A New DPC-SVM for Matrix Converter Used in Wind Energy Conversion System Based on Multiphase Permanent Magnet Synchronous Generator

E. Bounadja*(C.A.), Z. Boudjema* and A. Djahbar*

Abstract: This paper proposes a novel wind energy conversion system based on a Five-phase Permanent Magnetic Synchronous Generator (5-PMSG) and a Five to three Matrix Converter (5-3MC). The low cost and volume and also eliminating grid side converter controller are attractive aspects of the proposed topology compared to the conventional with back-to-back converters. The control of active and reactive power injected to the grid from the proposed system is carried out by a Direct Power Control (DPC) combined with a Space Vector Modulation (SVM). An advantage of this control, compared with the Conventional Direct Power Control (C-DPC) method, is that it eliminates the lookup table and lowers grid powers and currents harmonics through the use of a standard PI controller instead of hysteresis comparators. The efficiency of proposed whole system has been simulated by using MATLAB/Simulink environment.

Keywords: Five-Phase Permanent Magnetic Synchronous Generator (5-PMSG), Five to Three-Phase Matrix Converter (5-3MC), Grid Active and Reactive Powers, Direct Power Control (DPC), Space Vector Modulation (SVM), Wind Turbine.

1 Introduction

NOWADAYS the wind turbine conversion systems using the direct-driven three-phase Permanent Magnet Synchronous Generator (PMSG) are suitable and promising for application in wind farms [1-4]. The PMSG can be constructed with a large number of poles and can be operated as low speed direct-driven system without gearbox. This results in reduction of installation and maintenance costs and provides an advantage over the other types of generators. Furthermore, it has many advantages over induction generator, including: higher reliability, higher power, higher efficiency, higher torque, and simple control methods [3, 4]. On the other hand, multiphase PMSG shows other advantages over PMSG, such as reducing the amplitude and increasing the frequency of torque pulsations and higher reliability [5-7]. Therefore, multiphase PMSG is very attractive for application of renewable energy [8].

Several works on five phase PMSG based wind turbine with back-to-back converters have been studied recently as in [5-7]. However, the cost, volume and the number of power electronic converters increase the complexity of this topology. Due to these disadvantages, the MC can be used as an alternative to DC-link voltage-sourced converter for wind energy conversion systems. In addition, the main advantages of the MC are the ability to generate sinusoidal input-output voltage and current and the possibility of adjusting input power factor [8-14]. On the other hand, MC application has been adapted for specific objectives and has not been generalized for wind power conversion systems based on multiphase PMSG generators as in [10-14, 17, 18].

A review of the existing literature, the author in [8] proposed a wind energy conversion systems based on MC. The system studied by this author is based on a six-phase asymmetrical squirrel cage induction generator (SCIG) and MC as power electronic interface between six-phase SCIG and electrical network. However, the power control injected to the grid from this system has

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not been investigated. In this purpose, our article focuses on this issue and investigates the control of 5-phase PMSG in wind energy conversion system based on MC.

Most of studies for the control of PMSG based wind turbine have focused recently. For example, [3] proposed an improvement vector control algorithms for the machine side converter and for the grid side converter. The control of active and reactive power has been applied with the application of voltage oriented control. However, this strategy requires rotary coordinate transformation and depends on the system parameters.

One of most and recent methods in controlling wind powers is the Conventional Direct Power Control (C-DPC). This method is characterized by its fast dynamic response, simple structure and robust response against parameter variation. In C-DPC strategy, active and reactive powers are estimated, using current measurements, controlled directly with hysteresis comparators and using a switching table similar to the one used in direct torque control (DTC) applied for AC machines as presented in [15,16].

The use of the DPC method in wind energy conversion systems based on PMSG has been the subject of a few studies. Study [4] proposed a PMSG connected to the grid via back to back converter. In this paper, the control of machine side converter is achieved by a conventional DTC and the grid side converter is controlled by a DPC. However, the most significant drawback of this strategy is the variable switching frequency which mainly depends on the sampling frequency, the switching table structure, hysteresis bands, and the converter switching status. This variable switching frequency will produce a broadband harmonic spectrum in the AC line currents. For this reason, the design of filters in the AC line will be difficult and expensive [17, 19]. To surmount this inconvenience, we replace hysteresis comparators and swishing table existing in C-DPC by PI regulators with SVM resulting in a constant switching frequency of the power converter.

There are no researches in literature, to the best of our knowledge, of the use of DPC-SVM for the 5-phase PMSG based wind turbine using a 5-3MC. In this context, the present study was an attempt to combine the DPC approach with SVM for 5-phase PMSG connected to the grid via 5-3MC. This combination enables 5-phase PMSG based wind turbine to obtain the unit input power factor and lowers the grid powers and current harmonics. Therefore, it improves the control performance of the system. In addition, the proposed approach eliminates the lookup table and the nonlinearity effect of the hysteresis blocks through the use of the PI controller. Finally, a comparison of whole system performances, obtained by the proposed DTC-SVM and those determined by the C-DPC, is presented and validated by simulation in Matlab/Simulink.

2 General System Description

As shown in Fig.1, the system analysed is a variable speed wind turbine based on a 5-PMSG and 5-3MC connected to the grid via RL filter. Due to the low generator speed, the rotor shaft is coupled directly to the generator, which means that no gearbox is needed.

2.1 Wind Turbine Aerodynamic Model

The mechanical power produced by wind turbine can be expressed as below:

\[ P_m = \frac{1}{2} \rho A C_p (\lambda, \beta) v_w^3 \]  

(1)

where: \( \rho \) is air density, \( A = \pi R^2 \) is area swept by the rotor blades, \( R \) is turbine blade radius, \( C_p \) is wind turbine power coefficient, \( \beta \) is blade pitch angle, \( v_w \) is wind speed, \( \lambda \) is tip speed ratio, which is defined as:

\[ \lambda = \frac{\Omega R}{v_w} \]  

(2)

where \( \Omega_m \) is angular speed of turbine rotor.

The mechanical equation of wind turbine system is given by:

\[ T_m + T_em = K_f \Omega_m + J \frac{d\Omega_m}{dt} \]  

(3)

where \( T_m \) is the mechanical torque of wind turbine, \( T_em \) is the electromagnetic torque of generator, \( J \) is the total inertia of the system, \( K_f \) is the coefficient of viscous friction.

The power coefficient \( C_p \) can be approximated, as relationship of tip speed ratio \( \lambda \) and blade pitch angle \( \beta \), by the following expression [4]:

\[ C_p(\lambda, \beta) = C_1 \left( \frac{1}{\lambda + 0.08 \beta - 0.035 \beta^3 + 1} \right) - C_5 \beta - C_4 \times \exp \left( -C_3 \left( \frac{1}{\lambda + 0.08 \beta - 0.035 \beta^3 + 1} \right) \right) + C_6 \lambda \]  

(4)

where \( C_1 = 0.5176, C_2 = 116, C_3 = 0.4, C_4 = 5, C_5 = 21, C_6 = 0.0068. \)

2.2 Modelling of 5-PMSG

The stator voltage equations of the 5-PMSG in the

Fig. 1 Diagram of the grid connected 5-PMSG based on 5-3MC.
synchronous rotating $dq$ reference frame can be described as follows \[5-7\]:

\[
\begin{align*}
\psi_d &= R_i \psi_d + \frac{d\psi_d}{dt} - \omega_r \psi_q \\
\psi_q &= R_i \psi_q + \frac{d\psi_q}{dt} + \omega_r \psi_d
\end{align*}
\]  

(5)

The components of stator flux vector in this reference frame can be given by:

\[
\begin{align*}
\psi_d &= L_i \psi_d \\
\psi_q &= L_i \psi_q + \psi_f
\end{align*}
\]

(6)

The additional stator equations, which describe the generator in the $(x-y)$ plane, are:

\[
\begin{align*}
\psi_x &= R_i \psi_x + \frac{d\psi_x}{dt} \\
\psi_y &= R_i \psi_y + \frac{d\psi_y}{dt}
\end{align*}
\]

(7)

\[
\begin{align*}
\psi_x &= L_i \psi_x \\
\psi_y &= L_i \psi_y
\end{align*}
\]

(8)

The electromagnetic torque of 5-PMSG can be expressed by the following equation:

\[
T_{em} = \frac{5}{2} p \psi_f i_q
\]

(9)

### 2.3 Five to three-phase MC

The topology of the 5-3MC discussed in this paper is shown in Fig. 2. Its configuration is fictitiously divided into a rectifier input stage and an inverter output stage, which are directly connected on the DC side. In inverter output stage, SVM method is applied for output voltage space vectors. Then the AC-AC converter is derived by eliminating the fictitious DC link.

The switching function of each electronic power switch of the considering 5-3MC is defined as follows:

\[
S_{mn} = \begin{cases} 
1 & \text{if } S_m \text{ closed} \\
0 & \text{if } S_m \text{ open} 
\end{cases} \quad m \in \{A, B, C, D, E\}, \quad n \in \{a, b, c\}
\]

(10)

The input phase should never be short-circuited; therefore, only one switch can be in on-state in each leg at any instant:

\[
S_{aa} + S_{ab} + S_{ac} + S_{ba} + S_{bc} = 1, \quad n \in \{a, b, c\}
\]

(11)

The proposed 5-3MC output phase voltages are made up of its input phase voltages as below:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c \\
V_d \\
V_e
\end{bmatrix} =
\begin{bmatrix}
S_{aa} & S_{ab} & S_{ac} & S_{ba} & S_{bc} \\
S_{aa} & S_{ab} & S_{ac} & S_{ba} & S_{bc} \\
S_{aa} & S_{ab} & S_{ac} & S_{ba} & S_{bc} \\
S_{aa} & S_{ab} & S_{ac} & S_{ba} & S_{bc} \\
S_{aa} & S_{ab} & S_{ac} & S_{ba} & S_{bc}
\end{bmatrix}
\begin{bmatrix}
V_{ia} \\
V_{ib} \\
V_{ic} \\
V_{id} \\
V_{ie}
\end{bmatrix}
\]

(12)

#### 2.3.1 Five-Phase Rectifier Input Stage

According to Fig.3, the virtual intermediate voltage $V_{ib}$ can be deduced as below:

\[
V_{ib} = V^+ - V^-
\]

(13)

The virtual potentials $V^+$ and $V^-$ will be varying as function of the five-phase inputs and the rectification control functions as follows:

\[
\begin{bmatrix}
V^+ \\
V^-
\end{bmatrix} =
\begin{bmatrix}
A^+ & B^+ & C^+ & D^+ & D^+
\end{bmatrix}
\begin{bmatrix}
V_{ia} \\
V_{ib} \\
V_{ic} \\
V_{id} \\
V_{ie}
\end{bmatrix}
\]

(14)

where $m^+$ and $m^-$ $(m \in \{A, B, C, D, E\})$ are the rectification control functions, defined by:

\[
m^+ = \begin{cases} 
1 & \text{if } V_{ia} \text{ is the most positive input phase} \\
0 & \text{if not}
\end{cases}
\]

(15)

\[
m^- = \begin{cases} 
1 & \text{if } V_{ie} \text{ is the most negative input phase} \\
0 & \text{if not}
\end{cases}
\]

The virtual intermediate voltage $V_{ib}$ are illustrated in Fig. 4.
2.3.2 Three-Phase Inverter Output Stage

A Inverter Output Voltages

The link between the virtual middle potential and the output voltages of 5-3MC (Fig. 3) is given as follows:

$$
\begin{bmatrix}
V_{a0} \\
V_{b0} \\
V_{c0}
\end{bmatrix} =
\begin{bmatrix}
a^+ & a^- & 0 \\
b^+ & b^- & 0 \\
c^+ & c^- & 0
\end{bmatrix}
\begin{bmatrix}
V^+ \\
V^- \\
0
\end{bmatrix}
$$

(16)

where \(n^+\) and \(n^-\) \((n=\{a, b, c\})\) are the modulation functions (binary signals) similar to that used in conventional SVM control of standard inverter. It will be synthesized in the following section.

B SVM of Three-Phase Inverter Output Stage

Six power switches have eight possible switching combinations in the Three-phase DC-AC converter. So there are 8 voltage space vectors defined by these 8 switching combinations, which consist of a circle including six effective space vectors and two zero ones. The circle is divided into 6 equal sectors. The demanded output voltage space vector \(V_s\) located in a sector can be synthesized by the adjacent two effective vectors and one zero vector consisting of this sector according to SVM method [19]. The basic output voltage space vectors and the corresponding switching states are represented in Fig. 5.

Suppose \(V_s\) locates in the sector \(k\) which is made up of two adjacent effective vectors \(V_k\) and \(V_{k+1}\) and a zero one \(V_z\) \((Z=0, 7)\), and \(V_s\) leads \(a\)-axis by \(\phi\), then \(V_s\) can be composed of \(V_k\), \(V_{k+1}\) and \(V_z\), as below:

$$
V_s = \frac{T_i}{T_z} V_k + \frac{T_{k+1}}{T_z} V_{k+1} + \frac{T_0}{T_z} V_z
$$

(17)

with

$$
T_i = \frac{\sqrt{3} V_r}{V_n} \sin(\phi + \frac{k \pi}{3}),
T_{k+1} = \frac{\sqrt{3} V_r}{V_n} \sin(\phi - \frac{(k-1) \pi}{3}),
T_0 = T_z - T_i - T_{k+1}
$$

(18)
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Fig. 5 Input voltages and virtual potentials.

Fig. 6 Input voltages and virtual potentials.

where $T_s$ is the switching period and $T_k, T_{k+1}, T_0$ are the switching-on time of voltage vectors $V_k, V_{k+1}$ and $V_z$ respectively.

The modulation functions $n^+ (n=\{a, b, c\})$ are obtained as represented in Fig. 6.

The modulation functions $n^- (n=\{a, b, c\})$ can similarly be obtained as fellow:

$$n^- = 1 - n^+$$

2.3.3 Five to Three MC Switching Functions

The above-mentioned DC-link is imaginary that is say the rectifying and inverting of 5-3MC are conducted at the same time. Therefore this DC-link should be eliminated by substitution of (14) in (16), so, the output-line voltages are obtained as follows:

$$[V_{oa} \ V_{ob} \ V_{oc} \ V_{oa}'] = \begin{bmatrix} a^+ & a^- & b^+ & b^- & c^+ & c^- \end{bmatrix} \begin{bmatrix} A' & B' & C' & D' & D' \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \\ V_D \\ V_E \end{bmatrix}$$

(20)
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4 Simulation Results

The simulation model of wind energy conversion takes the form as illustrated in Fig. 8.

3.2 Synthesis of Grid Active and Reactive Power Controllers

To ensure a pure active power exchange from the wind generator and maintain the reactive power exchange to the grid, which guarantees a desirable power factor during the generator function, an orientation of $d$-axis of the synchronous reference frame with grid voltage vector is required [20, 21]. So (26) becomes as follows:

$$\begin{align*}
v_{gd} &= V_g \\
v_{gq} &= 0
\end{align*}$$

The grid active and reactive power in $(dq)$ coordinates has the form after orientation as below:

$$\begin{align*}
p_s &= \frac{3}{2} V_{gd} i_{gd} - \frac{3}{2} V_{gq} i_{gq} \\
q_s &= \frac{3}{2} V_{gd} i_{gq} + \frac{3}{2} V_{gq} i_{gd}
\end{align*}$$

Based on the above equations, the schematic diagram of power control loops take the form as illustrated in Fig. 8.
The obtained simulation results of considered wind energy conversion system are presented in Figs. 9-22. The considered control of whole system has been tested for the wind speed \( v_w \) during the period of the 10s, while, the average wind speed \( v_{wa} \) has been adopted as equal to 11m/s as presented in Fig. 9.

Fig. 10 shows the waveforms of optimal \( \Omega_{g-opt} \) and measured angular speed \( \Omega_g \) of 5-PMSG obtained from simulation of control system. It can be seen, that the generator speed \( \Omega_g \) is accurately adjusted to the waveforms of optimal speed \( \Omega_{g-opt} \), which is obtained from MPPT algorithm.

The obtained waveforms of power coefficient \( C_p \) and tip speed ratio \( \lambda \) at various wind speeds have been presented in Figs. 11-12. Fig. 13 presents the responses of electromagnetic torque \( T_{em} \) of 5-PMSG and mechanical torque \( T_m \) of
Table 1 Grid parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Frequency $\omega_g$</td>
<td>$2\pi 50$ [rad/s]</td>
</tr>
<tr>
<td>Grid resistance $R_g$</td>
<td>0.015 [Ω]</td>
</tr>
<tr>
<td>Grid inductance $L_g$</td>
<td>0.002 [H]</td>
</tr>
</tbody>
</table>

Table 2 Wind turbine parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor radius $R$</td>
<td>1.8 [m]</td>
</tr>
<tr>
<td>Air density $\rho$</td>
<td>1.225</td>
</tr>
</tbody>
</table>

Table 3 Five phase PMSG parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power $P_n$</td>
<td>4.8 [kW]</td>
</tr>
<tr>
<td>Rated Torque $T_n$</td>
<td>76 [N.m]</td>
</tr>
<tr>
<td>Pairs poles number $p$</td>
<td>5</td>
</tr>
<tr>
<td>Stator resistance $R_s$</td>
<td>0.425 [Ω]</td>
</tr>
<tr>
<td>Stator $dq$-axis inductance $L_s$</td>
<td>0.00835 [H]</td>
</tr>
<tr>
<td>Inertia $J$</td>
<td>0.01197 [kg.m$^2$]</td>
</tr>
<tr>
<td>Flux linkage $\psi_f$</td>
<td>0.433 [Wb]</td>
</tr>
</tbody>
</table>

Fig. 9 Waveforms of average wind speed $v_{wa}$ and real wind speed $v_w$ [m/s].

Fig. 10 Waveforms of the reference speed $\Omega_{g-opt}$ and the actual speed $\Omega_g$ of PMSG.

Fig. 11 Waveform of power coefficient of wind turbine $C_p$.

Fig. 12 Waveforms of tip speed ratio $\lambda$. 
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wind turbine during the considered variation of wind speed. The considered control system allows fast responses of the electromagnetic torque $T_{em}$ of 5-PMSG during temporary time variations of the wind speed.

Figs. 14-15 show the waveforms of machine $dq$-axis and $xy$-axis currents. The response of current vector components ($i_d$, $i_q$) is practically changing according to variations of wind speed. However, the components ($i_x$, $i_y$) have been kept at zero value, as desired.

Figs. 16-17 display the three-phase current waveforms injected to the grid by the conversion system controlled by both C-DPC and DPC-SVM. It can be seen, that this current has a sinusoidal form and changing according to the variations of wind speed for both methods. The effectiveness of proposed strategy is shown in these figures. Also, Figs. 18-19 show the improvement of stator currents THD where it clear to see that by using the SVM strategy the current THD decreases justifying the use of the proposed control, (THD of 107.75 % for the C-DPC and 51.44% for the proposed DPC-SVM).
In Fig. 20 the active and reactive powers injected to the grid, controlled via the proposed DPC-SVM, are displayed, while, in a comparative way, Fig. 21, describes these quantities under the conventional direct power control (C-DPC). One can conclude that, under the proposed control algorithm, the grid power amounts track their references values with smooth profiles, with ripple-free. Also, from these figures, it can be noticed, that only the active power generated by the proposed system is fully delivered to the AC grid, while the reactive power is equal to zero.

Finally, Fig. 22 shows the waveform of the grid voltage and current delivered by the generating system, between 0 s and 0.15 s. It can be seen that the voltage is in phase opposition with the current, which proves that the 5-PMSG, drives with unitary factor power, as can be checked on Fig. 21.
5 Conclusion

In this paper, a new scheme for grid connected 5-PMSG has been presented. The conventional back-to-back converter has been replaced by a 5-3MC. In the proposed scheme, bulky DC-link capacitors and also the grid side converter has been eliminated. In this study, a simple way to control the 5-3MC by considering a virtual DC link between two conversions stage (rectification and inversion) is used. In order to control the active and reactive power injected to the grid a DPC with SVM have been explored. This method eliminates the lookup table and reduces the grid powers and currents harmonics by replacing hysteresis comparators with PI controllers. Another advantage of the propounded approach is that it achieves the unit input power factor. A simulation of the considered control algorithms, with a suitable wind variation, has been applied to whole system. Simulation results show good performances. Therefore, the control method objectives are achieved.

References


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