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VOLTAGE REGULATION OF A THREE PHASE PWM INVERTER OF A STANDALONE DG UNIT USING FUZZY CONTROLLER

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Abstract— **This paper provides a control scheme for regulating the voltage of the three phase PWM inverter of a standalone DG unit. The standalone and grid connected operations of DG helps in generation by improving power quality and reliability. This control scheme regulates the voltage effectively in the presence of system uncertainties without much reduction when compared to the supply voltage. Fuzzy controller is used to regulate the voltage and also controls the current and harmonics. The proposed controller works effectively even in the existence of non linear load. The proposed system further lowers the THD value to give better performance.**

Keywords— Fuzzy controller, Distributed Generation (DG) unit, voltage control, standalone.

Introduction

DG unit can operate in both grid connected and standalone mode, in grid connected mode the grid faults may occur. In case of these faults, it gets isolated and operates in standalone mode to provide electricity to local loads simultaneously. While in standalone operation DG units are able to feed local loads with accurate voltage and frequency. With power demand dependency multiple DG units can be connected in parallel which causes load sharing issues between these units. Many control methods based on cascade control structure has been designed to avoid those issues which happens when connecting multiple DG units in parallel. The cascade control structure comprises of active & reactive power controllers in outer loop and load & frequency controllers in inner loop using droop and phase-locked loop controllers respectively [2]-[4]. A load current observer based adaptive control technique of a standalone DG unit is employed using voltage control strategy. It combines both adaption control term and state feedback control term. The adaption control term compensates for system uncertainties and state feedback control term converges the error dynamics to zero. It provides better performance under variable load conditions but the controller and observer used in this technique depends on the filter capacitance value. It also lacks in design procedure for tuning the gain of feedback control term [5]. An another method known as adaptive voltage control method which is applied for standalone DG unit which has adaptive compensating term and stabilizing control term. The adaptive compensating term is used to avoid calculating the time derivatives of the state variable directly and stabilizing control term is used to stabilize the error dynamics of the system asymptotically. This control algorithm is complicated and the cost is also high because it requires load current sensor behalf of load current observer [6]. Feedback linearization control technique provides a power balance between the inverter output terminal and the load condition. The input output linearization can make the non linear model to linear which can guarantee fast dynamic response and reduces the THD to lower level. But this algorithm also depends on the parameters of LC filter [7]. Differential flatness technique based control method is used to define the behavior of the state variable system in the steady state as well as in transients. It uses only one control loop which can obtain high dynamic properties of the system and reduces the harmonic distortion of the output voltage. However, this algorithm provides sluggish transient response and meets high computational burden [8].

A load current observer is used to predict the behavior of the output voltage switching state for a sampling interval and enhancing the behavior by load current estimation without increasing the number of sensors. This observer gain highly depends on the accuracy of filter capacitance and inductance and the THD is still high [9]. An iterative learning control strategy comprises of two methods, which includes direct iterative learning control and hybrid iterative learning control schemes. A zero- phase filter is designed in the frequency domain which is applied to provide compensation for resonant peak and to ensure error convergence. It can achieve good performance and increases the robustness but the design procedure is complicated [10].

This paper presents a fuzzy adaptive voltage control strategy for the three phase PWM inverter of a standalone DG unit in the presence of system uncertainties. It includes voltage control technique which has simple control structure and regulates the voltage effectively. Even though the voltage is regulated it does not differ much from supply voltage even in the existence of non linear load using the fuzzy controller. The voltage is controlled precisely in the presence of non linear load and the harmonic content is very small using fuzzy controller. While using filter, the current is highly controlled and reduces the harmonic contents. The proposed controller is robust to system uncertainties as they do not require information regarding system parameters and load currents. Simulation results are given to confirm the validity of the proposed controller based control scheme under non linear load.

The outline of the paper is as follows. A space vector PWM inverter is analyzed in section I, a fuzzy controller is described in section II, simulation results are presented in section III and conclusions are summarized in section IV.

I. DESIGN OF SVPWM

Space vector is a digital modulating technique whose objective is to generate PWM load line voltages which are in average equal to a given load line voltage. The approximation of sinusoidal line modulating signal with eight space vectors is the objective of space vector switching. Space vector PWM is utilized in order to generate symmetrical PWM pulse to six power switches of the three phase inverter because of its advantages of providing the load with less harmonic voltages. The selection of the states and their time periods are accomplished by the space vector (SV) transformation.

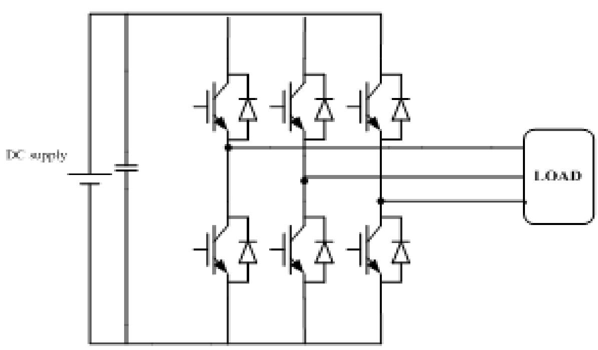

Fig. 1. Three phase PWM inverter

A. Space Vector Transformation

The three phase voltages of a balanced supply v_a, v_b and v_c with a peak value V_m are given by,

$$v_a = V_m \sin \omega t \quad (1)$$

$$v_b = V_m \sin(\omega t - 2\pi/3) \quad (2)$$

$$v_c = V_m \sin(\omega t + 2\pi/3) \quad (3)$$

Thus, the space vector representation is

$$v(t) = V_m e^{j\theta} = V_m e^{j\omega t}$$

which is a vector of magnitude V_m rotating at a constant speed in rads per second.

The vectors of three phase modulating signals $[v_s]_{abc}$=$[v_{sa} v_{sb} v_{sc}]^T$ can be represented by the complex vector $G^* = V_s = [v_s]_{\alpha\beta} = [v_{s\alpha} v_{s\beta}]^T$ are given by

$$v_{s\alpha} = \frac{2}{3}[v_{sa} - 0.5(v_{sb} + v_{cs})] \quad (4)$$

$$v_{s\beta} = \frac{\sqrt{3}}{3}(v_{sb} - v_{sc}) \quad (5)$$

The approximation of the line modulating signal V_s with the eight space vectors ($V_z, z = 0,1,....,7$) can be used by a sampling period with intervals given by T_1, T_2,… T_z respectively.

(i) $\vec{v}_1$ - $\vec{v}_2$ - $\vec{v}_z$

(ii) $\vec{v}_z$ - $\vec{v}_1$ - $\vec{v}_2$ - $\vec{v}_z$

(iii) $\vec{v}_z$ - $\vec{v}_1$ - $\vec{v}_2$ - $\vec{v}_1$ - $\vec{v}_z$

(iv) $\vec{v}_z$ - $\vec{v}_1$ - $\vec{v}_2$ - $\vec{v}_z$ - $\vec{v}_1$ - $\vec{v}_2$ - $\vec{v}_z$

which is defined by SVM.

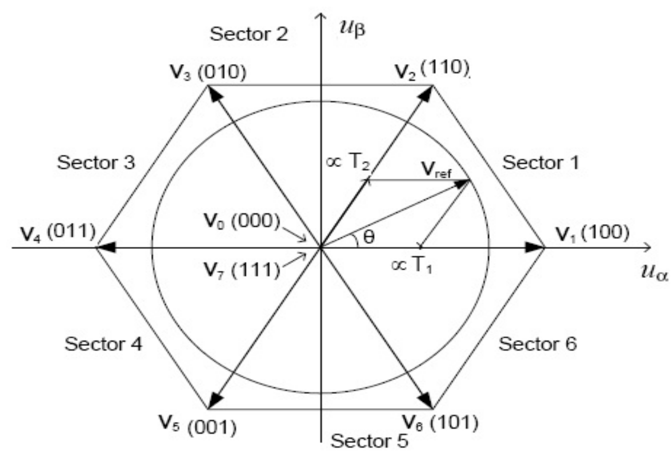

Fig. 2. Space vector transformation

B. Space- vector sequences and Zero Space- vector Selection

The sequence has to be used featuring quarter wave symmetry should ensuring load line voltages in order to reduce unwanted harmonics in their spectra (even harmonics). Moreover the zero SV selection must be done for reducing the switching frequency. Even though there is a systematic approach to generate SV sequence which can provide high performance to minimize the unwanted harmonics and to reduce the switching frequency.

The normalized carrier wave frequency in three phase carrier based PWM techniques can be used to minimize parasitic or non- intrinsic harmonics in the PWM waveforms. Likewise, there is a similar approach to minimize uncharacteristic harmonics which is normalized sampling frequency f_{sn} that should be an integer multiple of 6. PWM controls the average output voltage over a sufficiently small period called sampling period or sub-cycle by producing pulses of variable duty-cycle.

II. DESIGN OF FUZZY CONTROLLER

Fuzzy logic is a mathematical method used to solve complex problems with input and output variables. Fuzzy logic can provide results in the form of recommendation for a specific interval of output state. In this terminology, a fuzzy control rule is a conditional statement in which the antecedent is a condition in its application domain and the consequent is a control action for the system under control. Fuzzy logic has the advantages of providing solution to the problem that can be understand by human operator which can be used in the design of the controller.

A. Fuzzy Controller

The input variables of the fuzzy control system can be mapped by sets of membership functions using fuzzy sets. Here the fuzzification process is accomplished by converting the crisp values into fuzzy values. The mappings of input variables into membership functions to make decisions based on set of fuzzy rules. In this paper, the fuzzy logic controller determines the dynamic behavior of a fuzzy system that can be characterized by a set of linguistic description rules based on expert knowledge. The fuzzy system can be accomplished by system's operational specifications with its inputs and outputs. The fuzzy controller consists of five parts which are rule base, database, decision making unit, fuzzification interface and defuzzification interface. The rules are framed in rule base and the membership function is defined in database. The decision making unit determines the interference operation, the fuzzification interface converts crisp inputs into linguistic fuzzy sets and the defuzzification interface converts those sets into crisp outputs.

B. Fuzzy Logic Rules

The fuzzy rules are represented by a sequence of the form antecedent and consequent for describing on action or output must be taken by currently observed information which includes both input and feedback. The fuzzy rule associates a condition using linguistic variables and fuzzy sets to an output or a conclusion. The fuzzy control rules used in this paper is based on fuzzy implication rules which describes a generalized logic implication relationship between inputs and outputs. Fuzzy implication rules are related to classical multiple valued logic in this system. This work has 2 inputs and 7 membership function and forms 7*7 combinations thus giving 49 rules. These rules make all possible combinations for providing the essentials of this system to get the required results in voltage regulation. The fuzzification process compares the input values with their membership functions to obtain a linguistic fuzzy variable. Combine those membership values and generate qualified consequents to obtain a crisp output by defuzzification process.

The fuzzy implication rules framed in this paper is based on mamdani fuzzy interference system. This system when provided by fuzzy toolbox has a output membership functions with fuzzy sets. After aggregation the fuzzy set for each output variable needs defuzzification. These rules are a collection of linguistic statements which describes the making of the decision of fuzzy interference system regarding classifying an input and controlling an output. This interference system enhances the efficiency of defuzzification process which simplifies the computation needs required by other FIS.

ce / e	**LN**	**MN**	**SN**	**ZO**	**SP**	**MP**	**LP**
LN	LP	LP	LP	MP	MP	SP	ZO
MN	LP	MP	MP	SP	ZO	SN	SN
SN	LP	MP	SP	SP	ZO	SN	MN
ZO	MP	MP	SP	ZO	SN	MN	MN
SP	MP	SP	ZO	SN	SN	MN	LN
MP	SP	ZO	SN	MN	MN	MN	LN
LP	ZO	SN	MN	MN	LN	LN	LN

Table 1. Fuzzy rules

The above fuzzy inference rules provides the proper conditions for the controller to which the control system has to be operated in the desired way. Finally the output provides a specific control output value based on the above rules and specifications.

III. SYSTEM DESCRIPTION & RESULTS

In this paper, the standalone DG unit is made of four parts such as a dc-link voltage (V_{dc}) from renewable energy sources, a three phase PWM inverter, an LC output filter (L_f and C_f), and a three phase load. The reference voltage is given as dc-link voltage which provides 230V supply in the source side. This dc-link voltage supply is fed to the source side of the inverter to generate pulses using the controller. In this work, the Space Vector Pulse Width Modulation inverter is utilized in order to generate symmetrical PWM pulse to six power switches of the three phase inverter which can provide the load with less harmonic voltages. The fuzzy model along with its input variables are extracted from the input output data of the system that is being modeled with the help of rules derived. The proposed controller directly fed to the gate pulses of the inverter which controls and rectifies the voltage as well as current given to the system. It also reduces the level of harmonics present in the system to produce a desired performance.

The gate pulses which are controlled is fed to the inverter and the controlled signals are given to the filter which lowers the power quality issues and provides better reliability and integrity to the system. The LC filter is used in this work to reduce the Power Quality issues caused by the system. The component L in the filter is the total inductance includes source or line inductance and is generally placed at the input side to act as an inductance instead of dc choke. The component C has to be large so that its voltage is ripple free with an average value of V_{dc}. The filter is connected to the load so that the voltage does not get affected as the filter can be capable of reducing the harmonic contents. The load can be any sort such as non linear loads, unbalanced loads, the system provides good results. The proposed method gives better outcome even in the existence of non linear load. The block diagram for the proposed system is given by fig. 3.

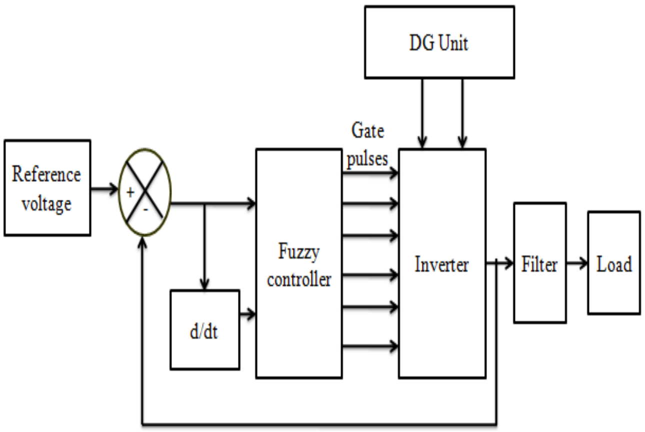

Fig. 3. Block diagram for the proposed work

The conventional voltage controllers need the information of the time derivative of the load voltage. This derivative term can be directly calculated from the load voltage. However this direct method cannot accurately obtain the derivative term due to high frequency noises. The proposed system also enhance the control performance (i.e., low THD). The control performance can get better if the number of the fuzzy rules and membership functions increased. In order to assess the voltage regulation, a three phase PWM inverter which is connected to an RLC load on the DC side is utilized as a nonlinear load. In this case, the non linear load is considered to demonstrate the robustness for the system. The results are analysed when the controller is tuned with and without filter.

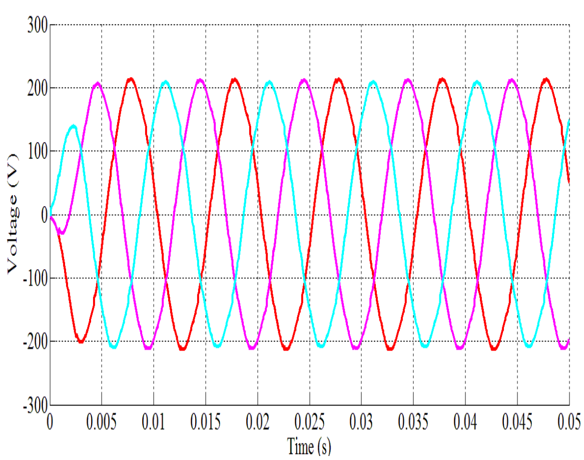

Fig. 4. Output voltage of the inverter using Fuzzy controller without filter

When analyzing the controller output without filter, the wave shape of the output voltage is shortly distorted and the harmonic presence is slightly greater than output voltage with filter. While analyzing the controller output without filter, the wave shape of the output current is highly distorted and the harmonic presence is slightly greater than output current with filter. It can be validated by the THD analysis of the output voltage of the inverter without and with filter.

The supply voltage given to the inverter is 230 V which is connected to the non linear load. Now the voltage is regulated using fuzzy controller. Even then it produces above 200 V which denotes the efficiency of the controller is shown in fig. 4. Thus it shows the clear benefit of using this fuzzy controller for voltage regulation.

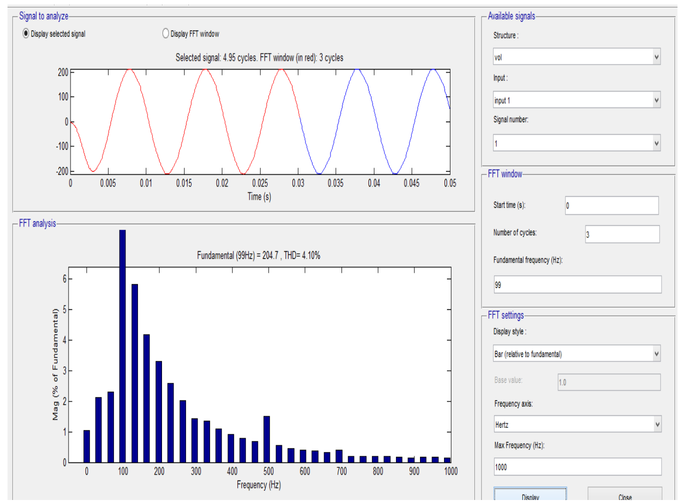

Fig. 5. THD analysis for the output voltage of the inverter without filter

The presence of harmonic content is less because the THD is basically low even without filter. The THD of output voltage of the inverter without filter is 4.1% is shown in fig. 5. which is very less when compared to the conventional techniques [1].

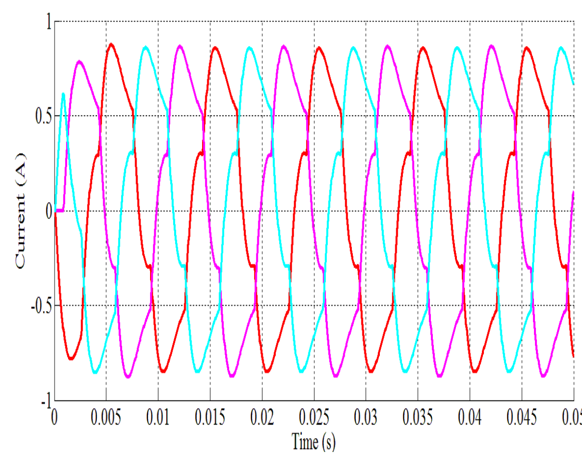

Fig. 6. Output current of the inverter using Fuzzy controller without filter

The main theme of this work is to regulate the voltage but while using this fuzzy controller the current is also controlled up to certain level which also denotes the efficiency and robustness of the controller is shown in fig. 6.

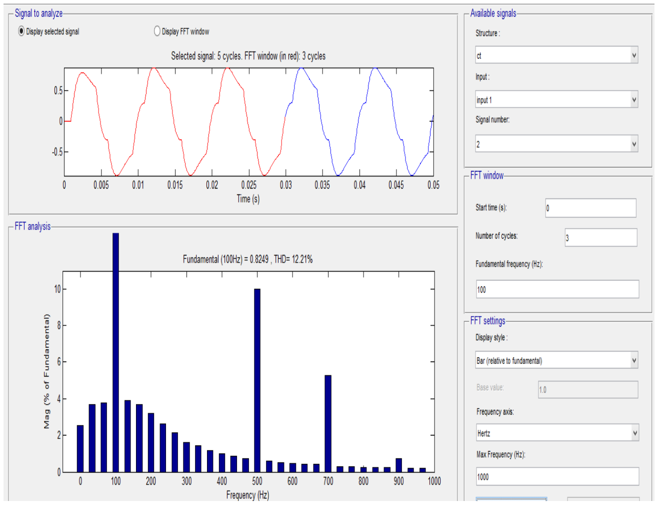

Fig. 7. THD analysis for the output current of the inverter without filter

The presence of harmonic current is clearly visible as the THD is 12.21% without filter which is comparatively high is shown in fig. 7. The current is controlled precisely using fuzzy controller but the THD is high without filter.

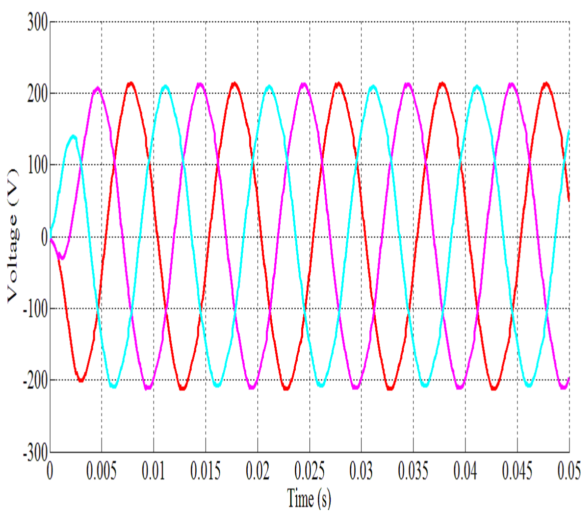

Fig. 8. Output voltage of the inverter using Fuzzy controller with filter

The output voltage of the inverter using filter is much similar to that of using without filter which is shown in fig. 8. The only difference is that the THD value is slightly reduced and the RMS value of the voltage is same.

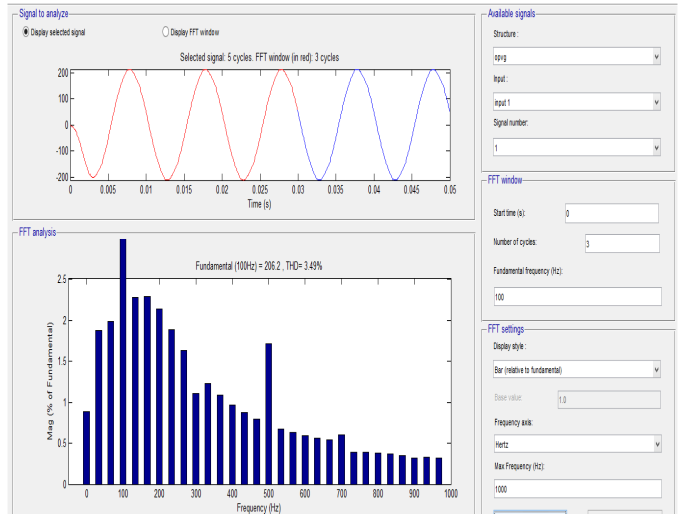

Fig. 9. THD analysis for the output voltage of the inverter with filter

The THD of output voltage of the inverter with filter is 3.49% is shown in fig. 9. Thus voltage can be regulated efficiently even without filter using Fuzzy controller which proves the robustness and cost effectiveness of the system.

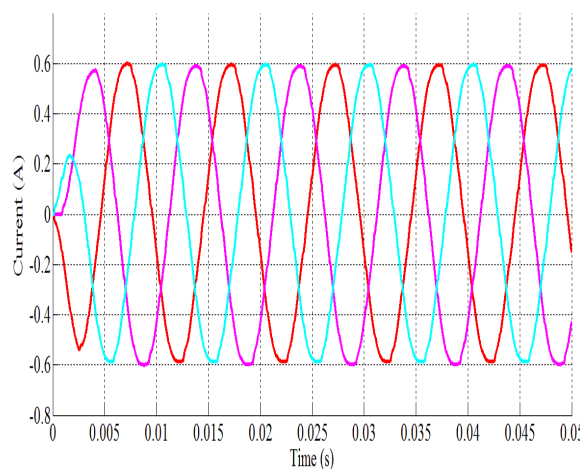

Fig. 10. Output current of the inverter using Fuzzy controller with filter

The current is controlled to the maximum extent as it produces the sinusoidal voltage when non linear load is given to the inverter. This sinusoidal waveform depicts the reduction in harmonic contents present in this system as the THD is 6.85% with filter which is shown in fig. 11. The THD becomes less while using filter.

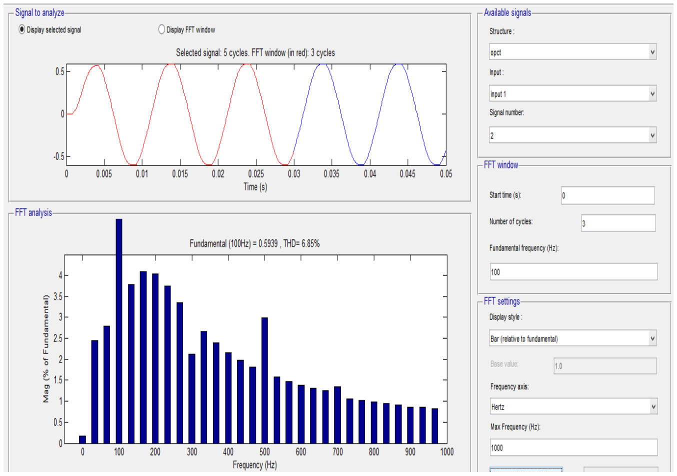

Fig. 11. THD analysis for the output current of the inverter with filter

It is seen that the steady state response of the fuzzy control system achieves lower THD when compared to other control schemes [1]. It is evident that the load voltage of the fuzzy controller is recovered to steady state is faster. The output voltage of the inverter using fuzzy controller is regulated to RMS value even without filter.

IV. CONCLUSION

In this work, the fuzzy controller regulates the voltage and current for the three phase PWM inverter of a standalone DG unit. This system provides a voltage control loop which directly controls the voltage which in turn controls the current and thus provides fast transient response. This control method gives a lower THD in the presence of non linear load. The voltage is regulated to the higher extent without filter and the current is controlled to certain level using filter. The fuzzy controller, however, regulates the voltage and controls the current even in the existence of above uncertainties and provides better performance.

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