# HARMONIC FILTERING AND POWER GENERATION USING A SYNCHRONOUS MACHINE FOR WIND POWER APPLICATIONS

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***Abstract****- The aim of this paper is to present a new integrated control system of the total active and reactive power which is generated by the wind synchronous generator and the cancellation of the harmonics created by the non linear load connected to the grid. This technique can be used to cancel the harmonics current of the nonlinear load with the injection of his image in rotor field circuit. The synchronous generator is connected in a shunt manner between the non-linear load and the grid. Analysis and simulation results are presented to demonstrate the effectiveness of the proposed technique.*

***Key words:*** *Active power filter, Synchronous Generator, Wind power, PWM rectifier,*

## 1. Introduction

People have used wind turbines to pump water and mill grain, along with many other uses can be traced back approximately 4000 years, there has been a renewed interest in the subject in recent years. One important aspect of wind turbine applications, especially in an industrial environment, is that wind turbines generate electricity without creating pollution. Since the second half of the 1980's, a higher research effort has been devoted to Wind Energy Conversion Systems (WECSs), because of the increasingly world interest for achieving a sustainable development by using renewable energies [9-13]. It is predicted that by 2020 up to 12% of the world's electricity will be supplied by wind power. Many countries are targeting increases in the amount of electrical energy produced by renewable energy sources. But even if it is a clean source and it is zero fuel cost, there are some problems when trying to connect this kind of distributed generation to the electric grid. A standard wind energy converter of today has a constant turbine speed of 30 to 50 rpm and uses a gearbox and four or six pole synchronous generator, directly grid connected. This concept is very simple and reliable and it can be made of standard components [12].

Synchronous generators (SG) have been widely used as hydro-generators, engine generators, wind generators, and so forth to transform mechanical into electrical energy at a much defined frequency, (SG) is an ac rotating machine whose speed under steady state condition is proportional to the frequency of the current in its armature [14-16]. The magnetic field created by the armature currents rotates at the same speed as that created by the field current on the rotor, which is rotating at the synchronous speed, and a steady torque results. Since the reactive power generated by a synchronous machine can be adjusted by controlling the magnitude of the rotor field current, unloaded synchronous machines are also often installed in power systems solely for power factor correction or for control of reactive kVA flow. There are two types of rotor structures: round or cylindrical rotor and salient pole rotor.

The use of power electronics-based equipment in high-voltage power transmission and in low-voltage distribution has increased steadily. Notwithstanding their great many operational benefits, they also have increased the risk of introducing harmonic distortion in the power system because several of these devices achieve their main operating state at the expense of generating harmonic current. The non-linear currents drawn by the rectifiers are rich in harmonics with the order of 6k±1, that is 5, 7, 11, 13, etc. consist of harmonics of the line frequency and reactive components that distort the line voltage of the distribution system due to the impedance of the distribution lines. In three-phase systems, the non-linear currents can lead to voltage unbalance and excessive currents in the neutral line, which is not designed to carry large currents. The result is harmonic pollution that degrades the power quality [1-3].

The prevalent method for removing harmonic currents produced by non-linear loads has been to use shunt passive filters placed near the loads. There are several problems associated with this type of filter. One major problem is due to the low source impedance of utility systems; the filter impedance must be low compared to the source impedance at the harmonic frequency [23, 26].

The shunt active power filter is controlled to draw harmonic currents from the source to compensate for the harmonic currents drawn by nonlinear loads. The active filter can also be connected in series with the power lines. The series active filter injects correcting voltages to the power lines through a matching transformer [26].

Many papers proposed a method to absorb the power line harmonics by using a synchronous generator and can be applicable either to active system or to passive one. In [1] Fuyuta T and all, the field winding are self-excited passively by resonant capacitors without controller. T. Abolhassani and all [2] propose an electromechanical active filter to cancel the most dominant harmonics generated by nonlinear loads. Specifically, $5^{th}$ and $7^{th}$ harmonics are suppressed and $11^{th}$ and $13^{th}$ harmonics are significantly reduced. In [4] P. Poure and all, and [5], [6] T. Abolhassani, give a study of grid's harmonics filtering using a double fed induction generator.

In this paper, the synchronous generator is used to improve the power quality of the grid utility lines by compensating and cancelling the current harmonics caused by the nonlinear loads injecting an appropriate current in the field winding. The proposed solution allows also the power factor correction and reactive power control. Simulations are curried out to validate the theoretical analysis.

## 2. Wind turbine modeling

With the advancement of aerodynamic designs, the kinetic energy of moving air molecules may be converted to rotational energy by the rotor of a wind turbine, which in turn may be converted to electrical energy by the wind turbine generator. The optimal mechanical power obtained from a given wind speed is commonly expressed by the following equation [1, 2, 13]:

$$p_m = \frac{1}{2}\rho C_p A V^3 \tag{1}$$

Being $C_p(\lambda,\beta)$ the optimal power coefficient of the wind turbine for a given wind speed, $A$ ($m^2$) the effective area covered by the turbine blades, $V$ (m/s) the wind speed and $\rho$ ($Kg/m^3$) is air density.
The tip-speed ratio of a turbine is given by:

$$\lambda = \frac{R_m w}{V} \tag{2}$$

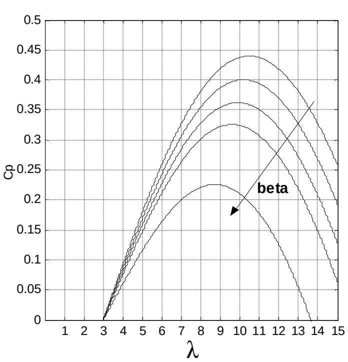


Fig.1. $C_p$ characteristic of wind turbine

Where, $R_m$ the turbine-rotor radius in metres; and $w$ is the rotor speed in radians per second, $\beta$ is the pitch blade inclination.
The calculation of the optimal power coefficient $C_p$ can be obtained from the following function:

$$C_p = (0.44 - 0.0167\beta)\sin\left[\frac{\pi(\lambda-3)}{15-0.3\beta}\right] - 0.0184(\lambda-3)\beta. \tag{3}$$

The power output of a wind turbine is proportional to the cube of the wind speed. Its theoretical limit is 59.3% of the wind power input.

## 3. Synchronous generator model

The model commonly used for the synchronous generator is the Park's model [15]. To simplify the study, the rotor variables will be referred to as the stator. Although a synchronous rotating reference frame is often used, a static stator oriented reference frame is more suitable for the purpose of this paper. Linear magnetic circuits and no damper windings are assumed Fig.2. Using the motor convention, the Park's model can be expressed as [1-3, 15, 20]:

- Stator equations:

$$V_d = R_s i_d - w_s L_q i_q + \frac{d}{dt}(L_d i_d + M_{fd} i_f) \tag{3}$$

$$V_q = R_s i_q + w_s (L_d i_d + M_{fd} i_f) + \frac{d}{dt} L_q i_q \tag{4}$$

- Rotor equation:

$$V_f = R_f i_f + \frac{d}{dt}(M_{fd} i_d + L_f i_f) \tag{5}$$

With $v$ being the voltage, $i$ the current, $R$ the resistance, and $\square_s$ the rotor electrical speed. The subscripts $s$ and $f$ indicate stator and rotor quantities. In a wind turbine, the stator is directly connected to the grid, which means that the stator voltage $vs$ is determined by the grid. The rotor voltage $vf$ is controlled by a converter and used to perform the machine control.

$Ldq$ and $Lf$ are the stator and rotor inductance, respectively. $Mfd$ is the magnetizing inductance. Fig. 3 shows the equivalent electrical circuit corresponding to the previous equations. The rotor voltage is one of the most important variables for the converter.

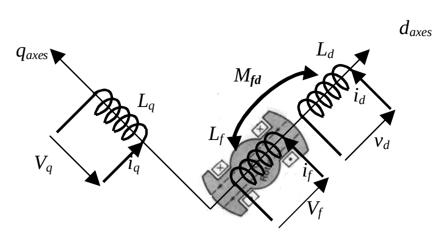


Fig.2. Equivalent electrical circuit in dq coordinate

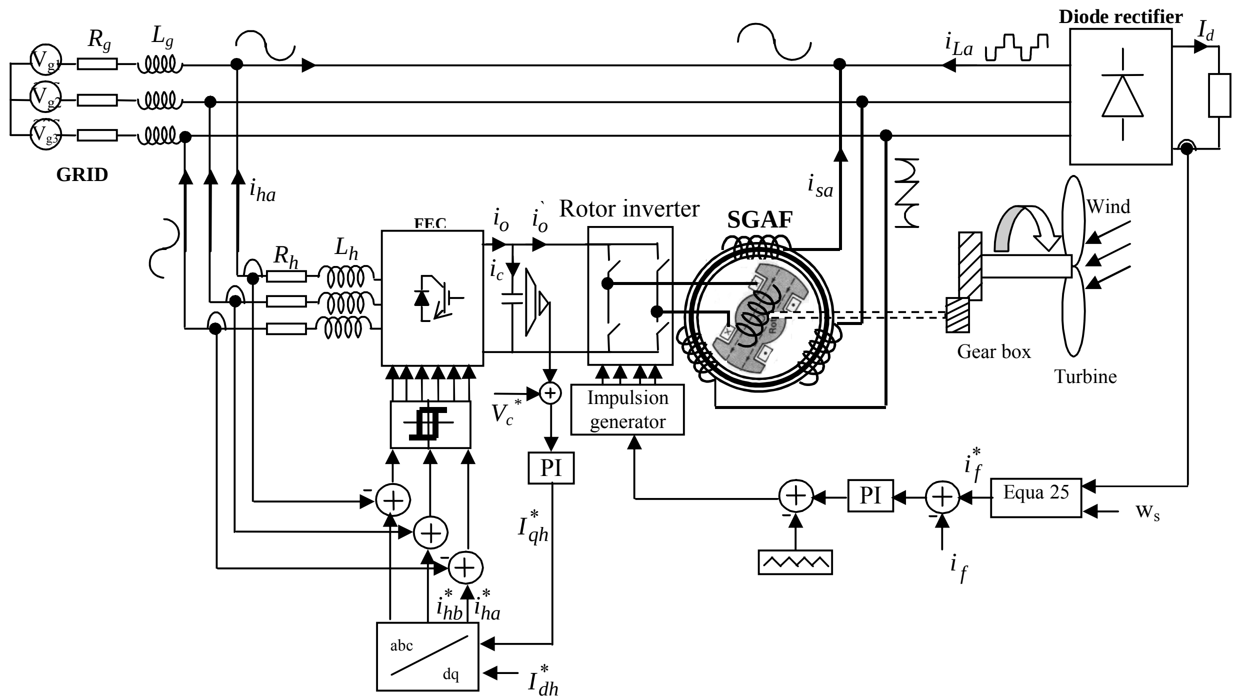


Fig.3. Block diagram of the proposed method.

In order to present the generator equations in the standard state space form, it is necessary to solve them for the state derivatives and collect the input and state variables into matrixes. The three equations (3), (4), (5) containing the state derivatives may be represented as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \quad (6)$$

This system of first order differential equations is known as the state equations of (6); *x(t)* is the state vector and *u(t)* is the input vector. The second equation is referred to as the output equation.

*A* is called the state matrix, *B* the input matrix, *C* the output matrix and *D* the direct transition matrix.

where :

$$B = inv[A1] \quad (7)$$

$$A = -[B][B1] \quad (8)$$

and :

$$[B1] = \begin{bmatrix} R_s & -w_s L_q & 0 \\ w_s L_d & R_s & 0 \\ 0 & 0 & R_f \end{bmatrix} \quad (9)$$

$$[A1] = \begin{bmatrix} L_d & 0 & M_{fd} \\ 0 & L_q & 0 \\ M_{fd} & 0 & L_f \end{bmatrix} \quad (10)$$

The electromechanical torque is given by:

$$C_{em} = \frac{3}{2} P[(L_d - L_q) i_d i_q + \phi_f i_q] \quad (11)$$

The flux linkages are expressed as:

$$\phi_f = L_f i_f + M_{fd} i_d \quad (12)$$

$$\phi_d = L_d i_d + M_{fd} i_f \quad (13)$$

$$\phi_q = L_q i_q \quad (14)$$

Assuming that the stator resistance is negligible compared with the magnetizing reactance and also that the stator flux vector has a constant magnitude and rotates at a constant angular speed equal to the supply frequency, and alginate stator vector flux with the d axis, we can write:

$$\phi_d = \phi_s \quad (15)$$

$$\phi_q = 0 \quad (16)$$

This yields:

$$V_d = 0 \quad (17)$$

$$V_q = w_s \phi_s \quad (18)$$

From Eq. 4., the reference rotor current can be computed as:

$$i_f^* = \frac{1}{M_{fd}} \left( \frac{V_q}{w_s} - L_d i_d^* \right) \quad (19)$$

with :

$$i_d^* = \frac{P^*}{V_d} \quad (20)$$

and $P^*$ is the active power active on stator side connected to the grid.

From Eqs. 13 and 15, the rotor voltage can be rewritten as:

$$V_f = R_f i_f + (L_f - \frac{M_{fd}^2}{L_d})\frac{d}{dt} i_f \qquad (21)$$

## 4. Description of the proposed method

Synchronous generators active filters SGAF can be used to reduce harmonics generated by non-linear industrial loads. Usually the control circuit of the SGAF detects the non-linear load harmonics and controls the rotor field circuit to inject the compensating harmonic in stator windings with an opposite phase.

The complex vector of the reference current $i_d^*$ in the stationary reference frame is given by:

$$i_d^* = I_1^{ref} e^{j(wt-\phi_1^{ref})} + \sum_m I_m^{ref} e^{j(mwt-\phi_m^{ref})} \qquad (22)$$

With:

$$m = 1 \pm 6k,\ k = 1,2,3,... \qquad (23)$$

The control structure detects the amplitude and phase of $m = 1 \pm 6k$ harmonics; it performs the required excitation current and regulates it to cancel completely the $m = 1 \pm 6k$ harmonics components present in the nonlinear load current. A PWM inverter generates the required excitation current.

Eq. 22. can be rewritten as:

$$i_d^* = \sum_{k=1}^{\infty} \sqrt{2} i_{6k-1} \sin[(6k-1)(w_s t - \varphi_{6k-1})] + \sqrt{2} i_{6k+1} \sin[(6k+1)(w_s t - \varphi_{6k+1})] \qquad (24)$$

The harmonics current image in the rotor is:

$$i_{d1}^* = \sum_{k=1}^{\infty} \sqrt{2} i_{6k-1} \sin[(6k-2)(w_s t - \varphi_{6k-1})] + \sqrt{2} i_{6k+1} \sin[(6k)(w_s t - \varphi_{6k+1})] \qquad (25)$$

where:

$$\sqrt{2} i_{6k-1} = (-1)^k (\frac{I_d}{6k-1}) \qquad (26)$$

$$\sqrt{2} i_{6k+1} = (-1)^k (\frac{I_d}{6k+1})$$

Finally the current injected in the rotor circuit by inverter to compensate harmonics generated by non linear load in the grid can be given by:

$$i_f^* = \frac{1}{M_{fd}} (\frac{V_q}{w_s} - L_d i_{d1}^*) \qquad (27)$$

Fig. 3 shows the general structure of the SGAF for non linear load.

## 5. Regulator syntheses

From Eq.21. the transfer function of rotor became:

$$RF = \frac{1}{R_f + (L_f - \frac{M_{fd}^2}{L_d}) p} \qquad (28)$$

In order to eliminate the zero present in the transfer functions see Fig.5.

$$\frac{K_p}{K_i} = \frac{1}{R_f} (L_f - \frac{M_{fd}^2}{L_d}) \qquad (29)$$

The transfer function in closed loop is:

$$Tf = \frac{1}{1 + \frac{R_f}{K_i} p} \qquad (30)$$

and the system time constant is:

$$\tau = \frac{R_f}{K_i} \qquad (31)$$

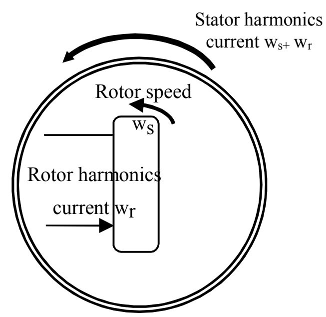


Fig.4. Frequency relation between stator/rotor currents

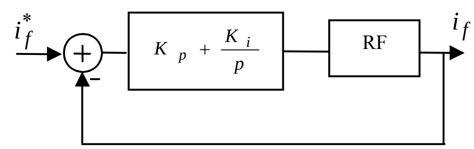


Fig.5. Schema bloc of regulation system

## 6. Front end converter control

The PWM rectifier provides front-end three-phase-to-dc power conversion from the grid or electric generator to the dc bus. The rectifier operates with unity power factor and draws sinusoidal currents from the three-phase source. When the output current reverses its direction, the boost rectifier reverses the power flow through it and operates as a voltage source inverter.

By averaging the switching action of the semiconductor switches and applying the *dq* transformation to the resulting average model, a large signal average model in *dq* coordinates is obtained. The equivalent circuit is shown in Figure 1 and described by equations [32]:

$$
\begin{aligned}
\frac{di_{dh}}{dt} &= \frac{1}{3L_g}\left(V_{gd} + 3\omega L i_{qh} - d_{dh}V_o\right)\\
\frac{di_{qh}}{dt} &= \frac{1}{3L_g}\left(V_{gq} - 3\omega L i_{dh} - d_{qh}V_o\right)\\
\frac{dV_c}{dt} &= \frac{1}{C}\left(\frac{3}{2}\left(d_{dh}i_{dh} + d_{qh}i_{qh}\right) - i_o\right)\\
V_o &= V_c + R_c\left(\frac{3}{2}\left(d_{dh}i_{dh} + d_{qh}i_{qh}\right) - i_o\right)
\end{aligned} \tag{32}
$$

With $L = L_g + L_h$ and $R = R_g + R_h$

the current $i_o$ is given by:

$$i_o = \frac{3}{2}(d_{dh}i_{dh} + d_{qh}i_{qh}) \tag{33}$$

where

$i_h$ grid inverter current

So, the current $i_o$ is given by:

$$i_o = S_1 i_{af} + S_2 i_{bf} + S_3 i_{cf} \;\&\; i_o^{`} = S_1^{`} i_f \tag{34}$$

$S^{`}$ Rotor inverter switch

$S$ Grid inverter switch

## 7. Simulation results

### *Case1: Synchronous generator like an active power filter*

The shunt active filter/synchronous generator (SGAF) is controlled to mitigate both current harmonics and reactive power. This way, it is expected that the source current becomes sinusoidal and also, in phase with the fundamental source voltage. Diode rectifier has been connected to the utility and draws a non-linear load current where phase (A) current is shown on Fig. 6 (*ila*).

In this case, we applied a new SGAF command strategy for the operation mode in active filtering; it is observed that the current after filtering is sinusoidal with the harmonics inherent in commutations of the inverter (*isa*). We note that the SGAF eliminates well the harmonic components low frequency corresponding to the quench frequency from the inverter is far from the area of interest. The load current is that consumed by a diodes bridge, having a strong inductive load. It can be approximated by a square signal of which we consider only the first 100 harmonics (*ila*). Figure 6 describe the action of the SGAF filter on the grid current. The spectrum analysis of the grid current (*isa)* and the nonlinear current (*ila*) figure 7.a and 7.b shows a strong attenuation of the harmonics components while that of the fundamental component remain unchanged. The Total harmonics distortion (THD), reduced of 31% at roughly 3,8%.

Table I summarizes the supply current THD and the ratio of each harmonic current with respect to the fundamental current. The THD value is calculated for harmonics up to the 31st order. The THD of the nonlinear load current (*ila*) reached 30.9% because it contains a large amount of the 5th and 7th harmonics current.

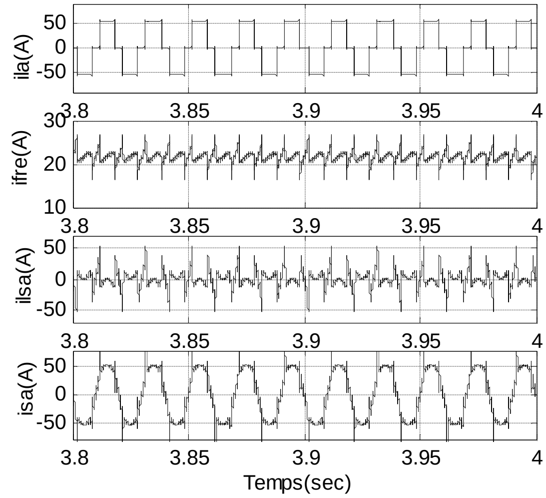


Fig. 6: Performance of the proposed Synchronous generator/Active filter

Dynamic compensation of a three phase diode rectifier. Traces from top to bottom (phase A): ***(ila) Waveform Current of Nonlinear Load. (ifre) Rotor current with reference. (ilsa) Current of Synchronous Generator (Harmonic current). (isa) Current of Utility.***

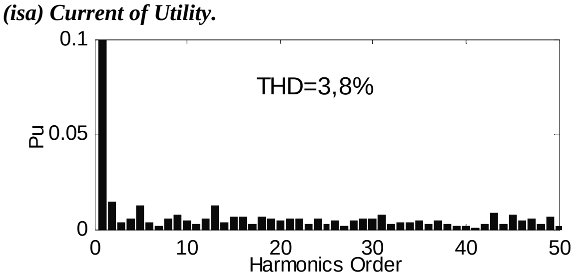


Fig7.a. load current harmonic spectrum after filtering

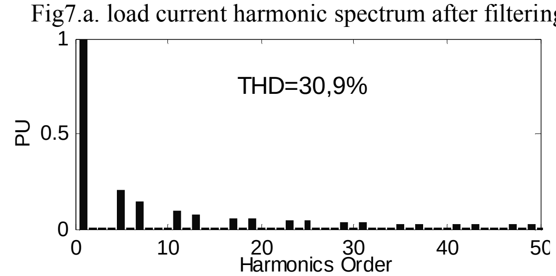


Fig7.b. current harmonic spectrum before filtering

***Case2: SG generated only active and reactive power***

Different kind of tests has been done to analyse the performance of the system. To maintain the power factor at unity, the grid reactive power (Q) is fixed to zero.

The results simulation are obtained for reactive power (Q=0), and active power P=7Kw and a step to 16Kw at time t=3.5sec, Fig.8. Show the active and reactive power generated by the SG, electromagnetic torque, and finally the good response of the stator and rotor currents for this step.

Table 1
Supply Current THD And Harmonics Before And After Starting The Filtering Expressed As The Harmonic-To-Fundamental Current Ratio[%]

| | $2^{nd}$ | $5^{th}$ | $7^{th}$ | $11^{th}$ | $13^{th}$ | $17^{th}$ | $19^{th}$ | $29^{th}$ | 31th | THD |
|---|---|---|---|---|---|---|---|---|---|---|
| Before% | 0.0 | 20.0 | 14.0 | 9.0 | 7.0 | 5.5 | 5.0 | 3.5 | 3.2 | 30.9 |
| After% | 0.15 | 0.13 | 0.07 | 0.07 | 0.15 | 0.06 | 0.06 | 0.08 | 0.1 | 3.8 |

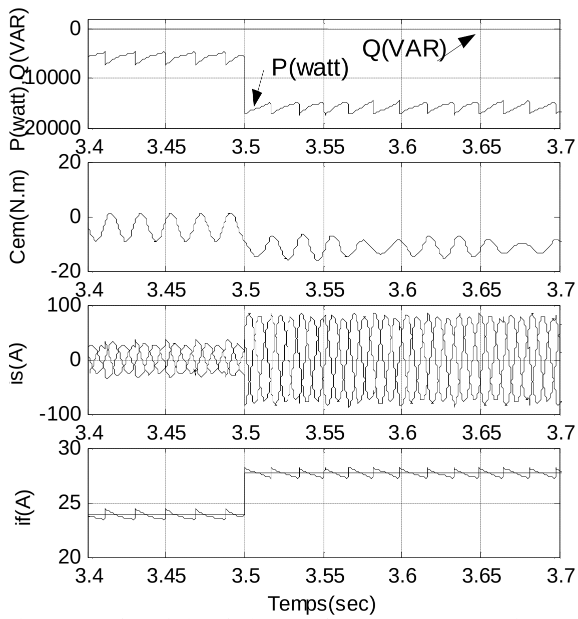

Fig.8. Results of simulation study. SG generate active and reactive power

***(P,Q) Stator Active and reactive power. (Cem) Torque developed by the SG. (is) Stator currents. (if) Rotor current with reference***

### *Case3: SG like an active power filter and both*

In this case we study the power generation, reactive power compensation and harmonic cancellation features are activated. We applied an active power variation of a step equal to 16Kw at t=3.5s with the wind speed constant. The performances of active filtering capability of the SGAF for the compensation of all harmonic currents can be seen on fig.9 and fig.10.

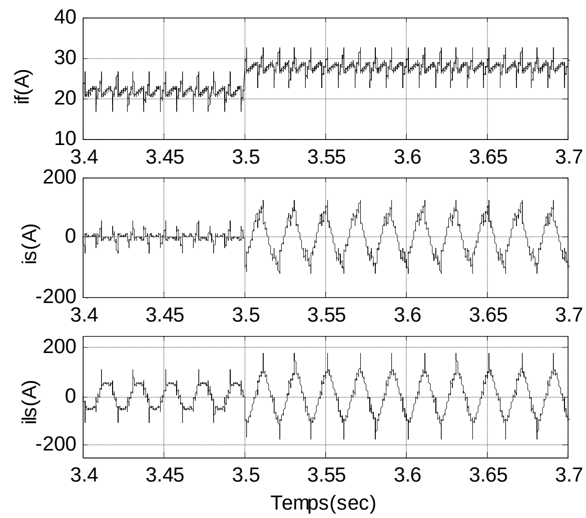

Fig. 9: Results of simulation study. SG generates active and reactive power and cancelled harmonics

***(ifre) Rotor current. (Is) Stator currents. (ils) Current of utility.***

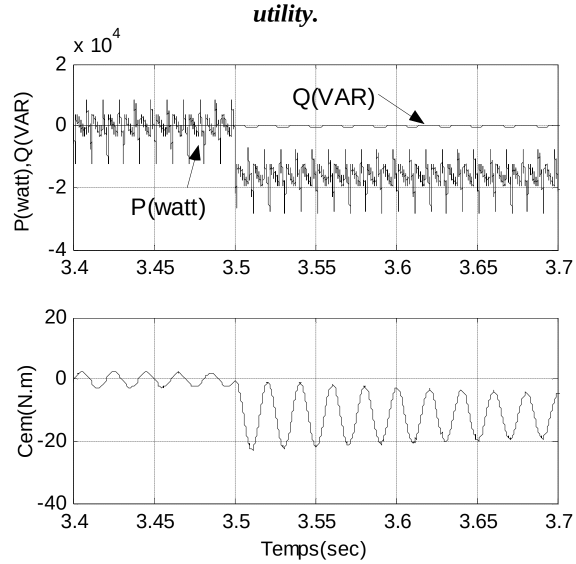

Fig.10. (P,Q) Active and Reactive power in stator. (Cem) torque developed by the machine

## 8. Conclusion

Procedure or regulations for harmonic improvement are necessary and would be efficient in overcoming `harmonic pollution`. Clients pay for the price of high effectiveness, energy savings, high performances, reliability and compactness brought by power electronic technology. But they are reluctant to pay for the cost of suppressing or removing the current pollution generated by non linear load unless guidelines or regulation are enacted. It is accepted that the continuous efforts of power electronics and electromechanical generator researchers will achieve significant development of advanced active power filtering

This paper has provided an advanced solution for eliminating the harmonics current generated by nonlinear load by applying a synchronous generator field oriented control/active filtering for grid connected. With the proposed method, it is possible to capture the maximum wind power while harmonics currents of the utility can simultaneously be compensated.

By using this active power filtering technique with SGAF, there is no need for the harmonic current separator, low and high filters, also we avoid going through estimations.

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