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Application of Fuzzy PI Control Algorithm as Stator Power Controller of a Double-Fed Induction Machine in Wind Power Generation Systems

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ABSTRACT

This paper addresses the output control of a utility-connected double-fed induction machine (DFIM) for wind power generation systems (WPGS). DFIM has a back-to-back converter to control outputs of DFIM driven by the wind turbine for WPGS. To supply commercially the power of WPGS to the grid without any problems related to power quality, the real and reactive powers (PQ) at the stator side of DFIM are strictly controlled at the required level, which in this paper is realized with the Fuzzy PI controller based on the field orientation control. For the Sinusoidal Pulse Width Modulation (SPWM) converter connected to the rotor side of DFIG to maintain the controllability of PQ at the state side of DFIM, the DC voltage of the DC link capacitor is also controlled at a certain level with the conventional Proportion-Integral (PI) controller of the real power. In addition, the power quality at the grid connected to the rotor side of DFIM through the back-to-back converter is maintained in a certain level with a PI controller of the reactive power. The controllers for the PQ at the stator side of DFIM, the DC link voltage of the back-to-back inverter and the reactive power at the grid connected to the rotor side of DFIM are designed and simulated in the PSIM program, of which the result verifies the performance of the proposed controllers.

Keywords: Wind power generation system, Double-fed induction machine, SPWM converter, Vector control, PQ control, DC voltage control, Fuzzy PI control, PSIM simulation

1. Introduction

Recently, due to the environmental issues and the high price of oil, research has been focusing on the development of wind power generation systems (WPGS). The key devices for WPGS are the wind turbine to convert the wind power to mechanical power, the generator to convert the mechanical power to the electric power and the controller to extract maximum power available from the wind. Many types of electric machines have been considered as candidates for the generator. Double-fed induction machine (DFIM) is one of them.

A Saber simulation study of the back-to-back converter for DFIM of WPGS was reported to prove the independent control of the real and reactive powers at the stator side of the DFIM [1]. FACT capability of the grid side converter of DFIM to enhance power quality of the distribution

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network was studied in a MATLAB/Simulink simulation study [2]. A PACAD simulation and laboratory test with 2[hp] wound rotor induction machine driven by a 2[hp] dc motor reported that the back-to-back PWM converter of DFIM regulates the real and reactive powers independently [3].

Sensorless position estimation of DFIM to obtain the decoupled control of the stator active and reactive powers was studied [4-6]. A Cycloconverter[7], SCR converter[8] and four-quadrant IGBT converter[9] were studied for WPGS. An active filtering application of DFIM in WPGS connected to the diode rectifier as a nonlinear load was studied[10]. A doubly-excited brushless reluctance machine for WPGS was studied due to the potential of high efficiency, good flexibility and low cost of the machine[11]. Some in the mentioned studies were verified with the implementation of laboratory test models[3,4,5,6] due to the difficulty of applying the proposed research to the real WPGS. Others were verified only with the simulation results[1,2,8,12].

In the previous studies accompanying the detailed analysis of the DFIM[13,14], the conventional PID control was adopted as the error amplifier of the feedback loop. The conventional PID control has been known to have difficulty dealing with dynamic speed tracking, parameter variations and load disturbance. Fuzzy control with the easy linguistic implementation is one of the alternatives to overcome the difficulties of the conventional PID control.

Motivated by the successful applications of the fuzzy control method to the three-phase current-controlled voltage source inverter [15,16], this paper proposes the simple fuzzy PI control algorithm to control the stator active and reactive powers of DFIM independently. The Sinusoidal PWM (SPWM) converter is used for the grid/rotor converters of the back-to-back converter. The SPWM converter has a 10[kHz] switching frequency. The fuzzy PI control algorithm for DFIM in WPGS is tested in the PSIM simulation program with the dynamic linking library developed with a C program. The results show the satisfactory performance of the fuzzy PI controller designed without the detailed small signal modeling of WPGS.

2. Wind Power Generation System with Double-Fed Induction Machine

Fig. 1 shows a wind power generation system (WPGS) with a double-fed induction machine (DFIM) as a generator, a back-to-back converter as a power flow controller and a WPGS optimum controller. The WPGS

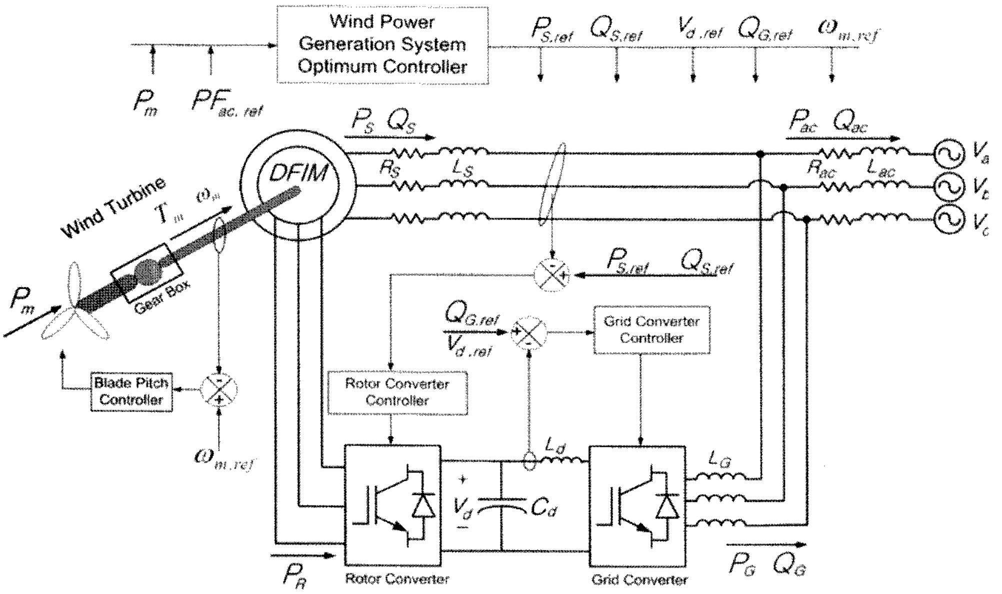


Fig. 1 Wind power generation system with double-fed induction machine as a generator

optimum controller calculates the best operating condition of the WPGS from the given wind speed and the power requirement of the power system. It consists of 3 sub controllers: The grid converter controller, the rotor converter controller, and the blade pitch controller. The grid converter controller regulates the magnitude of DC link voltage V_d and the reactive power Q_G at the grid side. The rotor converter controller controls the real power P_s and the reactive power Q_s at the stator side. The blade pitch controller controls the rotor at the mechanical rotor speed $\omega_{m,ref}$ given by the Maximum Power Point Tracking (MPPT). The control strategy of the WPGS optimum controller and the blade pitch controller are omitted in this paper because it is beyond the present research's scope.

The back-to-back converter has two SPWM converters, a DC link capacitor as a voltage source and an inductor as a smoothing reactor. The one side of the converter is connected to the rotor of DFIM and the other side is connected to the gird. The rotor converter controls the real power P_S and the reactive power Q_S at the stator side of DFIM, which converts the mechanical power of the wind turbine (WT) to the electrical power. The grid converter controls the DC voltage of the DC link capacitor and the reactive power at the grid side to achieve better power quality.

In Fig. 1, the WT is modeled as

$$P_m = \frac{1}{2}\rho A C_p V^3 \tag{1}$$

where P_m is the mechanical power of the WT, ρ is the air density, A is the swept area, C_p is the coefficient of WT and V is the wind velocity[17]. In this paper, the WT is assumed to be regulated at the optimum speed given by the MPPT algorithm, which extracts the maximum power from an available wind speed.

3. Power Control of DFIM in the Stator Flux-Oriented Reference Frame

Figure 2 shows the reference frames used for the dq axis analysis of DFIM. DQ axis is for the stationary reference frame, $\alpha\beta$ axis is for the rotor reference frame and the xy axis is for the stator flux-oriented reference frame. The ρ_s is the stator flux angle and the θ_r is the rotor angle.

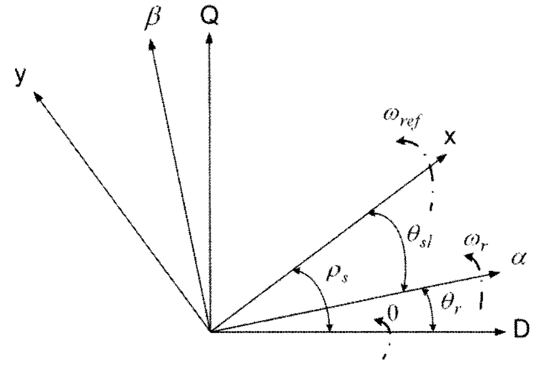


Fig. 2 Reference frames for double-fed induction machine

From the vector analysis of DFIM[3], the real power P_s and reactive power Q_s at the stator side of DFIM in the stator flux-oriented reference frame are represented as

$$P_s = \frac{3}{2}|V_s|\frac{L_m}{L_s}i_{ry} \tag{2}$$

and

$$Q_s = \frac{3}{2}|V_s|\frac{L_m}{L_s}(|i_{ms}| - i_{rx}) \tag{3}$$

where V_s is the stator voltage connected to the power line, i_{ms} is the stator magnetizing current, and i_{rx} and i_{ry} are the rotor currents in the stator flux-oriented reference frame. From (2) and (3), the real power P_s and reactive power Q_s at the stator side of DFIM can be independently controlled with the rotor current vector control.

Due to the nonlinear characteristics of WPGS, the precise mathematical modeling of the WPGS including the back-to-back converter for calculating the conventional PI feedback control gains has been a difficult task.

The fuzzy logic control can be used to control the output powers at the stator side of DFIM. The fuzzy logic control design has been easily realized by the operator understanding the converter's characteristics and linguistic rules of the type: "IF the error of the output is positive, then reduce the duty cycle slightly."[16, 18]

For the fuzzy PI inference to regulate the output powers (P_s and Q_s), there are two input variables (the output power error, *e(t)*, and the change in error, *ce(t)*, which are written as follows:

$$e(t) = P_{ref} - P_s \tag{4}$$

$$ce(t) = e(nT_S) - e((n-1)T_S) \tag{5}$$

The output error as the first input (the IF) variable has the nine fuzzy subsets (NVB, NB, NM, NS, Zero, PS, PM, PB, PVB) and the triangle membership function[18]. The change of the error as the second input variable has seven fuzzy subsets (NB, NM, NS, Zero, PS, PM, PB) and the triangle membership function. The new output of the fuzzy PI controller has nine fuzzy subsets which are defined as the singleton-type membership function[18]. The fuzzy rule table for the output voltage regulation has 63 rules of the following type:

Rule i : IF (the voltage error *e(t)* is NS (negative small))
AND the change of the error *ce(t)* is PS (positive small),
THEN the change of the command is ZE (zero),
where $i = 1, \ldots, 63$.

In order to defuzzify the fuzzy output to the crisp output, *dz*, the fuzzy inference process uses the simple and effective Sugeno zero-order reasoning method[18] of the following:

$$di = \sum_{i=1}^{n} [\mu_i(z) z] \Big/ \sum_{i=1}^{n} \mu_i(z) \tag{6}$$

The new current commands, i_{rx} of (2) and i_{ry} of (3), based on the fuzzy PI inference can be written as

$$i(nT) = i((n-1)T) + di(nT) \tag{7}$$

Using (7) with the vector control generates i_{rx} of (2) and i_{ry} of (3), which are the rotor currents in the stator flux-oriented reference frame. For the simple output control of the SPWM converter in this paper, the current commands are changed to voltage commands for the voltage controlled field orientation in the induction machine.[19] shown in Fig.3.

4. DC Link Voltage and Reactive Power Control at the Grid Converter

To control the real power P_s and reactive power Q_s strictly at the stator side of DFIM, the magnitude of DC link voltage is kept as a constant irrespectively although the real power flowing through the back-to-back converter changes. The DC link voltage and the energy stored in the DC capacitor are expressed as

$$E_d = \frac{1}{2} C_d V_d^2 \tag{8}$$

and

$$P_R - P_G = C_d V_d \frac{dV_d}{dt} \tag{9}$$

where P_R is the real power flowing from the rotor side of DFIM and should be equal to P_G flowing from the grid side. Even though P_R changes continuously, the DC link voltage V_d can be controlled with the rapid control of the

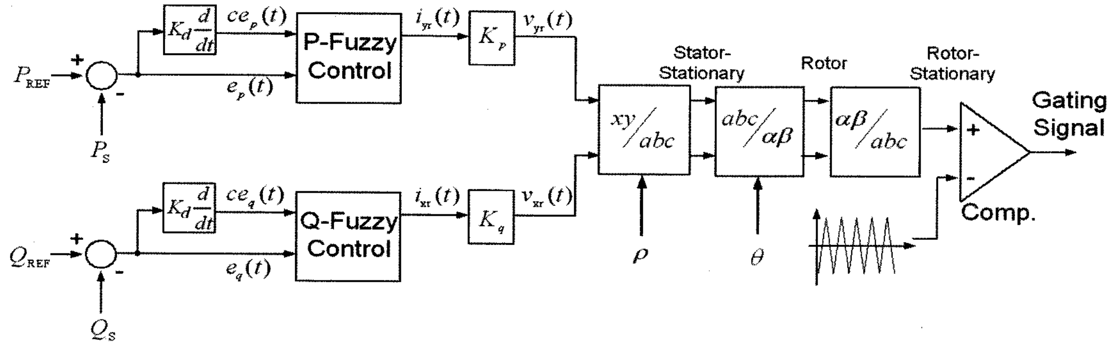


Fig. 3 Real and reactive power controller for wind power generation system with double-fed induction machine as generator

real power, P_G,

The d-axis component of the output voltage at the grid side of the back-to-back converter, expressed in the synchronous reference frame, controls the DC link voltage. The q-axis component of the output voltage at the grid side of the back-to-back converter, expressed in the synchronous reference frame, controls the reactive power to keep the unit power factor.

5. SPWM Converter for DFIM Vector Control

The Sinusoidal PWM (SPWM) converter has been known to be effective from the point of harmonics and switching power losses. The back-to-back converter at the rotor side of DFIM consists of two SPWM converters. One is connected to the rotor of DFIM, which is used as a controller of output powers at the stator side of DFIM in WPGS. The other is connected to the utility, which controls the DC voltage of the DC link capacitor to the constant value and the reactive power at the utility side of the back-to-back converter in order to obtain the unity power factor.

6. Design Example and PSIM Simulation

In this section, we present numerical simulations of the fuzzy controlled WPGS which has a DFIM to convert the mechanical power of wind turbine to electric power. The back-to-back SPWM converter controls the real and reactive powers at the stator side of DFIM, and the DC voltage and the power factor at the utility connected to the rotor. We consider the WPGS with the system parameters of Table 1[19].

Simulation results carried out with PSIM[20] for the designed fuzzy PI controller are shown in Fig. 4. The parameters of the fuzzy membership functions for (4), (5), (6) and (7) are $[e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8, e_9]$=[-5.0, -2.5, -1.0, -0.5, 0.0, 0.5, 1.0, 2.5, 5.0] and $[ce_1, ce_2, ce_3, ce_4, ce_5, ce_6, ce_7]$=[-2.0, -1.0, -0.4, 0, 0.4, 1.0, 2.0]. The output of the fuzzy rule base in (6) are $[u_1, u_2, u_3, u_4, u_5, u_6, u_7, u_8, u_9]$=[-0.25,-0.1,-0.01,-0.005, 0.0, 0.005, 0.01, 0.1, 0.25].

The operating conditions to verify the performance of the fuzzy PI controller for DFIM in WPGS are changed in time as the following:

Table 1 Parameters of wind power generation system with double-fed induction machine[19]

Parameters	Value	Unit
Real power at stator, P_s	16	kW
Reactive power at stator, Q_s	0	kVar
Peak value of line voltage, V_{AC}	180	V
Frequency of line voltage, f	60	Hz
Stator resistance of DFIM, R_s	0.531	Ω
Rotor resistance of DFIM, R_r	0.408	Ω
Stator leakage inductance of DFIM, L_{ls}	2.52	mH
Rotor leakage inductance of DFIM, L_{lr}	2.52	mH
Mutual inductance of DFIM, L_m	84.7	mH
No. of poles of DFIM, p	4	
Inertia of DFIM, J	0.1	kg-m^2
DC link voltage, V_{dc}	400	V
Reactive power at grid converter, Q_{ac}	2	kVar
DC link capacitor, C_{dc}	2200	μF`
AC resistance at grid converter, R_{ac}	0.1	Ω
Switching frequency, f_s	10	kHz

1) The grid converter of the back-to-back converter starts to work from the beginning of the simulation.
2) The wind turbine starts to work with speed control at 1800 [rpm] as the simulation starts.
3) The fuzzy PI controller begins to work at 1[ms].
4) DC link voltage command changes 10% in magnitude and 2[Hz] in frequency.
5) RPM of wind turbine changes from 1500 to 2100 with 1[Hz].
6) The stator power reference changes 12[kw] at 1[ms], 18[kw] at 1.5[ms] and 15[kw] at 2.25[ms]
7) Reactive power controllers start to work at 1[ms] with unity power factor requirement at the grids of stator and rotor of DFIM.

The WPGS operation combined by the above 7 operating conditions demonstrates the proposed fuzzy PI controllers of the WPGS to be controllable and robust in load disturbance situations.

Figure 4(a) shows the rotor speed of DFIM regulated by the WT controller. Here, the rotor speed changes from the synchronous speed, 1800[rpm], to 1500 [rpm] at 1.75[ms], 2100[rpm], at 2[s] and back to 1500[rpm] at 2.5[s], which means that the operation mode of WPGS is changed from the super-synchronous mode to the sub-synchronous mode. Figure 4(b) shows that the DFIM generates the real power, 0[kW] with the short circuit condition of the synchronous speed rotor from 0[s] to 1[s], 12[kW] from 1[s] with the back-to-back inverter control algorithm of the rotor side proposed in this paper, 18[kW] at 1.5[s] and 15[kW] at 2.5[s]. Figure 4(c) shows that the DFIM regulates the reactive power, 0[kVAR] from 1[s]. The power factor at the stator side of WPGS maintains the unit.

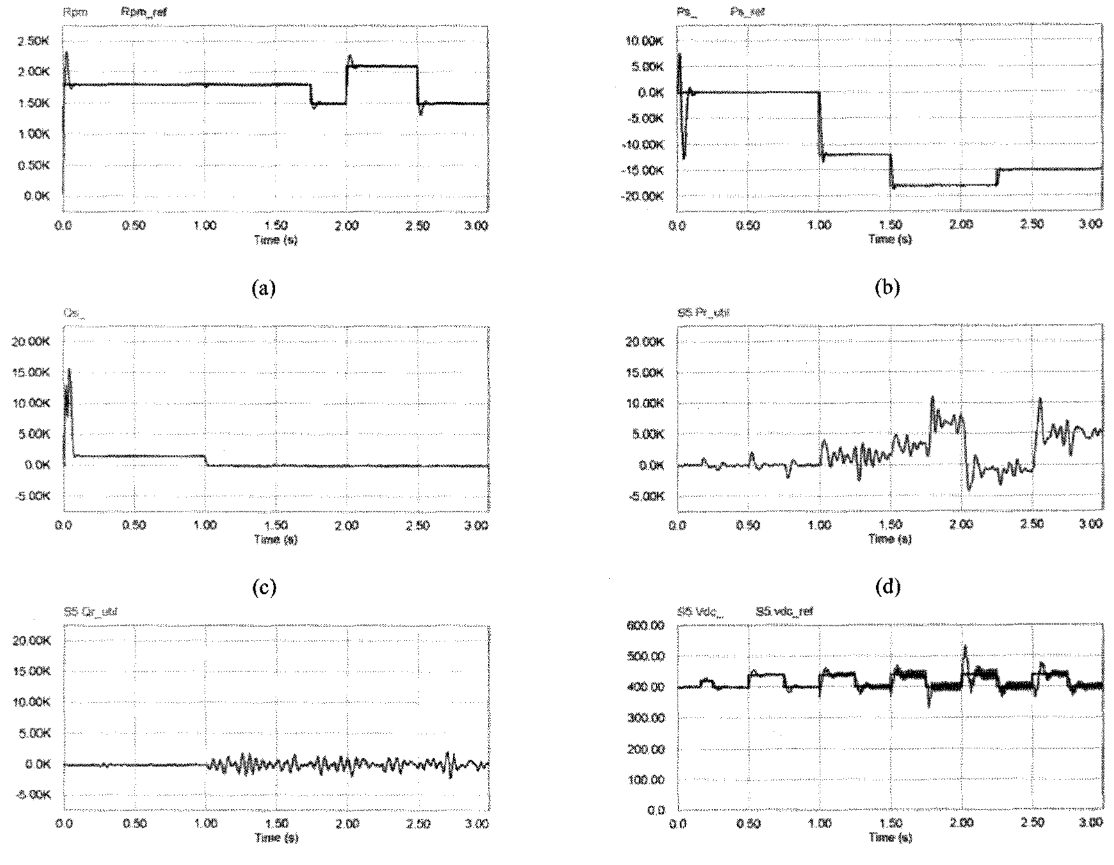
Figure 4(d) shows the slip power, P_G, at the grid converter in sub-synchronous mode and super-synchronous mode. Depending on the operation modes, the real power at the rotor side flow from the grid to the converter or from the converter to the grid, which can be controlled by the back-to-back inverter of DFIM.

Figure 4(e) shows that the grid converter regulates the reactive power at the grid side of WPGS, which changes around the unity power factor.

Figure 4(f) shows the dc link voltage controller regulates the dc link voltage at the required value. However, the dc link voltage has a ripple on it, which depends on the size of the dc link capacitor.

Figures 5(a), (b) and (c) are the three-phase line currents of the WPGS. Compared with the magnitude of the stator side current, the magnitude of the rotor grid side current is relatively small. However, its magnitude changes very fast since the rotor side current controls the stator side power of DFIM in WPGS. The magnitude of the utility currents, i_{ac}, in Fig. 5(c) is almost the same as the magnitude of the stator currents because of the power factor correction.

Figure 5(d) shows harmonics in current, i_{ac}, beyond the PCC(Point of Common Coupling), which means that instruments such as harmonic filters should be installed in order to protect the electric devices connected to the WPGS.



(a) (b)

(c) (d)

(e) (f)

Fig. 4 Outputs of DFIM of WPGS with fuzzy PI controller considered in this paper: (a) Rotor speed, RPM, (b) real power at stator, P_S, (c) reactive power at stator, Q_S, (d) real power at grid side of rotor, P_G, (e) reactive power at grid side of rotor, Q_G, (f) DC link voltage, V_d

From the simulation results, one can see that the fuzzy PI controller regulates the output powers of DFIM strictly even though the DC link voltage has ripples on it and the operating conditions of WPGS continue to change abruptly.

7. Conclusions

In this paper, the fuzzy PI control algorithm is applied to control the real and reactive powers at the stator of DFIM in WPGS with DFIM independently.

After analyzing the relationship between the dq components of rotor current in the stator flux-oriented reference frame and the real and reactive powers at the stator of DFIM, the back-to-back SPWM converter is adopted as the power controller of WPGS.

The conventional PI control approach is also applied to the utility side of the back-to-back converter to control the DC link voltage and the reactive power at a certain value so that the converter continues to control the output powers and the power factor of the WPGS independently.

To test the proposed control algorithm, the PSIM simulation studies are performed. The results show that the fuzzy PI controller works efficiently for WPGS with DFIM and a back-to-back SPWM converter.

This paper intended to show that the proposed fuzzy controller can control power flows in WPGS with DFIG like the conventional PI controller. The fuzzy PI controller in this paper is a kind of PI controller elaborated with linguistic rules. It can be designed without knowing the exact system parameters required in a conventional PI design method. Therefore, the authors are sure that the design method of the proposed fuzzy controller based on linguistic rules will be required when WPGS will operate in more complicated and high-level control strategies.

Further investigations yet to be done include the hardware experiments of DFIM in WPGS to verify the proposed approach and develop the high level control strategies for the wind power generation system optimum controller.

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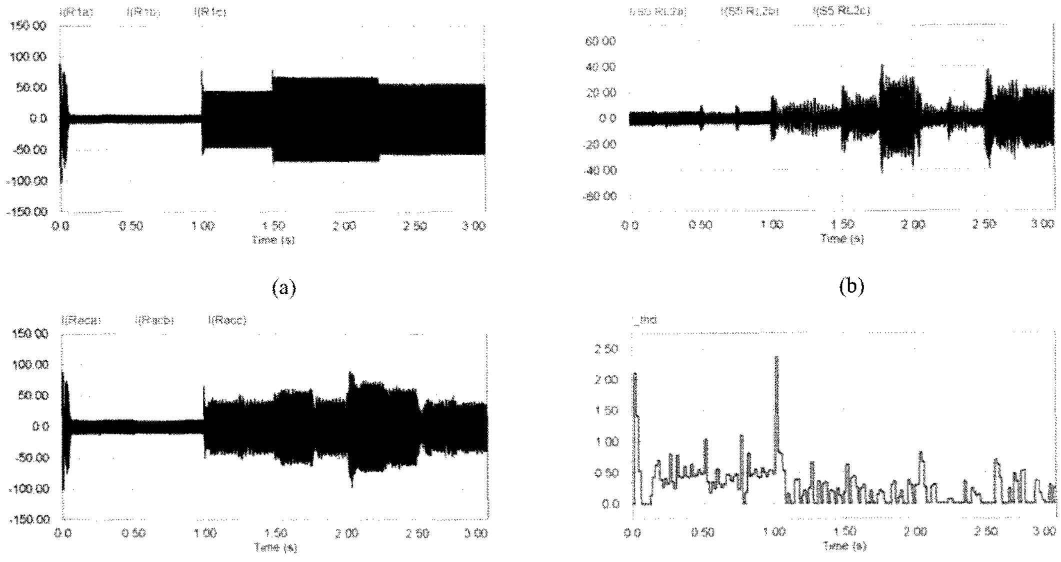

(a) (b)

(c) (d)

Fig. 5 Outputs of DFIM of WPGS with fuzzy PI controller considered in this paper: (a) stator currents of DFIM, (b) current at grid side of rotor, (c) utility line current after point of common coupling, (d) THD of utility line current

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