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International Review of Automatic Control (IREACO)

Theory and Applications

Contents

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International Review of Automatic Control (I.RE.A.CO.), Vol. 10, N. 2
ISSN 1974-6059
March 2017

A Backstepping Sliding Mode Dual-Excitation and Steam-Valving Control of Synchronous Generators

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Abstract – *A nonlinear dual-excited and steam-valving controller for synchronous generators based on a combination of backstepping and sliding mode control methods is presented in this paper. The proposed controller is designed to enhance the power system stability and voltage and frequency regulation of an electric power system. This strategy is capable of achieving the desired dynamic performances and guaranteeing that the closed-loop system is transiently stable. Simulation results show better transient behavior of the proposed nonlinear controller as compared with the conventional backstepping strategy and an immersion and invariance (I&I) strategy. In addition, they can accomplish transient stability enhancement together with frequency and voltage regulation despite large disturbances.*

***Keywords**: Dual-Excitation Control, Steam-Valving Control, Backstepping Control, Sliding Mode Control, Backstepping Sliding Mode Control*

Nomenclature

δ	Power angle
ω and ω_s	Rotor speed and rotor synchronous speed
E_d', E_q'	The d-axis and q-axis internal transient voltage source
P_m	Mechanical input power
D	Damping constant
P_e	Electrical power delivered by the generator to the infinite bus voltage
M	Moment of inertial constant
V_∞	Voltage at infinite bus
$X'_{d\Sigma}, X'_{q\Sigma}$	Reactance consisting of the direct axis transient reactance of synchronous generator, the transformer, and the transmission line
X'_d, X'_q	Direct axis transient reactance
X_T and X_L	Reactance of the transformer and transmission line, respectively
T_d, T_q	The d-axis and q-axis transient open-circuit time constants
$T_{H\Sigma}$	The equivalent time constant of steam valve control systems
u_G	The steam-valving control input to be designed
u_{fd}, u_{fq}	The d-axis and q-axis field voltage control input to be designed
$x(t)$	State vector of nonlinear system

I. Introduction

It is well known that improving and maintaining the power system transient stability of a synchronous generator (SG) is a challenging problem for power system stability and operations. Due to an occurrence of severe disturbances such as a short circuit on the network buses or transmission, the design of a nonlinear controller to stabilize the closed-loop dynamics of nonlinear power systems is an essential topic that has been widely researched by many authors. Generally, in order to overcome this problem, there are two major promising ways: an excitation control scheme [1]-[7] and a steam-valving control scheme [8]-[10]. These strategies not only stabilize the closed-loop system dynamics of generators, but also achieve the desired control objectives simultaneously. On the contrary, in order to enhance the system stability of synchronous generators and simultaneously improve power system operation, it was found that a coordination of generation excitation and steam-valving control became a promising and effective way. This scheme has attracted a great attention in the power engineering literature [11]-[14]. According to the result in [11], a nonlinear variable structure single-excited and steam-valving control strategy is applied to achieve satisfactory dynamic performance and good robustness with the aid of the differential geometry theory and variable structure control theory. Using a Hamiltonian function methodology, a nonlinear single-excitation control of synchronous generators with steam valve control [12], [13] has been introduced. In accordance with that work, the control signal is designed for attenuating external disturbances, and dealing with unknown parameters.

A modification of this same compensation algorithm was presented in [14], in that work a family of robust adaptive single-excited and steam-valving control for

https://doi.org/10.15866/ireaco.v10i2.11366

synchronous generators has been presented. Moreover, it provides an opportunity to offer a degree of freedom for achieving further desired control performances. On the aforementioned references above, note that as for the excitation control, we always assume throughout consideration that the d-axis field voltage is viewed as a constant. Therefore, there is the only q-axis field voltage that is controlled for accomplishing the desired control objectives. On the other hand, the idea of increasing greater flexibility to improve the system stability is a combination of d-axis and q-axis field voltages, called dual-excitation. This method can use the additional degree of freedoms to enhance the system performance. It also provides an opportunity to find the effective control signals since the dual-excited control of SGs with d-axis and q-axis field windings can be independently controlled. Consequently, the desired control objectives can be accomplished through this combination. Concerning stabilizing the power system model and improving dynamic performances, there were a lot of related technical researches devoted to the design of linear and nonlinear controllers of dual-excited synchronous generators alone as presented in [15] – [17]. As far as the authors know, considerable research has focused on the coordination of single-excited and steam-valving control, with less attention devoted to the coordination of dual-excited and steam-valving control of synchronous generators. A systematic procedure to synthesize a nonlinear feedback stabilizing control law on the basis of a coordinated passivation strategy was proposed in [18].

Moreover, it has shown that the corresponding time responses has been greatly improved and provided better damping behaviors than the feedback linearization scheme. Reported on [19], [20] is a sliding mode based control technique that was proposed for designing a dual-excited and steam-valving controller of the SGs with matched and mismatched perturbations. In that work, the obtained control law can overcome the mismatched perturbation, and some power qualities are further enhanced. An algorithm for a nonlinear power system with dual-excitation and steam-valving control is designed using I&I strategy as reported on [21]. The resulting control law was developed for the system stability and voltage regulation enhancement of a single-machine infinite bus system. Accordingly, this method is capable of accomplishing power angle stability along with frequency and voltage regulation, and ensuring that the closed-loop system dynamics are transiently and asymptotically stable.

Even though the I&I design has become an effective tool in feedback control design, there are main drawbacks from this scheme. This paper still continues this line of investigation but the combination of the backstepping technique and the sliding mode technique are developed to overcome difficulties arising from the I&I technique [21]. Therefore, this paper proposes a nonlinear dual-excited and steam-valving control design algorithm that combines backstepping and sliding modes. In addition, the obtained control law has a rather simpler design procedure than the I&I scheme and can achieve power angle stability along with frequency and voltage regulation. Furthermore, it keeps the system transiently stable. Simulation results are performed on the SMIB model with a SG, including dual-excited and steam-valving control, connected to the infinite bus.

The remainder of this paper is organized as follows. After an introduction in this section, simplified dynamic models of a SG are briefly described in Section 2. Nonlinear controller design is given in Section 3. Simulation results are given in Section 4, while a conclusion is stated in Section 5.

II. Power System Models

In this section, the dynamic models of the synchronous generator are briefly provided. A dynamic model of a synchronous generator (SG) is obtained as:

$$\begin{aligned}
&\dot{\delta} = \omega - \omega_s, \\
&\dot{\omega} = \frac{1}{M}\left(P_m - P_e - D(\omega - \omega_s)\right), \\
&\dot{P}_m = -\frac{P_m - P_{me}}{T_{H\Sigma}} + \frac{C_H}{T_{H\Sigma}} u_G, \\
&\dot{E}_q' = -\frac{X_{d\Sigma}}{X_{d\Sigma}' T_d} E_q' + \frac{\left(X_{d\Sigma} - X_{d\Sigma}'\right)}{X_{d\Sigma}' T_d} V_\infty \cos\delta + \frac{u_{fd}}{T_d}, \\
&\dot{E}_d' = -\frac{X_{q\Sigma}}{X_{q\Sigma}' T_q'} E_d' - \frac{\left(X_{q\Sigma} - X_{q\Sigma}'\right)}{X_{q\Sigma}' T_q} V_\infty \sin\delta + \frac{u_{fq}}{T_q}
\end{aligned} \tag{1}$$

with:

$$P_e = \frac{E_q' V_\infty \sin\delta}{X_{d\Sigma}'} + \frac{E_d' V_\infty \cos\delta}{X_{q\Sigma}'} + \frac{\left(X_{d\Sigma}' - X_{q\Sigma}'\right) V_\infty^2 \sin 2\delta}{2 X_{d\Sigma}' X_{q\Sigma}'}$$

For the sake of simplicity, we choose the following coordinated transformation:

$$\begin{aligned}
&x_1 = \delta - \delta_e, \\
&x_2 = \omega - \omega_s, \\
&x_3 = P_m - P_{me}, \\
&x_4 = \frac{E_q' V_\infty \sin(x_1 + \delta_e) - E_{qe}' V_\infty \sin(\delta_e)}{X_{d\Sigma}'} \\
&\qquad + m\left(\sin 2(x_1 + \delta_e) - \sin 2\delta_e\right), \\
&x_5 = \frac{E_d' V_\infty \sin(x_1 + \delta_e) - E_{de}' V_\infty \sin(\delta_e)}{X_{q\Sigma}'},
\end{aligned} \tag{2}$$

which satisfies the following equilibrium:

$$P_{me} + \frac{E'_{qe}V_\infty sin(\delta_e)}{X'_{d\Sigma}} + \frac{E'_{de}V_\infty cos\,\delta}{X'_{q\Sigma}} - m\,sin\,2\delta_e = 0,$$

thus, the nonlinear power system model considered has the form given by (3):

$$\dot{x} = f(x) + g(x)u(x) \tag{3}$$

with:

$$f(x) = \begin{bmatrix} f_1(x) & f_2(x) & f_3(x) & f_4(x) & f_5(x) \end{bmatrix}^T$$
$$f_1(x) = x_2,$$
$$f_2(x) = \frac{1}{M}(x_3 - Dx_2 - x_4 - x_5),$$
$$f_3(x) = -\frac{1}{T_{H\Sigma}}(x_3 - P_{me}),$$
$$f_4(x) = \left(-a_q E'_q + b_q cos(x_1+\delta_e)\right)\frac{V_\infty sin(x_1+\delta_e)}{X'_{d\Sigma}},$$
$$f_5(x) = -\left(a_d E'_d + b_d sin(x_1+\delta_e)\right)\frac{V_\infty cos(x_1+\delta_e)}{X'_{q\Sigma}},$$

$$g(x) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & g_{42}(x) & 0 \\ 0 & 0 & g_{53}(x) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \frac{V_\infty sin(x_1+\delta_e)}{X'_{d\Sigma}} & 0 \\ 0 & 0 & \frac{V_\infty cos(x_1+\delta_e)}{X'_{q\Sigma}} \end{bmatrix},$$

$$u(x) = \begin{bmatrix} \frac{C_H u_f}{T_{H\Sigma}} & \frac{u_{fd}}{T_d} & \frac{u_{fq}}{T_q} \end{bmatrix}^T$$

where:

$$a = \frac{X_s}{(X_1+X_2)T_0}a_q = \frac{X_{d\Sigma}}{X'_{d\Sigma}T_d}, a_d = \frac{X_{q\Sigma}}{X'_{q\Sigma}T_q},$$
$$b_q = \frac{\left(X_{d\Sigma} - X'_{d\Sigma}\right)V_\infty}{X'_{d\Sigma}T_d}, b_d = \frac{\left(X_{q\Sigma} - X'_{q\Sigma}\right)V_\infty}{X'_{q\Sigma}T_q},$$
$$m = \frac{X'_{d\Sigma} - X'_{q\Sigma}}{2X'_{d\Sigma}X'_{q\Sigma}}V_\infty^2.$$

The region of operation is defined as the set $\tilde{D} = \left\{x \in S \times R \times R \times R \times R \mid 0 < x_1 < \frac{\pi}{2}\right\}$. The open loop operating equilibrium is denoted by $x_e = [0,0,0,0,0]^T$.

From (3), it is observed that this system has the control law $u(x)$ consisting of the following three control inputs: $\frac{C_H u_G}{T_{H\Sigma}}, \frac{u_{fd}}{T_d}$, and $\frac{u_{fq}}{T_q}$. Thus, the objective of this paper is to determine the control law $u(x)$ in (3) based on the backstepping sliding mode methodology in order to achieve transient stabilization of the overall closed-loop system dynamics and to accomplish the two requirements: (1)The desired equilibrium point x_e is asymptotically and transiently stable and (2) Power angle stability, voltage and frequency regulation are simultaneously achieved.

III. Backstepping Sliding Mode Design

The presented controller is designed via backstepping and sliding mode techniques [23]-[27] so that the state trajectories can approach a specified hyperplane. The methodology developed is divided into two parts. In the first part, the backstepping is used to recursively design the virtual control. Then, in the second part, the sliding mode is combined with the backstepping in the final step to synthesize the desired control law to stabilize the overall closed-loop system. In order to design the nonlinear stabilizing controller based on the combined backstepping and sliding mode schemes, let us define the error variable by:

$$\begin{cases} z_i = x_i - \alpha_i, (i = 1,2,3,4,5), \\ \alpha_1 = 0, \alpha_2 = -c_1 x_1, \\ \alpha_3 = -\frac{1}{3}\left(c_2 M z_2 + M z_1 + (c_1 M - D)x_2\right), \\ \alpha_4 = \alpha_5 = \frac{1}{3}\left(c_2 M z_2 + M z_1 + (c_1 M - D)x_2\right), \end{cases} \tag{4}$$

where α_i denotes the virtual control.

Therefore, the backstepping sliding mode control approach is expressed in the following theorem.

Theorem 1: Consider the system (3), the following backstepping sliding mode control law:

$$\begin{cases} \frac{C_H u_G(x)}{T_{H\Sigma}} = -\begin{pmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + \dot{\alpha}_2(z_1,z_2) + f_3(x) \\ +h_3 S_3 + \beta_3\, sgn(S_3) - z_3 \end{pmatrix}, \\ \frac{u_d(x)}{T_d} = -\frac{\begin{pmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + \dot{\alpha}_3(z_1,z_2) + f_4(x) \\ +h_4 S_4 + \beta_4\, sgn(S_4) - z_4 \end{pmatrix}}{g_{42}(x)}, \\ \frac{u_q(x)}{T_q} = -\frac{\begin{pmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + \dot{\alpha}_4(z_1,z_2) + f_5(x) \\ +h_5 S_5 + \beta_5\, sgn(S_5) - z_5 \end{pmatrix}}{g_{53}(x)}, \end{cases} \tag{5}$$

where $g_{42}(x) \neq 0$ and $g_{53}(x) \neq 0$. $c_i > 0, d_i > 0, h_j > 0, \beta_j > 0 \ (i = 1,2, j = 3,4,5)$ are positive design parameters. These design parameters make the matrix Q in (22) to be positive definite. Then, it can be concluded that the closed-loop system has an asymptotically equilibrium point x_e.

Proof: In the following, the control law is designed by the backstepping sliding mode scheme.

Step 1: We start the backstepping procedure by considering the first subsystem of the system (3). Let us define the error variable $z_1 = x_1$. In order to design the virtual control input α_2 for the first subsystem, by differentiating z_1, it results in:

$$\dot{z}_1 = x_2 \tag{6}$$

We assume that x_2 is viewed as the virtual control input. Then, the virtual control of x_2 is chosen as $\alpha_2 = -c_1 x_2$, where $c_1 > 0$ is a design constant. Let us define the error variable $z_2 = x_2 - \alpha_1(z_1)$ and $z_1 = x_1$. Then, we have:

$$\dot{z}_1 = z_2 - c_1 z_1. \tag{7}$$

For the system (7), the Lyapunov function is chosen as $V_1 = \frac{1}{2} z_1^2$. Subsequently, take derivative of V_1 along the system trajectory, and we can get:

$$\dot{V}_1 = e_1(e_2 - c_1 e_1) = -c_1 e_1^2 + e_1 e_2. \tag{8}$$

According to (8) that if $e_2 = 0$, then $\dot{V}_1 \leq 0$.

Step 2: Design the virtual control input α_3, α_4, and α_5 for $\dot{x}_2$. We proceed in the same way as in backstepping scheme by defining the augmented Lyapunov function of Step 1 as $V_2 = V_1 + \frac{1}{2} z_2^2$. Notice that the error dynamics of z_2 can be directly computed as follows:

$$\begin{aligned} \dot{z}_2 &= \dot{x}_2 - \dot{\alpha}_2(z_1) \\ &= \frac{(x_3 - Dx_2 - x_4 - x_5)}{M} + c_1 x_2. \end{aligned} \tag{9}$$

The time derivative of V_2 along the system trajectory becomes:

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + z_2 \dot{z}_2 \\ &= -c_1 z_1^2 + \frac{z_2}{M} \begin{pmatrix} Mz_1 + x_3 - Dx_2 \\ -x_4 - x_5 + c_1 M x_2 \end{pmatrix} \end{aligned} \tag{10}$$

From (10), it can be seen that the system is not a strict feedback form of nonlinear systems [22]. This means that the state variables x_3, x_4, and x_5 appear at the same step. Thus, select the state variables x_3, x_4, and x_5 as the virtual control, respectively, as follows:

$$x_3 - x_4 - x_5 = -\begin{pmatrix} c_2 M z_2 + M z_1 + \\ (c_1 M - D) x_2 \end{pmatrix}, c_2 > 0. \tag{11}$$

We define the virtual control (11) as given in (4):

$$\begin{cases} x_3 = \alpha_3(z_1, z_2) = -\frac{1}{3}\begin{pmatrix} c_2 M z_2 + M z_1 \\ +(c_1 M - D) x_2 \end{pmatrix}, \\ x_4 = \alpha_4(z_1, z_2) = \frac{1}{3}\begin{pmatrix} c_2 M z_2 + M z_1 \\ +(c_1 M - D) x_2 \end{pmatrix}, \\ x_5 = \alpha_5(z_1, z_2) = \frac{1}{3}\begin{pmatrix} c_2 M z_2 + M z_1 \\ +(c_1 M - D) x_2 \end{pmatrix}, \end{cases} \tag{12}$$

Since x_3, x_4, and x_5 are not actually control inputs, but rather virtual variables, the following variables shift are introduced:

$$\begin{cases} \dot{z}_3 = \dot{x}_3 - \dot{\alpha}_3(z_1, z_2) \\ \quad = f_3(x) + \frac{C_H u_G}{T_{H\Sigma}} - \dot{\alpha}_2(z_1, z_2), \\ \dot{z}_4 = \dot{x}_4 - \dot{\alpha}_4(z_1, z_2) \\ \quad = f_4(x) + g_{42}(x) \frac{u_{fd}}{T_d} - \dot{\alpha}_3(z_1, z_2), \\ \dot{z}_5 = \dot{x}_5 - \dot{\alpha}_5(z_1, z_2) \\ \quad = f_5(x) + g_{53}(x) \frac{u_{fq}}{T_q} - \dot{\alpha}_4(z_1, z_2), \end{cases} \tag{13}$$

Then it holds:

$$\dot{V}_2 = -c_1 z_1^2 - c_2 z_2^2 + \frac{z_2}{M}(z_3 - z_4 - z_5). \tag{14}$$

Step 3: In this final step, the modification is carried out by incorporating an appropriate sliding mode surface which can be defined in terms of the error coordinates as following. The sliding mode surface with an integral action S_{k+2} is defined as follows:

$$S_{k+2} = d_1 z_1 + d_2 z_2 + z_{k+2} + \int_0^t z_{k+2} dt, (k = 1,2,3) \tag{15}$$

Thus, the time derivative of the sliding surface with the integral action along the system trajectories (6), (8), and (13) is obtained as follows:

$$\dot{S}_{k+2} = d_1\dot{z}_1 + d_2\dot{z}_2 + \dot{z}_{k+2} + z_{k+2}, (k = 1,2,3) \quad (16)$$

where $d_i, (i = 1,2)$ are positive design parameters. $\dot{z}_1, \dot{z}_2$, and $\dot{z}_{k+2}, (k = 1,2,3)$ can be straightforwardly computed from (9)-(10) and (13).

Thus, the augmented Lyapunov function with the sliding surface in (13) is obtained as follows:

$$V_3(z) = \frac{1}{2}\left(z_1^2 + z_2^2\right) + \sum_{k=1}^{3} S_{k+2}^2 \quad (17)$$

which is a positive definite function. The derivative of V_3 with respect to time is given by:

$$\begin{aligned} \dot{V}_3 &= \dot{V}_2 + S_3\dot{S}_3 + S_4\dot{S}_4 + S_5\dot{S}_5 \\ &= -c_1z_1^2 - c_2z_2^2 + \frac{z_2}{M}(z_3 - z_4 - z_5) \\ &+ S_3\begin{bmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + f_3(x) \\ + \frac{C_H u_G}{T_{H\Sigma}} - \dot{\alpha}_2(z_1, z_2) + z_3 \end{bmatrix} \\ &+ S_4\begin{bmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + f_4(x) \\ + g_{42}(x)\frac{u_d}{T_d} - \dot{\alpha}_3(z_1, z_2) + z_4 \end{bmatrix} \\ &+ S_5\begin{bmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + f_5(x) \\ + g_{53}(x)\frac{u_q}{T_q} - \dot{\alpha}_4(z_1, z_2) + z_5 \end{bmatrix}. \end{aligned} \quad (18)$$

According to the sliding mode control design, it is straightforward to select the following dynamics to the sliding surface in (15) as:

$$\dot{S}_{k+2} = -\left(h_{k+2}S_{k+2} + \beta_{k+2}\, sgn(S_{k+2})\right), (k = 1,2,3) \quad (19)$$

where $h_{k+2} > 0, \beta_{k+2} > 0$. The sliding mode occurs if $S_{k+2} = \dot{S}_{k+2}$ are enforced to the specified hyperplane under the proposed control law.

Therefore, the combined backstepping and sliding mode control law $u(x)$ can be defined as:

$$\begin{cases} \dfrac{C_H u_G(x)}{T_{H\Sigma}} = -\begin{pmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + \dot{\alpha}_2(z_1, z_2) + f_3(x) \\ + h_3S_3 + \beta_3\, sgn(S_3) - z_3 \end{pmatrix}, \\ \dfrac{u_d(x)}{T_d} = -\dfrac{\begin{pmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + \dot{\alpha}_3(z_1, z_2) + f_4(x) \\ + h_4S_4 + \beta_4\, sgn(S_4) - z_4 \end{pmatrix}}{g_{42}(x)}, \\ \dfrac{u_q(x)}{T_q} = -\dfrac{\begin{pmatrix} d_1\dot{z}_1 + d_2\dot{z}_2 + \dot{\alpha}_4(z_1, z_2) + f_5(x) \\ + h_5S_5 + \beta_5\, sgn(S_5) - z_5 \end{pmatrix}}{g_{53}(x)}, \end{cases} \quad (20)$$

where $g_{42}(x) \neq 0$ and $g_{53}(x) \neq 0$. $d_i > 0, (i = 1,2), h_j > 0, \beta_j > 0, (j = 3,4,5)$ are positive design parameters. By substituting $u(x)$ into (14) in order to stabilize the whole closed-loop system (3), we obtain:

$$\begin{aligned} \dot{V}_3 &= \dot{V}_2 + S_3\dot{S}_3 + S_4\dot{S}_4 + S_5\dot{S}_5 \\ &= -c_1z_1^2 - c_2z_2^2 + \frac{z_2}{M}(z_3 - z_4 - z_5) \\ &- \sum_{k=3}^{5}\left(h_kS_k + \beta_k\, sgn(S_k)\right) \\ &\leq -z^T Qz - \beta|S|, \end{aligned} \quad (21)$$

where:

$$\beta = [\beta_3 \quad \beta_4 \quad \beta_5], |S| = [|S_3| \quad |S_4| \quad |S_4|]^T,$$

$$z = [z_1 \quad z_2 \quad z_3 \quad z_4 \quad z_5]^T$$

and Q matrix is defined as follows:

$$Q = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & Q_{14} & Q_{15} \\ Q_{12} & Q_{22} & Q_{23} & Q_{24} & Q_{25} \\ Q_{13} & Q_{23} & Q_{33} & 0 & 0 \\ Q_{14} & Q_{24} & 0 & Q_{44} & 0 \\ Q_{15} & Q_{25} & 0 & 0 & Q_{55} \end{bmatrix} \quad (22)$$

where:

$$\begin{aligned} &Q_{11} = c_1 + d_1^2(h_1 + h_2 + h_3), \\ &Q_{12} = d_1d_2(h_1 + h_2 + h_3) \\ &Q_{13} = d_1h_1, Q_{14} = d_1h_2, Q_{15} = d_1h_3, \\ &Q_{22} = c_2 + d_2^2(h_1 + h_2 + h_3), Q_{23} = d_2h_1 + \frac{1}{2M}, \\ &Q_{24} = d_2h_2 - \frac{1}{2M}, Q_{25} = d_2h_3 - \frac{1}{2M}, \\ &Q_{33} = h_1, Q_{44} = h_2, Q_{55} = h_3. \end{aligned}$$

With the help of Lyapunov stability theorem, we needs to show that the time derivative of V_3 in (21) is negative definite so that we conclude that the error dynamics $z_i, (i = 1,2,3,4,5)$ will converge to zero as $t \to \infty$.

Therefore, in order to guarantee the negativity of the Lyapunov function $\dot{V}_3$, the matrix Q in (22) needs to be positive definite.

Thus, the following conditions is its leading principal minors that are positive definite, i.e.:

$$Q_{11}>0,\begin{bmatrix}Q_{11} & Q_{12}\\ Q_{12} & Q_{22}\end{bmatrix}>0,\begin{bmatrix}Q_{11} & Q_{12} & Q_{13}\\ Q_{12} & Q_{22} & Q_{23}\\ Q_{13} & Q_{23} & Q_{33}\end{bmatrix}>0,$$
$$\begin{bmatrix}Q_{11} & Q_{12} & Q_{13} & Q_{14}\\ Q_{12} & Q_{22} & Q_{23} & Q_{24}\\ Q_{13} & Q_{23} & Q_{33} & 0\\ Q_{14} & Q_{24} & 0 & Q_{44}\end{bmatrix}>0, Q>0. \tag{23}$$

It is easy to see under the control law (16) that once $\dot{V}_3 \le 0$, it implies that $V_3(t) \le V_3(0)$ i.e., $z_i, (i=1,2,3,4,5)$ are all bounded. Let us define

$$W(t) = z^T Qz + \beta|S| \tag{24}$$

From (21), it is easy to see that $\dot{V}_3 \le -W(t) \le 0$. It is seen that this yields $\lim_{t\to\infty} S_{k+2} = 0, (k=1,2,3)$ and $\lim_{t\to\infty} z_i = 0, (i=1,2,3,4,5)$. From integrating the expression (23), we have $\int_0^t W(\tau)d\tau = V_3(0) - V_3(t)$. It can be seen that $V_3(0)$ is bounded, whereas $V_3(t)$ is non-increasing and bounded. Subsequently, $\lim_{t\to\infty}\int_0^t W(\tau)d\tau < +\infty$. Additionally, from (24) because $\dot{W}$ becomes bounded and uniformly continuous. As a consequence of Barbalat's lemma [22], it means $\lim_{t\to\infty} W = 0$ holds. Thus, with the help of the backstepping sliding mode strategy, we can conclude that $\lim_{t\to\infty} z_i = 0$.

From the definition of the system state variables x_i, $\alpha_i, (i=1,2,3,4,5)$, and $S_{k+2}, (k=1,2,3)$, it is apparent that x_i also converges to zero. Finally, the overall closed-loop nonlinear system is asymptotically stable. Thus, the proposed control law can guarantee that the overall closed-loop system is asymptotically stable and achieves the desired requirements. This completes the proof.

Remark: Even though the nonlinear control algorithms [18]-[21] mentioned in Section I can achieve the acceptable performance, there are some drawbacks as follows. In [19],[20], the sliding mode control has been effectively employed due to its robustness against parameter variation and disturbances. Nevertheless, unwanted chattering arising from discontinuous control is an unavoidable drawback of this technique. Besides, although the I&I based control law [21] can be applied successfully for enhancing power system stability, the design procedure becomes rather complex. In addition, the dual-excited and steaming valving control system can be designed via a feedback linearization (FBL) method [9], but the scheme is dependent on the construction of a coordinate transformation transforming an affine nonlinear system into the so-called normal form with the appropriate selection of an output function. This may make the control design more complicated. In this paper, we focus on the combined advantages of both backstepping and sliding mode control techniques. In general, most of nonlinear control techniques are designed via Lyapunov approach that is used to find a control law and to stabilize the closed-loop system. However, finding a Lyapunov function for designing the desired nonlinear controller is not easy. Fortunately, backstepping scheme is a systematic design procedure that is used to systematically determine the desired control law by selecting an appropriate Lyapunov function and changing the coordinates so that the complete closed-loop system becomes asymptotically stable.

Consequently, the combined backstepping and sliding mode method can be regarded as a recursive design techniques and provides benefits from both methods. In comparison with other control techniques, the proposed control law has quite simpler structure and design procedure than the I&I method [21], the FBL method [9], while the improved transient performances are satisfactory. Apart from this, this combine strategy inherits the robustness property from sliding mode control. Note that the combined control design has not been utilized for the dual-excited and steaming-valving control system in the existing references. This paper presents and designs a backstepping sliding mode method for the SG. This developed method not only achieves the desired requirements, but also provides the acceptance control performance. Thus, the control scheme of the dual-excitation and steam-valving model of SG is valuable for improving transient stability and regulating both voltage and frequency of power systems.

IV. Simulation Results

In this section, in order to demonstrate the ability of the proposed approach for designing the nonlinear controller for transient stability enhancement and as well as voltage and frequency regulation, it is implemented on the SMIB model as shown in Figure 1.

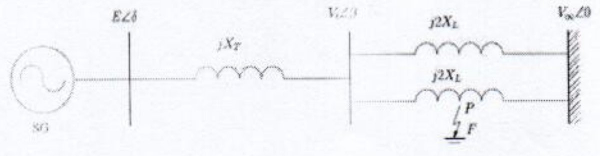

Fig. 1. A single line diagram of SMIB system

From the proposed controller obtained through the algorithm in (18), the analysis is based on the results of time domain simulations in MATLAB environment. The contingency is a three-phase a three-phase short circuit fault that occurs at the point P. In order to verify the performance of the designed control law in the SMIB power system, when there is the three-phase fault occurring at $t_0 = 0.5$ s, then the fault is cleared at $t_c = 1$ s. Eventually, the transmission line is recovered without the fault at $t_r = 1.5$ s. In addition, to evaluate the dynamic behavior of the developed control law, the performances of the proposed control strategy are compared with those of other nonlinear control design approaches, namely, the I&I controller [21] and the conventional backstepping controller [22].

In the study, it is assumed that the pre-fault system is running at the operating point $\left(\delta_e, \omega_s, P_{me}, E_{eqe}, E_{ede}\right)$ before the three-phase fault occurs. The system parameters (pu.) for this power system model are given in [21]. In order to satisfy the conditions in (21), the design parameters can be selected as:

$$c_1 = c_2 = h_1 = h_2 = h_3 = \beta_1 = \beta_2 = \beta_3 = 100.$$

The simulation results are presented and discussed below.

Time trajectories of a power angle, SG relative speed (frequency), the mechanical power, active power, and terminal voltage under the different controllers are shown in Figs. 2-3, respectively.

It can be seen that once the fault is removed from the network, three controllers are able to bring the system to the desired equilibrium point quickly; however, it is seen that there are different rates of convergence to their post-fault state. Note that, due to the presence of the temporary fault on the network, in comparison with the backstepping controller, in Fig. 2, time trajectories of the proposed coordinated (dual excitation/steam-valving control) controller, particularly power angles and relative speeds, have obviously better performance such as smaller overshoot, shorter transient time, and faster reduction of oscillation. Regarding the dynamic responses of active power and voltage regulation as shown in Fig. 3, the presented controller gives obviously the satisfactory damping performances over the backstepping controller. Time responses can quickly settle to their pre-fault steady state. These results indicate that the combination of dual excitation and steam-valving control can obviously further improve transient stability along with improving transient properties as compared to the backstepping controller. In other words, once time histories of the proposed controller are compared with those of the I&I controller. It can be found that the obtained results of the proposed strategy are almost the same as those of the I&I one. It is well-known that the I&I design is recently an advanced nonlinear control technique, and has a more complicated design procedure than the proposed one. On the other hand, the proposed design procedure is rather simpler than the I&I one is quite easy, and can overcome difficulties in designing a nonlinear stabilizing feedback controller via the I&I controller. From Figs. 2-3, it can be observed that independent of the steady-state operating point of the system and the temporary fault sequence above, the developed control law can achieve the expected requirements and accomplish improved transient behavior of the closed-loop systems even at a severe disturbance compared to the other control strategy. Finally, Fig. 4 illustrates that time histories of the sliding surfaces S_3, S_4, and S_5 in (13) converge to zero as expected.

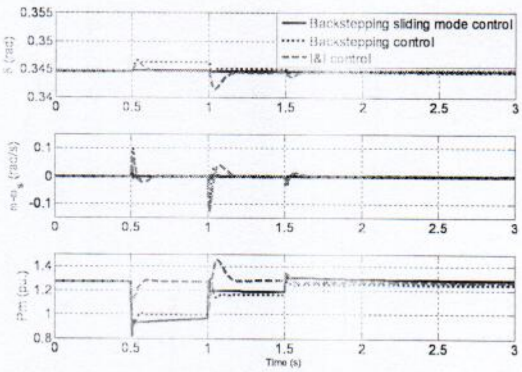

Fig. 2. Time histories of power angle, relative speed, mechanical power

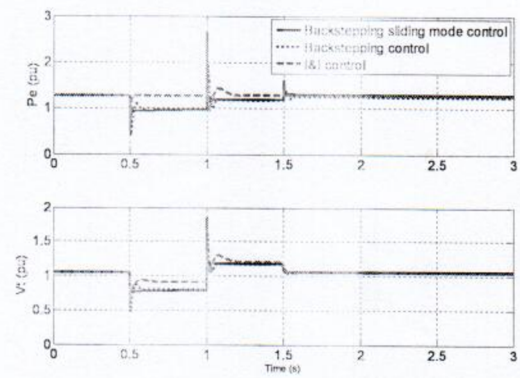

Fig. 3. Time histories of active power and terminal voltage

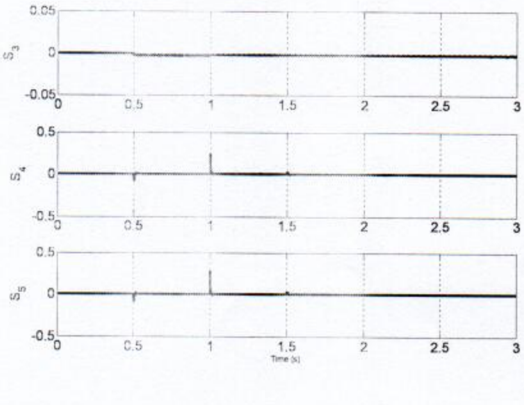

Fig. 4. The sliding variables S_3, S_4, and S_5

From the simulation results above, it can be concluded that not only transient stability is improved, but also power angle stability together with frequency and voltage regulations can be simultaneously accomplished according to the two expected requirements under the proposed controller. Furthermore, it can be observed that in terms of dynamic properties (improved transient performances), the proposed control strategy provides the similar results as those of the I&I method while it clearly outperforms the backstepping scheme.

V. Conclusion

This paper has successfully proposed a nonlinear dual-excited and steam-valving control design algorithm that combines backstepping and sliding modes for synchronous generators. Using this approach, the control law obtained using the proposed methodology is directly applied to the SMIB power system and makes the overall closed-loop system transiently stable. It can also improve effectively the transient stability, power angle stability as well as frequency and voltage regulations. From the simulation results, the performances of the proposed controller design are further improved, and compared with those of two nonlinear design approaches, namely, the backstepping and the I&I controllers. In comparison with two design schemes above in terms of dynamic performance, the proposed controller provides the results which are almost equal to the I&I controller, but superior to the backstepping one. Moreover, the developed method not only achieves transient stability enhancement, but also accomplishes a good regulation of frequency and terminal voltage as expected. Extension of this approach to robust control in the presence of disturbances and unknown parameters deserves further study.

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e-ISSN: 1974-6067

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