

# Power Smoothing Control of Wind Farms Based on Inertial Effect of Wind Turbine Systems

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**Abstract** – This paper proposes a novel strategy for attenuating the output power fluctuation of the wind farm (WF) in a range of tens of seconds delivered to the grid, where the kinetic energy caused by the large inertia of the wind turbine systems is utilized. A control scheme of the two-level structure is applied to control the wind farm, which consists of a supervisory control of the wind farm and individual wind turbine controls. The supervisory control generates the output power reference of the wind farm, which is filtered out from the available power extracted from the wind by a low-pass filter (LPF). A lead-lag compensator is used for compensating for the phase delay of the output power reference compared with the available power. By this control strategy, when the reference power is lower than the maximum available power, some of individual wind turbines are operated in the storing mode of the kinetic energy by increasing the turbine speeds. Then, these individual wind turbines release the kinetic power by reducing the turbine speed, when the power command is higher than the available power. In addition, the pitch angle control systems of the wind turbines are also employed to limit the turbine speed not higher than the limitation value during the storing mode of kinetic energy. For coordinating the de-rated operation of the WT and the storing or releasing modes of the kinetic energy, the output power fluctuations are reduced by about 20%. The PSCAD/EMTDC simulations have been carried out for a 10-MW wind farm equipped with the permanent-magnet synchronous generator (PMSG) to verify the validity of the proposed method.

**Keywords:** Inertia effect, Pitch angle control, PMSG, Power smoothing, Supervisory control, Wind farm

## 1. Introduction

In recent years, the increasing penetration of wind energy into the power grid has changed the role of the wind farm. This makes the wind farms integrated with the grid be considered no longer as a passive load [1]. Since the wind energy is not constant and the wind power is proportional to the cube of the wind speed, the output power of the wind farm is fluctuated due to the wind speed variation. This power fluctuation may lead to several problems for the power system operation such as power quality, system stability, system controls, especially if wind farm is connected to the weak grid or isolated island grids [2-5].

In order to reduce a negative impact of the output power fluctuation from the wind farms, the wind output power should be smoothed before delivering into the grid [6, 7]. Minimization of the output power fluctuation can be realized by either controllers without additional apparatus or utilization of additional devices. In [8] and [9], a strategy using the pitch angle control system has been

presented, where no additional device is required. However, all available energy extracted from the wind is not captured due to an increase of the pitch angle. Several studies have suggested a utilization of the turbine inertia to smoothen the output power fluctuation [4, 10]. However, this control strategy affects high stresses on the turbine blades [7]. Another method to filter out the fluctuated output power is to use the external energy storage systems such as batteries, ultracapacitors, flywheels, etc [6, 11, 12]. With these external devices, the optimal wind energy is captured by the maximum power point tracking (MPPT) control. A main disadvantage of this method is that the capital and maintenance costs are high. It is also noted that no energy storage system can be 100% efficient [6].

This paper extends the work of [13] by suggesting the phase delay compensation for the power reference of the WF. Here, a new control strategy to smoothen the output power of the wind farm before delivering to the grid is proposed, in which the inertial effect of the wind turbines and coordinated operation of individual wind turbines (WT) are utilized. A two-level control scheme is applied to control the wind farm, which consists of a high-level control for the wind farm and low-level controls for individual WTs. The power references of the wind farm and each wind turbine generator are produced by the high-level controller, whereas the individual WTs are controlled

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Received: November 26, 2013; Accepted: March 7, 2014

to generate the power as commanded by the low-level controllers. With the control scheme, the output power of the WF is smoothed, even though the output powers of individual WTs are fluctuated. Based on the parameters and characteristic of wind turbines, a design procedure is described to determine the time constant of a low-pass filter applying to the available power of the wind farm. In order to reduce the effect of power mismatch between the input power of the turbine and output power of the generator due to the phase delay effect of the LPF, the lead-lag compensator is used for the power reference of the wind farm. The simulation results for a wind farm have shown that controlling the turbine speed and utilizing the kinetic energy from the turbine inertia can smoothen the output power of the wind farm.

## 2. Wind Farm Modeling and Power Control

### 2.1 Modeling of wind farm

Fig. 1 shows a single-line diagram of a wind farm integrated with the grid, which consists of five individual WTs equipped with the PMSGs. The individual WTs are connected at different points in parallel or series through the different distribution line impedances ( $r_i + jx_i$ ), and then connected to the grid through a transformer.

### 2.2 De-rated operation of turbines and inertial effect on power control

The MPPT operation of the wind turbine systems is briefly reviewed here that the output power of the wind

turbine is optimized when the wind turbine operates at the optimal speed. The turbine power,  $P_t$ , extracted from the wind is expressed as

$$P_t = 0.5 \cdot 1.225 \cdot R^2 \cdot C_p(\lambda, \beta) \cdot v^3 \quad (1)$$

where  $R$  is the blade radius,  $v$  is wind speed,  $C_p(\lambda, \beta)$  is the power coefficient, which depends on the tip-speed ratio  $\lambda$  and the pitch angle  $\beta$ .

The optimal power,  $P_{t,opt}$ , is achieved by

$$P_{t,opt} = P_t \Big|_{C_p=C_{pmax}} \quad (2)$$

$$C_{pmax} = C_p \Big|_{\lambda=\lambda_{opt}} \quad (3)$$

$$\lambda_{opt} = \lambda \Big|_{\omega_t=\omega_{t,opt}} \quad (4)$$

where  $\omega_t$  is the turbine speed, the subscript “opt” indicates the optimal values of variables, and  $C_{pmax}$  (equal to 0.41) is the maximum power coefficient.

Choosing  $\lambda = \lambda_{opt}$ , the maximum power is extracted, whereas a higher  $\lambda$  by which the wind turbine speed is higher than the optimal value captures the de-rated power.

The power balance relation in the wind turbine system with the losses neglected is expressed as [4]

$$P_{gen} = P_t - \frac{1}{2} J \frac{d\omega_t^2}{dt} = P_t - \Delta P_J \quad (5)$$

where  $P_{gen}$  is the generator power,  $J$  is a total inertia of the turbine and the generator, and  $\Delta P_J$  is the inertial kinetic power produced by the acceleration or deceleration of the turbine, expressed as [14]

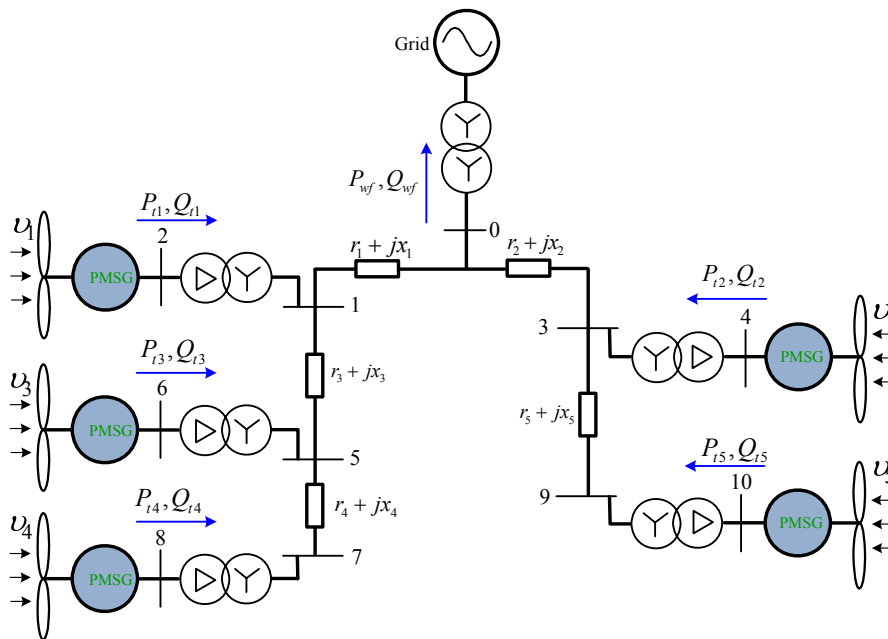


Fig. 1. Structure of a wind farm equipped with PMSGs

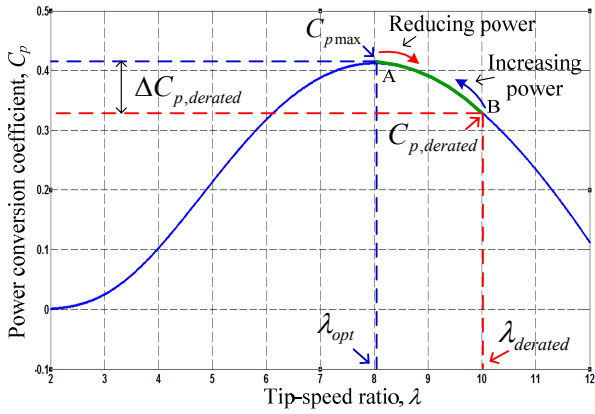


Fig. 2. Power coefficient versus tip-speed ratio of turbine.

$$\Delta P_J = \frac{1}{2} J \frac{d\omega_t^2}{dt} = H \cdot \frac{\omega_{t2}^2 - \omega_{t1}^2}{\Delta T} \quad (6)$$

in which  $H$  is the inertia constant of the wind turbine system,  $\Delta T$  is the time duration for the speed variation from  $\omega_{t1}$  to  $\omega_{t2}$ . It is assumed that a wind turbine normal operating speed is in the range of 0.7 ~ 1.2 p.u. [7].

Fig. 2 shows the curve of the power conversion coefficient,  $C_p$ , versus the tip-speed ratio,  $\lambda$ . It can be seen that the  $C_p$ , consequently the turbine output power, varies as the turbine speed changes. When the turbine speed is increased at the point B higher than the optimal value of the point A depicted in Fig. 2, the generator power can be rewritten as

$$\begin{aligned} P_{gen} &= (P_{t,opt} - \Delta P_{derated}) - \Delta P_J \\ &= P_{t,opt} - (\Delta P_{derated} + \Delta P_J) \end{aligned} \quad (7)$$

where  $P_{t,opt}$  is the optimal power,  $\Delta P_{derated}$  is the power difference between the optimal one and the actual one at the operating speed. In this case, the inertial kinetic power  $\Delta P_J > 0$  is used to accelerate the turbine, resulting in a reduction of the generator power.

Reversely, when the turbine speed is reduced to the point A from the point B, the inertial power is released to the generator. Then, the generator power is expressed as

$$P_{gen} = P_t + \Delta P_{derated} - \Delta P_J. \quad (8)$$

In this case,  $\Delta P_J$  is negative, which results in the increase of the generator power.

### 3. Proposed Control Strategy of Output Power Smoothing in Wind Farms

Fig. 3 shows a diagram of the control scheme of the two-level structure for the wind farm. The major task of the wind farm supervisory controller (WFSC) is to give the

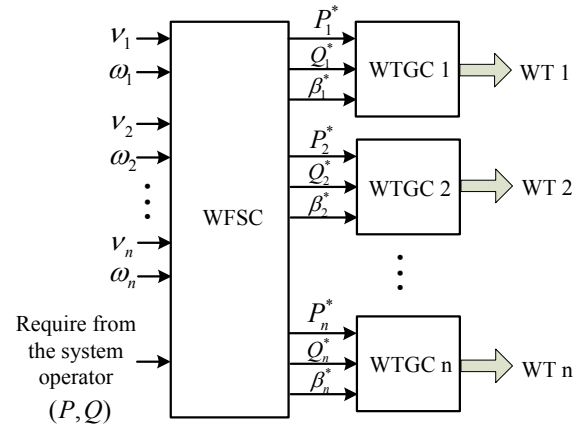


Fig. 3. Two-level control structure of wind farm.

commands to the individual wind turbines. From the power command of the wind farm, which is given by either the system operator or the requirement of the output power smoothing, the power references of the wind turbines are calculated from the WFSC. Also, the pitch angle commands of the individual WTs to limit the turbine power and speed are produced by the WFSC. Then, the PMSG wind turbines are controlled to generate the desired powers as commands.

#### 3.1 Derivation of power references for each WT

The information of the wind speeds for the individual WTs is given to the WFSC, which can be obtained by meters or by estimation. The available power of the individual WTs,  $P_{mpp(i)}$ , is calculated from the MPPT control as [14]

$$P_{mpp(i)} = 0.5 \rho \pi R^2 C_{p,max} v_i^3 \quad (9)$$

where  $\rho$  is a density of air, and  $v_i$  is the wind speed. Then, the available power of the wind farm,  $P_{mpp,wf}$ , is expressed as

$$P_{mpp,wf} = \sum_{i=1}^N P_{mpp(i)} \quad (10)$$

where  $N$  is the number of WT in the wind farm.

For the output power smoothing control in the wind farm, the power command of the WF,  $P_{wf}^*$ , is calculated

$$P_{wf}^* = LPF(P_{mpp,wf}) = \frac{\omega_c^2}{s^2 + 2\xi\omega_c s + \omega_c^2} P_{mpp,wf} \quad (11)$$

where a second-order low-pass filter (2<sup>nd</sup>-LPF) is applied to the available power,  $\omega_c$  is the cut-off frequency dependent on the requirement of the system operator and the responses of the WTs, and  $\xi = 0.707$ . In this work, it is assumed that 0.2 p.u. of the turbine output power can be

absorbed (or released), in which 0.1 p.u. can be decreased (or increased) by the de-rated operation and the other portion of 0.1 p.u. is used for the acceleration or deceleration of the turbine. The typical inertia constant of the wind turbine systems is chosen as 4.5 s. From (6), the time duration for the turbine speed variation range of 0.8~1.1 p.u. assumed is calculated as

$$\Delta T = H \cdot \frac{\omega_{t2}^2 - \omega_{t1}^2}{\Delta P_J} = 4.5 \cdot \frac{1.1^2 - 0.8^2}{0.1} = 25.65 \text{ [s]}.$$

Thus, the cut-off frequency of the LPF to filter out the available power of the wind farm is set as 0.0062 Hz.

It is known that the output component of the 2<sup>nd</sup>-LPF at the cut-off frequency is shifted 90 degrees compared with its original signal. Then, the lead-lag compensator is used to compensate for the phase delay of the power reference, of which the transfer function,  $H_{comp}(s)$ , is expressed as [15]

$$H_{comp}(s) = \frac{1 + sT_1}{1 + sT_2} \tag{12}$$

where  $T_1$  and  $T_2$  are the leading and lagging compensation time constants, respectively. The larger the leading time constant, the more the phase shift can be compensated. In this work, the lead-lag compensator is designed as

$$H_{comp}(s) = \frac{1 + 45.55s}{1 + s} \tag{13}$$

Thus, the power command of the WF can be rewritten as

$$P_{wf}^* = \frac{1 + 45.55s}{1 + s} \cdot \frac{\omega_c^2}{s^2 + 2\xi\omega_c s + \omega_c^2} P_{mppt,wf}. \tag{14}$$

Fig. 4 shows the Bode plots for the transfer functions of the power commands versus the available power with and without the phase compensation as expressed in (14)

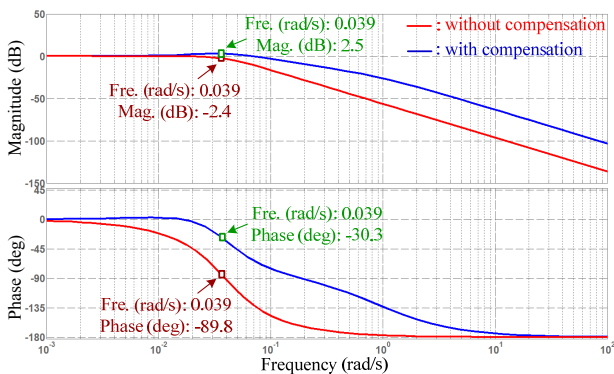


Fig. 4. Bode plots for the transfer functions of the power command.

and (11), respectively. With the lead-lag compensator, the phase shift of the power command is about 30 degrees compared with 90 degrees in the case of without compensation.

Next, the power reference of the individual WTs,  $P_{gen(i)}^*$ , is determined as

$$P_{gen(i)}^* = P_{mppt(i)} \frac{P_{wf}^*}{P_{mppt,wf}} \tag{15}$$

Since the high-frequency fluctuated component in available power of the wind farm is filtered out before being transmitted to the grid, the power reference of the individual WTs can be higher or lower than its instantaneous available power. The basic idea for producing the power reference of the individual wind turbines is described as follows.

If  $P_{gen(i)}^* < P_{mppt(i)}$ , then the output power of the corresponding individual wind turbines should be reduced. To do this, the WT is controlled to increase the rotating speed, resulting in a reduction of the turbine output power, since some portion of turbine output power is used for the acceleration with a high system inertia effect and de-rated operation of the WT as in (7). On the other hand, if  $P_{gen(i)}^* > P_{mppt(i)}$ , then the output power of the corresponding individual WTs should be increased. For this, the WT is controlled to reduce the turbine speed, resulting in an increase of the turbine output power due to a release of the kinetic energy stored and consequently the higher turbine power extracted from the wind as in (8).

It should be noted that the power reference of the individual WTs has to be limited below the power rating of the turbine,  $P_{max}$ . Also, when the turbine decelerates to release the power, its speed should be still kept higher than the optimal value. Otherwise, the operation of the turbine becomes unstable.

For the case of  $P_{gen(i)}^* \geq P_{max}$ , it indicates that the PMSG cannot produce the power as its reference due to the limitation of the generator and converter ratings. A lack amount of the power reference,  $\Delta P_{comp(i)}$ , from the  $i^{th}$ -wind turbine is calculated as

$$\Delta P_{comp(i)} = P_{gen(i)}^* - P_{max} \geq 0. \tag{16}$$

Then, the total lack power required is

$$P_{comp} = \sum_{i=1}^N \Delta P_{comp(i)} \tag{17}$$

In order to compensate for the lack power, the WFSC searches for the individual wind turbines operating at non-optimal point, in which  $\omega_{t,mppt(i)} < \omega_{t(i)}$ . The speed difference,  $\Delta\omega_{t,opt(i)}$ , between the optimal and current operating speed of the individual wind turbine is calculated as

$$\Delta\omega_{t,opt(i)} = \omega_{t(i)} - \omega_{t,mppt(i)} \geq 0. \quad (18)$$

Then, the compensated power of the  $i^{th}$ -individual wind turbine,  $\Delta P_{avai(i)}$ , is

$$\Delta P_{avai(i)} = \frac{\Delta\omega_{t,opt(i)}}{\sum_{j=1}^n \Delta\omega_{t,opt(j)}} P_{comp}. \quad (19)$$

The total available compensated power from the wind farm is

$$P_{comp,avai} = \sum_{i=1}^N \Delta P_{avai(i)}. \quad (20)$$

Finally, the resultant power reference of the individual wind turbine generators,  $P_{gen\_final(i)}$ , is expressed as

$$P_{gen\_final(i)}^* = P_{gen(i)}^* + \Delta P_{avai(i)} \frac{P_{comp}}{P_{comp,avai}} \leq P_{max}. \quad (21)$$

### 3.2 Pitch angle commands for individual WT systems

In the normal operation, the pitch angle system is used to limit the output power of the wind turbine. For the power smoothing control, in some cases, the wind turbine is accelerated to absorb its output power. This may lead to the over-speed for the wind turbine. Then, the pitch angle system is activated to prevent the wind turbine speed from increasing.

In this research, the pitch angle of the wind turbine,  $\beta$ , is assumed to be proportional to the amount of the turbine output power variation [16], which is expressed as

$$\beta = \beta_0 + k\Delta P \quad (22)$$

where  $\Delta P$  is the reduced amount of the turbine output power,  $\beta_0$  is the initial pitch angle and  $k$  is the constant depending on the characteristics of the turbine.

When the generator speed is higher than its limitation, the pitch angle command of the  $i^{th}$ -WT is determined according to (22). In this work,  $k$  is chosen as 10.

### 3.3 Control of individual PMSG WIND Turbine

Fig. 5 shows the control block diagram of the PMSG, in which a cascaded control structure is employed. An outer power control loop is used to regulate the generator output power, in which the generator power reference is produced by the WFSC. The inner  $d$ - $q$  current control loops under the field-oriented control operation are employed, in which the output of the outer control loop provides the  $q$ -axis current reference. The  $d$ -axis current reference is set to zero to achieve the control mode of the maximum torque per

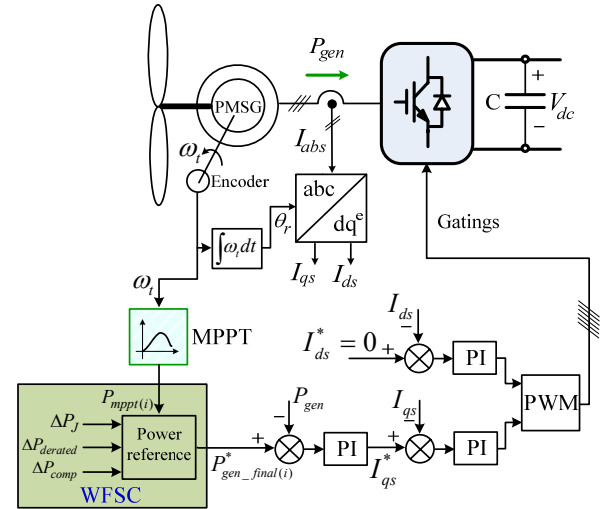


Fig. 5. Control block diagram of individual PMSG WT.

ampere in a surface-mounted PMSG [11].

## 4. Simulation Results

The effectiveness of the proposed strategy is examined by the simulation results, in which the studied system as shown in Fig. 1 is modeled by the PSCAD/EMTDC. The wind farm consists of five PMSG wind turbines, in which the rating of each WT is 2 MW. The parameters of the WT and PMSG are listed in Table 1 and Table 2, respectively.

Table 1. Parameters of wind turbine

Parameters	Values
Rated power	2 MW
Blade radius	44.18 m
Air density	1.225 kg/m <sup>3</sup>
Power coefficient	0.42
Optimal tip-speed ratio	8.0
Cut-in/cut-out speed	3 m/s / 25 m/s
Rated wind speed	11.25 m/s
Blade inertia constant	4 s
Gear ratio	1

Table 2. Parameters of PMSG

Parameters	Values
Rated power	2 MW
Stator voltage/frequency	690 V/16.6 Hz
Stator resistance	0.008556 Ω
Stator inductance	0.00359 H
Number of pole pairs	60
Generator inertia constant	0.5 s

Table 3. Power line characteristics

Lines	Bus 0-1	Bus 0-3	Bus 1-5	Bus 3-9	Bus 5-7
r(Ω/phase)	0.386	0.477	0.623	0.715	0.79
x(Ω/phase)	0.966	1.19	1.56	1.69	2.49

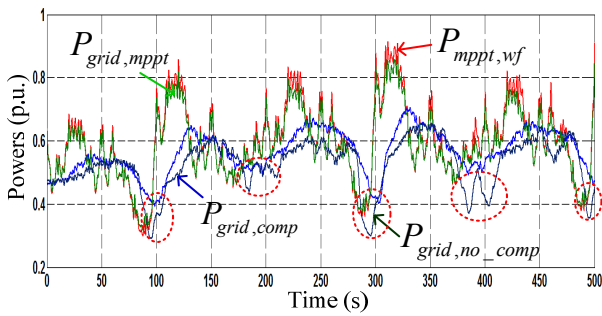


Fig. 6. Comparison for performance of WF power controls.

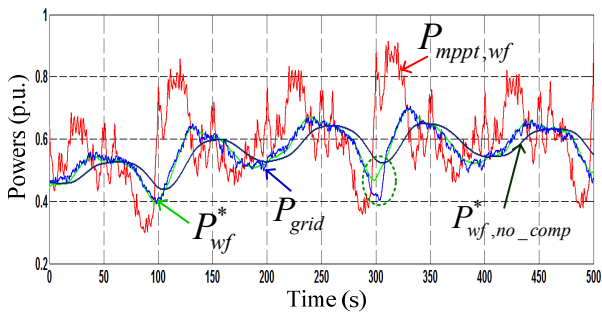


Fig. 7. Performance of WF power smoothing control.

The line impedances between the buses shown in Fig. 1 are listed in Table 3. With the given parameters of the wind turbines, the cut-off frequency of the second-order low-pass filter, has been selected to guarantee the stable operation of the WTs. For easy simulation, several assumptions are made. Firstly, the PWM back-to-back converters for controlling the PMSG are modeled as current sources. Secondly, the current controllers for the PMSG are operated ideally. Thirdly, the pitch angle control in the individual WTs is ideal.

Fig. 6 shows the performance of the WF power control by different control strategies. It is seen that by the MPPT control, the wind farm provides the optimized power to the grid. However, this power is much fluctuated, which does not satisfy the requirement of the system operator. To reduce the fluctuation of the WF output power, the power reference for the WF is filtered out from its available power. Fig. 6 also shows that the performance of the power control of the WF is degraded without the phase compensation for the power reference ( $P_{grid,no\_comp}$ ), whereas the power control is satisfied with the phase compensation by a lead-lag compensator.

For an investigation of power smoothing control strategy as proposed in this research for the wind farm, each wind turbine is operated at different wind speeds, as usual. Fig. 7 shows the performance of wind farm power control, in which the power reference of the WF is smoothed from the available power by applying the LPF with the cut-off frequency of 0.0062 Hz. Through a lead-lag compensator, the phase delay of the power reference is reduced. It can be seen in Fig. 7 that the grid power is much smoothed than the available power of the wind

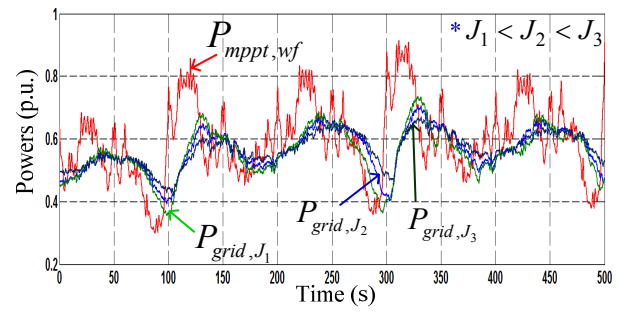


Fig. 8. WF power smoothing controls with different turbine inertia constants.

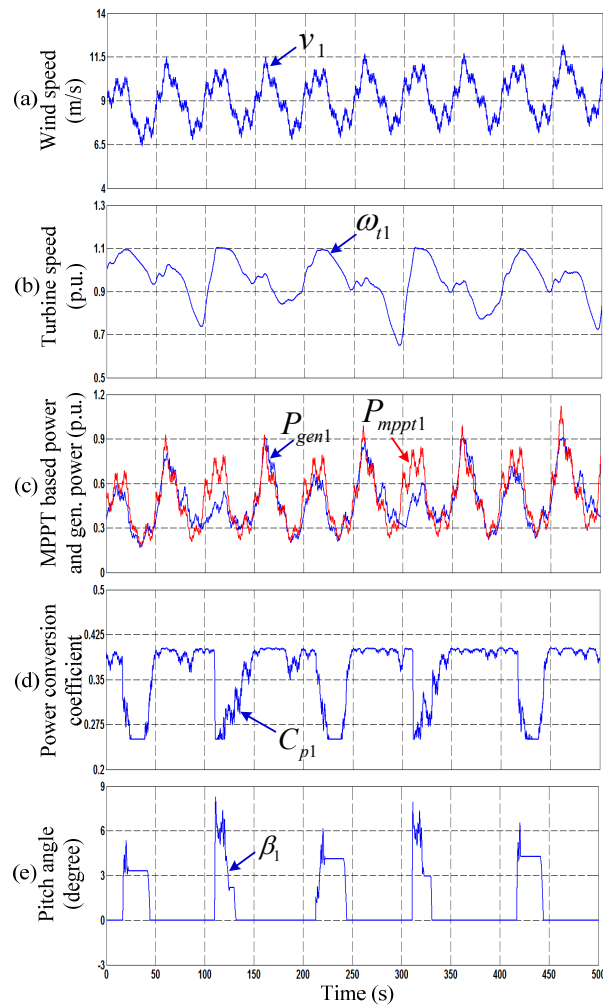


Fig. 9. Responses of WT generator #1: (a) Wind speed; (b) Turbine speed; (c) Available and generator powers; (d) Power coefficient. (e) Pitch angle.

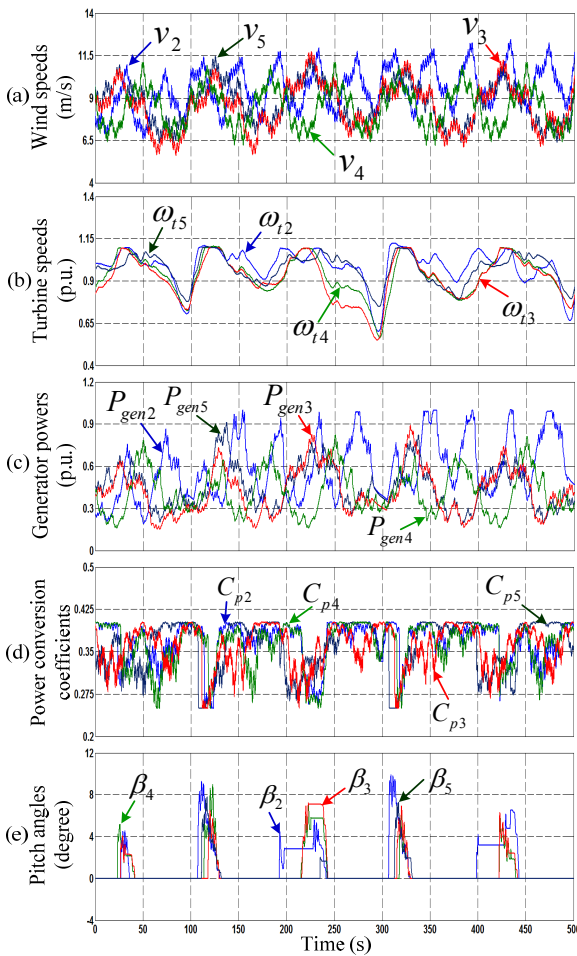
farm. It should be noted in Fig. 7 that the WF cannot produce the power as its command at near 300 s. The reason for this is that the power command is higher than the available power in this interval and the speed of the WTs cannot be reduced further for releasing the kinetic power.

Fig. 8 shows the output power smoothing of the wind

farm with different turbine inertia constants. The result shows that the higher the inertia constant is, the smoother the grid power is. In these simulations, the turbine inertia constants are set as  $J_1=2.5$  s,  $J_2=4.0$  s, and  $J_3=5.5$  s.

Fig. 9 shows a response of the PMSG wind turbine #1 under the wind speed condition as shown in Fig. 9(a). With this wind speed, the turbine speed is shown in Fig. 9(b), in which the high-frequency fluctuated components are filtered out due to the effect of the turbine inertia. Also, the turbine speed is not proportional to the wind speed, since the MPPT control is not achieved during some intervals for de-rated operation of the WTs. It can be seen in Fig. 9(c) that the generator output power is not equal to the maximum available power, which results from the power smoothing strategy for the wind farm control as seen in (21). Fig. 9(d) shows the power conversion coefficient of the wind turbine #1. When the turbine speed exceeds the limitation value as shown in Fig. 9(b), the pitch angle control system is activated and the pitch angle is increased as shown in Fig. 9(e).

Similarly, the responses of the wind turbine #2 to #5 are



**Fig. 10.** Response of WT generator #2 - #5: (a) Wind speeds; (b) Turbine speeds; (c) Available and generator powers; (d) Power coefficients; (e) Pitch angles

shown in Fig. 10. The wind speeds for each wind turbine are different as shown in Fig. 10(a). Then, the turbine speeds are also different as shown in Fig. 10(b). Fig. 7(c) shows the individual generator powers which are much fluctuated. It is also seen in Fig. 10(d) that the MPPT control of the wind turbine #2 to #5 is not achieved, in which the power conversion coefficients are not equal to the maximum values all the time as shown in Fig. 10(d). Fig. 10(e) shows the pitch angles of the wind turbine #2 to #5, in which the pitch systems of wind turbines are activated when the turbine speeds are higher than the limitation values as shown in Fig. 10(b).

## 5. Conclusions

A novel control strategy for the attenuation of output power fluctuation from the wind farm has been presented in this paper, in which the high inertia of the wind turbine is utilized. The power reference of the WF is determined through the second-order LPF, which is applied to the available WF power. Also, a lead-lag compensator is used to reduce the phase delay effect for the low-pass filter. For this control method, the kinetic energy from the turbine is stored or released by accelerating or decelerating the wind turbine, which can smoothen the output power of the wind farm. In addition, the pitch angle systems are employed to limit the turbine speed not higher than the allowable range during the releasing mode of the kinetic energy. By coordinating the de-rated operation of the WT and the storing or releasing modes of the kinetic energy, the output power fluctuations are reduced by 20%. The PSCAD/EMTDC simulation results for a 10-MW wind farm have verified the effectiveness of the proposed method.

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