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# ANFIS based Doubly Fed Induction Generator for WECS with LLCL-2TRP Filter

Ishteyaq Ahmad*, Rakesh Sharma**
*(Scholar, Email:-ishteyaq7@gmail.com)
** (Assistant Professor, Email:-rakesh09_09@rediffmail.com)
*,**Department of Electrical Engineering, BBDU, Lucknow, India

**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 traditional controllers for controlling the rotor side converters (RSC) for active power and MPPT are substitute with the adaptive neural fuzzy inference system (ANFIS). ANFIS basic structure and principle of working are presented in this paper. The Simulated result shows the performance of filter connected DFIG under the non-linear load with varying wind speed and also shows the improved response than conventional controller. 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).

## 1. Introduction

The researchers interest in renewable energy grown day by day, Because of the 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]. Due to the production cost the wind energy is more preferable than the others renewable energy [2].

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, and due to the cost and maintenance of converter DFIG is extensively used [3-4].These DFIGs are also provide damping for weak grid [5].

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 [6].

A composition of the flywheel energy storage system and DSTATCOM is used in wind conversion system for mitigating frequency disturbances and harmonics [7]. In [8] 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 [9],[10], 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 [11] 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 [12], 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. In [13] the authorpropose the LLCL filter with double trap for mitigating the harmonics and consider the application of the nonlinear loads, and significantly remove the harmonics as per IEEE-519 standards.

The handling of nonlinearity is a tough task and a traditional nonlinear control system based on the Jacobian linearization approach but it is limited to mild system performance and small dynamic regime.The author [14] uses the ANFIS DTC control for improving the performances and authors [15] also uses ANFIS for vector control of RSC and GSC, and compare result with the PI controller. In [14-17] the author compare the result of ANFIS based system with the PI and Fuzzy based system and concluded that the ANFIS has the improved response than the others.

In this work, the designing procedure for ANFIS carried out for improving the system performance. The ANFIS based controller applied on the RSC while the GSC is based on the PI controller. The non-linear load formed with the rectifier and RL circuits. The system modelling and simulation carried out in the platform of MATLAB/Simulink.

## 2. Control of Generator

The proper control of power converter and electric generator provide the maximum power extraction from the wind [5],[18].

### 2.1. 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 [5], $V_{ds}=V_s$. and $V_{qs}=0$. And $\Psi_{ds}=0$; $\Psi_{qs}=\Psi_s$.

The optimal speed obtained as equation

$$\omega_{turb\,,opt} = \frac{\lambda_{opt} * V_{wind}}{R}$$

Where $\omega_{turb\,,opt}$ =optimal speed of wind turbine

$\lambda_{opt}$ = Optimal Tip Speed ratio,

$V_{wind}$ = Speed of Wind,

R= Wind turbine rotor radius, and

Compare with the sensed speed $\omega_m$, the error is processed with the ANFIS based 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 [5].

$$\begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} I_{ra}\cos\theta_s + I_{rb}\cos(\theta_s - \frac{2\pi}{3}) + I_{rc}\cos(\theta_s + \frac{2\pi}{3}) \\ -I_{ra}\sin\theta_s - I_{rb}\sin\left(\theta_s - \frac{2\pi}{3}\right) - I_{rc}\sin(\theta_s + \frac{2\pi}{3}) \end{bmatrix} \quad (1)$$

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 ANFIS based controller, and we get the voltages $U_{dr}$ and $U_{qr}$.

The reference voltages are obtained by subtracting the decoupled term.

$$V_{dr}^* = U_{dr} - \omega_r \sigma L_r I_{qr} - \omega_r \frac{L_m}{L_s}\psi_s \quad (2)$$

$$V_{qr}^* = U_{qr} + \omega_r \sigma L_r I_{dr} \quad (3)$$

By using the conversion equation as per [5], we get the three-phase reference voltage from direct and quadrature axis voltage.

$$\begin{bmatrix} V_{ra}^* \\ V_{rb}^* \\ V_{rc}^* \end{bmatrix} = \begin{bmatrix} V_{dr}^*\cos\theta_s - V_{qr}^*\sin\theta_s \\ V_{dr}^*\cos(\theta_s - \frac{2\pi}{3}) - V_{qr}^*\sin(\theta_s - \frac{2\pi}{3}) \\ V_{dr}^*\cos(\theta_s + \frac{2\pi}{3}) - V_{qr}^*\sin(\theta_s + \frac{2\pi}{3}) \end{bmatrix} \quad (4)$$

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. (1).

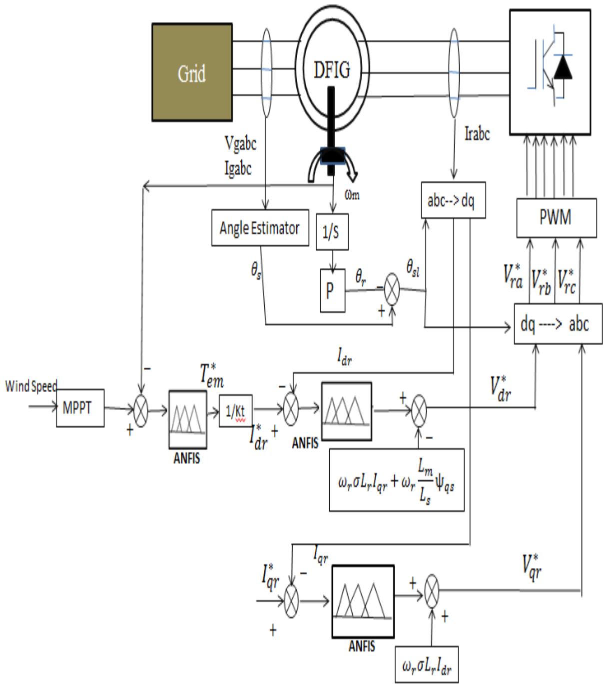



**Figure 1-**RSC control Scheme block diagram

### 2.2. 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. (2).

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 (1). 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 (4). $V^*_{abc}$ fed to PWM for converter switching pulses.

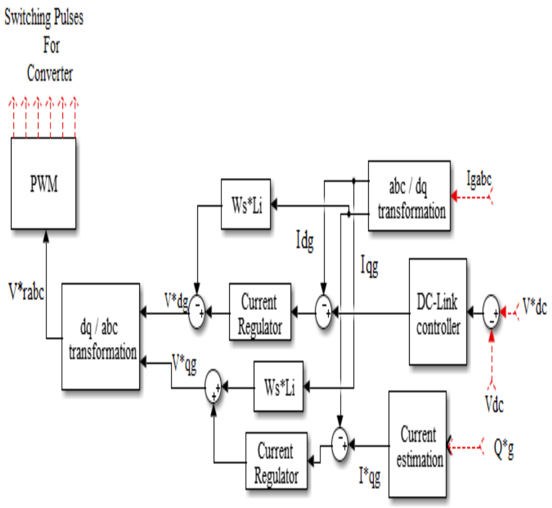



**Figure 2**-GSC control scheme block diagram

## 3. ANFIS Principle

Adaptive Neuro-Fuzzy Inference system is a powerful tool which inherits both the idea of fuzzy controller and artificial neural network.

The combined effect of fuzzy and neural makes it good learner, good interpreter. ANFIS controller selects a proper membership function.

### 3.1. ANFIS Structure and Design

The ANFIS support TL-FLC method. The general structure consists of five-layer which are shown in fig.(3).

Layer1-This layer consists of input variables and here the membership function for input selected as Gauss. This input layer supplies to the next layer.

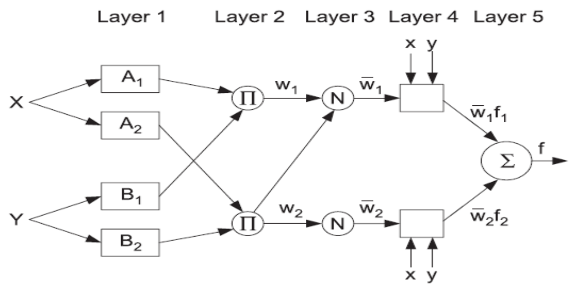


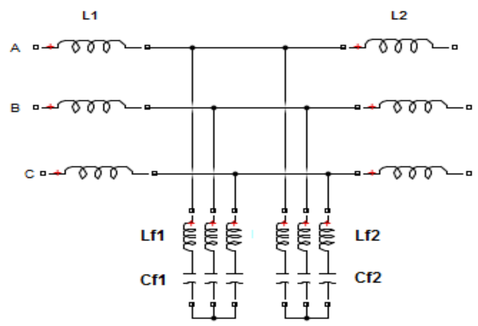

**Fig.3**-ANFIS architecture

Layer 2-This layer checks the weight of each MF. It calculates the value of MF that which input value belongs to the fuzzyset, whichsends to next layer as input.
Layer 3- Each node of these layers evaluate the weight that is normalized. In this layer match the activation of each rule with the number of the fuzzy rule.
Layer 4- This de-fuzzification layer provides the output values as consequence of inference rules. In this layer, normalization is performed by each neuron.
Layer 5- This is the output layer which sums all the inputs from layer-4 and transforms the fuzzy classification results into a crisp value.

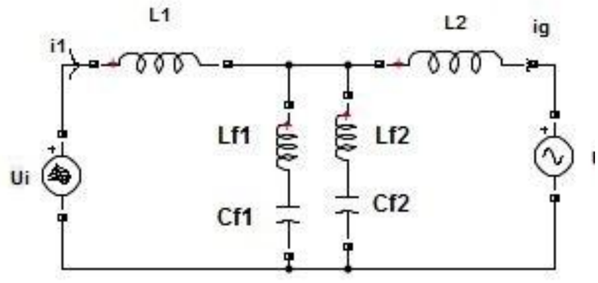
The design procedure of ANFIS is detailed explain in [20].The ANFIS inputsare error e(t) and change in error Δe(t), $\Delta e(t) = e(t) - e(t-1)$ and the training data are prepared through the simulated data, membership function are selected [21].

## 4. LLCL-2TRP Filter Architecture and Parameters

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.(4). 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.(4(a)).




(a)




(b)

**Figure 4-** LLCL filter architecture

Where $L_1$ is the inductor connected to GSC side and $L_2$ is the inductor connected to the grid side.

All the parameter of LLCL-2TRP filter designed procedure explained in the [13, 22-]. The parameter designed for this system is described in [13] and taken as it is for this system.

The Table-I shows the LLCL-2TRP filter parameters as per [13].

**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 |

## 5. 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 RL. The LLCL-2TRP filter 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.(5).

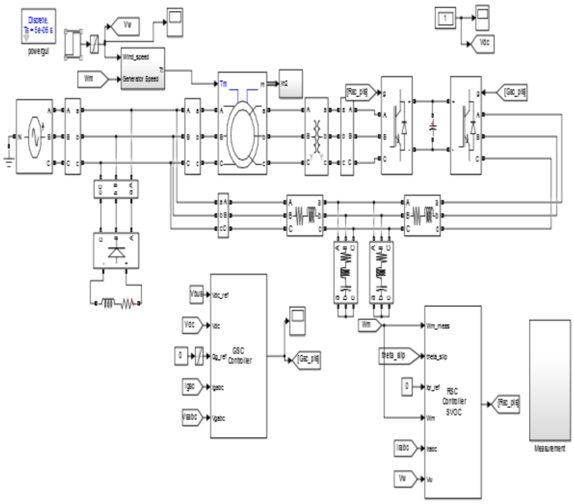


**Figure 5**- Complete MATLAB/Simulink model of DFIG connected with LLCL-filter with two traps

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.(6). The DC link Voltage shown in fig.(7).

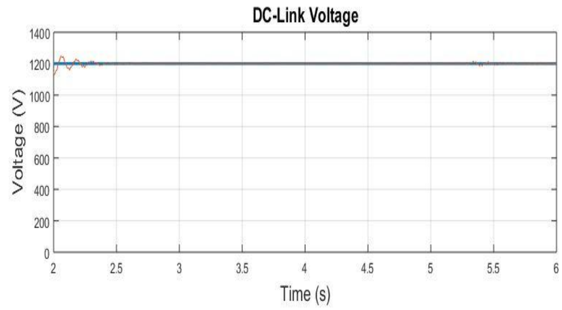



**Figure 6**-DC link Voltage profile

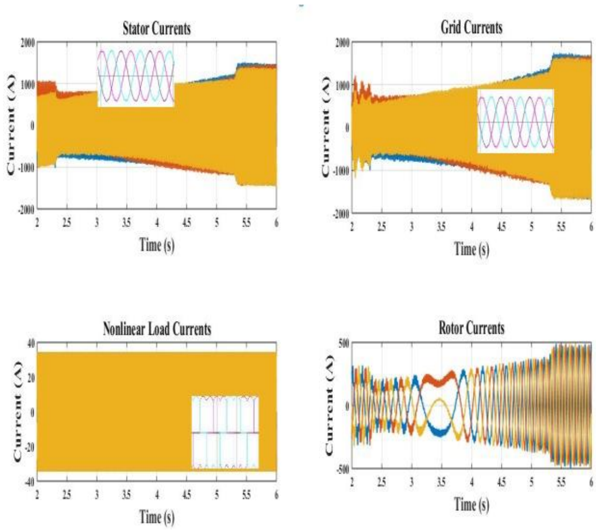



**Figure 7**- Stator Current, Grid Current, Load Current, and Rotor Current

In fig.(7), the stator current and load current are condensed so it is shown in a small window in expanded form.The above and below simulated results are obtained at variable wind speed, which is shown in fig.(8).

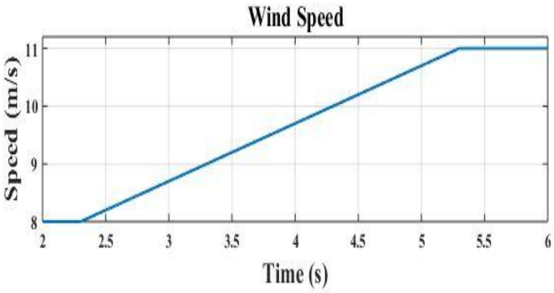



Fig. 8 Wind speed varying with time

The simulated active power of Grid, Stator, load and GSC are shown in Fig.(9), the magnitude of power varies with the Wind speed. The negative grid power shows that the power supplied to grid from stator.

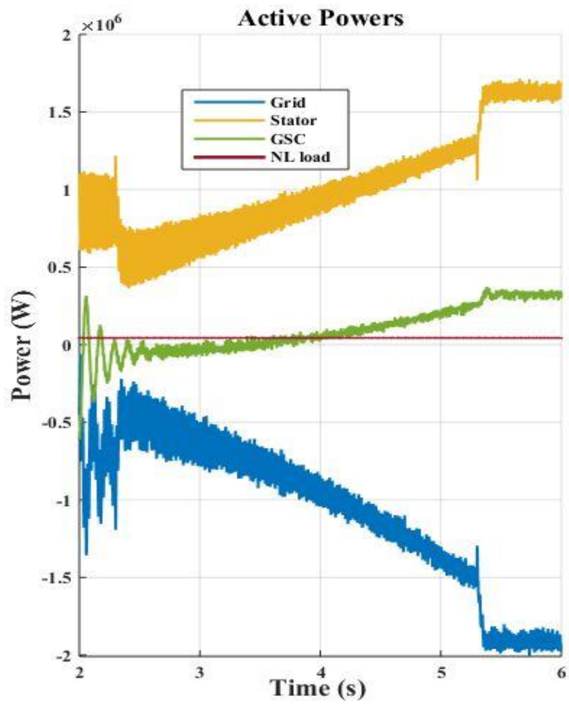



**Fig.9**-Active and Reactive powers of grid, stator and GSC varies with wind speed

The simulated results shown below indicate that the ANFIS have improved performance than the conventional PI controller. ANFIS has Fast response than the PI controller and also have less overshoots. The ANFIS controller is applied only on the RSC side for controlling the speed of the rotor and the d-q axes current of the rotor in order to achieve the required performance. Thus the simulated result with PI controller and with ANFIS controller is compare together for the speed and d-q current controller to point out, the improved performance of ANFIS controller. It is clearly verify through the simulated result shown in fig.(10).

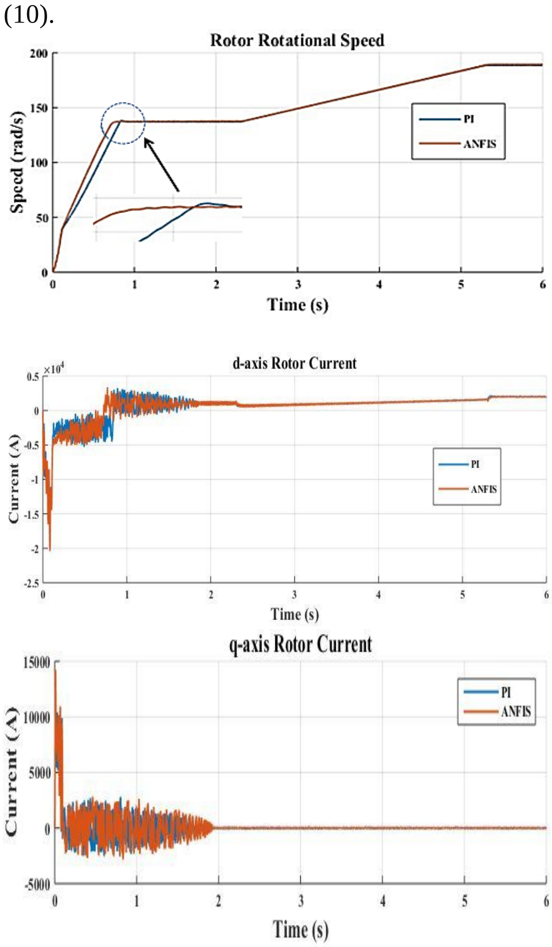
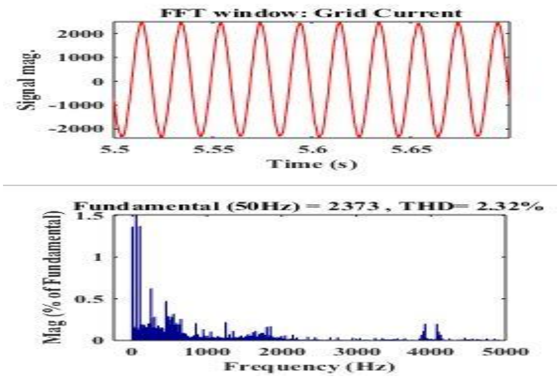



**Fig.10** Rotor speed**,** d-axis rotor current and q axis rotor current respectively with PI and ANFIS controller

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.



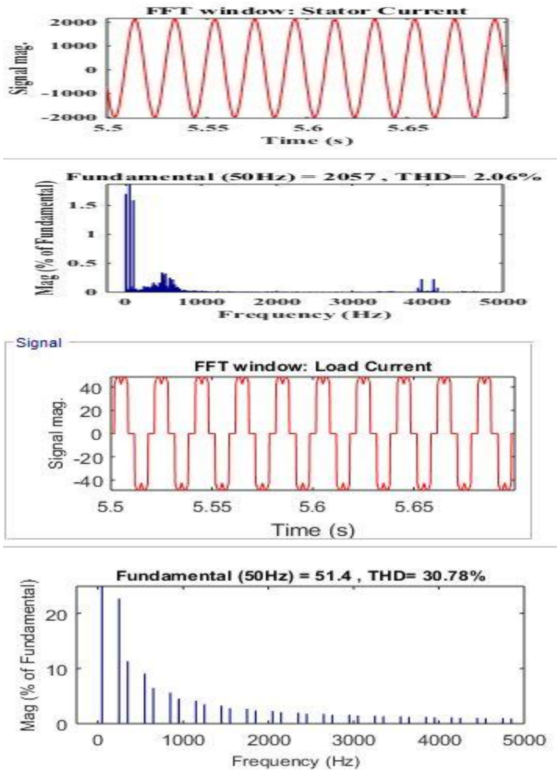



Fig.11- THD analysis of (a)grid Current (b) Stator Current (c) Load current

## 6. Conclusion

This work based on the role of the artificial based controller which were in trends, and mesmerize the performance study of DFIG with filter potentiality. In this work, the provision for the designing of ANFIS controller explains and easy to model. The LLCL filter shows the better harmonics reduction which was produced by the nonlinear loads. The simulated response shows that ANFIS provide the improved controlling than the PI controller.

## 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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