FUZZY LOGIC CONTROLLER BASED ON AN INDIRECT VECTOR CONTROL OF DUAL STATOR INDUCTION GENERATOR IN WIND ENERGY CONVERSION SYSTEM

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Abstract: -This paper investigates Fuzzy Logic Controller Based on an Indirect Vector Control of Dual Stator Induction Generator (DSIG)in Wind Energy Conversion System. In first step a field-oriented control of a DSIG is presented. In second step, in order to ensure an optimum operating point and an Maximum Power Point Track (MPPT) giving online a maximum production of electric power for different wind speeds, a conventional PI and then a fuzzy PI speed regulators have been used. Simulation results show clearly the effectiveness and the performance of the suggested fuzzy logic controller.

Keywords:: *Dual stator Induction generator, Field-Oriented Control, Classical PI controller, Fuzzy logic controller, Wind energy conversion system.*

I. INTRODUCTION

With exhausting of traditional energy resources and increasing concern of environment, renewable and clean energy is attracting more attention over the last few decades to overcome the increasing power demand. Wind energy is one of the most important and promising source of renewable energy all over the world, mainly because it is considered to be nonpolluting and economically viable. At the same time there has been a rapid development of related wind energy technology [1], [2].An induction generator, with its lower maintenance demands and simplified controls, appears to be an effective solution for small hydro and wind power plants [3].

To increase the power rating of an ac drive system a multi-phase induction machine is seemed an ultimate solution. In fact the advantages of multi-phase drive systems over conventional three-phase drives are : the total rating of system is multiplied, the torque pulsations will be smoothed, reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per voltage, power segmentation and high reliability [4],[5]. A common type of multi-phase machine is a the dual stator induction machine (DSIM), also known as the six phase induction machine.

Generally, variable speed wind energy conversion system with the dual stator induction generator require both wide operating range of speed and fast torque response, regardless of any disturbances and uncertainties (turbine torque variation, parameters variation and un-modeled dynamics). This leads to more advanced control methods to meet the real demand [3].

The fuzzy control is basically nonlinear and adaptive in nature, giving robust performance under parameter variation and load disturbance effect.

As an intelligent control technology, fuzzy control provides a systematic method to incorporate human experience and implement nonlinear algorithms, characterized by a series of linguistic statements, into the controller. In general, a fuzzy control algorithm consists of a set of heuristic decision rules and can be regarded as an adaptive and nonmathematical control algorithm based on a linguistic process, in contrast to a conventional feedback control algorithm [6].

The outline of this paper is as follows: in section II, the modelling of the wind generator and the maximum power point tracking (MPPT) are presented. Section III deals with the field oriented control (FOC) of a DSIG. The design of a FLC for speed regulation of a DSIG is presented in section IV. In section V the performances of the proposed control are illustrated by some simulation results. Finally some concluding remarks are given in section VI.

II. MODELING OF THE WIND GENERATOR

Modeling of the wind turbine and gearbox

The aerodynamic power, which is converted by a wind turbine, P_t is dependent on the power coefficient C_p .it is expressed as follows [6], [7]:

$$P_t = C_p(\lambda)\rho S V^3 \tag{1}$$

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Where ρ is the air density, R is the blade length and V is the wind velocity.

The turbine torque is the ratio of the out power to the shaft speed Ω_t, given by:

$$T_t = \frac{P_t}{\Omega_t} \quad (2)$$

The turbine is normally coupled to the generator shaft through a gearbox whose gear ratio G is chosen in order to set the generator shaft speed within a desired speed range. Neglecting the transmission losses, the torque and shaft speed of the wind turbine, referred to the generator side of the gearbox, are obtained as follows :

$$T_g = \frac{T_t}{\boldsymbol{G}} \quad , \quad \Omega_t = \frac{\Omega_r}{\boldsymbol{G}} \quad (3)$$

where the C_g driving is torque of the generator and Ω_r is the generator shaft speed.

The captured wind power is not converted totally by the wind turbine. $Cp\ (\lambda)$ Give us the percentage converted which is function of the wind speed, the turbine speed and the pith angle of specific wind turbine blades [7].

Although this equation seems simple, C_p is dependent on the ratio λ between the turbine angular velocity Ω_t and the wind speed V .this ratio is called the tip speed ratio expressed by:

$$\lambda = \frac{\Omega_t R}{V} \quad (4)$$

The areodynamique torque (wind) is determined the following equation [8]:

$$T_t = \frac{P_t}{\Omega_t} = C_p(\lambda) S \rho V^3 / 2\Omega_t \quad (5)$$

From the previous equations, a functional block diagram model of the turbine is established. it shows that the turbine rotation speed is controlled by acting on the electromagnetic torque of the generator. The wind speed is considered an entry disruptive to this system (see fig1).

The wind speed varies over time, and to ensure maximum capture of wind energy incident, the speed of the wind turbine should be adjustable permanently with that of the wind [7].

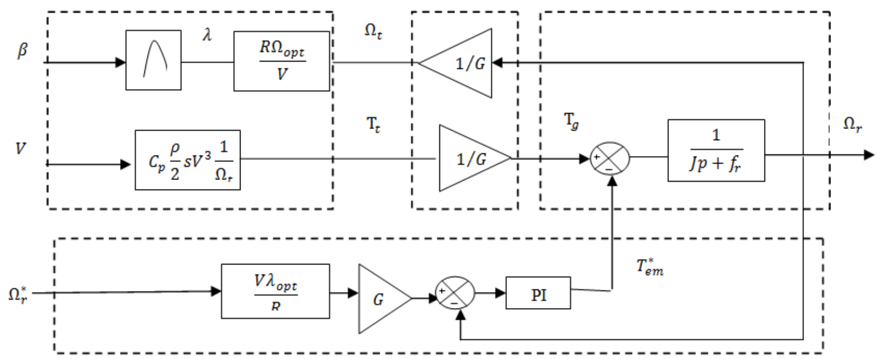

Figure. 1 Control of turbine

A. Dual star induction generator model

The mode of dual star induction generator is composed of a stator with two identical phase windings shifted by an electric angle $\alpha =$ 30°, and a squirrel cage rotor.

Under the assumptions of magnetic circuits linearity, and assuming sinusoidal distributed air-gap flux density, the equivalent two-phase model of dual stator induction machine, represented in asynchronous frame (d,q) and expressed in state-space form, is a fourth-order model [7]-[10]:

$$\left[\dot{I}\right] = [L]^{-1}\left\{[B][U] - \omega_{gl}[C][I] - [D][I]\right\} \quad (6)$$

$$[C] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ L_m & 0 & L_m & 0 & 0 & L_r + L_m \\ 0 & L_m & 0 & L_m & -(L_r + L_m) & 0 \end{bmatrix}$$

$$[L]=\begin{bmatrix} L_{s1}+L_m & 0 & L_m & 0 & L_m & 0 \\ 0 & L_{s1}+L_m & 0 & L_m & 0 & L_m \\ L_m & 0 & L_{s2}+L_m & 0 & L_m & 0 \\ 0 & L_m & 0 & L_{s2}+L_m & 0 & L_m \\ L_m & 0 & L_m & 0 & L_r+L_m & 0 \\ 0 & L_m & 0 & L_m & 0 & L_r+L_m \end{bmatrix}$$

$$[D]=\begin{bmatrix} R_{s1} & -\omega_s(L_{s1}+L_m) & 0 & -\omega_s L_m & 0 & -\omega_s L_m \\ \omega_s(L_{s1}+L_m) & R_{s1} & \omega_s L_m & 0 & \omega_s L_m & 0 \\ 0 & -\omega_s L_m & R_{s2} & -\omega_s(L_{s1}+L_m) & 0 & -\omega_s L_m \\ \omega_s L_m & 0 & \omega_s(L_{s1}+L_m) & R_{s2} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & 0 & 0 & R_r \end{bmatrix}$$

Where:

$$[U]=\left[V_{qs1}V_{ds1}\ \ V_{qs2}\,V_{ds2}V_{qr}\,V_{dr}\ \right]^t$$

$$[I]=\left[\ I_{qs1}I_{ds1}\ \ I_{qs2}I_{ds2}\ \ I_{qr}\ I_{dr}\ \right]^t\ ;$$

$$\left[\dot{I}\right]=\frac{d[I]}{dt}$$

$$[B]=diag[1\ \ 1\ \ 1\ \ 1\ \ 0\ \ 0]$$

Where: $\tau_r=\frac{L_r}{R_r}$

The mechanical modeling part of the system is given by [11]:

$$J\frac{d\Omega_r}{dt}=T_r-T_{em}-J\Omega_r \tag{7}$$

With:

$$T_{em}=\left(\frac{p}{2}\right)\left(\frac{L_m}{L_{md}+L_r}\right)\left[\left(i_{qs1}+i_{qs2}\right)\varphi_{dr}-\left(i_{ds1}+i_{ds2}\right)\varphi_{qr}\right] \tag{8}$$

III. FIELD ORIENTED CONTROL OF A DSIG

According to the field orientation theory [12], the machine currents are decomposed into i_{ds} and i_{qs} components, which are respectively, flux and torque components. The key feature of this technique is to keep namely $\varphi_{dr}=\varphi_r$ and $\varphi_{ar}=0$.

Hence, the flux and the electromagnetic torque are decoupled from each other, and can be separately controlled as desired. Then the drive behavior can be adequately described by a simplified model expressed by the following equations [8]:

$$i_{dr}=\frac{\varphi_r^*}{L_m+L_r}-\frac{L_m}{L_m+L_r}(i_{ds1}+i_{ds2}) \tag{9}$$

$$i_{qr}=-\frac{L_m}{L_m+L_r}(i_{qs1}+i_{qs2}) \tag{10}$$

$$\omega_{sl}^*=\frac{r_r L_m}{(L_m+L_r)}\frac{\left(i_{qs1}+i_{qs2}\right)}{\varphi_r^*} \tag{11}$$

Finally the electromagnetic expression can be represented by:

$$T_{em}^*=P\frac{L_m}{L_m+L_r}i_{qs1}+i_{qs2}\ .\varphi_r^* \tag{12}$$

A. Grid side power control

In grid-connected control mode, all the available power that can be extracted from the wind generator is transferred to the grid.Standard PI controllers are used to regulate the dc link voltage and the inverter output currents in the (abc) synchronous frame. To have the grid current vector in phase with the grid voltage vector, the reference reactive power Qshould be zero. The dc link voltage control is acting to supply the reference active power. The output of the current controllers sets the voltage reference for an average conversion control method that controls the switches of the grid inverter [8].

The dc link voltage is given by:

$$\frac{du_{dc}}{dt} = \frac{1}{C_{dc}}(i_{dc} - i_{ond}) \tag{13}$$

where,

$$i_c^* = i_{dc} - i_{ond} \tag{14}$$

The reference active power injected to the electrical supply network is given by:

$$P_g^* = u_{dc} i_{dc} - u_{dc} i_c^* \tag{15}$$

The reference voltages are expressed by

$$\begin{aligned} v_{d\_ond}^* &= v_{dg}^* + v_{dg} - \omega_s L_t i_{qg} \\ v_{q\_ond}^* &= v_{qg}^* + v_{qg} + \omega_s L_t i_{dg} \end{aligned} \tag{16}$$

To maintain constant the dc link voltage, we have recourse to use a proportional integral corrector. It is parameterized according to the capacitor value and the dynamics of the regulation loop. Network reference currents, expressed in d–q frame, are given by:

$$\begin{aligned} i_{dg}^* &= \frac{P_g^* v_{dg} + Q_g^* v_{qg}}{v_{dg}^2 + v_{qg}^2} \\ i_{qg}^* &= \frac{P_g^* v_{qg} - Q_g^* v_{dg}}{v_{dg}^2 + v_{qg}^2} \end{aligned} \tag{17}$$

IV. DESIGN OF FLC FOR DUAL STATOR INDUCTION GENERATOR SPEED CONTROL

The structure of a standard FLC can be seen as a traditional PI controller, where the speed error e and its variation Δe are considered as input linguistic variables and the electromagnetic reference torque change ΔT_{em} is considered as the output linguistic variable [13],[14].

For convenience, the inputs and output of FLC were scaled with three different coefficients k_e, $k_{\Delta e}$, and $k_{\Delta Tem}$.

These scaling factors can be constants or variables, and play an important role for FLC design in order to achieve a good behavior in both transient and steady state.

Seven membership functions with overlap, of triangular shape and equal width, are used for each input and output variable, so that a 49 rules base is created (see Fig.2).The sum-product inference algorithm is selected to complete the fuzzy procedure. And the FLC output is obtained by the gravity center defuzzification method [15],[16].

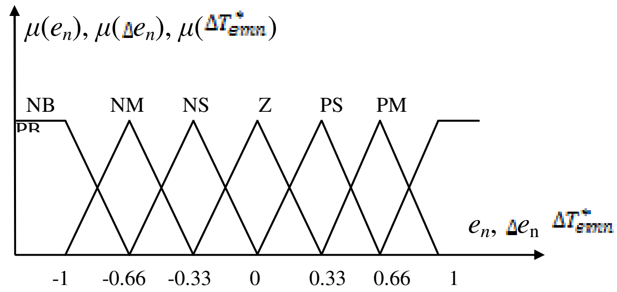

Figure.2 Membership functions of inputs and output of FLC

The suggested built inference rule table used for FLC is depicted in Table. I

TABLE I. INFERENCE RULES TABLE.

Δe_n/ e_n	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

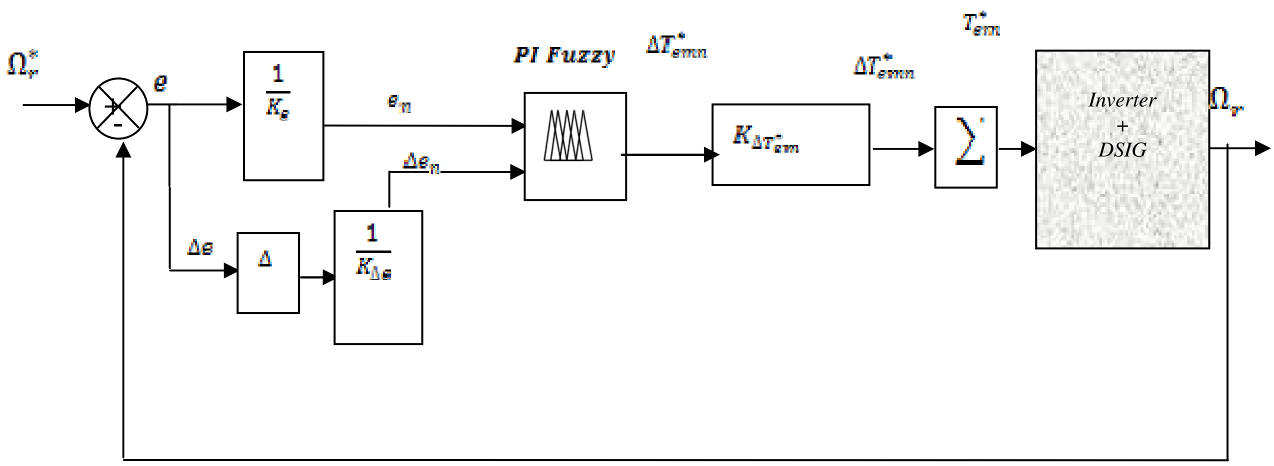

Figure. 3 The block diagram of a fuzzy speed control of dual stator induction generator

V. SIMULATION RESULTS AND DISCUSSION

In order to investigate the performance and accuracy of the proposed method control, simulation tests were performed for a 1 .5 MW DSIG using an FLC controller. The parameters of the test DSIG used in the simulation are given in Table II. The suggested control strategy is compared with conventional PI controller.

The results of simulations are obtained for reactive power Q = 0 for a unity power factor. From figure.5 the DSIG speed follow properly it optimal reference and has the same waveform as applied wind profile. The electromagnetic torque converges quickly to its reference see figure.6. The feature of vector control is shown in figure.7. From the stator voltage and current waveforms, it can be seen that, the stator operates nearly at unity power factor see figure. 8. The DC link voltage is maintained at a constant level (1130V) see figure.9; hence that the real power extracted from the wind energy conversion systems can pass through the grid. The grid active power tracks quite well its set-point up to the rated speed, when the reactive grid power is fixed to 0 VAR see figure.11.

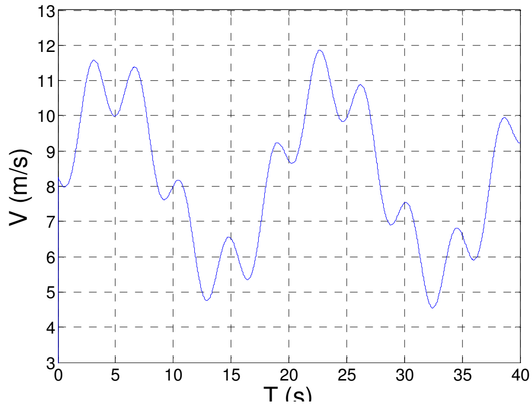

Figure.4 Random wind profile

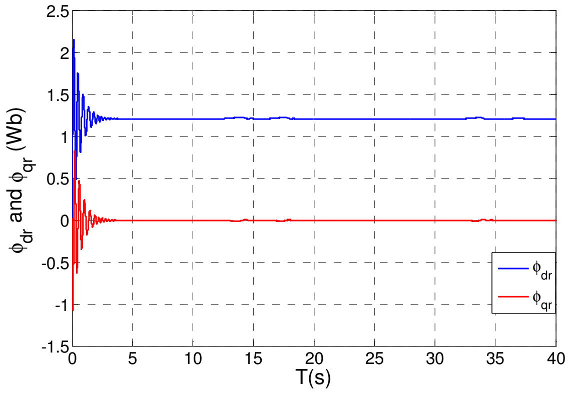

Figure.7 Direct and quadratic rotor flux

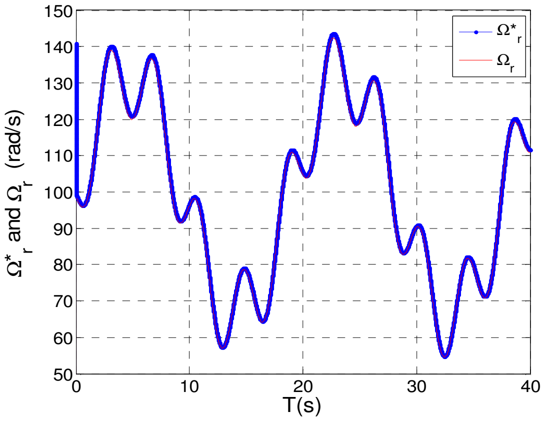

Figure.5 DSIG speed and its reference

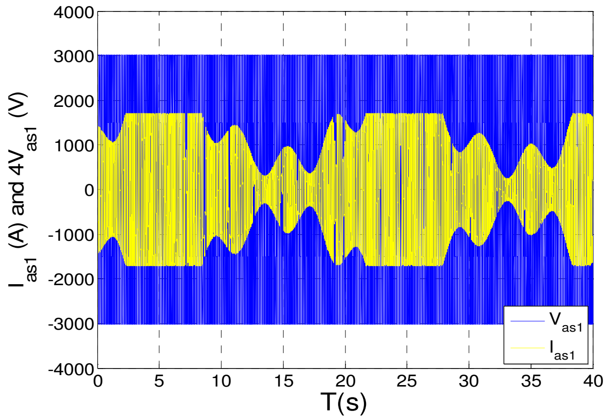

Figure. 8 Stator voltage and current for stator 1

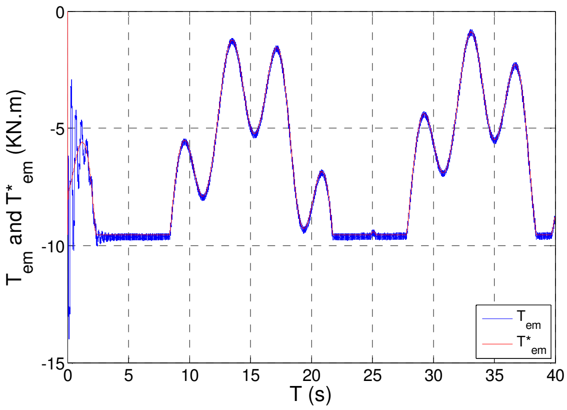

Figure.6 DSIG Torque and its reference

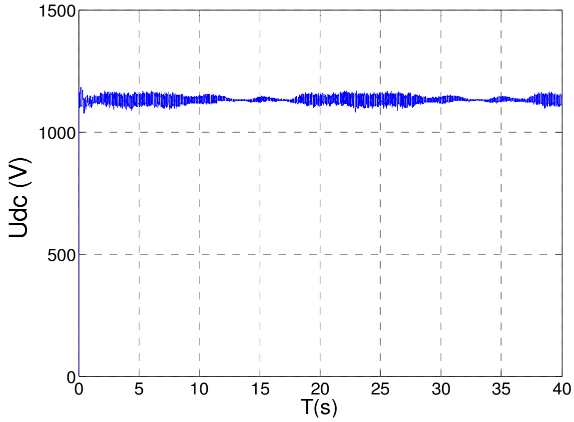

Figure. 9 DC link voltage

In order to show the effectiveness of the suggested FLC, it has used two wind profiles, constant and random. From figures 13, 14, 15 and 16, it can be seen that the proposed FLC has high accuracy and reliability in comparison with the PI controller, in tracking of the maximum power point in different wind speeds so that total error remarkably reduces. So, it is easily shown that the use of FLC improve very well the performance of wind energy conversion systems especially the power coefficient Cp and λ. In fact, the coefficient Cp close to its maximum value during the whole wind speed profile, same for tip speed ratio λ. Hence the efficiency of the maximum power extraction can be clearly observed as the power coefficient is fixed at the optimum value Cp =0.49 and λ= 9 compared with the PI and fuzzy control method, the possibility of designing a powerful PI and fuzzy, Tables II give the gain of PI conventional and PI fuzzy respectively.

TABLE II. NORMALIZATION FACTORS OF PI AND FLC.

PI	k_i =200000	k_p =40	
FLC	k_e =0.14	$k_{\Delta e}$ =0.003	$k_{\Delta c}$ =8.584

TABLE III. SUMMARY OF RESULT.

profile	controller	C_p error %	λ error %
constant	PI	0.0438	0.195
	FLC	0.0415	0.085
random	PI	0.042	0.14
	FLC	0.02	0.04

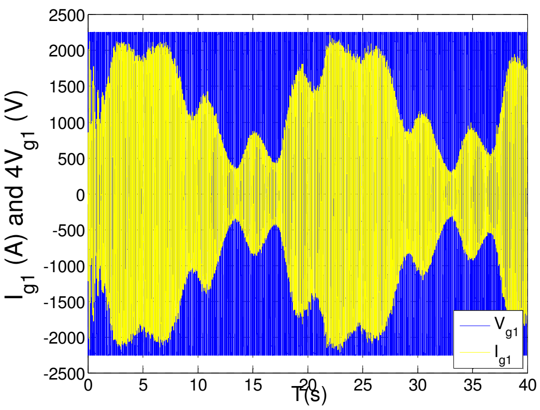

Figure.10 Grid voltage and current

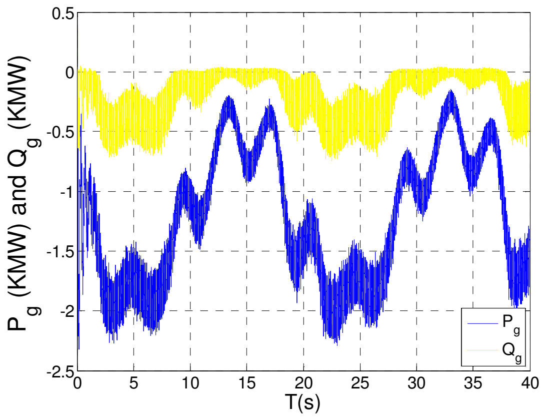

Figure.11 Grid active and reactive

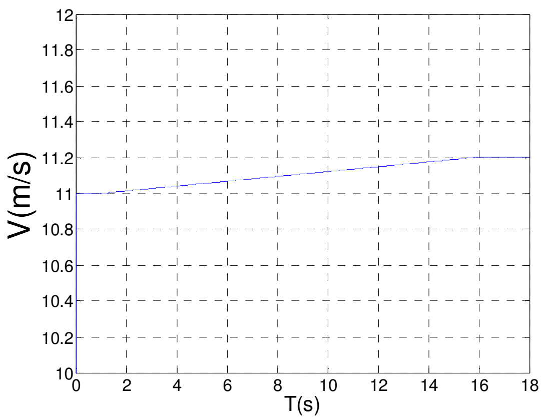

Figure.12 Constant wind

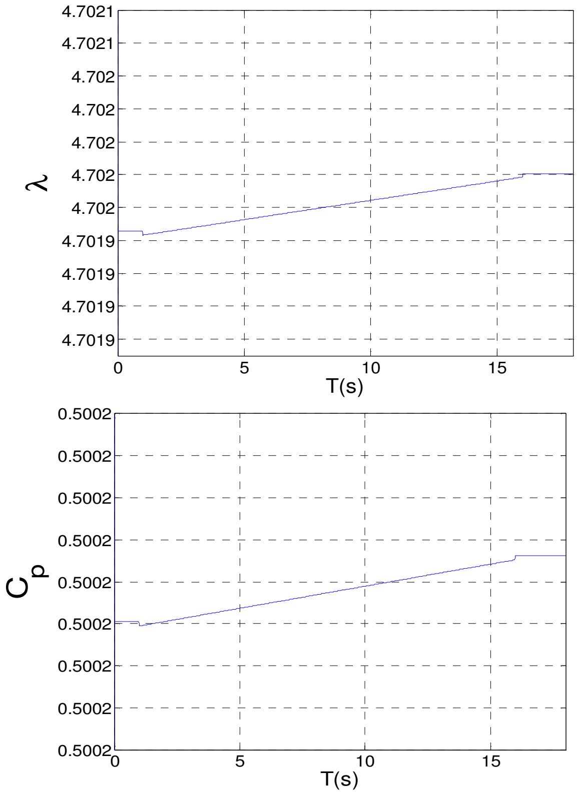

Figure.13 The tip speed and power coefficient

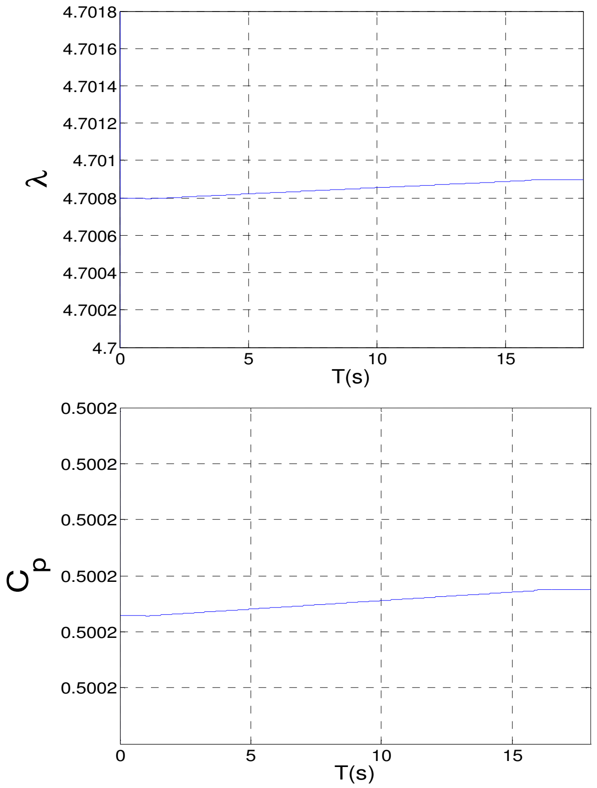

Fig.14 The tip speed and power coefficient with fuzzy PI for the constant profile

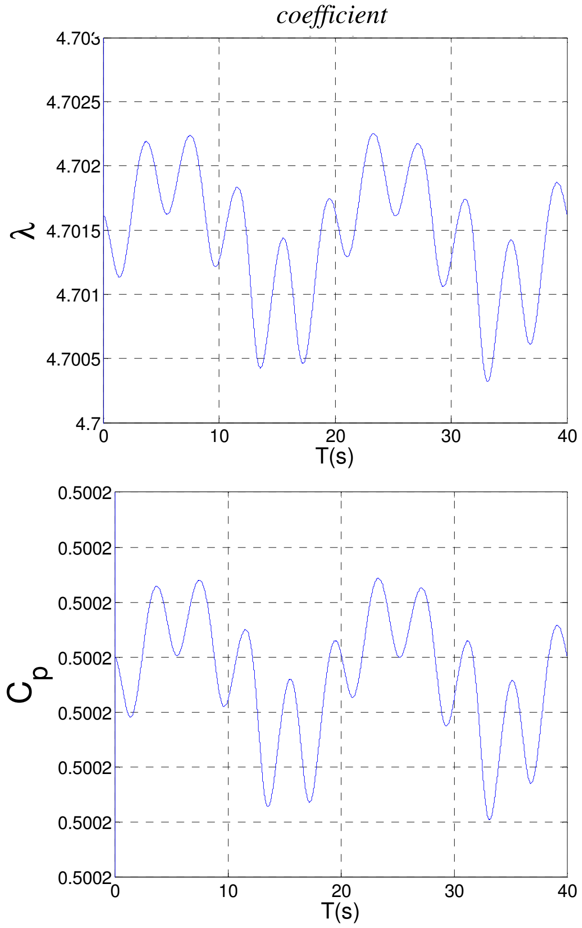

Fig.15 The tip speed and power coefficient with classical PI for the random profile

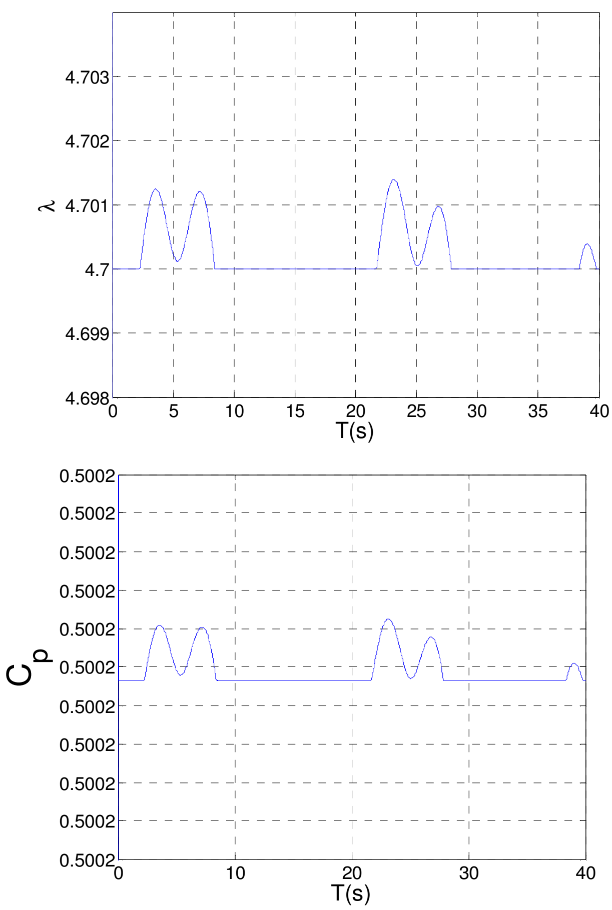

Fig.16 The tip speed and power coefficient with fuzzy PI for the random profile

VI. CONCLUSION

In this paper a fuzzy logic controller applied to speed regulation of a field-oriented dual stator induction generator used in a variable speed wind turbine connected to the grid is fully has been presented.

From this study, it can be concluded; that the fuzzy logic controller can improve greatly the performance of wind energy conversion system and one can conclude that the proposed scheme shows good support for change of the turbine and the generator as well as to electric grid disturbance.

APPENDIX.A. NOMENCLATURE

G	Gear ratio
V	Wind velocity
P_n	Nominal power
λ	Tip speed ratio
S	Area of the rotor
C_p	Power coefficient
Ω_r	Mechanical speed of the DSIG
Ω_t	Turbine speed
T_t	Aerodynamic torque
T_g	Generator torque
R_{s1} , R_{s2}	Per phase stators resistances
L_1, L_2	Per phase stators leakages inductances
L_m	Magnetizing inductance
R_r	Per phase rotor resistance
L_r	Per phase rotor leakage inductances
J	Inertia (turbine + DSIG),
f_r	Viscous coefficient
P	Number of pole pairs
tf	final time
p	Derivative operator
ω_s	Speed of the synchronous reference frame
ω_r	Rotor electrical angular speed
T^*_{em}	Electromagnetic torque reference
$V_{qs1}V_{ds1}$ V_{qs2} , V_{ds2}	"d–q" stators voltages
$I_{qs1}I_{ds1}$ $I_{qs2}I_{ds2}$	"q" stators currents
V_{qr} V_{dr}	"d–q" rotor voltages
I_{qr} I_{dr}	"d–q" rotor currents
NS,NM,NB	Negative Small, negative medium, negative big
PS,PM,PB	Positive Small, positive medium ,positive big
Z	(Approximately) Zero

APPENDIX.B PARAMETERS

DSIG: 1.5 MW, 400 V, 50 Hz, 2 pole pairs, $R_{s1} = R_{s2}$ = 0.008 X, $L_1 = L_2$ = 0.134 mH, L_m = 0.0045 H, R_r = 0.007 X, L_r = 0.067 mH, J = 104 kg m2 (turbine + DSIG), f_r = 2.5 N m s/rd: (turbine + DSIG).

Turbine: Radius = 35 m, Number of blades = 3, Hub height =85m ,

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