Nonlinear Adaptive Controller Design for Power Systems with STATCOM via Immersion and Invariance

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ABSTRACT

In this paper, a nonlinear adaptive control of generator excitation and Static Synchronous Compensator (STATCOM) is proposed to enhance the transient stability and voltage regulation of an electrical power system. The proposed controller is designed via an adaptive immersion and invariance (I&I) methodology. In particular, a nonlinear model of the power system including two unknown constant parameters, namely an unknown damping coefficient and an unknown perturbation in mechanical power, is considered. It will be shown that the adapive I&I control law and the parameter adaptation law proposed can accomplish the convergence of the system states to the real value of unknown parameters. The adaptive I&I controller is validated using a simulation study on a single-machine infinite bus (SMIB) power system and compared with the standard I&I controller and an adaptive backstepping controller. Simulation results are given to indicate the effectiveness of the proposed controller for the transient stabilization and voltage regulation. Besides, they show that our proposed controller has more advantages over the adaptive backstepping controller and the damping and the closed-loop system dynamics of the developed scheme are slightly different from those of the standard I&I one.

Keywords: Adaptive immersion and invariance method, Nonlinear control, STATCOM, Transient stabilization

1. INTRODUCTION

Because of power systems with the rapid increase of the size and complexity, power system stability is increasingly important. Generally, power system operation is faced with the difficult task of maintaining stability when small or large disturbances occur in the power system. Over the years, there have been numerous studies for improving power system stability. There are recently two major ways of dealing with this improvement. The first is an excitation control alone [1–7] while the second is an coordination of the excitation and Flexible AC Transmission System (FACTS) devices [8, 9]. Both ways have been devoted to not only enhance power system stability, but also achieve the desired control objectives.

Due to currently rapid developments in power electronic devices, a great attention has been paid on the development of FACTS devices. They not only provide an opportunity to effectively tackle the existing transmission facilities, but also overcome a large number of constraints to build new transmission lines. FACTS are mainly employed to improve the controllability of power flow and voltages augmenting the utilization and stability. FACTS are currently composed of SVC, STATCOM, TCSC, SSSC, and UPFC. Applications for FACTS are often employed in interconnected and long-distance transmission systems to enhance numerous technical problems, particularly, load flow control, voltage control, system oscillations, inter-area a oscillation, reactive power control, steady state stability, and dynamic stability. In this paper, among a variety of FACTS family, of particular interest in this work is the Static Synchronous Compensator (STATCOM)[8, 9] because it can increase the grid transfer capability through enhanced voltage stability, significantly provides smooth and rapid reactive power compensation for voltage support, and enhances both damping oscillation and transient stability. Until now the generator excitation [1] and STATCOM [9] have independently been employed to not only improve power system operations but also provide an opportunity to improve overall small-signal and transient stability of the power system. In order to further improve the transient stability of power systems, the coordination of generator excitation and STATCOM has attracted much attention in literature for years.

To the best of our knowledge, considerable research has addressed the application of STATCOM, with relatively little prior work using directly the nonlinear control theory devoted to the combination of generator excitation and STATCOM. With the help of generalized Hamiltonian control theory, an adaptive nonlinear coordinated generator excitation and STATCOM controller [10, 11] for multi-machine power systems has been proposed for stability enhancement. In [12], a coordinated controller for the single-machine infinite bus has been presented through the zero dynamics design theory and pole-assignment technique.

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A nonlinear coordinated controller [13] has been studied via the passivity and backstepping technique. The work in [14] has indicated the combination of generator excitation and STATCOM/battery energy storage for transient stability and voltage regulation enhancement using an interconnection and damping assignment-passivity based control IDA-PBC) strategy for mulit-machine power systems. An immersion and invariance nonlinear coordinated controller [15] have proposed to enhance transient stability and voltage regulation for power systems with STATCOM.

This paper continues this line of investigation and further extends the previous work reported in [15]. However, no parameter uncertainty in the system model was taken into account in the previous work and the references mentioned earlier. Although those resulting nonlinear coordinated controllers were used to effectively improve transient stability and voltage regulation, there was an important drawback in the resulting nonlinear controller. Thus, an adaptive control design which can handle with parameter uncertainties is developed in this paper. This proposed approach is more practical and suitable for the uncertainties in parameters such as the damping coefficient and a change of mechanical input power since these parameters uncertainties can be caused by the different condition of operating and hard to identify [16, 17]. It is well known that once a fault occurs in the system, an important issue needed to be considered is the stability and performance enhancement of power angle and voltage to handle the following problems: 1) the deviation of the power angle and synchronism angle goes beyond the safe boundary; and 2) the power quality could not be guaranteed and the power system stability will be eventually destroyed. Moreover, the operating system during critical voltage leads to instability and voltage collapse.

Therefore, the main contribution of this work is to find an adaptive I&I controller not only to ensure that the closed-loop system behaves asymptotically like the pre-specified target system, leading to achieving asymptotical model matching, but also to achieve the desired closed-loop system performance. This technique relies upon selecting a target dynamics that can capture the desired behavior of the closed-loop system to be controlled. The I&I method [18] was further extended to an adaptive I&I one for the solution of nonlinear adaptive control problems [19]. The key concept of I&I method is that using the notion of system immersion and manifold invariance allows one to design the desired controller independently from determining the Lyapunov function. Moreover, the corresponding adaptive controller can counter the effect of the uncertain parameters adopting a robust perspective. In this paper, the adaptive I&I scheme is applied on the power control system including STATCOM. In particular, the damping coefficient uncertainty and the perturbation in mechanical input power are considered as unknown constant parameters. Even though the dynamics model of power systems with STATCOM consists of two unknown constant parameters mentioned, the proposed controller is designed to not only simultaneously achieve power angle stability along with frequency and voltage regulation, but also keep the system transiently stable.

The paper is organized as follows. Simplified SG and STATCOM models are briefly described and power system analysis with STATCOM is considered in Section 2 while adaptive I&I methodology and controller design are given in Section 3 and Section 4, respectively. Simulation results are given in Section 5. Conclusions are given in Section 6.

2. POWER SYSTEM MODELS AND TRANSMITTED POWER WITH STATCOM

In this section, dynamic models of the synchronous generator is briefly provided.

2.1 Synchronous Generators: SG

A dynamic model of a synchronous generator (SG) in SMIB system can be obtained by representing the SG by a transient voltage source, E, behind a direct axis transient reactance, X_d' as follows:

$$\begin{cases} \dot{\delta} &= \omega - \omega_s \\ \dot{\omega} &= \frac{1}{M}\left(P_m - P_E - D(\omega - \omega_s)\right) \\ \dot{E} &= -\frac{X_{d\Sigma}}{X_{d\Sigma}' T_0'} E + \frac{X_d - X_d'}{X_{d\Sigma}' T_0'} V_\infty \cos\delta + \frac{u_f}{T_0'} \end{cases} \tag{1}$$

where δ is the power angle of the generator, ω denotes the relative speed of the generator, $D \geq 0$ is a damping constant, P_m is the mechanical input power, E denotes the generator transient voltage source, $P_E = \frac{EV_\infty \sin\delta}{X_{d\Sigma'}}$ is the electrical power, without STATCOM, delivered by the generator to the voltage at the infinite bus V_∞, ω_s is the synchronous machine speed, $\omega_s = 2\pi f$, H represents the per unit inertial constant, f is the system frequency and $M = 2H/\omega_s$. $X_{d\Sigma}' = X_d' + X_T + X_L$ 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 SG. T_0' is the direct axis transient short-circuit time constant. u_f is the field voltage control input to be designed.

2.2 STATCOM Model

In this work, the STATCOM can be modeled as a shunt controllable current source I_Q as shown in Fig. 1, where the STATCOM is used to regulate the terminal voltage ($V_t\angle\beta$) by controlling the reactive power injected or absorbed from the power system. For instance, once there is a fault occurring in power networks, this leads to temporary differences in the power balance between the mechanical power (assumed constant) and the electrical power and subsequently the excess energy. So, STATCOM can be used to absorb such excess energy and to suppress the large transient induced electromechanical oscillations. It can also support electrical power for power networks that have poor voltage and power system instability (small-signal and large-signal (transient)), [8, 9], and references therein.

For simplicity, the dynamic behavior of the STATCOM is regarded as a first-order differential equation; thus, the STATCOM dynamic model is expressed as follows:

$$\dot{I}_Q \quad = \quad \frac{1}{T}(-(I_Q - I_{Qe}) + u_q) \tag{2}$$

where I_Q denotes the injected or absorbed STATCOM currents as a controllable current source, I_{Qe} is a equilibrium point of STATCOM currents, u_q is the STATCOM control input to be designed, and T is a time constant of STATCOM models.

2.3 Transmitted Power with STATCOM

In this section, we study the transmitted power characteristics with a simplified model consisting of conventional power generators, especially SG and STATCOM.

Consider the network shown in Figure 1 where X_1 (or $X_d' + X_T$) denotes the reactance which takes into account the direct axis transient reactance (X_d') of the SG and the transformer reactance (X_T). X_2 (or X_L) denotes the transmission line reactance between the bus terminal voltage V_t and the infinite bus voltage V_∞. I_Q represents the STATCOM current that is always quadrature with its bus terminal voltage.

Using some length, but straightforward, calculation [15], we have the power, P_E, transmitted from bus 1 to the infinite bus is:

$$\begin{aligned} P_E &= P_e + P_s \\ &= \frac{EV_\infty \sin\delta}{(X_1 + X_2)} + \frac{EV_\infty \sin\delta}{(X_1 + X_2)} \frac{I_Q X_1 X_2}{\Delta(\delta, E)} \end{aligned} \tag{3}$$

where

$$\Delta(\delta, E) = \sqrt{(EX_2)^2 + (V_\infty X_1)^2 + 2X_1 X_2 E V_\infty \cos\delta}.$$

Remark 1: From the transmitted power between the SG and the infinite bus, there are two terms as follows. The first is the active power, P_e, from the generator while the second is the active power, P_s, from the STATCOM. In order to further improve the transient stability and voltage regulation, we can extend the obtained results to SMIB power systems with a combination of STATCOM and energy storage, as given in [14], which will be reported in the future.

As the STATCOM is included as shown in Figure 1, the dynamic models of power system including

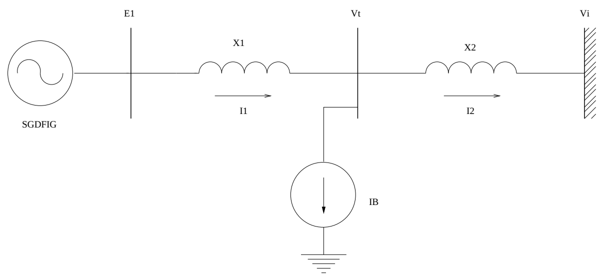

Fig.1: *Network.*

STATCOM can be expressed as follows:

$$\begin{cases} \dot{\delta} &= \omega - \omega_s \\ \dot{\omega} &= \frac{1}{M}\left(P_m - P_e - P_s - D(\omega - \omega_s)\right) \\ \dot{E} &= -aE + b\cos\delta + \frac{u_f}{T_0'} \\ \dot{I}_Q &= \frac{1}{T}(-(I_Q - I_{Qe}) + u_q) \end{cases} \tag{4}$$

where $a = \frac{X_{d\Sigma}}{(X_1+X_2)T_0'}$ and $b = \frac{X_d - X_d'}{(X_1+X_2)T_0'} V_\infty$.

Since the generator transient voltage source E in (3) is often physically immeasurable, let us define two active electrical power P_e and P_s in the power system model (4) as new state variables. Then, differentiating two active power P_e and P_s, respectively, in (3) yields

$$\begin{cases} \dot{P}_e &= (-a + \cot\delta(\omega - \omega_s))P_e + \frac{bV_\infty \sin 2\delta}{2(X_1+X_2)} \\ &\quad + \frac{V_\infty \sin\delta}{(X_1+X_2)} \cdot \frac{u_f}{T_0'}, \\ \dot{P}_s &= \mathcal{N}(\delta, P_e, P_s)(-a + \cot\delta(\omega - \omega_s))P_e \\ &\quad + \frac{\mathcal{N}(\delta,P_e,P_s) bV_\infty \sin 2\delta}{2(X_1+X_2)} + \frac{\mathcal{N}(\delta,P_e,P_s)V_\infty \sin\delta}{(X_1+X_2)} \cdot \frac{u_f}{T_0'} \\ &\quad + \frac{P_e X_1 X_2}{\Delta(\delta,P_e)} \cdot \frac{1}{T}\left(-\left(\frac{P_s \Delta(\delta,P_e)}{P_e X_1 X_2} - I_{qe}\right) + u_q\right), \end{cases} \tag{5}$$

where $\Delta(\delta, P_e)$ and $\mathcal{N}(\delta, P_e, P_s)$ are given in the top of the next page.

From the dynamic models above, it is easy to see that all state variables $(\delta, \omega, P_e, P_s)$ are measurable, e.g., the power (rotor) angle can recently be monitored via Phasor Measurement Units (PMUs) in a wide-area measurement system. The remaining state variables, (ω, P_e, P_s), are directly measured.

For simplicity, let us define the state variables $x_1 = \delta,\ x_2 = \omega - \omega_s,\ x_3 = P_e$, and $x_4 = P_s$. Consequently, the dynamic model of power systems including STATCOM can be expressed as an affine nonlinear system as follows:

$$\dot{x} = f(x) + g(x)u(x) \tag{6}$$

where $f(x), g(x)$ and $u(x)$ are provided in (7).

In addition, the open loop operating equilibrium is denoted by $x_e = [x_{1e},\ 0,\ P_m,\ 0]^T$ and the region of operation is defined in the set $\mathcal{D} = \{x \in \mathcal{S} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} |\ 0 < x_1 < \frac{\pi}{2}\}$.

Considering the model stated above, it is easy to see that all state variables can be measured in this system. In (6)-(7), there is also a nonlinear controller $u = [u_f/T_0', u_q/T]^T$ to be designed. On the other

$$
\begin{aligned}
\Delta(\delta, P_e) &= \sqrt{\left(\frac{P_e(X_1+X_2)X_2}{V_\infty \sin\delta}\right)^2 + (V_\infty X_1)^2 + 2X_1X_2P_e(X_1+X_2)\cot\delta},\\
\mathcal{N}(\delta, P_e, P_s) &= \frac{P_s}{P_e} - \frac{P_s}{\Delta(\delta, P_e)^2}\left(X_1X_2\cot\delta(X_1+X_2) + P_e\left(\frac{X_2(X_1+X_2)}{V_\infty\sin\delta}\right)^2\right),\\
P_e &= \frac{EV_\infty \sin\delta}{(X_1+X_2)},\ P_s = \frac{P_eI_QX_1X_2}{\Delta(\delta, E)},\ I_Q = \frac{P_s\Delta(\delta, P_e)}{P_eX_1X_2}.
\end{aligned}
$$

$$
\begin{cases}
f(x) &= \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \end{bmatrix} = \begin{bmatrix} x_2 \\ \frac{1}{M}\left(P_m - x_3 - x_4 - Dx_2\right) \\ (-a + x_2\cot x_1)x_3 + \frac{bV_\infty \sin 2x_1}{2(X_1+X_2)} \\ \mathcal{N}(-a + x_2\cot x_1)x_3 + \frac{\mathcal{N}bV_\infty \sin 2x_1}{2(X_1+X_2)} - \frac{x_3X_1X_2\left(\frac{x_4\Delta(x_1,x_3)}{x_3X_1X_2} - I_{qe}\right)}{\Delta(x_1,x_3)} \end{bmatrix}, \\
g(x) &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ g_{31}(x) & 0 \\ g_{41}(x) & g_{42}(x) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{V_\infty \sin x_1}{(X_1+X_2)} & 0 \\ \frac{\mathcal{N}V_\infty \sin x_1}{(X_1+X_2)} & \frac{x_3X_1X_2}{\Delta(x_1,x_3)} \end{bmatrix},\ x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix},\ u(x) = \begin{bmatrix} \frac{u_f}{T_0'} \\ \frac{u_q}{T} \end{bmatrix}.
\end{cases}
\tag{7}
$$

hand, there is no parameter uncertainty in the system model in (7).

It is known well that unknown parameters in the system model always exist in reality. They happen from the following facts. In general, the damping coefficient cannot be measured accurately in practical engineering applications [16]; thus the estimation online and real time of this unknown and/or uncertain constant parameter is needed. Additionally, an unknown mechanical input power and a sudden mechanical perturbation are important uncertainties in the power system; therefore it may destabilize the operating conditions. In particular, as the mechanical power is perturbed to a new constant value, the equilibrium of the system will shift to a new corresponding point. Further, the new point will be unknown if the mechanical power is unknown [20–23]. More practically, there are also other unknown parameters appearing in power systems [17].

For notational convenience, let us define $\theta = [\theta_1, \theta_2]^T = [-D, P_m]^T$ as two unknown constant parameters of interest, then the system (6)-(7) can be rewritten as follows.

$$
\begin{cases}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \frac{1}{M}(\theta_2 + \theta_1 x_2 - x_3 - x_4) \\
\dot{x}_3 &= f_3(x) + g_{31}(x)\frac{u_f}{T_0'} \\
\dot{x}_4 &= f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_q}{T}
\end{cases}
\tag{8}
$$

Thus, the objective of this paper is to solve the problem of the transient stabilization of the system (8) with unknown constant parameters θ, which can be formulated as follows: with the help of the adaptive immersion and invariance methodology, to design an adaptive (state) feedback controller:

$$
\begin{cases}
u &= \varphi(x, \hat{\theta}) \\
\dot{\hat{\theta}} &= \varpi(x, \hat{\theta})
\end{cases}
\tag{9}
$$

such that the resulting closed-loop system is asymptotically stable at the only equilibrium $(x_e, \hat{\theta}_e)$ and $x \to x_e$ as $t \to \infty$ where $\hat{\theta}$ is the estimate of $\theta = [\theta_1, \theta_2]^T$

3. ADAPTIVE IMMERSION AND INVARIANCE METHOD

The I&I method for stabilizing nonlinear systems was first proposed in [24] and summarized in [18]. The method is based on the notion of invariant manifolds and system immersion. This methodology carries out from transforming the original state of the system $x(t)$ into two new states, namely $\xi(t)$ and $z(t)$. The dimension of state $\xi(t)$ becomes strictly less than the dimension of state $x(t)$. The new reduced state $\xi(t)$ is called the target dynamics and the transformation employed to get these states defines the invariant manifold. The state $z(t)$ is called the off-the-manifold state and complements the dimension of $\xi(t)$. The resulting control law is designed to ensure that the original state $x(t)$ is bounded, that the manifold is rendered invariant, and that the off-line-manifold state $z(t)$ converges asymptotically to the origin. Besides, the original state $x(t)$ will converge to a desired equilibrium point with a dynamic behavior converging to that of the target dynamical system.

This method is applicable to practical control design problems for many types of systems, refer to [18] for further details. In particular, transient stability and voltage regulation enhancement of power systems with excitation control, other kinds of FACTS devices, and a superconducting magnetic energy storage (SMES) system has been presented in [15, 23, 25–28].

In addition, this strategy was further extended to an adaptive I&I control one as reported by [19]. The concept of I&I adaptive control depends on the notion of system immersion and invariant manifold. Further, The knowledge of a Lyapunov function is not required for this method. This leads that the obtained adaptive control methods counter the effect of uncertain parameters adopting a robust perspective.

The following results, revealed in those papers, are used to design this proposed nonlinear adaptive coordinated controller for power systems including generator excitation and STATCOM controllers.

Consider the nonlinear system[1] [19]

$$\dot{x}(t) = f(x, u, \theta) \tag{10}$$

with state $x \in \mathbb{R}^n$ and control input $u \in \mathbb{R}^m$, and an assignable equilibrium point $x_e \in \mathbb{R}^n$ to be stabilized. Define the augmented system

$$\begin{cases} \dot{x}(t) & = f(x, u, \theta), \\ \dot{\hat{\theta}} & = \varpi(x, \hat{\theta}) \end{cases} \tag{11}$$

where $\hat{\theta} \in \mathbb{R}^q$ and $\varpi \in \mathbb{R}^q$ is a new control signal. The adaptive stabilization problem can be posed, informally, as follows.

Find (if possible) a state feedback control law described by equations of the form (9) such that all trajectories of the closed-loop system (12)-(13) are bounded and

$$\lim_{t\to\infty} x(t) = x_e \tag{12}$$

Note that, since $f(\cdot)$ is only partially known, it is not required that $\hat{\theta}$ converges to any particular equilibrium, but merely that it remains bounded. The following Theorem, presented in the major result of [19], not only offers conditions under which the above problem is solvable through the I&I strategy, but also is used to design this proposed adaptive controller for power systems with STATCOM.

Theorem 1: [19] Consider the nonlinear system and an equilibrium point $x_e \in \mathbb{R}^n$. Let $p \leq n, \xi \in \mathbb{R}^p, \zeta \in \mathbb{R}^{n-p}$, $z \in \mathbb{R}^q$. Assume that there exist smooth mappings $\alpha(\xi,\theta) \to \mathbb{R}^p$, $\pi(\xi,\theta) \to \mathbb{R}^n$, $c(\xi,\theta) \to \mathbb{R}^m, \phi(x,\theta) \to \mathbb{R}^{n-p}$, $u(x,\zeta,z+\theta) \to \mathbb{R}^m, \varpi(x,\zeta,z+\theta) \to \mathbb{R}^q$ and $\beta(x) \to \mathbb{R}^q$ such that the following hold.

(H1) (Target system) The system

$$\dot{\xi} = \alpha(\xi, \theta) \tag{13}$$

has an asymptotically stable equilibrium at $\xi_e \in \mathbb{R}^p$ and $x_e = \pi(\xi_e, \theta)$.

(H2) (Immersion condition) For all $\xi \in \mathbb{R}^p$

$$f(\pi(\xi,\theta), c(\xi,\theta), \theta) = \frac{\partial \pi}{\partial \xi}\alpha(\xi,\theta). \tag{14}$$

(H3) (Implicit manifold) The following set identity holds

$$\begin{aligned} \mathcal{M} &:= \{x \in \mathbb{R}^n | x = \pi(\xi,\theta) \text{ for some } \xi \in \mathbb{R}^p\} \\ &= \{x \in \mathbb{R}^n | \phi(x,\theta) = 0\} \end{aligned} \tag{15}$$

(H4) (Manifold attractivity and trajectory boundedness) All trajectories of the system

$$\begin{cases} \dot{\zeta} & = \frac{\partial \phi}{\partial x} f(x, u(x,\zeta,z+\theta),\theta) + \frac{\partial \phi(x,\hat{\theta})}{\partial \hat{\theta}}\omega(x,\zeta,z+\theta) \\ \dot{z} & = \varpi(x,\zeta,z+\theta) + \frac{\partial \beta(x)}{\partial x} f(x, u(x,\zeta,z+\theta),\theta) \\ \dot{x} & = f(x, u(x,\zeta,z+\theta),\theta) \end{cases} \tag{16}$$

are bounded and satisfy

$$\begin{cases} \lim_{t\to\infty} \zeta(t) = 0 \\ \lim_{t\to\infty} [\phi(x(t), z(t)+\theta) - \phi(x(t),\theta)] = 0, \end{cases} \tag{17}$$

Then all trajectories of the closed-loop system[2]

$$\begin{cases} \dot{x} & = f(x, u(x, \phi(x, \hat{\theta}+\beta(x)), \hat{\theta}+\beta(x), \theta) \\ \dot{\hat{\theta}} & = \varpi(x, \phi(x, \hat{\theta}+\beta(x)), \hat{\theta}+\beta(x)) \end{cases} \tag{18}$$

are bounded and satisfy (12). Finally,

$$\lim_{t\to\infty} x(t) - \pi(\xi(t),\theta) = 0,$$

and, if $\phi(x(0),\hat{\theta}(0)) = 0, \hat{\theta}(0) - \theta + \beta(x(0)) = 0$ and $\xi(0) = \pi(x(0),\theta), x(t) = \pi(\xi(t),\theta)$ for all $t \geq 0$.

Definition 1: The system (10)-(11) is said to be adaptive I&I stabilizable with target dynamics (13) if (H1)-(H4) of Theorem 1 are satisfied.

4. ADAPTIVE I&I CONTROLLER DESIGN

The proposed adaptive I&I control approach is expressed in the following proposition.

Proposition 1: Consider the system (8), the adaptive I&I control law:

$$u(x,\hat{\theta}) = \begin{bmatrix} u_f(x,\hat{\theta}) \\ u_q(x,\hat{\theta}) \end{bmatrix} \tag{19}$$

as given in (21)-(22) with the parameter adaption law given by:

$$\begin{cases} \dot{\hat{\theta}}_1 & = \varpi_1(x,\hat{\theta}) = \frac{\gamma_1 x_2 \dot{\hat{x}}_2}{M}, \gamma_1 > 0 \\ \dot{\hat{\theta}}_2 & = \varpi_2(x,\hat{\theta}) = \frac{\gamma_2 \dot{\hat{x}}_2}{M}, \gamma_2 > 0. \end{cases} \tag{20}$$

[1] It is assumed that throughout this paper all functions and mappings are $\mathbb{C}^\infty$.

[2] Note that the function $\varpi(\cdot)$ in the $\hat{\theta}$ equation is a function of x and $\hat{\theta}$ consistently with (11).

$$\frac{u_f(x,\hat{\theta})}{T_0'} = \frac{1}{g_{31}(x)}\Big[-f_3(x)+(\beta M\cos(x_1-x_{1e})+\varpi_1(x,\hat{\theta}))x_2+\varpi_2(x,\hat{\theta})+\delta(x,\hat{\theta})\dot{\tilde{x}}_2-\sigma_1(x,\hat{\theta})\zeta_1\Big] \quad (21)$$

$$\frac{u_q(x,\hat{\theta})}{T} = \frac{1}{g_{42}(x)}\Big[-f_4(x)-g_{41}(x)\frac{u_f}{T_f}-\gamma_d\dot{\tilde{x}}_2-\sigma_2\zeta_2\Big] \quad (22)$$

is such that all trajectories of the closed-loop system are bounded. Furhter, it ensures that the equilibrium point x_e is an asymptotically stable equilibrium of the closed-loop system.

Proof: According to Theorem 1, we can proceed from checking the four conditions via adaptive I&I approach as follows.

(H1) Target system: Specification of the target system

In order to design a stabilizing controller and verify the condition according to Theorem 1, we start with selecting the target dynamics ($\dot{\xi}=\alpha(\xi,\theta)$) as the mechanical subsystems (e.g., a simple damped pendulum system)

$$\begin{cases}\dot{\xi}_1 &= \xi_2,\\ \dot{\xi}_2 &= -\frac{\partial V(\xi_1)}{\partial \xi_1}-R(\xi)\xi_2\end{cases} \quad (23)$$

where $V(\xi_1)$ and $R(\xi)$ represent the potential energy and a damping function of the pendulum systems, respectively, which both are to be selected. The pendulum system considered with a stable equilibrium point $\xi_e=(\xi_{1e},0)^T$ has the potential energy $V(\xi_i)$ satisfying the following two assumptions (i) $\frac{\partial V(\xi_{1e})}{\partial \xi}=0$ (ii) $\frac{\partial^2 V(\xi_{1e})}{\partial^2 \xi}>0$, the damping function verifying $R(\xi_e)\geq 0$, and the energy function $H(\xi)=\frac{1}{2}\xi_2^2+V(\xi_1)$.

(H2) Immersion condition: Computation of the mapping $\pi(\xi,\theta)$

As the desired target systems has been selected, a mapping $\pi:\mathcal{S}\times\mathbb{R}\times\mathbb{R}\rightarrow\mathcal{S}\times\mathbb{R}\times\mathbb{R}\times\mathbb{R}$ is the following.

$$\pi(\xi_1,\xi_2,\theta):=\begin{bmatrix}\xi_1, & \xi_2, & \pi_3(\xi,\theta), & \pi_4(\xi,\theta)\end{bmatrix}^T, \quad (24)$$

where $\pi_3(\xi,\theta)$ and $\pi_4(\xi,\theta)$ are to be selected. Besides, the condition of Theorem 1 gives the constraints, namely $\xi_{1e}=x_{1e},\xi_{2e}=x_{2e}=0,\pi_3(\xi_e)=x_{3e},\pi_4(\xi_e)=x_{4e}=0$. We can choose $\pi_3(\xi,\theta)$ and $\pi_4(\xi,\theta)$ to satisfy the condition (14) as follows: We can choose the potential energy $V(\xi_1)$ along two assumptions given above as $V(\xi_1)=-\bar{\beta}\cos\tilde{\xi}_1$, $\tilde{\xi}_1=\xi_1-\xi_{1e}$, for some $\bar{\beta}>0$ and $R(\xi)=\frac{\gamma_d}{M}$. Consider the second row of (25), therefore we have

$$\frac{1}{M}\left(\theta_2-\pi_3(\xi,\theta)-\pi_4(\xi,\theta)+\theta_1\xi_2\right) = -\frac{\partial V(\xi_1)}{\partial \xi_1}-R(\xi)\xi_2=-\bar{\beta}\sin(\tilde{\xi}_1)-\frac{\gamma_d}{M}\xi_2,$$

From the expression above, in order to simplify our derivations, we choose $\pi_4(\xi_2,\theta)=x_{4e}-\gamma_d\xi_2$. Consequently, we can compute $\pi_3(\xi,\theta)$ as follows:

$$\begin{aligned}\pi_3(\xi,\theta) &= \theta_2+\bar{\beta}M\sin\tilde{\xi}_1+(\gamma_d+\theta_1)\xi_2-\pi_4(\xi,\theta)\\ &= \theta_2+\bar{\beta}M\sin\tilde{\xi}_1-x_{4e}+(2\gamma_d+\theta_1)\xi_2\end{aligned} \quad (26)$$

It is obvious that π_3 is a function of both ξ_1,ξ_2 and θ, and defined in $\mathcal{D}$.

As the mapping $\pi(\xi)$ has been chosen, by using some lengthy, but straightforward, calculation from the third and forth rows, respectively, we have the control input $\left(\frac{u_f}{T_0'},\ \frac{u_q}{T}\right)^T = (c_1(\pi(\xi,\theta)),\ c_2(\pi(\xi,\theta)))^T$ in (25) that renders the manifold $\mathcal{M}$ invariant.

(H3) Implicit manifold: Derivation of the manifold $\phi(x,\theta)$

From the result above, the mapping $\pi(\xi,\theta)$ has been defined and then the condition in (15) is verified. This subsection is to find an implicit definition of the manifold $\mathcal{M}$ that can be implicitly described by $\mathcal{M}=\{x\in\mathcal{S}\times\mathbb{R}\times\mathbb{R}\times\mathbb{R}|\ \phi(x,\theta)=0\}$ and the mapping $\phi(x,\theta)$ can be defined as follows:

$$\phi(x,\theta)=\begin{bmatrix}\phi_1(x,\theta)\\ \phi_2(x,\theta)\end{bmatrix} \quad (27)$$

With the direct correspondances of $\pi_1(\xi)=x_1,\pi_2(\xi)=x_2$, the manifold $\phi(\xi,\theta)$ is constructed by

$$\begin{cases}\phi_1(x,\theta) &= x_3-\Big[\theta_2+\bar{\beta}M\sin(x_1-x_{1e})\\ & \qquad -x_{4e}+(2\gamma_d+\theta_1)x_2\Big]\\ \phi_2(x,\theta) &= x_4+x_{4e}-\gamma_d x_2\end{cases} \quad (28)$$

(H4) Manifold attractivity and trajectory boundedness

In this subsection, a control law $u(x,\hat{\theta})$ and a parameter adaptation law $\varpi(x,\hat{\theta})$ are designed to ensure that all trajectories of the closed-loop system are bounded and converge to the manifold $\mathcal{M}$.

Let $\zeta=\phi(x,\hat{\theta})$ be the off-the-line manifold coordinate where $z=\hat{\theta}-\theta-\beta(x)$. Subsequently, from

$$\begin{bmatrix} \xi_2 \\ \frac{1}{M}\left(\theta_2 - \pi_3(\xi,\theta) - \pi_4(\xi,\theta) + \theta_1\xi_2\right) \\ (-a+\xi_2\cot\xi_1)\pi_3(\xi,\theta) + \frac{bV_\infty \sin 2\xi_1}{2(X_1+X_2)} \\ \mathcal{N}(-a+\xi_2\cot\xi_1)\pi_3(\xi,\theta) + \frac{\mathcal{N}bV_\infty\sin 2\xi_1}{2(X_1+X_2)} - \frac{\pi_3(\xi,\theta)X_1X_2\left(\frac{\pi_4(\xi,\theta)\Delta(\xi_1,\pi_3)}{\pi_3(\xi,\theta)X_1X_2} - I_{qe}\right)}{\Delta(\xi_1,\pi_3)} \end{bmatrix}$$
$$+\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{V_\infty\sin\xi_1}{(X_1+X_2)} & 0 \\ \frac{\mathcal{N}V_\infty\sin\xi_1}{(X_1+X_2)} & \frac{\pi_3(\xi,\theta)X_1X_2}{\Delta(\xi_1,\pi_3(\xi,\theta))} \end{bmatrix}\begin{bmatrix} c_1(\pi(\xi,\theta)) \\ c_2(\pi(\xi,\theta)) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \frac{\partial\pi_3(\xi,\theta)}{\partial\xi_1} & \frac{\partial\pi_3(\xi,\theta)}{\partial\xi_2} \\ \frac{\partial\pi_4(\xi,\theta)}{\partial\xi_1} & \frac{\partial\pi_4(\xi,\theta)}{\partial\xi_2} \end{bmatrix}\begin{bmatrix} \xi_2 \\ -\frac{\partial V(\xi_1)}{\partial\xi_1} - R(\xi)\xi_2 \end{bmatrix} \tag{25}$$

(16), straightforward calculations show that

$$\begin{aligned}
\dot{\zeta}_1 &= f_3(x) + g_{31}(x)\frac{u_f}{T_0'} \\
&\quad -\Bigg[(\bar{\beta}M\cos(x_1 - x_{1e}) + \dot{\hat{\theta}}_1)x_2 + \dot{\hat{\theta}}_2 \\
&\quad +\frac{1}{M}\left(\frac{\partial\beta_2}{\partial x_2} + 2\gamma_d + \dot{\hat{\theta}}_1 + \beta_1(x) + \frac{\partial\beta_1}{\partial x_2}x_2\right)\dot{\bar{x}}_2\Bigg] \\
\dot{\zeta}_2 &= f_4(x) + g_{41}(x)\frac{u_f}{T_0'} + g_{42}(x)\frac{u_q}{T_q} + \gamma_d\dot{\bar{x}}_2 \\
\dot{z}_1 &= \dot{\hat{\theta}}_1 + \frac{\partial\beta_1}{\partial x_1}x_2 + \frac{\partial\beta_1}{\partial x_2}\dot{\bar{x}}_2 - \frac{1}{M}\frac{\partial\beta_1}{\partial x_2}(z_2 + z_1x_2) \\
\dot{z}_2 &= \dot{\hat{\theta}}_2 + \frac{\partial\beta_2}{\partial x_2}x_2 + \frac{\partial\beta_2}{\partial x_2}\dot{\bar{x}}_2 - \frac{1}{M}\frac{\partial\beta_2}{\partial x_2}(z_2 + z_1x_2) \\
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \frac{1}{M}(-z_2 - (z_1+\gamma_d)x_2 - \bar{\beta}M\sin(x_1 - x_{1e}))
\end{aligned} \tag{29}$$

where

$$\dot{\bar{x}}_2 = \frac{1}{M}\left(\hat{\theta}_2 + \beta_2(x) - x_3 - x_4 + (\hat{\theta}_1 + \beta_1(x))x_2\right).$$

By an appropriate definition of the control law $u(x,\hat{\theta})$ in (19) and the parameter adaptation law $\dot{\hat{\theta}}_1, \dot{\hat{\theta}}_2$ as given in (20) and selecting the function $\beta_1(\cdot)$ and $\beta_2(\cdot)$ as

$$\begin{cases} \beta_1(x) &= \frac{\gamma_1 x_2^2}{2M}, \gamma_1 > 0, \\ \beta_2(x) &= \frac{\gamma_2 x_2}{2M}, \gamma_2 > 0, \end{cases} \tag{30}$$

then, the system (29) can be expressed in the (ζ, z, x)-coordinate as:

$$\begin{cases} \dot{\zeta}_1 &= -\sigma_1\zeta_1 + \frac{1}{M}\delta(x,\hat{\theta})(z_2 + z_1x_2) \\ \dot{\zeta}_2 &= -\sigma_2\zeta_2 - \frac{\gamma_d}{M}(z_2 + z_1x_2) \\ \dot{z}_1 &= -\frac{\gamma_1 x_2}{M^2}(z_2 + z_1x_2) \\ \dot{z}_2 &= -\frac{\gamma_2}{M^2}(z_2 + z_1x_2) \\ \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{1}{M}(-z_2 - (z_1+\gamma_d)x_2 - \bar{\beta}M\sin(x_1 - x_{1e}) \end{cases} \tag{31}$$

where $\delta(x,\hat{\theta}) = \frac{\gamma_2}{M} + 2\gamma_d + \hat{\theta}_1 + \frac{3\gamma_1 x_2^2}{2M}, \sigma_1(x,\hat{\theta}) = \lambda_1 + \epsilon\delta(x,\hat{\theta})^2, \sigma_2 = \lambda_2, \lambda_i > 0, i = 1,2$ and $(\gamma_1, \gamma_2, \gamma_d, \epsilon, \bar{\beta})$ are positive design parameters.

In accordance with condition (H4), we need to prove that boundedness of the trajectories of the closed loop behavior of the state equation (16) with the control law (19)-(20) and the off-the-manifold coordinate ζ. From the target dynamical system in (23), it is can be seen that x_1, x_2 are bounded and eventually settle to the equilibrium point $(x_{1e}, 0)$. In addition, according to selecting the function $\beta_1(\cdot)$ and $\beta_2(\cdot)$ in (30), consider the candidate Lyapunov function $W = \frac{1}{2\gamma_1}z_1^2 + \frac{1}{2\gamma_2}z_2^2$ and note that $\dot{W} = -\frac{1}{M^2}(z_2 + z_1x_2)^2 \leq 0$, hence $z = 0$ is a stale equilibrium and $z(t) \in \mathcal{L}_2$. Additionally, $\lim_{t\to\infty}\beta_1(x) \to 0, \lim_{t\to\infty}\beta_2(x) \to 0$; thus, we obtain $\lim_{t\to\infty}\hat{\theta}_1 \to \theta_1$ and $\lim_{t\to\infty}\hat{\theta}_2 \to \theta_2$. Subsequently, it is obvious that the off-the-manifold coordinate ζ is bounded and from (31) $\lim_{t\to\infty}\zeta(t) = 0$. Apart from this, boundedness of x_3 and x_4 immediately follows from the fact that $x_3 = \zeta_1 + \pi_3(x_1, x_2, \theta)$ and $x_4 = \zeta_2 + \pi_4(x_2)$. From (26), we obtain that x_3 and x_4 are bounded, and thus we can conclude boundedness of x_3 and x_4, respectively. Finally, boundedness of all trajectories of (31) has been shown; thus, we can deduce that the system (31) has an asymptotically stable equilibrium at x_e. We can summarize the adaptive I&I controller design in the Proposition 1. This completes the proof.

5. SIMULATION RESULTS

In this section, the proposed control methodology is implemented on a SMIB power system with STATCOM and the closed-loop performance of the system is evaluated using computer simulation studies under disturbances. The time domain simulations are carried out to investigate the damping performance of the designed controller and the parameter adaptive law, as given in (19)-(20), in the system under study. The performance of the proposed controller (adaptive I&I controller) is compared with that of two existing nonlinear controllers and a traditional linear control as follows:

- An standard I&I controller (full-information) [15], which is obtained by assuming the two constant parameters (θ_1, θ_2) are precisely known.
- An adaptive backstepping controller [29] given in Appendix.

• A power system stabilizer and automatic voltage regulator (PSS/AVR) [1].

Remark 2: In this work, the backstepping method is used to compare with the proposed method because it is currently regarded as one of the standard nonlinear control techniques for nonlinear systems. However, this method cannot be directly used to design a nonlinear stabilizing feedback control law for power systems with STATCOM in (3)-(4). Although the dynamics of E and I_Q can be controlled through u_f and u_q, respectively, these enter as products on the second state equation of (4), in particular the third term (P_s). Thus, standard nonlinear control design, in particularly backstepping control, cannot be applied to stabilize this system whereas the I&I can. Additionally, in this work even if we propose a transformation to use two active electrical power P_e and P_s in (3) as state variables instead of E and I_Q, the resulting nonlinear power system with STATCOM as given in (6)-(7) is not the strict-feedback form [29] for backstepping design. Thus, the backstepping scheme needs to be further extended as provided in Appendix but the I&I controller developed in this work can be directly applied without any extensions.

Considering the single line diagram as shown in Fig. 2 where SG is connected through parallel transmission line to an infinite-bus, such SG delivers 1.0 per unit (pu.) power while the terminal voltage V_t is 0.9897 pu, and an infinite-bus voltage is 1.0 pu. However, once a three-phase fault (a large perturbation) occurs at the point, the midpoint of one of the transmission lines, it leads to rotor acceleration, voltage sag, and large transient induced electromechanical oscillations. Further, when there is a small perturbation, particularly the mechanical input power, on the network, this causes the system trajectories, induced by the perturbation, confined to a limited region in a neighborhood of a nominal operating trajectory.

We are, therefore, interested in the following two questions. The first becomes whether, after the fault is cleared from the network, the system including the unknown constant parameter θ will return to a post-fault equilibrium state or not. The second is whether, after the small perturbation disappears, the system can maintain stability or not.

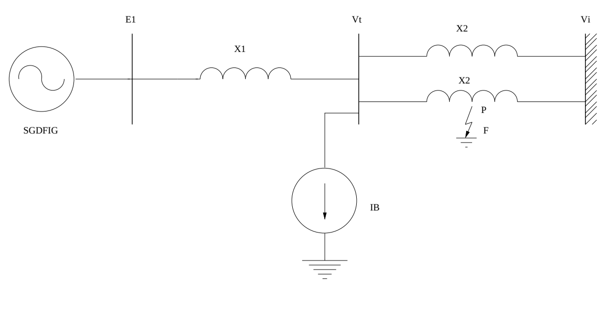

Fig.2: *A single line diagram of SMIB model with SMES.*

In the simulations, the fault of interest is a symmetrical three phase short circuit occurring on one of the transmission lines as shown in Fig. 2. The following two cases with a temporary fault sequence and an unknown small perturbation to mechanical power to synchronous generators in the system with unknown constant parameters are discussed.

Case 1: Temporary fault

The system is in a pre-fault steady state, a fault occurs at $t = 0.5$ sec., the fault is isolated by opening the breaker of the faulted line at $t = 0.7$ sec., the transmission line is recovered without the fault at $t = 2$ sec. Afterward the system is in a post-fault state.

Case 2: Unknown perturbation in mechanical input power

The system is in a pre-fault steady state, there is a unknown constant perturbation in the mechanical power between $t = 0.5$ sec. and $t = 1.5$ sec. Afterward the system is in a post-fault state.

The physical parameters (pu.) and initial conditions (δ_0, ω_0, P_{e0}, $P_{s0}, \hat{\theta}_{10}, \hat{\theta}_{20}$) for this power system model are given as follows:

$$\begin{aligned}
&\omega_s = 2\pi f \text{ rad/s}, D = 0.2, H = 5, f = 60 \text{ Hz},\\
&T_0' = 4, V_\infty = 1\angle 0^\circ, X_d = 1.1, X_d' = 0.2,\\
&X_T = 0.1, T = 1, X_2 = X_L = 0.2, P_m = 1,\\
&|I_Q| \le 2, \delta_0 = 0.4964 \text{ rad}, \omega_0 = \omega_s, P_{e0} = P_m,\\
&P_{s0} = 0, I_{Qe} = 0, \hat{\theta}_{10} = -0.3, \hat{\theta}_{20} = 0.8.
\end{aligned}$$

The tuning parameters of the proposed adaptive controller are $\bar{\beta} = 500, \gamma_d = 0.2; \gamma_1 = 0.5, \gamma_2 = 0.1, \lambda_1 = \lambda_2 = 100, \epsilon = 0.001$. The SMIB power system consisting of generator excitation and STATCOM has been simulated using the the physical parameters and initial conditions above.

For Case 1, it can be seen that Fig. 3 shows the time responses of power angle (δ), frequency ($\omega - \omega_s$), and terminal voltage (V_t), eventually returning to the pre-fault state values, under four controllers. Fig. 4 shows the STATCOM current, the parameter estimates $\hat{\theta}_1$ and $\hat{\theta}_2$ under the proposed adaptive control and the adaptive backstepping control. Observe that the time trajectories of the proposed adaptive strategy are not different from those the I&I controller in spite of having two unknown parameters. It is obvious that both controllers outcome on a more good transient behavior compared with the adaptive backstepping scheme and PSS/AVR. In particular, the convergence and damping of the proposed controller are much better compared with those of the adaptive backstepping one and PSS/AVR. It can be seen that the oscillations in the rotor angles and the relative speed are sluggishly damped by the the PSS/AVR. Further, the post-fault system responses are quite oscillatory and eventually settle to the pre-fault values after the fault is cleared. In contrast, the remaining controllers controllers stabilize the system without sustained oscillations. Moreover, the proposed adaptive scheme has an obvious advantage over the adaptive backstepping one. Especially, the parameter estimate of the proposed control converges to the real value of both the damping constant ($\hat{\theta}_1 \to \theta_1$) and mechanical input power ($\hat{\theta}_2 \to \theta_2$). In contrast, the the parameter estimate of the adaptive backstepping one converges to the real value of the only mechanical input power ($\hat{\theta}_2 \to \theta_2, \hat{\theta}_1 \nrightarrow \theta_1$).

Similar to Case 1, it is evident from Case 2 that Fig. 5 illustrates time trajectories of power angle, frequency, and terminal voltage setting to the pre-fault steady state despite having an unknown constant perturbation of mechanical input power. For this case, the mechanical power is varied from the unknown normal value to some unknown constant (in simulation $P_m = 1$ pu., $\Delta P_m = 0.3$ pu.). It can firstly observed that time responses of the proposed scheme do slightly differ from those of the I&I one despite having two unknown parameters. It is clear that the equilibrium can be recovered and the terminal voltage can be regulated to the prescribed value when the system is forced by the proposed adaptive control. Further, as compared with the adaptive backstepping scheme and PSS/AVR, the proposed adaptive controller not only effectively damps the oscillations of power angle and frequency, but also has superior performance in maintaining the terminal bus voltage magnitude close to its reference voltage values defined for the normal operating condition, and provides effective voltage regulation to the desired pre-fault steady-state values after the occurrence of an unknown perturbation in mechanical power. Identical to Case 1,, Fig. 6 show the time response of the STATCOM current together with the parameter estimate of the proposed control that can converge to the real value of both the damping constant and mechanical input power while the adaptive backstepping one cannot.

As indicated in the simulation results above. It can be, overall, concluded that the proposed adaptive control law is effectively designed for transient stabilization and voltage regulation following short circuit and unknown mechanical input change conditions. The adaptive I&I control can render the closed-loop system converge quickly to an equilibrium point and the terminal voltage can be quickly regulated to the reference voltage value in spite of having two unknown constant parameters. Even though the system considered has two unknown constant parameters, the time responses of the proposed adaptive scheme are slightly different from those of the standard I&I one. Furthermore, the proposed adaptive control method obviously outperforms the adaptive backstepping one and PSS/AVR in terms of fast convergence speed and shorter settling time as well as guaranteed convergence to the true value of two unknown constant parameters in both cases.

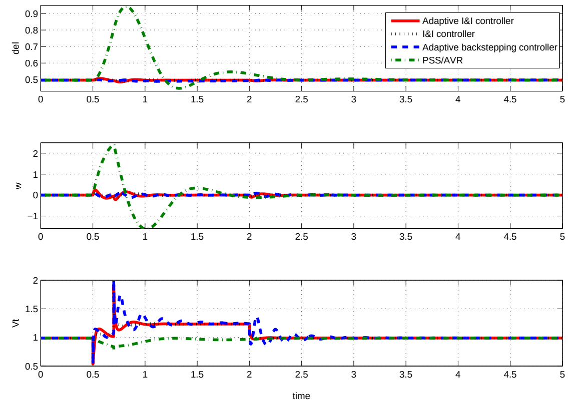

Fig.3: *Controller performance in Case 1Power angles (δ) (deg.), frequency ($\omega\omega_s$) rad/s. and Terminal voltage (V_t) pu.*

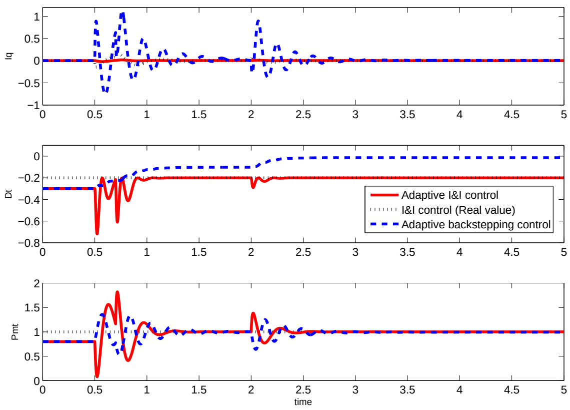

Fig.4: *Unknown constant paramters in Case 1 - STATCOM current (I_Q), damping coefficient estimate ($\widehat{\theta}_1$) and mechanical input power estimate ($\widehat{\theta}_2$)*

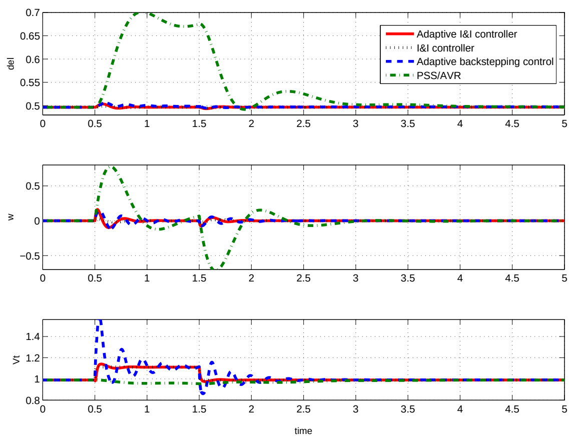

Fig.5: *Controller performance in Case 2Power angles (δ) (deg.), frequency ($\omega\omega_s$) rad/s. and Terminal voltage (V_t) pu.*

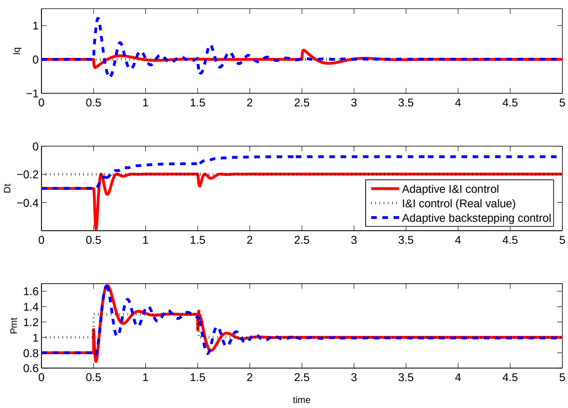

Fig.6: *Unknown constant paramters in Case 2 - STATCOM current (I_Q), damping coefficient estimate ($\widehat{\theta}_1$) and mechanical input power estimate ($\widehat{\theta}_2$)*

6. CONCLUSION

In this paper, we have used the adaptive I&I design tool to design the generator excitation and STATCOM controller. Also, the resulting controller can be effectively used to enhance transient stability and voltage regulation in the SMIB power system when the mechanical power and the damping constant are unknown constant parameters. Using a nonlinear power system model and the adaptive I&I design, simulation results have demonstrated that the proposed controller can drive the system to a stable equilibrium corresponding to the real value of two unknown constant parameters. The performance of the proposed adaptive control is compared with that of the standard I&I controller, the adaptive backstepping controller, and a traditional linear controller (PSS/AVR). It can be observed that the damping and the closed-loop system dynamics of the proposed control do not differ much from those the standard I&I one but perform much better than those of the adaptive backstepping one and PSS/AVR in terms of reduced overshoot and faster reduction of oscillations. The value of parameter estimate of the proposed control also converges toward the true parameter values in both cases. In addition, the presented controller simultaneously achieves transient stabilization and accomplishes a good regulation of the STATCOM terminal voltage.

7. ACKNOWLEDGMENTS

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8. APPENDIX

Adaptive backsteping controller [29]

In order to design a nonlinear adaptive controller based on backstepping scheme used to compare with the proposed adaptive controller, let us define the state variable by $x_1 = \delta - \delta_e, x_2 = \omega - \omega_s, x_3 = P_e - P_{ee}, x_4 = P_s - P_{se}, e_i = x - x_i^*, (i = 1,2,3,4), x_1^* = 0, x_2^* = -c_1 x_1, x_3^* = M e_1 + \frac{c_2 e_2}{2} + \hat{\theta}_2 + \hat{\theta}_1 x_2, x_4^* = c_1 M x_2 + \frac{c_2 e_2}{2}$. Hence, the adaptive backstepping control approach is expressed in the following Proposition.

Proposition 2: Consider the system (8), the adaptive backstepping control law is as follows:

$$\begin{cases} \frac{u_f(x,\hat{\theta})}{T_0'} &= \frac{1}{g_{31}(x)}\Big[\frac{e_2}{M} - f_3(x) + \varpi_2(x,\hat{\theta}) \\ & \quad + (M + \frac{c_1 c_2}{2} + \varpi_1(x,\hat{\theta}))x_2 \\ & \quad + (\frac{c_2}{2} + \hat{\theta}_1)\dot{x}_2 - c_3 e_3\Big] \\ \frac{u_q(x,\hat{\theta})}{T} &= \frac{1}{g_{42}(x)}\Big[\frac{e_2}{M} - f_4(x) - g_{41}(x)\frac{u_f}{T_0'} \\ & \quad + (\frac{c_2}{2} + c_1 M)\,\dot{x}_2 + \frac{c_1 c_2 x_2}{2} - c_4 e_4\Big] \end{cases} \tag{32}$$

with the parameter adaptive law given by:

$$\begin{cases} \dot{\hat{\theta}}_1 &= \varpi_1(x,\hat{\theta}) = \frac{\gamma_1}{M}\Big(e_2 - e_3(1+\hat{\theta}_1)x_2\Big) \\ \dot{\hat{\theta}}_2 &= \varpi_2(x,\hat{\theta}) = \frac{\gamma_2}{M}\Big(e_2 - e_3(1+\hat{\theta}_1)\Big) \end{cases} \tag{33}$$

where $\dot{\hat{x}}_2 = \frac{1}{M}(\hat{\theta}_2 + \hat{\theta}_1 x_2 - x_3 - x_4)$ and $c_i > 0, (i = 1,2,3,4), \gamma_j > 0, (j = 1,2)$ are positive design parameters. Then, the overall closed-loop system with the controller above is asymptotically stable. In this work, tuning parameters are chosen as $c_1 = c_3 = c_4 = 3, c_2 = 2, \gamma_1 = \gamma_2 = 1$.

Proof: In the following, the control law and the parameter adaptation law are designed by the adaptive backstepping scheme.

Step 1: For the first subsystem of the system (8), x_2 is considered as the virtual control variable. Then, the virtual control of x_2 is designed as $x_2^* = -c_1 x_1$, where $c_1 > 0$ is a design constant. Let us define the error variable $e_2 = x_2 - x_2^*$ and $e_1 = x_1$. Then, we have

$$\dot{e}_1 = e_2 - c_1 e_1 \tag{34}$$

For the system (34), we choose the Lyapunov function as $V_1 = \frac{1}{2}e_1^2$. The time derivative of V_1 along the system trajectory is $\dot{V}_1 = e_1(e_2 - c_1 e_1) = -c_1 e_1^2 + e_1 e_2$. It is clear that $\dot{V}_1 \le 0$ where $e_2 = 0$.

Step 2: Let us define the augmented Lyapunov function of Step 1 as $V_2 = V_1 + \frac{1}{2}e_2^2$. Notice that

$$\dot{e}_2 = \dot{x}_2 - \dot{x}_2^* = \frac{1}{M}(\theta_2 + \theta_1 x_2 - x_3 - x_4) + c_1 x_2 \tag{35}$$

Then the time derivative of V_2 along the system trajectory is

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + e_2\dot{e}_2 = -c_1 e_1^2 \\ & \quad + e_2\left[e_1 + \frac{1}{M}(\theta_2 + \theta_1 x_2 - x_3 - x_4) + c_1 x_2\right] \end{aligned} \tag{36}$$

From (35), x_3 and x_4 are taken as the virtual control variables. Define the error variables $e_3 = x_3 - x_3^*$ and $e_4 = x_4 - x_4^*$. Then two virtual control variables are chosen as $x_3^* = Me_1 + \hat{\theta}_2 + \hat{\theta}_1 x_2 + \frac{c_2 e_2}{2}$ and $x_4^* = c_1 M x_2 + \frac{c_2 e_2}{2}$, respectively, where $\hat{\theta}$ donotes the estimate of θ. Next, let us define the estimation error $\tilde{\theta} = \theta - \hat{\theta}$. Then it holds

$$\begin{aligned} \dot{V}_2 &= -c_1 e_1^2 - c_2 e_2^2 + \frac{1}{M}\tilde{\theta}_2 e_2 + \frac{1}{M}\tilde{\theta}_1 e_2 x_2 \\ &\quad - \frac{e_2}{M}(e_3 + e_4) \end{aligned} \tag{37}$$

Step 3: The presence of the parameter estimate $\hat{\theta}_1$ and $\hat{\theta}_2$ suggests the following augmentation of the Lyapunov function of Step 2 by

$$V_3(e, \tilde{\theta}) = V_2 + \frac{1}{2}(e_3^2 + e_4^2) + \frac{1}{2\gamma_1}\tilde{\theta}_1^2 + \frac{1}{2\gamma_2}\tilde{\theta}_2^2 \tag{38}$$

where $\gamma_1 > 0, \gamma_2 > 0$ are the design gain coefficients. In addition, note that $\dot{\tilde{\theta}} = -\dot{\hat{\theta}}$ and $e_i = x_i - x_i^*, (i = 3, 4)$, the time derivative of V_3 along the system trajectory becomes

$$\begin{aligned} \dot{V}_3 &= \dot{V}_2 + e_3\dot{e}_3 + e_4\dot{e}_4 + \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\tilde{\theta}}_1 + \frac{1}{\gamma_2}\tilde{\theta}_2\dot{\tilde{\theta}}_2 \\ &= -c_1 e_1^2 - c_2 e_2^2 + \frac{1}{M}\tilde{\theta}_2 e_2 + \frac{1}{M}\tilde{\theta}_1 e_2 x_2 \\ &\quad - \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\hat{\theta}}_1 - \frac{1}{\gamma_2}\tilde{\theta}_2\dot{\hat{\theta}}_2 + e_3\Big[- \frac{e_2}{M} + f_3(x) \\ &\quad + g_{31}(x)\frac{u_f}{T_0'} - (M + \frac{c_1 c_2}{2} + \dot{\hat{\theta}}_1)x_2 - \dot{\hat{\theta}}_2 \\ &\quad - \left(\frac{c_2}{2} + \hat{\theta}_1\right)\dot{x}_2 - \frac{1}{M}\left(\frac{c_2}{2} + \hat{\theta}_1\right)(\tilde{\theta}_2 + \tilde{\theta}_1 x_2)\Big] \\ &\quad + e_4\Big[- \frac{e_2}{M} + f_4(x) + g_{41}(x)\frac{u_f}{T_0^0} + f_{42}(x)\frac{u_q}{T} \\ &\quad - \left(\frac{c_2}{2} + c_1 M\right)\dot{x}_2 - \frac{c_1 c_2 x_2}{2}\Big]. \end{aligned} \tag{39}$$

We can choose the feedback control law and the parameter adaptation law as given in (32)-(33), thereby resulting in $\dot{V}_3 = -\sum_{i=1}^4 c_i e_i^2 \leq 0$, where $c_i > 0, (i = 1, 2, 3, 4)$ are positive constants. Thus, under the feedback control law (32) and the parameter adaptation law (33), the error system representation of the resulting closed-loop adaptive system:

$$\begin{cases} \dot{e}_1 &= e_2 - c_1 e_1, \\ \dot{e}_2 &= -c_2 e_2 + \tilde{\theta}_2 + \tilde{\theta}_1 x_2 - e_3 - e_4, \\ \dot{e}_3 &= -c_3 e_3 - \frac{e_3}{M}(\frac{c_2}{2} + \hat{\theta}_1)(\tilde{\theta}_2 + \tilde{\theta}_1 x_2) \\ \dot{e}_4 &= -c_4 e_4 \\ \dot{\hat{\theta}}_1 &= \gamma_1\left(e_2 - e_3(1 + \hat{\theta}_1)x_2\right), \\ \dot{\hat{\theta}}_2 &= \gamma_2\left(e_2 - e_3(1 + \hat{\theta}_1)\right), \end{cases} \tag{40}$$

is asymptotically stable. It is easy to see from (39) that $\dot{V}_3 \leq 0$. This implies that $V_3(t) \leq V_3(0)$ i.e., $e_i, (i = 1, 2, 3, 4)$ are all bounded. We define $\Omega = -\dot{V}_3$, then we have $\int_0^t \Omega(\tau)d\tau = V_3(0) - V_3(t)$. Because $V_3(0)$ is bounded and $V_3(t)$ is non-increasingly bounded, then $\lim_{t\to\infty}\Omega(\tau)d\tau < +\infty$. Additionally, because $\dot{\Omega}$ is bounded, $\lim_{t\to\infty}\Omega = 0$ holds due to Barbalat's lemma [29]. Thus, we can conclude that $\lim_{t\to\infty} e_i = 0$. From the definition of the system state variables x_i, and $x_i^*, (i = 1, 2, 3, 4)$, it is apparent that x_i also converges to zero. This completes the proof.

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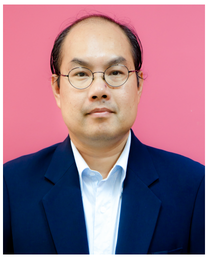

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