Wind Generation System with Fault Ride Through Capability

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***Abstract*— The aim of this work is to propose a new strategy for FRT capability of a wind turbine without the need of any external equipment. Nowadays, the Grid Codes require that wind generation systems stay connected during voltage dips, to avoid cascading effects due to the lack of power, and this is the reason why Fault Ride Through has emerged as a new requirement for wind turbines. The proposed wind generation system is equipped with a Permanent Magnet Synchronous Generator (PMSG) and a Matrix Converter. The Maximum Power Point Tracking (MPPT) has been guaranteed by a speed controller that establishes the reference torque. Then, the reference torque will establish the reference currents for the matrix converter. In the occurrence of sags, the wind generation system no longer guarantees the MPPT mode. Then, a reference torque is established, limiting the currents in the matrix converter and the PMSG stator windings. With this approach it is possible to guarantee that the PMSG is not disconnected from the grid, in the presence of a voltage sag of 80% during 500ms.**

Keywords — Fault Ride Trough, Permanent Magnet Synchronous Generator, Matrix Converter, Voltage Sag.

I. INTRODUCTION

Wind power is one of the most promising renewable energies, and in 2014 the installed power reached 112 GW [1]. In some countries wind was become one of the largest electricity renewable sources. The advantages are clear but wind power generation has some drawbacks that must be taken in account.

The most common type of wind turbine is the fixed-speed wind turbine with the induction generator connected directly to the grid. This system, however, does not allow voltage control.

The variable-speed turbines, as Doubly-Fed Induction Generator (DFIG) or Permanent Magnet Synchronous Generator (PMSG), despite improving the maximum power point tracking and the power quality in the connection to the grid, their operation still presents some challenges during grid faults or in case of severe voltage sags.

The voltage sags result in an increase of the current in the stator windings of the wind turbine, which lead to the destruction of the converter. To avoid this problem, most of the wind turbines are automatically disconnected from the grid in case of fault or severe sags. However, due to the high installed power it is not possible to disconnect an entire wind farm without affecting the stability of the power system. The sudden loss of wind turbines during a fault could generate control problems of frequency and voltage in the system.

According to the new grid codes the wind turbines must remain connected to the network in the occurrence of grid faults or severe voltage sags. This feature is known as Fault Ride Through capability.

Flexible AC Transmission Systems (FACTS) based solutions as Dynamic Voltage Restorers (DVR) or Static Compensator (STATCOM) are often used to improve the FTR capability.

The proposed wind generation system is equipped with a PMSG and with a power electronic converter connected between the generator and the network. The AC/AC power converter is a Matrix Converter (MC). This converter is a single stage AC/AC bidirectional power converter capable of establishing a desired output frequency and voltage and nearly unitary power factor in the connection to the grid. The MC is composed exclusively by semiconductors and with no energy storage components.

The system (Fig. 1) is based on a wind turbine model that defines the optimum speed of PMSG according to the wind speed. Taking into account the real speed and the optimum, a reference torque is generated in order to reach the optimum speed as soon as possible. The MC uses the Space Vector Representation (SVR) and the Sliding Mode Control (SMC) to control the PMSG currents necessary to satisfy the established reference torque and extract the maximum power from the wind.

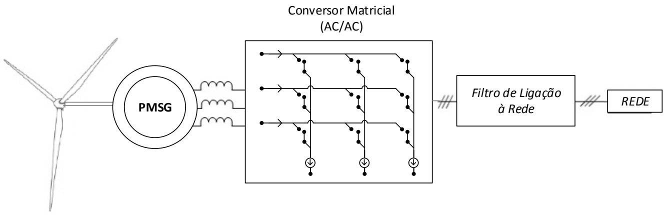

Fig. 1. Global model of the system

The main aim of this paper is to propose a new strategy for FRT capability in a matrix converter based wind turbine, without the requirement of external devices or FACTS.

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II. EQUIPMENT

A. Wind Turbine Model

The wind power that it is possible to extract with the wind turbine is given by (1) [2]:

$$P_e = \frac{1}{2}A\rho u^3 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{12.5}{\lambda_i}\right)} \quad (1)$$

Where ρ is the air density (kg/m^3), A is the swept area (m^2) by the wind turbine, u is the wind speed (ms^{-1}), β is the pitch angle and λ is the tip-speed ratio (TSR), witch can be obtained by:

$$\lambda_i = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right)^{-1} \quad (2)$$

$$\lambda = \frac{\omega_T . r}{u} \quad (3)$$

The mechanical torque extracted from the turbine rotor is obtained by:

$$T_T = \frac{P_e}{\omega_G} \quad (4)$$

B. Permanent Magnet Synchronous Generator

This wind generation system is equipped with a PMSG. The model of the PMSG is represented in a *dq*-frame where d-axis is aligned with the PMSG rotor position and *q* axis is in quadrature with *d* axis [3].

The voltages applied to the stator windings are given by (5).

$$\begin{cases} u_{ds} = r_s \cdot i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e \cdot \psi_{qs} \\ u_{qs} = r_s \cdot i_{qs} + \frac{d\psi_{qs}}{dt} - \omega_e \cdot \psi_{ds} \end{cases} \quad (5)$$

The stator fluxes are obtained by (6).

$$\begin{cases} \psi_{ds} = \psi_{f0} + L_{ds} \cdot i_{ds} \\ \psi_{qs} = L_{qs} \cdot i_{qs} \end{cases} \quad (6)$$

The electromagnetic torque of the PMSG is (7).

$$T_{em} = p(\psi_{ds} \cdot i_{qs} + \psi_{qs} \cdot i_{ds}) \quad (7)$$

C. Matrix converter

Matrix converter allows direct AC-AC conversion, without any intermediate stage (Fig. 2). This converter is an array of nine bi-directional switches, which allow the connection of a voltage source to a current source. The power switches S_{kj} ($k,j \in \{1,2,3\}$) can be represented with two possible stages. If "$S_{kj}=1$" the switch is ON and if "$S_{kj}=0$" the switch is OFF. The nine matrix converter switches should be represented as 3x3 matrix **S,** (8). The relations between input phase voltages (V_a, V_b, V_c) and output phase voltages (V_A, V_B, V_C) depends on matrix **S** (9). In the same way output phase currents (i_A, i_B, i_C) are related to the input phase currents (i_a, i_b, i_c), (10) [4].

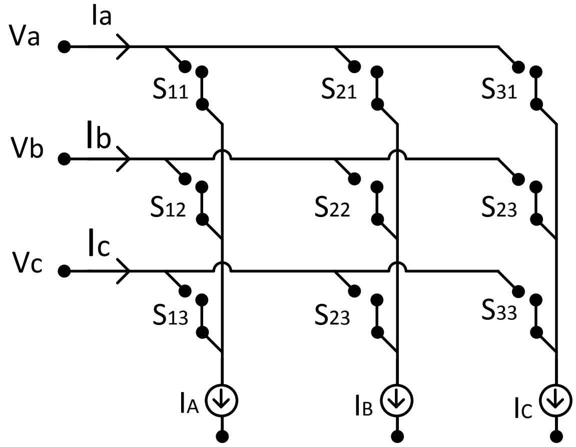

Fig. 2. Three-Phase Matrix Converter

$$\mathbf{S} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \mathbf{S} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \mathbf{S} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (10)$$

However, to guarantee that the input phases are never short-circuited and that the output phases are never open, the sum of all S_{kj} corresponding to each one of matrix **S** rows must always equal to 1 (11). Due to this constrains there are only 27 possible switching combinations.

$$\sum_{j=1}^{3} \boldsymbol{S}_{kj} = 1, \; k \in \{1,2,3\} \quad (11)$$

The state-space vectors are obtained representing the output voltages and the input currents as vectors in the αβ plane. Using the transpose of Concordia transformation, abc→αβ. These vectors can be grouped in three different categories, according to their amplitude and phase characteristics:

- 6 vectors with fixed amplitude and time varying phase;
- 18 vectors with fixed phase and time-varying amplitude;
- 3 null vectors.

In the proposed approach, only the vectors with fixed phase and time-varying amplitude will be used to control this system.

III. SYSTEM CONTROL

Under normal operation conditions, the system guarantees the MPPT through the speed control. The set speed, the optimal operating speed, is directly proportional to the wind speed and allows extracting the maximum power.

From the speed control it is established the reference torque, which is directly proportional to the PMSG stator current i_q component. Then the i_{abc} currents, obtained with the Park transformation, are the reference currents used by the control of the matrix converter.

Following the reference current MC, using SVR and SMC, the voltages at the entrance of PMSG are established, which in turn produce the torque corresponding to the conditions imposed by the speed control and the drive control.

In the presence of a voltage sag, a reference torque is established to guarantee that the maximum current ratings are not overcome.

A. PMSG controller

The generator currents are controlled using the rotor flux oriented control. The *dq* frame is related to the linkage flux ψ_s which enables the establishment of a linear relation between the electromagnetic torque and the stator i_q current (12).

$$i_{qs} = \frac{T_{em}}{p \cdot \psi_{fo}} \quad (12)$$

As the stator current i_d is zero, the linkage flux is equal to the permanent flux (13) and i_{qs_ref} becomes (14).

$$i_{qs\_ref} = \frac{T_{MPPT}}{p\psi_{fo}} \quad (14)$$

That is the reference current to control matrix converter.

B. Matrix converter controller

The purpose is to control the matrix converter output currents using the SVR associated to the non-linear SMC [5], [6].

The currents measured at the output of the converter are compared to the reference values, established by (14). Depending on the difference between the measured and the reference values (15) it is chosen the most adequate vector from the 18 vectors with fixed phase and time-varying amplitude. The chosen vector should follow the reference and guarantee the sliding mode stability condition (16).

$$\begin{cases} S_\alpha(e_\alpha, t) = k_\alpha(i_{\alpha\_REF} - i_\alpha) \\ S_\beta(e_\beta, t) = k_\beta(i_{\beta_{REF}} - i_\beta) \end{cases} \quad (15)$$

Where the k_α and k_β should be greater than zero.

$$\begin{cases} S_\alpha(e_\alpha, t)\dot{S_\alpha}(e_\alpha, t) < 0 \\ S_\beta(e_\beta, t)\dot{S_\beta}(e_\beta, t) < 0 \end{cases} \quad (16)$$

From (15) and (16), Table I synthetizes the space vector selection criteria.

TABLE I. SPACE VECTOR SELECTION CRITERIA

Level	$S_{\alpha\beta}$	Criterion
+1	$S_{\alpha,\beta} > \Delta$	Vector that increases $i_{\alpha,\beta}$
0	$-\Delta < S_{\alpha,\beta} < \Delta$	Vector that does not change $i_{\alpha,\beta}$
-1	$S_{\alpha,\beta} < -\Delta$	Vector that decreases $i_{\alpha,\beta}$

With this technique, there are two possible different vectors to apply in order to control the output current.

To control the input power factor of the matrix converter and to obtain a nearly unitary power factor at the entrance of the converter, it is mandatory that the reactive power is nearly zero. From (17), considering a reference frame synchronous with the grid voltage (18), reactive power is given by (19).

$$\begin{cases} P = u_d i_d + u_q i_q \\ Q = u_q i_d - u_d i_q \end{cases} \quad (17)$$

$$u_q = 0 \quad (18)$$

$$Q = u_d i_q \quad (19)$$

Depending on the difference between the measured and the reference value (20) it is chosen the most adequate vector that guarantees the sliding mode stability condition (21).

$$S_{Q_i}(Q_i, t) = k_{Q_i}(Q_{i\_REF} - Q_i) \quad (20)$$

$$S_{Q_i}(e_{Q_i}, t)\dot{S_{Q_i}}(e_{Q_i}, t) < 0 \quad (21)$$

From (20) and (21), Table II synthetizes the space vector criteria.

TABLE II. SPACE VECTOR SELECTION CRITERIA

Level	$S_{\alpha\beta}$	Criterion
+1	$S_{Qi} > \Delta$	Vector that increase Q_i
-1	$S_{Qi} < -\Delta$	Vector that decreases Q_i

C. Speed controller

The speed controller extracts the maximum power from the wind by establishing an optimal speed based on the MPPT requirement. To obtain the optimal speed value, it is necessary to determine the maximum available mechanical power supplied by the wind turbine (22), (23).

$$\frac{dP_e}{d\omega_T} = 0 \tag{22}$$

$$\omega_{Topt} = \frac{6.32497u}{r} \tag{23}$$

The generator speed reference is given by (24) where G is the gain of the gearbox.

$$\omega_{G\_ref} = G\,\frac{6.32497u}{r} \tag{24}$$

The model of the speed controller is presented in figure 3.

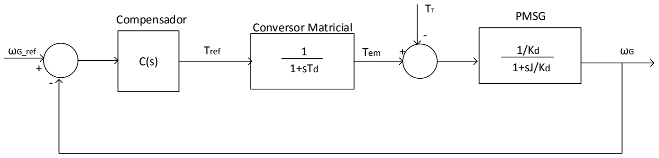

Fig. 3. Speed controller.

The compensator C(s), will produce a reference torque, T_{REF}, that will establish the reference output current i_q. Its sizing has to be done admitting that it is a 2nd order open-loop chain, without any poles at complex plan origin and with 2 real poles at $-1/T_d$ and $-K_d/J$. The system has a perturbation, T_T, in order to minimize the effect of disturbance and to get a zero static error, the compensator is a proportional-integral (PI), (25).

$$C(s) = K_p + \frac{K_I}{s} = \frac{1+s\cdot T_Z}{s\cdot T_p} \tag{25}$$

The closed-loop transfer function of the system is given by (26).

$$G(s) = \frac{\omega_G}{\omega_{G\_ref}} = \frac{\frac{1}{T_p K_d T_d}}{s^2+\frac{1}{T_d}s+\frac{K_t}{K_d T_d T_p}} \tag{26}$$

To cancel the low frequency pole of the system at $-K_d/J$, the zero of PI compensator, T_Z is given by (27):

$$T_z = \frac{J}{K_d} \tag{27}$$

The T_p is given by (28)

$$T_p = \frac{1}{{\omega_0}^2 K_d T_d} \tag{28}$$

When a voltage dip occurs, the torque is directly controlled to guarantee that the maximum current ratings are not overcome, and the wind generation system is not disconnected from the grid. MPPT will no longer be guaranteed, and the generator speed will adjust according to a new operating point.

IV. SIMULATION RESULTS

In this section the simulation parameters and results are presented.

Simulation conditions are show from Table III, to Table V.

TABLE III. WIND GENERATOR PARAMETERS

R [m]	u_0[ms^{-1}]	$u_N[ms^{-1}]$	u_{max}[ms^{-1}]	P_N [MW]	V_N [V]
37.5	3	12 a 13	25	2.3	690

TABLE IV. PMSG PARAMETERS

ψ_{f0}[Wb]	L_{ds} [mH]	L_{qs} [mH]	R [mΩ]	J [kgm^2]	p	P_N [MW]	V_N [V]
0.91	0.0235	0.0235	0.4	1000	4	2.3	690

TABLE V. SPEED CONTROLLER PARAMETERS

K_t	T_d[ms]	ξ	T_z[s]	ω_0[rad /s]	T_p[s]	K_p	K_i
1	1	$\frac{\sqrt{2}}{2}$	2000	707.11	0.04	50 000	25

The simulation period is 24s. As the simulation period was reduced to 24 s due to hardware limitations, the inertia of the “turbine+generator” was also reduced to obtain scaled results.

Figure 4 shows the voltage sag chart, with a depth of 80% and a duration of 500ms.

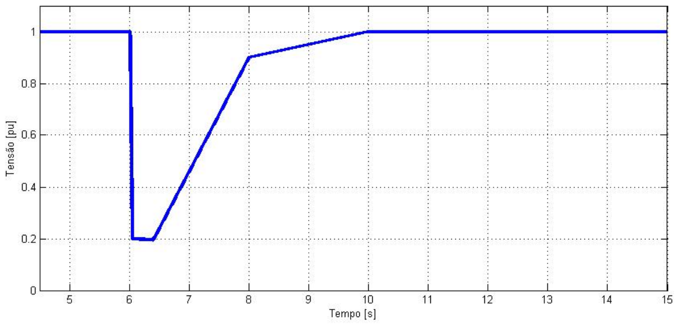

Fig. 4. Voltage sag chart.

Figure 5 present the generator speed tracking the reference, where it is clear that after the voltage sag the generator takes about 3 seconds to track the reference speed established by the speed controller. This behaviour is due to the large inertia of the "turbine+generator".

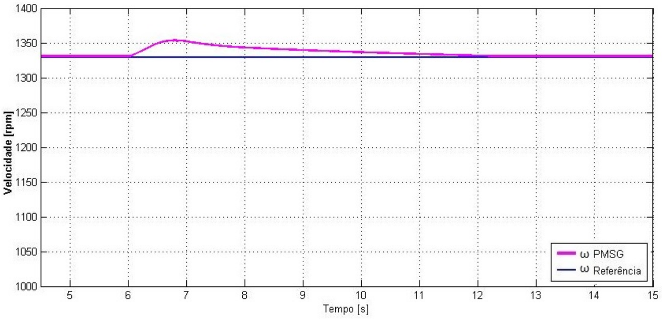

Fig. 5. Generator speed tracking the reference.

Figure 6 shows the PMSG torque. Out of voltage sag, the torque tracks the reference.

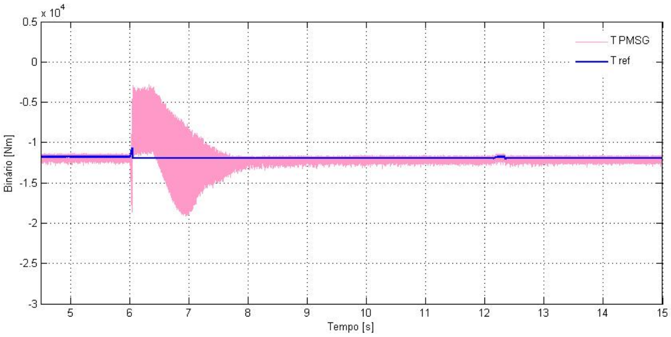

Fig. 6. Generator torque tracking the reference.

The voltage sag occurs at *t*=6 s (fig.7), there is an increase of the output current controlled by the inverter. Still, the maximum currents value will not damage the converter and the system supports the voltage sag.

In the detail of the current, it appears that these are sinusoidal and the frequency decreases as the system stabilizes. This is because the generator speed decreases.

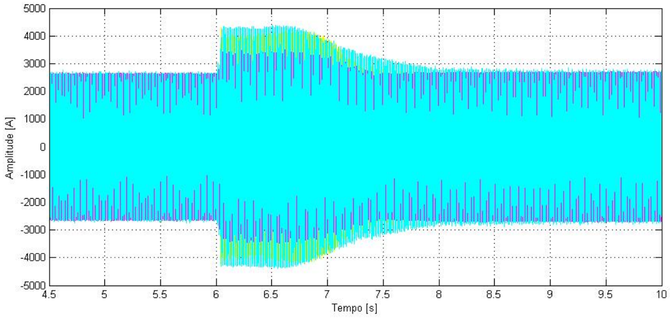

Fig. 7. Matrix converter output currents.

Before a reduction of the supply voltage, the torque reference reduces in order to reduce i_{q_REF} and maintains the system connected to the network. It is important that during the transitional period, accompanied by a decrease in speed, the currents do not increase to the point of damaging the converter semiconductors.

Despite of this, the currents remain sinusoidal, with a frequency of 50 Hz, so the AC / AC conversion is nearly not affected from the disturbance on the network.

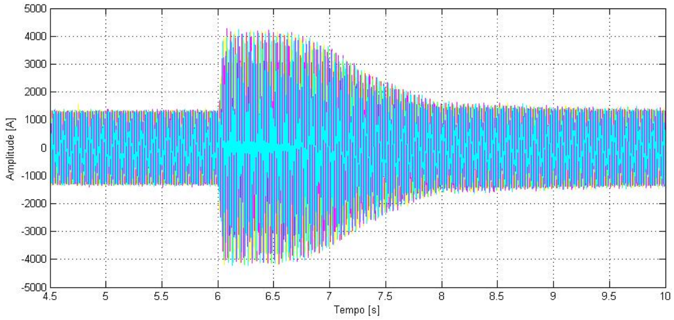

Fig. 8. Currents injected into the network

Figure 9 shows that the reactive power is approximately zero for the simulated operating conditions.

Concerning to Figure 9, there are an increase of the active power, when the voltage sag appears, but lower than the nominal power.

The reactive power is nearly zero, due to the control of the power factor, by the matrix converter.

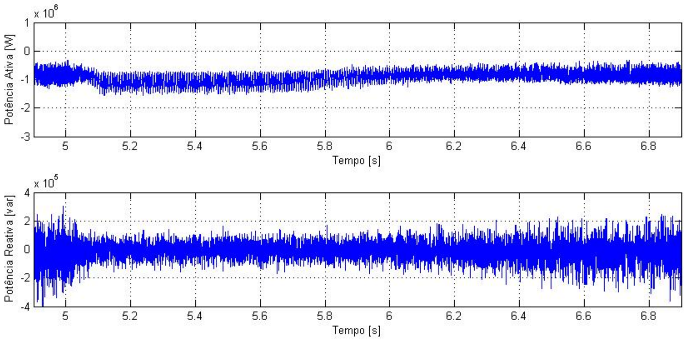

Fig. 9. Active and reactive power injected into the network.

V. CONCLUSIONS

In this work, it is proposed a wind generation system equipped with a PMSG and a Matrix Converter, with FRT capability, without the use of any external equipment. Under normal operation conditions a speed controller guaranteed the MPPT. In the occurrence of sags, a reference torque is established, to limit the currents in the matrix converter and in the PMSG stator windings. With this approach it was possible to guarantee that the PMSG was not disconnected from the grid, in the presence of voltage sags of 80% during 500ms. The currents in the converter, which would otherwise be destructive, were maintained under the values supported by the semiconductors.

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