REAL-TIME IMPLEMENTATION OF A ROBUST NONLINEAR CONTROL FOR ROTOR SPEED STABILITY AND VOLTAGE REGULATION OF POWERS SYSTEMS

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Abstract: In this paper, a new real-time implementation of a Robust Nonlinear Controller to the multi-input multi-output model of a power system is outlined. The experimental setup of this power system includes a DC motor and synchronous machine connected to a large power system through a transmission line. Some responses of the system when the reactance of the transmission line changes after a sudden short-circuit, and when the mechanical power abruptly changes are presented. It is also shown that the system still keeps transient stability for slightly more severe faults. The nonlinear controller practical results is compared to the performance of a standard controllers such as, the automatic voltage regulator (AVR) and power system stabilizer (PSS).

Keywords: Decentralized model, robust nonlinear control, rotor speed regulation, voltage regulation, transient stability.

1. INTRODUCTION

The linear controllers such as the automatic voltage regulator (AVR) and power system stabilizer (PSS) has been hence still used actually by industrial applications for power systems stability (kundur, 1994). These controllers work well for some ranges of operation points and have been efficient for a long time. But as systems grow in complexity and size, they are not able to keep the stability when sudden faults appear in the transmission line. It is then necessary to develop new controllers. Recently a number of contributions in the area of nonlinear controllers which are independent of the equilibrium point and take into account the severe nonlinearities of the power system model, has been proposed (Marino, et al., 2000; Kelemen, et al., 2000; Bazanella and Kokotović, 1997; Wang, et al., 1993). These new controllers of power system theoretically guarantee the stability of synchronous generator in a certain domain when the reactance of the transmission line X_e changes after a sudden short-circuit, or when the mechanical power P_m abruptly changes. Unfortunately some of them supposed that the power angle is available or measurable this assumption is quite impossible to obtain in practice. The controller proposed here is based on the work of (Kelemen, et al., 2000). Its main goal is to control the rotor speed as well as the terminal voltage, in order to improve the system stability under large disturbances and to obtain good post-fault voltage regulation. Most of the methods in the literature require the direct measure of the power angle. Unfortunately this quantity is quite difficult to obtain in practice. The main advantage of our method is the fact that we do not assume the direct availability of the power angle. In fact we propose to rebuilt the power angle through available measures. Therefore, practical implementations are possible.

The paper is organized as follows. The second section presents a new model of the power system. In the third section, we present the multivariable voltage and speed controller design. The algorithm for the computation of the power angle is presented in the fourth section. In the fifth section, we describe the real-time interface and the main experimental results of this work obtained for one machine connected to a large power system through a short line transmission are presented. Section 6 concludes the paper.

2. NEW MODEL OF THE POWER SYSTEMS

Several different modelling approaches exist for the design of power system controllers. On the one hand, the single machine infinite bus approach is simple and suitable for voltage and speed regulator synthesis. However, since remote dynamics are neglected, the regulator may not perform well when inter-area oscillations occur for instance. On the other hand, in global N-generators modelling approach, all the generator dynamics are represented. Speed (or power angle) controllers based on this model damper very well inter machine and inter-area oscillations. However, a coordinated voltage and speed regulator based on this modelling approach has never been proposed. (Okou, et al., 2003) has recently introduced a novel power systems model. It combines the advantages of both previous modelling approaches. The new modelling approach consists in partitioning the power system into the generator to-be-controlled and the rest of the grid represented by a time- varying impedance. In other words, each generator views the rest of the network as a dynamic load. The resulting model contains then time varying parameters modelling operating condition variations and interactions between generators. Hence, it captures the main characteristics of multi-machine power systems. The sequel presents this new power systems model. Each generator consists of a synchronous machine and a DC motor providing the mechanical power.

2.1 Synchronous generator dynamical model

A synchronous machine consisting of three stator winding, one field winding and two damper windings is used as alternator. Its full order model in the *d-q* reference frame is a ninth-order nonlinear differential equation (see for instance (Peter Sauer and Pai, 1998)) which takes into account the stator very fast dynamics, the damper-windings and field subtransient and transient dynamics respectively. For stability and control design, various simplified models are adopted in the literature (Peter Sauer and Pai, 1998). In this paper the well-known two-axis model is used to represent the synchronous machine. The stator dynamics and the subtransient damper-windings dynamics are neglected.

$$
\begin{aligned}
T'_{q0}\frac{dE'_d}{dt} &= -E'_d + (X_q - X'_q)I_q \qquad (1)\\
T'_{d0}\frac{dE'_q}{dt} &= -E'_q + (X_d - X'_d)I_d + E_{fd}\\
\frac{2H}{\omega_s}\dot{\omega} &= T_m - [(X'_q - X'_d)I_dI_q + E'_qI_q + E'_dI_d] - K_D\omega\\
\dot{\delta} &= \omega - \omega_s
\end{aligned}
$$

where δ is the power angle, E_{fd} the equivalent EMF in the excitation coil. I_d, I_q, X_d and X_q represent the current and the reactance of the generator in the *d-q* reference frame. E'_d, E'_q, ω, P_e and T_m represent the transient EMF in the direct axis, the transient EMF in the quadrature axis, the rotor speed, the electrical power and mechanical torque. The stator is represented by the following two algebraic equations in which $R_s = 0$, usually.

$$
\begin{aligned}
V_d &= E'_d - R_sI_d + X'_qI_q\\
V_q &= E'_q - R_sI_q - X'_dI_d \qquad (2)
\end{aligned}
$$

in which X'_d, X'_q, V_d and V_q represent the transient reactance and the voltage of the generator in the *d-q* reference frame.

2.2 The rest of the network model

The rest of the power system, is considered after partitioning, as a dynamic load for the generator under consideration. This load is represented by instantaneous effective impedance described by the following equation

$$
\begin{aligned}
v(t) &= r(t)i + \frac{d}{dt}(K(t)i)\\
&= (r(t) + \frac{dK}{dt})i + K(t)\frac{di}{dt} \qquad (3)\\
&= R(t)i + K(t)\frac{di}{dt}
\end{aligned}
$$

The resistor part models the active power exchange, whereas the reactive part is for the reactive power exchange; v and i, are instantaneous terminal voltage and stator current of the generator. Note that equation (3) is an inductive type representation. The conclusion remains unchanged however if we use a capacitive type representation. In the d-q reference frame, after applying a Park transformation on equation (3), we get,

$$\begin{aligned} V_d &= R(t)I_d - K(t)\omega I_q + K(t)\frac{dI_d}{dt} \\ V_q &= R(t)I_q + K(t)\omega I_d + K(t)\frac{dI_q}{dt} \end{aligned} \tag{4}$$

Applying the two axis model assumption (i.e. neglecting the stator current dynamics), we obtain

$$\begin{aligned} V_d &= R(t)I_d - K(t)\omega I_q \\ V_q &= R(t)I_q + K(t)\omega I_d \end{aligned} \tag{5}$$

From (5) we can solve for I_d and I_q,

$$\begin{aligned} I_d &= \frac{R(t)V_d + K(t)\omega V_q}{R^2(t) + (K(t)\omega)^2} \\ I_q &= \frac{R(t)V_q - K(t)\omega V_d}{R^2(t) + (K(t)\omega)^2} \end{aligned} \tag{6}$$

Equation (6) can be rewritten in the following closed form

$$\begin{aligned} I_d &= a(t)V_d + b(t)V_q \\ I_q &= a(t)V_q - b(t)V_d \end{aligned} \tag{7}$$

where $a(t)$ and $b(t)$ are given by

$$\begin{aligned} a(t) &= \frac{R(t)}{R^2(t) + (K(t)\omega)^2} \\ b(t) &= \frac{K(t)\omega}{R^2(t) + (K(t)\omega)^2} \end{aligned} \tag{8}$$

Expressing $a(t)$ and $b(t)$ in terms of the d-q axis voltage and current gives a better understanding of the approach,

$$\begin{aligned} a(t) &= \frac{V_d I_d + V_q I_q}{V_t^2} \\ b(t) &= \frac{V_q I_d - V_d I_q}{V_t^2} \end{aligned} \tag{9}$$

Indeed, it is easy to see that in steady state, $a(t)$ and $b(t)$ are proportional to respectively the active power and reactive power delivered by the generator (they are equal to the active and reactive power respectively when the terminal voltage is 1 [pu] in steady state). In the transient period, $a(t)$ and $b(t)$ represent the admittance and the susceptance seen by the generator, respectively, and give information about the *state* or operating conditions of the rest of the grid.

2.3 New power system model for the design of decentralized controller

The computation involved in the modelling process is essentially a change variable. The terminal voltage V_d and V_q components are the new state variables instead of $E_d^{'}$, and $E_q^{'}$. Using (2) and (7) we can show that $E_d^{'}$ and $E_q^{'}$ are given by

$$\begin{aligned} E_d^{'} &= (1 + R_s a(t) + X_q^{'} b(t))V_d + (R_s b(t) - X_q^{'} a(t))V_q \\ E_q^{'} &= (1 + R_s a(t) + X_d^{'} b(t))V_q + (X_d^{'} a(t) - R_s b(t))V_d \end{aligned} \tag{10}$$

From (10) we can also show that the expressions of V_d and V_q are a function of $E_d^{'}$ and $E_q^{'}$ (see Appendix). After some algebraic manipulations using equations (1), (7), and (10), we can now give a new power system model by the following equations

$$\begin{aligned} \dot{V}_d &= \alpha(t)V_d + \beta(t)V_q + g_1(t)E_{fd} \\ \dot{V}_q &= \sigma(t)V_d + \gamma(t)V_q + g_2(t)E_{fd} \\ \dot{\omega} &= \frac{1}{2H}(T_m - a(t)(V_q^2 + V_d^2)) - K_D\omega \\ \dot{\delta} &= \omega - 1 \end{aligned} \tag{11}$$

The terminal voltage of one generator is given by the following equation

$$V_t = \sqrt{V_d^2 + V_q^2} \tag{12}$$

It is important to note that the modelling approach leads to a model, with locally measurable state variables. V_d and V_q are used as state variables leading to a simpler expression for the terminal voltage as an output variable. The time-varying parameters $\alpha(t)$, $\beta(t)$, $\sigma(t)$, $\gamma(t)$, $g_1(t)$ and $g_2(t)$ depend on $a(t)$ and $b(t)$ hence on the operating conditions of the power system. They have fixed values in steady state and their expressions are given in the Appendix section. These parameters encapsulate the interactions between the generator to-be-controlled and the rest of the power system. It is shown in (Okou, et al., 2003) that each time-varying parameter $\alpha(t)$, $\beta(t)$, $\sigma(t)$, $\gamma(t)$, $g_1(t)$ and $g_2(t)$ can be decomposed into two parts: a fixed part and a time varying one. The electrical part of the model can then be written as:

$$\begin{aligned} \dot{V}_d &= (\alpha_0 + \alpha_t)V_d + (\beta_0 + \beta_t)V_q + (g_{10} + g_{1t})E_{fd} \\ \dot{V}_q &= (\sigma_0 + \sigma_t)V_d + (\gamma_0 + \gamma_t)V_q + (g_{20} + g_{2t})E_{fd} \\ \dot{\omega} &= \frac{1}{2H}(T_m - a(t)(V_q^2 + V_d^2)) - K_D\omega \end{aligned} \tag{13}$$

where the parameters α_0, β_0, σ_0 γ_0, g_{10} and g_{20} are the fixed parts and depend on the steady state active and reactive power delivered by the generator to-be-controlled (see Appendix). α_t, β_t, σ_t, γ_t, g_{1t} and g_{2t} are the dynamic parts of the parameters. They represent the rest of the power system influence on the generator under consideration. Therefore, when the generator interacts with an infinite bus, they can neglected and then set to zero in equations (13).

2.4 DC *motor dynamic model*

The synchronous generator is driven by a DC motor. The dynamic model of the DC motor is given by the following equations

$$
\begin{aligned}
\dot{i}_a &= \frac{1}{L_a}(-R_a i_a - K_m\omega + u_a) \\
T_m &= K_m i_a
\end{aligned} \tag{14}
$$

3. MULTIVARIABLE VOLTAGE AND SPEED CONTROLLER DESIGN

The goal of the control is to keep all states and output bounded and asymptotically converging to their reference values. Because the system considered is nonlinear, the determination of stability depends upon finding a suitable Lyapunov function or some equivalent method. This section deals with a procedure for the synthesis of a power system controller solving simultaneously the transient stability and the voltage regulation, when the system undergoes severe disturbances. The system to-be-controlled consists of a synchronous machine connected to a large power system through a short transmission line. A separated excited DC motor provides the generator mechanical power. The system dynamics can be described by the following equations

$$
\begin{aligned}
\dot{V}_d &= \alpha_0 V_d + \beta_0 V_q + g_{10} E_{fd} \\
\dot{V}_q &= \sigma_0 V_d + \gamma_0 V_q + g_{20} E_{fd} \\
\dot{\omega} &= \frac{1}{2H}(K_m i_a - a(t)(V_q^2 + V_d^2)) - K_D\omega \\
\dot{i}_a &= \frac{1}{L_a}(-R_a i_a - K_m\omega + u_a) \\
\dot{\delta} &= \omega - 1
\end{aligned} \tag{15}
$$

The variables i_a and u_a are the DC motor armature current and voltage respectively; K_m, R_a, H and K_D are the motor torque constant, the armature resistance, the inertia constant and the damping torque coefficient respectively.

The design process is now described in two steps consisting of linearizing the dynamics (15) by a suitable change of coordinates and inputs, and stabilizing the partially linear model obtained.

Step 1: Linearizing control

An integral action is introduced in the controller by redefining the system outputs to be the integral of the errors on the terminal voltage and the rotor speed, respectively.

$$
\begin{aligned}
y_1(t) &= \int_0^t (V_d^2(\tau) + V_q^2(\tau) - 1)d\tau \\
y_2(t) &= \int_0^t (\omega(\tau) - 1)d\tau
\end{aligned} \tag{16}
$$

Remark: the second equation (16) can be interpreted as an indirect utilisation of the power angle in the design process.

The first part of the design procedure consists of finding a nonlinear change of coordinates transforming system into a canonical form and a partially linearizing nonlinear state feedback control law (Akhrif, et al., 1999; Isidori, 1989). Let us consider the following time-varying change of coordinates,

$$
\begin{aligned}
z_1 &= \int_0^t (V_q^2 + V_d^2 - 1)d\tau \\
z_2 &= (V_q^2 + V_d^2 - 1) \\
z_3 &= \int_0^t (\omega - 1)d\tau \\
z_4 &= (\omega - 1) \\
z_5 &= \frac{\omega_s}{2H}(K_m i_a - a_0(V_q^2 + V_d^2) - K_D\omega) \\
\eta_1 &= E_d^{'}
\end{aligned} \tag{17}
$$

Differentiating equations (17) and introducing the

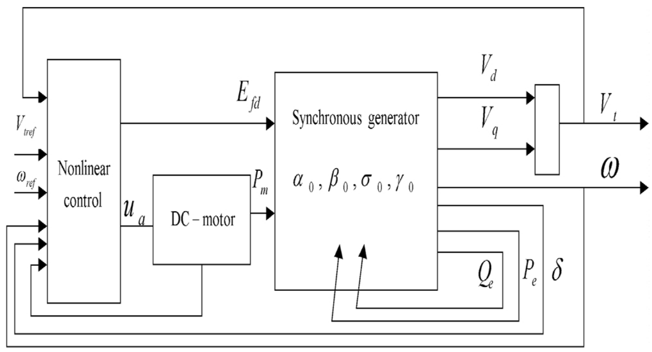

Fig. 1. Functional block diagram of the multivariable voltage and speed controller

parameters estimated values where necessary, we get the system dynamics in the new coordinates,

$$
\begin{aligned}
\dot{z}_1 &= z_2 \\
\dot{z}_2 &= F_2(V_d, V_q) + G_2(V_d, V_q)E_{fd} \\
\dot{z}_3 &= z_4 \\
\dot{z}_4 &= z_5 \\
\dot{z}_5 &= F_5(i_a, V_d, V_q, E_{fd}) + G_5 u_a
\end{aligned} \tag{18}
$$

Note that internal variable η_1 is not considered in the sequel since the associated zero dynamics are stable.

The expression of the nonlinear functions involved in the canonical form are

$$
\begin{aligned}
F_2(V_d, V_q) &= 2(\alpha_0 V_d^2 + \gamma_0 V_q^2 + \beta_0 V_d V_q + \sigma_0 V_d V_q) \\
G_2(V_d, V_q) &= 2(g_{10} V_d + g_{20} V_q) \\
F_5 &= -\frac{a_0 \omega_s}{2H}(F_2 + E_{fd} G_2) - \frac{K_m \omega_s}{2HL_a}(K_m \omega + R_a i_a) \\
G_5 &= \frac{K_m \omega_s}{2HL_a}
\end{aligned} \tag{19}
$$

The generator excitation and the DC motor input are used to cancel some of the nonlinear terms in (20), thus partially linearizing the system. Note that $K_D = 0$, we choose the two inputs control such as

$$
\begin{aligned}
E_{fd} &= \frac{v_1 - 2(\alpha_0 V_d^2 + \gamma_0 V_q^2 + (\beta_0 + \sigma_0) V_d V_q)}{2(g_{10} V_d + g_{20} V_q)} \\
u_a &= \frac{2HL_a}{\omega_s K_m}(v_2 - (\frac{K_m^2 \omega_s}{2HL_a}\omega - \frac{K_m R_a \omega_s}{2HL_a} i_a - \frac{a_0 \omega_s}{2H} v_1))
\end{aligned} \tag{20}
$$

The variables v_1 and v_2 are auxiliary inputs yet to be determined and are used to stabilize the closed loop system and attenuate the perturbations effects. Note that $G_2(V_d, V_q) = 0$ during a short-circuit at the generator terminal, the excitation E_{fd} equals E_{fdmax} or E_{fdmin} depending on the sign of v_1.

Step 2: The stabilizing auxiliary input
Replacing equations (20) in the canonical form (18), we get the system closed loop dynamics equation

$$
\dot{X} = AX + BV \tag{21}
$$

where A and B are defined in Appendix, with

$$
\begin{aligned}
X &= \begin{bmatrix} z_1 & z_2 & z_3 & z_4 & z_5 \end{bmatrix}^T \\
V &= \begin{bmatrix} v_1 & v_2 \end{bmatrix}^T
\end{aligned}
$$

We propose to choose the linear stabilizing auxiliary control V of the form

$$
V = \begin{bmatrix} v_1 \\ \\ v_2 \end{bmatrix} = - \begin{bmatrix} k_{v1} & k_{v2} & k_{v3} & k_{v4} & k_{v5} \\ k_{w1} & k_{w2} & k_{w3} & k_{w4} & k_{w5} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{bmatrix}
$$

The gain K is such that $A_s = A - BK$ is stable.

4. POWER ANGLE ALGORITHM

Using Park transformation, the electrical active power and reactive power output of the generator in terms of *d*-*q* axis can be written as follows:

$$
\begin{aligned}
P_e &= V_d I_d + V_q I_q \\
Q_e &= V_d I_q - V_q I_d
\end{aligned} \tag{22}
$$

To illustrate the procedure of finding the power angle, we consider the algorithm described in (Damm, 2001) which uses the transmission line reactance X_e, the electrical power P_e, the terminal voltage V_t and the infinite bus voltage V_s, where the generator terminal voltage V_t and the active power P_e are measurable, then the main result of this section is

$$
\delta = arc\cot\left(\frac{V_s}{X_e P_e}\left(-\frac{X_d V_s}{X_{ds}} + \sqrt{V_t^2 - \frac{X_e^2 P_e^2}{V_s^2}}\right)\right) \tag{23}
$$

where X_d is the direct axis reactance, with $X_{ds} = X_e + X_d$

5. IMPLEMENTATION AND RESULTS

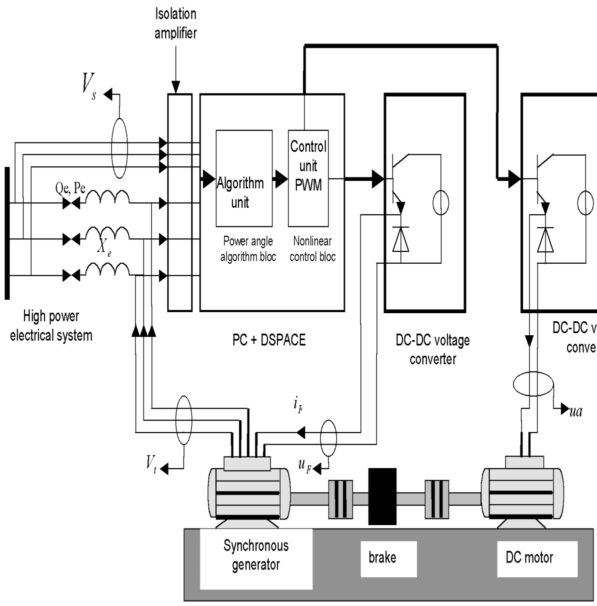

Fig. 2. Simplified representation of the power system experimental setup

This section covers experimental aspects. We consider the case of a synchronous generator connected to a large power system through a transmission line.

5.1 *Per unit constants*

In this work, the nominal values of voltage, current, power and impedance are respectively $V_N = 230$ [V], $I_N = 2.2$ [A], $S_N = 1518$ [VA] , $Z_N = 104.55[\Omega\ ]$.
We should note that, in practice all the three-currents and three-voltages values are measured, and all quantities are normalized with respect to the nominal values. This means that quantities are expressed in per unit. We calculate the instantaneous three-phases power output of the generator in terms of *d*-*q* axis.

5.2 DC motor

Synchronous generator is driven by a DC motor described by the electrical parameters such as: the voltage is $u_a = 0.956[pu]$, and the current is $i_a = 4.09[pu]$; which supplies the mechanical power. Note that the DC motor voltage is supplied by a unit converting DC voltage to DC voltage tuning. The DC motor constants are given as follows
$R_a = 0.0459[pu]$; $L_a = 0.1893[pu]$; $\tau_e = 0.0133[s]$; $\tau_{em} = 0.373[s]$; $K_m = 0.2690$

5.3 Synchronous generator

The synchronous generator is connected in a wye, and described by the electrical parameters such as: the terminal voltage is $V_t = 1[pu]$, and the electrical power is $P_e = 1[pu]$; the synchronous field current is $i_F = 0.863[pu]$ at $u_F = 0.208[pu]$. The field voltage is supplied at synchronous generator by a unit converting DC voltage to DC voltage tuning.
The synchronous generator delivers electrical power to a large power system, the three-phases transmission line has the same impedance value.
The synchronous machine and line constants are given (in per unit) as follows:
$X_d = 1.0216$; $X_d^{'} = 0.707$; $X_q = 0.613$
$X_q^{'} = 0.950$; $H = 0.197$; $K_D = 0$; $T_{d0}^{'} = 0.266[s]$
$T_{q0}^{'} = 0.044[s]$; $R_s = 0.044$; $X_e = 4.4$; $R_e = 0.1243$
The generator controller's gain is give by

$$K = \begin{bmatrix} 5.9994 & 4.7392 & -10.1081 & -10.7310 & -3.3936 \\ -4.3229 & -2.4662 & 35.4354 & 37.6049 & 19.9608 \end{bmatrix}$$

which is computed by pole position methods

5.4 Real time interface (DSPACE software)

For the software implementation we use two modules, the PC and the Digital Signal Processor (DSP) system, as it is shown in fig. 2. A synchronous machine connected to a large power system is studied using a Digital Signal Processor. The DSPACE's real-time board is installed to the PC via a bus interface. To observe the variables of a running real-time application we use a ControlDesk programm which is in the DSPACE system. MATLAB/Simulink is used for constructing control models; the C code is automatically generated by the real time workshop (RTW) in connection with DSPACE's real time interface (RTI) for the DS1103PPC Controller board (RTI1103). RTI is the interface between Simulink and the various DSPACE platforms.

5.5 Experimental results

When the generator has just been synchronized to the infinite bus, at the synchronization $\delta = 0$, the generator is rotating at synchronous speed corresponding to 50 [Hz]. In this section we present some practice results obtained when one of the three-lines is out of service after a short-circuit fault at $t = 6.4$ [s] and when the mechanical power abruptly changes at $t = 33$ [s]. We consider the operating point of the power system where $\delta = 1.02$ radians, $P_e = 0.163$ [pu] and $V_t = 1.02$ [pu]. It can be seen (figures 3-7) that nonlinear control maintains the transient stability and achieves satisfied post fault voltage level of the power system for slightly more severe fault.

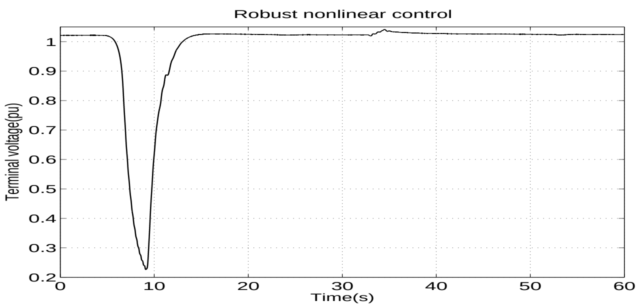

Fig. 3. Terminal voltage of the generator after a short-circuit and when the mechanical power abruptly changes.

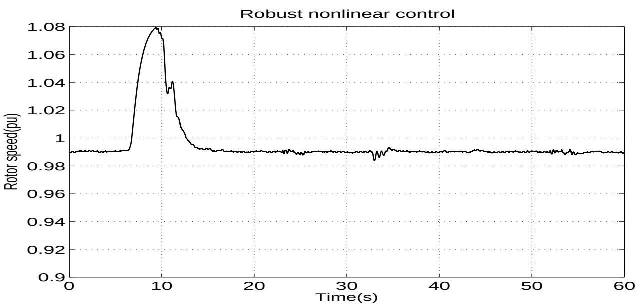

Fig. 4. Rotor speed of the generator after a short-circuit and when the mechanical power abruptly changes.

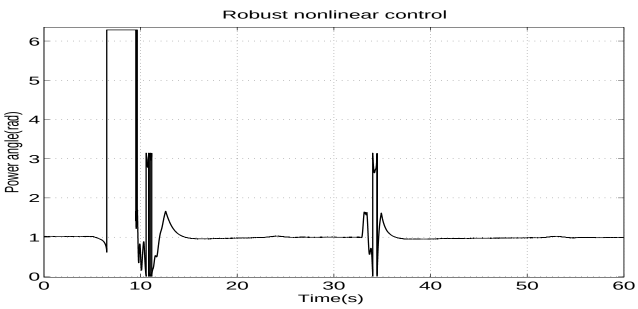

Fig. 5. Power angle after a short-circuit and when the mechanical power abruptly changes.

5.6 Transient stability and voltage regulation

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. The key question of transient

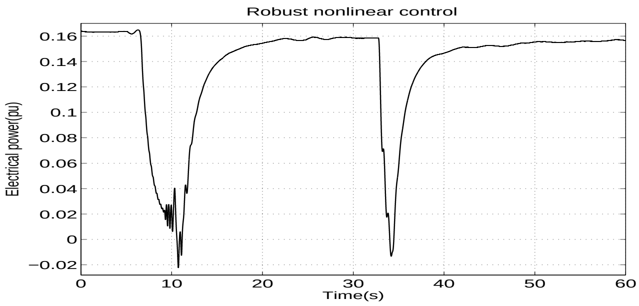

Fig. 6. Electrical power after a short-circuit and when the mechanical power abruptly changes.

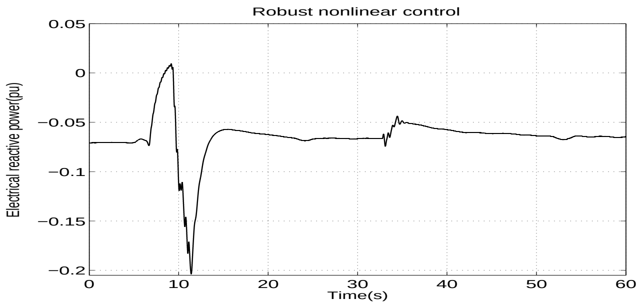

Fig. 7. Electrical reactive power after a short-circuit and when the mechanical power abruptly changes.

stability is : After the transient period, will the system lock back into a steady-state condition, maintaining synchronism ? If it does the system is said to be transient stable (Bergen, 2000).
Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. In this work, we test the system under different faults. Firstly when a sudden fault occurs close to the generator terminal at $t = 6.4$ [s]. Next, when the mechanical power P_m delivered by the DC motor abruptly changes at $t = 33$ [s]. The figures (3-7) show the following dynamics responses: the terminal voltage V_t, the speed rotor ω, the power angle δ, the electrical power P_e, the reactive electrical power Q_e
The results of the implementation shown in the figures, where all plotted quantities are given in pu, prove that the post-fault generator speed is practically equal to $\omega_s = 1$ [pu]. Then the speed deviation $\Delta\omega$ is very much smaller than ω_s; hence the system still keep transient stability as it can be seen. From the practice results, it can be observed that the controller stabilizes the disturbed system and the post-fault voltage is equal to the pre-fault value.
As it clear from the figures (8-12), the Robust Nonlinear Controller performance is compared to linear controller (AVR/PSS) performance; from dynamics time responses we can see that, the terminal voltage and the rotor speed converge to their reference values. The Robust Nonlinear Controller guarantees a good post-fault voltage regulation and controls the speed generator as well as the terminal voltage.

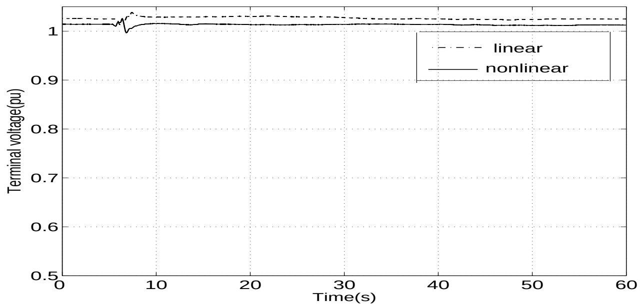

Fig. 8. Linear and nonlinear controllers; generator terminal voltage, when a large disturbance occurs

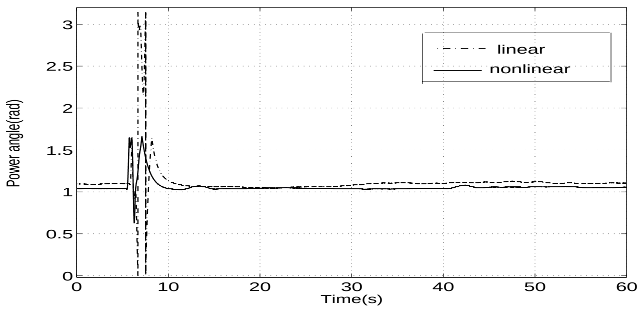

Fig. 9. Linear and nonlinear controllers; power angle, when a large disturbance occurs

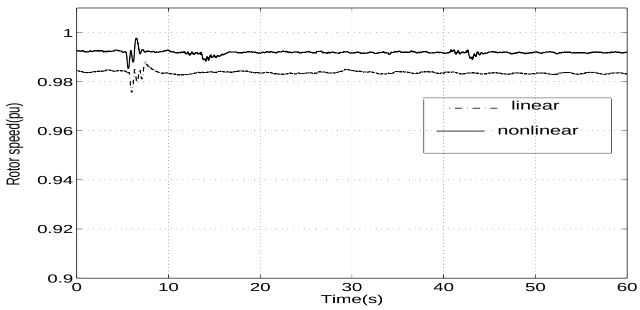

Fig. 10. Linear and nonlinear controllers; generator speed, when a large disturbance occurs

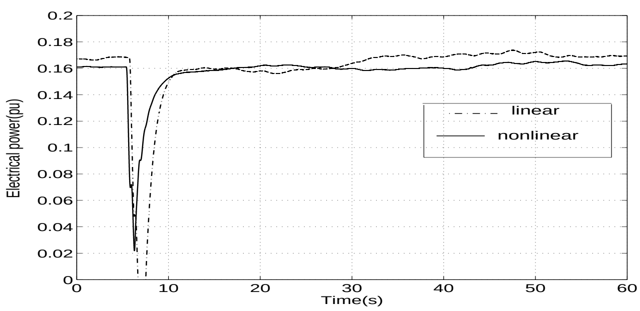

Fig. 11. Linear and nonlinear controllers; electrical power, when a large disturbance occurs

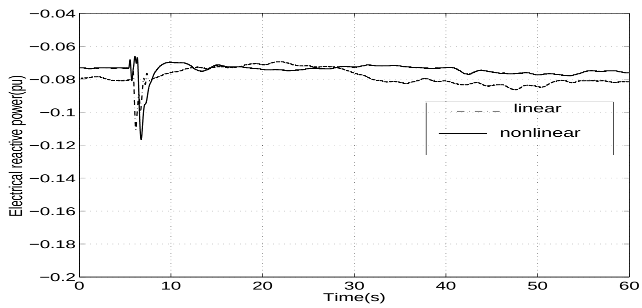

Fig. 12. Linear and nonlinear controllers; electrical reactive power, when a large disturbance occurs

6. CONCLUSION

In this paper we propose a new Robust Nonlinear Controller for a one machine connected to a large power system as an alternative solution to solve some difficult problems frequently encountered in real-time implementations of Powers systems.
First, the practical results observed by nonlinear controller show that the nonlinear control can greatly improve transient stability and achieve voltage regulation, when the transmission line reactance changes.
Second, the power angle algorithm and all of our approach is robust as it is shown in the practice results (fig.3, fig. 4, fig. 8 and fig. 9). Finally the nonlinear controllers using δ as state variable can be easily implemented.
Future work will consist in extending the application of this Robust Nonlinear Control to a multi-machine system.

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APPENDIX

$$D=(1+R_s a(t)+X_d^{'}b(t))(1+R_s a(t)+X_q^{'}b(t))+(-X_d^{'}a(t)+R_s b(t))(-X_q^{'}a(t)+R_s b(t))$$

$$D_0=-T_{q0}^{'}T_{d0}^{'}((b_0R_s-a_0X_q^{'})(a_0X_d^{'}-b_0R_s)+(1+a_0R_s+b_0X_q^{'})(1+a_0R_s+b_0X_d^{'}))$$

$$\alpha_0=\frac{(-T_{q0}^{'}(b_0R_s-a_0X_q^{'})(b_0R_s-a_0X_d)-T_{d0}^{'}(1+a_0R_s+b_0X_d^{'})(1+a_0R_s+b_0X_q))}{D_0}$$

$$\beta_0=\frac{(T_{q0}^{'}(-a_0X_q^{'}+b_0R_s)(1+a_0R_s+b_0X_d)-T_{d0}^{'}(1+a_0R_s+b_0X_d^{'})(a_0X_q-b_0R_s))}{D_0}$$

$$\sigma_0=\frac{(T_{d0}^{'}(a_0X_d^{'}-b_0R_s)(1+a_0R_s+b_0X_q)+T_{q0}^{'}(1+a_0R_s+b_0X_q^{'})(-a_0X_d+b_0R_s)}{D_0}$$

$$\gamma_0=\frac{(-T_{d0}^{'}(a_0X_d^{'}-b_0R_s)(a_0X_q-b_0R_s)-T_{q0}^{'}(1+a_0R_s+b_0X_q^{'})(1+a_0R_s+b_0X_d))}{D_0}$$

$$E_{fd}=\frac{M_F\omega_s}{\sqrt{2}r_F}u_F$$

$$V_d=\frac{(1+R_sa_0+X_d^{'}b_0)}{D}E_d^{'}-\frac{(-X_q^{'}a_0+R_sb_0)}{D}E_q^{'}$$

$$V_q=\frac{(1+R_sa_0+X_q^{'}b_0)}{D}E_q^{'}+\frac{(-X_d^{'}a_0+R_sb_0)}{D}E_d^{'}$$

$$g_{10}=\frac{-T_{q0}^{'}(-a_0X_q^{'}+b_0R_s)}{D_0}$$

$$g_{20}=T_{q0}^{'}\frac{(1+a_0R_s+b_0X_q^{'})}{D_0}$$

$$a_0=\frac{P_e}{V_t^2}$$

$$b_0=\frac{Q_e}{V_t^2}$$

L_a: DC motor inductance;
R_a: DC motor resistor;
i_a: DC motor current;
u_a: DC motor voltage;
K_m: DC motor static gain;
τ_e: DC motor electrical time constant;
τ_{em}: DC motor electrical and mechanical time constant;
I_d, I_q: direct axis and quadrature axis currents ;
V_d, V_q: direct axis and quadrature axis terminal voltages;

$$A=\begin{bmatrix}0&1&0&0&0\\0&0&0&0&0\\0&0&0&1&0\\0&0&0&0&1\\0&0&0&0&0\end{bmatrix}$$

$$B=\begin{bmatrix}0&0\\1&0\\0&0\\0&0\\0&1\end{bmatrix}$$

u_F: excitation voltage(input of the a unit converting dc voltage to dc voltage tuning of the generator);
ω_s: synchronous speed ;
ω_g: generator speed ;
ω: relative speed of generator;
δ:Power angle;
Q_e: reactive power;
P_e: active power (input of power control system);
V_s: infinite bus voltage;
E_{fd}: equivalent EMF in the excitation coil;
E_q: EMF in the quadrature axis;
$E_q^{'}$: transient EMF in the quadrature axis;
$T_{d0}^{'}$: direct axis transient open-circuit time constant (in s);
H: inertia constant (in s);
K_D: per-unit damping torque coefficient;
X_d: direct axis reactance;
X_q: quadrature axis reactance;
$X_d^{'}$: direct axis transient reactance;
$X_q^{'}$: quadrature axis transient reactance;
$X_{ds}=X_d+X_e$;
$X_{ds}^{'}=X_d^{'}+X_e$;
$E_d^{'}$:is the transient EMF in the direct axis;
$E_q^{'}$:is the transient EMF in the quadrature axis
$T_{d0}^{'}=\frac{L_F}{r_F}$:is the direct axis transient open-circuit time constant .
$T_{q0}^{'}$:is the quadrature axis transient open-circuit time constant