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## Maximum energy yield oriented turbine control in PMSG-based wind farm

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**Abstract:** In the modern power systems, with the fast integration of the wind power into the grid, it turns to develop large-scale offshore wind farms equipped with the permanent magnet synchronous generator (PMSG) wind turbine. In large-scale offshore wind farms, the wind turbine operating reliability and the wake effect in the wind farm became important issues. The pitch angle and tip speed ratio are the two degrees of freedom for the PMSG wind turbine active power control, which are also the determining factors of the wind turbine lifetime. As the energy production of the wind turbine is the product of its active power and lifetime, the energy production can be maximised by optimising its pitch angle and tip speed ratio. In this study, the energy production of a 2 MW PMSG wind turbine is maximised by optimising its pitch angle and tip speed ratio. Moreover, taking into account the wake effect, the energy production of a wind farm equipped with two 2 MW PMSG wind turbines is maximised by optimising the pitch angle and tip speed ratio of each wind turbine.

### 1 Introduction

According to IEA Wind 2015 Annual Report [1], 433 GW of wind power capacity has globally been installed by 2016, which met 4% of the world's electricity demand in 2015. With the increasing integration of the wind power into the grid, it tends to develop large-scale offshore wind farm. Due to the lower cost of power electronics and more stringent fault ride-through grid codes, the large-scale wind farm turns to the synchronous generator or asynchronous generator based turbines with the full-scale power converter.

As a popular candidate of full-scale power converter solution, the permanent magnet synchronous generator (PMSG) based wind turbine has two degrees of freedom for the active power control, which are the pitch angle and tip speed ratio [2]. The widely implemented active power control method in the PMSG wind turbine is the maximum power point tracking (MPPT), by which, each individual wind turbine generates the maximum active power at its current wind speed by adjusting its pitch angle and tip speed ratio. However, the MPPT method hardly considers the wind turbine lifetime and the wake effect in the wind farm.

In offshore wind farms, due to its expensive operation and maintenance cost, the wind turbine operating reliability became more and more important. The energy production capability of each wind turbine is related not just to its active power generation but also to its lifetime. A few studies have focused on this area. According to a field survey [3], the power converter in the wind turbine system has the most failure rate, which is 23%, compared with the other parts of the wind turbine components. Thus, by increasing the lifetime of the power converter, the energy production of the wind turbine can be increased [4].

It is not possible to calculate the exact lifetime of the power converter, as it is determined by many factors. Instead, the  $B_{10}$  lifetime is implemented [5]. The  $B_{10}$  lifetime is defined as the period during which there is 10% of the power module failed among the whole population. As presented in [6], in case of no reactive power integration from the wind turbine to the grid, the  $B_{10}$  lifetime of the machine-side converter (MSC) is smaller than that of the grid-side

converter (GSC). Thus, by increasing the lifetime of the MSC, the energy production of the wind farm can be increased. In [7], the  $B_{10}$  lifetime of the MSC in the PMSG-based wind turbine is estimated, which is determined by both the wind turbine pitch angle and the tip speed ratio. Thus, by using the trade-off between the wind turbine active power generation and the lifetime of the MSC, the energy production capability of the wind turbine can be maximised by optimising the pitch angle and tip speed ratio.

In large-scale wind farms, the active power loss due to the wake effect became an important issue. In offshore wind farms, the active power loss due to the wake effect could even reach up to 15% [8]. In the last few decades, wake models in the wind farm have been developed in complexity [8, 9]. According to the wake models, the active power loss of the downstream wind turbine is determined by the pitch angle and tip speed ratio of the upstream wind turbine. As a consequence, as presented in [10–12], compared with the MPPT method, the active power of the upstream wind turbine will be reduced by changing the pitch angle and tip speed ratio of the upstream wind turbine. However, the equivalent wind speed of the downstream wind turbine can be increased, which results in the active power increase of the downstream wind turbine. Totally, the active power of the wind farm can be increased. Thus, taking into account the wake effect in the wind farm, trading off among the wind turbine active power, the lifetime of the MSC and the active power loss in the wind farm by optimising the pitch angle and tip speed ratio of each wind turbine, the energy production of the wind farm can be maximised.

In this paper, first, based on the  $B_{10}$  lifetime estimation of the MSC in the PMSG-based wind turbine, trading off between the active power generation and the lifetime of MSC, the energy production of a 2 MW PMSG-based wind turbine is maximised by optimising the pitch angle and tip speed ratio of the wind turbine. Afterwards, taking into account the wake effect in the wind farm, trading off among wind turbine active power, the lifetime of the MSC and the active power loss in the wind farm, the energy production of a wind farm equipped with two 2 MW PMSG wind turbines is maximised by optimising the pitch angle and tip speed ratio of each wind turbine. Finally, conclusions are drawn.

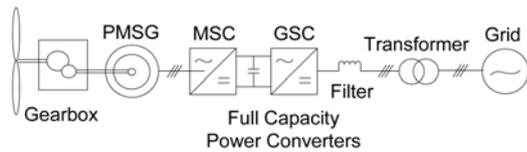


Fig. 1 Configuration of the PMSG-based wind turbine with full-scale power converters: MSC and GSC [2]

## 2 Energy production maximisation of a single wind turbine

In this section, the energy production of the 2 MW PMSG wind turbine is maximised by optimising its pitch angle and tip speed ratio. The configuration of the PMSG wind turbine is shown in Fig. 1.

### 2.1 Maximum power point tracking

The PMSG-based wind turbine has two degrees of freedom for active power control, which are the pitch angle and tip speed ratio [2]. The mechanical power generated by the PMSG wind turbine can be expressed by [2]

$$P_m = \frac{1}{2} \rho \pi R^2 C_p(\beta, \lambda) v^3 \quad (1)$$

where  $\rho$  is the air density,  $R$  is the rotor radius,  $C_p$  is the power coefficient, which is a function of the pitch angle  $\beta$  and tip speed ratio  $\lambda$ , and  $v$  is the wind speed. The tip speed ratio defined as the ratio of the blade tip speed over the speed of the incoming wind is given by [2]

$$\lambda = \frac{\omega_r R}{v} \quad (2)$$

where  $\omega_r$  is the rotor speed.

The power coefficient in terms of the pitch angle and tip speed ratio of the 2 MW PMSG wind turbine is shown in Fig. 2 [13], where the maximum power coefficient  $C_{p\_Max}$  is 0.45 obtained at the pitch angle of  $0^\circ$  and tip speed ratio of 8.2. According to (1), the maximum active power of the wind turbine can be obtained at the pitch angle of  $0^\circ$  and tip speed ratio of 8.2.

Assuming the air density of 1.225, the rotor radius of 41.3 m and the generator electrical efficiency of 0.994, at the wind speed of 9 m/s, the active power in terms of the pitch angle and tip speed ratio is shown in Fig. 3. Limited by the maximum rotor speed of 18 rpm, the upper limit of the tip speed ratio is 8.6. It can be observed in Fig. 3 that the maximum active power  $P_{Max}$  of 0.204 is obtained at the pitch angle of  $0^\circ$  and tip speed ratio of 8.2.

### 2.2 Lifetime estimation

The flowchart to estimate the  $B_{10}$  lifetime of the power converter is shown in Fig. 4 [4, 6, 7]. At a constant wind speed  $v$ , the active

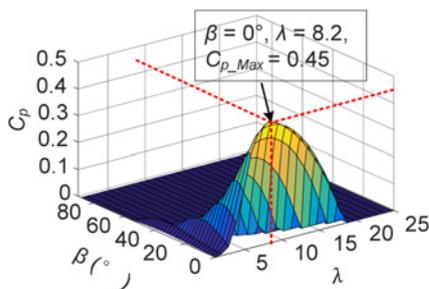


Fig. 2 Power coefficient in terms of the pitch angle and tip speed ratio [13]

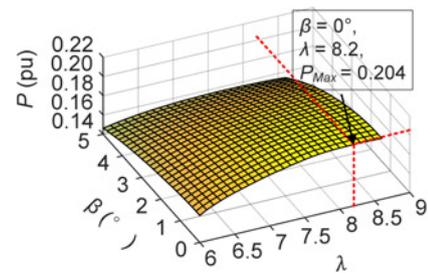


Fig. 3 Active power in terms of the pitch angle and tip speed ratio, at the wind speed of 9 m/s

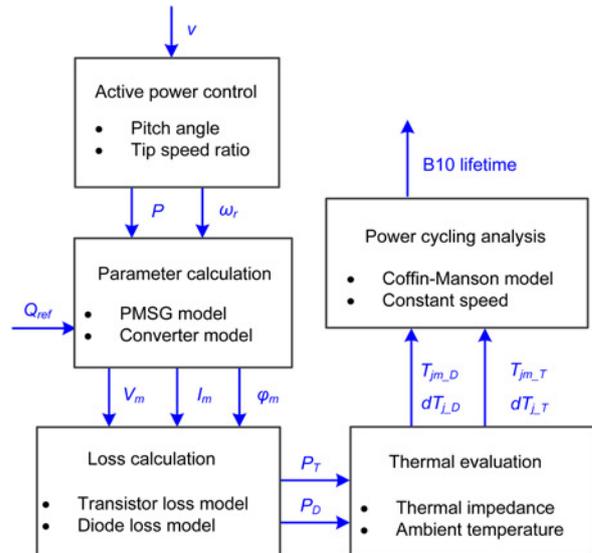


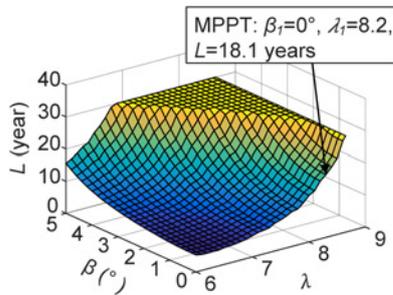
Fig. 4 Flowchart of the  $B_{10}$  lifetime estimation [4, 6, 7]

power  $P$  and the rotor speed  $\omega_r$  at a given pitch angle and tip speed ratio can be calculated by (1) and (2). Then, the voltage stress  $v_m$  and current stress  $I_m$  of the power converter can be calculated based on the PMSG model and the power converter model. In this paper, the reactive power is assumed to be 0. Then, the power loss including the conduction losses and the switching losses can be obtained [4, 7]. Afterwards, considering the thermal resistance and capacitance as well as the cooling system, the thermal profile in terms of the mean junction temperature  $T_{jm}$  and the junction temperature fluctuation  $dT_j$  can be calculated by the thermal model of the power module [4, 7]. Then, the  $B_{10}$  lifetime can be obtained from the manufacture at constant thermal stress. By using the Coffin-Manson model, it can be extended to the mean junction temperature and the junction temperature fluctuation at a certain level [4, 7]. It can be concluded that the  $B_{10}$  lifetime is determined by the pitch angle and tip speed ratio.

By assuming constant wind speed of 9 m/s, with the parameters as listed in Table 1 implemented, the  $B_{10}$  lifetime of the MSC of the 2 MW PMSG wind turbine in terms of the pitch angle and tip speed ratio is shown in Fig. 5. In Fig. 5, the  $B_{10}$  lifetime of the MSC is limited by 30 years. In case that the  $B_{10}$  lifetime of MSC is larger than 30 years, the lifetime of the wind turbine is determined by the other parts of the wind turbine components. According to (2) and (4), the upper limit of the tip speed ratio is 8.6. In Fig. 5, it can be observed, in case that the wind turbine is controlled by the MPPT method, the  $B_{10}$  lifetime is 18.1 years. By changing the pitch angle and tip speed ratio, the  $B_{10}$  lifetime can be increased to 30 years.

**Table 1** Parameters of the 2 MW PMSG wind turbine

Parameters	Value
rated mechanical power	2.0 MW
rated apparent power	2.2419 MVA
rated line-to-line voltage	690 V(rms)
rated phase voltage	398.4 V(rms)
rated stator current	1867.76 A(rms)
rated stator frequency	9.75 Hz
rated power factor	0.8921
rated rotor speed	22.5 rpm
number of pole pairs	26
rated mechanical torque	848.826 kN m
rated rotor flux linkage	5.8264 Wb (rms)
stator winding resistance, $R_s$	0.821 m $\Omega$
$d$ -axis synchronous inductance, $L_d$	1.5731 mH
$q$ -axis synchronous inductance, $L_q$	1.5731 mH
base flux linkage, $A_B$	6.5029 Wb
base impedance, $Z_B$	0.2124 $\Omega$
base inductance, $L_B$	3.4666 mH
base capacitance, $C_B$	76865.87 $\mu$ F



**Fig. 5**  $B_{10}$  lifetime of the MSC in terms of the pitch angle and tip speed ratio, at the wind speed of 9 m/s

### 2.3 Energy production maximisation

The capability of the wind turbine energy production is a function of its active power and lifetime. To maximise the energy production of the 2 MW PMSG wind turbine, the objective function can be expressed by

$$\text{Max}(E_p(P(\beta, \lambda)L_{MSC}(\beta, \lambda))) \quad (3)$$

where  $E_p$  is the energy production,  $P$  is the active power and  $L$  is the lifetime. The active power and the lifetime are all a function of the pitch angle  $\beta$  and the tip speed ratio  $\lambda$ .

Constraints

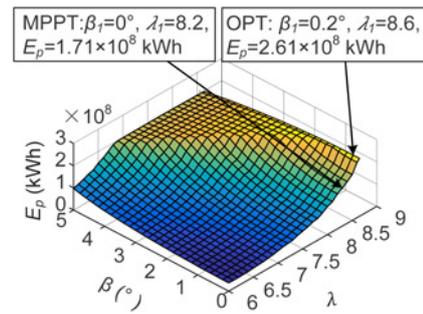
$$6 < \omega_r < 18 \quad (4)$$

$$P < 2 \times 10^6 \quad (5)$$

$$L_{MSC} < 30 \quad (6)$$

where the lower and upper limits of the rotor speed  $\omega_r$  are 6 and 18 rpm, respectively. The maximum active power is the rated power 2 MW. The  $B_{10}$  lifetime of MSC is limited by 30 years.

At the constant wind speed 9 m/s, the energy production of the 2 MW PMSG wind turbine in terms of the pitch angle and tip speed ratio is shown in Fig. 6. According to (2) and (4), the upper limit of the tip speed ratio is 8.6. In Fig. 6, it can be observed that the maximum energy production is  $2.61 \times 10^8$  kWh obtained at the pitch angle of  $0.2^\circ$  and the tip speed ratio of 8.6. Compared with the energy production of  $1.71 \times 10^8$  kWh controlled



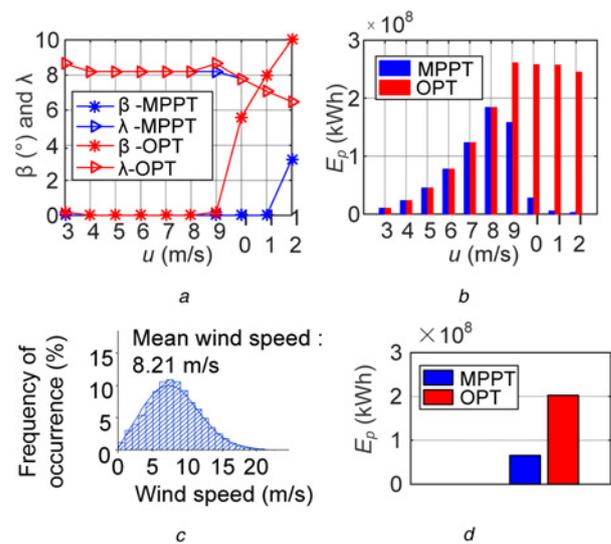
**Fig. 6** Energy production capability in terms of the pitch angle and tip speed ratio, at the constant wind speed of 9 m/s

by the MPPT method, 52.63% of energy production capability can be increased.

By the exhausted search method, the optimal pitch angle and tip speed ratio of the 2 MW PMSG wind turbine at the constant wind speeds from 3 to 12 m/s are selected and shown in Fig. 7a. The energy production of the 2 MW wind turbine is compared between the MPPT method and the proposed method in Fig. 7b. In Fig. 7b, it can be observed, the energy production can be significantly increased at the wind speed of 9 m/s and higher. At the lower wind speeds, controlled by the MPPT method, the lifetime of the MSC has reached to 30 years. The maximum energy production of the wind turbine is obtained by the MPPT method. With the annual wind speed distribution as shown in Fig. 7c adopted, the energy production capability of the wind turbine is shown in Fig. 7d. It can be observed that the energy production capability of the wind turbine can be significantly increased by the proposed method.

### 3 Energy production maximisation in a two-turbine wind farm

In this section, taking into account the wake effect, the energy production of a two-turbine wind farm equipped with the above mentioned PMSG wind turbine is maximised by optimising the pitch



**Fig. 7** Comparison between the MPPT method and the proposed method for a single wind turbine

- a Pitch angle and tip speed ratio at constant wind speeds
- b Energy production capability at constant wind speeds
- c Annual wind speed distribution
- d Annual energy production capability

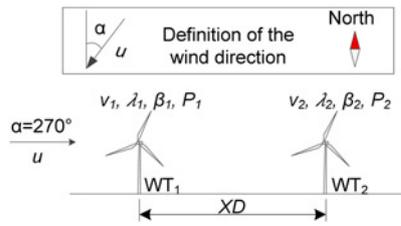


Fig. 8 Layout of the two-turbine wind farm

angle and tip speed ratio of each wind turbine. The layout of the wind farm is shown in Fig. 8. The distance between the two wind turbines is 6.5 rotor diameters.

### 3.1 Wake effect

In a wind farm, the upstream wind turbine causes the wind speed deficit to the downstream wind turbines. In this paper, the downstream wind speed deficit is estimated by one of the widely implemented Katic wake model, which is based on the momentum conversation theory [14].

As it is shown in Fig. 9, at the wind direction of  $270^\circ + \varphi$  and the ambient wind speed  $u$ , the wind speed of WT<sub>1</sub> is the same as the ambient wind speed. The Katic wake model estimates the wind speed of WT<sub>2</sub> by [12]

$$1 - \frac{v_2}{u} = \left(1 - \sqrt{1 - C_{t,1}(\beta_1, \lambda_1)}\right) \times \left(\frac{D}{D + 2kXD \cos(\varphi)}\right)^2 \frac{A_{ol,12}}{A_r} \quad (7)$$

where  $v_2$  is the wind speed of WT<sub>2</sub>,  $C_{t,1}$  is the thrust coefficient of WT<sub>1</sub>, which is a function of the pitch angle and tip speed ratio of WT<sub>1</sub>  $\beta_1$  and  $\lambda_1$ ,  $D$  is the rotor diameter,  $XD$  is the distance between the two turbines,  $A_{ol,12}$  is the overlap area between the wake area of WT<sub>1</sub> and the rotor sweep area of WT<sub>2</sub>,  $A_r$  is the rotor sweep area of WT<sub>2</sub> and  $k$  is the decay constant. In this paper, the typical decay constant of 0.04 for offshore recommended in the Wind Atlas Analysis and Application Program-WASP help facility [15] is implemented.

The thrust coefficient of the 2 MW PMSG wind turbine in terms of the pitch angle and tip speed ratio is shown in Fig. 10 [13]. At the wind direction of  $270^\circ$  and the ambient wind speed of 9 m/s, the wind speed of WT<sub>2</sub> in terms of the pitch angle and tip speed ratio of WT<sub>1</sub> calculated by (7) is shown in Fig. 11. In Fig. 11, it can be observed that the wind speed of WT<sub>2</sub> can be increased by increasing the pitch angle of WT<sub>1</sub> or reducing the tip speed ratio of the WT<sub>1</sub>. In the two-turbine wind farm, the wind speed deficit of WT<sub>2</sub> appears in the wind direction range of  $264\text{--}276^\circ$ . The wind speed deficit of WT<sub>1</sub> appears in the wind direction range of  $84\text{--}96^\circ$ .

### 3.2 Energy production maximisation

In the two-turbine wind farm, there is no wind speed deficit on both WT<sub>1</sub> and WT<sub>2</sub> at the wind direction ranges of  $0\text{--}83^\circ$ ,  $97\text{--}263^\circ$  and

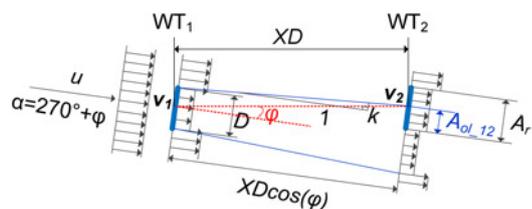


Fig. 9 Katic wake model [12, 14]

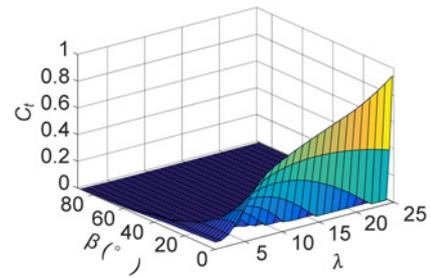


Fig. 10 Thrust coefficient in terms of the pitch angle and tip speed ratio [13]

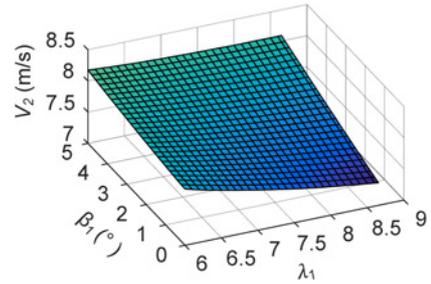


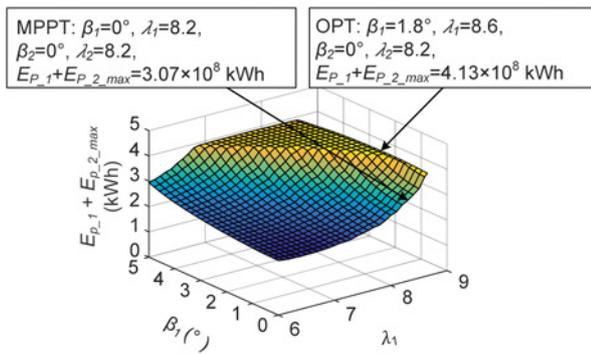
Fig. 11 Wind speed of WT<sub>2</sub> in terms of the pitch angle and tip speed ratio of WT<sub>1</sub>, at the wind direction of  $270^\circ$  and the ambient wind speed of 9 m/s

$277\text{--}360^\circ$ . At these wind directions, the maximum energy production of the wind farm is obtained at the maximum energy production of WT<sub>1</sub> and the maximum energy production of WT<sub>2</sub>. The optimal pitch angle and tip speed ratio of WT<sub>1</sub> and WT<sub>2</sub> can be selected separately and are the same as they are shown in Fig. 7a.

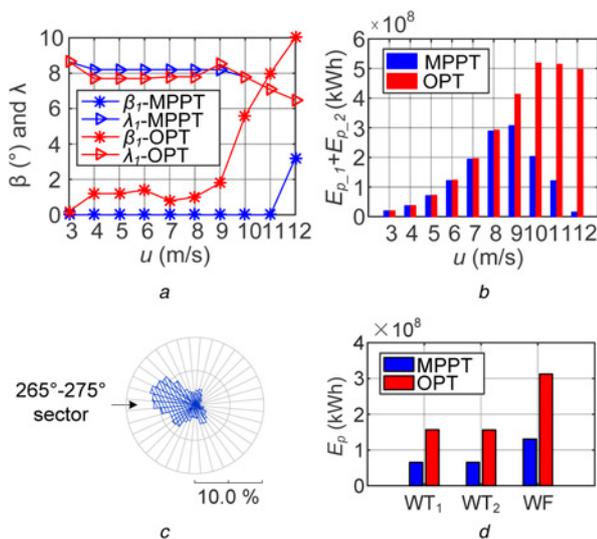
At the wind directions in the range of  $264\text{--}276^\circ$  and at a constant ambient wind speed, to maximise the energy production of the wind farm, there are four control parameters to be optimised, which are the pitch angle and tip speed ratio of WT<sub>1</sub> and WT<sub>2</sub>. At these wind directions, the active power of WT<sub>1</sub>, the MSC lifetime of WT<sub>1</sub> and the wind speed of WT<sub>2</sub> are all determined by the pitch angle and tip speed ratio of WT<sub>1</sub>. At each set of pitch angle and tip speed ratio of WT<sub>1</sub>, the energy production of WT<sub>1</sub> is a fixed value, and the maximum energy production of the wind farm is obtained at the maximum energy production of WT<sub>2</sub>. If the WT<sub>2</sub> is controlled by the optimised pitch angle and tip speed ratio which objects to maximise the energy production of WT<sub>2</sub> as they are shown in Fig. 7a, the maximum energy production of the wind farm can be obtained by optimising the pitch angle and tip speed ratio of WT<sub>1</sub>. Thus, the maximum energy production of the wind farm can be optimised by selecting the optimal pitch angle and tip speed ratio of WT<sub>1</sub>, while the optimal pitch angle and tip speed ratio of WT<sub>2</sub> are the same as they are shown in Fig. 7a.

At the wind direction of  $270^\circ$  and the ambient wind speed of 9 m/s, with the optimal pitch angle and tip speed ratio of WT<sub>2</sub> as they are shown in Fig. 7a implemented, the sum of the energy production of WT<sub>1</sub> and the maximum energy production of WT<sub>2</sub> in terms of the pitch angle and tip speed ratio of WT<sub>1</sub> are shown in Fig. 12. It can be observed that the maximum energy production of the wind farm is obtained at the  $1.8^\circ$  pitch angle and the 8.6 tip speed ratio of WT<sub>1</sub>.

By the exhausted search method, the optimised pitch angle and tip speed ratio of WT<sub>1</sub> at the wind speeds from 3 to 12 m/s is shown in Fig. 13a. The energy production of the wind farm is compared between the MPPT method and the proposed method in Fig. 13b. In Fig. 13b, it can be observed that the energy production capability of the wind farm is significantly increased at the wind speeds from 9 to 12 m/s. At the wind speeds from 3 to 8 m/s, the lifetime of WT<sub>1</sub> and WT<sub>2</sub> are both reached to 30 years. However,



**Fig. 12** Energy production of the wind farm in terms of the pitch angle and tip speed ratio of WT<sub>1</sub>, at the wind direction of 270° and ambient wind speed of 9 m/s



**Fig. 13** Comparison between the MPPT method and the proposed method for the two-turbine wind farm

- a Pitch angle and tip speed ratio of WT<sub>1</sub> at constant wind direction of 270° and constant wind speeds
- b Energy Production of the wind farm at constant wind direction of 270° and various wind speeds
- c Annual wind direction distribution
- d Annual energy production capability of the wind farm

the wind speed of WT<sub>2</sub> can be increased by larger pitch angle of WT<sub>1</sub>, which results in the active power increase of the WT<sub>2</sub>. Thus, the energy production capability of the wind farm can also be increased.

At the wind directions in the range of 264–276° and 84–96°, the optimal pitch angle and tip speed ratio of WT<sub>1</sub> and WT<sub>2</sub> can be selected by the same method as at the wind direction of 270°. With the annual wind direction distribution as shown in Fig. 13c and the annual wind speed distribution as shown in Fig. 7c adopted, the energy production capability of the WT<sub>1</sub>, WT<sub>2</sub> and the wind farm are shown in Fig. 13d. It can be observed the energy production capability of the wind farm can be significantly increased by the proposed method. As the wind speed deficit due to the wake effect just occurs at the rose sectors of 85–95° and 265–275°, the energy production capabilities of WT<sub>1</sub> and WT<sub>2</sub> are close to each other.

#### 4 Conclusions

In this work, an optimal active power control method is proposed to maximise the energy production in the PMSG wind turbine based

wind farm. For a single wind turbine, its active power and lifetime are both determined by the pitch angle and tip speed ratio. Compared with the MPPT method, by changing the pitch angle and tip speed ratio, the active power of the wind turbine will be reduced. However, the lifetime of the MSC can be increased. Thus, the energy production capability of the wind turbine, which is a function of the active power and the lifetime, can be increased.

As the MSC of the PMSG wind turbine has the most failure rate compared with the other parts of the wind turbine components, in this paper, the lifetime of the wind turbine is represented by the lifetime of the MSC. The lifetime of the MSG is limited by 30 years. In case that the MSG lifetime is higher than 30 years, the lifetime of the wind turbine is assumed to be determined by the lifetime of the other parts of the wind turbine components.

For the 2 MW PMSG wind turbine, controlled by the MPPT method, the lifetime of MSC has reached to 30 years at the lower wind speeds. The maximum energy production is obtained at the maximum active power. Thus, controlled by the MPPT method, the maximum energy production of the wind turbine has been reached. The energy production cannot be further increased. However, at higher wind speeds, the energy production of the wind turbine can be significantly increased due to the increase of the MSC lifetime.

In a wind farm, the upstream wind turbine causes the wind speed deficit to its downstream wind turbines. The downstream wind speed deficit is also determined by the pitch angle and tip speed ratio of the upstream wind turbine. As the wind speed of the downstream wind turbine can be increased by changing the pitch angle and tip speed ratio of the upstream wind turbine, the active power and the energy production of the wind farm can be increased at both of the lower wind speed and the higher wind speeds.

This optimisation method is studied on a single wind turbine and in a two-turbine wind farm. However, the proposed method can be implemented in any layout wind farm and at any wind directions and ambient wind speeds. The real wind profile can also be implemented in this proposed method.

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