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Wind Turbine Modeling Reduction of Harmonics Distortion in the Electrical Network

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Abstract— *Among the electrical network complementary sources of Energy ,Wind turbine is conceived in order to produce maximum power with an average intensity wind force and nominal power is reached [1].When the wind force increases in intensity, an electronic regulation is used to adjust the power to its maximum while controlling the load on the structure. At the limit speed the system is stopped because electronic regulation cannot adjust the overload occurring at that speed [2].*

This paper shows how to control the signal at the electrical network input in order to minimize harmonic distortions.

Keywords— *Filters, harmonics, signal distorsion, wind turbines*.

I. INTRODUCTION

Wind Turbine system is one of the best producer of clean energy. But adjustments and control are needed when connecting it to the electrical distribution network.

In order to study the physical effects encountered when connecting the wind energy source to the electrical network in place, an interface is designed and its output is adjusted in order to minimize distortions due to harmonics propagating across the network. This paper will show solutions after describing harmonic pollution causes and effects.

II. DESCRIPTION OF A WIND TURBINE

The wind turbine is mounted on a tower fixed on the ground, by a foundation base. Positioning the wind turbine on a high level where the wind speed is faster and using big bladders improves the energy production efficiency. In Fig. 1 the Nacelle made by metallic materials covers essentially a generator accompanied by a Gearbox. The rotor will turn under the wind effect. In the nacelle the principal axis will activate the alternator producing the electricity. The speed rotor (12 to 15 rounds/ mn) is increased up to 1500 rounds/mn to let the alternators function efficiently.

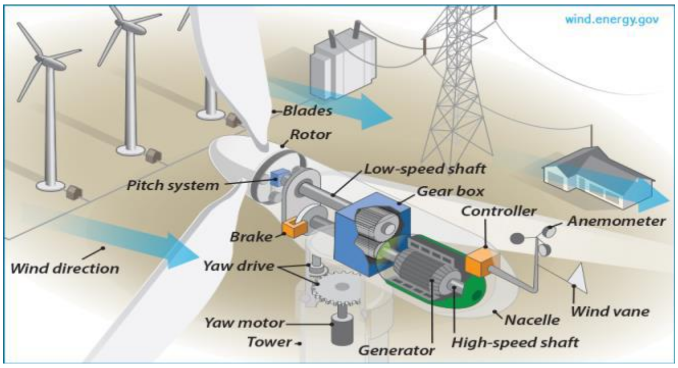

Fig. 1. Wind turbine description.

Electronic power converters adjust the output current frequency to fit the electric power network frequency while the rotor is functioning at a variable speed depending on the wind speed. The alternator produces between 600 to 1000 Volts; this amount is increased by a power transformer up to 20 to 30KV. This level will transport the energy over the electrical network.

III. HARMONICS

A. *Definition*

Electrical energy is a 3 phase sinusoidal system of 3 voltages. This system generates and transmits power at a fixed frequency of 50, 60 Hz with an almost constant voltage magnitude at the user side connection. Therefore the electrical network is characterized by the following parameters: Frequency, phase symmetry, voltage wave form. In case the latter is not sinusoidal, perturbations occur affecting equipments performance, as well as the good functioning of load components connected to the network.

Considering harmonics as periodical sinusoidal waves, harmonic frequencies are the fundamental frequency f_0, while the $h_{ièm}$ harmonic frequency will be hf_0.

The load connected at the user side of the electrical network as fluorescent lightning computers, televisions and electrical house wares, static connected converters such as UPS are at the origin of those harmonics polluting the network. Because even if the voltage supply has a constant magnitude, currents absorbed are in fact non sinusoidal, and those equipments are considered as nonlinear loads emitting harmonic currents with integer or non integer multiples of the fundamental frequency.

Those harmonics must be avoided in order to avoid their negative effects over the electrical network. [3].

B. *Negative Effects of Harmonics over the Network*

- Equipments heating.
- Interference due to the electromagnetic field coupling between communication and electrical networks introducing important noises.
- Malfunctioning of electrical equipments such as control systems, because currents and voltages have their polarity inverted in half period affecting sensible equipments.
- Resonance phenomenon occurs. Every circuit with transformers inductance, and cables capacity has high resonance frequency, when this frequency coincides with a harmonic frequency, the resonance becomes much higher and could destroy equipments connected on the network.

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- Equipments precision will be affected as well.

C. *Harmonic Pollution Measurement*

It is important to measure harmonic pollution in order to characterize installations and control the quality of energy distribution.

Several criteria can be used to measure those harmonic perturbations but the mostly used is the overall distortion of all the harmonics (THD).

The absorbed current at the equipments entry is defined by "(1):"

$$i(t)=\sum_{h=1}^{\infty} I_h \sin(\omega_h t+\varphi_h) \tag{1}$$

$$i(t)=\sqrt{2}I_1\sin(\omega_1 t+\varphi_1)+\sum_{h=2}^{\infty}\sqrt{2}I_h\sin(h\omega_1 t+\varphi_h)$$

With:

I_1 : Effective value of the current fundamental component;

I_h : Effective value of the current harmonic at order h;

φ_1 : Phase shift of the current fundamental component;

φ_h : Phase shift of the current harmonic at order h.

THD defines the ratio between the root mean square value of all harmonic components (h ≥2) and the fundamental of the current in percentile according to the following (2):

$$THD=\frac{\sqrt{I^2-I_1^2}}{I_1}=\frac{I_h}{I_1} \tag{2}$$

With

I : Effective value of current i(t).

I_h : Root mean square value of all harmonic components.

IV. MODELING

A. *Modeling the Wind*

In order to model the Aeolian rotor it is necessary to model the wind that is the principal source of energy so that we define the Aeolian working conditions of the wind turbine. [4], [5]

Wind is represented by Fourier series as a continuous signal decomposition as (3):

$$V_v(t)=A+\sum_{k=1}^{i} a_k \sin(\omega_k+t) \tag{3}$$

With A: Wind speed average value;

a_k : Harmonic of k order;

ω_k : Harmonic pulsation of k order;

i: Last Harmonic rank kept to describe the wind profile.

B. *Turbine Modeling*

To model the wind turbine it is necessary to find the torque that is exercised at the rotor level and that is extracted by the turbine from the Aeolian power according to the following: [6], [7]

$$P_{éol}=\frac{1}{2}.C_p(\lambda).\rho.S.v_v^2 \tag{4}$$

$$\lambda=\frac{R\Omega_{mec}}{v_v} \tag{5}$$

$$C_{éol}=\frac{1}{2}.\rho.\pi.R^3.v_v^2.\frac{C_p(\lambda)}{\lambda} \tag{6}$$

$$(J_t+J_m)\frac{d\,\Omega_{mec}}{dt}=C_{éol}-C_{em}-f_m\,\Omega_{mec} \tag{7}$$

With

$P_{éol}$: Aeolian power

λ : Relative turbine speed

Ω_{mec} : Rotation speed

v_v : wind speed

ρ : Air density

C_p : Power Coefficient

$C_{éol}$: Aeolian torque

J_t : Inertia of the turbine

J_m : Inertia of the machine

C_{em} : Electromagnetic torque

f_m : Viscous friction coefficient in the machine.

In order to extract the maximum power, despite the frequent variations of the wind speed, a servo-control of the rotation speed is used to maintain the maximum value of the power coefficient Cp which is the ratio of the extracted power over the maximum wind power. In order to do so, a speed regulator is used under the following conditions:

Maximum power coefficient $C_{pmax}=0.15$;

Maximum relative speed $\lambda_{opt}=0.78$;

The following graph Fig. 2. Shows the servo- control mechanism of the speed at the maximum power factor.

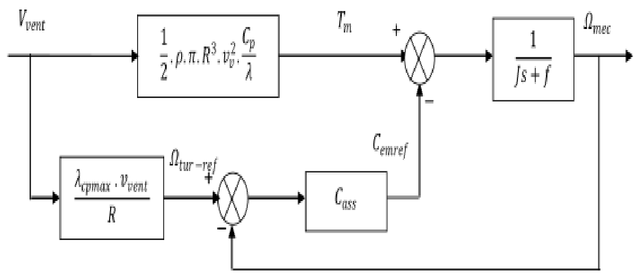

Fig. 2. Servo control mechanism of the rotor.

Being the main source of energy for the system operation, the wind provides aerodynamic torque Cm from which we subtract the electromagnetic torque created in the generator in order to get the mechanical torque giving the rotation speed. This calculated speed will be controlled by the speed corresponding to the maximum power coefficient .Then the electromagnetic torque reference is generated through a PI controller that acts on the difference between the reference speed and the rotational speed. The corresponding transfer function is given by the following equation (8):

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$$C_{em-ref}(s)=\left(k_i+\frac{k_p}{s}\right).(\Omega_{tur-ref}(s)-\Omega_{mec}(s)) \tag{8}$$

k_i : Integral Gain

k_p : Proportional Gain

The following graph Fig.. 3. Shows the speed regulation:

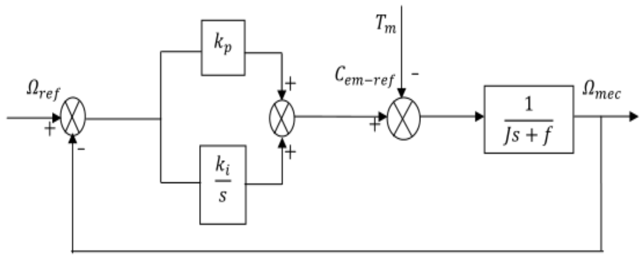

Fig. 3. Speed regulation.

$$\Omega_{mec}(s)=F(s).\Omega_{ref}(s)-P(s).T_m(s) \tag{9}$$

$$F(s)=\frac{k_p s+k_i}{Js^2+(f+k_p)s+k_i} \tag{10}$$

$$P(s)=\frac{s}{Js^2+(f+k_p)s+k_i} \tag{11}$$

$$\Omega_{mec}(s)=F(s).\Omega_{ref}(s) \tag{12}$$

$$k_i=\omega_n^2.J \tag{13}$$

$$k_p=2.\xi_n.\omega_n.J-f \tag{14}$$

C. Three- Phase Rectifier [8]

The Three-phase rectifier with double alternations uses six diodes (or thyristors for control). It rectifies a three phase source. The rectified signal has a frequency that is six times higher than the entry signal frequency. Fig. 4.

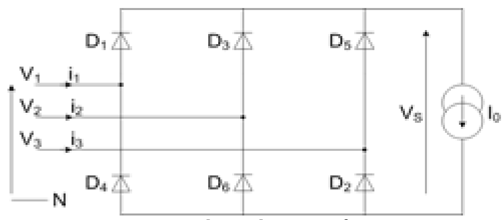

Fig. 4. Three phase rectifier.

Consider the Three-phase system:

- $V_1=V\sqrt{2}\sin(\omega t)$
- $V_2=V\sqrt{2}\sin(\omega t-\frac{2\pi}{3})$
- $V_3=V\sqrt{2}\sin(\omega t-\frac{4\pi}{3})$

If the period of the tensions is $T=\frac{2\pi}{\omega}$

Average value of the output tension is:

$$<V_s(t)>=\frac{1}{(\frac{T}{6})}\int_{\frac{-T}{12}}^{\frac{T}{12}}U_{13}(t)dt \tag{15}$$

$$U_{13}(t)=V\sqrt{3}\sqrt{2}\cos(\omega t) \tag{16}$$

$$<V_s(t)>=\frac{3\sqrt{3}\sqrt{2}}{\pi}V \tag{17}$$

D. Boost Chopper

The boost chopper Fig. 5. is a converter which transfers energy from a current source to a voltage source whose output voltage Us is greater than the input voltage Ue, hence the name of boost converter or booster converter (STEPUP converter). It is also called a "parallel" chopper (BOOST converter) because the controlled semiconductor output is delivered across the generator. The boost chopper is primarily used for DC / DC conversion.

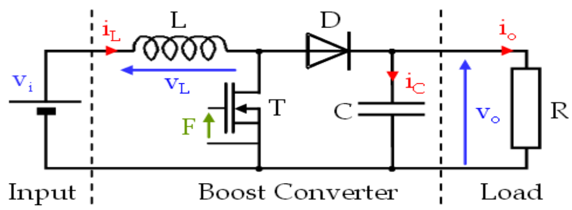

Fig. 5. Boost converter.

The strategy for controlling the power transmitted by the most common chopper is pulse width modulation (PWM). A control voltage Vm is compared with a triangular voltage Vt. The MOSFET is controlled by the difference between the voltages (Vm-Vt).

There are three modes of operation:

- K state ON and D state OFF
- K state OFF and D state ON
- K and D state OFF

The variation of the voltage across the inductance is given by (18):

$$v_L(t)=v_i(t).+(v_i(t)-v_0(t)).\bar{F}.sign(i_L) \tag{18}$$

With: v_i : input voltage

v_0 : charging voltage

F: Logical variable is equal to 1 only if *Vm* is superior or equal to *Vt*, 0 otherwise.

sign(i_L): Logical value 1 if i_L is positive, and 0 if i_L is null.

The variation of the current flowing in the capacitor depending on the mode of operation is given by:

$$i_C(t)=-i_0(t).F+i_L(t).\bar{F}.sign(i_L)$$

$$i_C(t)=C\frac{dv_o}{dt} \tag{19}$$

With i_0 : Charging current.

E. Filtering

- *Butterworth filter*

A Butterworth filter [15] is a type of linear filter, designed to have a gain as constant as possible in its bandwidth. In the breaking band its gain tends to 0. The Gain is:

$$G(w)=\frac{1}{\sqrt{1+\left(\frac{\omega}{\omega_c}\right)^{2n}}} \quad (20)$$

- *Bessel filter*

The Bessel filter, is a polynomial filter whose main characteristic is to offer a constant delay in bandwidth. Concretely, this means that all the pure frequencies, in band, cross it in a strictly equal time. The Bessel filter thus makes it possible to minimize the distortion that a complex signal undergoes during a filtering operation. The transfer function of the Bessel filter is a function whose denominator is a Bessel polynomial.

- *Chebychev filter*

Chebychev filters are a type of filter characterized by the acceptance of a ripple, either in pass band or in attenuated band. In the first case, we speak of Chebychev filters of type 1 or direct, in the second, filters of Chebychev type 2 or inverse. Filters that exhibit both undulating bandwidth and attenuated bandwidth are called elliptic filters.

There are two types of Chebychev filters and therefore two types of transfer functions for low-pass filters:
The most common type is type 1; Its gain is given by:

$$G(\omega)=\frac{H_0}{\sqrt{1+\varepsilon^2 C_n^2(\frac{\omega}{\omega_c})}} \quad (21)$$

With C_n (x): Polynomial of order n.

Type 2 inverted Chebychev is less common.

- *Elliptic filters*

Elliptic filters, also known as Cauer filters, are filters whose response is characterized by a ripple both in pass band and attenuated band.

In addition to poles, their transfer function has zeros. Its Gain is:

$$G(\omega)=\frac{1}{\sqrt{1+\varepsilon^2 R_N^2(\xi,\frac{\omega}{\omega_c})}} \quad (22)$$

R_N : Rational Chebychev function
N: filter order
ε : Ripple factor
ξ : Selectivity factor

V. SIMULATION

Simulation will be performed on the Simulink software. The purpose of this simulation is to compare different filters to determine the best possible filter.

The above Fig. 6 Shows the model on Simulink. The output of the wind turbine is connected to three-phase rectifier, then to chopper and inverter. 4 different filters will be tested to choose the one that will be the best for our case from the THD block, which allows to find the total harmonic distortion of each filter (less the THD is high, the more efficient the filter).

The output voltage of the wind turbine is modeled as the sum of fundamental voltage and several harmonics:

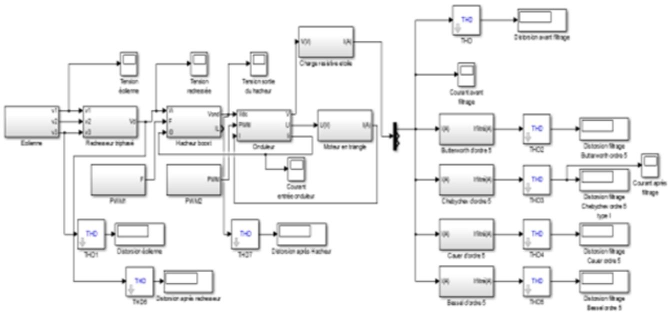

Fig. 6. Overall simulink model.

The wind turbine output voltage as observed is given in Fig. 7;

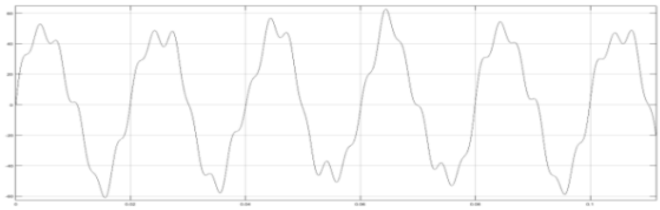

Fig. 7. One phase wind turbine output voltage.

It shows a total distortion rate of 17.66%. The rectifier output voltage is as follows Fig. 8. Its total distortion rate is of 567.9%.

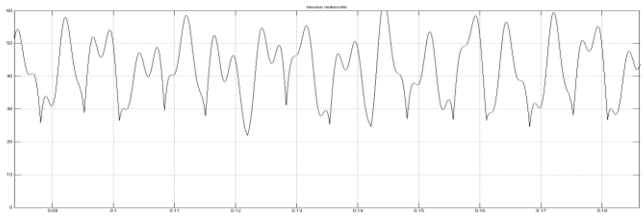

Fig. 8. The rectifier output voltage (V).

At the output of the booster chopper Fig. 9. The output voltage of the booster shows a distortion of 478.2%.

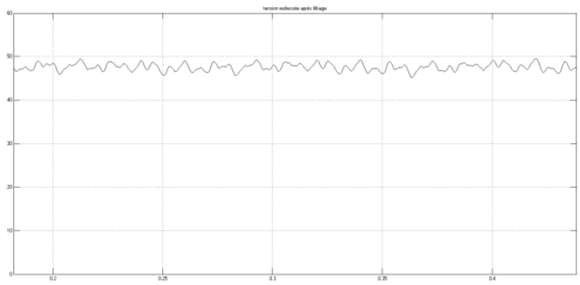

Fig. 9. Booster chopper voltage output (V)/time (s).

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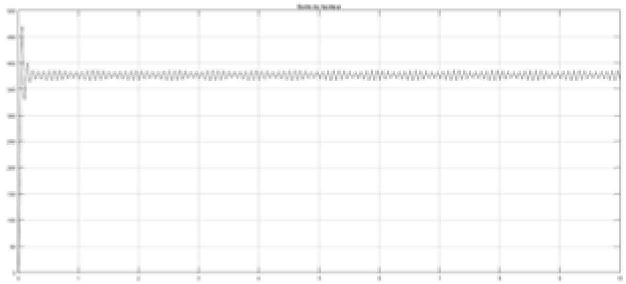

Fig. 10. Filtered output (V).

Since the output of the three-phase inverter has a high distortion rate 68%, filtering is required. The total harmonic distortion rate of the filtered signal for each filter is given in the following table:

TABLE I. Filters output.

Filter type	**Output signal distortion(THD)**
RLC	1,0534%
Butterworth	0, 8286%
Chebychev type I	0,3352%
Bessel	0,9027%
Cauer	0, 6457%

Chebychev type I filter is the most efficient, and its distortion 0.3352 % is less than the harmonic distortion rate acceptable according to the norms 1.6%.

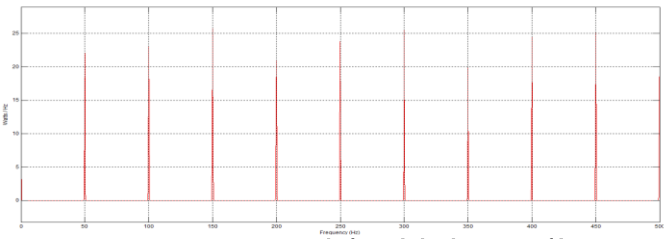

Fig. 11. Output current spectrum before Chebychev type 1 filtering.

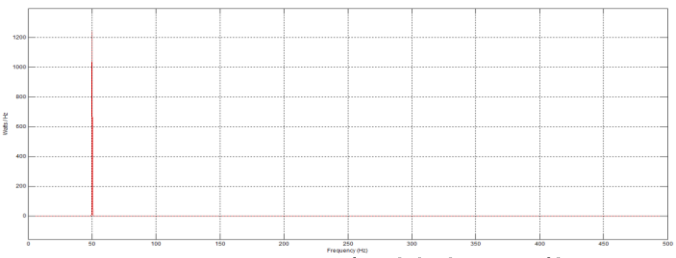

Fig. 12. Output current spectrum after Chebychev type 1 filtering.

Fig. 11, 12 shows the Chebychev filtered output current spectrum where the harmonics have disappeared for high frequencies.

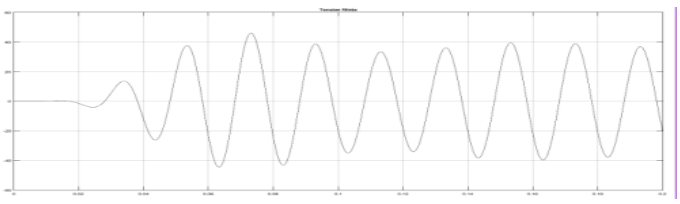

Fig. 13. Chebychev filtered inverter output voltage (V)/time (s).

VI. Conclusion

The system as described above is divided in two sections, one concerning the modeling of the wind turbine by modules in order to connect it to the electrical .The next section will be the filtering module.

Static converters are the main causes of harmonics, this in addition to wind speed. Irregularities and instability leads to an inefficient system to output tension to the electrical network. To overcome those problems several controls were introduced:

Control of the synchronous machine, control of active and reactive power delivered to the electrical network as well as control loops that will control the MLI commands of the chopper and inverter. Proportional and integral correctors will be used.

The second section is about the filtering, and the Chebychev filtering is very efficient. The Chebychev filter is best suited to the system. It reduces the total harmonic distortion rate to chopper and inverter. Proportional and integral correctors will be used. The second section is about the filtering, and the Chebychev filtering is very efficient. The Chebychev filter is best suited to the system. It reduces the total harmonic distortion rate to 0.3%. The total harmonic distortion rate is within the limit of standard norms (<1.6%). it can be concluded that the control of the power injected by the wind turbine will allow the practical implementation of the system enabling the injection of the produced power in the electrical network and the storage of this energy in batteries.

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