MODELAREA ŞI PROIECTAREA FILTRELOR DE REŢEA UTILIZATE PENTRU ATENUAREA RIPLURILOR DE CURENT

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REZUMAT. Lucrarea prezintă modelarea unei turbine de vânt cu viteză variabilă utilizând un generator de inducţie controlat cu ajutorul unui convertor de frecvenţă cu circuit intermediar de tensiune, conectat la reţea printr-un filtru de tip LCL. Sunt prezentate elementele componente ale întregului sistem, cât şi schemele de reglare şi control, utilizate pentru studiul diferitelor regimuri de funcţionare. De asemenea, este prezentat în detaliu modelul matematic al filtrului de reţea propus, cât şi metodologia de proiectare şi determinare a parametrilor acestuia în scopul reducerii riplurilor de curent datorate comutaţiei tranzistoarelor convertorului de frecvenţă.

Cuvinte cheie: convertoare de frecvenţă cu circuit intermediar de tensiune, filtre de tip LCL, generatoare de inductie, turbine eoliene cu viteză variabilă.

ABSTRACT. In this paper a variable-speed wind turbine generator system with a vector controlled back-to-back PWM-VSI on the stator side has been modeled, designed and simulated to study its steady state and dynamic behavior. The mathematical model and the design procedure of an LCL-filter are described in detail. To evaluate the performance and to reduce the current ripple due to the PWM modulator, an LCL-filter was proposed and designed.

Keywords: back-to-back PWM-VSI, LCL-filter, induction generator, variable-speed wind turbine.

1. INTRODUCTION

The use of cage rotor induction generators (CRIG) with a back-to-back pulse width modulation (PWM) voltage source converter (VSC), for direct grid connection wind energy conversion systems, has become a quite attractive in the last ten years, in both low power and very high power level [1, 3, 5, 9]. Small efficient wind turbines can be used to supply private houses or farms in remote locations in developing countries where low-cost access to the electrical power grid is impractical [1, 5, 9].

Due to the latest developments in power and digital electronics, the market for small distributed power generation systems connected to the domestic grid is increasing rapidly. Increased energy production at low wind speed (6-8 m/s), elimination of the capacitor bank necessary for magnetization, and the possibility for grid-connected and stand-alone operation modes can thus be achieved at the expense of a back-to-back converter with a flexible control [2-3].

The trend is that these systems should be able to work in stand-alone mode but also connected to isolated local grid in parallel with others generators, such as other wind turbines, photovoltaic or diesel generators [1, 9].

The variable speed wind turbines represent a new technology within wind power for large-scale applications and their models have to be set up for making power stability investigations. Therefore, this concept will be analyzed as follows. Also, the design of an LCL-filter is presented.

2. SISTEM DESCRIPTION

The power configuration of the developed system is depicted in Fig. 1. It consists of a three-phase cage-rotor induction generator, the generator converter to control the speed, a DC-link, and a full-bridge grid converter connected to the grid through an LCL-filter.

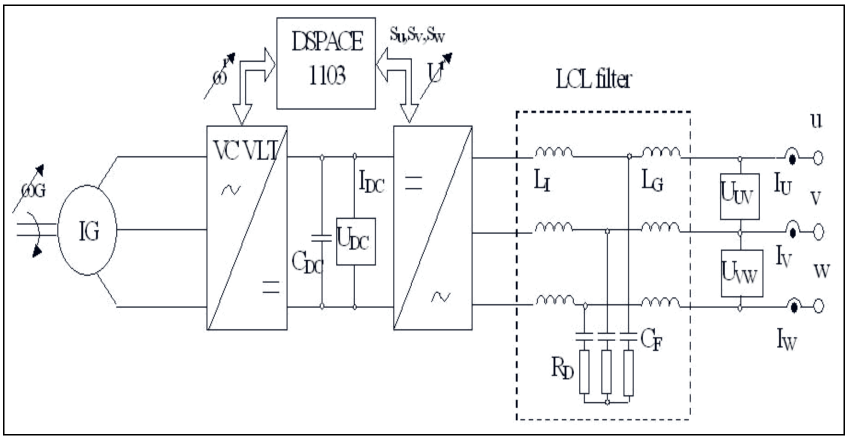


Fig. 1. The block diagram of the variable-speed wind generator emulator.

Three commercial frequency converters (Danfoss-VLT 5022) rated 18.5 kVA/400 V are used [3]. The first one uses a scalar open-loop torque control and is feeding a 15 kW induction motor in order to emulate the wind turbine. The second converter is used as generator converter and uses vector flux control to regulate the speed of the generator and to provide the magnetizing flux for the machine. The last converter is used as grid converter for controlling the active and reactive power independently and is connected to the grid through an LCL-filter. The LCL filter is used because it achieves better current ripple attenuation than L or RL-filters [8].

2.1. Wind turbine emulator

The wind turbine rotor is emulated using a standard 6-poles 15 kW/400 V cage-rotor induction machine controlled by a commercial frequency converter operated in open-loop torque control mode. The induction motor is mechanically coupled with the induction generator.

The aerodynamic model of the wind turbine rotor is based on the power coefficient (C_p), which represents the rotor efficiency of the turbine (aerodynamic efficiency of the blades), also taken from a look-up table. The aerodynamic torque is given by:

$$T_{rot} = \frac{P_{aero}}{\omega_{rot}} = \frac{1}{2 \cdot \lambda} \cdot \rho \cdot \pi \cdot R^3 \cdot u_{eq}^{\;2} \cdot C_p \tag{1}$$

where (P_{aero}) is the aerodynamic power developed on the main shaft of wind turbine with the blade radius (R), at a wind speed (u_{eq}) and the air density (ρ). The blade tip speed ratio (λ) depends on the rotor speed (ω_{rot}), blade radius and wind speed, according to:

$$\lambda = \frac{\omega_{rot} \cdot R}{u_{eq}} \tag{2}$$

The power coefficient (C_p) decreases when the wind speed (u_{eq}) increases (λ small) [5]. This fact is used in the passive stall controlled wind turbines (our case).

2.2. Induction generator control

The generator control (generator converter + controller) is working in closed-loop speed control mode where the speed reference is chosen in order to extract the power from the wind turbine to a certain wind speed. It is used to control mechanical power on the generator shaft.

The generator converter (AC/DC) is a sensorless vector controlled (VC) VLT connected to the induction generator and produces voltage on the DC-link, as is shown in Fig. 1.

The equation of motion at the induction generator shaft is given by:

$$T_{elm} - T_d = J \cdot \frac{\mathrm{d}\Omega_r}{\mathrm{d}t} \tag{3}$$

in which (T_{elm}) represents the electromagnetic torque of induction machine, (T_d) is the driving torque (positive in motoring mode and negative in generating mode), (J) represent the equivalent moment of inertia for induction machine and the driving mechanism and (Ω_r) is the mechanical rotor angular speed.

2.3. Grid converter control

The control structure for grid-connected control mode is shown in Fig. 2. Standard PI-controllers are used to regulate the grid currents in d-q synchronous frame in the inner control loops and the DC-voltage in outer loop.

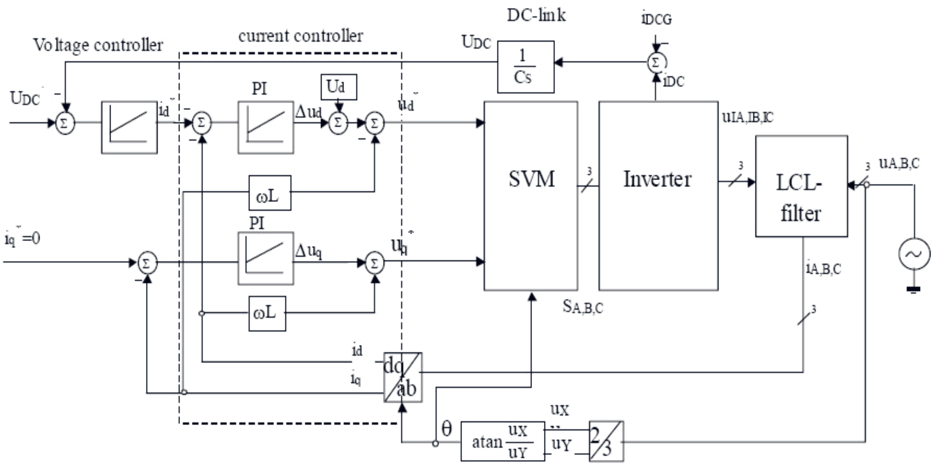


Fig. 2. Control structure for grid connected control mode.

A decoupling of the cross-coupling is implemented in order to compensate the couplings due to the output filter. The reference current in the *q*-axis of the current loop is set to zero in order to achieve zero phase angles between voltage and current. In this way the unity power factor can be achieved.

The output of the current controllers sets the voltage reference for the control strategy implemented-Space Vector Modulation (SVM), which controls the switches of the grid converter (Fig. 2). The synchronization with the grid is achieved by using a Phase-Locked-Loop (PLL).

3. MODELING AND SIMULATION OF THE LCL-FILTER

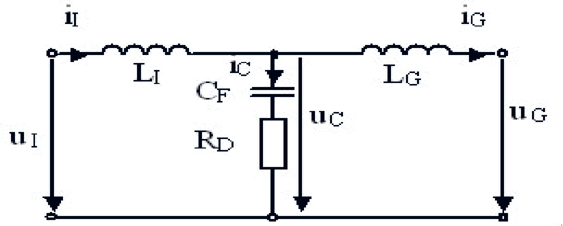
The main goal to implement an LCL-filter is to reduce the current ripple due to the PWM-modulator. In comparison with a standard RL-filter or an L-filter, an LCL-filter is smaller and less expansive and has the same attenuation levels of current ripple than RL-filter [1-2].

In a symmetrical three-phase system an equivalent single-phase LCL-filter can be represented as shown in Fig. 3 *a*).

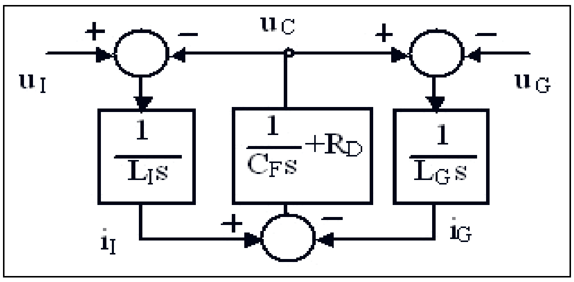
Parasitic serial resistances of the inductances are ignored; instead that resistance R_D is added for reducing the filter damping at its resonance frequency.

The mathematical model (s-plane) of the single-phase LCL-filter can be written as follows:

$$\begin{aligned} & i_I - i_C - i_G = 0 \\ & u_I(s) = i_I \cdot L_I \cdot s + u_C \\ & u_G(s) = -i_G \cdot L_I \cdot s + u_C \\ & u_C(s) = i_C \cdot \left(R_D + \frac{1}{s \cdot C_F} \right) \end{aligned} \tag{5}$$



a)



b)

Fig. 3. An equivalent single phase LCL-filter (a), and its model in s-plane (b).

From (5) we can get the grid current (i_G) and the inverter current (i_I):

$$\begin{aligned} & i_I(s) = \frac{1}{s \cdot L_I} \cdot \left(u_I - u_C \right) \\ & i_G(s) = \frac{1}{s \cdot L_G} \cdot \left(u_C - u_G \right) \end{aligned} \tag{6}$$

where: L_I represents the inverter-side inductance; L_G is the grid-side inductance and C_F is the filter capacitance.

From Fig. 3 *a*) can also be written the next equations:

$$\begin{aligned} & u_I(s) = z_{11} \cdot i_I + z_{12} \cdot i_G \\ & u_G(s) = z_{21} \cdot i_I + z_{22} \cdot i_G \end{aligned} \tag{7}$$

in which:

$$z_{11} = s \cdot L_I + \frac{1}{s \cdot C_F}; z_{12} = -\left(R_D + \frac{1}{s \cdot C_F}\right)$$
$$z_{21} = R_D + \frac{1}{s \cdot C_F}; z_{22} = -\left(R_D + s \cdot L_G + \frac{1}{s \cdot C_F}\right) \quad (8)$$

The transfer function in the s-plane of a single-phase LCL-filter with passive damping can be written as:

$$H(s) = \frac{i_I(s)}{u_I(s)} = \frac{z_{22}}{z_{11} \cdot z_{22} - z_{12} \cdot z_{21}} =$$
$$= \frac{L_G C_F s^2 + R_D C_F s + 1}{L_I L_G C_F s^3 + R_D C_F \cdot (L_I + L_G) \cdot s^2 + (L_I + L_G) \cdot s} \quad (9)$$

A simulation model is built in order to verify the validity of the designed controllers and the LCL-filter. The simulation model is implemented using MATLAB & Simulink software.

Simulation results are used for implementation and to verify the wind generator system model developed.

The Figure 4 shows a simulation comparison between inverter current and grid current, pointing out the current attenuation using LCL-filter.

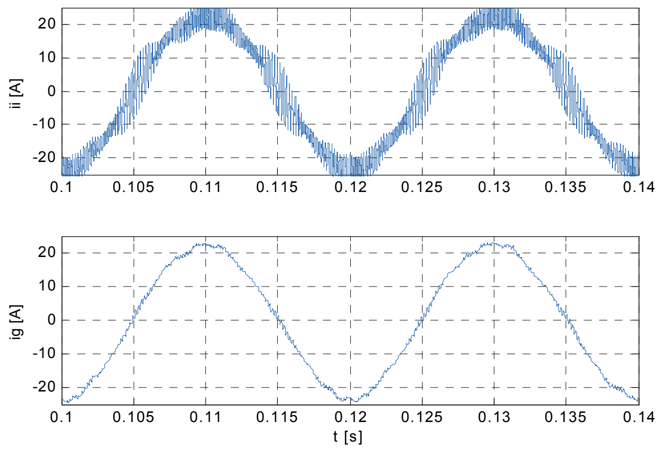


Fig. 4. Comparison between inverter current (i_i) and grid current (i_g) using LCL-filter.

The whole control strategy of the wind turbine emulator and LCL filter modeling is implemented in MATLAB & Simulink using a dSPACE – DS1103 controller. The dSPACE-DS1103 is a mixed RISK/DSP digital controller providing a powerful 64-bit floating point processor for calculations as well as comprehensive I/O capability.

4. LCL FILTER DESIGN

Design of the grid connection control mode is based on the mathematical model of the system. Complete controller design (Fig. 2) contains 3 main parts: current controller design, DC-link voltage controller design and LCL-filter design.

The LCL-filter gives a better attenuation of the switching ripple compared to a classic L-filter as it is a third-order filter (6), and therefore it can be designed using smaller components [1, 9].

When designing an LCL-filter the limits on the parameter values should be considered [6]:

- the capacitor value (C_F) is limited by the tolerable decrease of the power factor at rated power P_N (less than 5 %);
- the total value of the inductance should be lower than 10 % of the grid impedance (Z_b) to limit the DC-link voltage (voltage drops during operation);
- the resonance frequency should be included in a range between 10 times the line frequency and one half of the switching frequency in order not to create resonance problems in the lower and higher parts of the harmonic spectrum.

The passive resistors should be chosen as a compromise between the necessary damping and the losses in the system. The passive damping cannot be to low in order to avoid oscillations and the losses cannot be too high to not reduce efficiency.

Base values are calculated based on line-to-line voltage (E_N), nominal power (P_N) and grid frequency (ω_G):

$$Z_b = \frac{(E_N)^2}{P_N} = 14.55\ \Omega;\ C_b = \frac{1}{\omega_G \cdot Z_b} = 218.8\ \mu F \quad (10)$$

Total voltage drop on the filter should be less than 10 %, therefore total inductance should be less than:

$$L_{TOT} = \frac{0.1 \cdot Z_b}{\omega_G} = 4.6 \text{ mH} \quad (11)$$

The resonance frequency is set to half of the switching frequency (f_{sw} = 5 kHz):

$$\omega_{res} = k \cdot \omega_{sw} = 0.5 \cdot 2\pi \cdot f_{sw} = 15708 \text{ rad/s} \quad (12)$$

The factor (k) express how far is the switching frequency from the resonance frequency.

Adopting 2.7 % impedance for the converter side, a 10 % current ripple can be obtained when using only an L-filter. With additional LC part the aim is to reduce the ripple at 2 %:

$$Z_L = Z_b \cdot 2.7\% = 0.393\ [\Omega] \quad (13)$$

The inverter side inductance (L_I) is then:

$$L_I = \frac{Z_L}{\omega_G} = 1.25\ [\text{mH}] \quad (14)$$

Reactive power stored in the capacitor is 5 % of the system power rating, so the maximum capacitor value is:

$$C_{\max} = \frac{Q}{\omega_G \cdot E_N^{\ 2}} = 11\ [\mu\text{F}];\ Q = 0.05 \cdot P_N = 550\ [\text{VA}] \qquad (15)$$

The maximum capacitance within the limits is 11 [μF], and the selected value should be nearly half of that value [1], so that the capacitance of the filter is $C_F = 6$ [μF].

The aim is to obtain 20 % ripple attenuation that can be expressed by following equation [1]:

$$\frac{i_G(h_{sw})}{i_I(h_{sw})} = \frac{1}{\left|1 + r(1 - a \cdot x)\right|} = 0.2 \qquad (16)$$

where: $a = L_I C_b \omega_{sw}^{\ 2}$; $x = C_F/C_b = 0.0274$; $r = L_G/L_I > 1.1$.

Considering the reduction of the effectiveness caused by damping resistor chosen value is 1.2 and then grid side inductance is: $L_G = rL_I = 1.5$ [mH].

The solution of the damping resistance (R_D) is based on the impedance of the capacitor at the resonance frequency. Neglecting losses we get:

$$\omega_{res} = \sqrt{\frac{L_I + L_G}{L_I \cdot L_G \cdot C_F}} = 14.7 \cdot 10^3\ [\text{rad/s}]$$
$$f_{res} = \frac{1}{2\pi} \cdot \omega_{res} = 2.33\ [\text{kHz}] \qquad (17)$$

The damping is a compromise between power losses and stability requirements:

$$R_D = \frac{1}{3} \cdot \frac{1}{\omega_{res} \cdot C_F} = 3.79 \cong 4\ [\Omega] \qquad (18)$$

Bode Diagram of the transfer function (9) of the undamped and damped LCL-filter and of the L-filter is presented in Fig. 5.

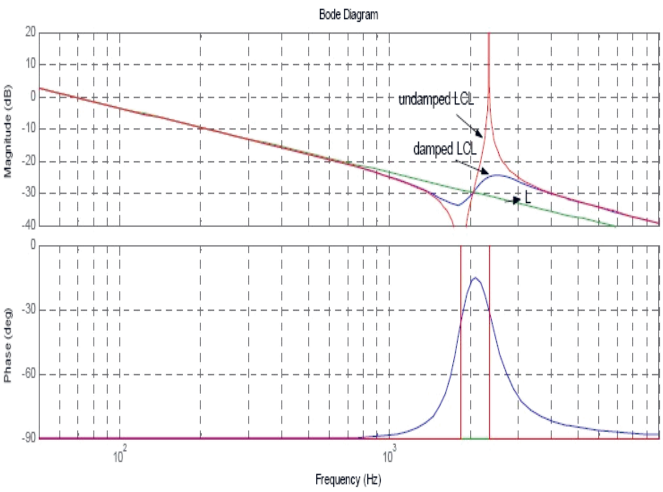


Fig. 5. Bode plot of the damped and undamped LCL-filter and of L-filter (L = 2.75 mH).

6. CONCLUSION

In this paper a variable-speed wind turbine concept using cage rotor induction generator connected to the grid through an LCL-filter has been presented.

The paper has also analyzed the mathematical model and the design procedure of an LCL-filter. The main aim was to provide a design procedure for the filter and to study the stability and the dynamic response of the overall system.

The design procedure has been tested in simulation and the desired current ripple attenuation has been achieved for the test system parameters.

The LCL-filter gives a better attenuation of the switching ripple compared to a classic L-filter as it is a third-order filter (6), and therefore it can be designed using smaller components.

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