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A synergetic control design of generator excitation and STATCOM of power systems

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Abstract

This paper designs a synergetic controller for an electrical power system with generator excitation and static synchronous compensator (STATCOM) to enhance transient stability and voltage regulation. With the help of synergetic control theory, the simplified nonlinear model of a power system with excitation and STATCOM can be derived and used to achieve not only power angle stability, but also frequency and voltage regulations during a large perturbation (or disturbance) on the transmission lines, such as a symmetrical three-phase short circuit fault. The simulation results show that the proposed controller can improve the system transient stability under severe disturbances and achieve power angle stability as well as frequency and voltage regulations.

Keywords: *transient stability, generator excitation, STATCOM, synergetic control theory*

บทคัดย่อ

บทความนี้สนใจ การออกแบบตัวควบคุมที่ทำงานประสานกันของระบบไฟฟ้ากำลังที่ประกอบด้วยตัวควบคุมการกระตุ้นของเครื่องกำเนิดไฟฟ้าซิงโครนัสและตัวชดเชยซิงโครนัสแบบสถิตเพื่อเพิ่มเสถียรภาพชั่วครู่และการควบคุมระดับแรงดัน โดยการใช้ทฤษฎีการทำงานร่วมกันเพื่อออกแบบตัวควบคุม แบบจำลองที่ไม่ซับซ้อนของระบบไฟฟ้าที่ประกอบด้วย การกระตุ้นของเครื่องกำเนิดไฟฟ้าและตัวชดเชยซิงโครนัสแบบสถิตถูกนำมาใช้ในการออกแบบตัวควบคุมเพื่อบรรลุเสถียรภาพของมุมกำลังและการควบคุมความถี่และแรงดัน ขณะที่มีสัญญาณรบกวนขนาดใหญ่บนสายส่งไฟฟ้า เช่นการเกิดกระแสลัดวงจรสามเฟสแบบสมมาตร จากผลการจำลองด้วยคอมพิวเตอร์ ตัวควบคุมนำเสนอสามารถทำให้ระบบมีเสถียรภาพแบบชั่วครู่ภายใต้สัญญาณรบกวนที่รุนแรง และยังบรรลุเสถียรภาพของมุมกำลังพร้อมทั้งการควบคุมความถี่และแรงดันของระบบไฟฟ้ากำลัง

คำสำคัญ*: transient stability, generator excitation, STATCOM, synergetic control theory*

1. Introduction

With continuing developments in power electronic technologies, Flexible AC Transmission System (FACTS) devices are employed mainly to increase the power transfer capability of AC transmission networks and to enhance the controllability of power flow and voltages augmenting the utilization as well as stability, and these devices are common equipment in the power industry. In addition, they have been used to replace a significant number of mechanical control devices (Song & John, 1999; Hingorani & Gyugyi, 1999). Applications for FACTS are often used in interconnected and long-distance AC transmission systems to improve several technical problems, e.g., load flow control, voltage control, system oscillation, inter-area oscillation, reactive power control, steady state stability, and dynamic stability.

Among the FACTS devices, the static synchronous compensator (STATCOM) is of particular interest in this study because this device can be used to improve the grid transfer capability through enhanced voltage stability, significantly provide smooth and rapid reactive power compensation for voltage support, and enhance both power damping oscillation and transient stability.

The aim of this paper is to design a stabilizing control law for the transient stability enhancement via the incorporation of generator excitation and STATCOM. In general, transient stability is associated with dynamic behavior of the trajectories before the fault is cleared from the system. Therefore, the question of interest becomes whether the system will settle to a post-fault equilibrium state when the fault is cleared from the transmission lines.

With only excitation control, a generator excitation controller is usually used to accomplish power angle stability and voltage regulation improvement (Lu, Sun, & Wei, 2001) but once a large fault occurs close to the generator terminal, the system stability (transient stability and voltage regulation) may not be maintained or may be difficult to achieve. Therefore, the incorporation of generator excitation and STATCOM becomes a promising way to further enhance power system stability control and operation.

So far, generator excitation and STATCOM have independently been used to improve power system operations. The use of a coordination of excitation and STATCOM provides an opportunity to improve overall small-signal and transient stability and enhance power angle stability along with voltage and frequency regulations of the power system.

To the best of our knowledge, although considerable research has addressed the control design of either generator excitation or STATCOM, less attention has been devoted to the combination of generator excitation and STATCOM based on nonlinear control theory (Liu, Sun, Shen, & Song, 2003; Gu & Wang, 2007; Wang & Crow, 2010; Zou & Wang, 2010).

More recently, Kanchanaharuthai (2012) has shown the combination of generator excitation and STATCOM for transient stability and voltage regulation enhancement via immersion and invariance (I&I) methodology. However, there is a practically immeasurable variable, particularly the generator transient voltage source that is used in the resulting control law.

This paper continues this line of investigation and particularly extends the work reported in Kanchanaharuthai (2012) by using a different technique based on synergetic control theory so as to simultaneously enhance the transient stability and voltage regulation of a power system interconnected to the grid. With the aid of synergetic control design, the objectives of this work are not only to design a state feedback control law where all measurable state variables can be known, but also to design the coordinated excitation and STATCOM controller capable of simultaneously achieving power angle stability as well as frequency and voltage regulations. In particular, it can provide some additional benefits beyond the existing controllers, e. g., a feedback linearization (FBL) controller, a conventional linear controller (PSS/AVR), and an I&I controller.

The paper is organized as follows. The problem formulation is provided in Section 2. A simplified dynamic model of a power system with generator excitation and STATCOM is briefly described in Section 3. Synergetic control and controller design are given in Section 4 and 5, respectively. Simulation results are given in Section 6 while a conclusion is drawn in Section 7.

2. Problem statement

In this paper, we are interested in studying the transient stability of a nonlinear power system including generator excitation and STATCOM. The considered nonlinear power system can be written in the general form as follows:

$$\dot{x}(t) = f(x) + g(x)u(x), \qquad (1)$$

where $x \in R^n$ is the state variable, $u \in R^m$ is the control action, and $f(x)$ and $g(x)$ are assumed to be smooth functions.

The problem of interest in this paper is the following: given a stable equilibrium point x_e, find a controller law $u(x)$ so that the closed-loop system satisfies:

1. The desired equilibrium point x_e is asymptotically and transiently stable.
2. Power angle stability along with voltage and frequency regulations is simultaneously achieved.

In the next section, we provide a simplified nonlinear model of a power system with generator excitation and STATCOM and use it to design a state feedback control law that meets these requirements.

3. Power system model

This section provides the dynamic equations of the power system including generator excitation and STATCOM considered in this paper.

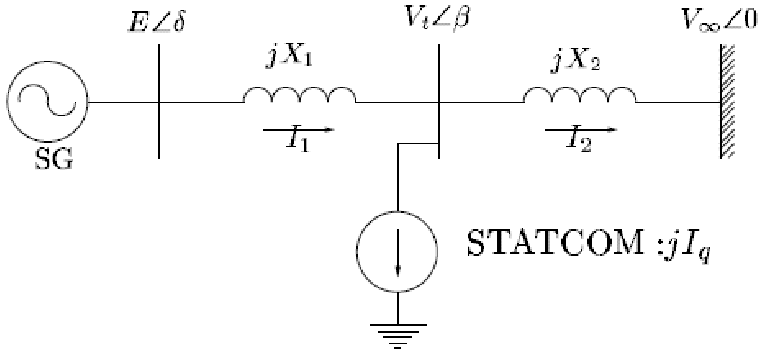


Figure 1 Network

Figure 1 shows a coordination operation of generator excitation from the synchronous generator and STATCOM employed to support an electrical power network that have poor voltage and power stability fpr both small-signal and large-signal (transient), (Song & John, 1999; Hingorani & Gyugyi, 1999) and references therein. For simplicity, the dynamic behavior of a generator excitation is based on a third-order generator model while that of a STATCOM is regarded as a first-order differential equation. Thus, the generator excitation/STATCOM dynamic model is expressed as

$$\begin{aligned}
\dot{\delta} &= \omega - \omega_s \\
\dot{\omega} &= \frac{1}{M}\left(P_m - P_E - D\left(\omega - \omega_s\right)\right) \\
\dot{E} &= -\frac{X_{d\Sigma}}{X_{d\Sigma}'T_0'}E + \frac{\left(X_{d\Sigma}' - X_{d\Sigma}\right)}{X_{d\Sigma}'T_0'}V_\infty \cos\delta + \frac{u_f}{T_0'} \\
\dot{I}_q &= \frac{1}{T_q}(-(I_q - I_{qe}) + u_q)
\end{aligned} \tag{2}$$

with

$$P_E = \frac{EV_\infty \sin\delta}{(X_1+X_2)} + \frac{EV_\infty \sin\delta}{(X_1+X_2)}\frac{I_q X_1 X_2}{\Delta(\delta,E)},$$

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

where $\Delta(\delta,E) = \sqrt{(EX_2)^2 + (V_\infty X_1)^2 + 2X_1X_2EV_\infty\cos\delta}$, δ is the power angle of the generator, E denotes a transient voltage source behind a direct axis transient reactance, ω denotes the relative speed of the generator, $D \geq 0$ is a damping constant, P_m is the mechanical input power, $P_e = \frac{EV_\infty \sin\delta}{X_{d\Sigma}'} = \frac{EV_\infty \sin\delta}{X_1 + X_2}$ is the electrical power, without STATCOM (which is delivered by the generator to the voltage at the infinite bus V_∞). $\omega_s = 2\pi f$ is the synchronous machine speed, H represents the per unit inertial constant, f is the system frequency and $M = \frac{2H}{\omega_s}$. Moreover, $X_{d\Sigma}' = X_d' + X_T + X_L = X_1 + X_2$ is the reactance consisting of the direct axis transient reactance of SG, the reactance of the transformer, and the reactance of the transmission line. Also, $X_2 = X_L$ denotes the reactance of the transmission line. 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. Additionally, T_0' is the direct axis transient short-circuit time constant, u_f is the field voltage control input that must 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 that must be designed, and T_q is a time constant of STATCOM models.

It is well-known that the transient voltage E of a generator excitation and STATCOM current I_q are often physically not measurable – whereas, in practice, an active electrical power P_e and a terminal (bus) voltage V_t are always monitored and measured. Thus, P_e and V_t can be considered as new state variables. After differentiating the electrical power P_e and the terminal voltage V_t and defining the variables $x_1 = \delta, x_2 = \omega - \omega_s, x_3 = P_e, x_4 = V_t$, the dynamic model of the power system including generator excitation and STATCOM can be expressed as the general form (1) as

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \end{bmatrix} = \begin{bmatrix} x_2 \\ \dfrac{1}{M}\left(P_m - \dfrac{x_3 x_4 (X_1 + X_2)}{\Delta(x_1, x_3)} - D x_2\right) \\ (-a + x_2 \cot x_1) x_3 + \dfrac{b V_\infty \sin 2x_1}{2(X_1 + X_2)} \\ M(x_1, x_3) x_2 + N(x_1, x_3) f_3(x) + \dfrac{x_4}{T} - \dfrac{\Delta(x_1, x_3)}{T(X_1 + X_2)} \end{bmatrix},$$

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, u(x) = \begin{bmatrix} \dfrac{u_f}{T_0'} \\ \dfrac{u_q}{T_q} \end{bmatrix}$$

$$g(x) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ g_{31}(x) & 0 \\ g_{41}(x) & g_{42}(x) \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \dfrac{V_\infty \sin x_1}{(X_1 + X_2)} & 0 \\ N(x_1, x_3) g_{31}(x) & -\dfrac{x_4}{T} + \dfrac{\Delta(x_1, x_3)}{T(X_1 + X_2)} \end{bmatrix} \quad (3)$$

where

$$M(x_1, x_3) = \frac{x_3 X_1 X_2 \csc^2 x_1}{\Delta(x_1, x_3)} + \frac{x_3^2 X_2^2 (X_1 + X_2) \cos x_1}{\Delta(x_1, x_3) V_\infty^2 \sin^3 x_1},$$

$$N(x_1, x_3) = \frac{X_1 X_2 \cot x_1}{\Delta(x_1, x_3)} + \frac{x_3 X_2^2 (X_1 + X_2)}{\Delta(x_1, x_3) V_\infty^2 \sin^2 x_1},$$

$$\Delta(x_1, x_3) = \sqrt{\left(\frac{x_3 (X_1 + X_2) X_2}{V_\infty \sin x_1}\right)^2 + (V_\infty X_1)^2 + 2 X_1 X_2 x_3 \cot x_1},$$

$$a = \frac{X_{d\Sigma}}{X_{d\Sigma}' T_{d0}'}, b = \frac{(X_{d\Sigma} - X_{d\Sigma}') V_\infty}{X_{d\Sigma}' T_{d0}'}$$

The region of operation is defined in the set $D = \{x \in S \times R \times R \times R \mid 0 < x_1 < \frac{\pi}{2}\}$. The open loop operating equilibrium is denoted by $x_e = [x_{1e}, x_{2e}, x_{3e}, x_{4e}]^T = [\delta_e, 0, P_{ee}, V_{\text{ref}}]^T$.

Remark 1: It is easy to see from (3) that the dynamic equations of the real power P_e, and terminal voltage V_t are included in lieu of generator transient voltage and STATCOM current dynamics that are shown in (2). Also, in practice it is more convenient to use them for the design of the desired coordinated controller.

Remark 2: There are currently many nonlinear control design techniques, such as feedback linearization scheme, immersion and invariance, control Lyapunov function, and so on. One of the most effective nonlinear control design techniques is a backstepping design (Krstic, Kanellakopoulos, & Kokotovic, 1995) which is a constructive control design method for nonlinear systems in a strict-feedback form. Unfortunately, the dynamic equation of the state $\omega - \omega_s$ depends upon the products between P_e and V_t. Consequently, the dynamic equation (3) is not the strict-feedback form. This disables the ability to directly apply the standard techniques (e.g., backstepping, control Lyapunov functions) unable to be directly applied to stabilize this system. Further, even if the I&I method can perform well, the problem for voltage regulation of this system cannot be solved in a permanent fault case which is mentioned in Section 6.

4. Synergetic control

Synergetic control theory was first introduced by Kolesnikov (Kolesnikov, 2000). This design procedure follows the analytical design of the aggregated regulator (ADAR) method (Kolesnikov, Veselov, Monti, Ponci, Santi, & Dougal, 2002). This technique has successfully been applied and employed in a wide range of applications, such as the area of power electronic controls. In this paper, we are particularly interested in the area of power system control and operation (Jiang, 2009; Ademoye & Feliachi, 2011; Ademoye, Feliachi, & Karimi, 2011; Ademoye & Feliachi, 2012). This method is used to design a stabilizing control law which can provide better performance than traditional power system stabilizers.

Let us consider the nonlinear dynamic equation[1] in the state space form as

$$\dot{x}(t) = f(x,u), \tag{4}$$

with state variable $x \in R^n$, control input $u \in R^m$, and an assignable equilibrium point $x_e \in \mathbb{R}^n$ to be stabilized. Basically, the synergetic control theory consists of the following three steps as follows.

(1) n order to construct a manifold for the nonlinear system, a macro-variable is assumed and defined as $\varphi = \varphi(x)$, where $\varphi(x)$ is a function of the system states. The synergetic synthesis provides a method to find a stabilizing control law $u(x) = u(\varphi(x))$ as a function of some specified macro-variable to force and restrict the system trajectories, and to operate on the manifold which is defined by $\varphi(x) = 0$. The behavior of the macro-variable can be selected by designers in accordance with the desired control specifications. Basically, a linear combination of the state variables is a simple case which can be chosen so as to achieve the control objective, the settling time, limitations in control output, and so on. Also, any variable constraints can be included to form the macro-variable.

(2) esign or synthesize a stabilizing state feedback controller in order to drive the system states to exponentially converge to, and then remain on the specified manifold M. The selected macro-variable is evolved in a desired manner by introducing a constraint that is expressed in the equation

$$T\dot{\varphi} + \varphi = 0,\ T > 0, \tag{5}$$

where T is a controller parameter indicating the speed of convergence of the macro-variable toward the manifold which is specified by $\varphi(x) = 0$.

(3) Differentiating $\varphi(x)$ by taking into account the chain rule of differentiation and substituting (1) or (4) into (5), we can obtain:

$$T\frac{\partial \varphi(x)}{\partial x} f(x,u) + \varphi(x) = 0,\ T > 0. \tag{6}$$

Then, we solve algebraic equation (6) so as to obtain the control law u, which is expressed as

$$u(x) = G(x, \varphi(x)) \tag{7}$$

Note that the following theorem is used for our nonlinear controller design of generator excitation and STATCOM of a power system.

Theorem 1: Consider a class of nonlinear systems (1) or (3). The system states and their rate will converge exponentially to zero with the speed of convergence depending upon the selected parameter T, if the control law is exerted as (7).

5. Synergetic controller design

In this section, a synergetic controller is designed to accomplish the expected requirements that are mentioned in Section 2. The aims are to define a stable and invariant manifold M and to design a control law that is capable of driving the system trajectories and forcing them to remain on the manifold.

[1] It is assumed that all functions and mappings are C^∞ throughout this paper.

Given a nonlinear power system with generator excitation and STATCOM described by (1) or (3), the synergetic synthesis of the considered power systems starts with defining two macro-variables as

$$\begin{aligned}\varphi_1 &= \beta_{11}(\omega-\omega_s)+\beta_{12}(P_e-P_{\text{ref}})\\ &= \beta_{11}x_2+\beta_{12}(x_3-P_{\text{ref}})\end{aligned} \tag{8}$$

$$\begin{aligned}\varphi_2 &= \beta_{21}(\omega-\omega_s)+\beta_{22}(V_t-V_{\text{ref}})\\ &= \beta_{21}x_2+\beta_{22}(x_4-V_{\text{ref}})\end{aligned} \tag{9}$$

with $\beta_{ij}>0,(i,j)\in\{1,2\}$ where $\omega_{\text{ref}}, P_{\text{ref}}$, and V_{ref} are the references of the rotational angular speed (frequency), active electrical power, and terminal voltage, respectively. The aims of the proposed controller design are to steer the system trajectories and force them to remain on the manifolds $\varphi_i(x)=0,\ \{i=1,2\}$.

In the dynamic of the evolution, each macro-variable is provided as

$$T_i\dot{\varphi}_i+\varphi_i=0,\ T_i>0,\ \{i=1,2\}. \tag{10}$$

where T_i are the pre-specified controller parameters indicating the converging speed of the closed-loop system to the manifolds $\varphi_i(x)=0,\{i=1,2\}$. After denoting $\omega-\omega_s, P_e$, and V_t by x_2, x_3 and x_4, respectively as well as by substituting (8), (9) and their derivatives into (10), the dynamic equations are

$$\beta_{11}\dot{x}_2+\beta_{12}\dot{x}_3=\frac{-1}{T_1}\left[\beta_{11}x_2+\beta_{12}\left(x_3-P_{\text{ref}}\right)\right] \tag{11}$$

$$\beta_{21}\dot{x}_2+\beta_{22}\dot{x}_4=\frac{-1}{T_2}\left[\beta_{21}x_2+\beta_{22}\left(x_4-V_{\text{ref}}\right)\right] \tag{12}$$

Rearranging (11) and (12), those expressions can be shown as

$$\dot{x}_3=\frac{-1}{\beta_{12}T_1}\left[\beta_{11}x_2+\beta_{12}\left(x_3-P_{\text{ref}}\right)\right]-\frac{\beta_{11}\dot{x}_2}{\beta_{12}} \tag{13}$$

$$\dot{x}_4=\frac{-1}{\beta_{22}T_2}\left[\beta_{21}x_2+\beta_{22}\left(x_4-V_{\text{ref}}\right)\right]-\frac{\beta_{21}\dot{x}_2}{\beta_{22}} \tag{14}$$

Directly substituting $\dot{x}_3, \dot{x}_4$ from (3) into (13)-(14), the resulting equations are

$$\begin{aligned}&(-a+x_2\cot x_1)x_3+\frac{bV_\infty\sin 2x_1}{2\left(X_1+X_2\right)}+\frac{V_\infty\sin x_1}{\left(X_1+X_2\right)}\cdot\frac{u_f}{T_0'}\\ &=-\frac{1}{\beta_{12}T_1}\left[\beta_{11}x_2+\beta_{12}\left(x_3-P_{\text{ref}}\right)\right]\\ &\quad-\frac{\beta_{11}}{\beta_{12}M}\left(P_m-\frac{x_3x_4(X_1+X_2)}{\Delta\left(x_1,x_3\right)}-Dx_2\right)\end{aligned} \tag{15}$$

and

$$\begin{aligned}&M\left(x_1,x_3\right)x_2+N\left(x_1,x_3\right)f_3\left(x\right)+\frac{x_4}{T}-\frac{\Delta\left(x_1,x_3\right)}{T\left(X_1+X_2\right)}\\ &+\frac{N\left(x_1,x_3\right)V_\infty\sin x_1}{\left(X_1+X_2\right)}\cdot\frac{u_f}{T_0'}-\left(-\frac{x_4}{T}+\frac{\Delta\left(x_1,x_3\right)}{T\left(X_1+X_2\right)}\right)\frac{u_q}{T_q}\\ &=-\frac{1}{\beta_{22}T_2}\left[\beta_{21}x_2+\beta_{22}\left(x_4-V_{\text{ref}}\right)\right]\\ &\quad-\frac{\beta_{21}}{\beta_{22}M}\left(P_m-\frac{x_3x_4(X_1+X_2)}{\Delta\left(x_1,x_3\right)}-Dx_2\right)\end{aligned} \tag{16}$$

After rearranging (15) and (16), the following control laws are obtained as:

$$\begin{aligned}\frac{u_f}{T_0'}=\frac{-\left(X_1+X_2\right)}{T_1\beta_{12}V_\infty\sin x_1}&\left[\frac{T_1\beta_{11}}{M}\left(P_m-\frac{x_3x_4(X_1+X_2)}{\Delta\left(x_1,x_3\right)}-Dx_2\right)\right.\\ &+T_1\beta_{12}\left((-a+x_2\cot x_1)x_3+\frac{bV_\infty\sin 2x_1}{2\left(X_1+X_2\right)}\right)\\ &\left.+\beta_{11}x_2+\beta_{12}\left(x_3-P_{\text{ref}}\right)\right]\end{aligned} \tag{17}$$

and

$$\frac{u_q}{T_q} = -\frac{1}{T_2\beta_{22}\left(-\frac{x_4}{T}+\frac{\Delta(x_1,x_3)}{T(X_1+X_2)}\right)}\left[\frac{T_2\beta_{21}\dot{x}_2}{M}\right.$$
$$+T_2\beta_{22}\left(+N(x_1,x_3)\dot{x}_3+\frac{x_4}{T}-\frac{\Delta(x_1,x_3)}{T(X_1+X_2)}\right)$$
$$\left.+T_2\beta_{22}M(x_1,x_3)x_2+\beta_{21}x_2+\beta_{22}(x_4-V_{\text{ref}})\right] \quad (18)$$

Based on selecting some suitable choices of the controller gains $(\beta_{11},\beta_{12},\beta_{21},\beta_{22},T_1,T_2)$, the proposed controller can not only achieve power angle stability, but also frequency and voltage regulations for the considered power system with a large disturbance. From the synergetic control approach mentioned earlier, it is obvious that regardless of the steady-state operating point of the system, the synergetic controller performs well on the fully nonlinear power system. In contrast to traditional control theory it does not need any linearization or simplification of the system model.

Remark 3: From the resulting control law (17) and (18), it is obvious that both control laws will work together to meet the expected performance requirements. In particular, power angle stability and frequency regulation can be achieved by using the control law $\frac{u_f}{T_0'}$ alone, while voltage regulation is fulfilled via the coordination of $\frac{u_f}{T_0'}$ and $\frac{u_q}{T_q}$.

Remark 4: From the synergetic controller design above, even though we present the further results of the work reported by Kanchanaharuthai (2012), the substantial differences with respect to the previous work are as follows:

1. The coordinated control of generation excitation and STATCOM can be further improved by using synergetic control theory to design a state feedback law where all measurable state variables can be known.
2. The dynamic equations of active electrical power and terminal voltage are included in the whole power system dynamics in place of transient voltage and STATCOM current. Therefore, with the help of the synergetic design technique, these dynamic equations can make us not only enhance the transient stability, but also achieve voltage regulation problems subject to the two fault sequences that are mentioned in the next Section.

6. Simulation

In this section, the simulation results of the coordination between generator excitation and STATCOM control in a SMIB power system are shown. Power angle stability as well as voltage and frequency regulations is used to point out the transient stability enhancement and dynamic properties.

Considering the single line diagram as shown in Figure 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 P, the midpoint of one of the transmission lines, it leads to rotor acceleration, voltage sag, and large transient induced electromechanical oscillations.

The interesting question is whether the system will return to a post-fault equilibrium state after the fault is cleared from the network.

In this paper, the faults of interest are the following two fault sequences, namely temporary and permanent faults (explained below). Usually, there are four basic stages associated with transient stability of a power system as follows:

Stage 1: The system is in a pre-fault steady state.

Stage 2: A fault occurs at t_0.

Stage 3: The fault is isolated by opening the breakers at t_c.

Stage 4: The transmission line is recovered without the fault at $t = t_r$ sec. Eventually, the system is in a post-fault state at $t = t_f$ sec.

Temporary fault

The system is in a pre-fault steady state, a fault occurs at $t_0 = 0.5$ sec., the fault is isolated by opening the breaker of the faulted line at $t_c = 0.8$ sec., and the transmission line is restored without the fault at $t_r = 0.81$ sec. Afterward the system is in a post-fault state.

Permanent fault

The system is in a pre-fault steady state, a fault occurs at $t_0 = 0.5$ sec., and the fault is isolated by permanently opening the breaker of the faulted line at $t_c = 0.8$ sec. Eventually the system is in a post-fault state.

The effectiveness is shown by transient stability enhancement of the coordinated (generator excitation/STATCOM) nonlinear control scheme. Power angle stability, as well as voltage, frequency, and power regulations, are investigated and compared with existing controllers, e.g., the feedback linearization controller, FBL (Gu & Wang, 2007), the conventional linear controller (PSS/AVR) (Kundur, 1994), and I&I controller (Kanchanaharuthai, 2012).

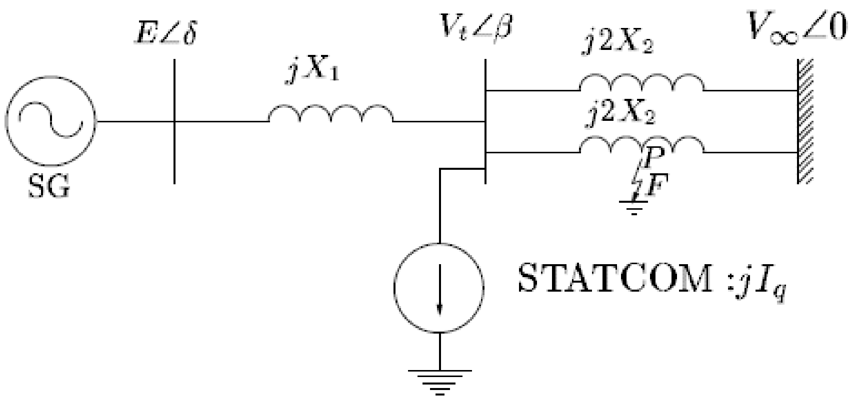


Figure 2 A single line diagram of SMIB

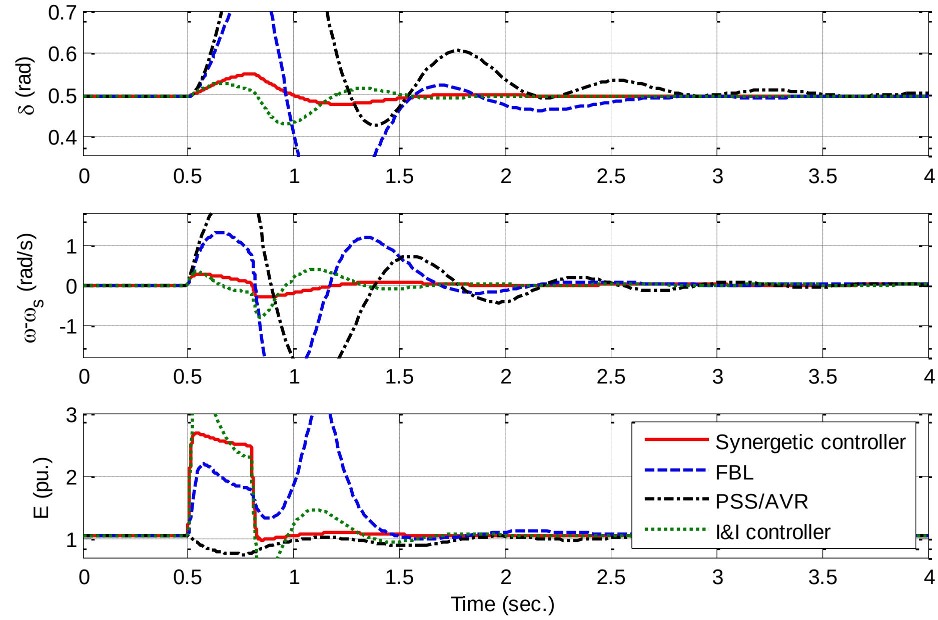
The physical parameters and the initial conditions $(\delta_e, \omega_s, P_{ee}, V_{\text{ref}})$ for this proposed power system model are given as follows.

$\omega_s = 2\pi f$ rad/s, $D = 0.2, M = 5, f = 60$ Hz,
$T_0' = 4, T_q = 1, V_\infty = 1\angle 0^\circ, X_d = 1.1, X_d' = 0.2,$
$X_T = 0.1, X_2 = X_L = 0.2, T = 1, P_m = 1,$
$|I_q| \le 4$ pu., $\delta_e = 0.4964$ rad, $\omega = \omega_s$,
$V_{\text{ref}} = 0.9897$ pu., $P_{ee} = P_m$.

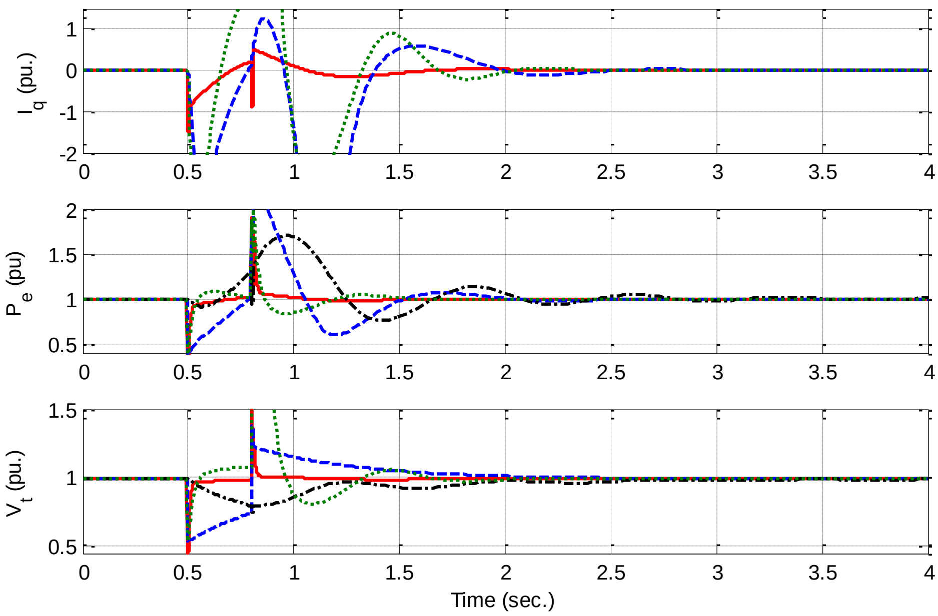
The tuning parameters of the coordinated controller were $\beta_{11} = 0.007, \beta_{12} = \beta_{22} = 1,$. $\beta_{21} = 0.05, T_1 = T_2 = 0.008$

Results showed that the transient stability of a power system with both generator excitation and STATCOM can be effectively improved by using the proposed nonlinear controller as seen in Figures 3 and 4. Although there is a large sudden fault (temporary or permanent) on the network, the system is able to stay transiently stable.

Temporary fault cases: Figures 3(a)-(b) show time trajectories of a power angle δ, SG relative speed (frequency), the transient voltage E of the proposed controller, the FBL controller, PSS/AVR, and I&I controller, respectively. After the temporary fault is cleared from the network, the power angle $\delta \to \delta_e$, the SG relative speed, $(\omega - \omega_s \to 0)$, the transient voltage $(E \to E_e)$, STATCOM current $(I_q \to 0)$, active electrical power $(P_e \to P_m)$, and terminal voltage $(V_t \to V_{\text{ref}})$ can be restored to the pre-fault steady state as expected. It is clear that time histories of the synergetic controller have small overshoot and effectively damp out the power oscillation in comparison with the FBL controller, PSS/AVR, and I&I controller excluding the only power angle response of the I&I controller with smaller overshoot. Furthermore, regarding active electrical power and voltage regulation as shown in Figure 3(b), the proposed synergetic controller not only provides clearly better transient responses (shorter rise time) than the FBL controller, PSS/AVR, and I&I controller, but also quickly settles to their pre-fault steady state of active electrical power. For this case, it can be concluded that even though all controllers (Synergetic, FBL, PSS/AVR and I&I controllers) are able to achieve the two expected performance requirements mentioned in Section 2, the proposed controller obviously performs best in terms of transient responses (dynamic properties).



(a)



(b)

Figure 3 Temporary fault case: Time histories of (a) Power angle (δ), relative speed $(\omega-\omega_s)$ and transient voltage (E), (b) STATCOM current (I_q), Active power (P_e) and terminal voltage (V_t).(Solid: Synergetic controller, Dashed: FBL controller, Dashdotted: PSS/AVR, Dotted: I&I controller)

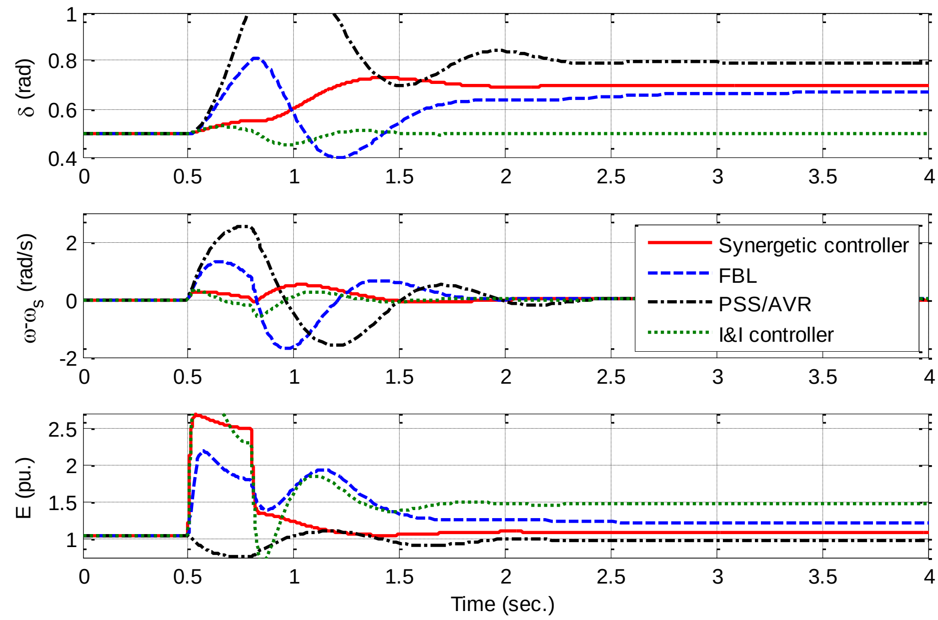
Permanent fault cases: Figures 4(a)-(b) illustrate time trajectories of a power angle δ, SG relative speed (frequency), the transient voltage E of the proposed controller, the FBL controller, PSS/AVR, and I&I controller, respectively. It is obvious from Figure 4(a) that due to the presence of network structure change, the power angle responses of the proposed controller, FBL controller, and PSS/AVR cannot go to the pre-fault state. Meanwhile the I&I controller can act and provides the smallest overshoot. Similarly, SG relative speed responses of I&I controller have the smallest overshoot, while the proposed controller provides the shortest settling time. For transient voltage responses, time trajectories of the proposed controllers can return to the steady-state values without oscillations while the other controllers cannot. Regarding STATCOM current responses, there are time responses of the proposed controller and the I&I controllers only capable of settling the pre-fault state. In comparison with the FBL controller, PSS/AVR, and the I&I controller in Figure 4(b), active electrical power responses of the proposed controller provide obviously the smaller overshoot along with faster reduction of oscillation. Furthermore, the synergetic controller performs slightly better than the I&I controller in terms of shorter rise time and settling time along with faster reduction of oscillation. Identically, there are only the proposed and FBL controllers capable of achieving the second desired performance requirements $(V_t \to V_{\text{ref}})$ since terminal voltage responses of both controllers settle to the desired reference values (V_{ref}). For this case, it can be overall seen that the proposed controller clearly outperforms other controllers (FBL, PSS/AVR, I&I controllers) even though power angle and transient voltage responses may not restore to the pre-fault steady state values. Furthermore, it is obvious that the I&I controller may be slightly superior to the proposed controller in terms of slightly shorter settling time and rise time, in particular power angle and SG relative speed. Eventually, the I&I controller is not able to accomplish the second expected performance requirement (voltage regulation), while the synergetic controller can.

The simulation results showed that, unlike the other controllers, the synergetic controller can enhance the system transient stability, achieve power angle stability along with frequency, power, and voltage regulations in accordance with the two expected requirements. Moreover, independent of the steady-state system operating point and two fault sequences earlier, the synergetic controller is able to accomplish the best dynamic properties as seen in faster transient responses of the closed-loop systems under a large sudden fault.

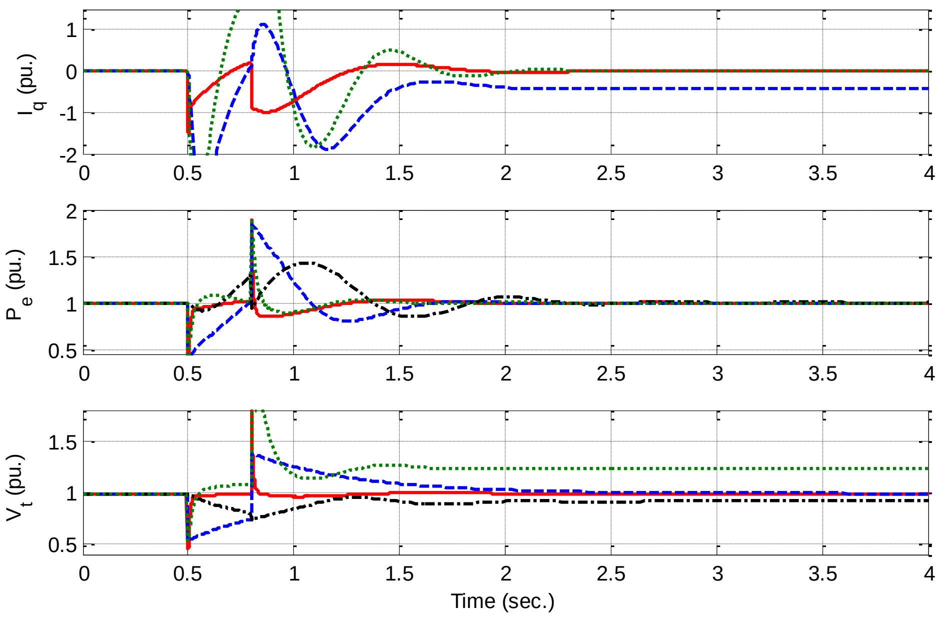
6. Conclusions

In this paper, a synergetic controller for a power system with a nonlinear generator excitation and STATCOM has been presented to improve effectively the transient stability, power angle stability as well as frequency and voltage regulations. In contrast to the dynamic equations in the work of Kanchanaharuthai (2012), the dynamic behaviors of active electrical power and terminal voltage are always measured and included in the power system dynamics. Additionally, the current simulation results have demonstrated that power angle stability along with voltage and frequency regulations are achieved following the large (transient) disturbances on the network via nonlinear model-based control design methodology. In particular, in spite of the occurrence of severe disturbances on the transmission line, the proposed coordinated controller can not only maintain the transient stability, but also accomplish better dynamic properties of the system compared to the operations of the feedback linearization scheme, the conventional controller (PSS/AVR), and Immersion and Invariance (I&I) methodology. Consequently, the results of this paper are of practical significance and applicable value.

This work studied how to use synergetic control to enhance power system stability of the coordination between generator excitation and STATCOM when connected to a large interconnected system or an infinite bus. Although in a large-scale power system there are a number of generators, it is often possible to reduce the system to a set of equivalent (one) machines that are of interest, and connected through an equivalent network (Thevenin equivalent circuit) as shown in Figure 1. However, if the reduced order power system is not an adequate representation of the system for transient stability studies in this paper, then we can extend the further results to multi-machine systems with STATCOM which will be reported in the future.



(a)



(b)

Figure 4 Permanent fault case: Time histories of (a) Power angle (δ), relative speed $(\omega-\omega_s)$ and transient voltage (E), (b) STATCOM current (I_q), Active power (P_e) and terminal voltage (V_t).(Solid: Synergetic controller, Dashed: FBL controller, Dashdotted: PSS/AVR, Dotted: I&I controller)

7. Acknowledgement

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