Predictive Control of Power Electronics Converters in Wind Energy Systems

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Abstract—In order to make a wind power generation truly cost effective and reliable, an advanced control techniques must be used. In this paper, we develop a new control strategy using Model Predictive Control (MPC) approach for permanent magnet synchronous generator based wind turbine system. The proposed control law is based on two points: MPC-based torque-current control loop for the generator-side converter to reach the maximum power point of the wind turbine, and MPC-based current control loop for the grid-side converter to satisfy the grid code and to help improve system stability. A small-scale wind turbine system prototype was built and tested in the laboratory, and the experimental results are provided to verify the validity of the developed control methods, MPPT algorithm and performance of the system operations.

Keywords-component; finite-set model predictive control (FS-MPC); permanent magnet synchronous generator (PMSG); wind energy conversion system (WECS); maximum power point tracking (MPPT) control; grid connected; experimental validation.

I. INTRODUCTION

Recently, wind energy has been considered to be one of the most promising non-conventional renewable energy sources, due to the energy shortage, security threats and environmental concerns. Among wind power generation systems, wind turbine based on permanent magnet synchronous generator (PMSG) are extremely used compared with other generators, due to their variable speed operation, fast dynamical response, higher reliability and efficiency [1]. However, the operation of PMSG strongly depends on how the wind turbine is controlled. Therefore, the role of power electronic converters and their corresponding control algorithms is becoming increasingly prominent.

In recent years different converter topologies, varying in cost and complexity have been proposed and investigated for power conditioning of PMSG based wind turbine generator systems [2]. However the most commonly used topology is formed by a turbine rotor, PMSG, uncontrolled bridge rectifier followed by a three phase voltage source inverter (VSI). The main drawback of this option is that the DC-link voltage may be too low for injecting to the grid, then a high turns-ratio step-up grid connection isolation transformer is necessary. Therefore, the inverter currents are high and consequently the inverter losses. Both the grid connection transformer and the grid filter become bulky due to the high inverter side current. If a higher efficiency and a lower size are desired, a DC–DC boost converter is usually connected between the rectifier and the inverter, achieving a higher inverter DC-link voltage, so that the grid connection transformer has a smaller turns-ratio, and thus lower inverter currents.

Due to this architecture, the controller design of the overall system becomes complicated for two reasons. On one hand, the generator dynamics cannot be neglected leading to a system behavior described by highly coupled set of nonlinear differential equations. On the other hand, due to the use of a simple generator and power electronic interface, the control authority is quite restricted. Several control techniques and strategies have been proposed and reported in the literature for the control of interfacing system between PMSG-wind turbine and power grid [3]. These include PI control [4], Fractional-order control [5-7] Sliding mode control [8], feedback linearization control [9], Fuzzy logic control [10] and others. However, Most of these schemes use the output voltage and currents with outer and inner control loops, requiring Proportional-Integral (PI) regulators and sinusoidal Pulse Width-Modulation (PWM or SVM) which complicate the control system, and much tuning effort is needed in practical implementation to ensure the system stability. Recently a control approach based on Model Predictive Control (MPC) was proposed, there is no need for linear controllers or modulators, and the scheme is simple and easy to implement with standard commercial microprocessors [11]. In this control, a discrete-time model of the system is used to predict the behavior of the system variables for each possible switching state of the system, and the optimal switching states with minimum cost function is then selected and applied during the next sampling interval. The control objectives of MPC can vary considerably according to the application. For example, in [11] the control objective is the inverter output voltage for a UPS system. In other applications, as in [12] the objectives become the active and reactive powers for a rectifier system, and the currents in [13] for inverters connected to an electrical machine or other electric load. Despite these systems, nevertheless, the MPC strategy for a renewable power generation system is seldom mentioned in the literature.

The main contribution of this paper is the design and a real time implementation of the novel Finite-Set Model Predictive
Control (FS-MPC) algorithm for grid integration of wind energy systems. By changing the cost function correctly this control strategy can be employed to ensure asymptotic convergence to the maximum power extraction point together with regulation of the DC-link voltage to their desired values, and flexible active and reactive current regulation of the electric grid. Furthermore, the proposed algorithm reduces the running time without affecting the control performance, and can be used in various circuit topologies and cases with multiple constraints.

The rest of this paper is organized as follows: The system under consideration is discussed in section 2. In section 3 details on the wind turbine characteristics and maximum delivered power are presented. Section 4 is related to the modeling of PMSG. The proposed control strategy for generator and grid-side converters is explained in section 5 and 6 respectively. Section 7 is related to the experimental results and contains a description of the testing setup followed by a complete experimental validation of the proposed control technique, the paper ends with comments about the performance of the proposed controllers, followed by the Conclusions (Section 8).

II. SYSTEM DESCRIPTION

The wind turbine used in this work is considered as a direct drive system. The generator is connected to the grid through a passive rectifier, a DC-DC boost converter, isolation transformer and an inverter. The torque produced by the wind turbine reflects to the PMSG and low voltage produced by the PMSG is rectified and boosted using a DC-DC boost converter and then transferred into the electric grid through a voltage source transformer–inverter. The Maximum Power Point Controller (MPPC) control the optimum speed of the generator for maximum power production of the wind turbine and the Finite-Set Model Predictive Current Controller (FS-MPCC) ensures the proper flow of power to the grid by maintaining an adequate DC-link voltage. During wind gust, the dump-load controller will be activated to maintain the output load voltage at the desired value. A complete schematic of the system is shown in Fig. 1.

![Figure 1. Considered wind energy system.](image)

III. WIND TURBINE CHARACTERISTICS

The output mechanical power available from a wind turbine can be expressed as follows [14]

\[ P_T = 0.5 \rho \pi R^3 C_p(\lambda, \beta) V_w^3 \]  \hspace{1cm} (1)

Where: \( R \) is the turbine radius (m), \( \rho \) is the air density (kg/m\(^3\)), \( V_w \) is the wind speed (m/s) and \( C_p \) is the power coefficient of the turbine, usually it is provided by the wind turbine manufacturer.

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

\[ TSR = \lambda = \frac{\omega_m R}{V_w} \]  \hspace{1cm} (2)

The wind turbine is characterized by \((C_p-\lambda)\) curve as illustrated in Fig. 2. The power conversion coefficient and the TSR depend on the aerodynamic characteristics of the wind turbine. From Fig. 2, the maximum turbine power is found at a point of \(\lambda_{opt}\) and \(C_{p, opt}\).

![Figure 2. Power coefficient versus tip-speed ratio.](image)

The target optimum power from a wind turbine can be written as follows

\[ P_{p, opt} = 0.5 \rho AC_{p, opt} \left( \frac{\omega_{m, opt} R}{\lambda_{opt}} \right)^3 = K_{opt} \left( \omega_{m, opt} \right)^3 \]  \hspace{1cm} (3)

where: \( A \) is the swept area of the turbine blade \((A = \pi R^2)\), \( \omega_{m, opt} \) is an optimum rotation speed to a specific wind speed and \( K_{opt} \) is an optimum wind constant given by equation (4).

\[ K_{opt} = 0.5 \rho AC_{p, opt} \left( \frac{\omega_{m, opt} R}{\lambda_{opt}} \right)^3 \]  \hspace{1cm} (4)

\[ \omega_{m, opt} = \frac{\lambda_{opt}}{R} V_w = K_w V_w \]  \hspace{1cm} (5)

Hence, the target optimum torque can be given by

\[ T_{w, opt} = K_{opt} \left( \omega_{m, opt} \right)^2 \]  \hspace{1cm} (6)

The mechanical power generated by the turbine as a function of the rotor speed for different wind velocity is shown in Fig.3. It is observed from this figure that for each wind velocity, there is a maximum power \((P_{opt})\) that the turbine could extract if operated at a particular (or optimum) rotor speed \((\omega_{m, opt})\). If the Maximum Power Point Tracking (MPPT) controller can properly follow the optimum curve, the wind turbine will produce maximum power at any speed within the allowable range.

![Figure 3. Relationship between the generator power and rotational-speed.](image)
IV. MODELING OF PMSG

PMSG is modeled by its d–q equivalent circuits. The equations of a surface-mounted PMSG are expressed in the synchronous d–q coordinates as

\[ V_{ds} = R_i i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_L L_{q} i_{iq} \]  
\[ V_{qs} = R_i i_{iq} + L_q \frac{di_{iq}}{dt} + \omega_L L_{q} i_{dq} + \omega_L \Psi \]  

Where: \( V_{ds} \) and \( V_{qs} \) are the stator voltages in the d and q axes, respectively, \( L_d \) and \( L_q \) are the d and q components of generator inductance, respectively, \( \omega_m \) is the generator speed, and \( \Psi \) is the magnetic flux. \( i_{dq} \) and \( i_{iq} \) are the stator currents in the d and q axes, respectively.

The generator electromagnetic torque equation can be given by

\[ T_e = \frac{3}{2} P \Psi i_{iq} \]  

The first term in the Eq. (9) is the interaction torque between the magnetic field and q-axis current, and in surface-mounted PMSG, d- and q-axis inductances are the same \( (L_d = L_q) \), then, the electromagnetic torque can be simplified as

\[ T_e = \frac{3}{2} P \Psi i_{iq} \]  

V. CONTROL OF SWITCH-MODE RECTIFIER WITH MAXIMUM POWER EXTRACTION

A. Proposed MPPT Control System

The structure of the proposed control strategy of switch-mode rectifier is shown in Fig.4.

Figure 4. PMSG control for Maximum Power Point Tracking (MPPT).

The control objective is to control the switch S to extract maximum power from the variable speed wind turbine and transfer the power to the grid inverter. The control algorithm includes the following steps

- Measure wind speed \( V_w \).
- Calculate the reference generator speed \( \omega_{m,opt} \) using the following equation

\[ \omega_{m,opt} = K_w V_w = \frac{L_{ds}}{R} V_w \]  

- The error between the reference speed and the actual speed is fed into (PI) controller to set the reference torque generator \( (T_{ref}) \). The reference torque generator can be expressed by the relation below

\[ T_{ref} = \frac{K_{ps} + K_{im}}{S} (\omega_{m,opt} - \omega_m) \]  

- The \( i_{iq} \) obtained from Eq. (14) and the actual inductor current \( (i_{id}) \), the converter input-output voltages \( (V_{in}) \) and \( (V_{dc}) \) are also designated as inputs to the digital predictive controller so as to obtain sufficient information in one sampling period and to generate control pulses for the IGBT based switch-mode rectifier operating the generator speed at optimum speed.

B. Predictive Controller Implementation

The main characteristic of FS-MPC technique is the use of the system model for predicting the future behavior of the variables to be controlled for each of the valid switching states. The controller uses this information to obtain the optimal control action, according to a predefined optimization criterion [15]. Fig.5 illustrates the graphical analysis of the DC-DC boost converter. There are only two switching states for this converter.

Figure 5. Two operating modes of the DC-DC boost converter circuit. (a) Open switch, \( S(t)=0 \), (b) Closed switch, \( S(t)=1 \).

As shown in Fig. 4(a) when the switch S is turned off \( (s(t)=0) \), the boost converter operation can be described by the well-known system of equations as follows

\[ \frac{di_{id}}{dt} = -\frac{1}{L} V_{in} + \frac{1}{L} V_{dc} \]  

When the switch S is turned on \( (s(t)=1) \), the first order terms disappear and the former equation system is of the following form

\[ \frac{di_{iq}}{dt} = -\frac{1}{L} V_{in} \]  

The discrete-time model of the DC-DC boost converter is used to derive Eq. (15) and (16), considering the sampling period \( T_s \), when the switch is turned on or off the predicted control variables is given by

\[ i_{id}(k+1) = i_{id}(k) + \frac{T_s}{L} (V_{in}(k) - V_{dc}(k)) \]  
\[ i_{iq}(k+1) = i_{iq}(k) + \frac{T_s}{L} V_{dc}(k) \]
The behavior of the controlled variables $i_L$ can now be predicted for the next sampling interval $t_{k+1}$, in order to obtain control actions for both the present time and a future period. One-step horizon predictive controller inputs measured values of $i_L$, $V_m$, and $V_o$ estimating the future behavior of the controlled variables based on the evaluation of a cost function. The determination of the cost function is a key factor in FS-MPC represents the deviation of the controlled variables from the desirable values of the reference current and is expressed as

$$J = \left| i_L(k+1) - i_L^* \right|$$  \hspace{1cm} (19)

The cost function assures the tracking of the inductor current $i_L$ from the reference current $i_L^*$ provided by MPPT algorithm. For each sampling step the cost function is evaluated twice for each switching state. Evaluation of cost function for different switching states determines the control actions for the next time instant. Fig.6 illustrates the FS-MPC process. The dotted line corresponds to the MPPT output, which define the reference current. At the sampling time $t_k$ the FS-MPC has to decide between $S_0$ and $S_1$ on basis of minimizing the cost function, the black lines corresponds to the finally performed actions, while the faded line are discarded choices. All steps of the proposed FS-MPC method are presented in Fig.7.

The control of grid-side converters is to keep the DC-link capacitor voltage at a set value regardless of the magnitude of the output power and to guarantee the unity power factor [16]. Since the switching states of the inverter are limited, and the discrete-time model of the system can be used to predict the behavior of the variables, finite set predictive control is an efficient scheme to control the inverter. There are eight admissible switching states for a two-level inverter given by

$$S = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}$$  \hspace{1cm} (20)

The idea of Finite Set Model Predictive Control (FS-MPC) is to select the optimal switching state which makes the predicted current $i(k+1)$ close to its reference $i^+(k+1)$ and applied to VSI during the interval between the $(k)$th and $(k+1)$th instants [17]. In case of two-level power converters, conventional Finite Set Model Predictive Control (FS-MPC) needs eight-time current prediction calculations. In this paper, the proposed predictive current control algorithm reduces the eight-time current predictions required by the conventional FS-MPC to one-time without affecting the control performance.

This algorithm uses the required voltage vector $V^*(k)$ instead of the current vector $i^+(k)$ for the prediction process. Fig.8 shows a block diagram of the grid-side converter controller whose FCS-MPC strategy performs a calculation of active and reactive current for all the switching combinations.

$$v_{af} = L \frac{di_{af}}{dt} + R i_{af} + e_{af}$$  \hspace{1cm} (21)

Where: $R$ and $L$ are the equivalent series resistance and inductance of grid filter, $v_{af}$ is the voltage applied to the AC grid by the voltage source inverter, $e_{af}$ represents grid voltage in the $a\beta$ reference frame.
The derivative of the grid current in the continuous-time model can be approximated on the basis of the forward Euler approximation

\[
\frac{di_{\alpha\beta}}{dt} \approx \frac{i_{\alpha\beta}(k+1) - i_{\alpha\beta}(k)}{T}
\]  

(22)

The grid current dynamics of Eq. (21) can then be represented in the discrete-time domain as

\[
i_{\alpha\beta}(k+1) = \left(1 - \frac{RT}{L}\right)i_{\alpha\beta}(k) + \frac{T}{L}(v_{\alpha\beta}(k) - e_{\alpha\beta}(k))
\]  

(23)

Assuming that the one-step future grid currents become equal to the one-step future current references of controller by applying the voltage reference, the grid dynamic in Eq. (23) can be expressed by the inverse dynamic model as

\[
v_{\alpha\beta}(k) = \left(\frac{L}{T}\right)i_{\alpha\beta}(k+1) + \left(\frac{R}{T}\right)i_{\alpha\beta}(k) + e_{\alpha\beta}(k)
\]  

(24)

By shifting the inverse model in Eq. (24) by one step forward, the future voltage reference at the (k+1)th instant is obtained as

\[
v_{\alpha\beta}(k+1) = \left(\frac{L}{T}\right)i_{\alpha\beta}(k+2) + \left(\frac{R}{T}\right)i_{\alpha\beta}(k+1) + e_{\alpha\beta}(k+1)
\]  

(25)

At the kth instant, the one-step future grid current \(i_{\alpha\beta}(k+1)\) required in Eq. (25) can be calculated by measuring the present grid current \(i_{\alpha\beta}(k)\), the present VSI voltage application \(v_{\alpha\beta}(k)\) and the present grid voltage \(e_{\alpha\beta}(k)\) as shown in Eq. (23). The future grid voltage \(e_{\alpha\beta}(k+1)\), needed in Eq. (25), can be estimated using an extrapolation of the past values of the grid voltage. Alternatively, as the frequency of the grid voltage is much smaller than the sampling frequency, in the sequel we will suppose that it does not change sufficiently in one sampling interval. So for simplicity, in Eq. (25) we will consider

\[
e_{\alpha\beta}(k+1) = e_{\alpha\beta}(k)
\]  

(26)

The one-step future current reference \(i_{\alpha\beta}^*(k+1)\) can be obtained by applying a second-order extrapolation algorithm

\[
i_{\alpha\beta}^*(k+1) = 3i_{\alpha\beta}(k) - 3i_{\alpha\beta}^*(k-1) + i_{\alpha\beta}^*(k-2)
\]  

(27)

The two-step future current reference \(i_{\alpha\beta}^*(k+2)\) required in Eq. (25) can be obtained by shifting by one step forward the future current reference \(i_{\alpha\beta}^*(k+1)\) in Eq. (27) as

\[
i_{\alpha\beta}^*(k+2) = 3i_{\alpha\beta}^*(k+1) - 3i_{\alpha\beta}^*(k) + i_{\alpha\beta}^*(k-1)
\]  

(28)

By applying the delay compensation technique, almost one sampling period can be assigned for the calculations and predictions required to determine the optimal voltage vector. Because the VSI can only generate eight possible voltage states, the eight voltage states are evaluated by a predefined cost function to select one optimal state closest to the future voltage reference in Eq. (25). By applying the optimal voltage state to the grid, the grid current generated by the VSI at the next sampling time can track the future current reference.

For each sampling time, the cost function will be calculated for all switching states. Then the proper control actions will be chosen for the next sampling interval.

The cost function of the three-phase inverter predictive controller is built as

\[
g(k+1) = (v_{\alpha}(k+1) - v_{\beta}(k+1))^2 + (v_{\alpha}(k+1) - v_{\beta}(k+1))^2
\]  

(29)

The proposed predictive current control algorithm is performed in four steps as detailed in Fig.9.

![Figure 9. Schematic diagram of the proposed FS-MPC for the main grid-side converter.](image)

### VII. EXPERIMENTAL RESULTS AND DISCUSSION

#### A. Hardware Implementation

In order to verify the performance of the proposed predictive control strategy, an experimental platform of the WECS has been developed in Automatic Laboratory of Sétif (LAS), Algeria, as shown in Fig.10. The control system is implemented on a platform consisting of two dSPACE 1104 cards and a complex programmable logic device. The controller performances was evaluated in both the generator-side switch-mode DC-DC converter and the grid-side voltage source inverter.

B. Generator-Side Control Performance

Fig. 11(a)-(h) show several experimental results recorded using the Control Desk™ software. The variables shown are the random wind speed sequence, the reference and real rotor speeds, the reference DC current and measured DC current, the performance coefficient \( C_p \), tip speed-ratio \( \lambda \), the generator torque, the power captured from wind and the power provided to the grid, the DC-link voltage, respectively. The values used in the wind model are varies from 7 to 13 m/s (mean wind speed of 10 m/s) according to the equivalent wind speed model provided in wind turbine blockset, Matlab/Simulink [18].

controller. The obtained results demonstrate that the predictive controller works very well and shows very good dynamic performance, and it is clear that the proposed controller can be used to extract maximum power from the variable speed wind turbine under fluctuating wind. Next, we look at the grid side control performance.

C. Grid Side Control Performance

After having synchronized and connected the WECS to the grid. The test is conducted on a chosen wind profile varying as step functions from 7 to 12 m/s and 12 to 7 m/s, respectively. For this operating condition, the waveforms of voltage and current on the utility grid are recorded by using digital oscilloscope. Fig.12 shows the experimental waveforms of the inverter output voltage and current. It is seen from Fig.12 that the generated grid-side current is in opposite phase to the grid voltage this verifies that the proposed power conversion system can convert the wind power generated from the PMSG to a high-quality AC power, and this AC power injects into the utility grid. The change of current peak value is created by varying wind speed. It is obvious that the system has an excellent dynamic performance.

The characteristics waveforms of grid interfaced WECS under steady state condition where the wind speed is assumed to be constant are shown in Fig13.a-d. It is clearly seen from Fig.13.a, that the total harmonic distortion (THD) of the injected current is less than the 5% limit imposed by IEEE-519 standard. Fig.13.b gives the measured results of the power factor of the system versus grid connected power. It is obvious that a unity power factor is achieved (PF=0.986), which can satisfies the PF demand in industrial applications.

Fig.14.a shows three phase injected currents waveforms. It is clear that the three phase currents are highly symmetrical and nearly sinusoidal shape. The DC-link voltage tracks perfectly its reference \( V_{out} = 300V \), and the injected current is 180° out of phase.
of phase with respect to grid voltage which implies feeding only real power to the grid, as indicated in Fig. 14.b.

Figure 14. Experimental steady-state waveforms

VIII. CONCLUSION

In this paper, a simple and intuitive approach using the predictive current control strategy has been presented for a direct drive variable-speed grid connected PMSG-based WECS. The proposed control decouples the current reference calculations for the grid-side converter while the maximum power tracking control is achieved by the generator-side converter, that enable full utilization of the wind energy. The wind turbine requirements, such as maximum power point tracking, active and reactive current generation, are modeled as the reference control variables. The generator and grid-side cost functions are defined to deal with these control objectives. During each sampling interval, the control goals are achieved based on minimization of cost functions. The effectiveness of the proposed system has been verified by experiments. The results showed fast, accurate, and effective responses in dynamic and steady-state operating conditions. The developed WECS with the proposed control strategy can be suitable for small and midsize WECSs connected to weak grids.

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<td>Air density ((\rho))</td>
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<td>Optimal tip speed ratio ((\lambda_{opt}))</td>
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<td>Maximum power coefficient ((C_{p,\text{opt}}))</td>
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TABLE II PMSG PARAMETERS

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<tr>
<th>Parameter</th>
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REFERENCES