Harmonic Reduction in Wind Energy Systems Using FLC and PI based Shunt Active Filter

S. G. Srivani, Karthik Suresh, Chethana

Abstract— **In recent years, the large scale use of the power electronic equipment has led to an increase in harmonics in power systems. Moreover, the use of wind energy system as the source introduces harmonics in the system due to inherent environmental fluctuations. It is vital that harmonics in the wind energy system are reduced before integrating it to the grid. Current harmonics are one of the most common power quality problems and are usually resolved by using shunt active filter (SHAF). The main objective of this work is to develop Proportional Integral (PI) and Fuzzy logic controllers (FLC) to analyze the performance of the Shunt Active Filter for mitigating current harmonics. A Shunt Active Filter controlled by PI and FLC to supply compensating current to the wind energy –non-linear load system is simulated in the MATLAB/SIMULINK environment. The performance of SHAF operated by PI Controller and FLC are compared and analyzed.**

Index Terms—**Current Harmonics, FLC, PI, Wind Energy Systems**

I. INTRODUCTION

The proliferation of non-linear loads in power systems has drawn attention of researchers in the field of power systems. Specifically, the current harmonics injected by these loads results in voltage distortions, overheating of the devices, low power factor and low system efficiency. The environmental fluctuations in the wind energy systems also introduces harmonics in the system thus causing an increase in harmonics. In order to overcome these issues, active power filters are used. Decisive linear mathematical models are needed for the PI controller which is arduous to attain and fails to produce assuasive results under load disturbances and varying conditions. Power Quality (PQ) is defined as "Any power problem established in voltage, current or frequency deviation which leads to damage and malfunctioning of the consumer equipment". Poor power quality causes damages to the system, and has an adverse economic impact on utilities and customers. Highly automatic electric equipment causes enormous economic loss every year. Conventionally, passive L-C filters were used to mitigate harmonics. Due to its inherent disadvantages like bulkiness, fixed compensation etc. they are replaced by active filters. The Shunt Active Power Filter (SHAF) based on voltage source inverter (VSI) structure is an attractive solution to harmonic current problems. The SHAF is a pulse width modulated (PWM) voltage source inverter that is connected in parallel with the load. It has the capability to inject harmonic current into the AC system with the same amplitude but opposite in phase with the load current. The principal function of shunt active filter is compensation of load harmonic current i.e. it confines the load harmonic current at the load terminals, hindering its penetration into power system. The performance of an active filter depends mainly on the technique used to compute the reference current and control method used to inject the desired compensation current into the line. The proposed work contains the three phase wind generator connected to the diode bridge rectifier (non-linear load). The active filter is connected in parallel to the load. The inverter uses IGBT because of its high switching frequency. The structure of the system with SHAF for three phase four wire system is shown in Fig.1.The inverter circuit triggering depends on the control circuit output. The proposed system use PWM control to produce the pulse to trigger gate of IGBT. Instantaneous Synchronous reference frame (SRF) method is used in the proposed system to derive the compensating signal.

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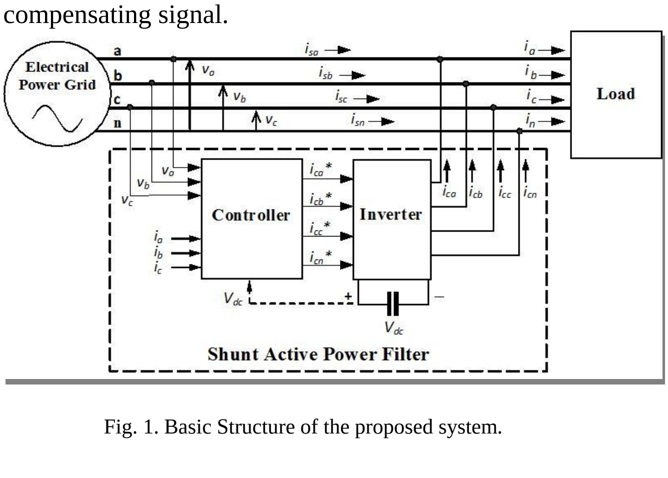

Fig. 1. Basic Structure of the proposed system.

II. HARMONICS IN ELECTRICAL SYSTEMS

A. Types of Harmonics and their Effects on the System

The presence of harmonics in electrical systems means that current and voltage waveforms are distorted and deviate from the sinusoidal waveform. One of the biggest problems

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in power quality aspects is the harmonic contents in the electrical system. Generally, harmonics may be divided into two types: 1) voltage harmonics, and 2) current harmonics. Current harmonics are usually generated by harmonics contained in voltage supply and different types of loads such as resistive load, capacitive load, and inductive load. Both harmonics can be generated by either the source or the load side. Harmonics generated by load are caused by nonlinear operation of devices, including power converters, arc-furnaces, gas discharge lighting devices, etc. Load harmonics can cause overheating of the magnetic cores of transformer and motors. On the other hand, source harmonics are mainly generated by power supply with non-sinusoidal voltage waveform. Voltage and current source harmonics imply power losses, Electromagnetic Interference (EMI) and pulsating torque in AC motor drives.

B. Quantifying Harmonics

Any periodic waveform can be shown to be the superposition of a fundamental and a set of harmonic components. By applying Fourier transformation, these components can be extracted. The frequency of each harmonic component is an integral multiple of its fundamental. There are several methods to indicate of the quantity of harmonics contents. The most widely used measure is the Total Harmonic Distortion (THD), which is defined in terms of the amplitudes of the harmonics, Hn, at frequency nW0, where Wo is frequency of the fundamental component whose amplitude of H1 and n is integer. The THD is mathematically given by

$$\frac{\sqrt{H_{(1)}^2 + H_{(2)}^2 + H_{(3)}^2 + \ldots\ldots}}{H_{(1)}} \quad (2)$$

III. SYSTEM DESCRIPTION

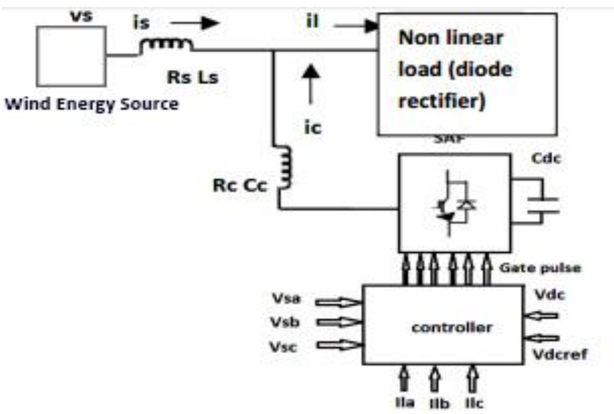

Fig. 2. Basic Structure of the SHAF

A. Wind turbine generator (WTG)

The wind turbine is intended to operate at a variable-speed over a wide range for the Wind Turbine Generator (WTG) to generate maximum power at low wind speeds, and to operate at constant speed and constant power at high wind speeds. Then, the conventional synchronous generator is used to produce AC electric energy of variable frequency over a wide range. Synchronous generators are preferred as they are cheaper than other generators which makes them economically viable. The WTG discussed in this paper consists of a) A wind turbine with horizontal axis 30 m three blade rotor that can produce 1.5 MW nominal power, b) A gear-box to multiply velocity from a 25 rpm turbine rotor to 1800 rpm generator rotor, c) A three- phase wound-rotor synchronous generator. The WTG equation is given by

$$Pm = 0.5Cp*\rho*A*(Vwind)^3 \quad (1)$$

Where Pm is the mechanical output power of the turbine (W), Cp is the performance coefficient of the turbine, ρ is the air density (Kg/m^3), A is the turbine swept area (m^2). Vwind is the wind speed (m/s).

B. SHAF and its Compensation Principle

The SHAF uses power electronic devices to mitigate the harmonic content in the power system. The filter consists of six IGBTs present in three arms of a bridge and a capacitor in parallel to the arms of the bridge named DC link capacitor. The gating pulses to these IGBTs are provided by the PWM pulse generator. The SHAF is controlled by using PI controller and FLC, to draw/supply the compensating current from/to the load to cancel out the current harmonics on AC side, to maintain the DC link voltage constant by maintaining the real power flow in the system and reactive power flow from/to the source, thereby making the source current in phase with source voltage. When the load condition changes, the real power in the system i.e. between the mains and the load also changes. Due to this imbalance of the real power in the system, the system performs improperly. This real power disturbance is cleared by the DC link capacitor. In doing so, voltage across the DC link capacitor changes to a value different compared to the reference value.

C Control Strategy

The control strategy proposed in this paper is the Synchronous Reference Frame Phase-Locked Loop (SRFPLL). Owing to its simple structure, robustness, and effectiveness, the SRFPLL is probably the most popular and widely used technique for extraction of information about the grid fundamental component in three-phase systems. The basic function of the PLL is a feedback system with a PI-regulator tracking the phase angle. Input is the three phase grid voltage and output from the PLL is the phase angle of one of the three phases. In the power supply substation there will be one inverter leg for each of the three phases Fig. 3 shows the block diagram description of this PLL. In this PLL, as shown, the stationary (αβ) coordinate voltages (which are obtained by applying the Clarke transformation to the three-phase voltages) are transformed to the synchronous reference frame by applying the Park transformation. The dq reference frame angular position is regulated using a feedback control loop which forces vq to zero. Typically, a proportional-integral (PI) controller is used as the loop filter (LF). The main advantage of this method is that it is efficient in harmonic compensation for both sinusoidal and non-sinusoidal sources.

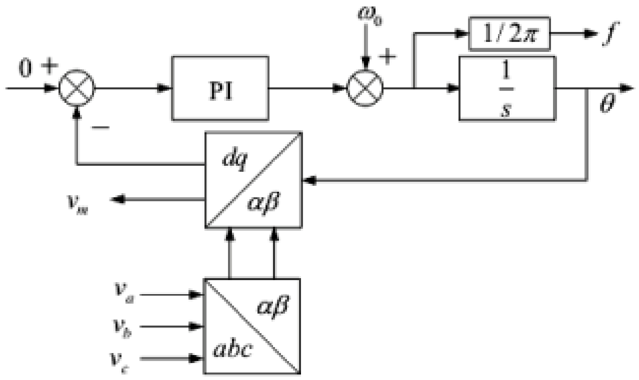

Fig. 3. SF-PLL Block Diagram.

IV. PI CONTROLLER

A. Working Mechanism of PI Controller

Proportional Integral Controller or PI controller is a control loop feedback mechanism. A PI controller continuously calculates the error between a set point value and the process variable. Fig. 5 shows the internal structure of the control circuit. The control scheme consists of PI controller, limiter and three phase sine wave generator for reference current generation and generation of switching signals.

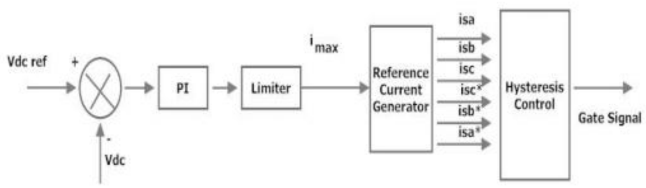

Fig. 5. Control Scheme with PI Controller.

Vdc ref is a user-defined reference value (say 500V), Vdc is the voltage across the DC link capacitor. The error signal after comparing these two voltages is given as the input to the PI Controller. The output of the controller is assumed as the maximum current imax. This signal is then passed through the limiter which keeps the current value in check. The PLL acts upon this signal and produces the reference currents. The reference current generation is explained in the next segment. These reference currents are compared with the three phase system currents and the error signal is given to the PWM pulse generator. The pulse generator produces six different gating pulses to turn on/off the six IGBTs in the inverter which in turn injects/withdraws compensating current from the circuit.

B. Generation of Reference Currents

There are several methods for reference current generation for shunt active power filters. One such technique is using PLL and PI controller. The block diagram of this controller is shown in Fig. 4. The controller design consists of PI controller, PLL and hysteresis band pass controller and then the inverter circuit. The DC side consists of a capacitor and the capacitor voltage is sensed and compared with the reference voltage. The error voltage is given to the input of the PI controller

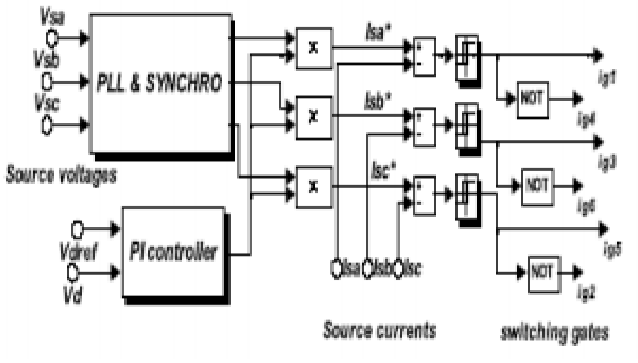

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Fig. 4. Reference Current Generation using SF-PLL technique

The PWM is used to control the voltage across the DC capacitor. The PI controller is used to minimize the error. The transfer function can be represented as follows.

$$H(S) = K_p + K_i/s \tag{3}$$

Where Ki is the integration constant that determines the settling time and Kp is the proportional constant. The Phase Locked Loop gets the system voltages (Vsa, Vsb, Vsc) as input. The output of PLL block is ia_1, ib_1, ic_1 three phase currents. The PLL output is multiplied with the PI controller and the output is the desired reference current. The next part is the hysteresis band pass controller. The Hysteresis band pass controller is one of the easiest way for giving signal to the inverter. An error signal is used to control the switches in a PWM-VSI. This error is the difference between the desired current reference signal and the current being injected by the inverter. If the error exceeds the upper limit of the hysteresis band, the upper switch of the inverter is turned on and the lower switch is turned on. As a result the current starts to decay. If the error current crosses the lower limit of the hysteresis band pass controller, the lower switch of the inverter is switched off and the upper switch is turned on. As a result the current value gets back into the hysteresis band.

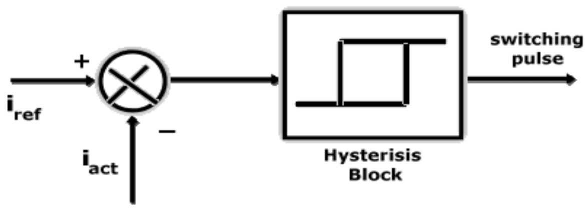

Fig. 6. Hysteresis control.

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V. FUZZY LOGIC CONTROLLER

A Fuzzy Control System is a control system based on fuzzy logic- a mathematical system that analyses analog input values in terms of logical variables which takes continuous values between 0 and 1, in contrast to digital logic which operates on discrete values of 0 or 1. The FLC system consists of the stages as shown in the Fig. 7.

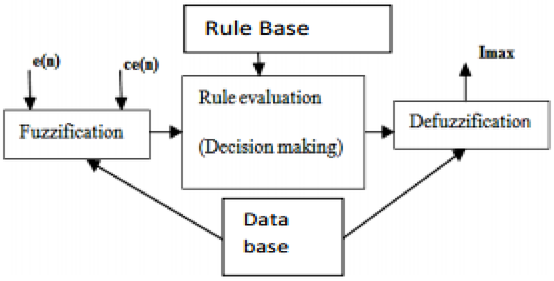

Fig. 7. FLC Block Diagram

A. Fuzzification

In a control system, error between reference and output can be labeled as zero (ZE), positive small (PS), negative small (NS), positive medium (PM), negative medium (NM). The process involves converting a numerical variable to a linguistic variable; five-set triangular membership function are developed for the fuzzification as shown in Fig.8.

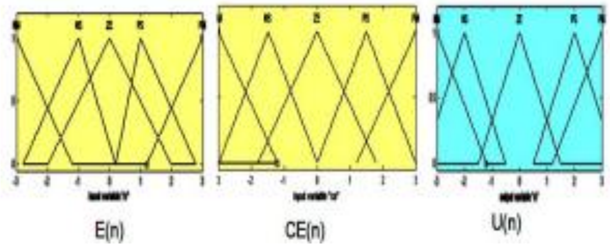

Fig. 8. Membership Function for Input and Output Variables

B. Rule Elevator

The basic fuzzy set operation needed for evaluation of fuzzy rules is AND (∩) OR (U), NOT (−).

C. Defuzzification

The rules of FLC generate required output in a linguistic variable format (fuzzy number), according to real world requirements, linguistic variables have to be transformed to crisp output (real number). In this paper, the Center of Gravity (COG) method of defuzzification was used. First, results of the rules must be added. Usually, the fuzzy membership functions are triangular. This triangle is chopped off at some height from the base forming a trapezoid. These trapezoids thus formed are superimposed and the centroid of the resultant geometric shape obtained is the crisp value.

D Rule Base

The Rule base stores the linguistic control rules required by rule evaluator, the 25-rules as shown in the table below.

Table 1: Rule Base Table.

e(n)\ce(n)	**NM**	**NS**	**ZE**	**PS**	**PM**
NM	**NM**	**NM**	**NM**	**NS**	**ZE**
NS	**NM**	**NM**	**NS**	**ZE**	**PS**
ZE	**NM**	**NS**	**ZE**	**PS**	**PM**
PS	**NS**	**ZE**	**PS**	**PM**	**PM**
PM	**ZE**	**PS**	**PM**	**PM**	**PM**

VI. FUZZY SYSTEM

Fig. 9 shows the internal structure of the control circuit for fuzzy logic controller. The control scheme consists of FLC, limiter and three phase sine wave generator for reference current generation and generation of switching signals.

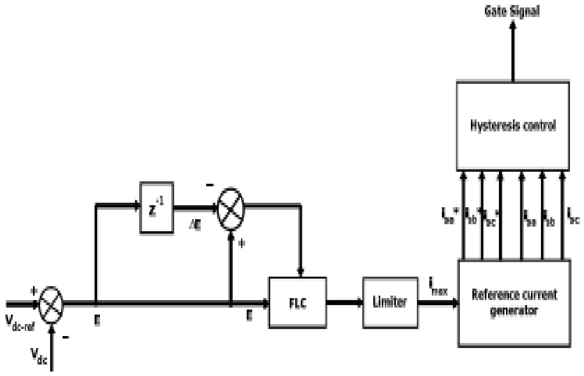

Fig 9. Control Scheme with FLC

The new value of capacitor voltage is now compared with a reference voltage and a difference signal or error signal is given to the FLC. The error signal is then processed through a FLC, which contributes to zero steady error in tracking the reference current signal. The output of the FLC is considered as peak value of the supply current (Imax) and using it the reference currents are generated and then through them the gating signals are generated. The only difference between PI and FLC is that FLC requires an additional input: the previous value of the error signal which is indicated by passing the error signal through the delay element (z^{-1}).

B. Reference Current Generation

The reference current generation scheme is same as that of PI controller.

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VII. SYSTEM DESIGN PARAMETERS

Table 2: System Design Specifications

Parameter	Numerical Value
Pitch angle of wind turbine	12 degrees
Initial wind speed of turbine	15 m/s
Nominal mechanical base power of wind turbine	1.5e6 W
DC capacitor and capacitor reference voltage	2e-3F, 500V
Source resistance, source inductance	30ohms, 10mH
Diode rectifier non-linear load resistance and inductance	25ohms,0.5mH
Filter inductance and capacitance	3mF, 10e-3mH
FIS type for FLC	Mamdani
Membership function	5*5 triangular
Implication for FLC	Min
Defuzzification method	Centroid

VIII. SIMULATION AND RESULTS

The system with PI and FLC controllers were both simulated in the Simulink environment. The Circuit Breaker is closed after 25s. Therefore, the waveform before 25s is the open loop and and that after 25s is the closed loop outputs. The output waveforms are as shown below.

A. PI Waveforms

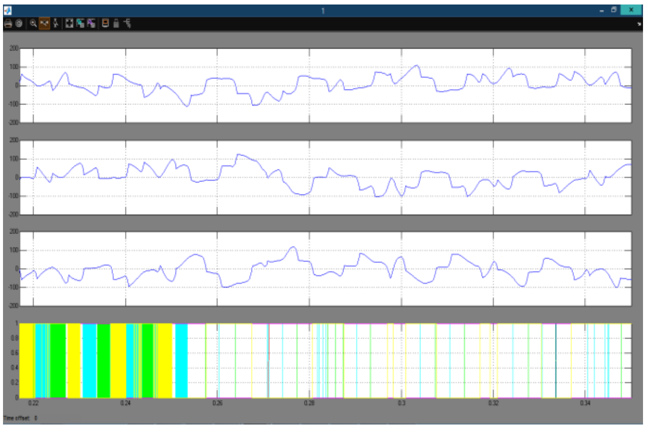

Fig. 10. Compensating Current from the SHAF vs time

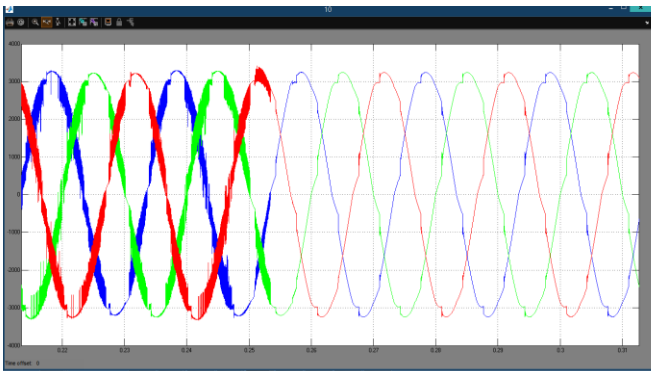

Fig. 10. System Current (Source side) vs time

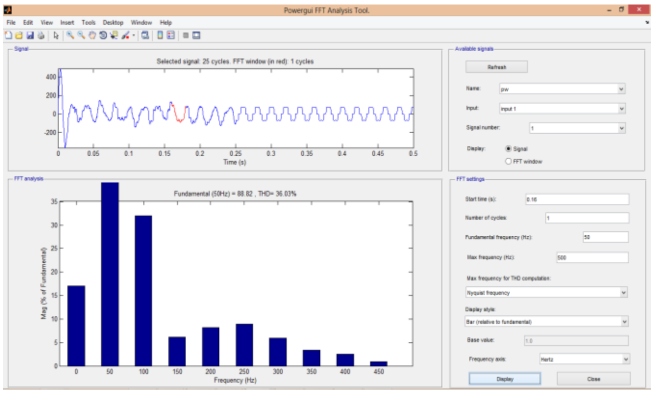

Fig. 11. THD and FFT analysis for the open loop system

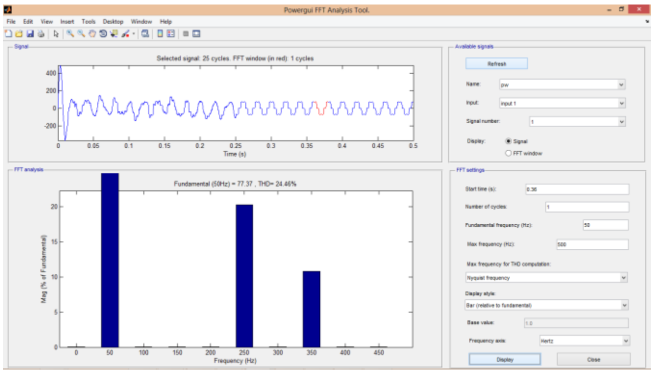

Fig. 12. THD and FFT analysis for the closed loop system

B. FLC Waveforms

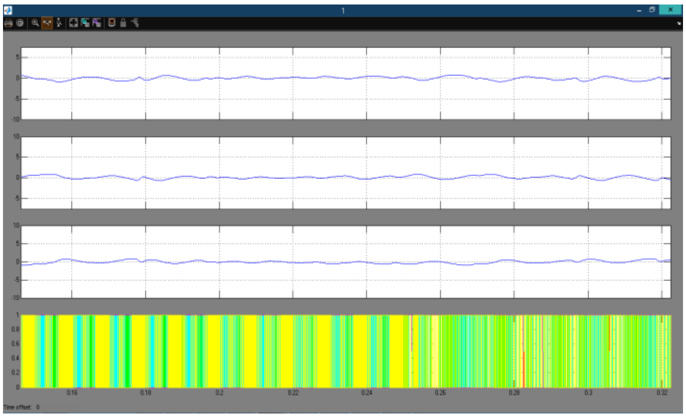

Fig. 13. Compensating Current from the SHAF vs time

Table 3: THD Values for Open Loop System.

CONTROL TYPE	THD (%)
OPEN LOOP	36.03
PI	24.46
FLC	10.32

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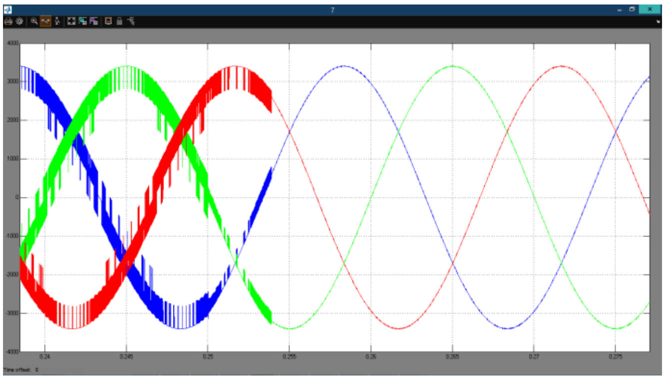

Fig. 14. System Current (Source side) vs time

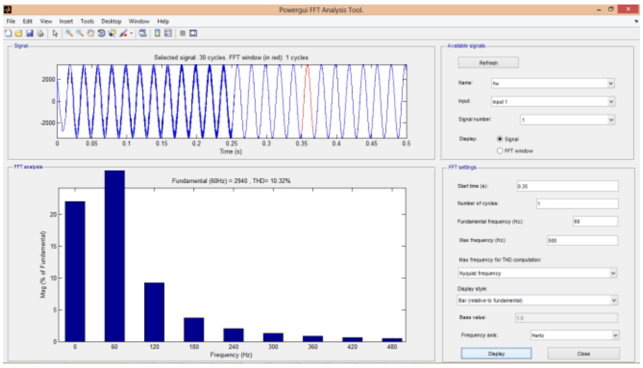

FIG. 15. THD AND FFT ANALYSIS FOR THE CLOSED LOOP SYSTEM

IX. ANALYSIS OF RESULTS

The THD values for the open loop, PI and FLC are tabulated in table. The THD values clearly indicate the superiority of FLC over PI controller. The output graphs in the previous section shows that the system contains more harmonics, i.e. there is more distortion in the waveform before 25s (open loop). The distortions have reduced after 25s for both the controllers, more significantly so for FLC. This observation is corroborated by the THD values of the system current at different times and different controllers. This is followed by replacing the wind turbine generator with an ideal three phase AC source. The results are tabulated in table 4. These results clearly indicate that the performance of PI (THD=7.24) and FLC (THD=5.12) are almost the same compared to the wind source load system where FLC (THD=10.32) has clearly outperformed the PI controller (THD=24.46).

Table 4: THD values for wind-load system

CONTROL TYPE	THD (%)
OPEN LOOP	29.31
PI	7.24
FLC	5.12

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