Optimization Fuzzy Speed Vector Control of Dual Stator Induction Generator System Applied in Wind Power Generation

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Abstract—**This paper focuses on the design and analysis of optimized PI conventional and fuzzy logic speed 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. In the final step, to improve the design of these two regulators, the technique of genetic algorithms is used to facilitate the design parameters determination and reduced time consumption comparatively to the "trial-error" method.**
Simulation results show clearly the effectiveness and the performance of the suggested optimization algorithm.

Index Terms—**dual stator induction generator, variable speed wind turbine, three-phase converters, field oriented control, conventional PI and fuzzy controllers, optimization method, genetic algorithms**

I. INTRODUCTION

Wind energy has an ecologically advantage over various other sources of energy such as coal, wood, and oil, but the initial cost is still high [1]. Squirrel cage induction motors are the most commonly used electrical machine in AC drives, because they are robust, cheap and have low maintenance cost . These advantages make the induction machine very attractive for wind power applications both for fixed and variable speed operation [2].

In order to increase the power of a drive system AC Power machine multi-Phase induction appeared an ultimate solution. Multiphase (more than three phases) drives have several advantages compared with conventional AC motors, such as reducing the amplitude and increasing the frequency of torque pulsations, reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per phase, lowering the dc-link current harmonics, and higher reliability. By increasing the number of phases it is also possible to increase the power /torque per rms ampere for the same volume machine [3]. A common type of multi-phase machine is the dual stator induction machine (DSIM), also known as the six phase induction machine.

Generally, in a variable speed wind energy system, below rated wind velocity, the electrical torque is controlled in order to drive the system into an optimum speed for maximum energy conversion [2].

The fuzzy logic control (FLC) 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 [4].

The major drawback of FLC is the lack of design techniques. Most fuzzy rules are based on human knowledge and differ among persons despite the same system performance. The selection of suitable fuzzy rules, membership functions, and their definitions in the universe of discourse invariable involves painstaking trial-error [5]. We address using genetic algorithms to overcome these drawbacks to make design tasks easier. Genetic Algorithms (GAs) is a search heuristic that mimics the process of evaluation. GAs can be applied to process controllers for their optimization using natural operators [6].

The main objective of the use genetic algorithms is to facilitate the design parameters determination and reduced time consumption comparatively to the "trial-error" method. Such an optimal FLC could provide ideal control performance and achieve desired speed.

Genetic algorithms are general-purpose optimization techniques that use the direct analogy of natural evolution involving survival of the fittest. GAs, developed by Holland in 1962, use multiple concurrent search points called chromosomes, that process three genetic operations: reproduction, crossover, and mutation to generate new search points called offspring for subsequent iterations.

Some or all members of the current solution set are replaced with newly created members to improve solution set quality with increasing numbers of iterations [5].

This paper is constructed as follows: in Section II, the modeling of the wind generator and the 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 genetic algorithms based PI conventional and FLC is proposed. In Section VI the performances of the proposed control are illustrated by some simulation results. Finally some concluding remarks are given in Section VII.

II. MODELING OF THE WIND GENERATOR

A. Modeling of the Wind Turbine and Gearbox

Wind turbine mechanical power is expressed as follows [7] and [8]:

$$P_t = C_p(\lambda)\rho S V^3 \qquad (1)$$

where C_p the power coefficient of the turbine, 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:

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

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:

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

where the T_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. $C_p(\lambda)$ Give us the percentage converted which is function of the wind speed, the turbine speed and the pith angle of specific wind turbine blades [9] and [10].

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:

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

The areodynamique torque (wind) is determined the following equation [9]:

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

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 Fig. 1).

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 [9].
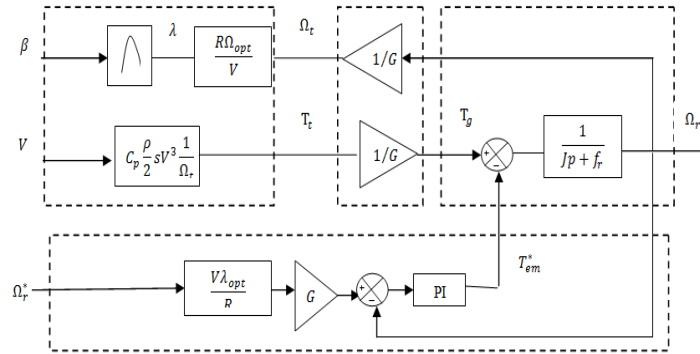

Figure 1.   Control of turbine.

B. Dual Stator Induction Machine Model

The model of dual stator induction machine 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 [8]-[10]:

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

Where:

$$\omega_{gl} = \omega_s - \omega_r;$$

$$\omega_r = P*\Omega_r;$$

$$[U] = \begin{bmatrix} V_{qs1} V_{ds1} & V_{qs2} V_{ds2} V_{qr} V_{dr} \end{bmatrix}^t;$$

$$[I] = \begin{bmatrix} I_{qs1} I_{ds1} & I_{qs2} I_{ds2} & I_{qr} I_{dr} \end{bmatrix}^t;$$

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

$$[B] = diag\begin{bmatrix}1 & 1 & 1 & 1 & 0 & 0\end{bmatrix}$$

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

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

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

C. Grid Side Power Control

In grid-connected control mode, is used injects the generated power into the grid. By using vector control techniques the currents in the ac side of the converter are controlled with very high bandwidth. The orientation of the reference frame is done along the supply voltage vector to obtain a decoupled control of the active and reactive power.

Usually the reactive power component current is set to zero for near unity power factor operation. The main aim of the front-end converter control strategy is to keep the DC link voltage E constant. It can be shown that the dynamic for the DC link voltage E, The dc link voltage is given by [9]:

$$\frac{du_{dc}}{dt} = \frac{1}{C_{dc}}(i_{dc} - i_{ond}) \qquad (9)$$

where,

$$i_c^* = i_{dc} - i_{ond} \qquad (10)$$

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

$$P_g^* = u_{dc}i_{dc} - u_{dc}i_c^* \qquad (11)$$

Where: $\quad \tau_r = \dfrac{L_r}{R_r}$

The mechanical modeling part of the system is given by [10]:

$$J\frac{d\Omega_r}{dt} = T_g - T_{em} - f_r\Omega_r \qquad (7)$$

With:

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

The reference voltages are expressed by [9]:

$$\begin{aligned} v_{d\_ond}^* &= v_{dg}^* + v_{dg} - \omega_s L_t i_{qg} \\ v_{q\_ond}^* &= v_{qg}^* + v_{qg} + \omega_s L_t i_{dg} \end{aligned} \qquad (12)$$

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:

$$\begin{aligned} i_{dg}^* &= \frac{P_g^* v_{dg} + Q_g^* v_{qg}}{v_{dg}^2 + v_{qg}^2} \\ i_{qg}^* &= \frac{P_g^* v_{qg} - Q_g^* v_{dg}}{v_{dg}^2 + v_{qg}^2} \end{aligned} \qquad (13)$$

III. FIELD ORIENTED CONTROL OF A DSIM

According to the field orientation theory [11], 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 $\varphi_{qr} = 0$.

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 [9]:

$$i_{dr} = \frac{\varphi_r^*}{L_m + L_r} - \frac{L_m}{L_m + L_r}(i_{ds1} + i_{ds2}) \quad (14)$$

$$i_{qr} = -\frac{L_m}{L_m + L_r}(i_{qs1} + i_{qs2}) \quad (15)$$

$$\omega_{gl}^* = \frac{r_r L_m}{(L_m + L_r)} \frac{\left(i_{qs1} + i_{qs2}\right)}{\varphi_r^*} \quad (16)$$

Finally the electromagnetic expression can be represented by:

$$T_{em}^* = P \frac{L_m}{L_m + L_r}\left(i_{qs1} + i_{qs2}\right).\varphi_r^* \quad (17)$$

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 $K_{\Delta Tem}$ is considered as the output linguistic variable [12] and [13].

For convenience, the inputs and output of FLC were scaled with three different coefficients K_e, $K_{\Delta e}$, $K_{\Delta Tem}$. 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. The sum-product inference algorithm is selected to complete the fuzzy procedure. And the FLC output is obtained by the gravity center defuzzification method [14].

V. GENETIC ALGORITHMS BASED CONVENTIONAL AND FUZZY LOGIC CONTROLLER

The genetic algorithm is applied to automate and optimize the PI conventional and FLC design process (see Fig. 2). This optimization requires a predefined of different parameter of GAs sash us coding, fitness, selection, mutation, and specifying of (Crossover probability, mutation rate, Population size and Number of generations), that detail explain in flowing [15]:

- Coding: we use real coding of each individual composed by genes.
- Fitness: the fitness or objectif function defined by this equation :

$$min\left(f_{obj} = \frac{1}{\left(\Omega_r^*\right)^2} \int_0^{tf} \left(\Omega_r - \Omega_r^*\right)^2 dt \right) \quad (18)$$

- Selection: we use the stochastic selection [15].
- Crossover: in this step we use the scattered crossover its probability equal *0.8*.
- Mutation: in this step we choose the uniform mutation and its rate equal *0.001*.
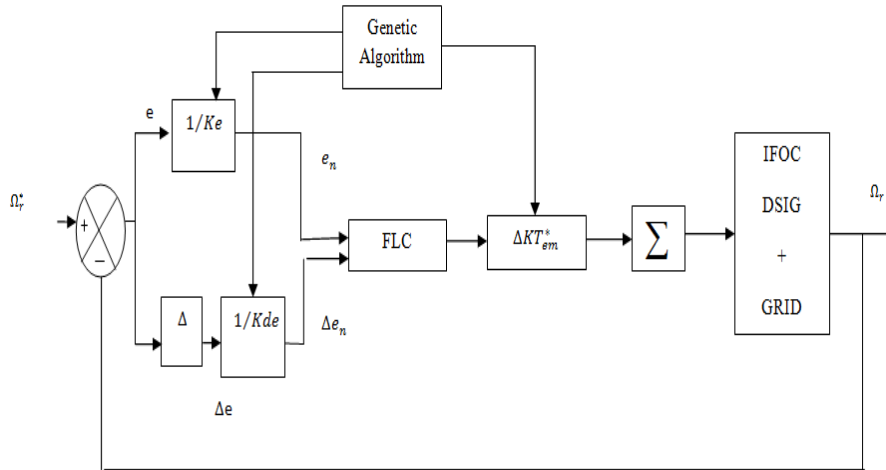

Figure 2.   Basic structure of the genetic algorithms based fuzzy logic controller for indirect field oriented control of DSIG.

The algorithm restore until the stop condition is reached $\left(\varepsilon = 10^{-6}\right)$, we take the best individual parameter controller. (The number of generations equal *200* and the population size equal *20*).

VI. SIMULATION RESULTS AND DISCUSSION

In order to verify the validity of the proposed controllers, the computer simulation results for a 1.5 MW DSIG using a PI and Fuzzy controllers optimized by the GA technique is compared to a conventional PI and fuzzy controllers whose parameters are determined by

trial-error" method. The dual-stator induction generator parameters used in the simulation are given in the Appendix B.

The results of simulations are obtained for reactive power $Q = 0$ and DC link voltage $U_{dc} = 1130$ V: Figure.3 shows the angular speed of the DSIG. The waveform of the generator torque is shown in Fig.4. The stator currents and voltages waveforms of the DSIG and the related expended plots are shown, respectively, in Fig.5. The feature of vector control is illustrated in Fig.6 and the grid voltage and current are given in Fig.7, The DC link voltage is maintained at a constant level (1130 V) (see Fig.8). It is clear from figures10, 12 that the introduction of the GA can improve greatly the performance of suggested system. In fact, it can be noted that the specific speed and coefficient speed are considerably ameliorated, which leads us to say that optimization by GA gives us the possibility of designing a powerful PI and fuzzy controllers by optimizing their parameters. Hence that the real power extracted from the wind energy conversion systems can pass through the grid. Figure 13 illustrates the grid active and reactive powers.

TABLE I. NORMALIZATION FACTORS OF PI FOUND BY GENETIC ALGORITHMS.

	k_i	k_p
PI	200000	40
PI-GA	300000	500

TABLE II. NORMALIZATION FACTORS OF FLC FOUND BY GENETIC ALGORITHMS.

	k_e	$k_{\Delta e}$	$k_{\Delta c}$
FLC	0.14	0.003	8.584
FLC-GA	6	4	70000

Fig. 3 indicate the random of wind speed the wind changes speed on a ramp to another value $V = 6.5025 m/s$ a time of 15 ,Fig. 4 shows the angular speed random of the DSIG. Fig. 5 shows the waveform of the generator torque. The decoupling effect of the between the direct and quadratic rotor flux of the DSIG is illustrated in Fig. 6. Show the regulation of the DC link voltage, It is maintained at a constant level (1130 V) in Fig. 11, finally, gives the grid active and reactive powers are shown in Fig. 12.

TABLE III. SUMMARY OF RESULT.

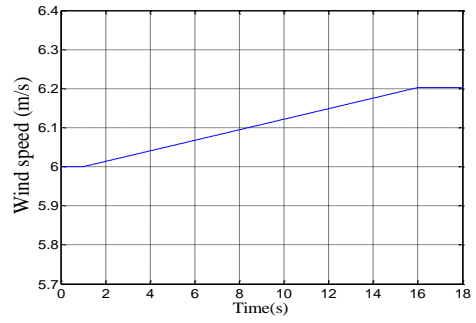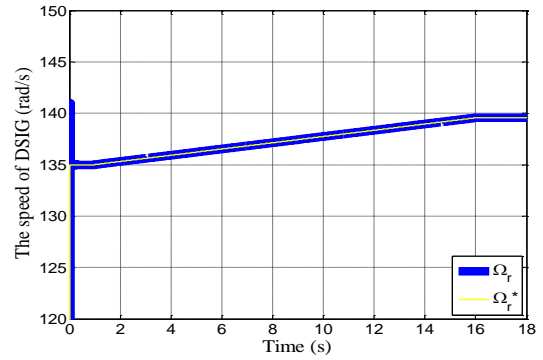|	C_p error $\%$	λ error %	The necissaire time to restore its initail value %
PI	0.07	2.4	15
GA-PI	0.04	2.4	15
FLC	0.0001	0.36	0.2
GA-FLC	0.0001	0.36	0.001

Figure 3. Random of wind speed.

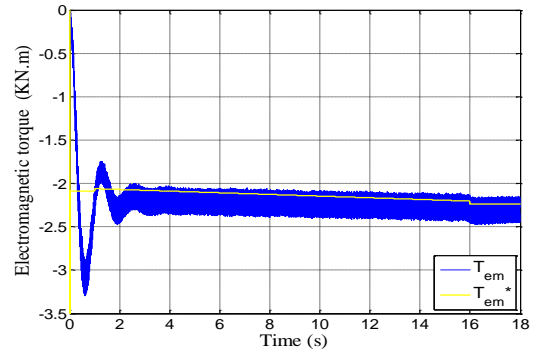Figure 4. DSIG speed and its reference.

Figure 5. DSIG Torque and its reference.
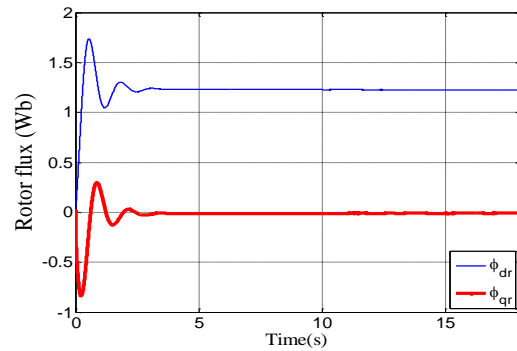

Figure 6. Direct and quadratic rotor flux.
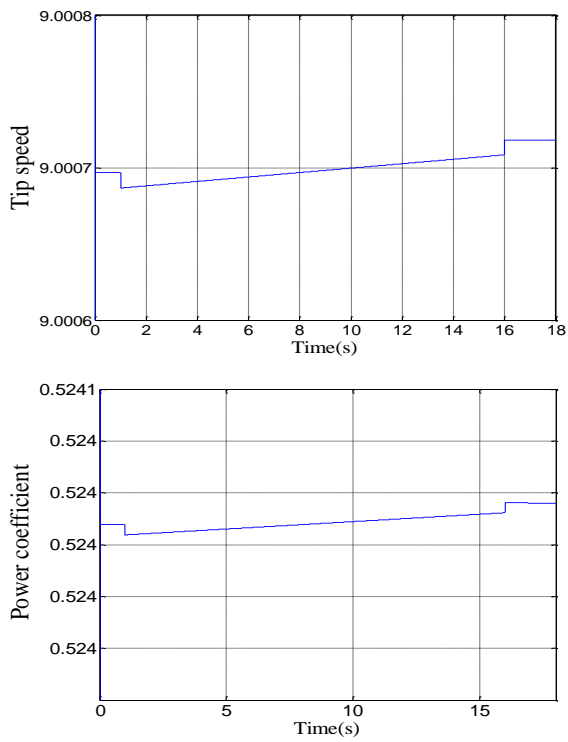
Figure 7.   The tip speed and power coefficient with conventional PI.
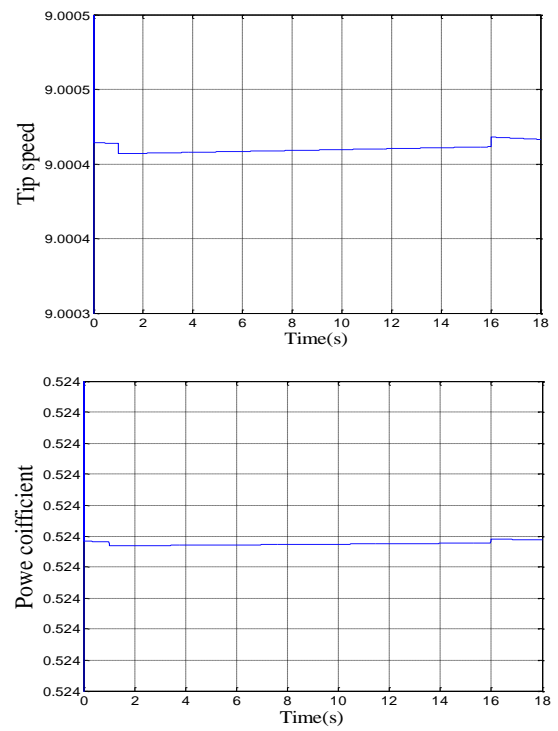

Figure 9.   The tip speed and power coefficient with PI optimized.
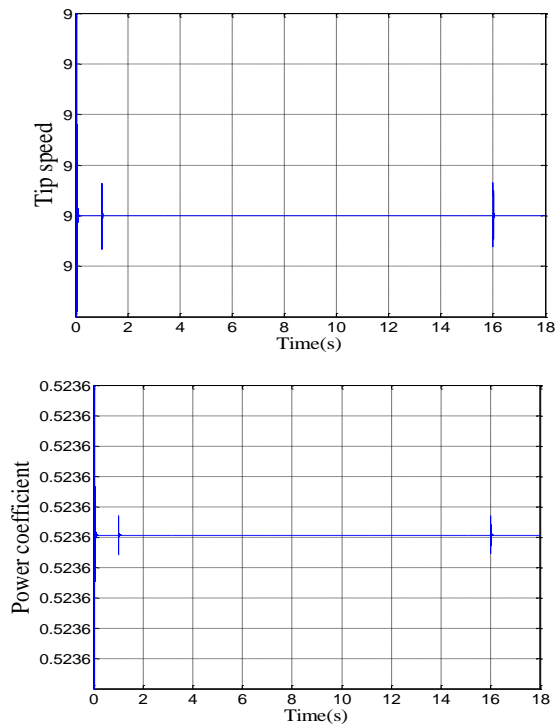

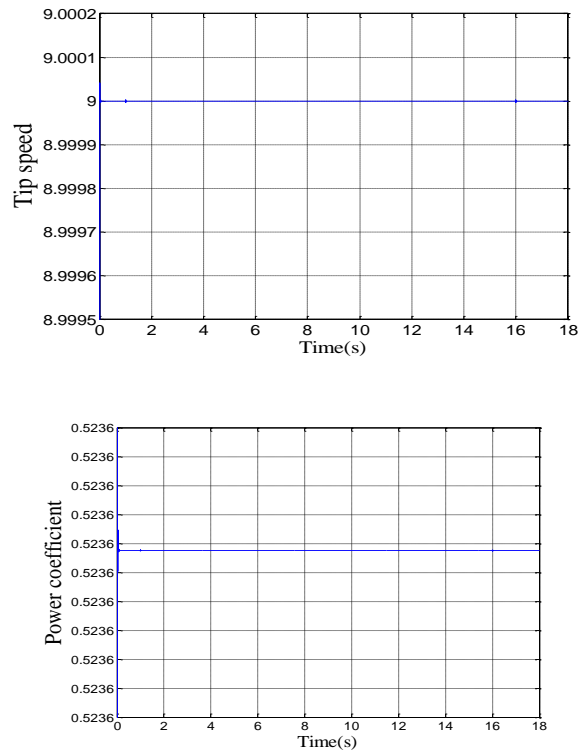Figure 8.   The tip speed and power coefficient with fuzzy PI.

Figure 10.   The tip speed and power coefficient with PI fuzzy optimized.
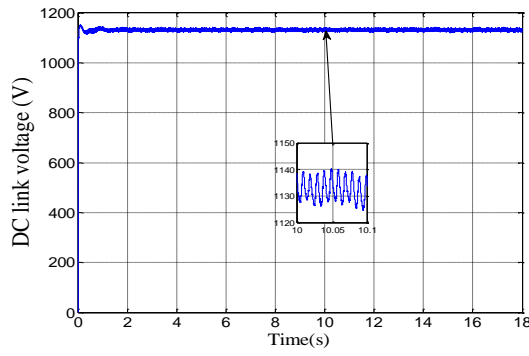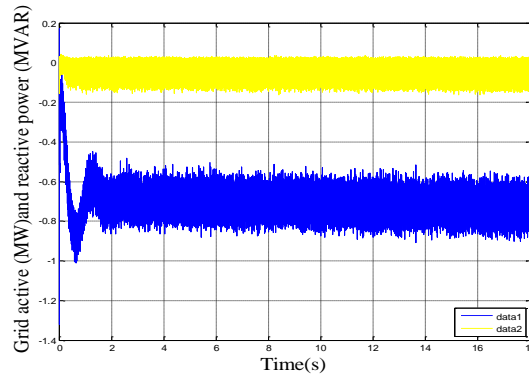
Figure 11.   DC link voltage.

Figure 12.   Grid active and reactive power.

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
ω_{gl}	Sliding 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

VII.   CONCLUSION

In this paper the genetic algorithms is applied to automate and optimize the PI and fuzzy logic speed vector control of   dual stator induction generator in wind energy conversion system connected to the grid. The validity of the proposed controllers is confirmed through the simulation results. It testifies that optimization method is not only robust, but also can improve dynamic performance of the system. The GA-PI and GA-FLC proposed approach achieves:

- Good pursuit of reference speed;
- Good support for changes of the turbine and the generator as well as to electric grid disturbances.

APPENDIX

A. PARAMETERS

Turbine: Diameter = 60 m, Number of blades = 3, Hub height =85 m, Gearbox = 90.

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).

B. NOMENCLATURE

G	Gear ratio
V	Wind velocity

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