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Application of a Multivariable Feedback Linearization Scheme for Rotor Angle Stability and Voltage Regulation of Power Systems

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Abstract – This paper investigates the application of a nonlinear controller to the multi-input multi-output model of a system consisting of a hydraulic turbine and a synchronous generator. The controller proposed is based on a feedback linearization scheme. Its main goal is to control the rotor angle as well as the terminal voltage, to improve the system's stability and damping properties under large disturbances and to obtain good post-fault voltage regulation. The response of the system is simulated in the presence of a short-circuit at the terminal of the machine in two different configurations and compared to the performance of a standard IEEE type 1 voltage regulator, PSS and a PID speed regulator.

Keywords: Hydraulic turbine generator, rotor angle stability, voltage regulation, nonlinear control.

1. INTRODUCTION

During the past decade, the size and complexity of power systems have increased considerably. These systems rely more and more on long distance transfers of bulk power between remote generation and load. A good example is the interface between large supplies of hydro power in Canada and load regions in the south. As a result, power engineers have had to confront some major operating problems such as voltage stability, rotor angle stability etc.... The rotor angle stability problem in particular is concerned, as defined in [7], with a power system's ability to preserve its synchronism under all types of disturbances.

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Traditionally, power systems are designed and operated conservatively in a region where behavior is mainly linear. In the case of small disturbances, linearized models of the power system around an equilibrium point are adequate for stability analysis and control design. Linear controllers such as the PSS (power system stabilizer) and AVR (automatic voltage regulator), based mainly on classical control algorithms, can be used effectively to provide necessary damping through excitation control and insure asymptotic stability of the equilibrium following a small perturbation (dynamic stability enhancement). In the event of a large fault, the operating point of the system may vary considerably; non linearities begin to have then significant effects and a linear controller may not be able to maintain asymptotic stability. Therefore, the need to investigate the use of nonlinear controllers which are independent of the equilibrium point and take into account the important non linearities of the power system's model is crucial.

The main goal of this paper is to investigate the application of a nonlinear control technique (exact feedback linearization) to a detailed multi-input multi-output nonlinear model of a power system (turbine + generator) in order to both improve its stability and damping properties even under large and sudden disturbances and to insure good post-fault voltage regulation.

The feedback linearization techniques were first explored in power system applications in [5] and later in [2,3]. The main objective in these studies was to enhance the system's stability and damping performance through excitation control. The system was exactly linearized using only the excitation input. Since the nonlinear model used in these studies was a reduced third order model of the machine, no internal dynamics were left to worry about. In [3], the authors integrated to this 3rd order model of the machine the dynamics of an already controlled steam turbine along with its governor. The added control input (the speed reference signal of the governor) was mainly used to improve the overall stability properties of the system. What characterizes all of these studies is the fact that the post-fault voltage regulation was not directly addressed.

In [8], the feedback linearization technique was used to enhance the transient stability and to achieve good post-fault voltage regulation. The model used is again a 3rd order model of the generator and a linearized turbine dynamics.

The authors show the trade-off between transient stability enhancement and good voltage regulation if only excitation control is used. They propose then a coordinated nonlinear controller which uses both the excitation voltage and the turbine valve control as input. Their control scheme switches between a controller at the transient period in which both the excitation and the fast valving inputs are dedicated to transient stability and a post-transient controller dedicated to improve post-fault regulation of the generator terminal voltage. This scheme is therefore, as mentioned in [8], a nonlinear alternative to the usual AVR/PSS combination in generator control. Note that the design of the excitation input is based on the assumption that the mechanical power is constant. Also, it is not clear how the switching times can be automatically determined (other than by trial and error) for different types of fault.

In this paper, we propose a nonlinear feedback linearizing controller which uses the excitation and the turbine's servo-motor input to control (simultaneously) the power angle and the terminal voltage at the generating plant. Contrary to [8], it does not use any switching techniques nor does it decouple at any time, the electrical and mechanical dynamics. It is based on a detailed 9-order model of a system which consists of a hydraulic turbine and a single machine infinite bus system. The model of the synchronous machine is a 7^{th} order model (5 for the electrical dynamics and 2 for the mechanical dynamics) which takes into account the stator dynamics as well as the amortisseur effects. A second order nonlinear model which takes into account the gate's servo-valve dynamics is considered for the turbine.

The nonlinear controller will be first applied on a single machine infinite bus configuration and then on one of the generators of a power system consisting of two machines connected to loads. The simulation model takes into account saturation effects and magnitude and speed limitations of control efforts (particularly, limitations of the turbine valve movement). The performance of the controller will be evaluated in the presence of a large disturbance, namely, a symmetrical three-phase short circuit fault at the terminal of the machine, and compared to the performance of a standard AVR/PSS and speed regulator.

2. MATHEMATICAL MODEL

The model on which the controller is based represents a system comprising a hydraulic turbine and a synchronous generator. The generator is connected to an infinite bus through a transmission line having resistance Re and inductance Le. The model of the synchronous generator on which the controller is tested uses the currents as state variables and is based on a classical representation of a machine with three stator windings, one field winding and two amortisseur or damper windings [1,7]. The model takes into account both field effects and damper-winding effects introduced by the different rotor circuits. As a result, we obtain seven nonlinear differential equations to which the classical Park's transformation is applied. The complete mathematical description includes also the load constraints, the excitation system and the mechanical torque equations. The dynamic characteristics of the hydraulic turbine represent an additional nonlinear differential equation combined with a nonlinear output equation. The complete ninth-order nonlinear model is a fairly complex system. For stability and control studies, a third order simplified model, the so-called one-axis or E'_q – model is traditionally adopted in the literature for the synchronous generator [2,3].

In this study however, no simplification is used in the control model. The computations involved in the design of the nonlinear controller will therefore be very lengthy because of the complexity of the model. The electrical dynamics of the synchronous generator model used in this study can be expressed as follows [1]:

$$\begin{bmatrix} L_d & 0 & -L_{md} & -L_{md} & 0 \\ 0 & L_q & 0 & 0 & -L_{mq} \\ L_{md} & 0 & -L_{fd} & -L_{md} & 0 \\ L_{md} & 0 & -L_{md} & -L_{kd} & 0 \\ 0 & L_{mq} & 0 & 0 & -L_{kq} \end{bmatrix} \begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{i}_{fd} \\ \dot{i}_{kd} \\ \dot{i}_{kq} \end{bmatrix} = \tag{1-1}$$

$$\begin{bmatrix} -R_s & \omega L_q & 0 & 0 & -\omega L_{mq} \\ -\omega L_d & -R_s & \omega L_{md} & \omega L_{kd} & 0 \\ 0 & 0 & R_{fd} & 0 & 0 \\ 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_{fd} \\ i_{kd} \\ i_{kq} \end{bmatrix} - \begin{bmatrix} v_d \\ v_q \\ v_{fd} \\ 0 \\ 0 \end{bmatrix}$$

where:

$i_d(t)$, $i_q(t)$:	direct-axis and quadrature-axis currents
$v_d(t)$, $v_q(t)$:	direct-axis and quadrature-axis terminal voltages
$i_{fd}(t)$:	field winding (excitation) current
$v_{fd}(t)$:	excitation control input
$i_{kd}(t)$, $i_{kq}(t)$:	direct-axis and quadrature-axis damper winding currents
R_s:	stator resistance
R_{fd}:	field resistance
R_{kd}, R_{kq}:	damper windings resistances
L_d, L_q:	direct and quadrature self-inductances
L_{fd}:	rotor self-inductance
L_{kd}, L_{kq}:	direct and quadrature damper windings self-inductances
L_{md}, L_{mq}:	direct and quadrature magnetizing inductances

The mechanical dynamics of the machine rotor are on the other hand given by the swing equations:

$$\dot{\delta} = \omega - 1$$
$$\frac{d\omega}{dt} = \frac{1}{2H}(T_m - T_e - F\omega) \qquad (1\text{-}2)$$

where

δ:	power angle of the generator
ω:	speed of the generator
T_m:	mechanical torque
T_e:	electromagnetic torque
H:	inertia constant
F:	damping constant

The torque T_e can be expressed in terms of the currents i_d i_q, i_{fd}, i_{kd} and i_{kq} as follows:

$$T_e = (L_q - L_d) i_d i_q + L_{md} i_{fd} i_q + L_{md} i_{kd} i_q - L_{mq} i_d i_{kq} \qquad (1\text{-}3)$$

Since the synchronous machine is connected to an infinite bus, the d-q terminal voltages v_d and v_q are constrained by the load equations. In the Park-transformed coordinates, we can write:

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = R_e \begin{pmatrix} i_d \\ i_q \end{pmatrix} + L_e \begin{pmatrix} \dot{i}_d \\ \dot{i}_q \end{pmatrix} - \omega L_e \begin{pmatrix} i_q \\ -i_d \end{pmatrix} + V^{\infty} \begin{pmatrix} \cos(\delta - a) \\ -\sin(\delta - a) \end{pmatrix} \qquad (1\text{-}4)$$

where V^{∞} is the rms value of the bus voltage and a is its phase angle. We note that all the state variables as well as the parameters used in this model are all normalized in per unit (p.u) values.

The model of the hydraulic turbine considered in this work follows from [4] and represents a turbine, with a pen stock, unrestricted head and tail race, and with either a very large or no surge tank. The dynamics of such a turbine are highly nonlinear and are given by:

$$\frac{dq}{dt} = \frac{1 - h - h_l}{T_w} \qquad (1\text{-}5)$$

$$h = \frac{q^2}{G^2} \qquad (1\text{-}6)$$

where:

q:	flow in the conduit
h:	head of the turbine
h_l:	head loss
G:	gate opening
T_w:	water time constant

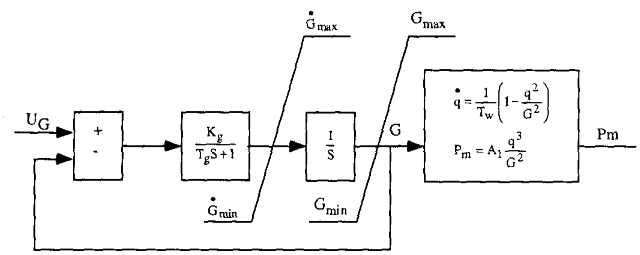
The turbine dynamics are related to the generator dynamics through the mechanical power P_m produced by the turbine. Neglecting the friction losses in the penstock, the mechanical power can be expressed as:

$$P_m = T_m \cdot \omega = A_t \cdot h(q - q_{nl}) = A_t \frac{q^3}{G^2} \qquad (1\text{-}7)$$

where:

A_t:	constant proportionality factor (calculated using the turbine MW rating and the generator MVA base)
q_{nl}:	per-unit no load flow

The transfer function of the gate servomotor will also be included in our analysis. The model of the turbine used will therefore be a second-order model represented as follows:



(1-8)

where K_g and T_g are the gate servomotor gain and time constant respectively. Note that the model takes into account physical limitations on both the magnitude and the rate of opening and closing of the gate during the fault. This insures that the control signal transmitted to the gate is indeed a practical one and is not harmful to the penstock.

Combining equations (1-1) to (1-4) with the equations of the turbine-gate servomotor (1-8), we can formulate the complete model of the turbine-generator system in the nonlinear state-space form:

$$\dot{x} = F(x) + G(x)u \qquad (1\text{-}9)$$

where $x = [i_d, i_q, i_{fd}, i_{kd}, i_{kq}, \delta, \omega, q, G]^T$ is the vector of state variables, $u = [U_{fd}, U_G]^T$ is the vector of control inputs and F(x) and G(x) are given by:

$$F(x)=\begin{bmatrix} A_{11}x_1+A_{12}x_3+A_{13}x_2x_7+A_{14}x_4+ \\ \quad A_{15}x_5x_7+A_{16}\cos(x_6-\alpha) \\ A_{21}x_1x_7+A_{22}x_2+A_{23}x_3x_7+A_{24}x_4x_7+ \\ \quad A_{25}x_5+A_{26}\sin(x_6-\alpha) \\ A_{31}x_1+A_{32}x_3+A_{33}x_2x_7+A_{34}x_4+ \\ \quad A_{35}x_5x_7+A_{36}\cos(x_6-\alpha) \\ A_{41}x_1+A_{42}x_3+A_{43}x_2x_7+A_{44}x_4+ \\ \quad A_{45}x_5x_7+A_{46}\cos(x_6-\alpha) \\ A_{51}x_1x_7+A_{52}x_2+A_{53}x_3x_7+A_{54}x_4x_7+ \\ \quad A_{55}x_5+A_{56}\sin(x_6-\alpha) \\ (x_7-1)\omega_R \\ A_{71}x_1x_2+A_{72}x_2x_3+A_{73}x_2x_4+A_{74}x_1x_5+ \\ \quad A_{75}x_7+A_{76}\dfrac{x_8^3}{x_7x_9^2} \\ A_{81}-A_{82}\dfrac{x_8^2}{x_9^2} \\ A_{91}x_9 \end{bmatrix} \tag{1-10}$$

and

$$G(x)=\begin{bmatrix} g_{11} & 0 & g_{31} & g_{41} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & g_{92} \end{bmatrix}^T = [G_1(x) \quad G_2(x)] \tag{1-11}$$

Where A_{ij}, i=1,7, j=1,6 are constants which depend on the generators parameters R_s, R_{kq}, R_{kd}, R_{fd}, L_d, L_q, L_{kd}, L_{kq}, L_{fd}, L_{md}, L_{mq} and on the load parameters R_e, L_e and V^∞. See [9] for details of the computations.

3. LINEARIZATION DESIGN

Nonlinear control based on feedback linearization techniques (input-state or input-output) is by now a well known area and several textbook references have been written on its subject [6].

In this section, we briefly describe the design of a nonlinear feedback linearizing controller. The control inputs used will be the excitation voltage and the reference signal at the entrance of turbine's gate servomotor as shown in the figure below:

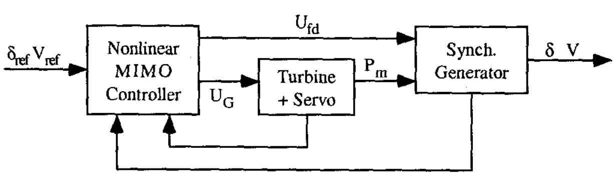


Figure 1 Block Diagram of the Proposed Nonlinear Scheme

Since we have two controls, we are able to influence independently two outputs and satisfy therefore the two objectives before mentioned, namely: rotor angle stability enhancement and voltage regulation. In order to reach these objectives, the first output to be chosen is the terminal voltage Vt, i.e.

$$y_1 = Vt = \sqrt{Vd^2+Vq^2} \tag{1-12}$$

The expressions of Vd and Vq as a function of the state variables can be obtained by combining equations (1-1) and (1-4).

$$\begin{aligned} Vd &= (Re+Le\,A_{11})x_1 + Le\,A_{12}x_3 + \\ &(Le\,A_{13}-Le)x_2x_7 + Le\,A_{14}x_4 + \\ &Le\,A_{15}x_5x_7 + (V^\infty + Le\,A_{16})\cos(x_6-a) + Le\,g_{11}u_1 \end{aligned} \tag{1-13}$$

$$\begin{aligned} Vq &= (Re+Le\,A_{22})x_2 + (Le\,A_{21}+Le)x_1x_7 + \\ &Le\,A_{23}x_3x_7 + Le\,A_{24}x_4x_7 + Le\,A_{25}x_5 + \\ &(Le\,A_{26}-V^\infty)\sin(x_6-a) \end{aligned} \tag{1-14}$$

Remark:

We note that the control input U_{fd} appears explicitly in the expression of Vd, the corresponding term being of a very small order of magnitude. We therefore neglect this direct dependence between Vd and U_{fd}. As a matter of fact, this dependence never appears in the reduced order models used in the literature.

In order to obtain the nonlinear controller U_{fd}, we compute the time derivative of the output y_1:

$$\frac{dy_1}{dt} = \frac{dV_t}{dt} = \alpha_1(x) + \beta_{11}(x)\cdot U_{fd} + \beta_{12}(x)\cdot U_G \tag{1-15}$$

where

$$\alpha_1(x) = \frac{\delta V_t}{\delta x}\cdot F(x) = \frac{1}{2V_t}\left(2Vd\frac{\delta Vd}{\delta x} + 2Vq\frac{\delta Vq}{\delta x}\right)\cdot F(x) \tag{1-16}$$

$$\beta_{11}(x) = \frac{\delta V_t}{\delta x}\cdot G_1(x) = \frac{1}{2V_t}\left(2Vd\frac{\delta Vd}{\delta x} + 2Vq\frac{\delta Vq}{\delta x}\right)\cdot G_1(x) \tag{1-17}$$

We can also easily show that:

$$\beta_{12}(x) = \frac{\delta Vt}{\delta x}G_2(x) \equiv 0 \tag{1-18}$$

The computations involved in obtaining the expressions (1-16) and (1-17) are straightforward but lengthy and will not be presented here for simplicity [9].

The second output y_2 is chosen as the angle δ in order to achieve our second objective, namely to insure a high performance stabilizing controller for the mechanical dynamics of the machine:

$$y_2 = \delta = x_6 \tag{1-19}$$

By differentiating this output successively we obtain:

$$\frac{d\delta}{dt} = \frac{dx_6}{dt} = \omega_R(x_7 - 1)$$

$$\frac{d^2\delta}{dt^2} = \omega_R \frac{dx_7}{dt} = \omega_R \cdot F_7(x)$$

$$\begin{aligned}\frac{d^3\delta}{dt^3} &= \omega_R \frac{\delta F_7}{\delta x} \cdot F(x) + \omega_R \frac{\delta F_7}{\delta x} G_1(x) U_{fd} \\ &+ \omega_R \frac{\delta F_7}{\delta x} G_2(x) U_G \\ &= \alpha_2(x) + \beta_{21}(x) U_{fd} + \beta_{22}(x) U_G\end{aligned} \tag{1-20}$$

We can see that while the relative degree corresponding to the first output $y_1 = Vt$ is $r_1 = 1$, the relative degree corresponding to the second output $y_2 = \delta$ is $r_2 = 3$. Combining equations (1-15) and (1-20), we obtain the input-output nonlinear system:

$$\begin{bmatrix} dV_t/dt \\ d^3\delta/dt^3 \end{bmatrix} = \begin{bmatrix} \alpha_1(x) \\ \alpha_2(x) \end{bmatrix} + \begin{bmatrix} \beta_{11}(x) & 0 \\ \beta_{21}(x) & \beta_{22}(x) \end{bmatrix} \begin{bmatrix} U_{fd} \\ U_G \end{bmatrix} \tag{1-21}$$

and using the nonlinear multi-variable controller:

$$\begin{bmatrix} U_{fd} \\ U_G \end{bmatrix} = \begin{bmatrix} \beta_{11}(x) & 0 \\ \beta_{21}(x) & \beta_{22}(x) \end{bmatrix}^{-1} \left[-\begin{pmatrix} \alpha_1(x) \\ \alpha_2(x) \end{pmatrix} + \begin{pmatrix} v_{fd} \\ v_G \end{pmatrix} \right] \tag{1-22}$$

We obtain the exactly linearized input-output system:

$$\begin{bmatrix} dV_t/dt \\ d^3\delta/dt^3 \end{bmatrix} = \begin{bmatrix} v_{fd} \\ v_G \end{bmatrix} \tag{1-23}$$

The nonlinear controller (1-22) has therefore transformed the MIMO power system's model into two SISO decoupled linear systems:

- A first-order model $\left(dV_t/dt = v_{fd} \right)$ obtained through the excitation loop which cancels the dynamics relating the excitation U_{fd} to the terminal voltage Vt.
- A 3rd order linear model $\left(d^3\delta/dt^3 = v_G \right)$ obtained through the cancellation of the mechanical and turbine dynamics.

Note that the linearized input-output system (1-23) is of order: 4 while the original nonlinear system is of order 9 (since only partial linearization has been achieved). The remaining 5th order dynamics are the so-called internal dynamics (since they cannot be seen from the input-output relationship (1-23)).

If these internal dynamics are asymptotically stable, the design of the linear inputs (v_{fd}, v_G) could be done in a straightforward manner using a classical linear control strategy such as pole placement or optimal control (LQR). As it turns out, in our case, the internal dynamics are not asymptotically stable. Indeed, while the internal electrical dynamics rendered unobservable by the excitation loop are inherently asymptotically stable, it is a known fact (which can easily be checked) that the turbine dynamics (1-8), when linearized, lead to a non-minimum phase transfer function. The unstable zero of the turbine dynamics winds up therefore as a pole in the internal dynamics and is introduced there by the nonlinear feedback U_G (1-22) which is based in principle on canceling all the system's non linearities. We must therefore be careful in the design of the linear inputs (v_{fd}, v_G) to make sure that the closed loop system remains stable. We propose therefore:

$$v_{fd} = k_{11}(Vt - Vt_{ref}) \tag{1-24}$$

$$\begin{aligned} v_G &= k_{21}(\delta - \delta_{ref}) + k_{22}(\dot{\delta} - \dot{\delta}_{ref}) \\ &+ k_{23}(\ddot{\delta} - \ddot{\delta}_{ref}) + k_{24}(G - G_{ref}) \end{aligned} \tag{1-25}$$

where k_{11}, k_{21}, k_{22}, k_{23} and k_{24} are selected by pole placement in order to stabilize simultaneously the linearized system (1-24) (1-25) and the remaining internal dynamics. The feedback of the gate in v_G is therefore introduced in order to provide additional damping and compensate for the unstable zero of the turbine dynamics.

Remarks:

- Since the control objective is to regulate the power angle δ to a constant value, $\dot{\delta}_{ref}$ and $\ddot{\delta}_{ref}$ will be taken zero in (1-25). The values of δ_{ref} and G_{ref} on the other hand correspond to the operating point of the machine and can be determined using a power flow simulation program.
- In this study, all the state variables are supposed to be available for control. In practice however, variables such as the angle δ and the rotor acceleration $\ddot{\delta}$ are difficult to measure. The proposed controller can be augmented as in [8] with an observer scheme which estimates the rotor angle δ and $\ddot{\delta}$.

4. SIMULATION RESULTS

Case 1:

First, the performance of the proposed MIMO controller was tested on the complete 9th order model of the turbine-generator system in a single machine infinite bus configuration as follows:

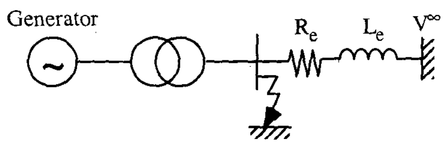


Figure 2 Single Machine Infinite Bus Configuration

The parameters of the system, in p.u, are:

R_s = 3.10^{-3}; R_{fd} = 6.3581.10^{-4}; R_{kd} = 4.6454 10^{-3}; R_{kq} = 6.8460.10^{-3}; L_{md} = 9.1763 10^{-1}; L_{mq} = 2.1763 10^{-1}; L_{fd} = 1.083; L_{kd} = 0.9568; L_{kq} = 0.2321; H = 3.195; F = 0; L_d = 1.116; L_q = 0.416; T_g = 0.3; T_w = 2.67; Kg = 1; $R_e = 20\,R_s$; $L_e = L_d/4.25$; $V^\infty = 1$ and a = 78.72 deg.

The physical limits of the control inputs are:

$$\max|U_{fd}| = 11.5\,\text{p.u}, \quad G_{max} = 0.975\,\text{p.u};$$

$$G_{min} = 0.01\,\text{p.u}, \qquad \max|\dot{G}| = 0.1\,\text{p.u}$$

The stability of the system is validated by simulating a three-phase short-circuit at the secondary of the generator's transformer for a period of 100 ms. The performance of the nonlinear controller is compared in Figures 3 to 7 to the performance of a standard IEEE type 1 voltage regulator combined with a standard speed regulator [7].

Figure 3 shows the response of the terminal voltage V_t during fault and post-fault regimes. It is shown how the stabilization of V_t is improved using the nonlinear controller compared to the one obtained using the linear AVR.

Figure 4 shows the dynamics of the rotor angle δ. It is seen how it takes a much shorter time for the oscillations on δ to decay with the nonlinear controller than with the standard linear scheme (1.5 sec compared to 4 sec). The nonlinear controller combines therefore the functions of an AVR, a speed regulator and a PSS. The response of the speed is also improved as is shown in Figure 5. The control efforts U_{fd} and G (gate opening) are shown in Figures 6 and 7.

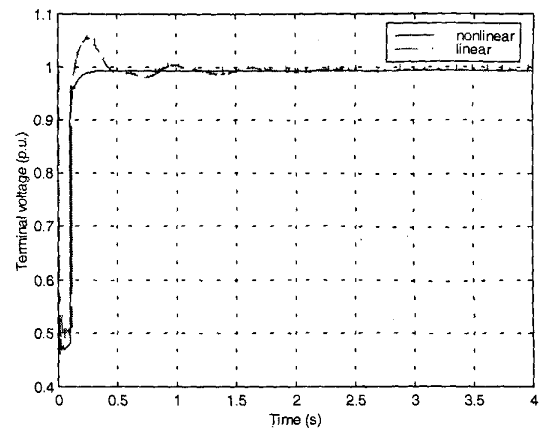


Figure 3 Terminal Voltage V_t

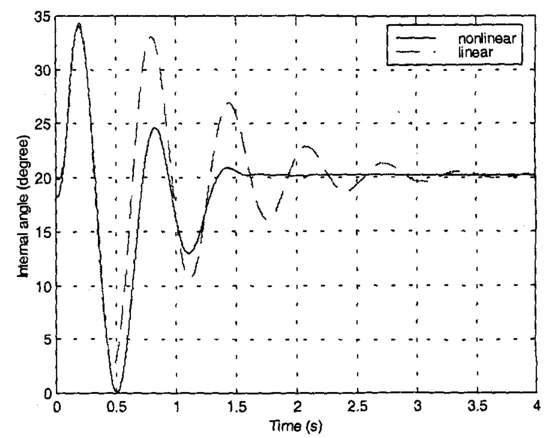


Figure 4 Rotor Angle δ

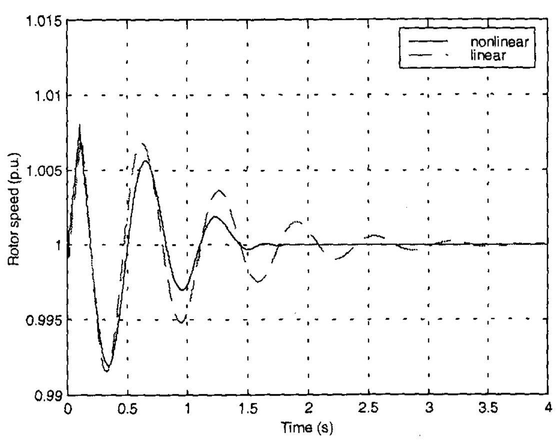


Figure 5 Speed ω

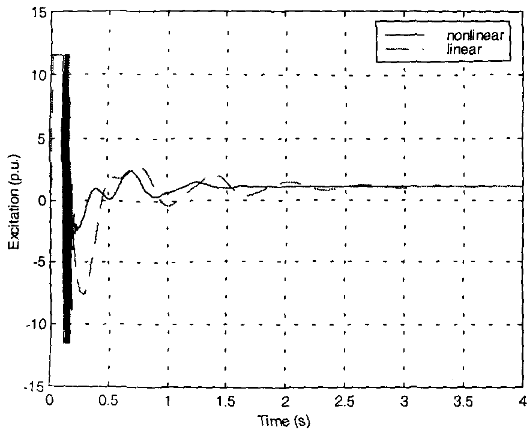


Figure 6 Excitation Voltage $u_1 = U_{fd}$

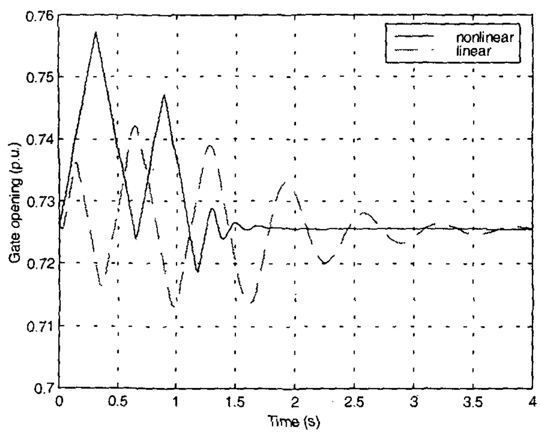


Figure 7 Gate Opening G

Case 2:

Next, the controller is validated in a more realistic setting, i.e. on a configuration comprising two machines as follows:

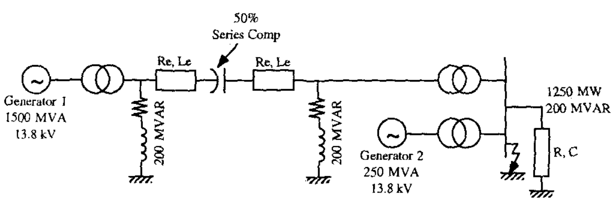


Figure 8

In order to match the single machine, infinite-bus configuration the controller is based upon, the network, seen from the outputs of Generator 2, was replaced by a Thevenin equivalent (Re, Le, V^{∞}). The nonlinear strategy was applied to Generator 2 and simulated on the full model of Figure (8) using the Mathworks "Power System" Blockset [11]. The parameters of Generator 2 in p.u. are:

$R_s = 0.0029$; $R_{fd} = 7.9947\ 10^{-4}$; $R_{kd} = 0.0161$; $R_{kq} = 0.0112$; $L_{md} = 1.1426$; $L_{mq} = 0.3116$; $L_{fd} = 1.3013$; $L_{kd} = 0.2507$; $L_{kq} = 0.1086$; $H = 2$ sec.; $F = 0$; $L_d = 1.305$; $L_q = 0.474$; $T_g = 0.3$, $T_w = 2.67$, $Kg = 1$.

The rest of the network is represented by the equivalent circuit, Le = 0.2531, Re = 0.0524, $V^{\infty} = 1$ and a = -24.52°.

Figure 9 shows that the nonlinear voltage regulator and the linear AVR give almost the same results. The stabilization of the rotor angle δ and the speed ω (Figures 10 and 11 respectively) is superior for the nonlinear control however. Overall though, the difference between the performance of the linear and nonlinear controls is not as striking as in the first case. This is to be expected for mainly 2 reasons:

- The nonlinear feedback linearization scheme is model based. Therefore, when applied to a model structure which is very different from the one the controller was based upon, the cancellation of nonlinear terms is not exact anymore nor is the decoupling between the electrical and mechanical dynamics.
- The linear controller (AVR + PSS + speed regulator) presented for comparison reasons was actually very carefully tuned, as in [10], in order to give the best possible results for the particular operating point of interest. Indeed, in [10], a novel tuning procedure for the AVR and the speed governor system based on a time-scale decomposition, is presented which decouples the electrical dynamics from the mechanical dynamics and allows to add significant damping to the local mode oscillations. An immediate benefit of this method is that the PSS can be partially or entirely released from the task of damping the local oscillations and can be designed mainly for damping the inter-area oscillations. Even when compared to this highly performant linear scheme, the nonlinear controller still gave better results.

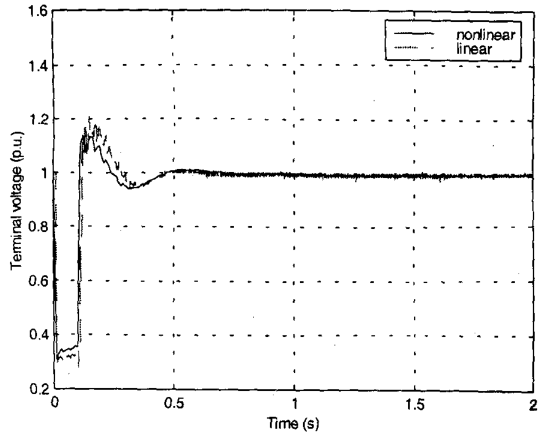


Figure 9 Terminal Voltage Vt

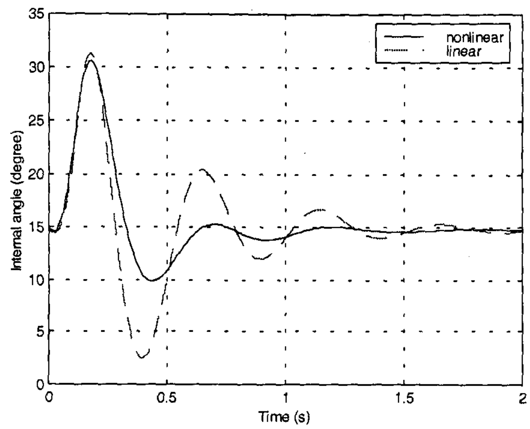


Figure 10 Stabilization of the Rotor angle δ

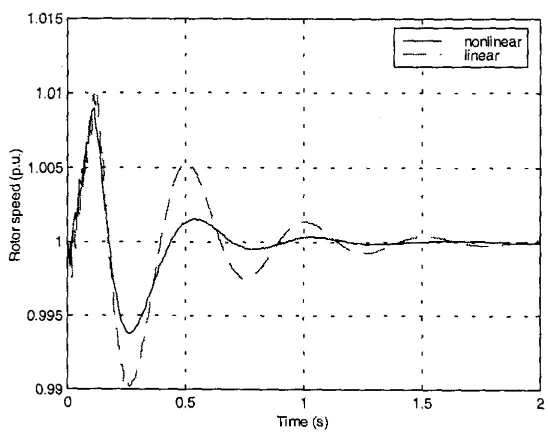


Figure 11 Stabilization of the Speed ω

5. CONCLUSION

In this paper, a multivariable nonlinear controller is proposed to achieve simultaneously rotor angle stability and good post-fault regulation of the generator terminal voltage.

The machine considered in this paper comprises a hydraulic turbine and a synchronous generator. The model used for control is a fully detailed nonlinear model which (contrary to the usual models adopted in the literature) takes into account all the interactions between the electromagnetic, mechanical and turbine dynamics.

The proposed nonlinear controller is based on partial feedback linearization and is therefore able to decouple systematically all the dynamical interactions afore mentioned. The new controller is tested through simulation in two different configurations and is compared for each case to the performance of a classical linear scheme. The simulation results show:

- The controller is able to improve both the power system damping and the post-fault regulation of the generator terminal voltage even when a large fault (a 100 ms short-circuit) occurs close to the generator terminals. Note that these two requirements are conflictive in nature and a compromise must be reached between the two when only excitation control is used as is the case for the classical AVR/PSS scheme.
- The nonlinear controller, contrary to its linear counterpart, is independent of the operating point of the system. To this effect, we have shown in [10] that the tuning of the linear AVR/PSS for a particular operating point is not an easy task and must be performed carefully. The nonlinear control saves us therefore this process.

This paper only presents preliminary results. Indeed, the nonlinear controller proposed is model-based and as such is sensitive to the structure of the model it is based upon. Furthermore, the parameters of the transmission network may be unknown or may vary during operation. A robust version of the controller is under study. This version is less sensitive to model uncertainties and possesses adaptive capabilities in order to deal with parametric uncertainties.

6. ACKNOWLEDGMENTS

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