -\omega L_{mq} \\ -\omega L_d & -R_s & \omega L_{md} & 0 & \omega L_{mq} & 0 \\ 0 & 0 & R_f & 0 & 0 & 0 \\ 0 & 0 & 0 & R_g & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix}$$

i_d and i_q are the direct-axis and quadrature-axis stator currents; i_f is the field current; i_{kd}, i_{kq} and i_g are the direct-axis and quadrature-axis damper windings currents; ω is the angular velocity; V_d and V_q are the direct-axis and quadrature-axis terminal voltages; V_f is the excitation control input; R_s and R_f are the stator and field resistances; R_g, R_{kd} and R_{kq} are the damper windings resistances; L_d and L_q are the direct-axis and quadrature-axis self-inductances; L_f is the rotor self-inductance; L_{kd} and L_{kq} are the direct-axis and quadrature-axis damper windings self-inductances; L_{md} and L_{mq} are the direct-axis and quadrature-axis magnetizing inductances.

The torque T_e can be expressed in terms of the currents as follows:

$$T_e = (L_q - L_d)i_d i_q + L_{md} i_q (i_f + i_{kd}) - L_{mq} i_d (i_g + i_{kq}) \tag{4}$$

The equilibrium equation for the external network of the synchronous machine connected to an infinite bus can be written as

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = L_e \begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} + R_e \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \omega L_e \begin{bmatrix} i_d \\ -i_q \end{bmatrix} + V^\infty \begin{bmatrix} \cos\delta \\ sin\delta \end{bmatrix} \tag{5}$$

where: V_d and V_q are d and q terminal voltages; V^∞ is the value of the infinite-bus voltage; L_e, R_e are the transformer plus transmission line resistance and inductance. It is more suitable the representation of the electrical dynamics in terms of the stator currents i_d and i_q, the field flux ψ_f and the rotor fluxes, ψ_{kd}, ψ_{kq} and ψ_g. This can be obtained from (3) using the following transformation between fluxes and currents:

$$\boldsymbol{\psi} = \mathbf{L}_0 \mathbf{i} \tag{6}$$

where $\boldsymbol{\Psi} = (\psi_f, \psi_g, \psi_{kd}, \psi_{kq})^T$ and

$$\mathbf{L}_0 = \begin{bmatrix} -L_{md} & 0 & L_f & 0 & L_{md} & 0 \\ 0 & -L_{mq} & 0 & L_g & 0 & L_{mq} \\ -L_{md} & 0 & L_{md} & 0 & L_{kd} & 0 \\ 0 & -L_{mq} & 0 & L_{mq} & 0 & L_{kq} \end{bmatrix}$$

Here all the state variables as well as the parameters of the model (1)-(6) are expressed in per unit.
Combining equations (1) to (5) and using relationship (6), the complete model of the generator is presented in the nonlinear state-space form:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, T_m) + \mathbf{b}u \tag{7}$$

where $\mathbf{x}^T = (\mathbf{x}_1^T, \mathbf{x}_2^T)$ is the state vector; $\mathbf{x}_1^T = (\delta, \omega, \psi_f)$, $\mathbf{x}_2^T = (\psi_g, \psi_{kd}, \psi_{kq}, i_d, i_q)$; $u = V_f$ is the control input; $\mathbf{f}^T = (\mathbf{f}_1^T, \mathbf{f}_2^T)$, $\mathbf{b}^T = (\mathbf{b}_1^T, \mathbf{b}_2^T)$, with $\mathbf{f}_1, \mathbf{f}_2, \mathbf{b}_1$ and $\mathbf{b}_2$ given by:

$$\mathbf{f}_1 = \begin{bmatrix} x_2 - \omega_s \\ f_{22}(\mathbf{x}_2) - a_{23}x_8x_3 + a_mT_m \\ -a_{33}x_3 + a_{35}x_5 - a_{37}x_7 \end{bmatrix}, \quad \mathbf{b}_1 = \begin{bmatrix} 0 \\ 0 \\ b_3 \end{bmatrix},$$

$$\mathbf{f}_2 = \begin{bmatrix} [-a_{44}x_4 + a_{46}x_6 - a_{48}x_8] \\ [a_{53}x_3 - a_{55}x_5 - a_{57}x_7] \\ [a_{64}x_4 - a_{66}x_6 - a_{68}x_8] \\ [-a_{71}\cos x_1 + a_{73}x_3 + a_{75}x_5 - a_{77}x_7 \\ + (-a_{74}x_4 - a_{76}x_6 + a_{78}x_8)x_2] \\ [-a_{81}\sin x_1 + a_{84}x_4 + a_{86}x_6 - a_{88}x_8 \\ + (a_{83}x_3 + a_{85}x_5 - a_{87}x_7)x_2] \end{bmatrix},$$

$$f_{22}(\mathbf{x}_2) = -a_{25}x_5x_8 + (a_{24}x_4 + a_{26}x_6 - a_{28}x_8)x_7;$$

$\mathbf{b}_2 = [0,0,0,b_7,0]^T$, a_{ij}, ($i = 2,...,8$; $j = 1,...,8$), a_m, b_3 and b_7 are positive constants depending on the generator parameters R_s, R_f, R_g, R_{kd}, R_{kq}, R_e, L_d, L_q, L_{kd}, L_{kq}, L_{md}, L_{mq}, L_e and V^∞. The mechanical torque T_m it is assumed to be a slowly varying function of time. Thus:

$$\dot{T}_m = 0 \tag{8}$$

It is assumed that the terminal voltage V_g, the speed x_2 and the stator currents x_7 and x_8 are available for measurement, and that the control input $u(t)$ should be bounded by

$$|u(t)| \le V_{fm} \tag{9}$$

where V_{fm} is the maximum value of the excitation voltage.

3. CONTROL LAW DESIGN

The sliding mode controller design will be divided into two steps. First, exploring the block control technique a sliding surface will be formed. Then, a discontinuous control law will be designed to make attractive this surface.

The control goal is to make the angle x_1 be equal to a reference signal δ_{ref}, and the speed x_2 be equal to the rated synchronous speed ω_s. In accordance with the block control technique [9], z_1 is set to

$$z_1 = x_1 - \delta_{ref} \tag{10}$$

and x_2 can be rewritten as a function of z_1 and a new variable z_2:

$$x_2 = -k_1z_1 + \omega_s + \dot{\delta}_{ref} + z_2 \tag{11}$$

where $k_1 > 0$. Using (10) and (11), the first two equations of (7) in terms of new variables become

$$\dot{z}_1 = -k_1z_1 + z_2$$
$$\dot{z}_2 = -k_1^2z_1 + k_1z_2 + f_{22}(\mathbf{x}_2) - a_{23}x_8x_3 + a_mT_m - \ddot{\delta}_{ref}$$

Now, we propose the control switching function s

$$s = x_3 - x_{3d}(\mathbf{x}, \delta_{ref}, \dot{\delta}_{ref}, \ddot{\delta}_{ref}, T_m) \tag{12}$$

where x_{3d} is the desired value of x_3 and is defined by

$$x_{3d} = \frac{1}{a_{23}x_8}\left(f_{22}(\mathbf{x}_2) + a_mT_m - \ddot{\delta}_{ref} + (k_1 + k_2)z_2 - k_1^2z_1\right)$$
$$= \frac{1}{a_{23}x_8}\begin{pmatrix} f_{22}(\mathbf{x}_2) + a_mT_m - \ddot{\delta}_{ref} + (k_1 + k_2) \\ \times(x_2 + k_1(x_1 - \delta_{ref}) - \omega_s - \dot{\delta}_{ref}) - k_1^2(x_1 - \delta_{ref}) \end{pmatrix}$$

Therefore, a sliding mode motion on the surface $s = 0$ is described by the following second order linear system

$$\begin{aligned} \dot{z}_1 &= -k_1z_1 + z_2 \\ \dot{z}_2 &= -k_2z_2 \end{aligned} \tag{13}$$

with desired eigenvalues $-k_1$ and $-k_2$.

Note that from $z_1 = 0$ and $z_2 = 0$ it follows $x_1 = \delta_{ref}$ and $x_2 = \omega_s + \dot{\delta}_{ref}$. Therefore, the control goal requires δ_{ref} be a constant. Thus, $\dot{\delta}_{ref}$ and $\ddot{\delta}_{ref}$ will be taken as zero in (12).

The switching function design has been outlined. Now a control will be investigated. Projection of the system motion on subspace $s = 0$ can be written as

$$\dot{s} = f_s(\mathbf{x}_1, \mathbf{x}_2, \delta_{ref}, T_m) + b_s(\mathbf{x}_2)u \tag{14}$$

where

$$f_s = (-a_{33}x_3 + a_{35}x_5 - a_{37}x_7) + \frac{\partial x_{3d}}{\partial \mathbf{x}_1}\mathbf{f}_1 + \frac{\partial x_{3d}}{\partial \mathbf{x}_2}\mathbf{f}_2$$

and $\quad b_s = 1 - \dfrac{b_7}{a_{23}x_8}(a_{24}x_4 + a_{26}x_6 - a_{28}x_8)$

and $b_s(t)$ is a positive function for $t \geq 0$. Now, considering the bound (9), a control strategy can be proposed by

$$u = -V_{fm}\,\mathrm{sign}(s) \tag{15}$$

The sliding mode condition existence for discontinuous control (15) gives [8]

$$\dot{s}s = \left\{ f_s(\mathbf{x}_1, \mathbf{x}_2, \delta_{ref}, T_m) - b_s(\mathbf{x}_2) V_{fm}\,\mathrm{sign}(s) \right\} s < 0$$

Therefore, assuming

$$V_{fm} > \left| u_{eq}(\mathbf{x}_1, \mathbf{x}_2, \delta_{ref}, T_m) \right| \tag{16}$$

where u_{eq} is the *equivalent control* calculated from $\dot{s} = 0$, resulting

$$u_{eq} = \left(b_s(\mathbf{x}_2)\right)^{-1} f_s(\mathbf{x}_1, \mathbf{x}_2, \delta_{ref}, T_m) \tag{17}$$

so that the values of s and $\dot{s}$ have opposite signs and the state reaches the sliding surface $s = 0$ after a finite time interval. Once this is achieved, the sliding motion is governed by the linear system (13) corresponding to the linearized mechanical dynamics of the closed-loop system.

A crucial property of the sliding mode control (15) when applied to (7) is that, it yields the invariant subspace $\{\xi = (x_{1ss}, 0, 0)^T, \ \mathbf{x}_2 \in R^5\}$ where $\xi = (z_1, z_2, s)^T$. The dynamic of $\mathbf{x}_2$ on this invariant subspace is referred to as the *zero dynamics*. To derive this dynamics, the equivalent control u_{eq} (17) must be substituted in the second subsystem of (7):

$$\dot{\mathbf{x}}_2 = \mathbf{f}_2(\mathbf{x}_1, \mathbf{x}_2) + \mathbf{b}_2 u_{eq}(\mathbf{x}_1, \mathbf{x}_2, \delta_{ref}, T_m)$$

The vector $\mathbf{x}_1$ is changed by ξ:

$$\begin{aligned}
\dot{\mathbf{x}}_2 &= \tilde{\mathbf{f}}_2(\xi, \mathbf{x}_2, T_m), \\
\tilde{\mathbf{f}}_2 &= \mathbf{f}_2(\mathbf{x}_1, \mathbf{x}_2)_{\mathbf{x}_1 = \varphi(\xi)} \\
&\quad + \left(b_s(\mathbf{x}_1, \mathbf{x}_2)\right)^{-1} \mathbf{b}_2 f_s(\mathbf{x}_1, \mathbf{x}_2, \delta_{ref}, T_m)_{\mathbf{x}_1 = \varphi(\xi)}
\end{aligned}$$

where mapping φ is defined by (11) and (12). Finally, the vector $\boldsymbol{\xi}$ is zeroed, thus:

$$\dot{\mathbf{x}}_2 = \tilde{\mathbf{f}}_2(0, \mathbf{x}_2, \delta_{ref}, T_m)$$

An equilibrium point for this system is defined by δ_{ref} and the value of the mechanical torque T_m. Simulation results show that this equilibrium point is asymptotically stable (see Section 5).

4. FLUXES OBSERVER DESIGN

As stated previously, we consider the speed $x_2(t)$ and stator currents $x_7(t)$ and $x_8(t)$ as measured signals, and the remaining state variables x_i, $i = 3,...,6$ and mechanical torque T_m can be estimated by means of the nonlinear observer proposed as

$$\begin{aligned}
\dot{\hat{x}}_2 &= -a_{23} x_8(t)\hat{x}_3 + a_{24} x_7(t)\hat{x}_4 - a_{25} x_8(t)\hat{x}_5 \\
&\quad + a_{26} x_7(t)\hat{x}_6 - a_{68} x_7(t) x_8(t) + a_m \hat{T}_m + l_1(x_2 - \hat{x}_2) \\
\dot{\hat{T}}_m &= l_2(x_2 - \hat{x}_2) \\
\dot{\hat{x}}_3 &= -a_{33}\hat{x}_3 + a_{35}\hat{x}_5 - a_{37} x_7(t) + u \\
\dot{\hat{x}}_4 &= -a_{44}\hat{x}_4 + a_{46}\hat{x}_6 - a_{48} x_8(t) \\
\dot{\hat{x}}_5 &= a_{53}\hat{x}_3 - a_{55}\hat{x}_5 - a_{57} x_7(t) \\
\dot{\hat{x}}_6 &= a_{64}\hat{x}_4 - a_{66}\hat{x}_6 - a_{68} x_8(t)
\end{aligned} \tag{18}$$

where: $\hat{x}_i$, $i = 2,...,6$, and $\hat{T}_m$ are the estimated variables; l_1 and l_2 are observer gains. The stability of observer (22) may now be analyzed by examining the following error dynamics equation:

$$\dot{\mathbf{e}} = \mathbf{A}(t)\mathrm{e} \tag{19}$$

where

$\mathbf{e} = (e_2, e_m, e_3, e_4, e_5, e_6)^T$,

$e_i = x_i - \hat{x}_i$, $i = 2,...,6$, $e_m = T_m - \hat{T}_m$,

$$\mathbf{A}(t) = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12}(t) \\ \mathbf{0} & \mathbf{A}_{22} \end{bmatrix}, \quad \mathbf{A}_{11} = \begin{bmatrix} -l_1 & a_{29} \\ -l_2 & 0 \end{bmatrix},$$

$$\mathbf{A}_{12}(t) = \begin{bmatrix} -a_{23}(t) & a_{24}(t) & -a_{25}(t) & a_{26}(t) \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{A}_{22} = \begin{bmatrix} -a_{33} & 0 & a_{35} & 0 \\ 0 & -a_{44} & 0 & a_{46} \\ a_{53} & 0 & -a_{55} & 0 \\ 0 & a_{64} & 0 & -a_{66} \end{bmatrix}, \quad \text{and}$$

$a_{23}(t) = a_{23} x_8(t)$, $a_{24}(t) = a_{24} x_7(t)$,
$a_{25}(t) = a_{25} x_8(t)$ $a_{26}(t) = a_{26} x_7(t)$.

The nonlinear observer (18) can be seen as a linear system with time varying parameters when the variables $x_7(t)$ and $x_8(t)$ are assumed known functions. It is easy to see that the spectrum of the block matrix $\mathbf{A}(t)$ (19) consists of the eigenvalues of diagonal blocks $\mathbf{A}_{11}$ and $\mathbf{A}_{22}$. The eigenvalues of $\mathbf{A}_{11}$ can be assigned by appropriate choice of observer gains l_1 and l_2. The matrix $\mathbf{A}_{22}$ is Hurwitz since its eigenvalues:

$$\lambda_{3,4} = -\frac{1}{2}(a_{33} + a_{55}) \pm \frac{1}{2}\sqrt{(a_{33} - a_{55})^2 + 4a_{35}a_{53}}$$

$$\lambda_{5,6} = -\frac{1}{2}(a_{44} + a_{66}) \pm \frac{1}{2}\sqrt{(a_{44} - a_{66})^2 + 4a_{46}a_{64}}$$

are real and negative. The parameters of $\mathbf{A}_{12}(t)$ and its derivatives are bounded, therefore, the linear system with time varying parameters (19) is asymptotically stable. The resulting estimates $\hat{x}_i$, $i = 2,...,6$ and $\hat{x}_m$ are employed in the control law (15) and (17).

5. SIMULATION RESULTS

This section presents some simulation results, emphasizing the effectiveness of the previously designed sliding mode controller. The performance of the proposed controller was tested on the complete 8^{th} order model of the generator connected to an infinite bus through a transmission line, Fig.1.

The parameters of the synchronous machine and transmission system, all in p.u., except where indicated, are:

$R_s = 0.003$, $R_f = 0.021$, $R_g = 0.725$, $R_{kd} = 10.714$, $R_{kq} = 8.929$, $R_e = 0.05$, $L_d = 1.81$, $L_q = 1.76$, $L_{kd} = 1.831$, $L_{kq} = 1.735$, $L_{md} = 1.66$, $L_{mq} = 1.61$, $L_e = 0.1$, $H = 3.525\,\text{sec}$. and $\omega_s = 377\, rad\ s^{-1}$.

Setting $T_m = 0.9463$ and $V^{\infty} = 1$, the steady state is computed and presented in Table 1.

Table 1. Steady State

$x_1(\infty)$	$x_2(\infty)$	$x_3(\infty)$	$x_4(\infty)$
1.3314	376.99	0.82038	-0.79228
$x_5(\infty)$	$x_6(\infty)$	$x_7(\infty)$	$x_8(\infty)$
0.62594	-0.79247	0.80354	0.49319

The controller gains were adjusted to k_1=7 and k_2=15, and the observer gains were chosen as l_1=200 and l_2=187, resulting in the eigenvalues $\lambda_1 = \lambda_2 = 100$. The remaining observer eigenvalues were calculated using (24) and (25) as $\lambda_3 = -0.123$, $\lambda_4 = -33.922$, $\lambda_5 = -0.883$ and $\lambda_6 = -16.179$.

Figures 2 and 3 depict results under three different events: *a)* simulation begins not from the equilibrium point; *b)* in *t* = 2 *s*, T_m experienced a pulse for 0.5 *s*; and *c)* in *t* = 4 *s*, a three-phase short circuit for a period of 150 *ms* is simulated at the transformer terminals.

Fig. 2 reveals some important aspects. 1) State variables hastily reach a steady state condition (see Table 1) after small and large disturbances, exhibiting the stability of the closed-loop system. 2) The estimated signals are closely related to the actual ones, exhibiting a robust performance of the observer. 3) The terminal voltage recovers their steady state value after the short circuit.

Fig.3 depicts the same simulation as before but considering that the value of parameter L_{md} experiences an increment of 20%, so introducing parameter uncertainties. We can observe that the estimated variables converge to an steady state defined by the new value of L_{md}, but the steady state of the outputs, namely δ and V_{gen} is invariant to observer one.

6. CONCLUSIONS

A sliding mode controller is proposed exhibiting robust stability and performance when the plant experiences small and large disturbances. The inclusion of an external load torque and the simulation of a short circuit demonstrate the capability of the controller in rejecting bounded disturbances.

The design process, including analysis of stability, is discussed. The formulation employed makes easy to design a nonlinear observer that exhibits a good performance.

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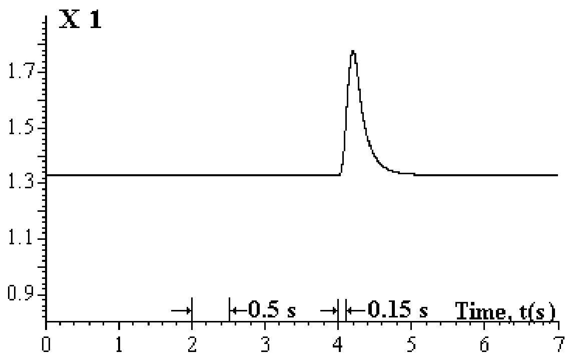

Fig. 2a. Angle δ (rad)

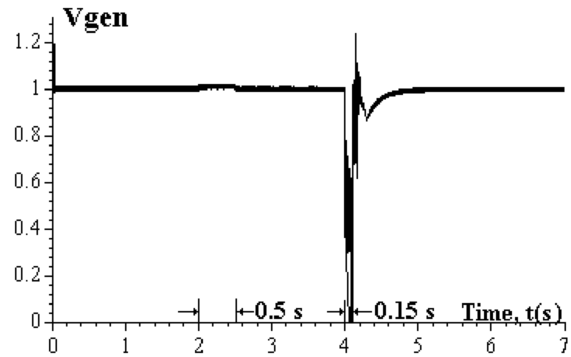

Fig. 2b. Terminal Voltage (p.u.)

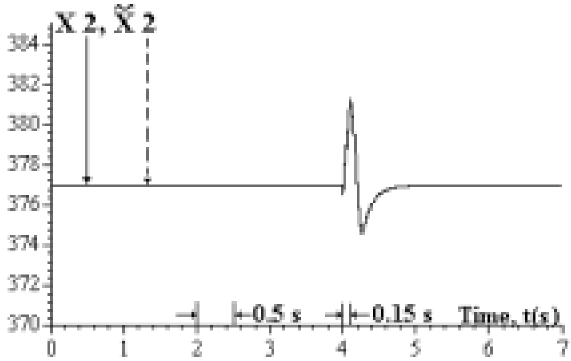

Fig. 2c. Speed ω (rad/s) and estimation.

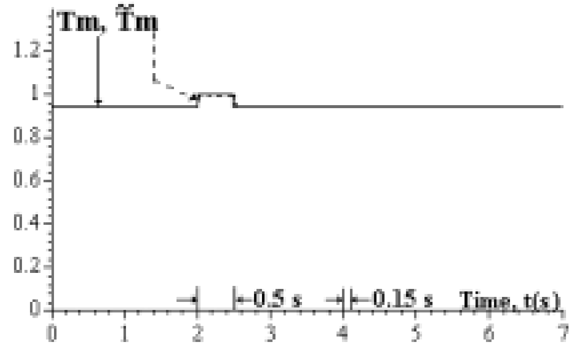

Fig.2d. Mechanical torque (p.u.) and estimation.

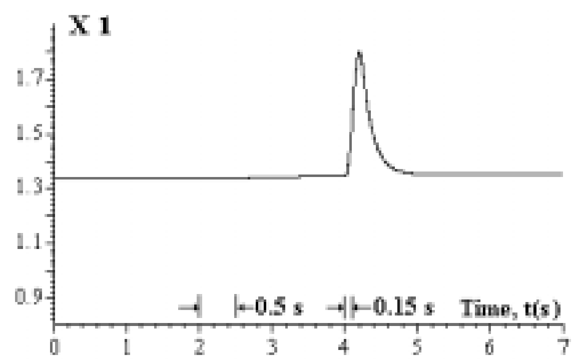

Fig. 3 a. Angle δ (rad)

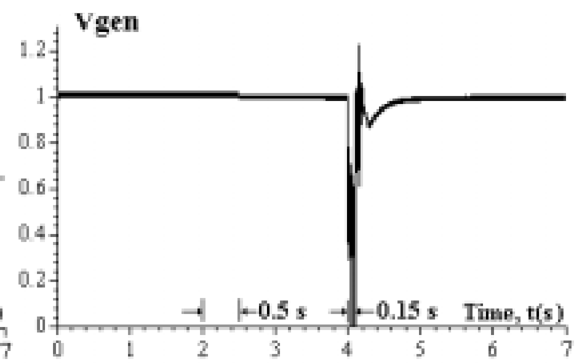

Fig. 3b. Terminal Voltage (p.u.)

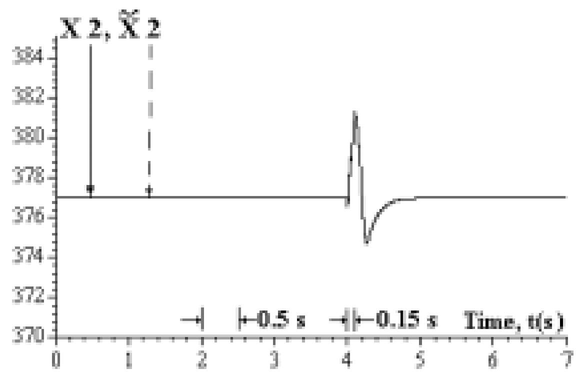

Fig. 3c. Speed ω (rad/s) and estimation.

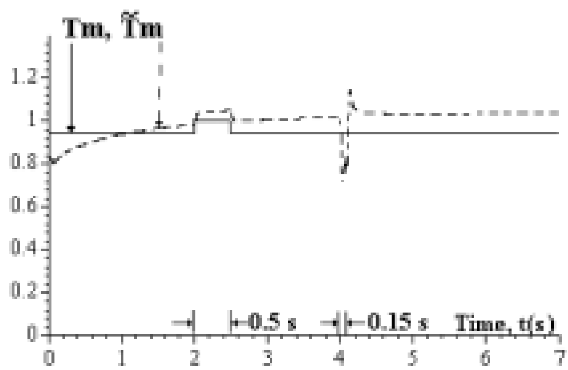

Fig.3d. Mechanical torque (p.u.) and estimation.