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Wind Energy Conversion System Performance Is Improved Using Integrated Multilevel Converter

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***Abstract* – Frequency converters are used in wind turbines because they make it possible to apply the variable-speed concept. They also make it possible for wind farm to become active element in the power system. The traditional frequency converter is back-to-back connected two-level converter, in which the output voltage has two possible values. In this paper, maximum power control of wind turbine and permanent magnet synchronous generator connected with five level three-phase flying-capacitor multilevel converter to grid are studied. This converter allows higher power handling, potentially lower power loss, lower harmonic distortion and hence less filtering requirements when compared with two-level converter.**

Keywords – multilevel converter, wind power, grid connection, permanent magnet synchronous generator.

I. Introduction

Nowadays, the demand for electricity is increasing. Faced with this problem, and so in order to limit the use of the fossil and natural resources such as uranium, hydrocarbons and water, and to reduce pollution, some countries, have turned to new forms of energy called "renewable". These energy sources use directly or indirectly solar energy. Among these, wind is clearly in good place, not to replace conventional sources, but as complementary energy booster [1].

Until now , there are two categories of wind turbines: fixed speed wind turbines which are directly connected to the grid through the stator and variable-speed wind turbines controlled by the stator or the rotor by means of the electronic power converters. The second category can increase the energy efficiency, reduce mechanical loads and improve the quality of the electrical energy produced, compared to fixed-speed wind turbines. However, the power transmitted through the IGBT converters is limited by the characteristics of the IGBT (maximum voltage and current supported). Commercial turbines currently reach 7.5MW and new developments are pushing to the 10MW milestone [2]. At this power level, multilevel converters and medium voltage operation becomes attractive, mainly due to improved power quality and higher efficiency. This is why several configurations proposed recently include multilevel converters.

II. Wind energy conversion systems

The conversion system wind power studied is shown in figure.1, it includes, in addition the synchronous permanent magnet generator, an IGBT converter, a DC-Link, a multilevel inverter, a connection to the grid via a filter, and a transformer. The IGBT converter is a three-phase PWM-controlled rectifier. This choice is justified by the fact that it can offer a fully reversible control of the instantaneous power, it can control the electromechanical variables such that the electromagnetic torque and the speed of the generator. The multilevel inverter controls the DC-Link voltage and active reactive power exchanged with the grid power.

III. Wind turbine modeling

The device studied, in this part, consists of a wind turbine including blades length R driving a generator via a gearbox with ratio G total kinetic power of the wind which passes through the wind turbine is given by the following equation:

$$P_w = \frac{1}{2}\rho R^2 v^3 \qquad (1)$$

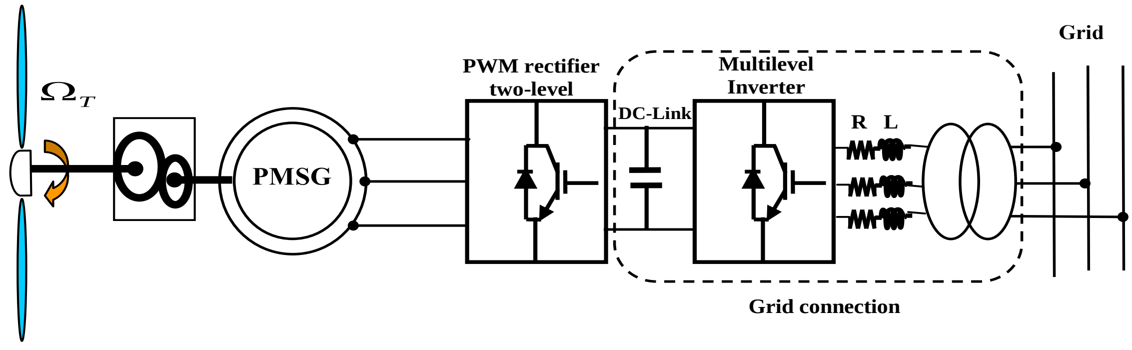

Fig.1 Wind energy conversion system

R : is the blade radius of the wind turbine (m);
ρ : represent air density (it is 1.25 kg / m in normal atmosphere);
v : is the wind speed (m/s);

Betz proved that the maximum power extractable by an ideal turbine rotor with infinite blades from wind under ideal conditions is 59.26% (0.5926 times) of the power available in the wind. This limit is known as the Betz limit .The extractable power can thus be written as:

$$P_{cap} = C_p(\lambda, \beta).P_w \qquad (2)$$

C_p : is the power coefficient which represents the aerodynamic efficiency of the turbine and also depends on speed ratio λ and the pitch angle β, the speed ratio is given by:

$$\lambda = \frac{\Omega_t R}{v} \qquad (3)$$

Models for power coefficient have been developed. For example [3] models C_p as a function of the tip speed ratio and the blade pitch angle Λ in degrees as :

$$C_p(\lambda, \beta) = c_1\left(c_2 \frac{1}{\Lambda} - c_3\beta - c_4\beta^x - c_5\right)e^{-c_6\frac{1}{\Lambda}} \qquad (4)$$

In this equation, the parameter Λ also depends β and λ .

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (5)$$

The values of the coefficients, c_1, c_2, c_3, c_4, c_5 et c_6 are given in Table I as:

Table I
Coefficients defining the evolution of C_p

coefficients	*values*
c_1	0.5
c_2	116
c_3	04
c_4	0
c_5	5
c_6	21

The difference between the curves of different wind turbines is small and can be neglected in the dynamic simulations. Knowing the speed of the turbine.

The aerodynamic torque developed (in Nm) can then be calculated:

$$C_{aer} = \frac{P_{aer}}{\Omega_t} = C_p.\frac{\rho.s.v^3}{2}\frac{1}{\Omega_t} \qquad (6)$$

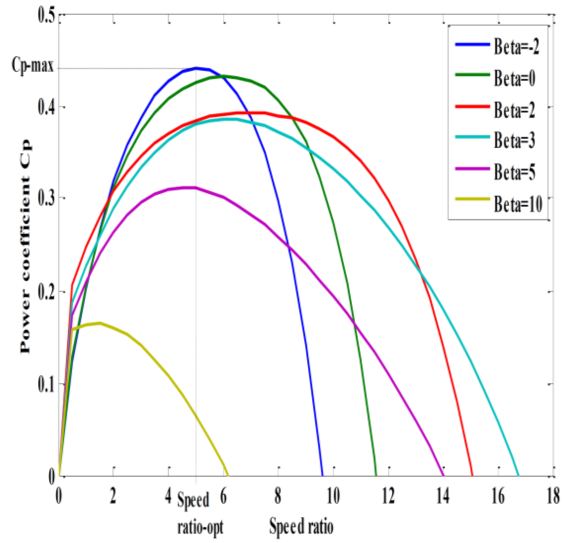

Fig.2 Power coefficient characteristic versus speed ratio λ and pitch angle β

IV. Control of permanent magnet synchronous generator PMSG

Figure.3 illustrates the tow control functions of the PMSG:

- Vector control of PMSG.
- Control of PWM converter.

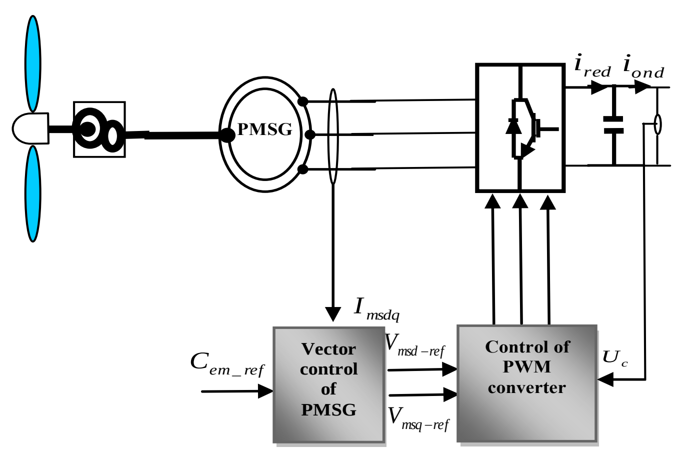

Fig.3 Control of permanent magnet synchronous generator PMSG

Control of AC machines is difficult because the mathematical model of the system is strongly coupled. All control devices are conceived with the aim of finding the ease and quality setting naturally offers DC machine. The similarity between the PMSG and DC machine is made possible by the vector control; the aim of this control is the decoupling of axes d-q. The model of the PMSG in the d-q synchronous reference frame is given by.

$$\begin{cases} V_{msd} = R_s.i_{msd} + L_{sd}.\dfrac{di_{msd}}{dt} - L_{sq}.\omega_r.i_{msq} \\ V_{msq} = R_s.i_{msq} + L_{sq}.\dfrac{di_{msq}}{dt} + L_{sd}.\omega_r.i_{msd} + \psi_f.\omega_r \end{cases} \quad (7)$$

$$C_{em} = p\left(\left(L_{sd} - L_{sq}\right)i_{msq}.i_{msd} + \psi_f.i_{msq}\right) \quad (8)$$

i_{msd} , i_{msq} : The stator currents

V_{msd} , V_{msq} : The stator voltages

R_s : Stator resistance

L_{sd} , L_{sq} : Stator inductances

ψ_f : Permanent magnetic flux

p : Number of pole pairs

$\omega_r = \dfrac{d\theta_r}{dt} = p\dfrac{d\theta_m}{dtdt}$: Represents the electrical speed of the rotor.

C_{em} : Electromagnetic torque

Among the strategies applied to vector control of a synchronous machine, which consists in imposing a direct current reference i_{msd} equal to zero is the most widely used. This choice is justified in order to avoid demagnetization of permanent magnets of the armature reaction along the axis of *d* [4]. The electromagnetic torque is given by.

$$C_{em} = \psi_f.i_{msq} \quad (9)$$

To control the generator power, it is enough to control the PMSG electromagnetic torque C_{em}, by regulation of the stator current and to know the rotational speed of the shaft.

V. Connection to the grid

The provided energy by the PMSG-based variable-speed wind turbine and transmitted on DC current is applied to a multilevel converter which makes it possible to control the continuous voltage and the active and reactive powers exchanged with the grid [5] [6]. An inductive filter *RL* has been designed to limit harmonic current injection into the grid figure.4.

The active and reactive powers passed through the grid are given in Park model by the following relations:

$$P_g = v_{sd}.i_{sd} + v_{sq}.i_{sq} \quad (10)$$

$$Q_g = v_{sd}.i_{sq} - v_{sq}.i_{sd} \quad (11)$$

By inversion of these relations, it is possible to impose some references for the active power p_{g-ref} and reactive power Q_{g-ref} while imposing the following reference currents:

$$i_{sd-ref} = \frac{p_{g-ref}.v_{sd-mes} + Q_{g-ref}.v_{sq-mes}}{v^2_{sd-mes} + v^2_{sq-mes}} \quad (12)$$

$$i_{sq-ref} = \frac{p_{g-ref}.v_{sq-mes} - Q_{g-ref}.v_{sd-mes}}{v^2_{sd-mes} + v^2_{sq-mes}} \quad (13)$$

A) Modeling and Control of Three Phase Inverter Multilevel

Three-phase five-level structure (*n+1*, with *n=4*) of a flying capacitor inverter studied, has three symmetrical arms of eight switches in series. Each switch consists of a switch IGBT and a diode connected in parallel provides the reversibility of the load current figure .5.

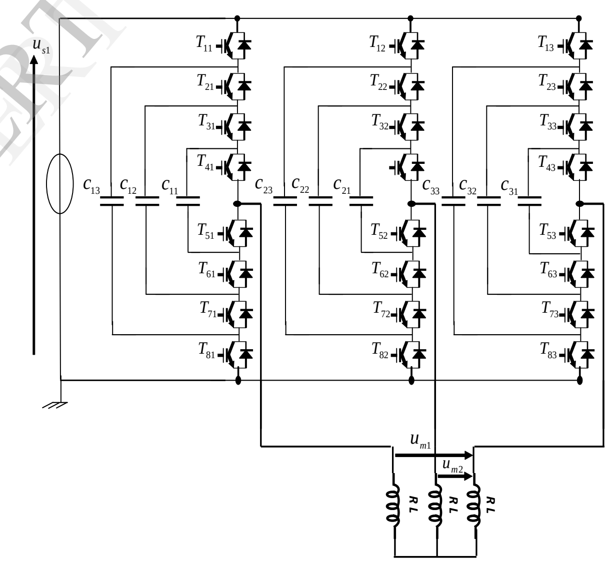

Fig.5 Three-phase five-level structure of a flying capacitor inverter.

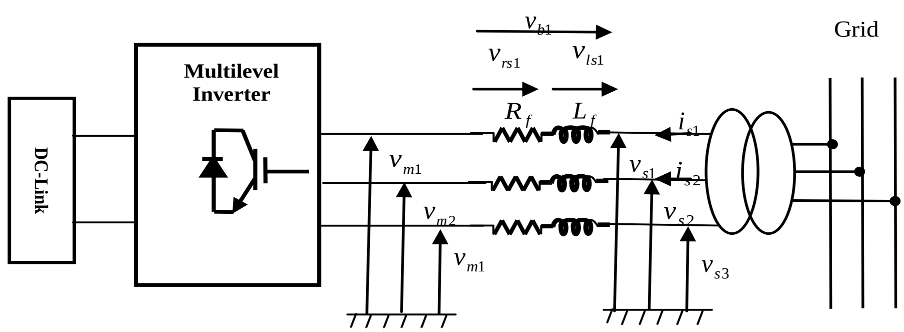

Fig.4 Grid connection studied

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This inverter uses a common DC bus and (*n-1*) DC bus in each arm. To produce (*n+1)* levels of output voltage, (*n-1)* capacitors are required. The circuits for each phase have an identical structure. Therefore, balanced voltage capacitors terminals c_{11}, c_{12} and c_{13} the phase 1 are independent for the phases 2 and 3. The three arms share a common DC voltage source. This flying capacitor multilevel converter has more degree of freedom and flexibility in level composite aspects than diode-clamped multilevel inverter. The advantages of flying capacitor multilevel converter are flexible switch mode, high protection ability to power devices, to control real power and reactive power conveniently [7].

Each arm is equivalent to a switching circuit to five ideal switches which switching functions are noted f_{rc} figure.6 $r \in \{1, 2, 3, 4, 5\}$ and $c \in \{1, 2, 3\}$. The status of the last switch is complementary to other states [8]:

$$f_{5c} = \bar{f}_{1c}.\bar{f}_{2c}.\bar{f}_{3c}.\bar{f}_{4c} \tag{14}$$

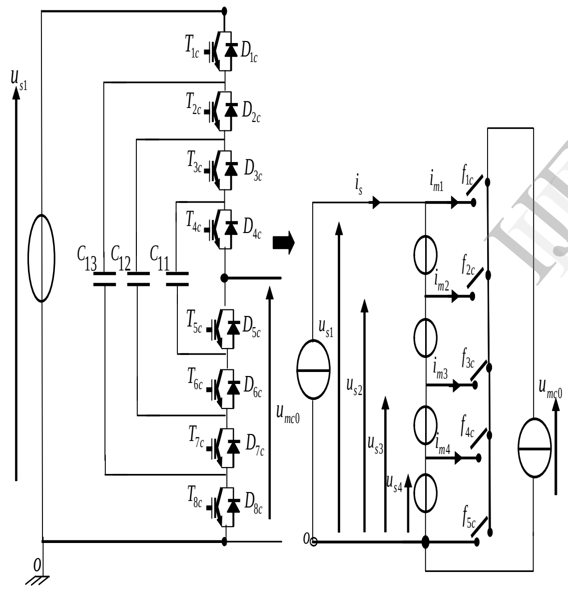

Fig.6 .Equivalent circuit of the C arm using the switching function.

The switching functions f_{rc} are related to gate signals of transistors T_{rc}. Each switching circuit *c*, there are 16 configurations, allowing connections between the different voltages balancing and load. Table II shows the possible combinations of switches and voltage levels corresponding.

Table II
Correspondence between the control signals and switching functions.

Control signals								Switching functions				u_{mc0}
T_{1c}	T_{2c}	T_{3c}	T_{4c}	T_{5c}	T_{6c}	T_{7c}	T_{8c}	f_{1c}	f_{2c}	f_{3c}	f_{4c}	
1	1	1	1	0	0	0	0	1	0	0	0	u_{s1}
0	1	1	1	0	0	0	1	0	1	0	0	$u_{s2} = 3u_{s1}/4$
1	0	1	1	0	0	1	0	0	1	0	0	
1	1	0	1	0	1	0	0	0	1	0	0	
1	1	1	0	1	0	0	0	0	1	0	0	
1	1	0	0	1	1	0	0	0	0	1	0	$u_{s3} = u_{s1}/2$
0	0	1	1	0	0	1	1	0	0	1	0	
1	0	1	0	1	0	1	0	0	0	1	0	
1	0	0	1	0	1	1	0	0	0	1	0	
0	1	0	1	0	1	0	1	0	0	1	0	
0	1	1	0	1	0	0	1	0	0	1	0	
1	0	0	0	1	1	1	0	0	0	0	1	$u_{s4} = u_{s1}/4$
0	1	0	0	1	1	0	1	0	0	0	1	
0	0	1	0	1	0	1	1	0	0	0	1	
0	0	0	1	0	1	1	1	0	0	0	1	
0	0	0	0	1	1	1	1	0	0	0	0	*0*

Three-phase five-level structure of a flying capacitor inverter is equivalent to a (3×5) matrix converter (with ideal switches) figure.7.

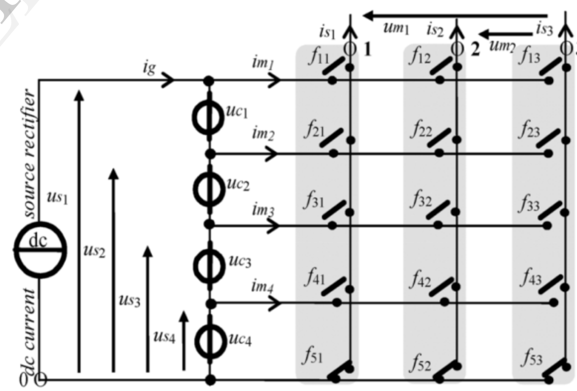

Fig.7. Equivalent matrix structure of the five-level flying capacitor inverter.

The modulated voltages are obtained from the capacitor voltage balancing and switching functions as:

$$u_{m1} = (f_{11} - f_{13})u_{s1} + (f_{21} - f_{23})u_{s2} + (f_{31} - f_{33})u_{s3} + (f_{41} - f_{43})u_{s4} \tag{15}$$

$$u_{m2} = (f_{12} - f_{13})u_{s1} + (f_{22} - f_{23})u_{s2} + (f_{32} - f_{33})u_{s3} + (f_{42} - f_{43})u_{s4} \tag{16}$$

These equations can be rewritten as:

$$u_{m1} = m_{11}.u_{s1} + m_{21}.u_{s2} + m_{31}.u_{s3} + m_{41}.u_{s4} \tag{17}$$

$$u_{m2} = m_{12}.u_{s1} + m_{22}.u_{s2} + m_{32}.u_{s3} + m_{42}.u_{s4} \tag{18}$$

This expression is used to define modulation function

$$m_{1c} = f_{1c} - f_{13}, m_{2c} = f_{2c} - f_{23}, m_{3c} = f_{3c} - f_{32}$$
$$m_{4c} = f_{4c} - f_{43}, \quad c = 1\, et\, 2 \qquad (19)$$

The purpose of the control system is to generate the equivalent mean value of modulated voltage references (written $\langle u_{mc}(t) \rangle$) inside each modulation period. The mean value of a modulated voltage during the modulation period T_m is expressed as [9]:

$$\langle u_{mc}(t) \rangle = \left[\frac{1}{T_m} \cdot \int_{k.T_m}^{(k+1).T_m} u_{mc}(t) dt \right], \quad avec\, k \in N.\ c \in \{1,2\} \qquad (20)$$

This quantity is linked to modulation functions and voltage sources, which are assumed to be nearly constant during the modulation period T_m :

$$\langle u_{mc} \rangle = \sum_{r=1}^{4} \langle m_{rc} \rangle . u_{sr},\ r \in \{1,2,3,4\} et\ c \in \{1,2\} \qquad (21)$$

For inverter operation, we wish to impose the following phase-to-neutral reference:

$$v_{c\_ref} = v_{\max}.\sin\left(\omega t - (c-1) \frac{2\pi}{3} \right), \ with \quad c \in \{1,2,3\} \qquad (22)$$

The reference voltages are calculated by:

$$\begin{cases} \langle u_{m1\_ref} \rangle = \langle v_{1\_ref} - v_{3\_ref} \rangle \\ \langle u_{m2\_ref} \rangle = \langle v_{2\_ref} - v_{3\_ref} \rangle \end{cases} \qquad (23)$$

B) Controlling the DC bus voltage:

The electrical equations of DC bus voltage are given by this expression.

$$U_c = \frac{1}{C} \int_{t_0}^{t_0+\Delta t} i_C + U_C(t_0) \qquad (24)$$

So:

$U_c(t_0)$: is the value of the DC voltage at the initial time.

The capacitor current is given by:

$$i_C = i_{red} - i_{ond} \qquad (25)$$

With:

i_{red} : rectified current;

i_{ond} : ripple current;

Adjusting the DC bus is composed of a control loop to maintain a constant DC bus voltage, with PI controller C_{i_C} and generating the reference current to be injected into the capacitor.

$$i_{C-ref} = C_{i_C} \left(U_{C-ref} - U_C \right) \qquad (26)$$

VI. Simulation results

Simulations have been performed using a wind generator based on a permanent magnet synchronous machine $(800KW)$ connected to the network via two kinds of inverters (two and five levels.) This chain conversion was simulated for a profile of mean wind around (12m / s) for a period of 20s figure.8.

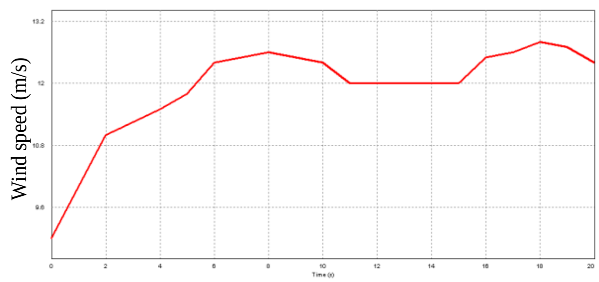

Fig.8 Wind speed profile

Figures 9 to 12 show simulation results using a two-level converter. Figure.9 shows the active power delivered by the wind and the active power sent to the grid connection, we see that the two powers following which shows the good performance of the system. Figure.10 shows the reactive grid power. So the generation system can operate at unit power-factor, absorbs or provides reactive power, figure.11 shows the first-phase line current end line voltage .The modulated voltage is shown in figure.12.

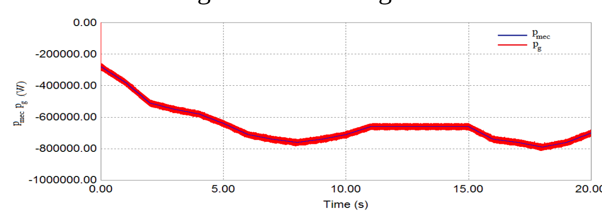

Fig.9. Wind power P_{mec} and active power transited to the grid connection P_g .

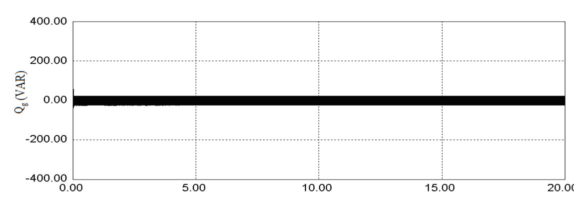

Fig.10 Reactive power transmitted to the grid connection

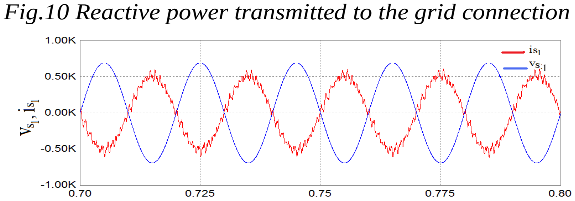

Fig.11 Voltage and current of the first phase of the grid connection.

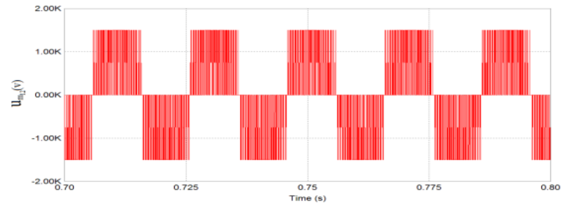

Fig.12. Modulated voltage u_{m12}.

Figures 13 to 16 show the simulation results using a five-level of a flying capacitor inverter. Figure.13 shows that the total active power generated is sent to the grid connection and practically $P_g = P_{mec}$. Reactive power is imposed zero figure.14. The modulated voltage has five levels figure.15. The phase between the grid voltage and current is π figure.16 and so the reactive power is null. The current is better than the current obtained using a two-level converter figure.11.

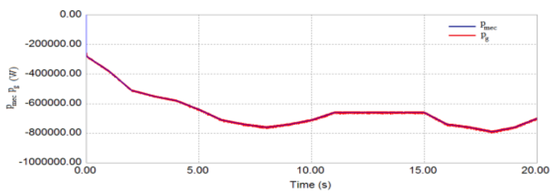

Fig.13 Wind power P_{mec} *and active power transited to the grid connection* P_g.

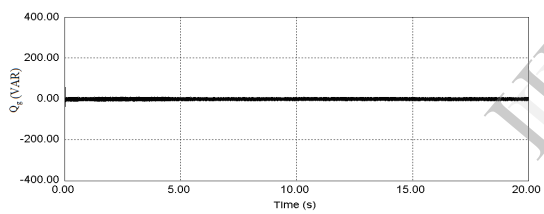

Fig.14 Reactive power transmitted to the grid connection

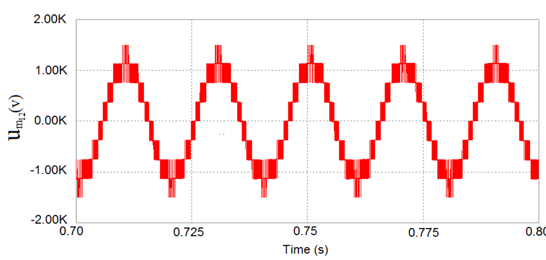

Fig.15 Modulated voltage u_{m12}.

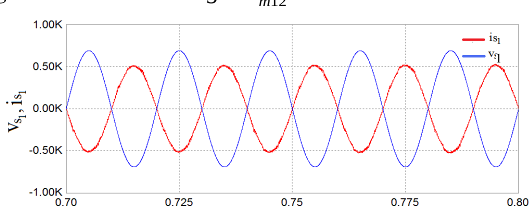

Fig.16 Voltage and current of the first phase of the grid connection.

VII. Conclusion

The modelling of a wind turbine with a permanent magnet synchronous generator connected to the grid via five-level of a flying capacitor inverter has been treated. This wind system was modelled using d-q rotor reference frame and is interfaced with the power system through an inverter and a filter modeled in the power system reference frame. The inverter control allowed, through grid current regulation, to achieve a decoupled active and reactive power control for operate with unitary power factor.

From the simulation results, the multilevel inverter topology can overcome some of the limitations than the standard two-level inverter. Harmonics decreases as the number of levels in the output voltage is increased.

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