Enhanced Operation of Grid Connected Wind Energy Conversion System

Keywords
Finite Set Model Predictive Control (FS-MPC); Permanent Magnet Synchronous Generator (PMSG); Wind Energy Conversion System (WECS); Maximum Power Point Tracking (MPPT) Control; Direct Matrix Converter (DMC); Grid Connected.

ABSTRACT
In this paper, a novel discrete time predictive control strategy applied to a direct matrix converter (DMC) which allows an optimal control of a variable speed permanent magnet synchronous wind generator is presented. The commutation state of the DMC in the subsequent sampling time according to an optimization algorithm given by a simple cost functional and the discrete system model without the need for any additional modulation scheme or internal cascade control loops. The control goals are regulation of the rotor torque and stator flux of the PMSG according to an arbitrary references established based on the maximum power point tracker (MPPT), and also a good tracking of the output reactive power to its reference ensures unitary power factor and improve the system stability. The complete control system has been developed, analyzed, and validated by time domain simulation. The simulation results exhibit good system performance and the efficiency control enhancement of the wind energy conversion system (WECS) using the direct matrix converter structure.

I. INTRODUCTION
The permanent magnet synchronous generator (PMSG) has many advantages for variable speed operation at low and medium power applications. The machine is robust, more reliable and requires little maintenance. The power electronics interface, usually consisting of two stage AC–DC–AC converter system, is connected between the generator and power grid and, for restricted speed range applications, is rated at only a fraction of the machine rated power [1], typically 30% of the nominal power, additionally large DC–link capacitors of an AC–DC–AC converter system make the system bulky, expensive and premature failure, also these are sensitive to electromagnetic interference (EMI) and other noises signals that may lead to short circuit fault.

In the latest years there has been increasing interest in the application of direct AC–AC frequency power converters, such as the direct matrix converter (DMC) and the indirect matrix converter (IMC) in AC drives, these topologies offer an all silicon solution for AC–AC conversion, with sinusoidal input and output currents, and arbitrary amplitude and frequency.

The matrix converter (MC) offers the same performance in terms of potential robustness, high reliability, bidirectional power flow, and unit power factor during motoring and regeneration operation. One of the favorable features of the MC is the absence of the bulky DC–link energy storage component (capacitors and/or inductors) existing in the back-to-back converter based systems [2], which allows for the construction of compact converters capable of operating under adverse environment conditions, such as
extreme pressures and wider temperature range [3]. These characteristics make the MC a suitable technology for high efficiency converters for specific applications such as military [4], variable speed operation of wind energy systems [5], aerospace [6], compact motor drives [7] and skin pass mill. But the major drawback of this technology is the great control complexity.

Many recent research papers have been interested by the control of the wind power generation systems based on PMSG. A part of papers dealt with the energy storage systems [8] where the others concerned the control techniques to improve the performances of the generation system [9]. Nevertheless, there are few papers introduced matrix converters in the wind generation systems these last years [10].

Most of these latter use the indirect topology of the matrix converters because it is a well developed one for more than a quarter century [11]. The direct topology of the matrix converters has been declared till now with the wind generation only by a little research papers [12]. From the new control strategies for power converters developed in the last years, the use of Finite Set Model Predictive Control (FS-MPC) is a very interesting alternative to the classical control methods, due to its intuitive concept, simple principle, good dynamic behavior and flexibility [13]. Moreover, this scheme does not require internal current control loops and modulators, which greatly reduces its complexity. The MPC allows controlling several different variables of a system taking into account nonlinearities and constraints.

The method requires a significant computational effort compared to classic control scheme. Fortunately the performance of the available computing hardware is sufficiently powerful to make this approach possible to command fast systems with shorter time steps, including aerospace, automotive and power converters applications. The main salient feature that distinguishes MPC from other control methods is the pre-calculation of the system behavior until a predefined horizon in time, and its consideration in the control algorithm before the difference between the reference and the measured value occurs, also an optimal aim is defined and solved in MPC to obtain the most appropriate control inputs to apply in the subsequent sampling time [14,15].

The aim of this paper is to investigate the advantages of the predictive control algorithms and the direct matrix converter to control in an easy, an intuitive and a new manner, the electromagnetic torque and stator flux variables of a PMSG, and at the same time, the control scheme is enhanced by including a reactive power minimization strategy with the goal to have unity power factor in the grid side of the converter. The proposed controller uses a discrete time model of the system to predict, at every sampling time, the torque, stator and rotor flux variables of a PMSG, and output reactive power for 27 possible switching state of the three phase direct matrix converter and then, a cost function is used for selecting the switching state that will be applied in the next discrete time interval on the base of minimization of the torque, stator flux and the output reactive power errors.

This is achieved with a single control loop without using a traditional cascaded control structures, and also avoid the use of complex modulation techniques (SVM or PWM modulators). Simulation results obtained in Matlab/Simulink® package program proved that the functional MPC is able to control successfully the wind generation system in the transient and steady state cases.

The work is presented as follows. Section 2 presents the overall system description, In section 3 details on the wind turbine characteristics and maximum delivered power are presented, Section 4 describes the mathematical model of the PMSG, Section 5 presents the fundaments of the direct matrix converter where is described its mathematical model and the relation between the input and output variables, section 6 depicts the control strategy proposed, validated with simulation results in Section 7, and finally conclusions are expressed in Section 8.
II. SYSTEM TOPOLOGY STRUCTURE

A three phase direct matrix converter, used as an interface between the PMSG and utility grid via an output power filter, is shown in Fig. 1. The input side of the DMC is controlled effectively for variable speed operation of the PMSG to enable the maximum power extraction from the available wind. The output side of the DMC converter controls the reactive power exchange between the wind generator and the power grid.

The proposed scheme allows for connecting individual wind turbines to the power grid. It also permits paralleling the outputs of several wind turbine generation units at the grid interface. The power handling capability of the system can be enhanced by adopting a multi-converter approach. In the following sections, different elements of proposed WECS will be modeled.

Fig. 1. Schematic diagram of proposed wind energy conversion scheme.

III. WIND TURBINE AERODYNAMIC MODEL

The output mechanical power available from a wind turbine can be expressed as follows [16]

\[
P_i = \frac{1}{2} \rho C_p(\lambda, \beta) R^2 V_w^3
\]  

Where \(\rho\) is the air density (kg/m\(^3\)), \(R\) is the wind turbine blade radius (m), \(\lambda\) is the tip speed ratio of the wind turbine, \(\beta\) is the rotor blade pitch angle (deg), \(C_p(\lambda,\beta)\) expresses the turbine power coefficient which is a non-linear function and depends on the blades aerodynamic design and wind turbine operating conditions, \(V_w\) is the wind velocity (m/s).

The power conversion coefficient of a wind turbine (Cp) is influenced by the pitch angle (\(\beta\)) and the tip-speed ratio (TSR), which is given by the following equation

\[
TSR = \frac{\omega_m R}{V_w}
\]

Where \(\omega_m\) is wind turbine angular shaft speed (rad/s).

When the pitch angle is fixed to zero, \(\lambda\) approaches the maximum value. Hence, the characteristics of the \(C_p\) mainly depend on only the \(\lambda\) and thus can be expressed by an approximate polynomial as follows

\[
C_{p_i}(\lambda, \beta) = C_i \left(\frac{C_{e_i}}{\lambda} - C_{e} \beta - C_{e} \lambda\right) e^{-\frac{\lambda}{\lambda_i}} + C_{e} \lambda
\]

Where

\[
\frac{1}{\lambda_i} = \frac{1}{\lambda} - 0.035
\]
The coefficients $C_1$ to $C_6$ depend on the shape of the blade and on its aerodynamic performance [17]. Fig. 2(a) shows an approximated ($C_p$–$\lambda$) curve using the following coefficient values: $C_1=0.5176$, $C_2=116$, $C_3=0.4$, $C_4=5$, $C_5=21$, $C_6=0.0068$.

The maximum power coefficient $C_{p\text{-max}}$ and the optimal TSR $\lambda_{opt}$ can be obtained directly from the curve. According to (1) and (2), the maximum mechanical power of wind turbine can be expressed as

$$P_{\text{mech\_max}} = \left(\frac{1}{2} \rho \pi R^4 C_{p\text{-max}} \theta_n^3\right)/V_w^3$$

Fig. 2(b) shows the mechanical power of wind turbine as a function of turbine speed at different wind velocity. It can be seen that the maximum power only exists at a particular (or optimum) rotor speed under a certain wind velocity. The TSR control strategy can be employed to calculate the reference rotor speed to realise the maximum power extraction by detecting the wind speed. Based on (2), the optimum speed of the rotor can be estimated according to the following equation

$$\omega_{\text{ref}} = \frac{\lambda_{opt} V_n}{R}$$

Fig. 2. Wind turbine characteristics. (a) Power coefficient versus TSR when $\beta$ is zero. (b) Turbine output power versus turbine speed at different wind velocity.

IV. PMSG MODELING

For surface mounted PMSG modeling, a fifth order dynamic model is used in this paper. The generator equations in a stationary reference frame can be described by using complex vectors as follows:

$$V_s = R_i + \frac{d\psi_s}{dt}$$

$$\psi_s = L_i + \psi_r$$

$$\psi_r = \psi_f e^{j\theta_e}$$

$$T_e = \frac{3}{2} p 3 m \bar{\psi}_s i_s$$

$$J \frac{d\omega_e}{dt} = T_e - T_w + F\omega_e$$

Where $V_s$ is the stator voltage vector (V), $i_s$ is the stator current vector (A), $R_s$ is the generator resistance ($\Omega$), $\psi_s$ is the stator flux vector (Wb), $\psi_r$ is the rotor flux vector (Wb), the inductances of d-q axes are equal ($L_d=L_q=L_s$), $\omega_e$ is the electrical speed (rad/s), $\theta_e$ is the electrical position ($d\theta_e/dt=\omega_e$), $\psi_f$ is the magnet.
flux (Wb), p is the pair of poles, F is the rotational friction (Nm s/rad), J is the total rotational inertia of the system (kg m²), and Tm is the mechanical torque produced by the turbine (Nm).

V. DYNAMIC MODEL OF DIRECT MATRIX CONVERTER

The direct matrix converter is a single stage AC-AC power converter, with nine bidirectional commanded insulated gate bipolar transistors (IGBTs) connecting directly a three phase voltage source to a three phase load and generating 27 valid switching states. The applicable states are generated based on the restriction of the direct matrix converter topology: the input terminals must not be shortened, and the output phase shall never be open [18]. The permitted switching states of a 3×3 DMC are shown in Table I, and have been classified into three groups, according to the kind of output voltage and input current vector that each switching state generates.

Table 1. Permitted Switching States of DMC

<table>
<thead>
<tr>
<th>Group states</th>
<th>Phase</th>
<th>Output voltage</th>
<th>Input current</th>
<th>Switching function values</th>
</tr>
</thead>
<tbody>
<tr>
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<td>I</td>
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<tr>
<td>i</td>
<td>abc</td>
<td>U_{AB}U_{BC}U_{CA}</td>
<td>i_a, i_b, i_c</td>
<td>1 0 0 0 1 0 0 0 1</td>
</tr>
<tr>
<td>ii</td>
<td>acb</td>
<td>-U_{AB}U_{BC}U_{AB}</td>
<td>i_a, i_b, i_c</td>
<td>1 0 0 0 1 0 0 0 1</td>
</tr>
<tr>
<td>iii</td>
<td>bac</td>
<td>-U_{AB}U_{CA}U_{BC}</td>
<td>i_a, i_b, i_c</td>
<td>0 1 0 1 0 0 0 0 1</td>
</tr>
<tr>
<td>iv</td>
<td>bca</td>
<td>U_{CA}U_{BC}U_{AB}</td>
<td>i_a, i_b, i_c</td>
<td>0 1 0 0 0 1 0 0 1</td>
</tr>
<tr>
<td>v</td>
<td>cab</td>
<td>U_{AB}U_{AB}U_{BC}</td>
<td>i_a, i_b, i_c</td>
<td>0 0 1 1 0 0 0 1 0</td>
</tr>
<tr>
<td>vi</td>
<td>cba</td>
<td>-U_{BC}U_{AB}U_{CA}</td>
<td>i_a, i_b, i_c</td>
<td>0 0 1 0 1 0 0 1 0</td>
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<tr>
<td>IIA</td>
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<td></td>
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<tr>
<td>i</td>
<td>acc</td>
<td>U_{CA}U_{CA}</td>
<td>i_a, -i_a</td>
<td>1 0 0 0 0 1 0 0 1</td>
</tr>
<tr>
<td>ii</td>
<td>bcc</td>
<td>-U_{BC}U_{BC}</td>
<td>i_a, -i_a</td>
<td>0 1 0 0 0 1 0 0 1</td>
</tr>
<tr>
<td>iii</td>
<td>baa</td>
<td>-U_{AB}U_{AB}</td>
<td>-i_a, i_a</td>
<td>0 1 0 1 0 0 1 0 0</td>
</tr>
<tr>
<td>iv</td>
<td>caa</td>
<td>U_{CA}U_{AB}</td>
<td>-i_a, -i_a</td>
<td>0 0 1 1 0 0 1 0 0</td>
</tr>
<tr>
<td>v</td>
<td>cbb</td>
<td>-U_{BC}U_{BC}</td>
<td>0, -i_a, -i_a</td>
<td>0 0 1 0 1 0 0 1 0</td>
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<tr>
<td>vi</td>
<td>abb</td>
<td>U_{AB}U_{AB}</td>
<td>0, -i_a, -i_a</td>
<td>1 0 0 0 1 0 0 1 0</td>
</tr>
<tr>
<td>IIB</td>
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<tr>
<td>i</td>
<td>cac</td>
<td>U_{CA}U_{CA}</td>
<td>i_b, 0, -i_b</td>
<td>0 0 1 1 0 0 0 0 1</td>
</tr>
<tr>
<td>ii</td>
<td>bbc</td>
<td>-U_{BC}U_{BC}</td>
<td>0, i_b, i_b</td>
<td>0 0 1 0 1 0 0 1 0</td>
</tr>
<tr>
<td>iii</td>
<td>aba</td>
<td>U_{AB}U_{AB}</td>
<td>-i_b, i_b, i_a</td>
<td>0 0 1 0 0 1 0 1 0</td>
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<tr>
<td>iv</td>
<td>aca</td>
<td>-U_{CA}U_{CA}</td>
<td>-i_b, 0, i_a</td>
<td>0 0 1 0 0 1 1 0 0</td>
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<tr>
<td>v</td>
<td>bcb</td>
<td>U_{BC}U_{BC}</td>
<td>0, -i_b, i_b</td>
<td>0 1 0 0 0 1 0 1 0</td>
</tr>
<tr>
<td>vi</td>
<td>bab</td>
<td>-U_{AB}U_{AB}</td>
<td>i_b, 0, -i_b</td>
<td>0 1 0 0 1 0 0 1 0</td>
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<td>IIC</td>
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<tr>
<td>i</td>
<td>cca</td>
<td>0-U_{CA}U_{CA}</td>
<td>i_c, 0, -i_c</td>
<td>0 0 1 0 0 1 1 0 0</td>
</tr>
<tr>
<td>ii</td>
<td>ccb</td>
<td>0-U_{BC}U_{BC}</td>
<td>0, i_c, -i_c</td>
<td>0 0 1 0 0 1 0 1 0</td>
</tr>
<tr>
<td>iii</td>
<td>aab</td>
<td>0-U_{AB}U_{AB}</td>
<td>-i_c, i_c, i_a</td>
<td>1 0 0 1 0 0 0 1 0</td>
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<tr>
<td>iv</td>
<td>aac</td>
<td>0-U_{CA}U_{CA}</td>
<td>-i_c, 0, i_a</td>
<td>1 0 0 1 0 0 0 1 0</td>
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<td>v</td>
<td>bcc</td>
<td>0-U_{BC}U_{BC}</td>
<td>0, -i_c, i_a</td>
<td>0 1 0 0 1 0 0 1 0</td>
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<tr>
<td>vi</td>
<td>bba</td>
<td>0-U_{AB}U_{AB}</td>
<td>i_c, -i_c, 0</td>
<td>0 1 0 0 1 0 1 0 0</td>
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<td>III</td>
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<tr>
<td>i</td>
<td>aaa</td>
<td>0 0 0</td>
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<td>1 0 0 1 0 0 1 0 0</td>
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<td>bbb</td>
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<tr>
<td>iii</td>
<td>ccc</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 1 0 0 1 0 0 1</td>
</tr>
</tbody>
</table>

Specifying the switching function of a single switch as:

$$S_{ij} = \begin{cases} 0 & \text{if switch } S_{ij} \text{ is open} \\ 1 & \text{if switch } S_{ij} \text{ is closed} \end{cases} \quad (12)$$
The constraints discussed above can be expressed by:

\[ S_{Aj} + S_{Bj} + S_{Cj} = 1, \quad j = \{a, b, c\} \]  

(13)

The state of the DMC switches can be represented by means of the direct instantaneous commutation matrix \( M \) which has the following form:

\[
M = \begin{bmatrix}
S_{Aj}(t) & S_{Bj}(t) & S_{Cj}(t) \\
S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\
S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t)
\end{bmatrix}
\]  

(14)

The vector of output phase voltages is related to the vector of input phase voltages (which are also the voltages present at the PMSG stator terminals) through the transfer matrix, as follows:

\[
\begin{bmatrix}
v_A(t) \\
v_B(t) \\
v_C(t)
\end{bmatrix} = \begin{bmatrix}
S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\
S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\
S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t)
\end{bmatrix} \begin{bmatrix}
v_A(t) \\
v_B(t) \\
v_C(t)
\end{bmatrix}
\]  

(15)

So, it can be written that

\[ V_o = MV_i \]  

(16)

Where, \( V_o \) is the converter output voltage defined as \( V_o = [v_A \ v_B \ v_C]^T \) and \( v_i \) is the converter input voltage

\[ V_i = [v_a \ v_b \ v_c]^T. \]

In the same form, the following relation is valid for the instantaneous output and input phase currents

\[ I_o = M^T I_i \]  

(17)

Where \( M^T \) is the transpose of the matrix \( M \), and \( I_o \) is the output phase current defined as \( I_o = [i_A \ i_B \ i_C]^T \), and \( I_i \) is the converter input current \( I_i = [i_a \ i_b \ i_c]^T. \)

The DMC includes an \( R_f L_f C_f \) power filter on the output side, which is used to prevent over-voltages and mitigate the harmonic distortion caused by the commutations and the inductive nature of the AC grid, the filter consists of a second order system described by the following differential equations

\[
\dot{I}_g(t) = L_f^{-1} \left( V_g(t) - V_o(t) \right) - R_f L_f^{-1} I_g(t)
\]

(18)

\[
V_o(t) = C_f^{-1} \left( I_o(t) - I_g(t) \right)
\]

(19)

Where \( L_f \) is the inductance, \( R_f \) the damping resistor and \( C_f \) the capacitor of the output power filter.

Based on the equations presented above, the output side can be represented by a state space form with the internal variables \( I_o \) and \( V_o \).

\[
\begin{bmatrix}
\dot{I}_g \\
\dot{V}_o
\end{bmatrix} = A \begin{bmatrix}
I_o \\
V_o
\end{bmatrix} + B \begin{bmatrix}
I_i \\
V_i
\end{bmatrix}
\]  

(20)

Where \( A \) and \( B \) are matrices of appropriate dimensions

\[
A = \begin{bmatrix}
0 & 1/C_f \\
-1/L_f & R_f
\end{bmatrix}, \quad B = \begin{bmatrix}
0 & -1/C_f \\
1/L_f & 0
\end{bmatrix}
\]  

(21)
VI. PROPOSED MODEL PREDICTIVE DIRECT TORQUE CONTROL

VI. Control Strategy

The proposed Predictive Direct Torque Control (PDTC) scheme for the direct drive PMSG is represented in Fig. 3(a).

![Diagram of proposed control scheme](image)

**Fig. 3.** Proposed Predictive Direct Torque Control (a) proposed control scheme, (b) flow diagram with weighting factor.

The approach aims of selecting one of the 27 feasible switching states of the DMC that leads the rotor torque $T_e(k)$ and the stator flux $\psi_s(k)$ closest to their respective references at fixed sampling time period while minimizing the instantaneous reactive power $Q_g(k)$ on the output side of the DMC.

These before mentioned constraints are fulfilled by the controller in the following five main steps as represented in Fig. 3(b) and as follows:

1) For the $k^{th}$ sampling instant, values of grid voltage $V_g(k)$, output voltage $V_o(k)$, stator voltage $V_i(k)$, stator current $I_i(k)$, and rotor speed $\omega_m(k)$ of the PMSG are measured.

2) The stator flux $\psi_{rref}(k)$ and rotor speed $\omega_{rref}(k)$ references are known values. A proportional integral (PI) controller is used to establish the torque reference $T_{rref}(k)$ from the error signal between the actual and reference speeds of the PMSG.

3) A flux estimator has been used to estimate the stator and rotor flux.

4) For each valid switching state of DMC, the model of the system is used to predict the values of rotor torque $T_e(k+1)$, stator flux $\psi_s(k+1)$ and the output reactive power $Q_s(k+1)$ in the next sampling time period $t(k+1)$.

5) As a final point, all the predictive values are compared with their respective references and determine the cost functions $f_i(k+1)$ for all 27 switching states of the DMC based on selected weighting factor. After that, the valid switching state that produces the minimum value of the cost function is selected and applied at the beginning of the next sample period.

All the steps are repeated each sampling period accounting for the new references and measurements in accordance with the receding horizon control.
VI.2 Measurements, References and Speed Control

To implement the PDTC algorithm it is necessary to obtain the measurements and references values of the interesting variables. The speed is controlled using an external controller which generates the torque reference $T_{ref}(k)$ that is then used to generate the gating patterns in order to extract the maximum mechanical power supplied by the wind turbine. The controller is a PI because the integral part is required in order to achieve zero steady state error, due to the fact that the PDTC fast dynamic can be represented just as a first order system between the reference and the controlled variables with a pole $-1/T_d$ dependent on the switching period, The PMSG may also be modeled as a first order system with one pole $-K_d/J$ dependent on the generator inertia. The model of the speed controller is presented in Fig. 4.

The PI controller choice is done admitting that the open loop chain is of second order, with two real poles at $-1/T_s$ and $-K_d/J$ and without any poles at the complex plan origin. Any second order system can be described by the transfer function represented in (22)

$$\frac{\omega_n(k)}{\omega_{ref}(k)} = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0s + \omega_0^2}$$

(22)

Where $\omega_n$ is the natural frequency and $\zeta$ the damping factor.

In order to minimize the effect of the disturbance $T_m$ and to guarantee fast response times and zero tracking error to the step response, a (PI) controller is used as $C(s)$ compensator

$$C(s) = \frac{1+T_zs}{T_p}\frac{s}{s} + K_p + K_r$$

(23)

The closed loop transfer function of the system can be represented as follows

$$G(s) = \frac{1/T_z K_p T_d}{s^2 + \frac{1}{T_d} s + K_p T_p/K_d T_d}$$

(24)

In order to cancel the low frequency pole of the system at $-K_d/J$, the PI compensator zero $T_z$ is given by

$$T_z = \frac{J}{K_d}$$

(25)

Comparing (22) and (24) the compensator parameters can be calculated

$$\omega_0 = \frac{1}{2\zeta T_d}$$

(26)

$$T_p = \frac{1}{\omega_0^2 K_p T_d} = \frac{1}{K_p T_d / (2\zeta T_d)^2}$$

(27)

VI.3 Flux Estimation

The block concerning estimation is used to calculate the variables that cannot be measured, such as the stator flux $\psi_s(k)$ and the rotor flux $\psi_r(k)$. In PDTC, estimations of the stator flux $\psi_s(k)$ and the rotor flux
ψ_s(k) are required at the present sampling step t(k). The stator flux estimation can be calculated using the stator voltage equation of the PMSG presented in equation (7). Using the forward difference Euler formula to discretize (7), the stator flux estimation can be calculated as below

\[ \psi_s(k) = \psi_s(k-1) + T_s V_s(k) - R_s i_s(k) \]  

(28)

Where \( T_s \) corresponds to the sampling period.

The rotor flux can be calculated using the equivalent equation of the stator dynamics of a PMSG in the standard state space form which gives

\[ \frac{di}{dt} = \frac{1}{L_s} (V_s - R_s i_s - jωψ_r) \]  

(29)

Discretizing (29), and replacing the derivatives by the Euler based backwards approximation, the rotor flux estimation \( ψ_r(k) \) is obtained

\[ ψ_r(k) = \frac{1}{L_s T_s} [i_s(k) - i_s(k-1)] - V_s(k) + R_s i_s(k) \]  

(30)

**VI.4 Predictive Torque and Flux Calculation**

After the rotor and stator flux estimations have been obtained, it is necessary to compute the predictions for the controlled variables. In the case of PDTC, the stator flux \( ψ_s(k) \) and the electromagnetic torque \( T_e(k) \) are predicted for the next sampling step \( t(k+1) \). For the stator flux prediction \( ψ_s(k+1) \), the same stator voltage equation used for its estimation is considered. By approximating the stator flux derivative, the prediction for the stator flux is as follows

\[ ψ_s(k+1) = ψ_s(k) + T_s V_s(k+1) - R_s i_s(k+1) \]  

(31)

The electromagnetic torque prediction depends directly on the stator flux and stator current according to (10). Hence, by considering the predicted values of the stator flux and stator current, the electromagnetic torque prediction can be predicted as

\[ T_e(k+1) = \frac{3}{2} p \Im \{ ψ_s(k+1) i_s(k+1) \} \]  

(32)

As observed in (31) and (32), a prediction of the stator current \( i_s(k+1) \) is needed to compute a prediction for the stator flux and electromagnetic torque. The prediction expression of the stator current \( i_s(k+1) \) is obtained using the equivalent equation of the stator dynamics of a PMSG presented in (7). Using Euler formula to discretize (7) and shifting the result to a single time step, the prediction equation of the stator current at the instant \( t(k+1) \) is obtained

\[ i_s(k+1) = \frac{T_s}{L_s} [V_s(k+1) - R_s i_s(k) - jωψ_s(k+1)] + i_s(k) \]  

(33)

**VI.5 Instantaneous Reactive Power Prediction**

A discrete time state space representation of the output side for a sampling time \( T_s \) can be employed to predict the internal behavior of the output current considering the capacitor voltages and output current
measurements at the k\textsuperscript{th} sampling time. The discrete time equivalent system of (20), when the input is generated by a zero order hold and all matrices are constant is given by

\[
\begin{bmatrix}
    I_s(k+1) \\
    V_s(k+1)
\end{bmatrix} = \varphi \begin{bmatrix}
    I_s(k) \\
    V_s(k)
\end{bmatrix} + \gamma \begin{bmatrix}
    I_s(k) \\
    V_s(k)
\end{bmatrix}
\]

(34)

Where

\[
\varphi = \begin{bmatrix}
    \varphi_{11} & \varphi_{12} \\
    \varphi_{21} & \varphi_{22}
\end{bmatrix} = e^{sT}, \quad \gamma = \begin{bmatrix}
    \gamma_{11} & \gamma_{12} \\
    \gamma_{21} & \gamma_{22}
\end{bmatrix} = e^{sT} B d \approx A^{-1} (\varphi - I_{2 \times 2}) B
\]

(35)

Assuming that

\[
\begin{align*}
V_s(t) &= V_s(kT_s) = V_s(k) \\
I_s(t) &= I_s(kT_s) = I_s(k)
\end{align*}
\]

for \( kT_s \leq t \leq (k+1)T_s \)

(36)

In this way, the output current and capacitor voltage can be easily derived by (37) and (38)

\[
\begin{align*}
I_s(k+1) &= \varphi_{21} V_s(k) + \varphi_{22} I_s(k) + \gamma_{21} V_s(k) + \gamma_{22} I_s(k) \\
V_s(k+1) &= \varphi_{11} V_s(k) + \varphi_{12} I_s(k) + \gamma_{11} V_s(k) + \gamma_{12} I_s(k)
\end{align*}
\]

(37)

(38)

The instantaneous reactive output power can be predicted based on the predictions of the output current and grid voltage as shown in (39)

\[
Q_s(k+1) = \text{Im} \left[ V_s(k+1) I_s(k+1) \right] = V_s \beta(k+1) I_s \alpha(k+1) - V_s \alpha(k+1) I_s \beta(k+1)
\]

(39)

Where the subscripts \( \alpha \) and \( \beta \) represent the real and imaginary components of the associated vector. Grid voltages are low frequency signals and it can be considered that \( V_g(k+1) \approx V_g(k) \).

\[ \text{VI.3 Cost function Calculation} \]

The quality function represents the evaluation criteria to decide which switching state is the best to apply among all the possible commutation state combinations. The predicted torque with its nominal value and predicted flux corresponding to the reference flux can be combined in a single term to express the cost function \( g_i(k+1) \).

\[
g_i(k+1) = \frac{T_{ref} - T_s(k+1)\kappa}{T_n} + \lambda_{\psi} \frac{\| \psi - \psi(k+1) \|}{\| \psi \|_{\text{nom}}},
\]

(40)

\[ i = 1, 2, 3, \ldots 27. \]

Where \( \lambda_{\psi} \) is weighting factor for stator flux, this factor can be also adjusted in order to increases or decreases the relative importance of the flux control compared to the torque control. If the same importance were assigned for both control objectives, this factor would correspond to the ratio between the nominal magnitudes of the torque \( T_n \) and stator flux \( |\psi_n| \)

\[
\lambda_{\psi} = \frac{T_n}{|\psi_n|}
\]

(41)

One of the most benefits of DMC is the possibility to control the displacement factor in the grid side by
minimizing the output reactive power. At the same time multiple objectives can be achieved by adding more functions in the global cost function $g_i(k+1)$ as [19]. The resulting cost function that includes both objectives is obtained simply by adding a third term to the cost function (40), thus

$$f_i(k+1) = \frac{P_{\alpha i} - T_{\alpha} (k+1)}{T_{\alpha}} + \lambda_\mu \left\| \nu_{\alpha i} \right\|_2 \left\| \nu_{\alpha} (k+1) \right\|_2 + \ldots$$

$$\lambda_\mu \left\| \nu_{\alpha} (k+1) - \nu_{\alpha i} (k+1) \right\|_2, i = 1, 2, 3, \ldots 27$$

The weighting factor $\lambda_\mu$ handles the relevance of this term to the other terms in the cost function. At every sampling interval, and for all 27 valid switching states of the DMC, the cost function is evaluated, and the commutation state that produces the smallest value of $f_i(k+1)$ is selected to actuate the DMC in the next sampling period.

VII. SIMULATION RESULTS AND DISCUSSION

In order to investigate the effectiveness of the proposed models and PDTC algorithms of the three phase grid connected WECS, extensive simulations are performed in Matlab/Simulink® package program using Sim Power Systems Library. A wind speed sequence as depicted in Fig. 5 has been adopted in the simulation. This wind fluctuates allows the evaluation of the wind turbine response in winds below and above the rated wind speed.

![Wind speed profile.](image)

The simulation results dictate that the control system succeeded in tracking the maximum power available from the wind turbine during the whole wind speed profile. As can be seen from Fig.6 the shaft speed tracks mean tendency of the optimal rotational speed $\omega_{ref}(k)$ and the efficiency of the maximum power extraction can be clearly observed as the power coefficient is close to the optimum value ($C_{p_{max}}=0.48$), as it shown in Fig. 7.
The extracted mechanical power is also shown in Fig. 8. Notice that the mechanical power and the rotational speed are correlated. The electromagnetic torque $T_e(k)$ is independently controlled to track the reference torque $T_{\text{ref}}(k)$. The torque controller achieves good performance while $T_e(k)$ and $T_{\text{ref}}(k)$ exhibit almost the same behavior as depicted in Fig. 9. Fig. 10 presents the stator flux $\psi_s(k)$, it is obvious that the stator flux reaches its desired reference $\psi_{\text{ref}}(k)$ with good approximation even during changes of mechanical speed.
Fig. 11 depicts the simulation waveform of the d-q axis stator currents of the power PMSG, which shows that the d component of the stator current is equal to zero, while the q component is proportional to the generator torque.

Fig. 12 shows the instantaneous three phase stator currents of the PMSG. As seen from the figure the three phase stator currents waveforms are nearly sinusoidal with a low total harmonic distortion (THD).

A zoomed view of Fig. 12 is also given in Fig. 13. Fig. 14 and Fig. 15 show one output phase voltage and current waveforms of the DMC feeding the utility grid respectively before filtering. As it’s clearly shown, the output voltage and current wave shapes is non sinusoidal and it contains harmonics.
Fig. 11. d-q axis currents.

Fig. 12. Stator currents

Fig. 13. Zoom of stator currents
Fig. 14. Unfiltered output phase voltage of the matrix converter

Fig. 15. Unfiltered output phase current of the matrix converter

Fig. 16 illustrates the instantaneous reactive power control capability of the proposed system. It has to be noted that the proposed WECS supplies grid system with a purely active power at all times.

Typical waveforms without and with output factor correction are shown in Fig. 17 and Fig. 18, respectively. Both cases present good behavior on the grid side, on the other hand, present significant differences. Implementing the method with $\lambda_q=0$, the grid current shows high distortion and phase shift with its phase voltage. Using the added reactive power compensation term to control the output factor and considering $\lambda_q>0$, the grid current is close to sinusoidal as well as unity power factor can be achieved, as
shown in Fig. 18.

Fig. 17. Grid voltage (divided by 10) and grid current without reactive power minimization.

Fig. 18. Grid voltage (divided by 10) and grid current with reactive power minimization.

VIII. CONCLUSION

A wind energy conversion scheme including a direct AC-AC matrix converter and model predictive control is presented in this paper. The matrix converter controls the generator speed so as to extract maximum wind turbine power at different wind velocities, as well as the unity displacement power factor at the interface with the grid to ensure purely active power injection into the grid for optimal utilization of the installed wind turbine capacity. Due to the scheme of examination of the cost function by applying feasible switching state the proposed controller is superior to the commonly used PI controller in that it does not require any additional modulation techniques or internal cascade control loops. The proposed approach is verified using the time domain simulation of a study system for PMSG wind energy systems. The simulation results show that the suggested model and control scheme can successfully track the rotor speed reference for capturing the maximum power from the wind at all wind velocities, while minimizing the instantaneous reactive power at the interface with the utility grid.

REFERENCES


