

DOUBLY FED INDUCTION GENERATOR BASED WIND ENERGY CONVERSION SYSTEM USING MATRIX CONVERTER WITH MODEL PREDICTIVE CONTROLLER

¹B.Kanagasakthivel, ²D.Devaraj, ³R.Narmatha Banu, ⁴V.Agnes Idhaya Selvi

¹Research Scholar/ EEE, ²Senior Prof/EEE, ⁴Asso.Prof/EEE

Kalasalingam Academy of Research and Education, Krishnan Koil

³Asso.Prof/EEE, Velammal College of Engineering and Technology,
Madurai

Abstract: The doubly fed induction generator (DFIG) has become the most suitable power generation element to be used with the wind turbine as it offers the advantages of sturdy mechanical structure along with exhibiting high overall efficiency. A matrix converter of the direct conversion principle with 18 switches along with the Space Vector Pulse Width Modulation System (SVPWM) can be used with the DFIG managed by a predictive control strategy. The rotor speed fluctuations and the stator current fluctuations can be checked to be under prescribed limits with the predictive control strategy. The proposed system of predictive control has been demonstrated using simulation carried out in the MATLAB / SIMULINK environment. The proposed control strategy, when used in a grid connected system exhibits improved power quality in terms of the Total Harmonics Distortion (THD) of the grid injection current as compared to the fixed band hysteresis controller.

Keywords: Wind Energy, DFIG, Predictive Controller, Matrix Converter, SVPWM, THD

1. Introduction

Wind energy is the best attractive alternative energy that guarantees green environment. The wind energy conversion schemes, although costlier as compared to other systems of generation of electricity is preferred as it does not require any fuel and fuel burning. The running cost of the wind turbine is virtually nil but for the periodic maintenance that it requires. The various types of electrical generators used usually in association with the wind turbines are the, Permanent magnet DC generator, Permanent Magnet Synchronous Generator (PMSG), Squirrel Cage Induction Generator(SCIG), Self Excited Induction Generator(SEIG), Synchronous Generator (SG) and, Doubly Fed Induction generator (DFIG). Of all these type the DFIG is the most popular scheme because it has several striking advantages over

the other types of electrical generators. The advantages of the DFIG are that they are suitable for operation where the wind velocities may undergo changes over a wide range. The electronic converter that is to be used with the DFIG needs to be of nearly 1/3rd the rating of the DFIG. DFIGs are used for large power conversion systems in the order of 100KW to about 7 MW range.

The DFIG is much similar to the Wound Rotor Induction Motor or the slip ring induction motor. Other than the usual three phase balanced stator windings, the rotor is also wound with a balanced three phase winding and the terminals of the rotor windings are brought over to a set of three slip rings.

The DFIG works in association with a power electronic system that consists of two number of back to back connected three phase Graetz bridge converters with a common DC link. The nodes of one of the two converters are connected to the rotor terminals of the DFIG. The nodes of the other converter are connected to the grid and these two converters are respectively named the machine side converter and the grid side converter.

The deep concern of the fast depletion rate of the fossil fuel all over the world has lead to the development of non conventional energy resources that included the wind and the solar power. However, among the various renewable energy resources the wind power conversion system is becoming the most attractive for large and medium power generation systems.

Hectic research activities are going on in the management of the DFIG with the intention of improving the performance of the DFIG based generation system that is reliable, efficient and of good power quality.

The function of the machine side converter is to drive the rotor with a variable frequency three phase power supply such that even when the wind turbine slows down because of reduced wind velocity, a Rotating Magnetic Field (RMF) of constant angular speed could be maintained. This ensures power delivery at the stator terminals at the frequency of the grid.

Although the machine as such can be operated in many modes of operation it is this particular operation that this work discusses about and proposes a novel methodology to improve the power harvesting phenomenon.

As for the existing literature, many researchers have contributed significantly for the development of the control schemes of the DFIG and the development process has taken place over a period of several decades and the significant contributions in the chronological order are reviewed herein.

In [1] the authors have developed a matrix converter based power conversion system to be used between the grid and the induction generator. The matrix converter is capable of delivering variable frequency and variable voltage from variable frequency and variable voltage input. Thus the idea presented in this work is suitable for applications where the wind velocity changes frequently over a wide range. However the system does not provide a means for temporary storage of electrical energy to be used under critical wind conditions.

A power smoothing controller has been put forward by the authors in [2]. Whenever there is excess wind velocity the energy available in excess is stored in the Super conducting Magnetic Energy Storage System. However the use of SMES makes it suitable for high power systems and not for medium power systems.

The authors in [3] have demonstrated an enhanced hysteresis-based current Regulators in Vector Control of DFIG Wind Turbines but they have demonstrated the proposed system only for limited wind speed variations.

A hybrid power conversion system involving wind, fuel cell and battery have been demonstrated by the authors in [4]. The proposed idea has been used for standalone applications and not grid based applications. A back stepping and sliding mode controller combined has been demonstrated by the authors in [5]. However the idea needs a separate PI controller for the management of the DC link voltage as well. A novel Cyclo converter based conversion scheme has been developed and presented by the authors in [6]. The authors have not demonstrated the case with an experimental verification.

Further in [7] the authors have demonstrated a non linear type of predictive controller and the proposed methodology involves much mathematical overheads although it is suitable for fairly wide variations in wind velocities.

Wind power harvesting and a scheme for the mitigation of harmonics have been proposed and demonstrated by the authors in [8] again this idea involves rigorous mathematical overhead and it becomes difficult to be accepted as a general purpose system to be adopted at large. Moreover adoption for other systems

also becomes difficult if the proposed ideas involve specific mathematical overheads.

A matrix converter based wind energy harvesting scheme has been proposed in [9]. The method has the major advantage of an all silicon device. The absence of a storage device is a handicap when it comes to situations like sudden rise or fall of wind velocity. A model based predictive rotor based controller has been proposed by the authors in [10]. The scheme uses a matrix converter. The disadvantage of a model based system is the lack of accuracy and reliability of the developed mathematical model and its inverse model.

The capabilities of the back to back converter as an active power filter are used in the work carried out by the authors in [11]. This leads to an increased overall capacity of the power electronic converter pair used which would be less if it were meant only for wind power conversion.

The usage of the Matrix converter for wind energy harvesting has been presented in the work of the authors in [12]. A detailed modelling of the 3*3 matrix converter is presented. The matrix converter lacks the storage element and even though the gadget becomes compact will all semiconductor design the dynamic operation loses the advantage of the energy available in the storage capacitor.

Grid synchronisation has been achieved with the matrix converter used along with the DFIG as presented in [13]. The system uses indirect matrix conversion system as it uses passive elements for filtering. In the design with matrix converters the removal of the DC link capacitor but inclusion of additional filtering capacitors sounds controversial.

A DFIG wind farm with HVDC system has been demonstrated in [14]. The proposed idea is good for large power long distance transmission.

The sliding mode control has also been used by many researchers and such a scheme is adopted by the authors in [15]. The disadvantage with the sliding mode control is that the switching frequency is not usually a fixed one but varies according to the operating conditions and the system parameters. As such the design of the filters become difficult and is practically not possible to design a filter that will suit all operating conditions.

Model predictive controllers have also been widely used in the management of DFIG based wind energy harvesting systems. The advantage of the work proposed in this work is that it uses the finite horizon style thus leading to a reduced mathematical overhead in every control cycle thus leading to improved dynamic response.

The paper is organised as follows: Section II gives the complete description of the Wind energy conversion system, Section III Presents the modelling of Wind energy conversion system, Section IV is devoted to the

details of proposed Predictive Controller, Section V Presents the Simulation results and in Section VI Conclusion are presented.

2. Wind Energy Conversion System

With reference to figure 1 the DFIG based WECS system consists of a wind turbine, a DFIG along with a matrix converter placed between the stator and the rotor.

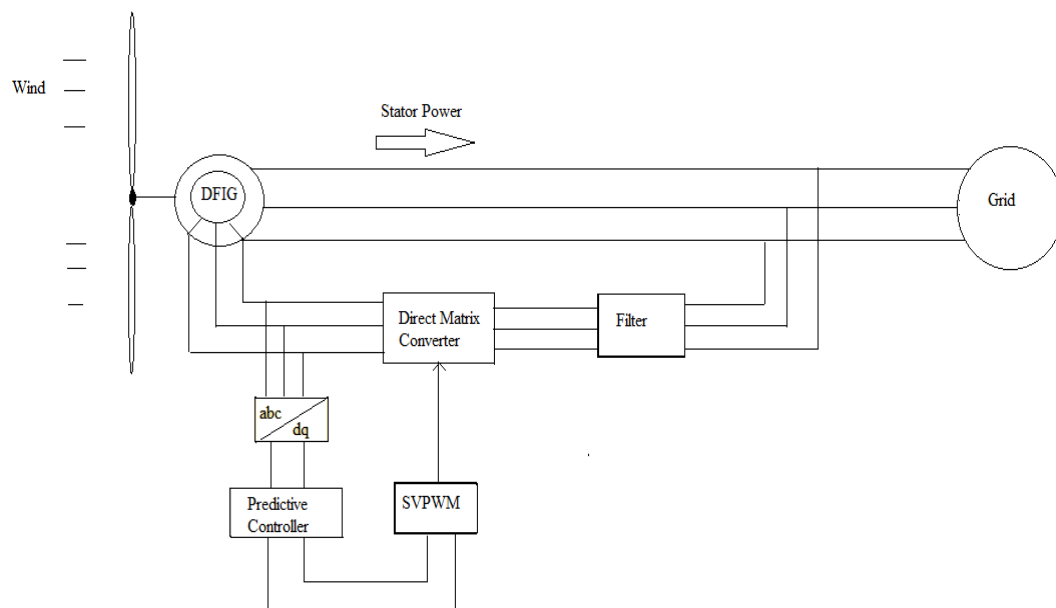


Figure 1. Block diagram representation of Wind Energy Conversion System

Structurally the DFIG resembles a wound induction machine with the stator and rotor windings. The power that flows into the grid can be either from the stator or the rotor thus two paths are available for power transaction between the grid and the generator and hence the name DFIG. From the fundamental principles there are two magnetic fields produced by the stator and the rotor and due to the interaction between these two magnetic fields a torque is produced. If the torque produced is positive then the machine runs as an induction motor and if the torque is negative the machine is in the generator mode.

The direction of power flow happening in the DFIG can be from the stator windings to the rotor windings and then taken over to the grid through the direct matrix converter (DMC). Various control schemes have been proposed and validated for the DMC used in the management of power flow in a DFIG based grid integration system.

Considering the advantages and disadvantages of the various techniques thus far reported the predictive

The figure 1 also includes the controller that works on the basis of Space Vector Pulse Width Modulation (SVPWM). The wind energy is converted into electricity at the DFIG and fed into the grid.

current control (PCC) is more promising. In the case of electrical machines operated with balanced three phase supply it is not directly possible without some special arrangements to control the field and torque individually. And therefore a conversion of the three phase into an orthogonal two phase system in the stationary or the rotating frame is required. Transforming the three phase inputs into a two phase system in the stationary frame is known as the Clarks transformation and further transforming this two phase system into two DC quantities of the rotating frame is called the Parks transformation. Upon transforming the three phase quantities into the dq domain the predictive control system is used and the output of the predictive controller is used to modulate the Sinusoidal Pulse Width Modulation unit. The DFIG is run with the wind turbine at the synchronous speed as aided by the available wind and as a result power flows into the grid.

3. Modelling of Wind Energy Conversion System (Weecs):

A. Wind Turbine

The kinetic energy of wind is converted into rotary mechanical energy in the wind turbine. The aerodynamically designed rotor of the wind turbine is used for this purpose. The mechanical power gained by the wind turbine from the wind is given by the relationship

$$P_t = 0.5 C_p(\lambda) A V_w^3 \quad (1)$$

where ρ is the air density in, λ is the tip-speed ratio, A is the area swept by the aerodynamic rotor, V_w is the velocity of wind speed in m/s, C_p is the power coefficient. The tip-speed ratio of the wind turbine is given by the following equation:

$$\lambda = \frac{R \omega_m}{V_w} \quad (2)$$

The power coefficient is the function of both tip-speed ratio and pitch angle as shown in Fig.2. The power coefficient variation depends on the tip-speed ratio, when the pitch is held constant.

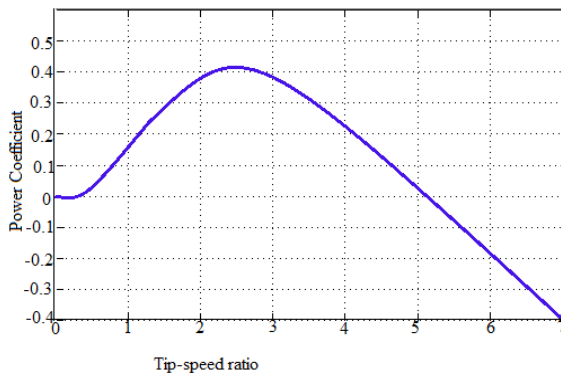


Figure 2. Tip-speed ratio vs. Power Coefficient

4. Doubly Fed Induction Generator

The Park model is the most widely used model of the induction machine that uses the stationary frame with the orthogonal parameters marked d and q. It is assumed throughout the model that the stator resistance is quite negligible.

$$\varphi_{SQ} = 0, \frac{d\varphi_{sd}}{dt} = 0, V_{sd} = 0, V_{sq} = -V_s \quad (3)$$

where V_s is the stator voltage. The reduced state model is obtained as follows:

$$V_{sq} = \sigma L_r \frac{di_{rq}}{dt} + R_r i_{rd} - (\omega_s - \Omega) \sigma L_r i_{rq} \quad (4)$$

$$V_{sd} = \sigma L_r \frac{di_{rd}}{dt} + R_r i_{rd} - (\omega_s - \Omega) \sigma L_r i_{rd} + \frac{M}{L_s} \varphi_{sd} (\omega_s - \pi) \quad (5)$$

where V_{rd} and V_{rq} are the d and q components of rotor voltage (V), v_{sd} and v_{sq} are the d and q components of stator voltage (V), i_{rd} and i_{rq} are the d and q components of rotor current (A), φ_{sd} and φ_{sq} are the d and q components of stator flux (wb), ω_s is the synchronous pulsation, Ω is the generator speed, L_s is the stator resistance, L_r and L_s are stator and rotor inductance (H), M is the mutual inductance (H) and σ is the leakage parameter given as $\sigma = 1 - \frac{M^2}{L_s L_r}$

A. Matrix Converter

A Matrix converter is a power electronic converter with a number of bi directional switches arranged in the form of certain number of rows and columns typically three rows and three columns. The bidirectional nature of the power switches will allow flow of power from the row side to the column side and in the reverse as well. The Matrix converter is a single stage power conversion meant for AC to AC conversion without any intermediate DC link or a DC link capacitor. As such its size becomes small and it enables the making of integrated power modules. The switches of the Matrix converter blocks voltages in both directions and allows flow of current only when enabled by the gate signal. In a typical matrix converter of size 3 * 3 there are nine bi directional switches and these switches are controllable by just nine gate signals. The Matrix converter is capable of generating a variable voltage and variable frequency output from a fixed voltage and fixed frequency source by strategically selecting and applying the switches and the switching pulses as dictated by the control mechanism. Although the number of switches in a matrix converter is just nine these nine switches can be operated in a number of combinations in the Off and On mode such that the two basic conditions that all the switches in a column shall never be turned on and at least one current path should be provided for the load current. While using the Matrix converter both MOSFETs and IGBTs can be used in the

place of the switches. However for medium voltage and high power IGBTs are preferred while MOSFETs are used with high voltage low current and high switching frequency based PWM techniques. Figure. 3 shows the matrix converter of nine bidirectional switches

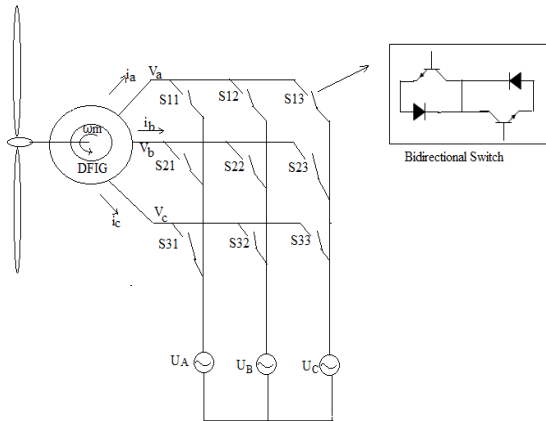


Figure 3. Structure of Matrix Converter

The equations of the matrix converter and the corresponding building blocks of the matrix converter are shown in herein. Figure 4 shows Input Modulation and Figure 5 shows the Sector Identification of Matrix Converter.

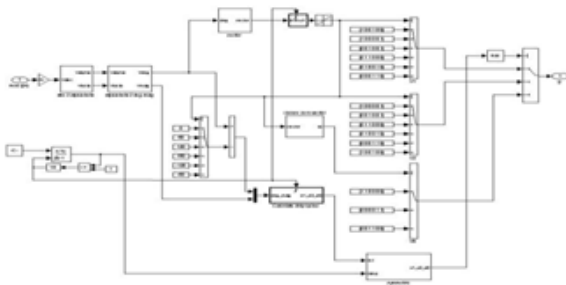


Figure 4. Input Modulation of Matrix Converter

The Matrix converter that we have used in this work is of the indirect conversion type. The whole matrix converter operation can be viewed as the combination of a rectifier and an inverter. The three phase input is first rectified by a controlled rectifier operation and the rectified DC is inverted by the inverter section. The rectifier and the inverter sections are implicit in the three by three matrix converter. To accomplish these two operations appropriate pulses are to the supplied to the matrix converter switches.

There are 9 bidirectional switches. In the space vector scheme of pulse generation six channels of pulses

are generated for the rectifier operation and another six pulses are generated for the inverter operation. These two sets of six pulses are first generated. Then these two sets of six pulses are multiplexed into nine pulses by a logical multiplexing sub system. This sub system receives the two sets of 12 pulses and the output of the sub system consists of the nine switching pulses to be supplied to the nine bidirectional switches.

In space vector modulation the rotating space vector is first generated. The rotating space vector traverses 360 degrees in each AC cycle of the source in the case of the source side controlled rectifier. Similarly on the inverter side also there is a rotating space vector and the space vector moves 360 degrees for every cycle of the output cycle. The 360 degree sweep space is divided into 6 consecutive regions of 60 degrees each and these 60 degree regions are called the sectors. The sectors are numbered 1 to 6 as shown in Figure.5 shows the sector identification.

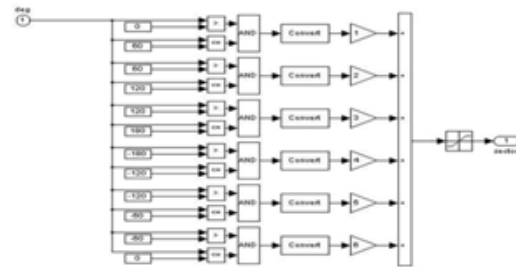


Figure 5. Sector Identification of Matrix Converter

The three phase input AC voltages are monitored. Then the space vector is found. The movement of the space vector is monitored and as the space vector crosses every 60 degrees the sector number is incremented. These sector numbers are used for the calculation of the dwell time of the selected switches.

Each switch is characterized by switching function, defined as follows and a connect or disconnect phase j of the input stage to phase m of the load.

$$S_{jm}(t) = 0, \text{ Switch } S_{jm} \text{ is open}$$

$$S_{jm}(t) = 1, \text{ Switch } S_{jm} \text{ is closed}$$

where $j = \{X, Y, Z\}$, $m = \{x, y, z\}$

j = input stage and m = load output voltage can be synthesized by switching according to proper combination of a switches. Control of matrix converter must comply with the following basics two rules. Firstly any two input terminals should never be connected to the same output line to prevent short-circuit, because the MC is fed by the voltage source. The other is that, output phase must never be open circuited, owing to the absence of the path for the inductive load current which leads to

the over voltages. The above two constraints can be expressed as (6)

$$\left. \begin{aligned} m_{xx}(t) + m_{yx}(t) + m_{zx}(t) &= 1 \\ m_{xx}(t) + m_{yx}(t) + m_{zx}(t) &= 1 \\ m_{xz}(t) + m_{yx}(t) + m_{zx}(t) &= 1 \end{aligned} \right\} \quad (6)$$

When these rules are provided, the 3x3 matrix converter can allow only 27 different switches states among the 512 switching combinations. so the modulation matrix is given as :

$$S(t) = \begin{bmatrix} m_{Xx} & m_{Yx} & m_{Zx} \\ m_{Xy} & m_{Yy} & m_{Zy} \\ m_{Xz} & m_{Yz} & m_{Zz} \end{bmatrix}$$

When ideal input voltage conditions, three phase sinusoidal voltage of the Matrix Converter is given as is given as :

$$V_{aj}(t) = V_{ajm} \begin{bmatrix} \cos(\omega t) \\ \cos(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t + \frac{4\pi}{3}) \end{bmatrix}$$

If S_{jm} is defined as the time during switch ,where is on and is the switching period, duty cycle of the switch is given as :

$$S_{jm}(t) = \frac{t_{jm}}{T_s} \quad (7)$$

In accordance with this, each output phase voltages with respect to the neutral point N of the grid can be expressed by

$$V_{jN}(t) = [M(t)] [V_{KN}(t)] \quad (8)$$

where are the load voltages with respect to the neutral point n of the star connected load, V_{KN} are the MC input voltages.

In the same way the input currents are also shown by the following expression

$$[i_k(t)] = [M(t)]^T [i_j(t)] \quad (9)$$

Where, $[M(t)]^T$ is the transpose matrix of $[M(t)]$.

5. System Description

A. Normal DFIG Model

An equivalent circuit of a DFIG as shown in figure 6 can be developed for the DFIG as observed from an arbitrary reference frame that rotates at the synchronous angular speed .

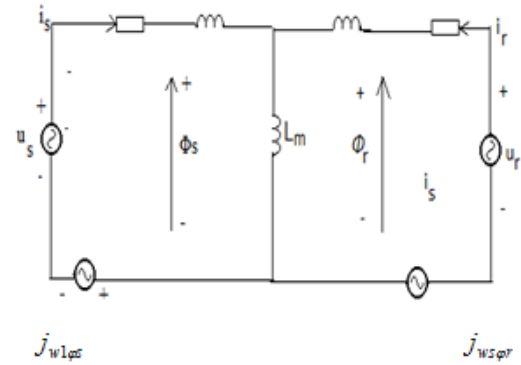


Figure 6. The equivalent circuit of a DFIG

With reference to figure 1 the stator and the rotor flux can be shown as

$$\left. \begin{aligned} \Phi_s &= L_s i_s + L_m i_r \\ \Phi_r &= L_m i_s + L_r i_r \end{aligned} \right\} \quad (10)$$

The equation includes the total self-inductance of the stator and the rotor comprising of stator and the rotor leakage inductances, mutual inductances, and stator and rotor currents.

Equation (11) describes the voltage

$$\left. \begin{aligned} u_s &= R_s i_s + \frac{d\Phi_s}{dt} + j\omega_l \Phi_s \\ u_r &= R_r i_r + \frac{d\Phi_r}{dt} + j(\omega_l - \omega_r) \Phi_r \end{aligned} \right\} \quad (11)$$

The voltage equation included the voltage drops due to equivalent resistances and the rate of change of flux linkages, the synchronous angular speed and the angular speed of rotor.

Neglecting the resistances the voltage equation can be rewritten in a reduced form as given in (11)

$$\left. \begin{aligned} u_s &= R_s i_s + j\omega_l \Phi_s \\ u_r &= R_r i_r + (L_m - \frac{L_r L_s}{L_m}) \frac{di_s}{dt} + j(\omega_l - \omega_r) \Phi_r \end{aligned} \right\} \quad (12)$$

Equations (10) and (11) can be combined to result in the system model given in (13)

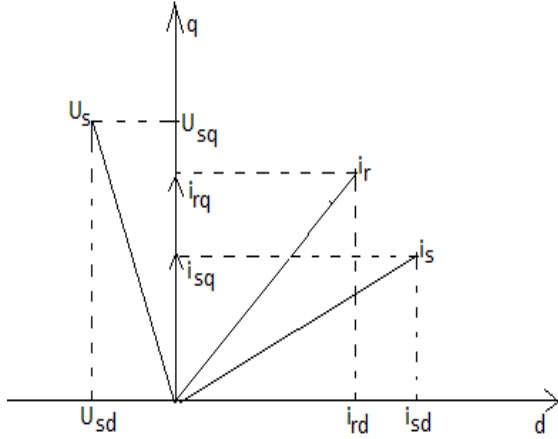
$$\left. \begin{aligned} u_s &= R_s i_s + \frac{d\Phi_s}{dt} + j\omega_l \Phi_s \\ u_r &= R_r i_r + (L_m - \frac{L_r L_s}{L_m}) \frac{di_s}{dt} + \frac{L_r}{L_r} \frac{d\Phi_s}{dt} + j(\omega_l - \omega_r) \Phi_r \end{aligned} \right\} \quad (13)$$

Equation (13) will be suitable for analysis with the grid being balanced or not balanced

B. The Nonlinear DFIG Model

In order to accommodate the voltage dips that could happen in the grid the stator flux considerations are essential. This leads to equation (14).

$$\Phi_s = (L_s - \frac{L_m}{L_r})i_s + \frac{L_m}{L_r}\Phi_r \quad (14)$$



$$|\Phi_s| = \Phi_s |\Phi_r| = \sqrt{i_{sd}^2 + i_{sq}^2} \sqrt{i_{rd}^2 + i_{rq}^2} = \sqrt{i_{sd}^2 + i_{sq}^2} \sqrt{u_{sd}^2 + u_{sq}^2}$$

Figure 7. Phasor diagram of stator flux orientation

The Phasor diagram representing the stator flux oriented (d-q) reference frames is given in figure 7. The equations 13 and 14 are considered to form the equation (15).

$$\left. \begin{aligned} u_{sd} &= R_s i_{sd} + (L_s - \frac{L_m^2}{L_r}) \frac{di_{sd}}{dt} + \frac{L_m}{L_r} \frac{d\Phi_{rd}}{dt} + \omega_l \Phi_{sq} \\ u_{rd} &= R_r i_{rd} + \frac{d\Phi_{rd}}{dt} (\omega_l - \omega_r) \Phi_{rq} \\ u_{sq} &= u_s = R_s i_{sq} + (L_s - \frac{L_m^2}{L_r}) \frac{di_{sq}}{dt} + \frac{L_m}{L_r} \frac{d\Phi_{rq}}{dt} + \omega_l \Phi_{sd} \\ u_{rq} &= R_r i_{rq} + \frac{d\Phi_{rq}}{dt} (\omega_l - \omega_r) \Phi_{rd} \end{aligned} \right\} \quad (15)$$

Also, with SFO, combining (10) and (15) leads to the differential equations about and

$$\left. \begin{aligned} i_{sd} &= \frac{L_m^2 R_r + L_r^2 R_s}{L_r L_m - L_s L_r} i_{sd} + \omega_s i_{sq} - \frac{L_m R_r}{L_r L_m - L_s L_r} \Phi_{rd} \\ &+ \frac{L_r}{L_s L_r - L_m^2} u_{sd} - \frac{L_m}{L_s L_r - L_m^2} u_{rd} \\ i_{sq} &= -\omega_l i_{sd} \frac{L_r R_s + L_s R_r}{L_m - L_s L_r} i_{sq} + \frac{\omega_l}{L_m - L_s L_r} \Phi_{rd} + \\ &\frac{L_m}{L_s L_r - L_m^2} \omega_s \Phi_{rd} + \frac{L_r}{L_s L_r - L_m^2} u_{sq} - \frac{L_m}{L_s L_r - L_m^2} u_{rq} \\ \Phi_{rd} &= \frac{L_m R_r}{L_r} i_{sd} - \frac{R_r}{L_r} \Phi_{rd} + \omega_s \Phi_{rq} + u_{rd} \\ \Phi_{rq} &= -\frac{L_s R_r}{L_m} i_{sq} - \omega_s \Phi_{rd} + u_{rq} \end{aligned} \right\} \quad (16)$$

The electromagnetic torque and movement equations are generally given as

$$M_e = P_N L_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \quad (17)$$

$$T_{ahs} - M_e = J \frac{d\omega_r}{dt} \quad (18)$$

Integrating (17), (18) and (10) obtains the differential equations about (19)

$$\left. \begin{aligned} \omega_s &= \frac{P_N (L_r L_s - L_m^2)}{J L_r} i_{sd} i_{sq} + \frac{P_N L_m}{J L_r} i_{sd} \Phi_{rd} \\ -\frac{1}{J} T_{ahs} \end{aligned} \right\} \quad (19)$$

The practical system outputs, are given as (20)

$$\left. \begin{aligned} P &= u_s i_{sq} \\ Q &= -u_s i_{sd} \end{aligned} \right\} \quad (20)$$

With (16), (19), and (20), the total equations are given in normal state-space form

$$\begin{aligned} \dot{x} &= f(\bar{x}) + g u_r \\ y &= \begin{bmatrix} h_1(\bar{x}) \\ h_2(\bar{x}) \end{bmatrix} = \begin{bmatrix} u_s(x_2) \\ -u_s(x_1) \end{bmatrix} \end{aligned} \quad (21)$$

where the state variables

$$\bar{x} = [i_{sd}, i_{sq}, \Phi_{rd}, \Phi_{rq}, \omega_s]^T$$

$$T_{ahs} = \frac{T_a}{P_N}, T_a = \frac{1}{2} \rho \pi R^3 C_q(\lambda, \beta) v^2$$

the control variables $u_r = [u_{rd}, u_{rq}]^T$, and the output variables $y = [PQ]^T$

$$f(\bar{x}) = \begin{bmatrix} f_1(\bar{x}) \\ f_2(\bar{x}) \\ f_3(\bar{x}) \\ f_4(\bar{x}) \\ f_5(\bar{x}) \end{bmatrix}$$

$$g = [g_1 g_2] = \begin{bmatrix} b_1 & 0 \\ 0 & b_1 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$$

$$b_1 = \frac{L_m}{L_s L_r - L_m^2}$$

It is quite obvious that there exists some definite nonlinearities as the equation contains non linear terms. Even though, in the DFIG control, the stator flux oriented modeling decouples the winding of the rotor and the stator, it does not decouple the d axis rotor voltage and the q axis rotor voltages leading to non linear entities.

6. Input-Output Feedback Linearization of the DFIG

The state-space model (12) should be linearised by an IOFL scheme [19]. The Input Output feedback linearization will be shown as Fig. 8.

The new state variables can be chosen as follows:

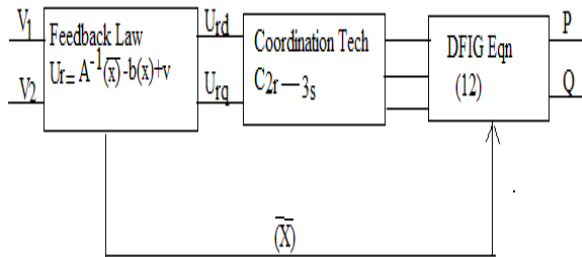


Figure 8. The diagram of input/output linearization

The new state variables can be chosen as follows:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \varphi_1(\bar{x}) \\ \varphi_2(\bar{x}) \end{bmatrix} = \begin{bmatrix} h_1(\bar{x}) \\ h_2(\bar{x}) \end{bmatrix} = \begin{bmatrix} \bar{x}_2 \\ \bar{x}_2 \end{bmatrix} \quad (22)$$

The new states are selected as

$$\eta = \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{bmatrix} = \begin{bmatrix} \varphi_3(\bar{x}) \\ \varphi_4(\bar{x}) \\ \varphi_5(\bar{x}) \end{bmatrix} = \begin{bmatrix} x_3 \\ x_4 \\ x_5 \end{bmatrix} \quad (23)$$

The Jacobian matrix

$$\frac{d\varphi}{d\bar{x}} = \begin{bmatrix} \frac{d\varphi_1}{d\bar{x}_1} & \frac{d\varphi_1}{d\bar{x}_5} \\ \frac{d\varphi_2}{d\bar{x}_1} & \frac{d\varphi_2}{d\bar{x}_5} \\ \frac{d\varphi_3}{d\bar{x}_1} & \frac{d\varphi_3}{d\bar{x}_5} \end{bmatrix} = \begin{bmatrix} 0 & u_s & 0 & 0 & 0 \\ -u_s & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (24)$$

The Jacobian matrix is non singular. The new state equations can be rewritten as

$$\left. \begin{aligned} \bar{x}_1 &= \tau_f h_1(\bar{x}) + \tau_g h_1(\bar{x}) u_{rq} \\ \bar{x}_2 &= \tau_f h_2(\bar{x}) + \tau_g h_2(\bar{x}) u_{rd} \end{aligned} \right\} \quad (25)$$

$$\left. \begin{aligned} \bar{\eta}_1 &= \tau_f \phi_3(\bar{x}) + \tau_g \phi_3(\bar{x}) u_{rq} \\ \bar{\eta}_2 &= \tau_f \phi_4(\bar{x}) + \tau_g \phi_4(\bar{x}) u_{rd} \\ \bar{\eta}_3 &= \tau_f \phi_5(\bar{x}) \end{aligned} \right\} \quad (25)$$

$$\left. \begin{aligned} \bar{x}_1 &= v_1 \\ \bar{x}_2 &= v_2 \\ \bar{\eta} &= \bar{q}(x, \eta) + \bar{p}(x, \eta) v \end{aligned} \right\} \quad (26)$$

$$\left. \begin{aligned} \text{The outputs are } h_1 &= x_1 \\ h_2 &= x_2 \end{aligned} \right\}$$

The linear state space equation for DFIG Model is

$$\left. \begin{aligned} \dot{x} &= Ax + Bv \\ y &= Cx \end{aligned} \right\} \quad (27)$$

A. The MPC Strategy Based on DFIG

The MPC strategy given by [18] can be used with the linear state-space system (27). The Discretization process on (27) will render (28) and (29).

$$x(k+1) = A_d x(k) + B_d v(k) \quad (28)$$

$$y(k) = C_d x(k) \quad (29)$$

$$\Delta_x(k+1) = x(k+1) - x(k)$$

$$\Delta v(k) = v(k) - v(k-1)$$

and new pair of state variable is $x_u(k) = [\Delta x(k)^T \ y(k)^T]^T$, and the improved system is

$$\begin{bmatrix} \Delta x(k+1) \\ y(k+1) \end{bmatrix} = \underbrace{\begin{bmatrix} A_d & 0_{2 \times 2} \\ C_d A_d & I_{2 \times 2} \end{bmatrix}}_{B_u} \underbrace{\begin{bmatrix} \Delta x(k) \\ y(k) \end{bmatrix}}_{x_u(k)} + \underbrace{\begin{bmatrix} B_d \\ C_d B_d \end{bmatrix}}_{B_u} \Delta v(k) \quad (30)$$

The future outputs are calculated from the state-space model sequentially as (31) and (32) and the matrix is formed as (33)

$$y(k+1) = C_u A_u x_u(k) + C_u B_u \Delta v(k) \quad (31)$$

$$y(k+N_p) = C_u A_u^{N_p} x_u(k) + C_u A_u^{N_p-1} B_u \Delta v(k) + C_u A_u^{N_p-2} B_u \Delta v(k+1) + \dots + C_u A_u^{N_p-N_c} B_u \Delta v(k+N_c-1) \quad (32)$$

$$Y = F x_u(k) + \Phi \Delta V \quad (33)$$

The object function to be minimized is a quadratic function. It has two parts. The first part is regarding the DFIG tracking property. The second part corresponds to the performance in terms of pumping higher active power.

$$J = J_1 - \eta J_2$$

$$J = (R_s - Y)^T (R_s - Y) + \Delta V^T R \Delta V - \eta (i_{sq} - i_{sqref})$$

$$\text{Subject to: } v_1 \leq v \leq v_u, \Delta v_l \leq \Delta v \leq \Delta v_u \quad (34)$$

Thus the solution of the linear Model Predictive Controller is formulated by the quadratic program that focus on the minimization of a convex quadratic function (34).

7. Model Predictive Controller

A Model Predictive Controller is a novel control scheme that compares the performance of the mathematical model of the plant and the physical model of the plant. The error is fed back to the input and the corrections are carried out in the actuating signal.

As for the internal model control scheme (IMC) the present error and the set point are the only considerations. However in model predictive controller system the present error and the possible errors in the next few control cycles are also taken into considerations and the decision is made for the present measurement cycle.

Model predictive controller may use a transfer function model if the system is of a typical single input single output type. But with more number of inputs and outputs the state space model is used and the future behaviour of the plant for the next few cycles are estimated.

When figure 9 shows the Terminal voltage across the load and the load current are shown with a step change of wind velocity at 0.5 Sec. The estimation of the output for the next few measurement cycles is carried out by an optimisation.

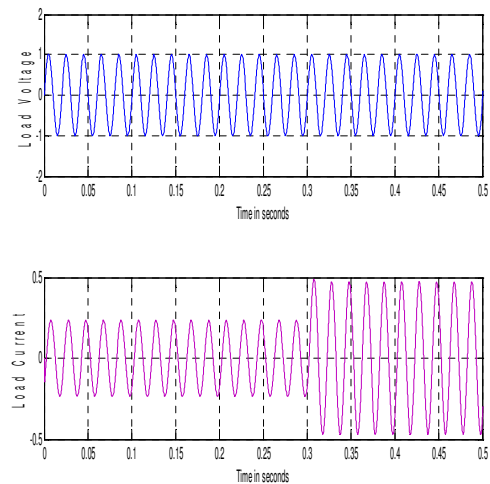


Figure 9. Terminal voltage across the load and load current

The block diagram of the predictive controller scheme as developed for a single input single output system is shown in figure 10.

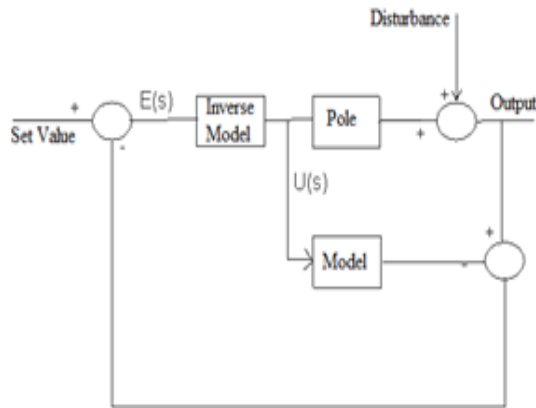


Figure 10. Basic Block Diagram of a Model Predictive Controller

The state space model used for the MPC is the equivalent of the transfer function used for the plant under consideration and it is

$$\dot{x} = Ax + BU \dots\dots (8)$$

$$\dot{y} = CX + DU \dots\dots (9)$$

$$A = \begin{bmatrix} 58.58 & 925.9 \\ 1 & 0 \end{bmatrix}$$

$$B = [1 \ 0]$$

$$C = [0.1706 \ 20.3900]$$

$$D = [0]$$

$$\text{Constraints : } N < N_{\max} \dots\dots (34)$$

$$D < D_{\max} \text{ (Corresponding to maximum Allowable Current)}$$

The two constraints involved are the maximum allowable speed of the wind turbine and the duty cycle of 1 which implies the current limitation. The first constraint is the maximum allowable speed and this constraint is necessary that the wind power harvesting system is operated under safe speed conditions.

The objective of the predictive controller is that it suitably selects the switches of the matrix converter from among the 18 switches and that the selected switches are turned on or off according to the requirement of the control objective. The converter is run as a Direct Matrix Converter and the grid current is smoothened even in the face of fluctuating wind velocities. With this strategy even at low wind speeds the appropriate power is harvested and fed into the grid. At higher wind velocities the rated power is delivered to the grid. Additional low pass filters are required so as to filter out the harmonics appearing at the switching frequency.

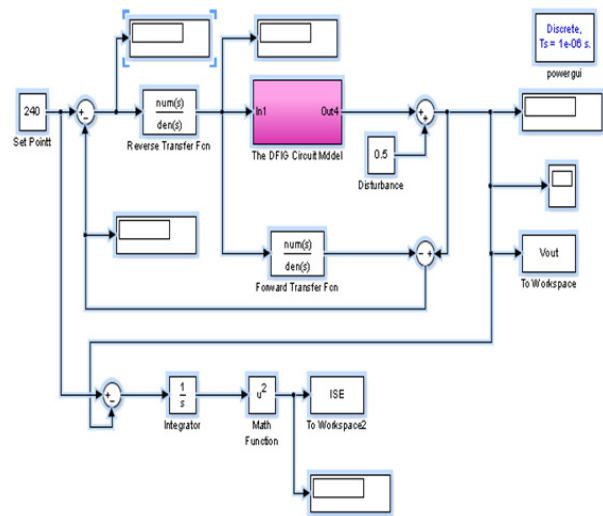


Figure 11. MATLAB implementation of the Model Predictive Controller.

Figure 11 shows the MATLAB implementation of the Model Predictive Controller. By implementing both the predictive controller and the hysteresis controller one after the other the study of power quality has been carried out and it was inference that the predictive controller offers far better power quality as compared to the conventional hysteresis controller.

In variable speed Wind Energy Conversion System different speeds of 14 and 18 m/sec are considered, 18 m/sec is the rated wind speed. Beyond the rated wind speed, pitch angle gets activated. The Power Coefficient of C_p is 0.42 at 14 m/sec and has changed to 0.38 at 18 m/sec. The main aim of the proposed controller for variable speed WECS with DFIG is to search the optimal power point for the wind turbines and to restrict the output power value at rated power for higher wind speeds and to control the

reactive power to the grid. The output of the predictive controller d -axis and q -axis is given by :

$$i_{dr}(A+1) = \frac{T_s}{\delta \cdot L_r} \cdot (V_{dr}(A) - R_r \cdot i_{dr}(A) + b \cdot \omega_s \cdot \delta \cdot L_i \cdot q_r(A)) \quad (35)$$

$$i_{qr}(A+1) = \frac{T_s}{\delta \cdot L_r} \cdot (V_{qr}(A) - R_r \cdot i_{qr}(A) + b \cdot \omega_s \cdot \delta \cdot L_i \cdot d_r(A))$$

(36)

The objective is to get high performance in terms of dynamic current control response by using a cost function that minimizes the error between reference current to the computed values. The cost function is formulated as :

$$C_{function} = (i_{dr*}(K+1) - i_{dr}(K+1) + (i_{qr*}(K+1) - (K+1)) \quad (37)$$

Generally the predictive control scheme reduces the grid current harmonics when it is interconnected with the rotor converter. The predictive control method is used to compensate the harmonic and the pitch angle control by using direct matrix converter. The pulse generated by using PWM in the switching states depends upon the sampling time period.

8. Simulation Result of Wind System

The wind energy conversion system is simulated using MATLAB/SIMULINK. The wind energy system consist of DFIG fed by DMC which is controlled by the matrix converter. The specification of the Wind turbine modeled in MATLAB, in Table I is as follows:

Table 1. Specification of Wind Turbine

S.No	Specification	Range /Value
1	Rating	1.5 MW
2	Rated RMS line to neutral voltage	2.2 kV
3	Number of blades	3
4	Grid Voltage	400 V
5	Grid Current	50 A
6	Power Coefficient	0.4
7	Cut-in speed	4 m/sec
8	Cut-out speed	25 m/sec
9	Number of poles	4
10	Air density	0.55 kg/m ³
11	Rated speed	18m/s

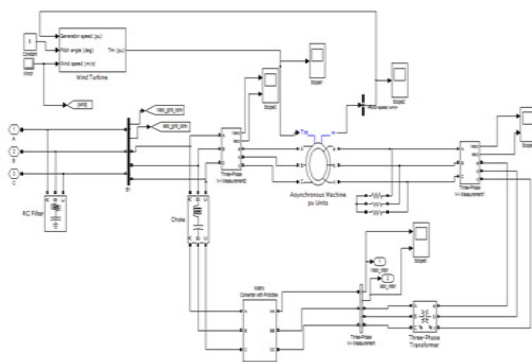


Figure 12. Simulation diagram of wind energy conversion with Predictive Controller

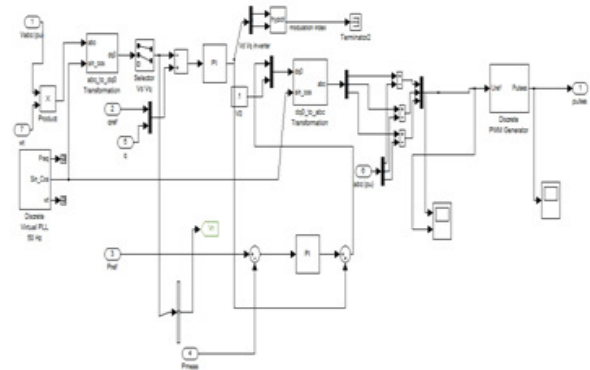


Figure 13. Simulation diagram of abc to dq conversion

Figure 12 and 13 shows the simulation diagram of WECS with Predictive controller and abc - dq conversion respectively.

The rating of the wind turbine is 1.5 MW which is connected to the 1.45 MVA, 2 KV, DFIG. Figure 14. shows the wind speed profile. The wind speed is changed from 14 to 18m/sec at (t = 5sec).

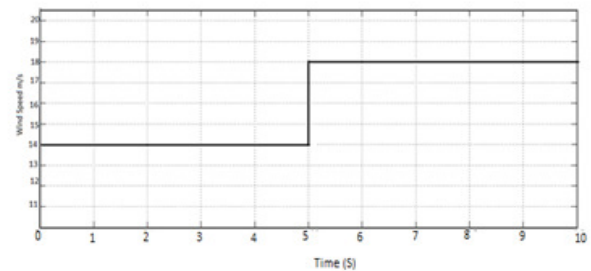


Figure 14. Wind Speed profile

Figure 15 shows at time t = (0-5) some oscillation is produced in the rotor speed when wind speed is 14m/s and at time (t = 5) distortion is reduced in the rotor speed when wind speed is 18 m/s. The wind speed reaches its steady state value of 1400 m/s with in 0.25s with the wind speed of 18m/s.

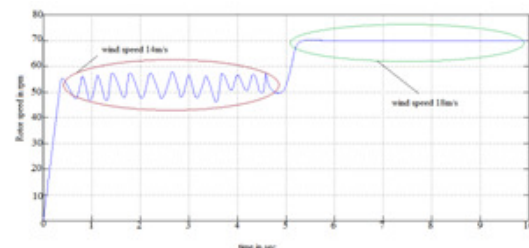


Figure 15. Rotor speed variation

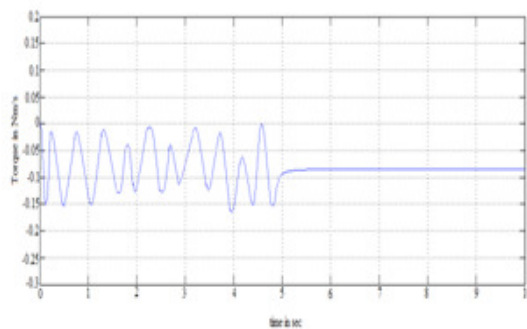


Figure 16. Torque variation

Figure.16 shows at time $t = 5$ there is no fluctuation in the torque with the wind speed of 18 m/s.

Figure 17(a) and 17(b) shows the line voltage and line current of the wind energy conversion system with variable wind speed conversion system the line voltage is 230V, and line current is 50A.

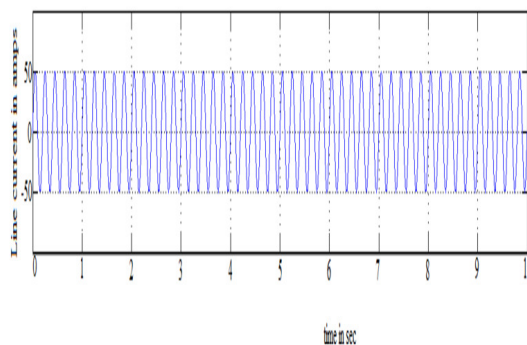


Figure 17(a). Line Current in amps

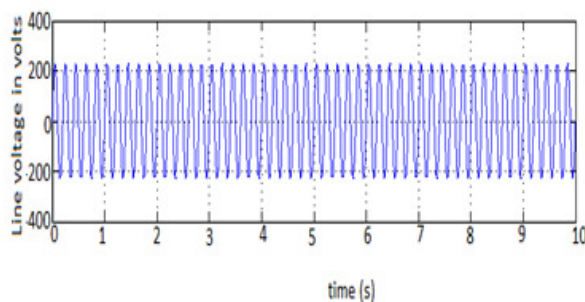


Figure 17(b). Line Voltage in volts

Figures 18 and 19 show the grid voltage and current which are found to be 400V and 50A respectively. The predictive control scheme is used in a DMC to produce the grid current of 50A.

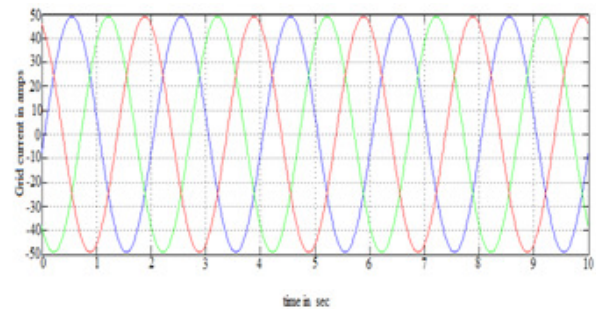


Figure 18. Grid voltage of Predictive Controller

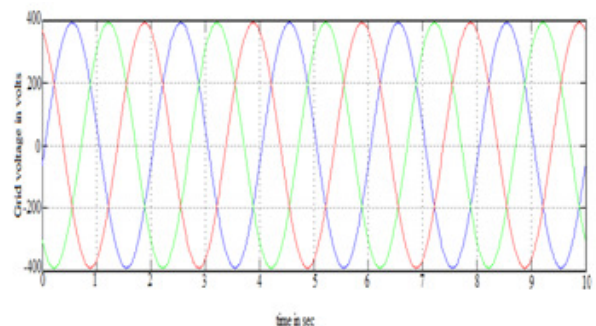


Figure 19. Grid current of Predictive Controller

For the purpose of comparison a hysteresis controller is used to control the DMC. The predictive controller is used to turn on the switches of DMC which drastically reduces the distortion in the grid side, when compared with hysteresis controller.

Figure.20(a) and 20(b) shows the generator rms voltage and generator rms current corresponding to the Wind Speed of 14 m/s; phase voltage is obtained around the value of 1.03 KV and RMS Phase current is 210.49 A. By using variable wind speed, the rms voltage and rms current produced in DFIG gets increased.

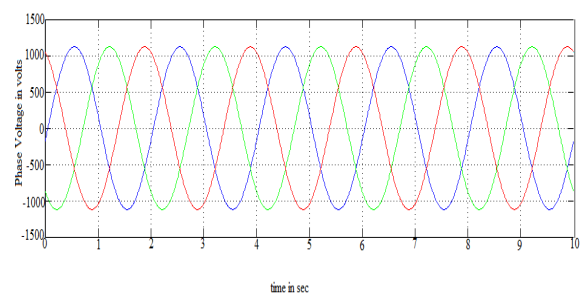


Figure 20(a). Generator rms voltage with wind speed 14m/s

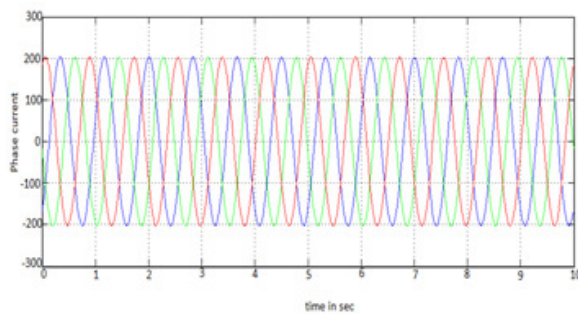


Figure 20(b). Generator rms current with wind speed 14m/s

Figure.21(a and b) shows the generator phase voltage or rms voltage and generator phase current or rms current with the Wind Speed of 18m/s ; The RMS voltage is obtained around the value of 2.2 KV , RMS phase current is 459.2 A. The output power at 18m/sec is greater than the output power at 14m/sec. When the wind speed is increased and the power output of the wind generator also gets increased.

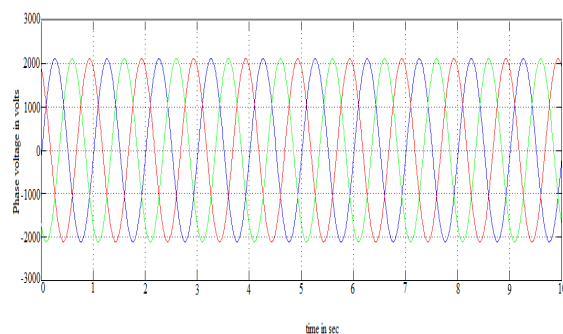


Figure 21(a). Generator rms voltage with wind speed 18m/s

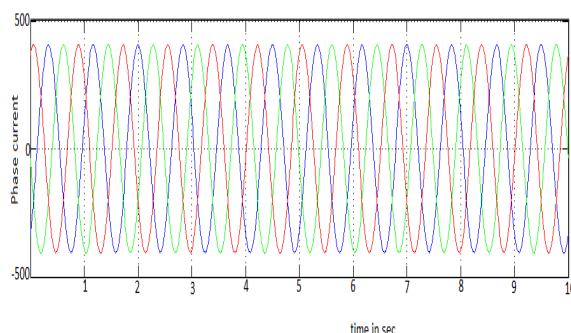


Figure 21(b). Generator rms current with wind speed 18m/s

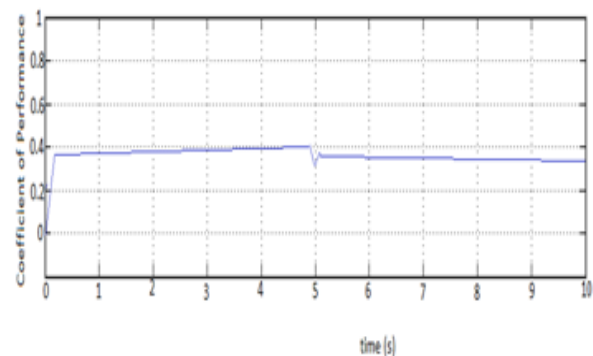


Figure 22. Coefficient of Performance

Figure 22. shows that the pitch controller does not respond for a wind speed of 14m/s, and the C_p max value is 0.44. When $t = 5$ sec., pitch angle controller gets activated at which the wind speed is at 18m/s. When the wind speed is increased, the turbine power is also gets increased. The variation in the pitch angle provides efficient generator power output. The coefficient of performance (C_p) is changed to 0.39 at 18m/sec

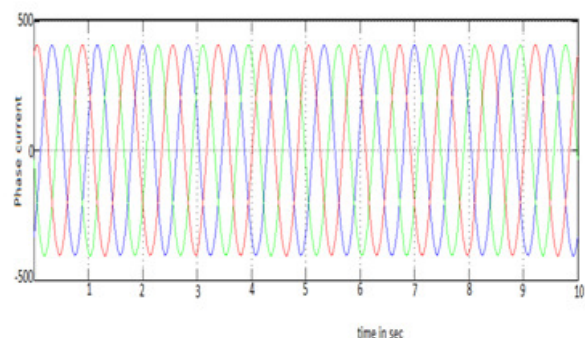


Figure 23. Tip Speed Ratio

Figure 23.shows the variation in tip speed ratio with respect to time. Also it is observed that the turbine speed is well controlled to sustain a finest tip speed ratio of 7 at time 0-5 sec and at wind speed 14m/sec but due to pitch angle control, it is kept at 7 only. This clearly states that the turbine speed is controlled to make a best possible Tip Speed Ratios (TSR) to obtain the maximum wind energy.

Figure.(24) and (25) represents the stator current with hysteresis and predictive controller. By using the hysteresis controller the stator current will produce more distortion in machine side. Also by using the predictive controller, the stator current reduces the distortion in the machine side.

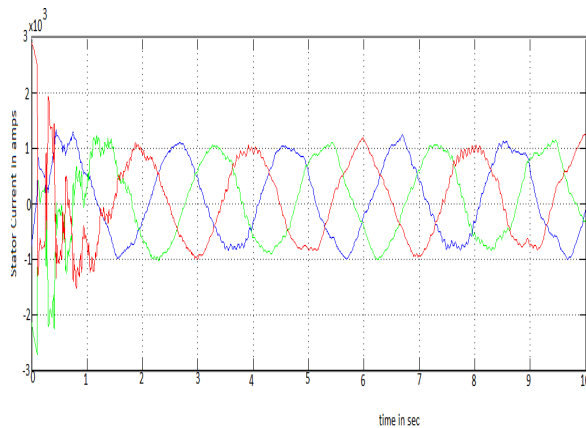


Figure 24. Stator current with Hysteresis Controller

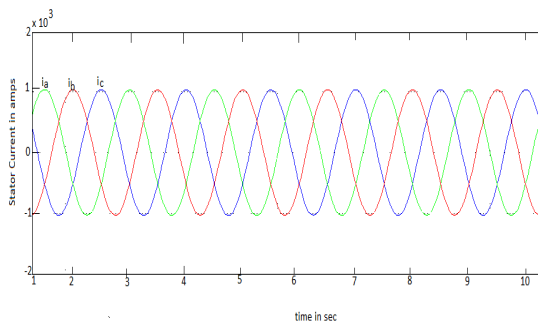


Figure 25. Stator current with Predictive Controller

Figure.26 (a and b) In this research the grid current is the prime concern and the quality of the grid current has to be maintained such that the THD of the grid current is less than 5 %. It reveals that Predictive controller produces THD of (2.8%) when compared to hysteresis controller and so it improves the power quality.

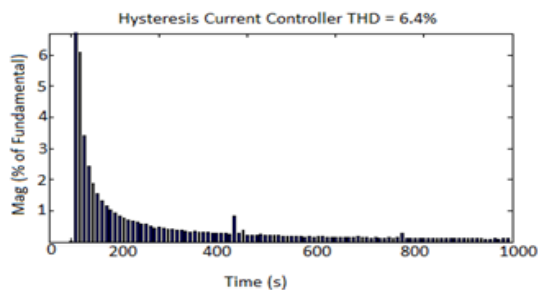


Figure 26(a). THD with Hysteresis Controller

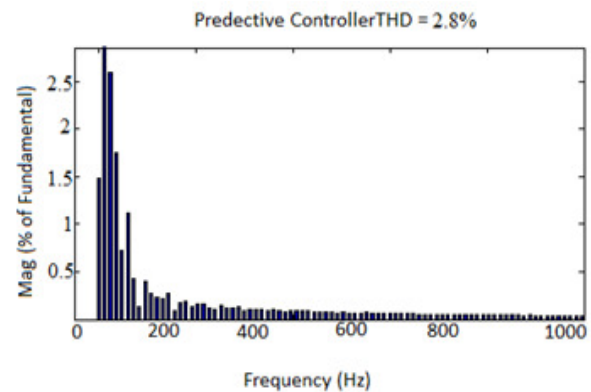


Figure 26(b). THD with Predictive controller

Figure 27 shows, at starting period of time the wind energy system get fluctuates for [0-1] sec and input current (i) will be highly distortional in different phase which affects the grid voltage. By using Predictive controller strategy which allows minimization of the reactive power flows between rotor and the grid as shown in fig.27. After 1 sec reactive power will be negative and input current will be sinusoidal and in phase with the grid voltage so the machine behaves in a synchronous mode.

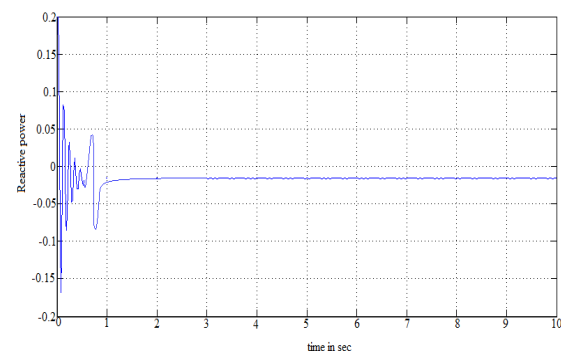


Figure 27. Reactive Power Minimization after $t= 1$ s.

9. Conclusion

A grid connected DFIG based wind energy harvesting system has been discussed in this paper. The novelty of the system discussed is the design and use of a hysteresis Current controller with the predictive control strategy. The system offers the advantage of limited reactive power flow into the grid from the rotor side of the DFIG system. The main power electronic converter used is the matrix converter. The proposed controller being the predictive controller its performance has been compared with the Hysteresis controller. It has been observed that

the THD of the current being injected into the grid is 6.4% in the case of the hysteresis controller as against an improved power quality of 2.8% THD in the case of that with the predictive controller. The major advantage of the DFIG system is that it can deliver the rated power even in the case of fluctuations in the wind velocity conditions. Thus when incorporated with the matrix converter controlled by a predictive controller the power fluctuations are mitigated and thus the smooth grid current at the required power quality is guaranteed. The results of the simulation have been recorded. The proposed system has been validated using MATLAB SIMULINK simulation environment.

The comparison of various control techniques in wind energy is shown in Table II

Table 1. Comparison of Various control techniques

Current Control Techniques in Wind	THD (%)
Hysteresis Current Controller	6.4%
Predictive Current Controller	2.8%

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