# An Optimized Adaptive Neural-Fuzzy Controller Based on an Indirect Vector Control of   Doubly Fed Induction Generator for Wind Power Generation

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*Abstract— This paper proposes a genetic algorithm optimized adaptive neural-fuzzy controller based on an indirect vector control of Doubly Fed Induction Generator (DFIG) for wind power generation. The goal of this paper is to optimize the performances of a wind energy conversion system based on DFIG. In a first step vector control applied to the stator flux of DFIG is presented. In a second step, to ensure the real-time tracking of the optimum operating point and Maximum Power Point Track  (MPPT) giving online a maximum production of electric power for different wind speeds, PI and fuzzy controllers are  used for speed control. In the last step, in order to improve the dynamic performance of proposed system, an Adaptive Neuro-Fuzzy Inference Systems (ANFIS) optimized by genetic algorithms is suggested for the speed regulation. The efficiency and validity of the proposed control strategy are illustrated by simulation results.*

*Keywords— Doubly Fed Induction Generator, Variable Speed Wind Turbine,Vector control, PI and fuzzy controllers,   ANFIS Controller, optimization method,Genetic algorithms.*

## 1.  Introduction

Over  the  past  few  years,  the  exploration  of renewable  energy  sources,  such  as  wind, photovoltaic, and hydro power plants have been the subject of increased attention. 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.  Several  electrical  machines can  be  used  to  implement  the  electromechanical conversion,  each  of  which  presents  different advantages  and  drawbacks  [1-4].  For  this  special operation,  the  induction  machine,  and  more precisely  the  doubly  fed  induction  generator, remains  widely  used  due  to  their  variable  speed feature  and  hence  influencing  system  dynamics. Indeed,  the  structure  is  robust,  needs  little maintenance, and is relatively inexpensive.

However, a variable speed wind energy conversion system  with  the  ***DFIG***  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 [4].

In  recent  years,  Artificial  Neural  Network intelligent  (ANN)  and  Fuzzy  Logic  Controller (FLC) have  gained  great    important  and  proved their  dexterity  of  many  respects  [5].  It  has  great potential using to neural topology does not need the mathematical model of the system to be controlled.

In other hand, the FLC has played an increasing and significant role in the development and design of  real-time  control  applications.  However, membership function type, number of rules and correct  selection  of  parameters  of  FLC  are  very important  to  obtain  desired  performance  in  the system.  The  selection  of  suitable  fuzzy  rules, membership functions, and their definitions in the universe  of  discourse  invariable  involves painstaking  trial-error.  The  main  purpose  of  using the  ANFIS   approach  is  to  automatically  realize  the

fuzzy system by using the neural network methods. The ANFIS architecture has well known advantages of modeling a highly non-linear system, as it combines the capability of fuzzy reasoning in handling the uncertainties and capability of artificial neural network (ANN) in learning from processes. A combination of the strengths of Fuzzy Logic controllers and Neural Networks creates systems capable of controlling complex systems and adaptively learning to optimize control parameters [3], [6].

These advantages justify the necessity of applying this kind for the DFIG used in wind energy conversion systems.

In order to improve the design parameters determination of ANFIS controller and reduced time consumption comparatively to the "trial-error" method, we address using genetic algorithms. Genetic Algorithms (GAs) is a search heuristic that mimics the process of evaluation. Genetic Algorithms can be applied to process controllers for their optimization using natural operators [7],[8]. Such an optimal ANFIS could provide ideal control performance and achieve desired speed.

The special merit of the suggested optimized ANFIS controller is a): To search the optimum operating point for wind power generation in speed control mode. b) To improve the performance of wind energy conversion systems especially the power coefficient of the turbine and λ which allows the optimization of the efficiency of the maximum power extraction.

The outline of this paper is as follows: in section 2, the modelling of the wind generator and the maximum power point tracking (MPPT) are presented. Section 3 deals with the stator field oriented control of a DFIG. The design of an ANFIS for speed regulation of a DFIG is presented in section 4. In section 5 genetic algorithms based ANFIS controller is proposed. In section 6 the performances of the proposed control are illustrated by some simulation results. Finally some concluding remarks are given in section 7.

## 2. Modeling of the wind generator

### A. *Modeling of the wind turbine and gearbox*

The aerodynamic power, which is converted by a wind turbine, is dependent on the power coefficient *Cp*. It is expressed as follows [2], [3],[9]:

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

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 $\Omega_t$, 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:

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

Where the $C_g$ driving is torque of the generator and $\Omega_r$ is the generator shaft speed. The captured wind power is not converted totally by the wind turbine. Cp (λ) give us the percentage converted which is function of the wind speed, the turbine speed and the pith angle of specific wind turbine blades [2],[9].

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

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

The aerodynamic torque (wind) is determined the following equation [2],[9]:

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

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 [2],[9].

## B. Doubly fed induction generator model

Under the assumptions of magnetic circuits linearity, and assuming sinusoidal distributed air-gap flux density, the equivalent two-phase model of DFIG motor, represented in a synchronous frame (d,q) and expressed in state-space form, is a fourth-order model [10-13]:

$$x^{\cdot} = Ax + Bv_s \qquad (6)$$

where :

$$x = \begin{bmatrix} i_{ds} & i_{qs} & \varphi_{ds} & \varphi_{qs} \end{bmatrix}^T$$

$$v_s = \begin{bmatrix} v_{ds} & v_{qs} & v_{dr} & v_{qr} \end{bmatrix}^T$$

The system matrices are given by:

$$A = \begin{bmatrix} \frac{1}{\sigma}\left(\frac{1}{\tau_s}+\frac{1}{\tau_r}\right) & (\omega_s - \omega_r) & \frac{1}{\sigma L_s \tau_r} & \frac{\omega_r}{L_s \sigma} \\ -(\omega_s - \omega_r) & -\frac{1}{\sigma}\left(\frac{1}{\tau_s}+\frac{1}{\tau_r}\right) & -\frac{\omega_r}{\sigma L_s} & \frac{1}{\sigma L_s \tau_r} \\ -R_s & 0 & 0 & \omega_s \\ 0 & -R_s & -\omega_s & 0 \end{bmatrix}$$
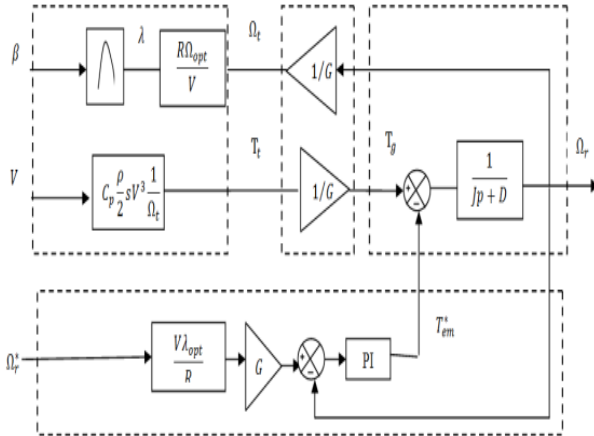


Fig. 1. Control of turbine.

And

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & -\frac{M}{\sigma L_s L_r} & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & -\frac{M}{\sigma L_s L_r} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

where $\sigma = 1 - \dfrac{M^2}{L_s L_r}$ and $\tau_r = \dfrac{R_r}{L_r}, \tau_s = \dfrac{R_s}{Ls}$

The mechanical modeling part of the system is given by:

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

Moreover, the electromagnetic torque is given by:

$$T_{em} = \frac{3}{2}P\left(\varphi_{ds}\, i_{qs} - \varphi_{qs}\, i_{ds}\right) \qquad (8)$$

## 3. Stator field oriented control

According to the field orientation theory [11-14], the machine currents are decomposed into $i_{sd}$ and $i_{sq}$ components, which are respectively, flux and torque components. The key feature of this technique is to keep namely $\psi_{sq} = 0$ and $\psi_{sd} = \psi_s$.

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 [11-14]:

$$T_{em} = -\frac{3}{2}p\frac{M}{L_s}\varphi_{ds}\, i_{qr} \qquad (9)$$

The expressions of the stator currents may be given as:

$$i_{ds} = -\frac{M}{L_s}i_{dr} + \frac{\varphi_{ds}}{L_s}$$
$$i_{qs} = -\frac{M}{L_s}i_{qr} \qquad (10)$$

The stator flux orientation is proportional to the grid voltage, Vs. Neglecting the small drop in the stator resistance.

$$v_{ds} = 0$$
$$v_{qs} = v_s = \omega_s \varphi_{ds} \qquad (11)$$

This, when the orienting the direct axis with the stator flux, the voltage aligns with the quadrature axis. The stator active and reactive power flow can then be written as:

$$P_s = v_{qs}\, i_{qs}$$
$$Q_s = v_{qs}\, i_{ds} \qquad (12)$$

Using equations (12) and equation (10), we obtain:

$$P_s = -\frac{3}{2} v_s \frac{M}{L_s} i_{qr}$$
$$Q_s = \frac{3}{2}\left(\frac{v_s{}^2}{L_s \omega_s} - \frac{M}{L_s} v_s i_{dr}\right) \qquad (13)$$

These equations indicate that, having a constant stator voltage magnitude, the stator active and reactive powers, $P_s$ and $Q_s$, can be controlled by the appropriate action on the rotor current components ($i_{rq}$) and ($i_{rd}$) respectively.

## 4. Design of ANFIS for doubly fed induction generator speed control

The suggested ANFIS controller has the speed error $e$ and its variation $\Delta e$ as inputs and the output is the electromagnetic reference torque change. At the input layer, the speed error and its variation are sampled and fuzzified according to pre-decided fuzzy rules.

The training procedure of ANFIS is based on FLC (See Fig. 2). For convenience, the inputs and output of ANFIS were scaled with three different coefficients $k'_e, k'_{\Delta e}, k'_{\Delta Temref}$. These scaling factors can be constants or variables, and play an important role for ANFIS design in order to achieve a good behavior in both transient and steady state. (See Fig. 2). In this work, the ANFIS parameters are chosen as follows:

- Takagi Sugeno Type ;
- Number of membership functions is 7 ;
- Number of iteration is 50;
- Error tolerance is $10^{-3}$.

## 5. Genetic algorithms based on an ANFIS controller

The genetic algorithm is applied to automate and optimize the ANFIS design process (see Fig.2). This optimization requires a predefined of different parameter of GAs such as: coding, fitness, selection, mutation, and specifying of (Crossover probability, mutation rate, Population size and Number of generations) [7],[8]. In this work it has used: - Real coding of each individual composed by genes. The fitness or objective function is defined by [2]:

$$\min\left(f_{obj} = \frac{1}{(\Omega_{rref})^2}\int_0^{t_f}(\Omega_r - \Omega_{rref})^2\, dt\right)$$

(14)

-Population sizes 50; -Selection of stochastic uniform; -Multiple Crossover with probability 0.8; -Uniform mutation with a probability of 0.001; - Number of generations is 100.

TABLE.1 OPTIMIZED SCALING FACTORS OF ANFIS FOUND BY GENETIC ALGORITHMS

| Controller | Scaling factors | | |
|---|---|---|---|
| | $k'_e$ | $k'_{\Delta e}$ | $k'_{\Delta Temref}$ |
| ANFIS | 3.9 | 0.1 | 400 |
| ANFIS-GA | 1.999 | 0.067 | 544.899 |

## 6. 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 DFIG using an ANFIS controller optimized by the GAs technique. The parameters of the test DFIG used in the simulation are given in Table 2 and Table 3. The suggested control strategy is compared with conventional PI and fuzzy controllers.

The results of simulations are obtained for reactive power Q = 0 and unity power factor. From figure.4 it can be seen that the wind power captured and DFIG speed follow properly their optimal reference and have the same waveform as applied wind profile. The electromagnetic torque converges quickly to its reference. The stator active power tracks quite well its set-point up to the rated speed and extracts the maximum power, when the reactive power is fixed to 0 VAR. From the stator voltage and current waveforms, it can be seen that, the stator operates nearly at unity power factor.

Figure. 4, a), b) and c) shows that the proposed optimized ANFIS has high accuracy and reliability in comparison with the PI and fuzzy logic controllers, in tracking of the maximum power point in different wind speeds so that total error remarkably reduces. So, it is easily seen that the use of an optimized ANFIS improve very well the performance of wind energy conversion systems especially the power coefficient $Cp$ and $\lambda$. In fact, the coefficient $Cp$ close to its maximum value during the whole wind speed profile, same for tip speed ratio $\lambda$. 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.



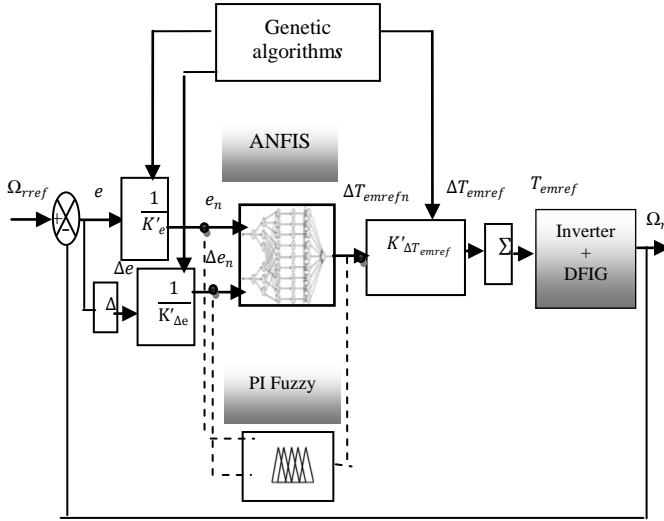Fig. 2. Basic structure of the optimized ANFIS controller based on an indirect field oriented control of DFIG.
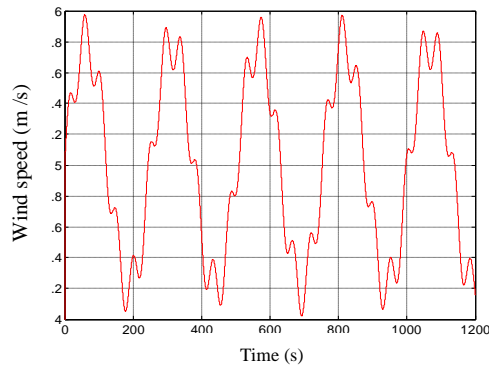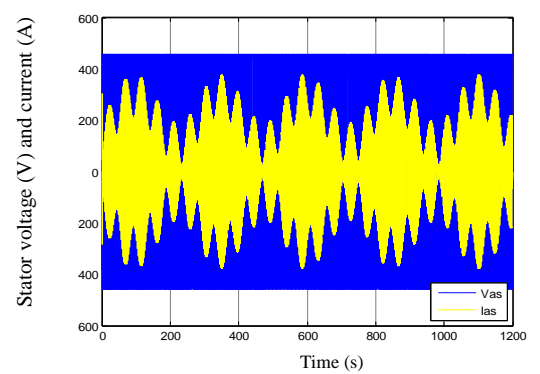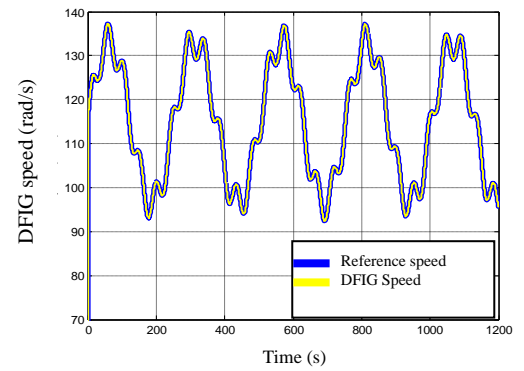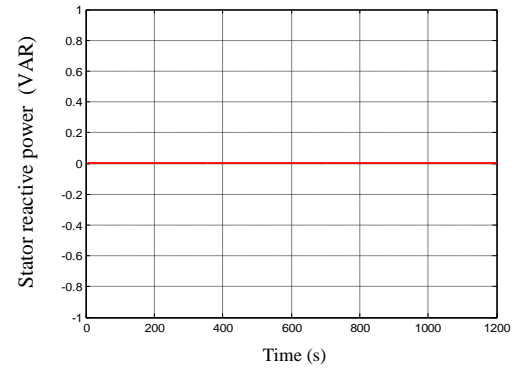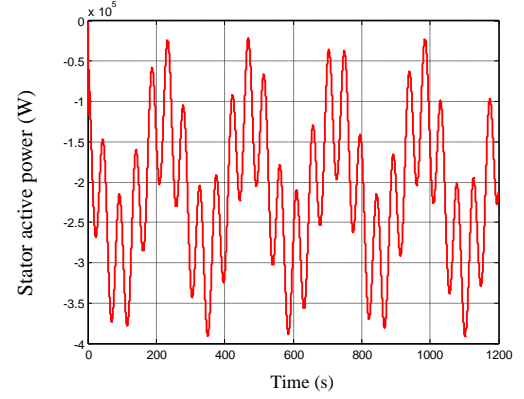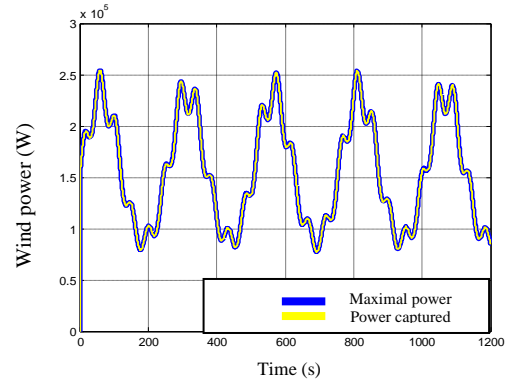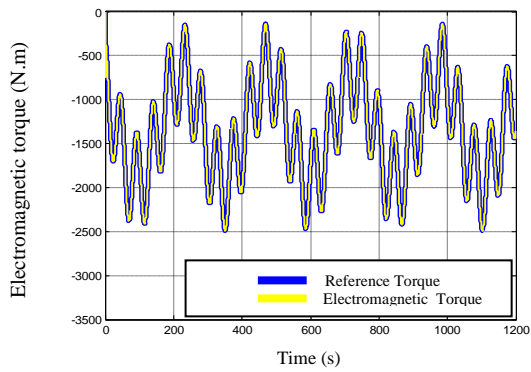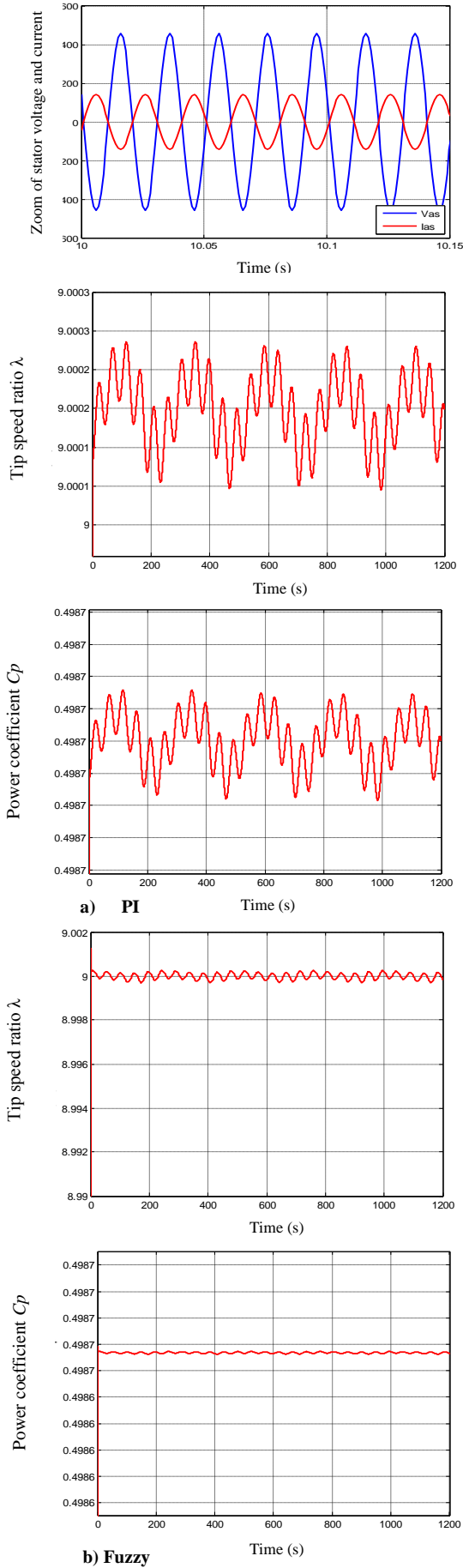


Fig. 3. Wind speed in form of random.

**c) ANFIS Optimized**

Fig. 4. Simulation results of a speed regulation using an optimized based on a stator field oriented DFIG.

## 7. Conclusion

In this paper, a new optimized adaptive neuro-fuzzy control for wind energy conversion system based on a doubly-fed induction generator has been presented. It has determined from simulation results, that the optimized ANFIS can greatly improve the power system performances. Besides the suggested optimized ANFIS controller achieves:

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

TABLE.2 TURBINE PARAMETERS

| Parameters | | |
|---|---|---|
| *Diameter* | *Number of blades* | *Gearbox* |
| 35.25m | 3 | 90 |

TABLE.3 DFGI PARAMETERS

| $P_n$ | 1.5 MW |
|---|---|
| $V_n$ | 398V |
| P | 2 |

**a) PI**

**b) Fuzzy**

| $R_s$ | $0.012\Omega$ |
|---|---|
| $R_r$ | $0.021\Omega$ |
| $L_s$ | $0.0137H$ |
| $L_r$ | $0.0136H$ |
| M | $0.0135H$ |
| J (turbine + DFIG) | $1000$ kg m$^2$ |
| D (turbine + DFIG) | $0.0024$ N. m.s/rad |

NOMENCLATURE

| G | Gear ratio |
|---|---|
| V | Wind velocity |
| $P_n$ | Nominal power |
| S | Area of the rotor |
| $\Omega_r, \Omega_t$ | Mechanical speed of DFIG, Turbine speed |
| $T_t, T_g$ | Aerodynamic torque, Generator torque |
| $R_s, L_s, M$ | Per phase stator resistance, leakage rotor inductance , Magnetizing inductance |
| $R_r, L_r$ | Per phase rotor resistance, rotor leakage inductance |
| J, D | Inertia (turbine+DFIG),Viscous coefficient |
| P, p | Number of pole pairs, Derivative operator |
| $\omega_s, \omega_r$ | Stator and rotor pulsation |
| Vas,Ias | Stator voltage and current |

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