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# Doubly Fed Induction Generator Based WECS With The Double Trap LLCL Filter For Harmonics Mitigation

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**ABSTRACT**
The wind energy conversion system integrated with a doubly fed induction generator. The PWM based back-to-back power converters produced harmonic and as well as the non-linear loads are also a contributor of harmonics. Filters are used to eliminate these harmonics. In this work,there is a proposal for the passive filter named LLCL-filter with two traps for mitigating the harmonics. The DFIG based WECS analyse the harmonics mitigation under the non-linear loads with LLCL filter. The design and calculation steps are plot in this work for designing the filter parameters. The Simulated result shows the performance of filter connected DFIG under the non-linear load with varying wind speed. The THD of signal carried out through FFT. Simulations in MATLAB/Simulink verify the responses of filter.

**Keywords-** Doubly Fed InductionGenerator (DFIG), LLCL-filter with double trap, Non-linear load, Stator voltage oriented control (SVOC), WindTurbine (WT).

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## I. INTRODUCTION

The researchers interest in renewable energy grown day by day, Because of the decrement in hydrocarbon deposition and increment in environmental concern. In recent years the production of electricity increases by some renewable resources like Geothermal, Tidal, ocean temp difference, Solar, Nuclear, and the Wind [1].The Renewable energy resources are eco-friendly and unlimited in availability[2]. Due to the production cost the wind energy is more preferable than the others renewable energy [3].

There were more than 54 GW of wind turbine installed, and the prognostication to achieve a Zero Emissions power system on or before 2050, by weighing concern about climate [4-7].

For variable speed operation of wind turbine, DFIG (Doubly fed induction generator) has dominant with reduced converter approximately 30% of the rated power of generator, while SCIG, WRSG (Wound Rotor Synchronous generator) and PMSG have used thefull capacity of power converters, and due to the cost and maintenance of converter DFIG is extensively used [7-8].These DFIGs are also provide damping for weak grid [9]. When the generated power level is significantly contributed to the grid then it is compulsory to smoothening the power and mitigates the harmonics. The power smoothening is done by the use of super magnetic storage system [10]. A composition of the flywheel energy storage system and DSTATCOM is used in wind conversion system for mitigating frequency disturbances and harmonics [11]. In [12] author proposes the super capacitor energy storage system for improving the reliability and power quality.

The reactive power and harmonic compensation are achieved by existing RSC, in [13],[14], the harmonics are injected through RSC into rotor winding to compensate but it is not effective because of losses and noise increase in the machine and also the rating of RSC increased.

Another approach is adopted in [15] to control harmonics and reactive power by GSC control, in this method harmonics,are not crosses the winding. Since the L and the LC filters are eliminated the higher frequency harmonics, and for the PWM the switching frequency is not so high, therefore to attenuate the harmonics in low frequencies large inductance is required. An LCL filter can attenuate higher harmonics than that of L filter. In [16], the author proposed the LCL filter for both side converters RSC and GSC and get the good response as compared to traditional L or LC filter, but it not consider the non-linear load condition. The LLCL filter used for improving the filter capability and have small size. The resonance frequency of LLCL filter for converter connected with grid sensitive to grid impedance and cable capacitance and this influence the stability and robustness of system, so proper designing constraints are necessary. In [17] author proposes the complete designing constraint and step for LLCL filter. There are various literatures for designing procedure for the LCL and LLCL filters. The author provide the step by step procedure to design the LLCL filter with one trap and with two trap LC filters, and compare the performance of the filter [18].

In this work, the designing procedure for LLCL carried out and the LLCL filter with two traps are connected between the GSC converter and grid to mitigate the harmonics produced by the non-linear loads. The non-linear load formed with the rectifier and RL circuits. The system modeling and simulation carried out in the platform of MATLAB/Simulink.

## II. MATHEMATICAL MODEL OF WIND TURBINE

The wind power is calculated air swept area and speed by the relation [7],[8]-

$$P_{wind} = 0.5\rho_{air}\pi R^2 V_{wind}^3 \quad (1)$$

Where $\rho_{air}$ is the density of Air (1.23Kg/m$^3$), R is the radius of the turbineblade, $V_{wind}$ is the speed of air.
The conversion relation of Airpower$P_{wind}$into turbine mechanical power $P_m$ is defined as-

$$P_m = P_{wind} * C_p \quad (2)$$

Where $C_p$ is power efficiency coefficient that shows, some fraction of Airpower can convert into mechanical power to drive the shaft of the turbine. The value of $C_p$ is 16/27 theoretically (Approx.0.593) and is known as Betz's Limit. But practically, the value of $C_p$is varied as per the manufacturers. $C_p$ is a function of Blade tip ratio λ, and Pitch angle β.

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^{C_5} - C_6\right)e^{-\left(\frac{C_7}{\lambda_i}\right)} \quad (3)$$

$$1/\lambda_i = \left(\frac{1}{\lambda+0.02\beta}\right) - \frac{0.003}{\beta^3+1} \quad (4)$$

Where, $C_1$=0.73,$C_2$=151,$C_3$=0.58,$C_4$=.002,$C_5$=2.14, $C_6$=13.2,$C_7$=18.4.
At β=0, the maximum value of Cp is 0.44 at the λ=7.2 and that λ is called optimal value. The Cp – λ curve at various pitch angle shown in fig. (1), it is clear from that the maximum Cp will obtain when pitch angle should be zero.

Theturbine torque can be calculated by the formula [7, 9,19]-

$$T_{mech} = \frac{P_m}{\omega_{turb}} \quad (5)$$

And, $$\omega_{turb,opt} = \frac{\lambda_{opt} * V_{wind}}{R} \quad (6)$$

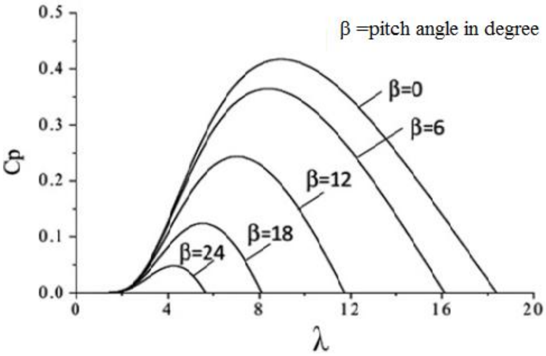



**Figure 1**-Cp- λ curve at different pitch angle

## III. DYNAMIC MODEL AND EQUATION OF DFIG

The stator is directly connected to the grid while the rotor is connected to the grid via power converter, harmonic filter, and transformer etc. As it is known that the maximum power of rotor is 30% of the stator power so the converter reduced to a significant level as compared to full capacity converters. The Dynamic model of DFIG is as given in fig.2a and 2b.

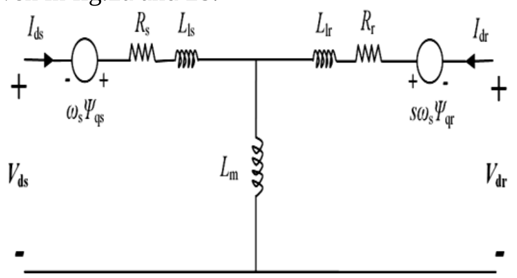



**Figure 2a**-Synchronous frame d-Axis Circuit

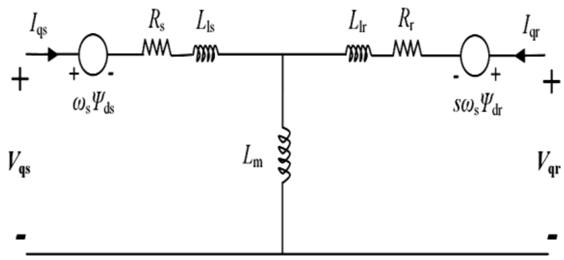



**Figure 2b**-Synchronous frame q-Axis Circuit

The dynamic equations of DFIG are as follows [7,9,16]:-
Stator Voltage Equation

$$V_{ds} = R_s I_{ds} - \omega_s\psi_{qs} + P\psi_{ds} \quad (7)$$
$$V_{qs} = R_s I_{qs} + \omega_s\psi_{ds} + P\psi_{qs} \quad (8)$$

Rotor Voltage Equation-

$$V_{dr} = R_r I_{dr} - s\omega_s\psi_{qr} + P\psi_{dr} \quad (9)$$
$$V_{qr} = R_r I_{qr} + s\omega_s\psi_{dr} + P\psi_{qr} \quad (10)$$

Flux Linkage Equation-

$\psi_{ds} = (L_{ls} + L_m)I_{ds} + I_{dr}$ (11)
$\psi_{qs} = (L_{ls} + L_m)I_{qs} + L_m I_{qr}$ (12)
$\psi_{dr} = (L_{lr} + L_m)I_{dr} + L_m I_{ds}$ (13)
$\psi_{qr} = (L_{lr} + L_m)I_{qr} + L_m I_{qs}$ (14)

Electromagnetic Torque,

$$T_e = 1.5N_p(\psi_{qs}I_{ds} - \psi_{ds}I_{qs}) \quad (15)$$

Equation of Motion of Generator,

$$\frac{d\omega_m}{dt} = \frac{T_m - T_e}{2H_m} \quad (16)$$

## IV. CONTROL OF GENERATOR

The proper control of power converter and electric generator provide the maximum power extraction from the wind [9],[20].The controlling of generator side can be generally done by (i) For DFIG (for RSC)-stator field oriented control (ii) Direct Torque Control(DTC), (iii)Direct Power Control(DPC).

### 4.1. Rotor Side Control (RSC)

The Author used here the stator voltage oriented control scheme for controlling the independent active and reactive power. The RSC control is to extract maximum power from wind. The optimum turbine speed is obtained from MPPT (Tip Speed Ratio).

In voltage oriented control [9], $V_{ds}=V_s$. and $V_{qs}=0$. And $\Psi_{ds}=0$; $\Psi_{qs}=\Psi_s$.

The optimal speed obtained as equation (6) and compare with the sensed speed $\omega_m$, the error is processed with the speed controller to get the direct axis reference rotor current, $I_{dr}^*$.

The referenced quadrature axis current,$I_{qr}^*$ is selected as zero.

Sensed rotor current is transformed into d-q current by the equation [9].

$$\begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} I_{ra}\cos\theta_s + I_{rb}\cos(\theta_s - \frac{2\pi}{3}) + I_{rc}\cos(\theta_s + \frac{2\pi}{3}) \\ -I_{ra}\sin\theta_s - I_{rb}\sin\left(\theta_s - \frac{2\pi}{3}\right) - I_{rc}\sin(\theta_s + \frac{2\pi}{3}) \end{bmatrix} \quad (17)$$

Where slip angle $\theta_s = \theta_e - \theta_r$.

Where, $\theta_e$ is estimated by using grid voltage $V_{gabc}$ and $\theta_r$ is estimated by the rotor speed.

The error between the referenced rotor current and sensed rotor current are processed through the controller, and we get the voltages $U_{dr}$ and $U_{qr}$.

The reference voltages are obtained by subtracting the decoupled term.

$$V_{dr}^* = U_{dr} - \omega_r\sigma L_r I_{qr} - \omega_r \frac{L_m}{L_s}\psi_s \quad (18)$$

$$V_{qr}^* = U_{qr} + \omega_r\sigma L_r I_{dr} \quad (19)$$

By using the conversion equation as per [9], we get the three-phase reference voltage from direct and quadrature axis voltage.

$$\begin{bmatrix} V_{ra}^* \\ V_{rb}^* \\ V_{rc}^* \end{bmatrix} = \begin{bmatrix} V_{dr}^*\cos\theta_s - V_{qr}^*\sin\theta_s \\ V_{dr}^*\cos(\theta_s - \frac{2\pi}{3}) - V_{qr}^*\sin(\theta_s - \frac{2\pi}{3}) \\ V_{dr}^*\cos(\theta_s + \frac{2\pi}{3}) - V_{qr}^*\sin(\theta_s + \frac{2\pi}{3}) \end{bmatrix} \quad (20)$$

These three phase referenced voltages compare with the triangular (Pulse Width Modulation) PWM carrier wave at a fixed frequency for generating the pulses for RSC. The controlling scheme for RSC is shown in fig (3).

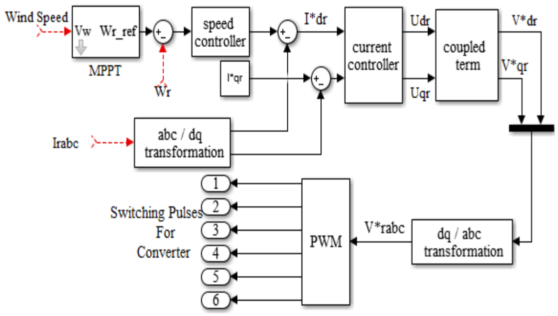



**Figure 3**-RSC control Scheme block diagram

### 4.2. Grid Side Converter Control

The Grid side converter (GSC) is controlled by the methods, Voltage Oriented Control (VOC). In technique VOC the dq axis grid currents regulation and active/reactive power are controlled. The reference dc bus voltage track and regulated by the DC- link controller. The reference d axis component of grid current ($I_{dg}^*$) obtain by the processing of DC –link voltage with PI controller. The GSC control scheme is shown in fig.(4).

For unity power factor operation of grid the grid reactive power can be set at zero or in other words, the reference q axis component of grid current ($I_{qg}^*$) can be set as zero. The three phase measured current is converted into d-q axis quantities by using the equation (17). These referenced currents, $I_{dg}^*$, $I_{qg}^*$ respectively compare with measured current and processed with PI controller. And after that adding the compensating terms, $-\omega_s * L_i * I_{qg}$, and $\omega_s * L_i * I_{dg}$ in $I_{dg}^*$, $I_{qg}^*$ respectively to get the referenced voltages $V_{dg}^*$, $V_{qg}^*$. These d-q referenced voltages are converted to three phase reference voltage as per equation (20). $V^*_{abc}$ fed to PWM for converter switching pulses.

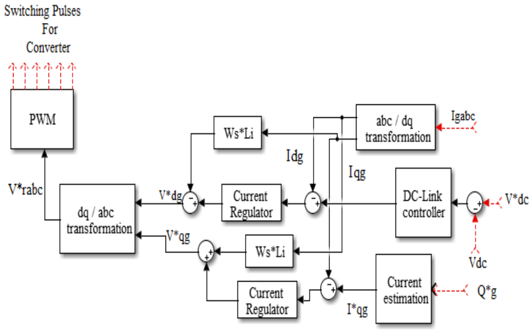



**Figure 4**-GSC control scheme block diagram

# V. LLCL FILTER DESIGN STEPS AND CONSTRAINTS

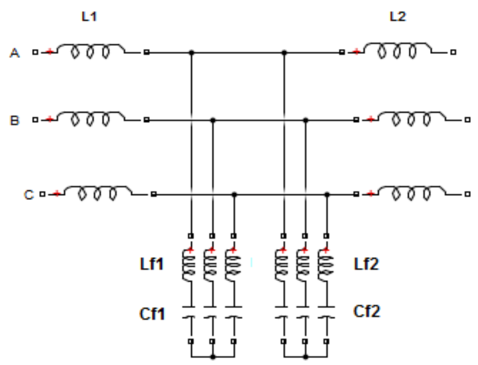
The resonance frequency of LLCL filter is sensitive to grid impedance, interaction between multi-converters, and it affect the stability and operation. For this the proper design method is applicable. The LLCL filter outline shown in fig.(6). In LLCL filter topology there are two resonant circuit one is with ripple inductor and the other is with the grid inductor to attenuate the harmonics around the switching frequency and the double of switching frequency respectively as shown in fig.(6(a)). The transfer function $i_g(s)/u_i(s)$ of LLCL with two traps are obtained by the equivalent circuit shown in fig. (6 (b)).

$$Z_1(s) = L_1 S\,;\;\; Z_2(s) = L_2 S$$

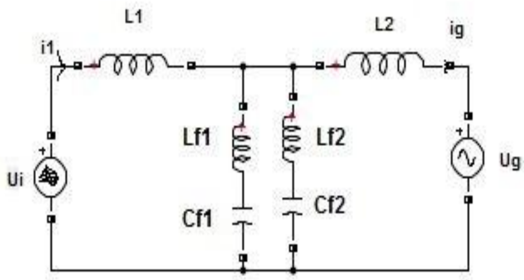
$$Z_c(s) = \frac{(L_{f1}C_{f1}S^2+1)(L_{f2}C_{f2}S^2+1)}{(L_{f1}C_{f1}C_{f2}+L_{f2}C_{f1}C_{f2})S^3+(C_{f1}+C_{f2})S} \quad (21)$$

At $u_g(s) = 0$;

$$G_{ui\to ig}(s) = \frac{i_g(s)}{u_i(s)} = \frac{Z_c(s)}{Z_1(s)Z_2(s) + Z_1(s)Z_c(s) + Z_2(s)Z_c(s)}$$




(a)




(b)

**Figure 6-** LLCL filter architecture

All the parameter of the LCL- filter, LLCL- filter with one trap, LLCL-filter with two traps is the same except for the resonance circuit.

5.1. Constraints for the Design of High Order Power Filter

The system impedance must be known, it is the basic requirement of design. The base value of system impedance, capacitance and the inductance are obtained by the given relation.

$$Z_b = \frac{V_n^2}{P_n};\; L_b = \frac{Z_b}{\omega_0};\qquad C_b = \frac{1}{Z_b * \omega_0} \quad (22)$$

Where, $V_n$ the line-line RMS voltage;
$\omega_0$ Grid frequency;
$P_n$ Rated active power

Constraints-

1-Total inductance ($L_1$+$L_2$)- the maximum limit for total inductance is 10% in order to limit DC-link voltage.

2- $L_1$ design- The value of $L_1$ (inverter side inductor) designed by the maximum ripple current. Maximum ripple current 15-25% or some literature shows 15-40%.

3- Filter capacitance $C_f$ design- Capacitance design should be in such that the maximum power factor variation at rated power is less than 5%.

$$C_f \le 5\%\; of\; C_B;\; C_f = C_{f1} + C_{f2}$$

4-Resonance Frequency of Filter- the resonance frequency of filter ranges from 10 times of grid frequency to one half of the switching frequency to avoid the major low harmonics.

5.2. Parameters Design Steps for LLCL-filter with two traps

The system base impedance $Z_b$ is 0.794 Ω, base inductance $L_b$ is 0.253 mH, and the base capacitance $C_b$ is 4.01mF as per the system parameter given in appendix (Table I),and the basic design steps are given below-

1-Converter side inductor should meet the current ripple. The inductor $L_1$ can be estimated by the given relation and selected as per the criteria given in constrains 1.

$$L_1 \ge \frac{V_{dc}}{8 * \alpha * I_{ref} * f_s}$$

Where, $\alpha$ =maximum ripple current ratio (here consider 28%);

$I_{ref}$ is the maximum peak current handled by the converter; and $f_s$ is the switching frequency (here 4 kHz). $L_1$ is selected as 0.19mH.

2- Capacitor $C_f$ estimation done with the help of constraint 3.$C_f$ maximum is the 0.05$C_b$. So choose the value below this limit. Here value selected as filter capacitance 181 μF ($C_f$ =181 μF; $C_{f1}$=$C_{f2}$=90.5 μF).

3-From the value of $C_{f1}$ and $C_{f2}$, the resonant circuit values of inductor $L_{f1}$ and $L_{f2}$ estimated by the given relation.

$$\omega_s = \frac{1}{\sqrt{L_{f1} * C_{f1}}};\;\; \omega_{s2} = \frac{1}{\sqrt{L_{f2} * C_{f2}}}$$

Where $\omega_s$ = Switching frequency; and $\omega_{s2}$=double of Switching frequency. If $f_s$ is switching frequency the $\omega_{s2} = 2 * 2 * pi * fs$.

4- Estimation of $L_2$ - For an LLCL-filter with two trap based three phase –inverter, $L_2$ can be calculated easily from the given equation [17-18], The above relation provide the good value of $L_2$. For the sake of easiness the approx. value for satisfactory operation will be taken as near the 10% of $L_1$.

5-Resonance frequency $\omega_r$ – Calculate the resonance frequency by the equation below-

$$\omega_r \approx \frac{1}{\sqrt{\left(\frac{L_1 L_2}{L_1+L_2}\right)(C_{f1}+C_{f2})}}$$

It is mandatory to check that this resonance frequency will lay within the range 10 times the line frequency and the half of the switching frequency, as per constraints 4. If it not satisfies then go to step 2 and increase the capacitance $C_f$ up to the maximum limit.

The table-I for the LLCL-filter with two trap parameters shown below as per the design.

**Table-I LLCL-filter with two traps Parameters**

| | |
|---|---|
| $L_1$ | 0.19 mH |
| $C_{f1}$ | 90.5 µF |
| $C_{f2}$ | 90.5 µF |
| $L_{f1}$ | 17.5 µH |
| $L_{f2}$ | 17.5 µH |
| $L_2$ | 0.055 mH |
| Resonance frequency, $f_r$ | 1813.79 Hz |

## VI. SYSTEM RESULT AND DISCUSSION

The system responses with non-linear load with filter and without filter are consider and simulated as in platform MATLAB/Simulink. The non-linear load are comprises with the rectifier and the $R_L$ (=20 ohm) and $L_L$ (=0.5mH). The LLCL-filter with two traps is easy to implement and significantly reduce the harmonics in the grid produced by the non-linear load. The total harmonic distortion will be studied by the FFT analysis of current signals. The complete Simulink model prepared in MATLAB/Simulink is shown in Fig.(7).

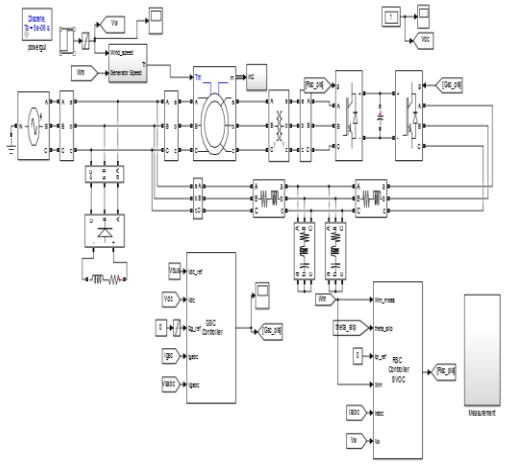


**Figure 7**- Complete MATLAB/Simulink model of DFIG connected with LLCL-filter with two traps

The simulated result obtained at variable speed varies from 8-11 m/s. The simulation result of stator current, rotor current and load current are shown in fig.(9). The DC link Voltage shown in fig.(8).

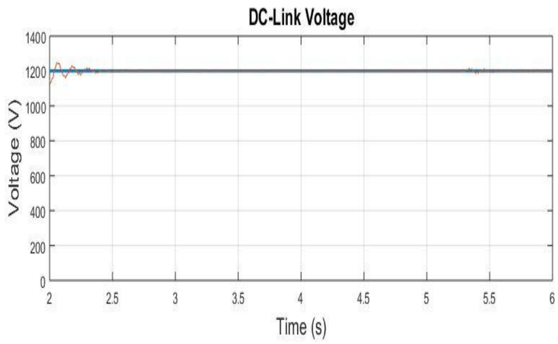



**Figure 8**-DC link Voltage profile

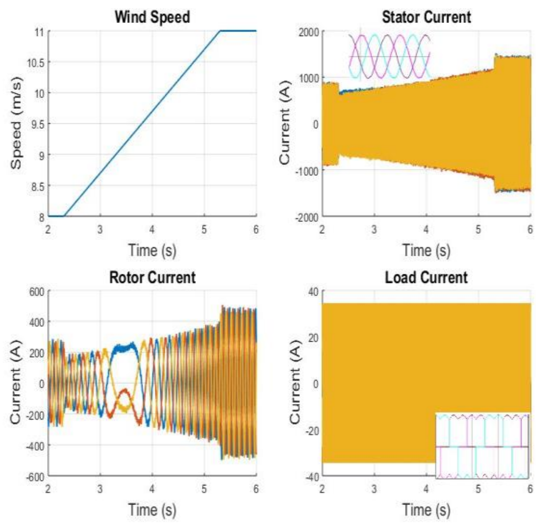



**Figure 9**- Wind Speed, Stator Current, Rotor Current, and Load current

In fig.(9), the stator current and load current are condensed so it is shown in a small window in expanded form. The simulated active and reactive power of Grid, Stator, and GSC are shown in Fig.(10), the magnitude of power varies with the Wind speed. The negative grid power shows that the power supplied to grid from stator.

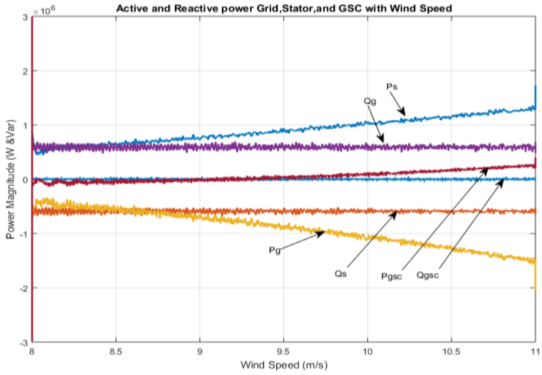
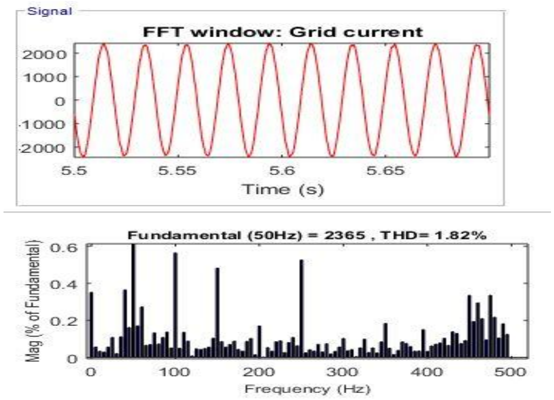
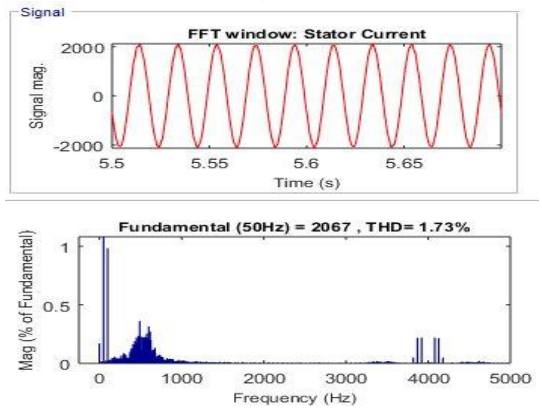



**Fig.10**-Active and Reactive powers of grid, stator and GSC varies with wind speed

The harmonics analysis of filter done with the FFT analysis of 'Powergui' system at 1000Hz frequency, and result shows the significant reduction of Harmonics produced by the non-linear loads. The THD of Stator current and Grid current shown in Fig.(11).The THD analysis done with 10 cycle of signals. In table-II, the THD of signals shown without filter and with Filter.




(a)

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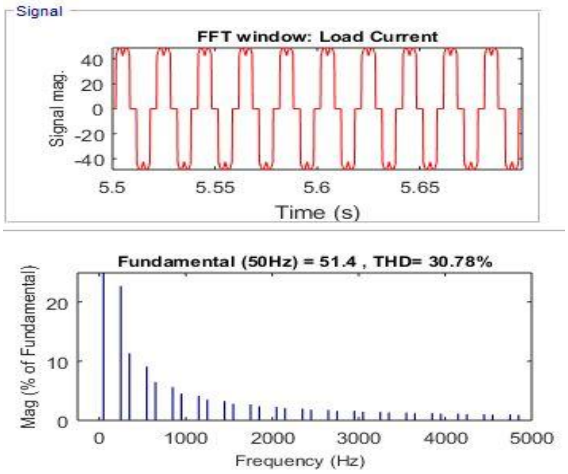


(c)

**Figure 11**-THD analysis of (a) Grid current (b) Stator current (c) Load Current

Table-II-THD of Signals without filter and with filter

| | Without filter | With L filter | With LLCL filter two traps |
|---|---|---|---|
| Grid Current, Ig | 24.86% | 9.2% | 1.73% |
| Stator current, Is | 11.13% | 8.8% | 1.82% |
| Load Current, Il | 30.78% | 30.78% | 30.78% |

## VII. CONCLUSION

This works just confine role of filters which were in trend, and mesmerize the performance study of DFIG with filter potentiality. In this work, the provision for the designing of LLCL filter with two traps explain and easy to determine. The LLCL filter shows the better harmonics reduction which was produced by the nonlinear loads. The harmonic mitigation comparison shown in tabulated form to easily find out the harmonics mitigation effects. The LLCL filter with two traps is easy to design for higher switching frequency from 8 kHz. In this work the design process carried out for LLCL with two traps for the medium switching frequency.

**Appendix**

**Table I-DFIG parameters**

| | | | |
|---|---|---|---|
| Rated Power | 2.0 MW | Line-Line Rated RMS Voltage | 690 V/50Hz |
| Stator Rotor Turn Ratio | 1/3 | Stator resistance, Rs | 2.6 mH |
| Rotor resistance, Rr | 2.9mH | Stator leakage inductance, Lls | 0.087 mH |
| Rotor leakage inductance, Llr | 0.087 mH | Magnetizing Inductance | 2.5 mH |
| DC bus Voltage | 1200V | Switching Frequency, Fs | 4 kHz |

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