THE SYMMETRICAL CONTROL LIMITS FOR ASYMMETRICAL H-BRIDGE CASCADED INVERTER IN WIND ENERGY CONVERSION SYSTEM

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Abstract: *The behavior of the Wind Energy Conversion System (WECS) is affected by wind speed, type of generator used and the conversion technology adopted. The power management in a stand-alone wind turbine installation has to be carefully studied due to the random aspect of the wind distribution. In this paper, a solution based on power segmentation methodology by using the H-Bridge cascaded inverters is proposed. This kind of converter is adapted to the situation of identical and non-identical continuous DC wind turbine sources. The symmetrical phase disposition pulse width modulation (PDPWM) control is used and its limitations are presented.*

Keywords: *Wind turbine; wind speed, Asymmetrical cascaded inverter, H-bridge inverter, symmetrical PDPWM*

1. Introduction

The world actually is facing a constant decrease in matter of natural resources (oil, coal …) to maintain the electricity producing process. As an alternative solution, the focus of the researchers has been shifted toward the green energy, which is not polluted and has no impact on the environment. The power of wind has the necessary qualifications to replace traditional fuel meanwhile it is not dangerous to global warming

The wind energy conversion system (WECS) is composed of wind turbine, pitch angle control, drive train, generator and power converter.

The wind turbine converts the wind energy into mechanical energy and then through the generator in electrical energy.

Nevertheless, the performances of the wind turbine is affected by wind speed and distribution. Thus, the design and analysis of a wind turbine require a tool that can estimate the behavior of the generator under various wind conditions. Therefore, there is a need for model that can provide realistic wind speed profiles[1-6]

The axial flux PMSG is a famous topology of the permanent magnet synchronous generator family [7-10]. It has better power density and operate more efficiently at low speeds comparing to the classic radial ones. Furthermore, it has smaller volume and lower mass by comparing it to the radial topology in the same power ratings. The advantage of using a permanent magnet synchronous generator PMSG in WECS is providing a direct drive connection without using gearbox. The gearbox increase the cost of maintenance, as well as the weight of the nacelle

The cascaded inverter seems to be an appropriate associated power stage to connect wind turbine to the AC loads. Moreover, this structure is advantageous according to several aspects such as reliability, flexibility, the extensibility and power segmentation.

The cascaded inverter also called cascaded H-bridge converter synthesizes an important output voltage from several small voltages. The total output voltage is the sum of the terminal voltages of the H-bridges installed in series [11-13].

Small scale multiple wind generator affected by constant and/or random wind speed and associated with multilevel H-bridge cascaded inverter will be the main subject discussed this paper.

In the first part, is about designing and simulating a on dimensional wind speed model. this model is based on the harmonics filter.

The second part, the authors develop an aerodynamic model of the small scale wind turbine model considering the direct drive nature of the axial flux permanent magnet wind generator.

An analysis in the third part of this paper is carried, considering different case scenario of the wind speed behaviour.

Finally, the DC output voltage generated from the different wind turbine will be the main input source of the multilevel H-bridge inverter.

2. The Wind distribution model

The energy contained in the wind is generated in dint of the rotor area, the air density and the wind speed. This energy is obtained by integrating the wind speed over a period time T, resulting the following:

$$Energy_{total} = \frac{1}{2}\rho A\int_0^T V(t)^3 dt \qquad (1)$$

To estimate the average energy rating from the average wind speed value using only Weibull distribution could lead to non-accurate and non-realistic results when computing the total energy using the previous equation. In literature, the wind form near the Earth's surface is characterized in general by a special three-dimensional speed distribution. In the purpose of developing the global wind speed behavior, some assumptions must be considered: the changes in wind direction are enough slow, also the rotor is maintained normal to the wind direction. In this case, the wind turbine model needs only the longitudinal wind speed to be modelled. Thus, only scalar (1D) wind speed will be used, by using the 1D-fixed-point method.

A non-stationary random process, giving the model of the wind speed by superposing two components, as shown in equation (2).

$$v(t) = v_m(t) + v_t(t) \qquad (2)$$

Where v_m(t) is the low-frequency component describing slow variations in long-term period. And v_t (t) is the turbulence component (high frequency and fast variations).

The spectral large band model was first published in; showing that the turbulence component can be modeled as a zero average random process even though it has small amount of energy in the spectral interval (between 2h and 10mn).

2.1. The Mean wind speed model

The low frequency component of the wind speed is described as quasi-steady mean wind speed or just mean wind speed. Its value is calculated as the instantaneous speed over an interval t_p:

$$V_m = \frac{1}{t_p}\int_{t_0-\frac{tp}{2}}^{t_0+\frac{tp}{2}} V(t)dt \qquad (3)$$

Knowing the mean wind speed that can be expected at a potential location is essential to select the wind energy conversion system WECS in order to maximize efficiency and durability.

Many methods were developed to generate and forecast wind time series based on wind speed measurements. Van der Hoven spectrum method is one of the most commonly used for this purpose.

To determine the new wind speed time series, the Van der Hoven spectrum (for a desired time span and sampling accuracy), is sampled. Specifically, the frequency range under the value (1/tp) is divided into m intervals. Finally, the mean speed is computed at every step as:

$$V_m(\mathrm{t}) = V_0 + \sum_{t=1}^{m} A_i \cos(\mathrm{w_i t} + \xi_\mathrm{i}) \qquad (4)$$

Where:

- $\omega_i = \overline{1, m+1}$; is the discretized angular frequency.
- ξ_i is a stochastic variable uniformly distributed.
- V_0 is the mean speed measured during a period longer than $\frac{2\pi}{\omega_i}$

And:

$$A_0 = \frac{2}{\pi}\sqrt{\left(\frac{1}{2}\left[S_{vv}(\omega_i) + S_{vv}(\omega_i + 1)\right](\omega_i + -\omega_i)\right)}$$

with $S_{vv}(\omega_\mathrm{i})$ is the power spectral density at ω_i

This method is characterized with its simplicity, besides, the generated wind speed time series has a similar spectrum then the original measurement data. In addition, this method preserve the periodical trends and the general data is more enduring.

2.2. The turbulence wind speed model

To compute the fast component, high frequency aspect of the wind speed model, the turbulence component shape from Van der Hoven spectrum is studied.

The approach adopted, for this matter, is to approximate the wind spectrum at high frequencies with the Kaimal or the von Karman spectrum.

Both models are presented as following:

$$\Phi(\omega)=\frac{K_v}{(1+\omega T_v)^{5/3}} \text{ , Kaimal spectrum} \quad (5)$$

$$\Phi(\omega)=\frac{K_v}{(1+(\omega T_v)^2)^{5/6}} \text{ , von Karman spectrum} \quad (6)$$

Where: K_v is the turbulence length scale and T_v is the turbulence intensity. Both parameters are dependent on the mean wind speed and the site specifications.

There are several methods to model the local effects of the wind speed. In this paper, the harmonic filter method is implemented, using the Kaimal spectrum for modelling the fast changing component. The wind speed computation is explained better in figure 1.

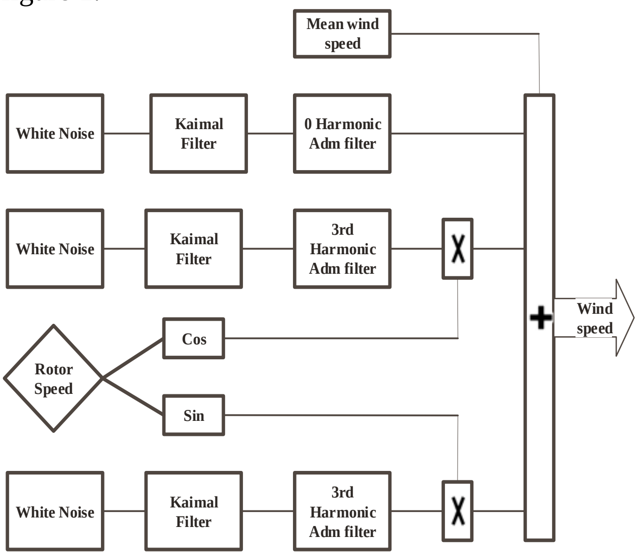

Fig. 1. The wind speed computed with harmonics filter method.

The transfer function of the zero harmonic admittance filter is presented by:

$$H_{adm\,0}(s)=\frac{4.7869d^2.s^2+0.9904}{7.6823d^2.s^2+7.3518d.s+1} \quad (7)$$

And the transfer function of the third harmonic admittance filter is calculated as:

$$H_{adm\,3}(s)=\frac{0.2766d^2.s^2+0.0307}{0.3691d^2.s^2+1.7722d.s+1} \quad (8)$$

This method allows us to produce a single equivalent wind speed as shown in figure 2. The wind speed model can be used as input to the wind turbine aerodynamic model.

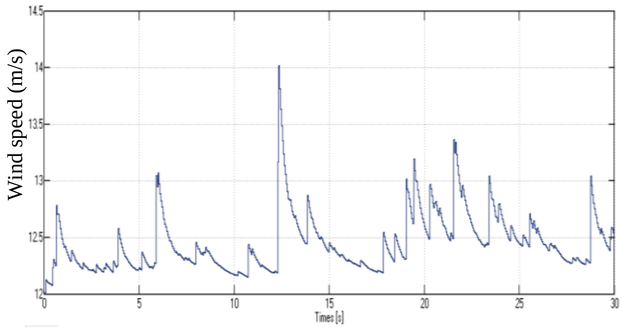

Fig. 2. Result of the simulated wind speed model.

3. The aerodynamic profile of the wind turbine

The aerodynamic model represents the interaction the turbine rotor and the wind field. The useful mechanical power extracted, depends on the blade diameter, the pitch angle, air density, and power coefficient [10-12].

The power captured is given by:

$$P_w=\frac{1}{2}C_p(\lambda,\beta)\rho A V_w{}^3 \quad (9)$$

Where: C_p (λ, β) is the power coefficient, ρ is the air density in Kg/m^3, V_w is the wind speed in m/s and A is the area swept by the rotor in m².

The power coefficient was introduced by the method of Betz; it shows that whatever the wind architecture (two-bladed or three bladed …) it does not gain more the rate of 59% of the energy from the wind, which means that the maximum theoretical value of C_{pmax} is equal to 0.59.

The power coefficient is function of pitch angle and tip speed, its value is calculated using equation (10).

$$C_p(\lambda,\beta)=c_1(\frac{c_2}{\lambda_i}c_3\beta-c_4)e^{\frac{-c_5}{\lambda_i}}+c_6\lambda \quad (10)$$

With:

$$\lambda_i=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1} \quad (11)$$

c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 5 and c_5 = 0.0068

The tip speed ratio is given by the equation (12).

$$\lambda=\frac{\omega_t R}{V_w} \quad (12)$$

The turbine output torque can be calculated from the expression of the turbine output power using relation (13).

$$T_{out\_turbine}=\frac{P_{out\_turbine}}{\omega_t} \quad (13)$$

The wind Turbine model is composed from: generator speed, wind model speed and the pitch angle as inputs, and the output is the torque, which is given to drive the generator, figure 3.

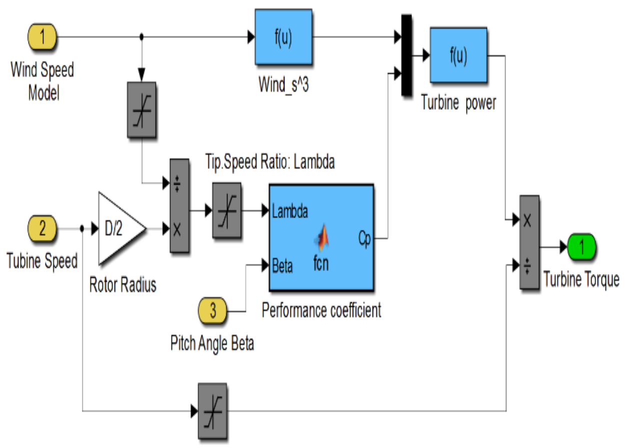

Fig. 3. Wind turbine aerodynamic model

4. The permanent magnet synchronous generator

The wind turbine generator studied in this paper, is the axial flux permanent magnet synchronous generator AFPMSG. This kind of electrical machine is suitable for the wind generation applications for many reasons: first, it is direct-drive so additional gear needed. Then, it has a simple winding structure, modular topologies, low cogging torque and noise, short axial length, and higher torque/volume ratio.

The generator dynamic equations is:

$$\begin{cases} v_q = e_q - R_{stator} i_q - \omega_e L_d i_d - L_q \dfrac{di_q}{dt} \\ v_d = e_d - R_{stator} i_d - \omega_e L_q i_q - L_d \dfrac{di_d}{dt} \\ v_0 = e_0 - R_{stator} i_0 - L_0 \dfrac{di_0}{dt} \end{cases} \quad (14)$$

The proposed generator is electrically balanced, and then the zero sequence quantities can be ignored. In addition, the d-axis reference frame is aligned along the permanent magnet flux position, as a result, the EMF in d-axis equal to zero.

Therefore, the generator dynamic equation will take the next form.

$$\begin{cases} v_q = K_{emf} \omega_e - R_s i_q - \omega_e L_d i_d - L_q \dfrac{di_q}{dt} \\ v_d = -R_s i_q - \omega_e L_q i_q - L_d \dfrac{di_d}{dt} \end{cases} \quad (15)$$

The d-axis and q-axis stator inductances in the synchronous reference frame are equal then: $L_s = L_q = L_d$

The above equation can be reduced to the following form:

$$\begin{cases} \dfrac{di_q}{dt} = \dfrac{1}{L_s} K_{emf} \omega_e - \dfrac{R_s}{L_s} i_q - \omega_e i_d - \dfrac{1}{L_s} v_q \\ \dfrac{di_d}{dt} = -\dfrac{R_s}{L_s} i_d - \omega_e i_q - \dfrac{1}{L_s} v_d \end{cases} \quad (16)$$

The expression of the electromagnetic torque Te of the generator is:

$$T_{em} = 0.371 \times n_{ph} \times p \times \Phi_{field} \times N_{1s} \times I_{stator} \quad (17)$$

With:

- n_{ph}: phase number of the generator.
- p: number of pole pairs.
- Φ_{field}: magnetic flux excited by PM.
- N_{1s}: number of turns per phase per stator.
- I_{stator}: is the phase stator winding current of single module.

5. Different output voltage turbine

5.1. Identical DC Sources

The full wind turbine model generating dc output voltage through rectifier power stage is shown in figure 4.

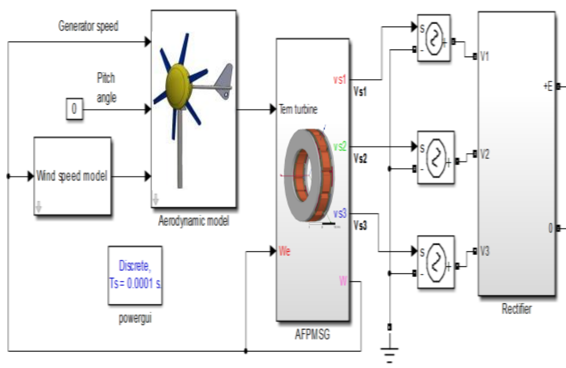

Fig. 4. Full wind turbine model.

Considering the three wind turbines receiving the same amount of wind distribution. Figure 5 is presenting both the AC and the DC output voltage of every PMSG wind turbine.

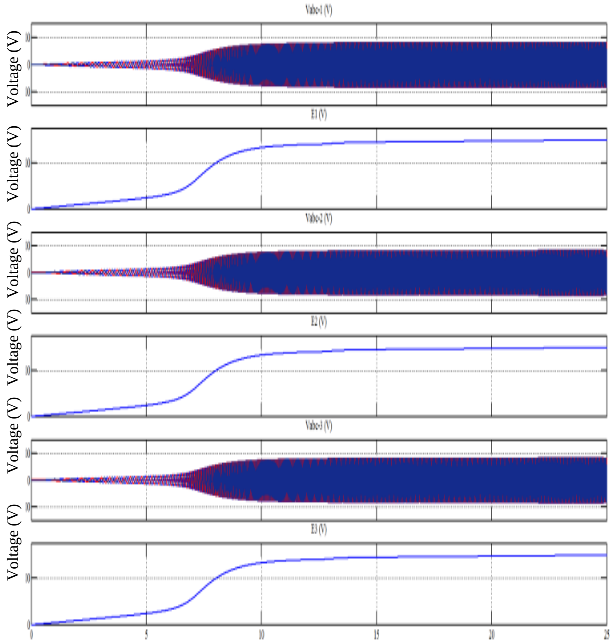

Fig. 5. Evolution of the three wind turbines output voltage for the same wind speed

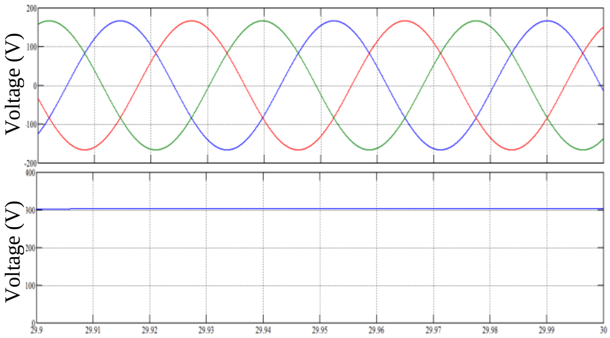

Fig. 6. Zoom of the three-wind turbines output voltage for the same wind speed.

5.2. Non-identical DC Sources

5.2.1. Different Output voltages but non-variable

The second scenario is where every wind turbine is exposed to different wind speed but still unchanged through long period, as simulated in figure 7.

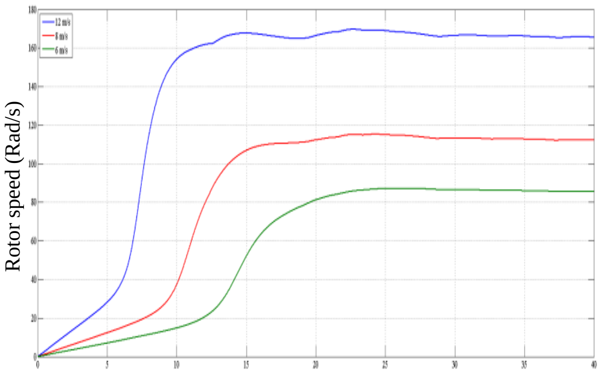

Fig. 7. The three wind turbines rotor speed

The PMSG are directly depending on the wind speed, as a result, the three wind turbines cannot provide the same output voltage. For further exploitation, a solution must be developed for this kind of situation as figure 8 shows.

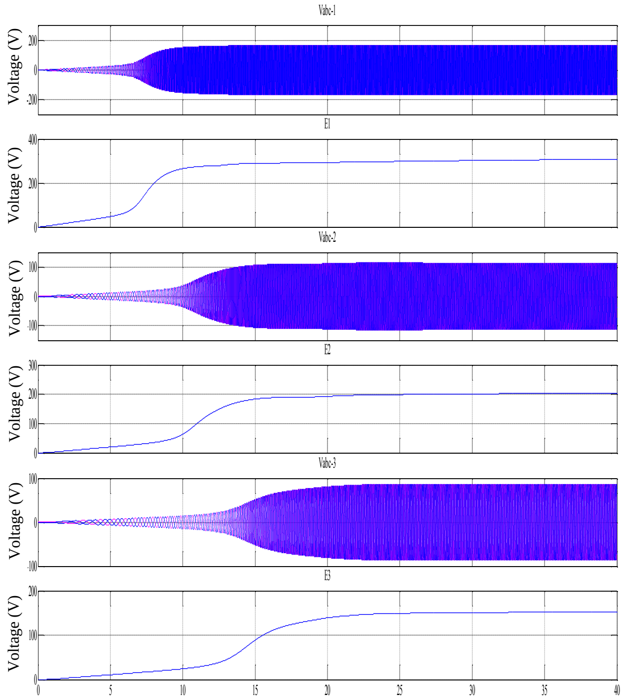

Fig. 8. The three wind generator AC and DC output voltage (case of different wind speed).

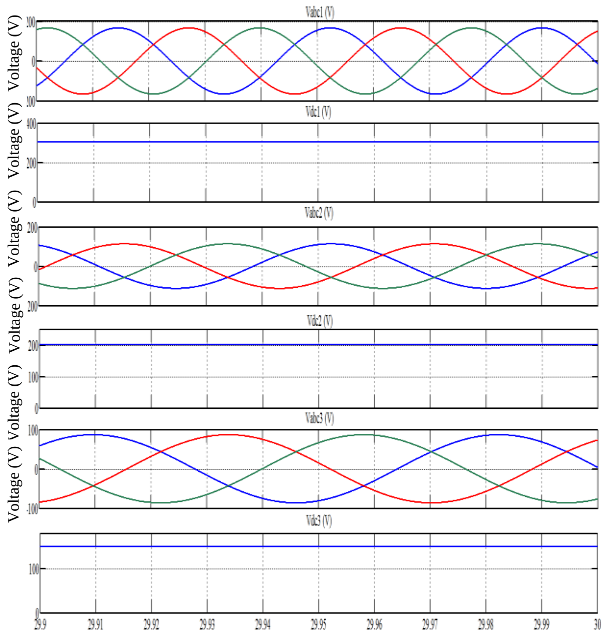

Fig. 9. Zoom-in on the previous output voltage of the wind generators.

5.2.2. Non-identical and variable Output voltages

For the final scenario, the direct-drive PMSG wind turbines are exposed to different wind speed. Although, the wind speed is changing during period of time. Figure 10, shows the evolution of the wind speed.

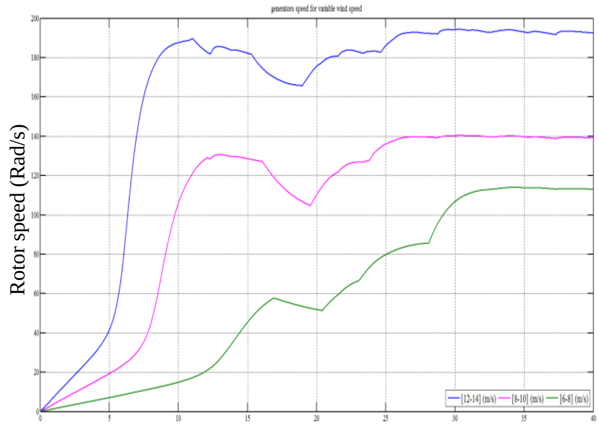

Fig. 10. Evolution of the three wind turbines rotor speed.

The output voltage of the three wind turbines, are not the same. The evolution of the AC/DC output follow the wind speed variations. Figure 11 represent clearly the output waveform changing in time.

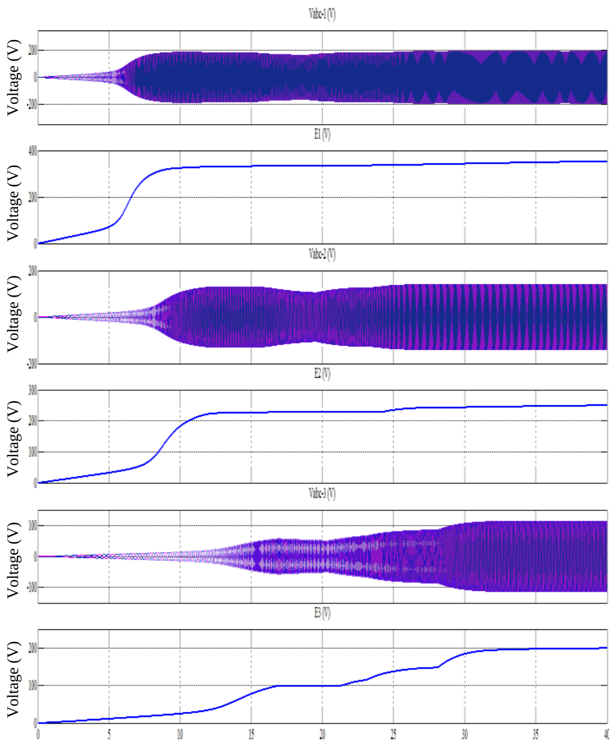

Fig. 11. Evolution of output voltage for different wind speed

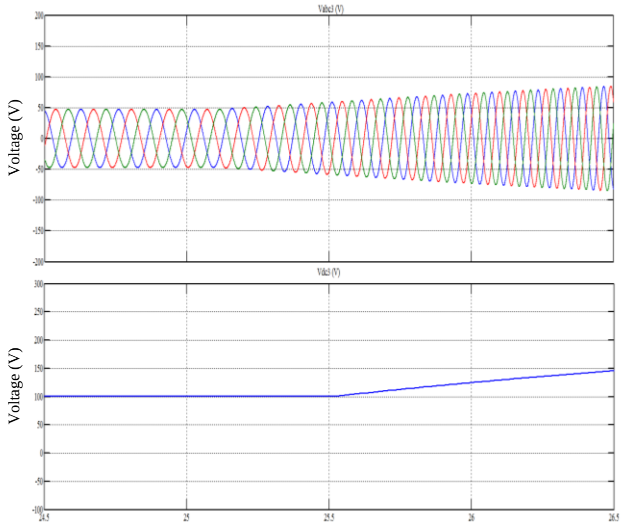

Fig. 12. Zoom-in on the previous output voltage for different wind speed variable in time.

The wind speed is has a major impact on the wind turbine generator. Although, the wind speed is generally randomly distributed, as a result, a stand-alone wind turbine installation may experience a non-uniform energy production. To remedy this natural phenomenon cause, a suitable power control technic must be used.

6. Integration of asymmetric cascaded inverter

A cascaded multilevel converter (CMC) consists of H-bridges or commutation cells connected in series and each one has its own continuous DC source. Every single H-bridge inverter is composed of two IGBT switches per leg: T_{1j} and T'_{1j}, figure 13. The continuous DC sources can be identical or not identical, from where the definition symmetrical or asymmetrical structures of the multilevel cascaded converters.

The output voltage of the CMC is the sum of the various output voltages of the H-bridges, which makes the waveform shape of staircase containing various levels.

The switching signals are respectively S1j and S2j ordering T_1j and T2j and S’1j and S’2j ordering T'_1j and T’2j.

The following notation Vc (1, j) is presented, where J is the number of the cell of the CMC, thus “S1j” the ordering of the cell number j of the CMC.

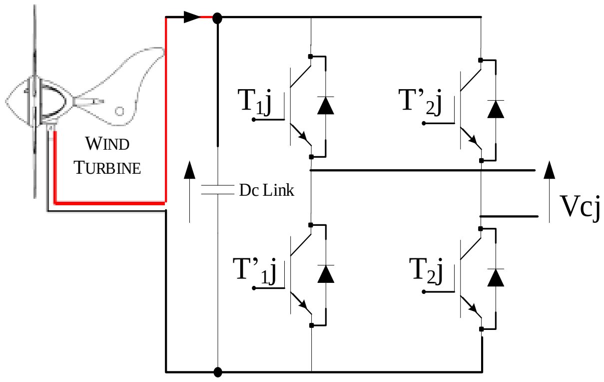

Fig. 13. Full H-bridge inverter

For each cell, the output variables are expressed according to the control signals as follows

$$Vj = (S1j + S2j - 1).Vcj \quad (18)$$

$$Ij = (S1j + S2j - 1).Icj \quad (19)$$

Sj function defined by

$$Sj = S1j + S2j - 1 \quad (20)$$

We obtain

$$Vj = Sj.Vcj \quad (21)$$

Consequently, the output voltage Vn is given by:

$$Vn = \sum_{j}^{n} Vj = \sum_{j}^{n} Sj.Vcj \quad (22)$$

For the asymmetrical CMC the coefficient called αj is introduced, it is the ratio of the Vj voltage by Vj-1 voltage

$$\alpha_j = \frac{V_j}{V_{j-1}} \quad (23)$$

In the case of the asymmetrical CMC, the uniformity is described by the coefficient αj if αj=constant. Thus, the output voltage Vn is given by the expression (24).

$$V_n = V_{c1}.\sum_{k=1}^{n}\left(\prod_{j=1}^{k}\alpha_j\right).S_k \quad (24)$$

Otherwise for a electric generator directly driven system receiving wind distribution and representing a DC input for the CMC inverter, the αj coefficient is generally random, the output voltage Vn is:

$$V_n = V_{c1}.\sum_{k=1}^{n} S_k.\alpha^{k-1} \quad (25)$$

For a symmetrical CMC Vcj = E; regardless j, αj = 1thus the output voltage is equal to:

$$Vn = (n-1).E \quad (26)$$

6.1. Symmetrical Phase disposition PWM Modulation

The peak-to-peak amplitude Am is equal to the sum of the voltages E of the DC continues bus of the CMC inverter. For n commutations cells, 2*n triangular carriers with the same frequency and same amplitude are in phase and disposed in adjacent bands. Figure 14, presents the technique of the phase disposition PWM modulation.

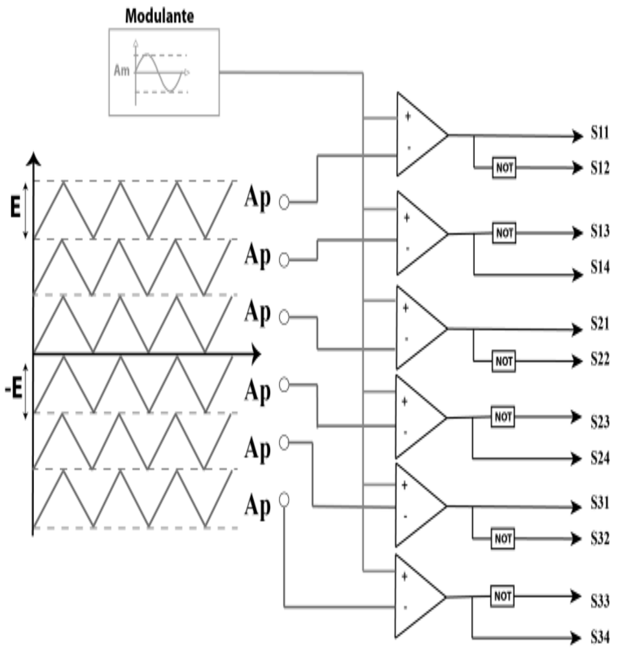

Fig. 14. Phase disposition PWM technique.

If the entrance of the full bridge of the inverter is a permanent DC source, both the triangular carriers and the reference signal are shown in figure 15.

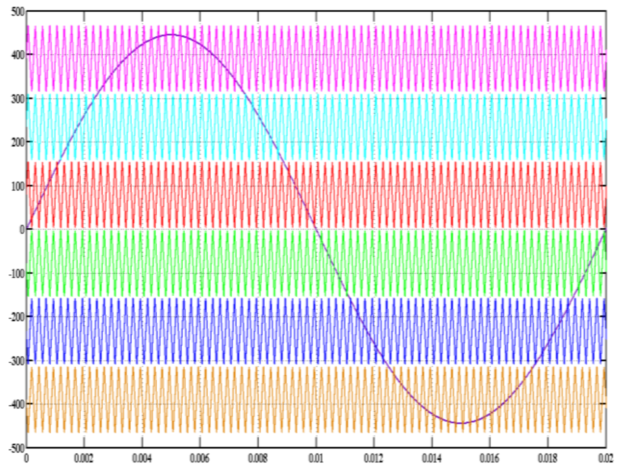

Fig. 15. Triangular carriers and the reference signal

6.2. Using the symmetrical PDPWM Modulation in case of constant DC sources

The inverter is receiving, three inputs from DC wind turbines, without any instantaneously modifications, the AC output obtained is a typical 7-level output voltage, as indicated in figure 16.

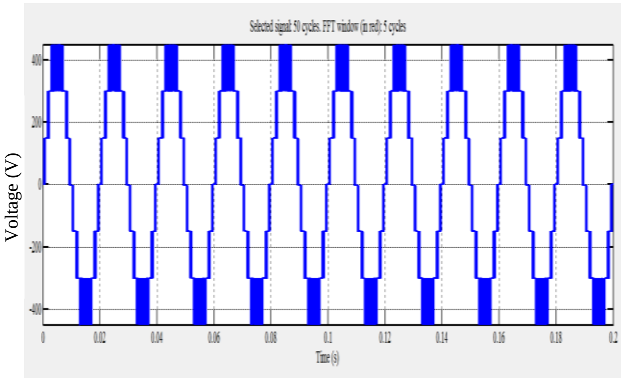

Fig. 16. 7-level output waveform from the H-bridge inverter.

As for the total harmonic distortion ratio, is calculated in figure 17.

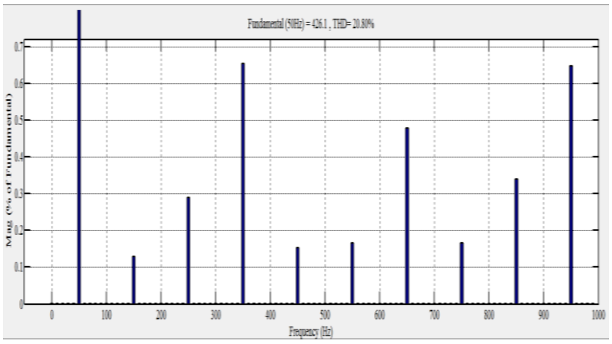

Fig. 17. The total harmonic distortion ratio.

For identical input sources, both output waveform and the THD ratio, the symmetrical PDPWM technique is suitable for this situation.

6.3. Using the symmetrical PDPWM Modulation in case of different DC sources

In our case, we have installed three wind turbines above our laboratory, as shown by figure 18.

The interest of next part consists in testing different wind speed variation by simulating the designed small scale WECS composed of H-bridge multilevel invert, direct-drive wind turbine generator connected to a resistive Load. For applying the PDPWM control, three wind turbines having different wind speed profile (based on the wind speed model earlier developed) are used. The configuration is represented in the synoptic figure 19.

Fig. 18. Three standalone wind turbines installed above our laboratory.

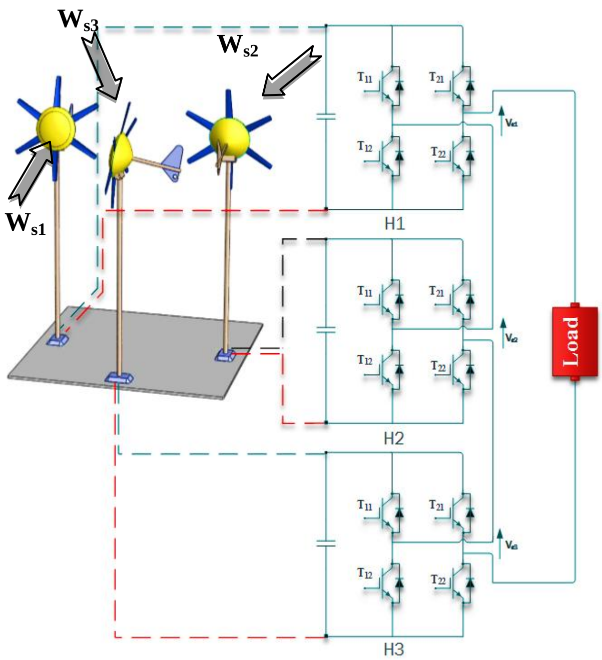

Fig. 19. Simplified scheme of the wind energy conversion system.

The arrangement of the wind turbines is such that they can be exposed sometimes to different wind distribution. Hence, they produce different output voltage.

The technique of modulation previously identified is putted on test in this section. Figure 20 is an output waveform of the three wind turbines, receiving the same wind speed.

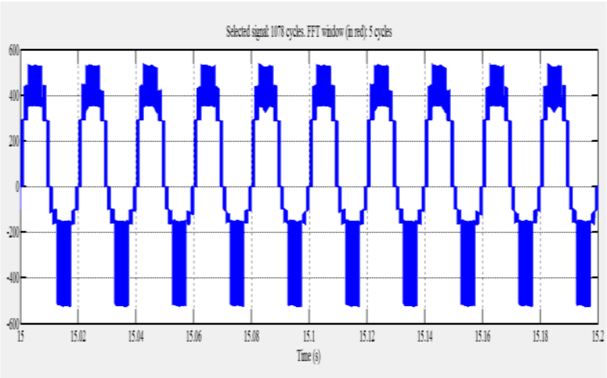

Fig. 20. Waveform of the Total voltage output

Figure 21 shows the THD ratio for this first simulation.

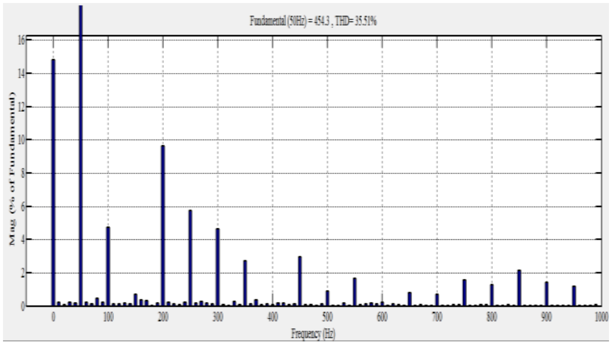

Fig. 21. The total harmonic distortion ratio.

The applied PDPWM has as consequence the loss of two voltage levels. The waveform of the output voltage has five levels instead of seven levels, as shown by the figure 22, we notice the fall of the RMS value of the output voltage, it is weak and declines provided energy from the Turbine generator.

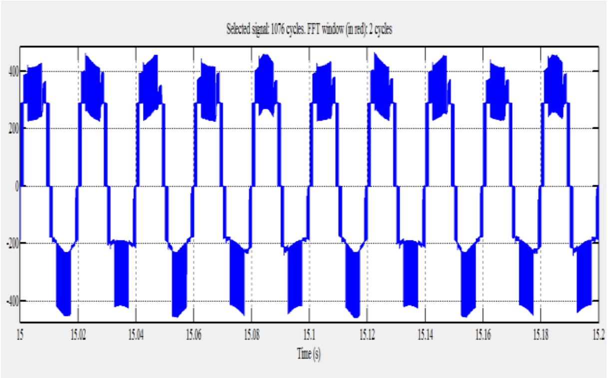

Fig. 22. Evolution of output voltage for different wind speed.

In addition, the THD ratio has increased as identified in figure 23.

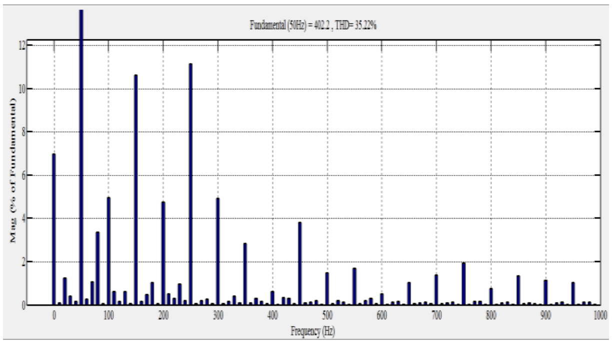

Fig. 23. Voltage THD using the symmetrical PWM technic

Applying symmetrical PDPWM technique for different and unbalanced voltage sources, has shown in return a low quality multilevel voltage, with high level of THD ratio.

7. Conclusion

Through this work, an interest has been awarded to the influence of wind speed distribution on stand-alone wind turbines for urban location. For that purpose, a Simulink based model was proposed, gathering a permanent magnet synchronous axial flux generator, and a wind speed model. Different simulations and analysis are applied to the stand-alone wind energy model, considering several scenario cases. The different wind speed simulation in real time shows its important impact on the output power. Then, therefore, to exploit several stand-alone wind turbines feeding electrical equipment, in a same zone, they do not necessarily provide the same output power due to the behavior of the wind speed.

The phase disposition PWM strategy proposed was not adapted to the variations of the wind speed and direction received by the installed wind turbine supplying the continuous DC buses of the multilevel converter. Indeed the symmetrical PWM applied in such wind conditions increases the harmonic rate of distortion for the voltage due to the low quality of the total output voltage obtained. to solve this issue, it is recommended to apply more suitable asymmetrical PWM control technique.

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