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State-of-the-art review on frequency response of wind power plants in power systems

Ziping WU[1], Wenzhong GAO[1], Tianqi GAO[1], Weihang YAN[1],
Huaguang ZHANG[2], Shijie YAN[2], Xiao WANG[2]

Abstract With an increasing penetration of wind power in the modern electrical grid, the increasing replacement of large conventional synchronous generators by wind power plants will potentially result in deteriorated frequency regulation performance due to the reduced system inertia and primary frequency response. A series of challenging issues arise from the aspects of power system planning, operation, control and protection. Therefore, it is valuable to develop variable speed wind turbines (VSWTs) equipped with frequency regulation capabilities that allow them to effectively participate in addressing severe frequency contingencies. This paper provides a comprehensive survey on frequency regulation methods for VSWTs. It fully describes the concepts, principles and control strategies of prevailing frequency controls of VSWTs, including future development trends. It concludes with a performance comparison of frequency regulation by the four main types of wind power plants.

Keywords Wind power plant, Inertial response, Primary frequency control, Automatic generation control (AGC), Variable speed wind turbine (VSWT)

1 Introduction

With an increasing penetration of wind energy incorporated into the existing utility grid, as well as scheduled retirement of fossil-fuelled power plants, system frequency regulation capability tends to deteriorate in the event of severe frequency disturbance. This is due to absence of inertial response and ancillary frequency support by a substantial amount of variable speed wind turbines (VSWTs) [1, 2], including doubly-fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSGs).

To achieve a reliable, secure and economic operation, the electrical grid is required to maintain the system frequency around the nominal value within a predetermined range at all times. As wind power plants (WPPs) gradually displace conventional synchronous generators in service, WPPs are expected to provide auxiliary frequency regulation capabilities through their fast and flexible active power control [3]. Currently, Regional Transmission Organizations (RTOs), Independent System Operator (ISOs) or equivalent entities in many countries come to realize the potential benefits of inertial response and frequency regulation from wind turbine generators (WTG) in maintaining

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✉ Wenzhong GAO
Wenzhong.Gao@du.edu

Ziping WU
wzpbsb@gmail.com

Tianqi GAO
sgao646@gmail.com

Weihang YAN
weihang.yan@gmail.com

Huaguang ZHANG
hgzhang@ieee.org

Shijie YAN
yanshijie@mail.neu.edu.cn

Xiao WANG
wangxiao.owl@gmail.com

[1] Department of Electrical and Computer Engineering, University of Denver, Denver, CO 80208, USA

[2] School of Information Science and Engineering, Northeastern University, Shenyang 110819, China

the dynamic active power balance between power supply and demand. So, a large number of wind generators equipped with frequency regulation functions are expected to be integrated into power systems, which in turn yields extra benefits by providing various ancillary services. With a great potential demand in the power market, wind plant manufacturers are encouraged to further improve the auxiliary frequency controls for VSWTs as well. In addition, especially when wind power needs to be dispatched down in case of low load and high wind speed or due to other operational constrains, a large amount of untapped wind power can be fully utilized as spinning reserve to support temporary frequency response in the event of severe disturbances [4]. For these reasons, a win-win solution can be achieved by implementing the frequency control methods into VSWTs, providing benefits to wind power plant owners, wind turbine manufacturers and power grid operators [5–10].

The main contributions of this work is a comprehensive survey on state-of-the-art inertial response and frequency regulation methods of VSWTs is conducted based on a great number of up-to-date literatures. It systematically introduces and evaluates different types of frequency control strategies in terms of their fundamental principle and control structure. Several key future development trends are discussed. Last but not least, the advantages and disadvantages of frequency regulation performance are compared for four common types of wind power plants.

2 Wind turbine inertial control

In principle, grid frequency response can be divided into four regulation stages in terms of different time scales: inertial response, primary frequency response, secondary frequency response and tertiary frequency response as illustrated in Fig. 1 [11]. Different control methods for maximum power point tracking (MPPT) operation are implemented in the rotor-side converter of VSWTs, consisting of torque-based, active power-based and rotor speed-based converter control [10, 12–16]. To make VSWTs properly perform the frequency regulation function following specific frequency regulation requirements, supplementary controllers should be designed and integrated into both the existing converter power control loop and the pitch angle control loop to manipulate the corresponding reference set points of torque, active power or rotor speed [12–19].

Due to a sudden and large power supply-demand imbalance, power system frequency changes at a certain rate initially determined by the cumulative inertia of all spinning generations (synchronous generators) and composite load damping (motor, pumps etc.) [20–22]. The

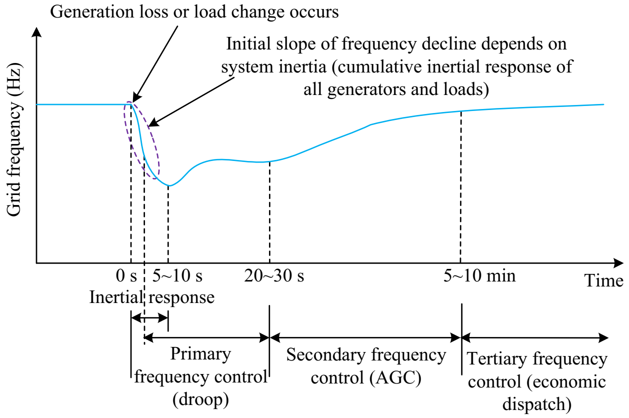

Fig. 1 Schematic diagram of comprehensive frequency control following a large generation loss or sudden load change based on EPRI

kinetic energy stored in the rotating mass of both wind turbine (WT) blades and generator rotors can be extracted through power converter control and then delivered into the power grid to arrest the rate of change of frequency (ROCOF). The typical value of wind turbine inertia is approximately 3.5 s [23]. It is worth noting that threshold value for ROCOF response is usually set in the range between 0.1 and 1.2 Hz/s for 60 Hz system or in the range between 0.1 and 1 Hz/s for 50 Hz system, and the delay time varies from 50 to 500 ms [24, 25].

Immediately following the frequency nadir, the kinetic energy extracted from rotating mass needs to be regained from currently available wind power so that the WT rotor speed and kinetic energy return to their pre-disturbance values or new optimal operation conditions. In this sense, WT inertial control is called an “energy neutral process” although the total amount of recovery energy seems larger than that of inertial response as a result of WT mechanical and electrical power losses [25]. During this recovery process, a secondary frequency drop (SFD) is likely to occur due to the reduced output power. That is to say, a large aggregated energy recovery from wind power plants performing inertial response may result in a severe SFD where the frequency drop is even lower than the initial frequency nadir in the under-frequency event [26–36]. With respect to the inertial recovery process, primary factors that determine its dynamic characteristics include the enabling time to reduce active power, the decreased power as a percentage of rated power (or percentage of actual power output for the inertial power recovery stage) as well as the duration of such wind power reduction [26]. A method that mitigates the SFD and assists the inertial response recovery is to extract the stored energy from the DC-link capacitors by properly reducing the DC-link voltage in proportion to the frequency deviation Δf when WTG starts to recover its rotor speed [37].

According to (1), the amount of kinetic energy ΔE for inertial response of a single wind turbine is a function of initial rotor speed ω_0; rotor speed reduction $\Delta\omega = \omega_0 - \omega_1$, $\Delta\omega > 0$; moment of inertia of wind turbine J and inertial response duration $(t_0 - t_1)$ [3, 38].

$$\begin{aligned}\Delta E_{in} &= \int_{t_0}^{t_1} \Delta P_{in}(t)\mathrm{d}t = \frac{1}{2}J(\omega_0^2 - \omega_1^2) \\ &= \frac{1}{2}J(2\omega_0\Delta\omega - \Delta\omega^2)\end{aligned} \tag{1}$$

The inertial response performance of a WPP is typically dependent on the wind power penetration level, the number of WTGs capable of providing inertial response, the initial operation mode of individual WTGs (under full load or partial load) as well as WTGs' physical characteristics. Relevant characteristics include upper and lower limits for rotor speed, over-loading capability of power converters, auxiliary frequency controller parameters and maximum power rate limit $(\mathrm{d}P/\mathrm{d}t)_{\max}$ [4, 31, 32, 38–42]. To alleviate mechanical stresses on the drive train and extend a WT's lifetime, the $(\mathrm{d}P/\mathrm{d}t)_{\max}$ should not exceed 0.45 p.u./s according to several manufacturers' datasheets [38]. Under medium and high wind conditions where WTGs are normally controlled to operate at MPP conditions, adequate kinetic energy is available to provide a useful inertial response. Under high wind speed conditions when rotor speed is constrained at the rated value, additional power provision can be fulfilled through pitch angle control to emulate an inertial response if temporary over-loading is allowed.

With the significant contribution of WTGs to enhance the system inertia, ROCOF and frequency nadir can be improved and this reduces the risks of load shedding triggered by UFLS (under frequency load shedding) and generation protection relays [43], thereby reinforcing system reliability and stability during large loss-of-supply events [44, 45]. At the same time, emulated inertial control can reinforce the system's small signal stability due to its damping effect pn the dominant oscillation mode [46].

As of now, three typical types of inertial control are proposed to enable VSWTs to supply emulated inertial response, which can be categorized into Natural Inertial Control, Step-wise Inertial Control and Virtual Inertial Control [17, 26–35]. Each of these is discussed in detail in the remainder of this section.

2.1 Natural inertial control

For natural inertial control, a WTG's active power output is changed following a frequency decline, in proportion to ROCOF or frequency deviation or both, in order to emulate the inertial response of a conventional synchronous generator [36, 45–48]. This is accomplished based on real-time measurements of frequency magnitude or ROCOF value. There are two main types of ROCOF dependent natural inertial control: one shot and continuous d*f*/d*t* control [45, 49].

A one shot d*f*/d*t* controller is designed to generate an initial power surge in proportion to the ROCOF when a severe frequency event occurs. This control scheme is implemented using a lookup table with initial d*f*/d*t* value as *X*-coordinate and corresponding active power increment as *Y*-coordinate. As it is shown in Fig. 2 for an example WTG under its rated operation, the peak active power output can be achieved within 200 ms and then declines exponentially over a specified duration of T_s. A short-term rotor speed restoration follows when active power declines below 1.0 p.u. (yet greater than 0.95 p.u.) [49].

A continuous d*f*/d*t* controller works in real time through the entire disturbance to regulate the additional active power provision based on ROCOF. Similarly to a synchronous generator, the incremental per-unit inertial power ΔP_{in} and per-unit inertial torque $\Delta\tau_{in}$ of WTG are expressed as:

$$\Delta P_{in} = K_{in}\omega_s \frac{\mathrm{d}\omega_s}{\mathrm{d}t} \tag{2}$$

$$\Delta\tau_{in} = K_{in} \frac{\mathrm{d}\omega_s}{\mathrm{d}t} \tag{3}$$

where K_{in} is the gain of inertial controller; ω_s is the per-unit synchronous generator speed; ΔP_{in} corresponds to the portion of rotor kinetic energy extracted for additional power delivery. Usually, the $\mathrm{d}\omega_s/\mathrm{d}t$ can be replaced by d*f*/d*t* in this control design, so that the magnitude of the WTG inertial response is directly proportional to the ROCOF. According to the swing equation, K_{in} can be simply chosen as twice total inertia constant H of the wind turbine [28, 50]. Natural inertial control is also called delta power control because the shape of inertial power output resembles "delta" throughout the overall response. Figure 3 shows the control block diagram of natural inertial response. The performance of natural inertial response can be enhanced by either increasing the auxiliary controller gain K_{in} or appropriately relaxing the limit on the power ramp rate [38].

It is noted that the measurement of d*f*/d*t* is inherently a noise amplifying process. Thus, a low-pass filter is added after the derivative function block to minimize the interference from measurement noise.

Up to now, there are two types of frequency-deviation-dependent natural inertial response: fixed-droop control and variable-droop control [47, 48]. The incremental per unit inertial power ΔP_{in} based on droop control is written as:

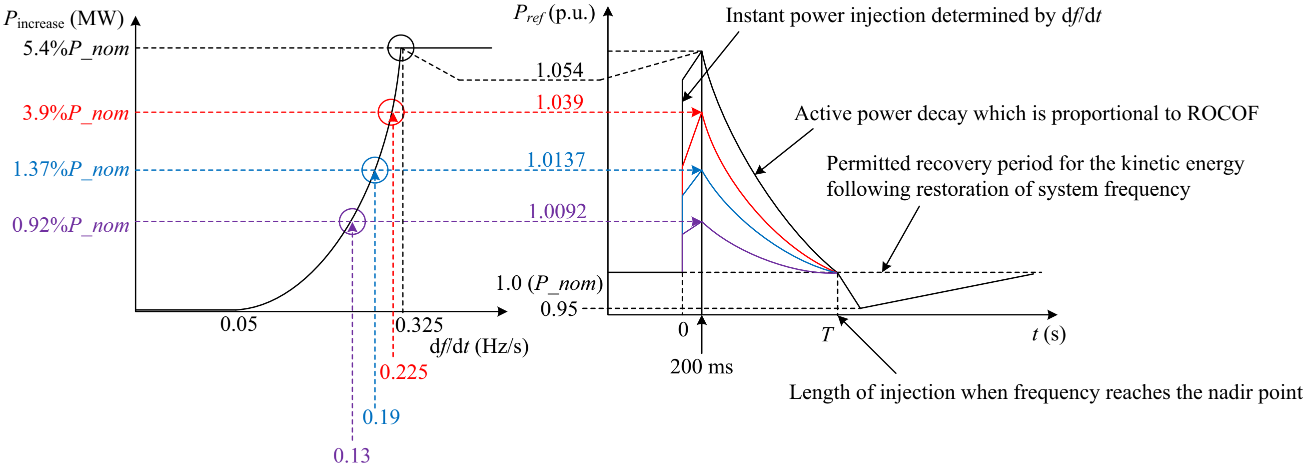

Fig. 2 Control strategy of one shot d*f*/d*t* controller

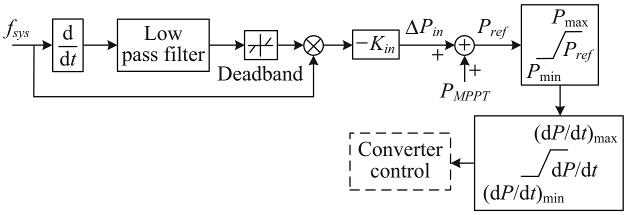

Fig. 3 Control block diagram of continuous d*f*/d*t* controller

$$\Delta P_{in} = \left(-\frac{1}{R_{dr}}\right)\Delta f \tag{4}$$

Figure 4 shows a typical fixed-droop controller and Fig. 5 depicts the configuration of a variable-droop controller with the droop coefficient as a function of ROCOF (d*f*/d*t*) and pre-disturbance rotor speed (ω_0). A high-pass filter is applied to prevent the persistent contribution of droop control to a post-disturbance steady-state error, so the WTG can return to MPPT operation [48, 51]. Actually, variable-droop control is based on fixed-droop control by dynamically adjusting the droop gain in terms of ROCOF and ω_0. In this way, the inertial response of a WTG can be optimized by raising the frequency nadir and preventing the subsequent over-deceleration.

In general, droop-dependent inertial response can significantly boost the frequency nadir as $1/R_{dr}$ increases. In contrast, ROCOF-dek lpendent inertial response can greatly mitigate the initial ROCOF as K_{in} increases, but it cannot improve the frequency nadir. Therefore, natural inertial response that combines both ROCOF-dependent and droop-dependent loops is able to increase the frequency nadir, arrest the ROCOF and also mitigate the SFD during the rotor speed restoration [47, 48].

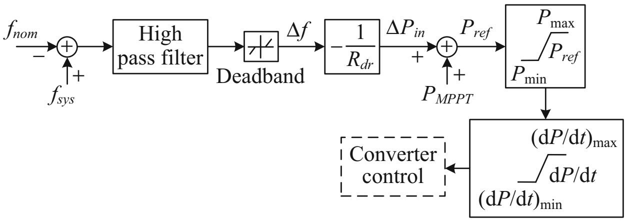

Fig. 4 Control block diagram of fixed-droop controller

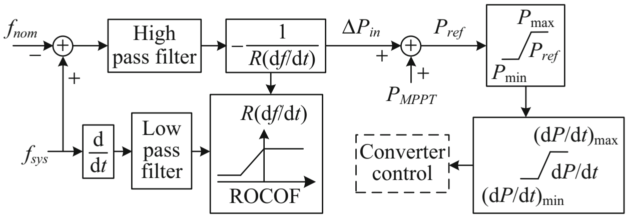

Fig. 5 Control block diagram of variable-droop controller based on ROCOF

2.2 Step-wise inertial control

Step-wise inertial control aims to provide a certain amount of active power, which is released from kinetic energy and sustained for up to ten seconds under various wind speed conditions [34, 35, 52–54]. Compared with natural inertial response, the inertial power using this control can be provided in different profiles in terms of its desired magnitude and duration. Meanwhile, its inertial response tends to be much faster and stronger because a step-wise inertial response is executed without measuring real-time frequency variations. Upon detecting an event, this control method can dramatically boost the frequency nadir and alleviate the effect of kinetic energy recovery by providing a smooth and steady additional power injection [36]. The effect of step-wise inertial response is usually dependent on several factors, including step power increment, time duration, ramp rate limit, wind speed as well as inertia constant H_{WT}.

One control method proposed to generate a constant inertial response for each step is to modify the rotor speed set point of rotor-speed-based VSWTs throughout the frequency event. The constant inertial power is derived from:

$$P_{in}t = \frac{1}{2}J\omega_{r0}^2 - \frac{1}{2}J\omega_{rt}^2 \tag{5}$$

where t is the duration for constant inertial power; ω_{r0} is the initial rotor speed; ω_{rt} is the rotor speed at the ending moment of inertial response. Therefore, the reference value of rotor speed is given as:

$$\omega_{ref} = \omega_{rt} = \sqrt{\omega_{r0}^2 - 2\frac{P_{in}}{J}t} \tag{6}$$

The control block diagram of constant inertial response is depicted in Fig. 6.

The other method proposed to achieve step-wise inertial control is for active-power-based VSWTs [22] to change their actual power reference by adding a temporary overproduction (TOP) value ΔP_{op} on top of the pre-event active power reference P_{MPPT} in case of frequency disturbance. The P_{op} is extracted from the kinetic energy stored in the rotating masses of WT. Thus, the generated electrical power output P_{ref} is defined as:

$$P_{ref} = P_{MPPT} + \Delta P_{op} \tag{7}$$

During normal operation, a VSWT runs on the MPP corresponding to the actual wind speed. When there is an under-frequency event, a constant over-production amount of ΔP_{op} is instantly delivered to the grid. As a result, rotor speed decelerates due to the increasing imbalance between mechanical and electromechanical torque. In Fig. 7, the basic principle of this control mechanism is illustrated. Note that the value of P_{ref} can be constant or variable, depending on the specific strategy chosen for the overproduction period.

Once the rotor speed slows down to a low value, e.g., $\omega_{\min}$, the overproduction process is terminated and the active power set point is reduced by a constant ΔP_{up}, so that the electrical power output is smaller than available mechanical power. For this reason, the rotor speed is able to return to previous MPPT point for a given wind speed or another operating point corresponding to current wind speed. By increasing this ΔP_{up}, the underproduction period tends to be shortened and meanwhile the wind turbine's rotor speed can be restored to the MPP more rapidly. However, the SFD issue is likely to become more severe if much larger ΔP_{up} is chosen. Thus, a TOP-based Improved Primary Frequency Response (IPFR) technique is proposed based on deloaded operation in [55] to eliminate the SFD issue and minimize the frequency deviation. Two other methods are proposed in [53–56] for DFIGs and PMSGs by adding an incremental active power based on the MPPT curve or torque limit curve to enable the rotor speed converge to a stable point when TOP ends.

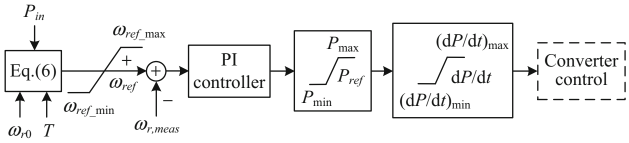

Fig. 6 Control block diagram of constant inertial response based on rotor speed regulation

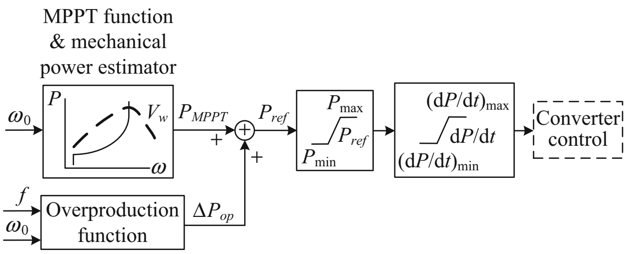

Fig. 7 Control block diagram of step-wise inertial response based on TOP

2.3 Virtual inertial control

Recently, another novel inertial control strategy named virtual inertia control (VIC) is proposed to utilize the "hidden inertia" of turbine blades to provide a fast dynamic frequency support. One method is to adjust the active power output based on the system frequency deviation. This type of regulation is implemented by means of shifting the operating point upward from the MPPT curve toward the VIC power tracking curve to compensate for power imbalance, and then the rotor speed is controlled to smoothly return to the initial MPP according to (8) [57]. The upper and lower limits of the VIC power curve are defined by applying $K_{VIC\_\max}$ and $K_{VIC\_\min}$ respectively to ensure that the VSWT can operate in a steady state under various wind speed conditions. The coefficient K_{VIC} is a function of frequency deviation:

$$K_{VIC} = \frac{\omega_{r0}^3}{(\omega_{r0} + 2\pi\lambda\Delta f)^3}k_{opt} \tag{8}$$

where λ is the virtual inertia coefficient, which can be expressed as $\lambda = \frac{\Delta\omega_r}{\Delta\omega_e} = \frac{\omega_{r1}-\omega_{r0}}{\omega_{e1}-\omega_{e0}}$. k_{opt} is the optimal power curve coefficient. Assuming that the rotor speed of the VSWT varies from ω_{r0} to ω_{r1}, so the kinetic energy to be released is equivalent to the amount of kinetic energy released from a synchronous generator with rotor speed declining from ω_{e0} to ω_{e1}. A wash-out block is used to remove the steady-state dc component of frequency error. The corresponding control block diagram is illustrated in Fig. 8.

An optimal controller for VIC is proposed in [35] to emulate the inertial response with the purpose of enhancing the frequency regulation in a diesel generator dominant system. The optimal virtual inertia factor K_{VIC} is identified using deterministic linear quadratic regulator (LQR) method. Although both VIC and natural inertial control rely on real-time frequency measurement and perform based on the MPPT operation of a VSWT, the main difference between these two control strategies lies in the fact that VIC cannot cause a SFD when a VSWT performs the inertial response according to (8).

In addition to the three classic types of inertial controls above, an alternative inertial control method was recently presented in [58] to make a DIFG provide inertial response by directly adjusting the PI control parameters in its phase locked loop (PLL). Another novel virtual synchronous control (VSynC) is proposed in [59] for a DFIG to supply inertia response when integrated into a weak ac power grid with low short-circuit ratio. Without relying on the traditional PLL technique, the VSynC enables a DFIG to synchronize with the grid directly through active power control, so that the DFIG can naturally deliver the inertial response to enhance the frequency stability like conventional synchronous generators.

In Fig. 9, comparative simulation results for a small power system with a large-scale wind farm are presented to show the frequency regulation performance for the three types of inertial control discussed above, namely, natural inertial control, step-wise inertial control and virtual inertial control. From the simulation results, it is observed that virtual inertial control's performance is the best by mitigating the ROCOF and boosting the frequency nadir. Step-wise inertial control can reduce ROCOF, but the SFD issue arises due to the WT's rotor speed recovery. However, this problem might be avoided by applying other inertial control methods.

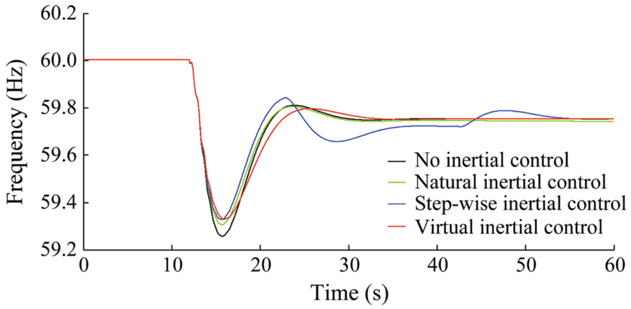

Fig. 9 Comparison results of various types of inertial controls

3 Wind turbine frequency control

3.1 Deloaded control

To participate in primary, secondary and tertiary frequency control, a VSWT needs to be operated in a suboptimal mode through the deloaded control so that a certain amount of spinning reserve margin or headroom is always available to supply additional active power in case of frequency contingency.

Nowadays, primary reserve is commonly achieved through either "Balance" control that reserves a constant percentage of rated power [50], or "Delta" control that reserves a fixed proportion of available maximum active power [6, 32, 60], or "Fixed reserve" control that reserves a fixed amount of active power [3]. The power references for these three types of deloaded operation are mathematically described as follows:

1) Balance

$$P_{ref} = \begin{cases} P_{de} & P_{de} \le P_{MPPT} \\ P_{MPPT} & P_{de} > P_{MPPT} \end{cases} \qquad P_{de} = [0, \ldots, P_{Rated}] \tag{9}$$

2) Delta

$$P_{ref} = \begin{cases} (1 - K_{Reserve})P_{MPPT} & P_{MPPT} \le P_{Rated} \\ (1 - K_{Reserve})P_{Rated} & P_{MPPT} > P_{Rated} \end{cases} \qquad K_{Reserve} = [0, \ldots, 1] \tag{10}$$

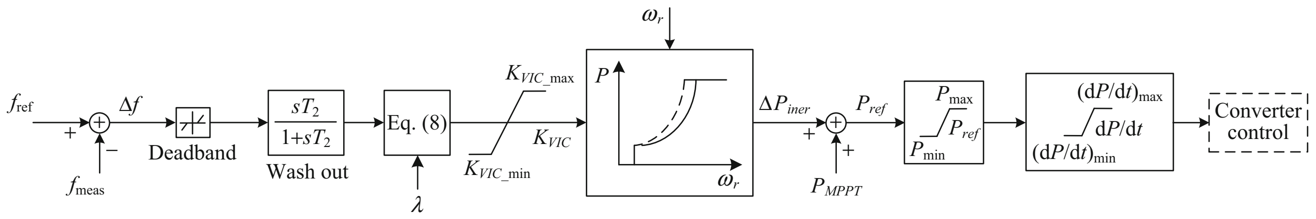

Fig. 8 Control block diagram of VIC

3) Fixed reserve

$$P_{ref} = \begin{cases} 0 & P_{MPPT} \leq \Delta P_{Reserve} \\ P_{MPPT} - \Delta P_{Reserve} & P_{MPPT} \leq P_{Rated} \\ P_{Rated} - \Delta P_{Reserve} & P_{MPPT} \geq P_{Rated} \end{cases} \qquad (11)$$
$$\Delta P_{Reserve} = [0, \ldots, \Delta P_{\max}]$$

where P_{ref} is the WTG active power reference; P_{Rated} is the WTG rated power; $\Delta P_{Reserve}$ is a fixed amount of active power serving as spinning reserve; P_{MPPT} is the maximum wind power; $K_{Reserve}$ is the fixed percentage of maximum wind power; $\Delta P_{\max}$ is the maximum fixed power reserve.

Compared with the balance type, the energy efficiency of delta or fixed reserve types is higher due to their long-term stable power reserve and reduced wind power curtailment. It is shown in [61] that modern offshore wind farms are capable of maintaining 5% of rated power as spinning reserve, sustained for up to 89% of the event duration under varying wind speed conditions. In contrast, rapid variations in WPP output can be effectively smoothed by balance type control, so that the uncertainty and variability of wind power production in power system operation and dispatch are minimized [5, 32, 45, 62, 63]. Note that the reserve margin level is dependent on prevailing wind speed magnitude, wind speed forecasting accuracy and allowable upper limit of the VSWT's rotor speed [38, 62]. One dynamic reserve allocation approach is presented in [64] to distribute the total wind farm reserve according to specific wind speed of each wind turbine. In Fig. 10, the comparative results of wind turbine steady-state power output are given for balance ($P_{de} = 0.8$), delta ($K_{Reserve} = 0.2$) and fixed reserve ($\Delta P_{Reserve} = 0.2$) deloaded controls. From this figure, it can be concluded that the amount of reserve margin for the delta type tends to increase as wind speed rises. Once it exceeds the rated value (12 m/s), the power margin will be held at 0.2 p.u. For the balance type, there is no reserve margin available when active power stays below 0.8 p.u. In that case, the WT only operates in MPPT mode. For fixed reserve type, the reserve margin is fixed as 0.2 p.u. of the rated wind power over a wide range of wind speeds, provided that the optimal power output is above 0.2 p.u.

As we discussed before, the deloaded margin can reinforce the VSWT's overall inertial response and enable primary frequency regulation by quickly delivering additional active power through power converter control [32, 64]. Meanwhile, investment in conventional spinning reserve can be reduced to a certain extent by deloaded operation of WT. Thus, deloaded control plays an essential role in supporting long-term frequency regulation from both perspectives of system stability and economics.

3.1.1 Rotor speed control

In accordance with the PMSG-WTG sub-optimum power extraction curve in Fig. 11, WTG power output is deloaded by shifting the operating point toward the left or right side of the MPPT curve while the rotor speed remains below its upper limit. The WTG output can be adjusted between P_{de} and $P_{\max}$ by adjusting its rotor speed between $\omega_{r,del}$ and $\omega_{\max}$ [34, 45]. The power reference (P_{ref}) of the deloaded WTG at the measured rotor speed is calculated by using a simplified linear equation (12) or referring to a predefined look-up table in [62]:

$$P_{ref} = P_{de} + (P_{\max} - P_{de})\left(\frac{\omega_{r,de} - \omega_{r,meas}}{\omega_{r,de} - \omega_{r,\max}}\right) \qquad (12)$$

where $P_{\max}$ is the maximum power; P_{de} is the deloaded power; $\omega_{r,\max}$ is the PMSG's rotor speed corresponding to $P_{\max}$; $\omega_{r,de}$ is the rotor speed corresponding to P_{de}; $\omega_{r,meas}$ is the measured rotor speed.

The left sub-optimal operating point is unstable since it is likely to cause the wind turbine to stall under a frequency disturbance. The wind turbine should operate on the right sub-optimal curve, so as to maintain stable operation when providing frequency response over a full range of wind speeds [45]. Another advantage of right sub-optimal

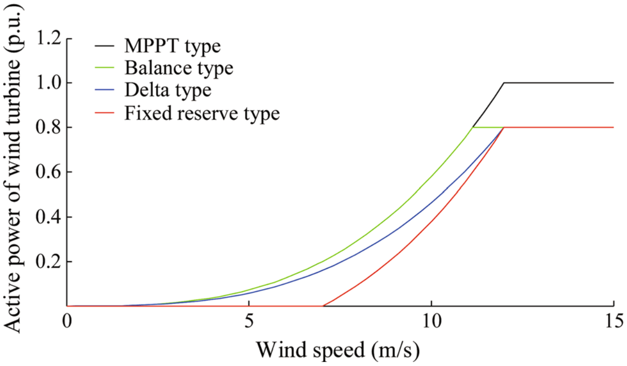

Fig. 10 Steady-state power output for each power reserve strategy as a function of wind speed

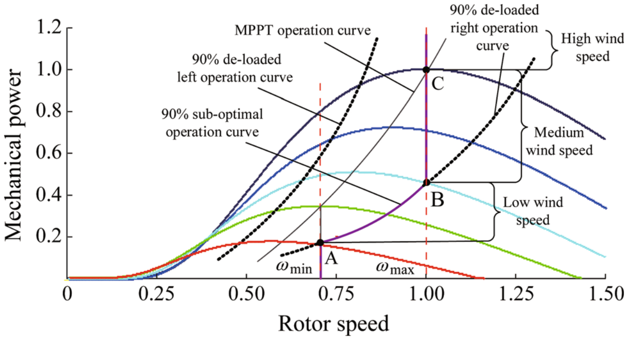

Fig. 11 90% PMSG-WTG deloaded operation curve with rotor speed limitation (0.5–1.0 p.u.) over a full scope of wind speeds

operation is to enable a PMSG-WTG to contribute a combination of reserved active power and greater kinetic energy to support primary frequency regulation, by allowing the rotor speed to decline from the deloaded operating point towards the maximum power point. Moreover, it can effectively reduce tear and wear losses associated with pitch angle actuation compared with using the pitch servo alone to curtail the wind power and perform primary frequency regulation. Note that this approach of right sub-optimal operation can be applicable to a DFIG-WTG as well.

Considering the fact that the rotor speed ω required for de-loaded operation may exceed the maximum value $\omega_{\max}$ for medium and high wind speeds, three wind speed modes are defined in terms of the deloaded control objective and secure operation constraints: low wind speed mode where deloaded operation is fulfilled merely by rotor speed control; medium wind speed mode where deloaded operation is conducted by combining pitch angle control and rotor speed control; and high wind speed mode where modified pitch angle control alone enables deloaded operation [12, 45, 51].

3.1.2 Pitch angle control

The original objective of pitch angle control in a WT is to prevent the generator and power converter from overloading and the rotor from being over speed [16]. To support a supplementary frequency regulation, the pitch control needs to be modified based on the wind conditions. Meanwhile, the initial pitch angle β_0 is set to maintain a certain power reserve for potential primary frequency regulation. Due to the servo time constant of the pitch controller, the response of pitch control appears to be slower than that of rotor speed control through the power converter.

3.2 Primary frequency control

Primary frequency control is an automatic governor response in proportion to the frequency deviation from the scheduled value. This response, also called frequency responsive reserve, is typically provided by a conventional generator with governor droop control to regulate its power output as a function of frequency deviation and droop setting [50, 64–68]. A WTG's primary frequency regulation resembles that of a conventional generator, which is usually activated within a few tens of seconds and sustained for up to 15 min once the grid frequency deviation exceeds the allowable threshold [67]. It plays an important role in mitigating the steady-state frequency deviation after inertial response until the secondary frequency control (automatic generation control, AGC) takes over to achieve zero frequency error in the steady-state condition.

Unlike the provision of inertial response, power output needs to be curtailed beforehand by deloaded control in order to carry out primary frequency regulation in response to an under-frequency disturbance. The abilities of WTG primary frequency regulation can be evaluated from the following perspectives: delay time, ramp rate, magnitude and response speed [10].

To emulate the traditional governor response for primary frequency regulation, droop control is implemented in a VSWT to correlate the variation in grid frequency with a corresponding change in active power output through power converter control. It responds to large deviations in grid frequency by increasing or decreasing power output during the frequency event. The relationship between active power change and frequency deviation can be expressed as $\Delta P_{dr} = K_{dr}(f - f_0)$, where f_0 is the nominal frequency. The parameter K_{dr} is the inverse of speed droop R as follows.

$$R = \frac{\Delta f}{\Delta P_{dr}} = -\frac{1}{K_{dr}} \tag{13}$$

The value of R usually lies in the range between 3% and 5% for conventional generators. Larger values of K_{dr} can further reduce the steady-state frequency deviation without obviously impacting the small signal stability of power system [32].

3.2.1 Droop curve parameters

As depicted in Fig. 12, there are several important parameters that determine the droop curve behavior, including the droop slopes (up and down), dead band and power ramp rate. These parameters should be appropriately selected to ensure that additional active power output through droop response remains within the available reserve margin [3, 11–39, 49, 69, 70]. Moreover, a droop curve with a suitable dead band can prevent the droop controller from frequent activation in response to small frequency fluctuations [4]. Note that either symmetrical droop or asymmetrical droop can be used to perform primary frequency regulation according to system operational requirements.

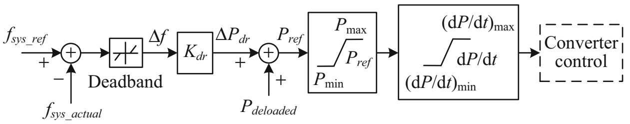

Fig. 12 Control block diagram of droop response

According to different frequency deviations in Fig. 13, the active power reference for primary droop control is calculated in accordance with the following equations:

$$P_{ref} = \begin{cases} P_{MPPT} & f \leq f_{\min} \\ P_{de} + (1/R_1)\Delta f & f_{\min} < f \leq f_{DB\_lower} \\ P_{de} & f_{DB\_lower} \leq f \leq f_{DB\_upper} \\ P_{de} - (1/R_2)\Delta f & f_{DB\_upper} < f \leq f_{switch} \\ P_{de} - (1/R_3)\Delta f & f_{switch} < f \leq f_{\max} \end{cases} \tag{14}$$

If the frequency declines below the dead band limit f_{DB_lower}, the active power reference of the WTG is increased based on droop-down control until it reaches P_{MPPT} at the present wind speed. On the other hand, if the frequency rises above the dead band limit f_{DB_upper}, the active power reference is reduced by accelerating the rotor speed. If frequency keeps going up until f_{switch} is reached, the rotor speed ceases to rise because of its upper limit. At this moment, the pitch angle controller is enabled to further reduce the WTG's active power output by increasing the pitch angle β. During this process, the rotor speed remains constant at the upper limit value, $\omega_{\max}$. It is worth noting that the slope value of R_3 is mainly dependent on the allowable variation range of β [18].

3.2.2 Static droop and dynamic droop control

Static droop control is quite similar to traditional governor control, providing additional active power based on the grid frequency deviation [10]. It features a droop curve with a fixed slope and a pre-defined dead band. According to simulation tests in [11–39, 49], this control can arrest system frequency decline and minimize the steady-state frequency deviation.

For dynamic droop control, the slope and dead band of droop curve are adjustable in real-time according to the ROCOF value, de-loaded level or variable wind speed conditions. Using this control method, a desirable tradeoff between improved frequency response and reduced impacts on the structural loading is attained. A study in [11] illustrates that dynamic droop curves can effectively enhance the primary response without dramatically adding extra structural loading to wind turbine components, such as the shaft and tower. Compared with the aggressive static droop curve, the frequency nadir, frequency deviation and frequency recovery process are also improved by using dynamic droop control. On the other hand, a WTG operating under low wind speed is unable to provide a strong primary frequency response due to limited reserve.

It is also beneficial to adjust the droop coefficient in real time. An overly small static droop coefficient is likely lead to WTG instability, while an overly large coefficient tends to induce noticeable oscillations in active power output during frequency recovery [4]. Variable droop control can optimize the additional active power shared among WTs, running in deloaded mode, so that the primary frequency contribution of each WT is based on its own available power reserve corresponding to the local wind speed it is experiencing. A similar variable droop control scheme is presented in [62] for DFIG wind farms to adjust their droop coefficients according to the variable power reserve, so that the total number of power output reversals in traditional units and the Root Mean Square (RMS) value of frequency deviations are dramatically diminished.

3.3 Secondary frequency control (AGC)

Secondary frequency control, also called AGC or load frequency control (LFC), is implemented during emergency frequency events as well as under normal operating conditions [50, 64]. Secondary frequency control starts within several tens of seconds and is sustained for up to

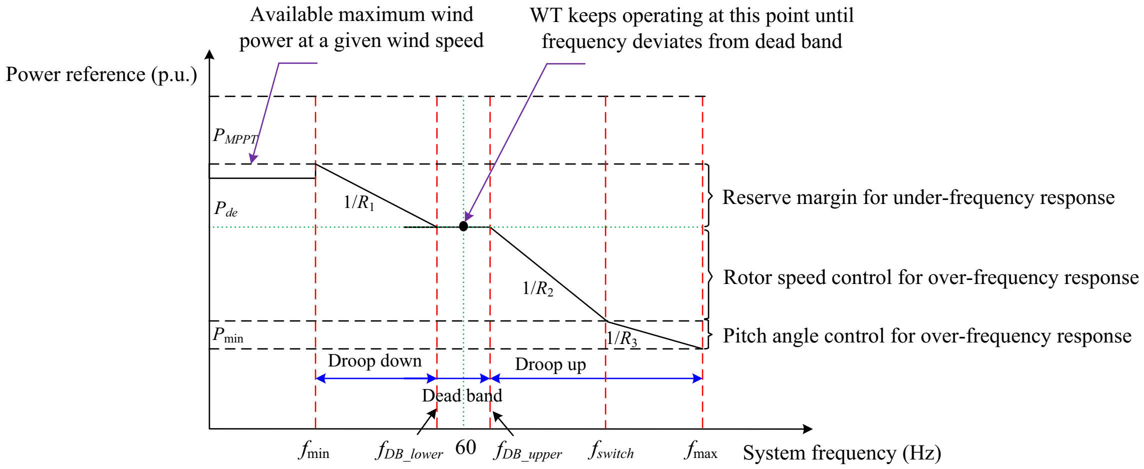

Fig. 13 Frequency-power characteristics of basic droop control

several tens of minutes [67]. This control is a continuous response on the minute timescale to allocate the load change among individual WTs for the purpose of maintaining the system frequency deviation and tie line power flow deviation at zero [41]. In Fig. 14, a simplified frequency control model is applied to validate the dynamic characteristics of a power system containing conventional power plants and WPPs [71]. The specific AGC set point for each WTG depends on PI controller parameters and participation factors (PFs). The optimal method to determine PFs is presented, and takes into account the up and down ramp rates, operating reserves, dispatch limits and generation costs [72].

A secondary frequency controller based on a supervisory wind farm control system (SWFCS) fully utilizes the secondary frequency reserve to follow commands from system operator, including AGC commands (updated power set point) and power flow adjustment [50, 64]. Another novel control scheme is proposed in [73] to enable WTs to change their active power reference in accordance with a power command, so as to meet the requirement of the system operator. In [72], a coordinated AGC control strategy between WTs and combined heat and power plants (CHPs) is proposed to mitigate the real-time power imbalance by down-regulating the wind power output when CHPs are not fast enough to track power commands. Due to the rapid ramp rate of WTs, the area control error (ACE) can be significantly reduced by this means.

3.4 Tertiary frequency control

Compared with the other frequency controls mentioned above, tertiary frequency control has a relatively long decision time step ranging from the order of minutes to hours, which takes effect following the secondary control [10, 67]. This control method comprises dispatching

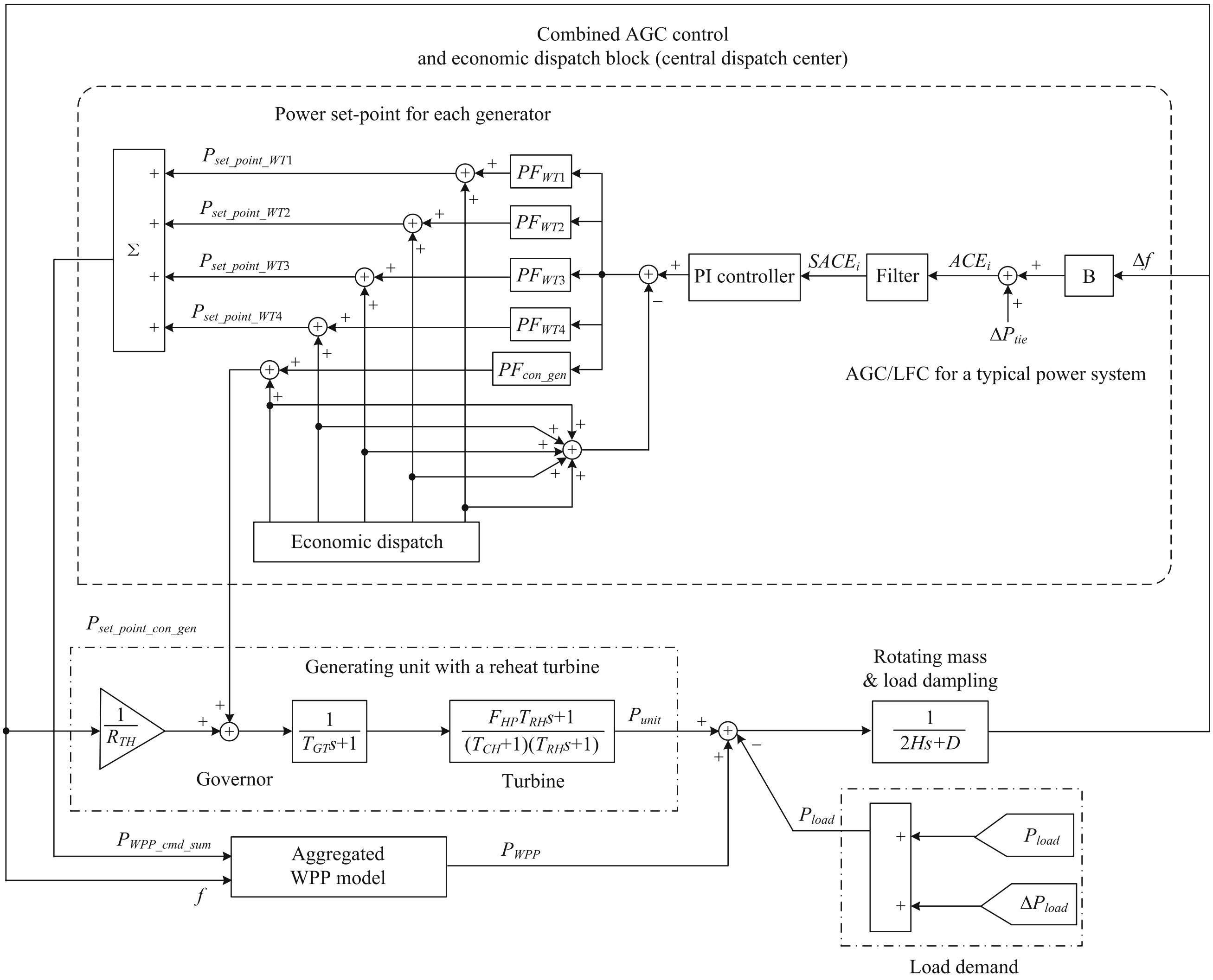

Fig. 14 Schematic diagram of load-frequency control loop

actions from the system operator, in order to achieve the power reserve deployment and restoration for the WTG's tertiary frequency control that enables unit commitment, economic dispatch and optimal power flow in accordance with market signals or other system requirements. As shown in Fig. 14, operational active power reference values for individual conventional generators and wind farms are equal to the sum of AGC and economic dispatch set points. Economic dispatch usually updates operational set points every 1–5 min while AGC refreshes every 0.1–1 s [74]. Nowadays, there are two types of power markets associated with tertiary frequency control, including intraday real-time market with minute-level economic dispatch and day-ahead market with daily economic unit commitment.

3.5 Coordinated frequency control

Considering a VSWT's initial operating condition and the frequency disturbance magnitude and duration, a combination of inertial response, primary frequency control and secondary frequency control can significantly enhance the overall frequency regulation performance of power system and alleviate frequency regulation stress for conventional units [10, 34, 38, 45]. The process of coordinated down-frequency regulation can be described as follows. During the initial transient process after a frequency drop event, inertial response plays an essential part in reducing ROCOF and boosting the frequency nadir point. Once the dead-band criterion is met for a specified delay time, the primary frequency response is triggered to further enhance frequency regulation through droop control until the frequency settles into a secondary steady state. At this point, the frequency nadir is further lifted and then frequency is restored to within an acceptable range. After that, AGC control takes over to achieve zero frequency error regulation using PI controller.

Several coordinated control strategies based on pitch angle control and rotor speed control have been proposed to improve VSWTs' frequency regulation capability over the full range of wind speed conditions and to damp frequency oscillations. Even without deloaded control, temporary frequency support can be realized by employing a coordinated strategy of pitch angle and rotor speed control [75].

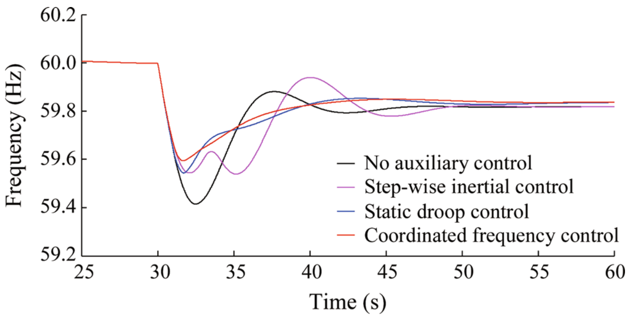

Fig.15 Comparative results between coordinated frequency control and other controls

The work in [50] presents a *K*-deviation method to perform frequency regulation in a real-time variance tracking mode. The study in [45] proposes a novel coordinated frequency regulation strategy suitable for active-power-control-oriented VSWT and perform the frequency response according to different wind speed modes. In [34], a coordinated frequency control scheme appropriate for rotor-speed-control-oriented VSWTs which perform frequency response according to different wind speed conditions. In [34], a frequency control scheme appropriate for rotor-speed-control-oriented VSWTs is proposed to coordinate rotor speed control and pitch angle control according to pre-defined wind speed zones. Another coordinated control strategy in [65] employs direct control of a DFIG-WTG's electromagnetic torque and rotor speed to allow for additional active power delivery based on the operator's request and allowing for varying wind conditions. In [63], Kinetic/Inertia, Proportional gain and Enhanced Pitch (KIPEP) control is presented to support both primary and secondary frequency regulation while also smoothing out the wind power output over short time frames.

In Fig. 15, comparative simulation results for a small power system with a wind power plant are provided to demonstrate the frequency regulation performance using step-wise inertial control only, static droop control only and coordinated frequency control including variable droop. Coordinated frequency control is superior to other methods in improving the overall frequency regulation performance in terms of ROCOF, frequency nadir, frequency recovery and steady-state frequency. Static droop control alone can increase the frequency nadir and reduce the steady-state frequency deviation. In contrast, step-wise inertial control can mitigate the ROCOF, but it tends to cause a SFD.

4 Frequency regulation performance comparison of different types of WTG systems

A WTG possesses a significant amount of kinetic energy in the rotating masses, which can be utilized to provide a short-term frequency support in the event of large power imbalance [76]. In general, wind turbines can be divided into two main groups: fixed-speed WTs (FSWT) and variable-speed WTs (VSWT). Each group has distinctive benefits and drawbacks in terms of their contributions to system frequency support. The FSWT can inherently provide a limited inertial response to mitigate the ROCOF. In contrast, VSWTs cannot naturally deliver any inertial power into the electrical grid due to partial or full decoupling between rotor speed and grid frequency via the power converter. Nevertheless, modern VSWTs are capable of providing an emulated inertial response that is superior to that of conventional generators, due to their faster, more accurate and flexible active power controls and the wide range over which the wind turbine rotor speed can vary [17, 23, 26, 33, 51]. Last but not least, a novel type of VSWT based on the electromagnetic coupler (WT-EMC) can provide frequency support through emulated inertial response and droop frequency regulation [19].

4.1 Type 1 and Type 2 FSWTs

Thanks to direct coupling between the rotor speed and the system frequency, a Type 1 Induction Generator with Fixed Speed can potentially provide limited inertial response. Its inertial response is a passive process, in which the kinetic energy stored in the generator, gearbox and wind blades is intrinsically released or absorbed as system frequency decreases or increases. Commercial fixed speed wind turbines (FSWT) with rated power above 1 MW have an inertial constant of 3–5 s. The stored energy in each FSWT is unrelated to wind speed, and the aggregated kinetic energy of a WPP increases with the number of turbines online [71]. However, it is difficult to tune the inertial response of Type 1 in order to meet specific grid frequency regulation requirements. Overall, the inertial response from Type 1 WTGs is restricted and uncontrollable. The Type 2 Wound-rotor Induction Generator with adjustable external rotor resistance and variable slip tends to maintain its power output at a fixed value even during an abrupt frequency decline, since the external rotor resistance maintains the power output at the target value at all times. Therefore, Type 2 WTGs hardly make any contribution to the system inertial response [6, 16].

However, it is noted that through deloading control both types can allocate a constant amount or a fixed proportion of available aerodynamic power as a reserve margin to enable primary frequency regulation with the aid of a pitch angle controller [77].

4.2 Type 3 and Type 4 VSWTs

Type 3 double fed induction generator (DFIG) and Type 4 direct drive permanent magnet synchronous generator (PMSG) VSWTs are capable of achieving rapid and accurate active power regulation by means of power converter control. These two types of VSWT act like a flywheel device to mitigate the power fluctuations resulting from variable wind conditions. In comparison with FSWTs, the inertial response of VSWTs is a proactive process where the system frequency or ROCOF is monitored and measured in a real-time manner, so it can be optimally and dynamically tuned by setting proper control parameters according to different wind speed conditions and disturbance magnitudes. To better arrest a frequency decline, allowing some headroom for the inertial power release is desirable for VSWTs to deliver additional active power within the maximum power capabilities of converters and generators [33, 34, 45].

In contrast to synchronous generators, due to their asynchronous operation, the speed variation of Type 3 WTGs is much larger than the permissible system frequency variation. Their rotor speed can be controlled between 0.7 and 1.2 using modern power converters [62]. Their emulated inertial constant can be set as large as several times their inherent inertial constant in an auxiliary control loop. The partial-scale power converter (20%–30% of full rating) in the rotor circuit of Type 3 WTGs imposes limitations on the deloaded operating level, maximum inertial response and rotational speed range (within ±20%–±30% of synchronous speed) [55]. Compared to Type 3 WTGs with the identical rated power capability and inertial constant, Type 4 WTGs are capable of providing stronger inertial response due to the wider operating range of their rotor speeds (0.5–1.2 p.u.) [34]. Moreover, the full-scale power converter allows Type 4 WTGs to possess a higher overloading capability, so that more temporary inertial power can be injected into grid for a short period [78]. In addition, Type 4 WTGs might utilize a larger amount of energy stored in the DC-link capacitor to enhance the emulated inertial response and compensate for the temporary power deficit during the rotor speed recovery [37].

5 Key technical development trends

The following trends have been identified in the literature reviewed for this paper.

5.1 Optimized coordinated frequency control between wind farms and traditional power plants

A coordinated frequency control strategy between wind farms and other power plants needs to be properly designed and implemented for an optimized and reliable frequency regulation in response to various frequency events. The sequence, duration, ramp rate and proportion of additional power provision through primary and secondary frequency responses are determined between wind farms and conventional power plants according to system requirements and targeted capital and operating costs. So, it is necessary to carry out more research to coordinate and optimize the inertial response, primary frequency regulation and secondary frequency regulation when taking into account specific types of wind turbine, the power reserve method, the active power control strategy, the wind power penetration level and stochastic wind speed conditions

5.2 Coordinated inertial response and frequency regulation for offshore wind farm through HVDC links

An HVDC line is perceived as a cost-effective technical solution to transmit large-scale wind power to a load center over a very long distance. As more and more wind farms are built offshore, HVDC links can be used effectively to mitigate wind power variability and enhance power supply reliability. However, the increasing VSWT penetration and associated HVDC interconnections can negatively impact the system ROCOF and frequency nadir due to the reduced inertia of overall power system. That is due to the fact that HVDC lines and VSWTs are insensitive to frequency changes through their power converters, which fully isolates kinetic energy stored in wind turbine and reserved wind energy from the grid frequency variations. In order to reinforce the transient frequency stability and enhance the power damping effect, it is essential to develop a coordinated control scheme for wind farms and HVDC links by taking advantage of VSWTs' fast inertial response and HVDC links' transient overload capability.

5.3 Advanced emulated inertial control of VSWTs

During the process of inertial response emulation, a sudden boost in active power output can lead to a sharp deceleration in rotor speed due to the imbalance between the electrical and mechanical torques. The undesirable consequence is that the turbine may stall due to taking excessive kinetic energy from the rotor as well as the intensive structural load on the mechanical components of wind turbine. Moreover, the associated recovery process following temporary overproduction results in decreased WT power output. Consequently, a SFD is likely to occur. Therefore, it is necessary to design appropriate control schemes to provide as much inertial response from VSWTs as possible, while preventing the rotor speed from over-deceleration and mitigating the impact of rotor speed recovery on the overall frequency performance.

5.4 Frequency support by energy storage to assist VSWTs' auxiliary frequency control

In order to fully eliminate the SFD issue and compensate for inadequate frequency regulation under low wind speed conditions, the fast and precise active power control of battery energy storage systems (BESSs) can be used to assist VSWTs in providing inertial response and primary frequency regulation. As a result, the burden of frequency response on both WTs and conventional generators will be eased in terms of response time and primary reserve margin. Therefore, it becomes important to conduct further studies on optimized coordinated control algorithms for inertial response and frequency regulation shared between VSWTs, BESSs and conventional generators. The main factors to consider include starting moment, duration and ending moment of inertial response, BESS lifespan and ancillary services revenue with the purpose of improving the system dynamic frequency response while achieving an optimal balance between cost and performance.

6 Conclusion

This survey elaborates the motivation, fundamental principles and various control schemes for frequency regulation by VSWTs. A variety of frequency regulation control schemes, including inertial response, primary droop control, secondary AGC control and tertiary frequency control, are explained in detail. To assess the effectiveness of various typical inertial responses, comparative simulations were performed. This showed that coordinated frequency control including variable droop is superior to other methods.

The merits and disadvantages of frequency regulation capabilities of various types of WTGs are briefly compared. Lastly, several key technical development trends frequency regulation by VSWTs are identified.

Based on the above analysis, a variety of effective methods exist to provide effective frequency regulation by VSWTs, exceeding in some respects the services offered by conventional generators. A combination of rotor speed control, pitch angle control, and deloading can be used according to operational requirements and wind speed conditions. There is room to improve the dynamic performance of frequency regulation controllers and the distribution of frequency regulation responsibilities between VSWTs and other generators.

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Ziping WU received the Ph.D. degree in electrical engineering from University of Denver, Denver, Colorado, U.S.A., in 2016 and the master degree in electrical engineering from North China Electric Power University, Beijing, China, in 2009. Since 2017, he has worked as a Power Research Engineer in the Information Trust Institute at the University of Illinois at Urbana-Champaign (UIUC). From 2009 to 2011, he was a power research engineer with the China Electric Research Power Institute, Beijing, China, with an emphasis on the dynamic simulation of real large-scale power grid containing multiple HVDC and HVAC links. His current research interests include power system operation and control, renewable power generation, cyber-physical security, PMU application, and microgrid.

Wenzhong GAO received his M.S. and Ph.D. degrees in electrical and computer engineering, specializing in electric power engineering, from Georgia Institute of Technology, Atlanta, USA, in 1999 and 2002, respectively. He is now with the Department of Electrical and Computer Engineering, University of Denver, Colorado, USA. His current teaching and research interests include renewable energy and distributed generation, microgrid, smart grid, power system protection, power electronics applications in power systems, power system modeling and simulation, and hybrid electric propulsion systems.

Tianqi GAO received his B.S. degree in engineering from Duke University in 2016. He is currently pursuing his M.S. degree in engineering at School of Engineering and Computer Science, University of Denver. His current research interests include renewable power generation, bio-medical technology, technology innovation and intellectual property.

Weihang YAN received B.S. degree and M.S. degree in Electrical Engineering from School of Information Science and Engineering, Northeastern University, Shenyang, China, in 2014 and 2016, respectively. Currently, he is pursuing the Ph.D. degree in Electrical Engineering at University of Denver, CO, USA. His research interests are modeling and control of microgrids, analysis of transient stability of power system, distributed generation technology, and renewable energy integration.

Huaguang ZHANG received the B.S. degree and the M.S. degree in control engineering from Northeast Dianli University of China, Jilin City, China, in 1982 and 1985, respectively. He received the Ph.D. degree in thermal power engineering and automation from Southeast University, Nanjing, China, in 1991. He is a Professor and Head of the Institute of Electric Automation, School of Information Science and Engineering, Northeastern University, Shenyang, China. He has authored and coauthored over 280 journal and conference papers, six monographs and co-invented 90 patents. He was awarded the Outstanding Youth Science Foundation Award from the National Natural Science Foundation Committee of China in 2003. He was named the Cheung Kong Scholar by the Education Ministry of China in 2005. He is a recipient of the IEEE Transactions on Neural Networks 2012 Outstanding Paper Award. He is also a recipient of Andrew P. Sage Best Transactions Paper Award 2015. His main research interests are fuzzy control, stochastic system control, neural networks based control, nonlinear control, and their applications.

Shijie YAN received B.S. degree, M.S. degree and Ph.D. degree in power electronics and drives from School of Information Science and Engineering, Northeastern University, Shenyang, China, in 1986, 1999 and 2002, respectively. His research interests are power electronics converter, microgrid, distributed generation, renewable energy and electric drives.

Xiao WANG received the B.S. degree in automation from the college of information science and engineering, Northeastern University of China in 2013, where he is pursuing the Ph.D. degree in control theory and engineering. Since September 2015, he visited University of Denver as a joint-training Ph.D. student, sponsored by the China Scholarship Council (CSC). He also worked as an intern student at the National Wind Technology Center of the National Renewable Energy Laboratory, Golden, USA. His research interests include the application of advanced controls for wind turbine system, and the transient stability of the power system related to the large-scale wind power integration.