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Voltage Control of Variable Speed Induction Generator Using PWM Converter

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Abstract— The paper describes a simple control structure for a stand-alone Induction Generator (IG) used to operate under variable speeds. Fuzzy Logic Control (FLC) has been developed to automatically vary the duty-cycle of the PWM converter such that to maintain the DC-link voltage constant. The required reactive power for the variable-speed IG is supplied by means of the PWM converter and a capacitor bank to build up the voltage of the IG without the need for a battery and to reduce the rating of the PWM converter with the need for only three sensors. This proposed scheme has been used efficiently for variable speed wind or hydro energy conversion systems. The measurements of the IG system at various speeds and loads are given and show that this proposed system is capable of good DC voltages regulation. The proposed system has been simulated using MATLAB-SIMULINK software and verified the theoretical analysis.

Index Terms— DC power applications, Induction Generator (IG), Pulse Width-Modulation (PWM) converter, voltage regulation.

I. INTRODUCTION

Energy is the primary and most universal measure of all kinds of work by human beings and nature. Everything that happens in the world is the expression of flow of energy in one of its forms Energy is an important input in all sectors of a country's economy. Conventional sources of energy are increasingly depleted. Hence, Non Conventional Energy Sources have emerged as potential source of energy in India and world at large. Among the various non-conventional energy sources, wind energy is emerging as the potential major source of energy for growth. Wind turbine generators (WTGs) can be divided into two basic categories: (i) fixed speed and (ii) variable speed. The fixed-speed generator has a low efficiency of wind power conversion and no ability to provide reactive power support. During the last few years, the variable speed wind turbines with Self-Excited Induction Generator (SEIG) dominant the wind energy conversion system (WECS).There are several reasons for using variable-speed SEIG based wind turbines; among those are (i)Possibilities to reduce stresses of the mechanical structure, (ii)Acoustic noise reduction and (iii) The possibility to control active and reactive power. The fixed-speed generator has a low efficiency of wind power conversion and no ability to provide reactive power support.

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It also imposes mechanical stress on the turbine and requires complex pitch control to maintain a constant rotor speed. During the last few years, the variable speed wind turbines with Self-Excited Induction Generator (SEIG) dominant the wind energy conversion system (WECS). There are several reasons for using variable-speed SEIG based wind turbines; among those are (i)Possibilities to reduce stresses of the mechanical structure, (ii)Acoustic noise reduction and (iii) The possibility to control active and reactive power.

The Induction Generator (IG), with its lower maintenance demands and simplified controls, appears to be a good solution for such applications [1]. For its simplicity, robustness and small size per generated kilowatt, the IG is favoured for small hydro-and wind-power plants. It has a great economic appeal. Standing alone, its maximum power does not go much beyond 15 kW [2]–[4]. So, we need to think in terms of a spectrum of power supplies from small (few watts) to large (close to 100 kW or more). However, the major drawbacks of the IGs are reactive-power consumption and poor voltage regulation under varying load or speed, but the development of static power converters has facilitated the control of the output voltage of the IG [5]–[9]. An induction-machine based stand-alone power generation scheme with a diode bridge rectifier and a PWM converter that uses the rotor field orientation has been proposed to control the output voltage of the diode-bridge rectifier [7]. The major drawbacks of this system are that there are serious voltage and current harmonics problems, because the output voltage is rectified by means of a diode-bridge rectifier to charge a battery and the rotor field orientation is presented to regulate the output voltage without filtering the generated current harmonics. Moreover, the magnetization curve of the IG has not been included in the proposed control system for improving the accuracy in calculating the rotor flux position. This is due to the fact that stable grid voltages are not available.

Based on the instantaneous reactive power theory, the use of a capacitor bank and an inverter simultaneously, without any mechanical speed sensor in the induction machine rotor, has been proposed [8]. In this paper, aspects are investigated related to voltage regulation, with Fuzzy logic control strategies, for a voltage source PWM converter connected to self-excited Induction Generator in wind, mini/micro-hydro energy application. Fuzzy logic based voltage controller has been proposed for voltage source PWM converter to regulate DC-link voltage. The fuzzy logic controller is designed to vary the duty-cycle of the PWM converter automatically such that to maintain the load voltage constant**.**

II. METHODOLOGY

A. Block Diagram

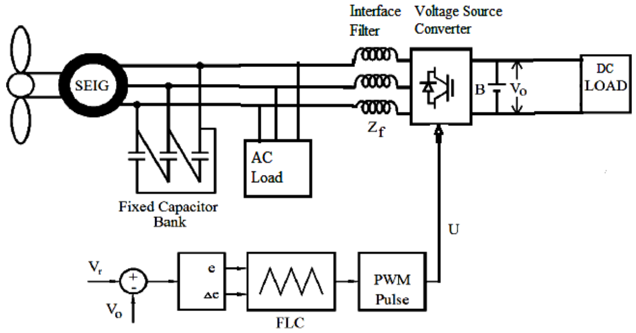


Fig. 1 Schematic diagram of voltage control of induction generator with PWM converter

The schematic diagram of the proposed induction generator is shown in Fig.1. This proposed IG consists on a conventional three-phase Self-Excited Induction Generator, wind turbine, fixed capacitor bank, voltage source PWM converter, Fuzzy Logic Controller (FLC), AC and DC loads. The Self-Excited Induction Generator (SEIG) is driven by a prime mover (PM). The stator of a induction machine is connected to an AC load, to a capacitor bank and to a voltage source converter with a DC load. The DC load may be employed in applications such as cogeneration, battery charging, heating or an association of these options. The AC load can be used in other applications, like pumping water to reservoirs in irrigation systems. The proposed control strategy is based on a Fuzzy logic controller which is useful to regulate the DC-link voltage under a variable load and speed conditions.

The fuzzy logic controller is designed to vary the duty-cycle of the PWM converter automatically such that to maintain the load voltage constant. The capacitor bank and a voltage source converter provide reactive current needed to excite the induction generator. Capacitor bank is used to supply reactive power and starting the stand alone induction generator without the need for a battery and to reduce the rating of the PWM converter. The output of an induction generator is three-phase AC source which is converted into DC using voltage source converter (VSC) and supply to the DC load. The voltage across the capacitor DC link voltage (V_o) is measured using voltage sensor and compared with the reference voltage (V_r) and an error (e) is generated. After a delay, change in error (Δe) is generated. The error and change in error is given as an input to the Fuzzy logic controller. The FLC generates gate signal which is given to the voltage source converter for appropriate IGBT switches. The FLC regulates the output voltage by generating the gate signal with appropriate duty cycle such that the voltage across the DC load is maintained constant. This proves the self-regulating mechanism of the proposed system.

B. Power Circuit and Control Schemes

Fig.2 represents the power circuit of the three-phase voltage-source converter using IGBT power modules. The output of an induction generator is converted into DC using voltage source converter (VSC) and supply to the DC load. As the converter DC voltage varies with variation in the supply voltage, to obtain constant voltage at the output terminal, a closed loop fuzzy controller is incorporated to automatically vary the duty cycle of the voltage source converter to obtain constant DC voltage. Duty cycle (D) is defined as the ratio of on time to the total time. The total time is equal to the sum of on time and off time.

$$\text{Duty cycle } (D) = \frac{T_{on}}{T} = \frac{T_{on}}{T_{on}+T_{off}}$$

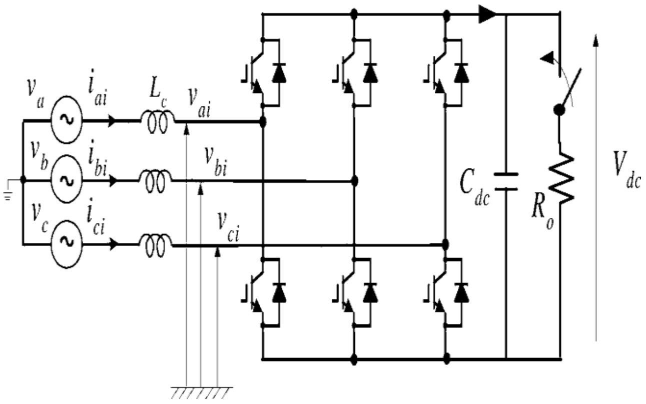


Fig. 2 Power circuit of three-phase voltage source converter using IGBT modules

C. Reactive Power Control and Capacitor Bank Switching Techniques

The equivalent circuit in Fig 3 is added to explain this situation of switching capacitor bank due to the duty cycle. The details of this circuit is given in [10]. For the circuit of Fig.3 the switches are operated in anti-phase, i.e., the switching function fs_2 which controls switch S_2 is the inverse function of fs_1 which controls switch S_1.

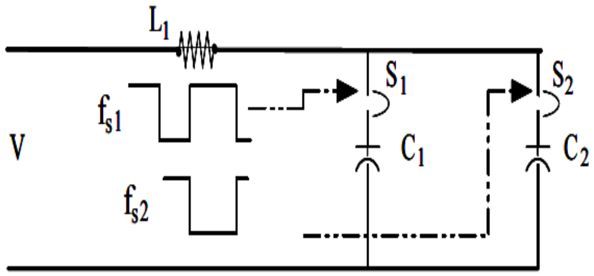


Fig. 3 Semiconductor switch (S_1, S_2) circuit for capacitor bank

In other words, switch S_2 is closed during the time when switch S_1 is open and vice versa. This mean that S_1 and S_2 of branch 1 and 2 are operated in such a manner that one switch is closed while the other is open. As shown in Fig 1, the input to the controllers is the voltage error while the output of the controllers is used to execute the duty cycle (D). The value of calculated D is used as an input to semiconductor switches to change the value of the capacitor bank according to the need for the effective value of the excitation. Accordingly, the terminal voltage is controlled by adjusting the self-excitation through automatic switching of the capacitor bank. There are different types of control schemes are Dead-beat controller, Direct vector control, Indirect vector control, Fuzzy logic controller, Direct torque control Among all the control schemes Fuzzy logic controller is highly accurate and simple. Some of the advantages of FLC over other control schemes are, simple control, very robust, can be easily modified, can use multiple inputs and outputs, much simpler than its predecessors, very quick and cheaper to implement, since they do not require the knowledge of the exact model.

III. FUZZY LOGIC CONTROLLER

Normally PI controller's used in control of PWM rectifier, here, in the control scheme; rule based fuzzy logic is established in the control strategy. One control loop are adopted, to achieve reference current tracking and DC-link regulation. The functions of the control scheme are to obtain improved power factor at the AC-side, and to obtain better voltage regulation. The use of fuzzy logic control has become popular over the last decade because it can deal with imprecise inputs, does not need an accurate mathematical model and can handle nonlinearity. Fuzzification comprises the process of transforming numerical crisp inputs into linguistic variables based on the degree of membership to certain sets. Membership functions are used to associate a grade to each linguistic term. The number of membership functions used depends on the accuracy of the controller. Fuzzy Logic Controller (FLC) is suitable for systems that are structurally difficult to model due to naturally existing non linear ties and other model complexities. A fuzzy controller determines the operating condition from the measured values and selects the appropriate control actions using the rule base creating from the expert knowledge. Fuzzy logic is appropriate for nonlinear control because it does not use complex mathematical equation. The two FLC input variables are the error (e) and change of error (Δe). The behavior of a FLC depends on the shape of membership functions of the rule base. Fig 4 shows the power circuit of fuzzy logic controller.

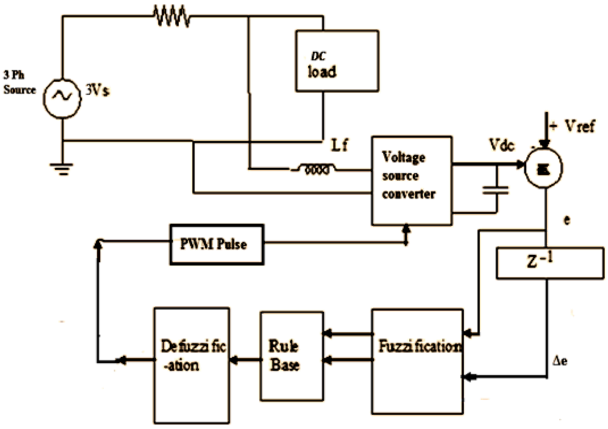


Fig. 4 Power Circuit of Fuzzy Logic Controller

Rule based fuzzy logic is used in control of PWM rectifier established in the control strategy. The functions of the control scheme are to obtain improved power factor and to obtain better voltage regulation. If the DC-side voltage is lower than the reference voltage, the output value of the Fuzzy controller will increase the amplitude of the line current command to increase the input AC power for compensation of DC-bus voltage drop. If the DC-bus voltage is higher than the reference voltage, the output value of fuzzy controller will decrease the input AC power for compensation the DC-side voltage.

A. Fuzzification

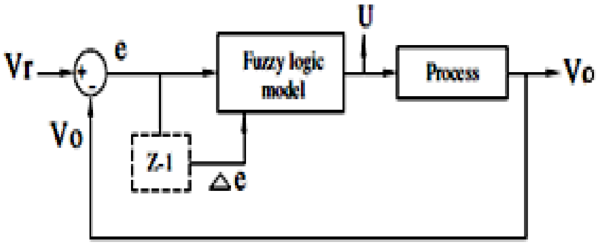


Fig. 5 Fuzzy logic control scheme

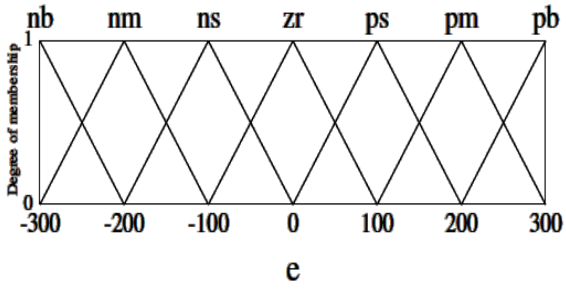
Fig 5 shows the Fuzzy logic control scheme. Fuzzification comprises the process of transforming numerical crisp inputs into linguistic variables based on the degree of membership to certain sets. Membership functions are used to associate a grade to each linguistic term. The number of membership functions used depends on the accuracy of the controller. Fuzzy Logic Controller (FLC) is suitable for systems that are structurally difficult to model due to naturally existing non linear ties and other model complexities. The membership function values are assigned to the Linguistic variables using seven fuzzy subset called as nb (negative big), nm (negative medium), ns (negative small), ze (zero), ps (positive small), pm (positive medium) and pb (positive big). Fuzzy associative memory for the proposed system is given in Table-1. Variable e and Δe are selected as the input variables, where e is the error between the reference voltage (Vr) and actual voltage (Vo) of the system, Δe is the change in error in the sampling interval. The output variable is the reference signal for PWM generator U. Triangular membership functions are selected for all these process. The range of each membership function is decided by the previous knowledge of the proposed scheme parameters.

B. Inference Engine

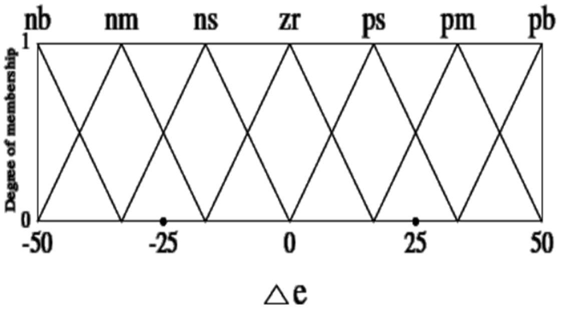
Inference engine mainly consist of Fuzzy rule base and fuzzy implication sub blocks. The inputs are now fuzzified are fed to the inference engine and the rule base is then applied. The output fuzzy set are then identified using fuzzy implication method. Here we are using MIN-MAX fuzzy implication method.

C. Defuzzification

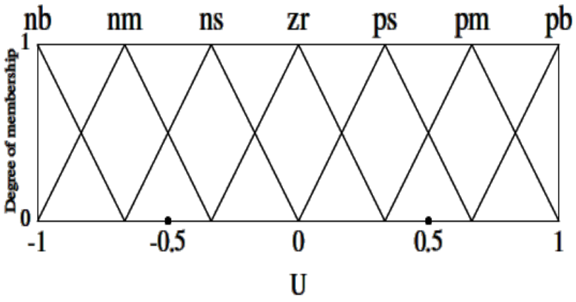
Once fuzzification is over, output fuzzy range is located. Since at this stage a non-fuzzy value of control is available a defuzzification stage is needed. Centroid defuzzification method [11] is used for defuzzification in the proposed scheme. The membership function of the variables error, change in error and change in reference signal for PWM generator are shown in Fig.6.



(a) Membership function plots for 'e'



(b) Membership function plots for ‘Δe’



(c) Membership function plots for ‘U’

Fig. 6 Membership function

Table 1. Fuzzy Associative memory for the proposed system

e	Δe						
	nb	nm	ns	zr	ps	pm	pb
nb	nb	nb	nb	nm	nm	ns	zr
nm	nb	nb	nm	nm	ns	zr	ps
ns	nb	nm	nm	ns	zr	ps	pm
zr	nm	nm	ns	zr	ps	pm	pm
ps	nm	ns	zr	ps	pm	pm	pb
pm	ns	zr	ps	pm	pm	pb	pb
pb	zr	ps	pm	pm	pb	pb	pb

IV. SIMULATION

The proposed system has been simulated using MATLAB simulink software and is shown in Fig.7. The machine parameters details are also given in table 2. The voltage and current characteristics are discussed, also, the voltage characteristics of the induction generator under varying speed and load conditions are discussed. The triggering pulses required for all switching devices are generated by using Fuzzy logic controller.

Table 2. Machine Parameters

Si No	Machine Parameters	Ratings
1	Source Voltage	200V-280V
2	Source Current	8A
3	R_S	0.9Ω
4	Frequency	50Hz
5	Inductance	5mH
6	Capacitance	100µF

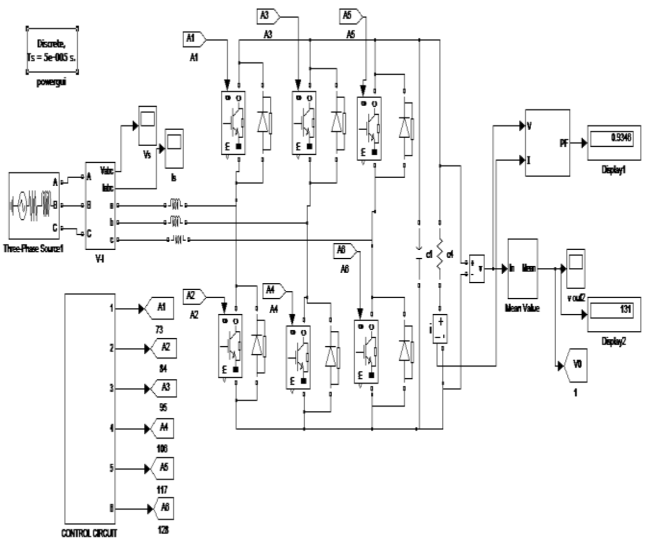
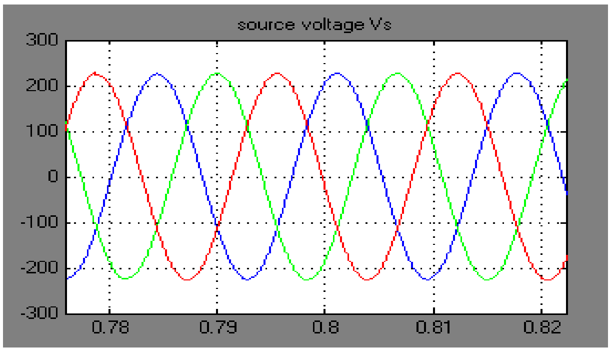


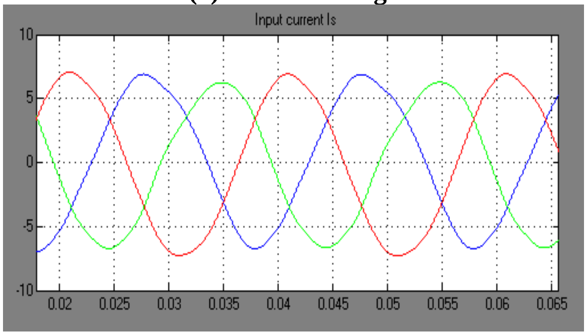
Fig. 7 Simulation diagram for Fuzzy logic Controller of IG with PWM Converter

A. *Results and Discussions*

The simulation results for three phase source current and source voltage of SEIG is shown in Fig (a) and (b). The given input voltage is varied from 200V to 280V at the same time the output voltage is maintained constant at 230V by varying the duty cycle of the voltage source converter automatically. Some harmonics have been introduced in the proposed scheme found in the waveforms it can be eliminated by introducing necessary filters. FLC is a simple control method to control the voltage across the load compared to the existing method. In the Fig (a) shows the input source voltage at 220V and the Fig (b) shows the source current at 8A..



(a) Source Voltage



(b) Source Current

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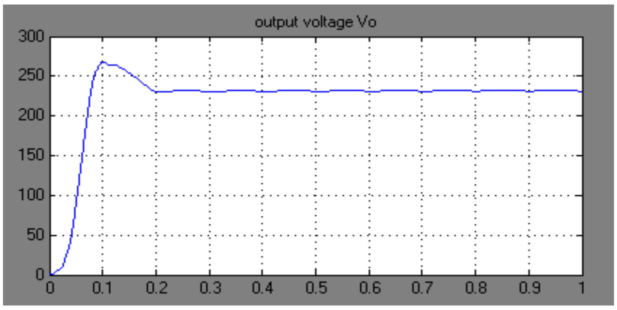
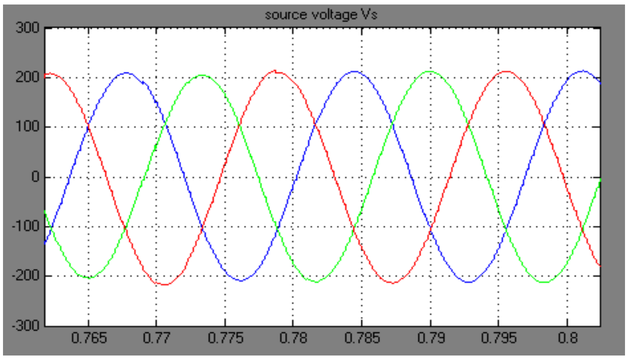


Fig. 8 Simulated Output Voltage Waveform for 230V Source Voltage

The simulated per phase voltage waveform across the load is shown in Fig 8. the output voltage is maintained constant at 237V under varying speed and load conditions. The FLC regulates the output voltage by generating the gate signal with appropriate duty cycle such that the voltage across the DC load is maintained constant.



(c) Source Voltage

In the Fig (c) shows the input source voltage at 210V. The input voltage is varied continuously with a specified limit the output voltage is maintained constant. Fig. 9 shows the output voltage.

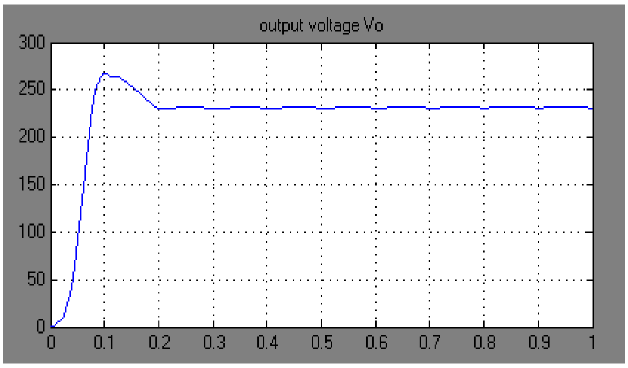


Fig. 9 Simulated Output Voltage Waveform for 210V Source Voltage

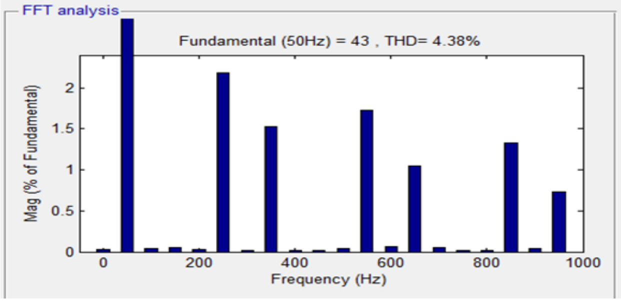


Fig. 10 FFT analysis of Source Current with Dead-Beat Controller

Fig.10 shows the FFT analysis of Source Current with Dead-Beat Controller. In the FFT analysis method used to reprsent the percentage of total harmonic distorsion available in the source current. The three phase input source current wave form is selected for harmonic analysis. In this fig 10 consider the sinusoidal input current wave form, 4.38% of the total harmonic distortion is present between the time period of 0.055 – 0.07S. Fig 11 shows the FFT analysis of source current for existing method of Dead-Beat controller. The total harmonic distortion for the existing method is 4.38%. The total harmonic distortion is reduced by fuzzy logic controller. The proposed method of fuzzy logic controller is developed for IG and PWM converter, the total harmonic distortion is reduced from 4.38% to 0.17%, and also the power factor has been improved.

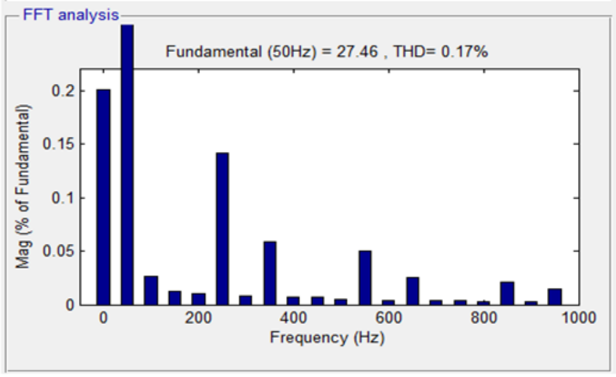


Fig. 11 FFT analysis of Source Current with Fuzzy logic control

V. CONCLUSION

In this paper, a fuzzy logic controller has been proposed for the stand-alone IG working with variable speed and supplying a DC load with voltage regulation. Fuzzy logic based voltage controller has been proposed for voltage source PWM converter to regulate DC-link voltage. In order to achieve the load voltage constant the actual voltage is compared with the reference maximum voltage and an error is calculated, accordingly the reference signal to the PWM generator is changed. The significant effects of the capacitor bank on the IG system, such as supplying reactive power and starting the stand-alone IG without the need for a battery are demonstrated. Hence, high system reliability and low system cost are achieved. In the proposed system the control of an SEIG using fuzzy logic controller is simulated in MATLAB/Simulink and the simulation results are compared with the dead-beat current controller. From the comparison, it was found that the SEIG with fuzzy logic controller attained more power factor and the total harmonic distortions were observed to be less compared with dead-beat current control. The results show that the fuzzy logic controller based SEIG has better performance which has improved harmonic profile and system performance and also better AC & DC voltage regulation can be achieved.

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