

A Fuzzy-Based Output Power Smoothing of WECS using Short-Term Ahead Prediction of Wind Speed

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Abstract—This paper presents a fuzzy-based output power smoothing method for a wind energy conversion system (WECS) using short-term ahead prediction of wind speed. The WECS is based on a permanent magnet synchronous generator (PMSG) and transmits its electrical power to an AC grid through an IGBT pulse-width modulation (PWM) converter. The power converter controls the torque of the PMSG according to the torque command, which is determined by using the fuzzy logic. The inputs of the fuzzy logic are the predicted wind speed and the difference between the wind turbine torque and the generator torque. By means of the proposed method, the generator torque is smoothed and the kinetic energy stored by the inertia of the wind turbine can be utilized to smooth the output power fluctuations of the PMSG. In addition, the wind turbine's shaft stress is mitigated compared to a conventional maximum power point tracking (MPPT) control. The effectiveness of the proposed method is verified by numerical simulations.

keywords—fuzzy logic, power smoothing, wind energy conversion system, wind speed prediction, wind turbine inertia.

I. INTRODUCTION

In recent years, there have been problems such as exhaustion of fossil fuels, e.g., coal and oil, and environmental pollution resulting from consumption of these fuels. For cleaner and economical energy characteristics, the world has been turning to alternatives of fossil fuels and wind energy conversion systems (WECS) have received increasing attention. Especially, variable speed wind turbine (VSWT) systems with power electronics interfaces have attracted interest. VSWT systems are usually based on doubly fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG) [1]-[6]. Currently, the use of PMSGs has increased because of its simple structure and efficient energy production. Therefore, it is expected that more large size wind turbine generator (WTG) systems will adopt the PMSG [1]-[4]. Usually, the WECS with a PMSG is connected to the grid via an AC-DC-AC converter system. In this system, the WECS does not need to synchronize its rotational speed with the grid frequency. Besides, the gearbox can be omitted due to the low rotational

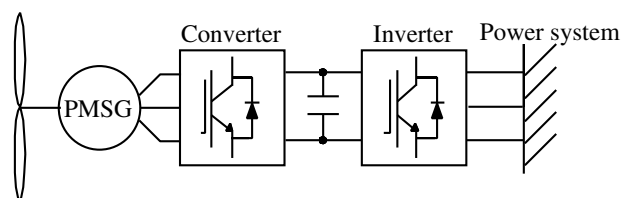


Fig. 1. Wind energy conversion system using PMSG.

speed of the WTG. On the other hand, wind energy is not constant and the wind turbine's power fluctuates. Since the output power fluctuations may cause grid frequency deviations, several literatures regarding the output power smoothing have been published such as the use of pitch angle control or the inertia of VSWTs [3]-[7].

This paper presents a fuzzy-based output power smoothing method for a WECS using short-term ahead prediction of wind speed. The WECS is based on a PMSG and transmits its electrical power to an AC grid through a IGBT pulse-width modulation (PWM) converter. The power converter controls the torque of the PMSG according to the torque command, which is determined by using the fuzzy logic. The inputs of the fuzzy logic are the predicted wind speed and the difference between the wind turbine torque and the generator torque. The short-term ahead wind speed is predicted by using least-squares method [7] and it is used to achieve more effective torque control of the PMSG for the wind speed variations. For high wind speed condition, the power fluctuations of the PMSG is smoothed with the pitch angle control. By using the proposed method, the torque of the PMSG is smoothed and the kinetic energy stored by the inertia of the wind turbine can be utilized to smooth the output power fluctuations of the PMSG. In addition, the wind turbine's shaft stress and the pitch action are mitigated compared to a conventional maximum power point tracking (MPPT) control. The effectiveness of the proposed method is verified by numerical simulations.

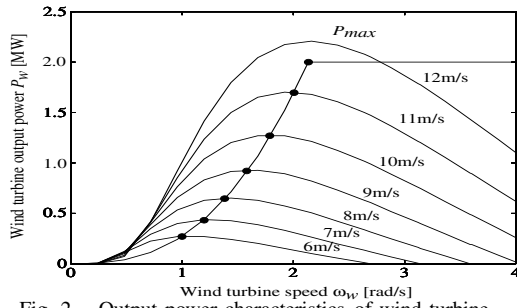


Fig. 2. Output power characteristics of wind turbine.

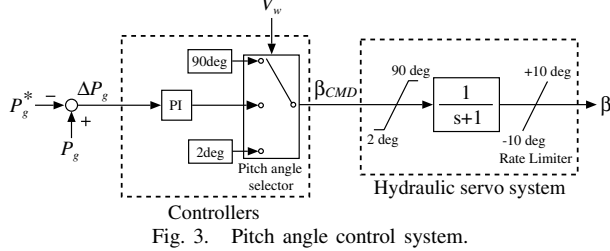


Fig. 3. Pitch angle control system.

II. CONVENTIONAL WECS

A. System Configuration

The system of the WECS is shown in Fig. 1. Wind energy obtained from the wind turbine is sent to the PMSG. To generate maximum power, rotational speed of the PMSG is controlled by a pulse width modulation (PWM) converter. The output power of the PMSG is supplied to the grid through a generator-side converter and a grid-side inverter.

B. Wind Turbine Model

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

$$P_w = 0.5C_p(\lambda, \beta)\rho\pi R^2 V_w^3 \quad (1)$$

$$T_w = 0.5C_p(\lambda, \beta)\rho\pi R^3 V_w^2 / \lambda \quad (2)$$

where V_w is the wind speed, ρ is the air density, R is the radius of the wind turbine, C_p is the wind turbine power coefficient, $\lambda = \omega_w R / V_w$ is the tip speed ratio, ω_w is the angular rotor speed of the wind turbine and β is the pitch angle. C_p is given by the following equations [3]:

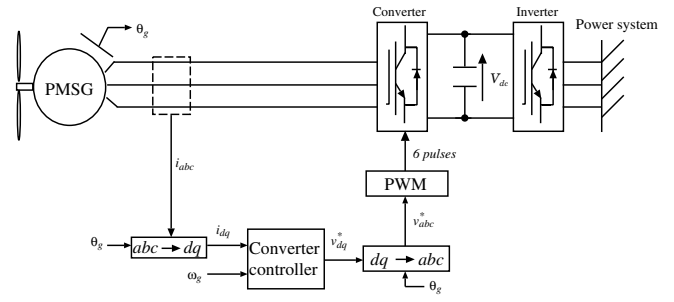
$$C_p = 0.22 \left(\frac{116}{\Gamma} - 0.4\beta - 5 \right) \exp^{-\frac{12.5}{\Gamma}} \quad (3)$$

$$\Gamma = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}} \quad (4)$$

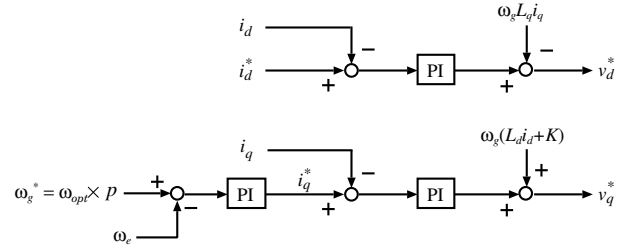
C. Maximum Power Point Tracking Control

The output power characteristics of the wind turbine are depicted in Fig. 2. Here, the pitch angle, $\beta = 2^\circ$. From this figure, it can be seen that there is a rotational speed, ω_{opt} , dotted by the black circles, for any particular wind speed. ω_{opt} is called the optimum rotational speed and generates the maximum power, P_{max} (MPPT control). ω_{opt} is approximated as follows [1]-[3]:

$$\omega_{opt} = 0.1874V_w. \quad (5)$$



(a) Configuration of power converter system



(b) Configuration of converter control system

Fig. 4. Configuration of PMSG control system.

Generally, the MPPT control is applied when the wind speed, V_w , is smaller than the rated speed. If V_w is greater than the rated speed, then output power of the PMSG is controlled by the pitch angle control system as shown in Fig. 3 [3]. The pitch angle is controlled in the region between the rated wind speed (12m/s) and the cut-out wind speed (24m/s). Subtraction of the output power command the PMSG, P_g^* , from the output power of the PMSG, P_g , gives the output error of the PMSG, ΔP_g , that evaluates the pitch angle command, β_{CMD} , via the pitch angle control system. The output power of the PMSG is controlled by a hydraulic servo system that drives the blades according to the pitch angle command, β_{CMD} . The output power command of the PMSG, P_g^* , is constant at the rated power (2MW).

D. PMSG Model

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

$$v_d = R_a i_d + L_d \frac{di_d}{dt} - \omega_g L_q i_q \quad (6)$$

$$v_q = \omega_g L_d i_d + R_a i_q + L_q \frac{di_q}{dt} + \omega_g K \quad (7)$$

$$T_g = p \{ K i_q + (L_d - L_q) i_d i_q \} \quad (8)$$

where v_d and v_q are the d - q axis voltages, i_d and i_q are the d - q axis currents, R_a is the stator resistance, L_d and L_q are the d - q axis inductances, ω_g is the generator rotational speed, K is the permanent magnetic flux, and p is the number of pole pairs. Generating operation starts when the electromagnetic torque, T_g , is negative. The motion equation of the PMSG is given as

follows:

$$J_{eq} \frac{d\omega_g}{dt} = T_w - T_g. \quad (9)$$

where $J_{eq}(=J_g+J_w)$ is the equivalent inertia, T_w is the wind turbine torque.

E. Configuration of Power Converter System

The configuration of the power converter control system is shown in Fig. 4(a). The power converter is standard 3-phase two-level unit, composed of six IGBTs and controlled by triangle-wave PWM law.

The conventional configuration of the power converter is shown in Fig. 4(b). By using vector control scheme, the power converter controls the rotational speed of the PMSG to achieve variable speed operation with the MPPT control. The speed control of the PMSG is realized on a rotating reference frame, where the rotational speed error is used as the input to a speed controller which produces q axis stator current command, i_q^* . A salient-pole synchronous machine is used in this paper. To achieve efficient operation of the PMSG, d axis stator current command, i_d^* , is determined by [8] and given as follows:

$$i_d^* = \frac{K}{2(L_d - L_q)} - \sqrt{\frac{K^2}{4(L_q - L_d)^2} + i_q^2}. \quad (10)$$

The error between the command d - q axis currents, i_d^* , i_q^* , and the actual d - q axis currents are used as inputs to the current controllers. The current controllers produce d - q axis voltage commands v_d^* , v_q^* after the decoupling. The angle θ_g , for the Park transformation, is calculated from the rotational speed of the PMSG.

III. PROPOSED WECS

This section presents the proposed fuzzy-based output power smoothing method using the inertia of the wind turbine.

A. Power and Torque Characteristics in WECS

The wind turbine output, P_w , the wind turbine torque, T_w , and the generator torque, T_g , versus the wind turbine speed, ω_w , curves are shown in Figs. 5 and 6, respectively [2, 5, 6]. Here, the wind speed is assumed as 12m/s. If a constant output power command, $P_{ref} = kP_{rated}$, is given for the PMSG, then the generator torque is expressed as $T_g = P_{ref}/\omega_g$, where, k is a multiplying factor. The generator torque for $k = 1.0$ and 0.7 is shown in Fig. 6. In the conventional MPPT control, the operating point of the wind turbine speed becomes the optimum rotational speed, ω_{opt} , as shown in Fig. 5. However, in the output power smoothing method using the inertia of the wind turbine, the wind turbine speed changes around ω_{opt} according to the actual wind speed. In Fig. 6, if the rotational speed of the wind turbine changes from ω_{min} to ω_{max} , then the kinetic energy stored by the wind turbine, ΔE , is expressed as follows [2]:

$$\Delta E = \frac{1}{2} J_{eq} (\omega_{max}^2 - \omega_{min}^2). \quad (11)$$

By controlling the rotational speed of wind turbine in the region of $\omega_{min} \sim \omega_{max}$, ΔE can be used for output power smoothing. Since stable operation of the wind turbine is

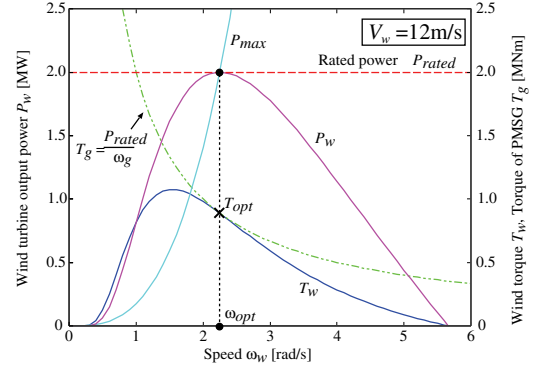


Fig. 5. Speed characteristics of WECS.

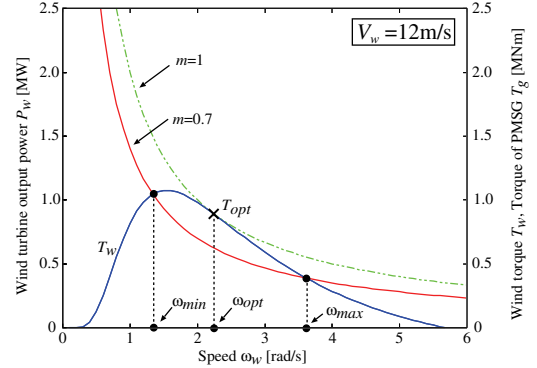


Fig. 6. Torques of PMSG for each output power.

achieved within a proper range, the upper and lower limits of the operation region are set to 0.6 pu and 1.4 pu. The rotational speed of the wind turbine is controlled within this region. Although Figs. 5 and 6 show the wind turbine characteristics at $V_w=12\text{m/s}$, wind turbine characteristics at $V_w = 5 \sim 12\text{m/s}$ can be obtained by using a lookup table which has prestored values of T_g and T_w as described in Fig. 6. Here, for the case of the constant power control, the rotational speed variations of the wind turbine will become large and will lead to the unstable operating of the WECS, increase of wind turbine's shaft stress. Therefore, this paper aims at the smoothing and controlling of the generator torque, T_g .

B. Torque Control Method using Fuzzy Logic

As described before, the generator-side converter smooths the generator torque for output power smoothing. The power fluctuations of the WECS can be leveled by smoothing the generator torque. For the proposed method, the generator torque command is determined by using the fuzzy logic. The fuzzy rules and membership functions are shown in Table 1 and Fig. 7, respectively. The inputs of the fuzzy logic are given by the following equations:

$$\Delta T = T_w - T_{g_opt} \quad (12)$$

$$\Delta \hat{V}_w = \frac{1}{T} \int_{t-T}^t \hat{V}_w dt - \hat{V}_w \quad (13)$$

where $\hat{V}_w$ is the predictive wind speed and it will be explained in next section. The output of the fuzzy logic is the torque

Table I. Fuzzy Rules

$\Delta \hat{V}_w$	ΔT							
	NB	NM	NS	NZ	PZ	PS	PM	PB
	NB	PB	PM	PS	NS	NM	NB	NB
	NM	PB	PM	PS	NS	NM	NB	NB
	NS	PM	PM	PS	PZ	NZ	NS	NM
	NZ	PM	PS	PZ	NZ	NZ	NS	NM
	PZ	PM	PS	PZ	NZ	NZ	NS	NM
	PS	PM	PM	PS	PZ	NZ	NS	NM
	PM	PB	PM	PS	NS	NM	NB	NB
	PB	PB	PB	PM	PS	NS	NM	NB

NB=Negative Big NM=Negative Medium NS=Negative Small
 PB=Positive Big PM=Positive Medium PS=Positive Small
 NZ=Negative Zero PZ=Positive Zero

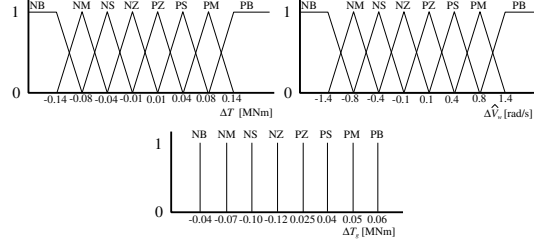


Fig. 7. Membership functions.

fluctuation index, ΔT_g . The increase and decrease of ΔT_g is determined by the input of ΔT , while the amount of ΔT_g is determined by the input of $\Delta \hat{V}_w$.

The reason for the use of (12) is based on (9) which is the system dynamics equation [6]. For (9), operating points, ω_{g0} , V_{w0} , T_{g0} , and T_{w0} are assumed. At the operating speed, ω_{g0} , if $d\omega_{g0}/dt = 0$ then $T_{w0} - T_{g0} = 0$. If the operating point, V_{w0} , increases and $T_{w0} - T_{g0} > 0$, then ω_{g0} should increase. The acceleration continues until $T_{w0} - T_{g0} = 0$. When $T_{w0} - T_{g0} = 0$, the operating speed, ω_{g0} , should remain at the operating point. If a decrease in wind speed occurs and $T_{w0} - T_{g0} < 0$, then ω_{g0} should decrease. The deceleration continues until $T_{w0} - T_{g0} = 0$. From these operations, by (12), if ΔT is increases, it means that the wind turbine torque, T_w , increases due to a increase in the wind speed. Therefore, the generator speed, ω_g , should increase, i.e., the generator torque, T_g , should decrease. On the other hand, if ΔT decreases, it means that T_w decreases due to a decrease in the wind speed. Therefore, ω_g should decrease, i.e., T_g should increase. Here, T_{g_opt} of (12) is the optimum generator torque in the MPPT control and can be calculated by the following equation [1]:

$$T_{g_opt} \approx T_{w_opt} = 1453.3\omega_g^2 \quad (14)$$

Here, T_{w_opt} is the optimum torque of wind turbine. (14) is derived assuming the wind rotor and the generator characteristics are at steady-state.

Equation (13) is used to evaluate the amount of ΔT_g . The first term of (13) is an average value of the predicted wind speed. To smooth the power fluctuations in the high frequency domain (above 0.1Hz), the value of T is set to 10s [2, 6]. If $\Delta \hat{V}_w$ is large, then it is seen that the wind speed variation is also large. Therefore, the amount of ΔT_g should be increased, and *vice-versa*. By using the predicted wind speed as the input of the fuzzy logic, more effective torque control can be achieved. Finally, the generator torque command, T_g^* , is determined by adding ΔT_g with T_{g_opt} as

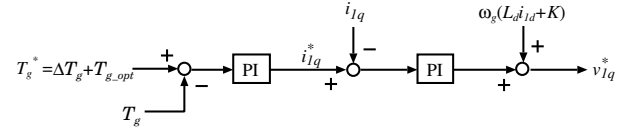


Fig. 8. Proposed configuration of converter.

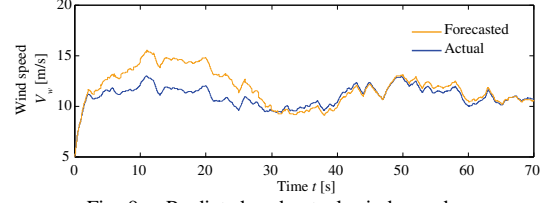


Fig. 9. Predicted and actual wind speeds.

shown in Fig. 8. In the proposed method, the fuzzy control is determined based on the motion equation of PMSG and the operating rotational speed. These are the fundamentals for the operations of WECS, and therefore, the fuzzy control can be used regardless of the kind of WECSs. On the other hand, the membership functions are needed to tune according to the specifications of generators and turbines. However, this is simple and flexible. The torque fluctuation index, ΔT_g , is determined by using several wind speed profiles in simulations. When using the proposed method in practical systems, one can simply determine the membership functions and the values of ΔT_g according to WECS's specifications and wind profiles.

C. Wind Speed Prediction by Least-Squares Method

In this paper, a short-term ahead wind speed is predicted by using the least-squares method [7].

The wind speed slope, $a(k)$, is derived by the wind speed from the past T_{pre} seconds (the sampling-period is 1s) as the following equation:

$$a(k) = \frac{T_{pre} \sum_{n=1}^{T_{pre}} n V_w(k-n) - \sum_{n=1}^{T_{pre}} n \sum_{n=1}^{T_{pre}} V_w(k-n)}{T_{pre} \sum_{n=1}^{T_{pre}} n^2 - \left(\sum_{n=1}^{T_{pre}} n \right)^2} \quad (15)$$

where k is the present time and $V_w(k-n)$ is the wind speed value of n intervals ago. If T_{pre} is set to 30s, then (15) is calculated as follows:

$$a(k) = \sum_{n=1}^{30} \frac{29-2(n-1)}{4495} V_w(k-n). \quad (16)$$

The predicted wind speed, $V_{wf}(k+T_f)$, is expressed as

$$V_{wf}(k+T_f) = V_w(k) + T_f a(k) \quad (17)$$

where T_f is the prediction time and set to 5s.

To investigate the effectiveness of the proposed prediction method, the simulation result of wind speed prediction is shown in Fig. 9. From this figure, it is seen that the prediction error is large by around $t = 30$ s because of the past wind

data is less than 30 points. After that, however, the prediction accuracy is improved and the percentage error becomes small.

IV. POWER SMOOTHING SIMULATION

A. Simulation Model

The system model used for the simulation is shown in Fig. 10. Here, the grid-side inverter is connected to an infinite bus through a LC filter, three-phase transformer, and single circuit transmission line in parallel with load. The parameters of the PMSG and the power converters are listed in Table II.

B. Simulation Results

To evaluate the effectiveness of the proposed method, WECS operation is examined by using the both methods (conventional and proposed). In the conventional method, the MPPT control described in Section II is employed. In the proposed method, the WECS initially operates as the MPPT control by regulating the optimum generator torque. At $t = 40$ s, the WECS starts the proposed method for output power smoothing. The simulation results are shown in Fig. 11. The wind speed shown in Fig. 9 is used for the both methods. Figs. 11(a)~(d) show the generator torque and the input-output of the fuzzy logic, respectively. From these figures, it is confirmed that the generator torque is smoothed by the proposed torque control method compared with that of the MPPT control. Around $t = 40 \sim 60$ s, short term variations of the wind speed frequently occur. However, the predicted wind speed is used as the input of the fuzzy logic, and therefore, the control performance is improved as shown in Fig. 11(d). The generator speed and its d - q axis currents are shown in Figs. 11(e) and (f). By smoothing the generator torque, the generator speed accelerates/decelerates according to the wind speed increasing/decreasing. The kinetic energy of wind turbine, the pitch angle, the power coefficient, the active power of the PMSG and its maximum energy function with the both methods are shown in Figs. 11(g)~(k), respectively. Here, the maximum energy function, P_{max} , is expressed as follows [10]:

$$P_{max} = \int_0^t P_g(t) dt. \quad (18)$$

In the conventional MPPT method, the pitch action increases when the wind speed fluctuates around the rated speed (see Fig. 11(h)). This results in the reduction of the power coefficient as shown in Fig. 11(i). On the other hand, the kinetic energy stored by the wind turbine is utilized for power smoothing, and therefore, the pitch action can be decreased. Consequently, as can be seen in Fig. 11(k), the maximum energy function, P_{max} , increases compared with the MPPT control. Fig. 11(l) shows the torque difference between the wind turbine and the generator. From this figure, it is found that the torque difference is smaller than that of the MPPT control and the mitigation of the wind turbine's shaft stress is achieved.

V. CONCLUSION

This paper presents a fuzzy-based output power smoothing method for a WECS using short-term ahead prediction of wind speed. In the WECS, the power converter controls the

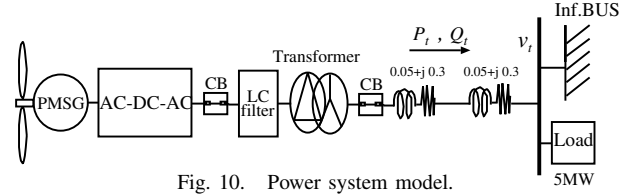


Fig. 10. Power system model.

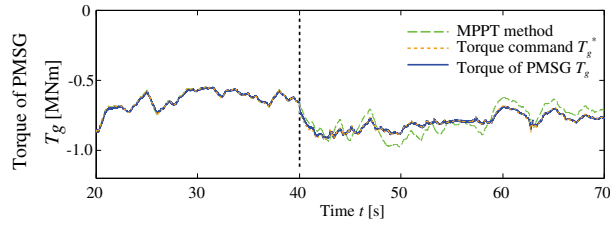
Table II. Simulation Parameters

Parameters of windmill	
blade radius R	39 m
air density ρ	1.205 kg/m ³
rated wind speed V_{w_rated}	12m/s
Parameters of PMSG	
rated output P_g	2 MW
armature resistance R_a	50 $\mu\Omega$
d axis inductance L_d	5.5 mH
q axis inductance L_q	3.75 mH
number of pole pairs p	11
field flux K	136.25 V·s/rad
equivalent inertia J_{eq}	300,000 kg·m ²
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
DC-link capacitor C	15,000 μ F

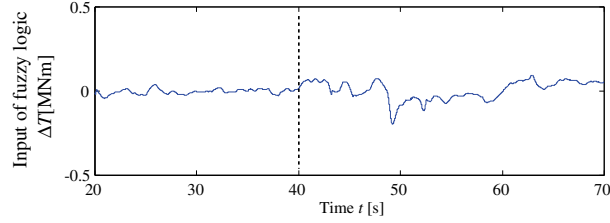
generator torque according to the torque command, which is determined by using the fuzzy logic. By using the proposed method, the generator torque is smoothed and the kinetic energy stored by the inertia of the wind turbine can be utilized for power smoothing. The effectiveness of the proposed method is verified by numerical simulations.

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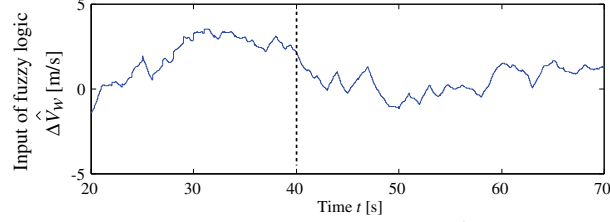
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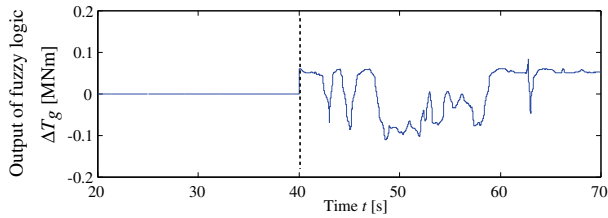
(a) Torque of PMSG.



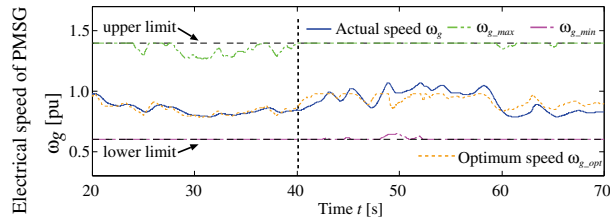
(b) Input of fuzzy logic ΔT .



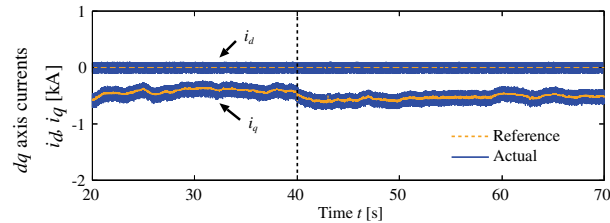
(c) Input of fuzzy logic $\Delta \hat{V}_w$.



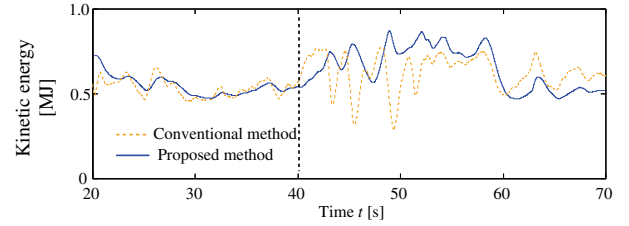
(d) Output of fuzzy logic.



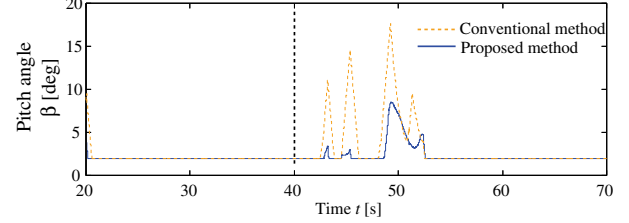
(e) Electrical speed of PMSG.



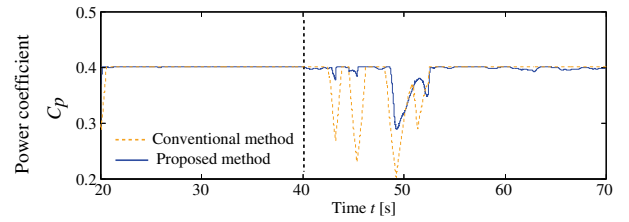
(f) d - q axis currents.



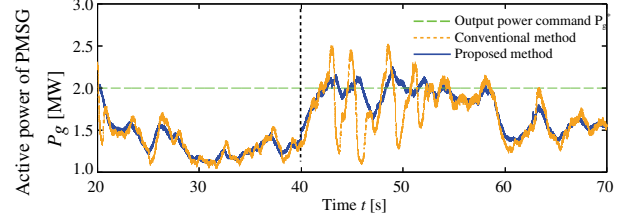
(g) Kinetic energy.



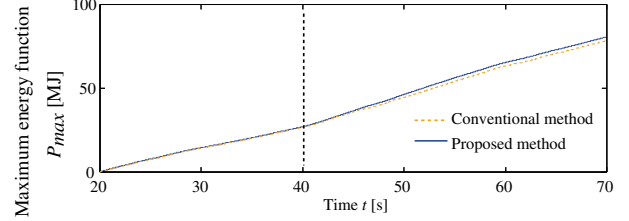
(h) Pitch angle.



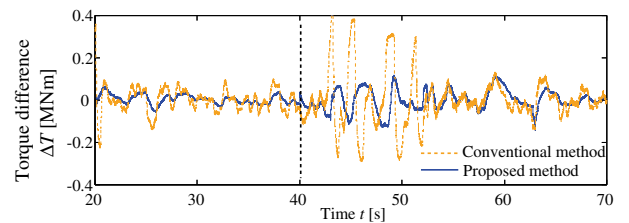
(i) Power coefficient.



(j) Active power of PMSG.



(k) Maximum energy function.



(l) Torque difference.

Fig. 11. Simulation results.