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Maximum Power Tracking of Doubly-Fed Induction Generator using Adaptive Neuro-Fuzzy Inference System

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Abstract— This paper deals with the Artificial Intelligent control of Doubly-Fed Induction Generator using Adaptive Neuro-Fuzzy Inference System in order to generate maximum power at variable wind speed. The rotor control is achieved here using the combined features of neural network and fuzzy logic controller.

Index Terms—Doubly-fed Induction Generator (DFIG), Wind Energy Conversion System (WECS), Adaptive Neuro-Fuzzy Inference System (ANFIS)

I. INTRODUCTION

Due to the depletion of fossil fuel and its high cost, renewable energy plays an alternate method to meet the power demand with environmental clean and cheapest resources. On the other hand, Wind power is plentiful, renewable, widely distributed, clean and produces no greenhouse gas emissions during operation and uses little land than other energy production systems. In wind energy conversion system, the wind energy is converted into mechanical energy in turbine by aerodynamic principle and again converted into electrical energy in generator by the principle of electromagnetic induction. By Betz limit, no wind turbine could convert more than 59.3% of the kinetic energy of the wind into mechanical energy. MPPT Controller is designed to use the minimum power extracted from the wind efficiently. This paper is organized as follows: Section II gives a brief introduction to wind turbine characteristics and to the DFIG wind generation system and its model. Section III gives a brief introduction to the proposed method of ANFIS. Section IV, the proposed ANFIS with DFIG is discussed as in [1]. Section V gives the simulation results for three different wind structures. Section VI gives the final conclusion of the paper.

II. WIND ENERGY CONVERSION SYSTEM

A. Wind Turbine

The wind turbine will rotate by consuming the power from the wind and convert it into electrical energy by using the Doubly-fed Induction generator.

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The wind power is given by the kinetic energy of the flowing air mass per unit time and given as in ([2]–[6]):

$$P_W = \frac{1}{2}\rho A v^3 \quad (1)$$

where,

P_W= Wind power (W)

ρ= Air density (~1.225kg/m^3)

A= Rotor area (m^2)

V= Wind velocity (m/s)

Wind turbines cannot able to consume wind power efficiently only part of the wind power those extracted mechanical power P_m of the wind turbine is given as follows,

$$P_m = \frac{1}{2} C_p(\lambda,\beta)\rho A v^3 \quad (2)$$

where,

P_m = Mechanical power of the turbine (W)

C_p = Power coefficient

λ = Tip speed ratio

β = Blade pitch angle (deg)

The coefficient of power of the wind turbine is a measurement of how efficiently the wind turbine converts the energy in the wind into electricity and is given as,

$$C_p(\lambda,\beta) = C_1\left[\left(\frac{C_2}{\lambda_1} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_1}}\right] + C_6\lambda \quad (3)$$

$$\frac{1}{\lambda_1} = \left[\frac{1}{\lambda + 0.08\beta}\right] + \left[\frac{0.035}{\beta^3 + 1}\right] \quad (4)$$

The coefficients C1 to C6 are,

C_1= 0.5176, C_2=116, C_3 =0.4, C_4 =5, C_5 =21 and C_6=0.0068

Tip speed ratio (TSR) of a wind turbine is given as,

$$\lambda = \frac{\omega R}{V} \quad (5)$$

where,

ω = Rotor speed (rpm)

R = Radius of the wind turbine blade (m)

In order to produce maximum power from the wind turbine, the rotor of the generator should be optimum which optimises the tip speed ratio (TSR). The maximum power can be described as,

$$P_{max} = \frac{1}{2}\rho\pi R^5 \frac{C_{p,max}}{\lambda_{opt}^3}\omega^3 \quad (6)$$

The Maximum torque of the wind turbine is given as,

$$T = \frac{P_{max}}{\omega} \quad (7)$$

where,

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T = Torque of the rotor.

B. *Doubly-Fed Induction Generator*

The DFIG is an adjustable-speed induction machine which is widely used in modern wind power industry. It consists of wound rotor and an AC/DC/AC converter where power is fed from both stator as well as rotor to the grid as in ([7],[8]). Power loss in the electronic converter will be minimum than the synchronous generator which has converter in series will consume more power than DFIG. Power electronic converter has the ability to absorb and generate the reactive power which eliminates the need of installing capacitor bank. DFIG rotor runs at variable speed in order to optimise the tip speed ratio and has the ability to operate always as a generator at both sub and super synchronous speed. Doubly-Fed Induction Generator (DFIG) has the stator directly connected to the grid whereas the rotor connected to grid through AC/DC/AC converter; therefore power absorbed by them will be only one-third of the generator power. This back-back converter has two converters where grid-side converter used to control the DC-link voltage and machine-side converter used to control power tracking as in [9]. Cut-in speed is the minimum speed about 3-6 m/s required for a generator to connect with the grid. Cut-out speed is the maximum speed about 20-25 m/s required for the generator in order to disconnect from the grid and starts working when it attains the required cut-in speed as in ([10],[11]).

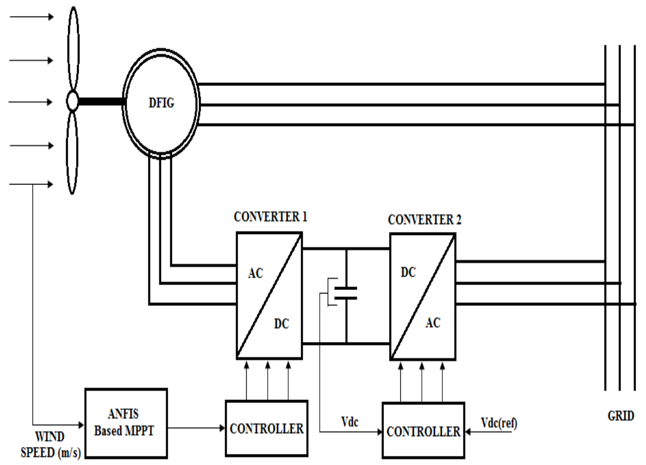

Fig. 1. DFIG modelling in Wind energy conversion system

C. *Mathematical model of DFIG*

The DFIG state model is represented by using synchronous reference frame as in [12].The direct and indirect Flux linkage of the stator and rotor windings can be given as:

$$\frac{d\Psi_{qs}}{dt} = \omega_b\left\{V_{qs} - \frac{\omega_e}{\omega_b}\Psi_{ds} + \frac{R_s}{x_{ls}}(\Psi_{mq} + \Psi_{qs})\right\} \quad (8)$$

$$\frac{d\Psi_{ds}}{dt} = \omega_b\left\{V_{ds} - \frac{\omega_e}{\omega_b}\Psi_{qs} + \frac{R_s}{x_{ls}}(\Psi_{md} + \Psi_{ds})\right\} \quad (9)$$

$$\frac{d\Psi_{qr}}{dt} = \omega_b\left\{V_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b}\Psi_{dr} + \frac{R_s}{x_{lr}}(\Psi_{mq} + \Psi_{qr})\right\} \quad (10)$$

$$\frac{d\Psi_{dr}}{dt} = \omega_b\left\{V_{dr} - \frac{(\omega_e - \omega_r)}{\omega_b}\Psi_{qr} + \frac{R_s}{x_{lr}}(\Psi_{md} + \Psi_{dr})\right\} \quad (11)$$

$$\Psi_{mq} = x_{ml}\left\{\frac{\Psi_{qs}}{x_{ls}} + \frac{\Psi_{qr}}{x_{lr}}\right\} \quad (12)$$

$$\Psi_{md} = x_{ml}\left\{\frac{\Psi_{ds}}{x_{ls}} + \frac{\Psi_{dr}}{x_{lr}}\right\} \quad (13)$$

The direct and indirect Current of the stator and rotor windings can be given as:

$$i_{qs} = \frac{1}{x_{ls}}(\Psi_{qs} - \Psi_{mq}) \quad (14)$$

$$i_{ds} = \frac{1}{x_{ls}}(\Psi_{ds} - \Psi_{md}) \quad (15)$$

$$i_{qr} = \frac{1}{x_{lr}}(\Psi_{qr} - \Psi_{mq}) \quad (16)$$

$$i_{dr} = \frac{1}{x_{lr}}(\Psi_{dr} - \Psi_{md}) \quad (17)$$

The Electrical Torque produced in generator is given as:

$$T_e = \frac{3p}{4\omega_b}(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \quad (18)$$

$$T_e - T_L = \frac{2J}{p}\frac{d\omega_r}{dt} \quad (19)$$

$$x_{ml} = 1/\left[\left(\frac{1}{x_m}\right) + \left(\frac{1}{x_{ls}}\right) + \left(\frac{1}{x_{lr}}\right)\right] \quad (20)$$

where,

d - direct axis,
q - quadrature axis,
s - stator variable,
r - rotor variable,
p- number of poles,
J - moment of inertia,
R_r- rotor resistance,
R_s- stator resistance,
x_{lr}- rotor leakage reactance,
x_{ls}- stator leakage reactance,
x_m- magnetizing impedance,
T_e- electrical output torque,
T_L- load torque,
ω_e- stator angular electrical frequency,
ω_r- rotor angular electrical speed,
P - active power,
Q - reactive power,
$\Psi_{qs,ds}$- stator flux linkages,
$\Psi_{qr,dr}$- rotor flux linkages,
$\Psi_{mq,md}$- q and d axis magnetizing flux linkages,
i_{qs},i_{ds}- q and d axis stator currents,
i_{qr},i_{dr}- q and d axis rotor currents.

III. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM (ANFIS)

Adaptive Neuro Fuzzy Inference System (ANFIS) is an artificial neural network which is based on Takagi–Sugeno fuzzy inference system. ANFIS combines both neural networks and fuzzy logic principles; therefore it has the potential to attain the benefits of both neural and fuzzy logic in a single workspace. Inference system of the ANFIS corresponds to a set of fuzzy IF–THEN rules that have learning capability to approximate nonlinear functions as in ([13],[14]). This results in a hybrid intelligent system that synergizes these two techniques by combining the human-like reasoning style of fuzzy systems and structure of neural networks. Neuro-Fuzzy hybridization is widely termed as Fuzzy Neural Network (FNN) or Neuro-Fuzzy System (NFS). Universal approximation is the main strength of Neuro-Fuzzy systems with the ability to solicit interpretable IF-THEN rules

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as in ([15], [16]). The strength of Neuro-Fuzzy systems involves two contradictory requirements in fuzzy modelling namely, interpretability versus accuracy. In practice, only one of the two properties exists. The Neuro-Fuzzy in fuzzy modelling research field is divided into two areas: linguistic fuzzy modelling and precise fuzzy modelling. The former is focused on interpretability, mainly the Mamdani model while the latter is focused on accuracy, mainly the Takagi-Sugeno-Kang (TSK) model.

IV. PROPOSED WECS WITH ANFIS CONTROLLER DESIGN

ANFIS is designed by tracking the rotor speed at which the generator produces the maximum power at variable wind speed by using the equation (6) as in [17]. As the wind speed varies the rotor speed of the generator also varies correspondingly, in order to reach maximum peak power (MaxPower) as shown in Fig. 2.

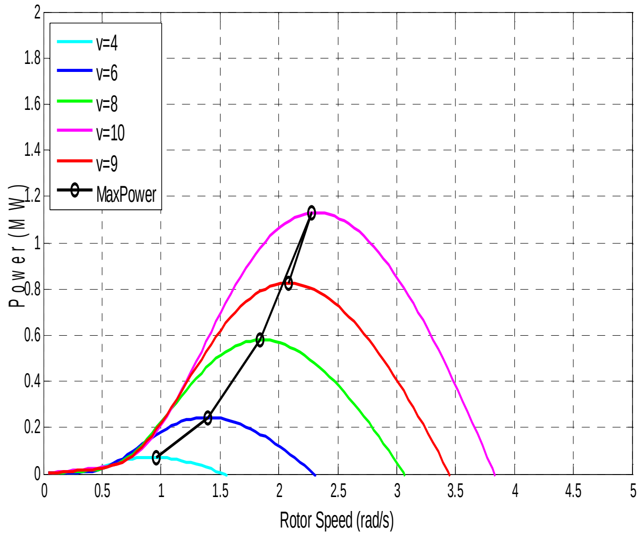

Fig. 2. MPPT of DFIG

The rotor speed is controlled according to the variation of wind speed by using ANFIS based MPPT. Fig. 3 shows the block of ANFIS Training Data, where the wind speed is given as input (data set index) and required rotor speed is given as output as in ([18]–[20]).

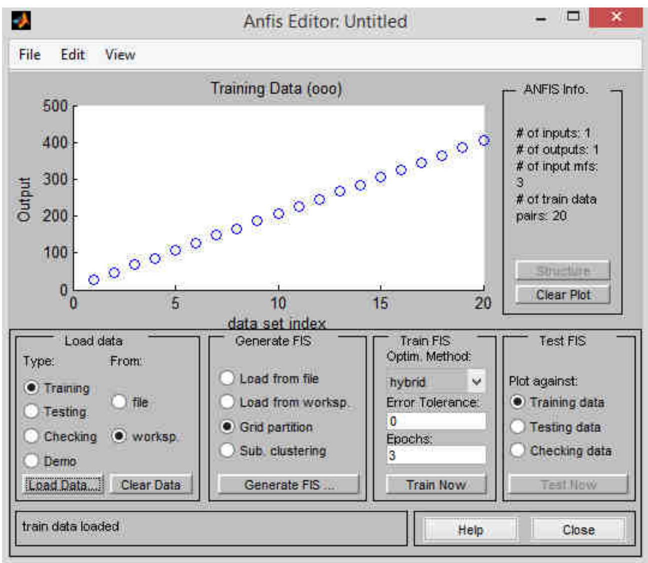

Fig. 3. Training Data

Fig. 5 shows the block of ANFIS Membership Function.

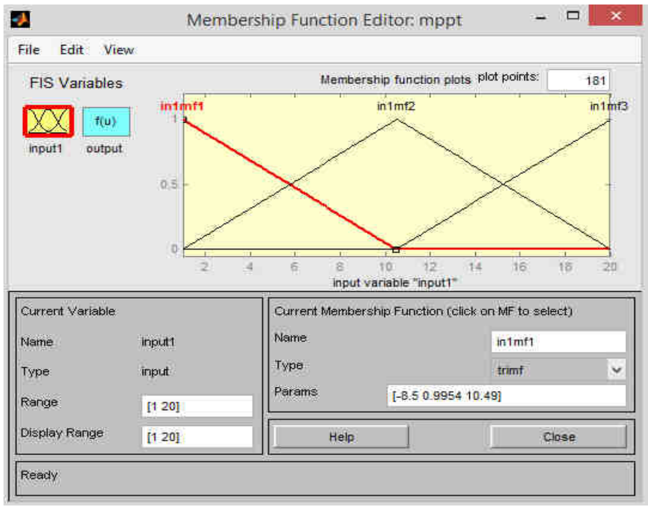

Fig. 5. Membership Function

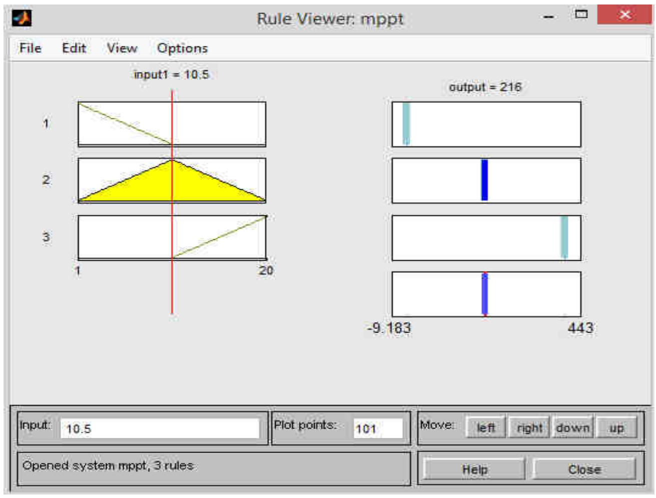

Fig. 6. Rule Viewer of ANFIS

Fig. 7 shows the implementation of ANFIS controller with Doubly-Fed Induction Generator in wind energy conversion system where the wind speed and constraints where given as input to the fuzzy logic controller.

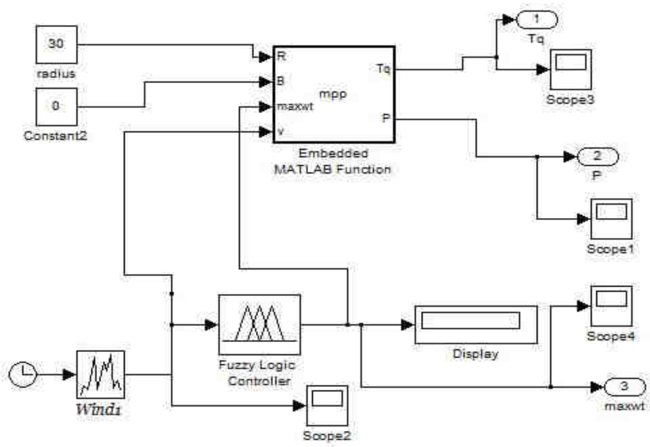

Fig. 7. DFIG with ANFIS Controller

V. SIMULATION RESULTS AND DISCUSSION

DFIG is modelled for various wind structure and simulation results obtained from various wind structure are shown in CASE-I, II and III.

CASE I

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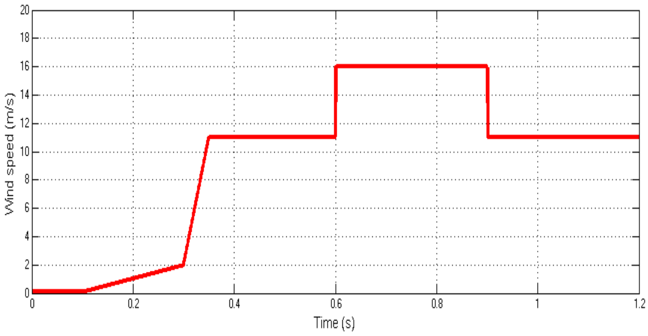

Fig. 8. Wind speed

Fig. 8 shows that the wind speed keep on increasing from the 0.1 sec to the 0.6 sec and be constant till at the time period of 0.9 sec, again reducing its speed.

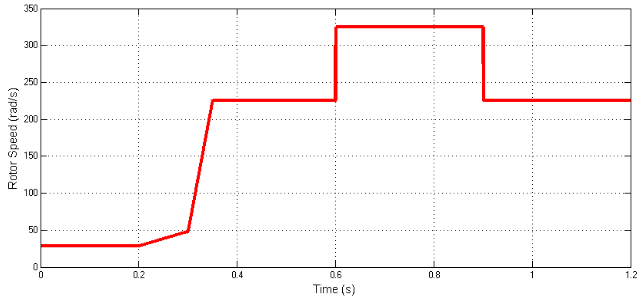

Fig. 9. Maximum Rotor speed

Fig. 9 shows the maximum rotor speed required for DFIG according to the variation of wind speed in order to generate maximum power. If the speed of the wind increases the rotor speed also increases and vice versa.

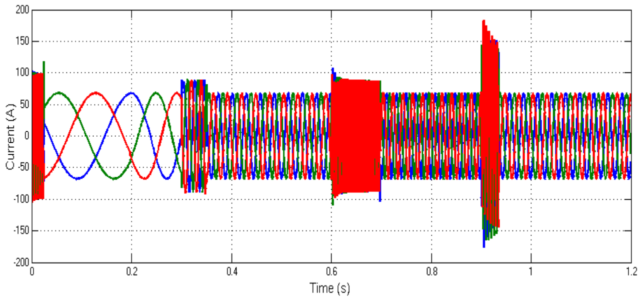

Fig. 10. Output Current

Fig, 10 shows the output current of the generator. If the speed of the wind increases, the frequency and the speed of the rotor will increase and hence the output power is optimum.

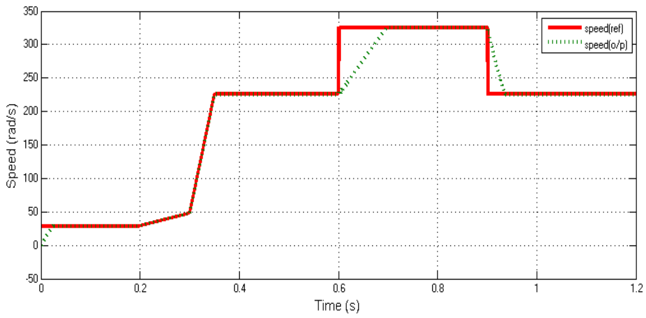

Fig. 11. Speed

Fig. 11 shows that the actual speed (dotted line) of the DFIG is tracking the maximum rotor speed which assumed as reference speed.

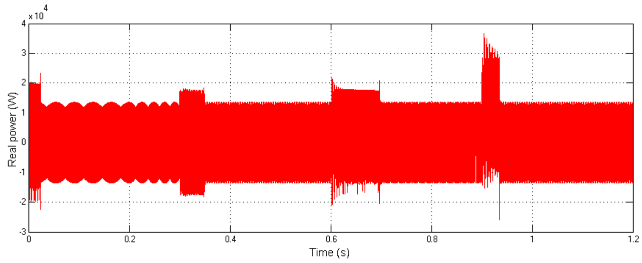

Fig. 12. Real Power

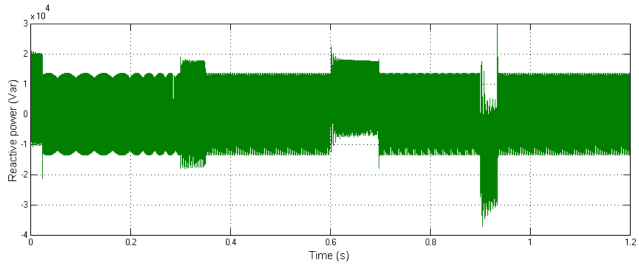

Fig. 13. Reactive Power

CASE III

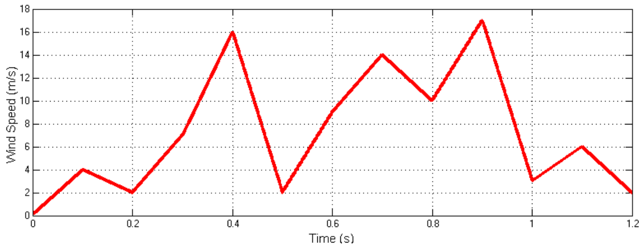

Fig. 20. Wind speed

Fig. 20 shows the rapid variation of wind speed at every time interval 0.1 sec. Wind speed reaches maximum at the time of 0.9 sec where the generator have speed up the rotor to utilize the power extracted by turbine efficiently.

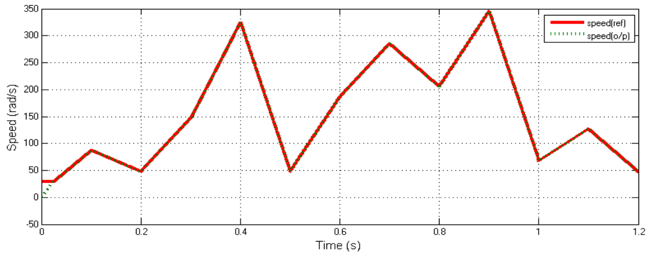

Fig. 21. Maximum rotor speed

Fig. 21 shows the maximum rotor speed required for DFIG according to the variation of wind speed in order to generate maximum power. If the speed of the wind increases the rotor speed also increases and vice versa.

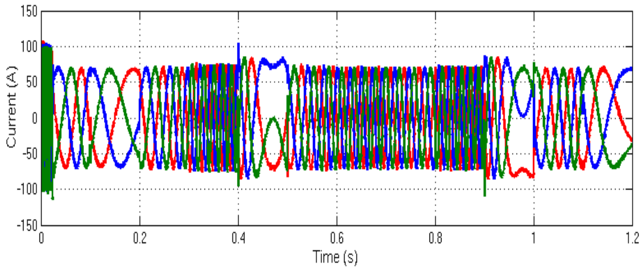

Fig. 22. Output current

Fig, 22 shows the output current of the generator. If the speed of the wind increases, the frequency and the speed of the rotor will increase and hence output power is optimum.

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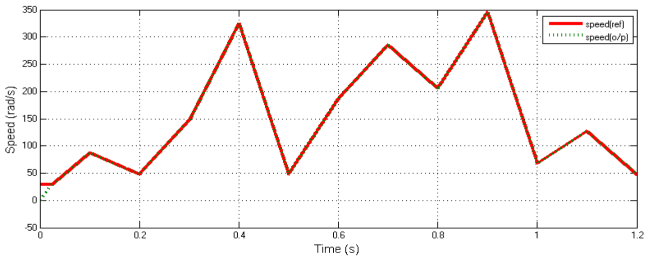

Fig. 23. Speed

Fig. 23 shows that the actual speed (dotted line) of the DFIG is tracking the maximum rotor speed which assumed as reference speed.

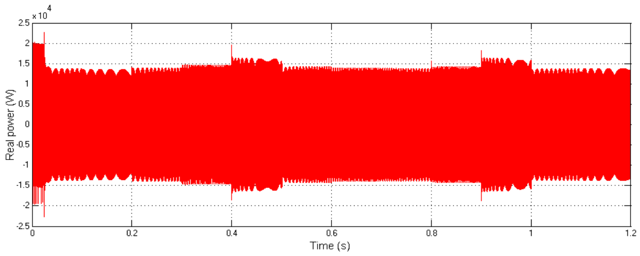

Fig. 24. Real power

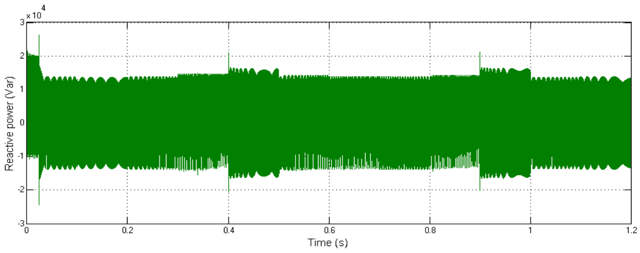

Fig. 25. Reactive power

VI. CONCLUSION

Doubly-Fed Induction Generator is the machine uses widely in Wind Energy Conversion Systems. From the simulation results, we observed that as the wind speed increase the frequency of the Doubly-Fed Induction Machine also increases which indirectly increases the voltage of the machine. Due to increase in voltage the power output of the generator increases and maximum power is obtained for various wind structure.

VII. SYSTEM PARAMETERS

10hp Induction Machine
Rotor resistance = 0.39 ohms
Stator resistance = 0.19 ohms
Stator inductance = 0.21 mH
Rotor inductance = 0.6 mH
Magnetizing inductance = 4 mH
Base frequency = 100 Hz
Number of poles = 4
Moment of inertia = 0.0226
DC link voltage = 300 V

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