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TRANSIENT STABILITY ENHANCEMENT AND VOLTAGE REGULATION FOR POWER SYSTEMS WITH STATCOM VIA A BACKSTEPPING-LIKE SCHEME

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Abstract. *This paper presents the development of a backstepping-like control design for power systems with STATCOM for transient stability enhancement and voltage regulation. With the help of this algorithm, the presented control strategy is rather simple, but effective. Despite small and large disturbances, it can not only improve transient stability, but also maintain the terminal STATCOM voltage close to the desired reference voltage. Based on the Lyapunov direct method, the closed-loop stability is proved to ensure that the equilibrium point is asymptotically and transiently stable. The effectiveness and feasibility of the developed strategy are verified on a single-machine infinite bus power system with STATCOM. The simulation results demonstrate the proposed control capable of effectively improving dynamic performances, rapidly reducing power oscillations, and performing better than a conventional backstepping-like design approach.*
Keywords: Backstepping-like control, Transient stability, Voltage regulation, STATCOM, Generator excitation

1. **Introduction.** Maintaining power system stability and operation is being paid significant attention due to increasing growth in the size and complexity of modern power systems. It is well-known that such power systems become highly nonlinear and complicated, resulting in difficulties to maintain power system stability and operation. To deal with the effects of complicated nonlinear dynamic behavior from complex power system networks, there exist a variety of attempts to determine effective and promising approaches for system stability enhancement and improved transient performances despite disturbances. One of major effective approaches used to enhance power system stability and to achieve the desired control objectives is the use of a combination of generator excitation and Flexible AC Transmission System (FACTS) devices [1, 2].

Recently, the use of FACTS devices has been a very active research area in the power system engineering community because of fast continuous developments in power electronic devices. The combined generator excitation control and FACTS devices have been developed to deal with several problems like providing variable reactive power in response to voltage variations and supporting the grid stability together with supporting the electric network having a poor power factor and poor voltage regulation. Among FACTS

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famiy, Static Synchronous Compensator (STATCOM) [1, 2] is utilized to increase the grid transfer capability, improve voltage stability, damp out power oscillation, and enhance transient stability. Also, the coordination of generator excitation and STATCOM is regarded as an effective approach to cope with a lot of issues arising in power systems.

To the best of our knowledge, there are a lot of advanced control algorithms using a coordination between generator excitation and STATCOM control [3-15] via nonlinear control techniques which have been studied. In [3], based on a combination of the zero dynamic method and the pole-assignment method, a nonlinear feedback linearizing control was presented to enhance transient stability of a Single-Machine Infinite Bus (SMIB) system. Kanchanaharuthai [4] proposed an immersion and invariance based nonlinear adaptive nonlinear control was proposed for power system stability enhancement of SMIB system while the authors [5, 6] developed the coordinated controller based on Hamiltonian theory for multi-machine power systems. In [7], a nonlinear control law based on a combined backstepping and passivity control technique was reported. Kanchanaharuthai et al. [8] proposed an IDA-PBC design for transient stability improvement together with voltage regulation. A nonlinear feedback stabilizing control law [9] was reported for SMIB power system including unknown parameters via an immersion and invariance. To deal with random loads appearing in both SMIB and large-scale power systems, an intelligent control scheme [10] was developed. In [11], a backstepping design without computing analytical differentiators was developed to cope with the problem of "explosion of complexity" inherent in conventional backstepping design [12]. There was recently a nonlinear controller [13] based on a combination of Dynamic Surface Control (DSC) [14], high-order sliding mode control, and fixed-time stability theory. This work focused on dealing with voltage stabilization, reducing chaotic oscillation in power systems with current source converter-based STATCOM, and achieving good choas suppression performances. In [15], despite having a simpler design procedure, a backstepping-like control law was developed for transient stability enhancement and voltage regulation without including terminal voltage dynamics.

Inspired by these advanced control schemes mentioned previously, this paper continues this line of investigation but focuses on a backstepping-like control design to solve the problem of transient stabilization as well as voltage regulation, simultaneously. Although the developed control design is rather simple and follows the idea presented in [15], the main differences are as follows: (i) the presented control deals with the design of a state feedback control law capable of achieving transient stability and voltage regulation at the same time; (ii) the dynamics of the terminal STATCOM voltage are included in the overall closed-loop system and stability analysis. Therefore, the major contributions of this paper are given as follows: (a) a backstepping-like control scheme capable of improving transient stability and regulating the terminal voltage of the power systems with STATCOM, simultaneously, has not been studied before; (b) the equilibrium point is asymptotically and transiently stable, (c) the developed control law is extended from the result of [15] to the state feedback design by including the terminal STATCOM voltage to the whole closed-loop system, and (d) compared with a conventional backstepping-like control, the proposed control law provides more advantages: satisfactory transient dynamic performances as well as transient stability enhancement and voltage regulation simultaneously.

The rest of this paper is organized as follows. Simplified synchronous generator and STATCOM models are briefly described and control problem formulation is given in Section 2. A backstepping-like design is given in Section 3. Simulation results are given in Section 4. Conclusions are given in Section 5.

Remark 1.1. *From the main contributions above, the proposed nonlinear backstepping-like control is rather effective. However, it has some limitations due to the developed controller only designed for a Single-Machine Infinite Bus (SMIB) power system. It is well-known that the SMIB model used is not an adequate representation of the real-world system for transient stability studies. Therefore, to increase the main academic contribution, the further results need to be extended to multi-machine power systems with STATCOM, which will be reported in the future.*

2. Power System Model Description.

2.1. Power system models with STATCOM. Consider the power system network in Figure 1, where X_1 denotes the transformer and the transient reactance of the Synchronous Generator (SG), and X_2 is the transmission line reactance between the bus terminal V_t and the infinite bus voltage V_∞. I_Q is the STATCOM current. E is the internal transient voltage of the SG.

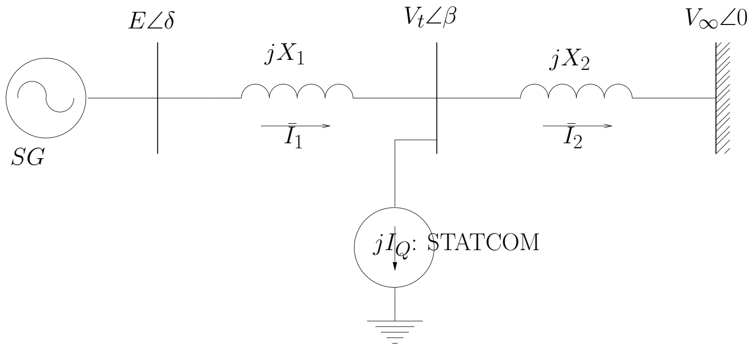

Figure 1. Network

Now, we investigate the transmitted power characteristics of STATCOM based on the SG model. Assuming that any losses in STATCOM are negligible and STATCOM system is modelled as a parallel current capable of injecting or absorbing reactive power. According to the results from [8] to compute $\bar{I}_1$ and $\bar{I}_2$, we have

$$P_E = \frac{EV_\infty \sin\delta}{(X_1+X_2)}\left(1 + \frac{I_Q X_1 X_2}{\Delta(\delta, E)}\right), \quad \Delta(\delta, E) = \sqrt{(EX_2)^2 + (V_\infty X_1)^2 + 2X_1X_2EV_\infty\cos\delta}$$

The dynamical model [4, 9] of the synchronous generator connected to an infinite bus with STATCOM can be expressed as follows:

$$\begin{cases} \dot{\delta} = \omega - \omega_s \\ \dot{\omega} = \dfrac{1}{M}\left(P_m - P_E - D(\omega - \omega_s)\right) \\ \dot{E} = -aE + b\cos\delta + \dfrac{u_f}{T_0'} \\ \dot{I}_Q = \dfrac{1}{T_q}(-(I_Q - I_{Qe}) + u_q) \end{cases} \tag{1}$$

with $a = \frac{X_{d\Sigma}}{(X_1+X_2)T_0'}$, $b = \frac{X_d - X_d'}{(X_1+X_2)T_0'}V_\infty$, 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 is the electrical power, with 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 $M = 2H/\omega_s$. $X'_{d\Sigma} = X'_d + X_T + X_L$ 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. Similarly, $X_{d\Sigma} = X_d + X_T + X_L$ is identical to $X'_{d\Sigma}$ except that X_d denotes the direct axis reactance of synchronous generators. 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_q is a time constant of STATCOM models.

To deal with the problem of voltage regulation at the terminal STATCOM voltage (V_t), let us define $\Delta V_t = V_t - V_{\text{ref}}$ as a voltage deviation where V_{ref} denotes the reference voltage and

$$V_t = \frac{\Delta(\delta, E)}{(X_1 + X_2)} + \frac{X_1 X_2}{X_1 + X_2} I_Q \tag{2}$$

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

$$\begin{cases} x_1 = \delta - \delta_e \\ x_2 = \omega - \omega_s \\ x_3 = P_E = \dfrac{E V_\infty \sin\delta}{(X_1 + X_2)} \left(1 + \dfrac{I_Q X_1 X_2}{\Delta(\delta, E)}\right) \\ x_4 = \int_0^t (V_t(\tau) - V_{\text{ref}}) d\tau \\ x_5 = V_t(t) - V_{\text{ref}} \end{cases} \tag{3}$$

Remark 2.1. *Our objective in this work is to find the desired controller capable of driving the new state variables (x_i, $i = 1, 2, 3, 4, 5$) above to the equilibrium point at steady state. 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 $x_e = [0,\ 0,\ x_{3e},\ 0,\ 0]^T = [0,\ 0,\ P_m,\ 0,\ 0]^T$. This means that after disturbances disappear, all state variables settle down to the desired equilibrium $\left(\delta \to \delta_e,\ \omega \to \omega_s,\ P_E \to P_m,\ \int_0^t (V_t(\tau) - V_{\text{ref}}) d\tau \to 0,\ V_t \to V_{\text{ref}}\right)$.*

Subsequently, using differentiating the state variables (3), one has the power system including STATCOM which can be written as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dfrac{1}{M} (P_m - x_3 - x_4 - D x_2) \\ \dot{x}_3 = F_{P_E}(x) + v_1 \\ \dot{x}_4 = x_5 \\ \dot{x}_5 = F_{V_t}(x) + v_2 \end{cases} \tag{4}$$

where

$$\begin{aligned} F_{P_E}(x) &= \frac{\partial P_E}{\partial x_1} x_2 + \frac{\partial P_E}{\partial E} (-aE + b\cos x_1) + \frac{\partial P_E}{\partial I_Q} \frac{1}{T_q} (-(I_Q - I_{Qe})), \\ F_{V_t}(x) &= \frac{\partial V_t}{\partial x_1} x_2 + \frac{\partial V_t}{\partial E} (-aE + b\cos x_1) + \frac{\partial V_t}{\partial I_Q} \frac{1}{T_q} (-(I_Q - I_{Qe})), \\ v_1 &= \frac{\partial P_E}{\partial E} \frac{u_f}{T'_0} + \frac{\partial P_E}{\partial I_Q} \frac{u_q}{T_q}, \quad v_2 = \frac{\partial V_t}{\partial E} \frac{u_f}{T'_0} + \frac{\partial V_t}{\partial I_Q} \frac{u_q}{T_q}, \\ \frac{\partial P_E}{\partial x_1} &= \frac{E V_\infty \cos x_1}{X_1 + X_2} \left(1 + \frac{X_1 X_2 I_Q}{\Delta(x_1, E)}\right) + \frac{\left(E^2 I_Q V_\infty^2 X_1^2 X_2^2 \sin^2 x_1\right)}{(X_1 + X_2) \Delta(x_1, E)^3}, \end{aligned}$$

$$\frac{\partial P_E}{\partial E} = \frac{V_\infty \sin x_1}{X_1+X_2}\left(1+\frac{X_1X_2I_Q}{\Delta(x_1,E)}\right) - \frac{(EI_QV_\infty X_1X_2\sin x_1)\left(EX_2^2+V_\infty X_1X_2\cos x_1\right)}{(X_1+X_2)\Delta(x_1,E)^3},$$
$$\frac{\partial P_E}{\partial I_Q} = \frac{EV_\infty X_1X_2\sin x_1}{(X_1+X_2)\Delta(x_1,E)}, \quad \frac{\partial V_t}{\partial x_1} = -\frac{EV_\infty X_1X_2\sin x_1}{(X_1+X_2)\Delta(x_1,E)},$$
$$\frac{\partial V_t}{\partial E} = \frac{EX_2^2+V_\infty X_1X_2\cos x_1}{(X_1+X_2)\Delta(x_1,E)}, \quad \frac{\partial V_t}{\partial I_Q} = \frac{X_1X_2}{X_1+X_2}.$$

Problem statement: The goal of this paper is to solve the problem of the transient stabilization and voltage regulation of the power systems with STATCOM (4) simultaneously. We can formulate the control problem as follows. For the system (4), with the help of the backstepping-like control approach, find out, if possible, a nonlinear controller $u(x)$ in order to accomplish transient stabilization of the overall closed-loop system and to achieve two requirements: 1) the desired equilibrium is asymptotically and transiently stable; 2) transient stability enhancement and voltage regulation are simultaneously accomplished.

For the developed design procedure in the next section, the backstepping-like strategy design will be developed to obtain a feedback stabilizing nonlinear control. In the following section, the developed control is designed step by step to achieve the desired performances and requirements.

3. **Backstepping-Like Nonlinear Control.**

The developed control approach is expressed in the following theorem.

Theorem 3.1. *Consider the nonlinear power system with STATCOM in (4), the backstepping-like controller is as follows:*

$$\frac{u_f}{T_0'} = \frac{1}{\mathcal{R}}\left(\frac{\partial V_t}{\partial I_Q}v_1 - \frac{\partial P_E}{\partial I_Q}v_2\right) \tag{5}$$
$$\frac{u_q}{T_q} = \frac{1}{\mathcal{R}}\left(-\frac{\partial V_t}{\partial E}v_1 + \frac{\partial P_E}{\partial E}v_2\right) \tag{6}$$

where $\mathcal{R} = \frac{\partial P_E}{\partial E}\cdot\frac{\partial V_t}{\partial I_Q} - \frac{\partial P_E}{\partial I_Q}\cdot\frac{\partial V_t}{\partial E} \neq 0$. *Then the equilibrium point of the system (4) is asymptotically and transiently stable. This implies that* $\lim_{t\to+\infty} x_i = 0$, $(i = 1,2,4,5)$, $\lim_{t\to+\infty} x_3 = P_m$.

Proof: For the purpose of designing a nonlinear controller, let us define the following Lyapunov candidate as follows

$$V_1 = \frac{1}{2}x_1^2 \tag{7}$$

Then the derivative of (7) becomes

$$\dot V_1 = x_1x_2 = -c_1x_1^2 + x_1(c_1x_1+x_2) \tag{8}$$

where $c_1 > 0$. From (8), it is easy to see that the term $x_1(c_1x_1+x_2)$ is not always negative; thus, this term should be eliminated from the aforementioned equation. In order to do this, we choose the Lyapunov function candidate as:

$$V_2 = \frac{1}{2}x_1^2 + \frac{1}{2}(c_1x_1+x_2)^2 \tag{9}$$

Remark 3.1. *It is easy to observe that the weight setting of* $1/2$ *for the two terms in (9) is used like conventional backstepping design.*

By computing the derivative of (9), we have

$$\begin{aligned}\dot{V}_2 &= -c_1x_1^2 + x_1(c_1x_1 + x_2) + (c_1x_1 + x_2)(c_1\dot{x}_1 + \dot{x}_2)\\ &= -c_1x_1^2 + (c_1x_1 + x_2)(x_1 + c_1x_2 + \dot{x}_2)\\ &= -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 + (c_1x_1 + x_2)\mathcal{P} \qquad (10)\end{aligned}$$

where c_2 is a positive design constant and $\mathcal{P} = (c_1c_2 + 1)x_1 + \left(c_1 + c_2 - \frac{D}{M}\right) x_2 + \frac{(P_m - x_3)}{M}$. It can be observed that the last term of (10) is not always negative; thus, this term needs to be canceled. To this end, we introduce the following terms into V_3 and then obtain

$$V_3 = \frac{1}{2}x_1^2 + \frac{1}{2}(c_1x_1 + x_2)^2 + \frac{1}{2}\mathcal{P}^2 \qquad (11)$$

By calculating the derivative of (11) along the system trajectory, one obtains

$$\begin{aligned}\dot{V}_3 &= -c_1x_1^2 + c_2(c_1x_1 + x_2)^2 + \mathcal{P}\left[c_1x_1 + x_2 + \dot{\mathcal{P}}\right]\\ &= -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 - c_3\mathcal{P}^2 + \mathcal{P}\left[c_3\mathcal{P} + c_1x_1 + x_2 + \dot{\mathcal{P}}\right]\\ &= -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 - c_3\mathcal{P}^2 + \mathcal{P}\left[\tilde{\mathcal{P}} - \frac{\dot{x}_3}{M}\right] \qquad (12)\end{aligned}$$

with $\tilde{\mathcal{P}} = c_3\mathcal{P} + c_1x_1 + (c_1c_2 + 1)x_2 + \left(c_1 + c_2 - \frac{D}{M}\right)\dot{x}_2$, where $c_i > 0$, $(i = 1, 2, 3)$ are positive design parameters.

After substituting $\dot{x}_3$ into (12), one has

$$\dot{V}_3 = -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 - c_3\mathcal{P}^2 + \mathcal{P}\left[\tilde{\mathcal{P}} - \frac{1}{M}\left(F_{P_E}(x) + v_1\right)\right] \qquad (13)$$

Therefore, if we choose

$$v_1 = M\tilde{\mathcal{P}} - F_{P_E}(x) = \frac{\partial P_E}{\partial E} \cdot \frac{u_f}{T_0'} + \frac{\partial P_E}{\partial I_Q} \cdot \frac{u_q}{T_q} \qquad (14)$$

Then, under the feedback control law (14) to enhance transient stability, Equation (13) turns into

$$\dot{V}_3 = -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 - c_3\mathcal{P}^2 \le 0 \qquad (15)$$

To deal with the problem of voltage regulation, let us define the following Lyapunov candidate as follows:

$$V_4 = \frac{1}{2}x_4^2 \qquad (16)$$

Then the derivative of (16) becomes

$$\dot{V}_4 = x_4x_5 = -c_4x_4^2 + x_4(c_4x_4 + x_5) \qquad (17)$$

where $c_4 > 0$. From (17), it is easy to see that the term $x_4(c_4x_4 + x_5)$ is not always negative; thus, this term should be eliminated from the aforementioned equation. In order to do this, we choose the Lyapunov function candidate as:

$$V_5 = \frac{1}{2}x_4^2 + \frac{1}{2}(c_4x_4 + x_5)^2 \qquad (18)$$

After calculating the derivative of (18), we have

$$\begin{aligned}\dot{V}_5 &= -c_4x_4^2 + x_4(c_4x_4 + x_5) + (c_4x_4 + x_5)(c_4\dot{x}_4 + \dot{x}_5)\\ &= -c_4x_4^2 + (c_4x_4 + x_5)(x_4 + c_4x_5 + \dot{x}_5)\\ &= -c_4x_4^2 - c_5(c_4x_4 + x_5)^2 + (c_4x_4 + x_5)\left(\mathcal{Q} + \dot{x}_5\right) \qquad (19)\end{aligned}$$

where $\mathcal{Q} = c_5(c_4x_4 + x_5) + x_4 + c_4x_5$, $c_5 > 0$.

After substituting $\dot{x}_5$ into (19), one has

$$\dot{V}_5 = -c_4x_4^2 - c_5(c_4x_4 + x_5)^2 + (c_4x_4 + x_5)\left(\mathcal{Q} + F_{V_t}(x) + v_2\right) \tag{20}$$

Therefore, we choose

$$v_2 = -\tilde{\mathcal{Q}} - F_{V_t}(x) = \frac{\partial V_t}{\partial E} \cdot \frac{u_f}{T_0'} + \frac{\partial V_t}{\partial I_Q} \cdot \frac{u_q}{T_q} \tag{21}$$

Under the feedback control law (21) to drive the voltage deviation ΔV_t to zero at steady state, Equation (20) becomes

$$\dot{V}_5 = -c_4x_4^2 - c_5(c_4x_4 + x_5)^2 \leq 0 \tag{22}$$

According to two control law (14) and (21) developed to achieve both transient stability improvement and voltage regulation, we choose the actual control laws, as given in (5) and (6), as follows.

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P_E}{\partial E} & \dfrac{\partial P_E}{\partial I_Q} \\ \dfrac{\partial V_t}{\partial E} & \dfrac{\partial V_t}{\partial I_Q} \end{bmatrix} \begin{bmatrix} \dfrac{u_f}{T_0'} \\ \dfrac{u_q}{T_q} \end{bmatrix}$$

$$\begin{bmatrix} \dfrac{u_f}{T_0'} \\ \dfrac{u_q}{T_q} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P_E}{\partial E} & \dfrac{\partial P_E}{\partial I_Q} \\ \dfrac{\partial V_t}{\partial E} & \dfrac{\partial V_t}{\partial I_Q} \end{bmatrix}^{-1} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}, \quad \det\left(\begin{bmatrix} \dfrac{\partial P_E}{\partial E} & \dfrac{\partial P_E}{\partial I_Q} \\ \dfrac{\partial V_t}{\partial E} & \dfrac{\partial V_t}{\partial I_Q} \end{bmatrix}\right) \neq 0.$$

To analyze the overall closed-loop system stability, let us define the composite Lyapunov function as follows:

$$V = V_3 + V_5 = \frac{1}{2}x_1^2 + \frac{1}{2}(c_1x_1 + x_2)^2 + \frac{1}{2}\mathcal{P}^2 + \frac{1}{2}x_4^2 + \frac{1}{2}(c_4x_4 + x_5)^2 \tag{23}$$

After calculating the derivative of (23), we have

$$\dot{V} = -c_1x_1^2 - c_2(c_1x_1 + x_2)^2 - c_3\mathcal{P}^2 - c_4x_4^2 - c_5(c_4x_4 + x_5)^2 \leq 0 \tag{24}$$

Also, it is obvious that with the help of Lyapunov stability theory, we obtain

$$\begin{cases} \lim_{t\to+\infty} x_1 = 0 \\ \lim_{t\to+\infty}(c_1x_1 + x_2) = 0 \\ \lim_{t\to+\infty} \mathcal{P} = \lim_{t\to+\infty}\left[(c_1c_2 + 1)x_1 + \left(c_1 + c_2 - \dfrac{D}{M}\right)x_2 + \dfrac{(P_m - x_3)}{M}\right] = 0 \\ \lim_{t\to+\infty} x_4 = 0 \\ \lim_{t\to+\infty}(c_4x_4 + x_5) = 0 \end{cases} \tag{25}$$

These expressions above imply that $\lim_{t\to+\infty} x_1 = \lim_{t\to+\infty} x_2 = \lim_{t\to+\infty} x_4 = \lim_{t\to+\infty} x_5 = 0$ and $\lim_{t\to+\infty} x_3 = P_m$. This completes the proof.

4. **Simulation Results.** This section presents performance verification and indicates the effectiveness of the developed controller. The proposed controller is evaluated via simulations on a Single-Machine Infinite Bus (SMIB) power system including STATCOM as shown in Figure 2. The performance of the proposed control scheme is evaluated in MATLAB environment.

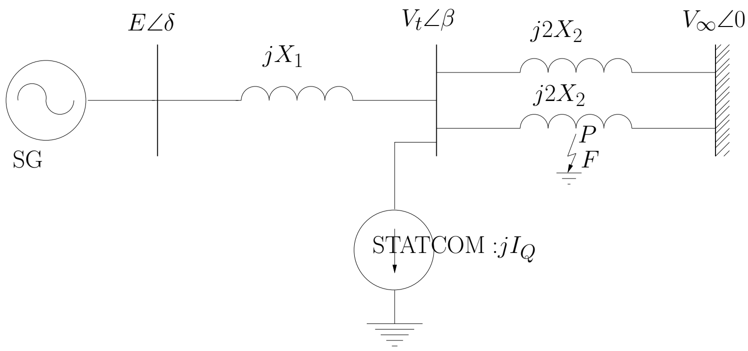

FIGURE 2. A single line diagram of SMIB model with STATCOM

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

- The parameters of synchronous generators, STATCOM, and transmission line: $\omega_s = 2\pi f$ rad/s, $D = 0.2$, $H = 5$, $f = 60$ Hz, $T_0' = 4$, $V_\infty = 1\angle 0°$, $X_d = 1.1$, $X_d' = 0.2$, $X_T = 0.1$, $T = 1$, $X_2 = X_L = 0.2$, $P_m = 1$.
- The control parameters of the proposed controller are $c_i = 100$, $(i = 1, 2, 3, 4, 5)$.
- Initial parameters $\delta_e = 0.4964$ rad, $\omega_e = \omega_s$, $P_{ee} = 1$ pu., $V_{\text{ref}} = 0.9896$.

The time domain simulations are carried out to evaluate the presented control law, as given in (14), for the stability enhancement and improved transient performances.

The performance of the proposed nonlinear controller is compared with that of the Conventional Backstepping-Like Control (CBSLC) (26) as follows:

$$\begin{cases} u_{fc} = -\dfrac{T_0'}{g_{31}(x)}\left[f_3(x) - M\left(c_2\bar{\mathcal{P}} + c_1x_1 + (c_1+3)\dfrac{x_2}{2} + \left(c_1 + 1 - \dfrac{D}{M}\right)\dfrac{\dot{x}_2}{2}\right)\right] \\ u_{qc} = -\dfrac{T_q}{g_{42}(x)}\left[f_4(x) + g_{41}(x)\dfrac{u_f}{T_0'} - M\left(c_3\bar{\mathcal{Q}} + c_1x_1 + (c_1+3)\dfrac{x_2}{2} + \left(c_1 + 1 \right.\right.\right. \\ \qquad \left.\left.\left. - \dfrac{D}{M}\right)\dfrac{\dot{x}_2}{2}\right)\right] \end{cases} \tag{26}$$

where $f_3(x)$, $f_4(x)$, $g_{31}(x)$, $g_{41}(x)$, $g_{42}(x)$, $\bar{\mathcal{P}}$ and $\bar{\mathcal{Q}}$ are given in [15]. The controller parameters of this scheme are set as $c_i = 100$, $(k = 1, 2, 3)$.

For the simulations, the performances of the developed control law and CBSLC are validated in two cases. One is a symmetrical three phase short circuit occurring on the middle of the transmission lines as shown in Figure 2. The other is a small perturbation to mechanical power to synchronous generators in the system. The two cases of interest are as follows.

Case 1: Effect of severe disturbance

Assume that there is a three-phase fault occurring at the point P as shown in Figure 2. For this case, we assume that there are five stages of interest as follows. Firstly, all state variables are at pre-fault steady state. The fault occurs at $t = 0.5$ sec, After that, the fault is isolated by opening the breaker at $t = 0.8$ sec. The transmission line can be restored at $t = 1.5$ sec. Eventually, the system returns to a post-fault state.

Case 2: Effect of small disturbance due to small perturbation in mechanical power

For this case, we assume that there are three stages of interest as follows. First, the system is in a pre-fault steady state. Subsequently, there is a 30% increase in the mechanical power between $t = 0.5$ sec. and $t = 1.5$ sec. After that, the system is in a post-fault state.

The simulation results obtained are shown in Figures 3 and 4 and discussed as follows. It is seen from Case 1 that Figure 3 illustrates the time responses of power angle (δ), frequency ($\omega - \omega_s$), transient voltage (E), STATCOM current (I_Q), and integral of voltage deviation $\left(x_4 = \int_0^t (V_t(\tau) - V_{\text{ref}})d\tau\right)$, respectively. According to the results of the presented and CBSLC schemes, all time responses settle down to the pre-fault state values. Figure 4 shows the active power (P_E) and terminal STATCOM voltage (V_t) under the proposed control and the CBSLC methods. It is easy to observe that both power angle and frequency responses of the developed method have much faster convergence rate and no oscillations compared with the CBSLC. It is seen that transient voltage (E) and STATCOM current (I_Q) responses of the presented control are higher than those of the CBSLC because both are used to improve transient stability and regulate the terminal voltage, simultaneously. In contrast, the CBSLC focuses on improving transient stability alone and does not include the terminal STATCOM voltage dynamics. However, both E and I_Q under two controllers offer good responses and fast convergence rate as well. Further, the integral of voltage deviation x_4 converges to zero as expected. This means that the terminal voltage can track the desired reference voltage. It is clear that the active power responses of both controller are almost the same except the fault duration (stage 2), thereby resulting in maintaining transient stability. It is obvious from fault and isolated fault durations that the terminal voltage response of the presented control can rapidly drive the terminal voltage to $V_{\text{ref}} = 0.9896$ pu. However, the voltage response of the CBSLC cannot settle down to V_{ref} in fault and isolated fault durations. From the simulations of Case 1, with the simple design procedure, these confirm obviously that the proposed controller scheme achieves both transient stability enhancement and voltage regulation, simultaneously, together with improved dynamic performances. Nevertheless, this scheme may have higher transient voltage and STATCOM current than the CBSLC.

Similarly, for Case 2, under the effect of a 30% perturbation ($\Delta P_m = 0.3P_m$) of mechanical input power, the time responses of power angle, frequency, active power, STATCOM current, and integral of voltage deviation, and terminal voltage are shown in Figures 5 and 6. The dynamic performances under two controllers are improved. In particular, the terminal voltage response of the presented scheme shows dynamic performances superiority of the proposed control over the CBSLC method. Also, it can be observed that although there is the perturbation of mechanical power, the terminal voltage response of our design hardly changes.

Practically, it is well-known that a perfect dynamic model of the system considered is unavailable. As a result, it needs to investigate the sensitivity analysis of the proposed control scheme with system parameter variations. The system parameter variations need to be considered for sensitivity analysis of the developed controller. Especially, the different parameter settings of synchronous generators for the SMIB system should be considered, i.e., the inertial constant H and the time constant T_0'. It is also difficult to estimate precisely these parameters. Consequently, to study the sensitivity analysis, testing a robustness of the system in the presence of uncertainties has been carried out by considering a changing of two generator parameters from their nominal values, i.e., the inertial constant H and the time constant T_0' of Case 1. In particular, a $\pm 50\%$ of variation in the value of H as well as a $\pm 30\%$ of variation in value of T_0' is taken into account for this test. As compared with the system responses under normal conditions, it can be

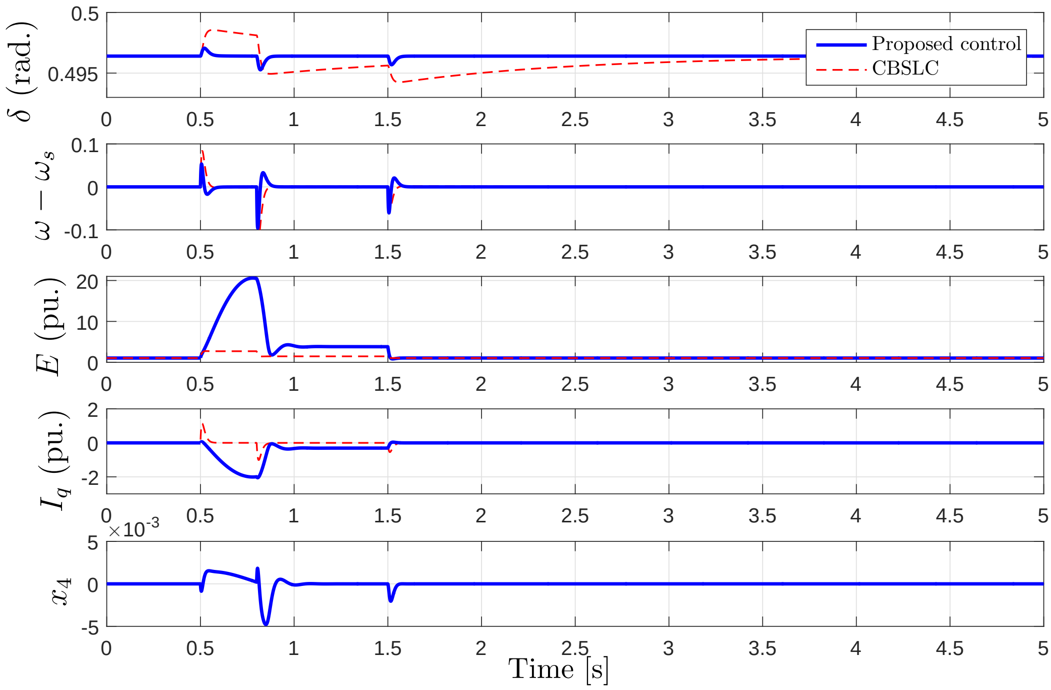

FIGURE 3. Case 1: Controller performance – Power angles (δ) (rad.), frequency ($\omega - \omega_s$) rad/s, transient voltage (E), STATCOM current (I_Q), and $x_4 = \int_0^t (V_t(\tau) - V_{\text{ref}})d\tau$ (Solid: Proposed control, Dashed: Conventional Backstepping-Like Control: CBSLC)

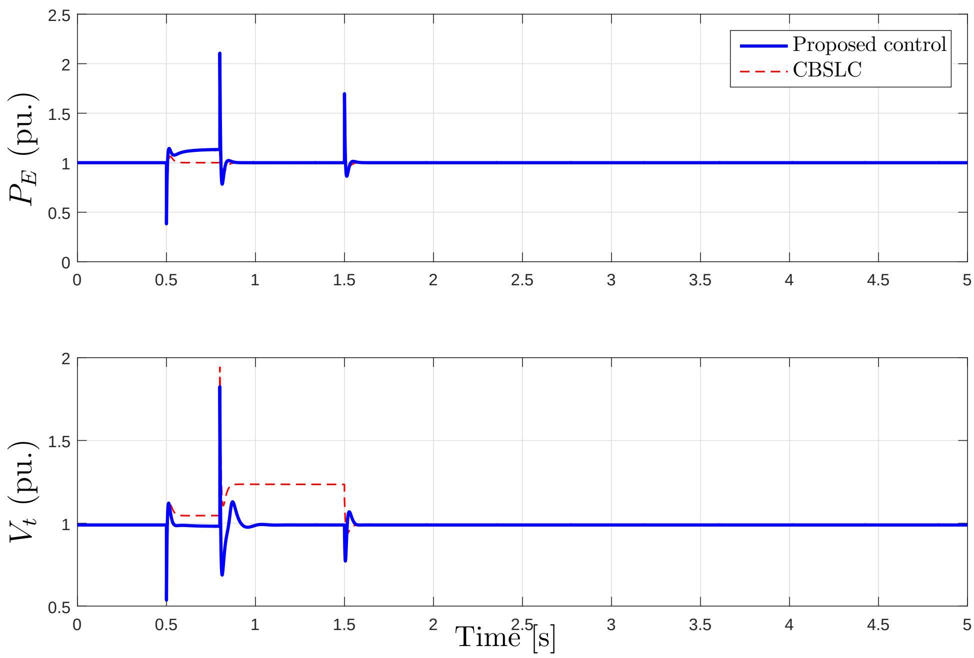

FIGURE 4. Case 1: Controller performance – Active power P_E (pu.) and the terminal STATCOM voltage (V_t) (pu.) (Solid: Proposed control, Dashed: Conventional Backstepping-Like Control: CBSLC)

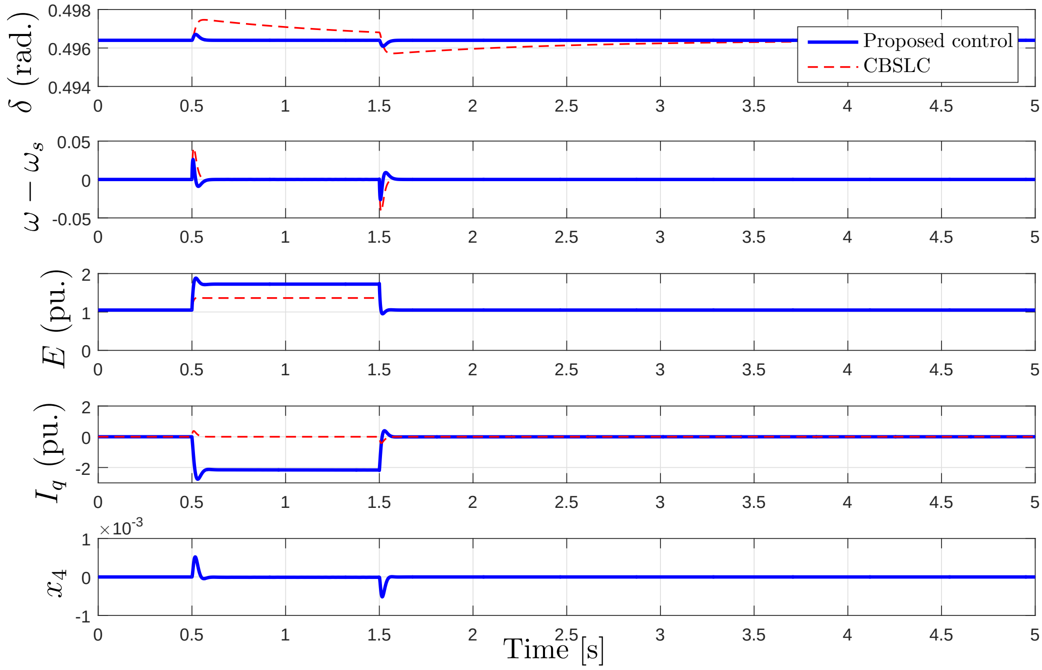

FIGURE 5. Case 2: Controller performance – Power angles (δ) (rad.), frequency ($\omega - \omega_s$) rad/s, transient voltage (E), STATCOM current (I_Q), and $x_4 = \int_0^t (V_t(\tau) - V_{\text{ref}})d\tau$ (Solid: Proposed control, Dashed: Conventional Backstepping-Like Control: CBSLC)

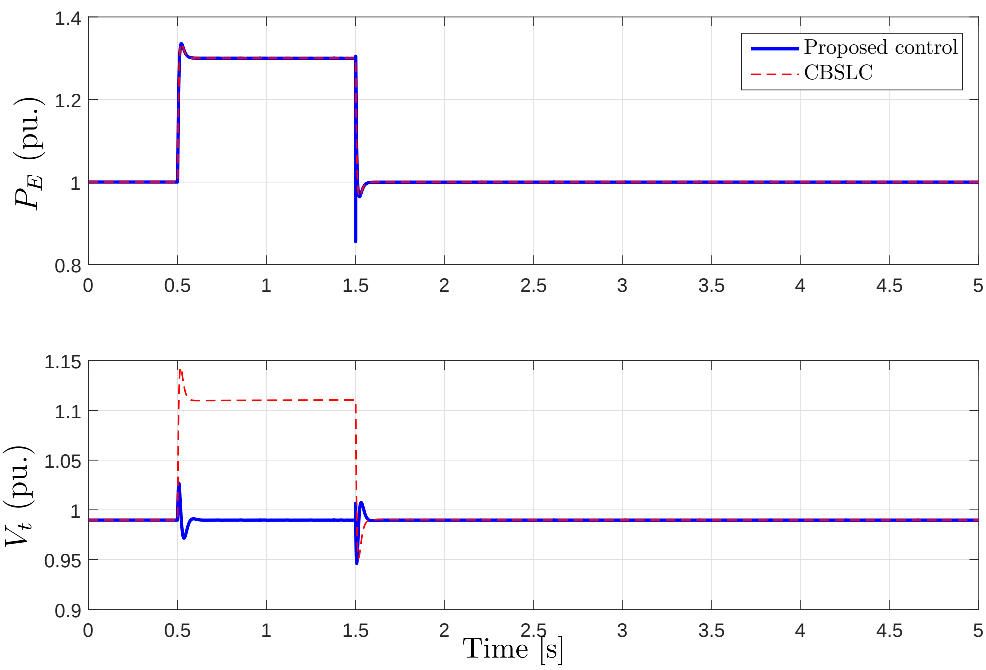

FIGURE 6. Case 2: Controller performance – Active power P_E (pu.) and the terminal STATCOM voltage (V_t) (pu.) (Solid: Proposed control, Dashed: Conventional Backstepping-Like Control: CBSLC)

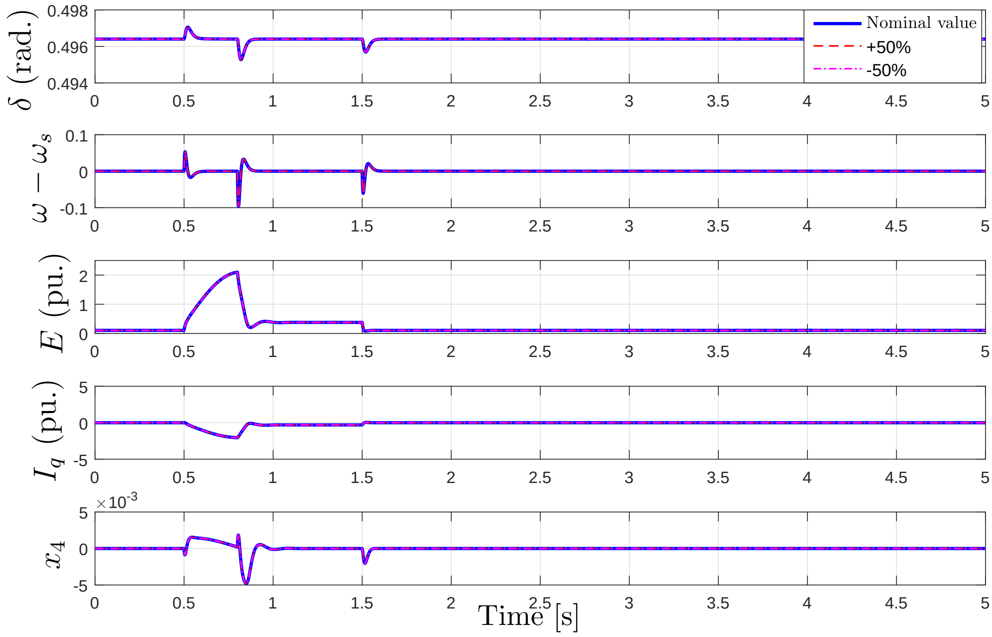

FIGURE 7. Time histories of power angles (δ) (rad.), frequency ($\omega - \omega_s$) rad/s, transient voltage E, STATCOM current I_Q, and $x_4 = \int_0^t (V_t(\tau) - V_{\text{ref}})d\tau$ under parameter variations of the inertial constant H (Solid: nominal value, Dashed: +50%, Dashdotted: −50%)

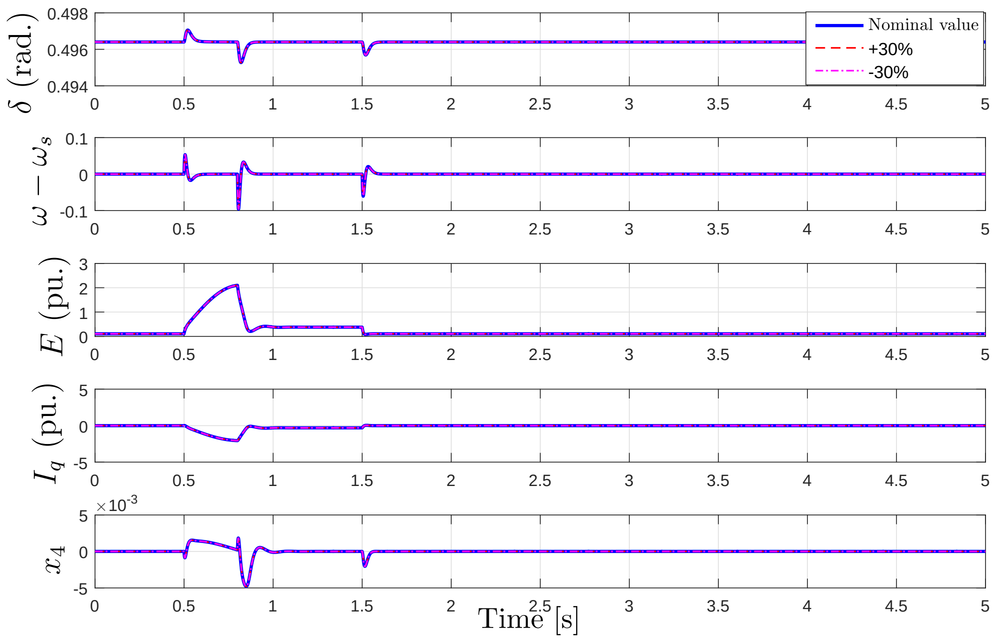

FIGURE 8. Time histories of power angles (δ) (rad.), frequency ($\omega - \omega_s$) rad/s, transient voltage E, and STATCOM current I_Q, and $x_4 = \int_0^t (V_t(\tau) - V_{\text{ref}})d\tau$ under parameter variations of time constant T_0' (Solid: nominal value, Dashed: +30%, Dashdotted: −30%)

seen from Figures 7 and 8 that despite the variations in system parameters, the presented design can still offer consistent control performance. Consequently, we can conclude that the obtained control design is not sensitive to parameter variations.

From the simulation results above, it is clear that as the presented method is applied to the SMIB power system with STATCOM, there are the advantages over conventional backstepping-like control [15] as follows: (i) the developed scheme is designed to enhance transient stability and to drive the voltage deviation between the terminal STATCOM voltage and the reference voltage to zero, simultaneously, while the conventional backstepping-like scheme cannot, (ii) the state variables of closed-loop dynamics with very fast convergence rates and no oscillations are forced to the desired equilibrium despite unavoidable large and small disturbances, and (iii) the proposed design procedure is hardly complicated compared with other existing controllers in the literature. Especially different from other existing techniques, the terminal voltage dynamics are included in the overall complete dynamic model and the overall stability analysis.

5. **Conclusion.** In this paper, a backstepping-like control scheme has been designed for power systems with STATCOM. With the aid of this approach, it can enhance transient stability and regulate the terminal STATCOM voltage to the reference voltage, simultaneously, in spite of having small and large disturbances. Additionally, the developed design procedure is rather simple and adds the voltage dynamics to the overall complete dynamic model and the overall stability analysis. The simulation results have indicated the efficiency and superiority of the proposed method that offers better transient performances than the conventional backstepping-like method. Besides, it can make the terminal voltage track rapidly the reference value despite undesired disturbances while the conventional backstepping-like method cannot. Extension of this scheme of this paper into a nonlinear backstepping-like control for multi-machine power systems with STATCOM or other kinds of FACTS devices is our future direction. Additionally, this technique can be extended to power systems with renewable energy [16].

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