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Review

Enabling Inertial Response of Variable-Speed Wind Turbines: A Survey and New Perspectives

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Abstract: With the rapid development of wind power generations, the inertial response of wind turbines (WTs) are widely concerned recently, which is important for grid frequency dynamic and stability. This paper recognizes and understands the inertial response of type-3 and type-4 WTs from the view of equivalent internal voltage, in analogy with typical synchronous generators (SGs). Due to the dynamic of the equivalent inertial voltage different from SGs, the electromechanical inertia of WTs is completely hidden. The rapid power control loop and synchronization control loop is the main reasons that the WT's inertial response is disenabled. On the basis of the equivalent internal voltage's dynamic, the existing inertia control method for WTs are reviewed and summarized as three approaches from the view of WT's control, i.e. optimizing the power control or synchronization control or both. At last, the main challenges and issues of these inertia controls are attempted to explain and address.

Keywords: inertial response; internal voltage; variable speed wind turbines

1. Introduction

Recently, the installed capacity of wind power generations are growing rapidly. For example, in 2015 the added capacity of wind power generation is 30.5 GW [1][2] and the total capacity reaches to 145.1 GW in China. 186.3 TWh of electricity is generated [1][2], representing 3.3% of total electricity consumption of state [1][2]. Wind power has become the third largest power source in China. It is forecast that the wind capacity will reach 250 GW by 2020 in China as part of the government's pledge [3].

The modern wind farm are mostly equipped with variable-speed wind turbines (WTs) [3]-[6] due to its excellent performance. Based on power-electronic technology, the variable-speed WTs decouples WT's rotor from grid in order to obtain well control and regulation performance, while the electromechanical inertia is also simultaneously hidden [7]. With more and more wind power generations integrated into grid via power-electronic interface, the inertia loss are widely concerned and much-maligned [7]-[8]. The inertial response of devices is the important feature of frequency response [9], which is effective to reduce the change rate of grid frequency. With the reduction of inertia, the change rate and nadir of grid frequency are increased, which is harmful for the frequency stability and the operations of grid-connected devices [10].

Last decades, there were many inertia control methods developed for type-3 [11] and type-4 [12] wind turbines (WTs) to enable the inertial response of WTs. For example, the *df/dt* [13] is added into WT's torque reference to respond and improve grid frequency change rate (*df/dt*), which is a direct improved control

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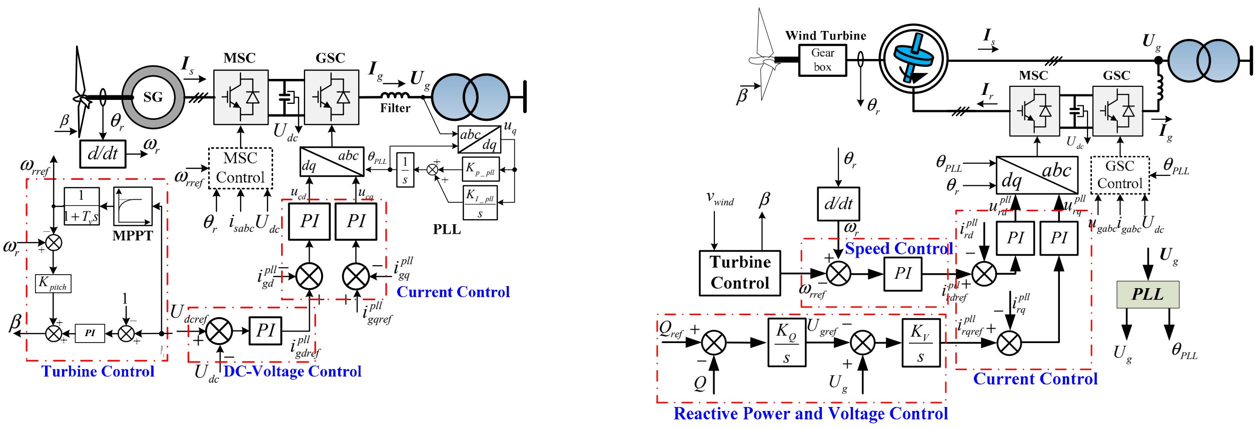
method to enable the inertial response. Moreover the virtual synchronous generator [14] is initially proposed to feature inertia nature in voltage source converters (VSCs) and to provide inertial response by VSCs as virtual synchronous generators. Wang *et al.* employs the virtual synchronous control in DFIG-based WTs to enable its inertial response [15]. The contribution of WT's inertial response to grid frequency dynamic and frequency regulations has been studied and discussed [16]-[17], but various inertia control methods are not systematically summarized and classified. Thus a survey is necessary to further understand and recognize the inertia control of WTs, which will be the main contribution of this paper.

This paper presents a review on the inertia control methods to enable the inertial response of WTs from the view of WT's equivalent internal voltage's dynamic. Firstly, based on the general control and simplified model, the basic concept and dynamic of WT's equivalent internal voltage are presented referring to the typical synchronous generators (SGs). Especially the hidden inertial response of WTs are explained and illustrated. Moreover, on the basis of the equivalent internal voltage, the existing inertia controls for WTs are summarized and unified as three kinds for convenient and deep understanding i.e. modifying the dynamic of synchronization control or power control or both in WTs, respectively. Finally, the main issues and challenges are attempted to address and explain.



(a) Type-4 WTs (b) Type-3 WTs

Fig. 1 Basic control block diagram of WTs. (a) Type-4 WTs, (b) Type-3 WTs.

2. General Control and Simplified Model of Type-3 and Type-4 Wind Turbines

2.1. WT's General Controls

The general control block diagrams of type-3 and type-4 variable speed wind turbines (WTs) [11]-[12] are shown as Fig. 1 (a) and (b). General control of WTs usually includes two main part, i.e. mechanical and electrical parts. The mechanical part mainly includes turbine control and speed control. The turbine control aims to control the pitch angle to regulate the captured mechanical power from wind. The speed control is

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to control the rotating speed by regulating electromagnetic torque. The mechanical part control of type-3 and type-4 WTs is the same as Fig. 1 (a)

For type-4 WTs, a back-to-back full-capacity converter is used completely to decouple the generator with grid as Fig. 1 (a), which is called machine side converter (MSC) and grid side converter (GSC), respectively. While type-3 WT is integrated into grid through both back-to-back part-capacity converter and the stator of generator as Fig. 1 (b). The main function of GSC is usually to control the DC-link voltage through cascaded DC-voltage control and current control. The MSC is to regulate the electromagnetic torque. A phase-locked loop (PLL) is used as a synchronization and measurement unit to synchronize WTs with grid.

2.2. WT's Simplified Models

Neglecting the dynamic of current control and filters, the *dq*-axis actual grid (I_d^{pll} , I_q^{pll}) and rotor currents (I_{rd}^{pll} , I_{rq}^{pll}) are equal to the current references (I_{dref}^{pll} , I_{qref}^{pll} and I_{rdref}^{pll} , I_{rqref}^{pll}) in the PLL's reference frame, respectively, viz.

$$\begin{cases} I_d^{pll} = I_{dref}^{pll} \\ I_q^{pll} = I_{qref}^{pll} \end{cases} \quad \begin{cases} I_{rd}^{pll} = I_{rdref}^{pll} \\ I_{rq}^{pll} = I_{rqref}^{pll} \end{cases} \tag{1}$$

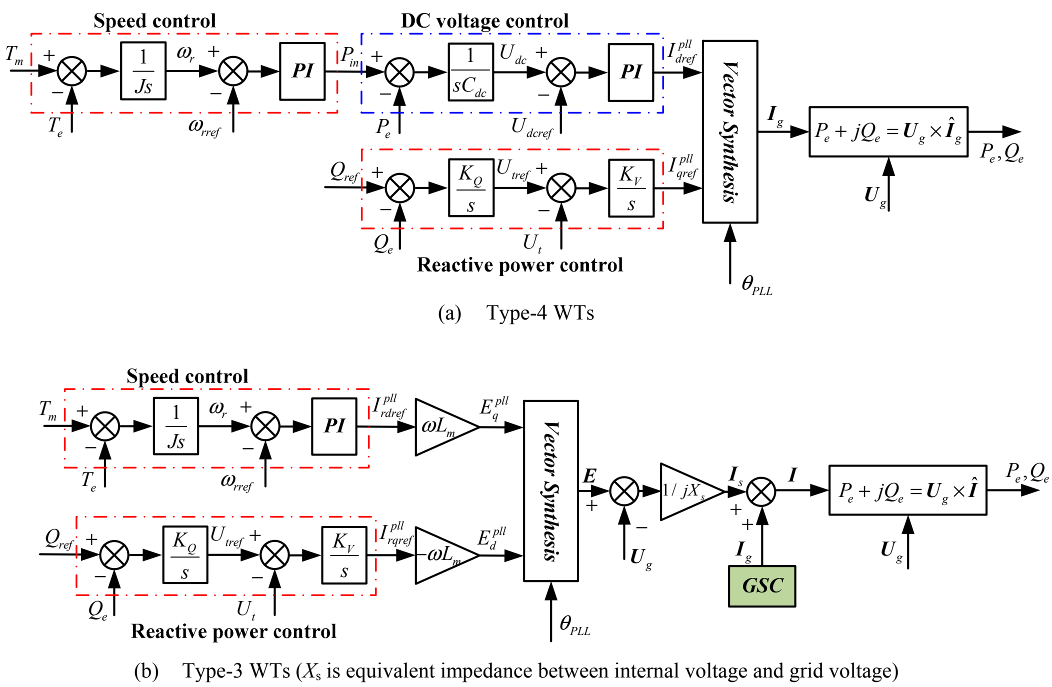

Fig. 2 Simplified control block diagram of WTs. (a) Type-4 WTs, (b) Type-3 WTs.

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Not considering the turbine control with slow electromechanical dynamic, the models of WTs can be further deduced and simplified as Fig. 2 (a) and (b). For type-4 WTs, the DC voltage controller is equivalent to a rapid power control, which aim to rapidly maintain the output electromagnetic power constant in the DC capacitor and equal to the electromagnetic power from generators during grid disturbance.

While for type-3 WTs, the gird side converter is similar with type-4 WTs, which is simply represented by GSC in Fig. 2 (b). The *dq*-axis current references of machine side converter are regulated according to the rotating speed and reactive power control. The *dq*-axis rotor currents can produce an electromotive force (E_d^{pll}, E_q^{pll}) through the mutual inductance (L_m) of DFIG. The electromotive force will produce stator current ($\boldsymbol{I}_s$) interacting with grid voltage ($\boldsymbol{U}_g$).

3. WT's Equivalent Internal Voltage

3.1. Internal Voltage and its Dynamic of Synchronous Generators

Synchronous generators (SGs) are well-known key elements of power system [10]. From the view of power system, SGs can be approximatively regarded as a rotating voltage phasor, i.e. internal voltage ($\boldsymbol{E}$) which is aligned with rotor as Fig. 3 (a). The internal voltage is coupled with grid through stator's equivalent impedance. All the dynamics of SGs are behaved through the behaviors of the equivalent internal voltage. SG's internal voltage is rotating along with rotor relying on the well-known rotor swing motion.

$$J\frac{d\omega_{SG}}{dt} = T_m - T_e \tag{2}$$

Fig. 3 Schematic diagram of SGs' internal voltage.

Once the disturbance occurs in grid, the grid voltage jumps from $\boldsymbol{U}_g$ to $\boldsymbol{U}_g'$. Not considering the action of excitation system, the internal voltage ($\boldsymbol{E}$) maintain original movement state ($\boldsymbol{E}'$) due to the intrinsic rotating inertia ($\boldsymbol{J}$) of rotor as Fig. 3 (b). The power angle immediately and dynamically enlarges to provide the synchronized power for grid support and the re-synchronization of itself. In this process, the inertia i.e., the kinetic energy stored in the rotor of SGs, is spontaneously used for the dynamic energy support of grid frequency.

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3.2. Equivalent Internal Voltage and Inertial Response of Variable-Speed WTs

From the perspective of power grid, the variable-speed WT can be regarded as an equivalent internal voltage coupling with grid through an equivalent impedance. But the movements of the internal voltage are much more complicated than SGs because it is the result of the sequential action of a series of multi-time-scale power controllers in WTs.

3.2.1 Equivalent Internal Voltage Definition of Type-4 WTs

The equivalent internal voltage of type-4 WTs can be defined as Fig. 4.

$$\begin{cases} \boldsymbol{E} = E_d + jE_q = Ee^{j\theta_e} \\ E = \sqrt{E_d^2 + E_q^2} \\ \tan\theta_e = \dfrac{E_q}{E_d} \\ E_d = U_{gd} - X_f I_q \\ E_q = U_{gq} + X_f I_d \end{cases} \tag{3}$$

where θ_e and E are the phase and magnitude of the equivalent internal voltage under the reference frame rotating at ω_0. E_d, E_q, U_{gd}, U_{gq}, I_d and I_q are the *dq*-axis components of equivalent internal voltage, grid voltage and current, respectively. X_f is the impedance of filter.

The phase of internal voltage is mainly constituted by the PLL's phase (θ_{PLL}) and the phase (θ_{PC}) decided by a series of power controls as Fig. 4.

$$\begin{cases} \theta_e = \theta_{PC} + \theta_{PLL} \\ \tan\theta_{PC} = \dfrac{E_q^{pll}}{E_d^{pll}} \\ E_d^{pll} = U_{gd}^{pll} - X_f I_{qref}^{pll} \\ E_q^{pll} = U_{gq}^{pll} + X_f I_{dref}^{pll} \end{cases} \tag{4}$$

where E_d^{pll} and E_q^{pll} are controlled by the *dq*-axis currents components, which are decided by active and reactive power control. θ_{PC} is the phase angle between the equivalent internal voltage and PLL's phasor which is decided by power control.

Under steady state, the internal voltage is synchronously rotating with grid voltage. The phase difference, i.e. power angle (δ) between internal voltage and grid is constant, thus the output power is stable and constant. The output electromagnetic power can be expressed as

$$\begin{cases} P_e = \dfrac{EU_g}{X_f}\sin\delta \\ \delta = \theta_e - \theta_g \end{cases} \tag{5}$$

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where δ is power angle, and θ_g is the phase of grid voltage.

3.2.2 Equivalent Internal Voltage Definition of Type-3 WTs

The equivalent internal voltage of type-3 WTs should be synthesized by generators' stator side and GSC. The dynamic of GSC is similar with type-4 WTs and GSC's capacity is much smaller than generators' stator side. For simplified analysis, the effect of GSC can be neglected in the inertial voltage of type-3 WTs.

The equivalent internal voltage of type-3 WT is similarly defined as Fig. 4.

$$\begin{cases} \boldsymbol{E} = E_d + jE_q = Ee^{j\theta_e} \\ E = \sqrt{E_d^2 + E_q^2} \\ \tan\theta_e = \dfrac{E_q}{E_d} \\ E_d = U_{gd} - X_s I_{sq} \\ E_q = U_{gq} + X_s I_{sd} \end{cases} \tag{6}$$

where X_s is the equivalent impedance between the equivalent internal voltage and grid. I_{sd} and I_{sq} are the dq-axis current components of WT's stator.

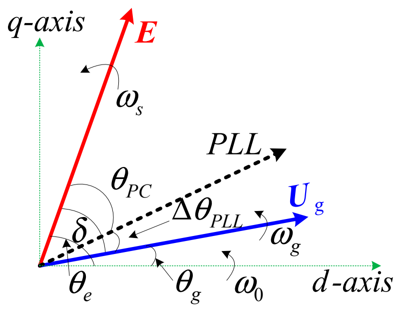

Fig. 4 Equivalent internal voltage of WTs.

The phase of internal voltage is mainly constituted by the PLL's phase (θ_{PLL}) and the phase (θ_{PC}) decided by a series of power controls as Fig. 4.

$$\begin{cases} \theta_e = \theta_{PLL} + \theta_{PC} \\ \tan\theta_{PC} = \dfrac{E_q^{pll}}{E_d^{pll}} \\ E_d^{pll} = -X_m I_{rqref}^{pll} \\ E_q^{pll} = X_m I_{rdref}^{pll} \end{cases} \tag{7}$$

where E_d^{pll} and E_q^{pll} are proportional to the dq-asix rotor currents (I_{rdref}^{pll}, I_{rqref}^{pll}), which are decided by power or torque regulations in WT's speed control.

The output active power and power angle can be expressed as

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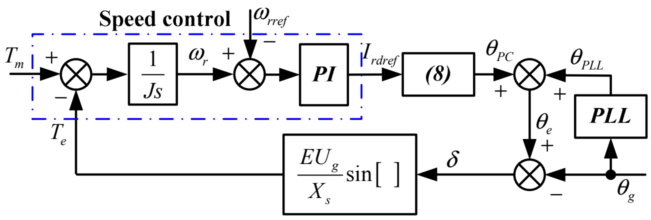
$$\begin{cases} P_e = \dfrac{EU_g}{X_s}\sin\delta \\ \delta = \theta_e - \theta_g \end{cases} \quad (8)$$

The power angle can also express as (9), whose dynamic is also decided by both PLL's phase error and power controls. The phasor diagram of equivalent internal voltage is also plotted as Fig. 4.

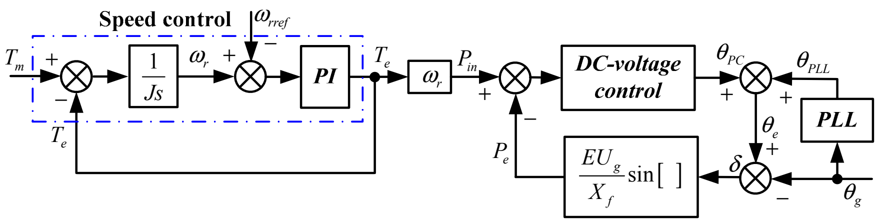
$$\begin{cases} \delta = \theta_e - \theta_g = \Delta\theta_{PLL} + \theta_{PC} \\ \Delta\theta_{PLL} = \theta_{PLL} - \theta_g \end{cases} \quad (9)$$

3.2.3 Inertial Response Analysis of WTs

WTs have enough kinetic energy stored in turbine rotor for inertial response which is the basis for inertial response, thus additional power storage is usually unnecessary. But due to the phase motion dynamic of WT's equivalent internal voltage different from typical SGs, the electromechanical inertia of WTs is fully hidden, thus there is no inertial response from typical type-3 and type-4 WTs in the electromechanical time scale.



(a) Type-3 WTs



(b) Type-4 WTs

Fig. 5 Brief phase motion diagram of equivalent internal voltage of type-3 and type-4 WTs.

For type-3 WTs, the phase motion diagram is further deduced as Fig. 5 (a). The power angle is collectively decided by speed control (θ_{PC}) and PLL ($\Delta\theta_{PLL}$). In typical type-3 WTs, the PLL usually has enough bandwidth to follow grid electromechanical dynamic and to isolate the electromechanical dynamic from WTs. Due to rapid PLL's decoupling, the electromechanical disturbance from grid and WT's electromechanical motion are completely separated, which is the main reason for the inertia of type-3 WTs hidden.

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For type-4 WTs, the phase motion diagram is further simplified as Fig. 5 (b). The equivalent internal voltages of type-3 and type-4 WTs have similar form of expression. The main difference is that there is an equivalent rapid power control loop generated by the DC voltage control. The equivalent power control loop directly regulates the partial phase's dynamic (θ_{PC}) of internal voltage and roughly forms a control close loop in power angle as Fig. 5 (b). Usually the DC voltage control has a control bandwidth of about 10-Hz, which can follow the electromechanical dynamic of grid and keep the output power constant when the electromechanical disturbance occurs in grid. Thus the electromechanical dynamic of type-4 WTs is separated from grid not only by rapid PLL but also by the equivalent power control loop in DC voltage. This is the main reasons for the inertia of type-4 WTs hidden.

4. Main Inertial Response Release Methods

Based on the equivalent internal voltage of WTs and its dynamic analysis, the rapid PLL and power control loops completely separate the swing motion of WT's rotor from grid and hide the rotor inertia of WTs, which makes the equivalent internal voltage of WTs with very small inertia feature and nearly without any inertial response. Thus the phase dynamic of equivalent internal voltage should be improved for the inertial response of WTs. To enable the inertial response of WTs, the swing equation of WT's rotor needs to be coupled with grid and to feel the grid disturbance in electromechanical time scale. All the existing inertia control for WTs can be classified as modifying power control, optimizing the dynamic response of synchronization control, or both.

4.1. Attaching Supplementary Signal into Power Control

The most common and representative way for WTs to make inertial response available is to provide a supplementary signal associated with the detected grid frequency variations or its differential to the torque/power or speed reference value to be tracked as Fig. 6 (a), which is suitable for both type-3 and type-4 WTs [18]-[28].

For example, the original torque controller is modified by adding a signal corresponding to $\Delta T=2H(df/dt)$ to the set torque. As the grid frequency drops, the modified set point torque is increased slowing the rotor and extracting the stored kinetic energy. And in order to remove the measurement noise, and minimise the impact of the supplementary control on mechanical drive train loads, the rate of change of power injection is usually modified by adding a first-order filter after *df/dt* input [18]. GE's WindINERTIA™ feature provides an inertial response capability for WTs by introducing a washout filter to temporarily increase the output power [19] as Fig. 6 (b). A washout filter is also used in [20] to make WTs only act in a transient way using the stored kinetic energy. [21] proposes another different control scheme to create inertial

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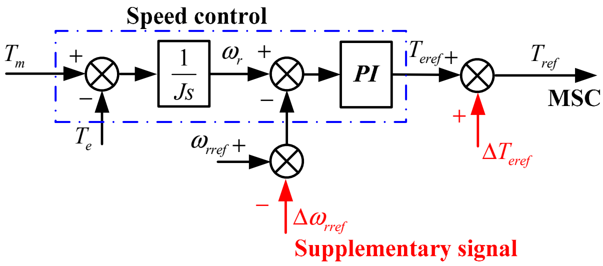
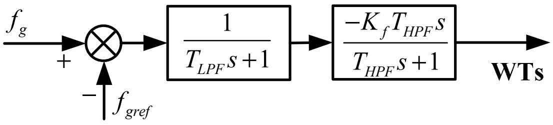
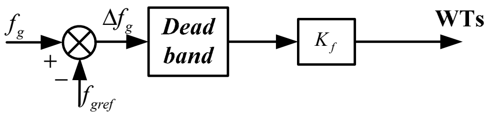
response, that is, the additional torque setpoint is based on the absolutely deviation of the frequency from the nominal value, i.e., $\Delta T=K_f(f_g - f_{gref})$ as Fig. 6 (c). ENERCON IE is implemented by using the frequency deviation relative to the trigger level that responds to a drop in grid frequency by temporarily increasing active power beyond the available power from the wind [22] as Fig. 6 (d). Similarly, [23] develops a control scheme to improve the frequency response capability of type-4 WTs actually by a combination of the abovementioned two kinds of terms associated with frequency differential and its absolutely deviation.



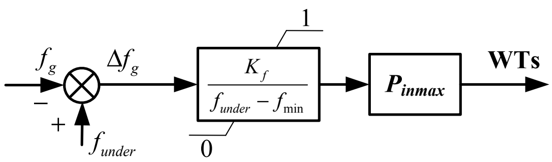
(a) Overall control block of WT's inertia control based on supplementary signal



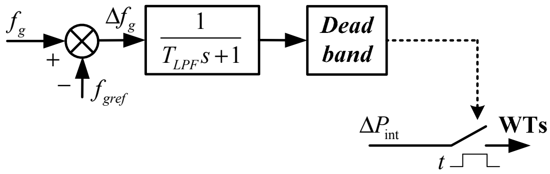
(b) *df/dt* method



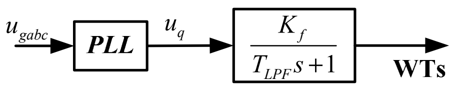
(c) Δf method



(d) Enercon IE (f_{under} is the set value of under-frequency event. f_{min} is the minimum grid frequency, P_{inmax} is the maximum power increase of WTs)



(e) Frequency deviation trigger (ΔP_{int} is the increased power)



(f) PLL's error

Fig. 6 Several inertia controls of WTs based on supplementary signals. (K_f is the gain, T_{LPF} and T_{HPF} are the time constants of filters, f_g and f_{gref} are the measured and nominal grid frequency.)

Besides, there are also some other methods to improve WTs' inertial response capability. An approach which utilises slip to supply the short-term frequency support is discussed in [24]. [25] proposes a method to provide the dynamic frequency support through properly altering the maximum power point tracking

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(MPPT) curve coefficient, which is a function of grid frequency deviation. [26] introduces the phase-locked error of the optimized PLL to modify the speed set point for type-4 WTs to provide inertial support as Fig. 6 (f). An algorithm to extract the maximum kinetic energy without stalling WT is proposed in [27], in which the electric torque is increased step-wisely and then ramped down considering the governor time constant. Similarly, Senvion's (formally Repower) MM82 2MW DFIG-based WTs also increase the active power independently of the system frequency deviation as Fig. 6 (e), i.e., a step function operating at a specific threshold [28]. The public reported inertia control of several WTs manufacturers are presented in Table I.

All in all, though the implementations listed above have some differences, they are essentially the same. They all emulate the inertial response by changing the response behaviours of the commonly designed power control system when triggered by frequency events, by altering reference value of either active power/torque or speed. More essentially speaking, they finally change the power angle dynamic behaviours of WT's equivalent internal voltage through some modifications in the power control, i.e. modifying the dynamic of θ_{PC}.

Table I The public reported inertia control of main WTs manufacturers

	df/dt	*Δf*
Added to speed reference	GE[19]	Enercon[22], Senvion (RePower) [28]
Added to torque reference (output of speed controller)	/	Senvion (RePower) [28]

4.2. Optimizing the Dynamic Response of Synchronization Control

As a measurement and synchronization unit, the performance requirement for PLL currently is as fast and accurate as possible to capture the phase angle of grid voltage. As a result, the electromechanical inertia of WTs is completely hidden without any response to the electromechanical disturbance in grid. In order to release the inertial response of WTs, the dynamic response of PLL can be optimized and PLL's dynamic is utilized to enable the inertial response [29].

For type-3 WTs, the partial phase of WT's equivalent internal voltage (θ_{PC}) is decided by the speed controller with electromechanical dynamic. The power angle is equal to the sum of θ_{PC} and PLL's phase error ($\Delta\theta_{PLL}$). Once the bandwidth of PLL is reduced and its dynamic is slow down, the power angle will obviously enlarge (from δ to δ') with the electromechanical disturbance in grid as Fig. 7 (a). As a result, the spontaneous and natural inertial response of type-3 WTs is enabled. The inertia constant of the equivalent internal voltage is related to PLL's bandwidth [29].

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Fig. 7 Phasor diagram with reducing the control bandwidth of PLL.

While for type-4 WTs, only reducing the dynamic response of PLL cannot enable its inertial response due to the effect of equivalent rapid power control loop in DC voltage. The slow dynamic response of PLL and the PLL's error are produced with reduced bandwidth during electromechanical disturbance, but the equivalent power control in DC voltage is still able to rapidly regulate the *dq*-axis internal voltage components under PLL's frame (E_d^{pll} and E_q^{pll}) through altering the *dq*-axis current reference. The phase θ_{PC} is regulated to θ_{PC}' to maintain the power angle and output power constant as Fig. 7 (b), viz. $\delta = \delta'$. Thus the electromechanical rotating inertia of type-4 WTs is still hidden when the dynamic of PLL is slow down.

Through optimizing PLL's dynamic response, the inertial response of type-3 WTs can be enabled. Based on this method, the control structure of type-3 WTs is not required any modifications and changes, and only PLL's parameters need to be regulated and optimized. The inertial response released by this method is spontaneous, passive and natural. It should be pointed out that the inertial response is directly related the disturbance in grid without any close-loop control, which can take faster response but may arouse over inertial response to threaten the safe and stability of WT's operations.

4.3. Virtual Synchronous Control

Virtual synchronous control is developed to emulate SGs to embed inertial response in grid-connected voltage source converters (VSCs) [30]-[45] as virtual synchronous generators/machines recently, which has been discussed and studied in energy storage [31], Statcom [32], VSC-HVDC [33]-[36], distributed generation [37]-[39], micro grid [40] and etc.. Essentially the virtual synchronous control regulates the magnitude and phase of VSC's output voltage according to active and reactive power errors as Fig. 8. Zhong *et al.* proposes a virtual synchronous control method as synchronverter by implementing the whole equation of SGs to emulate full dynamic of SGs in VSCs [41]-[42]. Moreover, Ise *et al.* employs a second-order SG's rotor swing equation to regulate required voltage according power errors and then an inner voltage loop is used to produce the required voltage, which can feature inertial response in VSCs [43]. In addition, a linear power-damping and synchronizing controller is used to emulate SG's dynamic performance in VSCs by

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Mohamed *et al.* [44]-[45]. While the most common and representative virtual synchronous control methods are developed to enable the inertial of type-3 and type-4 WTs in [46] and [47].

The virtual synchronous control is implemented in type-3 WTs to motivate the inertial response. The most representative is VSynC. The VSynC features a well-known synchronization mechanism of SGs in rotor side converter of type-3 WTs relying on active power. In VSynC, the second-order motion equation is employed to control the excited voltage from machine side converter according to the power output by WT's stator. The phase dynamic of WT's equivalent internal voltage is constituted by the second-order controller of VSynC and WT's rotor swing. As a result, the inertial response of type-3 WTs is able to spontaneously be provided and the VSynC can enhance the operation stability of WTs integrated into weak grid.

While for type-4 WTs, if only the grid side converter is modified by employing the virtual synchronous control, the inertial response cannot be provided to support the electromechanical frequency dynamic of grid due to the limitation of rapid power control in DC-link voltage. Thus in order to release rotor's energy for dynamic support of frequency, the functions of grid-side and machine-side converters are exchanged, i.e. the DC-voltage is controlled by machine side converter and the grid side converter is used to regulate the electromagnetic torque of generators as Fig. 9 (b). Through the exchanging, the rapid power control loop (DC voltage control) is cut from grid as an inner power loop with the connection to grid and WT's rotor is able to directly relate to grid and to respond grid disturbance in electromechanical time scale. As a result the kinetic energy in rotor is released and the inertial response can be provided spontaneously and naturally with the electromechanical disturbance in grid.

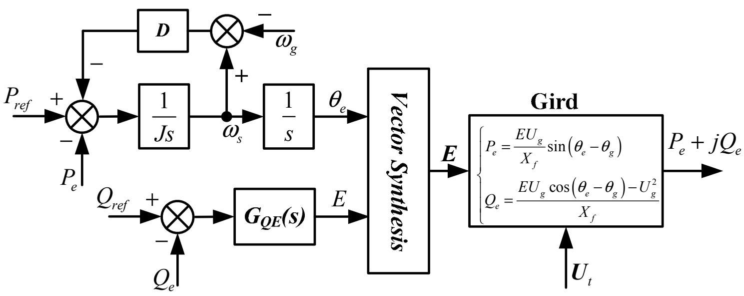

Fig. 8 Typical virtual synchronous control.

The virtual synchronous control alters the synchronization and power control method of WTs together. Due to removing the PLL, WTs can get more stability in weak grid based on the virtual synchronous control. The virtual-synchronous-control-based inertial response is spontaneous and natural without feedback or close loop control, which can get excellent dynamic support capacity of grid frequency but overlarge grid disturbance may arouse quite sharp inertial response to affect WT's safe and stability.

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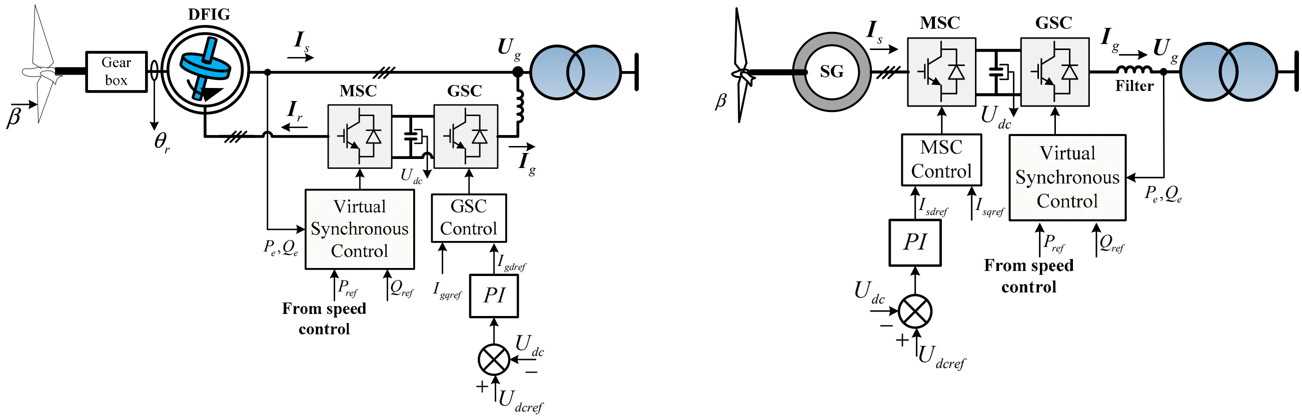

(a) (b)

Fig. 9 Enable inertial response of type-3 and type-4 WTs based on virtual synchronous control.

5. Key challenges and future researches

Enabling the inertial response of WTs will pose new issue and challenges in the WT itself even and the control of whole power system. Here, some issue and challenges are presented and briefly explained.

5.1. Assessing Mechanical Loading and Stress of WTs

During the inertial response, the electromechanical motion of WT's rotor is coupled with grid. The WT blades, drive chain and etc. will suffer from some power and stress shock during frequent grid disturbance. The mechanical loading and stress should be analysed and studied to guarantee WT's safe and stability for inertial response.

5.2. Unified Description of WT's Inertial Response Characteristics and its Effect on Grid Frequency Dynamic

When WT's inertial response is enabled, the basic characteristics of the inertial response based on different inertia control methods should be evaluated, described and distinguished. WT's inertial responses need to be compared with the one of typical SGs. Moreover the relation and interaction between the inertial response featured by different methods and grid frequency dynamic should be further analysed and studied.

5.3. Operating Under Grid Faults

The action of the control to feature inertia in WTs needs to be further studied during grid faults. The fault current is analysed and limited especially for virtual synchronous control methods. And the interaction between the inertia control and typical fault ride through controls should be analysed and coordinated.

5.4. Inertial Responses from Multi-WTs

The relations and interaction between the inertial responses from multi-WTs should be studied and evaluated. The inertial response should be coordinated to avoid the clash and competition between WT-to-

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WT, wind farm to wind farm, wind farms to SGs, especially for the adding supplementary signal methods. The inertia control parameters should be analysed and optimized.

5.5. Grid Codes

On the basis of the key basic characteristics of inertial response and its effect on grid frequency, the unified grid code for WT's inertial response needs to be formulated and revised to standardize WT's inertial response, which is helpful for the development of wind power generations and further promotes the penetration of wind power in grid.

6. Conclusion

This paper reviews and summarizes the control methods to enable both type-3 and type-4 WT's inertial response from the view of WT's equivalent inertial voltage. The rapid synchronization control by PLL and rapid power control loop by DC voltage control fully isolate the rotor swing dynamic of equivalent internal voltage from grid, which is the radical reasons for WT's inertia hidden.

These existing inertia control methods is mainly classify three kinds, i.e. supplementary signal into power control, optimizing synchronization control's dynamic and virtual synchronous control. These control methods modify the phase dynamic characteristics of WT's equivalent internal voltage through improving synchronization control or power control or both, respectively. The supplementary signal and virtual synchronous control are effective for both type-3 and type-4 WTs. Optimizing PLL's dynamic is effective to enable the inertial response of type-3 WTs through improving the dynamic of synchronization control. The supplementary signal method is an active feedback control method by improving the dynamic of power control.

The inertial response from the supplementary signal method is active and controllable but the delays are introduced inevitably. While for the optimizing PLL's dynamic and virtual synchronous control methods, the inertial response is spontaneous and passive nearly without any time delays but the inertial response strength is not fully controllable, which may arouse the undue inertial response.

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