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Cascaded Boost-Inverter Topology for Solid Oxide Fuel-Cell

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ABSTRACT
The surge in energy requirements within the industrial sector has propelled studies towards renewable energy sources and the enhancement of energy efficiency. The voltage generation system utilizing SOFC integrates multiple components, including the SOFC stack, DC-DC Boost converter, DC-AC inverter, and various controllers tailored for Boost-Inverter and cascaded boost-inverter configurations. This paper outlines a DC-DC boost converter, showcasing diverse control methodologies that elevate the SOFC's initially low DC output voltage to a required level. It explores different feedback control strategies, including the use of Proportional-Integral (PI) controllers, Proportional-Integral-Derivative (PID) controllers, and Fuzzy Logic Controllers (FLC), proposing enhancements for effective energy conversion. Apart from this a Boost-Inverter topology has been discussed to convert, the boosted DC voltage output of the Boost converter into AC voltage output. Further two Boost-Inverter circuit have been cascaded to get a higher voltage output with reduced harmonics. A pulse width modulation (PWM) generator has been attached to each inverter to supply gate pulse .Only a single controller is used to control both the cascaded converters, which makes this system cost effective and more efficient. The proposed cascaded boost-inverter topology improves the SOFC generated 15V DC voltage to a 60V AC voltage with 34.61% total harmonic distortion (THD).

Keywords:- *SOFC, DC-DC Converter, FLC, PWM, Boost-inverter, THD*

INTRODUCTION

Energy being an important factor in the field of sustainable development should be rated as a priority topic of discussion. Due to global warming the average surface temperature of earth has risen at the rate of 0.17°F/decade in the past few decades which has created a critical need of cleaner and environment friendly energy alternatives[1]. Fuel cell provides a definite solution for this. Fuel cells are becoming more preferable alternative energy provider due to their featherlike weight, small dimension and undemanding maintenance, less noise and minimum chemical emissions. They often fulfils energy requirements of many important areas like electricity generation, transportation, temperature regulation in industries and rural energy services. Electric service with renewable energy is much more efficient, economic and helps in conservation of primary energy sources.

Electrochemical devices known as fuel cells transform the chemical energy from fuel gases directly into electrical energy, bypassing the need for combustion. Among these, Solid Oxide Fuel Cells (SOFCs), recognized for their ability to operate at elevated temperatures, are gaining prominence for decentralized power generation. Unlike their low-

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temperature counterparts, SOFCs offer numerous benefits, including enhanced efficiency, the capability to utilize impure and noxious gases, and superior performance in power generation. SOFCs are made using solid oxide as the electrolyte material. These cells enable the transport of negatively charged oxygen ions from the cathode side to the anode side. At the anode, this movement allows for the oxidation process of either hydrogen or carbon monoxide. A noteworthy advancement in this domain is the development of proton-conducting SOFCs (PC-SOFCs), which utilize protons instead of oxygen ions for electrolyte transfer. This innovation significantly reduces the operational temperatures of SOFCs, allowing them to function more efficiently compared to conventional models [2].

For a sustainable better global future only energy alternatives are not enough as it require to be padded with energy conservation with improved energy efficiency, energy storage, and energy consumption. As we all are working towards an eco-friendly balanced environment with some renewable source of energy in our bag; creates an obvious need to develop an efficient, economical, and user-friendly energy conservation system [3].

LITERATURE REVIEW

An energy harvesting system for the fuel cell is necessary to meet the demands of the load. This system also requires a boost converter to improve the DC voltage that the fuel cell harvests and feeds back into the converter. The output of sustainable energy sources, such as fuel cells and solar cells, is DC voltage. However, there are ripples in the DC output voltage and it is insufficient to meet the load's requirements [4].

To compensate the disturbance present in the converters output and to maintain the output at the desired level; controllers are introduced to the energy conversion system. Different types of static and dynamic control strategies are present for the converters. However, the converters can also be controlled by a feedback control system; where the converter output voltage is used as a feedback to the controller [5].

The optimum feedback control loop for the converter circuit is selected by comparing the characteristics provided by the conventional and intelligent controllers like PID and Fuzzy Logic Controller respectively. For practical applications and the distribution of power, it is essential to transform the DC voltage output from the converter into the necessary AC voltage. This necessitates the integration of an inverter into the system. The paper employs a boost-inverter configuration to simultaneously perform voltage boosting and inversion in a singular operation. This configuration is advantageous for the energy conversion system, offering heightened efficiency in conversion, economic benefits, and reduced size due to the utilization of a shared controller for both the converter and inverter functions [6].

Fuel cell generated electricity is also equivalent to the grid generated electricity which is being used conventionally till now. One of the most promising type fuel cell which can generate electricity from natural gas is Solid Oxide Fuel Cell. Many energy generation systems having SOFC as input source have been developed and utilized in many levels for industrial as well as residential applications. Many developed countries like Japan, Korea and US are approaching many advanced SOFC based power generation system which can be used in varieties of applications like transportation, military, medical, commercial etc. In the other side, India is lagging in production of Fuel Cell. To

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overcome this difference in production sector of Fuel Cell and to make it widely available in Indian market, some advance development has to be done for fuel cell energy generation as well as energy management system.

The useful advantages of digital systems made it more preferable over analogue systems. Similarly high switching frequency converters with analogue controllers are being replaced with high speed digital circuits having digital controllers. The feedback control of boost-inverter circuit helps the system to provide required supply to the load. So an optimum control technique is required for the converter-inverter topology. Hence the primary motivation is to provide a compact and efficient control technique for the boost-inverter topology provided in the SOFC energy conversion system. This system then can be used as a backup energy provider to the commercial as well as residential units [7].

METHODS

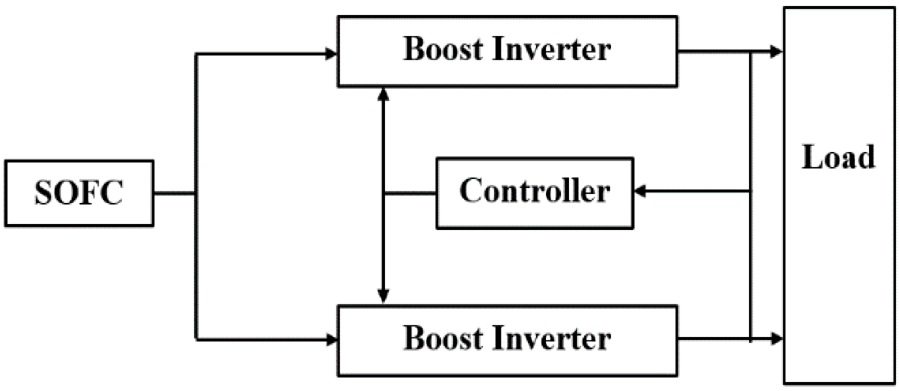

Fig.1:- *Block diagram of SOFC Energy Conversion System.*

A. Fuel Cell Description

Now-a-days global warming and environmental problems are exponentially increasing due to effluent gas emissions. Fuel Cells are the answer to these problems; we are facing today. Fuel cell can provide us a pure, productive and sustainable energy. These fuel cells convert fuel gas chemical energy into electricity without any combustion.

Both fuel cell and batteries have similar operation; which is electrochemical combination of reactants to generate electricity. Hence the mixture of fossil fuel and an oxidizing agent present in the form of gas, got through electrodes produces electricity. The basic advantage of this FC is; it does not require repeated recharging like a battery. A FC can operate continuously until both the supply of fuel and oxidants are uninterrupted. SOFCs are by far the most preferable one because these are most efficient electricity generators, having a range of fuel to choose, cost effective and have a long life.

The design of SOFC consists of two electrodes covered by ceramic electrolyte. The electrodes are used to bring out the reaction between the reactant and the electrolyte without corrosion. The anode holds the negative post of SOFC while the cathode holds the positive post.

Anode disperses hydrogen gas and cathode allows the oxygen available in the environment; to enter into the cell. The combustion of hydrogen-based fuel reduces the oxygen concentration dramatically. The electrode which are

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porous in nature diffuses the supplied fuel and the air into the electrolyte. Then the by-products generated by the electrochemical reaction which occurred at the anode passes out from the cell. The electrolyte facilitates the transfer of oxygen ions, which carry a negative charge, from the cathode to the anode. Following this, the fuel that has permeated reacts with the oxygen ions, leading to the release of electrons that then move through an external circuit [8].

The continuous flow of electron in the external circuit stays intact till the supply of the reactants for the electrodes remains constant. Water and heat are the by-product generated by this process. The basic principle of operation is shown in Figure 2.

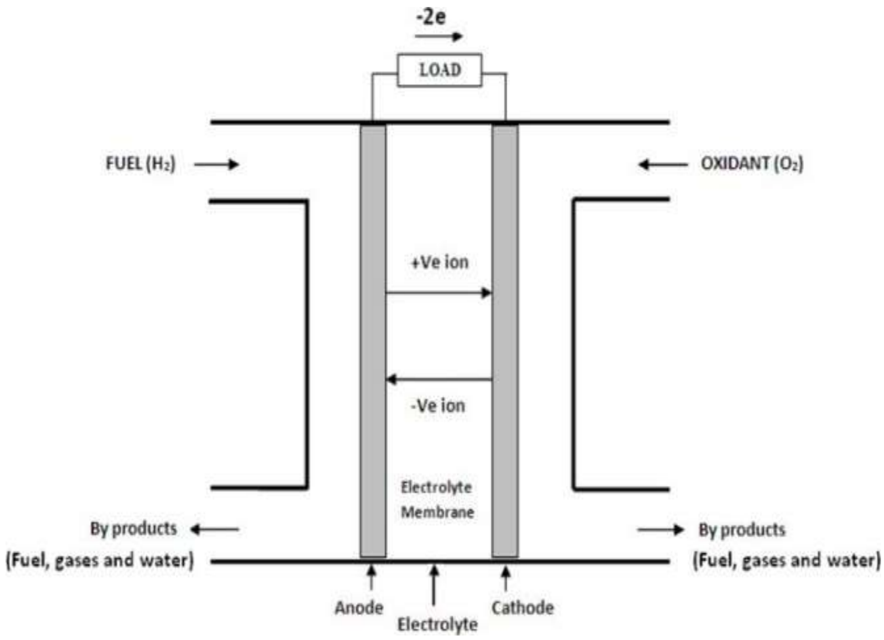

Fig.2:- *Equivalent Circuit of Solid Oxide Fuel Cell.*

The electrochemical reactions of SOFC includes
Anode Side

$$H_2 \rightarrow 2H_2 + 2e^- \quad (1)$$

Cathode Side

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O \quad (2)$$

Overall reaction

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Heat \quad (3)$$

Isolated type and non-isolated type converters are the two most popular types of DC-DC converter. In isolated converters, input and outputs are electrically isolated by the use of a transformer. Non-isolated converters can be differentiated by elements connection such as boost, buck, CUK and SEPIC converter. A power converter which provides a higher level DC output voltage than its input DC voltage is called boost converter [10].

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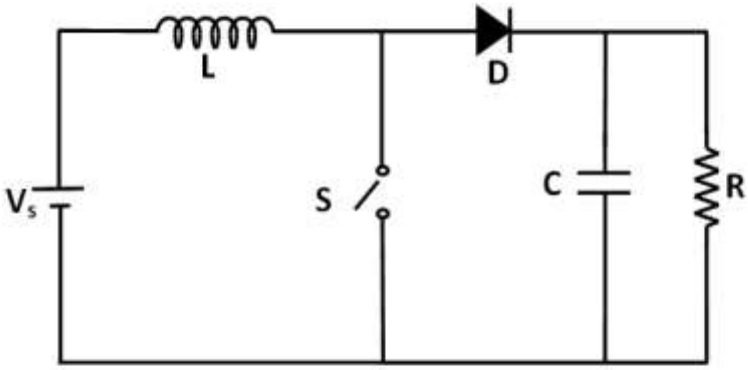

***Fig.3:-** Schematic of Boost Converter.*

B. Control Strategies for DC-DC Converter

Various methods, including analog integrated circuit technology and linear control strategies, have been traditionally employed to manage DC-DC converters. Recently, digital controllers have started to take precedence over analog counterparts due to their ability to handle higher switching frequencies. Controlled power supplies are generally favored over their uncontrolled counterparts for their capability to deliver outputs that are both effective and efficient. Among the myriad of feedback controllers, the Proportional-Integral (PI) controller stands out as a time-honored choice across numerous control systems owing to its straightforward design, reliable performance, and ease of use. The mathematical representation of the PI controller is depicted in a block diagram, referred to here as Figure 4.

Proportional action provides necessary speed of response; any corrective action will always leave out an error between the set point and steady state value. This is called OFFSET error. This steady state error can be eliminated by incorporating Integral control action in the controller. This control technique reduces the error over period of time.

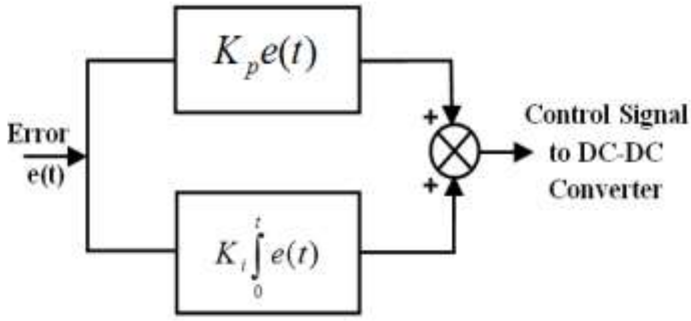

***Fig. 4:-** Converter Block Diagram form PI Controller*

Figure 5 shows the block diagram of PID controller. One of the application of PID controller is to be used in the feedback control loop in the industrial control system to provide continuous control. The controller calculates the error from the difference between the reference point and measured value. Then according to the calculated error it applies corrective measures.

To minimize the steady state error and to enhance the dynamic response of the system PID controller is used. The propotional control improves response time, the integral control reduce the steady state error and the derivative control enhances the dynamic response of the system [11].

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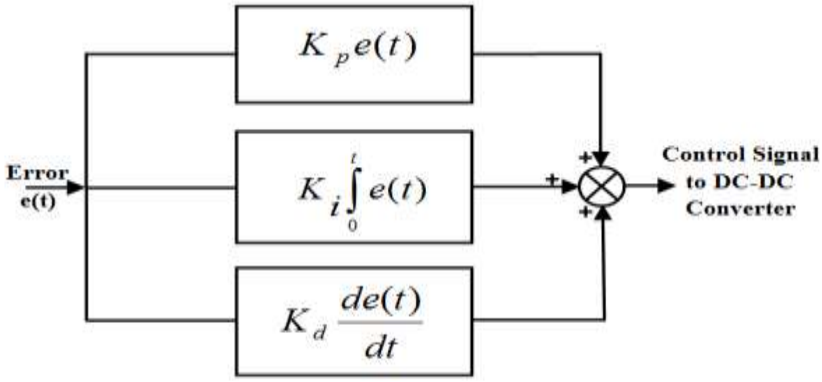

***Fig.5:-** Block Diagram form PID Controller.*

Mathematically the PID controller can be represented as;

$$y(t) = K_p e(t) + K_I \int e(t)dt + K_D \frac{d}{dt} e(t) \quad (5)$$

The expression of PID controller in the s-domain can be represented as;

$$Y(S) = \left[K_P + \frac{K_I}{S} + K_D(S)\right] E(S) \quad (6)$$

Generally P, PI, PID controllers are used in the feedback control loop for the electronic appliances; but recently these conventional controllers are being replaced with some modern controllers like Fuzzy Logic Controller (FLC). FLC works on the concept of soft computing which deals with verbal parameters instead of any calculative approach. It operates on linguistic parameters like “many”, “low”, “medium”, “often”, “few” etc. The systems which works on fuzzy logic provides better approximation approach. Hence, systems having FLC provides a fast-moving and smooth output response as compared to the systems using conventional control techniques. Figure 6 shows the basic block diagram of a fuzzy Logic Controller [12].

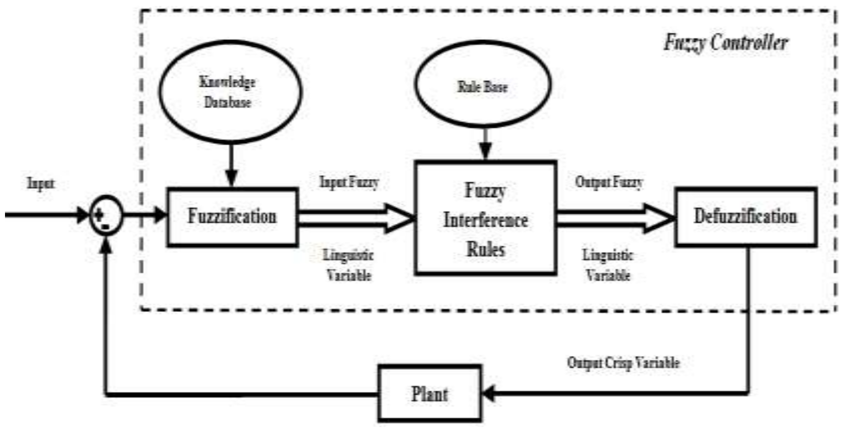

***Fig.6:-** Block Diagram of Fuzzy Logic Controller.*

According to above block diagram there are four major units of FLC.

- Fuzzification – the function of this block is to measure the input variables, to perform a scale mapping and to convert the input data into linguistic parameters to be used in fuzzy rules.
- Knowledge Database – It provides all the input-output data, required definitions and membership function for fuzzy rule base.
- Rule Base – It provides the

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knowledge about the set of verbal control rules.

- Fuzzy Inference Engine – The kernel of an FLC is the decision making unit. It has the ability to simulate human decision by using fuzzy approximation..
- Defuzzifier – Provides a non-fuzzy control action to achieve crisp values from fuzzified values.

C. Design of FLC for Boost Converter

Fuzzy Logic Controller (FLC) is a soft computing generated smart controller which deals with words. It provides technique which works with some linguistic parameters like "many", "low", "often", "medium", "few" etc. By using Fuzzy Logic an inference structure can be developed to interpret human decision making capability. Design of FLC involves determination of input and output variables, tuning of pre-processing and post processing scaling factor and defining the rule base [13]. The FLC needs to control the DC output voltage of the converter circuit. As it is being used in the feedback path, the error should be calculated as the difference between the measured value and the reference value. Then the FLC will take the calculated the error (e) and change in error (ce) as the inputs to generate change in duty cycle (Δd) as output variable [14].

Where, the values of e and ce belongs to set of values [-1, 1]. The two inputs are multiplied by the scaling factor s0 and s1 respectively and fed to the controller. Input scaling factor are provided to bind the input of the fuzzy controller with in a range. The fuzzy sets are defined for each variable within the universe of discourse. In this work universe of discourse is divided into five groups; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PB: Positive Big, PS: Positive Small. The partition of fuzzy subsets and the shape of MFs are shown in Figure 7.1 and Figure 7.2.

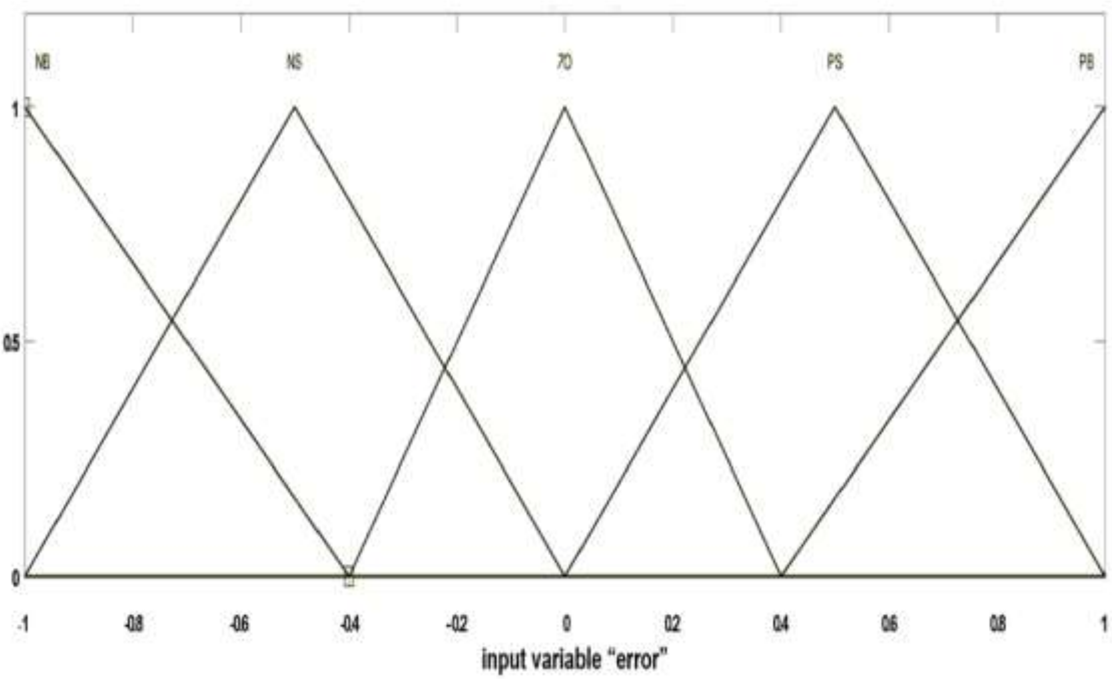

Fig. 7.1:- *Membership Function for Error (e).*

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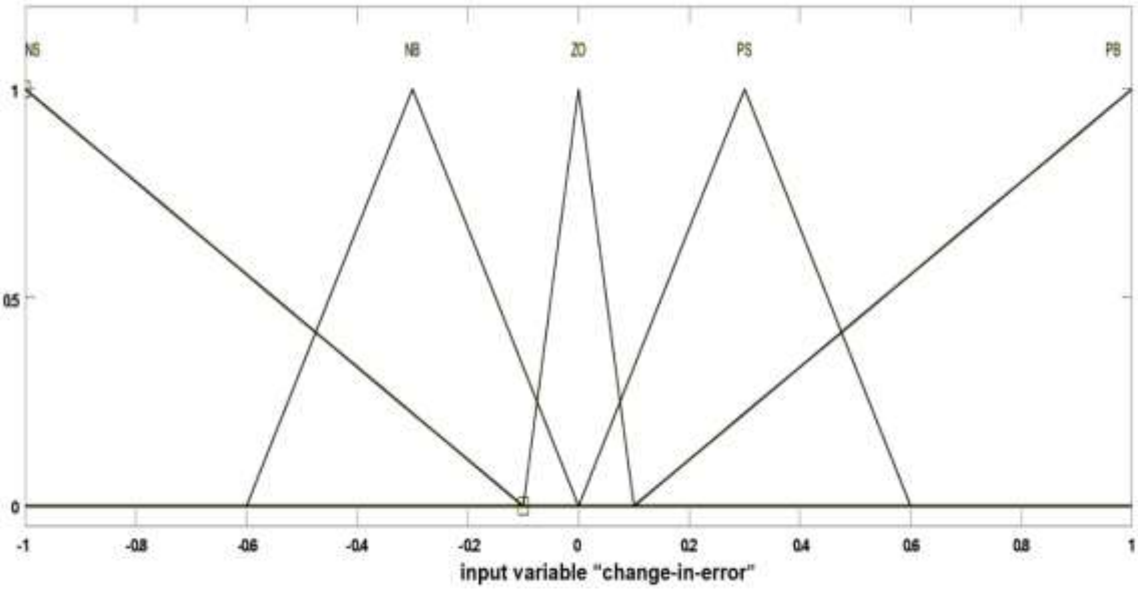

Fig. 7.2:- *Membership Function for Change in Error (ce).*

The principles guiding the Fuzzy Rule base are conditional, particularly regarding the adjustment of the duty cycle. When there's a significant discrepancy between the desired set-point and the actual output, the modification to the duty cycle should be substantial. Conversely, as this deviation decreases, the adjustments to the duty cycle should become less pronounced. To maintain a stable output, especially when the actual output is close to or matches the target value, the duty cycle alterations should be kept steady to prevent any further discrepancies. However, if the actual output surpasses the target value, then adjustments to the duty cycle need to be made in the reverse direction to correct this overachievement. The Fuzzy Logic Controller (FLC) employs a set of 25 specific rules, which govern the actions based on the error and the rate of change of the error, as detailed in a designated table, referred to here as Table 1.

Table 1:-*Fuzzy Rule Base.*

(e) / (ce)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

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D. Boost-Inverter Topology for SOFC

For real time applications SOFC generated DC voltage needs to be converted to AC with a required amount of amplification. Hence, a boost-inverter strategy is developed. It will work in two parts i.e. boost and inverter. First the SOFC generated small DC output voltage will get enhanced to a desired level by the converter and then the inverter will help to convert the boosted DC output voltage to an AC output voltage. The voltage source inverter is controlled by PWM based technique [15-16].

A single phase VSI is attached to the boost converter to design the boost-inverter topology. For the inverter either we can choose a half-bridge VSI or a full-bridge VSI design. But according to the proposed topology it involves the full-bridge VSI. The full-bridge VSI is being attached to the converter circuit through a capacitor. In this circuit a DC supply is fed in the input side while an increased AC signal is generated as output.

The connection is made in such a way that the higher level DC output voltage generated by the boost converter is fed as input of the VSI. The capacitor of boost converter acts as the DC link capacitor for the inverter. In this way the cost of the capacitor can be reduced. A high AC voltage can be cultivated by using this method with low harmonic distortion [17-18].

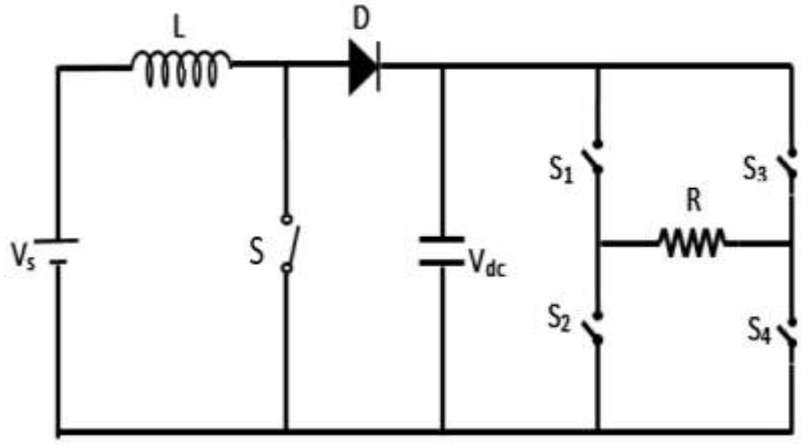

Fig. 8:- *Circuit Diagram of Boost-Inverter*.

E. Cascaded Boost-Inverter Topology

In this cascaded configuration two Boost-Inverters are connected in series to give an increased performance. The basic objective of this configuration is to get an increased AC output voltage with low THD. While designing this circuit only one PWM generator has used for providing pulses to the IGBTs of inverters. Four pulses are generated simultaneously by the PWM generators and fed to switching devices associated with the inverters.

To make this configuration cost effective only a single controller has used for controlling the DC output voltage of both the Boost converters.

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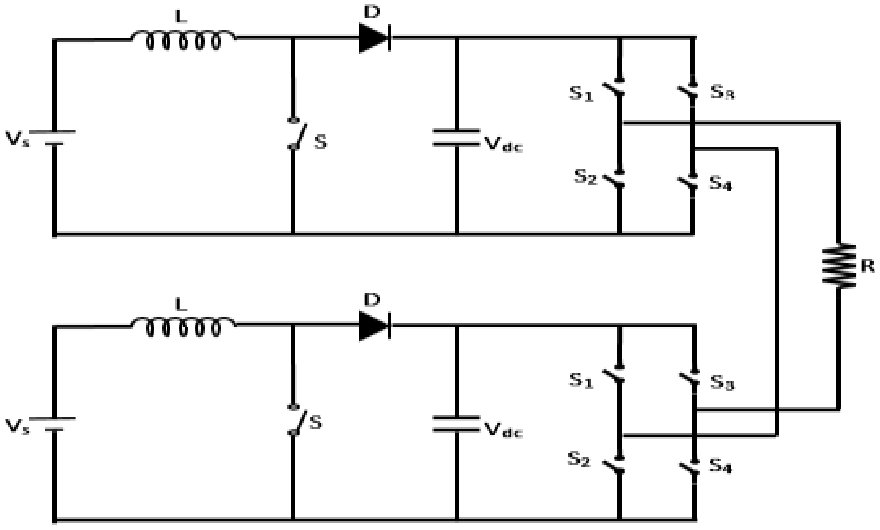

***Fig. 9:-** Circuit Diagram of cascaded Boost-Inverter.*

SIMULATION RESULTS

The characteristic of Fuel Cell as a voltage source in the energy conversion system is discussed below. A single fuel cell can generate up to 1.2V DC output voltage ideally. This small DC voltage then needs to be enhanced to a required voltage level by using boost converter circuit. Then the performance of the boost converter circuit with different control strategies like PI, PID and Fuzzy Logic controller is analyzed. SOFC stack is used as a DC voltage source for the energy conversion system. This SOFC stack provides a constant 15V DC voltage to the circuit. The voltage output plot of SOFC stack has shown in Figure 10. A constant 15V DC voltage has acquired which is shown in the plot.

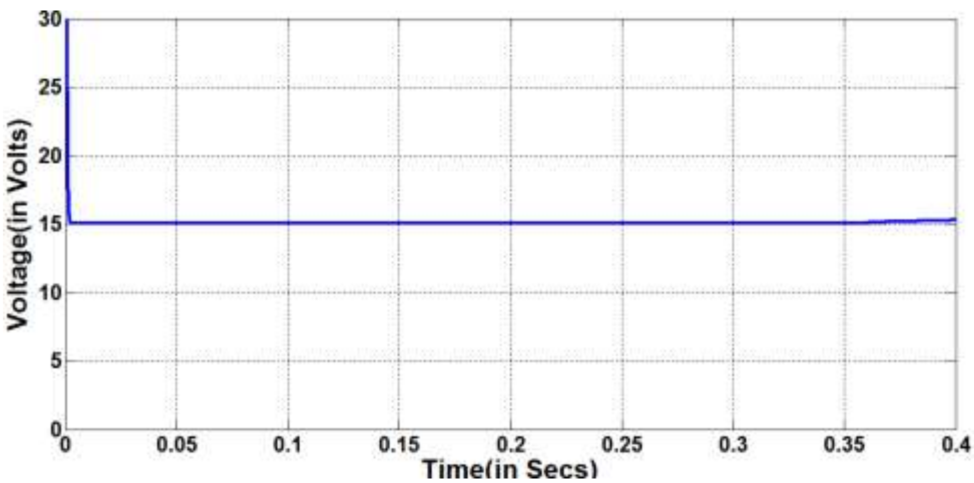

***Fig.10:-** Output Voltage of SOFC Stack.*

A. Boost Converter with PI Controller

To generate a 15V DC output voltage from a SOFC stack, a Boost converter has used. This will provides a higher level DC output voltage to match load requirement.

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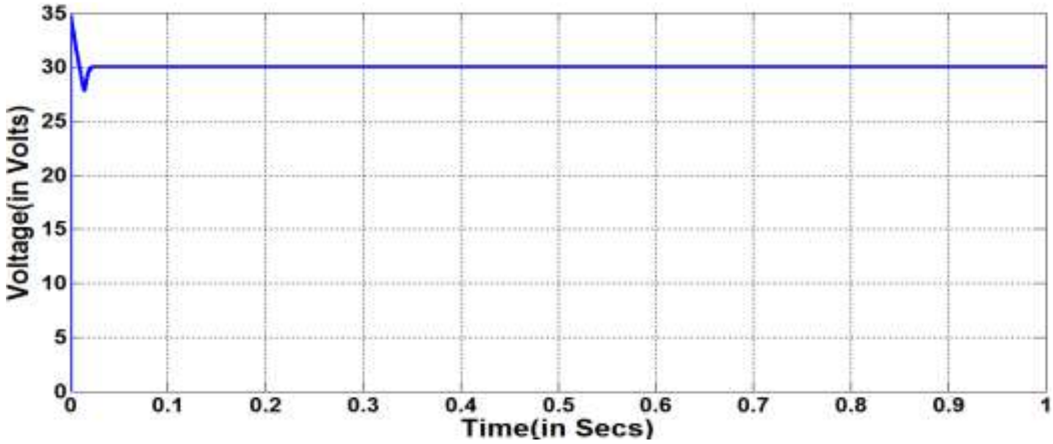

Fig. 11:- *Voltage Output of Boost-converter with PI Controller*.

Figure 11 shows the simulation result of SOFCs energy conversion system using PI controller. From the above response it is clear that peak overshoot is 16%, rise time 0.0025secs and settling time 0.03secs.

B. Boost Converter with PID Controller

The PID controller has used for predict what will happen with the error in future. The output voltage of DC-DC Boost converter has fed to the PID controller for better results.

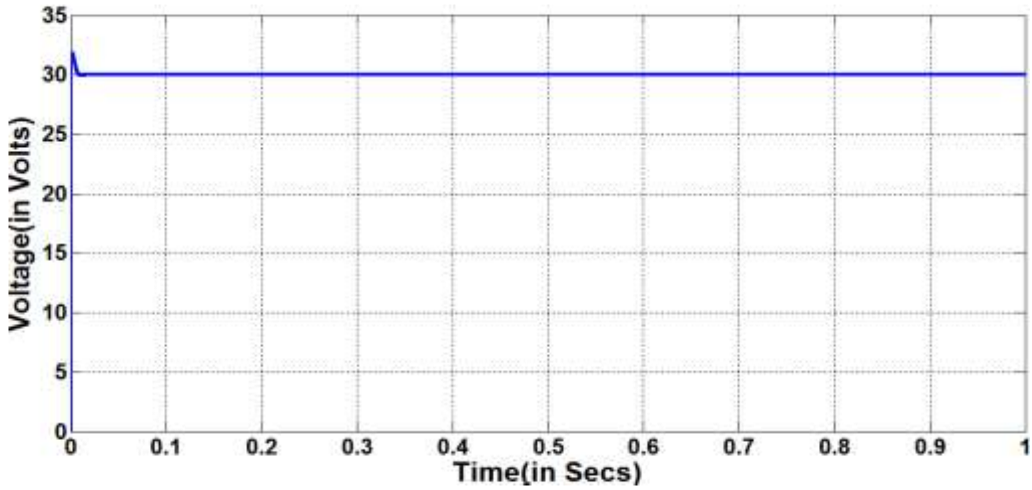

Fig. 12:- *Voltage Output of Boost-converter with PID Controller.*

Figure 12 shows the simulation result of SOFCs energy conversion system using PID controller. From the above simulation result it is clear that peak overshoot is 6.26%, rise time 0.002secs and settling time 0.02secs.

C. Boost Converter with Fuzzy Logic Controller

Fuzzy system focuses on quantification and approximation of human observation.

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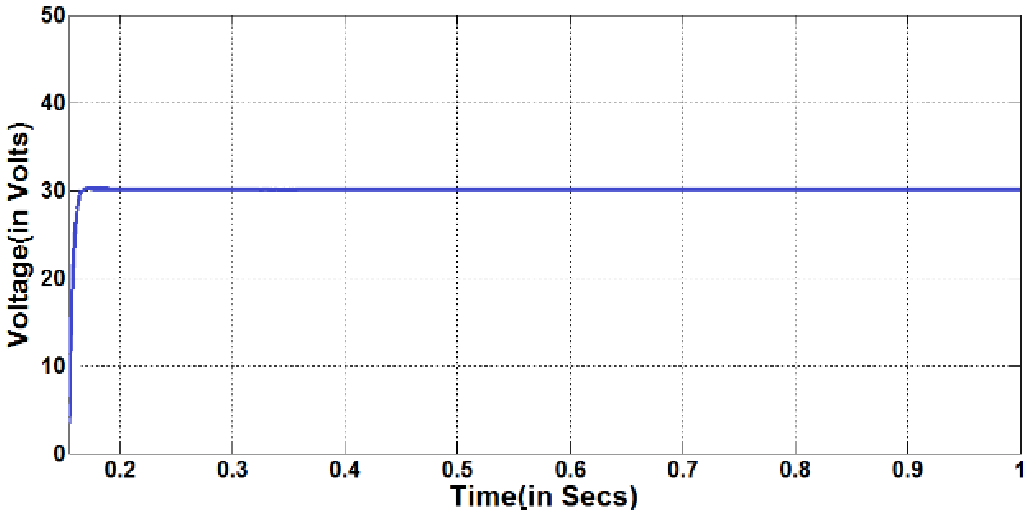

Fig. 13:- *Voltage Output of Boost-converter with Fuzzy Logic Controller.*

Figure 13 shows the results of the simulation of SOFCs energy conversion system using FLC. This response shows that the peak overshoot is eliminated, rise time 0.001secs and settling time 0.018secs, which is much lower as compare to that of other two controllers.

D. SOFC Voltage Generation System with Boost-Inverter

The boost-inverter is being achieved by introducing an inverter circuit with the boost converter circuit. As previously discussed with only boost converter a desired DC voltage level has been achieved. To make this high level DC voltage available for all ac driven load; an inverter is being attached. The capacitor of the boost converter acts as DC-link capacitor for the inverter circuit. This capacitor helps to reduce the ripple generated by the converter.

The VSI using PWM switching technique converts the DC input to AC output. The inverter is provided input DC voltage through a controlled voltage source. Figure 14 shows the voltage output waveform of Boost-Inverter with single phase full bridge configuration.

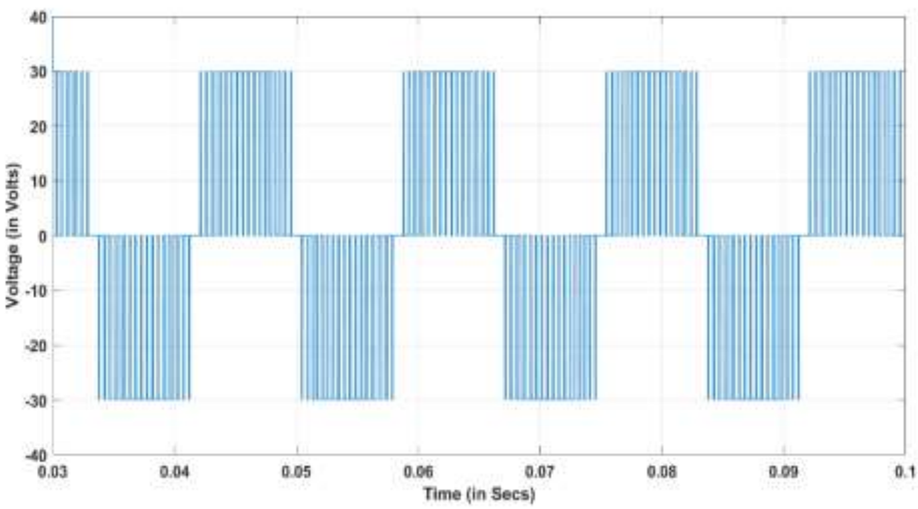

Fig. 14:- *Voltage Output of Boost-Inverter.*

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An inverter has attached with the Boost converter to convert the DC output voltage of the converter to a required AC voltage.

In the above plot it is shown that a 30V AC output voltage has achieved after using the inverter.

E. Cascaded Boost-Inverter Topology for SOFC Voltage Generation System

In this cascaded configuration two Boost-Inverters are connected in series to give an increased performance. The basic objective of this configuration is to get an increased AC output voltage with low THD.

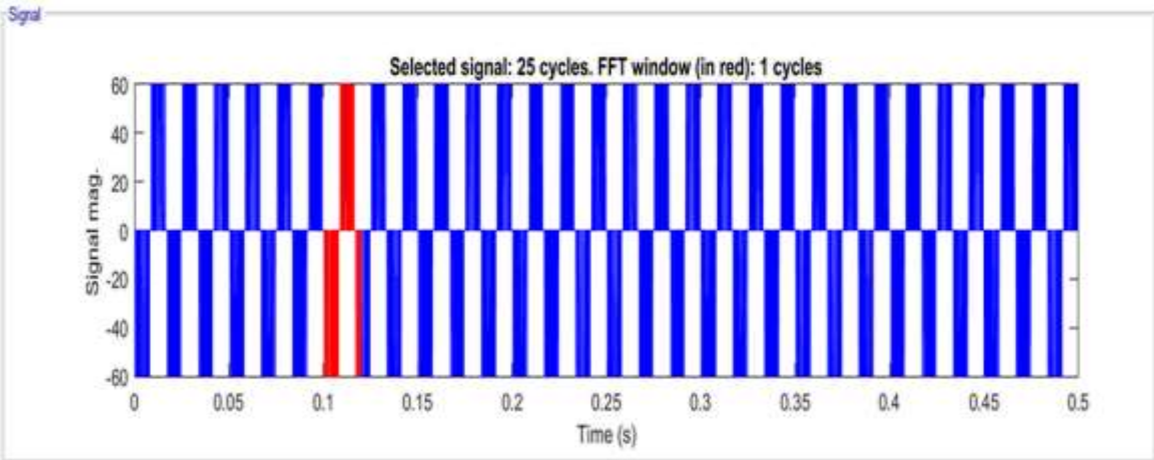

Fig. 15:- *Output Voltage Plot of Cascaded Boost-Inverter SOFC Voltage Generation System.*

From the above graph it is shown that a 60V AC signal has generated from the cascaded boost-inverter. The voltage input provided to the boost converter from SOFC is 15V and the DC output voltage is 30V. So, the input fed to the inverter circuit is the output of Boost converter; i.e. 30V.

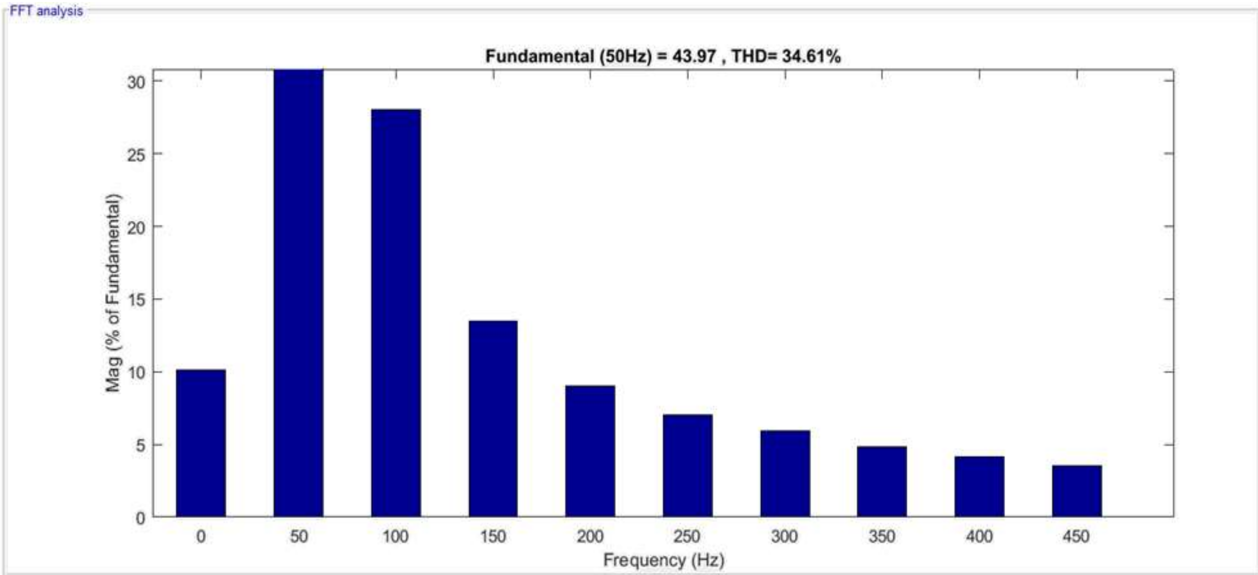

Fig. 16:- *THD Calculation of Cascaded Boost-Inverter.*

THD of the AC voltage output of cascaded Boost-Inverter has been calculated, 34.61%. This value can be reduced by using a filter circuit.

CONCLUSIONS

An efficient SOFC energy conversion system using DC-DC converter has been planned. The Boost converter captures the energy from SOFC and at the same time forms the energy into a usable shape. Different control strategies for the Boost converter have been designed. Output voltage plot of DC-DC Boost converter with different controller has been generated and analyzed. The output voltage of boost converter associated with SOFC with different control strategies like PI, PID and FLC has been observed. As per the observations an improved output response is achieved by using FLC for the boost converter.

Furthermore inverters have been modeled for each converter and cascaded to form a cascaded Boost-Inverter. After using cascaded Boost-Inverter, a 60V AC voltage is generated with 34.61% harmonics. Both the converters used in cascaded Boost-Inverter are controlled by a single controller, which makes this system cost effective.

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