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Design and Performance analysis of Solid Oxide Fuel Cell based Energy System with Cascaded H-Bridge Multilevel Inverter

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Abstract-Nowadays there is a growing trend towards the use of Fuel Cell based energy systems for various applications. This is supplemented by swift advancements in Fuel cell technology. These systems have aroused enormous interests among researchers across the globe due to their clean, efficient nature and remains one of the core research fields. Fuel Cell based energy systems can be effectively integrated into the conventional power system or for remote electrification as well as for stationary applications. These systems bring very notable applications of power electronic devices in this domain. In this paper, a qualitative comparison of the performance of Cascaded H-Bridge Multilevel Inverter has been comprehensively investigated with a conventional Two Level Inverter for these applications. The whole arrangement considered in this work comprises the models of Solid Oxide Fuel Cell systems (SOFC) interfaced with the two inverter topologies. The developed models are put forward to confirm the operational performance of the proposed system and methodology. To assess the efficacy of the proposed methodology, extensive simulation studies have been carried out in the MATLAB/SIMULINK environment using power system block set toolboxes.

Keywords— SOFC, Fuel Cell, Hybrid Electric Vehicle, Multilevel inverter,Cascaded H-Bridge Inverter.

1. INTRODUCTION

Falling oil reserves, coal stocks, growing environmental concerns and green legislations have all paved way for the use of new advanced clean energy conversion technologies. Due to tremendousresearch over decades, considerable advancements and developments have been accomplished in the overall technological, economical and operational performance of small, modular units. Fuel Cell (FC) is regarded as an environmental friendly energy source having higher efficiencies and reliability due to less moving parts as compared to other conventional energy sources [1-2]. FC based small electrical generation systems offer an alternative way to power, particularly remote areas where grid connection is not viable from an economic perspective [3]. This concept is further strengthened due to frequent developments in power electronics devices and energy storage systems to account for temporary backup. SOFC based Distributed Generation System (DGS) is gaining momentum due to numerous advantages apart from being environmentally friendly such as modular electrical production, improved reliability, continuous power generation and reasonable scope for expansion [4-5]. For FCs energy integration into the conventional AC system, efficient power electronic converters are required. Two Level Inverters (2L-Inverters) are generally used for household applications, but they are not preferred for High Voltage (HV) applications due to the restrictions and constraints over the issues of switching device stress and high Total Harmonic Distortion (THD) content in output voltage. Among all the Multilevel Inverters (MLIs), Cascaded-H Bridge (CHB) topology is most prominently used because of its symmetry, modular construction, fault tolerant capability and high reliability in the field of Renewable Energy Systems (RES) and FC based systems [6-7].Proton Exchange Membrane (PEM) has numerous advantages like excessive power density, rapid initiation, less expensive, long working life and roughly appropriate for all applications. But the Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell(SOFC) are the premier choice for medium and large power implementations due to their favorable efficiency, interior adjustment and cumulative heat and power generation of hybrid systems [8]. In this paper, two identical SOFCprototype models are developed. The operating characteristics like Stack Power vs.Current and Stack Voltagevs. Current of the Fuel Cell Stack (FCS) models are plotted to investigate the performance and the power handling capability. Further, these FCS models are integrated to the proposed MLI to estimate the overall performance and efficiency of the system at various loading conditions.

2. SOLID OXIDE FUEL CELL (SOFC)MODELLING

Figure 1shows a schematic diagram of SOFC.Under standard operation a single FC usually provides 0.5-0.9V at its output [9]. For distributed generation, relatively high power levels are required so FCs can be grouped into a number of individual cells to form FCS to obtain a desired power level, the number of cells in an FCS ultimately decides voltage which is available at the output terminal of the cell stack. Modelling of FC plays a pivotal role in overall system design.The aim is to develop simple and accurate model so that interfacing with other components primarily power electronic converters or storage systems becomes easier for a particular application without adding on to further complexity into the system. The main motive behind taking SOFC is the fact that when operating within its high temperature range its thermal output can be utilized effectively by the system, leading to more efficiency when compared to other FC systems [10]. Also, it has been reported in previous literature that for distributed generation (DG) in the range of 5KW-3MW, the % efficiency of SOFC based systems is 45-65 which is much higher than other FC based DG systems [11]. Under normal operation, the SOFC power dynamic model to investigate its performance is provided based on [12]. Undoubtedly, Carbon monoxide can be used as one of the fuels in SOFC. However,if water is present in the operating fuel, due to the favorable nature of H_2in system designs, the following reaction is used:

$$H_2O + CO \rightarrow CO_2 + H_2 \quad (1)$$

So ultimately H_2 and O_2 are the fuels that enter the SOFC. Fuel utilization is the fraction of fuel flow that reacts and interacts to input fuel flow. So, it can be deduced that [12]

$$U_{H_2} = \frac{q^{react}H_2}{q^{enter}H_2} \quad (2)$$

Where $q^{react}H_2, q^{enter}H_2$ are hydrogen fuel flow at input and while it reacts in $k.mol/s$.

Fuel utilization in the range of 80-90% is generally employed.In the present model the fuel utilization is limited to 90, 80 and 85 for maximum, minimal and optimal cases.As per the following equations the current and voltage of the SOFC stack can be determined [12].

2.1 *Current estimation*

$$q^{react}H_2 = \frac{N_S I^r_{fc}}{2F} = 2K_r I^r_{fc} \quad (3)$$

Where $N_S$is the number of cells in series in cell stack, I^r_{fc} is the actual output current of the FC.

The current demanded by the fuel cell system for particular input hydrogen fuel flow fall within the range:

$$\frac{0.8q^{enter}H_2}{2K_r} \le I^{in}_{fc} \le \frac{0.9q^{enter}H_2}{2K_r} \qquad (4)$$

Where I^{in}_{fc} is the demand current of FC and K_r is a constant equal to $\frac{N_S}{4F}$.

The actual output current of SOFC can be measured by controlling the input fuel flow to control fuel utilization to 85% [12]. So we have $q^{enter}H_2 = \frac{2K_r I^r_{fc}}{0.85}$ (5)

2.2*Voltage estimation*

By applying Nernst equation and Ohm's law, the stack voltage on the assumption that only ohmic losses occur inside the cell as the two extreme regions on current curve where concentration and activation losses occurs is not in the region of interest can be expressed as [13]

$$V = N_s * \left\{ E_0 + \frac{1}{2} * \frac{RT}{F} \left[\ln \frac{pH_2 \, pO_2^{1/2}}{pH_2O} \right] \right\} - O_h * I_{fc} \qquad (6)$$

Where E_0=1.18V depends upon temperature and represents voltage value at standard pressure, R=8.314kJ/kmol.K is universal gas constant, T is operating temperature of FC in Kelvins, pH_2, pH_2O, pO_2 are partial pressures of hydrogen, water and oxygen respectively, whereas, F=96486C/mol is Faraday Constantand O_h represents current flow resistance within the FC in ohms, equal to 0.126Ω[14].Figure 2shows operating characteristics of SOFC considered during this paper and Table 1 shows different parametric values for the SOFC model.

3. CASCADED H-BRIDGE MULTILEVEL INVERTER (CHB MLI) SYSTEM

a) *Converter topology:*Figure 3(a) shows proposed open loop FC based energy system employing two identical SOFC sources connected to AC load via a single phase CHB MLI. The motive behind using CHB MLI is the fact that it not only brings flexibility to the network as it employs full bridge modular chopper cells, which are connected in series to form each arm, but also facilitates the use of two separate/isolated DC sources making it highly suitable for integration with renewable energy hybrid systems utilizing PV, wind, FC based systems etc. The switching sequence for the proposed system is illustrated in Figure 3(b).

b) *Sinusoidal Multilevel PWM Scheme:*An*m*-level converter using level-shifted multicarrier modulation scheme requires (*m–1*) triangular carrier signals, all bearing the same frequency and peak-to-peak amplitude. The (*m–1*) triangular carrier signals are vertically disposed such that the bands they occupy are contiguous. The frequency modulation index (m_f) remains same as per the required AC output voltage, frequency whereas the amplitude modulation index (m_a) is defined as:[15]

$$m_a = \frac{V_m}{V_{cr}(m-1)}$$

The control scheme is illustrated by Table 4 showing PWM digital output states. For remaining switches $S'_x = \overline{S_x}, \in x = 1, 2, 3, ...m-1$, where *m*= level of the converter, where*m*=*5* in the 5-level MLI.

The CHB MLI based system performance is compared with a 2L-Inverter based system at different loading conditions to estimate power flow capability and overall efficiency of the system with proposed methodology.

4. PERFORMANCE ANALYSIS

Simulation study has been carried out in order to investigate the performance of conventional 2L-Inverter and proposed CHB MLI based SOFC energy system. Identical parameters are considered in both inverter based systems as shown in Table 2.

4.1 With 2L- Inverter

The AC side load voltage and current waveforms are shown in Figure 4(a) and 4(c) with a voltage of 363.3V and 7.25A peak to peak respectively. The harmonic spectrums of the AC side load voltage and current are shown in Figure 4(b) and 4(d).The AC side load voltage and current THD are about 63.54% and 8.98%

with the RMS value of 256.7V and 5.1A respectively.The voltage stress across each switching device i.e. Peak Inverse Voltage (PIV) in this inverter based system is 400V i.e., equal to total DC source voltage of inverter as it is evident from Figure 5(a). Active power delivered to the load in this system is about 1300W as shown in Figure 5(b) whereas reactive power is approximately 82VAR as depicted in Figure 5(c).

4.2 With Cascaded H-bridge (CHB) MLI

The AC sideload voltage and current waveforms are shown in Figure 6(a) and 6(c) with a voltage of 391.8V and 7.8A peak to peak respectively.The AC side load voltage waveform possesses an equal and symmetrical level of voltages that justifies the five level operation of CHB MLI topology. The harmonic spectrums of the AC side load voltage and current are shown in Figure 6(b) and 6(d). The load side voltage and current THD are about 28.47% and 6.98% with the RMS value of 277V and 5.5A respectively. The PIV across each switching device in this inverter based system is 200V i.e., equal to the DC source voltage in the respective H-Bridge cell, and it is evident from Figure 7(a).Active power delivered to the load in this MLI based system is about 1400W as shown in Figure 7(b) whereas reactive power is approximately 85VAR as depicted in Figure 7(c).

4.3 Observations and Discussions

From the harmonic analysis, the AC load side voltage waveform of the CHB MLI based SOFC system is maintaining better power quality compared to the 2L-Inverter based system. This in fact improves the load current power quality too. Moreover, the voltage and current in case of MLI based system is more sinusoidal and it is free from lower order harmonics with less THD as shown in their respective harmonic spectrum. Also, in this work it is quite important to note that the voltage stress across each switching device in case of CHB MLI based system is less (half times), compared to the 2L-Inverter based system. Hence the dv/dt losses are reduced and improves the efficiency of the system. The proposed system can be extended to high voltage/power capacity FC based system. As power handling capability of the proposed system can be enhanced, the overall system efficiency also improves. Hence, for different loading conditions the proposed system is tested and verified which is demonstrated from the efficiency curve as shown in Figure 8.

5. CONCLUSION

In this paper, an open loop FC based energy system interfaced to CHB MLI is developed with MATLAB/SIMULINK. Proposed system developed comprises two identical SOFCs as isolated DC input sources for the inverter system. Performance of CHB MLI and 2L-Inverter based FC system is comprehensively investigated for various loading conditions. The comparison is based on: no. of switches, voltage stress across each switching device, load voltage and current THD, power delivered and efficiency. The results clearly show that the performance of the CHB MLI based system is superior to conventional inverter based system, making CHB MLIs a preferred choice over conventional inverters for application in FC based energy system when more flexibility and power handling capability is desired. The proposed system canbe introduced in Hybrid Electric Vehicles and can meet the high power drive requirement of these systems leading to enhancement in their performance due to the many advantages offered by SOFC based MLIs as discussed in this work.

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TABLES

Table 1. Parameters used for SOFC modelling [10]

Absolute Temperature, T	1273K
Faraday's Constant, F	96487 C/mol
Universal gas constant, R	8314 J/kmol.K
Standard Potential, E_0	1.18 V
No. of series connected cells in the stack	384
Fuel Utilization [Max, Min, Opt.]	[0.9, 0.8, 0.85]
Ohmic loss	0.126Ω
Valve molar constant for [H_2, H_2O, O_2]	[8.43e-4, 2.81e-4, 2.52e-3]
Response time(in secs) for flow of [H_2, H_2O, O_2]	[26.1 78.3 2.91]

Table 2. Parameters used in simulation studies

Parameters	**2L-Inverter**	**CHB MLI**
Number of modules/ cell	1	2
Number of switches in each cell/modules	4	4
Each Cell DC Input Voltage	100V	100V
Modulation Index	0.95	0.95
Switching Frequency	2500Hz	2500Hz

RL Load	R= 50Ω L= 10mH	R= 50Ω L= 10mH

Table 3: Performance of the 2L-Inverter and CHB MLI based system

Parameters	**2L-Inverter based system**	**CHB MLI based system**
Voltage stress across the switch	400V	200V
Fundamental output voltage	256.7V	277V
Fundamental output current	5.1A	5.5A
Voltage THD	63.54%	28.47%
Current THD	8.98%	6.98%

Table 4: Employed Control logic for CHBMLI based system

Control Signal of Switch	**When switching condition is**	**PWM digital output is**
S_1	if m> cr_1	1
	else	0
S_2	if m> cr_2	1
	else	0
S_3	if m> cr_3	1
	else	0
S_4	if m> cr_4	1
	else	0

FIGURES

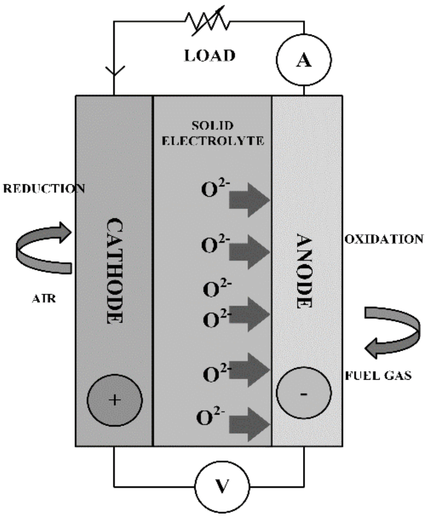
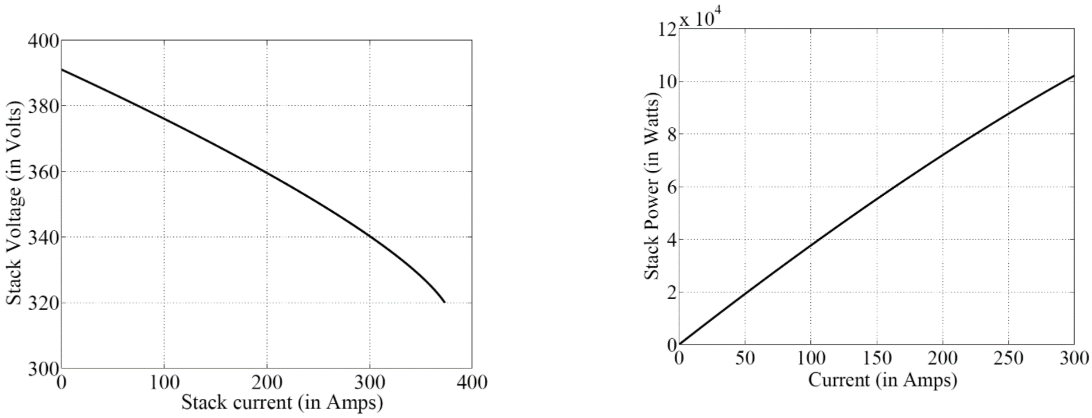


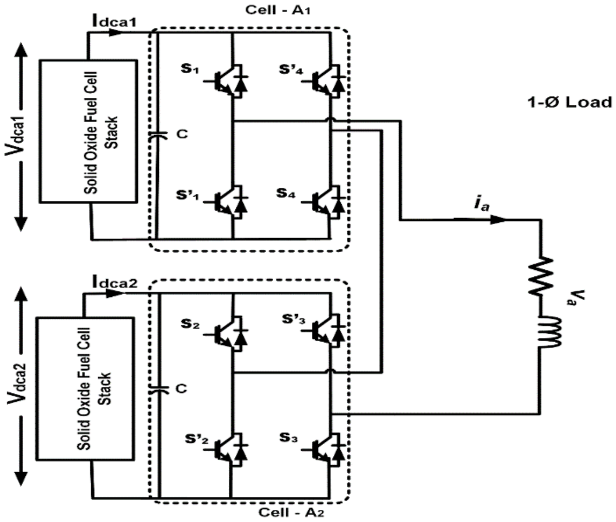
Figure 1: A schematic diagram of SOFC



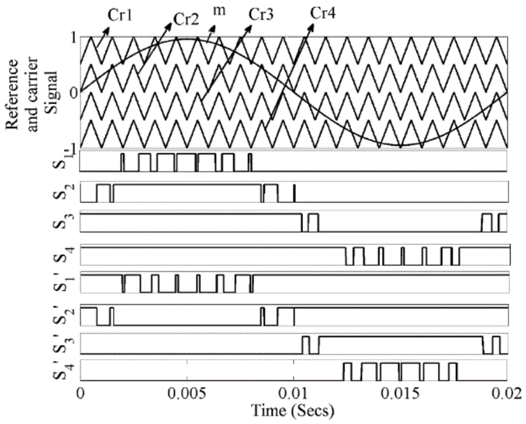
2(a) Stack voltage Vs. Stack current

2(b) Stack Power Vs. Stack current

Figure 2. Operating characteristics of SOFC



3(a) Circuit diagram of Cascaded H-Bridge MLI based SOFCenergy system



3(b) PWM Switching scheme for CHBMLI system
Figure 3. Proposed CHBMLI based SOFC energy system

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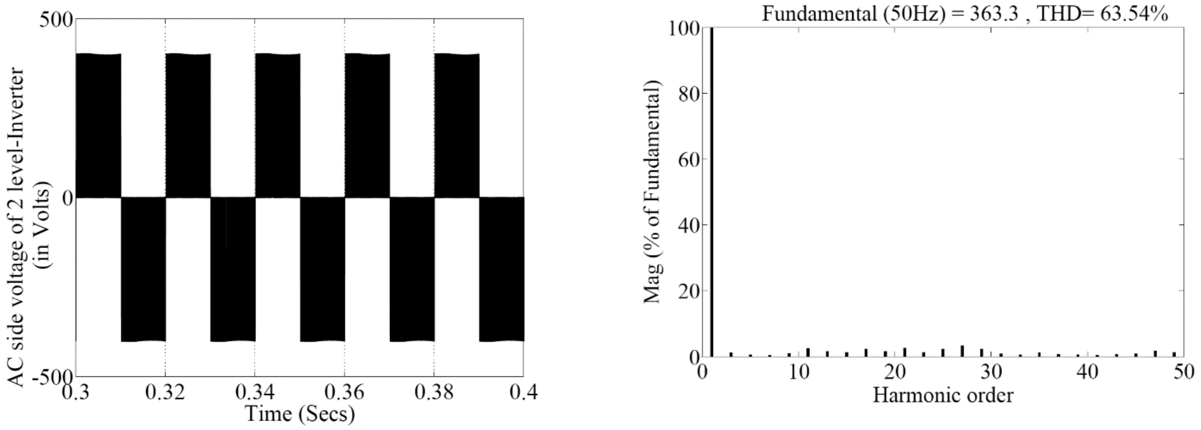
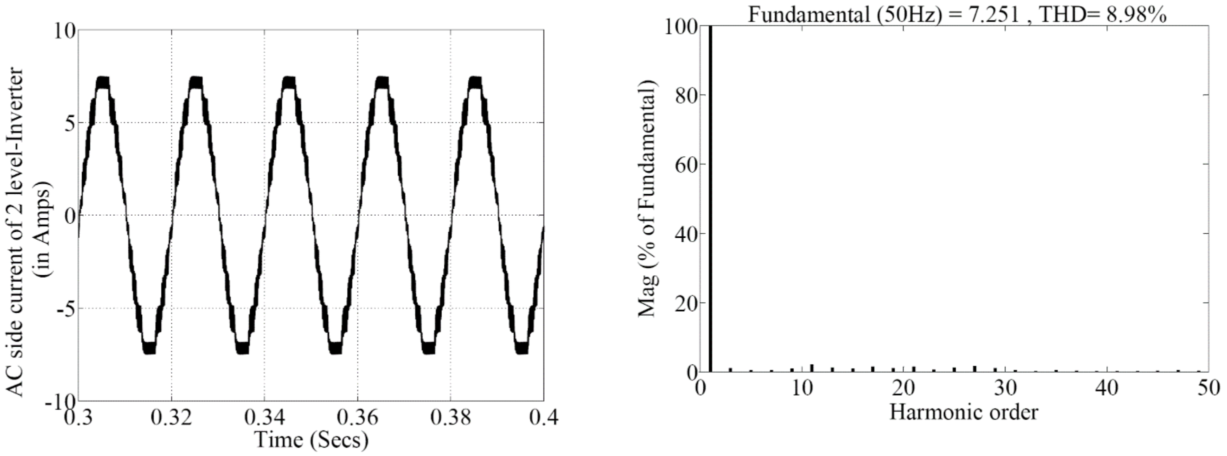


4(a) AC side Voltage

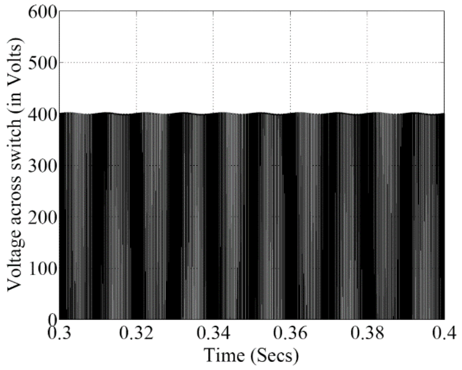
4(b) Load voltage THD



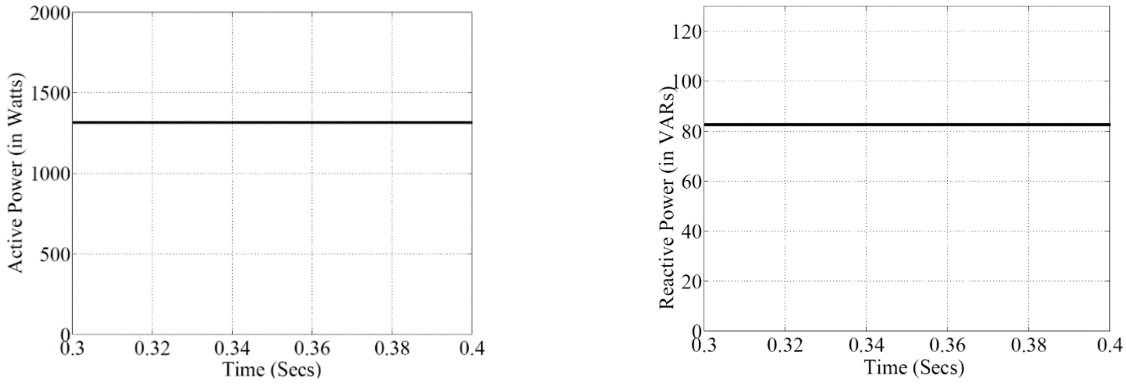
4(c) AC side Current

4(d) Load current THD

Figure 4. Load voltage and current profile with 2L-Inverter based system



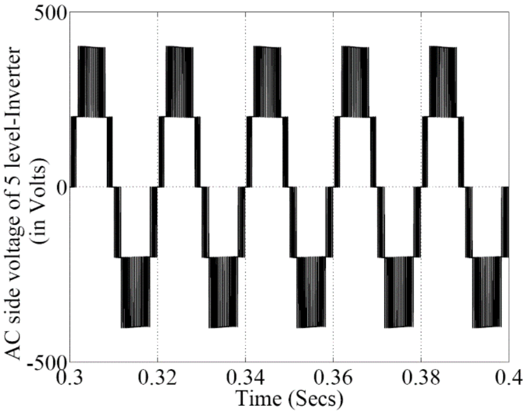
5(a) Peak Inverse Voltage (PIV) across switching device



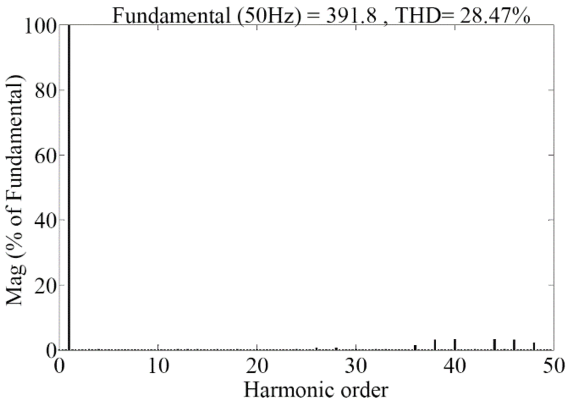
5(b) Active Power drawn by the AC load

5(c) Reactive Power drawn by the AC load

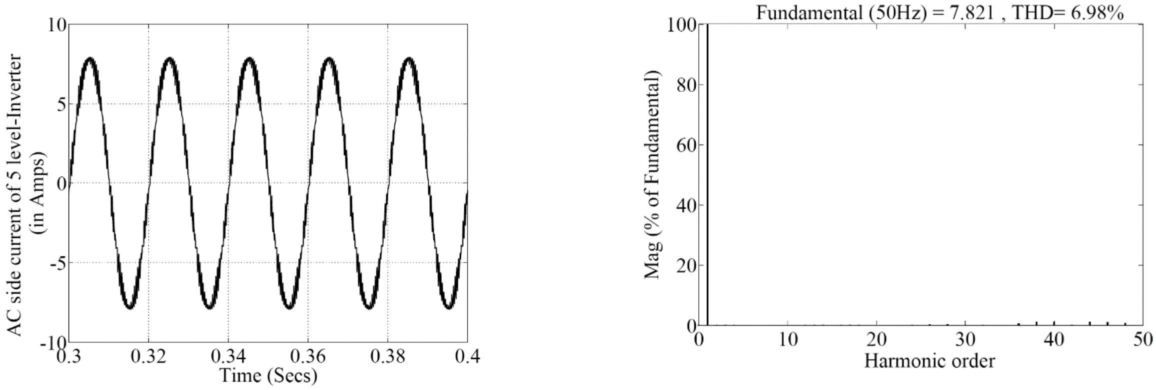
Figure 5. Performance of 2L-Inverter based SOFC energy system.



6(a) AC side voltage

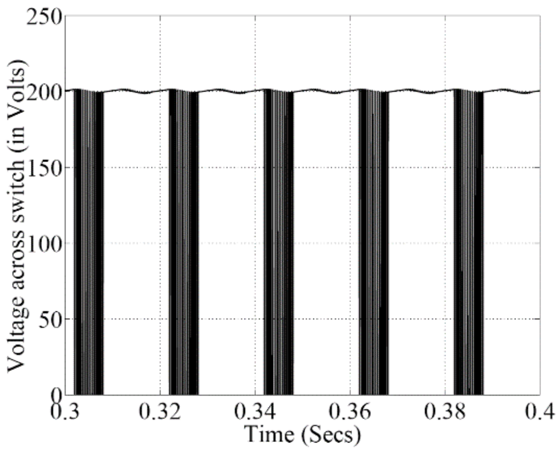


6(b) Load voltage THD

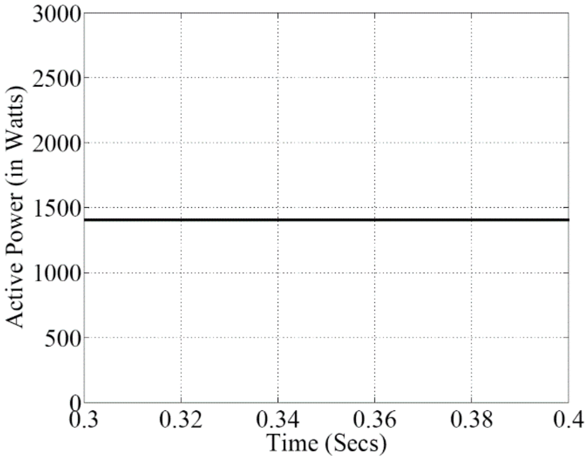


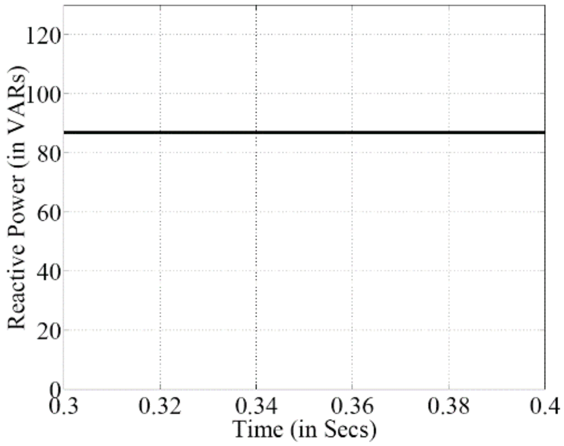
6(c) AC side current 6(d) Load current THD

Figure 6. Load voltage and current profile with CHBMLI based SOFC energy system



7(a) Peak Inverse Voltage (PIV) across switching device





7(b) Active Power drawn by the AC load 7(c) Reactive Power drawn by the AC load

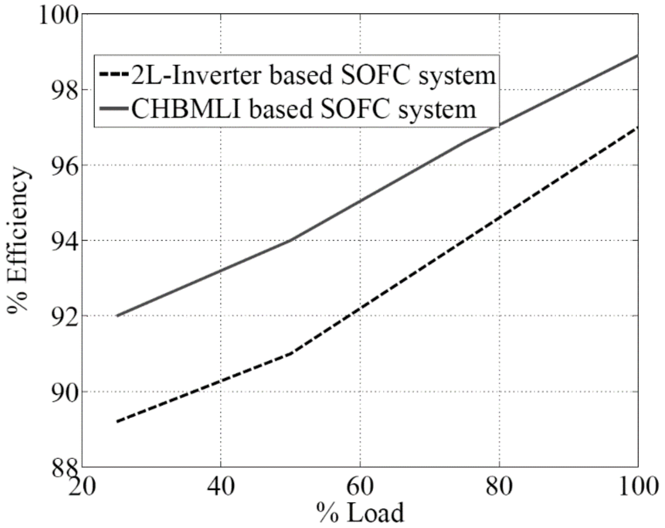


Figure 8. Efficiency curves for both the inverter based systems with SOFC