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The Future of Fuzzy Logic Based Wind Energy Conversion System with Solid Oxide Fuel Cell and the Passions of Radical Pedagogy

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***Abstract*— This paper presents a novel control system for wind energy conversion system integrated with Solid oxide fuel cell (SOFC).In recent years the Double-Fed Induction Generator (DFIG) gaining more popular due to their variable speed and variable pitch control. A dynamic model of SOFC fuel cell integrated with a doubly fed induction generator to maintain grid voltage constant 440 V and 50 Hz. The conventional vector control technique is used in the variable speed DFIG to maintain constant frequency. Existing literature used PI controller based vector control technique for the control of DFIG. In this work, fuzzy logic controller is proposed to decrease total harmonic distortion in grid current. The performance of the system for sudden load changes with PI control and proposed control technique has been obtained and compared, by using MATLAB SIMULINK.**

Keywords— Proportional-Integral Controller (PI), Fuzzy Logic Controller (FLC), Double Fed Induction Generator (DFIG), Solid Oxide Fuel Cell (SOFC).

I. INTRODUCTION

Wind energy is the fastest developing renewable energy source due to their cleanliness, safety and they can serve for a long duration. Last decade, many large wind farms have already with a cumulative installed capacity of over 17,000 MW, wind power currently accounts for almost 70 percent of the total installed capacity in the renewable energy in INDIA [1]. Recently, there has been rigorous research work on a wind energy system by using slip ring induction motors which having variable speed and variable pitch control [2].

Double-fed induction generator extracts the maximum energy from wind energy comparing to other generators. It has two main parts stator winding which directly connects to the grid where as rotor winding is connected to the grid via coupling transformer and PWM converter to operate at variable frequencies. This helps the double fed induction generator to operate in both sub and super- synchronous speeds. The DFIG wind turbine is used in varying speeds and variable pitch control application in a finite range around the synchronous speed, for example ±25-30% due to decrease in the power rating of the frequency converter. Now a day's DFIG wind turbine are the common variable speed wind turbines [3], [4]. Also, it has the capability of capturing more energy and less noise compared to other machines. It can control active and reactive power for better grid integration.

There are various control algorithms and method for controlling of power conversion. The prominent conventional control methods for DFIG is vector control technique uses rotor currents which are decoupled into stator active power and reactive power and these two currents are controlled by using a reference frame fixed to stator flux This method has limitations that accurate values of DFIG parameters like resistance and inductances are required. These parameters are easily varied due to unpredictability in the model due to changes in wind, wind turbine, etc., the PI parameters facing major problems to control these values during temperature, actions or unforeseeable wind speeds [5], [6].

Using fuzzy control, we can use linguistic variables and rule base or fuzzy sets is easily altered to produce controller outputs more predictable. It allows for accelerated prototyping because the system designer doesn't need to know everything about the system before starting. The fuzzy logic control has the capability that it can operate accurately without using an exact mathematical model of the system. The operation of the system can varied by using the observation of the system operation and performance. The adjustment of parameters is varied very comfortably[7], [8].

This paper examines closely about the dynamic modeling of a variable speed DFIG wind turbine with the SOFC fuel cell energy system is used to obtain reliable operation of the power system. The SOFC fuel cell model is based on Nernst equation and response of sudden load variation are examined in MATLAB/SIMULINK. For different operation conditions the hybrid model with the fuzzy logic controller (FLC) and PI controller is compared by using simulation results.

II. PRINCIPLE OF OPERATION

Figure.1 represents the block diagram of a double fed induction generator with SOFC fuel cell. The doctrine of the DFIG consists of two parts, stator side winding directly connects to the grid, while the rotor side winding is fed from the PWM converter via slip rings to the grid as shown in the figure. 1. The advantage of DFIG is it can operate at a variable speed conditions with respect to wind speed. The main aim is to maintain frequency and grid voltage constant irrespective of wind speed by controlling the PWM converter. DFIG at below synchronous speed stator generates the power, but some part of it returns to the rotor. At above synchronous speeds both stator and rotor generate power to the grid. The DFIG has the capability to operate in four quadrant operation. These characteristics make the DFIG to carry power in both directions, i.e., to the grid from the rotor and rotor to the grid controlling the stator side or rotor side converters in both above and below synchronous speed ranges.

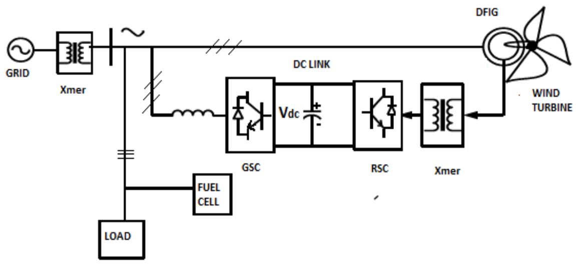

Fig.1 Block diagram of DFIG-SOFC system.

III. MATHEMATICAL MODELLING OF DFIG

The main parts of DFIG are stator winding and rotor winding. The DFIG parts are represented in state space model by using dq-frame theory (reference frame), park's transformation help for converting three phase winding into two phases and vice versa. The DFIG voltage equation is given as

$$V_{qs} = r_s I_{qs} + \omega_e \lambda_{ds} + d/dt(\lambda_{qs}) \qquad (1)$$
$$V_{ds} = r_s I_{ds} + \omega_e \lambda_{qs} + d/dt(\lambda_{ds}) \qquad (2)$$
$$V_{qr} = r_r I_{ds} - (\omega_e - \omega_r)\lambda_{dr} + d/dt(\lambda_{qr}) \qquad (3)$$
$$V_{dr} = r_r I_{dr} + (\omega_e - \omega_r)\lambda_{qs} + d/dt(\lambda_{dr}) \qquad (4)$$

Where λ_{qs},λ_{ds},λ_{qr} andλ_{dr} are the q and d-axis stator and rotor fluxes, respectively; I_{qs},I_{ds},I_{qr} and I_{dr} are the q and d-axis stator and rotor currents, respectively; V_{qs},V_{ds},V_{qr},$V_{dr,}$ the q and d-axis stator and rotor voltages are respectively. r_s and r_r are the stator and rotor resistances, respectively; ω_e is the angular velocity of the synchronously rotating reference frame. ω_r is rotor angular velocity. The flux linkage equations are given as:

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \qquad (5)$$
$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \qquad (6)$$
$$\lambda_{qr} = L_m I_{qs} + L_r I_{dr} \qquad (7)$$
$$\lambda_{dr} = L_m I_{ds} + L_r I_{dr} \qquad (8)$$

Where L_r,L_s and L_m are the rotor, stator and mutual inductances, respectively, with and $L_s = L_{ls} + L_m$ and $L_{qr} = L_{lr} + L_m$; being the 3 self inductance of the stator and L_{lr} being the self inductance of the rotor.

Solving equations (5)-(8) in terms of current equations:

$$I_{qs} = (1/(\sigma L_s))\lambda_{qs} - (L/(\sigma L_s L_r))\lambda_{dr} \qquad (9)$$

$$I_{ds} = (1/(\sigma L_{ds}))\lambda_{ds} - (L/(\sigma L_s L_r))\lambda_{dr} \qquad (10)$$

$$I_{qr} = (1/(\sigma L_s L_r))\lambda_{qs} - (L/(\sigma L_r))\lambda_{qr} \qquad (11)$$

$$I_{dr} = (1/(L_s L_r))\lambda_{ds} - (L/(\sigma L_r))\lambda_{dr} \qquad (12)$$

Where leakage coefficient $\sigma = (L_s L_r - L^2_m)/(L_s L_r)$

IV. CONSTRUCTIONAL FEATURES OF DFIG

A DFIG/SOFC fuel cell hybrid system consists of the main parts like Generator, Line side converter, Rotor side converter, coupling transformer, DC-link capacitor, A dynamic model of SOFC and protection system as shown in figure 1.

A) Rotor Side Converter (RSC)

To maintain rotor speed constant the rotor side converter is operated in such away that at any wind speed the rotor speed must constant. While i_d control active power whereas i_q control reactive power in vector control technique as shown in figure2.;where as in fuzzy logic control rotor side uses the only rotor speed to control rotor side converter.

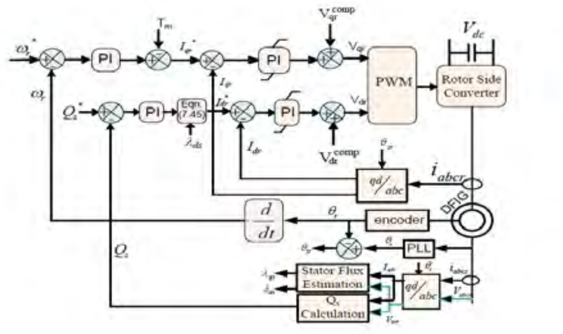

Fig2. Block diagram of the rotor side converter by using vector control technique.

B) Line Side Converter (LSC)

The line side converter is operated such that to control the DC-link voltage constant. The vector control technique is used to measure the power delivered by DFIG and by comparing the reactive power and required reactive power generates the error i_{dr}^* and by comparing the DC voltage across the capacitor and constant speed generates the error i_{qr}^* those errors are sent to PI controllers to reduce the error as shown in the fig.3.

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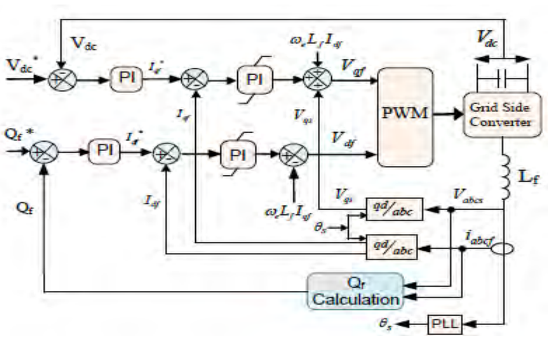


Fig3. Block diagram of the line side converter by using vector control technique.

V. FUEL CELL

A fuel cell is a static device, which converter electrochemical energy into electrical energy from oxidizing fuels. Fuel cells are mainly classified into four types by their electrolyte material. They are:

1. Proton exchange membrane (PEM) fuel cell is a low temperature fuel cell.
2. Phosphoric acid fuel cell (PAFC) is a medium temperature fuel cell.
3. Molten carbonate fuel cell (MCFC) is a high temperature fuel.
4. Solid oxide fuel cell (SOFC) it is operated around 1000°C.

High temperature SOFCs has a solid oxide or ceramic, electrolyte. Advantages of SOFC fuel cells include high efficiency, long-term establishment, fuel flaccidity, low noise, less pollutant output, and comparably low cost.

Solid oxide fuel cells are characterized by an electrolyte. SOFC consists of and Y_2O_3 doped ZrO_3.

A) SOFC is modeling

The modeling SOFC assumes the following:

1) The fuel cell gases are ideal.
2) Only one pressure is defined in the interior of the electrodes.
3) The fuel cell temperature is invariant.
4) Nernst's equation applies.

The flow of electrons to the cathode through an external circuit produces direct-current electricity.

The equation (15) represents the typical anode and cathode reaction.

$$H_2 \ \square\ 2H^+ + 2e^- \qquad (14)$$

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \ \square\ H_2O \qquad (15)$$

By Nernst's equation DC voltage V_{dc} across stack of the fuel cell at current I is given by the following equation (16).

$$V_{fc} = N_0(E_0 + (RT/2F)\ln(pH2pO_2^5) - rI_{fc} \qquad (16)$$

Where

V_{fc} - Operating fuel cell DC voltage (V)
E_0 - Standard reversible cell potential (V)
P_i - Partial pressure of species I (Pa)
N_0 - Number of cells in stack
R - Universal gas constant (J/mol K)
T - Stack temperature (K)
F - Faraday's constant (C/mol).
I_{fc} - Fuel cell current (A).

VI. FUZZY CONTROL SYSTEM

A) Fuzzy Set

Fuzzy set allows partial membership. A fuzzy set is a set having degrees of membership between 0 & 1. The membership in a fuzzy set need not be complete, i.e., a member of one fuzzy set can also be members of other fuzzy sets in the same universe.

I. Fuzzification is known as converting crisp quantity into fuzzy quantities.
II. The rules are formed by the given information by using membership functions and truth value and controlling the output variables.
III. These results are in fuzzy quantity and converting fuzzy quantity into crisp quantity known as "defuzzification".

This is the heart of the fuzzy logic control system. Here we are going to give the crisp inputs or fuzzy inputs to a fuzzy interface system (FIS). The fuzzy inference system is shown in fig4.

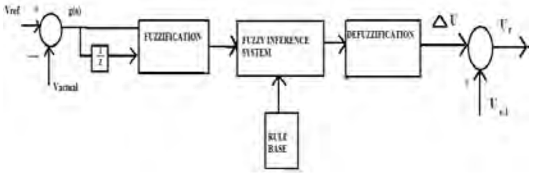


Fig 4: Block diagram of Fuzzy Inference System

Table I
Fuzzy Logic Rules

e \ Δe	NB	NS	PS	PB
NB	PB	PB	NB	NB
NS	PS	PS	NS	NS
PS	NS	NS	PS	PS
PB	NB	NB	PB	PB

To control the grid side converter and rotor side converter the PI controller has limitations of tuning the PI parameter is the major problem when a parameter of inductance and resistance are diverse in a wind turbine. The tracking technique should be quick to handle any variation in load or weather conditions. Therefore the fuzzy logic controller (FLC) is used fast to locate the values.

$$\Delta\omega_r = \Delta\omega_r(k) - \Delta\omega_r(k-1) \qquad (17)$$

$$\Delta V_{dc} = \Delta V_{dc}(k) - \Delta V_{dc}(k-1) \qquad (18)$$

and the output equation is

$$\Delta I_{g,ref} = \Delta I_{g,ref}(k-1) - I_{g,ref}(k-1) \qquad (19)$$

Where $\Delta\omega_r$ and ΔV_{dc} is the DFIG rotor speed and DC capacitor voltage change, $\Delta I_{g,ref}$ is the grid current reference, and k is the sample instant value. The fuzzy subsets are divided into four types with input and outputs as NB(Negative Big), NS(Negative Small),PS(Positive Small)and PB(Positive Big). Due to be 4-ruled input variables, therefore 16 rules can be constructed and the rules are formed based on regulation of the hill climbing algorithm, as shown in the Table I. The fuzzy logic controller uses Mamdani method with MAX-MIN combination.

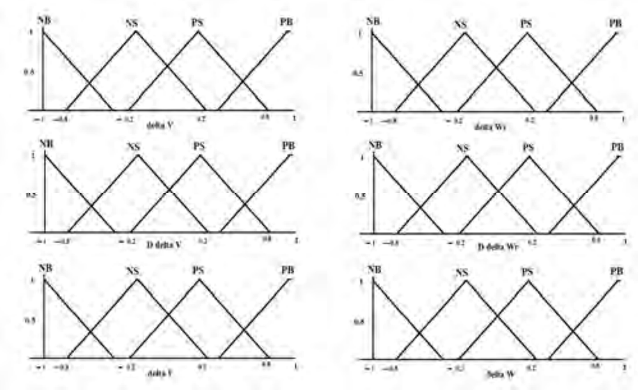


Fig 5(a) input and output of rotor side converter;5(b) input and output of grid side converter.

The shapes and fuzzy subset are divided and controlled from the responses of controller inputs and output and the membership function is represented in both input and output in fig 5(a),5(b). At the defuzzification stage to convert the fuzzy subset into real numbers, uses centre of area algorithm has been used.

$$\Delta I_{g,ref} = \sum^{n}_{i} \mu(I_{g,ref,i}) I_{g,ref,i} / \sum^{n}_{i} \mu(I_{g,ref,i}) \qquad (20)$$

VII. SIMULATION OF DFIG-SOFC GRID TEST SYSTEM

The fig.6 Repreents the simulink model of the Double-fed induction generator and Solid oxide fuel cell are interconnected with a Grid/ a stand alone condition.

Fig.7, 8, represents the rotor side converter and grid side converter with fuzzy controller technique and fig.9 represents the simulation model of Solid oxide fuel cell.

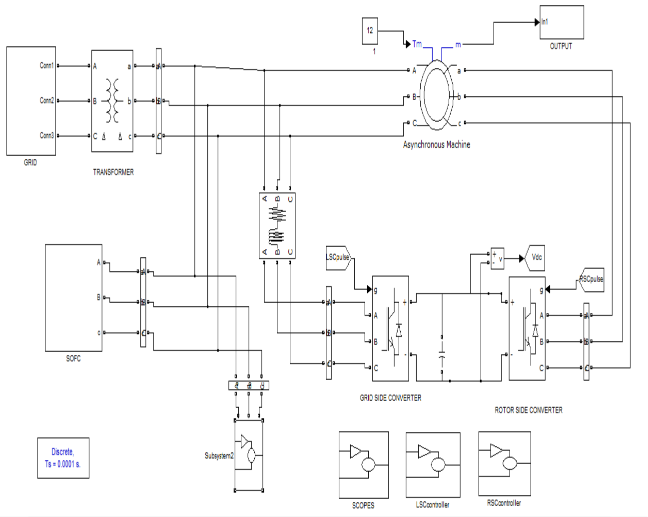


Fig6: Simulink model of WECS with Fuel cell system.

A) Fuzzy controller based rotor side converter

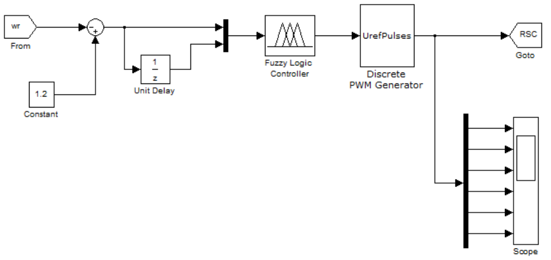


Fig7: Simulink configuration of fuzzy controller base rotor side converter.

B) Fuzzy controller based line side converter

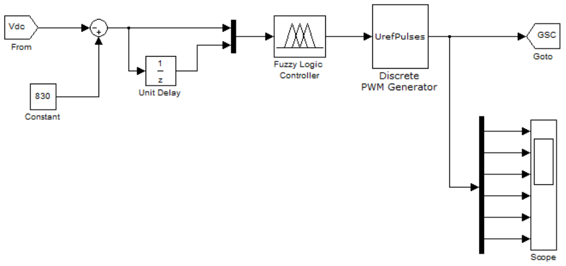


Fig.8: Simulink configuration of fuzzy controller based line Side Converter.

C) Simulink of SOFC

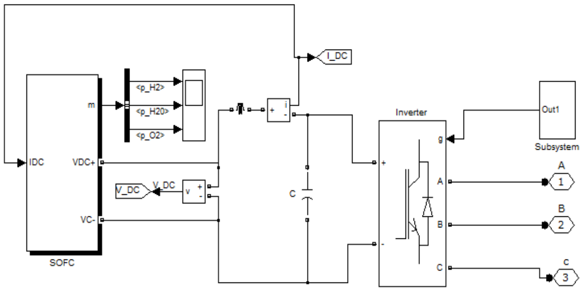


Fig.9. Simulink block of sofc fuel cell.

D) Simulink results

In this test system the DFIG output voltage is maintained constant by controlling line side converter and rotor side converter by taking the references DC capacitor voltage and rotor speed as references and the following waveform compares the PI controller and fuzzy controller waveform of grid voltage and current. Power waveforms of SOFC, Load, DFIG, Grid waveforms are shown in the figures 10, 11, 12.

At t=0. 25 Sec, when the load is increased to 50 kW to 100 kW, the power contribution of the system is a shown in fig10, 11. To obtain unity power factor we assumed reactive power is zero. fig10, 11 The DFIG/SOFC hybrid system contributes 50kW to the grid as shown in the. The grid voltage and current waveforms are shown in fig12. Fuzzy controller r.

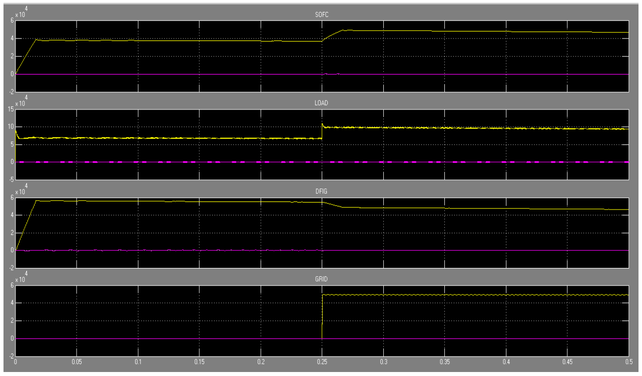


Fig10. Power waveforms of SOFC, Load, DFIG and Grid with PI controller.

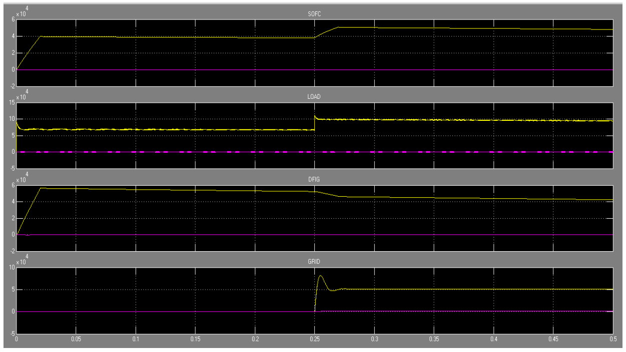


Fig11. Power waveforms of SOFC, Load, DFIG, Grid with Fuzzy Controller.

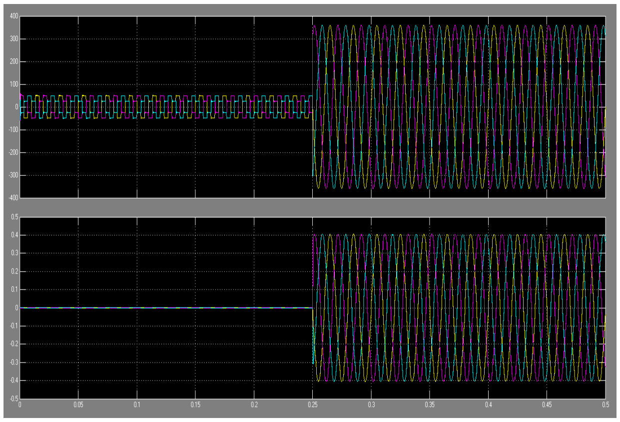
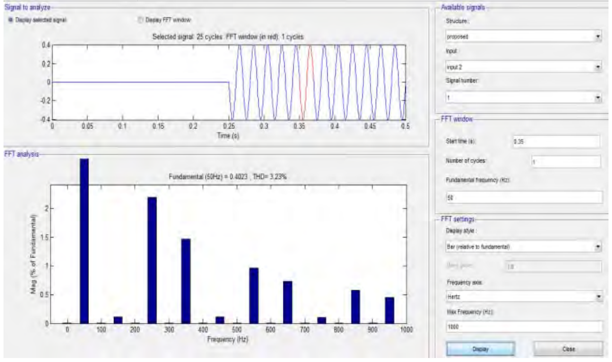


Fig.12 Grid Voltage and Current waveforms with fuzzy controller.



Selected signal: 25 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 0.4023 , THD= 3.23%

Structure: proposed

Input: input 2

Signal number: 1

Start time (s): 0.35

Number of cycles: 1

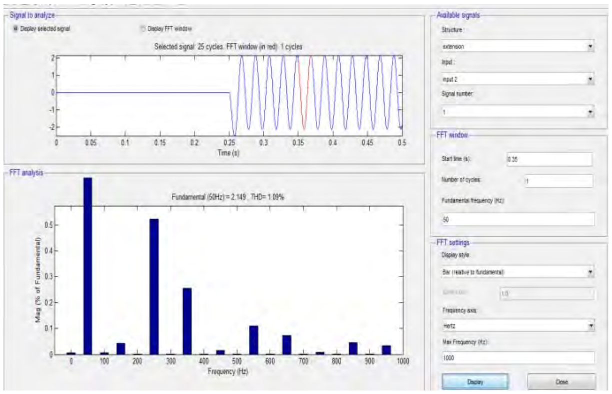
Fundamental frequency (Hz): 50

Display style: Bar (relative to fundamental)

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig.13 Total harmonic distortion using PI Controller.



Selected signal: 25 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 2.149 , THD= 1.09%

Structure: extension

Input: input 2

Signal number: 1

Start time (s): 0.35

Number of cycles: 1

Fundamental frequency (Hz): 50

Display style: Bar (relative to fundamental)

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig 14: Total harmonic distortion using Fuzzy Controller.

VIII. CONCLUSION

The active and reactive power of the grid and WECS with SOFC has been synchronized perfectly and comparing PI controller and fuzzy controller based DFIG/SOFC waveforms both have been obtained similar characteristics. Fuzzy logic has decreased total harmonic distortion (THD) 3.23 to 1.09 for grid current compared to the PI controller as shown in figure13, 14. This paper has shown simulation results of DFIG with SOFC Fuel cell with PI and Fuzzy controllers.

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