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RESEARCH ARTICLE

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Application of fuzzy logic control algorithm as stator power controller of a grid-connected doubly-fed induction generator

Abstract This paper discusses the power outputs control of a grid-connected doubly-fed induction generator (DFIG) for a wind power generation systems. The DFIG structure control has a six diode rectifier and a PWM IGBT converter in order to control the power outputs of the DFIG driven by wind turbine. So, to supply commercially the electrical power to the grid without any problems related to power quality, the active and reactive powers (P_s, Q_s) at the stator side of the DFIG are strictly controlled at a required level, which, in this paper, is realized with an optimized fuzzy logic controller based on the grid flux oriented control, which gives an optimal operation of the DFIG in sub-synchronous region, and the control of the stator power flow with the possibility of keeping stator power factor at a unity.

Keywords doubly-fed induction generator (DFIG), vector control, fuzzy logic controller, optimization, power factor unity, active and reactive power

1 Introduction

Recently, the doubly-fed induction generator (DFIG) is becoming the main configuration of wind power generation because of its unique advantages. Vector control strategy is used to control the generator, and the rotor of the DFIG is connected to an AC excitation of which the frequency, phase, and magnitude can be adjusted [1]. With the DFIG, generation can be accomplished in variable speed ranging from sub-synchronous speed to super-synchronous speed (±30% around the synchronous speed) [1,2]. So to exploit these advantages in the wind power generation area, a strategy of control should be made by taking into account the structure complexity of the DFIG and the quality of energy to be generated, because of the lack or scarcity of control of the produced active and reactive powers, many problems arise, when the generator is connected to the grid, such as the low power factor and harmonic pollutions.

Several designs and arrangements have been investigated by using predictive functional and internal mode controller, where a satisfactory power response is obtained in compared comparison with the ones of the power response of traditional method when the conventional PI controlleris uxed. However, it is hard to implement one, due to their complicated structures [3]. An alternative approach has been proposed in this paper using an optimized fuzzy logic controller to control the active and reactive powers through the rotor circuit, so we have taking preferred this type of controller (fuzzy) under many benefits which it has, like [4]:

1) Fuzzy controllers are more robust than PI controllers because they can cover a much wider range of operating conditions, and can operate with noise and disturbances of different natures.

2) Developing a fuzzy controller is cheaper than developing a model-based or other controller.

3) Fuzzy controllers are customizable, since it is easier to understand and modify their rules, which not only use a human operator's strategy but also are expressed in natural linguistic terms.

4) It is easy to learn the operation of fuzzy controllers and the design and application of them to a concrete application.

So to achieve this control objective, an adopted structure of control is needed as presented in Fig. 1, when a wound-rotor induction generator fed with variable frequency rotor voltage is used. This allows the fixed-frequency electric power to be extracted from the stator of the DFIG. One of

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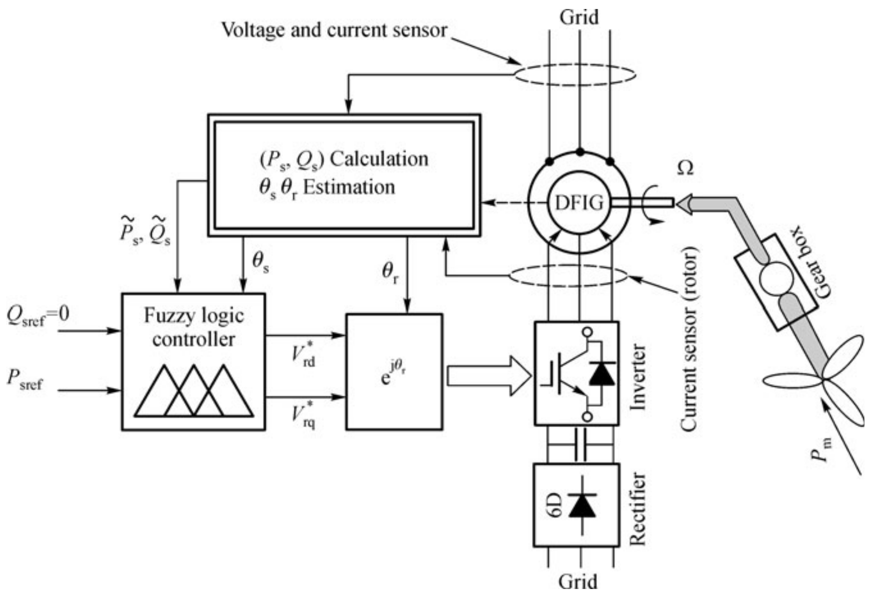

Fig. 1 DFIG structure control

the main advantages of this structure of control is that, if the rotor current is well governed, applying a grid-flux-oriented vector control (see Fig. 2 for the design of transformation angles) to the commercial machine side rotor IGBT PWM converter, a decoupled control of stator side active and reactive power will simply be achieved [1].

The work presented in this paper is used in exploitation of the fuzzy logic theory when an optimized fuzzy logic controller is designed in order to regulate the stator active and reactive powers flow of a DFIG connected to a powerful grid [5].

2 Model of a doubly-fed induction machine

The complex DFIM model in the synchronous reference frame is written as follows [3]:

The voltage equations are

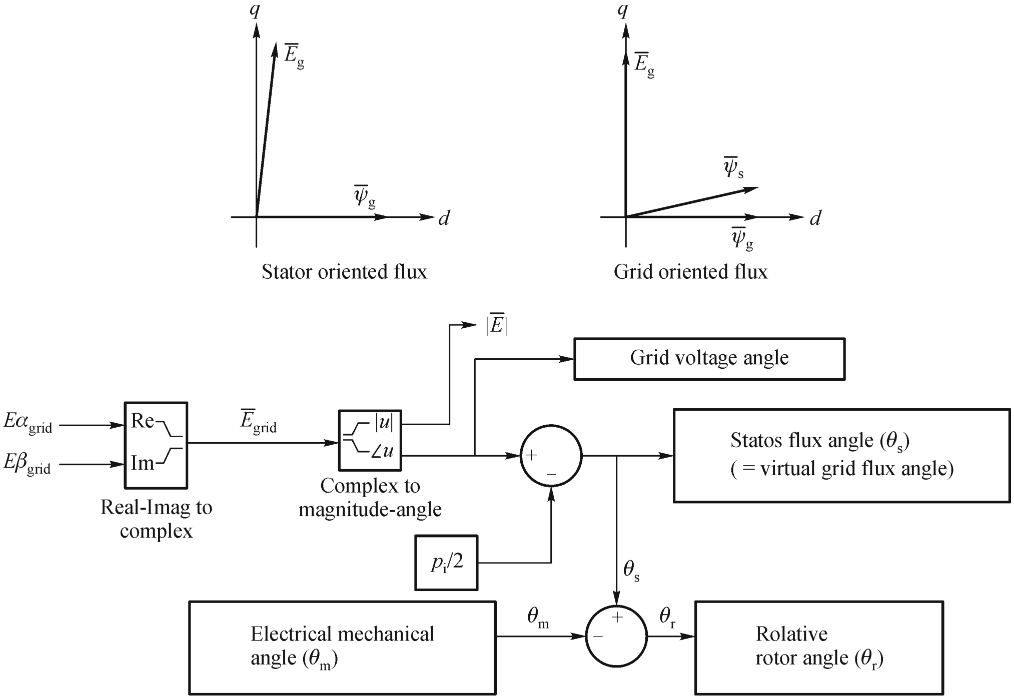

Fig. 2 Oriented flux and angle calculation

$$\overline{V}_{\mathrm{s}} = R_{\mathrm{s}}\bar{i}_{\mathrm{s}} + \frac{\mathrm{d}\overline{\Phi}_{\mathrm{s}}}{\mathrm{d}t} + \mathrm{j}\omega_{\mathrm{s}}\overline{\Phi}_{\mathrm{s}},$$

$$\overline{V}_{\mathrm{r}} = R_{\mathrm{r}}\bar{i}_{\mathrm{r}} + \frac{\mathrm{d}\overline{\Phi}_{\mathrm{r}}}{\mathrm{d}t} + \mathrm{j}(\omega_{\mathrm{s}} - \omega)\overline{\Phi}_{\mathrm{r}}. \tag{1}$$

The current-flux equations are

$$\overline{\Phi}_{\mathrm{s}} = L_{\mathrm{s}}\bar{i}_{\mathrm{s}} + M\bar{i}_{\mathrm{r}}, \overline{\Phi}_{\mathrm{r}} = L_{\mathrm{r}}\bar{i}_{\mathrm{r}} + M\bar{i}_{\mathrm{s}}. \tag{2}$$

The electromagnetic torque expression is

$$C_{\mathrm{em}} = \frac{3}{2}M\mathrm{Im}\left(\bar{i}_{\mathrm{s}} \otimes \bar{i}_{\mathrm{s}}^{*}\right). \tag{3}$$

The stator power expressions are

$$\begin{aligned} P_{\mathrm{s}} &= \mathrm{Re}\left(\overline{V}_{\mathrm{s}} \otimes \bar{i}_{\mathrm{s}}^{*}\right), \\ Q_{\mathrm{s}} &= \mathrm{Im}\left(\overline{V}_{\mathrm{s}} \otimes \bar{i}_{\mathrm{s}}^{*}\right). \end{aligned} \tag{4}$$

3 Vector control strategy

To simplify calculations, let us consider the stator voltage constraint and the method of angles calculation given as follows [6]:

In *dq*-axis, there is

$$\begin{aligned} V_{\mathrm{ds}} &= 0, \\ V_{\mathrm{qs}} &= V_{\mathrm{s}}. \end{aligned} \tag{5}$$

If the virtual grid flux vector $\overline{E}_{\mathrm{g}}$ is aligned on the d axis (Fig. 2), it is found that

$$\begin{aligned} \Phi_{\mathrm{ds}} &= L_{\mathrm{s}}i_{\mathrm{ds}} + Mi_{\mathrm{dr}} = Mi_{\mathrm{ms}}, \\ 0 &= L_{\mathrm{s}}i_{\mathrm{qs}} + Mi_{\mathrm{qr}}. \end{aligned} \tag{6}$$

Substitute Eq. (6) into Eq. (2), it is found that

$$\begin{aligned} \Phi_{\mathrm{dr}} &= \sigma L_{\mathrm{r}}i_{\mathrm{dr}} + \frac{M}{L_{\mathrm{s}}}i_{\mathrm{ms}}, \\ \Phi_{\mathrm{qr}} &= \sigma L_{\mathrm{r}}i_{\mathrm{qr}}, \end{aligned} \tag{7}$$

where σ is the dispersion factor.

$$\sigma = 1 - \frac{M^2}{L_{\mathrm{s}}L_{\mathrm{r}}}.$$

The electromagnetic torque becomes

$$C_{\mathrm{em}} = -P\frac{M}{L_{\mathrm{r}}}i_{\mathrm{ms}}i_{\mathrm{qr}}. \tag{8}$$

Similarly, suppose that the stator resistance is neglected ($V_{\mathrm{sn}} \approx \mathrm{d}\Phi_{\mathrm{sn}}/\mathrm{d}t$), it is found that

$$V_{\mathrm{s}} = \omega_{\mathrm{s}}\Phi_{\mathrm{s}} = \omega_{\mathrm{s}}Mi_{\mathrm{ms}}. \tag{9}$$

Then the stator active and reactive power expressions become

$$\begin{aligned} P_{\mathrm{s}} &= -k_{\mathrm{t}}\omega_{\mathrm{s}}\frac{M^2}{L_{\mathrm{r}}}i_{\mathrm{ms}}i_{\mathrm{qr}}, \\ Q_{\mathrm{s}} &= k_{\mathrm{t}}\omega_{\mathrm{s}}\frac{M^2}{L_{\mathrm{r}}}i_{\mathrm{ms}}(i_{\mathrm{ms}} - i_{\mathrm{dr}}). \end{aligned} \tag{10}$$

The stator powers are decoupled and they are dependents to the components rotor currents [7].

Substitute Eq. (7) into Eq. (1), the flowing equations can be obtained:

$$\begin{aligned} V_{\mathrm{dr}} &= R_{\mathrm{r}}i_{\mathrm{dr}} + \sigma L_{\mathrm{r}}\frac{\mathrm{d}i_{\mathrm{dr}}}{\mathrm{d}t} + \frac{M^2}{L_{\mathrm{s}}}\frac{\mathrm{d}i_{\mathrm{ms}}}{\mathrm{d}t} - \omega_{\mathrm{r}}\sigma L_{\mathrm{r}}i_{\mathrm{qr}}, \\ V_{\mathrm{qr}} &= R_r i_{\mathrm{qr}} + \sigma L_{\mathrm{r}}\frac{\mathrm{d}i_{\mathrm{qr}}}{\mathrm{d}t} + \omega_{\mathrm{r}}\frac{M^2}{L_{\mathrm{s}}}i_{\mathrm{ms}} + \omega_{\mathrm{r}}\sigma L_{\mathrm{r}}i_{\mathrm{dr}}. \end{aligned} \tag{11}$$

The above equations are coupled between themselves, so the coupling terms are considered as disturbances which will be removed [7,8].

In this paper, an optimized fuzzy logic controller is proposed and designed in order to control the stator powers flow with desired performances. This controller is chosen because of its competence in control and its simplicity in implantation [9].

4 Fuzzy logic controller design

The classical design scheme contains the following steps [4]:

1) Define the input and control variables — determine which states of the process shall be observed and which control actions are to be considered;

2) Define the condition interface — fix the way in which observations of the process are expressed as fuzzy sets;

3) Design the rule base — determine which rules are to be applied under which conditions;

4) Design the computational unit — supply algorithms to perform fuzzy computations which will generally lead to fuzzy outputs;

5) Determine rules according to which fuzzy control statements can be transformed into crisp control actions.

The typical structure of the fuzzy controller is depicted in Fig. 3. For the design of this fuzzy controller, the following steps should be tracked:

First, the variables which can be measured are chosen which become the inputs of the controller, as shown in Fig. 4. Next, the inputs are fuzzified, and the output is defuzzified. Finally, a nine classes of functions are applied for each of them to build the membership functions given in Fig. 5.

Because the fuzzy controller has two inputs and one output, its rule table is written as listed in Table 1 [9].

The two blocs named normalization and denormalization algorithms are a mathematical algorithms based on

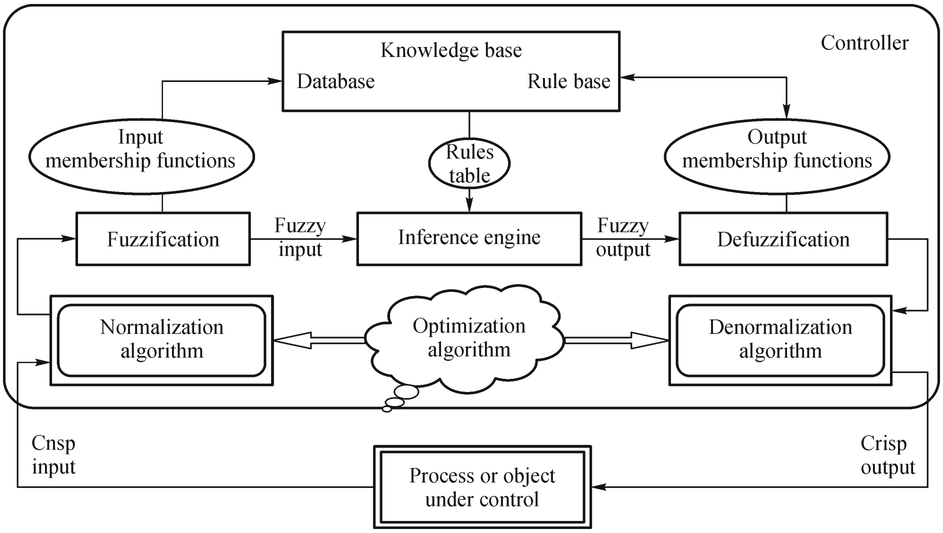

Fig. 3 Fuzzy controller interne structure

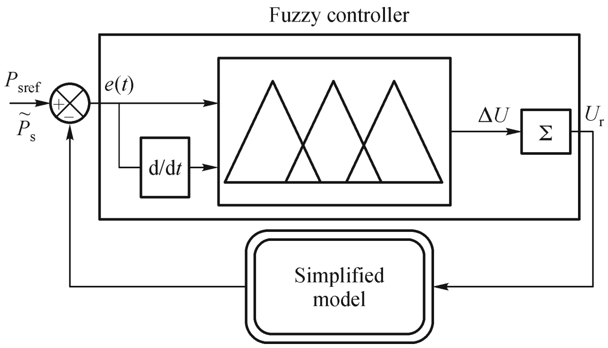

Fig. 4 Block diagram of DFIG control scheme

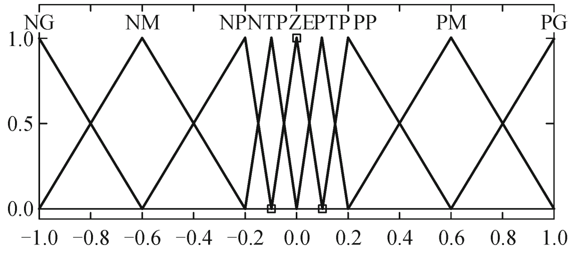

Fig. 5 Membership functions for inputs and output

geometrical notions which boost and optimize the work of the fuzzy controller through the just conversion between the real and fuzzy values.

5 Simulation results

5.1 Setpoint profiles

The machine data are given in appendix. In order to validate the approach, a digital simulation has been conducted using the Matlab/Simulink® software, where the quality of a control system is often judged by observing the system response and its parameters. Hence the obtained results are organized respectively according to the following specifications. When the speed is fixed at 151.83 rad/s, the active power is varied between −2, −7.5 and −5.5 kW respectively at 1, 2 and 4 s. The reactive power is fixed at 0VAR. After that we try to see better the ability and robustness of optimized fuzzy controller under an abnormal conditions such as the incertitude parameters, which often can be in the rotor and stator resistances due to the overheating of the DFIG coils.

5.2 Setpoint responses

By observing the responses of the stator active power and those of the reactive power (Fig. 6), theirs stability (which is usually the most important issue to examine in determining the quality of the responses of a system) and performance evaluations can be observed, from where the good tracking of theirs setpoints can be observes clearly which reflect the well dynamics of the system, responding to the changes of the inputs. This judgment comes from the good values of the performance indicators such as the overshoot, rise time, and the settle time. It can also be seen that the stator power factor (Fig. 7) is easily maintained to unity. It is noted that the stator voltage and current (Fig. 8) are in opposite phases, which shows that the machine is operating in generation mode ($\cos\varphi = -1$).

5.3 Test of control robustness

Figure 9 displays the stator active and reactive power response while Fig. 10 demonstrates the stator power factor. These two figures indicate that the stator and rotor parameter variations do not have a notable effect on the

Table 1 Rule table of the fuzzy controller

E, ΔU_r, dE	NG	NM	NP	NTP	ZE	PTP	PP	PM	PG
NG	NG	NG	NG	NG	NG	NM	NP	PTP	ZE
NM	NG	NG	NG	NG	NM	NP	PTP	ZE	PTP
NP	NG	NG	NG	NM	NP	PTP	ZE	PTP	PP
NTP	NG	NG	NM	NP	PTP	ZE	PTP	PP	PM
ZE	NG	NM	NP	PTP	ZE	PTP	PP	PM	PG
PG	NM	NP	PTP	ZE	PTP	PP	PM	PG	PG
PM	NP	PTP	ZE	PTP	PP	PM	PG	PG	PG
PP	PTP	ZE	PTP	PP	PM	PG	PG	PG	PG
PTP	ZE	PTP	PP	PM	PG	PG	PG	PG	PG

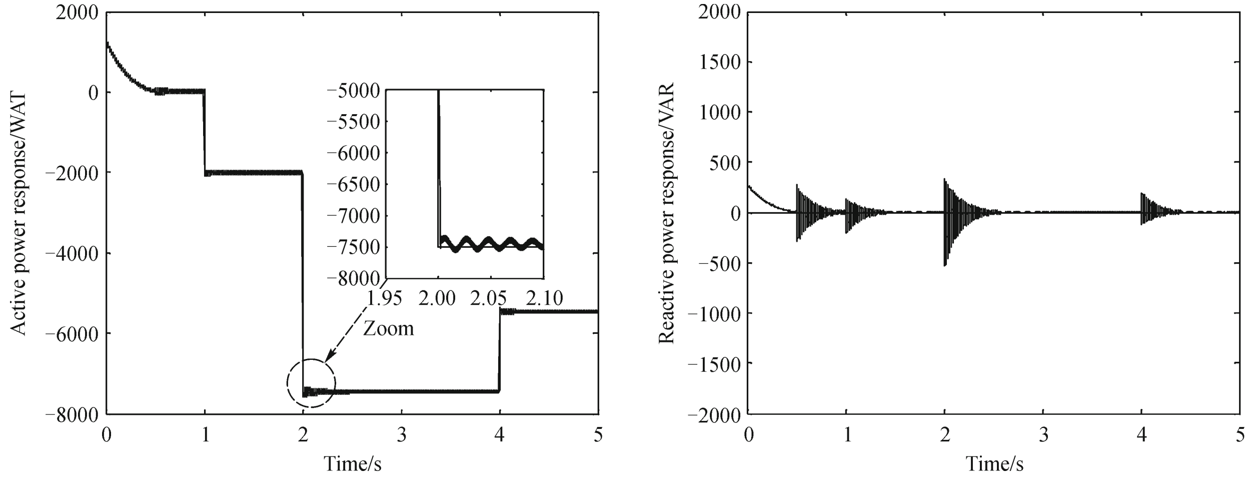

Fig. 6 Stator active (WAT) and reactive power (VAR) response

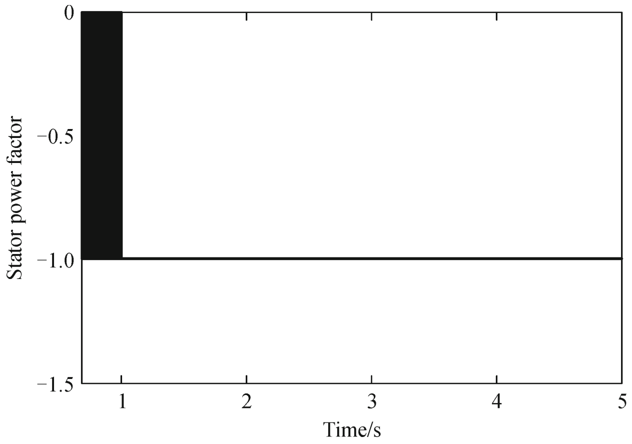

Fig. 7 Stator power factor

stator active and reactive power responses. This means that the optimized fuzzy controller is very robust which confirms that the adopted structure of control can operate under special conditions such as uncertainty parameters and instantaneous setpoint changes.

6 Conclusions

The DFIM double accessibility is an important advantage. This induces good control of the power flow between the machine and the grid permitting the injection of the power such that the grid power factor is close to unity. In this paper, a vector control strategy has been investigated based on the oriented grid flux intended for the DFIG, which can control the stator active and reactive powers independently with desired performances as stability and robustness of the global structure. The vector control is achieved using an optimized fuzzy controller. The controller is designed by taking into account the similarity of the conventional PI controller actions but with some optimization in order to approve and ameliorate its behavior. The obtained results demonstrate that the proposed DFIG system control based

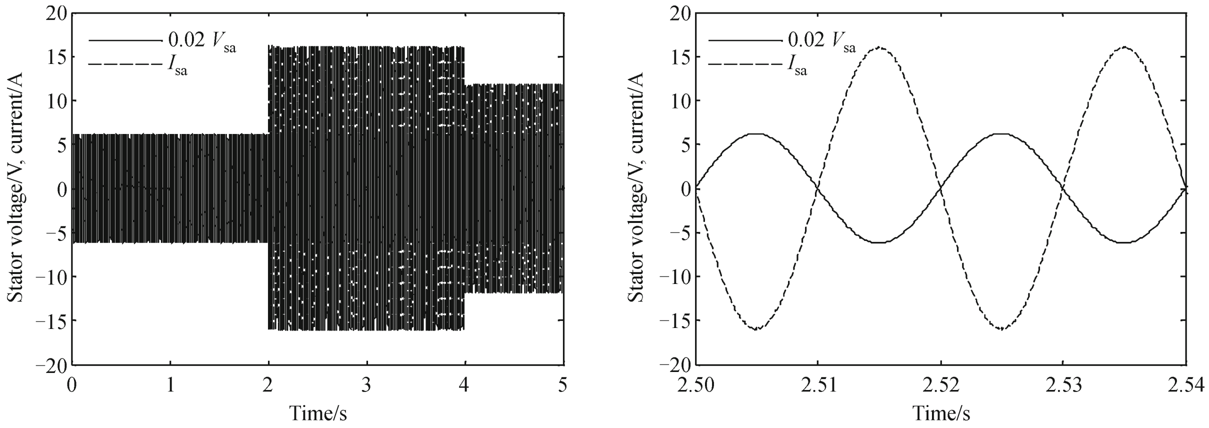

Fig. 8 Stator voltage (V) and current (A)

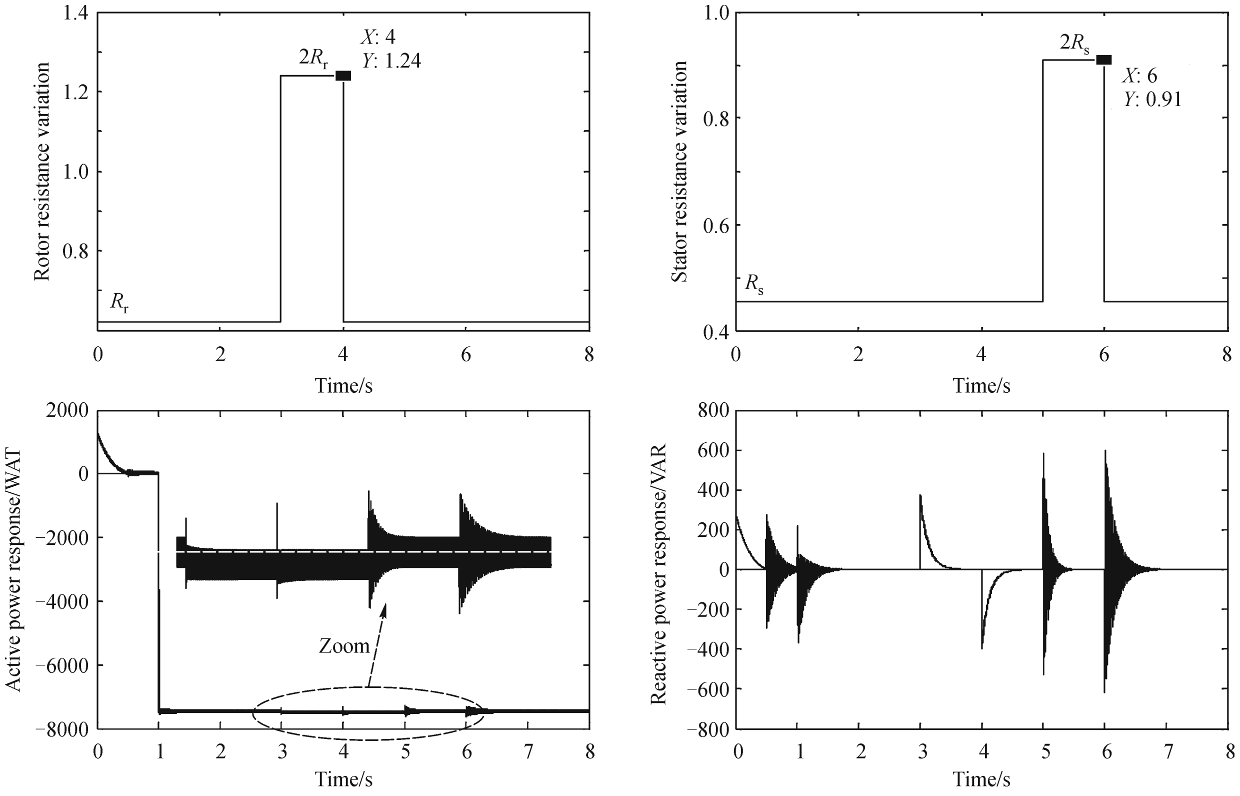

Fig. 9 Stator active (WAT) and reactive (VAR) power responses

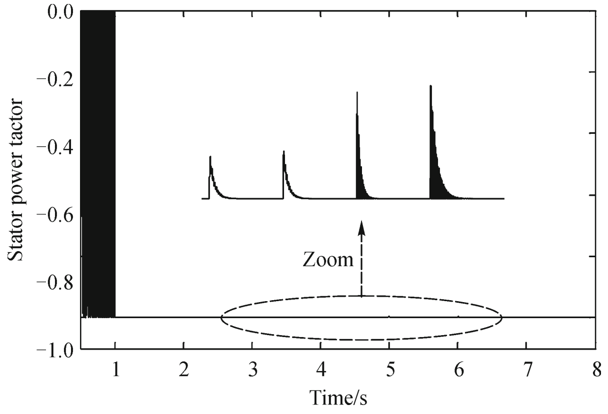

Fig. 10 Stator power factor

on the optimized fuzzy logic controller may be considered as an interesting solution in the wind power generation area.

Appendix

The machine parameters are listed in Table 2.

Table 2 Machine parameters

Parameter	Value
Output power P_n/kW	7.5
Stator resistance R_s/Ω	0.455
Rotor resistance R_r/Ω	0.62

(*Continued*)

Parameter	Value
Stator inductance L_s/H	0.084
Rotor inductance L_r/H	0.081
Mutual inductance M_{sr}/H	0.078
Number of poles	4
Inertia moment $J/(\mathrm{N\cdot m\cdot s^2})$	0.3125
Rubbing factor F	$6.73e^{-3}$

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