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Coordinated passivation control for power systems with STATCOM and energy storage

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Abstract

This paper deals with a coordinated passivation controller design for an electrical power system with static synchronous compensator (STATCOM) and (battery) energy storage to enhance transient stability and voltage regulation. This design technique is developed for multi-machine power systems and its performance is evaluated on a classic four-machine benchmark system consisting two synchronous generators and two doubly-fed induction generators (DFIG) together with STATCOM and battery energy storage. This method is able to use to achieve not only power angle stability but also voltage regulations during a large perturbation (or disturbance) on the transmission lines, such as a symmetrical three-phase short circuit fault and a load change. The simulation results show that the proposed controller can improve the system transient stability as well as frequency and voltage regulations simultaneously. Furthermore, the proposed controller has more advantages over the existing nonlinear controllers and a linear controller, especially, a feedback linearizing controller, an interconnection and damping assignment passivity based controller from our previous work, and a power system stabilizer, respectively.

Keywords: *Transient stability, battery energy storage, STATCOM, coordinated passivation control.*

1. Introduction

Renewable energy is receiving increasing interest in power system applications with efforts to integrate wind power into the conventional power grid (Ackermann, 2005; Heier, 2006). Consequently, when the diversity of the generation mix increases and larger amounts of power are being obtained from renewable generating sources, there are rapid increases of the size and complexity of power systems. These lead to the fact that power system stability and performance are of increasing importance in the operation of power systems. Further, challenges with integrating renewable generation into a power system are related to intermittent power availability as well as differences in their dynamic response characteristics as compared to conventional synchronous machines. Accordingly, this investigative paper is aimed to study transient stability and voltage regulation problems in power systems that include renewable energy, in particular wind energy, after occurrence of severe disturbances. It is well-known that power system models are highly nonlinear which is hard to stabilize the power systems including renewable energy, while maintaining the desired performances simultaneously. Hence an effective control strategy for improvement of power system stability is desired to enhance the system performance and overcome these difficulties. In particular, the design of an advanced nonlinear control has been greatly emphasized to improve power system stability margins, enhance controllability, and increase power transfer capability. Although there have been intensively various studies for power system stability enhancement, an effective and promising approach to improve the power system stability uses generator excitation control in combination with an energy storage device and flexible AC transmission system (FACTS) devices. It is apparent that energy storage technologies (Ribeiro, Johnson, Crow, Arsoy, & Liu, 2000), such as the super conducting magnetic energy storage (SMES), flywheel energy storage system (FESS), and battery energy storage system (BESS), etc. are important for dealing with the intermittency of many alternative energy sources. These also provide the opportunity to improve power quality, especially frequency and power angle stability, as reported in (Lu, Liu, & Wu, 1995; Wang, Feng, Cheng, & Liu, 2006; Wan, & Zhou, 2013; Kim, Song, & Yoon, 2015). For stability enhancement of wind energy conversion systems, energy storage (Muyeen, Tamura, & Murata, 2009; Ali, 2012) has been used to improve frequency stability through the regulation of active power levels. Therefore, energy storage can be employed to reduce the power fluctuations from large wind farms, to deliver large amounts of energy in a short time period when needed, and to regulate active power output to improve the economics of wind farms. Of particular interest in this work is battery energy storage that is capable of providing smooth and rapid active power compensation for frequency support as well as damping and transient enhancement.

With continuing developments in power electronic technologies, 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. These devices are common equipment in the power industry. In addition, they have been used to replace a significant number of mechanical control devices (Hingorani & Gyugyi, 1999; Song & John, 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 family of FACTS devices, the Static Synchronous Compensator (STATCOM) is of particular interest in this study because of its ability to provide smooth and rapid reactive power compensation for voltage support and to slightly improve damping of oscillations and transient stability.

Until now, STATCOM and battery energy storage systems have separately been used to improve power system operations and integrating these devices provides an opportunity to improve overall small-signal and transient stability of the power system. To the best of our knowledge, although considerable research has addressed the control design of either STATCOM or battery energy storage, less attention has been devoted to the integration of STATCOM and energy storage. Research by Yang, Shen, Crow and Atcitty (2001), Baran, et al. (2008), and Chakraborty, Musunuri, Srivastava and Kondabathini (2012) has shown that the integration of STATCOM and battery can provide additional benefits beyond the STATCOM in conventional power systems and a wind farm application. For multi-machine power system applications, the integration of STATCOM and numerous types of energy storage has indicated more effective than the STATCOM alone in wind power systems (Muyeen et al., 2009; Ali, 2012)

More recently, Kanchanaharuthai, Chankong, & Loparo (2015) has shown the combination of STATCOM and battery energy storage for transient stability and voltage regulation enhancement via an interconnection and damping assignment passivity-based control (IDA-PBC) methodology. According to the results presented in Kanchanaharuthai et al. (2015), even if this strategy has a universal stabilization property and provides a good dynamic performance, the obtained nonlinear controller is highly based on selecting the desired interconnection structure, dissipation matrices and the energy function as well as solving the partial differential equation (PDE). Further, suitable selection of these is essential for the success of the IDA-PBC design and there is recently no general method for selecting them. These result in a drawback of IDA-PBC design procedure. In contrast, this paper is concerned with a coordinated passivation control scheme that provides a simpler design procedure than the IDA-PBC approach and does not require selecting the desire structure matrices and the energy function as well as solving the PDE. Therefore, the proposed design procedure is rather simple as compared with the IDC-PBC design.

This paper continues this line of investigation and examines the application of an integrated STATCOM and energy storage system via an advanced nonlinear controller to enhance the transient stability of a power system that includes both conventional SG and DFIG as found in wind energy conversion systems. The coordinated passivation control methodology is used to achieve power angle stability and to provide both frequency and voltage regulation. To evaluate the effectiveness of the proposed approach for improving transient stability, simulation studies are carried out on a classical four-machine benchmark system, and performance results of the proposed system are compared to conventional control system implementations.

The aims of this paper are: (1) to use of a STATCOM and battery energy storage combination for transient stability and voltage regulation enhancement in conventional and wind power generation systems and (2) to demonstrate the applicability of the coordinated passivation control theory for designing a stabilizing feedback controller in multi-machine power systems to improve the system performance. In particular, it can provide some additional benefits beyond the existing controllers, e.g., a feedback linearization controller, a conventional linear controller (PSS), and the IDA-PBC controller.

The paper is organized as follows. A dynamic model of multi-machine power systems including STATCOM and battery energy storage is described in Section 2. Coordinated passivation control and design are given in Section 3 and 4, respectively. Simulation results are given in Section 5, while a conclusion is drawn in Section 6.

2. System model

In this section, the mathematical models of synchronous and doubly-fed induction generators, STATCOM and battery are briefly presented. Considering the power system network, it is modeled as an n-machine conventional power system, and includes an m-machine wind power system (DFIG) with a STATCOM/Battery unit and load that is modeled as constant impedances. The dynamic models of multi-machine power systems can be divided into three main groups: namely, synchronous generators, DFIGs, and STATCOM/Battery models as follows.

2.1 Synchronous generators: SG

For the n-machine conventional power system, the nonlinear dynamic model of the ith generator can be written as follows (Lu, Sun, & Mei, 2001)

$$\dot{\delta}_i = \omega_i - \omega_s,$$
$$\dot{\omega}_i = -\frac{D_i}{M}(\omega_i - \omega_s) - \frac{1}{M}(P_{mi} - P_{iE}),$$
$$\dot{E}'_{qi} = \frac{1}{T_{d0i}}(u_{fi} - E'_{qi} - (X_{di} - X'_{di})I_{di}), i = 1, 2, \ldots, n. \tag{1}$$

where $I_{di} = B_{ii}E'_{qi} - \sum_{j=1, j\neq i}^{n} E_{qj}B_{ij}\cos(\delta_i - \delta_j).$

δ_i is the power angle of the ith generator, in radians; ω_i is the rotor speed of the ith generator, in rad/s, $\omega_s = 2\pi f$; E'_{qi} is the internal voltage, in pu.; X_{di} is the d-axis reactor, in pu.; X'_{di} is the d-axis transient reactor of the ith generator, in pu.; u_{fi} is the voltage of the field circuit of the ith generator, the control input, in pu.; M_i is the inertia coefficient of the ith generator, in seconds; D_i is the damping constant, in pu.; T_{d0i} is the field circuit time constant, in pu.; P_m is the mechanical power, in pu.; I_{di} is the d-axis current, in pu. G_{ik}, B_{ik} denote the real and imaginary parts of the (i,k)th element of the system admittance matrix.

2.2 Doubly-fed induction generators: DFIGs

Similarly, for the m-machine wind power system, the nonlinear dynamic equations of the kth doubly fed induction generator having a similar form as those of the synchronous generator can be written as (Kanchanaharuthai et al., 2015):

$$\begin{aligned}
\dot{\delta}_k &= \omega_k + \frac{X_{dk} - X'_{dk}}{X'_{dk}}\frac{V_{rk}\sin(\delta - \theta_{rk})}{E'_k \bar{T}'_{d0k}} + \frac{\omega_s V_{rk}\cos(\delta_k - \theta_{rk})}{E'_k},\\
\dot{\omega}_k &= \frac{1}{M_k}(P_{mi} - P_{kE})T_{d0k},\\
\dot{E}'_k &= -\frac{X_{dk}}{X'_{dk}}E'_k + \frac{X_{dk} - X'_{dk}}{X'_{dk}}V_k\cos(\delta_k - \theta_{rk}) + T_{d0k}\omega_s V_{rk}\sin(\delta_k - \theta_{rk}),\\
&\quad k = n+1, n+2, \ldots, n+m.
\end{aligned} \tag{2}$$

where $V_{rk}\angle\theta_{rk} = V_{drk} + jV_{qrk} = |V_{rk}|(\cos\theta_{rk} + j\sin\theta_{rk})$ denotes the d and q axis rotor voltage input of the kth DFIG. E'_k denotes the internal voltage behind transient reactances X'_{dk} and is regarded as a polar variable converted from rectangular variables, the d and q axis voltages behind the transient reactances E'_{dk} and E'_{qk}, respectively, with the transformation $E'_k = \sqrt{(E'_{dk})^2 + (E'_{qk})^2}$.

Similarly, δ_k denotes a polar variable converted by the transformation $\delta_k = \tan^{-1} E'_{qk} / E'_{qk}$. V_k is the stator terminal voltage. T_{d0k} is the rotor circuit constant.

2.3 STATCOM/battery energy storage system

In this section, the model of an integrated STATCOM and battery energy storage system, as shown in Figure 1, is developed. This system relies on a power electronic voltage-source converter and will be used as a regulating device in the AC transmission network by delivering and absorbing both active and reactive power simultaneously. The system can support electricity networks by improving power factor and voltage regulation, helping to damp electromechanical oscillations, and enhancing transient stability of the first swing dynamics that result from severe fault conditions.

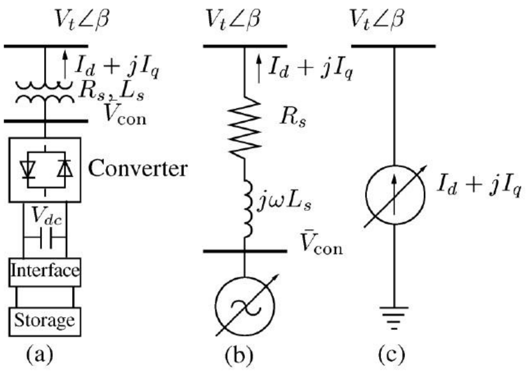

Figure 1 STATCOM/battery model: (a) Schematic diagram, (b) Equivalent circuit (controllable voltage source), and (c) Equivalent circuit (controllable current voltage) (Kanchanaharuthai et al., 2015)

The combined nonlinear STATCOM and Battery state equations for the equivalent circuit model, particularly the controllable shunt current source that is used to describe the transient performance of the STATCOM and Battery, are explained as follows.

In the $d-q$ coordinates, the dynamic models of a STATCOM and battery are as follows (Yang et al. 2001):

$$\begin{aligned}
\dot{I}_d &= -\frac{R_s\omega_s}{L_s} I_d + \omega I_q + hk\cos(\gamma+\beta) - \frac{\omega_s V_t}{L_s},\\
\dot{I}_q &= -\omega I_d - \frac{R_s\omega_s}{L_s} I_q + hk\sin(\gamma+\beta), \qquad (3)\\
\dot{V}_{dc} &= -\frac{1}{C}\Big(\frac{R_b R_{dc}}{R_{dc}+R_b}\Big)V_{dc} - \frac{\omega_s I_d}{C} k\cos(\gamma+\beta)\\
&\quad -\frac{\omega_s I_q}{C} k\sin(\gamma+\beta) + \frac{\omega_s V_b}{R_b C},
\end{aligned}$$

where I_d and I_q are the injected or absorbed per unit $d-q$ Battery and STATCOM currents, respectively. V_{dc} is the per unit voltage across the capacitor C, R_s and L_s model the STATCOM/Battery transformer losses, V_b denotes the per unit Battery voltage, $V_t\angle\beta$ represents the per unit system side (AC) bus voltage, and $h = \frac{\omega_s V_{dc}}{L_s}$. R_b and R_{dc} model the Battery and the switching losses, respectively. k and γ represent the PWM modulation gain and firing angle, respectively. V_{dc} is assumed to be a constant voltage in this work, see Yang et al., (2001) for more details. Based on our assumption that V_{dc} is constant, the STATCOM/Battery dynamic models become:

$$\begin{aligned}
\dot{I}_d &= -\frac{R_s\omega_s}{L_s} I_d + \omega I_q + hk\cos(\gamma+\beta) - \frac{\omega_s V_t}{L_s}, \qquad (4)\\
\dot{I}_q &= -\omega I_d - \frac{R_s\omega_s}{L_s} I_q + hk\sin(\gamma+\beta).
\end{aligned}$$

Let us define two control variables that need to be chosen as follows:

$$\begin{aligned}
u_d &= -a_d I_{de} + \omega I_q + hk\cos(\gamma+\beta) - \frac{\omega_s V_t}{L_s},\\
u_q &= -a_q I_{qe} - \omega I_d + hk\sin(\gamma+\beta),
\end{aligned}$$

with $a_d = a_q = \frac{R_s\omega_s}{L_s}$. Therefore, the STATCOM/Battery dynamic models become:

$$\begin{aligned}
\dot{I}_d &= -a_d(I_d - I_{de}) + u_d,\\
\dot{I}_q &= -a_q(I_q - I_{qe}) + u_q.
\end{aligned}$$

Besides, the STATCOM/Battery bus voltage shown in Figure 1 may be written as follows.

$$V_t = \frac{\tilde{\Pi}}{\tilde{\Lambda}}\sqrt{(1+\tilde{M})^2 + \tilde{N}^2}$$

where

$$\tilde{M} = \frac{I_q \prod_{j=1}^{n+m} X_j}{\tilde{\Pi}}, \tilde{N} = \frac{I_d \prod_{j=1}^{n+m} X_j}{\tilde{\Pi}}, \tilde{\Pi} = \sqrt{\tilde{A}^2 + \tilde{B}^2},$$

$$\tilde{A} = X_2 X_3 \cdots X_{n+m} E_1' \cos\delta_1 + X_1 X_3 \cdots X_{n+m} E_2' \cos\delta_2 + \cdots + X_1 X_2 \cdots X_{n+m-1} E_{n+m}' \cos\delta_{n+m},$$

$$\tilde{B} = X_2 X_3 \cdots X_{n+m} E_1' \sin\delta_1 + X_1 X_3 \cdots X_{n+m} E_2' \sin\delta_2 + \cdots + X_1 X_2 \cdots X_{n+m-1} E_{n+m}' \sin\delta_{n+m}.$$

For both conventional (SG) and wind power systems (DFIG) including STATCOM/Battery, the output electrical power of the ith synchronous generator and the *k*th DFIG can be computed, and after some lengthy but straightforward calculations (Kanchanaharuthai et al., 2015), they are written as follows.

$$P_{lE} = (G_{ll} E_l'^2 + E_l' \sum_{j=1, j\neq l}^{n+m} E_j' B_{lj} \sin(\delta_l - \delta_j)) \times (1+\tilde{M}) + (E_l' \sum_{j=1}^{n+m} E_j' B_{lj} \cos(\delta_l - \delta_j))\tilde{N}, l = \{i,k\}. \quad (5)$$

Remark 1: From the STATCOM/Battery model presented, it is clear that it is simple and does not contain the full model of the converter, STATCOM, interface device and the battery energy storage system. Provided that we include the full model of these devices into the complete dynamic model, the design of the nonlinear controller becomes further complicated. Further studies will incorporate additional details of the STATCOM/Battery energy storage system into the system model and investigate the impact of these on overall transient system performance.

3. Coordinated passivation control

In recent years, even though a number of nonlinear control design techniques have been proposed to stabilize and control nonlinear dynamical systems, the feedback passivation scheme (Khalil, 2002) has been a popular method to nonlinear control design. Also, passivity gives us with a physical insight for analysis and design of systems. A coordinated passivation (Larsen, Jankovic, & Kokotovic, 2003) used herein is further improved from the passivity method. This method is applicable to practical control design problems, in particular, for SMIB power systems (Chen, Ji, Wang, & Xi, 2006; Sun, Zhao, & Dimrovski, 2009). There has, however, been currently no report available for the development of coordinated passivation controller design for multi-machine power systems.

3.1 Passivity

First we recall some definition from the literature. Consider a dynamical system represented by the model

$$\dot{x} = f(x,u), \quad y = h(x,u), \quad (6)$$

where $f: R^{\tilde{n}} \times R^p \to R^{\tilde{n}}$ is locally Lipschitz, $h: R^{\tilde{n}} \times R^p \to R^q$ is continuous, $f(0,0) = 0$ and $h(0,0) = 0.$

Definition 1: The system (6) is said to be passive if there exists a continuously differentiable positive semi-definite function $V(x)$, called the storage function, such that

$$u^T y \ge \dot{V} = \frac{\partial V}{\partial x} f(x,u), \ \forall (x,u) \in R^n \times R^p \quad (7)$$

Moreover, it is said to be

- lossless if $u^T y = \dot{V}$.
- input-feedback passive if $u^T y \ge \dot{V} + u^T \varphi(u)$ for some function φ.
- input strictly passive if $u^T y \ge \dot{V} + u^T \varphi(u)$ and $u^T \varphi(u) > 0, \ \forall u \ne 0$.
- output-feedback passive if $u^T y \ge \dot{V} + y^T \rho(y)$ for some function ρ.
- output strictly passive if $u^T y \ge \dot{V} + y^T \rho(y)$ and $y^T \rho(y) > 0$, $\forall y \ne 0$.
- strictly passive if $u^T y \ge \dot{V} + \psi(x)$ for some positive definite function ψ.

In all cases, the inequality should hold for all (x,u). From Definition 1 we know that if the system (7) is passive. We can easily find a controller u to achieve $\dot{V} \le 0$, which ensures stability. To get asymptotic stability, we introduce zero-state observability and give a lemma as follows.

Definition 2: The system (6) is said to be zero-state observable if no solution of $\dot{x} = f(x,0)$ can stay identically in $\mathbb{S} = \{x \in R \mid h(x,0) = 0\}$, other than the trivial solution $x(t) \equiv 0$.

Lemma 1: Consider the system (6). The origin of $\dot{x} = f(x,0)$ is asymptotically stable if the system is

- strictly passive or
- output strictly passive and zero-state observable

Furthermore, if the storage function is radially unbounded, the origin will be globally asymptotically stable.

3.2 Coordinated passivation

The relative degree of nonlinear system is the number of times that the output $y(t)$ needs to be differentiated for the input $u(t)$ to appear. Feedback passivation method requires the relative degree must exist and be zero or one as well as the zero dynamics must be stable, which is a rigorous condition for many systems. Coordinated passivation gives a way to solve the problem. For simplicity, we choose a normal system as follows to introduce the coordinated passivation method.

Lemma 2: Consider the zero-state observable system

$$\dot{z} = q(z,y) + p(z,y)u_2, \tag{8}$$

$$\dot{y} = \alpha(z,y) + \beta_1(z,y)u_1 + \beta_2(z,y)u_2, \tag{9}$$

where the state $z \in R^{\tilde{n}}, y \in R^{\tilde{m}}$ are treated as output and input, $u_1 \in R^p, u_2 \in R^q$ and the input-output pairs (u_1, y) are selected for which the vector relative degree is zero or one.

Based on the coordinated passivation technique, we can proceed in the following two steps: zero dynamics stabilization and feedback passivation.

The aim of the first step is to find a control Lyapunov function (CLF), $W(z)$, for the zero dynamics subsystem, that is, (8) with $y = 0$, for which there exists a control law $u_2 = \gamma(z)$ such that

$$\dot{W} = \frac{\partial W}{\partial z}(q(z,0) + p(z,0)\gamma(z)) < -\alpha(\|z\|), \forall z \neq 0, \tag{10}$$

where α denotes a class-K function (Khalil, 2002).

Then, the goal of the second step is to accomplish the feedback passivation of the whole system (8) and (9) with the input u_1 and the output y. Consequently, the zero dynamics (8) with $u_2 = \gamma(z)$ can be rewritten as

$$\dot{z} = q(z,y) + p(z,y)\gamma(z) = \tilde{q}(z) + \tilde{p}(z,y)y, \tag{11}$$

where $\tilde{q}(z) = q(z,0) + p(z,0)\gamma(z)$.

Select the storage function $V = W(z) + \frac{1}{2}y^2$ whose the derivative along the trajectory of (8) and (9) becomes

$$\begin{aligned}\dot{V} &= \frac{\partial W}{\partial z}\dot{z} + y\dot{y} \\ &= \frac{\partial W}{\partial z}[\tilde{q}(z) + \tilde{p}(z,y)y] \\ &\quad + y[\alpha(z,y) + \beta_1(z,y)u_1 + \beta_2(z,y)u_2].\end{aligned} \tag{12}$$

Then the control law is designed as follows.

$$u_1 = \beta_1^{-1}(z,y)\left[-\beta_2(z,y)u_2 - \alpha(z,y) - \frac{\partial W}{\partial z}\tilde{p}(z,y) + v\right]. \tag{13}$$

According to the passivity property, it is easy to see from the resulting control law u_1 that $\dot{V} = \frac{\partial W}{\partial z}\tilde{q} + vy \leq vy$, leading to passivity. Further, if the system considered is zero state observable and the output feedback $v = -\phi(y)$ is selected to satisfy sector nonlinearity $y\phi(y) > 0$ for $y \neq 0$ and $\phi(0) = 0$, this accomplishes $\dot{V} \leq -y\phi(y) \leq 0$, resulting in the fact that the system is asymptotically stable.

4. Coordinated passivation design control

Consider the dynamic models including n-SG, m-DFIG and s-STATCOM/Battery unit. Further, the whole power system model can be expressed as follows:

$$
\begin{aligned}
&\dot{\delta}_i = \omega_i - \omega_s \\
&\dot{\omega}_i = \frac{-D_i(\omega_i - \omega_s) + P_{mi} - P_{iE}}{M_i}, \\
&\dot{E}_i' = -a_i E_i' + b_i \sum_{j=1, j\neq i}^{n+m} E_j' \cos(\delta_i - \delta_j) + \frac{u_{fi}}{T_{i0}'}, \\
&\qquad\qquad i = 1,2,\ldots,n \\
&\dot{\delta}_k = \omega_k - \omega_s - c_{k-n} \sum_{p=1, p\neq k}^{n+m} \frac{E_p' \sin(\delta_k - \delta_p)}{E_k} \\
&\qquad + \frac{\omega_s (V_{dr(k-n)} \cos\delta_k + V_{qr(k-n)} \sin\delta_k)}{E_k}, \\
&\dot{\omega}_k = \frac{P_{mk} - P_{kE}}{M_k}, \\
&\dot{E}_k' = -a_{k-n} E_k' + b_{k-n} \sum_{p=1, p\neq k}^{n+m} E_p' \cos(\delta_k - \delta_p) \\
&\qquad + \omega_s (V_{dr(k-n)} \sin\delta_k - V_{qr(k-n)} \cos\delta_k), \\
&\qquad\qquad k = n+1, 2, \ldots, n+m, \\
&\dot{I}_{dj} = -a_{dj}(I_{dj} - I_{dej}) + u_{dj} \\
&\dot{I}_{qj} = -a_{qj}(I_{qj} - I_{qej}) + u_q, \; j = 1,2,\ldots,s.
\end{aligned} \tag{14}
$$

with $a_l = \dfrac{1 + X_{ml} B_{ll}}{T_{l0}'}$, $b_l = \dfrac{X_{ml} B_{lj}}{T_{l0}'}$, $l = i, k-n$,

and $c_{k-n} = \dfrac{X_{mk} B_{kp}}{T_{dk0}'}$. .

With coordinated passivation technique, the nonlinear controller will be proposed for the transient stability enhancement for the multi-machine power system with STATCOM/Battery (14) at a desired equilibrium point

$$
\begin{aligned}
x_e = [&\delta_{1e}, \omega_s, E_{1e}', \ldots, \delta_{ne}, \omega_s, E_{ne}', \delta_{(n+1)e}, S_1\omega_s, \\
&E_{(n+1)e}', \ldots, \delta_{(n+m)e}, S_m\omega_s, E_{(n+m)e}', I_{de}, I_{qe}]^T
\end{aligned} \tag{15}
$$

In this multi-machine power system application, the coordinated passivation approach is used to find the nonlinear controller which globally asymptotically stabilizes the system (14). Additionally, the proposed controller is capable of achieving the desired closed-loop system performance requirements, namely (1) the equilibrium point x_e is asymptotically stable and (2) power angle stability along with voltage and frequency regulation are simultaneously achieved.

4.1 Controller design

A globally asymptotically stabilizing feedback controller for the system (14) will be designed through this subsection.

Let us define the state variable as $x_{1i} = \delta_i - \delta_{ie}, x_{2i} = \omega_i - \omega_s, x_{3i} = E_i', x_{1k} = \delta_k - \delta_{ke}$, $x_{2k} = \omega_k - S_{k-n}\omega_s, x_{3k} = E_k', y_{1j} = I_{dj} - I_{\text{dej}}, y_{2j} = I_{qj} - I_{qej}$, $i = 1,2,\ldots,n, k = n+1, n+2, \ldots, n+m, j = 1,2,\ldots,s$

Besides, let us introduce variable V_{fl} that could be regarded as a new input of the system. As a result, the system (14) is represented by

$$
\begin{aligned}
\begin{bmatrix} \dot{x}_{1l} \\ \dot{x}_{2l} \\ \dot{x}_{3l} \end{bmatrix} &= \begin{bmatrix} x_{2l} \\ \lambda_{1l} x_{2l} + \lambda_{2l} f_1(x_{1l}, x_{3l}) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ f_2(x_{1l}, x_{3l}) \\ 0 \end{bmatrix} y_{2j} \\
&\quad + \begin{bmatrix} 0 \\ f_3(x_{1l}, x_{3l}) \\ 0 \end{bmatrix} y_{1j} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} V_{f_l} \\
&= Q(x_l) + Q_{2j}(x_l) y_{2j} + Q_{3j}(x_l) y_{1j} + T_V
\end{aligned} \tag{16}
$$

$$
\begin{cases} \dot{y}_{1j} = -a_d y_{1j} + u_d, \\ \dot{y}_{2l} = -a_q y_{2j} + u_q, \end{cases} \tag{17}
$$

where

$\lambda_{1l} = -\dfrac{D_l}{M_l}, \lambda_{2l} = \dfrac{1}{M_l}$,

$$f_1(x_{1l}, x_{3l}) = (G_{ll} E_l'^2 + E_l' \sum_{j=1, j\neq l}^{n+m} E_j' B_{lj} \sin(\delta_l - \delta_j)),$$

$$f_2(x_{1l}, x_{3l}) = (G_{ll} E_l'^2 + E_l' \sum_{j=1, j\neq l}^{n+m} E_j' B_{lj} \sin(\delta_l - \delta_j)) \frac{\prod_{j=1}^{n+m} X_j}{\tilde{\Pi}},$$

$$f_3(x_{1l}, x_{3l}) = (E_l' \sum_{j=1, j\neq l}^{n+m} E_j' B_{lj} \cos(\delta_l - \delta_j)) \frac{\prod_{j=1}^{n+m} X_j}{\tilde{\Pi}}, l = \{i, k\},$$

$$Q(x_l) = \begin{bmatrix} x_{2l} \\ \lambda_{1l} x_{2l} + \lambda_{2l} f_1(x_{1l}, x_{3l}) \\ 0 \end{bmatrix}, Q_{2j}(x_l) = \begin{bmatrix} 0 \\ f_2(x_{1l}, x_{3l}) \\ 0 \end{bmatrix},$$

$$Q_{3j}(x_l) = \begin{bmatrix} 0 \\ f_3(x_{1l}, x_{3l}) \\ 0 \end{bmatrix},$$

and

$$V_{fl} = -a_i E_i^{'} + b_i \sum_{j=1, j\neq i}^{n+m} E_j^{'} \cos(\delta_i - \delta_j) + \frac{u_{fi}}{T_{i0}^{'}}, l = i,$$

$$V_{fl} = -a_{k-n} E_k^{'} + b_{k-n} \sum_{p=1, p\neq k}^{n+m} E_p^{'} \cos(\delta_k - \delta_p)$$
$$+ \omega_s (V_{dr(k-n)} \sin\delta_k - V_{qr(k-n)} \cos\delta_k), l = k.$$

From (17), it is evident that the relative degree from the input u_d and u_q to the output y_{1j} and y_{2j}, respectively, is equal to one.

The controller design herein is divided into two parts. First, we design the new control input $V_{fl}, l = \{i, k\}$ to stabilize the zero dynamics (16). Subsequently, with the help of passivation strategy, we design the control inputs u_d and u_q to stabilize the whole system.

1) Design of V_{fl}: In order to construct the desired feedback law, we introduce the following coordinated transformation:

$$\begin{aligned} \xi_{1l} &= x_{1l}, \\ \xi_{2l} &= k_l x_{1l} + x_{2l}, \\ \xi_{3l} &= \Phi_l(x_{1l}, x_{2l}, x_{3l}), \end{aligned} \tag{18}$$

where k_i is a given non-negative constant and Φ_l $(\Phi_l(0,0,0) = 0)$ is a smooth nonlinear function to be designed. From the new coordination, the system (16)-(17) is expressed as

$$\begin{aligned} \dot{\xi}_{1l} &= x_{2l} = -k_l x_{1l} + \xi_{2l}, \\ \dot{\xi}_{2l} &= k_l x_{2l} + (\lambda_{1l} x_{2l} + \lambda_{2l} f_1(x_{1l}, x_{3l})), \\ \dot{\xi}_{3l} &= \frac{\partial \Phi_l}{\partial x_{1l}} \dot{x}_{1l} + \frac{\partial \Phi_l}{\partial x_{2l}} \dot{x}_{2l} + \frac{\partial \Phi_l}{\partial x_{3l}} \dot{x}_{3l}. \end{aligned} \tag{19}$$

We now design the nonlinear controller by the Lyapunov-based recursive argument (Hu, Mei, Lu, Shen, & Yokyama, 2002).

Step 1: Define $V_{1l}(\xi_{1l}) = \frac{1}{2}\xi_{1l}^2$. Along any trajectory of the system, it is straightforward to show that

$$\dot{V}_{1l} = \xi_{1l}(-k_l x_{1l} + \xi_{2l}) = -k_l x_{1l}^2 + x_{1l}\xi_{2l}. \tag{20}$$

Step 2: Define $V_{2l}(\xi_{1l}, \xi_{2l}) = V_{1l}(\xi_{1l}) + \frac{1}{2\lambda_{2l}}\xi_{2l}^2$.

Then, it is easy to see that

$$\begin{aligned} \dot{V}_{2l} &= \dot{V}_{1l} + \frac{1}{\lambda_{2l}}\xi_{2l}\dot{\xi}_{2l} = -k_l x_{1l}^2 \\ &+ \xi_{2l}\left[x_{1l} + \frac{k_l + \lambda_{1l}}{\lambda_{2l}} x_{2l} + f_1(x_{1l}, x_{3l})\right]. \end{aligned} \tag{21}$$

Select the function Φ_l as $\xi_{3l} = \Phi_l(x_{1l}, x_{2l}, x_{3l}) = x_{1l} - x_{3l}$.

Subsequently, we have

$$\begin{aligned} \dot{V}_{2l} &= -k_l x_{1l}^2 + \xi_{2l}\left[x_{3l} + \frac{k_l + \lambda_{1l}}{\lambda_{2l}} x_{2l} + f_1(x_{1l}, x_{3l})\right] \\ &+ \xi_{2l}\xi_{3l}. \end{aligned} \tag{22}$$

Step 3: It is easy to find that

$$\dot{\xi}_{3l} = \frac{\partial \Phi_l}{\partial x_{1l}} \dot{x}_{1l} + \frac{\partial \Phi_l}{\partial x_{2l}} \dot{x}_{2l} + \frac{\partial \Phi_l}{\partial x_{3l}} \dot{x}_{3l} = x_{2l} - V_{fl}.$$

Select the storage function by

$$V_{3l}(\xi_{1l}, \xi_{2l}, \xi_{3l}) = V_{2l}(\xi_{1l}, \xi_{2l}) + \frac{1}{2}\xi_{3l}^2.$$

Then we obtain

$$\begin{aligned} \dot{V}_{3l} &= \dot{V}_{2l} + \xi_{3l}\dot{\xi}_{3l} = -k_l x_{1l}^2 \\ &+ \xi_{2l}\left[x_{3l} + \frac{k_l + \lambda_{1l}}{\lambda_{2l}} x_{2l} + f_1(x_{1l}, x_{3l})\right] \\ &+ \xi_{2l}\xi_{3l} + \xi_{3l}(x_{2l} - V_{fl}) \\ &= -k_l x_{1l}^2 + \xi_{3l}(F(x,\xi) - V_{fl}) \end{aligned}$$

where

$$\begin{aligned} F(x,\xi) &= \frac{\xi_{2l}}{\xi_{3l}}\left[x_{3l} + \frac{k_l + \lambda_{1l}}{\lambda_{2l}} x_{2l} + f_1(x_{1l}, x_{3l})\right] \\ &+ \xi_{2l} + x_{2l}. \end{aligned}$$

Therefore, we can design the feedback controller as

$$V_{fl} = F(x,\xi) + \xi_{3l}, l = \{i, k\} \tag{23}$$

thereby resulting in $\dot{V}_{3l} = -k_l x_{1l}^2 - \xi_{3l}^2 \le 0.$ Moreover, we can straightforwardly compute the excitation controller u_{fi} and DFIG rotor voltage input (V_{dr}, V_{qr}) from new control input V_{fl} in (23). For the zero dynamics of the whole multi-machine system (16) excluding dynamics of STATCOM/Battery, we define the storage function as

$$V(x_1, x_2, \ldots, x_{n+m}) = \sum_{i=1}^{n} V_{3i} + \sum_{k=n+1}^{n+m} V_{3k}$$

Then

$$\dot{V} = \sum_{i=1}^{n} \dot{V}_{3i} + \sum_{k=n+1}^{n+m} \dot{V}_{3k} \le 0. \qquad (24)$$

Therefore, under the feedback control law (23), the zero dynamics closed-loop system is asymptotically stable.

2) Design of u_{dj} and u_{qj} by the coordinated passivation strategy.

The whole system (14) can be stabilized by the controllers u_{dj} and u_{qj} via the feedback passivation. We now select the storage function as $W = V + \frac{1}{2}\sum_{j=1}^{s}(y_{1j}^2 + y_{2j}^2)$ then its derivative is

$$\begin{aligned} \dot{W} &= \dot{V} + \sum_{j=1}^{s}(y_{1j}\dot{y}_{1j} + y_{2j}\dot{y}_{2j}) \\ &= \frac{\partial V}{\partial \xi}\dot{\xi}\,|_{y_{1j}=0,y_{2j}=0} + \frac{\partial V}{\partial \xi}Q_{3j}(x_l)y_{1j} \\ &\quad + \frac{\partial V}{\partial \xi}Q_{2j}(x_l)y_{2j} + \sum_{j=1}^{s}(y_{1j}\dot{y}_{1j} + y_{2j}\dot{y}_{2j}). \end{aligned} \qquad (25)$$

Therefore, we select the control law

$$\begin{cases} u_{dj} = \left[-\frac{\partial V}{\partial \xi}Q_{3j}(x_l)y_{1j} + v_{1j} \right], \\ u_{qj} = \left[-\frac{\partial V}{\partial \xi}Q_{2j}(x_l)y_{2j} + v_{2j} \right], \end{cases} \qquad (26)$$

where

$$v_{1j} = -\beta_{1j}y_{1j}, v_{2j} = -\beta_{2j}y_{2j}, \beta_{1i} > 0,$$
$$\beta_{2j} > 0, j = 1, \dots, s.$$

After substituting (26) into (25) and combining with (24), we obtain

$$\begin{aligned} \dot{W} &= \frac{\partial V}{\partial \xi}\dot{\xi}\,|_{y_{1j}=0,y_{2j}=0} + \sum_{j=1}^{s}v_{1j}y_{1j} + \sum_{j=1}^{s}v_{2j}y_{2j} \\ &\le -\sum_{j=1}^{s}(a_d y_{1j}^2 + a_q y_{2j}^2) + \sum_{j=1}^{s}(v_{1j}y_{1j} + v_{2j}y_{2j}) \end{aligned} \qquad (27)$$

From Definition 1, it is obvious that the closed-loop whole system is output strictly passive. Apart from this, we can easily show that the system (16)-(17) is zero-state observable. Thus, the whole multi-machine system with STATCOM/Battery are asymptotically stable according to Lemma 1. The main result summarizing the coordinated passivation approach can be established in the following theorem.

Theorem 1: Consider the multi-machine power system including STATCOM and battery energy storage in (14). The overall closed-loop system is output strictly passive and can accomplish the expected closed-loop system performance requirements (1)-(2) with the following state feedback control law:

$$\begin{aligned} &\frac{u_{fi}}{T_{i0}'} = F_i + a_i E_i' - b_i \sum_{j=1, j\ne i}^{n+m} E_j' \cos(\delta_i - \delta_j)\,, \\ &\qquad\qquad i = 1, 2, \dots, n, \\ &\omega_s V_{dr(k-n)} = X_{k-n}\cos\delta_k + Y_{k-n}\sin\delta_k\,, \\ &\omega_s V_{qr(k-n)} = X_{k-n}\sin\delta_k - Y_{k-n}\cos\delta_k\,, \\ &\qquad\qquad k = n+1, n+2, \dots, n+m, \\ &u_{dj} = -\left[\frac{\partial V}{\partial \xi}Q_{2l}(x) + \beta_{2j} \right](I_{dj} - I_{dej}), j = 1, 2, \dots, s, \\ &u_{qj} = -\left[\frac{\partial V}{\partial \xi}Q_{3j}(x) + \beta_{1j} \right](I_{qj} - I_{qej}), \end{aligned} \qquad (28)$$

with

$$\begin{aligned} F_i &= \frac{k_i\Delta\delta_i + \Delta\omega_i}{\Delta\delta_i - E_i'}\left[E_i' + \frac{k_i + \lambda_{1i}}{\lambda_{2i}}\Delta\omega_i + f_i(\Delta\delta_i, E_i') \right] \\ &\quad + k_i\Delta\delta_i + 2\Delta\omega_i + E_i', \\ X_{k-n} &= s_{k-n}\omega_s E_k' + c_k \sum_{p=1, p\ne k}^{n+m} E_p' \sin(\delta_k - \delta_p), \\ Y_{k-n} &= F_k + a_k E_k' - b_k \sum_{p=1, p\ne k}^{n+m} E_p' \cos(\delta_k - \delta_p), \end{aligned} \qquad (29)$$

where $\Delta\delta_l = \delta_l - \delta_{le}, \Delta\omega_i = \omega_i - \omega_s, \Delta\omega_k = \omega_k - S_{k-n}\omega_s$, and E_l' are the state variables of the ith synchronous generator and the kth DFIG; k_l, λ_{1l} and λ_{2l} are given in (18)-(19) and $S_{k-n} = 1 - s_{k-n} = 1 - \omega_{ke}/\omega_s$ is the rotor slip of the kth DFIG. Besides, the whole system is asymptotically stable and the system is zero-state observable.

Proof: The proof of Theorem 1 is based on the above-given arguments.

Remark 2: From the coordinated passivation control design above, it is evident that the design procedure has two parts: (1) the recursive approach is used to design the generator excitation controller and the DFIG rotor controller; and (2) the passivation strategy is employed to design the STATCOM/battery controller. As compared with IDA-PBC method, this design procedure is rather simpler because it does not require selecting the structure matrices and the energy function.

5. Simulation results

In order to gain insight into the performance improvements that can be achieved in larger-scale power systems using the proposed control design approach, we study a classical four-machine power system (Kundur, 1994) shown in Figure 2. In particular, we evaluate the effectiveness of the proposed control design methodology on transient stability enhancement when a STATCOM/battery is installed at the midpoint of the transmission line between area 1 consisting of two synchronous generators (SG_1 and SG_2) and area 2 consisting of two DFIGs ($DFIG_1$ and $DFIG_2$). The parameters and the initial operating conditions of the power system are provided in Kundur (1994) while Data for wind generators (DFIGs) and STATCOM/battery are given in Kanchanaharuthai et al. (2015). All simulations are carried out by wind average speed of 10 m/s. We investigate the effectiveness of STATCOM and battery energy storage along with the nonlinear control design methodology to improve transient (power angle) stability as well as voltage, frequency, and power regulation. Of particular interests in this work are two different types of contingencies used: short circuits and load variations.

5.1 Three-phase fault test

It is well-known that a three-phase fault on the transmission network is the most severe disturbance to a power system. In this paper, there is a symmetrical three-phase fault which occurs at bus 9 and the following fault sequence is used to evaluate the proposed controller performance:

(i) A fault occurs at t = 1 sec.
(ii) The fault is isolated by opening the breaker of the faulted line at t=1.1 sec.
(iii) The transmission line is restored without the fault at t=1.11 sec. Afterward the system is in a post-fault line.

In general when a three-phase fault occurs, the dynamics during the post-fault period may lead to instability due to insufficient damping provided from the excitation systems of each generator. Thus, this instability is necessary to be resolved and some additional damping to the system is provided via PSSs in conventional power systems. In this work, integration of the STATCOM/Battery into a power system including both conventional and wind power generators (DFIGs) is able to offer additional degrees of freedom to add damping to the power system beyond that of the PSS alone, if managed appropriately, and help mitigation the instability problem.

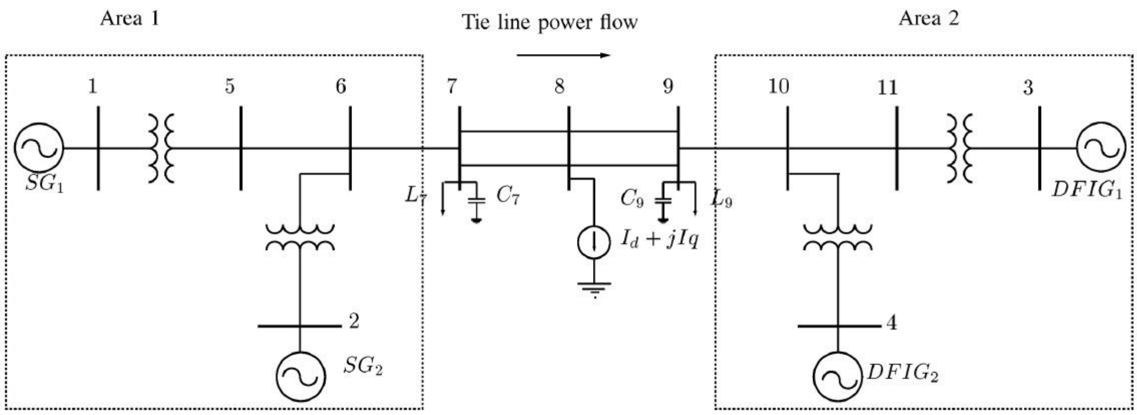

Figure 2 A simple two-area system with STATCOM/battery

Time trajectories of the relative rotor angle responses of SG_2, $DFIG_1$, $DFIG_2$ with respect to SG_1 are shown in Figure 3(a). It can be observed that with the PSS, it sluggishly damps out the oscillation in the relative rotor angles. The post-fault system responses are quite oscillatory and eventually settle to the pre-fault values after the transient fault is cleared. On the other hand, the addition of STATCOM/Battery and advanced controllers (CPC, IDA-PBC and FBL) can damp out the oscillation effectively. Further, they apparently provide the more stabilizing effect and stabilize the system without sustained oscillations by providing additional damping to the system beyond that of the PSS. It is also clear that time histories of the proposed controller have not only faster transient response performance and smaller overshoot, but also effectively damp out the oscillation in comparison with the FBL controller and the IDA-PBC controller.

Figure 3(b) depicts the terminal voltage at Bus 8 as well as power transfer from area 1 to area 2. It illustrates that both voltage and transferred power experience a brief transient period in response to changes in the network configuration of the power system; however they eventually settle back to their original steady-state (equilibrium) points. It can seen that the proposed controller, the FBLC and the IDA-PBC provide better transient response characteristics than the conventional PSS controller. As compared with the FBLC, the performance of the proposed controller is much better when a three-phase short circuit fault occurs at Bus 9. In contrast, the IDA-PBC controller may slightly outperform the proposed one in terms of slightly shorter settling time and rise time. Although the dynamic performance of the proposed controller is not superior to that of the IDA-PBC one as seen in Figure 3(b), our proposed scheme has considerably simpler design procedure than the IDA-PBC one. In this case, it can be concluded that even though all controllers (IDA-PBC, FBL, PSS and the proposed controllers) are able to achieve the two expected performance requirements mentioned in the end of Section 4, the proposed controller obviously performs best in terms of transient responses (dynamic properties) except time histories of terminal voltage and power transfer from area 1 to area 2 of the IDA-PBC controller.

5.2 Load change test

It is known that load changes are considered as a type of transient disturbance in this study. For example, a sudden increase (or decrease) in load demand at particular buses can induce transients in the system, that if inadequate damping can result in system instability. In order to investigate the performance of the two area power system, assume that there is a transient 50% decrease of the load at Bus 7 during the time period $t = 0.9 - 1.1$ sec. As a result, such a decrease in load causes changes to the values of conductance and susceptance in the system's bus admittance matrix. Further, this affects the network configuration and the power transfer characteristics of the power system. It is well known that when there are temporary differences in the power balance between the mechanical power (assumed to be constant) and the electrical power of each machine, they can lead to acceleration (deceleration) of rotor angles for the entire power system. For this test, the STATCOM/Battery system is installed to provide some additional damping to the system to mitigate the acceleration (or deceleration) that results after the occurrence of load changes.

The response of the relative rotor angles, power exchanged between area 1 and area 2, and terminal voltage at Bus 8 are illustrated in Figure 4(a)-(b), respectively. These figures exhibit that the results are similar to those of the previous short-circuit fault test, even if the post-fault responses of the PSS are quite oscillatory, they eventually return to the post-fault steady-state within a prolonged time period. On the other hand, with adequate damping provided by the proposed controller, FBLC and IDA-PBC controller, their post-fault responses are hardly oscillatory and quickly settle back to the post-fault steady-state. In particular, the proposed controller can act and provide the best transient response performance in terms of rise time and settling time along with fast reduction of oscillation. However, the IDA-PBC controller performs slightly better that the proposed controller, particularly in the voltage terminal response.

From these simulation results of two tests above, based on the characteristics of the transient dynamic after the disturbance, we conclude that the proposed controller performs better than the FBLC and IDA-PBC and the conventional PSS. The simulation results indicate that the proposed controller can enhance the system transient stability, achieve power angle stability along with power and voltage regulations in accordance with the two expected requirements. Moreover, independent of the steady-state system operating point and two tests earlier, the proposed controller is capable of accomplishing the best dynamic properties as seen in faster transient responses, especially in relative rotor angles, of the closed-loop systems under two different types of contingencies.

6. Conclusions

In this paper, we have used the coordinated passivation design tool to design the generator excitation, DFIG, and STATCOM/battery controllers. Also, the resulting controller can be effectively used to enhance transient stability and voltage regulation in multi-machine power system after the occurrence of the three-phase fault and load variations. Using a classical four-machine benchmark system model and the coordinated passivation design, simulation results have demonstrated the effectiveness of the proposed controller in terms of achieving closed-loop system transient stability, in particular relative rotor angle stability along with transmission power between two areas and voltage regulation, and providing better improved transient responses than the existing controllers, e.g., IDA-PBC, FBLC and PSS. Further, the coordinated passivation control scheme provides a considerably simpler design procedure than IDA-PBC one from our previous work. It is obvious that our proposed method is simple and does not require selecting the desire structure matrices and the energy function as IDA-PBC one; however, it can obviously enhance transient stability and provide better transient response performances than those of IDA-PBC one.

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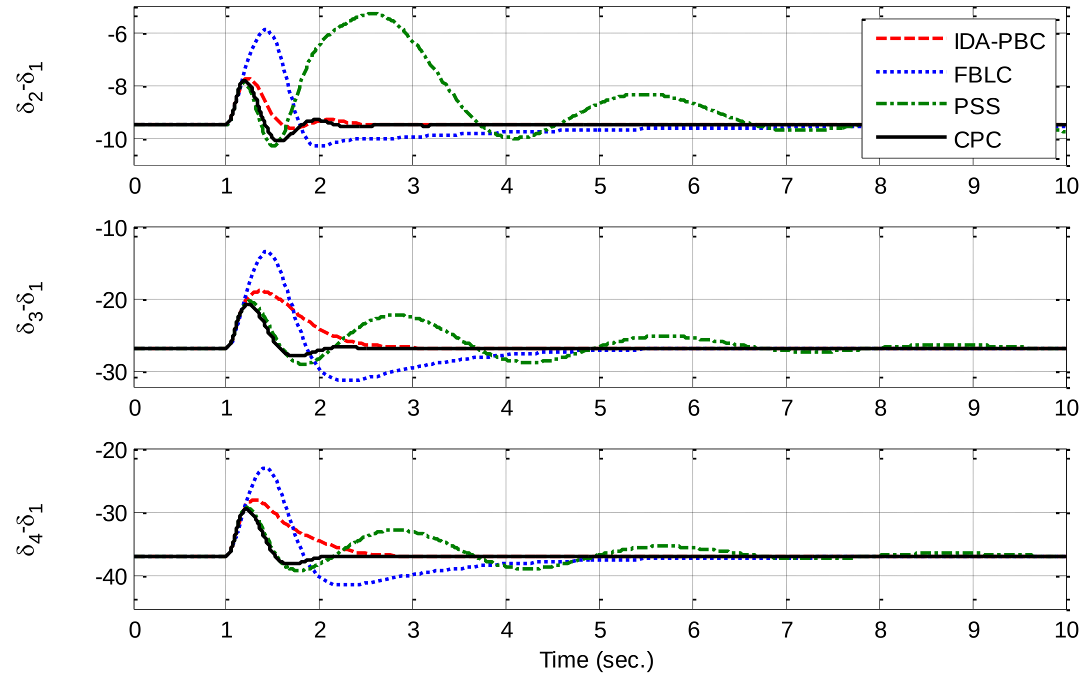
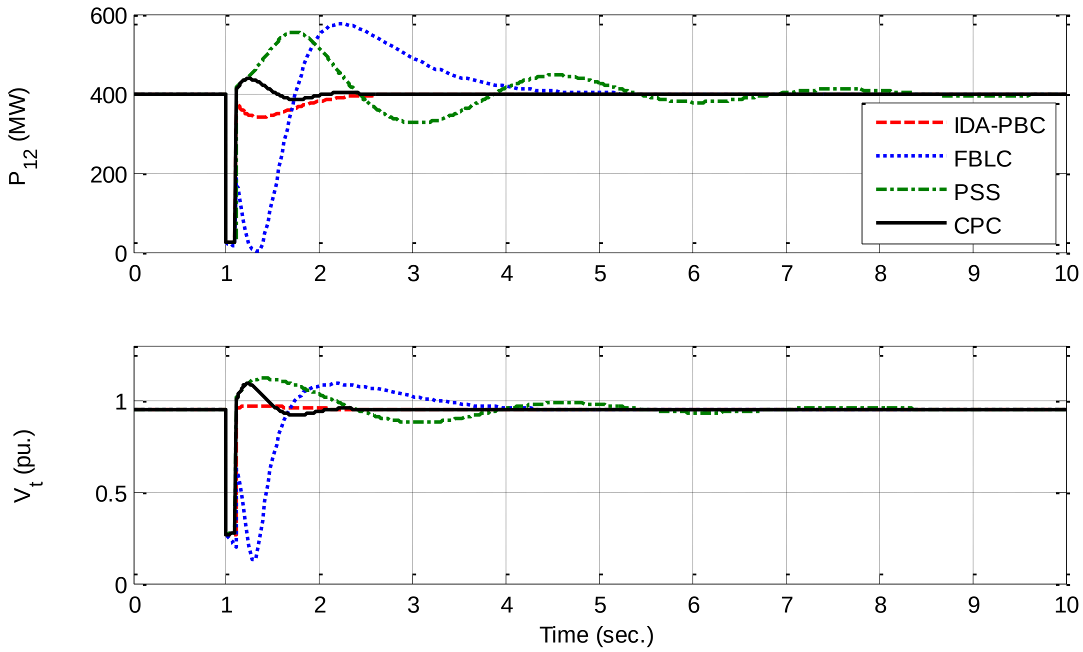
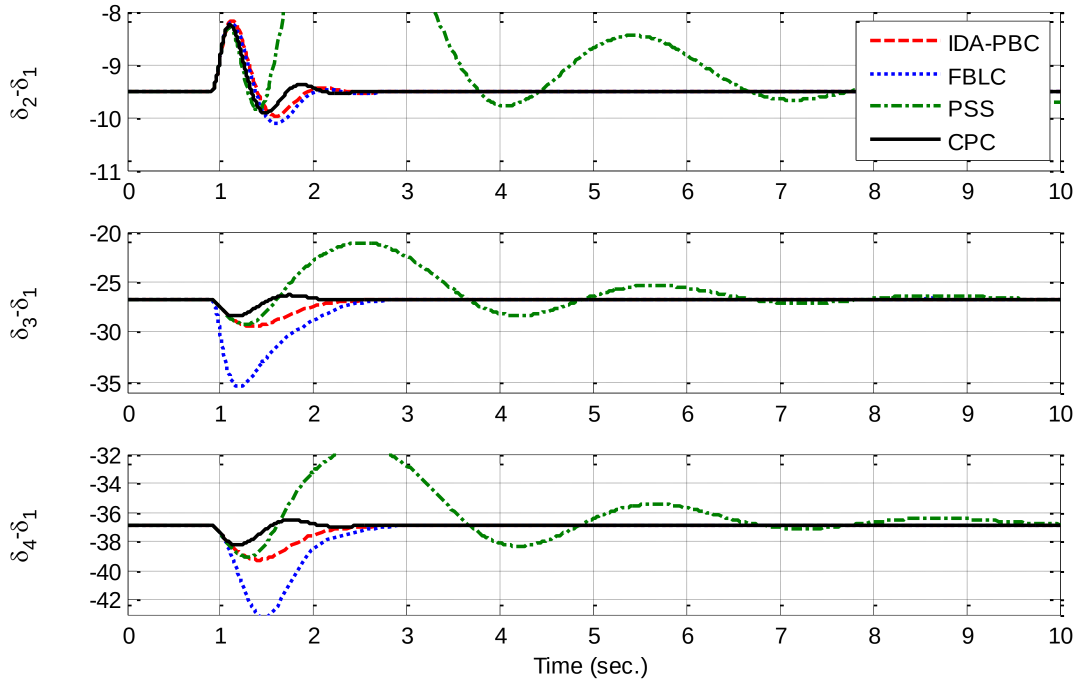


(a)



(b)

Figure 3 Short circuit test: Time histories of (a) Relative rotor angles $\delta_2 - \delta_1, \delta_3 - \delta_1,$ and $\delta_4 - \delta_1$ (deg.) (b) Transmission power area 1 to area 2 $\left(P_{12}\right)$ and terminal voltage at Bus 8 $\left(V_t\right)$ (Solid: CPC, Dashed: IDA-PBC, Dashdot: PSS, Dotted: FBLC)



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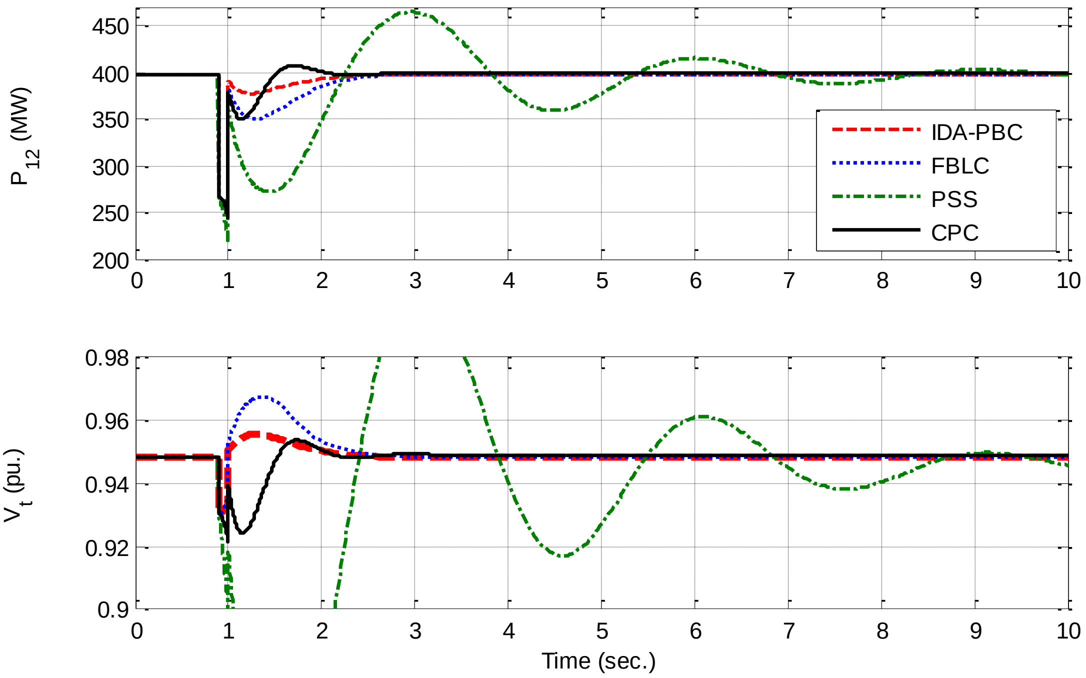

(b)

Figure 4 Load change test: Time histories of (a) Relative rotor angles $\delta_2 - \delta_1, \delta_3 - \delta_1,$ and $\delta_4 - \delta_1$ (deg.)(b) Transmission power area 1 to area 2 (P_{12}) and terminal voltage at Bus 8 (V_t) (Solid: CPC, Dashed: IDA-PBC, Dashdot: PSS, Dotted: FBLC)