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STABILITY AND FREQUENCY CONTROL OF POWER GENERATING SYSTEMS BASED ON THE SLIDING MODE TECHNIQUE

التحكم فى تردد وإستقرار منظومات القوى الكهربية باستخدام نظرية الهياكل المتغيره

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ملخص البحث:

يقدم البحث دراسة جديدة عن كيفية التحكم فى منظومات توليد القوى الكهربية حيث تم إقتراح خوارزم جديد للتحكم فى تردد المنظومة وخرجها وذلك باستخدام نظرية الهياكل المتغيره. وتتميز منظومات الهياكل المتغيره بخاصية الحركة الإنزلاقية التى تجعل المنظومة غير حساسة للإضطرابات الخارجية أو لتغير المعاملات. والخوارزم المقترح لتصميم حاكم توافقي للمنظومة لايحتاج إلى معلومات دقيقة عن المنظومة أو معاملاتها أو كيفية تغير هذه المعاملات ويكفى فقط معرفة الحدود القصوى والدنيا لهذا التغير.

وقد تم تصميم حاكم توافقى لمنظومة توليد القوى باستخدام الخوارزم المقترح ووظيفة هذا الحاكم هو ضبط خرج المنظومة وكذلك ترددها تحت ظروف الاضطرابات الداخلية والخارجية. وتم تطبيق ذلك باستخدام مثال عددى وأثبتت نتائج المحاكاة فعالية الطريقة المقترحة وفعالية الحاكم المقترح تحت تأثير إضطراب خارجى فجائى.

ABSTRACT

In the present paper, a new algorithm for solving the control problem in electrical power systems, is introduced. This new algorithm is based on the sliding mode property existing in variable structure system (VSS). The resulting control law is discontinuous by its nature. However, it does not require accurate informations about the system parameters or its manner of variation. The only requirements are the maximum and minimum limits of variation for each parameter.

An adaptive controller is designed for an electrical power system, on the basis of that new algorithm. The main function of the controller is the frequency control of the electrical power system, meanwhile, it can be used for stability improvement.

Theoretical and computational results, using that controller insure the frequency control property in the electrical power system model. The adaptive property verifies under rapid and wide range of parameters variation and also, under the effect of a unit step external disturbance.

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1. INTRODUCTION

Control of electrical power systems seems to be a complicated problem if we tried to solve it using classical methods of control. This complication arises due to :

1- Lack of information about parameters variation.
2- Existence of external disturbances.

Discontinuous control methods such as self-oscillating adaptive control [2,9]; high gain co-efficient control and those methods based on the theorems of liapounov and hyper-stability criterion, can not overcome the parameters variation in wide range as well as the effect of external disturbances.

Variable structure systems [1] are able to solve this problem. This type of discontinuous control has an important property known as sliding mode [2]. Once in a control system a sliding mode is realized, the system becomes insensitive to parameters variation as well as, to external disturbances. For realizing sliding modes in control systems, a new general approach was developed [3]. This approach does not need any information about the parameters variation as well as, the level of external disturbances. Only, the upper and lower limits of these variations are to be known. On the basis of this approach, a new algorithm for adaptive control of electrical power systems, is developed.

The paper contains the development of a power system model. Then, the evaluation of VSS technique is presented.

2. MATHEMATICAL MODEL

Consider an interconnected power system comprising N subsystems. The block diagram, representing the jth subsystem is shown in figure (1). Where reheat turbines are considered. The transfer functions of the reheat turbines are given by :

$$G(s) = \frac{\Delta P_{gi}(s)}{\Delta Xsi(s)} = \frac{1 + sk_{ri}T_{ri}}{(1 + sT_{ri})(1 + sT_{ti})}, \quad i = 1,2..........N......................(1)$$

If k_{ri} =1 ; G(s) reduces to $\frac{1}{1 + sT_{ti}}$. representing the transfer function of nonreheat turbines. The shown controller, in conventional case, has the transfer function $-k_{i}$. However, the case of VSS control the controller is modified as shown in figure (2).

Suppose that the dynamics of interconnected power system is described by the state equation.

$$\dot{x} = A(x,t)x + B(x,t)u + D(x,t).F(t),; \quad xR^{n}; uR^{m}, PR^{l}..................(2)$$

where;
A(x,t) - (nxn) functional matrix of the state vector;

$B(x,t)$ - (nxm) functional matrix of the controlling input;
$D(x,t)$ - (nx1) functional matrix of external disturbance;
x - state vector; u- controlling input; F - external disturbance.
Matrix $A(x,t)$ is in the form :

$$A(x,t) = \begin{bmatrix} A_{11} & A_{12} & A_{1i} & A_{1N} \\ A_{21} & A_{22} & & \\ & & & \\ A_{i1} & & A_{ii} & \\ A_{N1} & A & A_{Ni} & A_{NN} \end{bmatrix}$$

matrix $B(\dot{x},t)$ has the form ;

$$B(x,t) = [\,B_1 \quad B_2 \,\ldots\ldots\ldots\, B_i \,\ldots\ldots\ldots\, B_N\,]^T .$$

and matrix $D(x,t)$ is given by

$$D(x,t) = [\,D_1 \quad D_2 \,\ldots\ldots\ldots\, D_i \,\ldots\ldots\ldots\, D_N\,]^T .$$

Considering the i th subsystem

$$A_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2\pi T.T_{ij} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & & \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad ;\ i \neq j ;\quad i = 1,2,\ldots,N;$$

$$B_i = \begin{bmatrix} 0 & \dfrac{1}{T_{gi}} & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad ;\quad i = 1,2,\ldots,N \quad ;$$

$$D_i = \begin{bmatrix} 0 & 0 & 0 & \dfrac{-K_{p1}}{T_{p1}} & 0 & 0 \end{bmatrix}^T \quad ; i = 1, 2, \ldots, N$$

And

$$A_{ii}= \begin{bmatrix} 0 & 0 & 1 & v_i & 0 & 0 \\ 0 & -\frac{1}{T_{gi}} & 0 & \frac{-1}{T_{gi}\ T_i} & 0 & 0 \\ 0 & 0 & 0 & 2\pi T_i \sum_{i|\neq j} T_{ij} & 0 & 0 \\ 0 & 0 & \frac{-K_{pi}}{T_{pi}} & \frac{-1}{T_{pi}} & \frac{K_{pi}}{T_{pi}} & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{ti}} & \frac{1}{T_{ti}} \\ 0 & (\frac{1}{T_{ri}}-\frac{K_{ri}}{T_{gi}}) & 0 & \frac{-K_{ri}}{T_{gi} R_i} & 0 & \frac{-1}{T_{ti}} \end{bmatrix}$$

where :

k_{ri} : = reheat co-efficient;
T_{ri} : = reheat time constant;
T_{ti} : = turbine time constant;
v_i : = frequency bias setting;
T_{gi} : = governor time constant;
K_{pi} : = power system gain;
T_{pi} : = power system time constant;
T_{ij} : = synchronizing co-efficient between subsystems i & j;
R_i : = speed regulation due to governor action;

3. STATEMENT OF THE PROBLEM

It is required to design a controller, which generates an actuating signal to control the frequency deviation Δf_i , as well as the tie - line power change ΔP_{tie} resulting from sudden changes in the load ΔP_{di} .

The following set of minimum requirements are stated [4] by the North American Power System Interconnection Committee ;

i) The static frequency error following a step load change must be zero;
ii) The transient frequency swings should not exceed ± 0.02 Hz under normal conditions
iii) The static change in tie-line flow following a step change in each must be zero,
iv) The individual generators within each area should divide their loads for optimum economy.

4. A NEW ALGORITHM FOR REALIZING A SLIDING MODE IN POWER SYSTEMS

The vectorial control problem could be divided into m-scalar problems as follows :

From the state equation (2) we can write :

$$x = A(x,t).x(t) + b^1(x,t)u_1 + b^2(x,t)u_2 + \dots\dots\dots +$$
$$+ b^m(x,t)u_m + D(x,t).F(t) \dots\dots\dots\dots\dots\dots\dots (3)$$

where :

$b^1(x,t)$; $b^2(x,t)$ .....; $b^m(x,t)$ are the columns of matrix $b(x,t)$.

Hence, a set of sliding modes could be organized simultaneously on the m-hyperplanes

σ_1 , σ_2 ,................, σ_m

where :

$\sigma_1 = C^{1T}\ x$; C^1 - (n) vector column ; $x \in R^n$

$\sigma_2 = C^{2T}\ x^1$; C^2 - (n-1) vector column ; $x^1 \in R^{n-1}$

.... ; ....

$\sigma_m = C^{mT}\ x^{m-1}$; C^m - (n-m+1) vector column ; $x^{m-1} \in R^{n-m+1}$

The elements of vector columns C^1, C^2, ... C^m could be determined using the standard coefficient method [5]. The necessary and sufficient condition for realizing a sliding mode on the plane σ_1 is $\sigma_1 . \dot{\sigma}_1 < 0$ [2]. To achieve this condition we shall require that the following conditions must be realized :

$C^{1T}\ b^1\ (x,t) \neq 0$.. (4a)

$C^{1T}\ b^1\ (x,t).\ \phi_1\ (\sigma_1) < 0$ when $\sigma_1 > 0$ (4b)

$C^{1T}\ b^1\ (x,t).\ \phi_1\ (\sigma_1) < 0$ when $\sigma_1 > 0$ (4c)

$$|C^{1T}\ b^1\ (x,t).\ \phi_1\ (\sigma_1)| < |C^{1T}\ A\,(x,t).x(t) + C^{1T}\ b^2\,(x,t)u_2 + \dots$$
$$+ C^{1T}\ b^m\,(x,t)u + C^{1T}\ D\,(x,t).\ F(t)\ | \dots\dots\dots\dots \quad (4d)$$

Condition (4a) could be realized if the following conditions were satisfied :

i) The element C_{n-m+1} in the vector row C^{1T} has a nonzero value, i.e. if C^{1T} had the form :

$C^{1T} = (\ C_1\ ,\ C_2\ , \dots ,\ C_{n-m+1}\ ,\ 0\ ,\ 0\ , \dots,\ 0\ )$ (5a)

ii) The vector column has the form :

$$b^1\ (x,t) = [\ 0 \quad 0 \ldots\ldots\ b_m \quad b_{m-1} \quad b_1\ ]^T \ldots\ldots\ldots\ldots \tag{5b}$$

Conditions (4b), (4c), and (4d) could be realized, if the function $\phi_1(\sigma_1)$ was chosen as a nonlinear multi-valued function having the following properties :

a- multi-valued and limited;
b- closed at $\sigma_1 = 0$ as a set and limited;
c- semi-continuous at $\sigma_1 = 0$;
d- values of $\sigma_1, \sigma_2, \ldots\ldots, \sigma_m$ in the neibourhood of $\phi(\sigma_0, t) \in \phi(\sigma_0)$.

The above mentioned multi-valued function is shown in figure (3). After satisfying conditiona (4a), (4b), (4c) and (4d) we get;

$$\sigma_1 = C^{1T}\ x \ldots \tag{6a}$$

$$\begin{aligned}\dot{\sigma}_1 &= C^{1T}\ \dot{x}\\ &= C^{1T}\,[A(x,t).x(t) + b^1\ (x,t)\,\phi_1(\sigma_1). + b^2\ (x,t)\,u_2\ +\\ &\quad + b^3\,(x,t)\,u_3 + \ldots\ldots + b^m\,(x,t)\,u_m + D(x,t).P(t)\,] \ldots\ldots\ldots\end{aligned} \tag{6b}$$

From (6a) and (6b) we have ;

$$\begin{aligned}\sigma_1 . \dot{\sigma}_1 = \sigma_1 . C^{1t}\, b^1\ (x,t)\,\phi_1(\sigma_1).+ (\sigma_1).C^{1t}\,[A(x,t).x(t) +\\ + b^2\,(x,t)\,u_2 + \ldots\ldots + b^m\,(x,t)\,.F(t)\,] \ldots\end{aligned} \tag{7}$$

From (7) it is easy to show that the inequality $\sigma_1 . \sigma_1 < 0$ will be always satisfied ; i.e. there will be a permanent sliding motinn on the hyperplane σ_1 .

Existenee of a sliding mode on the plane σ_1 means that the motion of system (3) can be described by the following equations :

$$\begin{aligned}x = A(x,t).\ x(t) + b^2\,(x,t).u_2. + \ldots\ldots + b^m\,(x,t).u_m\\ + D(x,t).\ F(t) + b^1\,(x,t).\zeta_1 \ldots\ldots\end{aligned} \tag{8a}$$

$$C^{1T}\ x(t) = 0 \ldots\ldots \tag{8b}$$

where :

ζ_1 = a single valued (scalar) function or the first component of the nonlinear predetermined vector function - (additional controlling input) and is given by :

$$\begin{aligned}\zeta_1 = [\,C^{1T}\ \ b^1\ (x,t)\,]^{-1}.\ \{-C^{1T}\ [A(x,t).x(t) + b^2\ (x,t).u_2 + \ldots\\ + b^m\,(x,t).u + D(x,t).F(t)]\} \ldots\ldots\ldots\end{aligned} \tag{9}$$

Similarly, it is possible to establish another sliding modes on the hyperplanes σ_2 , ... σ_m using the same technique. The multi-valued function could be generated using a multiplier as shown in figure (4) .

A flow-chart for a computer program to carry-out the suggested algorithm is shown in figure (5).

In the flow chart, the following symbols are used
i) A_0 and B_0 are the steady state matrices for the controlled system.
ii) w_0 : = a scalar which determines the response speed of the controlled system at steady-state [6].
iii) NT : = number of computation points ;
NK1: = number of points from starting till applying the change external disturbance
NK: = number of points from starting till applying the adaptive control vector ;
NST: = additional variable cycle .
iv) $e_i = x_i - x_{oi}$ - error between the state vectors of the system under consideration and its steady-state values .

5- EXAMPLE

Consider an interconnected power system consisting of two subsystems (identical steam plants). The case of nonreheat turbines will be considered.

For comparison purposes, The same values of the system parameters contained in [7] are used ;

$P_s = 0.425$ p.u. MW,	$T_t = 0.39$,	$K_p = 120$ Hz/p.u. MW,
$R = 2.4$ Hz/p.u. MW ,	$T_g = 0.85$,	$T_t = 20$ Sec. ,
$T = 10$ Sec,	$K_r = 1.0$,	$2\pi T_{12} = 0.545$ p.u.

The system matrices are given by ;

$$A_{11}=A_{22}=\begin{bmatrix} 0 & 0 & 1 & 0.425 & 0 \\ 0 & -12.5 & 0 & -5.206 & 0 \\ 0 & 0 & 0 & 0.545 & 0 \\ 0 & 0 & -6 & -0.500 & 0 \\ 0 & 3.33 & 0 & 0 & -3.33 \end{bmatrix} \qquad A_{12}=A_{21}=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.545 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B_1 = B_2 = [\,0 \quad 12.5 \quad 0 \quad 0 \quad 0 \quad 0\,]^T$$
$$D_1 = D_2 = [\,0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1\,]^T$$

Consider two different control schemes, where no physical constraints are imposed on the system variables.

i) For conventional control, the control laws are assumed to be [7];

$$u_i = -0.7x_{i1} , \qquad i = 1, 2 \quad \ldots\ldots \quad (10)$$

ii) For VSS control, using the new algorithm we obtain;
The switching hyperplanes are given by ;

$$\sigma_i = C_i^T . x_i \quad , \; i = 1,2 \,, \quad \text{where} \;;$$

$$C_i = [\, 0.082 \;\; -33.2 \quad 0 \quad 6.02 \quad 33.3 \,]$$

Figure (6) shows the simulation results of ΔF_1, ΔP_{gi}, , ΔP_{tie}, ΔF_2, ΔP_{g2} when subsystem 1 is subjected to a step load change of 0.01 p.u. Results using conventional control are also included for comparison purpose.

6. CONCLUSION

Controller for an electrical power system is suggested, using the main property of VSS-(sliding modes) . This controller insures the adaptive control of the system and its invariance to the external disturbance. Design of this controller does not need information ahout either the system parameter or external disturbance variation. It is required only to know their upper and lower limits of variation .

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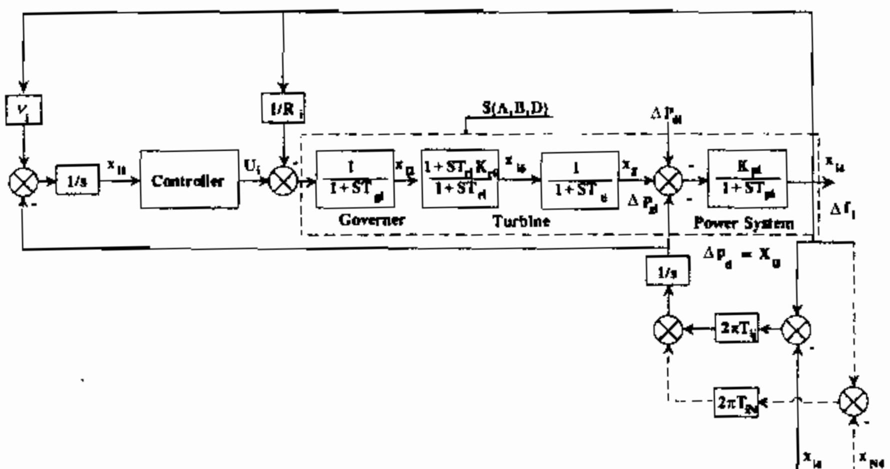

Fig. (1) : Power System Model

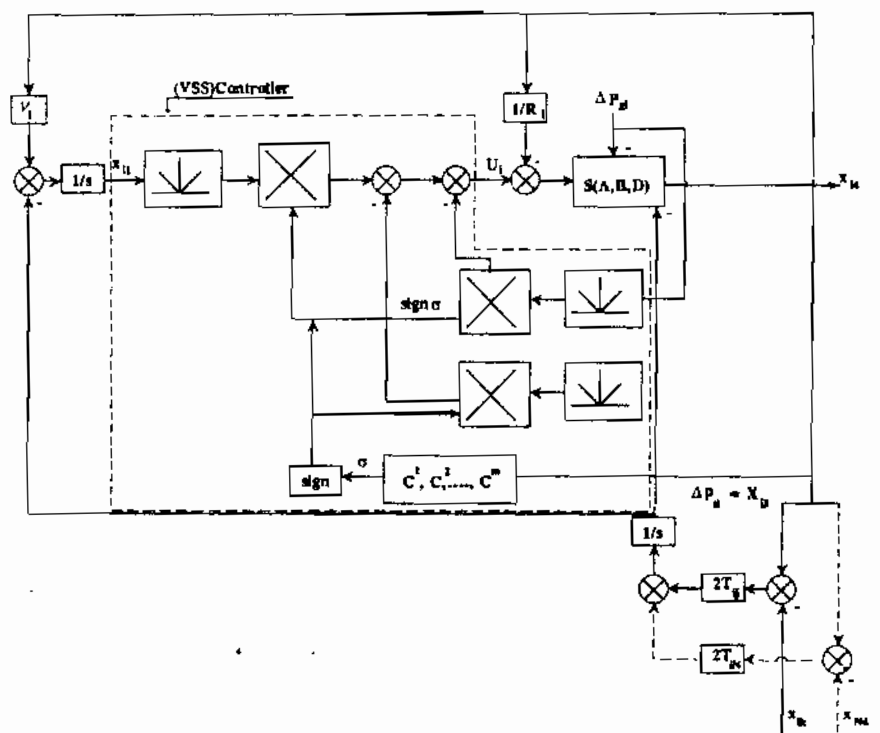

Fig. (2) : "VSS" Controller

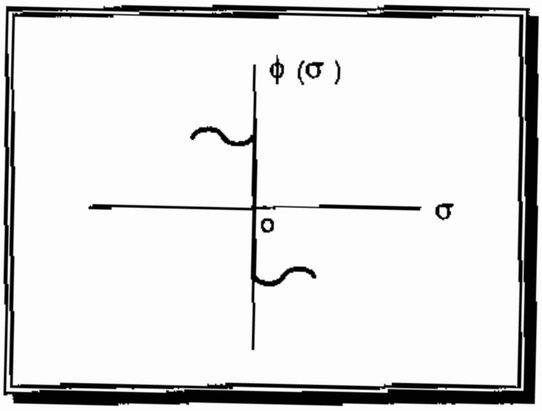

Fig. (3) : Multivalued Function.

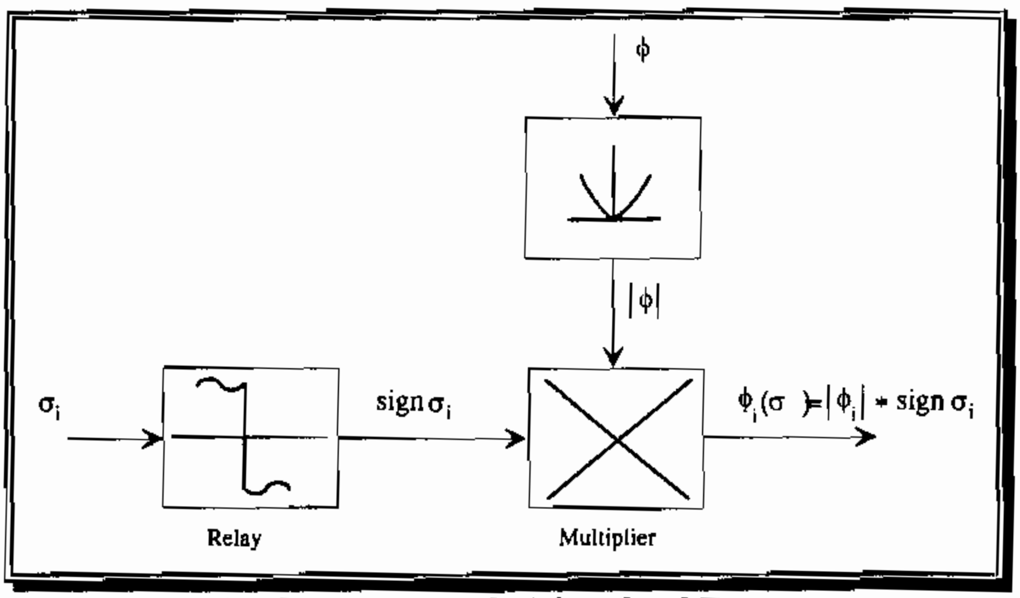

Fig. (4) : Generation Of Multivalued Function.

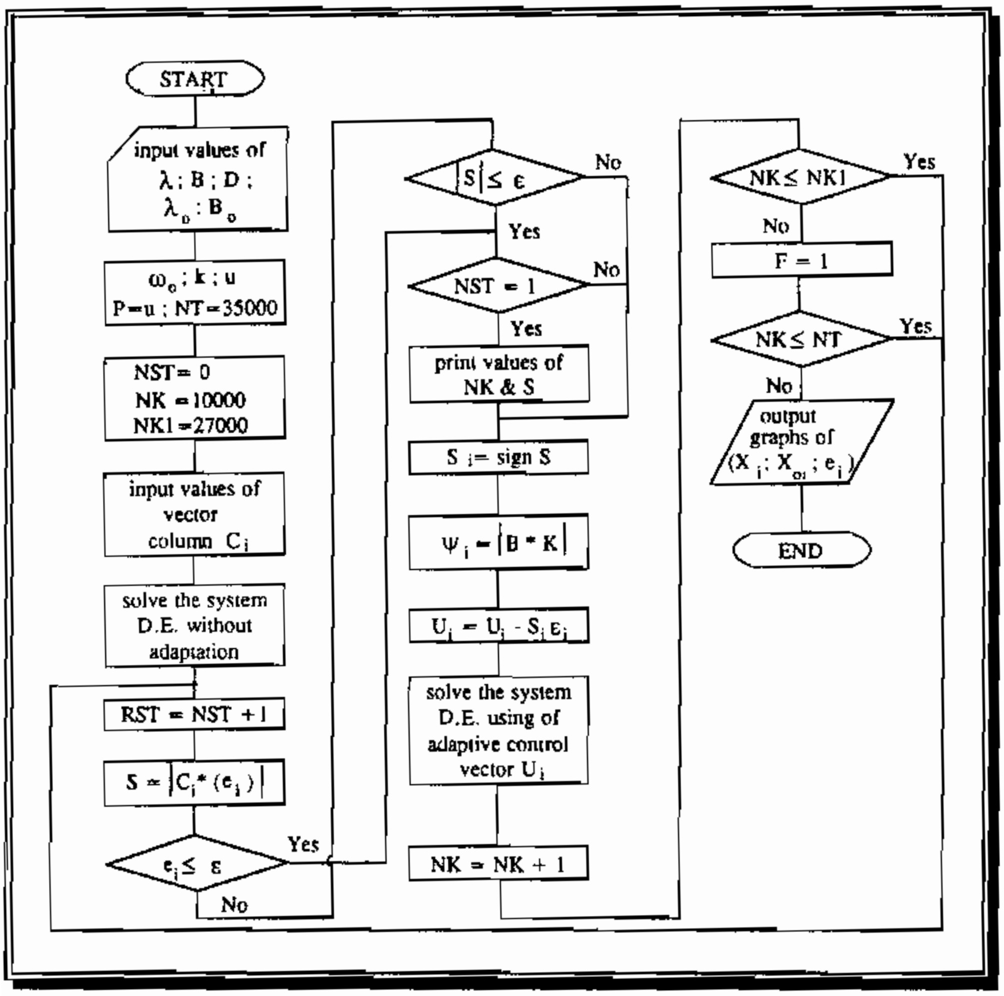

Fig. (5) : Flow Chart

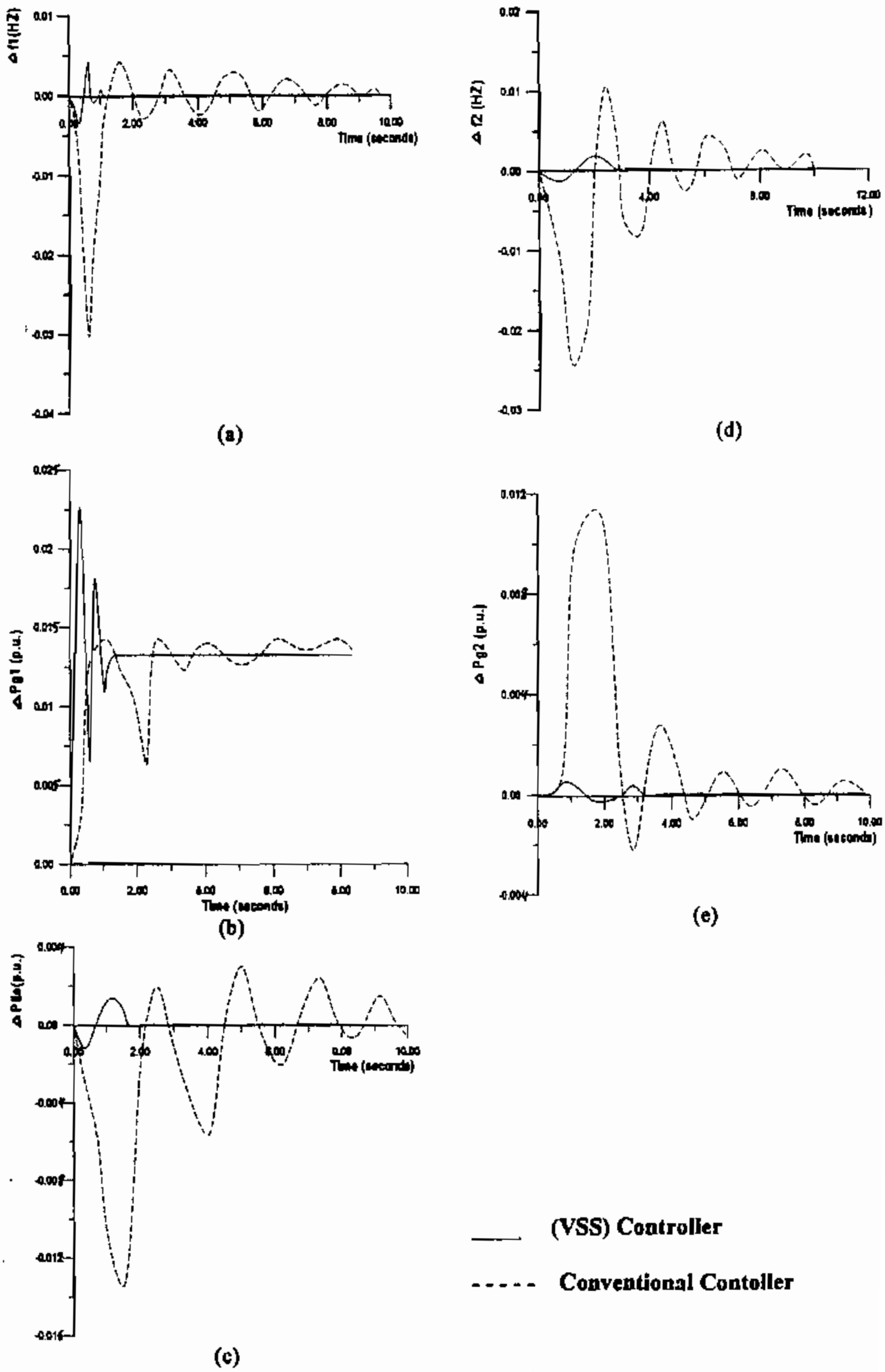

Fig. 6 Simulation Results