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Wind Power Smoothing by Controlling the Inertial Energy of Turbines With Optimized Energy Yield

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ABSTRACT Power fluctuations caused by wind speed variations affect power quality, especially in weak or isolated grids, and degrade the reliability of wind power converters. This paper develops a wind power smoothing scheme by making use of the large inertial energy of a wind turbine system (WTS). The proposed method, which explores the energy storage capability of the WTS shaft, is easy to implement by adding two additional terms into the existing maximum power point tracking (MPPT) control reference. Based on the law of conservation of energy, the new controller includes two parts: one part is to duplicate the original power trajectory under the MPPT control and the other is to compensate the fluctuations of it. In this way, two control objectives, namely, optimized wind power capture and its smoothing can be achieved simultaneously since the rotor rotates around the optimum speed points. Meanwhile, the mechanical stress of a WTS is alleviated with less oscillating torque reference, and the stability of a WTS is maintained by disabling the smoothing function when the rotor speed hits the speed limits. RTDS simulations of double-fed induction generator-and direct-driven permanent magnet synchronous generator-based WTSs are used to demonstrate the effectiveness of the proposed power smoothing control algorithm. The proposed method is validated on both a single WTS and a wind farm. Quantitative analysis is then carried out to evaluate the relationship between the smoothing performance and the efficiency of wind energy capture.

INDEX TERMS Wind farm, wind power smoothing, power quality, stability, energy storage.

I. INTRODUCTION

Nowadays the level of wind energy penetration in modern power system increases rapidly [1]. However, wind power fluctuates due to the stochastic characteristics of wind, which not only influences power quality [2], increases the power loss on the transmission lines and operation cost of the transmission devices, but also degrades the reliability of wind power converters [3]. Therefore, restraining the fluctuations of the output power is of practical significance. Wind power can vary in different timescales, and this paper focuses on variations in a few to tens of seconds in particular.

Different schemes have been proposed to smooth the power fluctuations in this timescale. One solution is to install additional energy storage systems (ESSs) [2], [4]–[6], such as ultra-capacitors, batteries and flywheels. However, the implementation and maintenance of ESSs are expensive and the

thermal excursions of the back-to-back conversion devices are still not improved [7]. Another alternative is to use the energy stored within wind turbine systems (WTSs), including kinetic energy of the rotor, discarded wind energy by pitch control, and the energy stored in DC link capacitors in permanent magnet synchronous generator (PMSG)-based WTSs. Since DC link capacitor has very limited capacity, it is always utilized together with other energy sources [8], [9]. The pitch angle control to smooth wind power increases the blade pitching, therefore reduces the lifetime of wind turbines [9], [10].

Compared with the above two strategies, the wind power smoothing method that utilizes the large rotor kinetic energy of a WTS can well smooth the wind power and has little loss of wind power procurement if the WTS is well controlled. This approach is thus preferred in many previous works [7], [8], [11]–[16].

It has been shown in [13] that the smoothing of wind power fluctuations by inertia energy can be achieved through properly designing the power reference as a function of rotor speed. In [13], the performances of three methods were compared: the maximum power point tracking (MPPT) control, the constant power control, and the linear slope strategy. It has also been shown that the WTS can be unstable if the smoothing power reference is not appropriately given. Paper [12] presented a simple smoothing method by designing the power reference as $K_{opt}\bar{w}_r^3$, where K_{opt} is a constant parameter and \bar{w}_r is the average rotor speed over time. This method can effectively smooth wind power subject to ideal wind characteristic, and it is not an active way to utilize the kinetic energy of a WTS. The similar way of [12] is used in paper [7]. However, in [7] the smoothing function was achieved through letting the rotor speed follow the reference calculated from the filtered output power according to MPPT principle. An optimized PI controller of the rotor speed is used to ensure the stability of the WTS. However, the way of selecting an appropriate filter time constant of the output power has not been discussed. Paper [8] used a fuzzy logic smoothing controller. It has been shown in the simulation results of [8] that its smoothing capability is very limited and the required torque measurement is difficult to obtain in real operations. In [11] a new control structure has been proposed to enable WTSs output suboptimal filtered power. However, systematic design procedures of the suboptimal power coefficient and the filter time constant were not provided. In [14] and [15], a fuzzy PID and an optimal smoothing strategy were developed based on a trade-off between the optimum power capture and power smoothing effect, respectively. Paper [16] converted the smoothing problem into an optimization problem using second-order cone programming control. However, it requires an accurate model of a WTS and it is thus difficult to implement in practice.

According to the above background, the smoothing effect and wind power capture efficiency still need to be improved. This inspires the proposal in this paper of a new wind power smoothing approach by controlling the rotating kinetic energy of the WTSs in a wind farm, which has not been applied in previous works. This work focuses on the MPPT operating region (operation Region 2) of a WTS, since in operating Region 3 the output wind power is kept constant by pitch control. In the MPPT operating region, it is important to design a proper power reference to smooth the fluctuations as much as possible, whilst keeping a high efficiency of wind energy yield and the stability of the WTS. In this way, the power reference of the proposed new control strategy includes two parts: one part is used to duplicate the original power trajectory under the MPPT control and the other is used to compensate the fluctuations of the former. Hence, the proposed design, which explores the energy storage capability of the WTS shaft, can ensure the rotor of a WTS operate around the optimum speed points resulting in little loss of the wind energy conversion.

Compared to the existing literature, this work is advantageous in the sense that it has all of the following merits under variable wind speeds:

- It smooths the wind power output as much as possible while still able to keep a high energy capture efficiency;
- It maintains the stability of the WTSs;
- It alleviates the mechanical stress of a wind turbine and thus expands its lifetime;
- It is easy in practical implementation without modification of the readily installed devices or adding extra physical devices.
- It can smooth the output power from a wind farm instead of from a single WTS, considering the inherent smoothing effect of a wind farm.

It should be noted that in our previous work [17] the kinetic energy of a WTS is also controlled to smooth the fluctuating power of a wave farm. In [17] the compensation power is known to the WTS and the wind speed is assumed to be constant within a particular wave period. However, in this paper the unknown compensation power of the wind itself need to be estimated where the wind speed is treated as a real-time variable.

The paper is organized as follows. Section II presents the detailed control designs for a single WTS, and then a wind farm. The performance of the proposed control method is verified in Section III by real-time simulations of a single DFIG- and PMSG- based WTSs and quantitative analysis of the dynamic performance is also carried out. In Section IV simulation results are presented to show that the coordination of two WTSs in a wind farm further improves the efficiency. Finally, Section V concludes the study.

II. DEVELOPMENT OF THE WIND POWER SMOOTHING CONTROL

A. CONTROL DEVELOPMENT FOR SMOOTHING A SINGLE WTS

The power or torque reference of the smoothing controller in our previous work [18] is designed as

$$P_{ref} = K_{opt}w_r^3(t) + K \int_{t_0}^t \Delta P_c dt * w_r(t) + \Delta P_c \quad (1)$$

$$T_{ref} = K_{opt}w_r^2(t) + K \int_{t_0}^t \Delta P_c dt + \frac{\Delta P_c}{w_r(t)} \quad (2)$$

where $K = \frac{2K_{opt}}{J}$, J is the total inertia of the wind turbine system, and $w_r(t)$ is the real-time rotor speed under the smoothing condition. In this paper, the structure of the wind power smoothing controller can also be designed as (1) or (2). In the previous work, the compensation power ΔP_c is the external power (fluctuations of wave power). However, in this paper, ΔP_c is the internal power (fluctuations of wind power). Therefore, K and ΔP_c need to be re-designed.

The following paragraphs will explain how to calculate the value of K . In the classical MPPT control [18], the power or torque reference of a WTS is

$$P_{ref0} = K_{opt}w_{r0}^3(t) \quad (3)$$

$$T_{ref0} = K_{opt}w_{r0}^3(t) \quad (4)$$

With the purpose of smoothing the fluctuations of the maximum power, the power reference of the proposed smoothing method should be

$$P_{ref} = P_{ref0} - \varepsilon(t) + \Delta P_c \quad (5)$$

where $\varepsilon(t)$ is a small time-varying value representing the loss of the wind power capture due to the smoothing action. ΔP_c is used to compensate the fluctuations of the P_{ref0} and its average value is zero in the long term.

However, in order to automatically follow the change of the wind speed and maintain the stability of WTS, in principle the power reference of the smoothing situation still needs to use the cubic of the real-time rotor speed, like that in the MPPT control. Therefore, the power reference given in (1) can be re-written as:

$$P_{ref} = T_{new1}w_r(t) + \Delta P_c \quad (6)$$

where

$$T_{new1} = K_{opt}w_r^2(t) + K \int_{t_0}^t \Delta P_c dt \quad (7)$$

Note that the aim of the proposed control design is to make the power reference in (5) equal to that in (6), i.e.,

$$T_{new1}w_r(t) = P_{ref0} - \varepsilon(t) \quad (8)$$

Because of the fast characteristics of Voltage Sourced Converters (VSC), the output power of the generator in a WTS can be seen to be the same as the power reference. Therefore, on one hand, under variable wind speed, from time t_0 to t , the change of the kinetic energy under the MPPT control (3) is

$$\int_{t_0}^t [P_{in0}(t) - P_{ref0}(t)]dt = \frac{J}{2}[w_{r0}^2(t) - w_0^2] \quad (9)$$

where $P_{in0}(t)$ is the real-time captured wind power in the MPPT control.

On the other hand, now under the same variable wind speed, the kinetic energy change in the proposed smoothing control (6) is

$$\int_{t_0}^t [P_{in}(t) - P_{ref}(t)]dt = \frac{J}{2}[w_r^2(t) - w_0^2] \quad (10)$$

where $P_{in}(t)$ is the real-time captured power in the proposed control. w_0 in (9) and (10) is the rotor speed at the time t_0 when the smoothing begins.

The captured power of the smoothing control is less than that of the MPPT control. As in (5) the loss of the captured wind power is already defined as $\varepsilon(t)$, the relationship of $P_{in}(t)$ and $P_{in0}(t)$ is

$$P_{in}(t) = P_{in0}(t) - \varepsilon(t) \quad (11)$$

Substituting (8) and (11) into (9) gives

$$\int_{t_0}^t [P_{in}(t) - T_{new1}w_r(t)]dt = \frac{J}{2}[w_{r0}^2(t) - w_0^2] \quad (12)$$

By minus (12) from (10), it holds that

$$\int_{t_0}^t [P_{ref}(t) - T_{new1}w_r(t)]dt = \frac{J}{2}[w_{r0}^2(t) - w_r^2(t)] \quad (13)$$

Substituting (6) into (13) yields

$$\int_{t_0}^t \Delta P_c dt = \frac{J}{2}[w_{r0}^2(t) - w_r^2(t)] \quad (14)$$

By further employing (3), (7) and (14) into (8), the unknown K is deduced as

$$K = \frac{2}{J} \frac{K_{opt}[w_{r0}^3(t) - w_r^3(t)] - \varepsilon(t)}{w_r(t)[w_{r0}^2(t) - w_r^2(t)]} \quad (15)$$

As can be seen in section III. A, the loss of captured wind power, $\varepsilon(t)$, is relatively small that could be ignored. Therefore, the parameter can be calculated as

$$\begin{aligned} K &\approx \frac{2}{J} \frac{K_{opt}[w_{r0}^3(t) - w_r^3(t)]}{w_r(t)[w_{r0}^2(t) - w_r^2(t)]} \\ &= \frac{2K_{opt}}{J} \frac{[w_{r0}^2(t) + w_{r0}(t)w_r(t) + w_r^2(t)]}{w_r(t)[w_{r0}(t) + w_r(t)]} \end{aligned} \quad (16)$$

In order to calculate the parameter K from (16), $w_{r0}(t)$ has to be known. However, it cannot be measured directly now under the smoothing condition. One method is to estimate it from the measured wind speed, which is presented in Section II-B.

The following paragraphs explain how to obtain ΔP_c .

As illustrated before, ΔP_c is the compensation of the fluctuations of output power $K_{opt}w_{r0}^3(t)$ under the MPPT control. Considering that $T_{new1}w_r(t)$ is approximately equivalent to $K_{opt}w_{r0}^3(t)$ of the MPPT control, ΔP_c is calculated by

$$\Delta P_c = \overline{P_{opt}} - P_{opt} \quad (17)$$

where

$$P_{opt} = T_{new1}w_r(t) \quad (18)$$

$\overline{P_{opt}}$ is the average of P_{opt} through a Moving Average Filter (MAF). The output of a MAF is the average of the last N input samples within a time window where is the number of points to be averaged.

Now K and ΔP_c are known, then the reference (1) or (2) can be sent to the controller of a single WTS where the control structure is shown in Fig. 1.

Summing up, the basic idea behind the proposed control described in (1) is that: its first part $K_{opt}w_r^2(t) + K \int_{t_0}^t \Delta P_c dt * w_r(t)$ is to mimic the trajectory of the output power of the MPPT control, which can be seen from (8), while the second part ΔP_c is to compensate the fluctuations of the former. This means that the output power with the proposed smoothing controller can always approximately follow the average output power of the MPPT control.

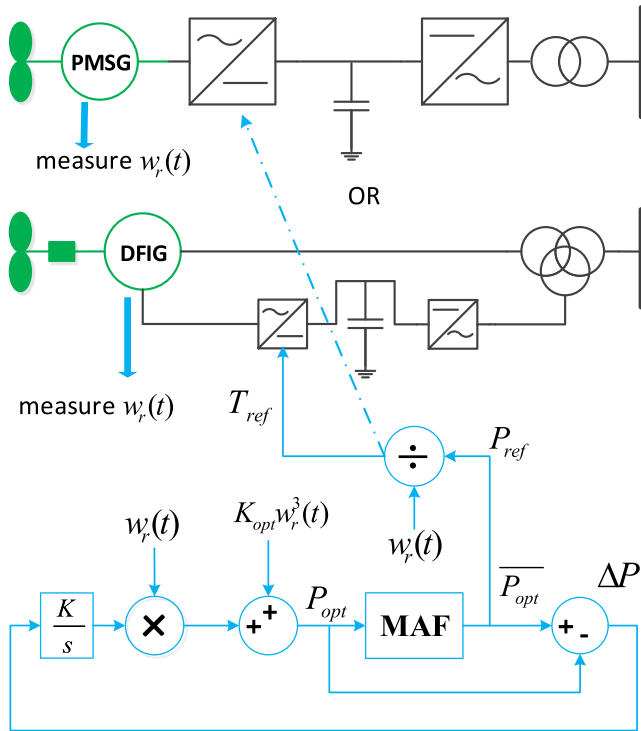


FIGURE 1. The proposed control structure of a single DFIG-based or PMSG-based WTS.

B. ESTIMATION OF THE PARAMETER $w_{r0}(t)$

Because of the inherent inertial effect of a WTS, $w_{r0}(t)$ under the MPPT control is not equal to but is the delayed approximation of the optimum rotor speed $w_{opt}(t)$ which is calculated from the real-time wind speed $v_w(t)$. Their relationship in s-domain can be

$$w_{r0}(s) \approx \frac{w_{opt}(s)}{Ts + 1} = \frac{\lambda_{opt} v_w(s)/R}{Ts + 1} \quad (19)$$

where λ_{opt} is the optimum tip speed ratio, is the rotor length of the turbine, and T is a constant related to the inertia of a WTS. Thus $w_{r0}(t)$ can be estimated by

$$w_{r0est}(s) = \frac{\lambda_{opt} v_w(s)/R}{Ts + 1} \quad (20)$$

Figure 2 shows that the estimated rotor speed $w_{r0est}(t)$ is an accurate approximation of the actual $w_{r0}(t)$ under the MPPT control. With the estimation of $w_{r0}(t)$, K can be calculated from (16).

C. COORDINATING CONTROL FOR SMOOTHING A WIND FARM

There is an inherent smoothing effect in a wind farm since each WTS has different wind speeds, the fluctuating wind power from the wind farm can be naturally smoothed. The control structure for a wind farm is shown in Fig. 3.

From Fig. 3, it can be seen that the total compensated wind power of the whole farm is allocated to each individual WTS according to the ratio of the square of its rotor speed to the sum of the square of all the rotor speeds in the farm.

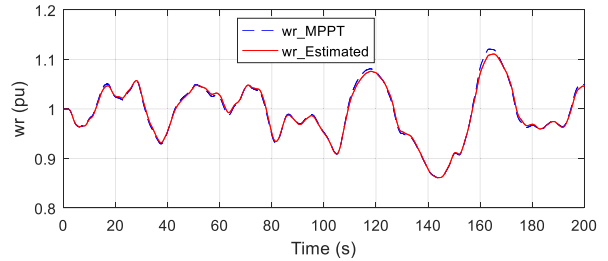


FIGURE 2. The real-time rotor speed of the MPPT control and its estimated value by (20).

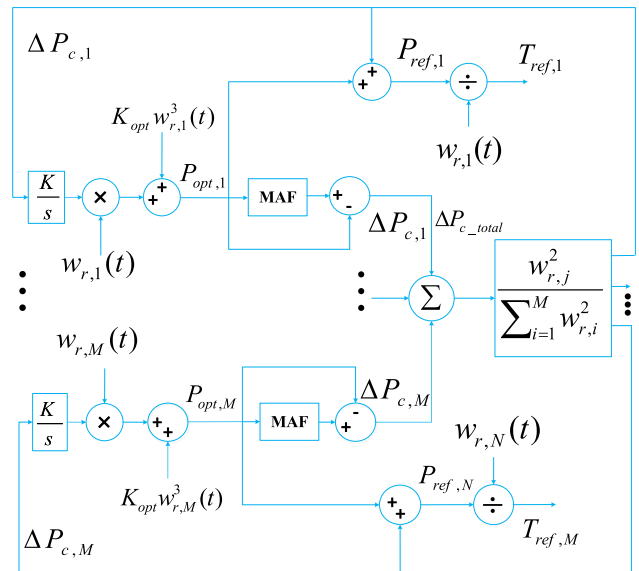


FIGURE 3. The proposed control structure of a wind farm.

This allocation principle is reasonable, since kinetic energy of a WTS is proportional to the square of its rotor speed. Through such an allocation, the total loss caused by the smoothing action can be reduced [14], [15].

The deduction procedure of the proposed control for a wind farm directly follows that in Section II-A, so the details of it is thus omitted here. The obtained controller can be summarized as follows:

$$\Delta P_{c,i,total} = \overline{P_{total}} - P_{total}, P_{total} = \sum_{i=1}^M P_{opt,i} \quad (21)$$

$$P_{opt,i} = [K_{opt} w_{r,i}^2(t) + K_i \int_{t_0}^t \Delta P_{c,i} dt] * w_{r,i}(t) \quad (22)$$

$$\Delta P_{c,i} = \frac{w_{r,i}^2(t)}{\sum_{i=1}^M w_{r,i}^2(t)} * \Delta P_{c,i,total} \quad (23)$$

$$T_{ref,i} = K_{opt} w_{r,i}^2(t) + K_i \int_{t_0}^t \Delta P_{c,i} dt + \frac{\Delta P_{c,i}}{w_{r,i}(t)} \quad (24)$$

$$K_i = \frac{2K_{opt} [w_{r0,i}^2(t) + w_{r0,i}(t)w_{r,i}(t) + w_{r,i}^2(t)]}{J_i w_{r,i}(t)[w_{r0,i}(t) + w_{r,i}(t)]} \quad (25)$$

where M is the total number of the WTSs in the wind farm, $\Delta P_{c,i,total}$ is its total compensation power. For the i^{th} WTS, $\Delta P_{c,i}$ is the compensated power, $T_{ref,i}$ is the torque reference,

TABLE 1. Simulation parameters.

Symbol	Quantity	Value
DFIG		
S_b	Rated MVA	2.2 MVA
V_b	Rated Stator L-L RMS Voltage	0.69 V
f_b	Rated Frequency	60 Hz
R_s	Stator Resistance	0.00462p.u.
X_s	Stator Leakage Reactance	0.102p.u.
L_m	Unsaturated Magnetizing Reactance	4.348p.u.
R_r	Rotor resistance	0.0060p.u.
X_r	Rotor leakage inductance	0.08596p.u.
k	Rotor over Stator Turns Ratio	2.6377
H_t	Wind Turbine Inertia Constant	4.3s
H_g	Generator Inertia Constant	0.75s
PMSG		
S_b	Rated MVA	2.0 MVA
V_b	Rated L-L RMS Voltage	4k V
f_b	Rated Frequency	3.77 Hz
X_s	Stator Leakage Reactance	0.1p.u.
X_{md}	D-axis Unsaturated Magnet. React.	0.65p.u.
X_{ld}	D-axis Damper Leakage Reactance	2.5 p.u.
X_{mq}	Q-axis Magnetizing Reactance	1.0p.u.
X_{lq}	Q-axis Damper Leakage Reactance	2.5p.u.
R_s	Stator Resistance	0.01 p.u.
R_d	D-axis Damper Resistance	2.0 p.u.
R_q	Q-axis Damper Resistance	2.0 p.u.
C_d	Magnetic Strength	1.3 Norm
H	Inertia Constant	5.05s

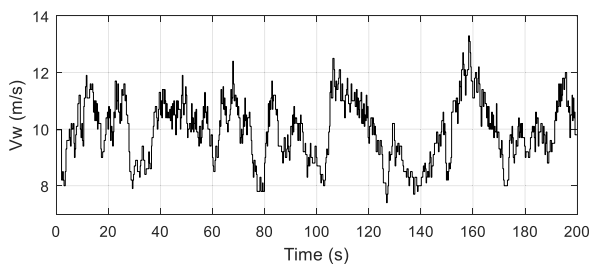


FIGURE 4. The real-time wind speed used in Cases 1-3 and used for WTS1 in Case 4.

$w_{r,i}(t)$ is the measured real-time rotor speed, and $w_{r0,i}(t)$ is the real-time rotor speed under the MPPT control, which is estimated by (20).

III. SIMULATION RESULTS

In order to demonstrate the smoothing effect of the proposed strategy, a single WTS based on DFIG and a direct-driven PMSG are simulated. Quantitative analyses of a DFIG-based WTS under different MAF windows are also given. Furthermore, simulations of a wind farm with two DFIG-based WTSs are provided to show the benefits of coordinated control.

The parameters of the simulated DFIG- and PMSG- based WTSs are given in Table 1 in the Appendix. In a DFIG-based WTS, only two masses are modelled, the turbine itself and the DFIG. The cut-in wind speed is 6m/s and the rated wind

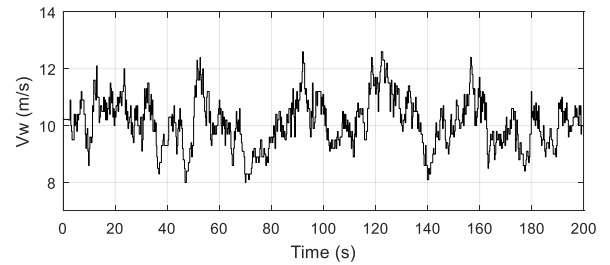
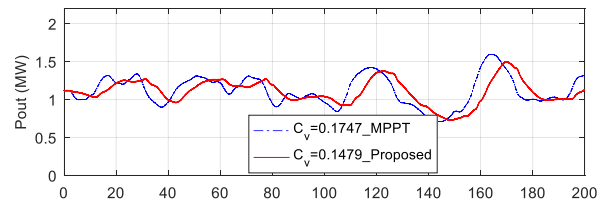
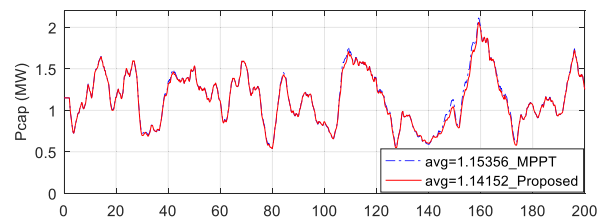


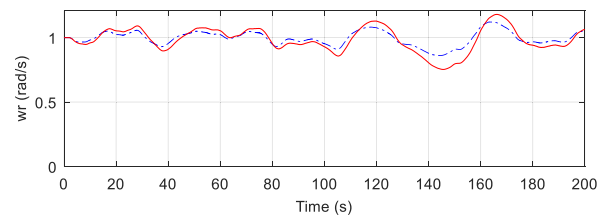
FIGURE 5. The real-time wind speed used for WTS2 in Case 4.



(a) The output power of the three-winding transformer



(b) The captured wind power



(c) The rotor speed

FIGURE 6. The output power of the three-winding transformer, the captured wind power, and the rotor speed by the MPPT and the proposed control with a 10s MAF window in a DFIG-based WTS.

speed is 12.5m/s. The real-time wind speed data used in the simulations are taken from [19] and are shown in Fig. 4 and Fig. 5. In all of the simulations, the number of sampling points of a MAF is fixed, but the MAF time window is varied.

The coefficient of variation c_v , also referred to relative standard deviation, is defined as the ratio of the standard deviation σ to the mean μ , i.e. $c_v = \frac{\sigma}{\mu}$. This coefficient is used as an index of the smoothing degree. Simulations are performed for the following 4 cases.

Case 1: Time domain simulations of a DFIG-based WTS using 10s and 20s MAF windows.

Case 2: Time domain simulations of a direct-driven PMSG-based WTS using a 10s MAF window.

Case 3: Quantitative analysis of a DFIG-based WTS under different MAF windows.

Case 4: Demonstration of the coordination benefits of two DFIG-based WTSs in a wind farm.

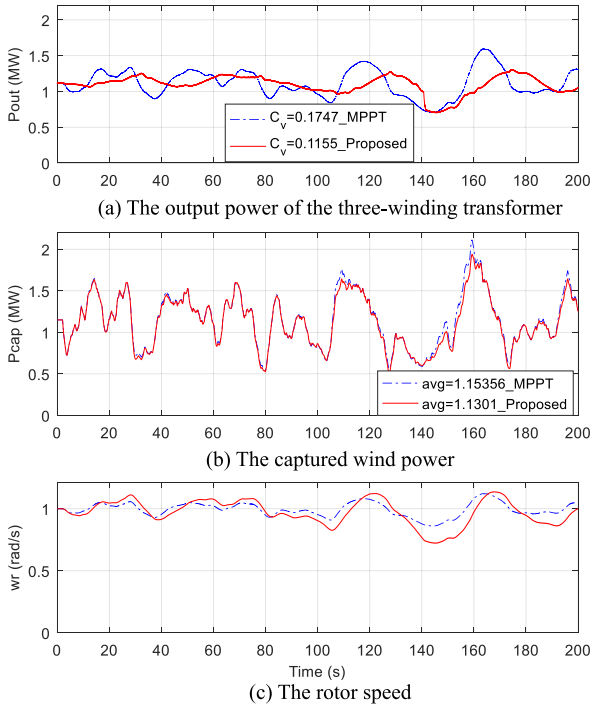


FIGURE 7. The output power of the three-winding transformer, the captured wind power, and the rotor speed by the MPPT and the proposed control with a 20s MAF window in a DFIG-based WTS.

A. CASE 1

The performances of a single DFIG-based WTS using the proposed control and the MPPT control with 10s and 20s MAF window are shown in Fig. 6 and Fig. 7, respectively. From Fig.6 (a) and Fig. 7 (a), it can be seen that the coefficient of variation c_v of the output power under the proposed control is smaller than that of the MPPT control. It can be seen from Fig. 6 (b) and Fig. 7 (b) that the average captured wind power under the proposed control is close to that under the MPPT control. This is because the rotor speed is always around the optimum speed, as shown in Fig. 6 (c) and Fig. 7 (c). These results verify that the proposed scheme can smooth the output power while optimize the wind energy yield. They also demonstrate the assumption that $\varepsilon(t)$ is negligible, as made in Section II, is rational.

It can be seen that compared with Fig.6, Fig.7 has smoother output power, less captured wind power, and more oscillatory rotor speed. The different results are due to the use of different MAF windows. This illustrates that the smoothing performance and the efficiency of wind power capture are two conflicted performance index, and they should be balanced when choosing the MAF window.

Meanwhile, it can be seen from Fig. 7 (a) that at $t = 140s$ there is a sudden drop in the output power. This is because the protection mode is activated by disabling the smoothing function when the rotor speed hits its limits. This phenomenon should be avoided as it can cause a step change in the torque and would significantly cause fatigue to the mechanical shaft of a WTS. One way to avoid the phenomenon is to decrease

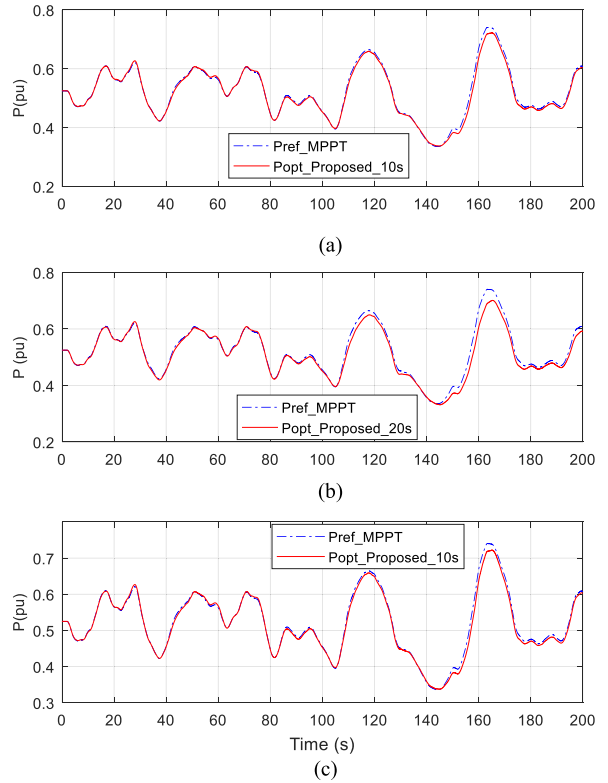


FIGURE 8. Verifying that the first part ($P_{opt} = T_{new1} w_r(t)$) of the proposed controller (Eq. 5) can duplicate the original power trajectory of the MPPT control with 10s and 20s MAF windows in a DFIG-based WTS, and in a PMSG-based WTS with a 10s MAF window. (a) 10s MAF window (DFIG). (b) 20s MAF window (DFIG). (c) 10s MAF window (PMSG).

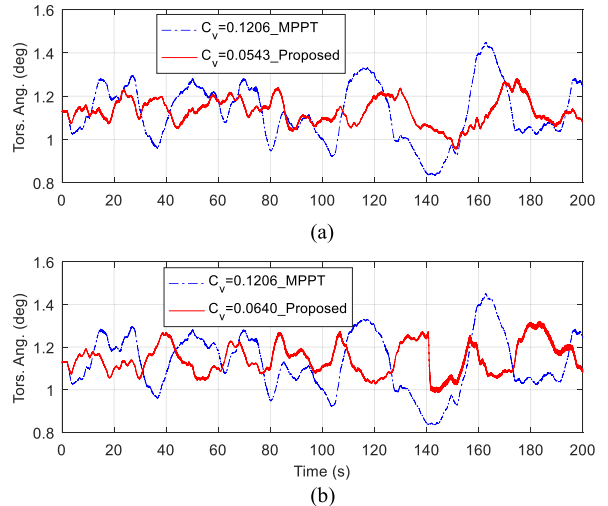


FIGURE 9. The torsional turbine angle under the MPPT and the proposed control with 10s and 20s MAF windows in a DFIG-based WTS. (a) 10s MAF window. (b) 20s MAF window.

the MAF window smoothly before the rotor speed goes too low.

From Fig. 8 (a) and Fig. 8 (b) it can be seen that the first part ($T_{new1} w_r(t) = P_{opt}$) in (5) can track the original power trajectory ($P_{out0} = K_{opt} w_{r0}^3(t)$) of the MPPT control well.

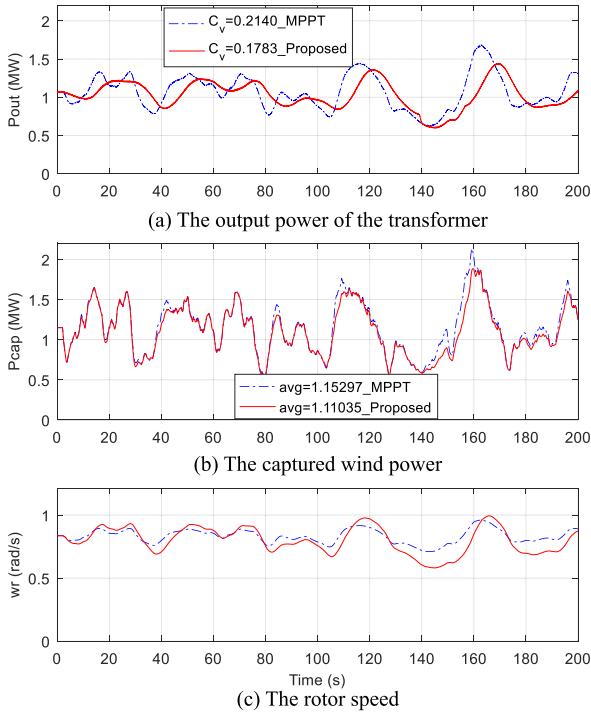


FIGURE 10. The output power of the transformer, the captured wind power, and the rotor speed by the MPPT and the proposed control with a 10s MAF window in a PMSG-based WTS.

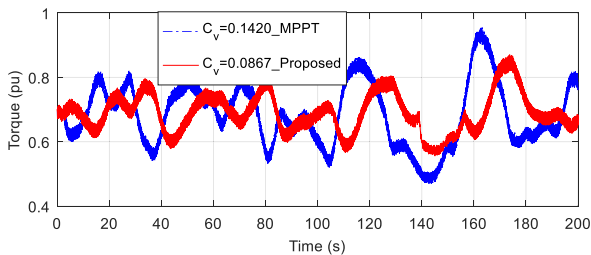


FIGURE 11. The torque of the PMSG by the MPPT and the proposed control with a 10s MAF window in a PMSG-based WTS.

This demonstrates that the proposed controller can duplicate the power trajectory of the MPPT control.

From Fig. 9 (a) and Fig. 9 (b) it can be seen that c_v of the torsional angles between the low speed shaft and the high speed shaft under the proposed control is less than that under the MPPT control. It is known that the shaft torsional angle is a measure of the mechanical stress of WTSs [7], [20]. Hence, the simulation results indicate that the proposed control can alleviate the mechanical stress, when compared with the MPPT control.

B. CASE 2

In this case the smoothing effect of a single PMSG-based WTS is simulated with a MAF window of 10s. The results shown in Fig. 10 and Fig. 8(c) are similar to those in Case 1, which further verify the effectiveness of the proposed control.

From Fig. 11 it can be seen that c_v of the torque of the PMSG under the proposed control is less than that using the

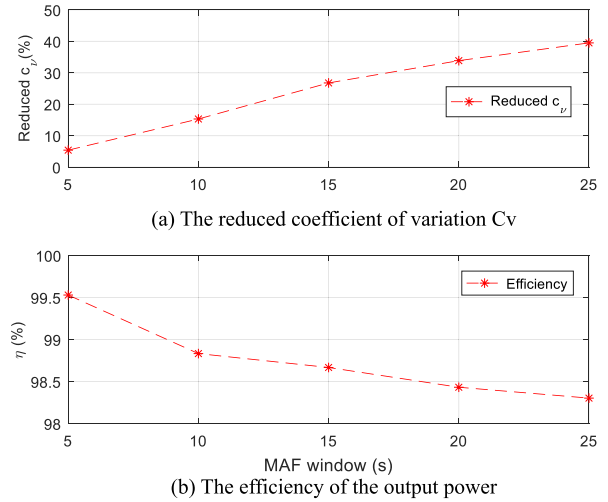


FIGURE 12. The reduced c_v and efficiency of the output power by the proposed control compared with the MPPT control under different MAF windows.

MPPT control. This shows that the mechanical stress of the PMSG-based WTS is also reduced.

C. CASE 3

Define efficiency η as the ratio of the output power under the proposed control to that under the MPPT control. Fig. 12 shows that by using the proposed smoothing control c_v of the output power is significantly reduced, with the power loss less than 2%. Although by using a bigger MAF window c_v of the output power can be further reduced, sudden drops of the output power will happen more frequently. To avoid this sudden-drop phenomenon, extra action is needed, as discussed in Case 1. Thus it is critical to choose an MAF window to avoid the sudden-drop phenomenon.

D. CASE 4

This case verifies that the coordination algorithm proposed in Section II-C can automatically allocate the compensated power among wind turbines in a multi-turbine system and decrease the loss of wind power capture. A wind farm consisting of two DFIG-based WTSs is studied in this case under the wind speed profiles shown in Fig. 4 and Fig. 5.

From Fig. 13 (a) it can be seen that c_v of the total output power using the proposed control is 36.11% less than that using the MPPT control. However, the average of the total output power under the proposed control is only 0.85% less than that under the MPPT control, which can also be seen from Fig. 13 (b) and Fig. 13 (c) where the captured wind power under the proposed control is little less than that under the MPPT control. Meanwhile, different from the single WTS case (Fig. 7 (a)), there is no sudden drop of the output power, even with the 20s MAF window. This is because, within the proposed smoothing approach, the compensated wind power is automatically distributed among the WTSs according to the square of their rotor speeds. If the rotor speed of one

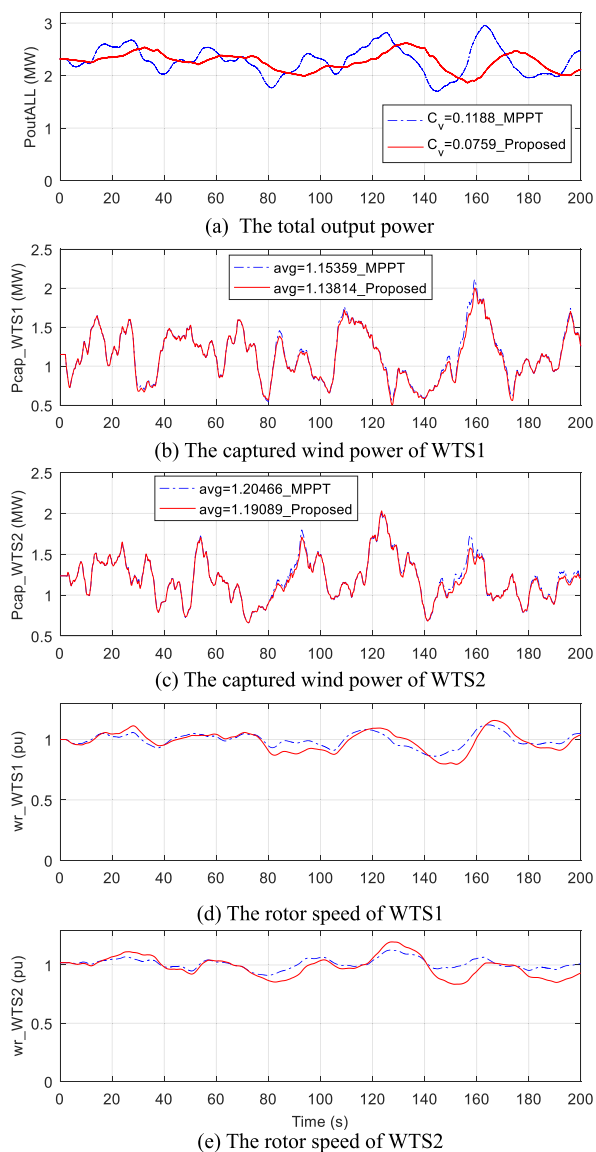


FIGURE 13. The total output power, the captured wind power, and the rotor speed of each WTS by the MPPT control and the proposed control with 20s MAF window in the wind farm in Case 4.

turbine goes low, the other WTSs with higher rotor speeds will output more power to help it to recover. It can be seen from Fig.13 (d) and Fig.13 (e) that at the time around 140s the rotor speed of WTS1 is low while that of WTS2 is high. Then the latter is distributed more of the compensated wind power to stop the rotor speed of the former decreasing further. Thus, WTS1 does not have the sudden drop of output power phenomenon and losses less captured wind power compared with that in red lines in Fig. 7 (a) and Fig. 7 (b) although under the same wind speed, and this is considered to be a great advantage of the proposed coordination control strategy.

IV. CONCLUSION

This paper has proposed a wind power smoothing method by making use of the large rotor inertia of turbines. In other

words, the proposed approach can explore the kinetic energy storage capability of WTS shafts and control this energy stored dynamically for the purpose of smoothing wind power outputs. Without changing the existing physical structure, the proposed method adds two additional terms to the existing MPPT controller. Unlike the conventional inertia energy smoothing methods, the proposed method can duplicate the trajectory of the MPPT control and in the meantime smooth the output power based on this trajectory. Thus, it makes the rotor speed always run around the optimum operating points, leading to little loss of wind energy yield. Considering the natural smoothing effect of a wind farm itself, a coordination algorithm has been proposed to dynamically allocate the required compensation power of a wind farm to all the participating WTSs, to achieve less loss of the wind power capture. The proposed smoothing scheme can be applied to both the DFIG-based and direct-driven PMSG-based WTSs.

The quantitative analysis of the smoothing effect and the efficiency of wind energy yield have been presented in the paper. It has provided guidance to choose the filtering time constant in order to balance the smoothing effect and the efficiency of the wind power capture. A single WTS based on the two mainstream generators (DFIG and direct-driven PMSG) and a wind farm consisting of two DFIG-based WTSs with real wind speed profiles have been simulated using the RTDS platform to verify the smoothing effect of the proposed smoothing algorithm. It has been shown that the proposed method can reduce the standard deviation of the output wind power by 5%-40% with less than 2% loss of the power. Moreover, the coordination of WTSs in a wind farm can further help improve the smoothing effect and reduce the efficiency loss. The RTDS simulations have shown that the proposed smoothing algorithm can reduce c_v of the wind farm output power by 36.11% with less than 1% loss of the wind energy yield.

APPENDIX

See Table 1.

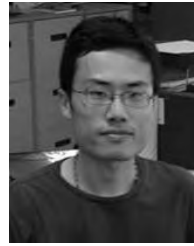
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