Evaluating Power Quality in Wind Power Generation Systems with Two-Level and Multi-Level Converters

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ABSTRACT: This paper is concerned with modeling and simulation in Matlab/Simulink of a wind power generation system with different topologies for the power converters, namely a two-level converter and a multi-level converter. We use pulse modulation by space vector modulation associated with sliding mode for controlling the converters, and we introduce power factor control at the output of the converters. We present a case study showing the harmonic behavior for the current injected in the electric network, computed by the Fast Fourier Transform. Finally, we draw comparative conclusions.

Keywords: Power quality, wind power generation, power electronic converters, sliding mode control.

I. INTRODUCTION

Electricity restructuring has offered us additional flexibility at both levels of generation and consumption. Also, since restructuring has strike the power system sector, developments in distributed generation technologies opened new perspectives for generating companies [1], in order to consider their energy supply portfolio with adequacy and advantage. Adequacy and advantage due to a better generation mix, concerning not only the traditional economic perspective, but also politic developments with strong social impact in power systems, imposing the internalization of costs formerly externalized.

Distributed generation technology is said to offer a clean emission-free energy source with fast ramp capability, and it goes on penetrating more and more power systems. Distributed generation technology includes, for instances, arrays of solar photovoltaic panels, wind farms, hydroelectric, biomass and tidal power plants. Among distributed generation technology, wind farms are the most commonly viewed on power systems, even envisaged as competing with the traditional fossil-fuelled thermal power plants in the near future.

The European Commission concerned with the climate change, due to the emission of greenhouse gases, put forward a set of proposals to create a new Energy Policy for Europe, cutting its own CO₂ emissions by at least 20% by 2020 and 50% until 2050, increasing the share of renewable energy sources in the overall generation mix.

Hence, it is expected that wind energy will turn out to be an important part of the future Energy Policy for Europe. In Portugal, the total installed wind power capacity reached 2375 MW in April 2008, and continues growing.

The increasing share of wind in power generation will change considerably the dynamic behavior of the power system [2], and may lead to a reduction of power system frequency regulation capabilities [3]. In addition, network operators have to ensure that consumer power quality is not compromised [4]. Hence, new technical challenges emerge due to increased wind power penetration, for instances: dynamic stability and power quality. These challenges imply research of more realistic physical models for wind power generation systems.

Power electronic converters have been developed for integrating wind power with the electric grid. The use of power electronic converters allows for variable speed operation of the wind turbine, and enhanced power extraction. In variable speed operation, a control method designed to extract maximum power from the turbine and provide constant grid voltage and frequency is required [5].

This paper is concerned with modeling and simulation in Matlab/Simulink of a wind power generation system with different topologies for the power converters, namely a two-level converter and a multi-level converter. We use pulse modulation by space vector modulation associated with sliding mode for controlling the converters, and we introduce power factor control at the output of the converters. We present a case study showing the harmonic behavior for the current injected in the electric network, computed by the Fast Fourier Transform, FFT [6]. Finally, we draw comparative conclusions.

II. MODELING

A. Turbine and Mechanical Drive Train

The mechanical power of the turbine is given by:

\[ P_m = \frac{1}{2} \rho A u^3 c_p \]  

where \( P_m \) is the power extracted from the airflow, \( \rho \) is the air density, \( A \) is the area covered by the rotor turbine, \( u \) is the wind speed upstream of the rotor, and \( c_p \) is the performance coefficient or power coefficient.

The power coefficient is a function of the pitch angle of rotor blades \( \theta \), and of the tip speed ratio \( \lambda \), which is the
The ratio between blade tip speed and wind speed upstream of the rotor. The computation of the power coefficient requires the use of blade element theory and the knowledge of blade geometry. We consider the blade geometry using the numerical approximation developed in [7], assuming that the power coefficient is given by:

\[
c_p = 0.73 \left( \frac{151}{\lambda_i} - 0.58 \theta - 0.002 \theta^2 - 13.2 \right) e^{-\frac{18.4}{\lambda_i}}
\]  \hspace{1cm} (2)

where \( \lambda_i \) is given by:

\[
\lambda_i = \frac{1}{(\lambda - 0.02) - (0.03 + 1)}
\]  \hspace{1cm} (3)

The maximum power coefficient is given for a null pitch angle and is equal to:

\[
c_{p,\text{max}} = 0.4412
\]  \hspace{1cm} (4)

where the optimum tip speed ratio is equal to:

\[
\lambda_{\text{opt}} = 7.057
\]  \hspace{1cm} (5)

The equations for modeling the mechanical drive train are given by:

\[
\frac{d\omega_m}{dt} = \frac{1}{J_m} (T_m - T_{\text{ds}} - T_{\text{am}} - T_{\text{ts}})
\]  \hspace{1cm} (6)

\[
\frac{d\omega_e}{dt} = \frac{1}{J_e} (T_e - T_{\text{de}} - T_{\text{ae}} - T_{\text{ce}})
\]  \hspace{1cm} (7)

where \( \omega_m \) is the rotor speed of turbine, \( J_m \) is the turbine moment of inertia, \( T_m \) is the mechanical torque, \( T_{\text{ds}} \) is the resistant torque in the turbine bearing, \( T_{\text{am}} \) is the resistant torque in the hub and blades due to the viscosity of the airflow, \( T_{\text{ts}} \) is the torque of the torsional stiffness, \( \omega_e \) is the rotor speed of the electric machine, \( J_e \) is the electric machine moment of inertia, \( T_{\text{de}} \) is the resistant torque in the electric machine bearing, \( T_{\text{ae}} \) is the resistant torque due to the viscosity of the airflow in the electric machine, and \( T_{\text{ce}} \) is the electric torque. Thus, the two-mass model considered in this paper is given by (6) and (7).

B. Electric Machine

The equations for modeling a permanent magnetic synchronous machine, PMSM, can be found in literature [8]; using the motor machine convention, we have:

\[
\frac{di_d}{dt} = \frac{1}{L_d} (u_d + \rho \omega_e L_q i_q - R_d i_d)
\]  \hspace{1cm} (8)

\[
\frac{di_q}{dt} = \frac{1}{L_q} [u_q - \rho \omega_e (L_d i_d + M i_f) - R_q i_q]
\]  \hspace{1cm} (9)

where \( i_r \) is the equivalent rotor current, \( M \) is the mutual inductance, \( \rho \) is the number of pairs of poles; and where in \( dq \) axes, \( i_d \) and \( i_q \) are the stator currents, \( L_d \) and \( L_q \) are the stator inductances, \( R_d \) and \( R_q \) are the stator resistances, \( u_d \) and \( u_q \) are the stator voltages. A unity power factor is imposed to the electric machine in order to minimize power losses, implying a null reactive electric power \( Q_e = 0 \). The electric power \( P_e \) is given by:

\[
P_e = [u_d \ u_q \ u_f] [i_d \ i_q \ i_f]^T
\]  \hspace{1cm} (10)

The output power injected in the electric network characterized by \( P \) and \( Q \) in \( \alpha\beta \) axes [9] is given by:

\[
\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}
\]  \hspace{1cm} (11)

where in \( \alpha\beta \) axes, \( i_\alpha \) and \( i_\beta \) are the phase currents, \( u_\alpha \) and \( u_\beta \) are the phase voltages. The apparent output power [9] is given by:

\[
S = (P^2 + Q^2 + \delta^2)^{1/2}
\]  \hspace{1cm} (12)

where \( H \) [9] is the harmonic power.

C. Two-Level Converter

The two-level converter is an AC-DC-AC converter, with six unidirectional commanded IGBT's \( S_{ik} \) used as a rectifier, and with the same number of unidirectional commanded IGBT's used as an inverter.

The configuration of the wind power generation system with two-level converter is shown in Fig. 1.

The rectifier is connected between the PMSM and a capacity bank. The inverter is connected between this capacity bank and a first order filter, which in turn is connected to an electric network. A three-phase active symmetrical circuit in series models the electric network.

For the two-level converter modeling it is assumed that:

1) The voltage in the exit of the rectifier should always be \( v_{dc} > 0 \); 2) Each leg \( k \) of the converter should always have one IGBT on conduction state.

![Fig. 1. The wind power generation system with two-level converter.](image-url)
For the switching function of each IGBT, the switching variable $\gamma_k$ is used to identify the state of the IGBT $i$ in the leg $k$ of the converter. The index $i$ with $i \in \{1, 2\}$ identifies the IGBT. The index $k$ with $k \in \{1, 2, 3\}$ identifies the leg for the rectifier and $k \in \{4, 5, 6\}$ identifies the inverter one.

The two conditions [10] for the switching variable of each leg $k$ are given by:

$$\gamma_k = \begin{cases} 1, & (S_{1k} = 1 \text{ and } S_{2k} = 0) \\ 0, & (S_{1k} = 0 \text{ and } S_{2k} = 1) \end{cases} \quad k \in \{1, ..., 6\}$$  \hspace{1cm} (13)

Hence, each switching variable depends on the on/off states of the IGBT's.

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Hence, each switching variable depends on the on/off states of the IGBT's.

The phase currents injected in the electric network are modeled by the state equation:

$$\frac{d}{dt} i_k = \frac{1}{L_c + L_f} \left( u_{sk} - R_i i_k - u_k \right) \quad k \in \{4, 5, 6\}$$  \hspace{1cm} (14)

The voltage at the capacitor of the rectifier is modeled by the state equation:

$$\frac{dv_{dc}}{dt} = \frac{1}{C} \left( \sum_{k=1}^{3} \gamma_k i_k - \sum_{k=4}^{6} \gamma_k i_k \right)$$  \hspace{1cm} (15)

The two-level converter is modeled by (13) to (15).

D. Multi-Level Converter

The multi-level converter is an AC-DC-AC converter, with twelve unidirectional commanded IGBT's used as a rectifier, and with the same number of unidirectional commanded IGBT's used as an inverter.

The configuration of the wind power generation system with multi-level converter is shown in Fig. 2. The rectifier is connected between the PMSM and a capacity bank. The inverter is connected between this capacity bank and a second order filter, which in turn is connected to an electric network. A three-phase active symmetrical circuit in series models the electric network.

For the multi-level converter modeling it is also assumed that: 1) The voltage in the exit of the rectifier should always be $v_{dc} > 0$; 2) Each leg $k$ of the converter should always have two IGBT's on conduction state.

For the switching function of each IGBT, the switching variable $\gamma_k$ is used to identify the state of the IGBT $i$ in the leg $k$ of the converter. The index $i$ with $i \in \{1, 2, 3, 4\}$ identifies the IGBT. The index $k$ with $k \in \{1, 2, 3\}$ identifies the leg for the rectifier and $k \in \{4, 5, 6\}$ identifies the inverter one.

The three valid conditions [10] for the switching variable of each leg $k$ are as follows:

$$\gamma_k = \begin{cases} 1, & (S_{1k} = 1 \text{ and } S_{2k} = 0) \\ 0, & (S_{1k} = 0 \text{ and } S_{2k} = 1) \\ -1, & (S_{1k} = 1 \text{ and } S_{2k} = 1) \end{cases} \quad k \in \{1, ..., 6\}$$  \hspace{1cm} (16)

With the two upper IGBT's in each leg $k$ ($S_{1k}$ and $S_{2k}$) of the converters it is associated a switching variable $\Gamma_{1k}$ and also for the two lower IGBT's ($S_{3k}$ and $S_{4k}$) it is associated a variable $\Gamma_{2k}$, respectively given by:

$$\Gamma_{1k} = \frac{\gamma_k(1 + \gamma_k)}{2} ; \quad \Gamma_{2k} = \frac{\gamma_k(1 - \gamma_k)}{2} \quad k \in \{1, ..., 6\}$$  \hspace{1cm} (17)

Hence, each switching variable depends on the on/off states of the IGBT's.

The phase currents injected in the electric network are modeled by the state equation:

$$\frac{d}{dt} i_k = \frac{1}{L_c} \left( u_{sk} - R_i i_k - u_k \right) \quad k \in \{4, 5, 6\}$$  \hspace{1cm} (18)

The voltage $v_{dc}$ is the sum of the voltages $v_{C1}$ and $v_{C2}$ at the capacity banks $C_1$ and $C_2$, modeled by the state equation:

$$\frac{dv_{dc}}{dt} = \frac{1}{C_1} \left( \sum_{k=1}^{3} \Gamma_{1k} i_k - \sum_{k=4}^{6} \Gamma_{1k} i_k \right) + \frac{1}{C_2} \left( \sum_{k=1}^{3} \Gamma_{2k} i_k - \sum_{k=4}^{6} \Gamma_{2k} i_k \right)$$  \hspace{1cm} (19)

where (16) to (19) model the neutral point clamped multi-level converter for high voltage and high power applications [10] - [11].

III. CONTROL METHOD

The controllers used in the converters are PI. Also, pulse width modulation by space vector modulation associated with sliding mode is used for controlling the converters. The output voltage vectors in the $\alpha\beta$ plane for the two-level converter are shown in the Fig. 3. The output voltage vectors in the $\alpha\beta$ plane for the multi-level converter are shown in the Fig. 4.

![Fig. 2. The wind power generation system with multi-level converter.](image-url)
The converters are variable structure, because of the on/off switching of their IGBT's. Hence, the sliding mode control is important for controlling the converters, by guaranteeing the choice of the most appropriate space vectors.

The power semiconductors present physical limitations, since they cannot switch at infinite frequency. Thus, for a considered value of the switching frequency, an error \( e_{\alpha\beta} \) will exist between the reference value and the control value. In order to guarantee that the system slides along the sliding surface \( S(e_{\alpha\beta}, t) \), it is necessary to guarantee that the state trajectory near the surfaces verifies the stability conditions [10] - [11], given by:

\[
S(e_{\alpha\beta}, t) \frac{dS(e_{\alpha\beta}, t)}{dt} < 0
\]  

(20)

As power semiconductors can switch only at finite frequency, in simulation practice a small error \( \varepsilon > 0 \) for \( S(e_{\alpha\beta}, t) \) is allowed. Hence, a switching strategy has to be considered, given by:

\[
-\varepsilon < S(e_{\alpha\beta}, t) < +\varepsilon
\]  

(21)

A practical implementation of the switching strategy considered in (21) could be accomplished using hysteresis comparators at the simulation level.

IV. CASE STUDY

The wind power generation system has an electric power of 900 kW. The mathematical models for the wind power generation system with two-level and multi-level converters were implemented in Matlab/Simulink. We consider in the simulation a ramp increase wind speed upstream of the rotor, taking 2.5 s between the speed of 4.5 and 25 m/s and a time horizon for the simulation of 3.5 s.
The RMS current injected in the electric network for the two-level converter is shown in Fig. 9.

Fig. 9. The RMS current for the two-level converter.

The harmonic behavior computed by the FFT, for the current injected in the electric network for the two-level converter, is shown in Fig. 10.

Fig. 10. The harmonic behavior for the current for the two-level converter.

The voltage at the capacitors $v_{dc}$ and the voltages $v_{C1}$ and $v_{C2}$, for the multi-level converter, are shown in Fig. 11.

Fig. 11. Voltage at the capacitors for the multi-level converter.

The voltages across IGBT’s of the two-level converter, Fig. 7, are greater than those of the multi-level converter, Fig. 11. The current injected in the electric network for the multi-level converter is shown in Fig. 12.

Fig. 12. Current injected in the electric network for the multi-level converter.

The RMS current injected in the electric network for the multi-level converter is shown in Fig. 13.

Fig. 13. The RMS current for the multi-level converter.

The harmonic behavior computed by the FFT, for the current injected in the electric network for the multi-level converter, is shown in Fig. 14.

Fig. 14. The harmonic behavior for the current for the multi-level converter.
V. CONCLUSION

The increasing wind power penetration leads to new technical challenges, implying research of more realistic physical models for wind power generation systems. This paper presents a new integrated model, considering an accurate dynamic of the wind turbine, rotor, generator, converter and filter connecting the system to the network. A case study is presented, simulating two power converter topologies, a two-level and a multi-level converter, for the integration of wind power generation with the electric network. The simulations carried out reveal that our model for the simulation of wind power generation systems is not only more accurate but also computationally acceptable. Additionally, it shows that the proposed multi-level converter assures better performance comparatively to the two-level converter.

VI. REFERENCES


VII. BIOGRAPHIES

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