

Fuzzy Controller Based Output Power Leveling Enhancement for a Permanent Magnet Synchronous Generator

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Abstract—Due to irregular wind velocity, the output power of a wind turbine generator system (WTGS) is fluctuated. There are many methods to propose to generate smooth output power of a wind turbine. For example, energy storage devices, electric double layer capacitors, flywheels are well-known. But these methods are required a significant extra cost for installation and maintenance. In recent years, some researches have been conducted to generate smooth output power by using inertia or by controlling kinetic energy of a wind turbine. The major benefit of this method, it does not require extra energy storage to generate smooth output power. So, it can reduce of a system cost significantly. But this method is reduced output power radically at the steady wind velocity as compare with maximum power point tracking (MPPT) control method. To overcome this problem, this paper is proposed a fuzzy controller based output power smoothing method by controlling kinetic energy of a wind turbine. The generator electrical speed is controlled by the proposed method that helps to generate efficient smooth output power at different wind speeds. The proposed method is compared with conventional method and MPPT control method. The effectiveness of the proposed method is verified by MATLAB SIMULINK with *SimPowerSystems* and *Fuzzy Logic Toolbox*.

Keywords—wind turbine generator system; power leveling; kinetic energy; inertia; fuzzy controller.

I. INTRODUCTION

Due to crisis of fossil fuels (e.g. coal, oil, gas) and to reduce the emission of CO₂, the world is going to achieve safe, clean and economical energy. In recent years, wind turbine conversion systems (WTCS) have received increasing attention in order to lack of fossil fuels [1]. Especially, variable speed wind turbine (VSWT) system with a power electronics interface has attracted interest. The use of permanent magnet synchronous generator (PMSG) also have increased [2]. Because PMSG has simple structure and high efficiency, it is expected that more large size wind turbine generator (WTG) systems will adapt it. Currently, WTCS using PMSG generally uses AC-DC-AC methods. WTG system using the method does not need to synchronize the rotational speed of the WTG with power system frequency. Moreover, the gearbox can be omitted resulting in lower costs. However, wind energy has a drawback of having only 1/800 gm/cm³ density as compared with water energy and it is not

constant, and wind turbine output power is proportional to the cube of wind speed. As a result, the generated power of WTG is fluctuated. 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 [3], superconducting magnetic energy storage (SMES) [4], flywheel energy storage system (FESS) [5], storage batteries, aqua electrolyze fuel cell, and backup generator. 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 fuel cell system is very large. Back-up generator requires operational cost.

Among various control methods for a stand-alone WTGS output power control such as output power smoothing by using pitch angle control or the inertia of wind turbine [2,6,7]. The inertia stores kinetic energy during acceleration of a wind turbine at high wind velocity. It releases kinetic energy during deceleration of a wind turbine at low wind velocity. This phenomenon helps to generate smooth output power of a wind turbine. When wind velocity is fluctuated, the inertia power smoothing technique is effective. This method can generate efficient output power as compared with MPPT control method. On the other hand, when wind velocity moves to steady state, this method reduced output power rapidly as compared with MPPT control method. So, the total system efficiency is decreased at different wind velocities. It is important to overcome this problem.

This paper represents a fuzzy-controller-based output power smoothing method of a WTGS with a PMSG using the inertia. The fuzzy controller system adjust the integral/averaging time (T) at different wind speeds. In a conventional control system, the integral/averaging time ($T=6s$) remains constant. So, the final outcomes of the controller such as reference electrical speed for WTGS becomes more adjustable by using proposed method. It helps to generate smooth and efficient output power at different wind velocities. The proposed method is compared with conventional and MPPT control methods. The effectiveness of the proposed method is verified by MATLAB SIMULINK environment.

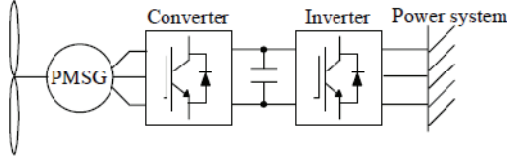


Fig. 1 Gearless wind generation system using PMSG

II. WIND TURBINE CONVERSION SYSTEM

A. System configuration

The system configuration of a WTG system is shown in Fig. 1. Wind power energy is obtained from the wind turbine. It is sent to PMSG. Due to generate maximum power and smoothing power, the rotational speed of PMSG are 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.

B. Wind turbine model

The input power of wind turbine P_{wind} is expressed as

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

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

$$T_{wind} = \frac{\lambda}{\omega_w} P_{wind} = \frac{1}{2} \rho \pi R_o^3 V_w^2 \quad (2)$$

where ω_w is the angular velocity of wind turbine and λ is the tip speed ratio, which can be defined as $\lambda = \frac{R_o \omega_w}{V_w}$. The

wind turbine output power P_w and windmill output torque T_w are given by the following equations:

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

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

where β is pitch angle. The wind turbine power coefficient C_p is defined by the following equation :

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

$$\Gamma = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}} \quad (6)$$

The motion equation of wind turbine is expressed as:

$$T_w = J_w \frac{d\omega_w}{dt} + T_{lw} \quad (7)$$

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

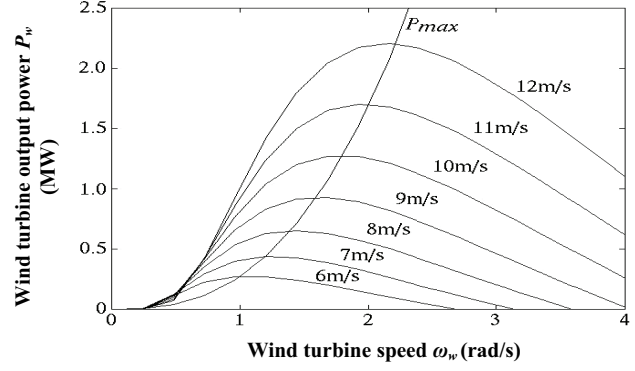


Fig. 2. Wind turbine output power characteristics.

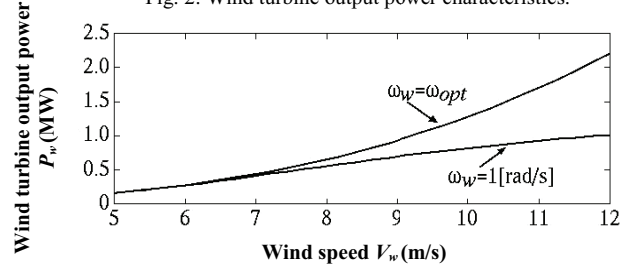


Fig. 3. Wind speed Vs. wind turbine output power characteristics.

power to the generator P_{in} is expressed as

$$P_{in} = -T_{lw} \omega_g \quad (8)$$

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

$$P_g = -T_e \omega_g \quad (9)$$

where T_e is the generator electric torque.

C. Maximum power point tracking control system

From equations (3) and (5), the wind turbine output power characteristics are described in Fig. 2, from which it can be realized 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. The optimum rotational speed ω_{opt} is calculated by differentiating C_p with respect to ω_w . Therefore, ω_{opt} is approximated by

$$\omega_{opt} = 0.2 V_w - 0.2 \quad (10)$$

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

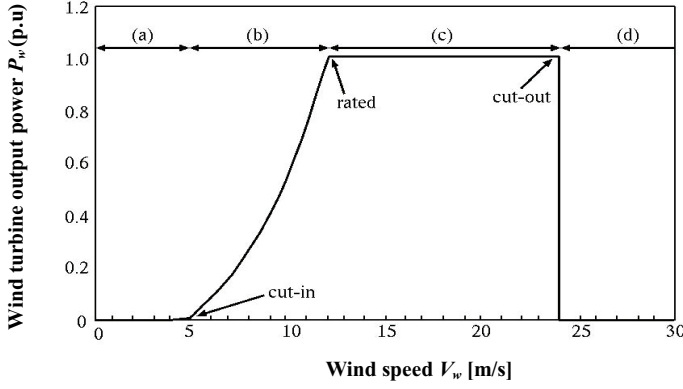


Fig. 4. Pitch angle control law.

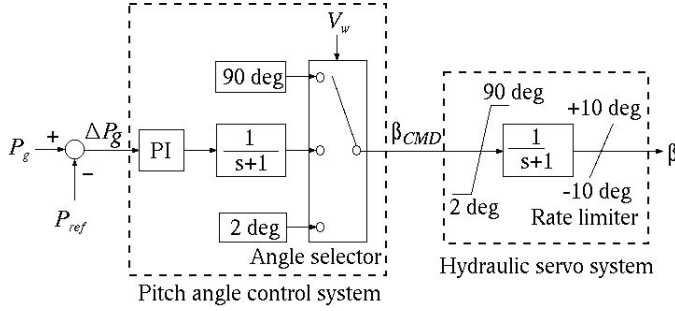


Fig. 5. Pitch angle control system.

PMSG is controlled by the 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 pitch angle is fixed at $\beta = 90^\circ$ because the energy of the wind turbine is smallest at 90° , (b) is $P_w = 0$ pu to $P_w = 1$ pu so that pitch angle is fixed as $\beta = 2^\circ$, (c) is $P_w = 1$ pu so that pitch angle β is selected to keep wind turbine output $P_w = 1$ pu, and finally, (d) is $P_w = 0$ pu so that pitch angle is fixed at $\beta = 90^\circ$ 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 PI controller. Actually, the pitch angle control system includes a hydraulic servo system. The system has nonlinear characteristics, but it is able to make first-order lag system. 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 $\pm 10^\circ/\text{s}$.

III. OUTPUT POWER SMOOTHING CONTROL

WTG system output power smoothing is controlled by the both charge and discharge of the kinetic energy in response to the wind speed. The charging stage is occurred when the wind turbine rotational speed accelerates at high wind speed, while discharge follows the deceleration of the wind turbine at low wind speed. Fig. 6 shows the power flow diagram for a WTG system.

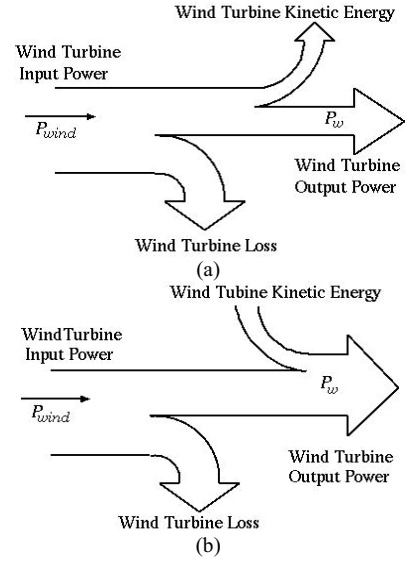


Fig. 6. Power flow (a) acceleration, (b) deceleration.

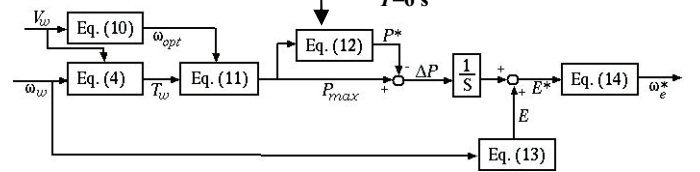


Fig. 7. Conventional power leveling control system.

A. Conventional power smoothing control system

The conventional output power smoothing control system is shown in Fig. 7. First, wind turbine maximum output power, P_{max} is calculated by

$$P_{max} = T_w \omega_{opt} \quad (11)$$

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

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

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

$$E = \frac{1}{2} J_{eq} \omega_w^2. \quad (13)$$

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

$$\omega_w^* = \sqrt{\frac{2E^*}{J_{eq}}} \quad (14)$$

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

$$\omega_e^* = R_n \omega_w^* p \quad (15)$$

and for the MPPT

$$\omega_e^* = R_n \omega_{opt} p \quad (16)$$

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

B. Fuzzy Controller based power leveling control system

The averaging time T in Eq. (12) is one of the key component for the conventional 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 the small averaging time, the output power of the WTG system tends to generate same power as the MPPT control system with fluctuation. If the wind velocity is fluctuated in any region, the averaging time will be large to generate smooth output power. On the other hand, when the wind velocity remains steady, the averaging time can be small to generate same power as MPPT control system. But wind velocity for a particular region can be both fluctuated and steady state. So, adjustment is required for the averaging time to achieve maximum efficiency from this power leveling method. Fig. 8 shows the characteristic between the averaging time and the output power of a WTG system. The dotted line is shown the maximum output power of a WTG system during a simulation time. The conventional method output power is moved to the maximum power when the averaging time becomes smaller. From this figure (Fig. 8), it can be realized that a constant averaging time can be decreased the system efficiency at different wind speeds. The conventional power smoothing control method using inertia or controlling kinetic energy is always measured by a constant averaging time.

So, an adaptive averaging time is necessary to improve overall performance of conventional power smoothing method (instead of constant averaging time) for a WTG system. It can be implemented by a fuzzy controller. The wind velocity and fluctuation of wind velocity are online determined an averaging time. The fluctuation of wind velocity is calculated by the first derivative of wind speed. It is an input of fuzzy controller. Another input of fuzzy controller is wind velocity.

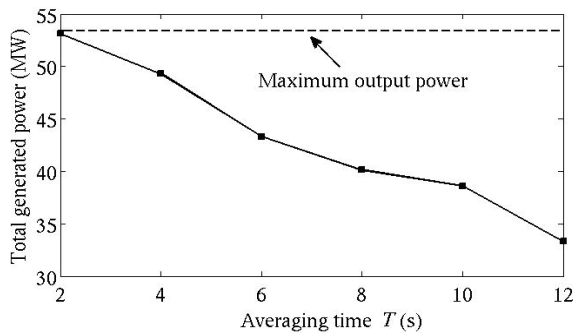
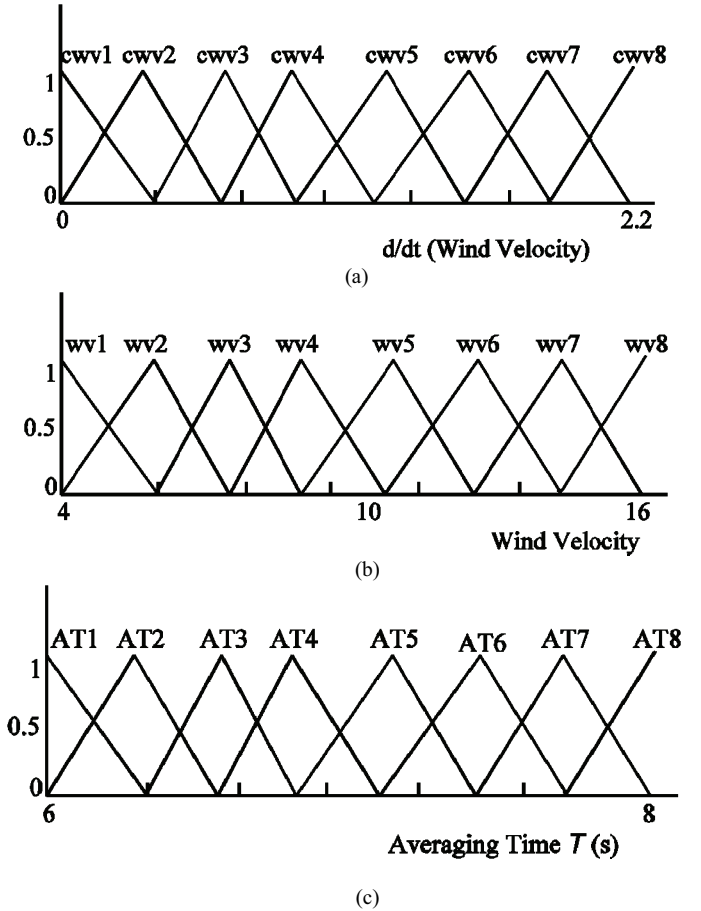


Fig. 8. Averaging time Vs. total generated power characteristics.

Depending on inputs, the fuzzy controller generates a averaging time (T) as an output. The fuzzy membership functions and fuzzy rules are shown in Fig. 9.

The fuzzy rules depict that when the change of wind velocity is large, the averaging time is set to large value. In contrast, the averaging time is small value, when the change of wind velocity is small. In case of wind velocity, when the wind velocity is very large, the averaging time is set to large value. The averaging time is set to small value, when the wind velocity becomes small.



cwv = Change of wind velocity
wv = Wind velocity
AT=Averaging time

		d/dt(V _w)							
		cwv1	cwv2	cwv3	cwv4	cwv5	cwv6	cwv7	cwv8
V _w	wv1	AT1	AT1	AT1	AT1	AT1	AT2	AT2	AT3
	wv2	AT1	AT1	AT1	AT1	AT2	AT2	AT2	AT3
	wv3	AT1	AT1	AT1	AT1	AT2	AT2	AT3	AT3
	wv4	AT1	AT1	AT1	AT1	AT2	AT3	AT3	AT4
	wv5	AT1	AT1	AT1	AT2	AT2	AT3	AT4	AT4
	wv6	AT1	AT1	AT2	AT2	AT3	AT3	AT5	AT6
	wv7	AT1	AT2	AT3	AT4	AT5	AT5	AT6	AT7
	wv8	AT2	AT3	AT4	AT5	AT6	AT7	AT7	AT8

(d)

Fig. 9. Fuzzy membership functions (a) & (b) Input membership functions (c) Output membership functions and (d) Fuzzy rules

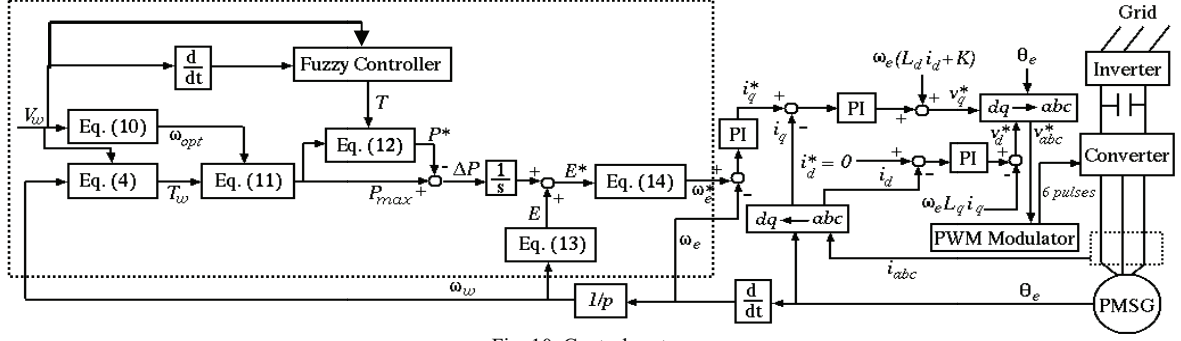


Fig. 10. Control system.

IV. SIMULATION RESULTS

The entire control system of power smoothing method is shown in Fig. 10. The dotted block represents the proposed power smoothing control system. The effectiveness of the proposed fuzzy controller based method is evaluated by the simulation results. The MPPT control method, conventional power smoothing method, and proposed fuzzy based output power smoothing method are compared in this simulation. Simulation parameters of a wind turbine, PMSG, and power converter are shown in Table 1.

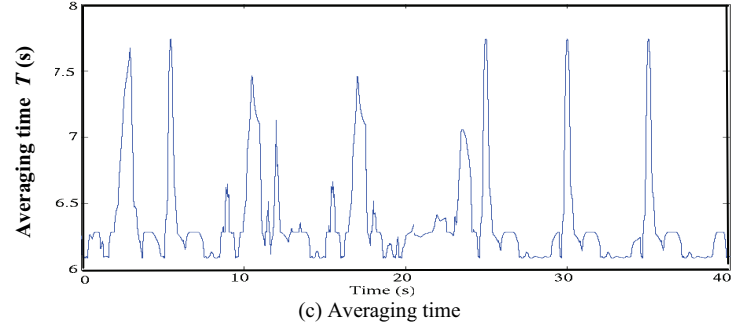
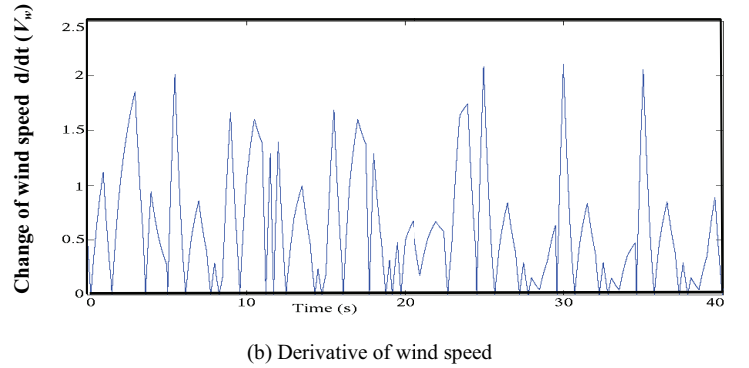
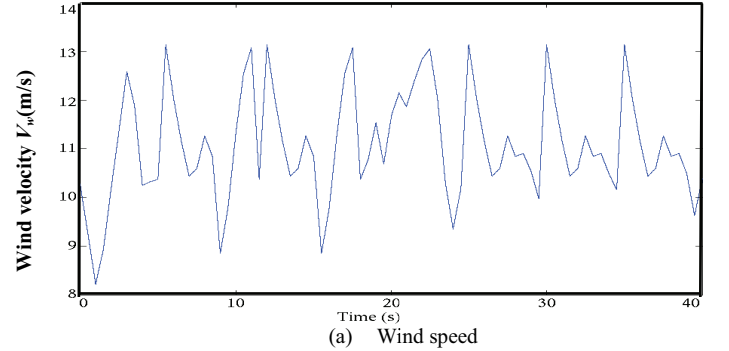
The wind velocity is shown in Fig. 11(a). This wind velocity data has significant fluctuation and speed. The Fig. 11(b) and 11(c) are input and output of fuzzy control. From Fig. 11(d), it is observed that the WTGS speed fluctuates significantly. As seen in Fig. 11(e), as the wind velocity increases, the turbine rotational speed accelerates thereby transforming the wind energy into wind turbine kinetic energy.

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	$V_{w \text{ rated}} = 12$ m/s
Averaging time (conventional method)	$T = 6$ s
Parameters of PMSG	
Rated power	$P_{g \text{ rated}} = 2$ MW
Number of poles pair	$p = 80$
Stator resistance	$R_a = 0.1$ Ω
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	$V_{dc \text{ rated}} = 7.1$ kV

Similarly, as the wind velocity decreases, a discharge of the wind turbine kinetic energy occur, through decrease in turbine rotational speed. Fig. 11(f) shows a comparison of the generator electric torque. The power smoothing method decreases the fluctuation of electric torque significantly as compare with MPPT.

This contributes the reduction of mechanical stress of generator. Fig. 11(g) shows the pitch angle of the wind turbine. Fig. 11(h) shows a comparison of generated output power from the PMSG. From this figure, the proposed method generates smooth output power with high efficiency as compared with conventional method. Both methods are compared with MPPT control method. The conventional method reduced output power significantly when wind velocity becomes steady as compare with MPPT control method.



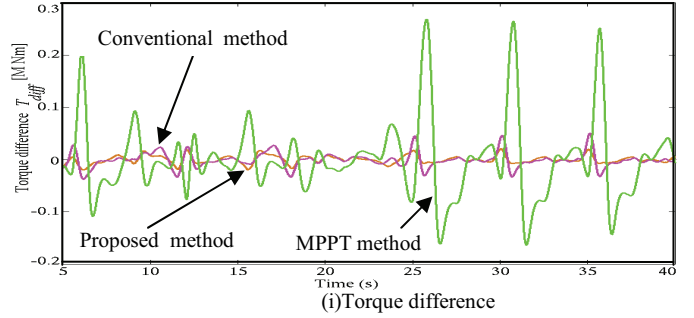
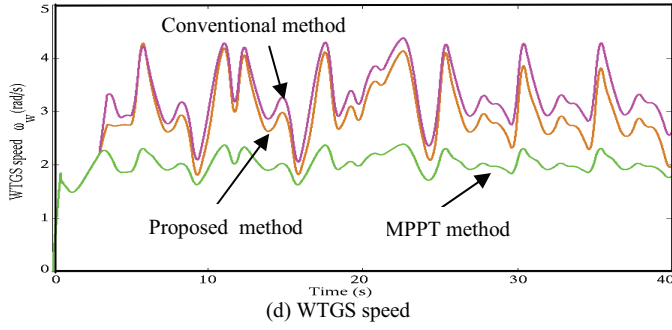


Fig. 11 Simulation results

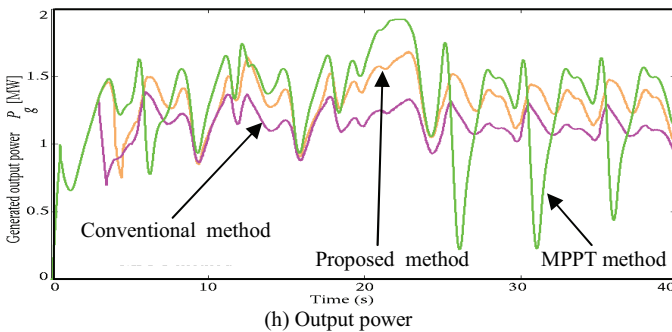
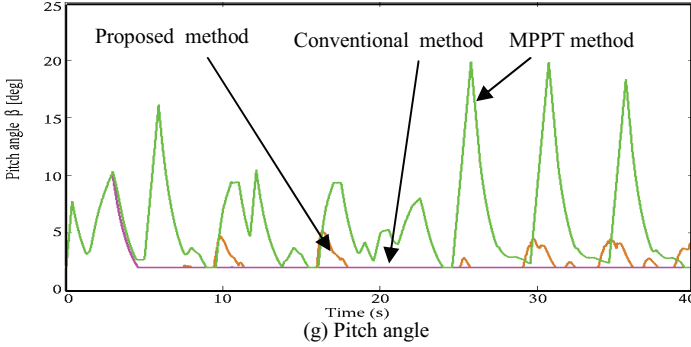
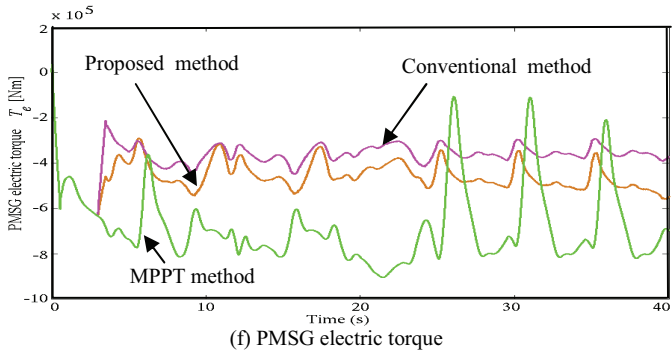
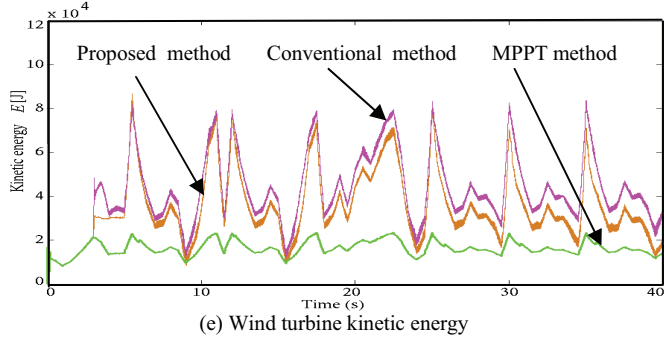


Fig. 11(i) shows the torque difference which is smoothed extensively as compare with MPPT control method. So, it is possible to mitigate the mechanical stress of the shaft in WTCS.

V. CONCLUSION

A fuzzy controller based output power smoothing method of a wind turbine has been proposed in this paper. It is simulated by using an adaptive averaging or integral time which depends on wind velocity and fluctuation of wind velocity. The conventional system is simulated by a constant averaging time ($T=6s$). If it is lower than 6s, the generated power will be fluctuated like MPPT method. Alternatively, if it is above than 6s, the performance will be more degraded. The propose method is compared with both conventional method and MPPT control method. The fuzzy based propose method can adjust the averaging time and generates efficient output power smoothing. From the simulation results, the overall performance are improved by using our proposed method.

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