

NEW METHOD AND OPTIMIZATION OF ELECTRICAL ENERGY PRODUCTION FROM A WIND TURBINE

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ABSTRACT

This paper deals with a complete 1.5 MW Horizontal Axis Wind Turbine (HAWT) design using a novel Maximum Power Point Tracking (MPPT) algorithm based on real time machine testing and a low cost network communication system. It also includes a blade design study and simulation for a maximum efficiency and a high control strategy for maximum energy production with a minimum harmonic distortion for the generated current. The parameters studied are varied: electrical characteristics, static and aerodynamic, blade geometric profiles, and the influence of wind speed. The wind turbine uses a doubly fed induction generator « DFIG » controlled by a Pulse Width Modulation (PWM) strategy for 27 levels Cascaded three H-Bridge voltage source inverter. It will allow us to control the rotor voltage in magnitude and phase angle more easily & with high efficiency. This wind turbine was used on a 15MW wind farm. The study was conducted through several simulation software (Matlab, Catia, and Solid works). The whole control strategy, design principle and simulation results are shown & discussed.

KEYWORDS

Doubly Fed Induction Generator – Wind Turbine Design – Cascaded H-Bridge Inverter – Pulse Width Modulation.

1. INTRODUCTION

Energy consumption from fossil fuels is considered the major factor of global warming and environmental degradation. The use of natural renewable energy sources such as solar cell, geothermal power, wind, wave power and tidal current has become a reality and a great alternative to generate electrical power.

In order to meet world power needs, without forgetting economic & environmental impacts, the wind energy is the most interesting & recommended source of energy. The wind turbine market does not stop growing. One of the main objectives of wind systems is to develop and improve the effectiveness and efficiency of the wind turbine. [7]

The rotation speed of the blades determines the efficiency of the conversion of wind energy into mechanical energy which is then converted into electrical energy for a given wind speed, precise blades geometry and orientation [6]. This paper studies the characteristics & design of a 1.5 MW HAWT design wind turbine using a Double-Fed Induction Generator (DFIG) (Figure 1).

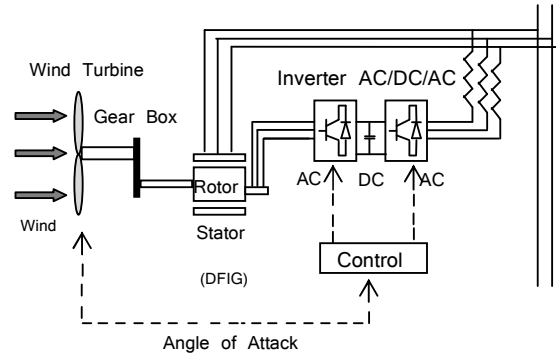


Figure 1. Wind Energy Conversion System based on a doubly fed induction generator

2. PROPOSED METHOD

Our work began by a structural study of the blades (airfoil shape) than an electrical study comes into play. Although wind turbine presents a non linear characteristics, the objectives of the various control approaches is to determine the optimum working point that allows the wind turbine to be extracted optimally at any time. A new Maximum Power Point Tracking (MPPT) algorithm based on real time machine testing and a low cost network communication system on a wind farm was developed and studied. The sensors implemented on only one wind turbine will check every N_{sec} the wind characteristics then will envy them to the controller station. This algorithm implemented on a micro-controller will use this information to calibrate the Nacelle angle and the blades angle to track the maximum power coefficient of the wind turbine & will apply these modifications to all the wind turbines via network. We will use also a Pulse Width Modulation (PWM) technique strategy of a 27 levels Cascaded three H-Bridge voltage source inverter to control the rotor voltage in magnitude and phase angle more easily and with high efficiency. This approach will improve the maximum electrical power generation with a minimum harmonic distortion. This wind turbine design and algorithm will be used into a 15MW wind farm.

3. MODELING OF THE WIND TURBINE

The following equations describe the relation between the mechanic power delivered by the wind turbine and the wind speed:

$$P_t = \frac{1}{2} \cdot \rho \cdot R^2 \cdot v^3 \cdot C_p(\lambda, \beta) \quad (01)$$

$$\lambda = \Omega_r \cdot \frac{R}{v} \quad (02)$$

Where C_p is the power Coefficient; β , Pitch angle (deg) ; λ , Tip speed ratio ; v , wind velocity (m/s) ; R , Radius of the wind turbine ; Ω_r , Turbine speed (rad/s) ; ρ , Air density (1.225 kg/m^3 at $T=15^\circ\text{C}$).

To model C_p , the following generic equation is used:

$$C_p = f(\lambda, \beta) = C_1 \cdot \left(\frac{C_2}{\lambda_i} - C_3 \cdot \beta - C_4 \right) \exp\left(\frac{-C_5}{\lambda_i}\right) + C_6 \cdot \lambda \quad (03)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (04)$$

The coefficients C_1 to C_6 are: $C_1=0.5176$, $C_2=116$, $C_3=0.4$, $C_4=5$, $C_5=21$ and $C_6=0.0068$.

The torque coefficient C_t will be expressed by:

$$C_t = \frac{C_p}{\lambda} \quad (05)$$

The following equation describes the produced torque:

$$T_t = \frac{P_t}{\Omega_r} = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^3 \cdot V^2 \cdot C_t(\lambda, \beta) \quad (06)$$

4. MODELING OF THE AIRFOIL SHAPE

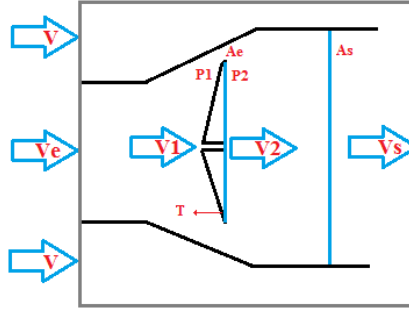


Figure 2. Influence of the wind on the wind turbine

If we consider that the environment is isobaric P_0 and with, A_s , the residual trail section and A_e , the turbine section. We will find:

$$T = \rho \cdot A_s \cdot V_s \cdot (V - V_s) \quad (07)$$

$$\text{If } V_1 = V_2 = V_s \text{ so } T = A_e (p_1 - p_2) \quad (08)$$

From equation (07) and (08) we find:

$$p_1 - p_0 = \rho \cdot \frac{V^2 - V_e^2}{2}, p_0 - p_2 = \rho \cdot \frac{V_e^2 - V_s^2}{2}, \quad p_1 - p_2 = \rho \cdot \frac{V^2 - V_s^2}{2} \quad (09)$$

From equation (07) and (08) we have also:

$$A_e \cdot (p_1 - p_2) = \rho \cdot A_s \cdot V_s (V - V_s) \quad (10)$$

And from equation (09) and (10) we find that:

$$\frac{A_s}{A_e} = \frac{V - V_s}{2V_s} = \frac{1+x}{2x} \text{ With } x = \frac{V_s}{V} \quad (11)$$

The ratio between the residual trail section A_s , and the turbine section A_e , is a function of the only coefficient "x" between the residual velocity and the wind velocity.

From figure 2, we find also:

$$P_e = \frac{V^2 - V_s^2}{2} \rho \cdot A_s \cdot V_s$$

$$P_e = \frac{A_s V_s}{A_e V} \left(1 - \frac{V_s^2}{V^2} \right) \frac{\rho \cdot A_e \cdot V^3}{2}$$

$$P_e = \frac{(1+x)(1+x^2)}{2} \frac{\rho \cdot A_e \cdot V^3}{2} \quad (12)$$

P_e , is the estimated wind turbine power.

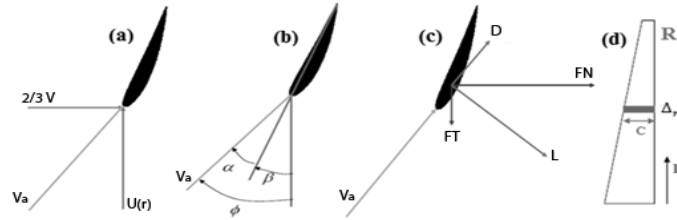


Figure 3. Blade characteristics

For any section along the blade we have:

$$U(r) = \frac{r}{R} \lambda V_a \quad (13)$$

$$\lambda = \frac{U(r=R)}{V_a} \quad (14)$$

Where V is the wind speed; U , the speed induced by the rotation; λ , tip speed ratio; V_a , the wind speed relative to the airfoil shape.

$$\phi = \text{atan} \left(\frac{2}{3\lambda} \left(\frac{R}{r} \right) \right) \quad (15)$$

Φ : is the angle between the velocity vector and on the vertical plane, it varies according to r .

β : is the pitch angle of the blade and the vertical plane, it varies according to r .

α : is the desired angle of attack, it depends on the chosen profile and the position r .

For Δ_r of the airfoil shape we have:

$$D = \frac{1}{2} \rho \cdot V_a^2 \cdot C_D \cdot c \cdot \Delta_r \quad (16)$$

$$L = \frac{1}{2} \rho \cdot V_a^2 \cdot C_L \cdot c \cdot \Delta_r \quad (17)$$

$$\text{With: } c = \frac{16\pi R}{9\lambda^2 \beta} \quad (18)$$

Where, L , is the Lift; C_L , Lift coefficient; D , Drag; C_D : Drag Coefficient; c , the chord of the blade.

The airfoil shape chosen to this study is the NACA-0012 Airfoil shape, the main characteristics of this profile is it finite thickness. That mean, the lift coefficient keeps increasing until the angle of attack reach 90° [11]. Figure 4 and Figure 5 shows the characteristics of the NACA-0012 airfoil shape as a function of angle of attack and Reynolds number.

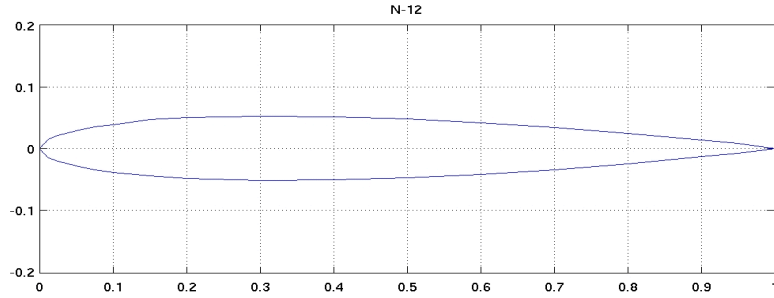


Figure 4. NACA-0012 airfoil shape, NACA Data-Base

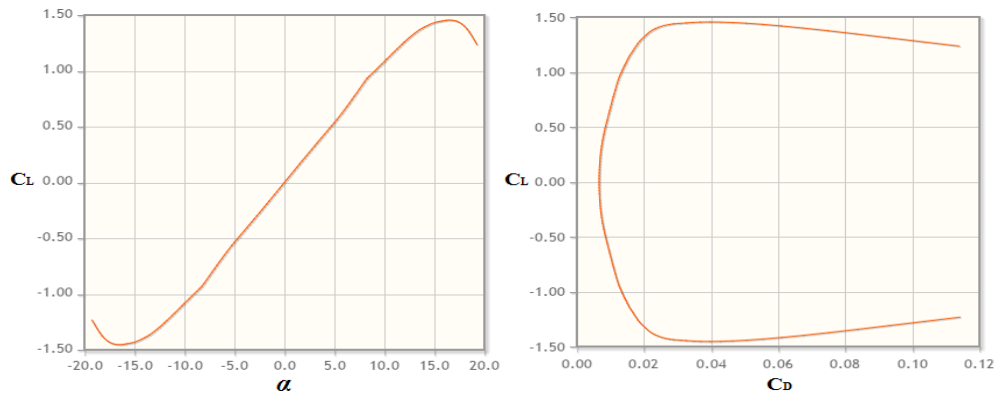


Figure 5. NACA-0012 characteristics, NACA Data-Base

5. MAXIMUM POWER POINT TRACKING

Currently there are a few MPPT algorithm developed for the existing wind turbine [8,9,10]. The most used method is the speed control; it acquires generator speed data and wind speed and direction data [7].

As we know, the Betz limit is the maximum ratio between the kinetic energy of the wind and the mechanical power of the wind turbine used to turn the rotor of the generator [8]. This limit is about $16/27 \approx 0.593$ [2]. In real world this ratio is between 0.40 to 0.50.

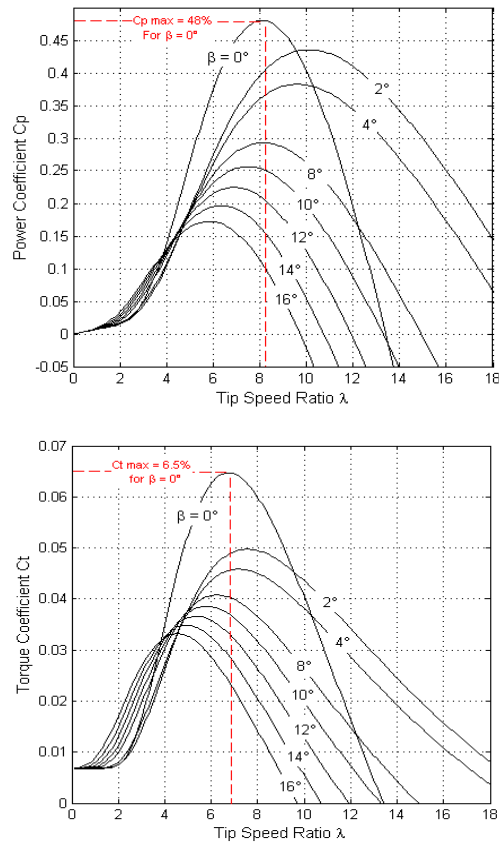


Figure6. Influence of pitch angle on the power coefficient (a) and torque coefficient (b)

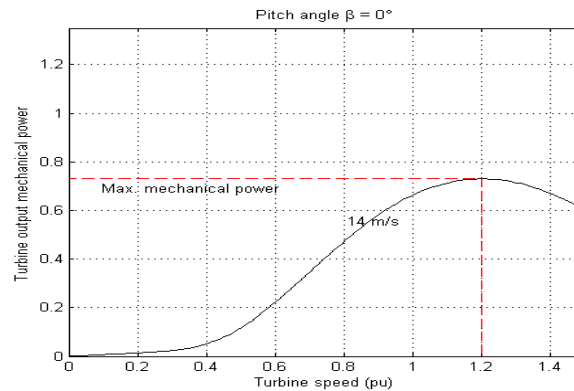


Figure7. Turbine output mechanical power characteristics

This algorithm is based on real time machine testing, it's implemented on a micro-controller and connected to a sensor placed on the top of only one wind turbine, this sensor is connected to a soft timer that will trigger a signal to check every N_{sec} the data of wind and the generator speed and envoy them to the control station via network, the algorithm will use them to compute the maximum Power coefficient ($C_p \text{ max}$), the basic principle of the algorithm is to change the value of pitch angle of the blades (β), then try to find the tip speed ratio (λ) for which the C_p value is at maximum, it will compute a multiple value of $C_p \text{ max}$ at each β ($0 < \beta < \text{Max}$) then it will compare these values to find the optimum condition (β value and λ value) for which $C_p = \text{max}$, this new condition (β and λ values) will be transmitted to the wind turbine. On a wind farm all

the wind turbines will be connected via low cost network to the control station, they will receive these new conditions at the same time, and the changes on β will be done for all wind turbines.

The approximate equation describing this algorithm is expressed as follow:

$$\beta_{ideal} = \arg \max_{\beta} \left(C_1 \cdot \left(\frac{C_2}{\lambda_i} - C_3 \cdot \beta - C_4 \right) \exp \left(\frac{-C_5}{\lambda_i} \right) + C_6 \cdot \lambda \right) \quad (19)$$

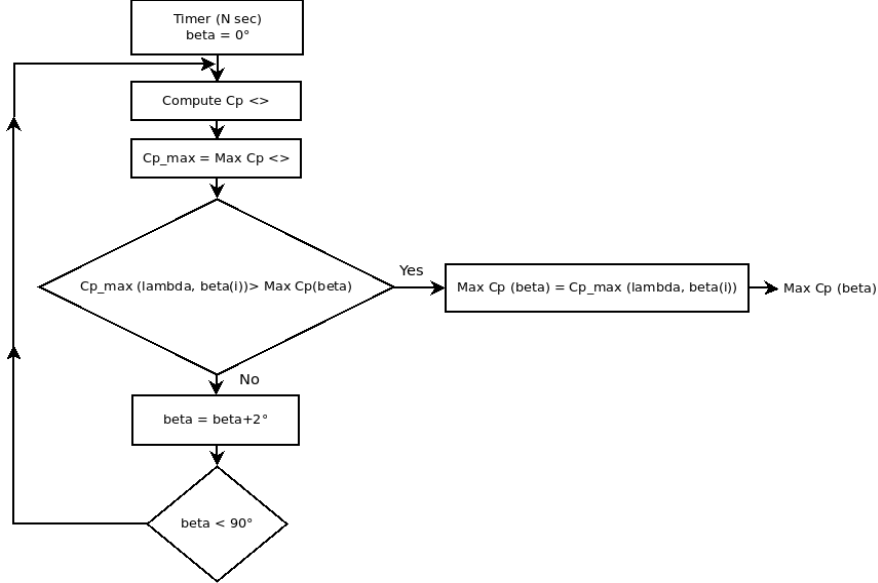


Diagram 1. MPPT algorithm principal and main function.

6. MODELING THE DFIG

The stator and rotor voltage equations of a doubly fed induction generator in the d-q reference frame are as follows:

$$\begin{cases} V_{ds} = R_s i_{ds} - \omega_s \varphi_{ds} + \tau \dot{\varphi}_{ds} \\ V_{qs} = R_s i_{qs} - \omega_s \varphi_{qs} + \tau \dot{\varphi}_{qs} \end{cases} \quad (20)$$

$$\begin{cases} V_{dr} = R_r i_{dr} - (\omega_s - \omega_r) \varphi_{qr} + \tau \dot{\varphi}_{dr} \\ V_{qr} = R_r i_{qr} - (\omega_s - \omega_r) \varphi_{dr} + \tau \dot{\varphi}_{qr} \end{cases} \quad (21)$$

With τ is the derivative symbol $\left(\frac{d}{dt} \right)$.

The stator and rotor flux components in the d-q frame are:

$$\begin{cases} \varphi_{ds} = (L_{is} + L_m) i_{ds} + L_m i_{dr} = L_s i_{ds} + L_m i_{dr} \\ \varphi_{qs} = (L_{is} + L_m) i_{qs} + L_m i_{qr} = L_s i_{qs} + L_m i_{qr} \end{cases} \quad (22)$$

$$\begin{cases} \varphi_{dr} = (L_{ir} + L_m) i_{dr} + L_m i_{ds} = L_r i_{dr} + L_m i_{ds} \\ \varphi_{qr} = (L_{ir} + L_m) i_{qr} + L_m i_{qs} = L_r i_{qr} + L_m i_{qs} \end{cases} \quad (23)$$

With:

$$L_s = L_{is} + L_m$$

$$L_r = L_{lr} + L_m$$

The electromagnetic torque of the DFIG will be expressed by:

$$T_{em} = \frac{-3}{2} p \left(\frac{L_m}{L_r} \right) (\varphi_{ds} i_{qr} - \varphi_{qs} i_{dr}) \quad (24)$$

Mechanical equations:

$$T_t = T_{em} + J\tau\Omega_r + f_r\Omega_r \quad (25)$$

The generator active and reactive power at the grid side is:

$$\begin{cases} P_s = \frac{3}{2} (V_{ds} i_{ds} + V_{qs} i_{qs}) \\ Q_s = \frac{3}{2} (V_{qs} i_{ds} - V_{ds} i_{qs}) \end{cases} \quad (26)$$

7. OVERVIEW OF THE SYSTEM

Figure8, represent the proposed system used and shows the modifications done to the inverter side [3].

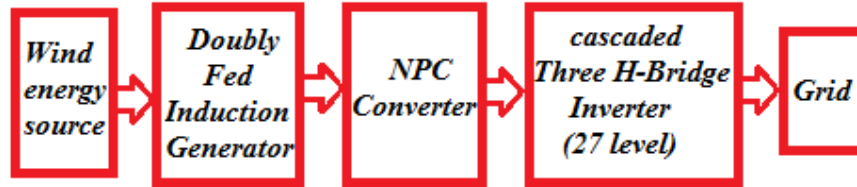


Figure8. General system diagram

Today it has become hard to connect a signal power semi-conductor switch directly to medium voltage grid [3], to work with higher voltage levels, the multilevel inverter were introduced to the market as a solution for this problems, the main feature of a multilevel inverter is the low distortion of the output voltage and current signal and the low operating switching frequency [5].

7.1. Generator Side Converter

The generator side converter is connected directly to the stator of the DFIG. Park's transformation is used for transforming the DFIG equations to the reference frame of park [3]. The current in the active power is proportional to the q-axis current. This way will help us to provide the maximum power at the grid side otherwise, the d-axis stator current is proportional to the reactive power [3] the reference value of the reactive power is set to zero to have a unity power factor operation [4] on the inverter and converter side we will use a PWM triangular signal carrier of a frequency of 1000Hz.

7.1. Generator Side inverter

The control of the grid side inverter help us to maintain the Dc-Link voltage constant and insure that the active power generated is fed back to the grid [3, 4], as we know the multilevel inverter have an efficiency of 99% at nominal operating point. The use of this typical configuration will help us to reduce the THD, as we also know the THD value is obtained by calculating the ration between the sum of all the harmonics powers and the power of the fundamental frequency.

This following expression determines the value of THD:

$$THD\% = \frac{100}{U_1} \sqrt{\sum_{h=2}^{\infty} U_h^2} \tag{27}$$

Where, U_1 is the first harmonic of the signal; h , is the harmonic order and U_h , is the harmonic that presents order h .

8. SIMULATION RESULTS

In this part we will check the performance of a 1.5MW DFIG connected to the grid (appendix) using Matlab/simulink software. The control strategy of the wind turbine is simulated and tested in terms of power and current harmonic distortion.

We simulate this configuration to see the performance, the reliability and the robustness of our system, at a super-synchronous speed. We can see that the active power (Figure 9) step changed from 1.5MW to 0.9 MW at $t = 0.1s$ and again from 0.9 MW to 2 MW at $t = 0.2s$, after $t = 0.3s$ the active power stabilize at around 1.5 MW for all the time of simulation.

For the reactive power (Figure 9) step changed from 0 MVAR to 0.6 MVAR at $t = 0.1s$ than from 0.6 MVAR to -0.2 MVAR at $t = 0.2s$, after $t = 0.3s$ the reactive power stabilize around 0 MVAR (reference value) for all time of simulation.

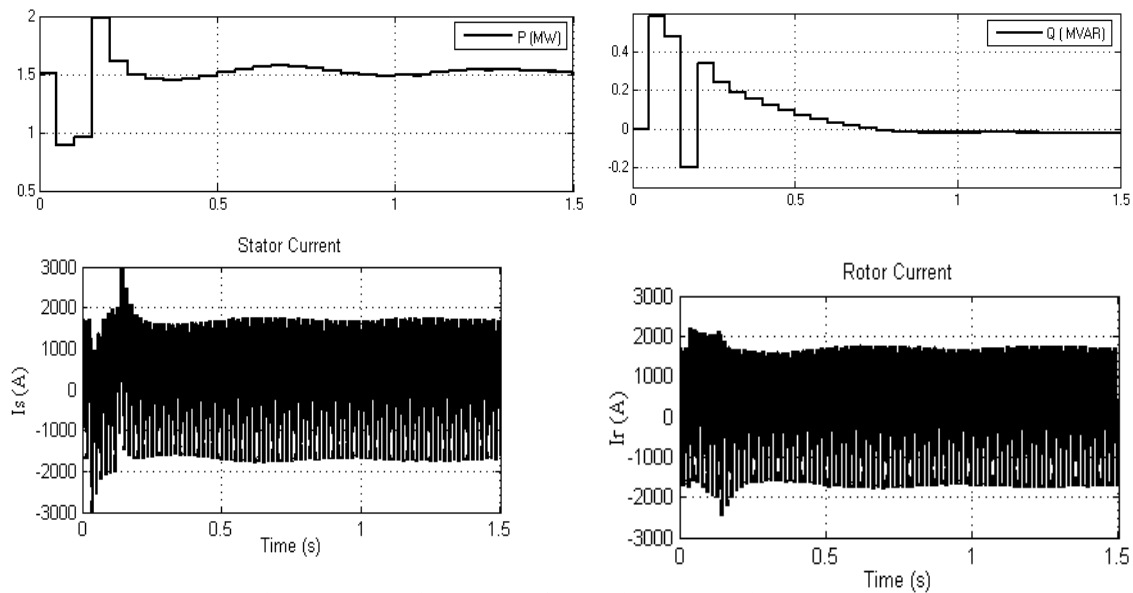
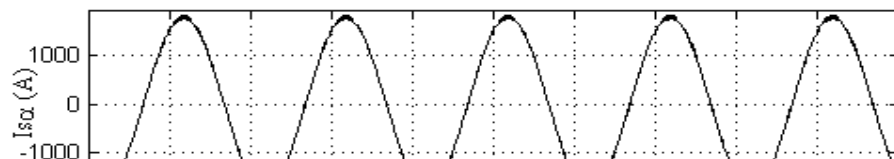


Figure9. Simulation results of the active and reactive power

We can see from Figure 9, the PWM control strategy can control the active and reactive powers of DFIG with a very fast time response and without errors. We can see also that the stator and rotor current are a suitable sinusoidal signal in the two cases.

To observe the effectiveness of the proposed control strategy, “NPC converter with a Cascaded Three H-bridge inverter 27 levels ” on the reduction of the harmonic distortion (THD) rate of the generated power and delivered current at the grid side, we used the FFT analyzer on the stator current waveform ($I_{s\alpha}$), the results are as follows:



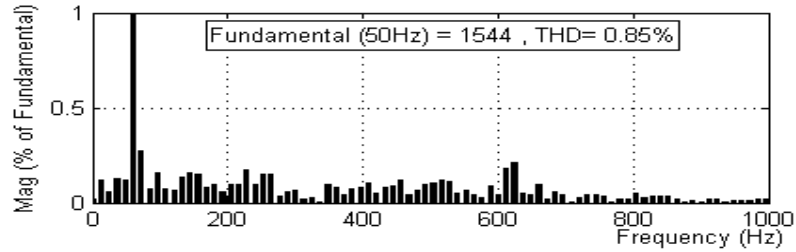


Figure10. THD rate for five cycles starting at t = 0.25 s

9. CONCLUSION

This paper presented an improved technique of energy production from a wind turbine, the MPPT algorithm implemented on the controller of the wind turbine has been proven to be useful, and with a fastest respond on the changes of the wind data and power coefficient to track the maximum power point, the Cascaded three H-Bridge inverter has shown also a good performance with a great reduction of the total harmonic distortion to 0.85%. This method can be used in the wind turbine conversion system. Further improvement can be done by testing other topologies.

Appendix

Table 1. Doubly Fed Induction Generator characteristics

Rated Power, Pn	1.5 MW
Stator rated voltage, Vs	690V
Rated Current, In	1900A
Rated DV-Link voltage, Udc	1200V
Stator rated frequency f	50 Hz
Number of pair of poles, p	2
Rotor inductance, Rr	0.021Ω
Stator inductance, Rs	0.012 Ω
Mutual inductance, Lm	0.0135 H
Rotor inductance, Lr	0.0136 H
Stator Inductance, Ls	0.0137H

Table 2. Wind turbine characteristics

Blade radius, R	29.85
Number of blades	3
Gearbox ratio, G	90
Moment of inertia, J	1000 kg.m ²
Viscous friction coefficient, fr	0.0024 N.m/s
Cut-in wind speed	6 m/s
Cut-out wind speed	26 m/s
Nominal wind speed, V	14 m/s

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