Control of a Grid-Connected Synchronous Generator WECS and Harmonic Current Filtering

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*Abstrac*t_: **Nonlinear devices, such as power electronics converters inject harmonic currents in the AC system and increase overall reactive power demanded by the equivalent load. Also, the number of sensitive loads that require ideal sinusoidal supply voltages for their proper operation has increased. In order to keep power quality under limits proposed by standards, it is necessary to include some sort of compensation. Different types of power quality compensators of higher or lower complexity have been reported. It is now well known that an active filter can easily compensate the harmonic current contents in the load current by inserting negative harmonics into the power network.**

The aim of this paper is to present the efficiency of the electrical part of a wind generation system with a synchronous generator. In attempt to minimize the commutation frequency harmonics in the current and voltage in the stator and to avoid the overlap phenomenon in the diode bridge, an LC filter is inserted between the excited circuit and the DC-DC converter. Simulation results are curried out to validate the proposed solution.

Key words: Synchronous generator, Wind power, Active power filter, LC filter, Power compensation.

I. INTRODUCTION

The increase rate of depletion of fossil energy resources in one hand and growing energy demand on the other hand has initiated considerable research activity worldwide to explore means for tapping of renewable energy resources. Many different concepts have been developed and tested over years. Activities in this field were encouraged by the oil crisis in 1973. Much of the growth in wind-produced energy is due to the development of more efficient turbines and making wind power competitive with other energy sources; because of its free availability and its clean and renewable character. **W**ind energy conversion systems provide cost-effective and reliable energy in many places in the world. During the last two decades, the production of wind turbines has grown in size from 20kW to 2MW[2,4,10,11,12].

Nonlinear devices, like power electronics converters, inject harmonic currents in the AC system and increase overall reactive power demanded by the equivalent load. Also, the number of sensitive loads that require ideal sinusoidal supply voltages for their proper operation has increased. In order to keep power quality under limits proposed by standards, it is necessary to include some sort of compensation [1,6].

Active power filters are gaining more popularity due to their ability of handling higher switching frequencies by using faster power switches. One of the active power filters, the shunt active filter has been researched and developed, and it has gradually been recognized as a feasible solution to the problems created by nonlinear loads. It is used to eliminate the unwanted harmonics and compensate fundamental reactive power consumed by nonlinear loads with injecting the compensation currents into the AC lines [6,7].

A new technique was launched by P. Poure & all [9] and developed with Abolhassani & all [10],[11] integrated doubly fed electric generator instead of the active filter (IDEA) for variable speed wind energy conversion systems, also at the same author [12] the proposed approach consists of a synchronous generator with modification to its field excitation. It is shown that, by injecting 2^{nd}, 4^{th} and 6^{th} harmonic currents into the field, a standard synchronous generator can be modified to generate 5^{th} and 7^{th} harmonics in the stator winding connected to the electric utility. But this technique creates strong torque ripples due to the harmonic currents and the disappearance of the current harmonics compensation in the absence of the wind.

In response to these concerns, this paper presents the analysis, control and simulation validation of a vector controlled constant speed SG supplying a grid connected. The inverter side grid has multiple functions, eliminated harmonic currents, store energy in SS (Fig.1) and provide the power in the rotor. An LC filter implanted between the rotor and the DC-DC converter to eliminate the commutation frequency harmonics in the current and voltage in the stator, to avoid the overlap phenomenon in the diode bridge, and ensure a good pace of current. In addition the absence of torque ripple and the continuity harmonic current filtering in wind absence, and generate power to the grid if nonlinear load arrest or both.

II. WIND TURBINE MODEL

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque. The power output, *P*, from a wind turbine is given by the well-known expression:

$$P_w = 0.5\rho\pi r^2 v^3 \quad (1)$$

$$P_T = P_w C_p \quad (2)$$

$$C_p = f(\lambda) \quad (3)$$

$$C_p = (0.44 - 0.0167\beta)\sin\left[\frac{\pi(\lambda-3)}{15-0.3\beta}\right] - 0.0184(\lambda-3)\beta. \quad (4)$$

$$\lambda = \frac{wr}{v} \quad (5)$$

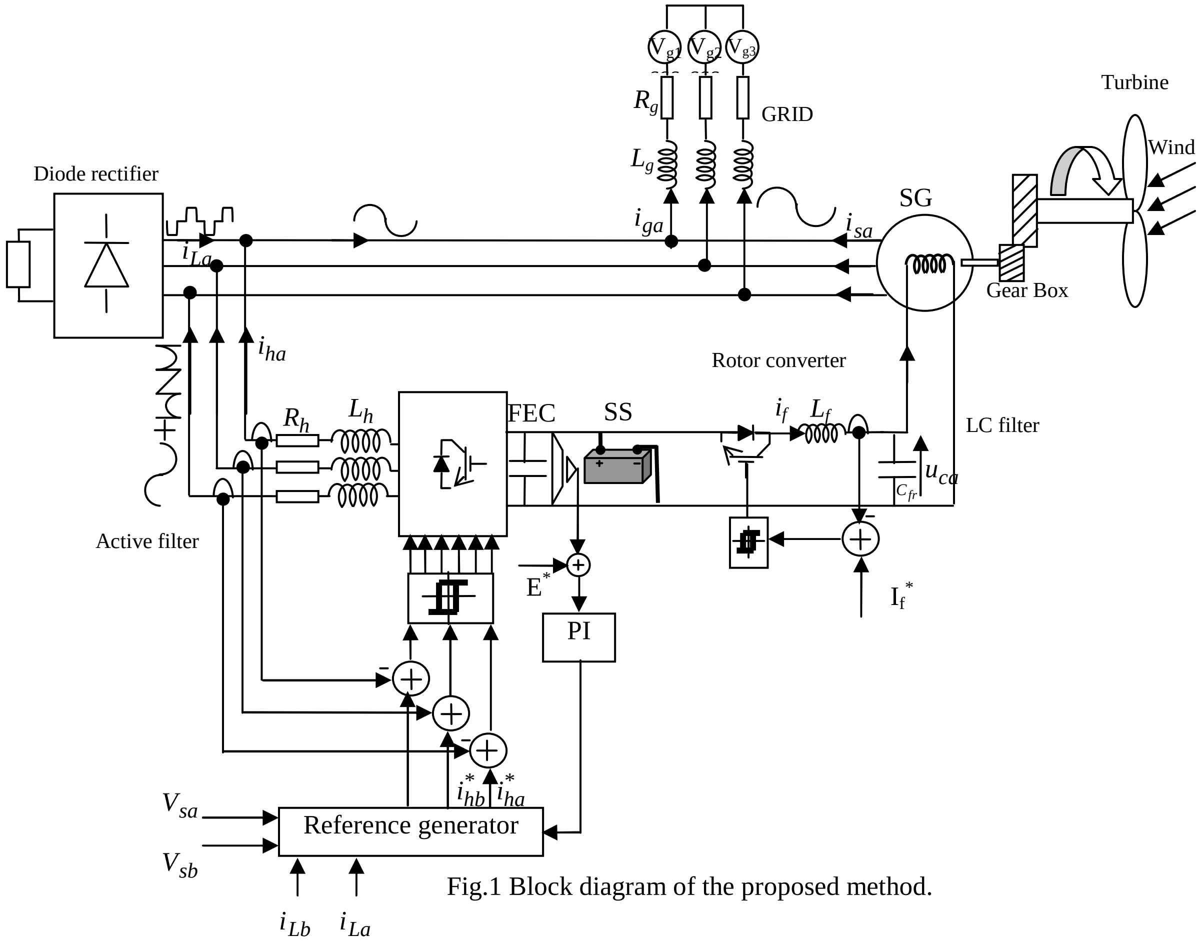

Fig.1 Block diagram of the proposed method.

Where P_w and P_T are wind power and mechanical power respectively, ρ is the density of air (*1,225 kg.m3*), C_P is the power coefficient, and v is the wind speed. λ the tip-speed ratio (rotor blade tip speed divided by the wind speed); and β is the blade pitch angle. The power extracted from the wind is maximized if the rotor speed is such that Cp is maximum, which occurs for a determined tip speed ratio.

The mechanical torque produced by the blades is given by

$$T_m = \frac{1}{2}\pi.\rho.C_p(\beta,\lambda).r^3 v^2 \qquad (6)$$

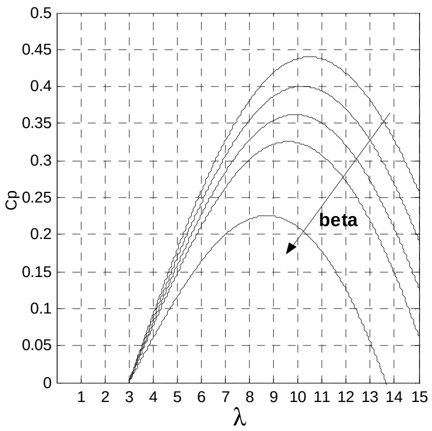

Fig.2 C_p characteristics of wind turbine

III. Machine Model Description

The structure of the synchronous machine model used in this study in a synchronously rotating *d–q* reference frame is given by the state space representation:

$$[\dot{I}] = [L]^{-1}[V] - [L]^{-1}[R][I] \qquad (7)$$

Where:

$$[I] = \begin{bmatrix} i_d \\ i_q \\ i_{fd} \\ i_{DK} \\ i_{Qk} \end{bmatrix} \qquad (8)$$

$$[V] = \begin{bmatrix} v_d \\ v_q \\ v_{fd} \\ 0 \\ 0 \end{bmatrix} \qquad (9)$$

$$[L] = \begin{bmatrix} -(L_{ls}+L_{md}) & 0 & L_{md} & L_{md} & 0 \\ 0 & -(L_{ls}+L_{mq}) & 0 & 0 & L_{mq} \\ -L_{md} & 0 & (L_{lfd}+L_{md}) & L_{md} & 0 \\ -L_{md} & 0 & L_{md} & (L_{lKd}+L_{md}) & 0 \\ 0 & -L_{mq} & 0 & 0 & (L_{lKq}+L_{mq}) \end{bmatrix} \qquad (10)$$

$$[R]=\begin{bmatrix} -Rs & w(L_{ls}+L_{mq}) & 0 & 0 & -wL_{mq} \\ -w(L_{ls}+L_{md}) & -R_s & wL_{md} & wL_{md} & 0 \\ 0 & 0 & R_{fd} & 0 & 0 \\ 0 & 0 & 0 & R_{Kd} & 0 \\ 0 & 0 & 0 & 0 & R_{Kq} \end{bmatrix} \quad (11)$$

Parameters and variables in the above equations have the following meanings:

w: rotor speed;
v_d: armature d axis terminal voltage;
v_q: armature q axis terminal voltage;
i_d: armature d axis terminal current;
i_q: armature q axis terminal current;
v_{fd}: field winding terminal voltage;
i_{fd}: field winding terminal current;
i_{kd}: d axis damper winding current;
i_{kq}: q axis damper winding current;
Φ_d: total armature flux in d axis;
Φ_q: total armature flux in q axis;
R_s: armature phase resistance;
L_{ls}: armature phase leakage inductance;
L_{md}: d axis coupling inductance;
R_{fd}: field winding resistance;
L_{lfd}: field winding leakage inductance;
R_{kd}: d axis damper wining resistance;
L_{lkd}: d axis damper winding leakage inductance;
L_{mq}: q axis coupling inductance;
R_{kq}: q axis damper winding resistance;
L_{lkq}: q axis damper winding leakage inductance.

where the inductance and mutual inductance are:

$$L_d = L_{ls} + L_{md}, \; L_q = L_{ls} + L_{mq},$$
$$L_f = L_{lfd} + L_{md}, \; L_D = L_{lKd} + L_{md}, \; L_Q = L_{lKq} + L_{mq},$$
$$M_{fD} = L_{md}, \; M_{dD} = L_{md}, \; M_{qQ} = L_{mq}$$

If the machine has not damper windings, the flux linkages and the electromechanical torque are given by:

$$C_{em} = \frac{3}{2}P[(L_d - L_q)i_d i_q + \phi_f i_q] \quad (12)$$
$$\phi_f = L_f i_f + M_{fd} i_d \quad (13)$$
$$\phi_d = L_d i_d + M_{fd} i_f \quad (14)$$
$$\phi_q = L_q i_q \quad (15)$$

If the flux vector is aligned with the d-axis in the synchronously rotating reference frame, then $\Phi_q = 0$, v_d=0 and the field rotor currents attracted the reference rotor current per following equation:

$$i_f^* = \frac{1}{M_{fd}}\left(\frac{V_q}{w_s} - L_d i_d^*\right) \quad (16)$$

IV. THE SECOND ORDER LC FILTER MODEL

The conversion system including the LC filter is shown in Fig. 3, where i_r and i_f are the input and output filter currents respectively, u_c is the capacitor filter voltage. The general state space model of the second order LC filter is given by [6]:

$$\dot{x} = Ax + Bu + Dv \quad (17)$$

where:

$$x = \begin{bmatrix} i_f & i_r & u_c \end{bmatrix}^t, \; v = \begin{bmatrix} u_c & 0 & 0 \end{bmatrix}^t; \; A = \begin{bmatrix} -\frac{R_f}{L_f} & 0 & -\frac{1}{Lf} \\ 0 & -\frac{R_r}{L_r} & -\frac{1}{L_r} \\ -\frac{1}{C_f} & \frac{1}{C_f} & 0 \end{bmatrix};$$

$$B = \begin{bmatrix} 0 & \frac{1}{L_r} & 0 \end{bmatrix}, \; D = \begin{bmatrix} \frac{1}{L_f} & 0 & 0 \end{bmatrix}$$

Fig.3. illustrates the equivalent circuit of the cascaded structure rotor inverter-LC filter-rotor SG circuit. The current ir across the filtering inductor can be expressed in terms of the rotor inverter voltage U and the rotor voltage V as:

$$i_r = F(p)U + G(p)V \quad (18)$$

where:

$$F(p) = \frac{1}{a_1 p^3 + a_2 p^2 + a_3 p + a_4} \quad (19)$$

$$G(p) = \frac{1 + C_f p(L_r p + R_r)}{(L_f p + R_f)(1 + C_f p(L_r p + R_r)) + (L_r p + R_r)} \quad (20)$$

The denominator coefficients in (19) are given by:

$a_1 = L_r L_f C_f$, $a_2 = L_r R_f C_f + L_f R_r C_f$,
$a_3 = L_r + L_f + R_r R_f C_f$, $a_4 = R_r + R_f$.

If the all resistances effects are neglected, relation (19) becomes:

$$F(p) \approx \frac{1}{L_r L_f C_f p^3 + (L_r + L_f)p} \quad (21)$$

Finally, the resonance frequency of the LC filter is computed as:

$$\omega_a = \frac{1}{\sqrt{\frac{L_r L_f}{L_r + L_f} C_f}} \quad (22)$$

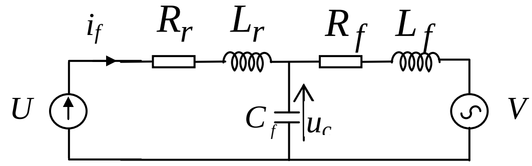

Fig.3. Equivalent circuit of rotor-LC filter system

V. DESCRIPTION OF THE PROPOSED METHOD

The design procedure for the load conditioner DC link voltage loop is very similar to that of a PWM rectifier. The difference is that the output of the load conditioner DC link voltage compensator is much smaller compared to that of a PWM rectifier under a heavy load. Since there is no load across the DC link capacitor, there is no active power delivered. The output of the voltage compensator keeps a small value to compensate the power losses.

a- Harmonic Current Extraction:

To perform the active filtering function, the load conditioner injects load harmonic currents. The power level of the load conditioner and the amplitudes of each individual harmonic current determine the lowest harmonic current that the load conditioner can handle.

Harmonic currents are obtained by subtracting the DC component from the total currents. The advantage of using this kind of high-pass filter structure is that there is no phase shift in the extracted harmonic components. A moving average operand is a good choice to implement the low pass filter due to its simplicity and accuracy.

The transformation α–β of a three-phase system without neutral connected is defined by the relations:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{23}$$

The instantaneous power for the three-phase system is as follows:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{24}$$

By observing the formulations of *P* and *Q*, it is possible to put them in the following form:

$$p = \overline{p} + \tilde{p} \tag{25}$$

$$q = \overline{q} + \tilde{q}$$

If we put

$$\Delta = v_\alpha^2 + v_\beta^2 \tag{26}$$

We have:

$$\begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{27}$$

Finally the current reference given by the:

$$\begin{bmatrix} i_{ha}^* \\ i_{hb}^* \\ i_{hc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} \tag{28}$$

The power converter system control block diagram is shown in Fig 1. The load conditioner is controlled with a current loop compensator superimposed by a voltage compensator to control its DC link voltage. The current reference generator is the key for the load conditioner to perform the active filtering. The most important control aspect of the load conditioner is the generation of the current references.

To obtain the references currents control of active filter, it is necessary to pass from the *abc* co-ordinates to the *dq* as follows:

$$\begin{bmatrix} i_{hd}^* \\ i_{hq}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\theta) & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \end{bmatrix} \begin{bmatrix} i_{ha}^* \\ i_{hb}^* \\ i_{hc}^* \end{bmatrix} \tag{29}$$

b- Front End Converter Control

The three phase AC/DC inverter shown in Fig.1 is an attractive topology for use as a front end power processing unit at higher power levels. It converts three phase input voltage to regulate DC link voltage with very low distortion in voltage and current on the AC side and DC side, minimum voltage and current stresses in the components, bidirectional power flow capability. Also, it provides unity power factor and draws continuous input currents.

The PWM rectifier has an inner current controller in rotating co-ordinates and an outer voltage loop. The DC error voltage is passed through a compensator to generate I_{ref}(current reference),as the q channel is responsible for the power transfer. The d-q co-ordinates axis are aligned with respect to the input line voltages such that V_d. as result, the d channel current reference, I_{dref} is set to zero in order to achieve unity power factor. The output of the current controller are the duty cycles d_d and d_q

The quadrature and direct grid side current demand can be derived from the active and reactive power references *P**,*Q**

$$\begin{cases} i_{d-reactive}^* = \dfrac{P_g^*}{v_{ds}} \\ i_{q-active}^* = \dfrac{Q_g^*}{v_{ds}} \end{cases} \tag{30}$$

and harmonic currents needed for compensation of non-linear load current. i_{hd}^* and i_{hq}^* can be derived as follows:

$$i_{hd}^* = i_{d-reactive}^* + i_{hd}^* \tag{31}$$

$$i_{hq}^* = i_{q-active}^* + i_{hq}^* \tag{32}$$

The controller voltage and current sources in the average model are represented in rotating co-ordinates as:

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

So, the current i_o is given by:

$$i_o = S * i_f \tag{33}$$

VI. Simulation Result:

In a first time the non linear load is not connected, the grid inverter gives an active power needed by the rotor of SG, sinusoidal current, at time t=2sec the diode bridge is connected, the grid inverter gives power to the rotor field and compensate harmonic currents Fig.4., at time t=2.5sec a step in the power where the generation of wind power stops, the grid inverter give a good hardness, with stability of DC bus and the *THDi* of nonlinear load reduced from 30.9% at 2.3%

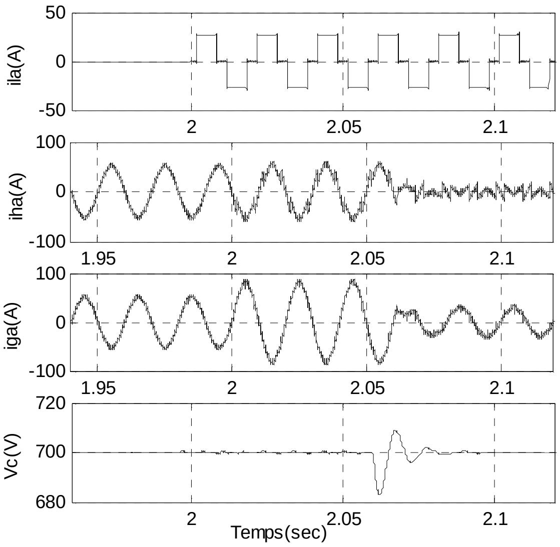

Fig.4. *il* Load current , *iha* grid converter current, *ira* grid current, *Vc* DC voltage,

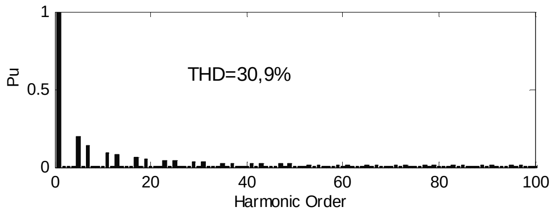

Fig5.a load current harmonic spectrum before filtering

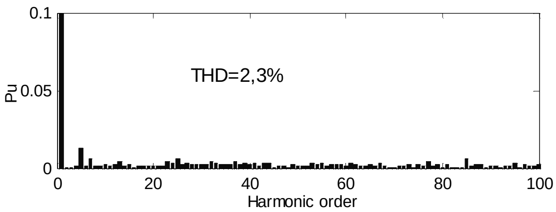

Fig5.b current harmonic spectrum after filtering

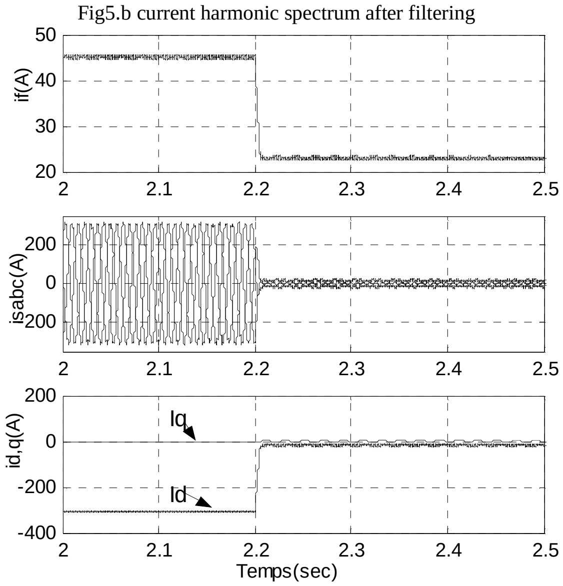

Fig.6. *if* rotor current, *isa* stator currents, *idq* stator currents in dq co-ordinates without *LC* filter

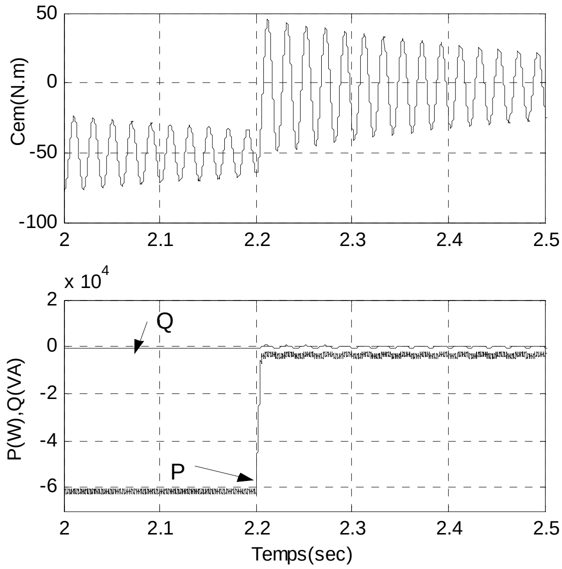

Fig.7. *Cem* electromagnetic torque, *P* and *Q* active and reactive power generated by SG without LC filter

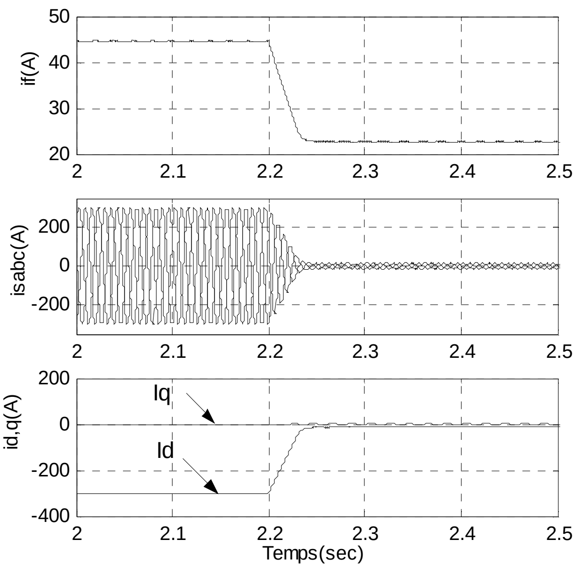

Fig.8. *if* rotor current, *isa* stator currents, *idq* stator currents in dq co-ordinates with *LC* filter

With LC filter the ripple torque, power and reactive power and commutation frequency in the rotor and stator current are eliminated. Fig.6, 7, 8 and 9 illustrate the LC filter effect on the power utility supply current.

Fig10. (a,b.c.d) illustrate the LC filter effect on the power utility supply current. The SG stator currents THD_i is significantly reduced from 13.2% to 1.8%.

Fig.10.a shows the current of the stator to grid. The stator current before installing of LC filter is given in Fig.10.c. After installing of the LC filter the distortion of the current of the stator is improved as shown in Fig.10.b.

Fig10 (b and d) shows the harmonic spectrum variation after adding of the LC filter

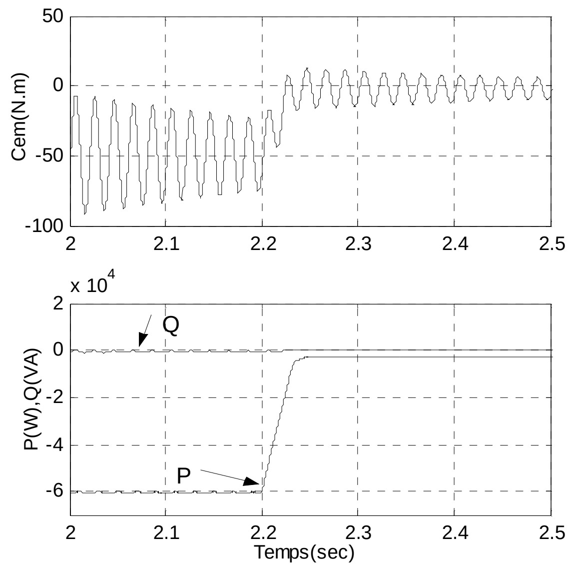

Fig.9. *Cem* electromagnetic torque, *P* and *Q* active and reactive power generated by SG with LC filter

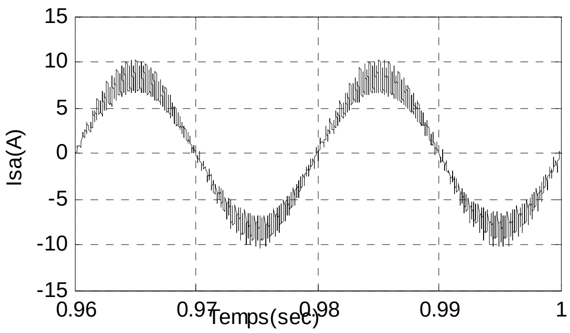

Fig.10.a SG's stator current performances without the *LC*

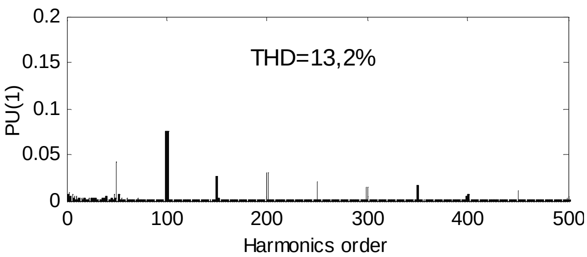

Fig.10.b SG's stator current harmonic spectrum without the *LC* filter

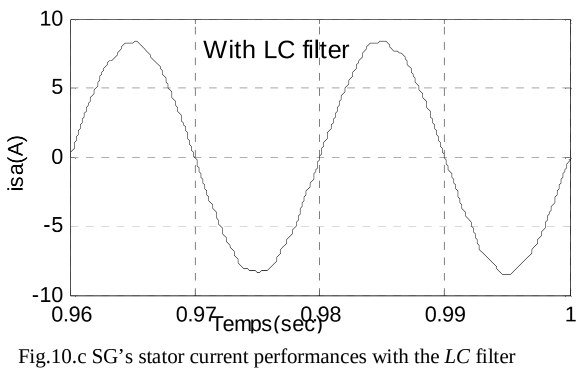

Fig.10.c SG's stator current performances with the *LC* filter

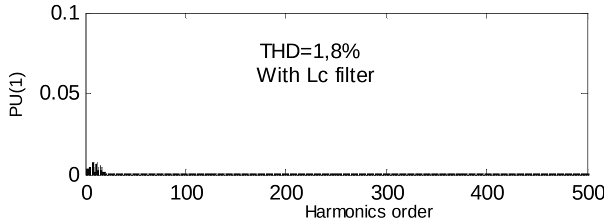

Fig.10.d SG's stator current harmonic spectrum with the *LC* filter

V. Conclusion

In this paper, a novel approach for grid power quality improvement using WECS with SG is discussed. In this method, one of the rotor current components is used to control the machine flux while the other is used to compensate harmonics. An LC filter is inserted between the excited circuit and the DC-DC converter to reduce the commutation frequency harmonics in the stator current and improve the power quality.

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