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A backstepping-like nonlinear controller design for power systems with SMES

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Abstract

The design of a backstepping-like control method applying on an electrical system is a main focus of this work. The proposed method is able to improve dynamic responses of the power system with SMES in terms of transient stability and performance. The power system considered in this work is contained with the following elements: (i) generator excitation, and (ii) super-conducting magnetic energy system (SMES). In order to gain the desired stability under the effect of the large or small disturbances, the backstepping-like control is synthesized to stabilize the power system. Considering the design procedure of the backstepping-like control method, it is clear that the developed design of the method is simpler than that of an advanced control method such as an immersion and invariance (I&I) control method. However, the method can provide the acceptable effectiveness for the control system. Illustration for the performance of the designed backstepping-like controller can be shown via the simulation. The controller is employed for stabilizing a single-machine infinite bus (SMIB) power system with SMES. It is clear that the presented controller can provide the desired characteristics including transient stability and the post-fault dynamic performance of the terminal voltage. Moreover, compared with I&I and the classical backstepping methods, using the backstepping-like method can achieve the desired performance of the considered power system with a simpler design procedure.

Keywords: *backstepping-like control, nonlinear control, nonlinear system, SMES, transient stability*

บทคัดย่อ

บทความนี้เกี่ยวกับการออกแบบตัวควบคุมที่ไม่เป็นเชิงเส้นที่เหมือนแบบแบคสเตปปิ้ง (backstepping-like nonlinear controller) สำหรับระบบไฟฟ้ากำลังเพื่อปรับปรุงเสถียรภาพชั่วครู่ (transient stability) และบรรลุถึงสมรรถนะผลตอบสนองชั่วครู่ที่ต้องการ ระบบประกอบด้วยการกระตุ้นของเครื่องกำเนิดไฟฟ้าซิงโครนัส (generator excitation) และระบบสะสมพลังงานแม่เหล็กที่มีสภาพตัวนำยิ่งยวด (SMES) ในวิธีการที่นำเสนอนี้เราได้รับกฎการควบคุมและสามารถบรรลุการปรับปรุงเสถียรภาพระบบกำลังเมื่อมีสัญญาณรบกวนขนาดใหญ่เกิดขึ้นในระบบ วิธีการที่ถูกพัฒนาขึ้นค่อนข้างง่ายแต่มีประสิทธิภาพเมื่อเปรียบเทียบกับวิธีการควบคุมแบบการฝังในและมีความยืนยง (immersion and invariance control technique) และวิธีการควบคุมแบบแบคสเต็ปปิ้ง (backstepping control technique) ผลการจำลองระบบได้ถูกดำเนินการขึ้นสำหรับระบบไฟฟ้าที่มีเครื่องจักรเดียวที่เชื่อมต่อกับบัสอนันต์ซึ่งประกอบด้วยระบบสะสมพลังงานแม่เหล็กที่มีสภาพตัวนำยิ่งยวด นอกจากนี้ ผลจำลองชี้ให้เห็นว่าวิธีการที่นำเสนอนี้สามารถบรรลุการปรับปรุงเสถียรภาพชั่วครู่และสมรรถนะหลังการเกิดผิดพร่องของแรงดันได้ ยิ่งไปกว่านั้นแม้ว่ามีกระบวนการออกแบบที่เรียบง่าย ผลตอบสนองเชิงเวลาของการควบคุมที่นำเสนอคล้ายอย่างมากกับผลของการควบคุมแบบการฝังในและมีความยืนยงทั้งยังให้ผลที่ดีกว่าการควบคุมแบบแบคสเต็ปปิ้งอย่างชัดเจน

คำสำคัญ*: การควบคุมที่เหมือนแบบแบคสเตปปิ้ง, การควบคุมที่ไม่เป็นเชิงเส้น, ระบบที่ไม่เป็นเชิงเส้น, ระบบสะสมพลังงานแม่เหล็กที่มีสภาพตัวนำยิ่งยวด, เสถียรภาพชั่วครู่*

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1. Introduction

The challenge in the power system control and operations arises from the increased size and complexity of the system. Thus, it becomes an important area of study in control problem. In particular, the goal of power system control is to maintain the transient stability under the disturbances. Thus, the generator excitation control can be generally utilized for this purpose. Furthermore, improvement of transient stability and dynamic performance over excitation control can be achieved by using energy storage which is becoming an important and promising device. Several researches involving the energy storage based on super conducting magnetic energy storage (SMES) have been presented, for example, flywheel energy storage system (FESS), and battery storage system (BESS) (for example: Ali, Wu, & Dougal, 2010; Kim, Song, & Yoon, 2015; Lu, Liu, & Wu, 1995; Ribeiro, Johnson, Crow, Arsoy, & Liu, 2000; Wan & Zhou, 2013; Wang, Feng, Chen, & Liu, 2006). Additionally, they have demonstrated the feasibility of using the energy storage to improve the transient stability and damping power system oscillation. As a result, the use of energy storage devices has recently attracted considerable attention to further enhance power transfer capability and augment both small-signal and transient stability power systems. In order to enhance stability, the energy storage system (Ali, 2012) has been employed to enhance frequency stability through the regulation of active power levels. Therefore, energy storage can be employed to reduce the power fluctuations from large wind farms, to deliver a large quantity of energy in a short time period when needed. Also, the betterment of the economics of wind farms can be achieved, since the active power output is regulated by using this device. One of energy storage technologies is the superconducting magnetic energy storage (SMES) which is interested in this study, because it can inject or absorb active and reactive power, simultaneously. Using SMES can increase grid transfer capability through enhanced dynamic voltage stability, provide smooth and rapid reactive power compensation for voltage support, and enhance both damping power oscillations and transient stability (Ali et al., 2010).

To the best of our knowledge, the study about the control of power system containing the coordination of generator excitation and SMES has been presented in a small number of researches. The development of a nonlinear adaptive excitation and a thyristor-controlled superconducting magnetic energy storage (SMES) controllers were presented to improve the transient stability of the power system, when the system is affected by unknown or varying parameters such as equivalent reactance of transmission lines (Tan & Wang, 1998). According to the result of Tan and Wang (2004), a robust nonlinear excitation and SMES controller were developed for a single-machine infinite bus (SMIB) system to improve the transient stability when a large sudden fault appears in the system. In order to gain the transient stability enhancement for power systems together with evaluation with experimental results, the feedback linearization and linear H_∞ controller were applied to the SME unit as reported in (Liu et al., 2004). With the help of a Hamiltonian function control strategy to enhance the system stability facing with disturbances and unknown parameters, Li and Wang (2007) proposed a robust adaptive control method of synchronous generators with SMES. Wang et al., 2006, presented an adaptive L_2 disturbance attenuation control of synchronous generators with SMES unit for multi-machine power systems based on the Hamiltonian function method. According to Wan and Zhao (2013), an extended backstepping strategy was designed for the generator excitation and SMES controller to stabilize the power angle, the generator terminal voltage, and the power oscillation along with improvement of the transient and steady-state performances. Very recently, Kanchanaharuthai, Chankong, and Loparo (2015) has proposed a design of an immersion and invariance (I&I) controller for improving the transient stability of the control system.

This paper continues this line of investigation and further investigates our previous work reported in Kanchanaharuthai et al. (2015). From our previous work, I&I controller relies upon selecting a target dynamical system capturing the desired behavior of the feedback system to be controlled. Besides, the designed control law has indicated that the feedback system behaves asymptotically the same as the pre-specified target system. Even though the I&I control methodology is much effective and applicable to practical control design problems for various types of systems (Astolfi, Karagiannis, & Oreta, 2008; Astolfi & Oreta, 2003; Kanchanaharuthai, 2014a; Kanchanaharuthai, 2014b; Kanchanaharuthai, 2014c; Kanchanaharuthai et al., 2015; Kanchanaharuthai, 2016a; Kanchanaharuthai, 2016b; Manjarekar & Banavar, 2012). However, the above-mentioned method has many significant difficulties once employed to determine the desired nonlinear controller. The difficulties of the method are as follows: (1) how the mapping from the algebraic equation is found; (2) how the suitable target dynamics capturing the desired dynamics of the feedback system to be controlled is selected; and (3) how the appropriate Lyapunov (energy function) is chosen. In addition, despite the extended backstepping method (Wan & Zhao,

2013) used effectively for nonlinear systems with the non-strict feedback form, it leads to the unavoidable complexity in the desired nonlinear control design. Although, the design methods mentioned above are capable of stabilizing the closed-loop system, these methods lead to significant drawbacks of this method and provide rather complicated controller design. Therefore, in order to overcome difficulties, this paper proposes a nonlinear controller via a backstepping-like procedure as reported in (Luo, 2015; Kanchanaharuthai & Boonyaprapasorn, 2016). This obtained controller is considerably simpler and more effective than the I&I one. With the help of this scheme, the power angle stability together with frequency and voltage regulation can be achieved. Moreover, the controlled system is stabilized simultaneously. The simulation results of the SMIB power system with generator excitation control and SMES control are provided.

The rest of this paper is organized as follows. A simplified mathematical model representing an SMIB power system with generator excitation and SMES is briefly described in Section 2. The nonlinear controller design is given in Section 3. Simulation results are presented in Section 4. Lastly, a conclusion is stated in Section 5.

2. Power system model

According to the results presented in Kanchanaharuthai et al., (2015), we have dynamic models of a SMIB system consisting of generator excitation control of SG and SMES control as follows:

$$\begin{aligned}
\dot{\delta} &= \omega-\omega_s,\\
\dot{\omega} &= \frac{1}{M}\left(P_m-P_e-P_d-P_q-D(\omega-\omega_s)\right),\\
\dot{P}_e &= (-a+(\omega-\omega_s)\cot\delta)P_e+\frac{bV_\infty\sin 2\delta}{2X'_{d\Sigma}}\\
&\quad +\frac{V_\infty\sin\delta}{X'_{d\Sigma}}\cdot\frac{u_f}{T'_0},\\
\dot{P}_d &= \frac{P_d}{P_e}\dot{P}_e+\frac{P_eX_2\cot\delta}{V_\infty}\cdot\frac{1}{T_d}\left(-\left(\frac{P_dV_\infty}{P_eX_2\cot\delta}-I_{de}\right)+u_d\right)\\
&\quad +\frac{I_dP_eX_2}{V_\infty}(\cot^2\delta+1)(\omega-\omega_s),\\
\dot{P}_q &= \frac{P_q}{P_e}\dot{P}_e+\frac{P_eX_2}{V_\infty}\cdot\frac{1}{T_q}\left(-\left(\frac{P_qV_\infty}{P_eX_2}-I_{qe}\right)+u_q\right),
\end{aligned} \tag{1}$$

where $a=\dfrac{X_{d\Sigma}}{X'_{d\Sigma}T'_0}, b=\dfrac{X_d-X'_d}{X'_{d\Sigma}T'_0}V_\infty$.

Consider the dynamic equations of a power system with generator excitation and SMES in (1). To facilitate the control design, let us introduce the state variable

$$\begin{aligned}
x &= \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \end{bmatrix}^T\\
&= \begin{bmatrix} \delta-\delta_e & \omega-\omega_s & P_e & P_d & P_q \end{bmatrix}^T.
\end{aligned}$$

Then the dynamic model of the power system considered is written into an affine nonlinear system as follows:

$$\dot{x} = f(x)+g(x)u(x) \tag{2}$$

where $f(x), g(x)$ and $u(x)$ are given in Kanchanaharuthai et al. (2015).

For notational convenience, the system (6) can be rewritten follows:

$$\begin{aligned}
\dot{x}_1 &= x_2,\\
\dot{x}_2 &= \frac{1}{M}\left(P_m-Dx_2-x_3-x_4-x_5\right),\\
\dot{x}_3 &= f_3(x)+g_{31}(x)\frac{u_f}{T'_0},\\
\dot{x}_4 &= f_4(x)+g_{41}(x)\frac{u_f}{T'_0}+g_{42}(x)\frac{u_d}{T_d},\\
\dot{x}_5 &= f_5(x)+g_{51}(x)\frac{u_f}{T'_0}+g_{53}(x)\frac{u_q}{T_q},
\end{aligned} \tag{3}$$

The aim of this paper is to solve the problem of the transient stabilization of the system (3) to design a coordinated stabilizing (state) feedback nonlinear controller u such that the corresponding closed-loop system is asymptotically stable at the only equilibrium (x_e) and $x\to x_e$ as $t\to\infty$.

3. Nonlinear controller design

For the purpose of designing a nonlinear controller such that $\lim_{t\to+\infty} x_i = 0, (i = 1, 2, 4, 5)$ and $\lim_{t\to+\infty} x_3 = P_m$ a Lyapunov function candidate is selected as follows:

$$V_1 = \frac{1}{2}x_1^2 \tag{4}$$

Then the time derivative of (4) along the system trajectory (3) becomes

$$\dot{V}_1 = x_1x_2 = -c_1x_1^2 + x_1\left(c_1x_1 + x_2\right), \tag{5}$$

where $c_1 > 0.$ From (5), it is evident that the second term $x_1(c_1x_1 + x_2)$ is not always negative; thus, this term should be eliminated from the aforementioned equation. In order to do this, we choose the Lyapunov function candidate as:

$$V_2 = \frac{1}{2}x_1^2 + \frac{1}{2}\left(c_1x_1 + x_2\right)^2 \tag{6}$$

Computing the time derivative of (6) and considering (3) yield

$$\begin{aligned}\dot{V}_2 &= -c_1x_1^2 + x_1\left(c_1x_1 + x_2\right) + \left(c_1x_1 + x_2\right)\left(c_1\dot{x}_1 + \dot{x}_2\right)\\ &= -c_1x_1^2 + \left(c_1x_1 + x_2\right)\left(x_1 + c_1x_2 + \dot{x}_2\right)\\ &= -c_1x_1^2 - \left(c_1x_1 + x_2\right)^2 + \left(c_1x_1 + x_2\right)\\ &\quad\times\left((c_1+1)(x_1+x_2) + \frac{1}{M}\left(P_m - Dx_2 - x_3 - x_4 - x_5\right)\right)\end{aligned} \tag{7}$$

It is seen that the third term of (7) is not always negative. Therefore, this term should be cancelled. To this end, we introduce the following terms into V_2 and then obtain

$$V_2 = \frac{1}{2}x_1^2 + \frac{1}{2}\left(c_1x_1 + x_2\right)^2 + \frac{1}{2}P^2 + \frac{1}{2}Q^2 + \frac{1}{2}R^2 \tag{8}$$

where

$$\begin{aligned}P &= \left[(c_1+1)\frac{x_1}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{x_2}{3} + \frac{\left(P_m - x_3\right)}{M}\right],\\ Q &= \left[(c_1+1)\frac{x_1}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{x_2}{3} - \frac{x_4}{M}\right],\\ R &= \left[(c_1+1)\frac{x_1}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{x_2}{3} - \frac{x_5}{M}\right].\end{aligned} \tag{9}$$

By calculating the derivative of (8) along the system trajectory, one obtains

$$\begin{aligned}\dot{V}_3 &= -c_1x_1^2 - \left(c_1x_1 + x_2\right)^2 + P\dot{P} + Q\dot{Q} + R\dot{R}\\ &= -c_1x_1^2 - \left(c_1x_1 + x_2\right)^2 - c_2P^2 - c_3Q^2 - c_3R^2\\ &\quad + P\left[\tilde{P} - \frac{\dot{x}_3}{M}\right] + Q\left[\tilde{Q} - \frac{\dot{x}_4}{M}\right] + R\left[\tilde{R} - \frac{\dot{x}_5}{M}\right]\end{aligned} \tag{10}$$

with

$$\begin{aligned}\tilde{P} &= c_2P + c_1x_1 + x_2 + (c_1+1)\frac{x_2}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{\dot{x}_2}{3}\\ \tilde{Q} &= c_3Q + c_1x_1 + x_2 + (c_1+1)\frac{x_2}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{\dot{x}_2}{3}\\ \tilde{R} &= c_4R + c_1x_1 + x_2 + (c_1+1)\frac{x_2}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{\dot{x}_2}{3}\end{aligned} \tag{11}$$

where $c_i > 0, (i = 1, 2, 3, 4)$ are positive design parameters. After substituting $\dot{x}_3, \dot{x}_4, \dot{x}_5$ into (11), we have

$$\begin{aligned}\dot{V}_3 &= -c_1x_1^2 - \left(c_1x_1 + x_2\right)^2 - c_2P^2 - c_3Q^2 - c_3R^2\\ &\quad + P\left[\tilde{P} - \frac{1}{M}\left(f_3(x) + g_{31}(x)\frac{u_f}{T_0'}\right)\right]\\ &\quad + Q\left[\tilde{Q} - \frac{1}{M}\left(f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_d}{T_d}\right)\right]\\ &\quad + R\left[\tilde{R} - \frac{1}{M}\left(f_5(x) + g_{51}(x)\frac{u_f}{T_0'} + g_{53}(x)\frac{u_q}{T_q}\right)\right]\end{aligned} \tag{12}$$

Therefore, if we choose

$$\begin{aligned}\frac{u_f}{T_0'} &= \frac{1}{g_{31}(x)}\left[-f_3(x) + M\tilde{P}\right],\\ \frac{u_d}{T_d} &= \frac{1}{g_{42}(x)}\left[-f_4(x) - g_{41}(x)\frac{u_f}{T_0'} + M\tilde{Q}\right],\\ \frac{u_q}{T_q} &= \frac{1}{g_{53}(x)}\left[-f_5(x) - g_{51}(x)\frac{u_f}{T_0'} + M\tilde{R}\right].\end{aligned} \tag{13}$$

Then, under the feedback control law (13), the equation (16) turns into $\dot{V}_3$ as (14).

$$\dot{V}_3 = -c_1x_1^2 - \left(c_1x_1 + x_2\right)^2 - c_2P^2 - c_3Q^2 - c_4R^2 \le 0. \tag{14}$$

With the help of Lyapunov stability theory, it is obvious that

$$\lim_{t\to+\infty} x_1 = 0,$$
$$\lim_{t\to+\infty}(c_1x_1 + x_2) = 0,$$
$$\lim_{t\to+\infty}\left[(c_1+1)\frac{x_1}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{x_2}{3} + \frac{(P_m - x_3)}{M}\right] = 0,$$
$$\lim_{t\to+\infty}\left[(c_1+1)\frac{x_1}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{x_2}{3} - \frac{x_4}{M}\right] = 0,$$
$$\lim_{t\to+\infty}\left[(c_1+1)\frac{x_1}{3} + \left(c_1 + 1 - \frac{D}{M}\right)\frac{x_2}{3} - \frac{x_5}{M}\right] = 0. \tag{15}$$

Therefore, it is easy to see from (15) that $\lim_{t\to+\infty} x_1 = \lim_{t\to+\infty} x_2 = \lim_{t\to+\infty} x_4 = \lim_{t\to+\infty} x_5 = 0,$ and $\lim_{t\to+\infty} x_3 = P_m.$ According to the aforementioned discussion, the following theorem obvious holds.

Theorem 1: For the system described by (3), if the controller (13) is employed, then the equilibrium point x_e of the system (3) is asymptotically stable.

Proof: The proof of Theorem 1 is based on the argument given above.

Remark 2: In accordance with the idea proposed in Luo (2015), after we have $\lim_{t\to+\infty} x_i = 0, (i = 1, 2, 4, 5),$ and $\lim_{t\to+\infty}(P_m - x_3) = 0,$ these can be concluded that the closed-loop system is asymptotically stable at the only equilibrium (x_e) and $x \to x_e$ as $t \to \infty.$

Remark 3: From the design procedure mentioned previously, there are two main differences between the proposed scheme and the traditional backstepping one as follows:

1. The developed method is not required to find the virtual variables $x_i^*, (i = 1, 2, 3, 4, 5)$ in each step of the control design,
2. Because the power system considered in (7) is not of strict-feedback form of nonlinear systems (Krstic, Kanellakopoulos, & Kokotovic, 1995), it results in the complicated design procedure when the traditional backstepping approach is directly used. However, the proposed strategy can be used to design the desired nonlinear controller in spite of having non-strict feedback form.

Remark 4: Equations (4)-(14) provide a simple procedure. The procedure can be employed to conclude that the closed-loop system becomes asymptotically stable while the traditional backstepping method is required to determine the virtual variables in each step.

Remark 5: In case of the presence of uncertain parameters in power systems, the results above can be further extended to robust and adaptive control design which will be reported in the future as presented in Kanchanaharuthai (2016a).

4. Simulation

In order to demonstrate the performance of the proposed scheme, the simulation results from the coordination between a generator excitation and SMES control in an SMIB power system are presented. Power angle stability together with the voltage and frequency regulations is utilized to indicate the improvement of transient stability and dynamic properties. Considering the single line diagram as shown in Figure 1, It can be seen in SG is connected through parallel transmission line to an infinite-bus and the SMES device is connected between the transformer and the parallel transmission line.

Assume that there are two cases of interest. In the first case, once a symmetrical three phase short circuit (a large perturbation) appears at the point P (the midpoint of one of the transmission lines), it can affect the system as follows: (i) rotor acceleration, (ii) voltage sag, and (iii) large transient induced electromechanical oscillations. In the second case, the system is under the effect of a small perturbation in the mechanical input power on the network. This results in the system trajectories induced by the perturbation which was confined to a limited region in a neighborhood of a nominal operating trajectory.

Case 1: Temporary fault

The system is affected by a pre-fault steady state, when the fault occurs at $t = 0.5$ sec. This fault can be isolated by opening the breaker of the faulted line at $t = 0.7$ sec., and the transmission line can be restored without the fault at $t = 2.0$ sec. Then, the system is in a post-fault state. Afterward the system is in a post-fault state.

Case 2: Small perturbation in mechanical input power

The system is in a pre-fault steady state. Then there is an unknown constant perturbation in the mechanical power between $t = 0.5$ sec and $t = 1.5$ sec. Eventually, the system is in a post-fault state. The effectiveness is shown by transient stability enhancement of the coordinated (generator excitation/SMES) nonlinear control scheme.

The effectiveness is shown by transient stability enhancement by using the coordinated nonlinear control scheme. Power angle stability including voltage, frequency, and power regulations of the proposed method, are analyzed and compared with those of the existing nonlinear controllers in the literature, e.g., the I&I controller (Kanchanaharuthai et al., 2015) and the backstepping controller (Krstic et al., 1995).

The physical parameters and the initial conditions $(\delta_0, \omega_s, P_{e0}, P_{d0}, P_{q0})$ for this proposed power system model are given in Kanchanaharuthai et al. (2015).

The tuning parameters of the proposed control are $c_1 = c_2 = c_3 = c_4 = 100$. The SMIB power systems, consisting of generator excitation and SMES, have been simulated using the physical parameters and initial conditions above.

For Case 1, Figure 2 shows the time responses of power angle, frequency, and transient internal voltage which are forced to the desired values, under the I&I control, the backstepping controller, and the proposed control, respectively. Apart from this, time responses of active power and terminal voltage are shown in Figure 3. It can be seen that the proposed controller and the I&I controller provide a similarly good transient behavior compared to that of the backstepping scheme. In comparison with the backstepping method, the convergence and damping of the designed controller are greatly better. Particularly, the proposed control yields better dynamic performances in terms of transient response performance with lower overshoot and faster reduction of oscillations.

Similar to Case 1, it is evident from Case 2 that Figures 4 and 5 illustrate time trajectories of power angle, frequency, transient internal voltage, active power and terminal voltage, respectively. All time trajectories settle to the pre-fault steady state, even though a small perturbation of the mechanical input power exists. For this case, the mechanical power is varied from the normal value to some constant (in simulation $P_m = 1$ pu., $\Delta P_m = 0.3$ pu.). Clearly, the equilibrium can be recovered and the terminal voltage can be regulated to the prescribed value when the system is forced by the proposed control. Further, as compared with the backstepping scheme, the proposed controller effectively damps the oscillations of power angle, frequency, active power and terminal voltage. It also has superior performance in maintaining the terminal bus voltage magnitudes that approach to their reference voltage values, in terms of smaller overshoot and shorter settling time, defined for the normal operating conditions. Besides, the proposed scheme provides effective voltage regulation to the desired pre-fault steady-state values after the occurrence of a small perturbation in mechanical power. Apart from this, time histories of the proposed controller are very similar to those of the I&I one which is an advance control design technique. On the other hand, the proposed design procedure hardly becomes complicated like the I&I one.

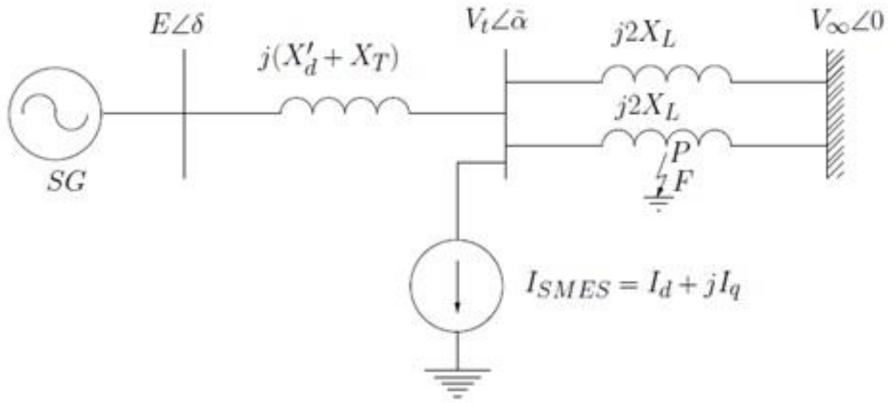

Figure 1 A single line diagram of SMIB system with SMES

As indicated in the simulation results above. It can be, overall, concluded that the proposed control law is effectively designed for transient stabilization and voltage regulation following short circuit and mechanical input change conditions. Similar to the advanced (I&I) controller, the proposed control law can render the controlled system converge quickly to a equilibrium point; meanwhile the active power and the terminal voltage can be quickly regulated to the reference values. Although the proposed design procedure developed becomes considerably simple, the time responses of the proposed method do slightly differ from those of the I&I one. Additionally, the proposed strategy obviously outperforms the backstepping one in terms of fast convergence speed and smaller overshoot magnitude.

Remark 6: The main purposes of this work are to propose a simple, but effective, design scheme for a nonlinear power system with SMES. Then, the proposed method is compared with the advanced (I&I) control and the traditional backstepping control in terms of the design results. Moreover, simulation results illustrate that the developed method provides the results which are very similar to those of the advanced methods. The proposed method performs better than the backstepping one does; however, the design procedure of the proposed method can be done simply.

5. Conclusion

In this paper, using of the backstepping-like procedure, a nonlinear controller for a single-machine infinite-bus power system with a nonlinear generator excitation and SMES controller has been proposed to improve effectively the transient stability, power angle stability as well as frequency and voltage regulations. Unlike the previous work with the complicated design procedure, in this paper the proposed controller is rather simpler. Additionally, the current simulation results showed that despite the simple design procedure, power angle stability along with voltage and frequency regulations are achieved following the large (transient) disturbances on the network via nonlinear model-based backstepping-like control design technique. In particular, in spite of the occurrence of severe disturbances on the transmission line and a small perturbation of mechanical input power, the proposed controller can manipulate the controlled system to a stable equilibrium. The performance of the proposed control is comparable to that of the I&I one and the backstepping one, respectively. It is evident that the damping power oscillations and the closed-loop system dynamics of the proposed controller do not differ much from those of the I&I one, but perform much better than those of the backstepping one does. In addition, under the presented controller, the transient stabilization and a good regulation of the SMES terminal voltage are simultaneously achieved.

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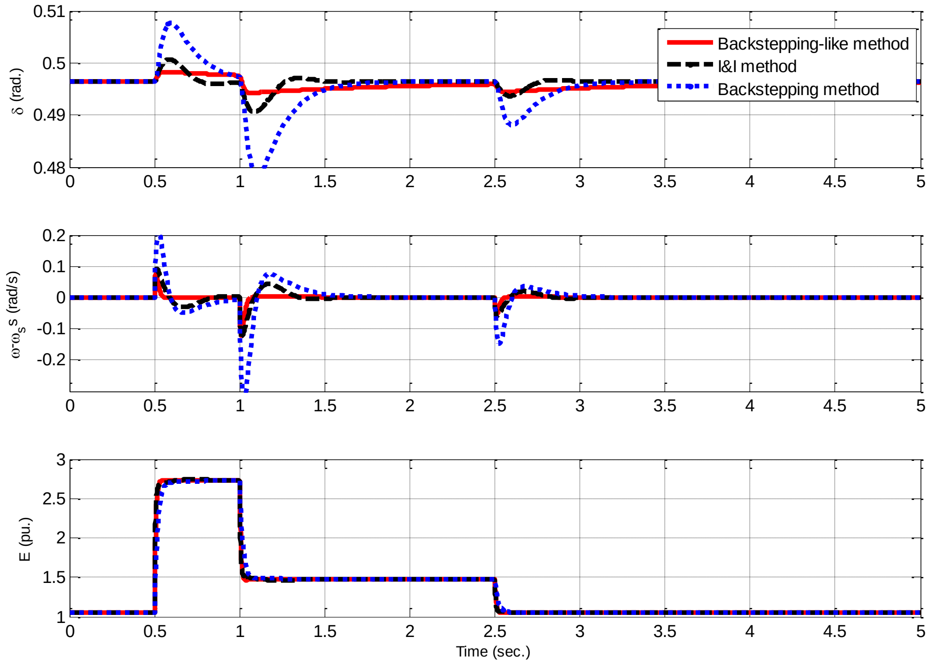

Figure 2 Controller performance in Case 1-Power angles (δ), relative speed $(\omega - \omega_s)$ and transient internal voltage (E) (Solid: Backstepping-like controller, Dashed: I&I controller, Dotted: Backstepping controller)

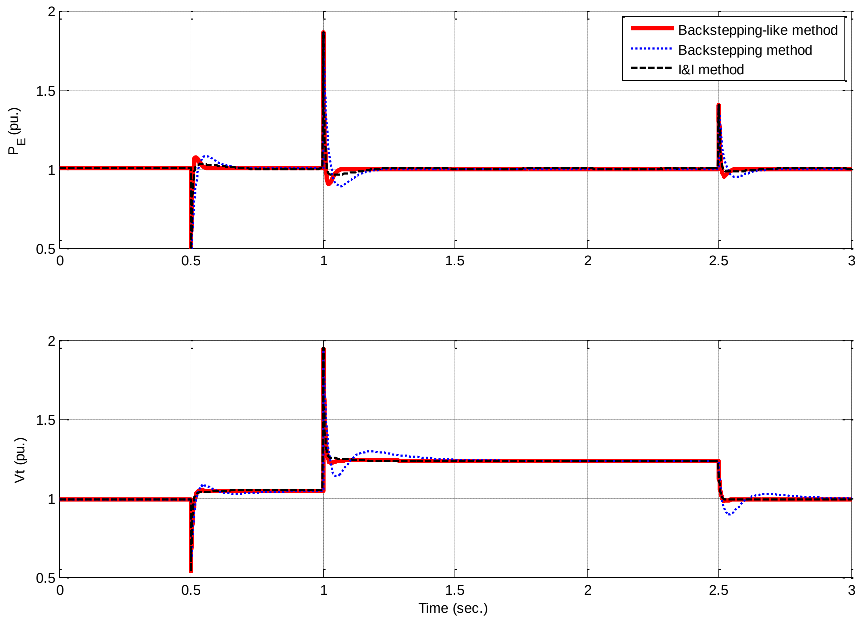

Figure 3 Controller performance in Case 1-Active power (P_E) and terminal voltage (V_t) (Solid: Backstepping-like controller, Dashed: I&I controller, Dotted: Backstepping controller)

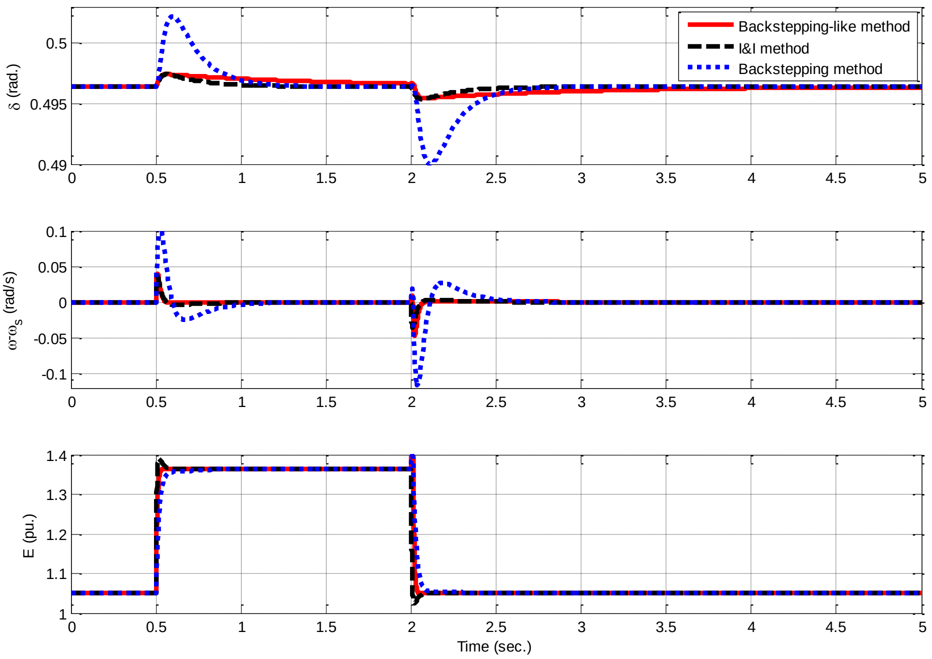

Figure 4 Controller performance in Case 2-Power angles (δ), relative speed $(\omega-\omega_s)$ and transient internal voltage (E) (Solid: Backstepping-like controller, Dashed: I&I controller, Dotted: Backstepping controller)

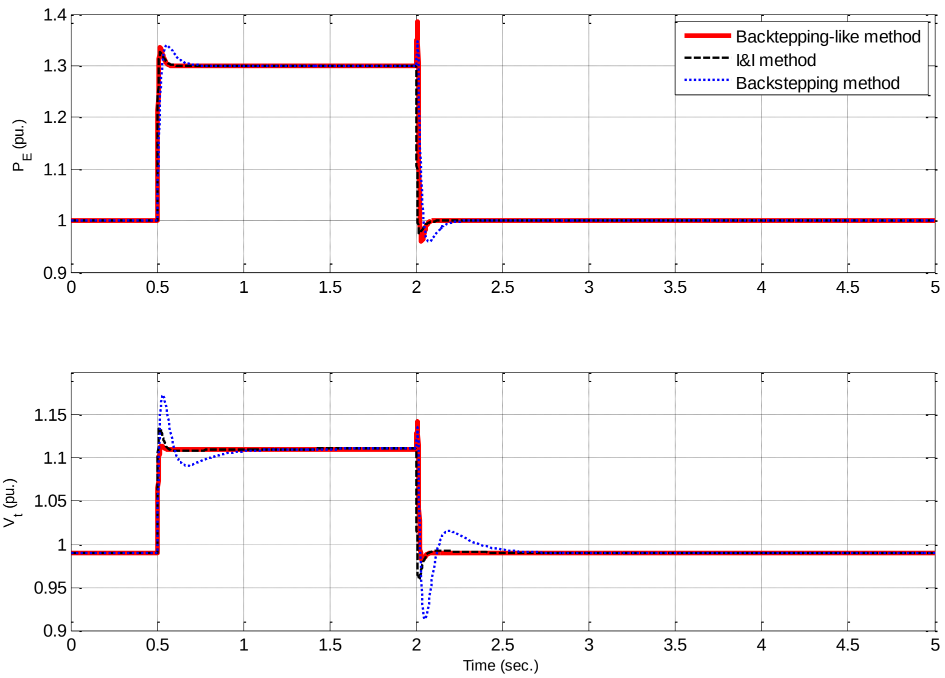

Figure 5 Controller performance in Case 2-Active power (P_E), and terminal voltage (V_t) (Solid: Backstepping-like controller, Dashed: I&I controller, Dotted: Backstepping controller)