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WIND FARM BASED ON DOUBLY FED INDUCTION GENERATOR ENTIRELY INTERFACED WITH POWER GRID THROUGH MULTILEVEL INVERTER

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Key words: Doubly fed induction generator (DFIG), Wind energy conversion systems (WECS), Five-level inverter, Power quality, Total harmonics distortion (THD).

This paper presents a theoretical study of wind farm based on doubly fed induction generator (DFIG), connected to the power grid through a five-level level neutral point clamped inverter (5-LNPCI). A dc filter model is proposed, proportional integral controllers are used for maintaining the dc voltages of each capacitor constant. Thus the imbalance capacitor voltage improved and the overvoltage on the semiconductors of the five-level inverter avoided. The proposed topology allows to: extract power over wide range of speed variation, control of active and reactive powers injected into the power grid, improve the quality of voltage waveform, reduce the harmonics content, improve the power injected into the grid and avoid the bulky connecting transformer. The system's mathematic model is implemented and simulated on software MATLAB/Simulink.

1. INTRODUCTION

Wind power generation has experienced a tremendous growth in the past decade; it is recognized as an environmentally friendly and economically competitive means of electric power generation [1]. In recent years, there has been an increasing interest in the integration of wind energy conversion systems into the power grid, so network operators have to ensure that consumer power quality is not compromised, such as the total harmonics distortion (THD) should be kept as low as possible, improving the power quality of the energy injected into the power grid [2–5].

Variable speed wind energy conversion systems (VSWECS) have many advantages over fixed speed ones, like increasing energy capture capability of operation at maximum power point (MPPT), improving efficiency and power quality [6, 7]. DFIG connected to the power grid through two power converters can operate the system conversion over a wide range of speed variation, and rise power capture until twice of the rated its power [8]. in this study a wind farm based on DFIG connected to the power grid through a five level NPC inverter (5-LNPCI) was investigated, the wind farm composed of four generators, each generator fed two rectifiers as shown on the Fig. 1.

The model and the control of the wind turbine and the DFIG were detailed in [8].

2. THE TWO LEVEL CONVERTERS MODEL AND THEIR CONTROL

The model of the two level powers electronics converters used is expressed as follows:

$$\begin{bmatrix} v_{a_{s,r}} \\ v_{b_{s,r}} \\ v_{c_{s,r}} \end{bmatrix} = \frac{1}{3} u_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} G_{11} \\ G_{12} \\ G_{13} \end{bmatrix}. \quad (1)$$

A switching function G_{jk} is defined for each power switch; it represents the ideal commutation orders and takes the values 1 when the switch is closed (on) and 0 when it is opened (off).

$v_{a_{s,r}}$: v_{as} or v_{ar} , $v_{b_{s,r}}$: v_{bs} or v_{br} , $v_{c_{s,r}}$: v_{cs} or v_{cr} , $k = \{1 \quad 2 \quad 3\}$ and $j = \{1 \quad 2\}$.

As ideal power switches are considered, the switches of the same arm are in complementary states:

$$G_{1k} + G_{2k} = 1 \; . \quad (2)$$

The direct current generated by rectifiers of each generator is given by the following function:

$$\begin{aligned} i_{dc} = & (G_{11} i_{as} + G_{21} i_{bs} + G_{31} i_{cs}) + \\ & + (G_{11} i_{ar} + G_{21} i_{br} + G_{31} i_{cr}). \end{aligned} \quad (3)$$

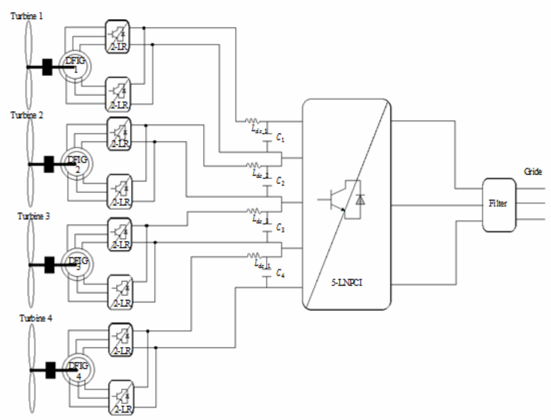

Fig. 1 – Five-level NPC inverter connected wind farm.

The PWM control strategy is executed for the rectifiers' control, a switching signal generation circuit where a carrier triangular waveform having a frequency much greater than the output voltage is compared with 3 phase reference sine wave signals synchronized with the mains supply.

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3. THE FIVE-LEVEL INVERTER MODEL AND ITS CONTROL

Figure 2 shows the five-level NPC inverter topology, the continuous voltage sources $U_{c1}, U_{c2}, U_{c3}, U_{c4}$ are provided by the common bus of each generator rectifier's side. The switch S_{ij} introduces a connection function F_{ij} that describes its state, such as $F_{ij} = 1$ if the switch S_{ij} closed, or if $F_{ij} = 0$ the switch S_{ij} open. To avoid short circuit of the voltage sources, a complementary control is imposed, so the connection functions of switches on each arm are given by the following equations system [9].

$$\begin{cases} F_{i4} = 1 - F_{i2} \\ F_{i5} = 1 - F_{i1} \\ F_{i6} = 1 - F_{i3} \\ F_{i7} = F_{i1} F_{i2} \left(1 - F_{i3}\right) \\ F_{i8} = F_{i4} F_{i5} (1 - F_{i6}). \end{cases} \quad (4)$$

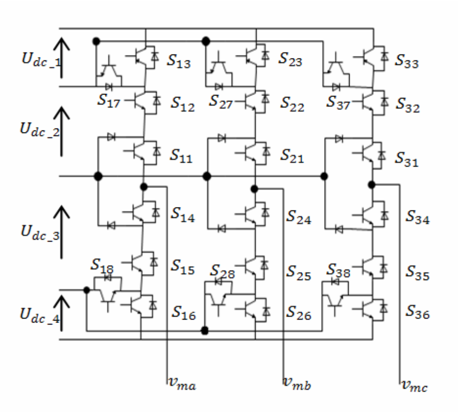


Fig. 2 – Five-level NPC inverter topology.

A connection functions of the half-arm, which are defined by $F_{ik}{}^{b}$, such as:

$$\begin{cases} F_{i1}{}^{b} = F_{i1} + F_{i2} + F_{i3} \\ F_{i0}{}^{b} = F_{i4} + F_{i5} + F_{i6} \end{cases}. \quad (5)$$

The dc voltage of each generator is regulated to maintain an equal constant value Fig. 3, so the following equation is imposed:

$$U_{dc\_1} = U_{dc\_2} = U_{dc\_3} = U_{dc\_4}. \quad (6)$$

The three phases output voltages referred to **o** are given by:

$$\begin{cases} v_{a0} = \left[(2.F_{11}{}^{b} + F_{17}) - (F_{12}{}^{b} + F_{18})\right] U_{dc} \\ v_{b0} = \left[(2.F_{21}{}^{b} + F_{27}) - (F_{22}{}^{b} + F_{28})\right] U_{dc} \\ v_{c0} = \left[(2.F_{31}{}^{b} + F_{37}) - (F_{32}{}^{b} + F_{38})\right] U_{dc} \end{cases} \quad (7)$$

The algorithm used for the five level inverter control, based on the triangular sinusoid four carried control. The carriers are bipolar, and having a shift of quarter of period. Two steps characterize the control algorithm:

Step one – Intermediate voltage determination

$$\begin{cases} v_{i\_ref} \geq U_{car\_1} \Rightarrow v_{i1} = U_{dc\_1} \\ v_{i\_ref} \prec U_{car\_1} \Rightarrow v_{i1} = 0 \\ v_{i\_ref} \geq U_{car\_2} \Rightarrow v_{i2} = (U_{dc\_1} + U_{dc\_2}) \\ v_{i\_ref} \prec U_{car\_2} \Rightarrow v_{i2} = U_{dc\_2} \\ v_{i\_ref} \geq U_{car\_3} \Rightarrow v_{i3} = 0 \\ v_{i\_ref} \prec U_{car\_3} \Rightarrow v_{i1} = -U_{dc\_3} \\ v_{i\_ref} \geq U_{car\_4} \Rightarrow v_{i4} = -(U_{dc\_3} + U_{dc\_4}) \\ v_{i\_ref} \prec U_{car\_4} \Rightarrow v_{i4} = -U_{dc\_4}. \end{cases} \quad (8)$$

Taking in account the equation (6), the system of equation (8) can be expressed as follow:

$$\begin{cases} v_{i\_ref} \geq U_{car\_1} \Rightarrow v_{i1} = U_{dc} \\ v_{i\_ref} \prec U_{car\_1} \Rightarrow v_{i1} = 0 \\ v_{i\_ref} \geq U_{car\_2} \Rightarrow v_{i2} = 2.U_{dc} \\ v_{i\_ref} \prec U_{car\_2} \Rightarrow v_{i2} = U_{dc} \\ v_{i\_ref} \geq U_{car\_3} \Rightarrow v_{i3} = 0 \\ v_{i\_ref} \prec U_{car\_3} \Rightarrow v_{i1} = -U_{dc} \\ v_{i\_ref} \geq U_{car\_4} \Rightarrow v_{i4} = -2.U_{dc} \\ v_{i\_ref} \prec U_{car\_4} \Rightarrow v_{i4} = -U_{dc}. \end{cases} \quad (9)$$

Step two – Output voltage determination

$$v_{i0} = v_{i1} + v_{i2} + v_{i3} + v_{i4}. \quad (10)$$

4. THE PROPOSED FILTER MODEL

As mentioned, the filter constituted of four capacitors and inductances, the capacitors used for filtering the voltage and the inductances for filtering the current provided by the aero generators rectifiers' side

The mathematic model of the filter is given by the following equations:

$$\begin{cases} U_{dc1} = u_{rd1} - L_1 \frac{\partial i_{rd1}}{\partial t} = \frac{1}{C_1} \int i_{c1} \mathrm{d}t \\ U_{dc2} = u_{rd2} - L_2 \frac{\partial i_{rd2}}{\partial t} = \frac{1}{C_2} \int i_{c2} \mathrm{d}t \\ U_{dc3} = u_{rd3} - L_3 \frac{\partial i_{rd3}}{\partial t} = \frac{1}{C_3} \int i_{c3} \mathrm{d}t \\ U_{dc4} = u_{rd4} - L_4 \frac{\partial i_{rd4}}{\partial t} = \frac{1}{C_4} \int i_{c4} \mathrm{d}t, \end{cases} \quad (11)$$

such as:

$$\begin{cases} i_{c1} = i_{rd1} - i_{d1} \\ i_{c2} = i_{rd2} - i_{rd1} - i_{d2} \\ i_{c3} = i_{rd3} - i_{rd2} - i_{d0} \\ i_{c4} = i_{rd4} - i_{rd3} - i_{d3} = i_{rd4} + i_{d4}. \end{cases} \quad (12)$$

i_{dk} with k = 0, 1, 2, 3, 4 are currents modulated by the five-level inverter. They are functions of the grid currents and

$$\begin{cases} i_{d1} = F_{11}{}^{b} i_{g1} - F_{21}{}^{b} i_{g2} + F_{31}{}^{b} i_{g3} \\ i_{d2} = F_{17}{}^{b} i_{g1} - F_{27}{}^{b} i_{g2} + F_{37}{}^{b} i_{g3} \\ i_{d3} = F_{18}{}^{b} i_{g1} - F_{28}{}^{b} i_{g2} + F_{38}{}^{b} i_{g3} \\ i_{d4} = F_{10}{}^{b} i_{g1} - F_{20}{}^{b} i_{g2} + F_{30}{}^{b} i_{g3}. \end{cases} \quad (13)$$

$$\begin{aligned} i_{d0} = {} & (i_{g1}+i_{g2}+i_{g3}) - (F_{17}+F_{18}+F_{11}{}^{b}) i_1 - \\ & -(F_{27}+F_{28}+F_{21}{}^{b}+F_{20}{}^{b}) i_2 - (F_{37}+F_{38}+F_{31}{}^{b}+F_{30}{}^{b}) i_3. \end{aligned} \quad (14)$$

the connection functions of the inverter.

5. GRID CONNECTION FILTER MODEL

The filter model in the d-q axes is given as follows:

$$\begin{cases} v_{md} = v_{gd} - R_f i_{gd} - L_f \dfrac{\mathrm{d}i_{gd}}{\mathrm{d}t} - L_f \omega_g i_{gq} \\ v_{mq} = v_{gq} - R_f i_{gq} - L_f \dfrac{\mathrm{d}i_{gq}}{\mathrm{d}t} - L_f \omega_g i_{gd}. \end{cases} \quad (15)$$

Filter currents are regulated by proportional integral (PI) controllers. Their references are calculated from the active and reactive power reference as shown in the following equations:

$$\begin{cases} i_{gd} = \dfrac{P_g{}^{*} v_{gd} + Q_g v_{gq}}{v_{gd}{}^{2} + v_{gq}{}^{2}} \\ i_{gq} = \dfrac{P_g{}^{*} v_{gq} - Q_g v_{gd}}{v_{gd}{}^{2} + v_{gq}{}^{2}}. \end{cases} \quad (16)$$

The control bloc diagram of the grid connection is shown in Fig. 3.

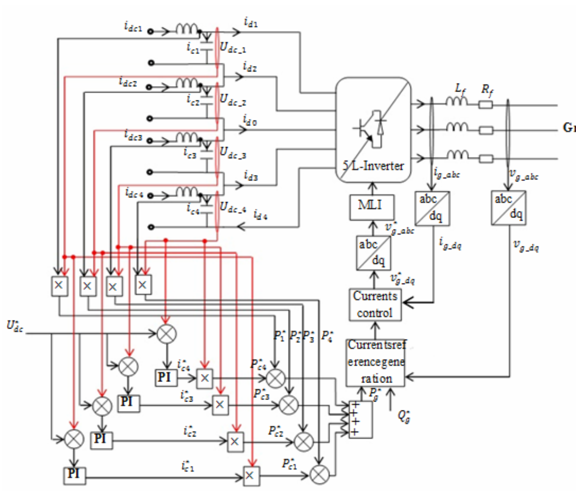


Fig. 3 – Five-level inverter control and dcs voltages regulation.

All the available power that can be extracted from the wind generators is transferred to the grid. Standard PI controllers are used to regulate the dc capacitors voltage and the inverter output currents in the (abc) synchronous frame.

The network is considered stable, so to have the grid current vector in phase with the grid voltage vector, the reference reactive power Q^* should be zero. The dc link voltage control is acting to supply the reference active power. The output of the current controllers sets the voltage reference for an average conversion control method that controls the switches of the grid inverter.

6. SIMULATION RESULTS AND DISCUSSION

The mathematic model of the system in Fig. 3 is implemented and simulated on MATLAB/Simulink. Aero-generator's wind profiles supposed different (Fig. 4), so the power provided by each generator is different to others, as shown in Fig. 5. The one generator rated power equal to 75 kW, and can provide until 150 kW, since the control strategy including the power law distribution allows to operate DFIGs over wide range of speed variation (twice of nominal speed).

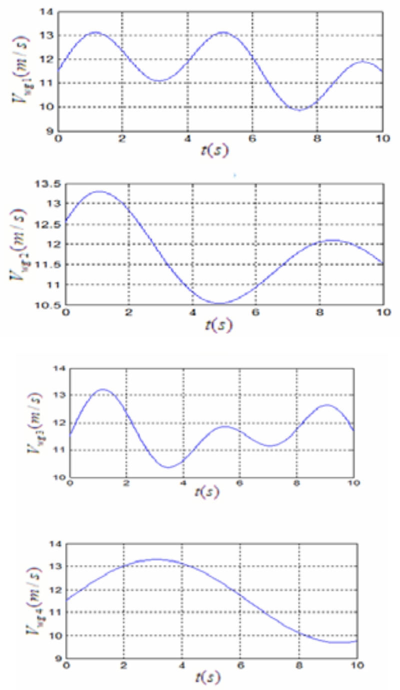


Fig. 4 – Aero-generators wind profiles [m/s].

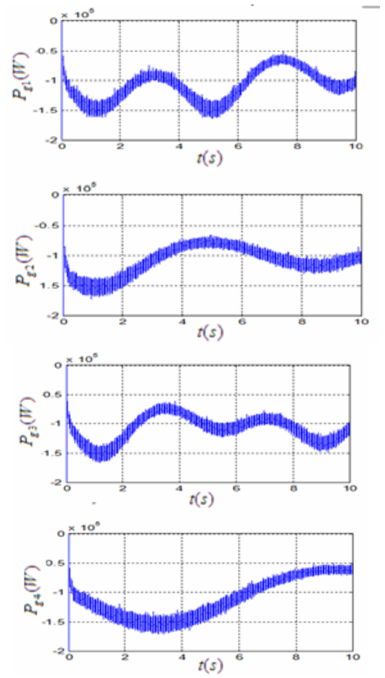


Fig. 5 – DFIGs active power [W].

According to Fig. 6 the active power injected into the grid through the five-level inverter equal to the sum of powers provided by the four aero-generators, and has less fluctuation. In addition the five-level inverter makes possibility to control the power factor of the system, such as in this work the power factor is maintained to the unity, so the reactive power injected into the grid equal to zero.

The one phase of five-level inverter voltage and current zoom are shown on Fig. 7; their respective harmonics spectrums are shown on Fig. 8. The five-level inverter provide a good current and voltage THD, such as the current THD equal to 2.03% and its fundamental amplitude equal to 208.1 A , the voltage THD equal to 23.62% and its fundamental amplitude equal to 1 222V . Consequently the five-level inverter provides a good power quality, and can ensure the requirements of grid integration.

The dc voltage provided by the first generator's rectifier is represented on Fig. 9, one can notice that the dc voltage is regulated to its reference value, and it is similar for others dcs voltages.

The PI regulators acting to hold constant the dc voltage of each capacitor; this solution allows to avoid the unbalancing dc capacitor voltage and the overvoltage on the semiconductors.

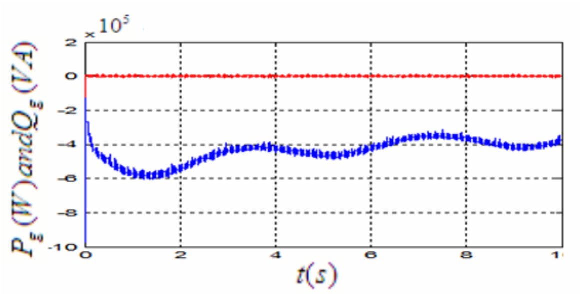


Fig. 6 – Active and reactive power injected into the grid [W].

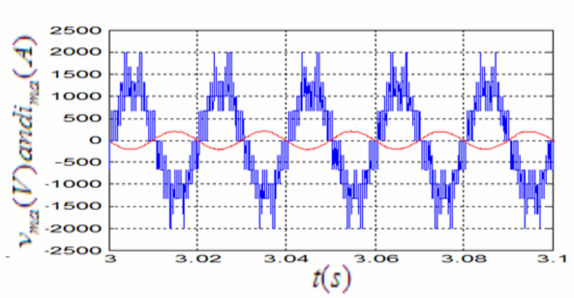
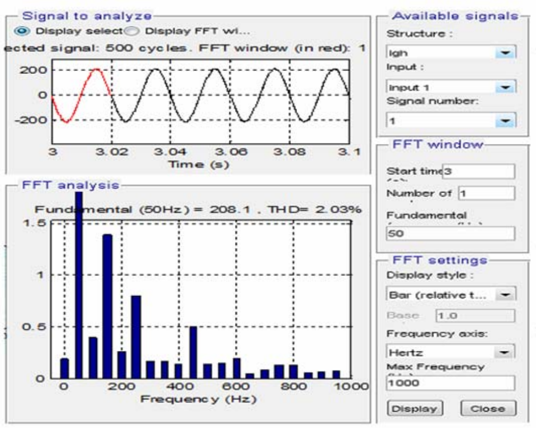


Fig. 7 – One phase voltage
and current modulated by the five-level inverter [V, A].



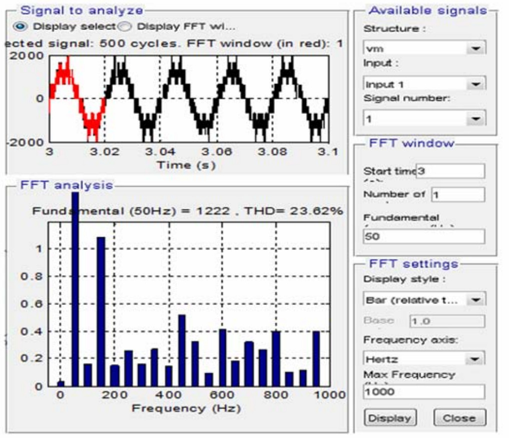


Fig. 8 – Five-level voltage and current harmonics analysis.

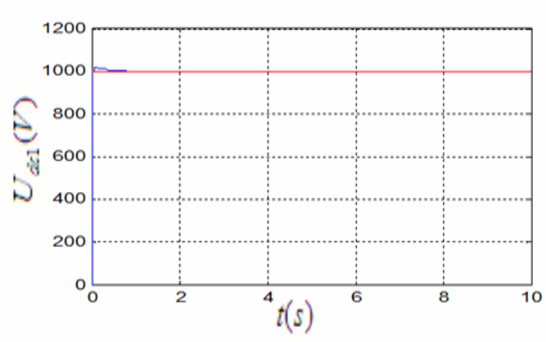


Fig. 9 – One dc capacitor voltage and its reference [V].

7. CONCLUSION

The work was aimed to study and analyze a wind farm connected to the power grid through a five-level NPC inverter, the contribution concerned the dc filter, such as each dc capacitor supplied by the DFIG rectifiers' side, and its voltage regulated to a constant value. The proposed topology allows: extract maximum power over wide range of speed variation, increase the aero-generator power density since the DFIG can provide twice of its nominal power, improve the power quality of energy injected into the grid, reduce the harmonic content, improve the output voltages waveform, decrease the stress across the swishes, don't suggest the bulky connecting transformer, and particularly avoid the unbalancing dc capacitor voltage due to the use of PI regulators for maintaining the dc voltage of each capacitor constant. In addition the network disturbances do not affect the wind farm.

NOMENCLATURE

i_{gd}, i_{gq} – Direct and quadrature grid current

i_{ma} – Current modulated by first arm of the five-level inverter

$i_{sa}, i_{sb}, i_{sc}, i_{ra}, i_{ab}, i_{rc}$ – Stator and rotor currents in the natural *abc* axes respectively

P_{g1} – Active power of the first generator

P_{g2} – Active power of the second generator

P_{g3} – Active power of the third generator

P_{g4} – Active power of the forth generator

P_g – Grid active power

Q_g – Grid reactive power

U_{dc} – dc capacitor voltage

v_{gd}, v_{gq} – Direct and quadrature grid voltages

v_{ma} – Voltages modulated by first arm of the five-level inverter

v_{md}, v_{mq} – Direct and quadrature voltages modulated by the five level inverter

$v_{sa}, v_{sb}, v_{sc}, v_{ra}, v_{ab}, v_{rc}$ – Stator and rotor voltages in the natural *abc* axes respectively

V_{wg1} – Wind speed of the first generator

V_{wg2} – Wind speed of the second generator

V_{wg3} – Wind speed of the third generator

V_{wg4} – Wind speed of the forth generator

ω_g – grid current pulsation

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