A Composite Nonlinear Controller for Power Systems with STATCOM under External Disturbances

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ABSTRACT

This paper concentrates on the design of a composite nonlinear stabilizing state feedback control for power systems with static synchronous compensator (STATCOM) with the help of a combination of backstepping strategy and a nonlinear disturbance approach. The disturbance observer is used to estimate unavoidable external disturbances. Thus, the obtained control law can be used to successfully stabilize the system and reject undesired external disturbances. In order to demonstrate the effectiveness of the developed process design, numerical simulation results are provided to indicate that the presented composite controller can improve dynamic performances, rapidly suppress system oscillations of the overall closed-loop dynamics, and despite having inevitable external disturbances, perform better than a conventional backstepping control technique.

Keywords: Backstepping Control, STATCOM, Generator Excitation, Disturbance Observer

1. INTRODUCTION

It is well-known that modern power systems have seen a rapid increase in size and complexity. When power system operation is confronted with unavoidable disturbances, maintaining power system stability is one of the most important problems. Therefore, this problem has attracted much attention from a number of researchers. Currently, there are three effective and promising methods that are used to improve system stability under unpredictable disturbances. The first method is a utilization of generator excitation control [1]–[7]. The second method is a combination of the excitation and energy storage system [23]. The third method is an coordination of the excitation and Flexible AC Transmission System (FACTS) devices [9, 10]. These schemes focus on improving power system stability and accomplishing the desired control objectives.

Since there are recent fast developments in power electronic devices, FACTS devices have been applied to not only provide an opportunity to effectively tackle the existing transmission facilities, but also deal with several constraints to build new transmission lines. In this paper, the Static Synchronous Compensator (STATCOM)[9, 10] of particular interest can be employed to increase the grid transfer capability through enhanced voltage stability, significantly provide smooth and rapid reactive power compensation for voltage support, and enhance both damping oscillation and transient stability. So far, the generator excitation controller [1] and STATCOM controller [10] have been separately designed. However, in order to further enhance the power system stability of power systems, the combination of generator excitation and STATCOM is a promising and effective method and has attracted much attention in literature for years.

To the best of our knowledge, based directly on the nonlinear control strategy, there is little prior work that has been devoted to a coordination of generator excitation and STATCOM. In [11, 12], an adaptive coordinated generator excitation and STATCOM control strategy was designed via generalized Hamiltonian control for stability enhancement of large-scale power systems. With the help of the zero dynamic design and pole-assignment scheme, a coordinated controller [13] for the single-machine infinite bus system was investigated. A nonlinear coordinated controller [14] has been developed through a combination of the passivity design and backstepping technique. Kanchanaharuthai et al. [15] has developed an interconnection and damping assignment-passivity based control (IDA-PBC) strategy for coordination of generator excitation and STATCOM/battery energy storage for transient stability and voltage regulation enhancement of multi-machine power systems. In [16], a coordinated immersion and invariance (I&I) control scheme has been developed for transient sta-

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bility improvement and voltage regulation. Kanchanaharuthai [17] presented an adaptive I&I control and adaptive backstepping scheme to enhance transient stability and voltage regulation for power systems with STATCOM in the presence of unknown parameters. Recently, based on a Takagi-Sugeno (T-S) fuzzy scheme, a nonlinear stabilizer design [18] for power systems with random loads and STATCOM was presented and tested on both single and multi-machine power systems.

It has been found that in practice, most engineering systems have frequent disturbances capable of inevitably degrading the desired control performance of the closed-loop dynamics. The disturbances considered include external disturbances, parametric uncertainties and other unknown nonlinear terms. Therefore, the desired control design method needs to include the disturbance dynamics to reject the effects of the abovementioned disturbances. Disturbance observer method is an approach for compensating the result from external disturbances and mismatched disturbances/uncertainties. This method has been widely accepted in compensating the effects of disturbances. The disturbance observer is utilized to estimate disturbances appearing in the system. There is current development of disturbance observer design combined with most popular nonlinear control methods such as backstepping method [19] and sliding mode method [20], as presented in [20]–[26]. Based on the abovementioned references, disturbance observer-based control is a promising method capable of rejecting external disturbances and improving robustness against uncertainties [20] simultaneously. It also provides an effective way to handle external disturbances and system uncertainties. Additionally, disturbance observer design method can be further extended to several problems in control system societies, such as adaptive control [27], finite-time control [28], tracking control [29], and so on. Further, this method can be successfully applied for numerous kinds of real engineering systems such as flight control systems [20], permanent magnet synchronous motors [20], air-breathing hypersonic vehicle systems [21], power systems [22, 23], active suspension system [24], electro-hydrolic actuator systems [29], and so on. Those indicate important application potentials of the disturbance observer-based control method to deal with the effect of unavoidable external disturbances. However, even though the control design methods presented in [11]–[16] have good control performances, external disturbances and uncertainties have not been taken into account before. These disturbances may lead to poor performances, and eventually make the system unstable.

This paper presents a systematic procedure to synthesize a nonlinear feedback stabilizing control law on the basis of a backstepping control [19] combined with the disturbance observer design, it is developed to cope with the adverse effects of external disturbances. Therefore, the merits of this work are as follows: (a) The use of a nonlinear disturbance observer-based backstepping control strategy to stabilize the system in the presence of external disturbances has not been investigated before for power systems with STATCOM; (b) The overall closed-loop system is input-to state despite external disturbances; (c) In comparison with a backstepping control, the developed control law offers better dynamic performances and a satisfactory disturbance rejection ability.

The rest of this paper is organized as follows. Simplified synchronous generator and STATCOM models are briefly described, and the problem statement is given in Section 2. Control design is given in Section 3. Simulation results are given in Section 4. Conclusions are given in Section 5.

2. POWER SYSTEM MODEL DESCRIPTION

2.1 Power system models with STATCOM

The complete dynamical model [16, 17] of the synchronous generator (SG) connected to an infinite bus with STATCOM dynamics can be expressed as follows:

$$\begin{cases} \dot{\delta} &= \omega - \omega_s + d_1 \\ \dot{\omega} &= \frac{1}{M}\left(P_m - P_e - P_s - D(\omega-\omega_s)\right) + d_2 \\ \dot{P}_e &= (-a + \cot\delta(\omega-\omega_s))P_e + \frac{bV_\infty \sin 2\delta}{2(X_1+X_2)} \\ & \quad + \frac{V_\infty \sin\delta}{(X_1+X_2)} \cdot \frac{u_f}{T_0'} + d_3, \\ \dot{P}_s &= \mathcal{N}(\delta,P_e,P_s)(-a+\cot\delta(\omega-\omega_s))P_e \\ & \quad + \frac{\mathcal{N}(\delta,P_e,P_s)bV_\infty \sin 2\delta}{2(X_1+X_2)} + \frac{\mathcal{N}(\delta,P_e,P_s)V_\infty \sin\delta}{(X_1+X_2)} \cdot \frac{u_f}{T_0'} \\ & \quad + \frac{P_e X_1 X_2}{\Delta(\delta,P_e)} \cdot \frac{1}{T}\left(-\left(\frac{P_s\Delta(\delta,P_e)}{P_e X_1 X_2} - I_{qe}\right) + u_q\right) + d_4, \end{cases} \tag{1}$$

with $\Delta(\delta, P_e), \mathcal{N}(\delta, P_e), P_e, P_s, a$ and b given in [16], where δ is the power angle of the generator, ω denotes the relative speed of the generator, $D \geq 0$ is a damping constant, P_m is the mechanical input power, E denotes the generator transient voltage source, $P_E = \frac{EV_\infty \sin\delta}{X_{d\Sigma'}}$ is the electrical power, without STATCOM, delivered by the generator to the voltage at the infinite bus V_∞, ω_s is the synchronous machine speed, $\omega_s = 2\pi f$, H represents the per unit inertial constant, f is the system frequency and $M = 2H/\omega_s$. X_d' denotes the direct axis transient reactance of SG and X_d denotes the direct axis reactance of SG. X_T is the reactance of the transformer, and X_L denotes the reactance of the transmission line. For simplicity, X_1 is the reactance consisting of the direct axis transient reactance of SG and the reactance of the transformer, and X_2 is the reactance of the transmission line. T_0' is the direct axis transient short-circuit time constant. u_f is the field voltage control input to be designed. I_Q denotes the injected or absorbed STATCOM current as a controllable current source, I_{Qe} is an equilibrium point of STATCOM currents, u_q is the STATCOM control input to be designed, and T is a time constant of the STATCOM model. $d_j(t), (j = 1, 2, 3, 4)$ are external disturbances and system parameter variations.

For convenience, let us introduce new state variables as follows:

$$x_1 = \delta - \delta_e, x_2 = \omega - \omega_s, x_3 = P_e, x_4 = P_s, \qquad (2)$$

Subsequently, after differentiating the state variables (2), we have the power system with STATCOM which can be written in the following form of an affine nonlinear system[1]:

$$\dot{x} = f(x) + g(x)u(x) + d(t), \qquad (3)$$

where $f(x), g(x), u(x)$ and $d(t)$ are given at the top of the next page. The region of operation is defined in the set $\mathcal{D}| = \{x \in \mathcal{S}| \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R}|\ 0 < x_1 < \frac{\pi}{2}\}$. The open loop operating equilibrium is denoted by $x_e = [x_{1e},\ 0,\ x_{3e},\ x_{4e}]^T = [\delta_e,\ 0,\ P_m, 0]^T$

For the sake of simplicity, the power system considered (3) can be expressed in the following form.

$$\begin{cases} \dot{x}_1 &= x_2 + d_1, \\ \dot{x}_2 &= \frac{1}{M}\left(P_m - Dx_2 - x_3 - x_4\right) + d_2, \\ \dot{x}_3 &= f_3(x) + g_{31}(x)\frac{u_f}{T_0'} + d_3, \\ \dot{x}_4 &= f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_q}{T} + d_4 \end{cases} \qquad (4)$$

2.2 Preliminaries

In this subsection, some important lemmas are mentioned as follows for convenience of the reader. Consider the following system

$$\dot{y} = f(t, y, u), y \in \mathbb{R}^n, u \in \mathbb{R}^m. \qquad (5)$$

Definition 1: [30] A continuous function $\alpha : [0, a) \to [0, +\infty)$ belongs to class $\mathcal{K}$ if it is strictly increasing and $\alpha(0) = 0$. It belongs to class $\mathcal{K}_\infty$ if $a = +\infty$ and $a(r) \to +\infty$ as $r \to +\infty$.

Lemma 1: [30] Let $V : [0, \infty) \times \mathbb{R}^n \to \mathbb{R}$ be a continuously differentiable function such that

$$\begin{aligned} \alpha_1(||y||) &\leq V(t, y) \leq \alpha_2(||y||) \\ \frac{\partial V}{\partial t} + \frac{\partial V}{\partial y} f(t, y, u) &\leq -W_3(y), \forall ||x|| \geq \rho(||u||) > 0, \end{aligned}$$

for all $(t, y, u) \in [0, \infty) \times \mathbb{R}^\ltimes \times \mathbb{R}^\gtrdot$, where α_1 and α_2 are class $\mathcal{K}$ functions, ρ is a class $\mathcal{K}$ function, and $W_3(y)$ is a continuous positive definite function on $\mathbb{R}^\ltimes$. Then, system (5) is input-to-state stable (ISS)

Lemma 2: [30] Consider the following system (5). If the following conditions are satisfied
- system $\dot{y} = f(t, y, u)$ is input-to-state stable.
- $\lim_{t\to+\infty} u = 0$.

then the states of the system (4) will asymptotically converge to zero, that is, $\lim_{t\to+\infty} y(t) = 0$.

Before stating the problem statement and control design, the following assumption needs to be made as well.

Assumption 1: The external disturbances $d_j(t), (j = 1, 2, 3, 4)$ are bounded. Also, the first derivatives of the disturbances above are also bounded.

Problem statement: The objectives of this paper are to stabilize the power system including STATCOM (4) with the external disturbance d and to accomplish the desired control performances, which can be formulated as follows: with the help of the nonlinear disturbance observer-based backstepping-like control technique [22], find out, if possible, a stabilizing (state) feedback controller $u(y)$ and disturbance estimation $\hat{d}$ as follows:

$$\begin{cases} u &= \phi(x, \hat{d}) \\ \dot{\hat{d}} &= \varphi(x, u, \hat{d}) \end{cases} \qquad (6)$$

such that the overall closed-loop system (4) and (6) is input-to-state stable, where $\hat{d}$ is the estimate of d

For the developed design procedure in the next section, a combination of the backstepping scheme and disturbance observer design will be developed to obtain a composite nonlinear controller (6). In comparison with the conventional backstepping and integral backstepping methods, the proposed approach will use the full information of the disturbance estimation into each step. Such information is also used for compensating the external disturbances at each step, and the estimation error dynamics are included for the closed-loop stability analysis. In addition, As the system is subjected to external disturbances, the proposed composite controller can offer the capability to maintain the power system stability, to reject undesired disturbances, and to improve transient control performances. In the following section, the developed controller is designed to achieve the desired performances.

3. CONTROLLER DESIGN AND STABILITY ANALYSIS

This section aims to determine the control laws for stabilizing the power system with STATCOM. The proposed design procedure is divided into three parts.
- The first part introduces a nonlinear disturbance observer technique to estimate the unknown, but bounded, disturbances and to compensate for the external disturbance.
- The second part proposes an approach consisting of the backstepping control method and the result of the disturbance estimator from the first part to find the desired controller in each design step.
- The last part shows that Lyapunov stability theorem is used to analyze the overall closed-loop system stability. Despite having disturbances in the system,

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It is assumed that all functions and mapping are smooth, i.e. $\mathbb{C}^\infty$, throughout this paper

$$\begin{cases} f(x) &= \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \end{bmatrix} = \begin{bmatrix} x_2 \\ \frac{1}{M}\left(P_m - x_3 - x_4 - Dx_2\right) \\ (-a + x_2 \cot x_1)x_3 + \frac{bV_\infty \sin 2x_1}{2(X_1+X_2)} \\ \mathcal{N}(x_1, x_3)(-a + x_2 \cot x_1)x_3 + \frac{\mathcal{N} bV_\infty \sin 2x_1}{2(X_1+X_2)} - \frac{x_3 X_1 X_2 \left(\frac{x_4 \Delta(x_1,x_3)}{x_3 X_1 X_2} - I_{qe}\right)}{\Delta(x_1,x_3)} \end{bmatrix}, \\ g(x) &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ g_{31}(x) & 0 \\ g_{41}(x) & g_{42}(x) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{V_\infty \sin x_1}{(X_1+X_2)} & 0 \\ \frac{\mathcal{N} V_\infty \sin x_1}{(X_1+X_2)} & \frac{x_3 X_1 X_2}{\Delta(x_1,x_3)} \end{bmatrix}, \ x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, \ u(x) = \begin{bmatrix} \frac{u_f}{T_0'} \\ \frac{u_q}{T} \end{bmatrix}, d(t) = \begin{bmatrix} d_1(t) \\ d_2(t) \\ d_3(t) \\ d_4(t) \end{bmatrix}. \end{cases}$$

the results indicate that it is capable of achieving both system stability and the desired control performances by the obtained controller.

3.1 Nonlinear disturbance observer design

The aim of designing the disturbance observer is to estimate the external disturbance and other uncertainties so that the effect of disturbances is removed and the whole system performance can be enhanced. The disturbance observer proposed in [20]–[22] is used to estimate the disturbance and is applied with the control input.

Therefore, the nonlinear disturbance observer for the system (4) is designed as

$$\begin{cases} \hat{d}_i &= \lambda_i(x_i - p_i), i = 1, 2, 3, 4, \\ \dot{p}_1 &= f_1(x) + \hat{d}_1, \\ \dot{p}_2 &= f_2(x) + \hat{d}_2, \\ \dot{p}_3 &= f_3(x) + g_{31}(x)\frac{u_f}{T_0'} + \hat{d}_3, \\ \dot{p}_4 &= f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_q}{T} + \hat{d}_4, \end{cases} \quad (7)$$

where $\lambda_j > 0$ is a design parameter. Thus, based on (7) the disturbance estimation dynamics can be expressed in the following form:

$$\dot{\hat{d}}_j = \lambda_i(\dot{x}_j - \dot{p}_j) = \lambda(d_j - \hat{d}_j), j = 1, 2, 3, 4. \quad (8)$$

Let us define the disturbance estimation error as $e_j = d_j - \hat{d}_j$, the estimation error dynamics can be expressed as follows.

$$\dot{e}_j = -\lambda_j e_j + \dot{d}_j. \quad (9)$$

3.2 Backstepping design

According to the concept reported in [22], the stabilization problem for the system (4) is solved by designing a backstepping control. The design procedure is developed step by step as follows.

Step 1: Considering, the first subsystem (4), a Lyapunov function is selected as

$$V_1 = \frac{1}{2}z_1^2 + \frac{1}{2}e_1^2, \quad (10)$$

where $z_1 = x_1$. Then the time derivative of V_1 along the system trajectories becomes

$$\dot{V}_1 = -\lambda_1 e_1^2 + z_1 x_2^* + z_1(x_2 - x_2^*) + z_1 d_1 + e_1 \dot{d}_1. \quad (11)$$

From (11), it is seen that x_2^* is regarded as the virtual control variable with the disturbance estimate $\hat{d}_1$ as follows.

$$x_2^* = -\left(k_1 + \frac{1}{4\epsilon_1}\right) z_1 - \hat{d}_1, \quad (12)$$

where $k_1 > 0$ and $\epsilon_1 > 0$. After substituting (12) into (11), we have

$$\begin{aligned} \dot{V}_1 &= -\left(k_1 + \frac{1}{4\epsilon_1}\right) z_1^2 - \lambda_1 e_1^2 + \frac{1}{4\epsilon_1} z_1^2 + \epsilon_1 e_1^2 \\ &\quad + z_1 z_2 + e_1 \dot{d}_1 \\ &= -k_1 z_1^2 - (\lambda_1 - \epsilon_1)e_1^2 + z_1 z_2 + e_1 \dot{d}_1, \end{aligned} \quad (13)$$

where $z = x_2 - x_2^*$.

Step 2: Let us define the Lyapunov function of Step 1 as $V_2 = V_1 + \frac{1}{2}z_2^2 + \frac{1}{2}e_2^2$. Then the time derivative of V_2 along the system trajectories is as follows:

$$\begin{aligned} \dot{V}_2 &= -k_1 z_1^2 - (\lambda_1 - \epsilon_1)e_1^2 - \lambda_2 e_2^2 + z_1 z_2 - \frac{1}{M} z_2 x_3^* \\ &\quad - \frac{1}{M} z_2 x_4^* - z_2 \frac{\partial x_2^*}{\partial z_1} x_2 + z_2 \Bigg[d_2 + \frac{1}{M}\Bigg(P_m - Dx_2 \\ &\quad - (x_3 - x_3^*) - (x_4 - x_4^*) - \frac{\partial x_2^*}{\partial z_1}(x_2 + d_1) \Bigg) \Bigg] \\ &\quad - z_2 \frac{\partial x_2^*}{\partial \hat{d}_1} \lambda_1 e_1 + e_1 \dot{d}_1 + e_2 \dot{d}_2. \end{aligned} \quad (14)$$

From (14), it can be observed that x_3^* and x_4^* are considered as the virtual control variables with the disturbance estimates $\hat{d}_1$ and $\hat{d}_2$ as follows.

$$\begin{cases} x_3^* &= \frac{M}{2}\Big[-\left(k_2 + \frac{1}{4\epsilon_2} + \hat{c}_2\right) z_2 - P_m - z_1 \\ &\qquad + \frac{Dx_2}{M} - \hat{d}_2 + \frac{\partial x_2^*}{\partial z_1}(x_2 + \hat{d}_1)\Big], \\ x_4^* &= x_3^* + \frac{MP_m}{2}, \end{cases} \quad (15)$$

where $k_2 > 0, \epsilon_2 > 0$ and $\hat{c}_2 = \frac{1}{4\epsilon_2}\left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right)^2$. After substituting (15) into (14), we obtain

$$\begin{aligned}\dot{V}_2 &= -k_1 z_1^2 - \lambda_1 e_1^2 - \left(k_2 + \frac{1}{4\epsilon_2} + \hat{c}_2\right) z_2^2 - \lambda_2 e_2^2 \\ &\quad -\frac{1}{M} z_2(x_3 - x_3^*) - \frac{1}{M} z_2(x_4 - x_4^*) + z_2 e_2 \\ &\quad -z_2\left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right) e_1 + e_1\dot{d}_1 + e_2\dot{d}_2. \quad (16)\end{aligned}$$

Based on Young inequality [31], the terms in (16) can be straightforwardly computed as

$$\begin{aligned} e_2 z_2 &\leq \frac{1}{4\epsilon_2} z_2^2 + \epsilon_2 e_2^2, \quad (17) \\ -z_2\left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right) e_1 &\leq \hat{c}_2 z_2^2 + \epsilon_1 e_1^2, \quad (18)\end{aligned}$$

where $\hat{c}_2 = \frac{1}{4\epsilon_2}\left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right)^2 \epsilon_1^2$.

Substituting (17)-(18) into (16) and then defining $z_i = x_i - x_i^*, i = 3, 4$, we get

$$\begin{aligned}\dot{V}_2 &\leq -k_1 z_1^2 - k_2 z_2^2 - (\lambda_1 - 2\epsilon_1)e_1^2 - (\lambda_2 - \epsilon_2)e_2^2 \\ &\quad -\frac{z_2}{M}(z_3 + z_4). \quad (19)\end{aligned}$$

Step 3: we select a Lyapunov function as follows:

$$V_3 = V_2 + \frac{1}{2}\sum_{i=3}^{4}(z_i^2 + e_i^2). \quad (20)$$

After taking derivatives of both sides of (20), one has

$$\begin{aligned}\dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 - (\lambda_1 - 2\epsilon_1)e_1^2 - (\lambda_2 - \epsilon_2)e_2^2 \\ &\quad -\frac{z_2}{M}(z_3 + z_4) + \sum_{i=3}^{4}\left[z_i\left(\dot{x}_i - \frac{\partial x_i^*}{\partial z_1}\dot{z}_1 - \frac{\partial x_i^*}{\partial z_2}\dot{z}_2\right.\right. \\ &\quad \left.\left.-\frac{\partial x_i^*}{\partial \hat{d}_1}\lambda_1 e_1 - \frac{\partial x_i^*}{\partial \hat{d}_2}\lambda_2 e_2\right) - \lambda_i e_i^2 + e_i\dot{d}_i\right]. \quad (21)\end{aligned}$$

Substituting $\dot{x}_i, (i = 3, 4)$ from (4), $\dot{z}_1, \dot{z}_2$ and x_2^* into (21) yields

$$\begin{aligned}\dot{V}_3 &\leq -k_1 z_1^2 - k_2 z_2^2 - (\lambda_1 - 2\epsilon_1)e_1^2 - (\lambda_2 - \epsilon_2)e_2^2 \\ &\quad -\sum_{i=3}^{4}(\lambda_i e_i^2 - e_i\dot{d}_i) + z_3\left[-\frac{z_2}{M} + f_3(x)\right. \\ &\quad +g_{31}(x)\frac{u_f}{T_0'} + d_3 - \frac{\partial x_3^*}{\partial z_1}(x_2 + \hat{d}_1) \\ &\quad -\frac{\partial x_3^*}{\partial z_2}(f_2(x) + d_2) + \frac{\partial x_3^*}{\partial z_2}\frac{\partial x_2^*}{\partial x_1}(x_2 + d_1) \\ &\quad \left.-\frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1 e_1\right] - z_3\left(\frac{\partial x_3^*}{\partial \hat{d}_1}\lambda_1 e_1 + \frac{\partial x_3^*}{\partial \hat{d}_2}\lambda_2 e_2\right) \\ &\quad +z_4\left[-\frac{z_2}{M} + f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_q}{T}\right. \\ &\quad +d_4 - \frac{\partial x_4^*}{\partial z_1}(x_2 + \hat{d}_1) - \frac{\partial x_4^*}{\partial z_2}(f_2(x) + d_2) \\ &\quad \left.+\frac{\partial x_4^*}{\partial z_2}\frac{\partial x_2^*}{\partial x_1}(x_2 + d_1) - \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1 e_1\right] \\ &\quad -z_4\left(\frac{\partial x_4^*}{\partial \hat{d}_1}\lambda_1 e_1 + \frac{\partial x_4^*}{\partial \hat{d}_2}\lambda_2 e_2\right). \quad (22)\end{aligned}$$

From (22), in order to achieve the desired control performance, we choose the control law as follows:

$$\begin{cases}\frac{u_f}{T_0'} &= \frac{1}{g_{31}(x)}\left[\frac{z_2}{M} - f_3(x) - \hat{d}_3 + \frac{\partial x_3^*}{\partial z_1}(x_2 + \hat{d}_1)\right. \\ &\quad +\frac{\partial x_3^*}{\partial z_2}\left(f_2(x) + \hat{d}_2 - \frac{\partial x_2^*}{\partial z_1}(x_2 + \hat{d}_1)\right) \\ &\quad \left.-\left(k_3 + \frac{1}{4\epsilon_3} + \hat{c}_{31} + \hat{c}_{32} + \hat{c}_{33} + \hat{c}_{34}\right) z_3\right] \\ \frac{u_q}{T} &= \frac{1}{g_{42}(x)}\left[\frac{z_2}{M} - f_4(x) - g_{41}(x)\frac{u_f}{T_0'} + \frac{\partial x_4^*}{\partial z_1}(x_2 + \hat{d}_1)\right. \\ &\quad +\frac{\partial x_4^*}{\partial z_2}\left(f_2(x) + \hat{d}_2 - \frac{\partial x_2^*}{\partial z_1}(x_2 + \hat{d}_1)\right) - \hat{d}_4 \\ &\quad \left.-\left(k_4 + \frac{1}{4\epsilon_4} + \hat{c}_{41} + \hat{c}_{42} + \hat{c}_{43} + \hat{c}_{44}\right) z_4\right]\end{cases} \quad (23)$$

where

$$\begin{cases}\hat{c}_{i1} &= \frac{1}{4\epsilon_1}\left(\frac{\partial x_i^*}{\partial z_1} + \frac{\partial x_i^*}{\partial \hat{d}_1}\lambda_1\right)^2, \\ \hat{c}_{i2} &= \frac{1}{4\epsilon_2}\left(\frac{\partial x_i^*}{\partial z_2} + \frac{\partial x_i^*}{\partial \hat{d}_2}\lambda_2\right)^2, \\ \hat{c}_{i3} &= \frac{1}{4\epsilon_1}\left[\frac{\partial x_i^*}{\partial z_2}\left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_i^*}{\partial \hat{d}_1}\lambda_1\right)\right]^2, \\ \hat{c}_{i4} &= \frac{1}{4\epsilon_2}\left[\frac{\partial x_i^*}{\partial x_2}\right]^2, i = 3, 4.\end{cases} \quad (24)$$

Substituting the presented control law (23) into

(22), we have

$$\begin{aligned}\dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 - (\lambda_1 - 2\epsilon_1)e_1^2 - (\lambda_2 - \epsilon_2)e_2^2 \\ &\quad - \sum_{i=3}^{4}(\lambda_i e_i^2 - e_i \dot{d}_i) + \sum_{i=3}^{4} z_i \Big[e_i - \frac{\partial x_i^*}{\partial z_1} e_1 \\ &\quad - \frac{\partial x_i^*}{\partial z_2} e_2 + \frac{\partial x_i^*}{\partial z_2}\frac{\partial x_2^*}{\partial z_1} e_1 - \frac{\partial x_i^*}{\partial x_2} e_2 \\ &\quad + \left(k_i + \frac{1}{4\epsilon_1} + \hat{c}_{i1} + \hat{c}_{i2} + \hat{c}_{i3} + \hat{c}_{i4}\right) z_i \Big] \\ &\quad - \sum_{i=3}^{4} z_i \Big[\sum_{k=1}^{2} \frac{\partial x_i^*}{\partial \hat{d}_k}\lambda_k e_k + \frac{\partial x_i^*}{\partial z_2}\frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1 e_1 \Big] \end{aligned} \quad (25)$$

It is observed that some terms of the last two lines in (25) can be changed into the following inequalities:

$$\begin{aligned} -z_i \left(\frac{\partial x_i^*}{\partial z_2} + \frac{\partial x_i^*}{\partial \hat{d}_2}\lambda_k\right) e_k &\leq \hat{c}_{i2} z_i^2 + \epsilon_k e_k^2, \\ -z_i \left[\frac{\partial x_i^*}{\partial z_2}\left(\frac{\partial x_i^*}{\partial z_1} + \frac{\partial x_i^*}{\partial \hat{d}_1}\lambda_1\right)\right] e_1 &\leq \hat{c}_{i3} z_i^2 + \epsilon_1 e_1^2 \\ -z_i \frac{\partial x_i^*}{\partial x_2} e_2 &\leq \hat{c}_{i4} z_i^2 + \epsilon_2 e_2^2, \end{aligned}$$

where $\hat{c}_{i2}, \hat{c}_{i3}$ and $\hat{c}_{i4}$ have been given in (24)

After substituting the three inequalities above and then combining those inequalities with (25), we have

$$\begin{aligned} \dot{V}_3 &\leq -\sum_{j=1}^{4}(k_j z_j^2 + e_j \dot{d}_j) - (\lambda_1 - 6\epsilon_1)e_1^2 \\ &\quad -(\lambda_2 - 2\epsilon_2)e_2^2 - \sum_{i=3}^{4}(\lambda_i - \epsilon_i)e_i^2 \end{aligned} \quad (26)$$

In the next subsection, the stability analysis of the closed-loop dynamics with the control law (23) is presented.

4. STABILITY ANALYSIS

In this subsection, the overall closed-loop stability of the system (4) with the the proposed control law (23) and the error estimation dynamics (9) are analyzed within the framework of Lyapunov theory.

Therefore, we can summarize the control design in the following theorem.

Theorem 1: Under Assumption 1, the nonlinear disturbance observer-based backstepping controller (23) can guarantee that the overall closed-loop system consisting of the system and the disturbance observer error dynamics with the developed controller is input-to-state stable.

Proof: To demonstrate the closed-loop stability of the the presented control strategy, let us define the following Lyapunov function for the closed-loop dynamics.

$$V_3 = \sum_{j=1}^{4} \frac{1}{2}(z_j^2 + e_j^2). \quad (27)$$

After computing the time derivative of the Lyapunov function candidate (27) and selecting $\lambda_1 = a_{01} + 6\epsilon_1, \lambda_2 = a_{02} + 2\epsilon_2, \lambda_i = a_{0i} + \epsilon_i, (i = 3, 4), a_{0j} > 0, (j = 1, 2, 3, 4)$, we obtain

$$\begin{aligned} \dot{V}_3 &\leq -\sum_{j=1}^{4} k_j z_j^2 - \sum_{j=1}^{4} a_{0j} e_j^2 + \sum_{j=1}^{4} e_j \dot{d}_j \\ &\leq -\sum_{j=1}^{4} k_j z_j^2 - a_0\|e\|^2 + \|e\|\|\dot{d}\|, \end{aligned} \quad (28)$$

where $e = [e_1, e_2, e_3, e_4]^T, \dot{d} = [\dot{d}_1, \dot{d}_2, \dot{d}_3, \dot{d}_4]^T, a_0 = \min\{a_{01}, a_{02}, \ldots, a_{04}\}$. The inequality (28) can be rewritten as

$$\begin{aligned} \dot{V}_3 &\leq -\sum_{j=1}^{4} k_j z_j^2 - (1-\theta)a_0\|e\|^2 - \theta a_0\|e\|^2 \\ &\quad + \|e\|\|\dot{d}\|, \end{aligned} \quad (29)$$

where $0 < \theta < 1$. If we select $\|e\| \geq \frac{\|\dot{d}\|}{a_0\theta}$, it is easy to obtain that $\dot{V}_3 \leq -\sum_{j=1}^{4} k_j z_j^2 - (1-\theta)a_0\|e\|^2 \leq 0$. Thus, the conditions of Lemmas 1 and 2 are satisfied with $\alpha_1(r) = c_1 r^2, \alpha_2(r) = c_2 r^2$, and $\rho(r) = (1/a_0\theta)r$, and we can conclude that the overall closed-loop system is input-to-state stable. This completes the proof.

Assumption 2: The disturbances satisfy the condition of $\lim_{t\to+\infty} \dot{d}_j(t) = 0$.

Theorem 2: Under Assumptions 1 and 2, the closed-loop dynamics under the control law (23) and the disturbance estimation (7) will asymptotically converge to zero.

Proof: It is seen from the closed-loop system that $\dot{d}_j$ can be regarded as an input of the system. After combining Theorem 1 with Assumption 2, it follows from Lemma 2 that $\dot{V}_3 \leq 0$. In accordance with Lyapunov control theory, it can be concluded that all trajectories of z_j and e_j of the closed-loop dynamics converge to zero. This means that $z_j \to 0$ and $e_j \to 0$ as $t \to +\infty$. This completes the proof.

5. SIMULATION RESULTS

In this section, in order to verify the effectiveness of the proposed nonlinear controller. The proposed controller is evaluated via simulations of a single-machine infinite bus (SMIB) power system consisting of dynamic model of synchronous generators and STATCOM as shown in Fig. 1. The performance of the proposed control scheme is evaluated in MATLAB environment under the presence of undesired external disturbances.

The physical parameters (pu.) and initial conditions ($\delta_e,\ \omega_s,\ P_{ee},\ P_{se}, \hat{d}_{10}, \ldots, \hat{d}_{40}$) for this power system model are are the same as those used in [16]. Additionally, the external disturbances ($d_j, j = 1, 2, 3, 4$) acting on the underlying system are assumed

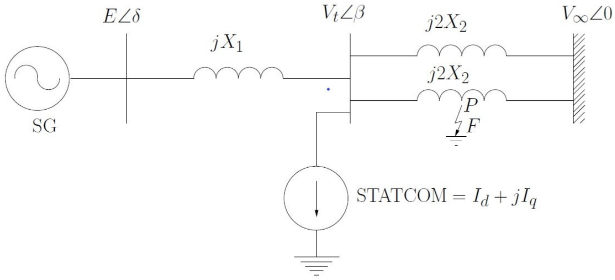

Fig.1: *A single line diagram of SMIB model with STATCOM*

to be:

$$d_1(t) = 0,\ 0 \le t \le 20, \quad (30)$$

$$d_2(t) = \begin{cases} 0.5\sin(2t), & 0 \le t < 5 \\ 1, & 5 \le t < 10, \\ 0.25\sin(2t)e^{-t}, & 10 \le t \le 20 \end{cases} \quad (31)$$

$$d_3(t) = \begin{cases} 0.15\cos(t), & 0 \le t < 5 \\ 2, & 5 \le t < 10, \\ 0.5\cos(t)e^{-2t}, & 10 \le t \le 20 \end{cases} \quad (32)$$

$$d_4(t) = \begin{cases} 0.25\sin(t), & 0 \le t < 5 \\ 2, & 5 \le t < 10, \\ 0.3\sin(t)e^{-3t}, & 10 \le t \le 20 \end{cases} \quad (33)$$

The controller parameters are set as $\epsilon_j = 10, k_j = 20, \lambda_j = 50, (j = 1, 2, \ldots, 4)$. The time domain simulations are carried out to investigate the system stability enhancement and the dynamic performance of the designed controller, as given in (23), in the system in the presence of external disturbances. The control performance of the proposed controller (nonlinear disturbance observer-based backstepping controller) is compared with that of a conventional backstepping controller (CBSC) [19] as shown below.

$$\begin{cases} \frac{u_f}{T_0'} = \frac{1}{g_{31}(x)}\Big[- k_3 z_3 - \frac{z_2}{M} - f_3(x) \\ \quad + \frac{1}{2}\Big(D\dot{x}_2 - M(k_2\dot{z}_2 + \dot{z}_1 + k_1\dot{x}_2)\Big)\Big], \\ \frac{u_q}{T} = \frac{1}{g_{42}(x)}\Big[- k_4 z_4 + \frac{z_2}{M} - f_4(x) \\ \quad - \frac{1}{2}\Big(D\dot{x}_2 - M(k_2\dot{z}_2 + \dot{z}_1 + k_1\dot{x}_2)\Big)\Big], \end{cases} \quad (34)$$

with $z_j = x_j - x_j^*, (j = 1, 2, 3, 4), x_1^* = 0, x_2^* = -k_1 z_1, x_3^* = -\frac{1}{2}(Dx_2 - M(k_2 z_2 + z_1 + k_1 x_2)) + P_m, x_4^* = x_3^* - P_m, \dot{z}_1 = -c_1 z_1 + z_2, \dot{z}_2 = f_2(x) + c_1 x_2$. The controller parameters of this scheme are set as $c_j = 50, (j = 1, 2, \ldots, 4)$.

The simulation results are presented and discussed as follows. Time histories of the power angle, frequency, transient internal voltage, and STATCOM current under two controllers are presented in Fig. 2. Also, the results of disturbance estimation and external disturbances together with disturbance estimation error is demonstrated in Figs. 3 and 4.

From these Figs., it can be seen that the developed method and the CBSC method is able to successfully stabilize the system despite having external disturbances given in (30)-(33). In addition, it can be observed that the presented control has not only better dynamic performances, but also satisfactory disturbance rejection ability such as a shorter settling time, a short rise time, and a faster convergence rate. Clearly, all time responses are significantly more damped with the proposed scheme than with the CBSC scheme. Compared with the presented method, the CBSC scheme has worse dynamic performances such as unsatisfactory overshoots and slowly suppressing system oscillations. This is because in the developed control framework the proposed nonlinear control combines the advanced feedback control law with the full use of disturbances information in each step to mitigate the effects of inevitable disturbances. In constrast, the BSC method does not include the effects of disturbances in the designed control law. Fig. 3 shows the disturbance estimators can rapidly track the unknown external disturbances with fast convergence rate and no oscillations. Also, the error between unknown disturbances and disturbance estimator is shown in Fig. 4.

From the simulation results mentioned above, it is evident that as the presented method combined with the disturbance observer design is applied to the SMIB power system with STATCOM under external disturbances, the advantages over the CBSC method are as follows.

- The proposed control law is effectively designed to stabilize the system in the presence of undesired disturbances.
- The developed control strategy can make the overall closed-loop dynamics converge more quickly to a desired equilibrium point. In particular, it obviously performs well and has considerably effective disturbance rejection ability. It offers obviously superior transient performances illustrated by the rapid suppression of system oscillations in all time trajectories in spite of having external disturbances.
- The process of designing the desired control law includes some auxiliary terms into the virtual control laws and the final controller. These terms can counteract the crossing terms arising from disturbances, compensation errors, and system states. In contrast, these terms are not included in the CBSC method, thereby leading to unsatisfactory control performances.

6. CONCLUSION

In this paper, a composite nonlinear control strategy has been developed for power systems with STATCOM under external disturbances. The presented composite control law has been designed based

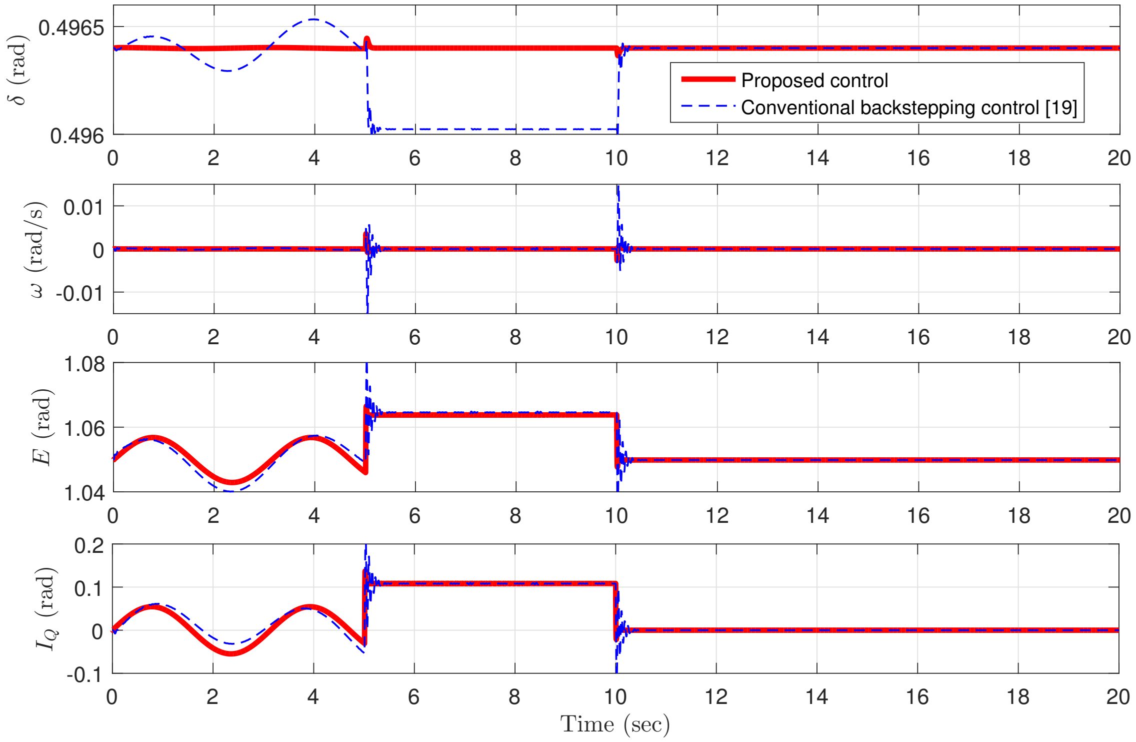

Fig.2: *Controller performance–Power angles (δ) (rad.), frequency ($\omega - \omega_s$) rad/s., transient voltage, and STATCOM current (Solid: The proposed control, Dashed: Backstepping control without disturbance observer)*

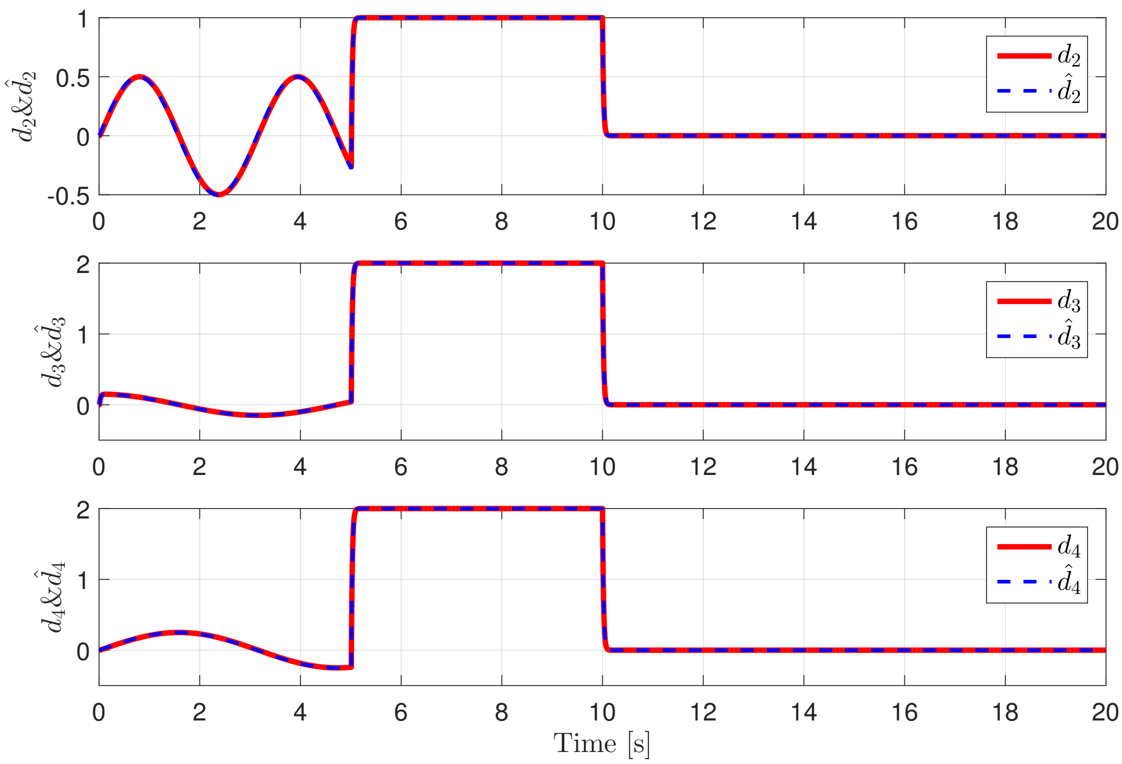

Fig.3: *External disturbances and disturbance estimations*

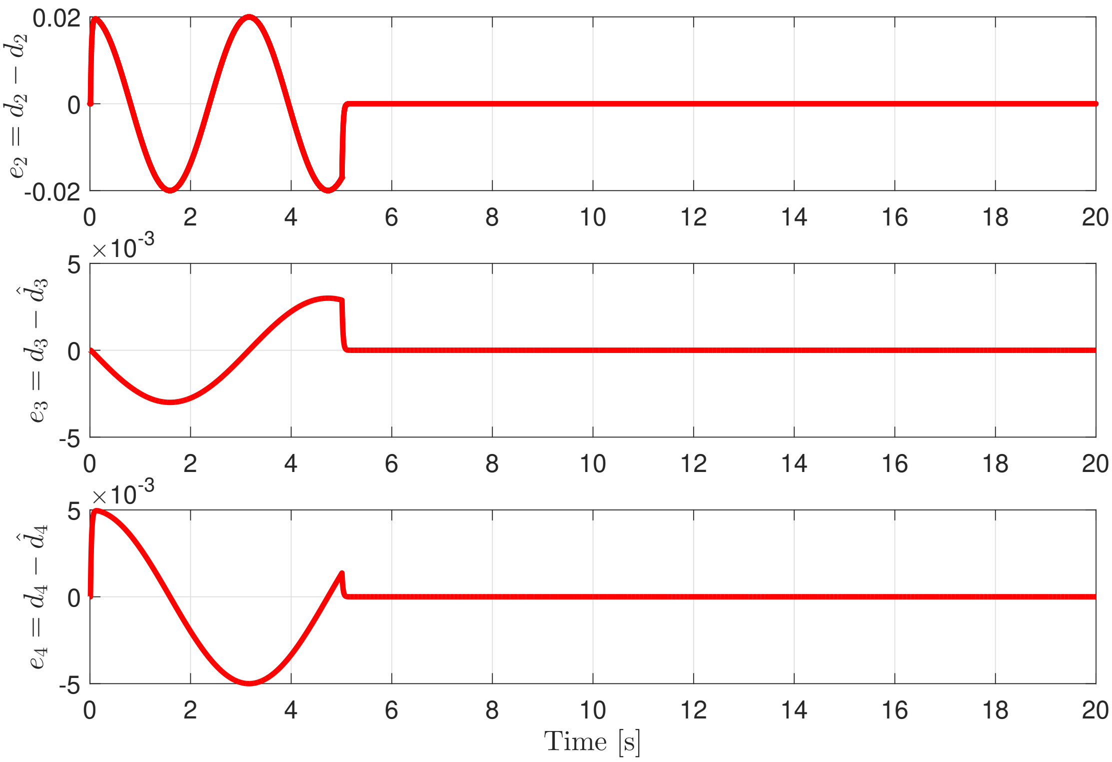

Fig.4: *Disturbance estimation error*

on a combination of backstepping control and a disturbance observer method. This combination can offer not only better dynamic performance, but also disturbance rejection ability as compared with the conventional backstepping control (CBSC). With the help of Lyapunov control theory, the stability analysis of closed-loop system has been provided in spite of having both non-vanishing and vanishing disturbances. The simulation results have confirmed that even though the CBSC method is an effective method to stabilize the overall closed-loop dynamics, the nonlinear composite control can clearly improve the transient performances and has better disturbance rejection property than the CBSC method.

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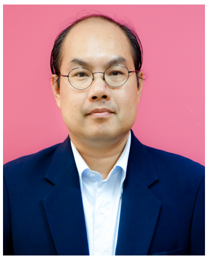

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