Hybrid fast damping control strategy for doubly fed induction generators against power system inter-area oscillations

Xu, Yan; Liao, Kai; Wang, Yao; He, Zhengyou; Marzoughi, Hesamoddin

2017

Liao, K., Xu, Y., Wang, Y., He, Z., & Marzoughi, H. (2018). Hybrid fast damping control strategy for doubly fed induction generators against power system inter-area oscillations. IET Renewable Power Generation, 12(4), 463-471.

<https://hdl.handle.net/10356/86132>

<https://doi.org/10.1049/iet-rpg.2017.0196>

© 2017 The Institution of Engineering and Technology (IET). This paper was published in IET Renewable Power Generation and is made available as an electronic reprint (preprint) with permission of The Institution of Engineering and Technology (IET). The published version is available at: [<http://dx.doi.org/10.1049/iet-rpg.2017.0196>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 23:32:15 SGT

Hybrid fast damping control strategy for doubly fed induction generators against power system inter-area oscillations

ISSN 1752-1416

Received on 22nd March 2017

Revised 24th November 2017

Accepted on 16th December 2017

E-First on 26th January 2018

doi: 10.1049/iet-rpg.2017.0196

www.ietdl.org

Kai Liao¹, Yan Xu¹ ✉, Yao Wang², Zhengyou He³, Hesamoddin Marzooghi⁴¹School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Ave., Singapore, Singapore²School of Electrical and Information Engineering, Southwest Minzu University, Chengdu 610041, People's Republic of China³School of Electrical Engineering, Southwest Jiaotong University, Chengdu 611756, People's Republic of China⁴School of Engineering and Technology, Central Queensland University (CQ University), Brisbane, QLD 4000, Australia

✉ E-mail: eeyanxu@gmail.com

Abstract: Here, a hybrid fast damping control strategy based on bang–bang modulation is proposed for doubly fed induction generators (DFIGs) against inter-area oscillations. Since the changes in active power modulation of DFIG may result in its interactive effect with torsional oscillations, this study relies on the modulation of DFIG reactive power to rapidly attenuate the system's critical oscillation mode. In order to overcome the buffeting of the bang–bang modulation, the proposed control strategy is designed as a hybrid scheme consisting of three operating modes which are switched based on the amplitude of the detected critical oscillation mode. The required lead phase for the proposed control strategy is determined using frequency domain analysis using detailed dynamic model of the DFIG. A comprehensive test is carried out by conducting simulation studies on a modified two-area system including an aggregated wind farm. It has been shown that the proposed strategy damps inter-area oscillations much quicker than the conventional continuous damping controller. Simulation results also showed that the control scheme is robust to the operation point variation and identification errors for practical application.

Nomenclature

DFIG	doubly fed induction generator
GSC, RSC	grid-side converter, and rotor-side converter
PSS	power system stabiliser
WT	wind turbine
PI	proportional–integral
WAMS	wide area measurement system
ω_t	turbine angular speed
ω_r	generator speed
ω_e	electrical base speed
T_e	electrical torque
T_m	mechanical torque
T_{sh}	shaft torque
H_t	inertia constant of turbine
H_g	inertia constant of generator
θ_{tw}	shaft twist angle
X	total impedance of AC transmission line
e'_d, e'_q	d - and q -axis voltages behind-transient reactance
i_d, i_q	d - and q -axis currents
i_{ds}, i_{qs}	d - and q -axis stator currents
i_{dr}, i_{qr}	d - and q -axis rotor currents
ω_s	grid frequency
L_{tr}, L_{ss}, L_m	self-inductance of rotor winding, self-inductance of stator winding, and mutual inductance of stator winding
P_r, P_g	active power at RSC and GSC sides
C	DC capacitor
u_{cd}, u_{cq}	d and q -axis voltage of the converter side
u_{sd}, u_{sq}	d - and q -axis voltage of the AC side
x_p, x_Q	extend state variables in active power and reactive power control loop
x_{iqr}, x_{idr}	extend state variables in the RSC current control loop
x_{vdc}	extend state variable of GSC DC voltage control loop
x_{iqg}, x_{idg}	extend state variables of GSC current control loop

P_{ref}	active power order
P_{mean}	measured active power
Q_{ref}	reactive power order
Q_{mean}	measured reactive power
K_{p1}, K_{p2}, K_{p3}	the proportionalities of the PI controller of the outer active power loop, inner current loop, and outer reactive power loop, respectively
K_{i1}, K_{i2}, K_{i3}	the integrals of the PI controller of the outer active power loop, inner current loop, and outer reactive power loop, respectively
V_{dref}	DC voltage order
v_{dc}	measured DC voltage
H_1, H_2	equivalent inertia of area I and area II in two-area system
P_{m1}, P_{m2}	input mechanical power of area I and area II in two-area system
Q_1, Q_w, Q_{s0}	reactive power from area I to area II, reactive power of DFIG, and reactive power of fixed shunt capacitive compensator, respectively

1 Introduction

The penetration of wind power has been significantly increased in power systems during the past decades. As one of the most mature variable-speed wind power generators, doubly fed induction generators (DFIGs) are advantageous for relatively small size, low power rating of power electronic converters, reduced mechanical loads on wind turbine (WT), and high energy efficiency [1]. However, with the rapid increase in DFIG-based wind farms, inter-area damping performance of power systems might be significantly affected [2]. Therefore, damping contribution of installed DFIGs is of significant importance [3].

DFIGs employ back-to-back converters consisting of a rotor-side converter (RSC) and a grid-side converter (GSC) as interface with power grids. The control capabilities of GSC and RSC result in more flexible modulation of both active and reactive power of DFIGs compared with conventional induction generators [4]. The flexible power modulation capabilities of DFIGs have been utilised

Fig. 1 Schematic diagram of DFIG-based wind energy conversion system

to enhance power system damping by introducing an auxiliary damping controller [5–8]. A power system stabiliser (PSS) for the RSC of DFIGs, which is similar to the one installed for a synchronous machine, has been proposed in [6] to improve the power system damping. The robust control algorithm and intelligent method have been applied to tune the PSS and its parameters for DFIGs in [7]. In [8], the oscillation signal containing the power system inter-area oscillation information is added into the outer active power control loop of the RSC to damp inter-area oscillations. An algorithm of eigenstructure is applied to design an active power regulation-based damping controller for DFIGs in [9]. Moreover, the bacterial foraging technique is applied to optimise parameters of proportional–integral (PI) and supplementary damping controllers for damping performance enhancement in [10]. However, in WTs, the frequency of both torsional oscillation and stiffness are quite low. Meanwhile, the active power is directly related to the electromagnetic torque. Thus, the modulation of active power for low-frequency oscillation damping may result in interactions with torsional oscillations. An alternative method for providing damping contribution is using reactive power modulation capability of DFIGs. Some studies made a step forwards this by adding additional continuous damping controllers to the reactive power control loop of DFIGs to damp inter-area oscillations [11–13]. The results presented in those papers showed that DFIGs employed an auxiliary controller into the reactive power control loop are able to damp inter-area oscillations, and it will not cause the torsional oscillations. Nonetheless, the damping performance of those continuous damping controllers may be limited as they cannot fully utilise the power modulation capability of DFIGs.

Besides conventional continuous damping control methods, modulation of DFIG reactive power based on the measured oscillation signal is another feasible way to damp inter-area oscillations. In this context, this paper proposes a bang–bang modulation-based hybrid control scheme for DFIGs to quickly damp inter-area oscillations. The proposed hybrid control strategy consists of three operating modes: (i) supervision mode, (ii) active mode, and (iii) continuous mode. These modes are switched according to the amplitude of the critical oscillation mode. In the supervision mode, the Prony algorithm monitors frequencies, amplitudes, and phases of oscillation modes. If an oscillation mode with large amplitude is detected consistently during a specified period, then the active control mode is activated. In the active control mode, the bang–bang modulation is employed aiming to maximise damping effect. To do so, bang–bang modulation switches the maximum/minimum value in phase with critical oscillation mode, to achieve maximum control effect and have minimum interactions with other system oscillation modes. When the amplitude of critical oscillation mode is reduced below a certain threshold, the active control mode is disabled, and the control scheme switches to continuous mode that uses a conventional continuous damping controller to regulate the reactive power of DFIGs. In the literature, this has been successfully applied for flexible AC transmission system control against transient oscillations [14, 15]. The promising results motivated us to leverage it for DFIG control against inter-area oscillations.

The hybrid damping control scheme proposed in this paper is based on the identified information related to critical oscillation mode in the power system. One advantage of our proposed scheme is that it does not rely on the linearisation model with respect to a

fixed operation point; therefore, it has wider adaptability. In this study, frequency domain analysis is employed to exactly detect the lead/lag phase for bang–bang modulation based on a detailed dynamic model of DFIGs. A comprehensive test is carried out to verify the performance of the proposed scheme. Moreover, a set of simulation including errors in the identified oscillation frequency and phase are carried out to investigate the robustness of the proposed scheme against these errors.

The remaining of this paper is organised as follows: the detailed dynamic model of DFIGs is described in Section 2. Section 3 introduces the inter-area oscillation of a power system briefly. Section 4 presents the designed hybrid damping control scheme. Simulation results and detailed discussion are presented in Section 5. Finally, Section 6 gives the conclusion.

2 Dynamic modelling of DFIG

The topology of a DFIG-based wind energy conversion system is shown in Fig. 1. For a DFIG, the stator supplies power to the grid directly, and the rotor supplies power to the grid with a back-to-back electric converter which is the key unit to achieve the control objectives of rotor speed, active and reactive power regulation. In this paper, the proposed strategy for DFIGs aims to damp the critical inter-area oscillation mode by determining the phase compensation of the bang–bang modulation, i.e. the controller attempts to keep the switching time of control variable (reactive power order of DFIGs) in phase with the oscillation mode. To achieve this, a detailed DFIG model including turbine shaft, induction generator, RSC, GSC, converter control systems, and DC link capacitor is used to determine the phase compensation of the bang–bang modulation. Such phase compensation is obtained by calculating the residue angle of the transfer function from system oscillation signal to reactive power order of DFIGs. The detailed models of DFIG components are given in the following subsections.

2.1 Drive train of WT

In this paper, a two-mass model is assumed to represent the dynamics of the WT shaft [8, 16]. This model takes the torsional flexibility into consideration to study the WT mechanical dynamics. Since this paper aims to capture the torsional dynamics, the two-mass model is sufficient to represent the interested dynamics, as given below

$$2H_t \frac{d\omega_t}{dt} = T_m - T_{sh} \quad (1)$$

$$2H_g \frac{d\omega_r}{dt} = T_{sh} - T_e \quad (2)$$

$$\frac{d\theta_{tw}}{dt} = \omega_c(\omega_t - \omega_r) \quad (3)$$

2.2 Generator

The commonly used synchronously rotating $d-q$ reference frame is employed to model the dynamic behaviour of the induction generator in DFIG-based wind energy conversion systems. Note that the voltage behind transient resistance and stator currents are

Fig. 2 Structure of voltage source converter and its control schemes
(a) Structure of voltage source converter, (b) Control scheme of RSC, (c) Control scheme of GSC

selected as state variables here. The differential equations of stator and rotor circuits of the induction generator in the $d-q$ reference frame are as follows [17]:

$$\frac{de'_d}{dt} = -\frac{X_s - X'}{T} i_{qs} - \frac{1}{T'_0} e'_d + s\omega_s e'_q - \frac{\omega_s L_m}{L_{rr}} v_{qr} \quad (4)$$

$$\frac{de'_q}{dt} = -\frac{X_s - X'}{T} i_{ds} - \frac{1}{T'_0} e'_q - s\omega_s e'_d + \frac{\omega_s L_m}{L_{rr}} v_{dr} \quad (5)$$

$$\begin{aligned} \frac{di_{ds}}{dt} = & \frac{\omega_s}{X'} v_{ds} - \left(\frac{\omega_s}{X'} R_s + \frac{1}{X' T'_0} (X_s - X') \right) i_{ds} \\ & + \frac{\omega_s (1-s)}{X'} e'_d - \frac{L_m \omega_s}{L_{rr} X'} v_{dr} + \frac{1}{X' T'_0} e'_q + \omega_s i_{qs}, \end{aligned} \quad (6)$$

$$\begin{aligned} \frac{di_{qs}}{dt} = & \frac{\omega_s}{X'} v_{qs} - \left(\frac{\omega_s}{X'} R_s + \frac{1}{X' T'_0} (X_s - X') \right) i_{qs} \\ & + \frac{\omega_s (1-s)}{X'} e'_q - \frac{L_m \omega_s}{L_{rr} X'} v_{qr} + \frac{1}{X' T'_0} e'_d + \omega_s i_{ds}, \end{aligned} \quad (7)$$

where $e'_q = \omega_s L_m (i_{dr} + (L_m/L_{rr}) i_{ds})$, $e'_d = -\omega_s L_m (i_{qr} + (L_m/L_{rr}) i_{qs})$, $X = \omega_s L_{ss}$, $X' = (\omega_s/L_{rr})(L_{ss}L_{rr} - L_m^2)$, and $T'_0 = (L_{rr}/R_r)$.

2.3 Dynamics of converters

The configuration of voltage source converter is shown in Fig. 2a, which is used for the GSC and RSC of DFIGs. The dynamics of the converter in the $d-q$ reference frame can be represented as shown in (8) and (9)

$$\frac{di_{dr}}{dt} = \frac{1}{L} u_{cd} - \frac{R}{L} i_d - \frac{1}{L} u_{sd} - \omega i_{qr}, \quad (8)$$

$$\frac{di_{qr}}{dt} = \frac{1}{L} u_{cd} - \frac{R}{L} i_q - \frac{1}{L} u_{sq} + \omega i_{dr}. \quad (9)$$

The dynamic models of RSC and GSC are similar. For RSC, the AC side is the rotor winding side, while for GSC, the AC side is the grid side.

2.4 Controller of DFIG converters

2.4.1 Controller for RSC: The control scheme of RSC, which is considered in this study, is shown in Fig. 2b. In the q -axis, voltage of RSC, u_{qr} , is employed to control the active power, while the d -axis voltage, u_{dr} , is used to control the reactive power. The d - and q -axis control loops are used to keep the output active and reactive powers of DFIG according to the reference value, respectively. The dynamic model of the RSC control system is given below [18]:

$$\frac{dx_P}{dt} = P_{ref} - P_{mean}, \quad (10)$$

$$\frac{dx_Q}{dt} = Q_{ref} - Q_{mean}, \quad (11)$$

$$\frac{dx_{igr}}{dt} = i_{qref} - i_{qr} = K_{p1}(P_{ref} - P_{mean}) + K_{i1}x_P - i_{qr}, \quad (12)$$

$$\frac{dx_{idr}}{dt} = i_{dref} - i_{dr} = K_{p3}(Q_{ref} - Q_{mean}) + K_{i3}x_Q - i_{dr}, \quad (13)$$

where $i_{qref} = K_{p1}(P_{ref}) - P_{mean} + K_{i1}x_P$, and $i_{dref} = K_{p3}(Q_{ref}) - Q_{mean} + K_{i3}x_Q$. As it can be seen in above equations, the active power and reactive power of DFIG can be independently modulated by controlling v_{qr} and v_{dr} , respectively.

2.4.2 Controller for GSC: The control objective of GSC is to maintain the DC line voltage during the operating of a DFIG. The control system of a GSC is shown in Fig. 2c. The dynamic model of the controller of a GSC is given as follows:

$$\frac{dx_{vdc}}{dt} = V_{dcref} - V_{dc}, \quad (14)$$

$$\frac{dx_{gigr}}{dt} = i_{gqref} - i_{gqr}, \quad (15)$$

$$\frac{dx_{gidr}}{dt} = i_{gdref} - i_{gdr} = K_{p4}(V_{dcref} - V_{dc}) + K_{i4}x_{vdc} - i_{gdr}, \quad (16)$$

where $i_{gqref} = 0$, and $i_{gdref} = K_{p4}(V_{dcref} - V_{dc}) + K_{i4}x_{vdc}$.

2.5 Dynamics of DC link

The dynamic of the DC link with a capacitor installed between the RSC and GSC can be represented by the dynamic of the DC voltage stabilisation capacity, which is a first-order dynamic model as follows:

$$C v_{dc} \frac{dv_{dc}}{dt} = P_r - P_g. \quad (17)$$

3 Inter-area oscillation in DFIG penetrated power systems

In this paper, a two-area power system [19], a benchmark system for inter-area oscillation study, integrating a DFIG-based wind farm is used to design and test the proposed control strategy. As shown in Fig. 3, the two areas, each with a local load, are connected through a double AC transmission line. In this study, the

DFIG-based wind farm is integrated to area I. A fixed shunt capacitive compensator is also connected at the same bus with the wind farm. Note that this compensator does not influence the dynamics of transfer function from system oscillation signal to reactive power order of DFIGs. Therefore, the compensator is considered as a static component, so its dynamics at the controller design stage is neglected.

The dynamic behaviours of the two-area power system without wind farm connection can be described using the swing equation as shown below [20–22]:

$$\begin{aligned}\dot{\delta}_{12} &= \omega_{12}, \\ \dot{\omega}_{12} &= \frac{1}{H_1}(P_{m1} - P_{L1}) - \frac{1}{H_2}(P_{m2} - P_{L2}) - \left(\frac{1}{H_1} + \frac{1}{H_2}\right) \frac{V_1 V_2}{X} \sin \delta_{12},\end{aligned}\quad (18)$$

where δ represents the generator rotor angle and ω the generator rotor speed. δ_{12} and ω_{12} are the relative rotor angle and relative rotor speed between the two areas, respectively, with $\delta_{12} = \delta_1 - \delta_2$ and $\omega_{12} = \omega_1 - \omega_2$.

When the wind farm is connected to area I, the system dynamic behaviours can be described as:

$$\begin{aligned}\dot{\delta}_{12} &= \omega_{12} \\ \dot{\omega}_{12} &= \frac{1}{H_1}(P_{m1} + P_w - P_{L1}) - \frac{1}{H_2}(P_{m2} - P_{L2}) - \left(\frac{1}{H_1} + \frac{1}{H_2}\right) \frac{V_1 V_2}{X} \sin \delta_{12}\end{aligned}\quad (19)$$

In the above system, the active power transmission is relevant with the angle difference between these two areas. The reactive power transmission from area I to area II is relevant with the magnitude of the voltage. In other words, the voltage magnitude will be influenced by the reactive power with the relationship shown in (20). The power swing damping can be improved by controlling the bus voltage via reactive power modulation [23]:

$$Q_1 = Q_w + Q_{s0} = \frac{V_2^2 - V_1 V_2 \cos \delta_{12}}{X}, \quad (20)$$

where Q_1 is the reactive power from area I to area II, Q_w the reactive power injected from the DFIG-based wind farm, and Q_{s0} the reactive power generated by fixed shunt capacitive compensators and synchronous generators.

It is known that the generators operate synchronously in the two areas under the steady-state conditions. The relative angle δ_{12} remains constant, and the relative rotor speed ω_{12} is zero. However, when a disturbance occurs, the balance between electrical power and mechanical power of generators is broken, which may lead to the power oscillation between the two areas. To maintain system stability, such power oscillation should be damped quickly. In this paper, a bang–bang modulation-based hybrid damping control strategy is proposed to rapidly damp the system inter-area oscillation by modulating the reactive power of the DFIG-based wind farm.

4 Bang–bang modulation-based hybrid damping control scheme

4.1 Proposed scheme

To quickly damp the critical inter-area oscillation in a high wind power penetrated power system, this paper proposes a bang–bang modulation-based damping control scheme for DFIGs, in which the reactive reference value of the DFIG is switched to its maximum/minimum value in phase with the changing rate of critical oscillation modes. Hence, the bang–bang modulation utilises the maximum power rating of DFIGs to quickly damp the critical inter-area oscillation mode. The bang–bang modulation is able to provide maximum damping effect, but it may lead to additional oscillation under small system oscillations, which is known as a drawback called buffeting. To avoid such drawback, this paper proposes a hybrid control scheme as shown in Fig. 4. The

controller employs Prony algorithm to identify the presence and parameters including frequency, initial phase, and amplitude of the critical oscillation mode online. The proposed scheme operates in three modes: (i) supervision mode, (ii) active mode, and (iii) continuous mode. In the supervision mode, the Prony algorithm monitors frequencies, amplitudes, and phases of oscillation modes. If an oscillation mode with large amplitude is detected consistently during a specified period, then the active control mode is activated. In the active control mode, the bang–bang modulation is used to maximise damping effect. This modulation is switched in phase of oscillation signal by introducing the oscillation frequency and lead phase from oscillation signal to control variable of the controller. When the amplitude of critical oscillation mode is reduced below a certain threshold, the active control mode is disabled, and the control scheme switches to continuous mode which uses a conventional continuous damping controller to regulate the reactive power of DFIGs. The conventional continuous damping controller is designed for the DFIG based on the method introduced in [11].

4.2 Bang–bang modulation for damping control

The single-machine infinite-bus test system shown in Fig. 5 is employed to illustrate the principle of bang–bang modulation-based damping control [23]. The power oscillation in grid can be damped by adjusting the voltage of mid-point bus as the function shown in (21):

$$\Delta V_m = K \frac{d\delta}{dt}. \quad (21)$$

where K is a constant, and $\Delta\delta$ the power angle. To damp an oscillation, (21) suggests that the modulated bus voltage should lead the observed oscillation in $\Delta\delta$ by 90° at oscillation frequency. Alternative signals for $\Delta\delta$ can also be used, e.g. transmission power P or machine speed ω [18, 23]. In this paper, control of bus voltage is done by reactive power modulation of DFIG. Equation (21) indicates that the reactive power reference value of DFIG can be switched to its maximum/minimum value in phase with the changing rate of oscillation signal to achieve maximum damping effect. This requires the switching time of DFIG reactive power to be in the same step with the frequency of the power oscillation associated with the critical oscillation mode.

If the power oscillation in the inter-area transmission line is

$$P_{cr} = A_{cr} e^{\sigma_{cr} t} \cos(\omega_{cr} t + \varphi_{cr}). \quad (22)$$

Then, the DFIG reactive power modulation signal should be:

$$Q_{ref} = Q_{mou} \text{sign} \left(\cos \left(\omega_{cr} t + \varphi_{cr} + \varphi_{lead} + \frac{\pi}{2} \right) \right). \quad (23)$$

As shown in (23), the switching frequency of the bang–bang controller is determined by the oscillation frequency, and the lead phase is determined by the phase response with respect to the oscillation frequency. Hence, the first step is to identify the frequency and phase of the critical oscillation mode. In this paper, the Prony algorithm is used to detect the frequency (ω_{cr}) and the initial phase (φ_{cr}) of the mode. The lead phase (φ_{cr}) is obtained from frequency domain analysis of the open loop transfer function from the control variable to the oscillation signal with respect to the frequency of critical oscillation mode. Hence, the lead phase can be derived based on the frequency domain analysis (Bode diagram) using the system dynamic model.

The control scheme monitors the oscillation signal continuously and uses Prony algorithm [24] to obtain the parameters of oscillation modes, including amplitudes, A_i , frequency, ω_i , and initial phase, φ_i . The signal used for oscillation mode identification can be the transmission power between the two areas (P), the angle difference between generators ($\Delta\delta$), or the rotor speed (ω). The amplitude of the critical oscillation mode is used to determine the activation time and deactivation time of the bang–bang control mode. The bang–bang control mode will be activated if an obvious

Fig. 3 Structure of the two-area power system with DFIG-based wind farm integrated

Fig. 4 Control scheme of the proposed bang-bang modulation-based hybrid damping control

Fig. 5 Single-machine infinite-bus system

oscillation mode is detected. When the amplitude of the critical mode reduces below the threshold, the bang-bang modulation will be switched to continuous mode with a conventional continuous damping controller.

5 Simulation evaluation

5.1 Test system description

In this section, time-domain simulations on a modified two-area four-machine power system with DFIG-based wind farm are carried out to investigate the performances of the proposed strategy. The structure of the simulation system is given in Fig. 6. The rated power of each synchronous machine is 900 MW. The parameters of the synchronous machines are given in the Appendix. Note that this system has been used for simulation study in the literature [8, 10, 11]. In this simulation, the DFIG-based

Fig. 6 Structure of the simulation system

wind farm is represented by one aggregated DFIG [17]. The size of wind farm is levelled for a penetration of 10% in area I. The parameters of the DFIG and the WT shaft are given in the Appendix. A three-phase short circuit is applied at bus 3 at $t = 1.0$ s and cleared after $t = 0.1$ s to active the oscillation. The bode diagrams of the open loop transfer function from the control variable to the rotor speed (ω) and to transmission power (P) are shown in Figs. 7a and b, respectively. As shown in the bode diagram, the dominant oscillation frequency of the system is 3.76 rad/s. The residue angles of transfer functions corresponding to rotor speed and transmission power, with respect to the dominant frequency, are 20 and 267°, respectively. That means the lead phase of the bang-bang modulation should be 20° if the rotor speed is employed as feedback oscillation signal, and it should be 267° if the transmission power is used as the feedback oscillation signal.

5.2 Damping performance

In this simulation, the transmission power between the two areas is employed as the feedback oscillation signal. Fig. 8 shows the transmission power and the identification results from Prony algorithm, where the time window is 1.5 s. Fig. 9 shows the system dynamic responses with the proposed damping control scheme. Observe that at $t = 3.05$ s, the proposed control scheme detects an oscillation mode with an amplitude of 25 MW and a frequency of 0.59 Hz (3.76 rad/s). This activates the bang-bang control mode with a switching frequency of 0.59 Hz and a lead phase of 267° to provide the maximum damping effect. The reactive power output of the DFIG given in Fig. 9b shows that the DFIG modulates its output reactive power to damp the system oscillation according to the order of additional damping controller when the system disturbance occurs. Through the reactive power modulation of DFIGs, the injected reactive power drives the bus voltage up and down. The changing of bus voltage, in turn, leads to acceleration or deceleration of the rotor of synchronous machine against the power oscillations. When the amplitude of the transmission power oscillation reduces to <2 MW at $t = 7.1$ s, the proposed strategy automatically switches from the active mode to the continuous mode.

For comparison study, a conventional continuous damping controller in [11] is simulated under the same event as above and the results are shown in Fig. 10. The comparison between Figs. 9 and 10 shows that our proposed scheme can damp the system oscillation much faster than the conventional continuous damping controller, where the oscillation time are 7.8 and 13.2 s, respectively. Another comparison of transmission power responses between the proposed scheme and the conventional continuous damping controller is shown in Fig. 11. Observe that the dashed lines correspond to the scenario without damping controller, the hyphen lines correspond to the scenario with the continuous damping control, and the solid lines correspond to the scenario with the proposed integrated damping control. The comparison results also clearly show that the proposed damping controller can damp the amplitude of the oscillation faster than the conventional continuous damping controller.

Fig. 7 Bode diagram of open loop transfer function from control variable to oscillation signals
(a) Q_{ref}/ω , (b) Q_{ref}/P

5.3 Robustness against variation of operation points

As a variable structure control method, bang–bang control is switched according to the measured oscillation trajectory, which is robust to the system operation point variations. To test this, oscillation time under different operation points are investigated in this section. The variation of operation points is simulated by changing the load in area I. For the initial operation point, the transmission power is 400 MW. The oscillation time in various operation points with the proposed damping controller are listed in Table 1. In this simulation, variation in transmission power is achieved by decreasing load in area I with a step of 25 MW. As shown in Table 1, the oscillation time with increased power transfer is slightly raised from 7.8 to 8.2 s. This illustrates that the proposed damping controller is robust to the variation of system operation point. For illustration purpose, Fig. 12 shows dynamic trajectories of relative rotor angle when the operation point changed to $P = 500$ MW. It can be seen that the performance of the controller remains satisfactory, under such a big variation for the system operation point.

5.4 Robust against the mode identification errors

The proposed damping control strategy relies on the identified frequency and initial phase of oscillation signal. In this section, the effects of the errors in identified frequency and initial phase on the effectiveness of the proposed scheme are examined. The dynamic responses of transmission power between the two areas with respect to frequency and phase errors are given in Figs. 13a and b, respectively. Fig. 13a shows that the bang–bang controller performance is not as satisfactory as before when the error range exceeds $\pm 4\%$ from exact oscillation frequency. Fig. 13b shows that the bang–bang control is effective with an error of ± 0.52 rad from

Fig. 8 Active power for Prony analysis and the frequency domain analysis results

Fig. 9 Simulation results with proposed control strategy
(a) Synchronous generator dynamic responses with proposed bang–bang modulation-based integrated damping control adopted to DFIG. From up to below: δ_{14} and δ_{24} ; rotor speeds of machines; bus voltage of bus 1 and bus 2, (b) Dynamic responses of DFIG with proposed bang–bang modulation-based integrated damping control adopted to DFIG. From up to below: voltage of wind farm connected bus; active power of wind farm; reactive power of wind farm; rotor speed of DFIG

Fig. 10 Simulation results with conventional control strategy

(a) Dynamic responses of synchronous machine with conventional continue damping control adopted to DFIG. From up to below: δ_{14} and δ_{24} ; rotor speeds of synchronous machines; bus voltage of bus 1 and bus 2, (b) Dynamic responses of DFIG with conventional continue damping control adopted to DFIG. From up to below: voltage of wind farm connected bus; active power of wind farm; reactive power of wind farm; rotor speed of DFIG

Fig. 11 Dynamic responses of the transmission power

exact lead phase. Therefore, it can be concluded that the bang-bang modulation is practically robust to the frequency and phase errors in real application. The system damping with respect to frequency and phase errors is shown in Fig. 14. Observe that with the proposed damping controller for DFIG, the system damping is significantly improved. Furthermore, the system damping is larger than the condition without damping controller in DFIGs, even with identification errors in frequency and phase.

Table 1 Oscillation time at different operation points

P , MW	400	425	450	475	500
oscillation time, s	7.8	7.8	8.0	8.1	8.2

Fig. 12 Dynamic responses when system operation point changes. From up to below: δ_{14} and δ_{24} ; rotor speeds of synchronous machines; bus voltage of bus 1 and bus 2

Fig. 13 Simulation results with various mode identification errors

(a) Dynamic response of transmission power between two areas with various frequency errors, (b) Dynamic response of transmission power between two areas with various phase errors

6 Conclusion

This paper made a further step towards designing a fast oscillation controller for DFIGs. The bang-bang control technique is employed to modulate the reactive power of DFIGs to achieve a fast damping control. To overcome the buffeting caused by the technique, a hybrid damping control scheme is proposed. The proposed control scheme can achieve the rapid damping effectively based on limited information, including the frequency, phase, and the open loop residue angle of the critical inter-area oscillation mode. Simulations conducted on a modified two-area four-machine power system show that the proposed scheme is able to damp the system oscillation much more rapidly than the conventional continuous damping method. The robustness test against frequency and phase errors shows that the proposed scheme is effective in an acceptable error range.

Fig. 14 Damping level with respect to various frequency and phase errors

7 Acknowledgment

This work is supported by the Singapore Ministry of Education (MOE) under an AcRF Tier 1 Project; Y. Xu's work is also supported by the Nanyang Assistant Professorship from Nanyang Technological University, Singapore.

8 References

- [1] Muller, S., Deicke, M., De Doncker, R.W.: 'Doubly fed induction generator systems for wind turbines', *IEEE Ind. Appl. Mag.*, 2002, **8**, (3), pp. 26–33
- [2] Gautam, D., Vittal, V., Harbour, T.: 'Impact of increased penetration of DFIG-based wind turbine generators on transient and small signal stability of power systems', *IEEE Trans. Power Syst.*, 2009, **24**, (3), pp. 1426–1434
- [3] He, P., Wen, F.S., Ledwich, G., *et al.*: 'Small signal stability analysis of power systems with high penetration of wind power', *J. Mod. Power Syst. Clean Energy*, 2013, **1**, (3), pp. 241–248
- [4] Eriksen, P.B., Ackermann, T., Abildgaard, H., *et al.*: 'System operation with high wind penetration', *IEEE Power Energy Manage.*, 2005, **3**, (6), pp. 65–74
- [5] Tsourakis, G., Nomikos, B.M., Vournas, C.D.: 'Contribution of doubly fed wind generators to oscillation damping', *IEEE Trans. Energy Convers.*, 2009, **24**, (3), pp. 783–791
- [6] Hughes, F.M., Anaya-Lara, O., Jenkins, N., *et al.*: 'A power system stabilizer for DFIG-based wind generation', *IEEE Trans. Power Syst.*, 2006, **21**, (2), pp. 763–772
- [7] Mishra, Y., Mishra, S., Tripathy, M., *et al.*: 'Improving stability of a DFIG-based wind power system with tuned damping controller', *IEEE Trans. Energy Convers.*, 2009, **24**, (3), pp. 650–660
- [8] Miao, Z., Fan, L., Osborn, D., *et al.*: 'Control of DFIG-based wind generation to improve interarea oscillation damping', *IEEE Trans. Energy Convers.*, 2009, **24**, (2), pp. 415–422
- [9] Kshatriya, N., Annakkage, U.D., Hughes, F.M., *et al.*: 'Optimized partial eigenstructure assignment-based design of a combined PSS and active damping controller for a DFIG', *IEEE Trans. Power Syst.*, 2010, **25**, (2), pp. 866–876
- [10] Mishra, Y., Mishra, S., Li, F., *et al.*: 'Small-signal stability analysis of a dfig-based wind power system under different modes of operation', *IEEE Trans. Energy Convers.*, 2009, **24**, (4), pp. 972–982
- [11] Fan, L., Yin, H., Miao, Z.: 'On active/reactive power modulation of DFIG-based wind generation for interarea oscillation damping', *IEEE Trans. Energy Convers.*, 2011, **26**, (2), pp. 513–521
- [12] Hansen, A.D., Sørensen, P., Iov, F., *et al.*: 'Control of variable speed wind turbines with doubly-fed induction generators', *Wind Eng.*, 2004, **28**, (4), pp. 411–434
- [13] Yang, L., Xu, Z., Ostergaard, J., *et al.*: 'Advanced control strategy of DFIG wind turbines for power system fault ride through', *IEEE Trans. Power Syst.*, 2012, **27**, (2), pp. 713–722
- [14] Hammad, A.: 'Analysis of power system stability enhancement by static var compensators', *IEEE Trans. Power Syst.*, 1986, **1**, (4), pp. 222–227
- [15] Lerch, E., Povh, D., Xu, L.: 'Advanced SVC control for damping power system oscillations', *IEEE Trans. Power Syst.*, 1991, **6**, (2), pp. 524–535
- [16] Singh, M., Allen, A.J., Muljadi, E., *et al.*: 'Interarea oscillation damping controls for wind power plants', *IEEE Trans. Sustain. Energy*, 2015, **6**, (3), pp. 967–974
- [17] Tang, Y., Ju, P., He, H., *et al.*: 'Optimized control of DFIG-based wind generation using sensitivity analysis and particle swarm optimization', *IEEE Trans. Smart Grid*, 2013, **4**, (1), pp. 509–520
- [18] Nguyen-Duc, H., Dessaint, L., Okou, A.F., *et al.*: 'A power oscillation damping control scheme based on bang-bang modulation of FACTS signals', *IEEE Trans. Power Syst.*, 2010, **25**, (4), pp. 1918–1927
- [19] Kundur, P.: 'Power system stability and control' (McGraw-Hill, New York, NY, USA, 1994)
- [20] Bergen, A.R.: 'Power systems analysis' (Prentice-Hall, Englewood Cliffs, NJ, 1986)
- [21] Anderson, P.M., Foad, A.A.: 'Power system control and stability' (IEEE Press, New York, 1994)
- [22] Miller, T.J.E.: 'Reactive power control in electric systems' (Wiley, New York, 1982)
- [23] Mathur, R.M., Varma, R.K.: 'Thyristor-based FACTS controllers for electrical transmission systems, ser. EPRI power systems engineering' (Wiley, New York, 2002)
- [24] Hauer, J., Demeure, C., Scharf, I.: 'Initial results in Prony analysis of power system response signals', *IEEE Trans. Power Syst.*, 1990, **5**, (1), pp. 80–89

9 Appendix

The main parameters of synchronous generators in the study system are given in Table 2. The parameters of the DFIG and its controller are listed in Table 3.

The structure and parameters of conventional continuous damping controller are given as:

$$H(s) = \frac{1s}{1 + 2s} \frac{1 + 2s}{1 + 1.02s} \frac{1 + 2s}{1 + 0.001s}$$

Table 2 Parameters of synchronous generator

X_d	X'_d	X'_q	X_q	r_s	H
1.8, pu	0.3, pu	0.55, pu	1.7, pu	0.0025, pu	6.5, s

Table 3 Parameters of DFIG (default pu)

r_s	L_m	L_{ls}	R_r	L
0.007	2.9	0.18	0.005	0.00178
K_{p1}	K_{p2}	K_{p3}	K_{p4}	K_{p5}
1	0.05	1	0.002	0.3
K_{i1}	K_{i2}	K_{i3}	K_{i4}	K_{i5}
100	5	100	0.05	5
C	V_{dc}	H_t	H_g	w_s
10, pF	1200, V	2.8	2.24	1