

Hybrid operation strategy of wind energy storage system for power grid frequency regulation

Jin Woo Choi, Shin Young Heo, Mun Kyeom Kim ✉

Department of Energy System Engineering, Chung-Ang University, 84 Heukseok-Ro, Dongjak-gu, Seoul 604-714, Republic of Korea
 ✉ E-mail: mkim@cau.ac.kr

ISSN 1751-8687

Received on 31st January 2015

Revised on 5th October 2015

Accepted on 2nd November 2015

doi: 10.1049/iet-gtd.2015.0149

www.ietdl.org

Abstract: This study presents a novel hybrid operation strategy for a wind energy conversion system (WECS) with a battery energy storage system (BESS). The proposed strategy is applied to support frequency regulation using coordinated control of WECS and BESS operations in power system. The coordinated control of the WECS consists of active power control and frequency support control based on permanent magnet synchronous generators for variable wind speed conditions. Active power control is achieved using maximum power point tracking and deloaded operation to ensure a certain power margin. In addition to this comprehensive control of the active power, frequency support control based on kinetic energy discharge control is developed to regulate the short-term frequency response and to ensure reliable operation of the power system. Concurrently, the output power command of the BESS is determined according to the state of charge and frequency deviations. The effectiveness of the hybrid operation strategy is verified by a numerical simulation in power system computer aided design/electro-magnetic transient direct current (PSCAD/EMTDC), and the results show that the proposed approach can improve the frequency regulation capability of the power system.

1 Introduction

Wind energy is one of the most rapidly growing renewable power sources worldwide, and wind power penetration of the power grid has been increasing [1]. In modern wind power systems, two of the most promising types of wind turbine generators are the doubly fed induction generator (DFIG) and the permanent magnet synchronous generator (PMSG). The mechanical connection between the wind turbine and the generator shaft in the DFIG is a gearbox, which provides an extensive range of rated speed [2], whereas a PMSG is connected directly to the wind turbine without a gearbox, offering low-speed operation that does not require any external excitation current. The PMSG is much less sensitive to parameter variations and exhibits better controllability than the DFIG [3, 4].

Since power systems are dynamic, the prevalence of large-scale wind energy conversion systems (WECSs) has motivated research on frequency control, which is necessary for reliable power system operation. Most variable-speed wind turbines generally have no inherent inertial response. The wind turbine has been decoupled from the power system by electronic converters because of the impacts of output stability and frequency variability on the power system. The wind turbines always operate under maximum power point tracking (MPPT) conditions without any power reserves; thus, they cannot supply any spinning reserve in response to frequency disturbances [5]. Accordingly, system operators request that wind turbines provide an ancillary service to enhance the frequency support capability using frequency control and active/reactive power control. To maintain the stability and reliability of a power system connected to a WECS, adequate frequency control research is required to determine a method for providing additional reserve.

Many researchers have studied the ability of frequency regulation in wind turbine generation to supply additional reserve. For example, frequency regulation can be implemented by inertial control, which is a means of releasing energy from the rotating mass [6–8]. The authors of [6] attempted to use an inertia contributing loop to enhance the inertia support from the wind turbine. In particular, the use of machine inertia to implement frequency control for

DFIG wind turbines was described [7], whereas the authors of [8] proposed to let a variable-speed wind turbine emulate inertia and support primary frequency control. However, because inertial control uses not the power margin but the stored kinetic energy (KE) in the rotor and blade of the wind turbine, it would decrease the power output necessary to recover the initial rotational speed during system frequency regulation. In [9], the moving-average method with K -deviation was introduced to preserve a certain amount of wind power reserve. In another literature survey [10], a deloaded (DL) control was also presented as a key solution to supply a primary frequency regulation capability within very short time spans in system containing wind turbines. In [11], Keung *et al.* proposed the KE discharge control in which a wind farm to actively provide primary reserve to support a frequency disturbance using the stored KE in a rotor. However, if the energy regain during acceleration is not controlled properly, it may cause another frequency disturbance. Therefore, it is necessary to optimise to the frequency control strategy to effectively use the stored KE.

Nowadays, an energy storage system (ESS) has been integrated with renewable sources that are connected to the power grid to maintain safe operation of the grid and to balance supply and demand. The ESS can meet the requirement for increasing the reserves to manage the uncertainty of wind generation. This can increase the system operation efficiency, enhance power absorption, and reduce carbon dioxide emissions. Among ESSs, the battery ESS (BESS) is one of the most rapidly growing storage technologies. The use of BESSs has focused attention on the reduction of adverse effects involving frequency deviations [12]. Moreover, combining a BESS with a WECS will improve the system availability and increase the amount of wind power that can penetrate the power grid without endangering system reliability. Previous work has explored the application of a BESS within a WECS for frequency support in a power system. In [13], Howlader *et al.* presented a minimal-order-observer-based frequency control approach for integrated small power system; in this approach, a strategy for coordinating a wind turbine generator and a BESS is applied. In [14], Khalid and Savkin proposed a method that solves a frequency control problem to obtain efficient

operation of a BESS using a predictive model. In [15], Serban *et al.* analysed the BESS to enhance the short-term frequency stability of autonomous microgrids that include both classical- and renewable-energy-source-based generators. In [16], Virulkar and Aware presented a control methodology for battery charging under constant current-constant voltage mode topology to regulate the active and reactive energy flows in a distributed power system network. In [17], Dali *et al.* performed a theoretical study, experimental test, and assessment of operation of a grid-connected hybrid photovoltaic (PV)–wind system that used a standalone inverter capable of working in grid-connection mode, but also in standalone mode as a micro-grid generator. In [18], the size of a PV–wind integrated hybrid energy system with battery storage was optimised under various loads and unit costs of auxiliary energy sources. However, most of this research focuses on a BESS control strategy for frequency regulation. Additional research is needed to improve the efficiency of these methods, which is still inadequate for practical applications. Furthermore, this research does not take into account the active power reserved by coordinated regulation of either rotor speed or active power control in WECS, which contributes to frequency support control. Only a few papers address operational approaches that include a frequency control strategy for a WECS with respect to the storage capability of a BESS. In this respect, to improve the frequency response in the power system, it is necessary to develop a new strategy for WECS and BESS operations. When system operators request that a wind ESS participates in frequency regulation, this improved operation strategy will provide information that enables more secure system operation and improves the frequency response compared with that of the previous approach.

This paper proposes a hybrid operation strategy for WECS and BESS operations in a power system. The proposed approach implements frequency control of the power system by coordinated control of WECS and BESS operations. Coordinated control of the WECS is applied using active power and frequency support control. A machine-side converter (MSC) and grid-side converter (GSC) are developed to achieve maximum power extraction, control the DC-link voltage and reactive power, and provide grid voltage support using standard vector control. The active power control attempts not only to operate at the MPPT for various wind speeds, but also to obtain the power margin to control DL operation. Next, frequency support control based on KE discharge control attempts to create frequency support capability for maintaining a stable wind turbine system. In addition to this coordinated control, the output power command of the BESS is determined according to the state of charge (SOC), frequency deviations, and load variation in the power system.

The remainder of this paper is organised as follows. Section 2 describes the configuration of a WECS with a BESS. Section 3 presents the hybrid operation strategy for coordinated control of WECS and BESS operations. Section 4 represents our simulation results. Concluding remarks are given in Section 5.

2 PMSG wind turbine with BESS

2.1 Wind energy conversion system

The WECS consists of a wind turbine, a PMSG, a MSC, and a GSC with an intermediate DC voltage link. The system converts the KE of the wind to mechanical energy through the wind turbine's rotor blades. The generator converts the mechanical power to electrical power [5]. The electrical power is fed to an electrical network through back-to-back converters.

2.1.1 Wind turbine characteristics: The maximum power extracted by a variable wind turbine from the wind is expressed as [1]

$$P_{\max} = \frac{1}{2} \rho \pi R^2 V^3 C_{p_{\text{opt}}}(\beta, \lambda_{\text{opt}}) \quad (1)$$

where ρ is the air density ($=1.225 \text{ kg/m}^3$), R is the rotator radius, V is the wind speed, λ_{opt} is the optimal tip speed ratio (TSR), β is the

pitch angle, and $C_{p_{\text{opt}}}$ is the optimal power coefficient, which is a function of the TSR and the pitch angle.

When the pitch angle β is set as zero during the MPPT operation, the optimal power coefficient is given by Lin and Hong [19]

$$C_{p_{\text{opt}}}(\lambda_{\text{opt}}) = 0.73 \left(\frac{151}{\lambda_i} - 13.2 \right) \exp \left(\frac{-18.4}{\lambda_i} \right) \quad (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda_{\text{opt}} - 0.02\beta} - \frac{0.003}{1 + \beta^3} \quad (3)$$

The optimal TSR of the mechanical output is defined as

$$\lambda_{\text{opt}} = \frac{\omega_{m,\text{opt}} R}{V} \quad (4)$$

where $\omega_{m,\text{opt}}$ is the optimal mechanical rotational speed [radians/seconds (*rad/s*)] for a given wind speed [metres/seconds (*m/s*)]. From (1) and (4), the maximum power value $P_{\max}$ can be obtained as a function of the shaft speed

$$P_{\max} = \omega_{m,\text{opt}}^3 \times K_{\text{opt}} \quad (5)$$

$$K_{\text{opt}} = \frac{1}{2} \rho \pi \left(\frac{C_{p_{\text{opt}}}}{\lambda_{\text{opt}}^3} \right) R^5 \quad (6)$$

where K_{opt} is the coefficient of rotational speed for the maximum power through $C_{p_{\text{opt}}}$ at the wind generator.

2.1.2 PMSG modelling: The mathematical model of a PMSG in the d – q reference frame is traditionally defined as [4]

$$V_{ds} = -R_s I_{ds} - L_s \frac{dI_{ds}}{dt} + \omega_e L_s I_{qs} \quad (7)$$

$$V_{qs} = -R_s I_{qs} - L_s \frac{dI_{qs}}{dt} - \omega_e L_s I_{ds} + \omega_e \Psi_f \quad (8)$$

where V_{ds} and V_{qs} are the stator voltages on the d and q axes, respectively; L_s and R_s represent the inductance and the resistance of the PMSG winding, respectively; Ψ_f is the magnetic flux; I_{ds} and I_{qs} are the direct and quadrature components of the stator currents, respectively; and ω_e represents the electrical rotational speed.

The electromagnetic torque T_e is given by Chinchilla *et al.* [3] and Tan and Islam [20]

$$T_e = \frac{3}{2} p_n \left[(L_d - L_q) I_{ds} I_{qs} + I_{qs} \Psi_f \right] \quad (9)$$

where L_d and L_q are the machine inductances on the d and q axes, respectively, and p_n is the number of pole pairs.

In surface-mounted PMSGs, $L_d = L_q = L_s$; therefore, the electromagnetic torque is expressed as

$$T_e = \frac{3}{2} p_n I_{qs} \Psi_f \quad (10)$$

The electrical angular speed ω_e and the mechanical angular speed of the generator rotor ω_m are related as [21]

$$\omega_e = \omega_m p_n \quad (11)$$

2.1.3 Converter control: To achieve optimum power efficiency despite wind speed variations, the MSC is used to control the wind turbine shaft speed [22]. Control of the MSC allows the generator to regulate the rotational speed according to the wind variation. To understand the control concept, the dynamic equation of the wind turbine is given as [23]

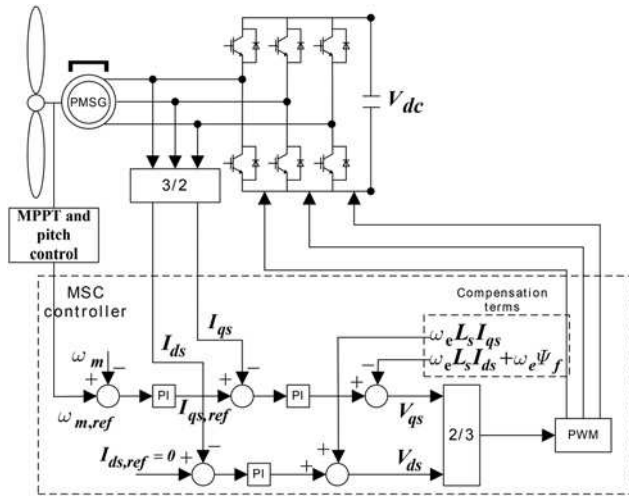


Fig. 1 MSC controller loop

$$J \frac{d\omega_m}{dt} = T_m - T_e - B\omega_m \quad (12)$$

where B is the friction coefficient of the generator, J is the moment of inertia (kg/m^2), and T_m is the mechanical torque.

The mechanical rotational speed of the PMSG rotor is given by

$$\omega_m = \omega_t G_r \quad (13)$$

where ω_t is the rotational speed of the turbine and G_r is the gear ratio. Among existing wind generators, for gearless, PMSG-based wind turbines, $G_r = 1$.

Fig. 1 shows the controller loop of the MSC which contains two cascaded loops. In the inner loop, current controllers regulate the

d - q -axis stator current to follow a reference, whereas a speed controller in the outer loop regulates the wind turbine speed such that it follows the reference value $\omega_{m,ref}$ and produces the q -axis current reference $I_{qs,ref}$. The stator current components cannot be controlled independently by the stator voltage components because of cross-coupling effects. These effects can be cancelled using the feed-forward compensation. The stator voltage components are decided by proportional–integral (PI) controllers and feed-forward compensation. Additionally, the d -axis reference current $I_{ds,ref}$ is set to zero to minimise the current and resistive losses for the given torque [3]. Then, we use pulse-width modulation to produce a switching signal for MSC control.

The GSC is normally controlled to achieve the following goals: (i) to maintain the reactive power exchange to the grid, which guarantees a desirable power factor or voltage during PMSG operation and (ii) to maintain the DC-link capacitor voltage at a set value, which ensures active power exchange from the PMSG to the grid [24]. Fig. 2 shows the controller loop of the GSC. The GSC consists of a power converter with two closed loops. The inner loops regulate the grid currents, whereas the outer loops control the DC voltage and reactive power delivered to the power system. The GSC control loops on the d - q -axis include a rotating reference frame and signal PI controllers. The active power reference P_{ref} is used to maintain a constant output voltage and Q_{ref} is determined by the power factor. Using a phase-locked loop, the three-phase current is converted to the d - q frame.

The dynamic model voltage equations of the grid connection in the d - q reference frame rotating synchronously are represented as follows [23]

$$V_{dg} = V_{cd} - R_g I_{dg} - L_g \frac{dI_{dg}}{dt} + \omega_g L_g I_{qg} \quad (14)$$

$$V_{qg} = V_{cq} - R_g I_{qg} - L_g \frac{dI_{qg}}{dt} + \omega_g L_g I_{dg} \quad (15)$$

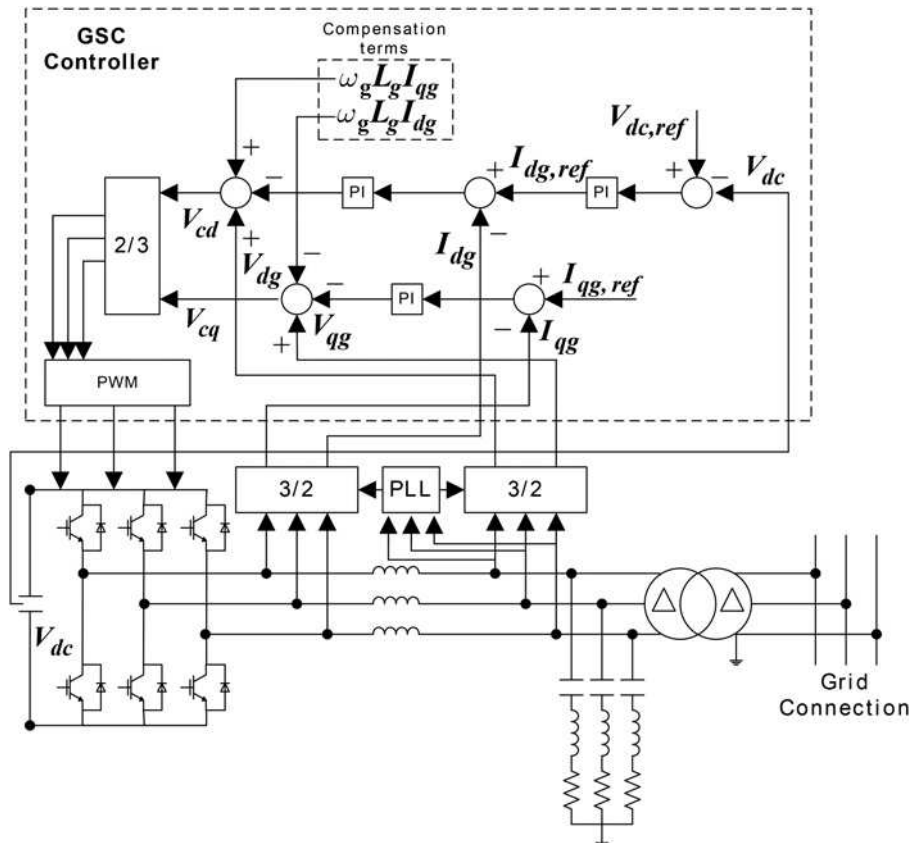


Fig. 2 GSC controller loop

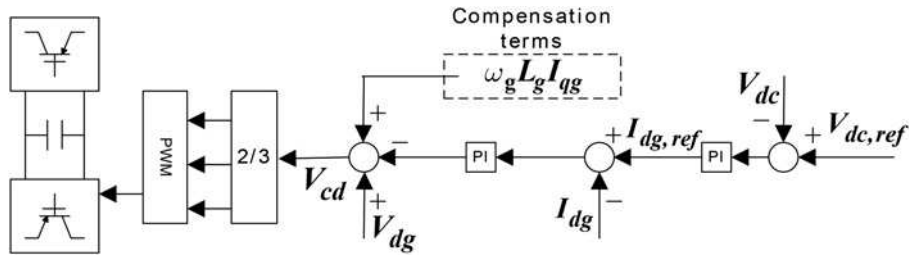


Fig. 3 DC-link controller loop

where V_{dg} and V_{qg} are the grid voltage components in the d - q frame; L_g and R_g are the grid inductance and resistance, respectively; ω_g is the angular speed of the grid; V_{cd} and V_{cq} are the converter voltage components; and I_{dg} and I_{qg} are the d -axis current and q -axis current of the electric grid, respectively.

The grid-side active and reactive powers can be expressed as follows

$$P_g = \frac{3}{2} V_{dg} I_{dg} \quad (16)$$

$$Q_g = \frac{3}{2} V_{dg} I_{qg} \quad (17)$$

Equations (16) and (17) show that the active and reactive powers are regulated to achieve the desired voltage by adjusting the respective current of the d - q -axis. To transfer all of the active power generated in the wind turbine, the DC-link voltage V_{dc} should be maintained at a constant value using the current control of the d -axis. The DC-link controller can be expressed as the following constraint

$$C \frac{dV_{dc}}{dt} = \frac{P_t}{V_{dc}} - \frac{P_g}{V_{dc}} \quad (18)$$

where C is the capacitance of the DC-link capacitor and P_t and P_g are the power of the wind turbine and the grid, respectively.

The DC-link controller controls the DC-link voltage by the DC voltage reference $V_{dc,ref}$ as shown in Fig. 3. The measured error in the DC-link voltage is used to determine the generator power set-point via the PI controller. The voltage is maintained at a constant value by adjusting the reactive power. To improve the efficiency of operation for WECS, this control strategy is changed to operate with fixed unit power factor.

2.2 Battery energy storage system

Among ESSs, the BESS has recently emerged as one of the most rapidly growing technologies for short-term energy storage owing to its advantages, which include cost efficiency and flexibility [25]. The aggregated BESS in a wind farm based on PMSGs is used to study the proposed strategy. The combined BESS and WECS can regulate the frequency by supplying an additional energy as well as the electric power delivered to the electrical network.

2.2.1 Aggregated BESS: With the flexible charging/discharging characteristics, BESS is considered as effective device to improve controllability not only of a wind farm, but also of the entire power system. The control and operation strategy of the BESS could be designed for different application purpose. Several aspects must be taken into account when integrating a BESS within a WECS such as technological capability, operation size, and interaction with other systems. The BESS integrated into the WECS can be configured either as an aggregated unit serving the entire wind farm or as distributed unit installed in each wind turbine generator. Owing to the smoothing effect of the spatial distribution of WECS, the fluctuation of the total wind farm power is lower than power output of every single wind turbine generator. Hence, an aggregated BESS outperforms a distributed BESS under the same capacity [26]. In this paper, these BESS configurations have been used to clarify the proposed hybrid operation strategy due to the above following reasons. Fig. 4 shows the configuration of wind ESS for the proposed hybrid operation strategy. Here, the symbols P_{BESS} , P_{wind} , and P_{total} are the output power of the BESS, the output power of the wind farm, and the combined power of the WECS and BESS, respectively. The aggregated BESS is charged/discharged through a power converter and is connected to the grid at the point of common coupling.

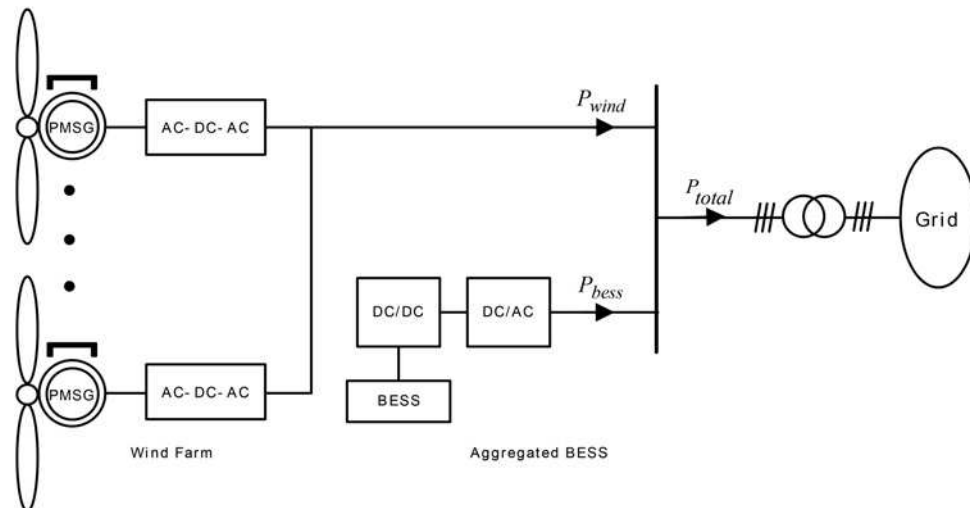


Fig. 4 Configuration of wind ESS

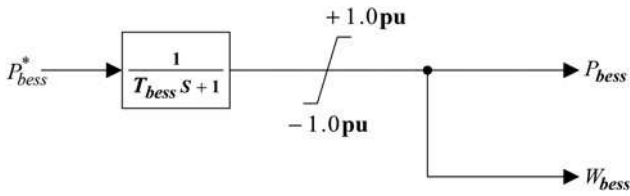


Fig. 5 BESS controller

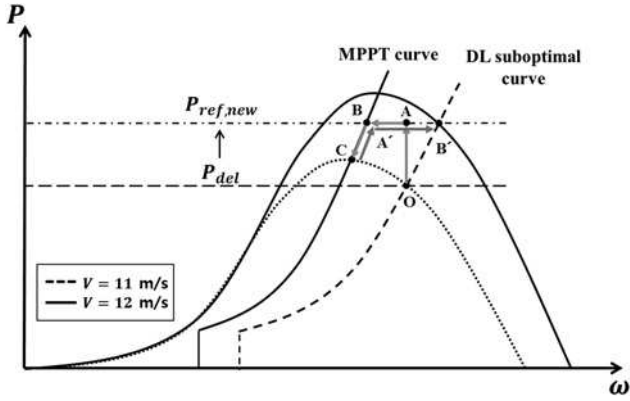


Fig. 6 DL suboptimal operating power point curve

2.2.2 BESS control: The main purpose of BESS control is not only to stabilise the power balance, but also to realise suitable management of energy storage so that the BESS does not become overloaded or run out of charge. Fig. 5 shows the block diagram of a controller for the BESS. In the BESS controller, P_{bess}^* is the output power command of the BESS, which is limited by the capacity. The SOC is calculated by integrating the power output of the BESS. T_{BESS} is a time constant, and W_{BESS} is the energy level of the BESS. Our study focused on relatively simple control considering the charge/discharge process and the SOC of the battery, without addressing the lifetime of the BESS. The basic controller design is used to keep the SOC of the battery in the proper range for reliable operation. Therefore, the SOC is maintained near 60% by the charge/discharge controller in this paper.

3 Proposed hybrid operation strategy

3.1 DL operation for optimal operating point

To participate in frequency regulation, it is necessary that the WECS should have sufficient power margin available at any instant. Thus, the PMSG wind generator needs to implement the DL operation to ensure a power margin. The DL control is dependent on the

application of the overspeeding technique at the right suboptimal curve. The DL power reference can be calculated as

$$P_{del} = K_{del} P_{max} \quad (19)$$

where

$$K_{del} = \left(1 - \frac{\%_{del}}{100}\right) \quad (20)$$

To utilise the proposed DL control method, the power margin P_{margin} can be calculated as

$$P_{margin} = P_{max} - P_{del} \quad (21)$$

Fig. 6 shows the DL optimal operating power point curve for a PMSG in high, medium, and low wind speed regions. To provide a power margin, the PMSG should operate along the 10% DL suboptimal curve. For a rated wind speed of $V = 11$ m/s, the PMSG should not operate at the maximum power point C, but instead at the point O, so that the system can obtain a 10% available power margin. If the frequency of the power system decreases, P_{del} becomes a new output reference, $P_{ref,new}$. The operating point is immediately moved from point O to point A using the KE reserve of the DL control. Then, the output is maintained during operation. At this time, the rotational speed should be continuously decreased because of the mismatch between the wind turbine output and the mechanical input. When point B is reached, the rotational speed and output are also decreased, following the MPPT curve. The rotational speed is stabilised at point C (the equilibrium point), which has equal mechanical output and the maximum possible power for the given rotational speed. This means that the system provides the maximum possible power until the frequency of the power system is stabilised. If the maximum possible power is higher than the output reference from the increased wind speed at 12 m/s, point C moves onto point A' to verify output reference, and then point A' moves to point B' to increase the rotational speed. The proposed DL operation is used to dynamically control the q -axis current of the MSC, as shown in Fig. 7. Here, f_{system} is the frequency of the power system, $f_{nominal}$ is the nominal frequency (60 Hz), and ω_r is the speed adjustment rate. In our paper, the DL operation consists of two modes: 90 and 95% of the suboptimal power curve.

3.2 Pitch angle control

Wind turbine systems typically operate at a wind speed ranging from 3 to 25 m/s, and the rated power can be extracted at a wind speed ranging from 12 to 16 m/s. The pitch angle controller is used to restrict the rotational speed to below the maximum speed. Fig. 8 shows the pitch angle controller used to regulate the rotational speed. When the generator power (or speed) is below the rated power (or the maximum speed), the pitch angle is set to zero to obtain maximum power. If the generated power is higher than the

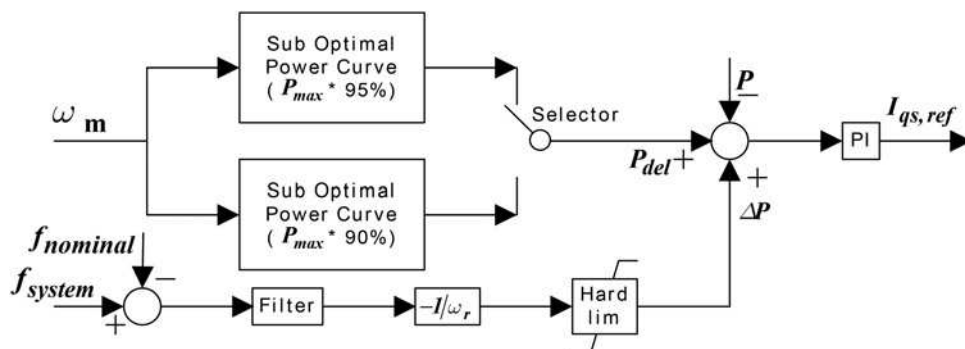


Fig. 7 Configuration of DL controller

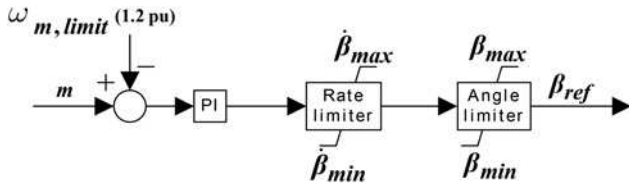


Fig. 8 Pitch angle controller

rated value, the pitch angle is adjusted to limit the power to the maximum rated value [27, 28]. This paper focuses on the $\omega_{m,limit}$ of 1.2 pu to consider the reliable operation range of the PMSG based on the current control of the MSC. The operating rotational speed should be limited between 0.7 and 1.2 pu. This controller adjusts the pitch angle on the basis of a comparison with ω_m and the reference pitch angle β_{ref} is defined by the PI controller.

3.3 Frequency support control

KE discharge control uses the characteristic of the full converter of the PMSG, which makes output control possible over a large operating range. When frequency control is required, it is also possible to receive additional power output from the KE, which is stored in the wind turbine and rotor [11]. However, excessive KE discharge control may rapidly decrease the rotational speed and cause instability in the PMSG. To solve this issue, the proposed frequency support control based on KE discharge control uses active power control to maintain system stability. It attempts to provide a larger contribution to the short-term frequency regulation by drawing from the KE reserve, which can be calculated as

$$KE_{res} = \frac{J}{2} (\omega_{del}^2 - \omega_{m,opt}^2) \quad (22)$$

where J is the moment of inertia of the wind turbine.

The KE reserve is sufficiently large that it can contribute significantly to frequency control. It can also improve the stable frequency recovery capability of the power system. Fig. 9 shows a schematic diagram of frequency support control. Under normal operating conditions, the PMSG attempts to control the output within the power margin in DL operation mode. If the frequency decreases because of disturbances in the power system, DL operation mode switches to KE discharge mode.

This change immediately increases the output P_{del} of the PMSG by the power increment ΔP_{KE} , and maintains its output by participating in frequency control during a support time $T_{support}$. In other words, P_{out} is increased by ΔP_{KE} and the rotational speed decreases because of KE discharge. The relationship between the mechanical output P_m and the rotational speed ω_m of the KE

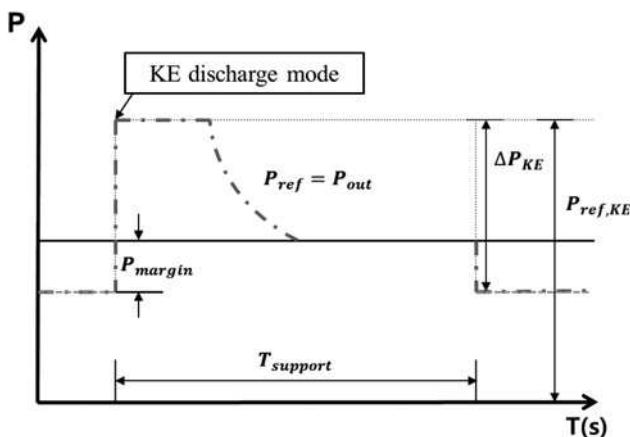


Fig. 9 Schematic diagram of frequency support control

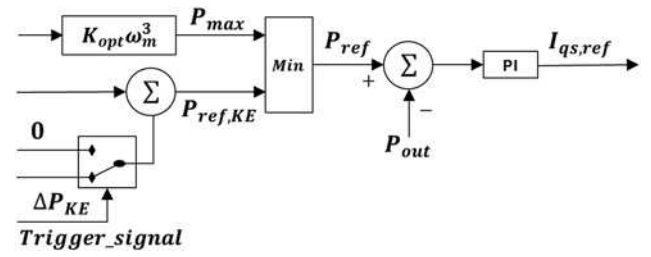


Fig. 10 Modified q -axis rotor current control

discharge control is defined as

$$J\omega_m \frac{d\omega_m}{dt} = P_m - (P_{ref} + \Delta P_{KE}) \quad (23)$$

When the output of the PMSG is equal to the maximum possible power, KE discharge mode operation must cease. After the PMSG has returned to normal operating conditions, the output can be recovered via the DL mode. Fig. 10 shows the modified rotor current control of the q -axis that performs the frequency support control. The trigger signal for changing to the KE discharge mode is determined according to the deviation of the frequency in the power system. The PMSG system operates as a KE discharge mode through the trigger signal when the critical frequency nadir is identified by the trigger module. Fig. 11 shows the frequency detection and trigger signal scheme; f_{ref} is the reference frequency. The event detector measures the power system frequency and the rate of change of frequency (ROCOF). It generates a trigger signal by continuous comparison of the predefined threshold value and the measured system frequency value. The ROCOF of the power system at the initial frequency event is determined as

$$\frac{df_{system}}{dt} = \frac{2H_{system}}{\Delta P_{loss} \cdot f_{nominal}} \quad (24)$$

where H_{system} is the equivalent inertia of the entire power system and ΔP_{loss} is the lacked active power under a grid fault. Equation (24) indicates that the amount of lacked active power can be calculated using the ROCOF of the power system and it represents the security index of the grid fault.

3.4 BESS operation

The main objectives of operating the active power charge/discharge using the BESS are to stabilise WECS operation and create suitable management of energy storage, thereby maintaining a balance between the wind power and load demand. Reliable BESS operation is required such that the battery should be neither completely discharged nor overcharged. Thus, the BESS must be kept within the proper SOC levels to ensure the battery lifetime [29]. According to the load profiles, BESS operation can be divided into discharging, charging, and float modes. If the generated power is larger than the load demand, the extra energy is stored in the battery for future use. On the other hand, when the

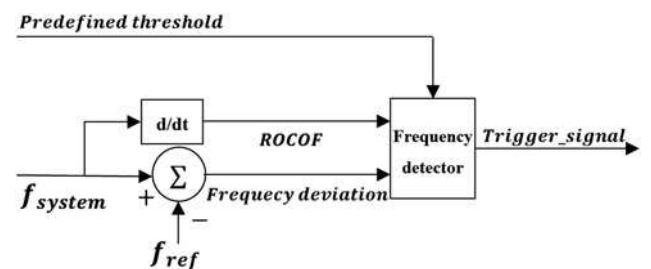


Fig. 11 Frequency detection and trigger signal scheme

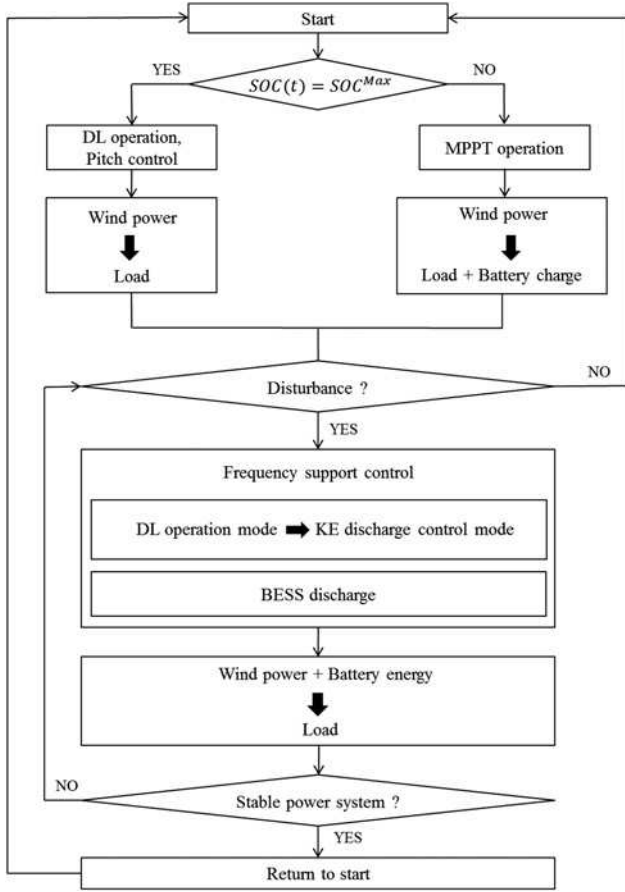


Fig. 12 Procedure of hybrid operation strategy

generated power is smaller than the load demand, the battery discharges the stored energy to the power system. Float mode is defined as that in which the generated power is equal to the load demand. Under the three-mode operation, the BESS can improve the reliability and stability of the wind power system and level the output of the wind generator against frequency fluctuation. The active power applied to the BESS is determined as

$$P_{\text{bess}} = P_{\text{load}} - P_{\text{wind}} \quad (25)$$

where P_{load} is the load demand and P_{wind} is the generated power output of the wind farm.

Another important issue regarding the BESS can easily be depleted or overcharged if the battery does not take SOC of limits. The SOC of the battery should be kept within proper limits (i.e. between 30 and 90%) and needs to be determined accurately for the BESS operation. The operation of BESS is subject to the following limitations

$$P_{\text{BESS}}^{\text{Chr, Max}} \leq P_{\text{BESS}}(t) \leq P_{\text{BESS}}^{\text{Dis, Max}} \quad (26)$$

$$\text{SOC}^{\text{Min}} \leq \text{SOC}(t) \leq \text{SOC}^{\text{Max}} \quad (27)$$

where $P_{\text{BESS}}^{\text{Chr, Max}}$ and $P_{\text{BESS}}^{\text{Dis, Max}}$ represent the maximum allowable charge and discharge powers for the BESS, and SOC^{Min} and SOC^{Max} are the minimum and maximum limits of SOC of the BESS, respectively.

SOC(t) and the energy charging process of the BESS are calculated as

$$\text{SOC}(t) = \frac{E_{\text{BESS}}(t)}{E_{\text{rated, BESS}}} \quad (28)$$

$$E_{\text{BESS}}(t+1) = E_{\text{BESS}}(t) + \Delta t \cdot P_{\text{BESS}}(t) - |P_{\text{BESS}}(t)| \cdot \eta_c \cdot \Delta t - E_{\text{BESS}}(t) \cdot \eta_l \cdot \Delta t \quad (29)$$

where E_{BESS} is the energy stored in the BESS, $E_{\text{rated, BESS}}$ is the rated energy capacity of the BESS, and η_c and η_l are the charge loss (%) and leakage loss factors (%/month) of the BESS, respectively. The SOC should always be maintained in the proper range for stable operation.

3.5 Strategy procedure

As shown in Fig. 12, the proposed operation strategy is implemented in a sequential manner.

Step 1: If the BESS reaches the maximum SOC limits, the WECS enters the DL operation to maintain the power margin. In addition, when the wind speed is greater than the rated wind speed, the pitch angle controller controls the output of the WECS within the rated power. Then, the WECS provides wind power to meet the load demand of the electrical network.

Step 2: If the SOC of the BESS is not at its maximum limit, the wind turbine extracts the maximum power according to wind speed variation. The WECS supplies the wind power to the load, and the BESS is charged by the wind power.

Step 3: If a frequency disturbance occurs, frequency support control exploits the additional power output from KE stored in the wind turbine and rotor. The WECS can also contribute to frequency control by using the power margin of DL operation. Discharging of the BESS is changed to satisfy the load demand.

Step 4: If the power system becomes stable through compensation by the operation strategy, then the system return to starting point. Otherwise, it goes to step 3. The wind power is used to charge the discharged BESS according to MPPT operation.

4 Simulation results

To verify the performance of the hybrid operation strategy of a WECS with a BESS, the following cases are considered

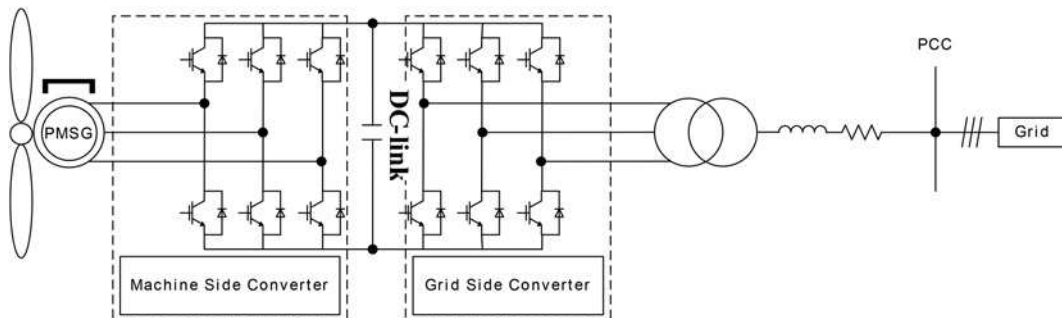


Fig. 13 Configuration in Case 1

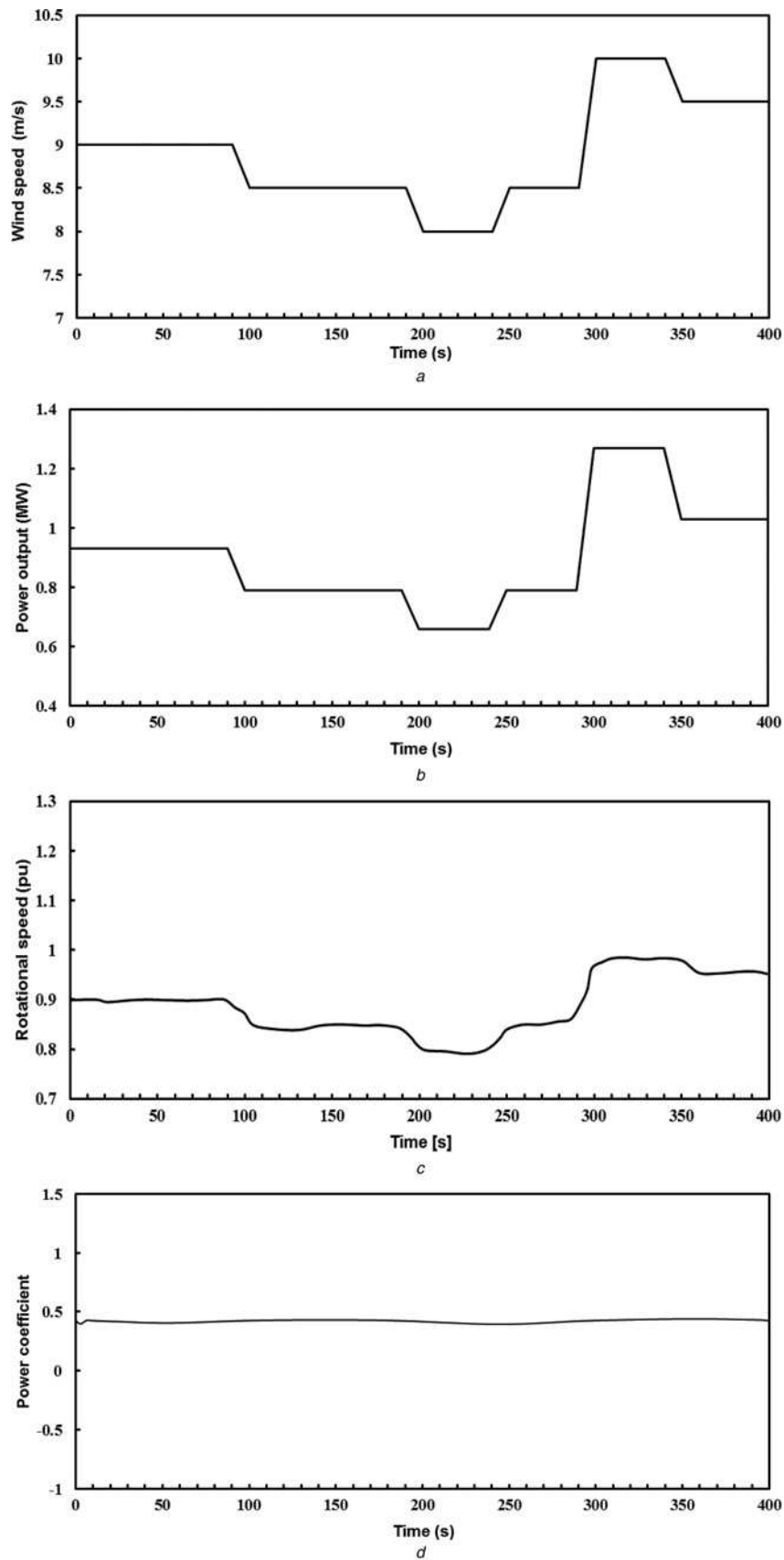


Fig. 14 Experimental results of WECS

- a Wind speed
- b Active power
- c Rotational speed
- d Power coefficient
- e TSR
- f Reactive power
- g DC-link voltage

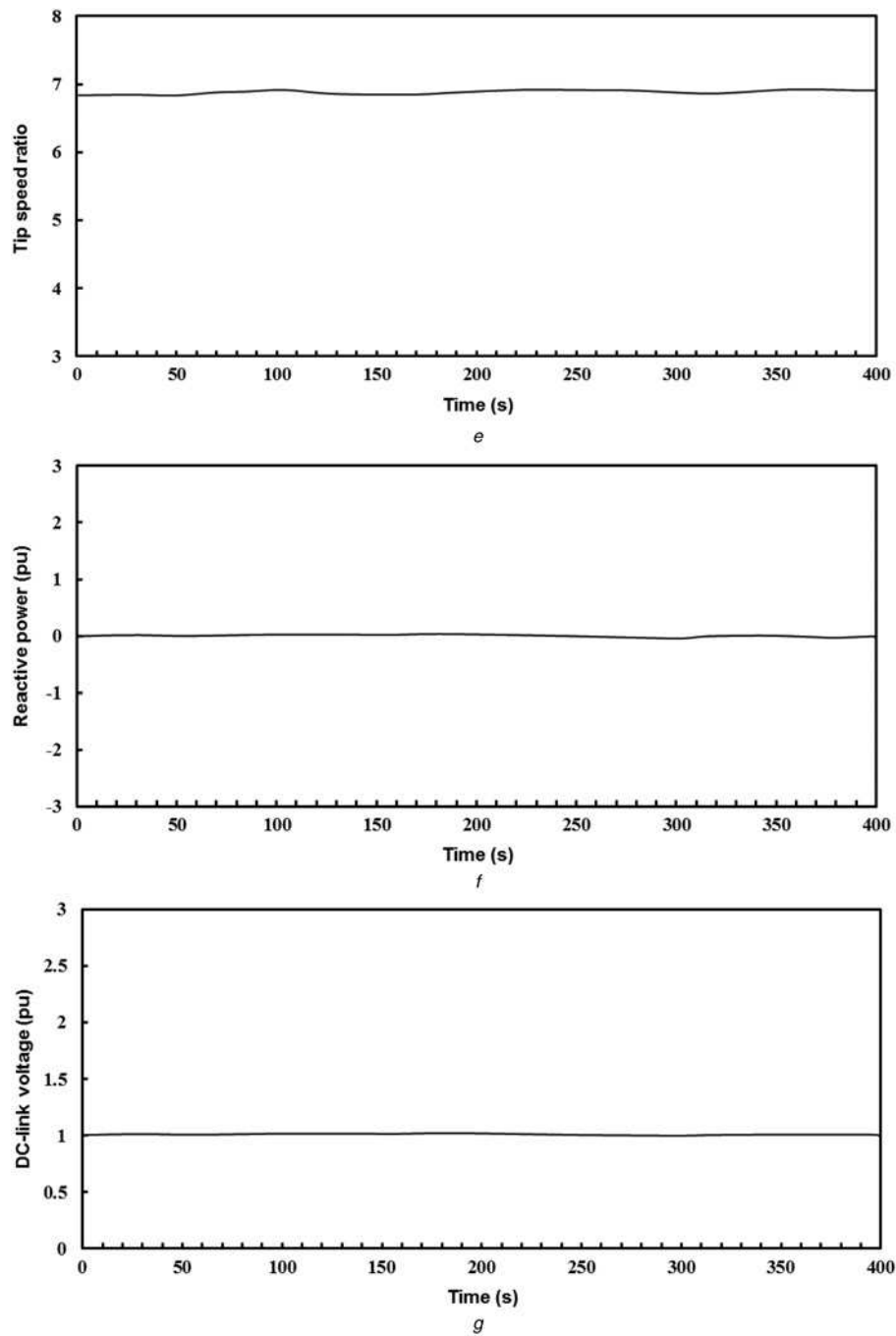


Fig. 14 Continued

Case 1: Response of a single 2 MW PMSG connected to an infinite bus.

Case 2: Performance of hybrid operation strategy according to the load condition.

These cases were studied to simulate the model for several wind speed variations. In this simulation, the performance of the controller was evaluated using PSCAD/EMTDC. The relevant parameters for the simulations are presented in the Appendix.

4.1 Case 1

In this case, a single 2 MW PMSG was used to examine active power control of the WECS for the desired power references. Fig. 13 shows the configuration in Case 1, which includes a wind turbine model and an integrated controller. Fig. 14 shows the experimental results of the

WECS. This simulation was conducted by applying a series of ascending and descending speed steps to the wind speed, as shown in Fig. 14a.

Figs. 14b and c show the active power and rotational speed responses during wind speed variation. The wind turbine operated at its maximum power coefficient and the pitch angle was kept at its optimal value. The measured active power loop accurately followed the desired reference. This result confirmed that the simulation was able to reach the maximum power point. Figs. 14d and e show the power coefficient and TSR, which are close to its maximum value during the wind speed profile. The efficiency of the maximum power extraction can be clearly observed as the power coefficient is fixed at the optimal value, $C_p = 0.4412$ and $\lambda = 6.9$. Figs. 14f and g show the resulting reactive power and DC-link voltage of the generator. The WECS operated at zero reactive power (unity power factor) during the entire simulation. The reactive power at the MSC was controlled to minimise the

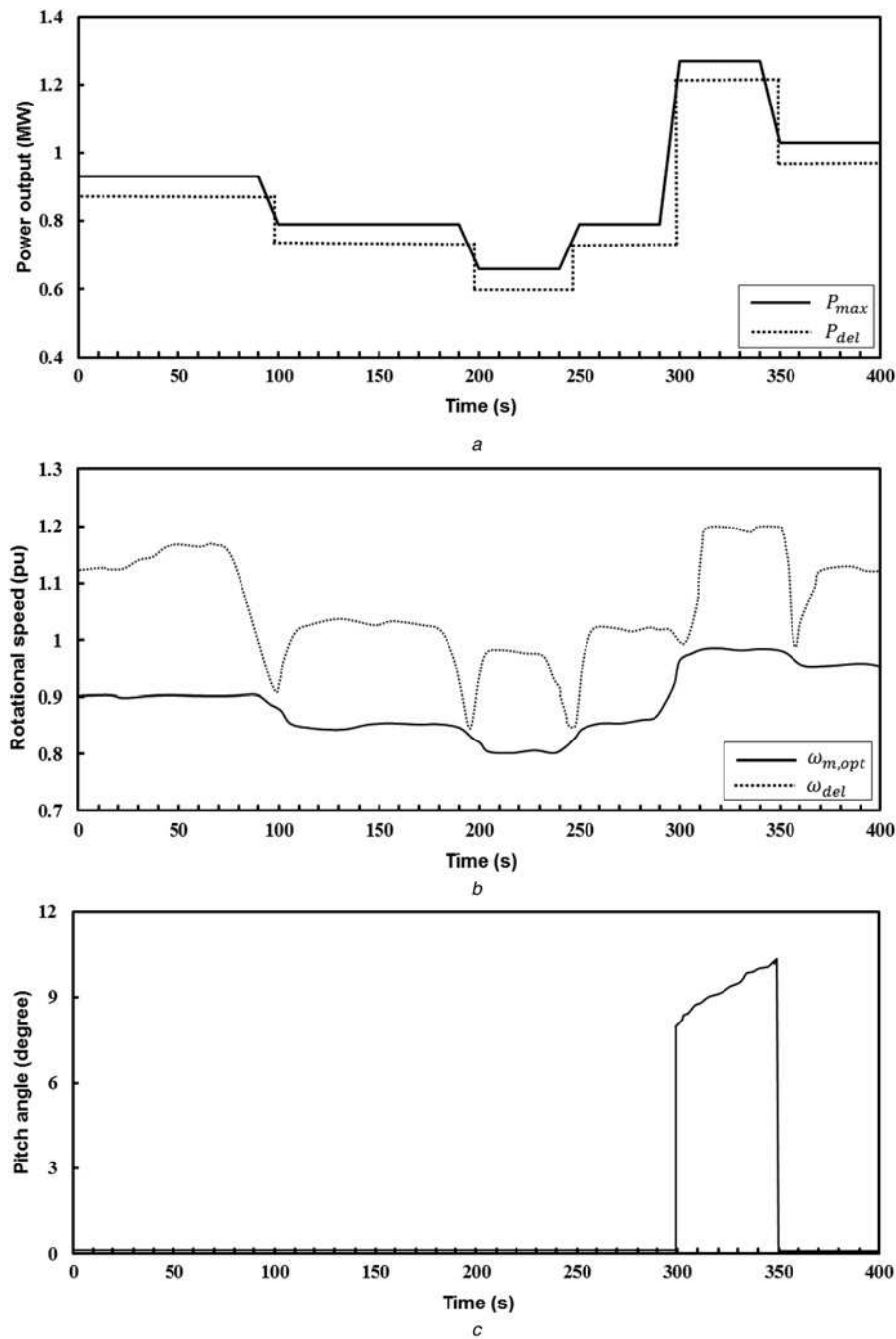


Fig. 15 Experimental results of WECS in DL operation mode 1

a Active power
b Rotational speed
c Pitch angle

power loss of the generator and to keep a constant voltage. The DC-link voltage controller tried to maintain the constant value over the simulation period so that the DC-link voltage had an almost constant value of 1 pu.

To evaluate the capability of the DL control, the WECS was controlled by the DL operation mode to obtain the power margin during 400 s. Fig. 16 shows the responses of the WECS in DL operation mode. Figs. 15a and b show the active power and rotational speed of WECS. The WECS was expected to operate at 5% initial DL operation. The rotational speed increased rapidly, while the active power decreased. It is noted that the additional KE reserve can be obtained from the rotating mass. Fig. 15c shows the performance of the pitch angle. When the PMSG wind turbines operated at DL operation mode near the rated wind speed,

the rotational speed was limited to the maximum rotational speed of 1.2 pu using pitch angle control. It was confirmed that the rotational speed was properly controlled within the allowable range (0.7–1.2 pu). The rotational speed loop follows the optimal speed within a limitation that is regulated by the pitch angle controller.

4.2 Case 2

To verify the performance of the hybrid operation strategy for a WECS with a BESS, the wind ESS in this case consists of a wind farm based on PMSG wind turbines and the aggregated equivalent of the BESS connected to the power system at the point of

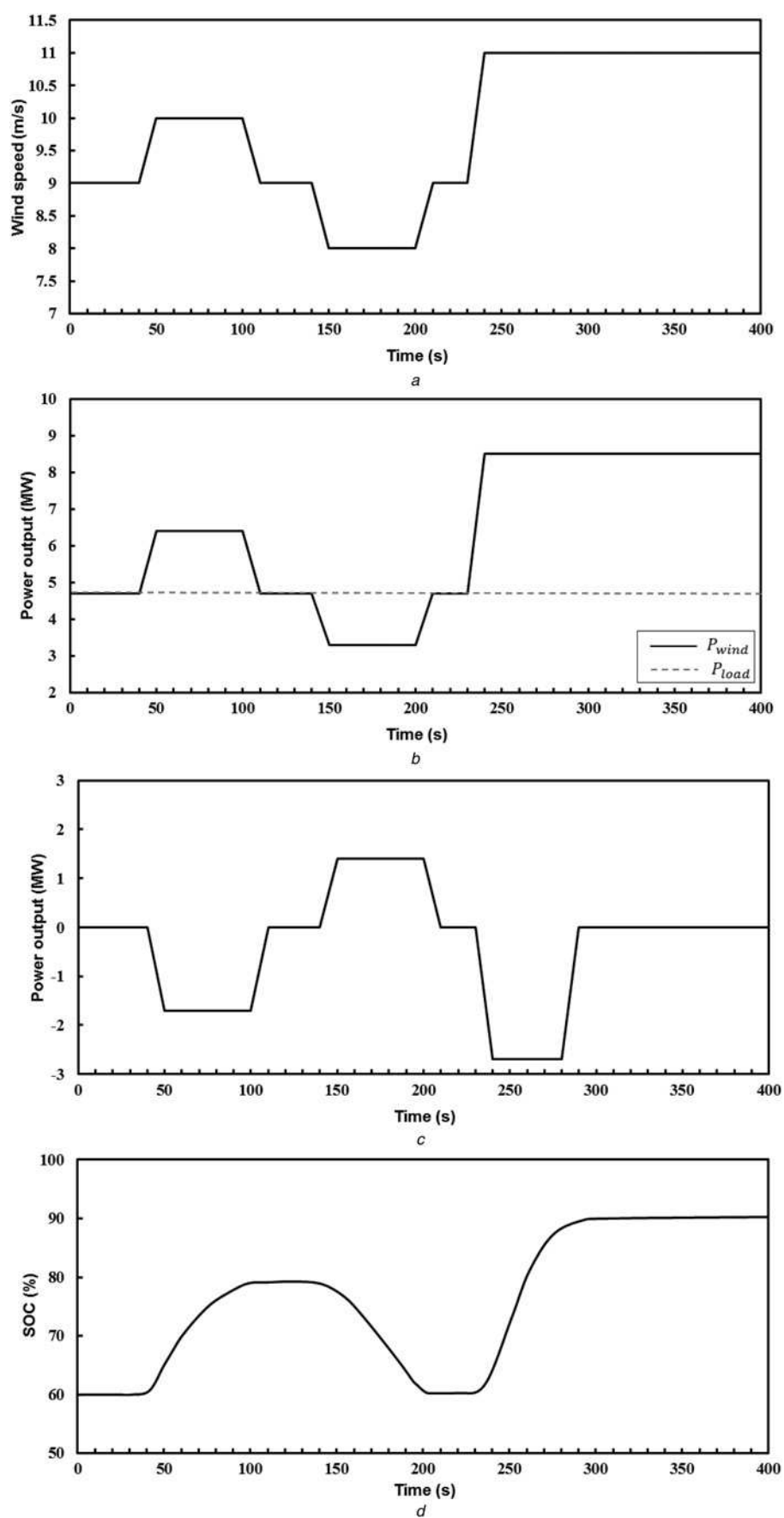


Fig. 16 Experimental results of wind ESS at a constant load

a Wind speed
b Active power of wind farm
c Power output of BESS
d SOC of BESS

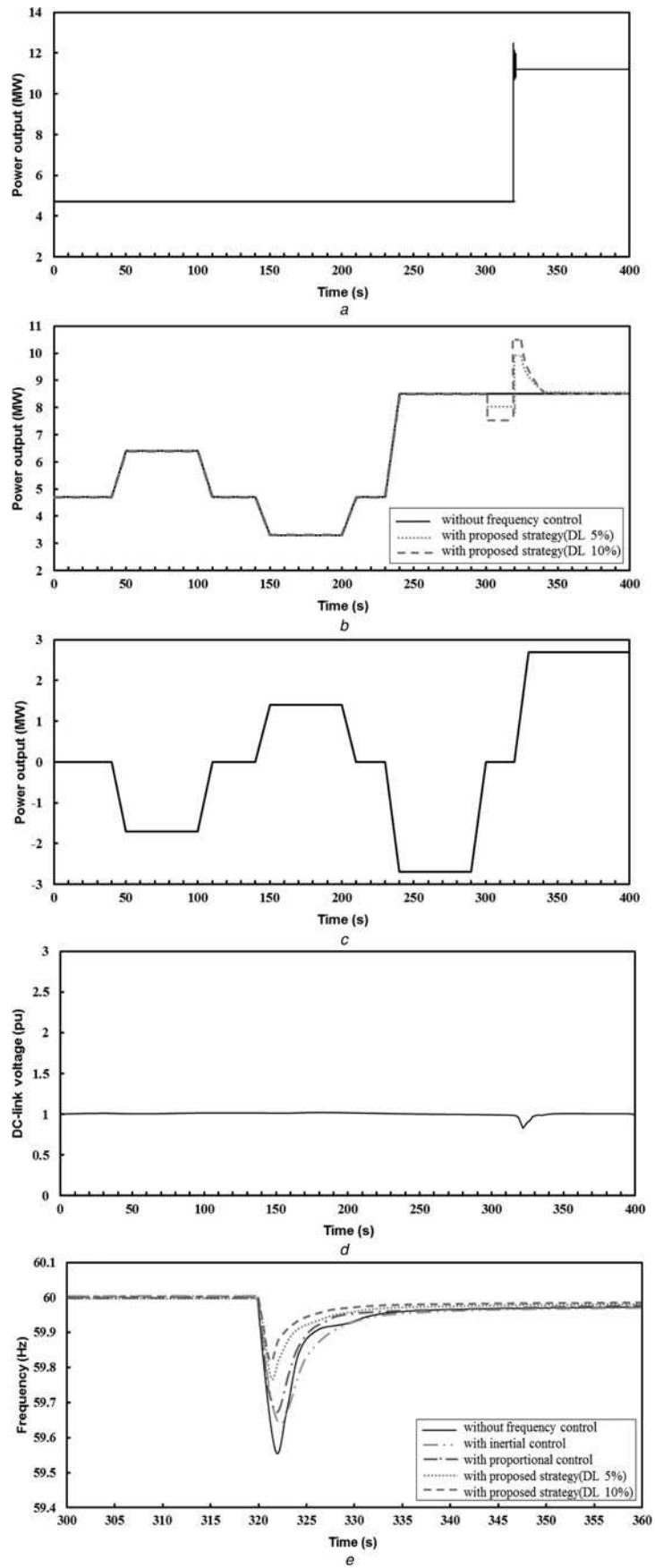


Fig. 17 Experimental results of wind ESS during a load variation

a Load demand
b Active power of wind farm
c Power output of BESS
d DC-link voltage
e Frequency responses

common coupling, as shown in Fig. 4. The wind farm is composed of five PMSGs; the rated power of all the PMSGs is 2 MW. The capacity of the BESS was determined by the fluctuation amplitude of the wind power. It is assumed that the capacity was set to 3 MW/1.5 MWh according to the 30% fluctuation amplitude of a 10 MW wind farm.

The proposed hybrid operation strategy was tested under a variable wind speed, as shown in Fig. 16a. Fig. 16b shows the measured active power from the wind farm based on the PMSG wind turbines, where the load demand is set to 4.7 MW. When the wind speed changed, the power output of the wind farm was sometimes lower than the load demand. However, this shortage of power was compensated for BESS operation in both charging and discharging modes, as depicted in Fig. 16c. Fig. 16d shows the SOC of the battery. The SOC was varied to satisfy the load demand. The initial charge of the battery was assumed to be 60% owing to the short simulation time. The simulated results show that wind ESS performed well, enabling the desired operation of the wind farm with a BESS.

A simulation test was also conducted in which the power system experienced a disturbance, as shown in Fig. 17. The proposed strategy was implemented using the three-mode operation:

Mode 1: The generated power of the wind farm is almost equal to the load demand, and it is confirmed that the BESS is not operated during this phase.

Mode 2: The generated power of the wind farm is greater than the load demand. The power gap in this range is balanced by the BESS. If the BESS is fully charged, the wind farm is operated in DL operation mode to obtain the power margin.

Mode 3: The generated power of the wind farm is less than the load demand. However, the KE reserve and BESS compensate for the power imbalance between the wind power and the load demand.

The load power, which is initially set to 4.7 MW, is presented in Fig. 17a. After $t = 320$ s, the power output of the load demand was suddenly increased to 11.2 MW by a system disturbance. Fig. 17b shows the active power of the wind farm using the coordinated control (DL 5 and 10%). When the battery storage reached its full capacity, the wind farm operated at 5 or 10% of the initial DL operation according to the wind speed at 300 s. The active power was reduced using the available overspeeding technique on the right suboptimal curve. At $t = 320$ s, the DL operation mode changed to the KE discharge mode because of a sudden increase in the load demand, thus releasing additional KE. It can be seen that the wind farm not only provides additional output to contribute to frequency control during a support time, but also operates in an MPPT control mode after the KE reserve is exhausted. Fig. 17c shows the output power of the BESS. The BESS was charged and discharged according to the power demand. Its power was increased to compensate for the difference between the wind farm output and the load demand. This means that the load demand is met by the BESS power supply, even under a lower wind speed. When the BESS is fully charged, the excess low-frequency power component should be absorbed by the dump load. Fig. 17d shows the DC-link voltage under load condition. It can be seen that the DC-link voltage is regulated near 1.0 pu with DC-link voltage controller and then has a very small variation. During the frequency support process, the DC-link voltage was well controlled.

Fig. 17e shows the grid frequency responses for the load increase. For comparative evaluation of the proposed strategy, two frequency regulation strategies were simulated. One is the well-known inertial control approach [8] and the other strategy used for comparison is based on proportional control [6]. When frequency drops because of the load increase, the minimum frequency responses of inertial control and proportional control were 59.65 and 59.68 Hz. Then, the grid minimum frequency with the proposed strategy DL operation 5 and 10% are improved from 59.55 to 59.76 and 59.82 Hz, respectively. These results indicate that the proposed approach can provide greater support in improving the minimum grid frequency than other controls. The proposed strategy managed to

inject much more KE compared with the other approaches. It can be observed that the proposed strategy had greater efficiency, a better transient response and more stability than other approaches. It could also help to increase system robustness by reducing frequency fluctuation under load demand. The BESS operation was an important factor for the effectiveness and feasibility of the proposed strategy. The hybrid control strategy can potentially be beneficial to system frequency response. Consequently, the proposed approach can not only supply more power to slightly improve the system frequency response, but also further develop the frequency support capability of a wind ESS.

5 Conclusion

This paper proposed the hybrid operation strategy for a WECS with BESS to support frequency control. The WECS was designed to have a PMSG model and integrated converter control. The aggregated BESS is connected to the WECS. Active power control focused on achieving MPPT and using DL operation to obtain a power margin. Frequency support control based on KE discharge control was used to enhance the frequency support capability. The output power command of the BESS was determined by three factors: the SOC, frequency deviation, and load variation. The effectiveness of the proposed approach was verified by simulation results. In the hybrid operation strategy, coordinated control of the WECS not only provided a power margin reserve by the DL suboptimal extraction curve, but obtained a KE reserve that is stored in the rotor. The good performance of the BESS provided a charge/discharge mode to maintain the power balance between the generation and load demand. The proposed hybrid operation strategy can also reduce the frequency deviations in a power system and achieve flexible, stable operation of the WECS and BESS. Consequently, the proposed operation strategy can significantly improve the initial and low-frequency response, and it makes a superior contribution to short-term frequency regulation. In the future, we will study an optimization method to greatly improve the frequency support capability of the WECS with BESS.

6 Acknowledgment

This research was supported by Korea Electric Power Corporation through Korea Electrical Engineering & Science Research Institute. This research was also supported by the Chung-Ang University Research Scholarship Grants in 2014.

7 References

- Heier, S.: 'Grid integration of wind energy conversion systems' (John Wiley & Sons, Chichester, England, 2006, 2nd edn.)
- Fernandez, L.M., Garcia, C.A., Jurado, F.: 'Comparative study on the performance of control systems for doubly fed induction generator (DFIG) wind turbines operating with power regulation', *Energy*, 2008, **33**, (9), pp. 1438–1452
- Chinchilla, M., Arnaltes, S., Burgos, J.C.: 'Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid', *IEEE Trans. Energy Convers.*, 2006, **21**, (1), pp. 130–135
- Zhang, S., Tseng, K.J., Vilathgamuwa, D.M., *et al.*: 'Design of a robust grid interface system for PMSG-based wind turbine generators', *IEEE Trans. Ind. Electron.*, 2011, **58**, (1), pp. 316–328
- Alaboudy, A.H.K., Daoud, A.A., Desouky, S.S., *et al.*: 'Converter controls and flicker study of PMSG-based grid connected wind turbines', *Ain Shams. Eng. J.*, 2013, **4**, (1), pp. 75–91
- Ramtharan, G., Ekanayake, J.B., Jenkins, N.: 'Frequency support from doubly fed induction generator wind turbines', *IET Renew. Power Gener.*, 2007, **1**, (1), pp. 3–9
- Ekanayake, J., Holdsworth, L., Jenkins, N.: 'Control of DFIG wind turbines', *Power Eng.*, 2003, **17**, (1), pp. 28–32
- Morren, J., de Haan, S.W.H., Kling, W.L., *et al.*: 'Wind turbines emulating inertia and supporting primary frequency control', *IEEE Trans. Power Syst.*, 2006, **21**, (1), pp. 433–434
- Chien, L.R.C., Lin, W.T., Yin, Y.C.: 'Enhancing frequency response control by DFIGs in the high wind penetrated power systems', *IEEE Trans. Power Syst.*, 2011, **26**, (2), pp. 710–718
- Almeida, R.G., Lopes, J.A.P.: 'Participation of doubly fed induction wind generators in system frequency regulation', *IEEE Trans. Power Syst.*, 2007, **22**, (3), pp. 944–950

- 11 Keung, P.K., Li, P., Banakar, H., *et al.*: 'Kinetic energy of wind turbine generators for system frequency support', *IEEE Trans. Power Syst.*, 2009, **24**, (1), pp. 279–287
- 12 Sebastian, R., Alzola, R.P.: 'Effective active power control of a high penetration wind diesel system with a Ni–Cd battery energy storage', *Renew. Energy*, 2010, **35**, (5), pp. 952–965
- 13 Howlader, A.M., Izumi, Y., Uehara, A., *et al.*: 'A minimal order observer based frequency control strategy for an integrated wind-battery-diesel power system', *Energy*, 2012, **46**, (1), pp. 168–178
- 14 Khalid, M., Savkin, A.V.: 'An optimal operation of wind energy storage system for frequency control based on model predictive control', *Renew. Energy*, 2012, **48**, (1), pp. 127–132
- 15 Serban, I., Teodorescu, R., Marinescu, C.: 'Energy storage systems impact on the short-term frequency stability of distributed autonomous microgrids, an analysis using aggregate models', *IET Renew. Power Gener.*, 2013, **7**, (5), pp. 531–539
- 16 Virulkar, V., Aware, M.: 'Integrated battery controller for distributed energy system', *Energy*, 2011, **36**, (5), pp. 2392–2398
- 17 Dali, M., Belhadj, J., Roboam, X.: 'Hybrid solar-wind system with battery storage operating in grid-connected and standalone mode: control and energy management – experimental investigation', *Energy*, 2010, **35**, (6), pp. 2587–2595
- 18 Ekren, B.Y., Ekren, O.: 'Simulation based size optimization of a PV/wind hybrid energy conversion system with battery storage under various load and auxiliary energy conditions', *Appl. Energy*, 2009, **86**, (9), pp. 1387–1394
- 19 Lin, W.M., Hong, C.M.: 'Intelligent approach to maximum power point tracking control strategy for variable-speed wind turbine generation system', *Energy*, 2010, **35**, (6), pp. 2440–2447
- 20 Tan, K., Islam, S.: 'Optimum control strategies in energy conversion of PMSG wind turbine system without mechanical sensors', *IEEE Trans. Energy Convers.*, 2004, **19**, (2), pp. 392–399
- 21 Li, S., Haskew, T.A., Xu, L.: 'Conventional and novel control designs for direct driven PMSG wind turbines', *Electr. Power Syst. Res.*, 2010, **80**, (1), pp. 328–338
- 22 Morimoto, S., Nakayama, H., Sanada, M., *et al.*: 'Sensorless output maximization control for variable-speed wind generation system using IPMSG', *IEEE Trans. Ind. Appl.*, 2005, **41**, (1), pp. 60–67
- 23 Qiao, W., Qu, L., Harley, R.G.: 'Control of IPM synchronous generator for maximum wind power generation considering magnetic saturation', *IEEE Trans. Ind. Appl.*, 2009, **45**, (3), pp. 1095–1105
- 24 Fernandez, L.M., Garcia, C.A., Jurado, F.: 'Operating capability as a PQ/PV node of a direct-drive wind turbine based on a permanent magnet synchronous generator', *Renew. Energy*, 2010, **35**, (11), pp. 1308–1318
- 25 Krishnan, V., Das, T., McCalley, J.D.: 'Impact of short-term storage on frequency response under increasing wind penetration', *J. Power Sources*, 2014, **257**, (1), pp. 111–119
- 26 Li, W., Joos, G.: 'Comparison of energy storage system technologies and configurations in a wind farm', *IEEE Power Electron. Spec. Conf.*, 2007, **17**, (21), pp. 1280–1285
- 27 Jannati, M., Hosseini, S.H., Vahidi, B., *et al.*: 'A survey on energy storage resources configurations in order to propose an optimum configuration for smoothing fluctuations of future large wind power plants', *Renew. Sustain. Energy Rev.*, 2014, **29**, pp. 158–172
- 28 Conroy, J.F., Watson, R.: 'Frequency response capability of full converter wind turbine generators in comparison to conventional generation', *IEEE Trans. Energy Syst.*, 2008, **23**, (2), pp. 649–656
- 29 Johnston, L., Diaz-Gonzalez, F., Gomis-Bellmunt, O., *et al.*: 'Methodology for the economic optimisation of energy storage systems for frequency support in wind power plants', *Appl. Energy*, 2015, **137**, (1), pp. 660–669

Table 1 Wind turbine model parameters

Parameter	Notation	Value
blade radius	R	39 m
air density	ρ	1.225 kg/m ³
maximum	$C_{p, \text{opt } t}$	0.4412
rated wind speed	V_{rated}	12 m/s

Table 2 PMSG generator model parameters

Parameter	Notation	Value
rated generator power	$P_{m, \text{rated}}$	2 MW
rated RMS line-to-line voltage	$V_{m, \text{rated}}$	0.69 kV
rated machine speed	$\omega_{m, \text{rated}}$	376.99 rad/s
pole pairs	P	11
generator and turbine inertia const.	H	5.7267 s
PM flux	Ψ_f	136 Wb
stator d -axis inductance	L_{md}	0.334 H
stator q -axis inductance	L_{mq}	0.217 H
stator leakage inductance	L_{si}	0.0334 H
stator resistance	R_s	0.08 Ω

8 Appendix

See Tables 1 and 2.