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Fuzzy Logic Controller Based Power Conversion System Fed from Fuel Cell

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Abstract: This study focuses on the control of fuel cell based boost converter in Distributed Generation (DG) systems in smart grid under voltage sag conditions. Different control strategies for the fuel cell based boost converter are designed. Moreover, the control strategies for boost converter are investigated for different types of loads in the power conversion system. The power conversion system is considered with different loads and the voltage sag is studied.

Key words: Fuel cell, PI controller, fuzzy logic controller, boost converter, power conversion systems, distributed generation, smart grid

INTRODUCTION

All over the world, a substantial increase in resources of Distribution Generation (DG) is due to the development in technologies and new guidelines in electricity regulation. A new development is emerging towards distribution energy generation, i.e., smaller generating units known as Power Conversion Systems (PCS) are located close to the energy consumers (Hajizadeh *et al*., 2010; El-Sharkh *et al*., 2004).

The DGs are connected to the grid which means that even if there is a problem in the generation the consumers can still get electricity from the main grid and can even contribute excess energy to the grid. The power conversion systems receive any type of fuel and convert it into a consumer's end use with minimum human intervention. The use of DG is optimised with the help of power conversion systems. Therefore, correct control of DG systems is necessary so that a lower cost and reliable energy is supplied to the consumers.

Several distributed generation systems, like Fuel Cells (FCs), wind turbines and photovoltaic cells, are connected to grid through power electronic converters in order to increase the system reliability, integrity and efficiency (Bayod-Rujula, 2009; Kazemi *et al*., 2011). In order to keep the consistency of the system under any variations in parameters and disturbances in the distribution system, it is significant to design the control strategies.

The power electronic converters which are connected to grid are highly subtle to grid disturbances such as transients, voltage sag, voltage swell, waveform distortion, interruptions, voltage fluctuations, etc. and it is essential to highlight the need to decrease the effects of voltage disturbances during the operation of power converters. Voltage Source Converters (VSCs) performance is severely affected by voltage sag. Voltage sag can be defined as the voltage drop for an interval between one half-cycle to a few seconds. Therefore, it is essential to investigate the condition and design control strategies for the converter to control the power quality disturbances.

In this study, the model of power generation system consists of integration of fuel cell, boost converter and inverter are explained in materials and method section. Followed by two different controlling strategies are discussed for boost converter. The simulation model of power generation system is designed and the simulation results of two controllers are compared. Final section concludes the merits of this study.

MATERIALS AND METHODS

Description and modelling of power generation system: Fuel Cell (FC) is an energy conversion device which converts chemical energy of the fuel cell into electric energy. The most commonly used fuel is hydrogen, but natural gas and methanol are also used sometimes. The FC power plant model mentioned in this study is the proton exchange membrane FC (PEMFC) stack model (El-Sharkh *et al*., 2004). In this study, FC is taken as a constant DC source, therefore there is no variation in the FC variables.

Due to the slow dynamics, fuel cell cannot respond instantly to demand in the power while start-up or rapid change in load (Candusso *et al*., 2002). Generally, FC is connected to a boost converter in order to increase the voltage, so that the fuel cell can be connected to the external system. The DC-DC

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boost converter not only increases the voltage, but also controls FC power and regulates the voltage. In this study two closed loop controls are used for the boost converter:

- PI controller
- Fuzzy controller

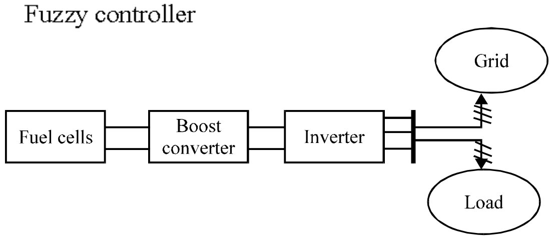

Fig. 1: Block diagram of power generation system

The power generation system is connected to different loads and the THD are compared for both the control strategies. The block diagram of the power generation system is as shown in Fig. 1.

DC-DC boost converter: Boost converter is a power converter which has output voltage more than the input voltage. It consists of two semiconductor switches such as transistor and diode and an energy storage device. In order to increase the performance of the converter's output, a filter made of the combination of inductor and capacitor is often used. Boost converter steps up a fixed input DC voltage to a desired high DC voltage.

The Simulink model of open loop FC with boost converter is given in Fig. 2 and the Simulation diagram of the boost converter subsystem is given in Fig. 3.

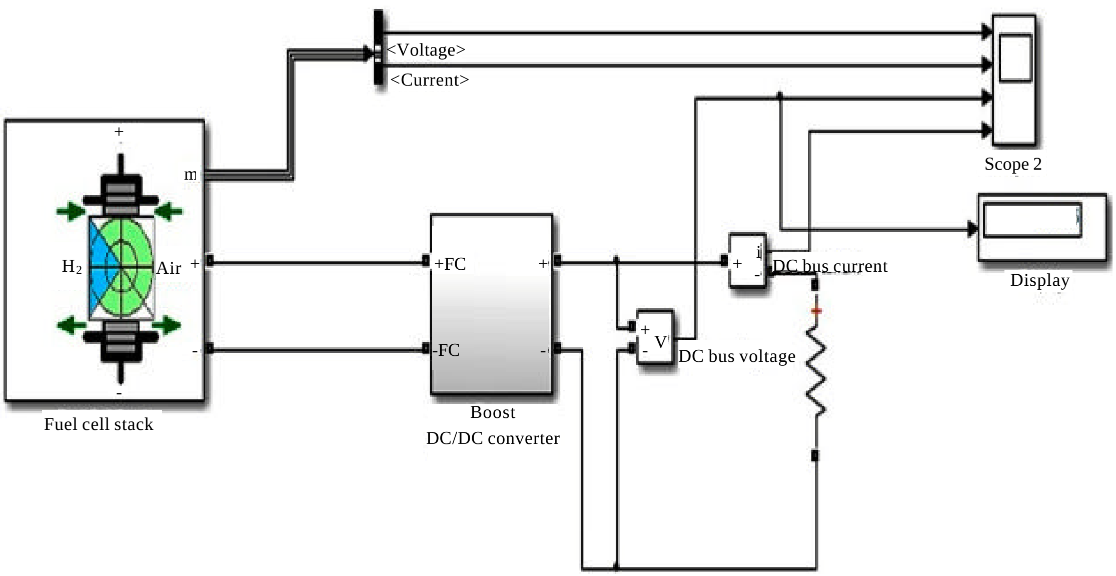

Fig. 2: Simulink model of open loop FC with boost converter

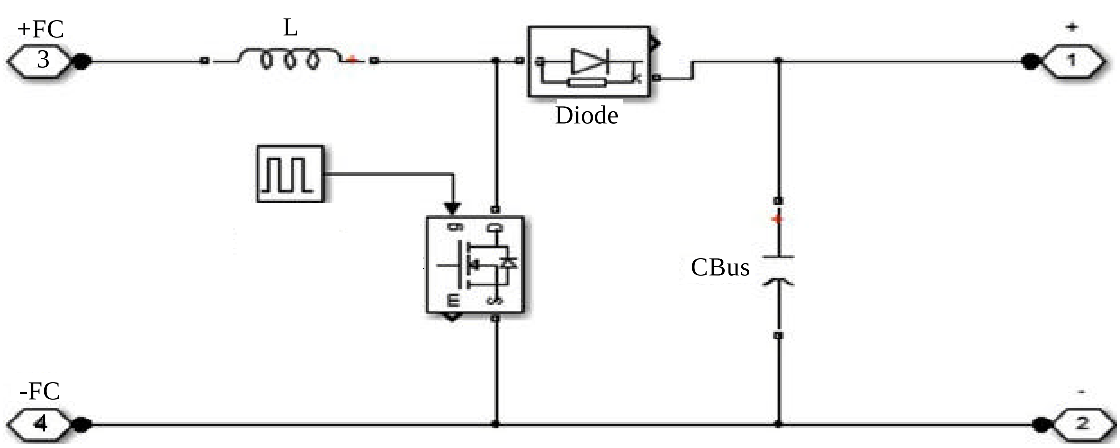

Fig. 3: Simulation model of boost converter

Closed loop PI controller: PI Controller is the most commonly used conventional controller. The proportional term produces an output proportional to the current error value and it can be tuned by multiplying with the suitable gain value. The integral term is proportional to the value of the error duration and error. The block diagram of the closed loop control using PI controller is given in Fig. 4.

A general approach is followed in tuning the controller. Initially, the integral value is set to zero and the proportional constant is increased until the satisfactory response is obtained. Then, the integral constant is added until the steady state error is removed in satisfactory time. Adjusting both the constant values the desired output is obtained and thus the PI controller is tuned. The closed loop Simulation diagram of boost converter is given in Fig. 5.

Design of Fuzzy Logic Controller (FLC): Fuzzy controller is one of the most intelligent controller. The robustness of dc-dc converters can be increased by the fuzzy logic controller. The mathematical system analyses analog logic variables that take continuous values between 0 and 1, in comparison to the digital logic, that functions on either 0 or 1. In this study, the error of boost output voltage is given to the fuzzy logic controller to produce suitable pulses to the switch of the boost converter. For many dc-dc converters like boost, buck and buck-boost converters FLC can be simply applicable (So *et al*., 1996; Yu *et al*., 2013; Akpolat, 2005; Yasin *et al*., 2011; Jha *et al*., 2011; Yu *et al*., 2007; Mamlook, 2006).

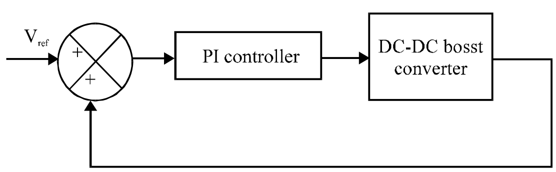

Fig. 4: Block diagram of the closed loop control with PI controller

Depending on the human knowledge of performance of the system, a set of rules are designed for an intelligent fuzzy logic control. FLC mainly consists of three parts, i.e., fuzzification, inference and rule formation and defuzzification. The block diagram of FLC is given in Fig. 6.

The error signal e(k), which is produced by the comparision of output voltage from the dc-dc converter and the desired voltage, is one of the inputs to the FLC. The change in error de(k) is another input to the FLC. A command signal is generated by the rule base to adjust the duty ratio (u) of the PWM generator of the converter. It changes the duty ratio accordingly and the output of the converter is adjusted. In this study Mamdani style fuzzy inference system is designed (Dursun, 2008; Slamnia *et al*., 2012; Ghasemi *et al*., 2009; Kharrati and Khanmohammadi, 2008). Fuzzy sets are well-defined for each input variable and output variable. Here there are three variables and seven membership functions each.

As given in Table 1, 7 fuzzy subsets Negative Big [NB]; Negative Medium [NM]; Negative Small [NS]; Zero [ZE]; Positive Small [PS]; Positive Medium [PM] and Positive Big [PB] are selected for the three variables (Nik Ismail *et al*., 2010). The triangular shapes are implemented for all the membership functions and by using suitable scale factors the values of input variables and output variable are normalized in [-1, 1]. The maximum or minimum (MOM) type of defuzzification is used. The input membership functions of error and change in error are given in Fig. 7a and b, respectively.

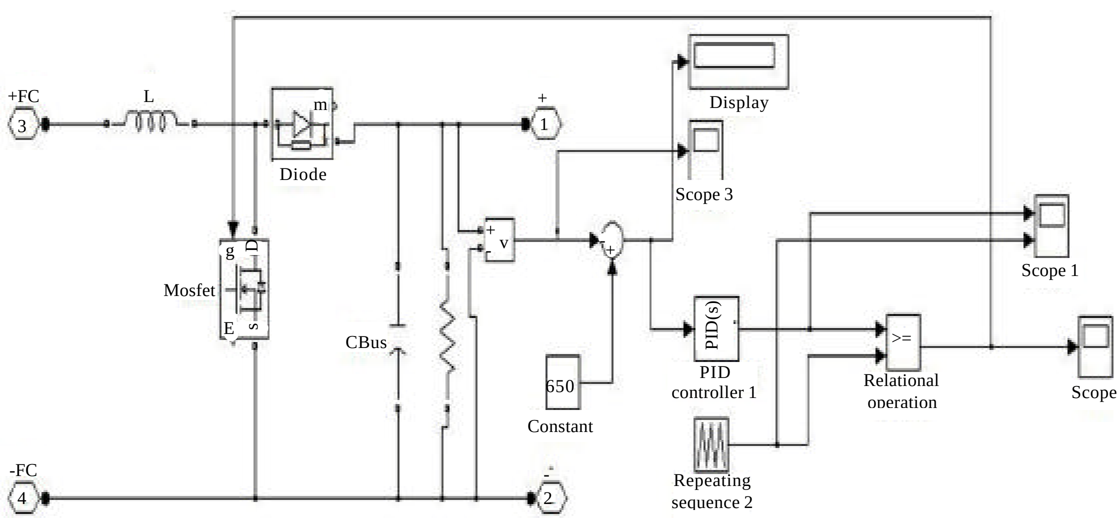

Fig. 5: Simulink model of closed loop control of boost converter using PI controller

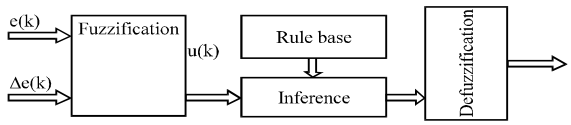

Fig. 6: Block diagram of FLC (Fuzzy Logic Controller)

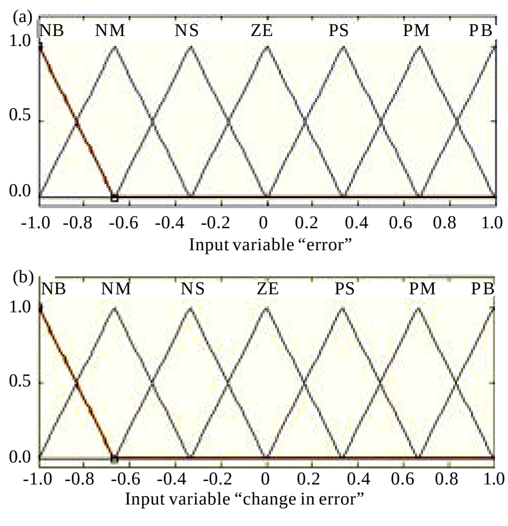

Fig. 7(a-b): Input membership function of (a) Error and (b) Change in error

Table 1: Rules of FLC

e*e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The number of rules set for the dc-dc converter control are forty nine, it is shown in Table 1. The output membership function and the fuzzy block which is used in the MATLAB is shown in the Fig. 8a and b, respectively.

The rules which are used in this study is represented in Table 1 and the rule surface is shown in Fig. 9.

The Simulink model of the closed loop control of boost converter using Fuzzy Logic Controller (FLC) is given in Fig. 10.

Modelling of inverter: Inverter changes Direct Current (DC) to Alternating Current (AC). Inverters are classified as voltage source inverters and current source inverters

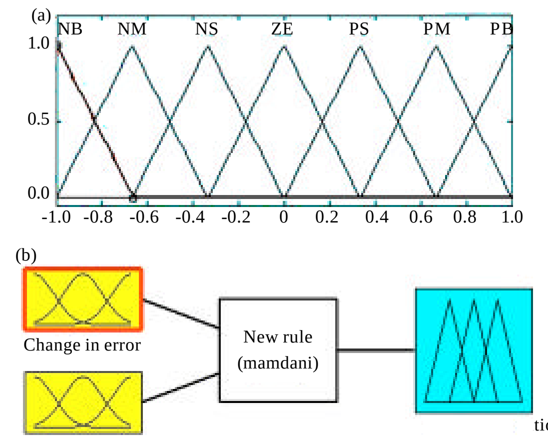

Fig. 8(a-b): Output membership fuction of (a) Change in duty ratio and (b) Fuzzy block

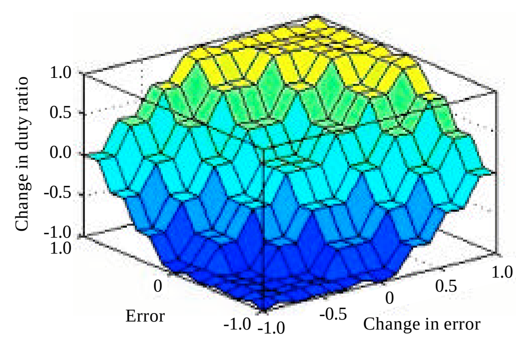

Fig. 9: Rule surface of FLC

depending upon the type of the supply source and the topology of the power circuit. The three phase VSIs are commonly used in motor drives, active filters and UPFC in power systems. The main purpose of 3-ph voltage source is to control the phase, frequency and amplitude of the voltages. The standard 3-ph inverter has six switches and the switching depends on the modulation scheme. In this study, the input dc voltage is obtained from the boost converter output and it is connected to a LCL filter before connecting it to the load (Yasin *et al*., 2011). The simulation diagram of the inverter is shown in Fig. 11.

The integrated system of fuel cell with boost converter connected to the inverter is given in Fig. 12.

Generally, fuel cell generates low voltage and this voltage is boosted up with the help of boost converter. Here, 195/650 V boost converter is used with two types of controlling strategies. Generated pulses are given to the

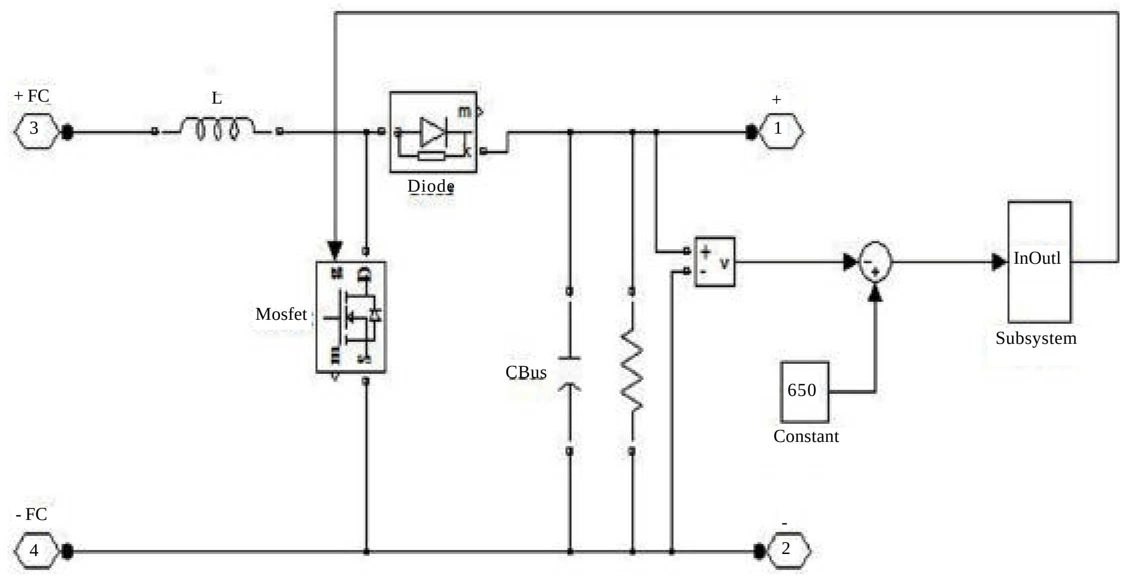

Fig. 10: Simulink model of boost converter with fuzzy logic controller subsystem

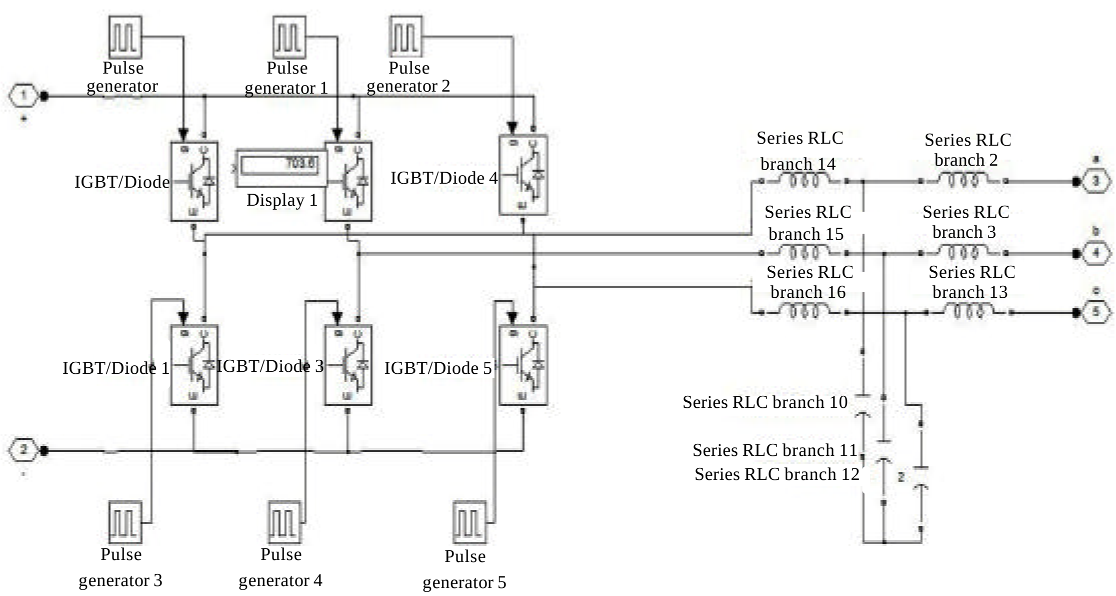

Fig. 11: Simulink model of inverter with LCL filter

MOSFET switch of the boost converter. The output of the boost converter acts as an input to the three phase inverter. The load that is connected to the inverter is varied and the THD is compared in both the controlling strategies.

The inverter is connected to the LCL filter in order to get the sinusoidal waveform and to reduce the total harmonic distortion of the voltage waveform. The inverter output can be connected to the grid and the voltage sag conditions can be studied. Here, different loads are considered and voltage sag conditions are checked by measuring the total harmonic distortion. The input voltages of the inverter can be in the range of 550-700 V as the inverter is designed for 650V/400 V. This is designed in order to connect it to the grid further.

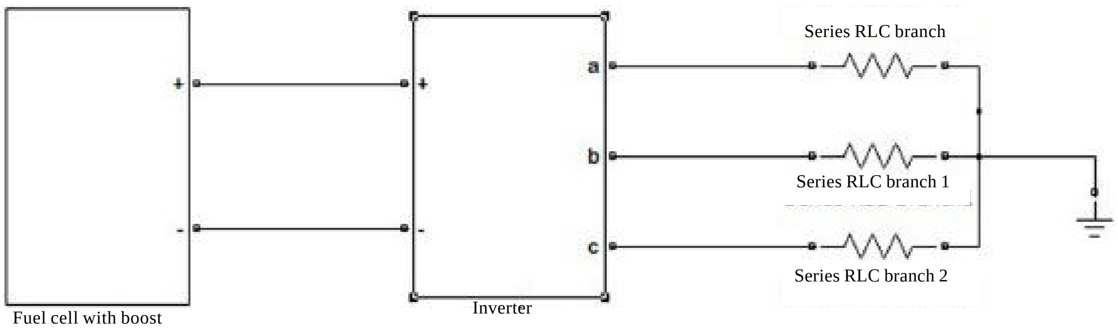

Fig. 12: Simulation diagram of fuel cell with boost converter subsystem and inverter connected to load

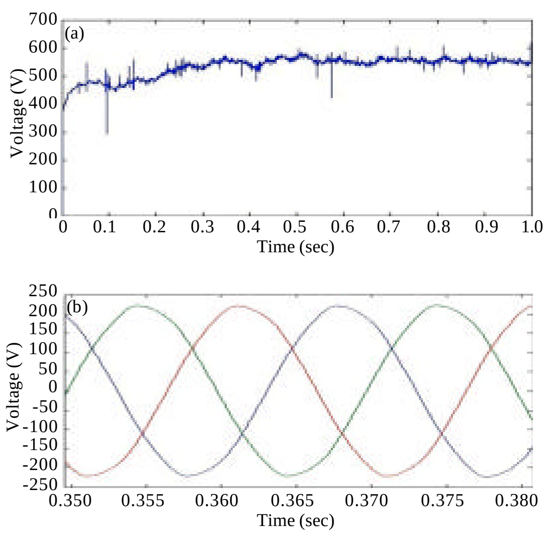

Fig. 13(a-b): (a) DC voltage waveform of R-load and (b) Three-phase voltage waveform of inverter using R-load

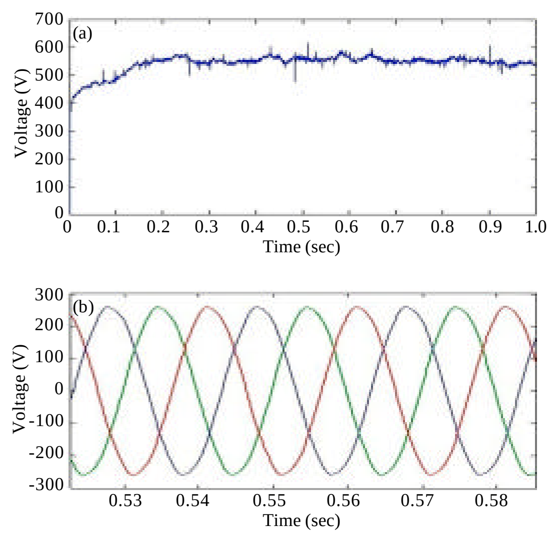

Fig. 14(a-b): (a) DC voltage waveform of RL-load and (b) Three-phase voltage waveform of inverter using RL-load

Table 2: Comparison of THD using PI controller and FLC for different loads

Types of load	PI controller (%)	Fuzzy logic controller (%)
R= 500 Ω	1.24	1.06
R= 500 Ω, L = 0.01 mH	1.36	1.05
R=500 Ω, L = 0.01 mH, C = 10 μF	1.23	1.08

Table 3: Comparison of different loads using FLC

Load	Input voltage (V)	Output voltage (V)	THD (%)
R	551	257	1.06
RL	538	260	1.05
RLC	545	254	1.08

RESULTS AND DISCUSSION

The results of PI controller and FLC controller are compared for different loads and tabulated in Table 2. The input and output voltage of the inverter with the corresponding THD for different loads are tabulated in Table 3.

The waveforms of the input dc voltage and the output three phase voltage waveform of R load using FLC are given in Fig. 13a and b, respectively.

The waveforms of the input dc voltage and the output three phase voltage waveform of RL load using FLC are given in Fig. 14a and b, respectively.

The waveforms of the input dc voltage and the output three phase voltage waveform of RLC load using FLC are given in Fig. 15a and b, respectively.

From Table 1, it is clear that the THD of PI controller is more than FLC for different loads and it can be concluded that FLC is more efficient than PI controller. From Table 2, it is evident that the inverter input voltage or the boost converter output voltage varies with load. The input voltage is more for the R load and it decreases for RL and RLC loads, this indicates that if there is a change in load then there is a voltage sag in the input voltage of the inverter.

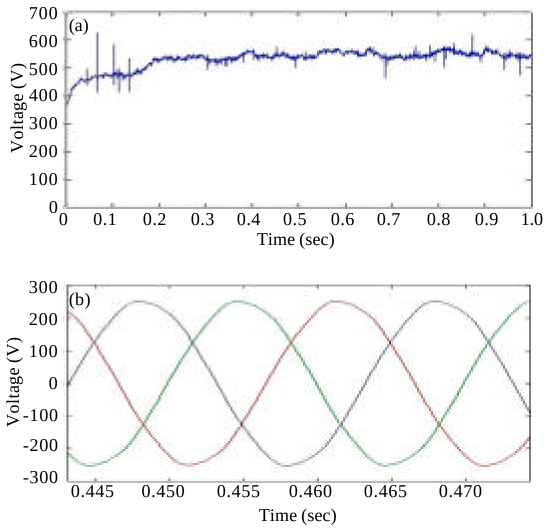

Fig. 15(a-b): (a) DC voltage waveform of RLC-load and (b) Three-phase voltage waveform of inverter using RLC-load

CONCLUSION

This study focused on the study of fuel cell based distribution system under voltage sag conditions. Voltage sag conditions are studied using different loads. Further, the FC with boost converter is designed and comparison of PI controller and FLC control strategies are performed. The simulation results indicate that Fuzzy Logic Controller (FLC) is more efficient than PI controller in terms of THD for different loads. The THD variation is also very less for different loads using FLC. It can be concluded that fuzzy logic controller is working efficiently under voltage sag conditions.

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