International Conference on Green Energy and Environmental Engineering(GEEE-2017)
International Journal of Control, Energy and Electrical Engineering - CEEE
Vol.4 pp. 55-59

Nonlinear Voltage regulation of SMIB power system

Salma KESKES[1], Nouha Bouchiba[2], Souhir SALLEEM[3], MBA KAMMOUN[4]

Research unit: Commande des Machines Electriques et Réseaux de Puissance (CMERP)
National Engineering school of Sfax, ENIS, Sfax, Tunisia
[1] salmakeskes@gmail.com
[2]bouchibanouha@gmail.com
[3] souhirsallem@gmail.com
[5] mbakammoun@gmail.com

Abstract— **In this paper, in order to improve the stability and the voltage regulation of a single machine infinite bus, a nonlinear voltage controller is proposed. The dynamical model of the studied system is presented and the design of the nonlinear controller which is based on the stability condition of Lyapunov function is described. In order to evaluate different performances of the studied controller, a comparison with the conventional automatic Voltage regulation AVR +PSS is made in this paper. In this context, in order to simulate the performance of the proposed controller, a symmetrical three phase short circuit fault is applied in one of transmission line of SMIB power system. Simulation results show that the proposed controller can achieve both of the system stability enhancement and voltage regulation and gives better dynamic performance and robustness than the conventional regulators (AVR/PSS).**

Keywords— SMIB power system, Nonlinear voltage controller, Lyapunov stability, AVR, PSS.

I. INTRODUCTION

Voltage quality is a very important index of power supply in power system operation. In fact, signal stability problems have been reported in power systems since the middle of the last century. The operation of electrical equipment at outside allowable range voltages can easily affect the equipment performances and can cause sometimes the total destruction of the system.

In the SMIB power system, the excitation system is considered the most important means of voltage control. The main role of this system is to maintain the generator terminal voltage constant under normal operating conditions and to regulate it quickly and effectively when a sudden fault is applied to the system.

This issue has sparked a number of recent investigations in the few past decades. In fact, additional control loops are required to prevent harmful voltage effects to the system operation.

The most commonly used type of controller is known as the automatic voltage regulator (AVR) to maintain the terminal voltage of the synchronous machine and the power system stabilizer (PSS) to enhance damping oscillations [1,2].

The AVR/ PSS regulator is considered as a conventionnel regulator system.

For the problem of stability enhancement and voltage regulation, many researches are found in the literature.

In [3], a nonlinear power system stabilizer is designed based on synergetic control theory.

In [4], a global controller based on fuzzy control is designed in order to maintain the transient stability and achieve satisfactory post-fault voltage level of synchronous generator in SMIB power system when subjected to a severe disturbance.

In [2, 5, 6], voltage regulation was achieved by introducing voltage feedback. However, the voltage controllers are only effective around an operation point, i.e., when a small disturbance occurs, but cannot survive a large disturbance.

The stability of SMIB power system is analysed by using the Lyapunov’s direct method is proposed in [9]. Lyapunov's function based stability analysis of power system was introduced in 1980’s [7, 8].

In this paper, a nonlinear voltage regulator is proposed based on Lyapunov control theory. The main idea of this proposed controller is to regulate the terminal voltage of the generator and maintain it constant under the effects of a symmetrical three phase short circuit fault.

The remainder of this paper is organized as follows. Section 2 presents the power system modelling.

The controller synthesis is detailed in section 3 of this paper which include the design of the conventional regulator AVR/PSS and the proposed nonlinear voltage regulator designing. In section 4, simulation results are presented, discussed and compared. Finally, conclusions are presented in Section 5.

II. DYNAMIC MODEL DESCRIPTION OF POWER SYSTEM

The single-machine-infinite-bus (SMIB) power system is considered in this study. This model consists of a single synchronous generator connected through two parallel transmission lines to a very large network approximated by an infinite bus. The model is shown in Fig.1.

ISSN 2356-5608

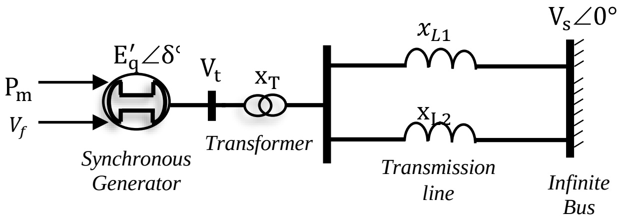

Figure 1. Single-machine infinite-bus power system

The dynamics of the single-machine infinite-bus power system are given by the following third-order model (Eq.1) [11,12].

This model is widely used in literature for the design of the excitation controllers [12,13] because it presents a simplification of the real generator model.

$$\begin{cases} \dot{\delta} = \omega \\ \dot{\omega} = -\frac{D}{H}\omega + \frac{\omega_s}{H}\left(P_m - P_e\right) \\ \dot{E}'_q = \frac{1}{T'_{d0}}\left(E_f - E_q\right) \end{cases} \qquad (1)$$

The active electrical power equation is given by (Eq.2).

$$P_e(t) = \frac{V_s E_q}{x_{ds}} \sin\delta(t) \qquad (2)$$

The EMF in the quadrature axis is given by (Eq.3).

$$E_q\,(t) = \frac{x_{ds}}{x'_{ds}} E'_q\,(t) - \frac{x'_d - x_d}{x'_{ds}} V_s \cos\delta(t) \quad (3)$$

Where:

δ is the power angle of the generator;

ω_s is the synchronous machine speed;

ω is the relative rotor speed of the generator ($\omega = \omega_g - \omega_s$ with ω_g being the generator angular speed);

H is the inertia constant; D is the damping constant;

$x_{ds} = x_d + x_T + x_L$: is the total reactance which takes into account x_d, the generator direct axis reactance;

$x'_{ds} = x'_d + x_T + x_L$: is the total reactance which takes into account x'_d, the direct axis transient reactance of the generator,

$x_L = \frac{x_{L1}x_2}{x_{L1}+x_{L2}}$ the transmission line reactance,

x_T the reactance of the transformer;

$E_f = k_c u_f$ the equivalent EMF in the excitation coil of the generator; k_c is the gain of the excitation amplifier;

u_f is the input to the SCR amplifier of the generator;

T'_{d0} is the direct axis transient open-circuit time-constant;

V_s is the infinite bus voltage;

P_e is the active electrical power;

P_m is the mechanical power input.

The generator terminal voltage expression is given by (Eq.4) [16]:

$$V_t = \frac{1}{x_{ds}}\sqrt{x_s^2 E_q^2 + V_s{}^2 x_d^2 + 2x_s x_d V_s E_q \cos\delta} \qquad (4)$$

where $x_s = x_T + x_L$ is the total line reactance which takes into account x_T.

III. CONTROLLER SYNTHESIS

In this section, two types of controllers are analysed and presented in order to regulate the terminal voltage of SMIB after a sudden fault which can causes variation in the electrical network.

A. *Conventional regulator AVR/PSS*

The Automatic Voltage Regulator (AVR) measures the terminal voltage of the synchronous generator V_t and compares it to a reference setting value V_{t-ref}.

The role of voltage regulators (AVR) is used to improve steady-state stability performance and remains limited to ensure transient stability. Therefore, the torque added by the AVR on the shaft of the machine is insufficient to damp the various oscillations in the power system. For this purpose, the power system stabilizer (PSS) was introduced into excitation control to overcome the problem.

The (PSS) is a device that improve power system stability when it is added to the automatic voltage regulator (AVR) of generator.

It is quite common nowadays to have a combination of an AVR and a PSS for excitation control of synchronous generators in SMIB power system.

The stabilization signal, V_{pss}, is superimposed on that of the AVR as shown in Figure 2.

The structure of the conventional regulator is shown in fig.2.

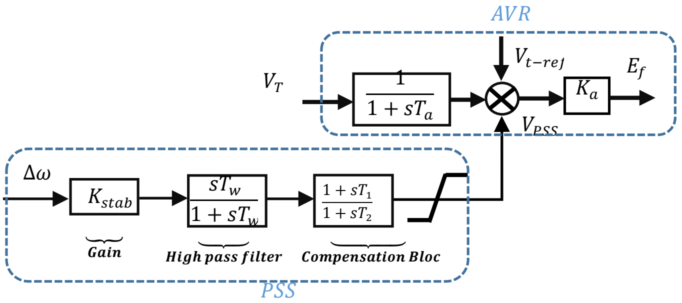

Figure 2. Structure of the conventional regulators AVR/PSS

B. *The proposed nonlinear voltage regulator design*

In this section, a nonlinear control approach based on Lyapunov stability condition is developed with the aim of replacing conventional AVR with a more robust one.

Starting from (Eq.4), its time derivative gives the dynamic of the generator terminal voltage as follows (Eq.5):

ISSN 2356-5608

$$\dot{V}_t = \frac{x_x^2 E_q + x_s x_d V_s \cos\delta}{x_{ds}^2 V_t}\left\{-\frac{x_{ds}}{T'_{d0} x'_{ds}} E_q + \frac{(x_d - x'_d)}{x'_{ds}}\, V_s\, \omega\, sin\delta + \frac{k_c}{T'_{d0}} \frac{x_{ds}}{x'_{ds}} u_f\right\} - \frac{x_s x_d V_s E_q \omega\, sin\delta}{x_{ds}^2 V_t} \tag{5}$$

Replacing the EMF in the quadrature axis E_q by its expression as a function of the active electrical power extracted from the (Eq.2), the dynamic of the generator voltage is expressed as (Eq.6):

$$\dot{V}_t = \frac{1}{x_{ds} V_t}\left(\frac{x_x^2}{V_s\, sin\delta} P_e + \frac{x_s x_d V_s \cos\delta}{x_{ds}}\right)\left(\frac{x_{ds}}{T'\, V_s\, sin\delta} P_e + \frac{(x_d - x'_d)}{x'_{ds}}\, V_s\, \omega\, sin\delta + \frac{k_c}{T'} u_f\right) - \frac{x_s x_d}{x_{ds} V_t} \omega P_e \tag{6}$$

In the following, V_t is considered as state variable. In fact, Eq.6 replaces the first equation of the SMIB model (Eq.1) to express an equivalent model with the measurable state vector (V_t, ω, P_e).

A high non-linearity is observed in this equation, which requires a non-linear control such as the Lyapunov technique.

As a first step, an error variable of the voltage regulation is chosen as following (Eq.7).

$$z = V_t - V_{tref} \tag{7}$$

Where V_{tref} is the reference value of the generator voltage.

Using Eq.6 and Eq.7 the time derivative of the error variable z will be expressed as (Eq.8):

$$\dot{z} = \frac{1}{x_{ds} V_t}\left(\frac{x_x^2}{V_s\, sin\delta} P_e + \frac{x_s x_d V_s \cos\delta}{x_{ds}}\right)\left(\frac{x_{ds}}{T'\, V_s\, sin\delta} P_e + \frac{(x_d - x'_d)}{x'_{ds}}\, V_s\, \omega\, sin\delta + \frac{k_c}{T'} u_f\right) - \frac{x_s x_d}{x_{ds} V_t} \omega P_e - \dot{V}_{tref} \tag{8}$$

The objective of the controller is to find the control signal that converges the error variable z to zero. Therefore, the Lyapunov function will be chosen by (Eq.9).

$$V = \frac{1}{2} z^2 \tag{9}$$

Using the equations (Eq.8) and (Eq.9), the time derivative of the Lyapunov function V can be written as (Eq.10).

$$\begin{aligned}\dot{V} &= z\dot{z} \\ &= z\left\{\frac{1}{x_{ds} V_t}\left(\frac{x_s^2}{V_s\, sin\delta} P_e + \frac{x_s x_d V_s \cos\delta}{x_{ds}}\right)\left(\frac{x_{ds}}{T'\, V_s\, sin\delta} P_e + \frac{(x_d - x'_d)}{x'_{ds}}\, V_s\, \omega\, sin\delta + \frac{k_c}{T'} u_f\right) - \frac{x_s x_d}{x_{ds} V_t} \omega P_e - \dot{V}_{tref}\right\}\end{aligned} \tag{10}$$

Based on the stability theory of Lyapunov, the time derivative of the Lyapunov function $\dot{V}$ should be a definite negative function as given in (Eq.11).

$$\dot{V} = -Kz^2 \tag{11}$$

Where K is a positive constant.

Consequently, the control law will be calculated basing on (Eq.12).

$$u_f = \frac{T'}{k_c} V_t\left(-Kz + \dot{V}_{tref} + \frac{x_s x_d}{x_{ds} V_t} \omega P_e\right)\left(\frac{x_{ds}^2 V_s \sin\delta}{x_s^2 x_{ds} P_e + x_s x_d V_s^2 \sin\delta\cos\delta}\right) + \frac{x_{ds}}{k_c\, V_s\, sin\delta} P_e - \frac{(x_d - x'_d)}{k_c x'_{ds}} T'\, V_s\, \omega\, sin\delta \tag{12}$$

IV. SIMULATION RESULTS AND DISCUSSION

The overall model of the studied system with different control designs was simulated in Matlab/ Simulink environment.

Different simulation parameters are given in appendix.

To show the efficiency of the proposed nonlinear voltage regulator, a fault is applied on the SMIB power system.

The fault considered in this paper is a symmetrical three phase short circuit which occurs on one of the transmission lines.

The following fault sequences are simulated as follows:

Stage 1: The system is in a pre-fault steady-state.

Stage 2: A three phase short circuit occurs in one of the three transmission lines occurs at t = 0.1s.

Stage 3: The fault is removed by opening the breaker of the faulted line at t = 0.2s.

Stage 4*:* The system is in a post-fault state.

Fig.3, Fig.4, Fig.5, Fig.6 and Fig.7 clearly demonstrate the simulation results which shows the effect of the behaviour of different SMIB model variables considered with AVR/PSS and with the proposed controller.

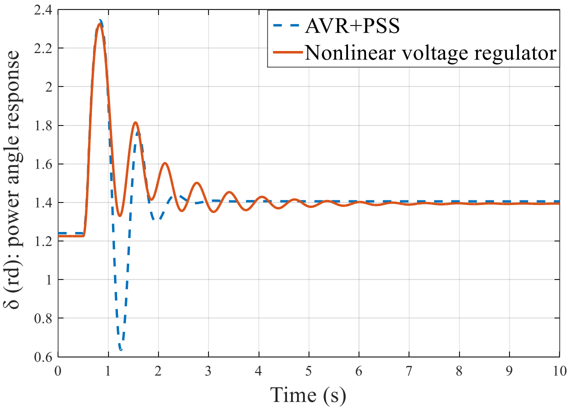

Figure 3. Responses of power angle

ISSN 2356-5608

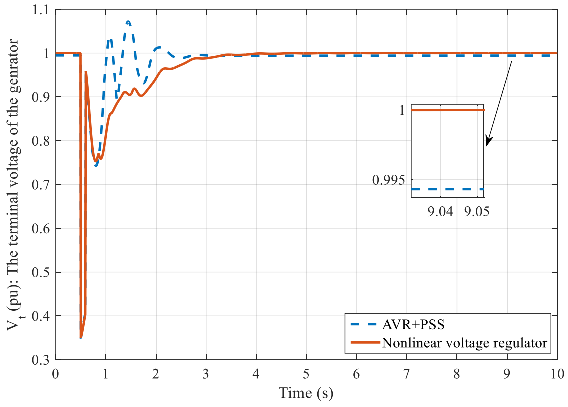

Figure 4. Responses of generator terminal voltage

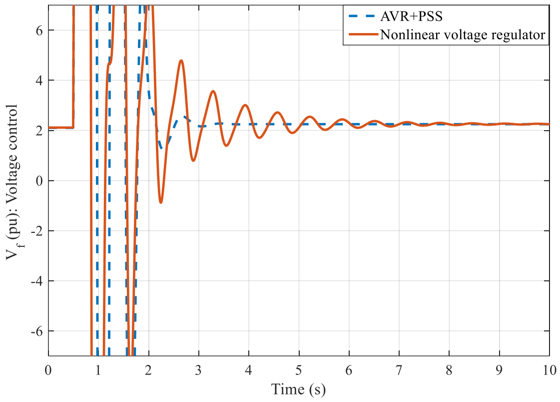

Figure 5. Responses of voltage control

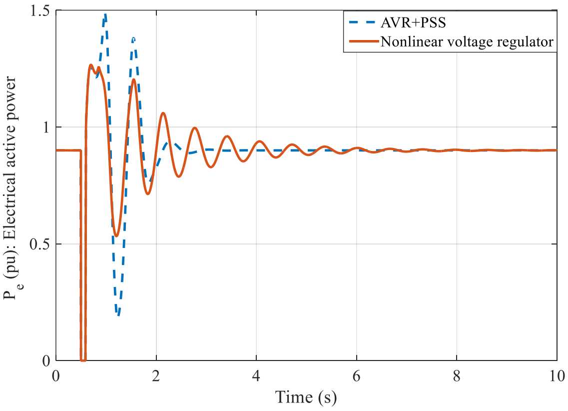

Figure 6. Responses of electrical active power

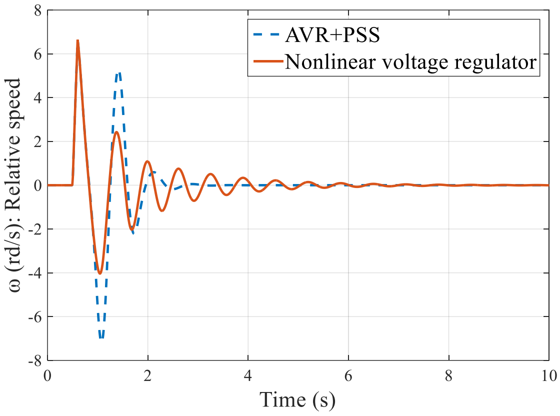

Figure 7. Responses of the rotor relative speed

It is obviously seen that the system is stable ($\delta < \frac{\pi}{2}$) as shown in Fig. 3. We can clearly remark that the rotor angle does not return to its initial value, due to the variation of the line impedance after the fault.

With the proposed nonlinear voltage controller, we note that the terminal voltage of the generator converges to the network voltage value after the fault elimination (fig.4) ($V_t = V_s = 1pu$) and even in the case of persistence of the permanent fault (parametric variation at the line reactance level x_l).

This is due to the high performance of the regulation and the robustness of the non-linear applied controller which allows a better control even in transient phase.

V. CONCLUSION

In this paper, a nonlinear voltage controller is proposed for single machine-infinite bus power systems in order to achieve both voltage regulation and system stability enhancement. Two different control strategies have been implemented. To obtain better performances then the conventional regulator AVR+PSS controller, a nonlinear voltage regulator based on the Lyapunov function has been used. Analysis and simulation results have been presented to demonstrate the effectiveness of Nonlinear voltage regulator.

ACKNOWLEDGMENT

Authors of this work would like to thank University of Sfax, TUNISIA and especially the research unit CMERP for providing the facilities and research grant to achieve this research and great thanks to the reviewers for their valuable comments

APPENDIX

Generator parameters:

Synchronous speed:	$\omega_0 = 314.159\ rd/s$
Damping constant:	$D = 5$
Inertia constant:	$H = 4$
Direct axis transient open circuit time constant:	$T'_{d0} = 6.9$
Generator direct axis reactance:	$x_d = 1.863$
Generator direct axis transient reactance:	$x'_d = 0.257$
Transmission line reactance:	$x_L = \frac{x_{L1}x_2}{x_{L1}+x_{L2}}, x_{L1} = 0.4853\ ; x_{L2} = 0.4853$
Transformer reactance:	$x_T = 0.127$

Excitation system parameters:

AVR	$K_a = 200$	$T_a = 0.15;$	$E_{fmax} = 7pu$	$E_{fmin} = -7pu$	$k_c = 1$
PSS	$T_1 = 0.154$	$T_2 = 0.154$	$T_w = 3$	$K_{stab} = 9.5$	

Network parameters:

$V_s = 1pu$	$f_0 = 50Hz$

REFERENCES

[1] H. Wang and W. Du , 'A Single-Machine Infinite-Bus Power System Installed with a Power System Stabilizer' Springer Science+Business Media New York 2016 , Power Electronics and Power Systems, DOI 10.1007/978-1-4899-7696-3_2

[2] C Zhu, R Zhou and YWang 'A new nonlinear voltage controller for power systems' Electrical Power & Energy Systems, Vol. 19, No. 1, pp. 19-27, 1997.

[3] Z. Jiang 'Design of a nonlinear power system stabilizer using synergetic control theory' Electric Power Systems Research, 79 (2009) 855–862

[4] Yi Guo, , David J. Hill, and Youyi Wang, 'Global Transient Stability and Voltage Regulation for Power Systems' IEEE transactions of power systems, Vol. 16, NO. 4, Novembre 2001.

[5] Youyi Wang, David J. Hill, Richard H. Middleton 'Transient stability enhancement and voltage regulation of power systems' IEEE Transactions on Power Systems, Vol. 8, No. 2, May 1993

[6] LONG GAO,~§ LIN CHEN, YUSHUN FAN and HAIWU Mal 'A Nonlinear Control Design for Power Systems' Automatica, Vol. 28, No. 5. pp. 975-979, 1992

[7] M. A. Pai, Energy Function Analysis for Power System Stability. MA: Kluwer Norwell, 1989.

[8] H. D. Chiang, et al. "Chaos in a simple power system," IEEE Trans. on Power Systems, vol. 8, no. 4, pp. 1407-1417, November, 1993.

[9] A. Cifci, Y. Uyaroglu, and A.T. Hocaoglu, "Voltage stability analysis using the variable gradient method," Int. Review of Electr. Engg., vol. 6,pp. 914-921, 2011.

[10] Anderson PM, Fouad AA. Power system control and stability. NJ: IEEE Press; 1994

[11] Arjona MA, Escarela-Perez R, Espinosa-Perez G, Alvarez-Ramirez J. Validity testing of third-order nonlinear models for synchronous generators. Electr Power Syst Res 2009;79:953–8

[12] G. Kenné, R. Goma, H. Nkwawo and J. C. Vannier, 'Real-time transient stabilization and voltage regulation of power generators with unknown mechanical power input' Energy Conversion and Management 51 (2010) 218–224.

[13] R. Benayache, W. Bahloul, L. Chrifi-Alaoui, P . Bussy and M. B. A. Kamoun, 'Transient stability of power systems using robust nonlinear secondorder sliding mode controller', American Control Conference, 2010.