Maximum Power Point Tracking of Matrix Converter Based Wind Systems with Permanent Magnet Synchronous Generator

Guilherme C. Fernandes[1], Sonia F. Pinto[1,2], and Jose Fernando Silva[1,2]

[1] Tecnico Lisboa, Universidade de Lisboa, Lisboa, Portugal
[2] INESC-ID, Lisboa, Portugal

Abstract. In this work, matrix converter based wind energy systems equipped with Permanent Magnet Synchronous Generators (PMSG) are proposed. To extract the maximum available power from the wind, the Matrix Converter is controlled using the Space Vector representation together with the Sliding Mode control technique, so that the converter supplies the generator with the required currents to provide the tracking of the established reference variables. The Maximum Power Point Tracking is achieved using two different approaches: speed control and torque control. To evaluate their performances, both control approaches are tested in MATLAB/SIMULINK. From the simulation results it is possible to confirm that with the Matrix Converter and adequate input filters it is possible to extract the maximum power from the wind with a nearly unitary power factor in the grid connection.

Keywords: Wind Energy, Matrix Converter, Space Vector Modulation, Maximum Power Point Tracking, Torque Control, Speed Control.

1 Introduction

Nowadays, wind power is one of the most promising renewable energies. In 1998 wind power capacity worldwide was around 10 GW and in the year 2012 it reached a record of 280 GW [1].

Modern wind turbines are usually equipped with a generator that may be a Variable-Speed Synchronous Generator or a Doubly-Fed Induction Generator. Both solutions use AC/AC power electronic converters to connect the generator to the grid. Usually, the AC/AC power converter is a rectifier-inverter pair structure with an intermediate DC-link with electrolytic capacitor banks, which result in increased losses, weight, size and costs of the equipment, as well as in decreased lifetime [2].

Due to these disadvantages, Matrix Converters [3,4] have become an alternative solution to the DC-link power converters, as they are single stage AC/AC bidirectional power converters capable of establishing the desired output voltages and currents with variable frequency, and nearly unitary power factor in the connection to the grid. Matrix Converters have a simple topology, are made almost exclusively by semiconductors and have nearly no energy storage components.

A.P. Moreira et al. (eds.), *CONTROLO'2014 - Proc. of the 11th Port. Conf. on Autom. Control*, Lecture Notes in Electrical Engineering 321, DOI: 10.1007/978-3-319-10380-8_29

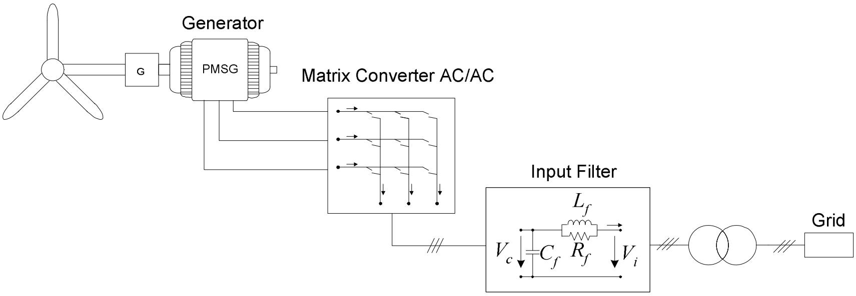

Fig. 1. Proposed wind generation system

The main goal of this work is to evaluate matrix converter based wind energy systems equipped with Permanent Magnet Synchronous Generators (PMSG) connected to the grid through matrix converters. Maximum Power Point Tracking (MPPT) is ensured using two different approaches: Speed Control and the Torque Control.

2 Maximum Point Power Tracking

2.1 Wind Turbine Model

The wind turbine should be controlled in order to extract the maximum available power from the wind. Usually the MPPT approach sets the pitch angle to zero and is applied when the wind speed u is between the cut-in speed and nominal speed of the wind generator. The application of this control strategy can be made by controlling the generator torque or the generator speed [5,6]. Both methods are described and compared in this paper. The power P_e extracted from the wind can be obtained from (1), where the power coefficient C_p is given by (2), ρ is the air density (Kg/m^3), A is the swept area (m^2) of the turbine rotor and u is the wind velocity [5,6].

$$P_e = \frac{1}{2}\, C_p(\,\beta, \lambda)\rho\, A\, u^3 \tag{1}$$

$$C_p = 0.22\left(\frac{116}{\lambda_i} - \,0.4\beta - 5\right)e^{-\frac{12.5}{\lambda_i}} \tag{2}$$

The power coefficient C_p depends on the pitch angle β and on the tip-speed ratio λ, defined as the ratio between the linear velocity of the blade tip ($R\ \omega_T$) and the wind velocity (u) (3):

$$\lambda = \frac{R\ \omega_T}{u} \tag{3}$$

$$\lambda_i = \frac{1}{\dfrac{1}{\lambda + 0.08\beta} - \dfrac{0.035}{1+\beta^3}} \tag{4}$$

The torque applied to the wind turbine rotor is then obtained from (5):

$$T_T = \frac{P_e}{\omega_T} \tag{5}$$

2.2 Optimum Speed

In order to obtain the optimum speed value, that guarantees the MPPT, it is required to determine the maximum available mechanical power supplied by the wind turbine (6):

$$\frac{dP_e}{d\omega_T} = 0 \tag{6}$$

From (1) and solving (6), for β=0 the generator speed reference is then given by (7), where *G* is the wind turbine gearbox ratio.

$$\omega_{opt} = G\,\frac{6.32497\,u}{R} \tag{7}$$

This optimum speed will be used as a reference for the speed control strategy.

2.3 Optimum Torque

Replacing (7) in (1), it is possible to determine the maximum power extracted from the wind. From (7), the torque that guarantees the MPPT is given by (8) [5,6].

$$T_{REF} = T_{MPPT} = \frac{0.843213\,R^3\,u^3}{G\,\omega_{Topt}} \tag{8}$$

Further, the matrix converter reference currents will be established from the reference torque (8) in order to extract the maximum power from the wind.

3 Permanent Magnet Synchronous Generator

The proposed wind generation system is equipped with a permanent magnet synchronous generator. In the rotating dq frame the voltages u_{ds}, u_{qs} applied to the stator windings are given by (9), where i_{ds}, i_{qs} are the stator currents, and ψ_{ds}, ψ_{qs} are the stator fluxes [7,8,9].

$$\begin{cases} u_{ds} = r_s\,i_{ds} + \dfrac{d\psi_{ds}}{dt} - \omega_e\,\psi_{qs} \\ u_{qs} = r_s\,i_{qs} + \dfrac{d\psi_{qs}}{dt} + \omega_e\,\psi_{ds} \end{cases} \tag{9}$$

The relation between the stator currents i_{ds}, i_{qs} and stator fluxes ψ_{ds}, ψ_{qs} is given by (10), where ψ_{f0} is the permanent magnet flux and L_{ds}, L_{qs} are the stator inductances:

$$\begin{cases} \psi_{ds} = \psi_{f0} + L_{ds}\,i_{ds} \\ \psi_{qs} = L_{qs}\,i_{qs} \end{cases} \tag{10}$$

The electromagnetic torque T_{em} of the generator is given by (11), where *p* is the PMSG number of pole pairs.

$$T_{em} = p\,(\psi_{ds}\,i_{qs} + \psi_{qs}\,i_{ds}) \tag{11}$$

3.1 Stator Flux Oriented Control

The Stator Flux Oriented Control approach is used to control the generator currents. The dq frame is aligned with the stator linkage flux ψ_{ds}, resulting in i_{ds}=0. Then, from (10) the stator flux will equal the permanent magnet flux $\psi_{ds} = \psi_{f0}$ and from (11) it is possible to establish a linear relation between the electromagnetic torque and the i_{qs} current (12).

$$i_{qs} = \frac{T_{em}}{p\,\psi_{f0}} \tag{12}$$

If T_{em} is the same as the reference torque, i_{qs} will be the reference current to the matrix converter current controller.

3.2 Speed Controller

The model of the speed controller is presented in figure 2 [10].

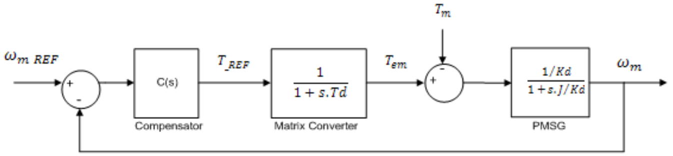

Fig. 2. Block diagram block of the speed controller

The reference torque establishes the currents that will be applied to the PMSG stator so that the generator speed can track its reference torque. The sizing of C(s) compensator is done considering that the open-loop chain is a second order system with two real poles at $-1/T_d$ and $-K_d/J$. In order to minimize the effect of the T_m disturbance and to guarantee fast response times and zero tracking error to the step response, a PI controller is used [10]:

$$C(s) = K_p + \frac{K_i}{s} = \frac{1 + s\,T_z}{s\,T_p} \tag{13}$$

To cancel the effect of the low frequency pole $-K_d/J$, the zero T_z of the PI compensator is given by (14):

$$T_z = \frac{J}{K_d} \tag{14}$$

From the closed-loop transfer function of the system and then comparing it to the transfer function of a second order system it is possible to obtain T_p (15):

$$T_p = \frac{1}{\omega_0{}^2 K_d T_d} \tag{15}$$

4 Matrix Converter

The three phase matrix converter is an array of nine bidirectional switches [3] S_{ij} (16) that allow the connection of any output phase to any input phase.

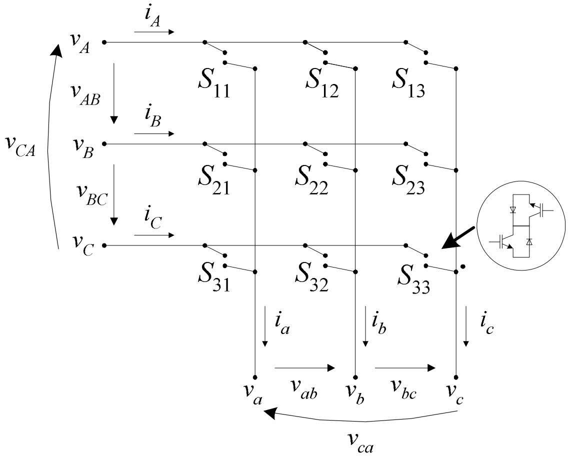

Fig. 3. Matrix converter

The power switches S_{ij} are usually represented as two possible logical states: $S_{ij} = 1$ if the switch is ON and $S_{ij} = 0$ if the switch is OFF. Due to topological restrictions, there are only 27 possible switching states.

$$\mathbf{S} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \tag{16}$$

$$\begin{gathered} [\mathrm{v}_a \quad \mathrm{v}_b \quad \mathrm{v}_c]^{\mathrm{T}} = \mathbf{S}\,[\mathrm{v}_A \quad \mathrm{v}_B \quad \mathrm{v}_C]^{\mathrm{T}} \\ [i_A \quad i_B \quad i_C]^{\mathrm{T}} = \mathbf{S}^{\mathrm{T}}\,[i_a \quad i_b \quad i_c]^{\mathrm{T}} \end{gathered} \tag{17}$$

The application of Concordia transformation to the 27 voltages and currents (17) that result from these switching states allow the representation of the input currents and output voltages as vectors in the αβ plane [4], [11]. This vector representation is useful to control the matrix converter output currents, which will be the PMSG currents, and the input power factor in the connection to the grid. The connection to the grid is made using a second order filter [4], [11] that minimizes the harmonics of the currents injected in the grid.

4.1 Control of Matrix Converter Output Currents

The reference currents are obtained from (12) and result from the PMSG speed or torque controller. The sliding surfaces used to control the matrix converters output currents are represented in (18) [11]-[13].

$$\begin{cases} S_\alpha(e_\alpha,t) = K_\alpha\,(i_\alpha^{REF} - i_\alpha) \\ S_\beta(e_\beta,t) = K_\beta\,(i_\beta^{REF} - i_\beta) \end{cases} \quad K_\alpha > 0, K_\beta > 0 \tag{18}$$

To assure that the system slides along the defined surfaces it is required that they verify the stability conditions (19):

$$\begin{cases} S_\alpha(e_\alpha,t) \cdot \dot{S}_\alpha(e_\alpha,t) < 0 \\ S_\beta(e_\beta,t) \cdot \dot{S}_\beta(e_\beta,t) < 0 \end{cases} \tag{19}$$

The Space Vector selection criterion is presented in table 1 and is based in equations (18) and (19).

Table 1. Criteria to choose the vector to control the PMSG currents

$S_{\alpha,\beta}$	**Space Vector Choice**	**Value of** $S_{\alpha,\beta}$
$S_{\alpha,\beta} > \Delta$	Vector that increases $i_{\alpha,\beta}$ value	+1
$S_{\alpha,\beta} > -\Delta$ and $S_{\alpha,\beta} < \Delta$	Vector that does not change $i_{\alpha,\beta}$	0
$S_{\alpha,\beta} < -\Delta$	Vector that decreases $i_{\alpha,\beta}$ value	-1

According to [11], in each time instant there are always two different vectors to apply in order to control the currents.

4.2 Power Factor Control in the Connection to the Grid

To control the Matrix Converter input currents and to obtain a nearly unitary power factor, the reactive power (20) in the connection to the grid should be nearly zero.

$$Q_{dq} = v_d i_q - v_q i_d \tag{20}$$

Choosing a dq reference frame synchronous with the grid voltage, then $i_{q\_ref} = 0$. To control the input power factor, the sliding surface is established [11].

$$S_{iq}(e_{iq},t) = K_{iq}(i_{q_{ref}} - i_q) \tag{21}$$

The sliding surface also has to guarantee the stability condition (22).

$$S_{iq}(e_{iq},t) \cdot \dot{S}_{iq}(e_{iq},t) < 0 \tag{22}$$

Table 2. Criteria to choose the vector to control the grid currents

S_{iq}	**Space Vector Choice**	**Value of** S_{iq}
$e_{iq} > \Delta$	Vector that increases i_q	+1
$e_{iq} < -\Delta$	Vector that decreases i_q	-1

The input current controller defines a criterion (table 2) that allows to choose which of the two available space vectors is the most adequate to apply [11]. The right choice of space vectors guarantees that the controlled variables track their references.

5 Simulation Results

The proposed system was tested in MATLAB/SIMULINK platform. The simulation was based on the Siemens wind turbine SWT-1.3-113 (table 3), PMSG parameters presented in table 4, and the speed controller parameters are presented in table 5.

Table 3. Characteristics of Siemens wind turbine SWT-1.3-113

$S_N\,[MVA]$	$V_N\,[V]$	Blade Length [m]	Gear Box ratio
2.3	690	55	77

Table 4. Permanent Magnet Synchronous Generator parameters

p	$r_s\ [m\Omega]$	L_d[mH]	L_q[mH]	B_m	$J_{in}[Kgm^3]$	$\psi_{f0}[Wb]$
4	2	0.09	0.09	0.05	100	0.865

Table 5. Speed Controller parameters

K_t	$T_d[ms]$	ξ	$T_z[s]$	$\omega_0[rad/s]$	$T_p[s]$	K_p	K_i
1	1	$\sqrt{2}/2$	2000	707.1068	0.04	50000	25

The wind chart of Fig. 4 was obtained based on average measurements of wind speed. Regarding the available simulation computer, the time span to be simulated had to be reduced to thirty seconds and the inertia of the turbine plus generator was also reduced in order to obtain scaled results.

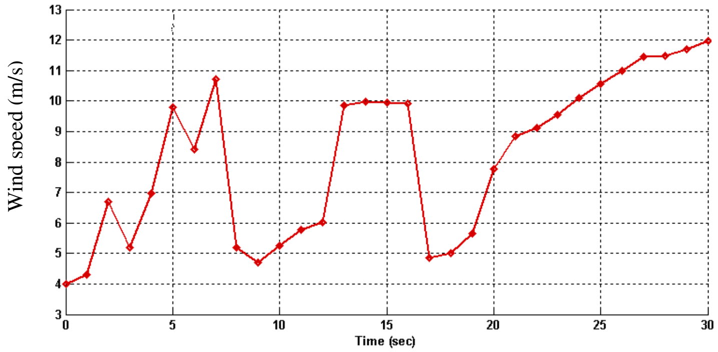

Fig. 4. Wind Speed Chart

From the obtained results, the MPPT speed controller can track the wind speed variations with adequate response times. As can be seen from figure 5, the speed reference established by the controller is tracked by the generator. Figure 6 represents the electromagnetic torque obtained for the speed control case.

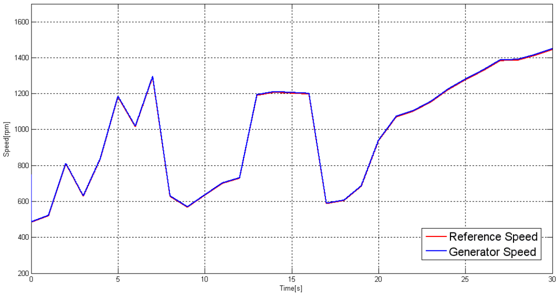

Fig. 5. Generator speed tracking the reference

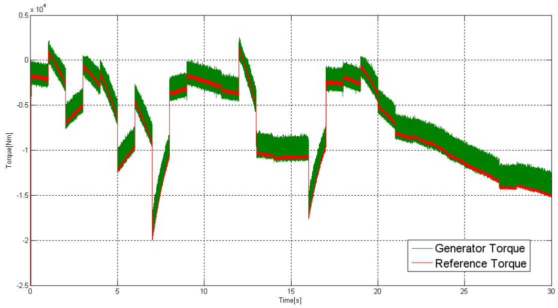

Fig. 6. Generator torque tracking the reference (speed control case)

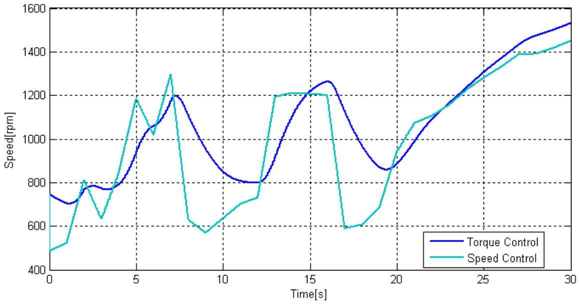

Fig. 7. Speed comparison of Torque Control and Speed Control

In contrast, the MPPT torque controller, although following the optimum torque slowly enforces the MPPT speed. As expected, the MPPT speed controller is much faster than MPPT torque controller. The speed controller allows the generator to accurately track the wind speed variation. The torque controller considers that the generator is always rotating at its optimal speed, as can be seen in figure 7, which can be a serious limitation when the wind speed changes fast.

Figure 8 represents the electromagnetic torque obtained for the torque control case. The electromagnetic torque produced by the generator tracks accurately the reference torque established by the torque control. As can be seen, the values of the electromagnetic torque obtained in this case are different from the ones obtained with the speed control.

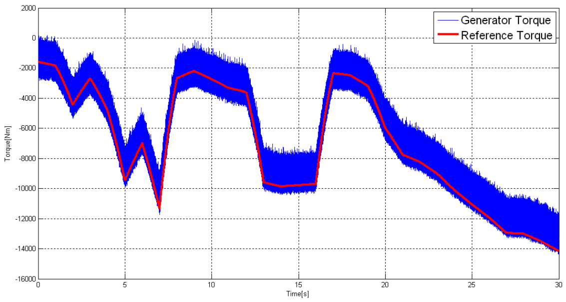

Fig. 8. Generator torque tracking the reference (torque control case)

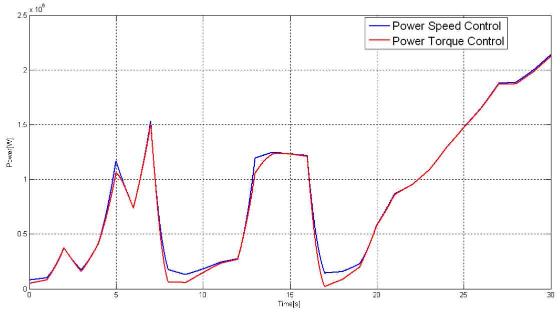

Fig. 9. Electric power in both approaches

Figure 9 represents the electric power generated using both approaches. It is possible to see that the speed controller is able to extract more power from the wind than the torque controller when the wind speed is between 4 and 7 m/s. The torque controller assumes the generator speed is at its optimal value and defines a torque reference to the generator controller. However, as can be seen from figure 7 when the wind speed values are low, the generator speed in the torque control case is much higher than the optimal speed. As a result it produces less power than the speed control approach.

Calculations were made in order to estimate the differences in the power extraction. The torque control case produced 5 kWh with a power coefficient of 42% and the speed control case produced 7.4 kWh with a power coefficient of 44%.

6 Conclusions

Both Maximum Power Point Tracking techniques were tested and produced different results. The speed controller extracts more power from the wind than the torque controller because the last does not perform well when wind speed values are near the cut-in speed limit. However, the reference for the electromagnetic torque to be produced by the generator in the speed control case has discontinuities when wind speed values change fast, and it reaches very high torque values when the wind speed is close to the nominal speed of the wind generator. These high values of torque result in overcurrents which are undesirable. In spite of extracting less power from the wind, the electromagnetic torque produced in the torque control case has lower values of torque and it is continuous and more stable than in the speed control approach.

From these results one might conclude that when wind speeds are closer to the wind generator cut-in speed, the best solution is to control the generator speed, because this controller extracts more power from the wind.

Acknowledgements. This work was supported by Portuguese national funds through FCT - Fundação para a Ciência e a Tecnologia, under project PEst-OE/EEI/LA0021/2013.

References

[1] GWEC, Global wind Statistics, Global Wind Energy Council (2013)

[2] Ristow, A., Begovic, M., Pregelj, A., Rohatgi, A.: Development of a Methodology for Improving Photovoltaic Inverter Reliability. IEEE Transactions on Industrial Electronics, Vo 55(7) (2008)

[3] Wheeler, P., Rodriguez, J., Clare, J., Empringham, L., Weinstein, A.: Matrix Converters: A Technology Review. IEEE Trans. on Industrial Electronics 49(2), 276–288 (2002)

[4] Monteiro, J., Silva, J.F., Pinto, S.F., Palma, J.: Linear and Sliding Mode Control Design for Matrix Converter Based Unified Power Flow Controllers. IEEE Transactions on Power Electronics 29(7), 3357–3367 (2014)

[5] Anaya-Lara, O., Jenkins, N., Ekanayake, J., Carthwright, P., Hughes, M.: Wind Energy Generation: Modeling and Control. John Wiley and Sons, Cardiff (2009)

[6] Pinto, S.F., Aparício, L., Esteves, P.: Direct Controlled Matrix Converters in Variable Speed Wind Energy Generation Systems. In: IEEE International Conference on Power Engineering, Energy and Electrical Drives, POWERENG 2007, Setúbal, Portugal, pp. 654–659 (May 2007)

[7] Jones, C.V.: The Unified Theory of Electrical Machines. Plenum Press (1967)

[8] Rolna, A., Luna, A.: Modelling of a Variable Speed Wind Turbine with a Permanent Magnet Synchronous Generator. In: IEEE Symposium in Industrial Electronics, ISIE 2009, Seoul Olympic Parktel, Seoul, Korea (July 2009)

[9] Ming, Y., Li, G., Zhou, M., Zhao, C.: Modeling of the Wind Turbine with a Permanent Magnet Synchronous Generator for Integration. In: Power Engineering Society General Meeting, Florida, USA (2007)

[10] Afonso, L., Pinto, S.F., Silva, J.F.: Maximum Power Point Tracker for Wind Energy Generation Systems Using Matrix Converters. In: Proc. POWERENG 2013, Istanbul, Turley (May 2013)

[11] Pinto, S., Silva, J.: Sliding Mode Direct Control of Matrix Converters. IET Electr. Power Appl. 1(3) (May 2007)

[12] Silva, J.F., Pinto, S.F.: Advanced Control of Switching Power Converters, Cap. In: Rashid, M.H. (ed.) Power Electronics Handbook, 3rd edn., vol. 36, pp. 1037–1113. Butterworth-Heinemann, Burlington (2011) ISBN: 978-0-12-382036-5

[13] Silva, J.F., Pires, V.F., Pinto, S.F., Barros, J.D.: Advanced Control Methods for Power Electronics Systems. Mathematics and Computers in Simulation 63(3), 281–295 (2003)