Power Fluctuation Reduction of Pitch-Regulated MW-Class PMSG based WTG System by Controlling Kinetic Energy

Abdul Motin Howlader*, Naomitsu Urasaki*, Atsushi Yona*, Tomonobu Senjyu*, and Ahmed Yousuf Saber**

Abstract – Wind is an abundant source of natural energy which can be utilized to generate power. Wind velocity does not remain constant, and as a result the output power of wind turbine generators (WTGs) fluctuates. To reduce the fluctuation, different approaches are already being proposed, such as energy storage devices, electric double layer capacitors, flywheels, and so on. These methods are effective but require a significant extra cost to installation and maintenance. This paper proposes to reduce output power fluctuation by controlling kinetic energy of a WTG system. A MW-class pitch-regulated permanent magnet synchronous generator (PMSG) is introduced to apply a power fluctuation reducing method. The major advantage of this proposed method is that, an additional energy storage system is not required to control the power fluctuation. Additionally, the proposed method can mitigate shaft stress of a WTG system. Which is reflected in an enhanced reliability of the wind turbine. Moreover, the proposed method can be changed to the maximum power point tracking (MPPT) control method by adjusting an averaging time. The proposed power smoothing control is compared with the MPPT control method and verified by using the MATLAB SIMULINK environment.

Keywords: Wind turbine generator system, Power fluctuation, Kinetic energy, Maximum power point tracking, Permanent magnet synchronous generator.

1. Introduction

The development of renewable energy systems have been increasing rapidly due to the crisis of depleting fossil fuels (e.g. coal, oil, gas) and environmental pollution resulting from consumption of these fuels. Among the different types of renewable sources, wind energy power systems are the most promising because of the environmental benefits and economic benefits of fuel savings [1]. The present target is to achieve 12% generation of the world's electricity from wind power by 2020 [2]. The trend of power systems is to employ large wind turbine generator (WTG) systems such as mega watt power capacity (2-5 MW) and to construct large wind farms [3]. Also, a small-power WTG system is a good candidate for micro-grid systems [4]. However, wind energy has the drawbacks of having only 1/800 gm/cm3 density as compared with water energy, and not being constant. Furthermore, wind turbine output power is proportional to the cube of wind speed. As a result, the generated power of WTG fluctuates. If the capacity ratio of the power source for WTG is small, the power source will not cause the frequency to fluctuate by output fluctuation.

However, if the ratio of WTG capacity is large, frequency fluctuation of the power system will be increased. A wind farm with many WTG has a tendency of smoothing output power. Various methods have been utilized to generate smooth wind power, including the use of ultra capacitors [5], superconducting magnetic energy storage (SMES) [6], flywheel energy storage systems (FESS) [7-9], storage batteries [10], aqua electrolyze fuel cells [11], and backup generators [12]. Each method has its advantages and disadvantages. The high frequency charge and discharges affect the efficiency of the lead-acid battery thereby shortening its life. SMES and capacitor are very expensive. Aqua electrolyze with a fuel cell system is very large. Back-up generator requires operational costs. In this paper, a new control method for smoothing wind turbine output power is presented. It is considered by two events [13]:

1. Increase in wind turbine kinetic energy due to the acceleration of the turbine rotational speed when wind speed rapidly increases.

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2. A discharge of wind turbine kinetic energy due to a decline in the wind turbine rotational speed when the wind velocity drops.

In other words, the kinetic energy works as an energy storage system in this method. The kinetic energy is stored in the wind turbine and generator inertia. One advantage of this method is that there is no need for additional energy storage devices. The output power is also very close to the MPPT control method of the wind turbine. This proposed method can be transferred to the MPPT control method by adjusting an averaging time. In this system, the pitch angle control system is included to maintain the generator rated power. It is activated above the rated wind speed [14-17], not in all the operating regions [18,19]. A gearless MW-class PMSG based wind turbine is introduced to analysis performance in this paper. Because of the simple structure and high efficiency of a PMSG, it is expected that larger sized WTG systems will adopt it. Since a PMSG can be operated without a gearbox, all difficulties that are created by a gearbox can be avoided. The large WTG system embodies considerable inertia. As such, it can store more charge than a small WTG system. This is why, the proposed method would become more effective in a large WTG system. The effectiveness of the proposed output power smoothing control is verified by simulation results using MATLAB SIMULINK.

This paper is organized as follows: Section II provides a configuration of the WTG system and equations. Section III describes the control method of the proposed system. Section IV depicts model and control of the PMSG. In Section V, the effectiveness of the proposed method is demonstrated by simulation results. The conclusion is given in Section VI.

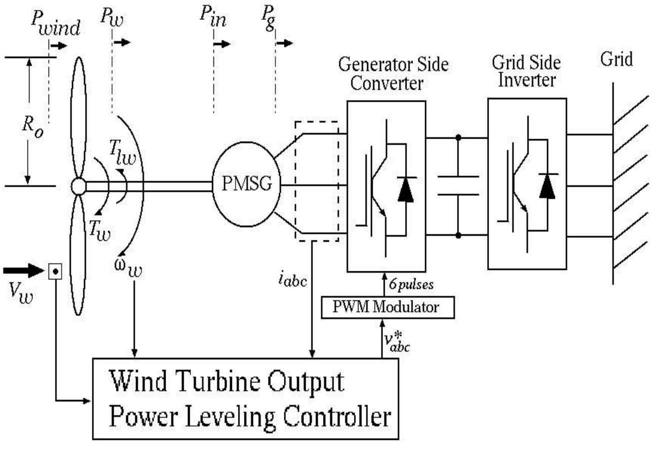


Fig. 1. Wind generation system configuration.

2. WTG System

The configuration diagram of the WTG system is shown in Fig. 1. Wind power energy is obtained from the wind turbine and is sent to the PMSG. In order to generate maximum power and smoothing power, the rotational speed of the PMSG is controlled by the generator-side converter. Here, PMSG output power is supplied to the power system through a generator-side converter and grid-side inverter.

2.1 Wind Turbine Model

If all the wind power is converted to mechanical power, the input power P_{wind} is expressed as

$$P_{wind} = \frac{1}{2}\rho\pi R_o^2 V_w^3 \tag{1}$$

where R_o is the wind turbine blade radius, V_w is the wind speed and ρ is air density. The wind turbine input torque T_{wind} can be described as

$$\begin{aligned} T_{wind} &= \frac{\lambda}{\omega_w} P_{wind} \\ &= \frac{1}{2}\rho\pi R_o^3 V_w^2 \end{aligned} \tag{2}$$

where ω_w is the angular velocity of the wind turbine and λ is the tip speed ratio: it can be defined as $\lambda = \dfrac{R_0\omega_w}{V_w}$. The windmill output power P_w and windmill output torque T_w are given by the following equations:

$$P_w = \frac{1}{2} C_p(\lambda,\beta)\rho\pi R_o^2 V_w^3 \tag{3}$$

$$T_w = \frac{1}{2} C_p(\lambda,\beta)\rho\pi R_o^3 V_w^2 / \lambda \tag{4}$$

where β is pitch angle. The windmill power coefficient C_p is defined by the following equation [21]:

$$C_p = 0.22\left(\frac{116}{\Gamma} - 0.4\beta - 5\right)\exp^{-\frac{12.5}{\Gamma}} \tag{5}$$

$$\Gamma = \frac{1}{\dfrac{1}{\lambda + 0.08\beta} - \dfrac{0.035}{\beta^3 + 1}} \tag{6}$$

The motion equation of the windmill is expressed as:

$$T_w = J_w \frac{d\omega_w}{dt} + T_{lw} \tag{7}$$

where J_w is the wind turbine inertia and T_{lw} is the load torque which corresponds to the input torque of the generator. Input power to the generator P_{in} is expressed as

$$P_{in} = -T_{lw}\omega_g \tag{8}$$

where ω_g is the angular velocity of the generator. The output power of generator P_g is expressed as:

$$P_g = -T_e \omega_g \tag{9}$$

where T_e is the generator electric torque.

2.2 MPPT Control System

From (3) and (5), the windmill output power characteristics are depicted in Fig. 2, from which it can be seen that, for any particular wind speed, there is a rotational speed ω_{opt}, called the optimum rotational speed, which generates the maximum power P_{max}. In this way, the MPPT control for each wind speed increases the energy generation in variable speed wind generation (VSWG) system. ω_{opt} is calculated by differentiating C_p with respect to ω_w. Therefore, ω_{opt} is approximated by [2]

$$\omega_{opt} = 0.2V_w - 0.2 \tag{10}$$

If $\omega_w = \omega_{\text{opt}}$, the windmill maximum output power P_{max} can be obtained. Fig. 3 shows the simulation results of wind speed versus windmill output power characteristics for fixed speed operation and variable speed operation with the MPPT control, where ω_{w} = 1rad/s is optimum rotational speed for V_w =6 m/s. In case of fixed speed operation, it is clear that energy loss for the windmill increases as the wind speed increases over 6 m/s. The MPPT control is applied when wind speed V_w is smaller than the rated wind speed $V_{\text{w-ref}}$. If wind speed V_w is greater than the rated wind speed $V_{w\text{-}ref}$, then the output power of PMSG is controlled by the pitch angle control system.

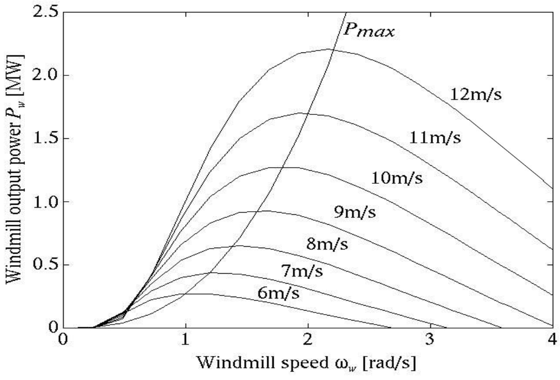


Fig. 2. Windmill output power characteristics.

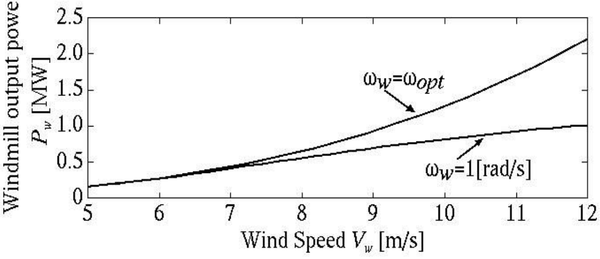


Fig. 3. Wind speed Vs. windmill output power characteristics.

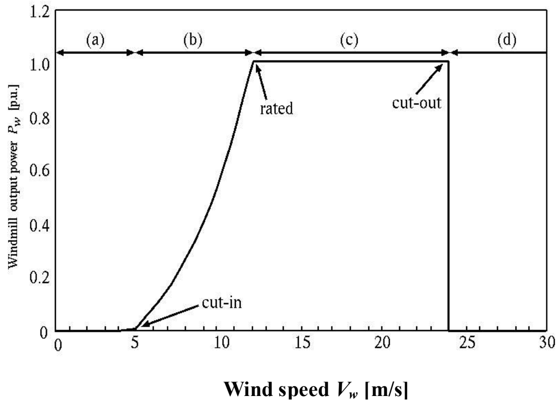


Fig. 4. Pitch angle control law.

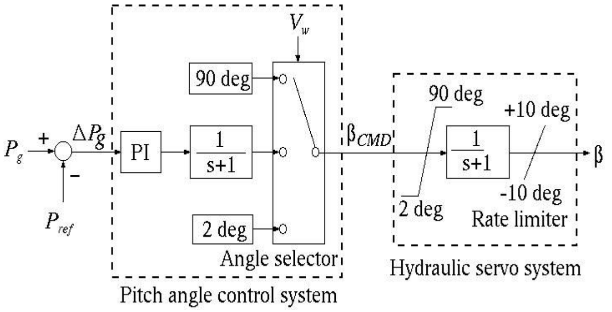


Fig. 5. Pitch angle control system.

Pitch angle β is controlled according to the pitch angle control law shown in Fig. 4. For example, in Fig. 4 (a) wind speed range is P_w = 0 pu so that the pitch angle is fixed at β= 90° because the energy of the windmill is smallest at 90°, (b) is P_w = 0 pu to P_w = 1 pu so that the pitch angle is fixed as β = 2°, (c) is P_w = 1 pu so that the pitch angle β is selected to keep windmill output P_w = 1 pu, and finally, (d) is P_w = 0 pu so that pitch angle is fixed at β = 90° for safety reasons.

Fig. 5 shows the pitch angle control system that resolves pitch angle β, where output power error ΔP_g is used as input into the PI controller. Actually, the pitch angle control system includes a hydraulic servo system. The system has nonlinear characteristics, but it is able to make a first-order lag system [22]. Therefore, in this paper it is simulated by a first-order lag system where the time constant is 1 s. Moreover, the pitch angle β is limited by a limiter in the range of 2°-90°, and the maximum rate of change is ±10°/s.

3. The PMSG Based Output Power Smoothing Control System

The pitch-regulated PMSG based output power fluctuation is controlled by kinetic energy of a large wind

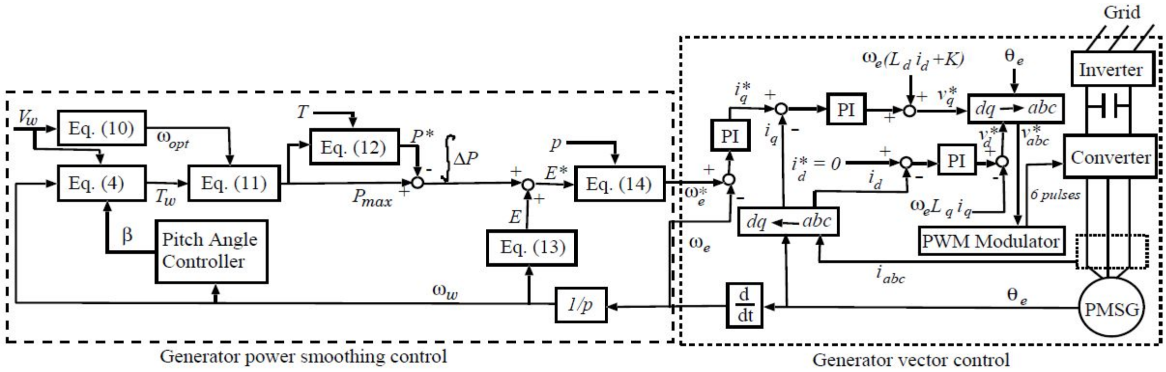


Fig. 6. A PMSG based output power smoothing control system

turbine. The kinetic energy is stored in the wind turbine and generator inertia when the wind speed increases, while restored storage kinetic energy due to wind velocity decreases. Fig. 6 shows the WTG system output power smoothing control system based on a MW-class PMSG. There are two parts: the generator power controller and the speed controller. The speed controlling method will be described in the next section. The power controlling method is described in this section. First, maximum wind turbine output power, *Pmax*, is calculated:

$$P_{\max} = T_w \omega_{opt} \tag{11}$$

Next, the average value of the maximum wind turbine output power is calculated as

$$P^* = \frac{1}{T}\int_{t-T}^{t} P_{\max} dt \tag{12}$$

where t denotes the present time and T is the averaging time. Then, the difference ΔP between the maximum output power and average value of the maximum output power is calculated.

The $\int \Delta P dt$ gives the wind turbine storing and restoring energy. Wind turbine kinetic energy, E, is determined as

$$E = \frac{1}{2} J_{eq} \omega_w^2 \tag{13}$$

where J_{eq}= generator inertia (J_g) + wind turbine inertia (J_w) is equivalent inertia. The wind turbine speed command, ω_w*, is determined from kinetic energy command, E* (sum of $\int \Delta P dt$ and E), as

$$\omega_w^* = \sqrt{\frac{2E^*}{J_{eq}}} \tag{14}$$

The generator electrical speed reference ω_e* for the proposed method, is determined from gear ratio, R_n, and number of pole pairs, p as

$$\omega_e^* = R_n \omega_w^* p \tag{15}$$

and for the MPPT

$$\omega_e^* = R_n \omega_{opt} p \tag{16}$$

In this paper, the gear ratio R_n is 1 because a gearless is PMSG considered.

The averaging time T in (12) is a key component in the proposed output power smoothing control. When the averaging time becomes large, the output power of the WTG system is reduced and generates smooth output power. In case of a short averaging time, the output power of the WTG system tends to generate the same power as the MPPT control system with fluctuation. In other words, by changing the averaging time, the proposed method can be easily converted to the MPPT control method. If the wind velocity fluctuates in any region, the averaging time will be large enough to generate smooth output power. On the other hand, when the wind velocity does not fluctuate, the averaging time to generate same power as the MPPT control system will be short. It depends on the environment of the wind farm. Fig. 7 shows the characteristics between averaging time and output power of a WTG system. The dotted line shows the maximum output power of a WTG system during the simulation time.

From this figure, the output of the MPPT method is similar as the proposed method during a short averaging time.

4. PMSG Based Output Power Smoothing Control System

4.1 PMSG model

Basically, the mass model of a PMSG is the same as a permanent magnet synchronous motor (PMSM). The voltage and torque equations of the PMSM in the synchronous reference frame is given by the following equations:

$$v_d = (R_a + PL_d) i_d - \omega_e L_q i_q \tag{17}$$

$$v_q = \omega_e L_d i_d + \left(R_a + PL_q\right) i_q + \omega_e K \tag{18}$$

$$T_e = p\left\{K i_q + \left(L_d - L_q\right) i_d i_q\right\} \tag{19}$$

where v_d and v_q are dq-axis voltage, i_d and i_q are dq-axis current, R_a is stator resistance, L_d and L_q are dq-axis inductance, ω_e is electrical rotational speed, K is permanent magnetic flux, and P is differential operator. Generating operation starts when the electromagnetic torque T_e is negative. In addition, the motion equation of the PMSG is given by the following equation:

$$T_e = J_{eq} \frac{d\omega_g}{dt} + D\omega_g + T_{lw} \tag{20}$$

where D is rotational damping. The models of the drive train and the PMSG are shown in Figs. 8 and 9 respectively.

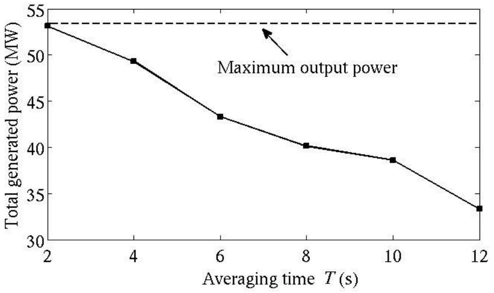


Fig. 7. Averaging time Vs. total generated power characteristics.

4.2 Control of the PMSG

A generator-side converter controls the rotational speed of the PMSG. The vector control scheme is used in the control methodology. Among the existing methods, Field Oriented Control (FOC) is used to perform the vector control of the generator side converter. FOC allows one to control flux and torque of the PMSG separately by using a current control loop with PI controllers. It is achieved by decomposing the stator current vector into i_d and i_q components, which control the flux and the torque respectively. The vector control scheme and the system configuration of the proposed operation system was shown in Fig. 6. The required dq components of the voltage vector are derived from two PI current controllers: one of them controls the d-axis component of the current and the other one the q-axis component. The speed control of the PMSG is realized on a rotating frame, where rotational speed error is used as input into speed controller which produces a q-axis stator current command, i_q^*. Generally, a cylindrical pole type synchronous machine is considered desirable to control d-axis stator current; i_d^* is set to zero. Therefore, in this paper, the d-axis stator current command, i_d^*, is set to zero. The error between the dq-axis current commands, i_d^*, i_q^*, and actual dq-axis currents are used as input into current controller. The current controller output produces dq-axis voltage commands v_d^*, v_q^* after decoupling. The angle θ_e, for the transformation between abc and dq variables is calculated from the rotational speed of the PMSG. Furthermore, the dq axis reference voltages are determined by the following equations by a PI controller using the current reference value [21]:

$$v_d^* = k_{Pi} e_{id} + k_{Ii} \int e_{id} dt - \omega_e L_q i_q \tag{21}$$

$$v_q^* = k_{Pi} e_{iq} + k_{Ii} \int e_{iq} dt + \omega_e \left(L_d i_d + K\right) \tag{22}$$

where k_{Pi} is the proportional gain for current controller, k_{Ii} is integral gain for current controller, $e_{id} = i_d^* - i_d$ is d-axis current error and $e_{iq} = i_q^* - i_q$ is q-axis current error. The PWM compares the duty cycles with the carrier signal in order to create the switching signals for the power converter semiconductors. The control requires the measurement of the stator currents, DC voltage, and rotor position [23].

5. Simulation Results

The effectiveness of the proposed method has been determined through simulation results. The simulation results are shown as a comparison between the MPPT control method and the proposed output power leveling method. The simulation parameters of a windmill, PMSG and power converter are shown in Table 1.

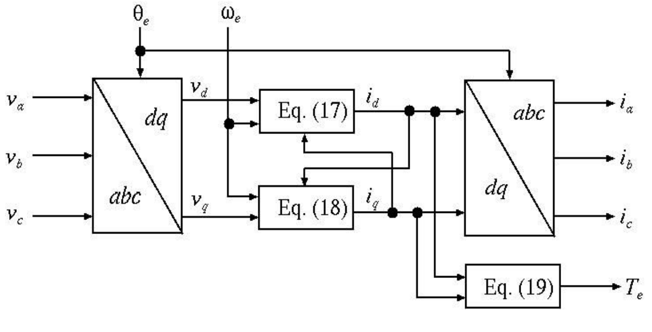


Fig. 8. Model of drive train

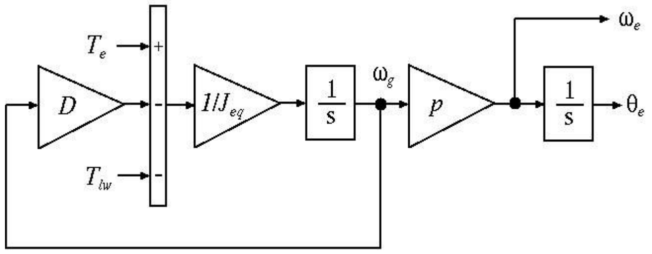


Fig. 9. Model of the PMSG

Table 1. Simulation parameters

Parameters of windmill	
Blade radius	$R_o = 41$ m
Air density	$\rho = 1.205$ kg/m^3
Gear ratio	$R_n = 1$
Equivalent inertia	$J_{eq} = 8000$ kg.m^2
Rated wind speed	$V_{w\_rated} = 12$ m/s
Averaging time	$T = 8$ s
Parameters of	PMSG
Rated power	$P_{g\_rated} = 2$ MW
Number of poles pair	$p = 80$
Stator resistance	$R_a = 0.1\ \Omega$
Inductance	$L = 0.005$ H
Field flux	$K = 10.68$ V.s/rad
Rotational damping	$D = 0$
Parameters of power converter	
PWM carrier frequency	$f_p = 10$ kHz
Rated DC-link voltage	$V_{dc\_rated} = 7.1$ kV

The wind velocity is shown in Fig. 10(a). This wind velocity data contains a significant fluctuation and high speed. From Fig. 10(b), it is observed that the wind turbine rotational speed fluctuates significantly by the proposed method as compared with use of the MPPT control method. As seen in Fig. 10(c), as the wind velocity increases, the turbine rotational speed accelerates thereby transforming the wind energy into wind turbine kinetic energy. Similarly, as the wind velocity decreases, there is a release of the wind turbine kinetic energy, through decrease in turbine rotational speed. Fig. 10(d) shows a comparison of the generator electric torque. The proposed method is reduced torque fluctuation as compared with the MPPT control method. As such, the proposed method can reduce the mechanical stress of a generator. Fig. 10(e) shows the pitch angle of the wind turbine. In case of the MPPT method, the pitch angle is activated to generate output power below the rated power. Due to the proposed control methodology (at averaging time T=8 s), the generated output power is below the rated power when the wind speed is high. This is why, the pitch angle is not changed as in the MPPT control method. When the averaging time T is small, the generated output power fluctuated as in the MPPT control method and the pitch angle also fluctuated similar to the MPPT control method as it attempted to maintain the rated output power. Fig. 10(f) depicts a comparison of the power coefficient of the two systems. The power coefficient C_p shows more fluctuation in the MPPT control method as compared with the proposed method.

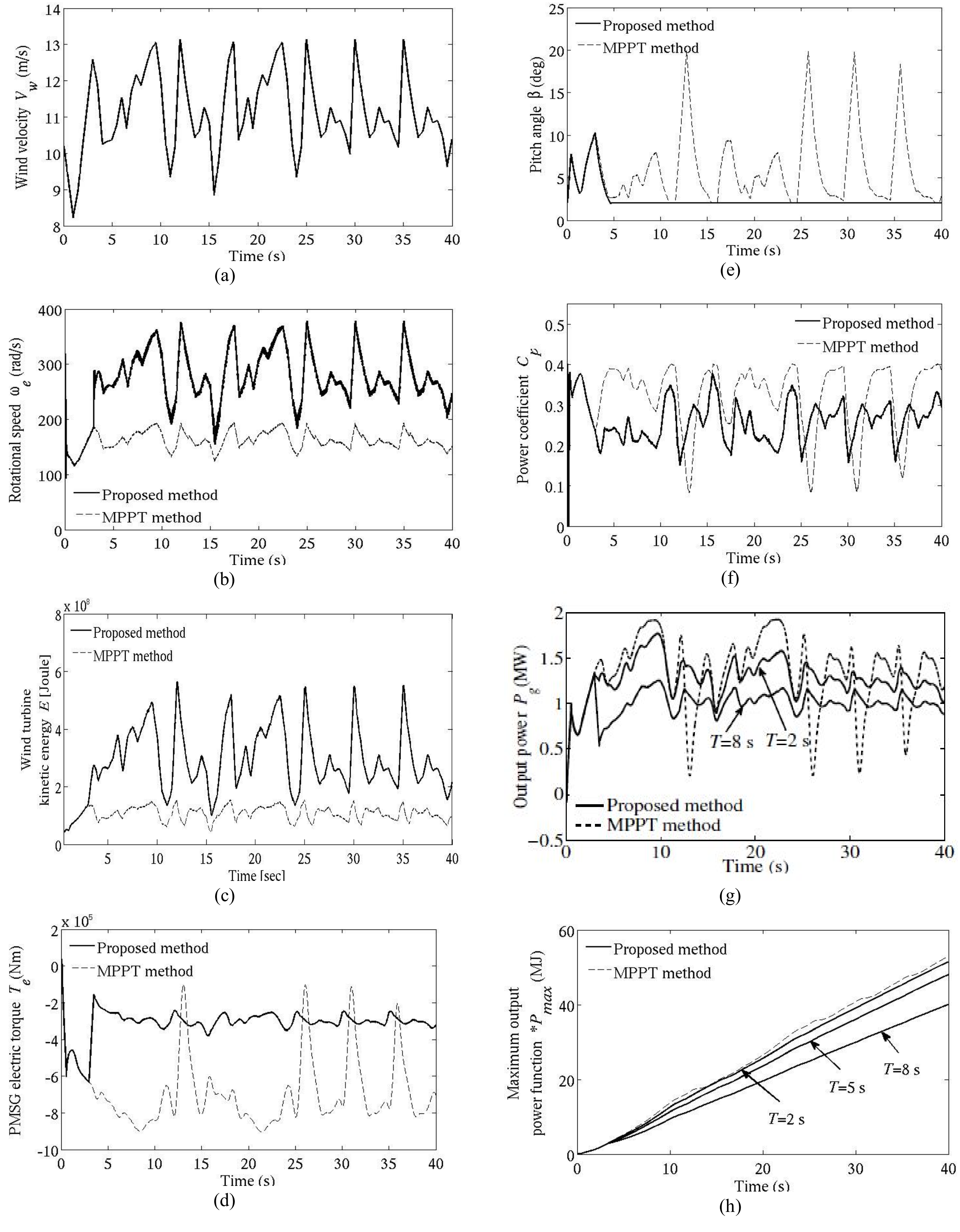
In fact, fluctuation of the WTG output power is reduced by the proposed method as compared with using the MPPT control method which is shown in Fig. 10(g). The proposed method is shown at the averaging times of 8 s and 2 s. During steady wind velocity, the averaging time T=2 s generates efficient output power with more fluctuation as compared with T=8 s. From this figure, the fluctuation reduced significantly using a long averaging time as compared with a short averaging time. So, depending on wind velocity of an area, the averaging time T becomes large or small. When wind velocity fluctuates highly, the large averaging time generates smoother output power. On the other hand, when the wind velocity becomes steady, the short averaging time generates efficient smooth output power.

Performance of output power P_g leveling is represented as maximum energy function $^*P_{max}$ and leveling function $^*P_{level}$, which are expressed as [18]

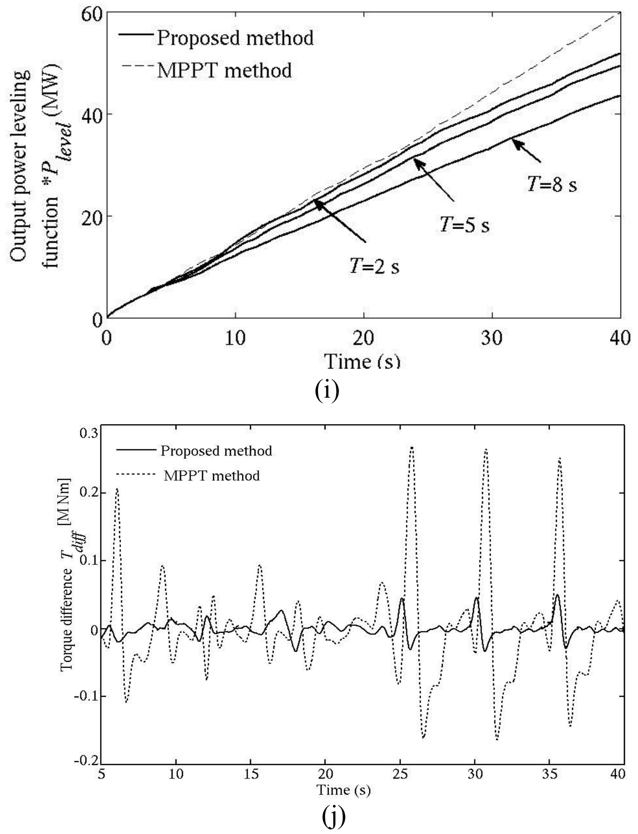
$$^*P_g = \int_0^t P_g \, dt \tag{23}$$

$$^*P_{level} = \int_0^t \left| \frac{dP_g(t)}{dt} \right| dt \tag{24}$$

If $^*P_{max}$ is large, the efficiency of the WTG has good performance. If $^*P_{level}$ is small, the output power fluctuation is small which reflects the good performance of the leveling of output power. Fig. 10(h) shows the maximum energy function, $^*P_{max}$. As compared with the MPPT control method, the proposed method dropped some energy. Since the purpose of this work is leveling the output power, a drop in the output power cannot be avoided. However, as compared with the MPPT control method, with the proposed method leveling function $^*P_{level}$ (see Fig. 10(i)) drops to about 2/3 (at averaging time T=8 s). Since the slope of $^*P_{level}$ for the proposed method is small as compared with the MPPT control method, when output power fluctuation is compensated by a power storage system, the capacity of the power storage system can be made smaller by applying the proposed method. The concept of this paper is more useful for a small isolated system (e.g. a diesel generator set in parallel with a few large turbines). With this concept the power fluctuation that can influence the frequency of the system can be controlled within an acceptable boundary. In this simulation, the averaging time T=8 s is used but the performance functions are shown in a different averaging time T. From the two figures (Fig. 10(h) and Fig. 10(i)), it is shown that when the averaging time T becomes small, the performance of the proposed method progresses to the MPPT control method. Fig. 10(j) represents an important parameter: torque difference T_{diff} between wind turbine torque T_w and generator electric torque Te. From this figure, the proposed method reduces torque difference extensively as compared with the conventional MPPT method. Therefore, it is possible to mitigate mechanical stress of the shaft in the WTG system.


(a) (b) (c) (d) (e) (f) (g) (h)

Wind velocity V_w (m/s)
Time (s)
Rotational speed ω_e (rad/s)
Proposed method
MPPT method
Time (s)
Wind turbine kinetic energy E [Joule]
x 10^8
Proposed method
MPPT method
Time [sec]
PMSG electric torque T_e(Nm)
x 10^5
Proposed method
MPPT method
Time (s)
Pitch angle β (deg)
Proposed method
MPPT method
Time (s)
Power coefficient C_p
Proposed method
MPPT method
Time (s)
Output power P_g (MW)
T=8 s
T=2 s
Proposed method
MPPT method
Time (s)
Maximum output power function $^*P_{max}$ (MJ)
Proposed method
MPPT method
T=2 s
T=5 s
T=8 s
Time (s)



(i)

(j)

Fig. 10. Simulation Results (a) Wind velocity V_w, (b) Generator electrical speed ω_e, (c) Wind turbine kinetic energy E, (d) Generator electric torque T_e, (e) Pitch angle β, (f) Power coefficient C_p, (g) Generated output power P_g, (h) Maximum output power function *P_{max}, (i) Output power leveling function *P_{level}, and (j)Torque difference T_{diff}

5. Conclusions

Power fluctuation reducing for a pitch-regulated large PMSG based wind turbine generator system has been analyzed in this paper. It is simulated through the transformation of wind energy into wind turbine kinetic energy. The large capacity (MW class) wind turbine can store more kinetic energy due to large inertia as compared with a small wind turbine. The effectiveness of the output power fluctuation reducing method is verified by simulation for the WTG system. From the simulation results, the proposed method can significantly reduced output power fluctuation. Additionally, the proposed method can reduce shaft stress which is ensured to improve the reliability and durability of a wind turbine. However, it may generate a similar level of output power to the MPPT control method when the averaging time is reduced to a smaller value.

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