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APPLICATION OF ADAPTIVE SYNERGETIC CONTROL TO POWER SYSTEMS WITH SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

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Abstract. *This paper deals with a nonlinear adaptive control design based on synergetic control theory to stabilize an electric power system including superconducting magnetic energy storage (SMES) system. With the help of this method, the developed controller can not only improve transient stability and voltage regulation of the system including SMES device, but also ensure the asymptotical stability of the overall closed-loop system by considering a damping coefficient and an unknown, but bounded, small perturbation in mechanical input as unknown parameters. The dynamic characteristics of the proposed control are studied in a single-machine infinite bus (SMIB) system with SMES. The simulation results are presented to validate the effectiveness and feasibility of the developed control scheme and compared with those of an adaptive immersion and invariance (I&I) technique. Further, they exhibit that even though the presented method has simpler design procedure, it can offer better transient performances than the adaptive I&I method in damping oscillations.*
Keywords: Transient stability, Generator excitation, SMES, Synergetic control theory

1. **Introduction.** There has been recently wide interest in the application of the energy storage system such as super conducting magnetic energy storage (SMES), flywheel energy storage system (FESS), battery storage system (BESS) [1-6] to improve power system stability and operation. In particular, they have shown the feasibility and effectiveness of energy storage to enhance transient stability and to damp power system oscillation. Consequently, considerable attention has been paid for the use of energy storage devices due to their ability to further enhance power transfer capability and to augment both small-signal and transient stability in the power systems. Among a family of energy storage technologies, a device of our particular interest is the superconducting magnetic energy storage (SMES) in this paper because active and reactive power can be injected and absorbed simultaneously. Also, this device is capable of increasing grid transfer capability through enhanced dynamic voltage stability, compensating reactive power for voltage regulation, improving transient stability, and suppressing power system oscillations in the systems [2]. Until now, there has been considerable research addressing the application of SMES with the help of the linearization method based on small perturbation theory and linearized dynamical models. However, there is less attention that has

devoted to a combination of generator excitation and SMES control based on nonlinear control strategy [7-13]. In [7], the authors presented a nonlinear adaptive algorithm for a power system including generator excitation, and a thyristor-controlled superconducting magnetic energy storage control to improve transient stability in spite of having unknown or varying parameters. In [8], despite having a large disturbance, a robust nonlinear excitation and SMES controller was proposed to enhance transient stability of a single-machine infinite bus (SMIB) system. A combination of the feedback linearization with $\mathcal{H}_\infty$ method was applied for the design of a combined generator excitation and SMES control for power systems. The strategy can achieve the desired transient stability improvement through both simulation and experimental results [9]. In spite of disturbances and unknown parameters in the system, a Hamiltonian function design strategy [10] was adopted for designing a robust adaptive controller of synchronous generators with SMES to enhance power system stability. In [6], a backstepping method has been further extended to the non-strict feedback form of a class of nonlinear systems. The scheme is used not only to design the generator excitation and SMES controller in the SMIB model, but also to improve the power system stability such as generator terminal voltage, and the power oscillation. Mahmud et al. [11] developed a dynamic model of SMES based on the equivalent circuit. Afterwards, the feedback linearizing control was designed to satisfy the stability requirements and simultaneously to improve the dynamic stability. An advanced control method, in particular, an immersion and invariance (I&I) method [12], was applied to the design of a nonlinear coordinated generator excitation and SMES controller for transient stability enhancement of power systems. Further, Kanchanaharuthai [13] proposed an adaptive nonlinear I&I controller for transient stability enhancement and voltage regulation of power systems with SMES, even if there are some unknown parameters in the system. The adaptive I&I control technique can guarantee the overall closed-loop dynamics and the great achievement of the desired dynamic performances but its design procedure was rather complicated. Additionally, although the I&I control methodology is the most effective and can be applied for various types of systems [14, 15], it has main disadvantages. In particular, this method has no systematic ways in selecting the mapping from an algebraic equation, an appropriate target dynamics, and a suitable Lyapunov (energy) function, respectively. These lead to main difficulties for using this method.

As a result, to overcome difficulties in the I&I strategy, this paper deals with the design of an adaptive nonlinear control for power systems with SMES via synergetic control theory. This method was first proposed by the Russian researcher Kolesnikov [16, 17]. A variety of successful applications of synergetic control approach, to a power electronics system [18, 19], a power system [20-26], a quadrotor helicopter system [27], a grid-connected photovoltaic system [28], a robotic manipulator [29], are reported in the literature. Therefore, the main features of the proposed method can be summarized as follows:

1) The use of a synergetic control scheme to stabilize the power systems including SMES has not been investigated before,
2) The overall closed-loop system is asymptotically and transiently stable at a desired equilibrium point in spite of having unknown parameters,
3) Enhancement of transient stability together with frequency and voltage regulations of the system considered is achieved, and
4) As compared with the adaptive I&I method [13], the developed design procedure is considerably simpler, but effective. Also, the presented control law offers better dynamic performance such as small overshoot and fast reduction of oscillation.

The rest of this paper is organized as follows. A dynamic model of an SMIB power system including SMES is briefly described in Section 2. Adaptive synergetic controller design and stability analysis are mentioned in Section 3 while simulation results are stated in Section 4. Finally, a conclusion is given in Section 5.

2. **Power System Model with SMES.** According to the result presented in [12, 13], an SMIB power system with generator excitation control of a synchronous generator (SG) and SMES control can be expressed as

$$\begin{cases} \dot{\delta} = \omega - \omega_s \\ \dot{\omega} = \dfrac{1}{M}\left(P_m - P_e - P_d - P_q - D(\omega - \omega_s)\right) \\ \dot{P}_e = (-a + (\omega - \omega_s)\cot\delta)P_e + \dfrac{bV_\infty \sin 2\delta}{2X'_{d\Sigma}} + \dfrac{V_\infty \sin\delta}{X'_{d\Sigma}} \cdot \dfrac{u_f}{T'_0} \\ \dot{P}_d = \dfrac{P_d}{P_e}\dot{P}_e + \dfrac{P_e X_2 \cot\delta}{V_\infty} \cdot \dfrac{1}{T_d}\left(-\left(\dfrac{P_d V_\infty}{P_e X_2 \cot\delta} - I_{de}\right) + u_d\right) \\ \qquad + \dfrac{I_d P_e X_2}{V_\infty}(\cot^2\delta + 1)(\omega - \omega_s) \\ \dot{P}_q = \dfrac{P_q}{P_e}\dot{P}_e + \dfrac{P_e X_2}{V_\infty} \cdot \dfrac{1}{T_q}\left(-\left(\dfrac{P_q V_\infty}{P_e X_2} - I_{qe}\right) + u_q\right) \end{cases} \tag{1}$$

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, P_e is the electrical power, without SMES, delivered by the generator to the voltage at the infinite bus V_∞, P_d and P_q are the electrical power from SMES, 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 $M = 2H/\omega_s$ is an inertia constant of SG. $X'_{d\Sigma} = X'_d + X_T + X_L$ 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. For SMES devices, I_d and I_q denote active and reactive currents in the synchronous $d-q$ frame. I_{de} and I_{qe} are equilibrium points of SMES currents, and T_d and T_q are time constants of SMES models. u_d and u_q are the SMES control input to be designed.

In order to simplify the state-space equation of the system (1), let us introduce the vector of the state variable as $x = [x_1, x_2, x_3, x_4, x_5]^T = [\delta, \omega - \omega_s, P_e, P_d, P_q]^T$. Thus, the dynamic model of the power system with SMES can be expressed as an affine nonlinear system as follows:

$$\dot{x} = f(x) + g(x)u(x) \tag{2}$$

where

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \\ f_5(x) \end{bmatrix} = \begin{bmatrix} x_2 \\ \dfrac{1}{M}\left(P_m - Dx_2 - x_3 - x_4 - x_5\right) \\ (-a + x_2\cot x_1)x_3 + \dfrac{bV_\infty \sin 2x_1}{2X'_{d\Sigma}} \\ \dfrac{x_4}{x_3}f_3(x) - x_3\tan x_1(\cot^2 x_1 + 1)x_2 - \dfrac{x_4}{T_d} + \dfrac{x_3 X_2 \cot x_1}{V_\infty T_d}I_{de} \\ \dfrac{x_5}{x_3}f_3(x) - \dfrac{x_5}{T_q} + \dfrac{x_3 X_2}{V_\infty T_q}I_{qe} \end{bmatrix}$$

$$g(x) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ g_{31}(x) & 0 & 0 \\ g_{41}(x) & g_{42}(x) & 0 \\ g_{51}(x) & 0 & g_{53}(x) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \dfrac{V_\infty \sin x_1}{X'_{d\Sigma}} & 0 & 0 \\ \dfrac{x_4 V_\infty \sin x_1}{x_3 X'_{d\Sigma}} & \dfrac{x_3 X_2 \cot x_1}{V_\infty} & 0 \\ \dfrac{x_5 V_\infty \sin x_1}{x_3 X'_{d\Sigma}} & 0 & \dfrac{x_3 X_2}{V_\infty} \end{bmatrix},$$

$$u(x) = \begin{bmatrix} \dfrac{u_f}{T'_0} \\ \dfrac{u_d}{T_d} \\ \dfrac{u_q}{T_q} \end{bmatrix}$$

The region of operation is defined as the set $\mathcal{D} = \left\{ x \in \mathcal{S} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} \mid 0 < x_1 < \frac{\pi}{2} \right\}$. The open loop operating equilibrium is denoted by $x_e = [x_{1e},\ 0,\ P_{ee},\ P_{de},\ P_{qe}]^T = [\delta_e,\ 0,\ P_m,\ 0,\ 0]^T$.

In this paper, the adaptive synergetic controller is developed to enhance the system stability of power systems with SMES by considering a damping coefficient and an unknown small perturbation of mechanical power as unknown parameters [13]. Let us define $\theta = [\theta_1, \theta_2]^T = [-D, P_m]^T$ as the vector of unknown constant parameters of interest; consequently, the system (2) and (3) can be expressed as follows.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dfrac{1}{M}(\theta_2 + \theta_1 x_2 - x_3 - x_4 - x_5) \\ \dot{x}_3 = f_3(x) + g_{31}(x)\dfrac{u_f}{T'_0} \\ \dot{x}_4 = f_4(x) + g_{41}(x)\dfrac{u_f}{T'_0} + g_{42}(x)\dfrac{u_d}{T_d} \\ \dot{x}_5 = f_5(x) + g_{51}(x)\dfrac{u_f}{T'_0} + g_{53}(x)\dfrac{u_q}{T_q} \end{cases} \tag{3}$$

Thus, the objective of this paper is to solve the problem of the transient stabilization of the system (3) with unknown constant parameters θ, which can be formulated as follows: with the help of the adaptive synergetic control technique, an adaptive control law and a parameter update law in (4) are expressed in the following form:

$$u = \phi\left(x, \hat{\theta}\right), \quad \dot{\hat{\theta}} = \varpi\left(x, \hat{\theta}\right) \tag{4}$$

where $\hat{\theta}$ is the estimate of $\theta = [\theta_1, \theta_2]^T$. Subsequently, the overall closed-loop system consisting of the power system dynamics together with the adaptive control and the update law in (4), namely,

$$\dot{x} = f(x) + g(x)\phi\left(x, \hat{\theta}\right), \quad \dot{\hat{\theta}} = \varpi\left(x, \hat{\theta}\right) \tag{5}$$

is asymptotically stable at the only equilibrium (x_e, θ) and $x \to x_e$, $\hat{\theta} \to \theta$ as $t \to \infty$.

3. Design of Adaptive Synergetic Controller.

3.1. Synergetic control method. In accordance with the result proposed in [16], synergetic control scheme is an invariant-manifold-based control method and can be applied for controlling nonlinear, dynamic, and high-dimensional systems. As mentioned previously in Section 1, this method has been successfully applied for many practical applications. The synergetic control technique based on the analytical design of the aggregated regulator (ADAR) method [16, 17, 30] is briefly mentioned.

Let us consider an n-dimensional nonlinear dynamic equation[1] in the following form:

$$\dot{x}(t) = f(x, u, t) \tag{6}$$

where $x \in \mathbb{R}^n$ denotes the system state variable vector, $u \in \mathbb{R}^m$ is the control input vector to be designed, t is time, and $x_e \in \mathbb{R}^n$ denotes an assignable equilibrium point to be stabilized, respectively. The synergetic control design procedure can be summarized in the following steps as follows.

- **Step 1:** Define a macro-variable as $\varphi(x)$ where $\varphi(x)$ is a function of the system states. Based on synergetic control theory, this macro-variable will be used to determine a stabilizing control law $u(x) = u(x, \varphi(x))$ capable of driving the system trajectories into the desired manifold $\mathcal{M}$ which is defined by $\varphi(x) = 0$ and achieving the desired control specifications.
- **Step 2:** Design a control law capable of steering the system states onto the specified manifold $\mathcal{M}$ and then remaining on this manifold thereafter, with an evolution constraint which can be expressed in the following equation

$$T\dot{\varphi}(x) + \varphi(x) = 0, \quad T > 0 \tag{7}$$

  where T is a controller parameter which affects the rate of convergence of the system trajectories reaching the manifold $\mathcal{M}$.
- **Step 3:** Take time derivative of the selected macro-variable $\varphi(x)$ with respect to the system variable x, take account of the chain rule of differentiation, and then substitute (2) or (6) into (7), and we have

$$T\frac{\partial \varphi(x)}{\partial x} f(x, u, t) + \varphi(x) = 0 \tag{8}$$

  Subsequently, by defining a suitable macro-variable and selecting the control parameter T, the expression above (8) can be directly solved to find the desired controller $u(x)$ which can be written as:

$$u(x) = \phi(x, \varphi(x), T, t) \tag{9}$$

It is easy to note from (9) that after solving the evolution constraint in (8), we have an analytical control law capable of guaranteeing the desired control specifications. The resulting control law relies upon the system state variable, the selected macro-variable, and the control parameter T, respectively. Based on these control parameters chosen by the designer, many interesting characteritics for the overall closed-loop dynamics such as global stability, parameter insensitivity, and dynamic properties can be obtained.

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

3.2. **Adaptive control design.** In this subsection, the design procedure based on synergetic control scheme above is developed step by step. From (3), an error coordinate variable is defined as:

$$e(t)=\begin{bmatrix} e_1(t)\\ e_2(t)\\ e_3(t)\\ e_4(t)\\ e_5(t)\end{bmatrix}=\begin{bmatrix} x_1-x_{1e}\\ x_2-x_{2e}\\ x_3-x_{3e}\\ x_4-x_{4e}\\ x_5-x_{5e}\end{bmatrix}=\begin{bmatrix} x_1-\delta_e\\ x_2\\ x_3-P_m\\ x_4\\ x_5\end{bmatrix} \tag{10}$$

Step 1: In order to apply the synergetic control to the modeled system, based on the error variables (10), let us introduce the following macro-variable:

$$\varphi(x)=\begin{bmatrix}\varphi_1(x)\\ \varphi_2(x)\\ \varphi_3(x)\end{bmatrix}=\begin{bmatrix} e_1(t)+e_2(t)+\beta_{11}(t)e_3(t)+\beta_{12}(t)\int_0^t e_3(\tau)d\tau\\ e_1(t)+e_2(t)+\beta_{21}(t)e_4(t)+\beta_{22}(t)\int_0^t e_4(\tau)d\tau\\ e_1(t)+e_2(t)+\beta_{31}(t)e_5(t)+\beta_{32}(t)\int_0^t e_5(\tau)d\tau\end{bmatrix} \tag{11}$$

where $\beta_{i1}(t)$, $\beta_{i2}(t)$, $(i=1,2,3)$ denote the adaptive rules which are continuous functions yet to be specified.

Step 2: The aims of the proposed controller design are to steer the system trajectories and force them to remain on the desired manifold $\varphi(x)=0$ thereafter. In the dynamic of the evolution, each macro-variable is provided as

$$T_i\dot{\varphi}_i+\varphi_i=0,\quad T_i>0,\quad i=1,2,3 \tag{12}$$

where T_i are the pre-specified controller parameters indicating the converging speed of the closed-loop dynamics to the desired manifold $\varphi(x)=0$.

Thus, the time derivative of the error variables (11) along the system trajectory (3) becomes

$$\begin{aligned}\begin{bmatrix}\dot\varphi_1(x)\\ \dot\varphi_2(x)\\ \dot\varphi_3(x)\end{bmatrix}&=\begin{bmatrix}\dot e_1(t)+\dot e_2(t)+\dot\beta_{11}(t)e_3(t)+\beta_{11}(t)\dot e_3(t)+\dot\beta_{12}(t)\int_0^t e_3(\tau)d\tau+\beta_{12}(t)e_3(t)\\ \dot e_1(t)+\dot e_2(t)+\dot\beta_{21}(t)e_4(t)+\beta_{21}(t)\dot e_4(t)+\dot\beta_{22}(t)\int_0^t e_4(\tau)d\tau+\beta_{22}(t)e_4(t)\\ \dot e_1(t)+\dot e_2(t)+\dot\beta_{31}(t)e_5(t)+\beta_{31}(t)\dot e_5(t)+\dot\beta_{32}(t)\int_0^t e_5(\tau)d\tau+\beta_{32}(t)e_5(t)\end{bmatrix}\\ &=\begin{bmatrix}-\frac{1}{T_1}\varphi_1(x)\\ -\frac{1}{T_2}\varphi_2(x)\\ -\frac{1}{T_3}\varphi_3(x)\end{bmatrix}\end{aligned} \tag{13}$$

Rearranging (13), the expression above can be shown as

$$\begin{cases}\dot e_3 &= f_3(x)+g_{31}(x)\frac{u_f}{T_0'}\\ &=-\frac{1}{\beta_{11}}\left(\dot e_1(t)+\dot e_2(t)+\dot\beta_{11}(t)e_3(t)+\dot\beta_{12}(t)\int_0^t e_3(\tau)d\tau+\beta_{12}(t)e_3(t)+\frac{1}{T_1}\varphi_1(x)\right)\\ \dot e_4 &= f_4(x)+g_{41}(x)\frac{u_f}{T_0'}+g_{42}(x)\frac{u_d}{T_d}\\ &=-\frac{1}{\beta_{21}}\left(\dot e_1(t)+\dot e_2(t)+\dot\beta_{21}(t)e_4(t)+\dot\beta_{22}(t)\int_0^t e_4(\tau)d\tau+\beta_{22}(t)e_4+\frac{1}{T_2}\varphi_2(x)\right)\\ \dot e_5 &= f_5(x)+g_{51}(x)\frac{u_f}{T_0'}+g_{53}(x)\frac{u_q}{T_q}\\ &=-\frac{1}{\beta_{31}}\left(\dot e_1(t)+\dot e_2(t)+\dot\beta_{31}(t)e_5(t)+\dot\beta_{32}(t)\int_0^t e_5(\tau)d\tau+\beta_{32}(t)e_5+\frac{1}{T_3}\varphi_3(x)\right)\end{cases} \tag{14}$$

Step 3: In order to design a stabilizing controller, Lyapunov stability strategy will be adopted to verify the stability of the overall closed-loop dynamics including unknown parameters. Since there are two unknown parameters in the system (3), for simplicity, let us define the estimation error $\tilde{\theta} = \theta - \hat{\theta}$. Thus, we define a Lyapunov function as follows:

$$V\left(\varphi, \hat{\theta}, t\right) = \frac{1}{2}\left(\varphi_1^2 + \varphi_2^2 + \varphi_3^2 + \frac{1}{\gamma_1}\tilde{\theta}_1^2 + \frac{1}{\gamma_2}\tilde{\theta}_2^2\right) \tag{15}$$

with constant adaptation gains $\gamma_1 > 0$, $\gamma_2 > 0$ and $\dot{\tilde{\theta}} = -\dot{\hat{\theta}}$. The time derivative of the Lyapunov function can be stated as

$$\dot{V}(t) = \varphi_1\dot{\varphi}_1 + \varphi_2\dot{\varphi}_2 + \varphi_3\dot{\varphi}_3 - \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\hat{\theta}}_1 - \frac{1}{\gamma_2}\tilde{\theta}_2\dot{\hat{\theta}}_2 \tag{16}$$

After differentiating (15) and substituting (13) into (16), we have

$$\begin{aligned}
\dot{V}(t) = {} & \varphi_1 \underbrace{\left[\dot{e}_1(t) + \dot{e}_2(t) + \dot{\beta}_{11}(t)e_3(t) + \beta_{11}(t)\dot{e}_3(t) + \dot{\beta}_{12}(t)\int_0^t e_3(\tau)d\tau + \beta_{12}(t)e_3(t)\right]}_{-\frac{1}{T_1}\varphi_1} \\
& + \varphi_2 \underbrace{\left[\dot{e}_1(t) + \dot{e}_2(t) + \dot{\beta}_{21}(t)e_4(t) + \beta_{21}(t)\dot{e}_4(t) + \dot{\beta}_{22}(t)\int_0^t e_4(\tau)d\tau + \beta_{22}(t)e_4(t)\right]}_{-\frac{1}{T_2}\varphi_2} \\
& + \varphi_3 \underbrace{\left[\dot{e}_1(t) + \dot{e}_2(t) + \dot{\beta}_{31}(t)e_5(t) + \beta_{31}(t)\dot{e}_5(t) + \dot{\beta}_{32}(t)\int_0^t e_5(\tau)d\tau + \beta_{32}(t)e_5(t)\right]}_{-\frac{1}{T_3}\varphi_3} \\
& - \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\hat{\theta}}_1 - \frac{1}{\gamma_2}\tilde{\theta}_2\dot{\hat{\theta}}_2
\end{aligned} \tag{17}$$

Based on Lyapunov stability theory, $\dot{V}(t)$ must be a negative definite function. Consequently, an appropriate control law is chosen as

$$u\left(x, \hat{\theta}\right) = \begin{bmatrix} \dfrac{u_f\left(x, \hat{\theta}\right)}{T_0'} & \dfrac{u_d\left(x, \hat{\theta}\right)}{T_d} & \dfrac{u_q\left(x, \hat{\theta}\right)}{T_q} \end{bmatrix}^T \tag{18}$$

with

$$\begin{cases}
\dfrac{u_f\left(x, \hat{\theta}\right)}{T_0'} = -\dfrac{1}{\beta_{11}(t)g_{31}(x)}\left[\beta_{11}(t)f_3(x) + x_2 + \dot{\hat{x}}_2 + \beta_{12}(t)e_3 + \dfrac{1}{T_1}\varphi_1\right] \\
\dfrac{u_d\left(x, \hat{\theta}\right)}{T_d} = -\dfrac{1}{\beta_{21}(t)g_{42}(x)}\left[\beta_{21}(t)\left(f_4(x) + g_{41}(x)\dfrac{u_f}{T_f}\right) + x_2 + \dot{\hat{x}}_2 + \beta_{22}(t)e_4 + \frac{1}{T_2}\varphi_2\right] \\
\dfrac{u_q\left(x, \hat{\theta}\right)}{T_q} = -\dfrac{1}{\beta_{31}(t)g_{53}(x)}\left[\beta_{31}(t)\left(f_5(x) + g_{51}(x)\dfrac{u_f}{T_f}\right) + x_2 + \dot{\hat{x}}_2 + \beta_{32}(t)e_5 + \dfrac{1}{T_3}\varphi_3\right]
\end{cases} \tag{19}$$

where $\dot{\hat{x}}_2 = \frac{1}{M}\left(\hat{\theta}_2 + \hat{\theta}_1 x_2 - x_3 - x_4 - x_5\right)$.

After substituting the control law $u\left(x, \hat{\theta}\right)$ given in (18), we have

$$\dot{V}(t) = \sum_{i=1}^{3}\left[-\frac{1}{T_i}\varphi_i + \dot{\beta}_{i1}(t)e_{i+2}(t) + \dot{\beta}_{i2}(t)\int_0^t e_{i+2}(\tau)d\tau\right]\varphi_i^2$$

$$+\underbrace{\tilde{\theta}_1\left(\frac{x_2}{M}(\varphi_1+\varphi_2+\varphi_3)-\frac{1}{\gamma_1}\dot{\hat{\theta}}_1\right)}_{-k_\gamma\tilde{\theta}_1^2}+\underbrace{\tilde{\theta}_2\left(\frac{1}{M}(\varphi_1+\varphi_2+\varphi_3)-\frac{1}{\gamma_2}\dot{\hat{\theta}}_2\right)}_{-k_m\tilde{\theta}_2^2} \tag{20}$$

According to the concept reported in [31], a suitable selection for the adaptive rules is given by

$$\dot{\beta}_{i1}(t)=-\eta_{i1}\varphi_i e_{i+2}(t),\quad \dot{\beta}_{i2}(t)=-\eta_{i1}\varphi_i\textstyle\int_0^t e_{i+2}(\tau)d\tau \tag{21}$$

where η_{i1} and η_{i2} are positive constants indicating the adaption speed of the control gains. After substituting the adaptive rules (21) into (20), we get

$$\dot{V}(t)=-\sum_{i=1}^{3}\underbrace{\left[\frac{1}{T_i}+\eta_{i1}e_{i+2}^2(t)+\eta_{i2}\left(\int_0^t e_{i+2}(\tau)d\tau\right)^2\right]}_{\alpha_i(t)}\varphi_i^2-k_m\tilde{\theta}_2^2-k_\gamma\tilde{\theta}_1^2\le 0 \tag{22}$$

where $\alpha_i(t)$ is always positive. It can be seen that there exists a time t_f such that $e_{i+2}(t)=0$, $i=1,2,3$ for all $t\ge t_f$ and eventually we have $\alpha_i(t)=\frac{1}{T_i}$ together with $\dot{V}(t)=-\sum_{i=1}^{3}\frac{\varphi_i^2}{T_i}-k_m\tilde{\theta}_2^2-k_\gamma\tilde{\theta}_1^2\le 0$. From (20), two unknown parameters of the controlled system can be straightforwardly estimated by the following parameter update laws:

$$\dot{\hat{\theta}}_1=\gamma_1\left[k_\gamma\tilde{\theta}_1+\frac{x_2}{M}(\varphi_1+\varphi_2+\varphi_3)\right],\quad \dot{\hat{\theta}}_2=\gamma_2\left[k_m\tilde{\theta}_2+\frac{1}{M}(\varphi_1+\varphi_2+\varphi_3)\right] \tag{23}$$

where γ_j, k_m, k_γ, $(j=1,2)$ are positive design parameters. In the next subsection, the stability analysis of the closed-loop dynamics with the control law (18) and (19) and the parameter adaptive law (23) is considered.

3.3. **Stability analysis.** In this subsection, the model-based adaptive synergetic control law (18) ensures the overall closed-loop stability of the power systems with SMES (3). Therefore, we can summarize the adaptive synergetic control design in the following theorem.

Theorem 3.1. *For the power system with SMES (3), the adaptive synergetic controller (18) and corresponding parameter update law (23) can guarantee that all state trajectories of the closed-loop adaptive system are bounded, that the unknown parameters are estimated* $\left(\lim_{t\to\infty}\left(\theta-\hat{\theta}\right)=0\right)$*, and that the overall closed-loop system (3) with the controller is asymptotically stable at the equilibrium point* (x_e,θ)*.*

Proof: To demonstrate the closed-loop stability of the presented control strategy, it is easy to see that based on Barbalat's Lemma [32], the developed controller will stabilize the system (3), even if there are unknown parameters in the system. This completes the proof.

4. **Simulation Results.** In this section, the proposed controller is tested via simulations of SMIB power system with SMES as shown in Figure 1 [13]. The performance of the proposed control scheme is evaluated and verified in MATLAB environment under the following large disturbance.

- **Effect of severe disturbance**
  The system is in a pre-fault steady state, a symmetrical three phase short circuit occurs at $t=0.5$ sec. The fault is removed 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. The system is eventually in a post-fault state.

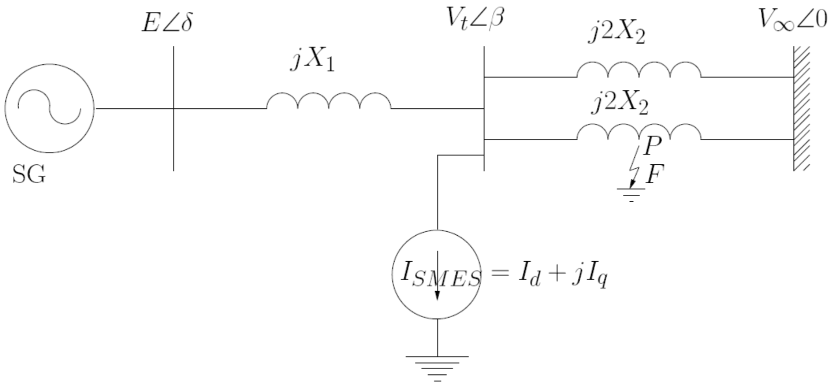

FIGURE 1. A single line diagram of SMIB model with SMES

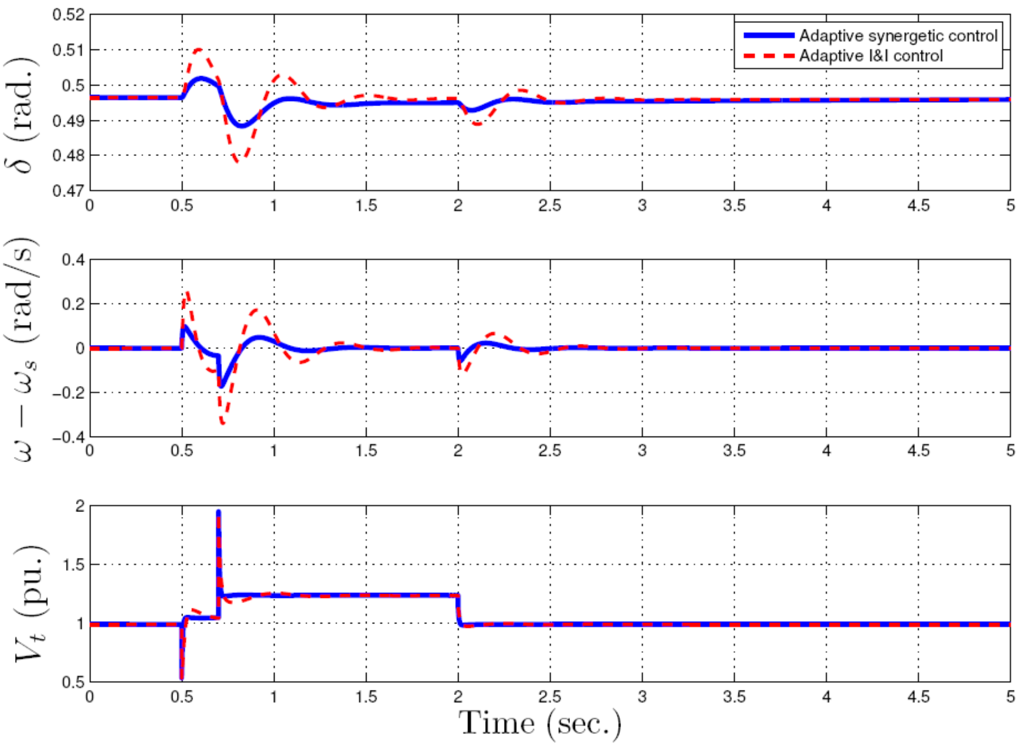

FIGURE 2. Controller performance in Case 1 – Power angles (δ) (rad.), frequency ($\omega - \omega_s$) rad/s. and terminal voltage (V_t) pu

The physical parameters (pu.), the controller parameters, and initial conditions used for this power system model are the same as those used in [13]. The time domain simulations are carried out to investigate the system stability enhancement and the dynamic performance of the designed controller and the parameter adaptive law, as given in (18) and (23), in the system under study. The performance of the proposed controller (adaptive synergetic controller) is compared with that of the adaptive I&I controller [13].

The simulation results are presented and discussed below. For this case, in order to demonstrate the results, time histories of power angle, frequency, and terminal voltage under the proposed method and the adaptive I&I method are shown in Figure 2. Figure 3 shows comparative plots of the parameter estimates for unknown parameters using different approaches. It can be observed from Figures 2 and 3 that the developed control

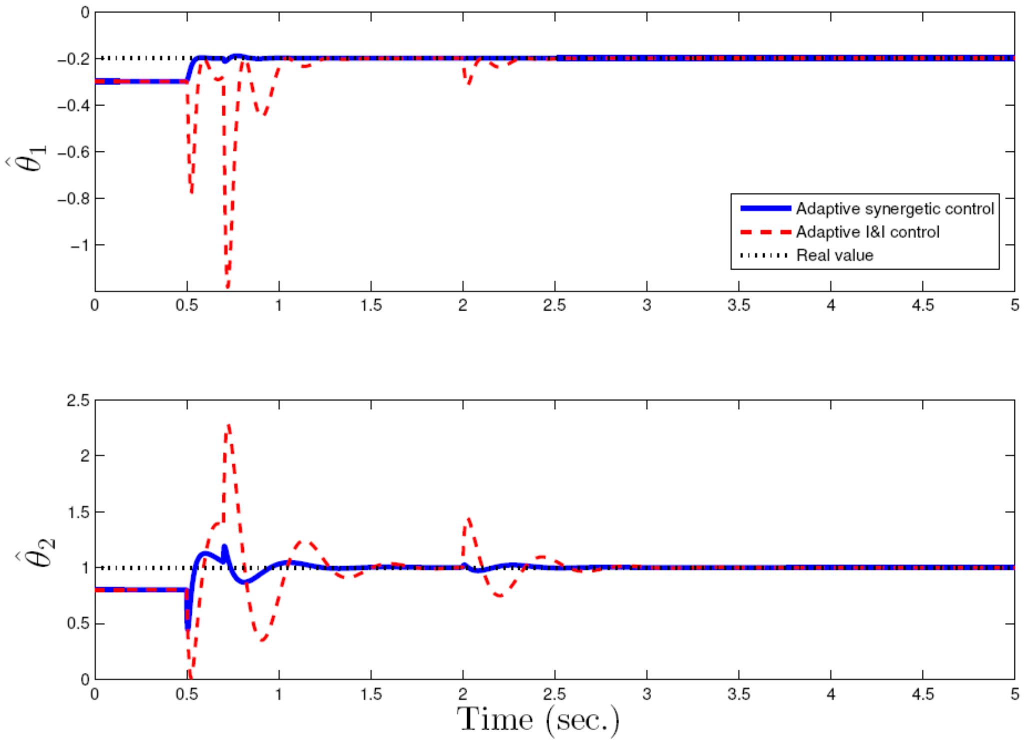

FIGURE 3. Unknown constant paramters in Case 1 – Damping coefficient estimate $\left(\hat{\theta}_1\right)$ and mechanical input power estimate $\left(\hat{\theta}_2\right)$

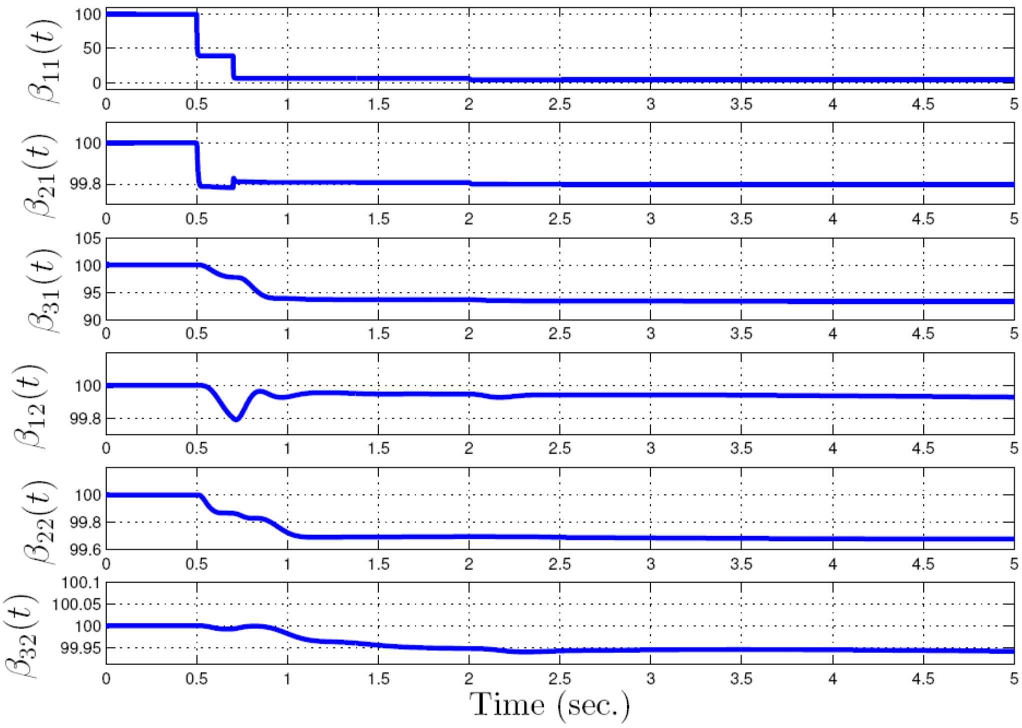

FIGURE 4. Adaptive rules for the control gains

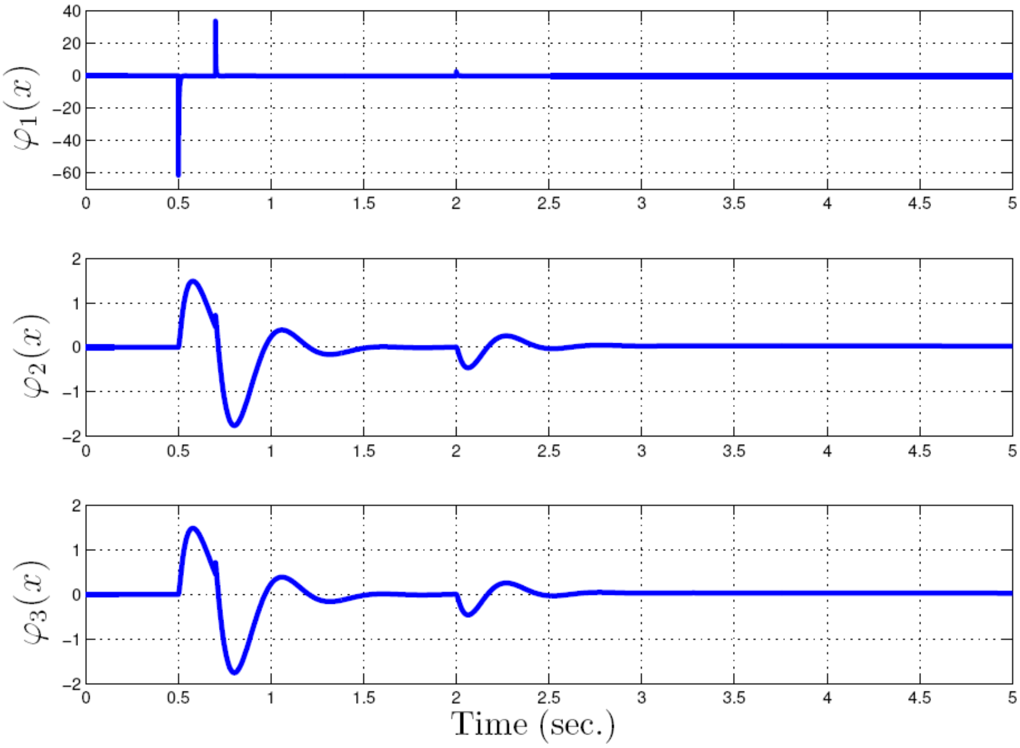

FIGURE 5. The selected macro-variable $\varphi(x) = [\varphi_1(x), \varphi_2(x), \varphi_3(x)]^T$

law can dampen the oscillation more effectively than the adaptive I&I controller. In particular, it is easy to observe that using the proposed method, the overshoot magnitude of oscillations, rising time, and settling time are obviously reduced, which indicate transient performances are improved. It is also seen from Figure 3 that the parameter estimate of the developed scheme quickly approaches to the real value of the damping coefficient constant and mechanical power input without any oscillations. On the contrary, even if the adaptive I&I controller eventually converges to the real value, it still has considerable oscillations. This indicates the proposed controller offers superiority over the adaptive I&I controller. Figure 4 shows the adaptive rules that can adjust themselves according to the changes in each stage. Figure 5 illustrates time responses of the selected macro-variable, capable of approaching to the desired manifold $\varphi(x) = 0$ after the fault is cleared.

From the simulation results with this case, it can be seen that when the adaptive synergetic control scheme is applied to the SMIB power system with SMES, the advantages over the result presented in [13] are as follows.

- The proposed control law is effectively designed for transient stabilization and voltage regulation following small and large disturbances.
- The developed control strategy can make the overall closed-loop dynamics converge more quickly to a desired equilibrium point than the advanced (I&I) strategy. In particular, it obviously outperforms the adaptive I&I one in terms of damping enhancement in the power oscillation together with smaller overshoot magnitude and shorter settling time.
- The process of designing the desired control law is seldom uncomplicated because it does not require the mapping from an algebraic equation, an appropriate target dynamics, and a suitable Lyapunov (energy) function, respectively, as required in [13].

5. **Conclusion.** In this work, the nonlinear adaptive controller has been constructed using the synergetic design for the transient stability enhancement and voltage regulations of a single-machine infinite-bus power system with superconducting magnetic energy storage system. The simulation results have shown that the developed control method is tested under large and small disturbances in the power systems and can stabilize the power angle, terminal voltage, and frequency. From the developed design procedure, it can be seen that the presented scheme is obviously simpler than the adaptive I&I one. In contrast, it provides better transient control performance than the adaptive I&I control. Moreover, despite having unknown parameters, the comparative results confirm the effectiveness of the proposed controller capable of damping power oscillations in the closed-loop system dynamics, improving voltage and frequency regulation, and enhancing transfer capability. Future study will be devoted to extension of this approach to a robust adaptive control design in the presence of matched and mismatched uncertainties together with external disturbances.

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