A NON-LINEAR CONTROLLER FOR A SYNCHRONOUS GENERATING UNIT

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ABSTRACT

In this paper the development of a novel non-linear controller for power system generating unit is presented. The design of the presented controller is based on Pontryagin maximum principle which uses the actual measurements of the synchronous machine output state variables. The controller is designed to overcome basic difficulties in power system controllers developed hitherto which were based on linear deviations from the reference values. This will enable the generator to accommodate large disturbances and accepts change in system configuration. The controller is simulated in conjunction with a hydro generating unit using a developed computer program. Response to severe disturbances are computed which show considerable enhancement in machine performance with the proposed controller.

Keywords : Non-Linear Controller, Synchronous Generating Unit, Pontryagin Maximum Principle

INTRODUCTION

Power system controllers were designed ,traditionally, using well established single input/single output techniques. This, however, doesn't take account of increasing complexity of power systems that requires power system engineers to search for methods of operation and control. The developments of control and various kind of digital and analogue simulation techniques have recently opened up new fields of application of new control strategies for synchronous machine. In particular, it is most feasible to use the recent developed thyristor exciter [1], and electro hydraulic governor systems [2], which are capable of providing fast control. This ---new application has , in turn, resulted in a need for new control schemes to be used to enhance the performance of such machines. Modern control theory offered an optimal multi variable controller that have been designed and implemented.

Most of these developed controllers were only tested by computer simulation and some of them were tested experimentally by means of laboratory models [3,4,5], where the problems of physical realization arise. One of these problems is that the measurements of some state variables are inaccessible. Another problem in practice is that the generator moves from one operating point to another due to either changes in load or system configuration changes. Multi variable controllers, which were designed by the direct application of optimal control theory, could cope with these problems only for small deviations. However, for large deviations, these controllers would lead to considerable offset in all state variables even with integral controls. This is mainly due to that the design of the controllers were based on linearization of the machine mathematical model.

New techniques such as Fuzzy Logic [6] and Artificial Neural Networks [7] have been used in designing different types of controllers which replace the conventional controllers of the automatic voltage regulator (AVR), the power system stabilizer (PSS), and speed governor. The design procedure of such controllers were also, based on linearization of the machine mathematical model.

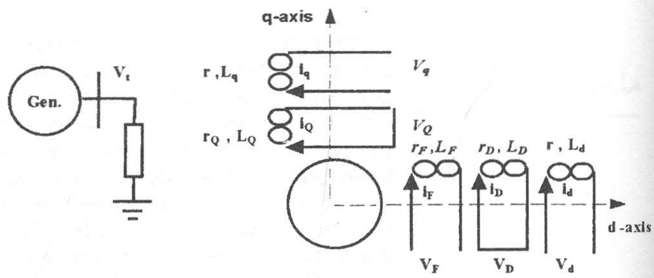
Due to the non-linear properties of the generating unit, attention has been made to use a non linear controller. Recently, a non-linear excitation controller that adopts non-linear state feedback and is microprocessor-based has been reported [8]. In this controller Lyapunov's direct method was used to design the feedback gain and the control signal considering a simplified mathematical model and neglects the effect of the speed governor.

In this paper an improved controller which is responsive to actual non linear deviations of the state variables from reference values is introduced. In this controller two additional control loops are employed. One of them for the governor and the other for the exciter. Design of these two loops are based on the theory of maximum principle hypothesized by Pontryagin [9,10], where the system behavior can be described by first order differential equations. The non linear current state space mathematical model of the generator, a non linear model of the turbine, exciter, and governor are considered. These mathematical models, in conjunction with the design procedure of the proposed controller are given in the subsequent sections.

SYSTEM DESCRIPTION AND REPRESENTATION

The system which is considered is of a 158 MVA hydro-generator which is directly supplying a local load as shown in Figure . 1. The generator voltage equations are represented by a set of first order differential equations using Park s transformation [11].

The adopted non-linear model of the hydro-turbine and its speed governing system are given as shown in Figures 2 and 3 as reported in [2]. In this model the penstock is represented assuming an incompressible fluid and a rigid conduit. The turbine gate is controlled by a two stage hydraulic position servo. The permanent droop R_p determines the speed regulation under steady state conditions. It is defined as the speed droop in pu required to drive the gate from minimum to maximum opening with change in speed reference.



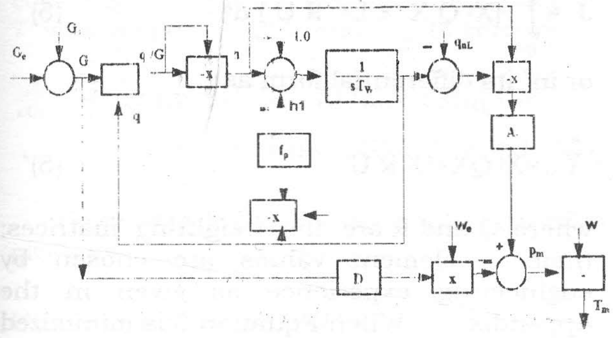
MVA = 158	r = 0.002	r_F = 0.00048	r_D= 0.0292
KV = 13.8	L_d = 0.92	L_F =1.0712 H	L_D=0.005989 H
Pf = 0.9	L_q =0.51		r_Q=0.0424
H = 3.177			L_Q=0.001423 H

Figure 1 Synchronous machine feeding an isolated load

Due to the peculiar dynamic characteristics of the hydraulic turbine, it is necessary to increase the regulation under fast transient conditions in order to achieve stable speed control. This is achieved by the parallel transient droop R_t branch with washout time constant T_R as shown in Figure 3. The values of the employed parameters are given under the relevant figure.

A thyristor exciter is adopted for this generating unit. This exciter is designed as continuously acting systems, where the excitation voltage is obtained through rectification of the terminal voltage [1]. This type of excitation system has the advantage of reversing the excitation level during transient periods from the positive to the negative ceilings in a negligible time. The adopted static exciter model is as that recommended by IEEE [12], and shown in Figure 4.

The mathematical model of the load is given in the Appendix.



D=0.75, t_u=1.58, A_r= 1.37,f_p=0.011

Figure 2 Hydro-turbine non-linear model

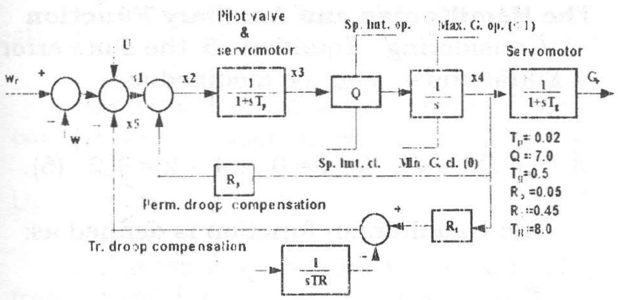


Figure 3 Hydro-turbine governor

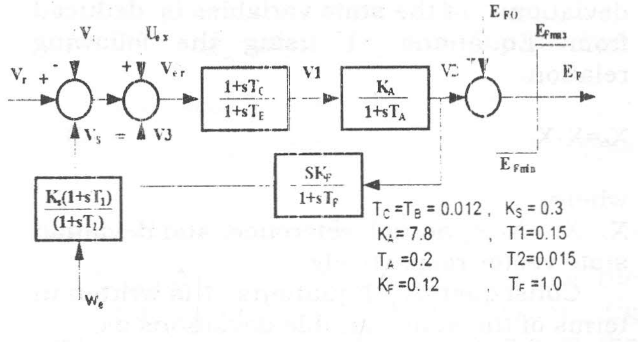


Figure 4 Static exciter

DESIGN OF THE PROPOSED CONTROLLER USING PONTRYAGIN MAX PRINCIPLE

The maximum principle is adopted to design an optimum controller for the synchronous machine using its non-linear mathematical model. Pontryagin max. principle requires that generator mathematical model, should be formed in the differential form and written in conjunction with the quadratic performance index. That is to construct the Hamiltonian function, in terms of the system parameters [9,10], which is used to derive the optimum control signals. The procedure followed to design the proposed control loops for both the machine exciter and the speed governor, using Pontryagin max. principle, is presented in the following sections:

Generator Model.

The generator differential equations considering the currents as state space variables are written in the following matrix form ,with the damping factor, D, is used to compensate for the absence of the damper windings which yields a fifth order model as :

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_F \\ \dot{i}_q \\ \dot{\omega} \\ \dot{\delta} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13}\omega & 0 & 0 \\ a_{21} & a_{22} & a_{23}\omega & 0 & 0 \\ a_{31}\omega & a_{32}\omega & a_{33} & 0 & 0 \\ c_{11}i_q & c_{12}i_q & c_{13}i_d & c_{14} & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_F \\ i_q \\ \omega \\ \delta \end{bmatrix} + \begin{bmatrix} b_{11}v_d + b_{12}v_F \\ b_{21}v_d + b_{22}v_F \\ b_{33}v_q \\ T_m / T_j \\ -1 \end{bmatrix} \quad (1)$$

Where the value of the partioned matrix elements, a_{ij} . b_{ij} and c_{ij} are given in the Appendix, (Table A-1).

Equation 1 is rewritten in terms of the voltages, which are controllable states rather than currents. This is carried out by eliminating both the stator current components using Equations A 1 and A 2, given in the Appendix, and the field current from Equations 1. The non-linear deviations of the state variables is deduced from Equations 1 using the following relation:

$$X_e = X - X_r \qquad (2)$$

where;

X, X_r, X_e = actual, reference, and deviation state vector respectively.

Consequently, Equations 1 is written in terms of the state variable deviations as:

$$\begin{bmatrix} \dot{v}_{de} \\ \dot{v}_{qe} \\ \dot{\omega}_e \\ \dot{\delta}_e \end{bmatrix} = \begin{bmatrix} m'_6 & m'_7(\omega_r+\omega_e) & m'_7 v_{qr} & 0 \\ m'_{10}(\omega_r+\omega_e) & m'_{11} - a'_{32} - m'_4(\omega_r+\omega_e)^2 & m'_{10} v_{dr} - a'_{32} m'_4 v_{qr}(2\omega_r+\omega_e) & 0 \\ c'_{11}(v_{qr} - v_{qe}) & c'_{11} v_{dr} - c'_{13}(\omega_r+\omega_e)(2v_{qr}+v_{qe}) & c'_{14} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_{de} \\ v_{qe} \\ \omega_e \\ \delta_e \end{bmatrix} + \begin{bmatrix} m'_9 & 0 & 0 \\ -m'_{12}(\omega_r+\omega_e) & 0 & 0 \\ -c'_{12}(v_{q_r}+v_{qe}) & 1/T_j & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_F \\ T_m \\ 1 \end{bmatrix} + \begin{bmatrix} c1 \\ c2 \\ c3 \\ c4 \end{bmatrix} \qquad (3)$$

Where the coefficient of each element is given in the Appendix (Table A-1).

Equations 3 can be written in its compact form as:

$$\dot{X}_I = F_i(X_i, U_k), \text{ for } i = 1,\ldots,4,\ k = 1,2 \qquad (4)$$

where

X_i = the machine state variable deviations vector;

$X^t = [V_{de}\ V_{qe}\ \omega_e\ \delta_e]$

U_k = Controller state variables vector;

$U_k^t = [U_1\ \ U_2]$

F_i = set of nonlinear functions.

Performance Index

The chosen performance index is the quadratic which is as given in Reference 9 and can be written as:

$$J = \int_0^{\alpha} [X^t Q X + U^t R U]\, dt \qquad (5)$$

or in its differential form as :

$$\dot{X}_0 = X^t Q X + U^t R U \qquad (5)'$$

where Q and R are the weighting matrices; their element values are chosen by engineering experience as given in the Appendix. When Equation 5 is minimized that is the state variable errors and the control effort are minimized which yields an optimum control.

The Hamiltonian and Auxiliary Function

Considering Equations 5' the state error of Equations 4. can be modified as:

$$\dot{X}_i = F_i(X_i, U_k), \text{ for } i = 0,\ldots,4, \quad k = 1,2 \qquad (6)$$

The Hamiltonian function is defined as:

$$H = \sum_0^4 \varepsilon_i(t) .\ F_i(X_i, U_k) \qquad (7)$$

where $\varepsilon_i(t)$ is defined as the auxiliary variables, $\varepsilon_D(t)$,..., $\varepsilon_4(t)$, and is related to H and X_i as:

$$\frac{d\varepsilon_i}{dt} = -\frac{\partial H}{\partial x_i} \qquad (8)$$

$$\frac{dx_i}{dt} = -\frac{\partial H}{\partial \varepsilon_i} \qquad (9)$$

Equations 8 and 9 are known as the canonically conjugate form of the Hamiltonian system [10].

Deduction of the Optimum Control Signals

Assuming $U_{ex} = U_1$, and $U_g = U_2$, the optimum control signals, U_{ex} and U_g , for the machine exciter and speed governing system respectively, are deduced by equating the partial derivative of Equations 7 with respect to U_{ex} and U_g to zero as :

$$\frac{\partial H}{\partial U_{ex}} = \varepsilon_0(t)(2r_{11}U_{ex}) + \varepsilon_1(t)\,(m_9)\;\varepsilon_2(t)([-m_{12})(\omega_r+\omega_e) + \sigma_2(t)[-c'_{12}\,(Vqr+Vqe)]=0 \quad (10)$$

From which the exciter control signal is given as:

$$U_{ex} = (-1/2r_{12}\;\varepsilon_0(t))\,[\,m'_9\,\varepsilon_1(t) - m_{12}\;(\omega_y+\omega_e)\;\varepsilon_2(t)) - c'_{12}\,(Vqr + V\,qe)\,\varepsilon_3(t))] \quad (11)$$

and:

$$\partial H/\partial U_g = \varepsilon_0(t)(2r_{22}\,u_g) + \varepsilon_3(t)(1/T_j) = 0 \quad (12)$$

From which the speed governing system control signal is given as:

$$U_g = -\varepsilon_3(t)(2r_{22}\;T_j\;\varepsilon_0(t)) \quad (13)$$

To eliminate the auxiliary function , $\varepsilon_i(t)$, from Equations. 11 and 13, substitute in Equations 7 and 8 for i = 0 through 4 and arranging yields:

$$d\varepsilon_0(t),\,/dt=0 \quad (14)$$

$$d\,\varepsilon_1(t)/\,dt = -(f_1\;\varepsilon_0(t) + f_2\;\varepsilon_1(t) + f_3\;\varepsilon_2(t) + f_4\;\varepsilon_3(t)) \quad (15)$$

$$d\,\varepsilon_2(t)/\,dt = -\,(\,f_5\,\varepsilon_0(t)\; + f_6\;\varepsilon_1(t) + f_7\;\varepsilon_2(t) + f_8\;\varepsilon_3(t)) \quad (16)$$

$$d\varepsilon_3(t)/\,dt = -(\,f_9\,\varepsilon_0(t) + f_{10}\;\varepsilon_1(t) + f_{11}\;\varepsilon_2(t) + f_{12}\;\varepsilon_2(t) + \varepsilon_4(t)) \quad (17)$$

$$d\varepsilon_4(t)/dt = -f_{13}\,\varepsilon_0(t) \quad (18)$$

Where f_1 to f_{13} are as given in the Appendix.

Solving Equations 14 to 18 for $\varepsilon_0(t)$,..., $\varepsilon_4(t)$,

and substituting in Equations. 11 and 13 results in :

$$U_{ex} = \frac{1}{1.6}\int \{\frac{4.8}{U_{ex}}[\omega_e(5.1\,\omega_e - 9.2\frac{V_{qe}}{U_{ex}}) + 2.3\,V_q\,V_{qe}] - 5.5\,U_{ex}\,\}\,dt + 2\,[\,\frac{V_{qe}}{U_{ex}}\,(\,V_{qe} - 1.75\omega V_{de}) - 6.55V_{de}] \quad (19)$$

$$Ug = \frac{1}{1.6}\int\;(2.2*10^{-2}\,\frac{V_{qe}}{U_{ex}} - 5.5\;Ug\,)\;dt \quad (20)$$

Equations. 19 and 20 provide the required exciter U_{ex} and governor Ug optimum control signals in terms of the machine state variable errors. Expressing these Equations. in terms of the machine terminal voltage, Vt, yields:

$$U_{ex} = \frac{1}{1.6}\int\{\,\frac{4.8}{U_{ex}}[\omega_e(5.1\,\omega_e\; - 8.2\frac{V_{te}}{u_{ex}}) + 1.8\,V_t\,V_{te}\;] - \;5.5\,U_{ex}\,\}\,dt + 1.6\;[1.1\frac{V_{te}}{U_{ex}}(V_{te} - 0.80\,\omega\,V_{te}) - 3.75V_{te}] \quad (21)$$

Similarly:

$$Ug = -\frac{1}{1.6}\int\;(1.06*10^{-2}\;\frac{V_{te}}{U_{ex}} - 5.5\;\;Ug)dt \quad (22)$$

The way by which the deduced control signals are attached to the hydro turbine synchronous machine is illustrated in the block diagram of Figure 5.

SIMULATION ALGORITHM.

The state space non-linear mathematical model equations of the turbine, speed governor and exciter are deduced from the block diagrams of Figures 2,3 and 4 respectively. This yields nine first order differential equations. These equations are solved in conjunction with both the generator 7th order mathematical models and the equations of the proposed controller using Runge-Kutta integration technique. To obtain high accuracy and stable solution a large number of iterations is considered and a suitable integration step length of 0.1 ms is adopted. A flow chart of the developed simulation algorithm is shown in Figure 6.

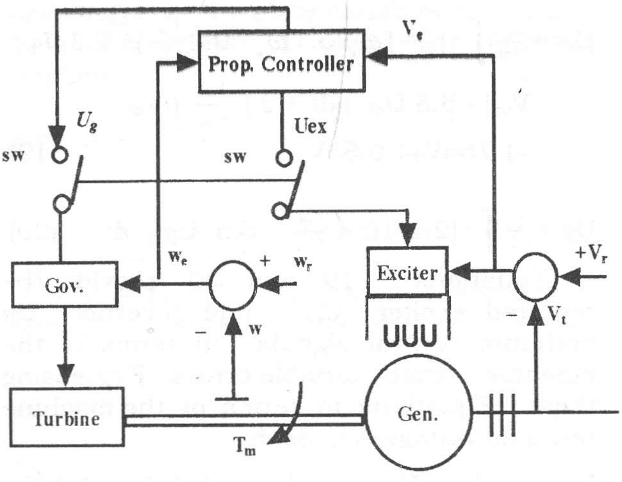


Figure 5 Connection of the proposed controller to the hydro-generating unit

SIMULATION TESTING AND RESULTS.

Different tests are considered in the presented digital program to asses the performance of the specified power system and to examine the capability of the proposed controller in improving that performance.

The proposed control signals are superimposed to the conventional controller by switching ON sw-sw shown in Figure 5.

Sudden load changes, symmetrical 3-ϕ short circuit and 3-ϕ short circuit followed by sudden removal of load are considered as severe disturbances and therefore, applied one at a time to the machine. The corresponding computed responses for δ, ω, V_t, E_F, i_F are given for the proposed and conventional controllers as shown in Figures 7 to 9. The response of the conventional controller is plotted by a dashed line, however, that of the proposed one by a solid line. Comparing the responses for all these disturbance cases reveals that a substantial improvement in the responses of the five considered variables has been achieved in the case of the proposed controller.

In Figure 7 the response is given for a sudden application of 100% increased in load. It can be seen that the oscillatory responses of the variables are suppressed faster in case of the proposed controller (solid lines) than conventional controller (dashed lines).

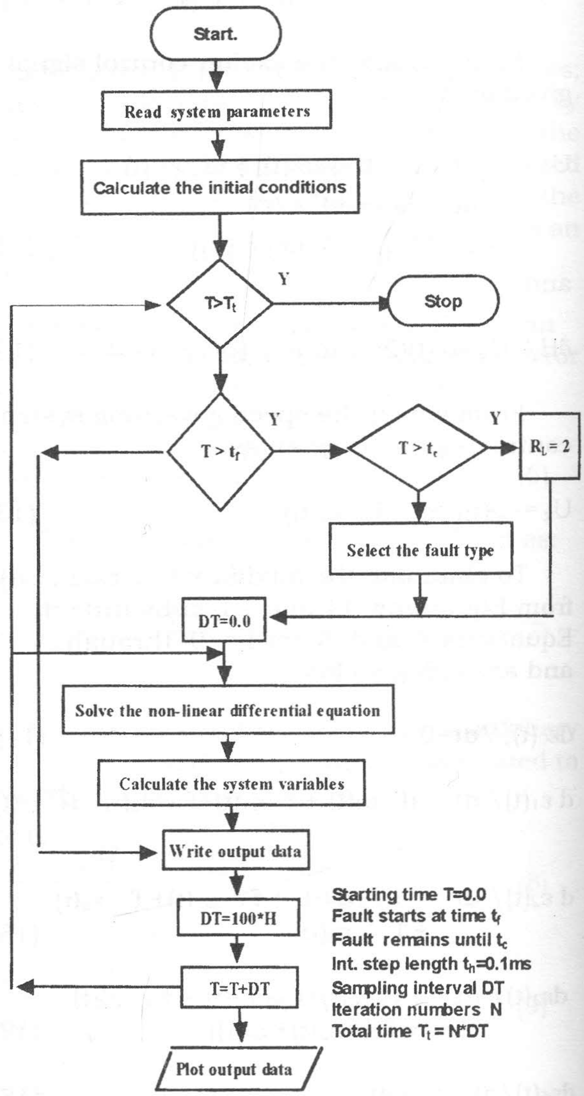


Figure 6 Flow chart of the developed program

In Figure 8 for 3-ϕ short circuit for a period of 0.5 s, the rotor angle δ displays 100 pole slipping for the conventional controller, where this number is reduced to 84 pole slipping with the proposed controller.

In Figure 9 the response for the application of 3-ϕ short circuit on the terminals of the machine for a period of 0.5 s followed by 66% sudden load removal. It can be seen that the number of pole slipping is reduced from 130 with conventional controller to 113 with the non-linear controller. The effectiveness of the proposed controller can also be seen on the steady value of ω ,where the conventional controller failed to bring the speed back to the desired reference value. Comparison of the results reveals that the proposed controller not only allows the machine variables to return to their prefault values but also improve the transient responses.

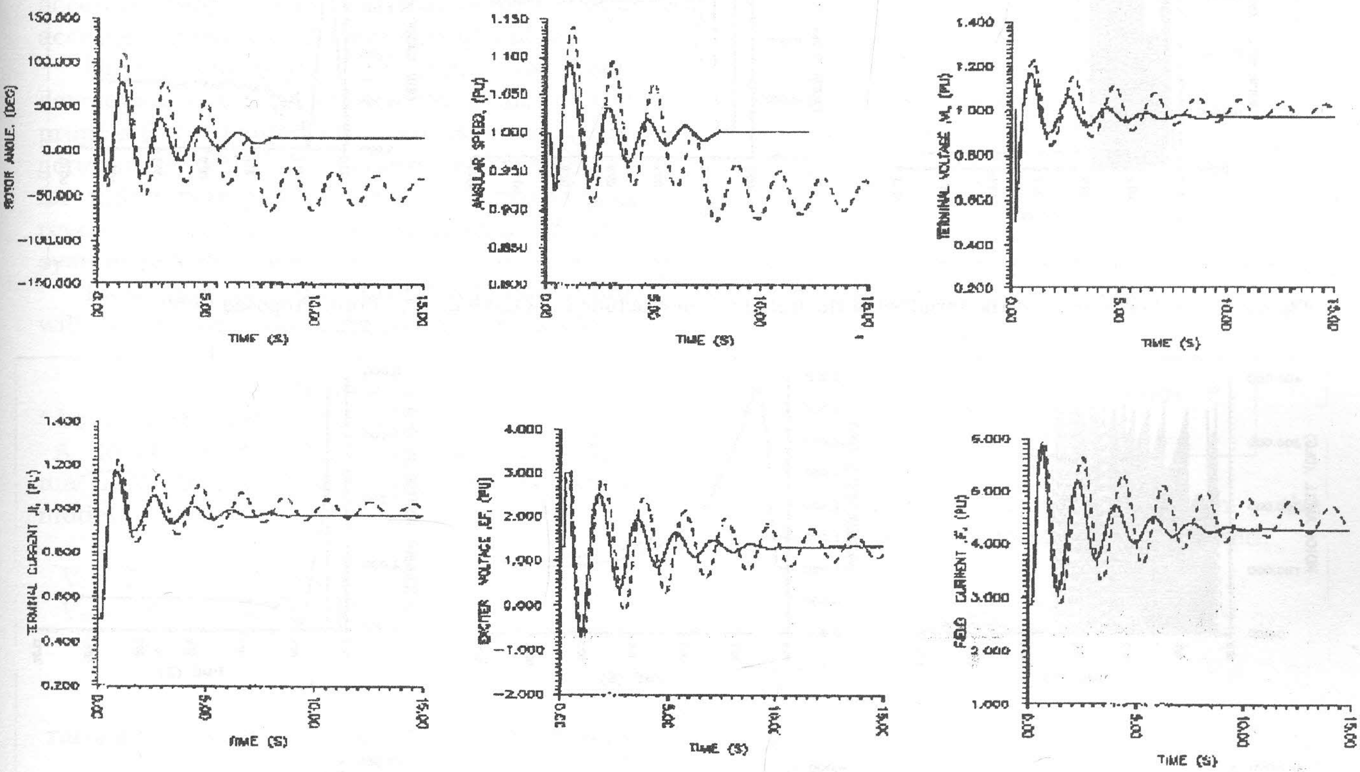


Figure 7 110% sudden application of load at the terminal of the initially loaded machine ---conven. Cont.____ Propoesd

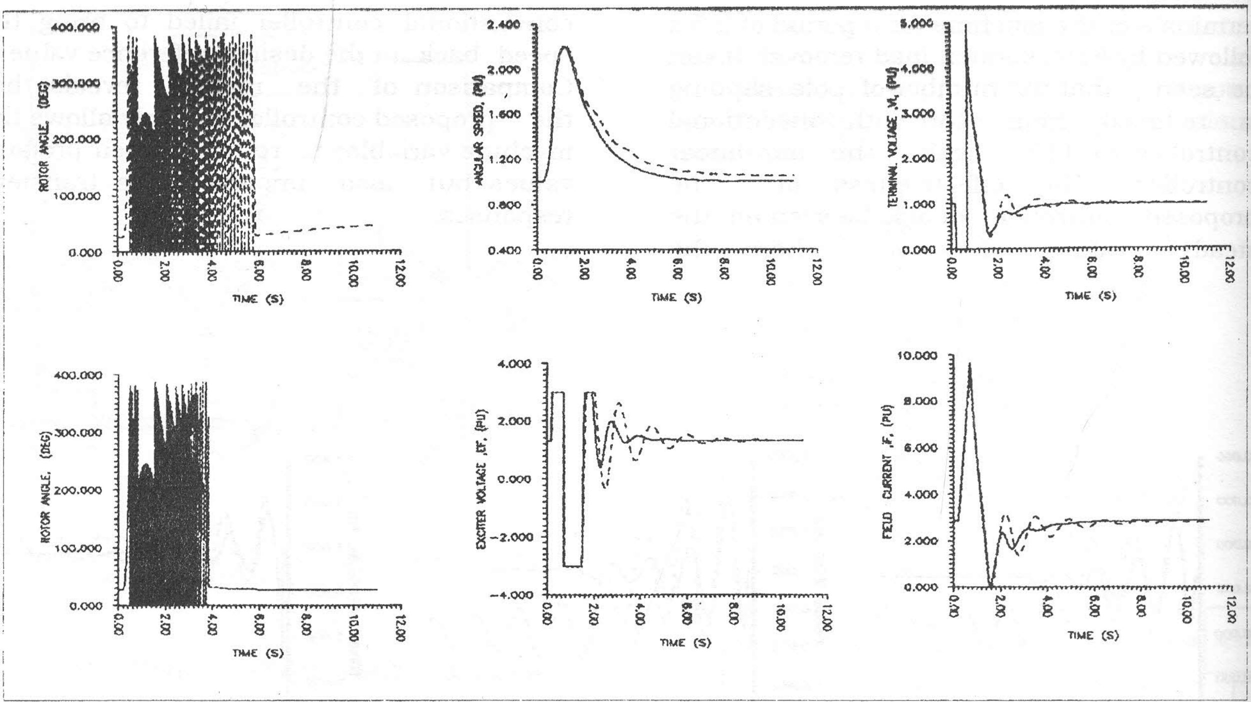


Figure 8 3-ϕShort circuit at the terminal of the initially load machine (----Conven. _____ Cont. Proposed Cont).

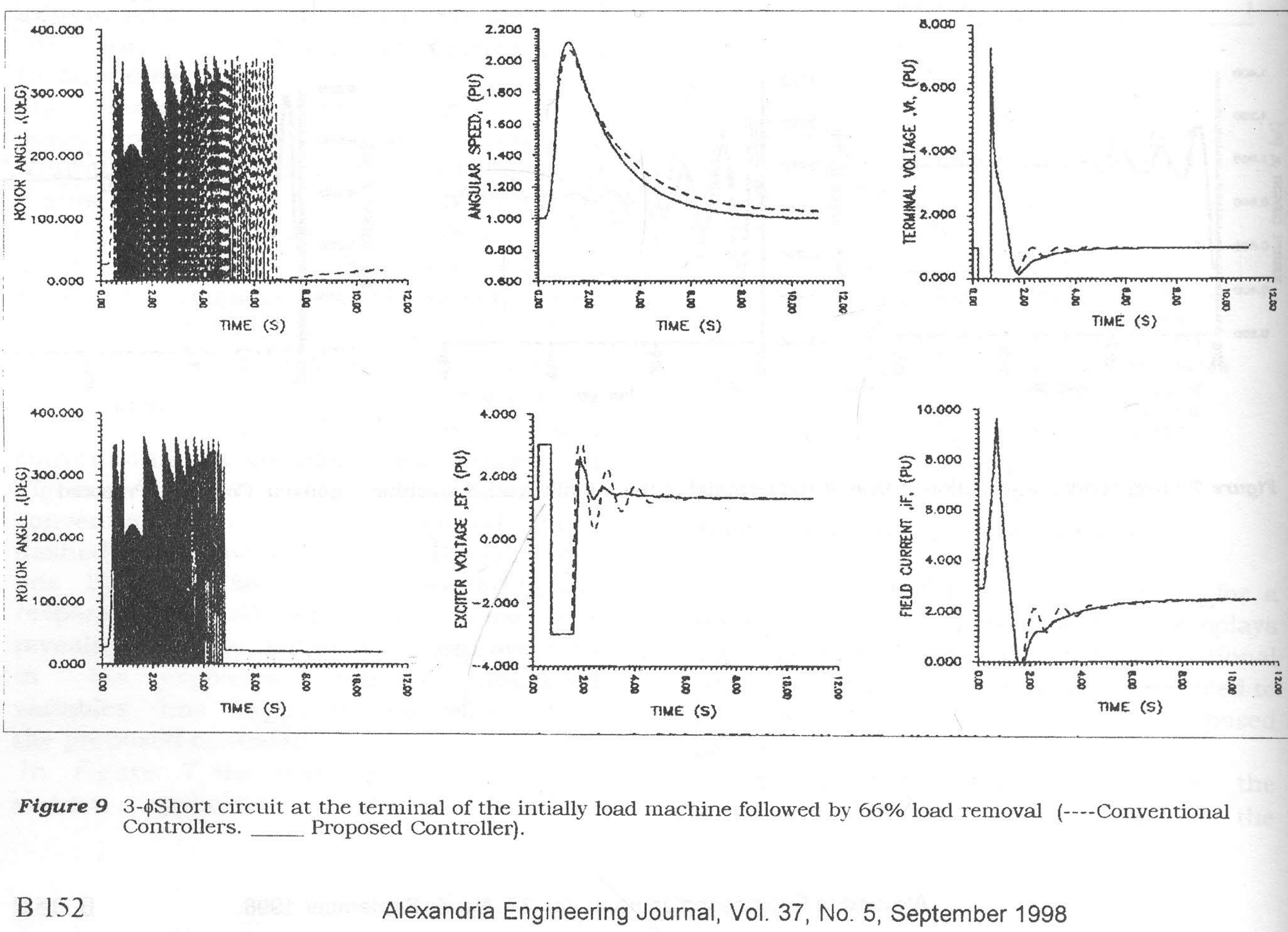


Figure 9 3-ϕShort circuit at the terminal of the intially load machine followed by 66% load removal (----Conventional Controllers. _____ Proposed Controller).

CONCLUSION

A non-linear controller for the exciter and governor of a synchronous machine has been proposed. The design of this controller was based on the Pontryagin maximum principle which used actual non-linear mathematical model of the machine. This controller provides control signals in response to the actual non-linear deviations of the machine state variables rather than the linearized deviations used for conventional controllers. Therefore, this controller enables the generator to accommodate large disturbances and accepts changes in system configuration.

Digital simulation program has been developed to asses the performance of the proposed controller on an isolated hydro generating unit. The computed responses for different types of severe disturbances reveal remarkable enhancements in the system performance.

Field test of this proposed controller will be worth examining in a future work.

APPENDIX

* Load Mathematical Model.

A local resistive load is attached at the machine terminal and has the following model :

$$V_d = 0.5\, i_d * R_L \quad \text{(A-1)}$$

$$V_q = 0.5\, i_q * R_L \quad \text{(A-2)}$$

Table A-1 Matrices Elements and Functions Coefficients

Eelement	Value
a_{11}	0.007
a_{12}	-0.002
a_{13}	1.749
a_{21}	-0.005
a_{22}	0.002
a_{23}	-1.372
a_{31}	- 1.849
a_{32}	-1.588
a_{33}	0.004
b_{11}	3.43
b_{22}	-3.13
b_{33}	2.01
$T_j = 2 H \omega_b$	1995
$c_{11} = - L_d / 3 T_j$	$-1.5 * 10^{-4}$
$c_{12} = - KM_F / 3 T_j$	$-1.3 * 10^{-4}$
$c_{13} = L_q / 3 T_j$	$0.85 * 10^{-4}$
$c_{14} = - D / 3 T_j$	$-0.10 * 10^{-4}$
$q_{11} = q_{22}$	2.0
q_{33}	5.0
q_{44}	3.0
r_{11}	1.0
r_{22}	1.0
$m_{11} = a_{33} + b_{33} R_L / 2$	2.014
$m_{12} = a'_{32}\ m'_1 R_L / 2$	3054
$c'_{11} = c_{11} - c_{12} m'_3 + c_{13}$	$-0.804 * 10^{-4}$
$c'_{12} = c_{12} m'_1$	-0.25
$c''_{12} = c_{12} m'_2$	$-1.07 * 10^{-4}$
$c''''_{12} = c_{12}\ m'_4$	$-0.13 * 10^{-4}$
$m_1 = KM_F b_{12} + L_F b_{22} - 1$	-2.027
$m_2 = KM_F b_{11} + L_F b_{21}$	$8.7 * 10^{-4}$
$m_3 = KM_F a_{11} + L_F a_{21}$	$4.95 * 10^{-4}$
$m_4 = KM_F a_{13} + L_F a_{23}$	$1.06 * 10^{-4}$
$m_5 = r_F + KM_F a_{12} + L_F a_{22}$	$1.05 * 10^{-4}$
$m_6 = a_{11} - a_{12}\ m'_3$	$7.94 * 10^{-4}$
$m_7 = a_{13} - a_{12}\ m'_4$	1.75
$m_8 = b_{11} - a_{12}\ m'_2$	3.432
$m_9 = b_{12} - a_{12}\ m'_1$	6.536
$m_{10} = a'_{31} - a'_{32}\ m'_3$	-1.103
$m'_1 = m_1 / m_5$	-1923
$m'_2 = m_2 / m_5$	0.825
$m'_6 = m_6 + m_8 R_L / 2$	3.44
$m'_9 = m_9 R_L / 2$	6.536
$m'_{10} = m_{10} - a'_{32}\ m'_3$	0.207
R_L	2.0
$\hat{c}_{12} = c'_{12} * 2 / R_L$	-0.25
$c'_{13} = c'''_{12} * (2 / R_L)^2$	$-0.13 * 10^{-4}$
$c''_{11} = c'_{11} (4 / R_L^2) - c''_{12} (2 / R_L)$	$0.27 * 10^{-4}$

The following relations of both the constants and functions are considered:

$$c'_{14} = c_{14} - c'_{13} V_{qr}^2 ,$$

$$a'_{13} = a_{13} / \omega \quad a'_{31} = a_{31} / \omega , \quad a'_{23} = a_{23} / \omega$$

$$a'_{32} = a_{32} / \omega$$

$$C1 = m'_6\ V_{dr} + m_7\ \omega_r V_{qr}$$

$$C2 = m'_{10}\ \omega_r\ V_{dr} + m_1\ V_{qr} - a'_{32}\ m'_4\ \omega_r^2\ V_{qr}$$

$$C3 = c''_{11}\ V_{qr} V_{dr} - c'_{13}\ \omega_r V_{qr}^2 + c_{14}\ \omega_r$$

$$\bar{C}4 = \omega_r - 1$$

$$f_1 = 2\, q_{11}\ V_{de} , \quad f_2 = m'_6 , \quad f_3 = m'_{10} (\omega_r + \omega_e)$$

$$f_4 = c''_{11} (V_{qr} + V_{qe}) , \quad f_5 = 2 q_{22} V_{qe}$$

$$f_6 = m_7\ (\omega_r + \omega_e),$$

$$f_7 = m_{11} - a'_{32}\ m'_4 (\omega_r + \omega_e)^2$$

$f_8 = c''_{11}(V_{dr} + V_{de}) - 2c'_{13}(\omega_r + \omega_e)(V_{qr} + V_{qe}) - \hat{c}_{12}\,U_{ex}$

$f_9 = 2q_{33}$, $f_{10} = m_7(V_{qr} + V_{qe})$

$f_{11} = m'_{10}(V_{dr} + V_{de}) - 2a'_{32}\,m'_4(\omega_r + \omega_e)(V_{qr} + V_{qe}) - m_{12}\,U_{ex}$

$f_{12} = -c'_{13}\,V_{qe}(2V_{qr} + V_{qe}) + c'_{14}$

$f_{13} = 2q_{44}\,\delta_e$

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حاكم غير خطى لوحدة توليد تزامنية

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ملخص البحث :

صمم حاكم غير خطى لوحدة توليد تزامنية اعتمادا على المبدأ الأقصى لبنترايجن حيث استخدمت القياسات الفعلية لمتغيرات ذلك المولد فى هذا التصميم والذى يهدف الى التغلب على المصاعب الأساسية التى صاحبت تصميم الحاكمات المعتادة وأهمها اعتماد النماذج الرياضية الخطية والتى تمثل الانحرافات الخطية الصغيرة حول نقط التشغيل لمتغيرات المولد التزامنى عن تلك القيم المرجعية .

وقد صمم أيضا برنامج لتمثيل هذا الحاكم المقترح اضافة الى عناصر وحدة التوليد المائية وكذا الحاكمات المعتادة حيث أظهر حساب استجابة متغيرات منظومة القوى الكهربية المختارة تحسن ملموس فى آدائها وذلك باستخدام الحاكم الغير خطى المقترح ، فعند تعرض تلك المنظومة لاضطرابات كبيرة أو للتغير فى شكلها فان الحاكم المقترح جعل استجابة متغيرات المولد التزامنى لتلك المؤثرات معبرة عن التغير الفعلى والغير خطى لها .