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A COMPOSITE NONLINEAR CONTROLLER FOR HIGHER-ORDER MODELS OF SYNCHRONOUS GENERATORS UNDER EXTERNAL DISTURBANCES

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Abstract. *This paper presents a composite nonlinear control strategy for higher-order models of synchronous generators under external disturbances. The proposed controller is designed via a combination of a backstepping-like control scheme and a high-gain disturbance observer technique. The disturbance observer is developed to estimate inevitably external disturbances and to compensate the adverse effects of disturbances in each design step. The resulting composite control law is utilized to improve the dynamic control performance, to obtain a disturbance rejection property, and to ensure that the states of the overall closed-loop system are ultimately bounded when there exist non-vanishing disturbances. In order to show the effectiveness of the presented design, simulation results indicate that the presented control can improve dynamic performances, rapidly suppress system oscillations of the overall closed-loop dynamics, and despite external disturbances, perform better than a conventional backstepping-like control technique.*
Keywords: Higher-order model of synchronous generators, Backstepping-like control, High-gain disturbance observer, Composite nonlinear control

1. **Introduction.** One of most important problems in modern power systems is how to maintain power system stability when confronted with unavoidable disturbances. This problem [1, 2, 3] has been extensively studied, and there are a lot of interesting results available in the literature. It is known well that there is currently rapid increase of the size and complexity; thus, modern power systems become highly nonlinear and interconnected systems. This leads to a requirement to operate close to stability limits to meet the increased load demands. Besides, such power systems often confront both small and large disturbances; subsequently, the stability margin of the overall system can be deteriorated and eventually the system may become unstable. Therefore, there are currently numerous attempts for finding high-performance stabilizing nonlinear controllers capable of alleviating the undesired effects arising from disturbances. An effective and promising way for maintaining power system stability is using an excitation control of synchronous generators [1]. For nonlinear systems, a lot of excitation control techniques have been proposed [4, 5, 6, 7, 8, 9, 10, 11] to effectively maintain and improve system stability enhancement. However, the power system model used in the design procedure in the

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above references is based on the only one-axis model of synchronous generators, and the dynamics of the automatic voltage regulation (AVR) are neglected. As presented in [12], an inclusion of the additional dynamics of the direct-axis transient voltage E'_d can significantly improve the performance and is a promising idea of increasing greater flexibility for the system stability enhancement. Further, this inclusion of the additional degree of freedoms offers an opportunity to determine the effective control due to both d-axis and q-axis field windings.

To the best of authors' knowledge, by using directly nonlinear control schemes, there is less attention devoted to the use of both d-axis and q-axis models (higher-order models) of synchronous generators including the dynamics of AVR [13, 14]. Based on adaptive backstepping control method, an adaptive excitation control [13] for the fifth-order models of synchronous generators connected to an infinite bus was reported to improve transient stabililty and voltage regulation. The obtained control law indicated the superiority over the adaptive design for the third-order models. In [14], a partial feedback linearing model predictve excitation control for the two-axis models of synchronous generators together with the dynamics of IEEE Type-II excitation system in multimachine power systems has been presented. The resulting control law can improve the dynamic stability under different operating conditions.

In practice, it can be often found that disturbances arise in most engineering systems. Such disturbances result in degrading the desired control performances of the system of interest. Often, the disturbances may be unknown external disturbances, parametric uncertainties and other unknown nonlinear terms. Therefore, if it is possible, the results of disturbances should be either rejected or compensated by an inclusion of additional dynamics, in particular disturbance observer dynamics, into the whole system. There is currently a disturbance observer scheme [15, 16] capable of compensating or rejecting the adverse effects arising external disturbances and mismatched disturbances/uncertainties effectively. This technique has been widely used to not only compensate the effects of disturbances, but also estimate unknown disturbances. Further, this method can be combined with advanced nonlinear control strategies [15, 25] to improve the control performances and to offer the disturbance rejection property simultaneously. Also, it can be successfully applied for numerous kinds of real engineering systems such as flight control systems [15], permanent magnet synchronous motors [15], electrohydrolic actuator systems [16] airbreathing hypersonic vehicle systems [17], power systems [18, 19], and active suspensions [20]. Those systems demonstrate important application potentials of the combination of disturbance observer design with nonlinear control designs to handle the adverse effect of external disturbances.

For power systems, the robust adaptive excitation control for a single-machine infinite bus (SMIB) power system reported in [13] performed well and indicated good control performances; however, external disturbances and uncertainties have not been considered before. Subsequently, the effects of disturbances may cause undesired control performances, and the system eventually became unstable. Additionally, a robust adaptive excitation control [21] for multimachine power systems under parametric uncertainties and external disturbances was proposed for transient stability enhancement. Even if the resulting control law provided robustness against disturbances, it included a discontinuous control signal which may lead to a chattering issue. Thus, the dynamics of disturbance observer should be included into the whole system to either compensate or reject external disturbances directly.

In this paper, a systematic control strategy to design a composite nonlinear controller for higher-order models of synchronous generators based on a backstepping-like control [22] combined with a high-gain disturbance observer technique [16] is developed to tackle the adverse effects arising from external disturbances. In [15, 16], although two popular nonlinear techniques, that is, sliding mode method and backstepping method, are combined with disturbance observer design, both techniques have major disadvantages. For sliding mode, the signum function is employed to bound external disturbances, resulting in the chatter problems. For backstepping, there are two important disadvantages, namely, the problem of "explosion of complexity" and a suitable selection of a suitable virtual control used in each design step to find out the final controller. In order to avoid these disadvantages, the combination of a backstepping-like control [22] and the high-gain disturbance observer design is used instead, because the obtained controller does not experience chattering problems and does not require the selection of virtual control as used in backstepping.

Therefore, the merits of this work are threefold: (i) The use of a composite nonlinear controller consisting of a high-gain disturbance observer design and backstepping-like control strategy to stabilize the power system in the presence of external disturbances has not been investigated before; (ii) All trajectories of the overall closed-loop system is ultimately bounded in spite of having non-vanishing external disturbances; and (iii) Compared with a conventional backstepping-like control, the developed control law offers better dynamic performances and a satisfactory disturbance rejection property.

The rest of this paper is organized as follows. A dynamic model of a higher-order model of synchronous generators is briefly presented, and the problem statement is given in Section 2. Controller design is developed in Section 3 while simulation results are mentioned in Section 4. Finally, in Section 5, a conclusion is given.

2. Power System Model Description.

2.1. Power system models. The two-axis model of synchronous generators along with the dynamics of an IEEE ST1 standard exciter or IEEE Type-II exciter [1, 23] is considered in this paper. Thus, the complete dynamical model of the synchronous generator connected to an infinite bus with the IEEE Type II excitation system can be expressed as follows:

$$\begin{cases} \dot{\delta} = \omega - \omega_s, \\ \dot{\omega} = \dfrac{\omega_s}{2H}\left(P_m - P_e - D(\omega - \omega_s)\right) + d_2(t), \\ \dot{E}'_q = \dfrac{1}{T'_{d0}}\left(-E'_q + (X_d - X'_d)I_d + E_{fd}\right) + d_3(t), \\ \dot{E}'_d = \dfrac{1}{T'_{q0}}\left(-E'_d - (X_q - X'_q)I_q\right) + d_4(t), \\ \dot{E}_{fd} = -\dfrac{E_{fd}}{T_A} + \dfrac{K_A}{T_A}\left(V_{ref} - V_t + u_c\right) + d_5(t), \end{cases} \tag{1}$$

with

$$P_e = E'_q I_q + E'_d I_d + (X'_d - X'_q)I_d I_q = \frac{E'_q}{X'_{d\Sigma}} V_\infty \sin\delta + \frac{E'_d}{X'_{q\Sigma}} V_\infty \cos\delta + \frac{X'_{d\Sigma} - X'_{q\Sigma}}{2X'_{d\Sigma}X'_{q\Sigma}} V_\infty^2 \sin 2\delta$$

$$I_d = \frac{V_\infty \cos\delta - E'_q}{X'_{d\Sigma}}, \quad I_q = \frac{E'_d - V_\infty \sin\delta}{X'_{q\Sigma}}$$

where δ is the power angle of the generator, ω denotes the relative speed of the generator, $D \geq 0$ is a damping constant, and E'_q and E'_d are the field variable proportional to field flux linkages and the damper variable proportional to the d-axis damper flux linkages, respectively. E_{fd} is the equivalent field excitation voltage. X'_d and X'_q are the d-axis and q-axis transient reactances, respectively. P_e is the electrical power 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, and f is the system frequency. $X'_{d\Sigma} = X'_d + X_T + X_L$ is the reactance consisting of the direct axis transient reactance of SG, the reactance of the transformer, and the reactance of the transmission line X_L. $X'_{q\Sigma}$ denotes the q-axis reactances. T'_{d0} and T'_{q0} are the d-axis and q-axis transient open-circuit time constants. u_c is the stabilizing signal which is the control input to be designed, respectively. T_A is the time constant of the voltage regulator connected to the synchronous generator. K_A is the gain of the voltage regulator connected to the synchronous generator. V_t and V_{ref} denote the terminal voltage of synchronous generators and the reference terminal voltage, respectively. I_d and I_q denote the d- and q-axes current components, respectively. $d_i(t)$, $(i = 2, 3, 4, 5)$ are external disturbances and system parameter variations.

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

$$x_1 = \delta - \delta_e, \quad x_2 = \omega - \omega_s, \quad x_3 = E'_q, \quad x_4 = E'_d, \quad x_5 = E_{fd}. \tag{2}$$

Subsequently, after differentiating the state variables (2), we have the higher-order model of synchronous generators with external disturbances which can be written in the following form of an affine nonlinear system:

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

where

$$\begin{cases} f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \\ f_5(x) \end{bmatrix} = \begin{bmatrix} x_2 \\ \theta_D x_2 + \theta_\omega P_m + \theta_d x_3 \sin(x_1 + \delta_0) \\ + \theta_q x_4 \cos(x_1 + \delta_0) + m \sin 2(x_1 + \delta_0) \\ a_q x_3 + b_q \cos(x_1 + \delta_e) + \dfrac{x_5}{T'_{d0}} \\ a_d x_4 + b_d \sin(x_1 + \delta_e) \\ \theta_1 x_5 + \theta_2 (V_{ref} - V_t) \end{bmatrix}, \\ g(x) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \theta_2 \end{bmatrix}, \; d(t) = \begin{bmatrix} 0 \\ d_2(t) \\ d_3(t) \\ d_4(t) \\ d_5(t) \end{bmatrix}, \; u(x) = u_c, \end{cases} \tag{4}$$

where $\theta_D = -\frac{\omega_s}{2H} D$, $\theta_\omega = \frac{\omega_s}{2H}$, $\theta_d = \frac{V_\infty}{X'_{d\Sigma}}$, $\theta_q = \frac{V_\infty}{X'_{q\Sigma}}$, $m = \frac{X'_{d\Sigma} - X'_{q\Sigma}}{2X'_{d\Sigma} X'_{q\Sigma}}$, $a_q = -\frac{X_{d\Sigma}}{X'_{d\Sigma} T'_{d0}}$, $a_d = -\frac{X_{q\Sigma}}{X'_{q\Sigma} T'_{q0}}$, $b_q = \frac{\left(X_{d\Sigma} - X'_{d\Sigma}\right)}{X'_{d\Sigma} T'_{d0}} V_\infty$, $b_d = \frac{\left(X_{q\Sigma} - X'_{q\Sigma}\right)}{X'_{q\Sigma} T'_{q0}} V_\infty$, $\theta_1 = -\frac{1}{T_A}$, $\theta_2 = \frac{K_A}{T_A}$. The region of operation is defined in the set $\mathcal{D} = \left\{ x \in \mathcal{S} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} \middle| \, 0 < x_1 < \frac{\pi}{2} \right\}$. The open loop operating equilibrium is denoted by $x_e = [0, 0, x_{3e}, x_{4e}, x_{5e}]^T = \left[0, 0, E'_{qe}, E'_{de}, E_{fde}\right]^T$.

For the sake of simplicity, the power system considering (3) and (4) can be expressed as follows.

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = f_2(x) + d_2(t), \\ \dot{x}_3 = f_3(x) + d_3(t), \\ \dot{x}_4 = f_4(x) + d_4(t), \\ \dot{x}_5 = f_5(x) + \theta_2 u_c + d_5(t). \end{cases} \tag{5}$$

Assumption 2.1. *The external disturbances $d_i(t)$, $(i = 2, 3, 4, 5)$ are bounded. Additionally, the first derivative of the disturbances above is also bounded such that* $\left|\dot{d}_i\right| \leq \dot{d}_{i\max}$.

2.2. **Problem statement.** The control objective of this paper is to solve the problem of the stabilization of the system (5) with the external disturbances d, which can be formulated as follows: with the help of the combination of the high-gain disturbance observer design [16] and backstepping-like control technique [22], to design a nonlinear controller $u(x)$ and disturbance estimation $\hat{d}$ as follows:

$$\begin{cases} u = \phi\left(x, \hat{d}\right), \\ \dot{\hat{d}} = \varphi\left(x, u, \hat{d}\right), \end{cases} \tag{6}$$

such that the state of the overall closed-loop systems (5) and (6) is ultimately bounded [26], where $\hat{d}$ is the estimate of d.

For the developed design procedure in the next section, a combination of the backstepping-like strategy and high-gain disturbance observer design will be presented to obtain a composite nonlinear controller (6). In comparison with the conventional backstepping-like 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. In addition, as the system is subjected to external disturbances, the proposed composite controller should have the ability to maintain the power system stability, reject undesired disturbances, and improve transient control performances. In the following section, the developed controller is designed to achieve the desired performances.

3. **A Composite Nonlinear Controller Design.** In this section, the desired control law for stabilizing the higher models of synchronous generators in the presence of external disturbances is presented. The main control development can be accomplished in the following two subsections.

- The first subsection is to develop a high-gain disturbance observer scheme to online identify the unknown, but bounded, disturbances and ensure that the disturbance estimation error converges to zero asymptotically.
- The second subsection is to develop a backstepping-like control combined with disturbance observer from the first subsection to ensure that the state of closed-loop dynamics is ultimate bounded despite non-vanishing disturbances. Then, with the help of Lyapunov stability arguments, the overall closed-loop system stability is investigated even though there exist non-vanishing and vanishing external disturbances in the systems.

3.1. **High-gain disturbance observer design.** In accordance with an idea reported in [16] which is used to guarantee the control performance of the system (5), we consider the dynamic model which can be rewritten as

$$d_i = \dot{x}_i + f_i(x), \quad i = 2, 3, 4, 5. \tag{7}$$

Define the estimations of the disturbances, $\hat{d}_i$, and estimation errors are defined as

$$\tilde{d}_i = d_i - \hat{d}_i. \tag{8}$$

Thus, based on (8) the disturbance estimation dynamics are designed as

$$\dot{\hat{d}}_j = \frac{1}{\epsilon_i}\left(\dot{x}_i + f_i(x) - \hat{d}_i\right), \tag{9}$$

where $1/\epsilon_i$ denotes the observer gain. Note that the dynamics of $\hat{d}_i$ given in (9) involve the derivative of the state. It is, therefore, easy that if observer gains increase, the noise is unavoidably amplified by the high gains. This means that the observer cannot practically be implemented. Thus, there is currently a possible way to avoid this problem. That is, auxiliary state variable ξ_i is employed according to the following theorem.

Theorem 3.1. [16] *Given the following auxiliary variables ξ_i defined as*

$$\xi_i = \hat{d}_i - \frac{x_i}{\epsilon_i}, \quad i = 2, 3, 4, 5. \tag{10}$$

Subsequently, after differentiating these auxiliary state variables (10), we have the dynamics of the auxiliary state variables as

$$\dot{\xi}_j = -\frac{1}{\epsilon_j}\left(\xi_j + \frac{x_j}{\epsilon_j}\right) - \frac{1}{\epsilon_j} f_j(x), \quad j = 2, 3, 4, \tag{11}$$

$$\dot{\xi}_5 = -\frac{1}{\epsilon_5}\left(\xi_5 + \frac{x_5}{\epsilon_5}\right) - \frac{1}{\epsilon_5}(f_5(x) + \theta_2 u_c). \tag{12}$$

By substituting (11) and (12) into the disturbance estimation error (8), we obtain the disturbance estimation error as follows:

$$\dot{\tilde{d}}_j = -\frac{1}{\epsilon_i}\tilde{d}_i + \dot{d}_i, \quad i = 2, 3, 4, 5. \tag{13}$$

Then, one obtain $\left|\tilde{d}_i\right| \leq e^{-(1/\epsilon_i)t}\left|\tilde{d}(0)\right| + \epsilon_i \rho_i(t)$ for an envelope function $\rho_i(t)$, such that $\rho_i(t) \geq |\dot{d}_i|$, $\forall t \geq 0$, $i = 2, 3, 4, 5$. Note that the upper bound of $\left|\tilde{d}_i(\infty)\right|$ depends upon the observer gain ϵ_i. This means that the fast convergence rate and the reduction of boundedness of the estimation error can be selected from the large observer gain ϵ_i. It is observed that both disturbance observer (11) and (12) and the auxiliary state variable (10) do not rely on the derivative of the state $\dot{x}_i$. Therefore, provided (11), (12) and (10) are utilized instead of (9) to estimate the disturbance, the use of high observer gain can directly decrease the effect of amplifying the measurement noise.

3.2. **Backstepping-like design.** In this subsection, the backstepping-like scheme [22] is used to find out the control law combining with the high-gain disturbance for compensating the external disturbances and achieving the desired control performances. The proposed control procedure is developed step by step as follows.

Step 1: First, we focus on the first subsystem (5), and then a Lyapunov function candidate is chosen as

$$V_1 = \frac{1}{2}x_1^2. \tag{14}$$

Then the time derivative of V_1 along the system trajectories becomes

$$\dot{V}_1 = x_1\dot{x}_1 = x_1 x_2 = -c_1 x_1^2 + x_1(c_1 x_1 + x_2), \tag{15}$$

where $c_1 > 0$ is a design parameter.

Step 2: From (15), it is observed that the second term can be neither positive nor negative. Thus, we can eliminate the result from the aforementioned equation by choosing the Lyapunov function candidate as:

$$V_2 = \frac{1}{2}x_1^2 + \frac{1}{2}(c_1 x_1 + x_2)^2 + \frac{1}{2}\tilde{d}_2^2. \tag{16}$$

By calculating the derivative of (16), we have

$$\begin{aligned}\dot{V}_2 =& -c_1x_1^2 + (c_1x_1 + x_2)(x_1 + c_1\dot{x}_1 + \dot{x}_2) + \tilde{d}_2\left(-\frac{1}{\epsilon_2}\tilde{d}_2 + \dot{d}_2\right)\\ =& -c_1x_1^2 + (c_1x_1 + x_2)\big[x_1 + c_1x_2 + \theta_D x_2 + \theta_\omega P_m + \theta_d x_3\sin(x_1 + \delta_0)\\ &+ \theta_q x_4\cos(x_1 + \delta_0) + m\sin 2(x_1 + \delta_0) + d_2\big] - \frac{1}{\epsilon_2}\tilde{d}_2^2 + \tilde{d}_2\dot{d}_2. \end{aligned} \tag{17}$$

After adding and subtracting $c_2(c_1x_1 + x_2)$, $c_2 > 0$, into the equation above, we have

$$\dot{V}_2 = -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 + (c_1x_1 + x_2)\mathcal{P} + (c_1x_1 + x_2)\tilde{d}_2 - \frac{1}{\epsilon_2}\tilde{d}_2^2 + \tilde{d}_2\dot{d}_2, \tag{18}$$

where $\mathcal{P} = (1+c_1c_2)x_1+(c_1+c_2+\theta_D)x_2+\theta_\omega P_m+\theta_d x_3\sin(x_1+\delta_0)+\theta_q x_4\cos(x_1+\delta_0)+\hat{d}_2$. In the same manner, it can be seen that the third term of (18) is not always negative. So, one needs to cancel this term.

Step 3: Let us define the Lyapunov function of Step 2 as

$$V_3 = V_2 + \frac{1}{2}\mathcal{P}^2 + \frac{1}{2}\tilde{d}_3^2 + \frac{1}{2}\tilde{d}_4^2. \tag{19}$$

Then the time derivative of V_3 along the system trajectories turns into as follows:

$$\begin{aligned}\dot{V}_3 =& -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 + (c_1x_1 + x_2)\mathcal{P} + \mathcal{P}\left(\sum_{j=1}^{4}\frac{\partial\mathcal{P}}{\partial x_j}\dot{x}_j + \frac{\partial\mathcal{P}}{\partial\hat{d}_2}\dot{\hat{d}}_2\right)\\ &+ (c_1x_1 + x_2)\tilde{d}_2 + \sum_{i=2}^{4}\left(-\frac{1}{\epsilon_i}\tilde{d}_i^2 + \tilde{d}_i\dot{d}_i\right)\\ =& -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 + \mathcal{P}\left[c_1x_1 + \left(1 + \frac{\partial\mathcal{P}}{\partial x_1}\right)x_2 + \frac{\partial\mathcal{P}}{\partial x_2}(f_2 + d_2) + \frac{\partial\mathcal{P}}{\partial x_3}(f_3 + d_3)\right.\\ &\left.+ \frac{\partial\mathcal{P}}{\partial x_4}(f_4 + d_4) + \frac{\partial\mathcal{P}}{\partial\hat{d}_2}\dot{\hat{d}}_2\right] + (c_1x_1 + x_2)\tilde{d}_2 + \sum_{i=2}^{4}\left(-\frac{1}{\epsilon_i}\tilde{d}_i^2 + \tilde{d}_i\dot{d}_i\right), \end{aligned} \tag{20}$$

where $\frac{\partial\mathcal{P}}{\partial x_1} = c_1c_2 + 1 + \theta_d x_3\cos(x_1 + \delta_0) - \theta_q x_4\sin(x_1 + \delta_0) + 2m\cos 2(x_1 + \delta_0)$, $\frac{\partial\mathcal{P}}{\partial x_2} = c_1 + c_2 + \theta_D$, $\frac{\partial\mathcal{P}}{\partial x_3} = \theta_d\sin(x_1 + \delta_0)$, $\frac{\partial\mathcal{P}}{\partial x_4} = \theta_q\cos(x_1 + \delta_0)$, $\frac{\partial\mathcal{P}}{\partial\hat{d}_2} = 1$.

Similar to Step 2, by adding and subtracting $c_3\mathcal{P}$, $c_3 > 0$, into (20), one has

$$\begin{aligned}\dot{V}_3 =& -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 - c_3\mathcal{P}^2 + \mathcal{P}\mathcal{Q} + (c_1x_1 + x_2)\tilde{d}_2\\ &+ \sum_{j=1}^{3}\mathcal{P}R_j\tilde{d}_{j+1} + \sum_{i=2}^{4}\left(-\frac{1}{\epsilon_i}\tilde{d}_i^2 + \tilde{d}_i\dot{d}_i\right), \end{aligned} \tag{21}$$

where $\mathcal{Q} = c_3\mathcal{P} + c_1x_1 + x_2 + \dot{\mathcal{P}}$, $\dot{\mathcal{P}} = \frac{\partial\mathcal{P}}{\partial x_1}x_2 + \sum_{i=2}^{4}\frac{\partial\mathcal{P}}{\partial x_i}\hat{f}_i$, $R_1 = \frac{\partial\mathcal{P}}{\partial x_2} + \frac{1}{\epsilon_2}\frac{\partial\mathcal{P}}{\partial\hat{d}_2}$, $R_2 = \frac{\partial\mathcal{P}}{\partial x_3}$, $R_3 = \frac{\partial\mathcal{P}}{\partial x_4}$, $\hat{f}_i = f_i(x) + \hat{d}_i$.

Step 4: Similarly, let us introduce the Lyapunov function of Step 3 as

$$V_4 = V_3 + \frac{1}{2}\mathcal{Q}^2 + \frac{1}{2}\tilde{d}_5^2. \tag{22}$$

Then the time derivative of V_4 along the system trajectories turns into as follows:

$$\begin{aligned}\dot{V}_4 =& -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 - c_3\mathcal{P}^2 + \mathcal{Q}\left(\mathcal{P} + \dot{\mathcal{Q}}\right) + (c_1x_1 + x_2)\tilde{d}_2\\ &+ \sum_{j=1}^{3}\mathcal{P}R_j\tilde{d}_{j+1} + \sum_{i=2}^{5}\left(-\frac{1}{\epsilon_i}\tilde{d}_i^2 + \tilde{d}_i\dot{d}_i\right)\end{aligned}$$

$$= -c_1x_1^2 - c_2(c_1x_1+x_2)^2 - c_3\mathcal{P}^2 + \mathcal{Q}\left(\mathcal{M} + \frac{\partial \mathcal{P}}{dx_3}\cdot\frac{\partial f_3}{dx_5}\left(f_5(x)+\theta_2u_c+\hat{d}_5\right)\right)$$
$$+(c_1x_1+x_2)\tilde{d}_2 + \sum_{j=1}^{3}\mathcal{P}R_j\tilde{d}_{j+1} + \sum_{k=1}^{4}\mathcal{Q}L_k\tilde{d}_{k+1} + \sum_{i=2}^{5}\left(-\frac{1}{\epsilon_i}\tilde{d}_i^2 + \tilde{d}_i\dot{d}_i\right), \quad (23)$$

where

$$\mathcal{M} = \mathcal{P} + c_3\dot{\mathcal{P}} + c_1x_2 + \hat{f}_2 + \left(\frac{\partial \mathcal{P}}{\partial x_1}\right)' x_2 + \left(\frac{\partial \mathcal{P}}{\partial x_1}\right)\hat{f}_2 + \left(\frac{\partial \mathcal{P}}{\partial x_3}\right)'\hat{f}_3$$
$$+\left(\frac{\partial \mathcal{P}}{\partial x_4}\right)'\hat{f}_4 + \frac{\partial \mathcal{P}}{\partial x_2}\left(\frac{\partial f_2}{\partial x_1}x_2 + \sum_{i=2}^{4}\frac{\partial f_2}{\partial x_i}\hat{f}_i\right) + \frac{\partial \mathcal{P}}{\partial x_3}\left(\frac{\partial f_3}{\partial x_1}x_2 + \frac{\partial f_3}{\partial x_i}\hat{f}_3\right)$$
$$+\frac{\partial \mathcal{P}}{\partial x_4}\left(\frac{\partial f_4}{\partial x_1}x_2 + \frac{\partial f_4}{\partial x_i}\hat{f}_4\right)$$
$$\left(\frac{\partial \mathcal{P}}{\partial x_1}\right)' = -\theta_d x_3\sin(x_1+\delta_0) + \theta_q x_4\cos(x_1+\delta_0) - 4m\sin 2(x_1+\delta_0)$$
$$+\theta_d\cos(x_1+\delta_0) - \theta_d\sin(x_1+\delta_0)$$
$$\left(\frac{\partial \mathcal{P}}{\partial x_3}\right)' = \theta_d\cos(x_1+\delta_0), \quad \left(\frac{\partial \mathcal{P}}{\partial x_4}\right)' = -\theta_q\sin(x_1+\delta_0).$$

From (23), in order to achieve the desired control performance, the presented control law is chosen as

$$u_c = -\frac{1}{\theta_2}\left[f_5(x) + \hat{d}_5 + \frac{1}{\frac{\partial \mathcal{P}}{\partial x_3}\frac{\partial f_3}{\partial x_5}}(c_4\mathcal{Q}+\mathcal{M})\right], \quad c_4 > 0. \quad (24)$$

By substituting the presented control law (24) into (23), we have

$$\dot{V}_4 = -c_1x_1^2 - c_2(c_1x_1+x_2)^2 - c_3\mathcal{P}^2 - c_4\mathcal{Q}^2 + (c_1x_1+x_2)\tilde{d}_2 + \sum_{j=1}^{3}\mathcal{P}R_j\tilde{d}_{j+1}$$
$$+\sum_{k=1}^{4}\mathcal{Q}L_k\tilde{d}_{k+1} + \sum_{i=2}^{5}\left(-\frac{1}{\epsilon_i}\tilde{d}_i^2 + \tilde{d}_i\dot{d}_i\right). \quad (25)$$

After straightforwardly computing (25), we have

$$\dot{V}_4 \le -c_1x_1^2 - c_2\left[(c_1x_1+x_2)^2 - \frac{1}{c_2}(c_1x_1+x_2)\tilde{d}_2\right] - \frac{c_3}{3}\sum_{j=1}^{3}\left[\mathcal{P}^2 - \frac{3}{c_3}\mathcal{P}R_j\tilde{d}_{j+1}\right]$$
$$-\frac{c_4}{4}\sum_{k=1}^{4}\left[\mathcal{Q}^2 - \frac{4}{c_4}\mathcal{Q}L_k\tilde{d}_{k+1}\right] + \sum_{i=2}^{5}\left(-\frac{1}{\epsilon_i}\tilde{d}_i^2 + \left|\tilde{d}_i\right|\left|\dot{d}_i\right|\right)$$
$$= -c_1x_1^2 - c_2\left(c_1x_1+x_2-\frac{\tilde{d}_2}{2c_2}\right)^2 - \frac{c_3}{3}\sum_{j=1}^{3}\left(\mathcal{P} - \frac{3R_j\tilde{d}_{j+1}}{2c_3}\right)^2 + \sum_{i=2}^{5}\frac{1}{4\lambda_i}\left|\dot{d}_i\right|^2$$
$$-\frac{c_4}{4}\sum_{k=1}^{4}\left(\mathcal{Q} - \frac{2L_k\tilde{d}_{k+1}}{c_4}\right)^2 - \sum_{i=2}^{5}\lambda_i\left(\left|\tilde{d}_i\right| - \frac{1}{2\lambda_i}\left|\dot{d}_i\right|\right)^2, \quad (26)$$

where $\lambda_2 = \frac{1}{\epsilon_2} - \frac{1}{4c_2} - \frac{3R_1^2}{4c_3} - \frac{L_1^2}{c_4}$, $\lambda_3 = \frac{1}{\epsilon_3} - \frac{3R_2^2}{4c_3} - \frac{L_2^2}{c_4}$, $\lambda_4 = \frac{1}{\epsilon_4} - \frac{3R_3^2}{4c_3} - \frac{L_3^2}{c_4}$, $\lambda_5 = \frac{1}{\epsilon_5} - \frac{L_3^2}{c_4}$. Because $\left|\dot{d}_i\right| \leq \dot{d}_{i\max}$, we obtain

$$\begin{aligned}\dot{V}_4 \leq & -c_1x_1^2 - c_2\left(c_1x_1 + x_2 - \frac{\tilde{d}_2}{2c_2}\right)^2 - \frac{c_3}{3}\sum_{j=1}^{3}\left(\mathcal{P} - \frac{3R_j\tilde{d}_{j+1}}{2c_3}\right)^2 + \sum_{i=2}^{5}\frac{1}{4\lambda_i}\dot{d}_{i\max}^2 \\ & - \frac{c_4}{4}\sum_{k=1}^{4}\left(\mathcal{Q} - \frac{2L_k\tilde{d}_{k+1}}{c_4}\right)^2 - \sum_{i=2}^{5}\lambda_i\left(\left|\tilde{d}_i\right| - \frac{1}{2\lambda_i}\left|\dot{d}_i\right|\right)^2. \end{aligned} \tag{27}$$

In order to conveniently derive the proposed scheme, the state of the closed-loop system is defined as

$$z_{cl} = \left[\begin{array}{cccccccc} x_1 & c_1x_1 + x_2 & \mathcal{P} & \mathcal{Q} & \tilde{d}_2 & \tilde{d}_3 & \tilde{d}_4 & \tilde{d}_5 \end{array}\right]^T. \tag{28}$$

Based on an idea reported in [24], it is clear from (27) that $\dot{V}_4$ is negative definite outside the compact set $M = \left\{z_{cl}|K(z_{cl}) \leq \sum_{i=2}^{5}\frac{1}{4\lambda_i}\dot{d}_{i\max}^2\right\}$, where $K(z_{cl}) = c_1x_1^2 + c_2\left(c_1x_1 + x_2 - \frac{\tilde{d}_2}{2c_2}\right)^2 + \frac{c_3}{3}\sum_{j=1}^{3}\left(\mathcal{P} - \frac{3R_j\tilde{d}_{j+1}}{2c_3}\right)^2 + \frac{c_4}{4}\sum_{k=1}^{4}\left(\mathcal{Q} - \frac{2L_k\tilde{d}_{k+1}}{c_4}\right)^2 + \sum_{i=2}^{5}\lambda_i\left(\left|\tilde{d}_i\right| - \frac{1}{2\lambda_i}\left|\dot{d}_i\right|\right)^2$. Further define a ρ-neighborhood of M with $\rho > 0$ as $M_\rho = \left\{K(z_{cl}) \leq \sum_{i=2}^{5}\frac{1}{4\lambda_i}\dot{d}_{i\max}^2 + \rho\right\}$, then $\dot{V}_4 \leq -\rho$. The state $z_{cl}(t)$ will enter the ρ-neighborhood, M_ρ, in finite time. Therefore, we have the following theorem for higher-order models of synchronous generators.

Theorem 3.2. *The higher-order model of synchronous generators (5) and the high-gain nonlinear disturbance observer (11) and (12) are considered. Subsequently, under Assumption 2.1, if the following two conditions such that*

1) The control law is given in (24) where $c_k > 0$, $k = 1, 2, 3, 4$,

2) $\epsilon_2 < \left(\frac{1}{4c_2} + \frac{3R_1^2}{4c_3} + \frac{L_1^2}{c_4}\right)^{-1}$, $\epsilon_3 < \left(\frac{3R_2^2}{4c_3} + \frac{L_2^2}{c_4}\right)^{-1}$, $\epsilon_4 < \left(\frac{3R_3^2}{4c_3} + \frac{L_3^2}{c_4}\right)^{-1}$, $\epsilon_5 < \left(\frac{L_3^2}{c_4}\right)^{-1}$, *and* $\lambda_i > 0$ *given in (25),*

are all satisfied, then $z_{cl}(t)$ *is ultimate boundedness* [26] *and enters to the set* M_ρ *in the finite time* $t_1 > 0$, *and stays within* M_ρ, $\forall t > t_1$.

Proof: The proof of Theorem 3.2 is based on the arguments given earlier.

Remark 3.1. *The novelty of this work lies in the following: 1) a composite nonlinear controller capable of stabilizing the power systems considered despite having external disturbance, making all trajectories ultimately bounded, and providing better disturbance rejection properties compared to a conventional backstepping-like controller; 2) the application of this innovative approach to several power systems such as multi-machine power systems, power systems including a flexible AC transmission system (FACTS), and so on.*

Remark 3.2. *Note that the observer gain can be selected to increase or decrease the size of* M_ρ *arbitrarily because its size depends upon both the controller parameters* c_k, $(k = 1, 2, 3, 4)$, *and the observer gain* (ϵ_i *and* λ_i, $(i = 2, 3, 4, 5)$). *Additionally, a suitable selection for these design parameters leads to the fast convergence rate and the size of boundedness of all trajectories in the system.*

Remark 3.3. *With Assumption 2.1 and an additional condition that* $\lim_{t\to+\infty}\dot{d}_i = 0$, *it follows directly from (27) that the disturbance estimation error converges to zero asymptotically and it can be also concluded that the adverse effects of the external disturbances* *are removed in each state variable. Besides, it can be observed that*

$$\dot{V}_4 \leq -c_1 x_1^2 - c_2(c_1 x_1 + x_2)^2 - c_3\mathcal{P}^2 - c_4\mathcal{Q}^2 \leq 0. \tag{29}$$

This implies that x_i, $(i = 1, 2, \ldots, 5)$ converge to the desired equilibrium point x_e asymptotically.

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

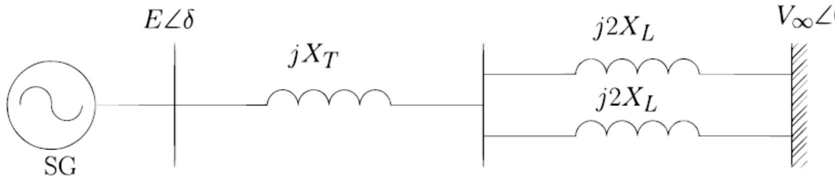

Figure 1. A single line diagram of SMIB model

The physical parameters (pu.), the controller parameters, and initial conditions used for this power system model are as follows.

- The parameters of high-order model of synchronous generators and transmission line: $\omega_s = 2\pi f$ rad/s, $D = 5$, $H = 4$, $f = 60$ Hz, $T'_{d0} = 0.4$, $T'_{q0} = 0.1$, $V_\infty = 1\angle 0°$, $\omega = \omega_s$, $X_q = 1.7$, $X'_q = 0.28$, $X_d = 1.8$, $X'_d = 0.17$, $X_T = 0.1$, $X_L = 0.15$.
- The controller parameters of the proposed controller are $\epsilon_j = 0.05$, $(j = 2, 3, 4, 5)$, $c_i = 10$, $(i = 1, 2, 3, 4)$.
- Initial conditions $\delta_e = 1.202$ rad, $\omega_e = \omega_s$, $E'_{qe} = 0.7327$, $E'_{de} = -0.7031$, $E_{fde} = 2.179$, $\hat{d}_{i0} = 0$, $(i = 2, 3, 4, 5)$. These initial parameters can be determined from setting all time derivatives of the complete dynamical model (1) to zero and then directly solved from the resulting algebraic equations.

Additionally, the external disturbances $(d_j,\ j = 2, 3, 4, 5)$ acting on the underlying system are assumed to be:

$$d_2(t) = \begin{cases} 0.5\sin(2t), & 0 \leq t < 5 \\ 1, & 5 \leq t < 10 \\ 0.25\sin(2t)e^{-t}, & 10 \leq t \leq 20 \end{cases}, \quad d_3(t) = \begin{cases} 0.15\cos(t), & 0 \leq t < 5 \\ 2, & 5 \leq t < 10 \\ 0.5\cos(t)e^{-2t}, & 10 \leq t \leq 20 \end{cases}$$

$$d_4(t) = \begin{cases} 0.25\sin(t), & 0 \leq t < 5 \\ 2, & 5 \leq t < 10 \\ 0.3\sin(t)e^{-3t}, & 10 \leq t \leq 20 \end{cases}, \quad d_5(t) = \begin{cases} 0.2\cos(t), & 0 \leq t < 5 \\ 1.5, & 5 \leq t < 10 \\ 0.4\cos(t)e^{-t}, & 10 \leq t \leq 20 \end{cases}$$

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 composite nonlinear controller (high-gain disturbance observer based control plus backstepping-like control) is compared with that of the conventional backstepping-like controller (CBLC) without disturbance observer design (30) as follows:

$$u_{\text{cbl}} = -\frac{1}{\theta_2}\left[f_5(x) + \frac{1}{\frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_3}\frac{\partial f_3}{\partial x_5}}\left(c_4\mathcal{Q}_{\text{cbl}} + \mathcal{M}_{\text{cbl}}\right)\right], \tag{30}$$

where

$$\mathcal{Q}_{\text{cbl}} = c_3\mathcal{P}_{\text{cbl}} + c_1x_1 + x_2 + \dot{\mathcal{P}}_{\text{cbl}}, \quad \dot{\mathcal{P}}_{\text{cbl}} = \frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_1}x_2 + \sum_{i=2}^{4}\frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_i}f_i,$$

$$\begin{aligned}\mathcal{M}_{\text{cbl}} =& \mathcal{P}_{\text{cbl}} + c_3\dot{\mathcal{P}}_{\text{cbl}} + c_1x_2 + f_2 + \left(\frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_1}\right)' x_2 + \left(\frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_1}\right) f_2 + \left(\frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_3}\right)' f_3 \\ &+ \left(\frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_4}\right)' f_4 + \frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_2}\left(\frac{\partial f_2}{\partial x_1}x_2 + \sum_{i=2}^{4}\frac{\partial f_2}{\partial x_i}f_i\right) + \frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_3}\left(\frac{\partial f_3}{\partial x_1}x_2 + \frac{\partial f_3}{\partial x_i}f_3\right) \\ &+ \frac{\partial \mathcal{P}_{\text{cbl}}}{\partial x_4}\left(\frac{\partial f_4}{\partial x_1}x_2 + \frac{\partial f_4}{\partial x_i}f_4\right),\end{aligned}$$

$$\mathcal{P}_{\text{cbl}} = (1 + c_1c_2)x_1 + (c_1 + c_2 + \theta_D)x_2 + \theta_\omega P_m + \theta_d x_3\sin(x_1 + \delta_0) + \theta_q x_4\cos(x_1 + \delta_0).$$

The controller parameters of this scheme are set as $c_k = 10$, $(k = 1, 2, 3, 4)$.

The simulation results are presented and discussed as follows. Time histories of the power angle, frequency, d-axis and q-axis transient internal voltages along with field voltage under two controllers are presented in Figures 2 and 3, respectively. Also, the results of disturbance estimation and external disturbances are depicted in Figure 4.

From these figures, it is easy to observe that even if there exist external disturbances in the system of interest, the proposed scheme and the CBLC scheme can successfully stabilize the system. However, the presented control offers obviously better transient performances and satisfactory disturbance rejection ability such as a shorter settling time,

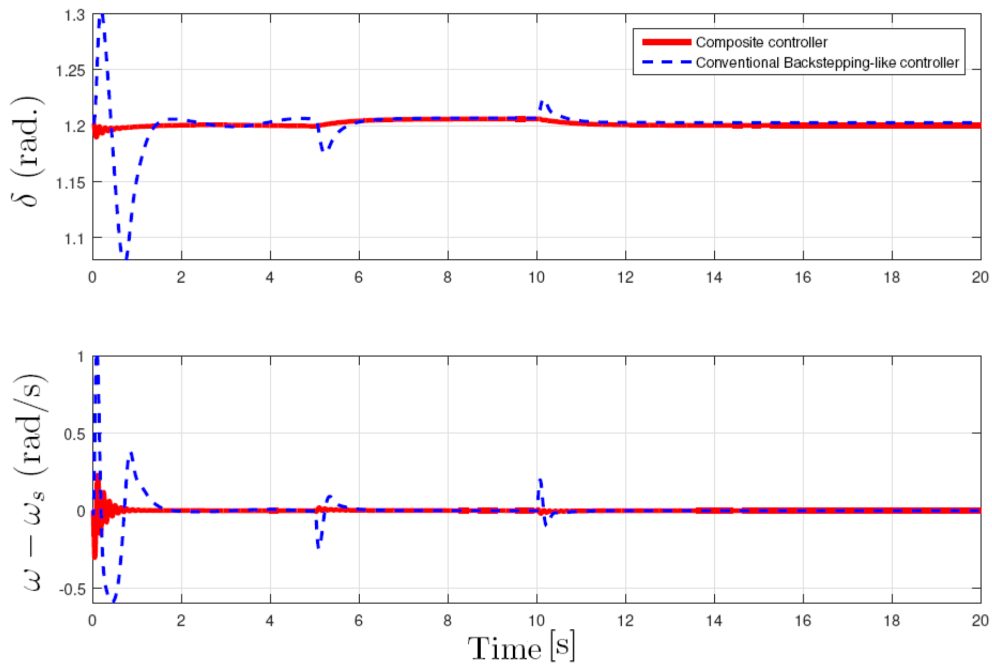

FIGURE 2. Controller performance – Power angles (δ) (rad.), and frequency ($\omega - \omega_s$) rad/s. (Solid: Composite control, Dashed: Conventional backstepping-like control)

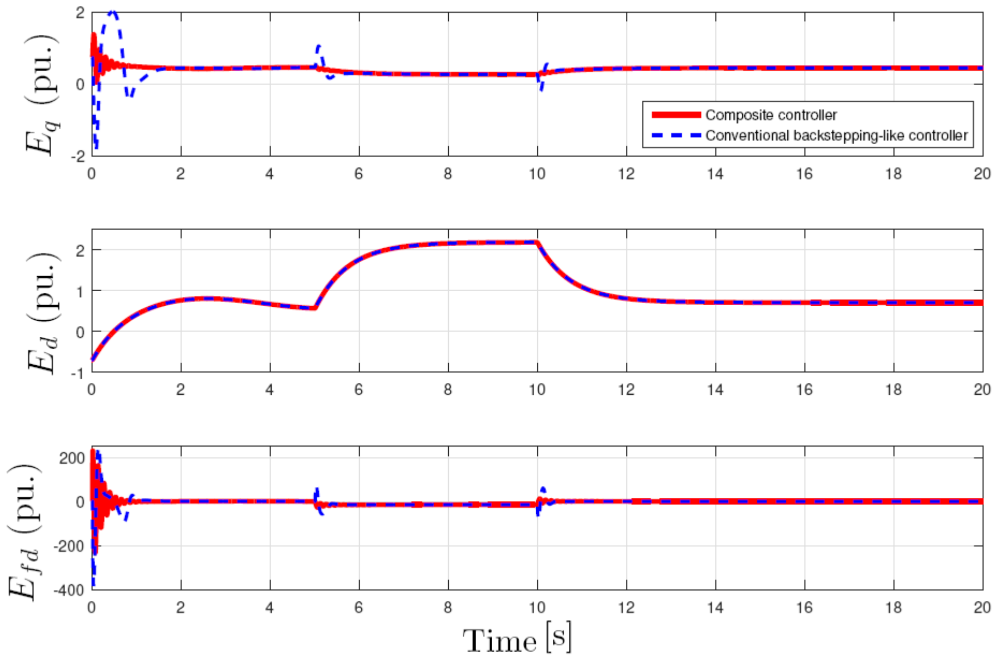

FIGURE 3. Controller performance – The q-axis transient internal voltage (E_q) (pu.) and the d-axis transient internal voltage (E_d) (pu.) and field voltage (E_{fd}) (Solid: Composite control, Dashed: Conventional backstepping-like control)

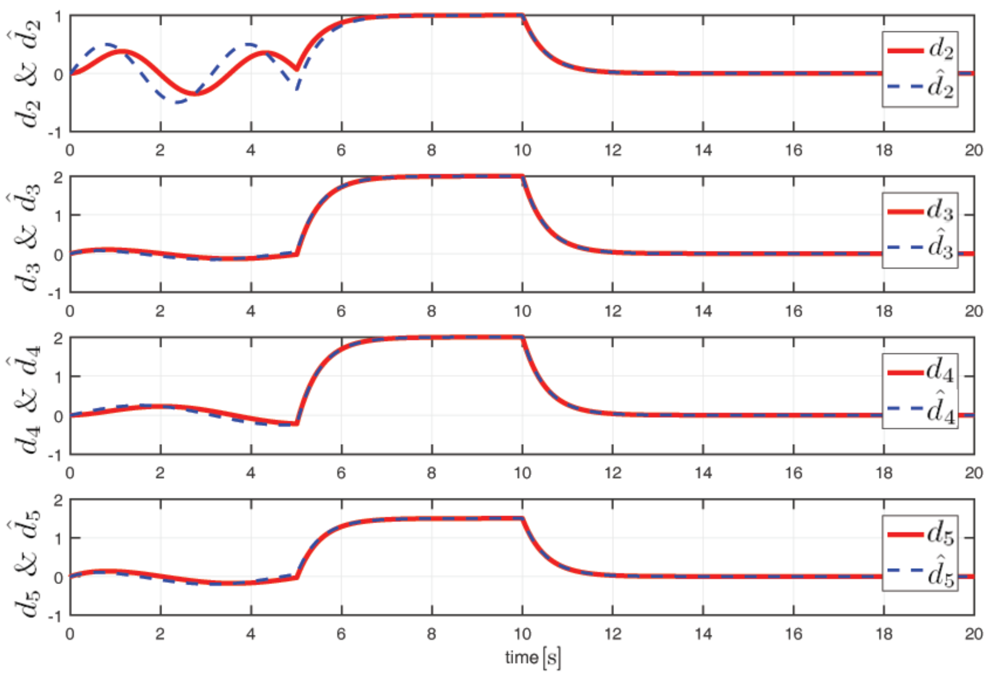

FIGURE 4. External disturbances and disturbance estimation

a short rise time, and a faster convergence rate. Clearly, all time responses are significantly more damped with the proposed scheme than with the CBLC scheme. Compared with the presented method, the CBLC strategy has a poor transient performance such as unsatisfactory overshoots and slowly suppressing system oscillations. This is because in the developed control framework the composite nonlinear scheme combines the advanced feedback control law with the full use of disturbances information in each design step to compensate the effects of inevitable disturbances. In other words, the CBLC method does not consider the effects of disturbances in the designed control law. Figure 4 indicates that the disturbance estimators tend to track the unknown external disturbances with fast convergence rate and no oscillations.

From the simulation results mentioned previously, it is evident that as the presented method combined with the disturbance observer scheme is applied to the SMIB power system with external disturbances, the advantages over conventional backstepping-like control are as follows.

- The proposed controller is synthesized to steer the state of closed-loop dynamics to the equilibrium rapidly without the oscillations despite undesired disturbances.
- The developed control strategy can guarantee that the state of closed-loop system is ultimately bounded. In particular, it obviously performs well and has considerably effective disturbance rejection ability. It offers obviously superior transient performances illustrated by the rapidly suppressing system oscillations in all time trajectories in spite of having external disturbances.
- The process of designing the desired control law adds the full use of disturbance information into each design step. The information is able to compensate the adverse effects arising from undesired disturbances, compensation errors, and system states. In contrast, the information is not employed for the conventional backstepping-like design, thereby resulting in unsatisfactory control performances.

5. **Conclusion.** In this paper, a composite nonlinear control strategy has been presented for higher-order models of synchronous generators under undesired external disturbances. The developed approach has been designed by combining backstepping-like control with high-gain disturbance observer method. The main contributions of the proposed strategy are: a) use of disturbance observer design to obtain better dynamic performances and a satisfactory disturbance rejection ability despite both non-vanishing and vanishing disturbances, b) demonstrating the application of the combination of backstepping-like control and disturbance observe scheme for the design of a composite nonlinear stabilizing feedback controller in higher-order models of synchronous generators with disturbances; c) developing a methodology that can include disturbance information which is used to compensate the inevitably adverse effects of external disturbances, and d) the simulation results indicating the composite nonlinear control capable of improving obvious transient performances and has better disturbance rejection property than the conventional backstepping-like method. Future study will be devoted to extension of this approach to a composite controller for multi-machine power systems in the presence of external disturbances.

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