A COMPOSITE NONLINEAR CONTROLLER FOR POWER SYSTEMS WITH STATIC SYNCHRONOUS COMPENSATORS UNDER EXTERNAL DISTURBANCES

Kruwan Wongsurith[1], Piraporn Konkhum[2], Suwit Wongkumsin[3], Adirak Kanchanaharutha[4], Somchai Poonyaniran[5] and Pinit Ngamsom[6]

[1,2,3]Lecturer, Faculty of Engineering, Kasem Bundit University, Bangkok, 10250, Thailand, [1]kruawan2011@gmail.com, [2]neckbu@gmail.com, [3]suwit.won@kbu.ac.th

[4,5]Lecturer, Department of Electrical Engineering, Rangsit University, Patumthani, 12000, Thailand, [4]adirak@rsu.ac.th, [5]poon_somchai@yahoo.com

[6]Lecturer, Department of Mechanical Engineering, Rangsit University, Patumthani, 12000, Thailand, ngamsomp@hotmail.com

ABSTRACT

This paper concentrates on the design of a composite nonlinear stabilizing state feedback control for power systems with static synchronous compensator (STATCOM) with a combined improved backstepping strategy and nonlinear disturbance approach. The disturbance observer is employed to estimate unavoidably external disturbances. Thus, the resulting controller enables us to successfully not only stabilize the system stability but also reject undesired external disturbances. To indicate the effectiveness and superiority of the developed process, numerical simulation results are given to show that the proposed composite control law can improve dynamic performances, rapidly suppress system oscillations of the overall closed-loop dynamics, and outperform a conventional backstepping control technique despite the presence of inevitably external disturbances

KEYWORDS: Backstepping control, STATCOM, generator excitation, disturbance observer.

1. Introduction

It is well-known that modern power systems have a rapid increase in the size and complexity. When power system operation is confronted with unavoidable disturbances, maintaining power system stability is one of the most critical problems. Therefore, this problem has attracted much attention from several researchers. Currently, three effective and promising methods are used to improve system stability under unpredictable disturbances. The first method is the utilization of generator excitation control [1-7]. The second method is a combination of the excitation and energy storage system [8, 9]. The third method is the coordination of the excitation and Flexible AC Transmission System (FACTS) devices [10, 11]. These schemes focus on improving power system stability and accomplishing the desired control objectives.

Because of recently fast developments in power electronic devices, FACTS devices have been employed to provide an opportunity to tackle the existing transmission facilities effectively and to deal with several constraints for building new transmission lines. Even although there are a variety of FACTS, the Static Synchronous Compensator (STATCOM) [10, 11] of particular interest in this paper 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 improve both damping oscillation and transient stability. So far, the generator excitation controller [1] and STATCOM controller [11] have separately designed. However, to further enhance the power system stability of power systems, the combination of generator excitation and STATCOM is a promising and useful method and has attracted much attention in literature for years.

To the best of our knowledge, based on directly the nonlinear control strategy, there is prior work devoted to synthesizing a combined generator excitation and STATCOM controller. In [12, 13], 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 [14] for the single-machine infinite bus system was investigated. A nonlinear coordinated controller [15] has been developed through a combination of the passivity design and backstepping technique. Kanchanaharuthai et al. [16] have 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 [17], a coordinated immersion and invariance (I&I) control scheme has been developed for transient stability improvement and voltage regulation. Kanchanaharuthai [18] presented an adaptive I&I control and adaptive backstepping control algorithm to enhance transient stability and voltage regulation for power systems with STATCOM in the presence of unknown parameters. In [19], Kanchanaharuthai and Boonyaprapasorn proposed a simple, but effective, nonlinear controller to enhance transient stability and voltage regulation for power systems including STATCOM via backstepping-like approach. Kanchanaharuthai and Mujjalinvimut [20] presented an adaptive backstepping coordinated excitation and STATCOM control for power systems in the presence of unknown parameters. Recently, based Takagi-Sugeno (T-S) fuzzy scheme, a nonlinear stabilizer design [21] for power systems with random loads and STATCOM was presented and tested on both single and multi-machine power systems. More recently, Kanchanaharuthai and Mujjalinvimut [22] proposed a nonlinear control strategy to avoid the problem of the explosion of terms arising in finding a derivative of virtual control functions in the conventional backstepping scheme. This paper introduced a rapid-convergent differentiator to estimate the derivative with high precision and no chattering phenomenon.

In practice, most engineering systems often have disturbances capable of degrading the desired control performances of the closed-loop dynamics inevitably. 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. Recently, a 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 are currently the developments of disturbance observer design combined with most popular nonlinear control methods such as backstepping method [23] and sliding mode method [24], as presented in [23-33]. Based on the abovementioned references, disturbance observer-based control is a promising method capable of rejecting external disturbances and improving robustness against uncertainties [23] simultaneously. It also provides an effective way to handle external disturbances and system uncertainties. Additionally, the disturbance observer design method can be further extended to a lot of problems in control system societies, such as adaptive control [31], finite-time control [32], tracking control [33], and so on. Further, this method can be successfully applied for numerous kinds of real engineering systems such as flight control systems [24], permanent magnet synchronous motors [24], airbreathing hypersonic vehicle systems [25], power systems [26, 27], active suspension system [28], electrohydrolic actuator systems

[33], and so on. Those indicate significant 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 [12-22] have good control performances, external disturbances and uncertainties have been not taken into account before. These external disturbances may lead to poor performances, and eventually, make the system unstable.

Even though we have so far proposed many prior works [16-20, 22] focusing on the design of nonlinear control schemes and adaptive control methods to stabilize power systems with STATCOM and accomplish the desired control performance simultaneously, those works have not included inevitably external disturbances into the system of interest. Therefore, this paper presents a systematic procedure to synthesize a composite nonlinear control law based on an improved backstepping control [9, 34-35] combined with the disturbance observer design [24]. The obtained controller is developed to cope with the adverse effects of unavoidable external disturbances. Therefore, the merits of this work are as follows: (a) The use of a nonlinear disturbance observer-based improved backstepping control strategy to stabilize the nonlinear power system with STATCOM in the presence of external disturbances has not been investigated before; (b) The overall closed-loop system dynamics are input-to-state in spite of external disturbances; (c) In comparison with a conventional 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. The 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 model with STATCOM

The complete dynamical model [17-20, 22] of the synchronous generator (SG) connected to an infinite bus with STATCOM dynamics can be expressed as follows:

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

with $\Delta(\delta, P_e)$, $\mathcal{N}(\delta, P_e)$, P_e, P_s, a and b given in [17-20, 22], 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, $P_E = \dfrac{EV_\infty \sin\delta}{X_{d\Sigma'}}$ 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 currents 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 STATCOM models. $d_j(t)$, $(j = 1, 2, 3, 4)$ denote external disturbances and system parameter variations.

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

$$x_1 = \delta - \delta_e,\ x_2 = \omega - \omega_s,\ x_3 = P_e, x_4 = P_s, \tag{2}$$

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 power system:

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

where

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \end{bmatrix} = \begin{bmatrix} x_2 \\ \frac{1}{M}\left(P_m - x_3 - x_4 - Dx_2\right) \\ (-a + x_2 \cot x_1)x_3 + \frac{bV_\infty \sin 2x_1}{2(X_1 + X_2)} \\ \mathcal{N}(x_1, x_3)(-a + x_2 \cot x_1)x_3 + \frac{\mathcal{N}bV_\infty \sin 2x_1}{2(X_1 + X_2)} - \frac{x_3 X_1 X_2\left(\frac{x_4 \Delta(x_1, x_3)}{x_3 X_1 X_2} - I_{qe}\right)}{\Delta(x_1, x_3)} \end{bmatrix}, \tag{4}$$

$$g(x) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ g_{31}(x) & 0 \\ g_{41}(x) & g_{42}(x) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{V_\infty \sin x_1}{(X_1 + X_2)} & 0 \\ \frac{\mathcal{N}V_\infty \sin x_1}{(X_1 + X_2)} & \frac{x_3 X_1 X_2}{\Delta(x_1, x_3)} \end{bmatrix}, \; x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, \; u(x) = \begin{bmatrix} \frac{u_f}{T_0'} \\ \frac{u_q}{T} \end{bmatrix}, \; d(t) = \begin{bmatrix} d_1(t) \\ d_2(t) \\ d_3(t) \\ d_4(t) \end{bmatrix}.$$

The region of operation is defined in the set $\mathcal{D} = \left\{ x \in \mathcal{S} \,|\, \times\mathbb{R} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} \,|\, 0 < x_1 < \frac{\pi}{2} \right\}$.

The open-loop operating equilibrium is denoted by $x_e = \left[x_{1e}, 0, x_{3e}, x_{4e}\right]^T = \left[\delta_e, 0, P_m, 0\right]^T$. For the sake of simplicity, the nonlinear power system dynamics including STATCOM given in (3)-(4) are written in the following form.

$$\begin{cases} \dot{x}_1 = x_2 + d_1, \\ \dot{x}_2 = \frac{1}{M}\left(P_m - Dx_2 - x_3 - x_4\right) + d_2, \\ \dot{x}_3 = f_3(x) + g_{31}(x)\frac{u_f}{T_0'} + d_3, \\ \dot{x}_4 = f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_q}{T} + d_4, \end{cases} \tag{5}$$

2.2 Preliminaries

In this subsection, for the convenience of the reader, some important definition and lemmas are given as follows. Consider the following dynamical system

$$\dot{y} = f(t, y, u), y \in \mathbb{R}^n, u \in \mathbb{R}^m. \tag{6}$$

Definition 1: [36] 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: [36] Let $V : [0, \infty) \times \mathbb{R}^n \to \mathbb{R}$ be a continuously differentiable function such tha $\alpha_1(\| y \|) \le V(t, y) \le \alpha_2(\| y \|)$, $\frac{\partial V}{\partial t} + \frac{\partial V}{\partial y} f(t, y, u) \le -W_3(y)$, $\forall \| x \| \ge \rho(\| u \|) > 0$, for all $(t, y, u) \in [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^m$, 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 $\mathbb{R}^n$. Then, the system (6) is input-to-state stable (ISS).

Lemma 2: [36] For the system (6), if the following two conditions are satisfied: (i) system $\dot{y} = f(t, y, u)$ is input-to-state stable and (ii) $\lim_{t \to +\infty} u = 0$, then the states of the system (6) will asymptotically converge to zero, that is, $\lim_{t \to +\infty} y(t) = 0$.

Before mentioning a problem statement and a control design procedure, we make the following assumption as well.

Assumption 1: The external disturbances $d_j(t), (j = 1, 2, 3, 4)$ are bounded, and 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 (5) 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 improved backstepping control technique [5], find out, if possible, a stabilizing (state) feedback controller u and disturbance estimation $\hat{d}$ as follows:

$$\begin{cases} u = \phi(x, \hat{d}), \\ \dot{\hat{d}} = \varphi(x, u, \hat{d}) \end{cases} \tag{7}$$

such that the overall closed-loop system (5) and (7) 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 improved backstepping scheme and disturbance observer design will be developed to obtain a composite nonlinear controller (7). In comparison with the conventional backstepping method, 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. Also, when 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

This section is aimed to determine a composite nonlinear controller for stabilizing the power system with STATCOM under external disturbances. The proposed design procedure is divided into three parts. The first part introduces a nonlinear disturbance observer technique to online estimate the unknown but bounded, disturbances and to compensate for the external disturbance. The second part proposes an approach consisting of the improved 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 the disturbances in the system, the results indicate that it is capable of achieving both the 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 either removed or compensated, and the whole system performance can be enhanced. The disturbance observer proposed in [21-23] is used to estimate the disturbance and is applied with the control input. Therefore, the nonlinear disturbance observer for the system (5) is designed as

$$\begin{aligned} \hat{d}_i &= \lambda_i (x_i - p_i), i = 1,2,3,4, \\ \dot{p}_1 &= f_1(x) + \hat{d}_1, \\ \dot{p}_2 &= f_2(x) + \hat{d}_2, \\ \dot{p}_3 &= f_3(x) + g_{31}(x)\frac{u_f}{T_0'} + \hat{d}_3, \\ \dot{p}_4 &= f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_q}{T} + \hat{d}_4, \end{aligned} \tag{8}$$

where $\lambda_j > 0$ is a design parameter. Thus, based on (8) the disturbance estimation dynamics can be expressed in the following form:

$$\dot{\hat{d}}_j = \lambda_i (\dot{x}_j - \dot{p}_j) = \lambda (d_j - \hat{d}_j), j = 1,2,3,4. \tag{9}$$

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

$$\dot{e}_j = -\lambda_j e_j + \dot{d}_j. \tag{10}$$

3.2 Improved backstepping design

According to the concept reported in [9,34-35], the stabilization problem for the system (5) is solved by designing an improved backstepping control combined with disturbance observer design in the previous subsection. The design process is developed step by step as follows.

Step 1: Considering the first subsystem (5), a Lyapunov function is selected as

$$V_1 = \frac{1}{2} z_1^2 + \frac{1}{2} e_1^2, \tag{11}$$

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

$$\begin{aligned}\dot{V}_1 &= z_1(x_2+d_1)+e_1(-\lambda_1 e_1+\dot{d}_1) = -\lambda_1 e_1^2 + z_1 x_2 + z_1 d_1 + e_1\dot{d}_1 \\ &= -\lambda_1 e_1^2 + z_1 x_2^* + z_1(x_2 - x_2^*) + z_1 d_1 + e_1 \dot{d}_1.\end{aligned} \tag{12}$$

From (12), it is seen that x_2^* is viewed as the virtual control variable with the disturbance estimate $\hat{d}_1$ as follows.

$$x_2^* = -\left(k_1 + \frac{1}{4\epsilon_1}\right) z_1 - \hat{d}_1 - p_2 z_2, 0 < p_2 < 1, \tag{13}$$

where $k_1 > 0$ and $\epsilon_1 > 0$. After substituting (13) into (12), we have

$$\begin{aligned}\dot{V}_1 &= -\left(k_1 + \frac{1}{4\epsilon_1}\right) z_1^2 - \lambda_1 e_1^2 + z_1 e_1 + (1-p_2) z_1 z_2 + e_1 \dot{d}_1 \\ &= -\left(k_1 + \frac{1}{4\epsilon_1}\right) z_1^2 - \lambda_1 e_1^2 + \frac{1}{4\epsilon_1} z_1^2 + \epsilon_1 e_1^2 + (1-p_2) z_1 z_2 + e_1 \dot{d}_1 \\ &\le -k_1 z_1^2 - (\lambda_1 - \epsilon_1) e_1^2 + (1-p_2) z_1 z_2 + e_1 \dot{d}_1\end{aligned} \tag{14}$$

where $z_2 = x_2 - x_2^*, \dot{z}_2 = \dfrac{1}{1-p_2}\left(\dfrac{1}{M}(P_m - Dx_2 - x_3 - x_4) + d_2 - \dfrac{\partial x_2^*}{\partial z_1}(x_2 + d_1) - \dfrac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1 e_1\right)$

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:

$$\begin{aligned}\dot{V}_2 &= -k_1 z_1^2 - (\lambda_1 - \epsilon_1)e_1^2 + (1-p_2) z_1 z_2 + e_1 \dot{d}_1 + e_2 \dot{d}_2 \\ &\quad + \frac{z_2}{1-p_2}\left(\frac{1}{M}(P_m - Dx_2 - x_3 - x_4) + d_2 - \frac{\partial x_2^*}{\partial z_1}(x_2 + d_1) - \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1 e_1\right) \\ &= -k_1 z_1^2 - (\lambda_1 - \epsilon_1)e_1^2 - \lambda_2 e_2^2 + \frac{z_2}{M(1-p_2)}\left[-(x_3 - x_3^*) - (x_4 - x_4^*)\right] \\ &\quad + z_2\left[(1-p_2) z_1 + \hat{d}_2 + \frac{1}{(1-p_2)}\left[\frac{1}{M}\left(P_m - Dx_2 - x_3^* - x_4^*\right) - \frac{\partial x_2^*}{\partial z_1}(x_2 + \hat{d}_1)\right]\right] \\ &\quad - z_2\left(\frac{\partial x_2^*}{\partial \hat{d}_1}\right)\lambda_1 e_1 + \frac{z_2 e_2}{(1-p_2)} - \frac{z_2 e_1}{(1-p_2)}\left(\frac{\partial x_2^*}{\partial z_1}\right)\lambda_1 e_1 + e_1 \dot{d}_1 + e_2 \dot{d}_2.\end{aligned} \tag{15}$$

Based on Young inequality [37], it can be straightforwardly computed some terms in (15) as

$$\frac{e_2 z_2}{(1-p_2)} \le \frac{1}{4\epsilon_2 (1-p_2)^2} z_2^2 + \epsilon_2 e_2^2,$$

$$-\frac{z_2}{(1-p_2)}\left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right) e_1 \le \hat{c}_2 z_2^2 + \epsilon_1 e_1^2,$$

where $\hat{c}_2 = \frac{1}{4\epsilon_2}\left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right)^2 \epsilon_1^2$. From (15), 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.

$$\begin{aligned}&x_3^* = x_{30}^* - p_3 z_3, 0 < p_3 < 1, x_4^* = x_{40}^* - p_4 z_4, 0 < p_4 < 1, \\ &x_{30}^* = P_m + \frac{L}{2}, x_{40}^* = \frac{L}{2}, \\ &L = M(1-p_2)^2 z_1 + Dx_2 + M\left(\hat{d}_2 + \frac{\partial x_2^*}{\partial z_1}(x_2 + \hat{d}_1) + \left(k_2 + \hat{c}_2 + \frac{1}{4\varepsilon_2 (1-p_2)^2}\right) M z_2 (1-p_2)\right), \\ &z_3 = x_3 - x_3^*, z_4 = x_4 - x_4^*,\end{aligned} \tag{16}$$

where $k_2 > 0, \epsilon_2 > 0$. After substituting (16) into (15), we obtain

$$\dot{V}_2 = -k_1 z_1^2 - \lambda_1 e_1^2 - \left(k_2 + \frac{1}{4\epsilon_2} + \hat{c}_2 \right) z_2^2 - \lambda_2 e_2^2 - \frac{(1-p_3)}{M(1-p_2)} z_2 (x_3 - x_3^*)$$
$$- \frac{(1-p_4)}{M(1-p_2)} z_2 (x_4 - x_4^*) + e_1 \dot{d}_1 + e_2 \dot{d}_2 \quad (17)$$
$$\le -k_1 z_1^2 - k_2 z_2^2 - (\lambda_1 - 2\varepsilon_1) e_1^2 - \lambda_2 e_2^2 - \frac{z_2 \left((1-p_3) z_3 + \left((1-p_4) \right) z_4 \right)}{M(1-p_2)} + e_1 \dot{d}_1 + e_2 \dot{d}_2 .$$

From the definition of $z_i = x_i - x_i^*, i = 3,4$, one has the time derivative of z_3, z_4 as follows:

$$\dot{z}_3 = \dot{x}_3 - \dot{x}_3^* = \dot{x}_3 - \dot{x}_{30}^* - p_3 \dot{z}_3 = \frac{1}{1-p_3} \left(\dot{x}_3 - \dot{x}_{30}^* \right),$$
$$\dot{z}_4 = \dot{x}_4 - \dot{x}_4^* = \dot{x}_4 - \dot{x}_{40}^* - p_4 \dot{z}_4 = \frac{1}{1-p_4} \left(\dot{x}_4 - \dot{x}_{40}^* \right), \quad (18)$$

Step 3: We select a Lyapunov function as follows:

$$V_3 = V_2 + \frac{1}{2} \sum_{i=3}^{4} (z_i^2 + e_i^2). \quad (19)$$

After taking derivatives of both sides of (19), one has

$$\dot{V}_3 = -k_1 z_1^2 - k_2 z_2 - (\lambda_1 - 2\epsilon_1) e_1^2 - (\lambda_2 - \epsilon_2) e_2^2 - \frac{z_2}{M(1-p_2)} \left((1-p_3) z_3 + \left((1-p_4) \right) z_4 \right)$$
$$+ \sum_{i=3}^{4} \left[\frac{z_i}{(1-p_i)} \left(\dot{x}_i - \frac{\partial x_i^*}{\partial z_1} \dot{z}_1 - \frac{\partial x_i^*}{\partial z_2} \dot{z}_2 - \frac{\partial x_i^*}{\partial \hat{d}_1} \lambda_1 e_1 - \frac{\partial x_i^*}{\partial \hat{d}_2} \lambda_2 e_2 \right) - \lambda_i e_i^2 + e_i \dot{d}_i \right]. \quad (20)$$

Substituting $\dot{x}_i, (i = 3,4)$ from (5) $\dot{z}_1, \dot{z}_2$ and x_2^* into (20) yields

$$
\begin{aligned}
\dot{V}_3 \le & -k_1 z_1^2 - k_2 z_2^2 - (\lambda_1 - 2\epsilon_1)e_1^2 - (\lambda_2 - \epsilon_2)e_2^2 - \sum_{i=3}^{4}(\lambda_i e_i^2 - e_i \dot{d}_i) \\
& + z_3\Bigg[-\frac{z_2(1-p_3)}{M(1-p_2)} + f_3(x) + g_{31}(x)\frac{u_f}{T_0'} + d_3 - \frac{\partial x_3^*}{\partial z_1}(x_2 + d_1) \\
& - \frac{\partial x_3^*}{\partial z_2}(f_2(x) + d_2) + \frac{\partial x_3^*}{\partial z_2}\frac{\partial x_2^*}{\partial x_1}(x_2 + d_1) - \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1 e_1\Bigg] - z_3\left(\frac{\partial x_3^*}{\partial \hat{d}_1}\lambda_1 e_1 + \frac{\partial x_3^*}{\partial \hat{d}_2}\lambda_2 e_2\right)\Bigg] \\
& + z_4\Bigg[-\frac{z_2(1-p_4)}{M(1-p_2)} + f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_q}{T} + d_4 - \frac{\partial x_4^*}{\partial z_1}(x_2 + \hat{d}_1) - \frac{\partial x_4^*}{\partial z_2}(f_2(x) + d_2) \\
& + \frac{\partial x_4^*}{\partial z_2}\frac{\partial x_2^*}{\partial x_1}(x_2 + d_1) - \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1 e_1\Bigg] - z_4\left(\frac{\partial x_4^*}{\partial \hat{d}_1}\lambda_1 e_1 + \frac{\partial x_4^*}{\partial \hat{d}_2}\lambda_2 e_2\right).
\end{aligned}
\tag{21}
$$

From (21), to achieve the desired control performance, two suitable control laws are chosen as follows:

$$
\begin{aligned}
\frac{u_f}{T_0'} = & \frac{1}{g_{31}(x)}\Bigg[\frac{z_2(1-p_3)}{M(1-p_2)} - f_3(x) - \hat{d}_3 + \frac{\partial x_3^*}{\partial z_1}(x_2 + \hat{d}_1) + \frac{1}{(1-p_2)}\frac{\partial x_3^*}{\partial z_2}\left(f_2(x) + \hat{d}_2 - \frac{\partial x_2^*}{\partial z_1}(x_2 + \hat{d}_1)\right) \\
& - \left(k_3 + \frac{1}{4\epsilon_3} + \hat{c}_{31} + \hat{c}_{32} + \hat{c}_{33} + \hat{c}_{34}\right)z_3(1-p_3) + \frac{\partial x_3^*}{\partial x_2}(f_2 + \hat{d}_2)\Bigg], \\
\frac{u_q}{T} = & \frac{1}{g_{42}(x)}\Bigg[\frac{z_2(1-p_4)}{M(1-p_2)} - f_4(x) - g_{41}(x)\frac{u_f}{T_0'} + \frac{\partial x_4^*}{\partial z_1}(x_2 + \hat{d}_1) - \hat{d}_4 + \frac{\partial x_4^*}{\partial x_2}(f_2 + \hat{d}_2) \\
& - \left(k_4 + \frac{1}{4\epsilon_4} + \hat{c}_{41} + \hat{c}_{42} + \hat{c}_{43} + \hat{c}_{44}\right)z_4(1-p_4) + \frac{1}{(1-p_2)}\frac{\partial x_4^*}{\partial z_2}\left(f_2(x) + \hat{d}_2 - \frac{\partial x_2^*}{\partial z_1}(x_2 + \hat{d}_1)\right)\Bigg],
\end{aligned}
\tag{22}
$$

where

$$
\begin{aligned}
& \hat{c}_{i1} = \frac{1}{4\epsilon_1(1-p_i)^2}\left(\frac{\partial x_i^*}{\partial z_1} + \frac{\partial x_i^*}{\partial \hat{d}_1}\lambda_1\right)^2, \hat{c}_{i2} = \frac{1}{4\epsilon_2(1-p_i)^2}\left(\frac{\partial x_i^*}{\partial x_2} + \frac{\partial x_i^*}{\partial \hat{d}_2}\lambda_2\right)^2, \\
& \hat{c}_{i3} = \frac{1}{4\epsilon_1(1-p_2)^2}\left[\frac{\partial x_i^*}{\partial z_2}\left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right)\right]^2, \hat{c}_{i4} = \frac{1}{4\epsilon_2(1-p_2)^2}\left[\frac{\partial x_i^*}{\partial z_2}\right]^2, i = 3,4.
\end{aligned}
\tag{23}
$$

Substituting the presented control law (22) into (21), we have

$$
\begin{aligned}
\dot{V}_3 &= -k_1 z_1^2 - k_2 z_2^2 - (\lambda_1 - 2\epsilon_1)e_1^2 - (\lambda_2 - \epsilon_2)e_2^2 - \sum_{i=3}^{4}(\lambda_i e_i^2 - e_i \dot{d}_i) \\
&\quad - \sum_{i=3}^{4}\left(k_i + \frac{1}{4\epsilon_1} + \hat{c}_{i1} + \hat{c}_{i2} + \hat{c}_{i3} + \hat{c}_{i4}\right) z_i^2 - \sum_{i=3}^{4}\frac{z_i}{1-p_i}\left[\left(\frac{\partial x_i^*}{\partial z_1} + \frac{\partial x_i^*}{\partial \hat{d}_1}\lambda_1\right)e_1 + \left(\frac{\partial x_i^*}{\partial x_2} + \frac{\partial x_i^*}{\partial \hat{d}_2}\lambda_2\right)e_2\right] \\
&\quad - \sum_{i=3}^{4}\frac{z_i}{1-p_2}\left(\frac{\partial x_i^*}{\partial z_2}\right)\left[e_2 - \left(\frac{\partial x_2^*}{\partial z_1} + \frac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right)e_1\right].
\end{aligned} \tag{24}
$$

It is observed that the last two terms (24) can be changed into the following inequalities:

$$
\begin{cases}
-\dfrac{z_i}{1-p_i}\left(\dfrac{\partial x_i^*}{\partial z_1} + \dfrac{\partial x_i^*}{\partial \hat{d}_1}\lambda_1\right)e_1 \le \dfrac{1}{4\epsilon_1(1-p_i)^2}\left(\dfrac{\partial x_i^*}{\partial z_1} + \dfrac{\partial x_i^*}{\partial \hat{d}_1}\lambda_1\right)^2 z_i^2 + \epsilon_1 e_1^2 = \hat{c}_{i1} z_i^2 + \epsilon_1 e_1^2, \\
-\dfrac{z_i}{1-p_i}\left(\dfrac{\partial x_i^*}{\partial x_2} + \dfrac{\partial x_i^*}{\partial \hat{d}_2}\lambda_2\right)e_2 \le \dfrac{1}{4\epsilon_2(1-p_i)^2}\left(\dfrac{\partial x_i^*}{\partial x_2} + \dfrac{\partial x_i^*}{\partial \hat{d}_2}\lambda_2\right)^2 z_i^2 + \epsilon_2 e_2^2 = \hat{c}_{i2} z_i^2 + \epsilon_2 e_2^2, \\
\dfrac{z_i}{1-p_2}\left[\dfrac{\partial x_i^*}{\partial z_2}\left(\dfrac{\partial x_2^*}{\partial z_1} + \dfrac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right)\right]e_1 \le \dfrac{1}{4\epsilon_1(1-p_2)^2}\left[\dfrac{\partial x_i^*}{\partial z_2}\left(\dfrac{\partial x_2^*}{\partial z_1} + \dfrac{\partial x_2^*}{\partial \hat{d}_1}\lambda_1\right)\right]^2 z_i^2 + \epsilon_1 e_1^2 = \hat{c}_{i3} z_i^2 + \epsilon_1 e_1^2, \\
-\dfrac{z_i}{1-p_2}\dfrac{\partial x_i^*}{\partial z_2}e_2 \le \dfrac{1}{4\epsilon_2(1-p_2)^2}\left[\dfrac{\partial x_i^*}{\partial z_2}\right]^2 z_i^2 + \epsilon_2 e_2^2 = \hat{c}_{i4} z_i^2 + \epsilon_2 e_2^2,
\end{cases} \tag{25}
$$

where $\hat{c}_{i1}$, $\hat{c}_{i2}$, $\hat{c}_{i3}$ and $\hat{c}_{i4}$ have been given in (23). After substituting the four inequalities above and then combining those inequalities with (24), we have

$$
\dot{V}_3 \le -\sum_{j=1}^{4}(k_j z_j^2 + e_j \dot{d}_j) - (\lambda_1 - 6\epsilon_1)e_1^2 - (\lambda_2 - 5\epsilon_2)e_2^2 - \sum_{i=3}^{4}(\lambda_i - \epsilon_i)e_i^2 \tag{26}
$$

In the next subsection, the stability analysis of the closed-loop dynamics with the control law (22) is presented.

3.3 Stability Analysis

In this subsection, the overall closed-loop stability of the system (5) with the proposed control law (22) and the error estimation dynamics (10) are analyzed within the framework of the Lyapunov theory analysis. Therefore, we can summarize the control design in the following theorem.

Theorem 1: Under Assumption 1, the nonlinear disturbance observer-based improved backstepping controller (22) 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 presented control strategy, let us define the following Lyapunov function for the closed-loop dynamics.

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

After computing the time derivative of the Lyapunov function candidate (27) and selecting $\lambda_1 = a_{01} + 6\epsilon_1,\ \lambda_2 = a_{02} + 5\epsilon_2,\ \lambda_i = a_{0i} + \epsilon_i, (i = 3,4),\ a_{0j} > 0, (j = 1,2,3,4)$, we obtain

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

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

$$\dot{V}_3 \le -\sum_{j=1}^{4} k_j z_j^2 - (1-\theta) a_0 \|e\|^2 - \theta a_0 \|e\|^2 + \|e\| \|\dot{d}\| \tag{29}$$

where $0 < \theta < 1$. Provided that one selects $\|e\| \ge \dfrac{\|\dot{d}\|}{a_0 \theta}$, it is not difficult to get that

$$\dot{V}_3 \le -\sum_{j=1}^{4} k_j z_j^2 - (1-\theta) a_0 \|e\|^2 \le 0. \tag{30}$$

Thus, the conditions of Lemmas 1 and 2 are satisfied with $\alpha_1(r)=c_1r^2, \alpha_2(r)=c_2r^2$, and $\rho(r)=(1/a_0\theta)r$, and we can conclude that the overall closed-loop system is input-to-state stable [37]. This completes the proof.

Remark 1: The control parameters (p_2, p_3, p_4) in the proposed controller (22)-(23) can be viewed as the additional degrees of freedom to improve system performances further. Provided that $p_2 = p_2 = p_4 = 1$ the proposed controller (22) becomes the nonlinear disturbance based backstepping control as reported in [27].

4. Simulation Results

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

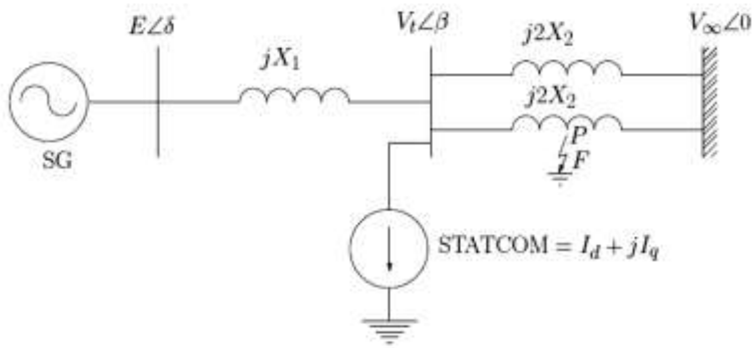

Figure 1 A single line diagram of the SMIB model with STATCOM

The physical parameters (pu.) and initial conditions $(\delta_e, \omega_s, P_{ee}, P_{se}, \ldots, \hat{d}_{40})$ for this power system model 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 to be:

$$
\begin{aligned}
& d_1(t)=0,0\le t\le 20,\\
& d_2(t)=\begin{cases}0.5\sin(2t), & 0\le t<5\\ 1, & 5\le t<10,\\ 0.25\sin(2t)e^{-t}, & 10\le t\le 20\end{cases}\\
& d_3(t)=\begin{cases}0.15\cos(t), & 0\le t<5\\ 2, & 5\le t<10,\\ 0.5\cos(t)e^{-2t}, & 10\le t\le 20\end{cases}\\
& d_4(t)=\begin{cases}0.25\sin(t), & 0\le t<5\\ 2, & 5\le t<10,\\ 0.3\sin(t)e^{-3t}, & 10\le t\le 20\end{cases}
\end{aligned}
\tag{31}
$$

The controller parameters are set as $\epsilon_j=10,\ k_j=20,\ \lambda_j=50,$ $p_2=p_3=p_4=0.5, (j=1,2,\ldots,4)$. The time domain simulations are carried out to investigate the system stability enhancement and the dynamic performance of the designed controller, as given in (24), in the system in the presence of external disturbances. The control performance of the proposed controller (nonlinear disturbance observer-based improved backstepping controller) in (22)-(23) is compared with that of a conventional backstepping controller (CBSC) [23] as below.

$$
\begin{cases}
\dfrac{u_f}{T_0'}=\dfrac{1}{g_{31}(x)}\left[-k_3z_3-\dfrac{z_2}{M}-f_3(x)+\dfrac{1}{2}\left[D\dot{x}_2-M(k_2\dot{z}_2+\dot{z}_1+k_1\dot{x}_2)\right]\right],\\
\dfrac{u_q}{T}=\dfrac{1}{g_{42}(x)}\left[-k_4z_4+\dfrac{z_2}{M}-f_4(x)-g_{41}(x)\dfrac{u_f}{T_0'}-\dfrac{1}{2}\left[D\dot{x}_2-M(k_2\dot{z}_2+\dot{z}_1+k_1\dot{x}_2)\right]\right],
\end{cases}
\tag{32}
$$

with

$z_j=x_j-x_j^*,\ (j=1,2,3,4),\ x_1^*=0,\ x_2^*=-k_1z_1,\ x_3^*=-\dfrac{1}{2}\left(Dx_2-M(k_2z_2+z_1+k_1x_2)\right)+P_m,$

$x_4^*=x_3^*-P_m,\ \dot{z}_1=-c_1z_1+z_2,\ \dot{z}_2=f_2(x)+c_1x_2$

The simulation results are discussed as follows. Time histories of the power angle, frequency, transient internal voltage, and STATCOM current under two controllers are presented in Figure 2. Also, the results of disturbance estimation and external disturbances, together with disturbance estimation error, are demonstrated in Figures 2 and 3. From these figures, it can be seen that the developed method and the CBSC method can successfully stabilize the system despite having external disturbances given in (32). Besides, it can be observed that the presented control has not only better dynamic performances, but also satisfactory disturbance rejection ability such as shorter settling time, a quick rise time, and a faster convergence rate. 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 poor dynamic performances such as unsatisfactory and higher overshoots and slowly suppressing system oscillations. These results are 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 compensate for the adverse effects of inevitable disturbances. In contrast, the CBSC method does not include the compensation of external disturbances in the designed control law (33). Figure 3 shows that the disturbance estimators can rapidly track the unknown external disturbances with a fast convergence rate and no oscillations. Also, the error between unknown disturbances and disturbance estimator is shown in Figure 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.

(i) The proposed control law is effectively designed to stabilize the system in the presence of undesired disturbances.

(ii) The developed control strategy can make the overall closed-loop dynamics converge more quickly to the desired equilibrium point. It is evident that the presented control law performs well and has considerable practical disturbance rejection ability. It offers superior transient performances illustrated by the rapidly suppressing system oscillations in all time trajectories in spite of having external disturbances.

(iii) The process of designing the desired control law includes some auxiliary terms into the virtual control laws and the final controller. These terms can deal with 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.

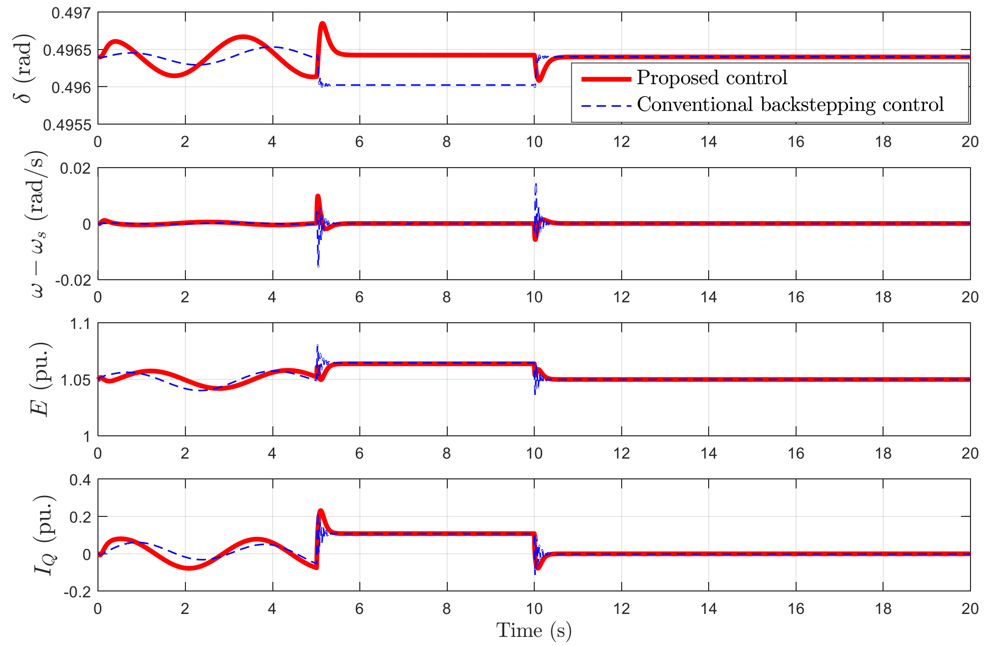

Figure 2 Controller performance- power angle (δ) (deg.), frequency $(\omega - \omega_s)$ rad/s. and Transient voltage (E) pu., and STATCOM current I_Q

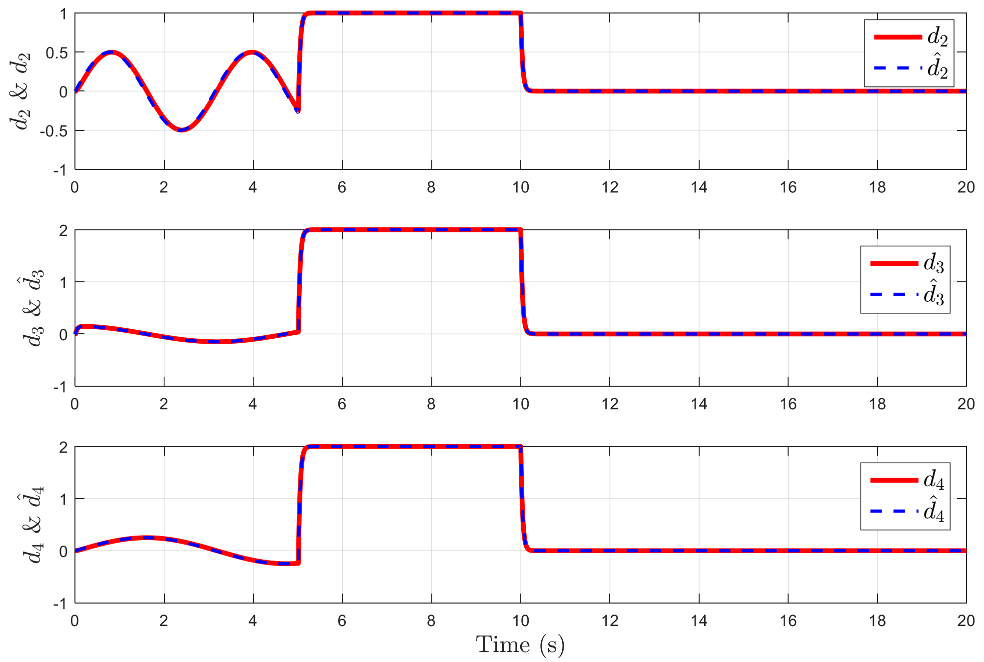

Figure 3 External disturbances and disturbance estimations

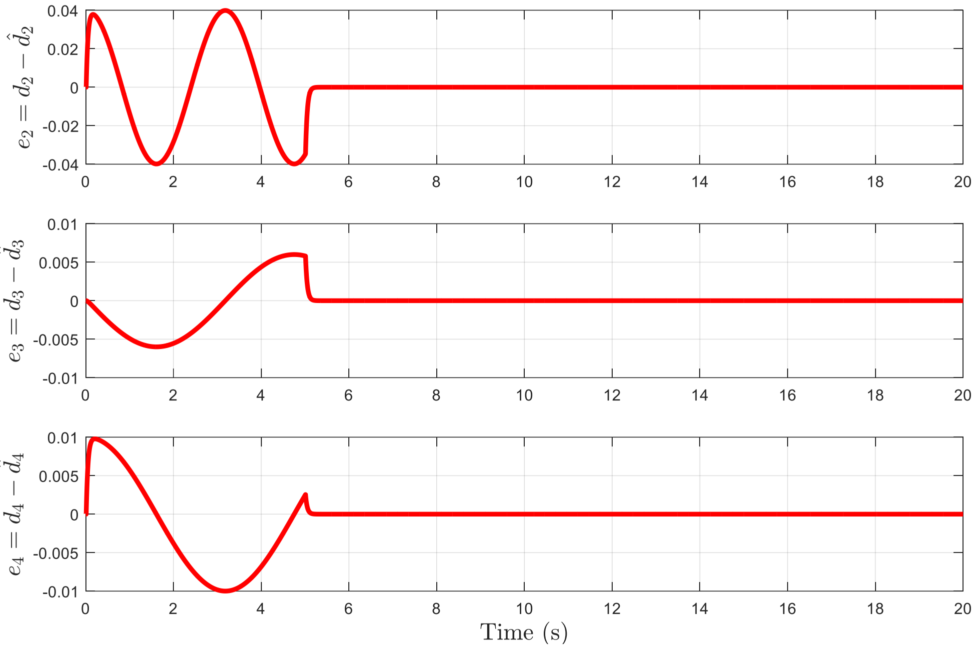

Figure 4 Disturbance estimation errors

5. Conclusions

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 on a combination of improved backstepping control and a disturbance observer method. This combination can offer not only better dynamic performance, but also effective 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 composite nonlinear control can improve obviously faster transient performances and has better disturbance rejection property than the CBSC method.

References

[1] Kundur P. Power System Stability and Control. New York: McGraw-Hill; 1994.

[2] Bazanella AS, Conceicao, CA. Transient stability improvement through excitation control. International Journal of Robust and Nonlinear Control 2004;14(9-10):891-910.

[3] Dib W, Kenne G, Lamnabhi-Lagarrigue F. An application of immersion and invariance to transient stability and voltage regulation of power systems with unknown mechanical power. Proceeding of Joint 48th IEEE CDC and 28th CCC.; Shanghai, P.R. China. 2009.

[4] Dib W, Ortega R, Astolfi A, Hill D. Improving transient stability of multi-machine power systems: synchronization via immersion and invariance. Proceedings of American Control Conference; San Francisco CA. 2011.

[5] Galaz M, Ortega R, Bazanella A, Stankovic A. An energy-shaping approach to excitation control of synchronous generators. Automatica 2003;39(1):111-9.

[6] Ortega R, Galaz M, Astolfi A, Sun Y, Shen T. Transient stabilization of multi-machine power systems with nontrivial transfer conductances. IEEE Transactions on Automatic Control 2005;50(1):60-75.

[7] Paul MO, Gerardo EP. Output feedback excitation control of synchronous generators. International Journal of Robust and Nonlinear Control 2004;14(9-10):879-90.

[8] Kanchanahanathai A, Chankong V, Loparo KA. Nonlinear generator excitation and superconducting magnetic energy storage control for transient stability enhancement via immersion and invariance. Transactions of the Institute of Measurement and Control 2015;37(10):1217-31.

[9] Kanchanaharuthai A, Mujjalinvimut E. An improved backstepping sliding mode control for power systems with superconducting magnetic energy storage system. International Journal of Innovative Computing, Information and Control 2019;15(3):891-904.

[10] Hingorani NG, Gyugyi L. Understanding FACTS: Concepts and Technology of flexible AC Transmission Systems. IEEE Press; 1999.

[11] Song YN, John AT. Flexible AC Transmission Systems (FACTS). London: IEE Power and Energy Series 30; 1999.

[12] Liu QJ, Sun YZ, Shen TL, Song YN. Adaptive nonlinear co-ordinated excitation and STATCOM based on Hamiltonian structure for multimachine-power-system stability enhancement. IEE Proceedings-Control Theory and Applications 2003;150(3):285-94.

[13] Wang K, Crow ML. Hamiltonian theory based coordinated nonlinear control of generator excitation and STATCOMs. Proceedings of North American Power Symposium. 2010.

[14] Gu L, Wang J. Nonlinear coordinated control design of excitation and STATCOM of power systems. Electric Power System Research 2007;77(7):788-96.

[15] Zou B, Wang J. Coordinated control for STATCOM and generator excitation based on passivity and backstepping technique. Proceedings of Electric Information and Control Engineering. 2010.

[17] Kanchanahanathai A. Immersion and invariance-based non-linear coordinated control for generator excitation and static synchronous compensator for power systems. Electric Power Components and Systems. 2014;42(10):1004-15.

[18] Kanchanahanathai A. Nonlinear adaptive controller design for power systems with STATCOM via immersion and invariance. ECTI Transactions on Electrical Engineering, Electronics, and Communications 2016;14(2):35-46.

[19] Kanchanaharuthai A, Boonyaprapasorn A. A backstepping-like approach to coordination excitation and STATCOM control for power systems. International Review of Automatic Control 2016;9(2):64-71.

[20] Kanchanaharuthai A, Mujjalinvimut E. An adaptive backstepping coordinated excitation and STATCOM control for power systems. International Review of Electrical Engineering 2016;11(4):391-8.

[21] Abolmasoumi AH, Moradi M. Nonlinear T-S fuzzy stabilizer design for power systems including random loads and static synchronous compensator. International Transactions on Electrical Energy Systems 2018;28(1):1-19.

[22] Kanchanaharuthai A, Mujjalinvimut E. A nonlinear controller for power systems with STATCOM based on backstepping and rapid-convergent differentiator. International Journal of Innovative Computing, Information and Control 2019;15(3):1079-91.

[23] Krstic M, Kanellakopoulos I, Kokotivic PV. Nonlinear and Adaptive Control Design. John Willey & Sons; 1995.

[24] Li S, Yang J, Chen WH, Chen X. Disturbance Observer-Based Control: Methods and Applications. CRC Press; 2014.

[25] Sun H, Li S, Yang J, Guo L. Non-linear disturbance observer-based back-stepping control for airbreathing hypersonic vehicle with mismathced disturbances. IET Ccntrol Theory Applications 2014;8(17):1852-65.

[26] Sun H, Li S, Yang J, Zheng WX. Global output regulation for strict-feedback nonlinear systems with mismatched nonvanishing disturbances. International Journal of Robust and Nonlinear Control 2015;25(15):2631-45.

[27] Kanchanaharuthai A, Mujjalinvimut E. Nonlinear disturbance observer-based backstepping control for a dual excitation and steam-valving system of synchronous generators with external disturbances. International Journal of Innovative Computing, Information and Control 2018;14(1):111-26.

[28] Suthisripok T, Wongrattanapornkul C, Poonyaniran S, Kanchanaharuthai A. Disturbance observer-based control for active suspension systems. International Journal of Innovative Computing, Information and Control 2018;14(6):2291-2305.

[29] Ginoya D, Shendge PD, Phadke SB. Disturbance observer based sliding mode control of nonlinear mismatched uncertain systems. Communications in Nonlinear Science and Numerical Simulation 2015;26(1-3):98-107.

[30] Yang J, Chen WH, Li S. Non-linear disturbance observer-based robust control for systems with mismatched disturbance/uncertainties. IET Control Theory Applications 2011;5(18):2053-62.

[31] Sun H, Guo L. Composite adaptive disturbance observer based control and back-stepping method for nonlinear system with multiply mismatched disturbances. Journal of the Franklin Institute 2014;351(2):1027-41.

[32] Liu X, Liu Z, Shan J, Sun H. Anti-disturbance autopilot design for missile system via finite time intergral sliding mode control method and nonlinear disturbance observer technique. Transactions of the Institute of Measurement and Control 2015;38(6):693-700.

[33] Kim W, Shin D, Won D, Chung CC. Disturbance-observer-based position tracking controller in the presence of biased sinusoidal disturbance for electrohydraulic actuators. IEEE Transactions on Control Systems Technology 2013;21(6):2290-8.

[34] Su Q, Quan W, Cai G, Li J. Improved adaptive backstepping sliding mode control for generator steam valves of nonlinear power systems. IET Control Theory & Application 2017;32(9):1414-9.

[35] Su Q, Quan W, Cai G, Li J. An improved adaptive backstepping approach on static var compensator controller for nonlinear power systems. International Journal of Adaptive Control and Signal Processing 2018;32(5):700-12.

[36] Khalil HK. Nonlinear Systems. Upper Saddle River, NJ: Prentice-Hall; 2002.

[37] Qian C, Lin W. Non-smooth stabilizers for nonlinear systems with uncontrollable unstable linearization. Proceedings of the 39th IEEE Conference on Decision and Control. Sydney, NSW, pp. 1655-1660, 2000.

Author's Profile

Kruawan Wongsurith received the M. Sc. degree in Chemistry from Srinakharinwirot University, Thailand, in 1994. She is currently a lecture in the faculty of engineering at Kasem Bundit University, Thailand. Her main research interests include nonlinear dynamics and applications of control system design to chemistry process.

Piraporn Konkhum received the MBA degree from Kasem Bundit University, Thailand, in 1996. She is currently a lecture in the faculty of engineering at Kasem Bundit University, Thailand.

Suwit Wongkumsin received the M.Sc. (Information technology) from King Mongkut's Institute of Technology Ladkrabang, Thailand. He is currently a lecture in the faculty of engineering at Kasem Bundit University, Thailand.

Adirak Kanchanaharuthai, faculty of the Department of Electrical Engineering at Rangsit University, Thailand. His main research interests include power system dynamics, stability and control.

Somchai Poonyaniran, faculty of the Department of Electrical Engineering at Rangsit University, Thailand. His main research interests include communication system and control.

Pinit Ngamsom received Ph.D. in Mechanical Engineering from Oklahoma State University, U.S.A. in 2001. He is now with Department of Mechanical Engineering at Rangsit University, Thailand. His main research interests include robotics and control systems.

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