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2015

Roomi, M. M., Maswood, A. I., & Dehghani Tafti, H. Performance Evaluation of Boost and Z-Source Converters for Fuel Cell Application. 2015 IEEE Innovative Smart Grid Technologies - Asia, ISGT Asia 2015, 1-7.

<https://hdl.handle.net/10356/82263>

<https://doi.org/10.1109/ISGT-Asia.2015.7387071>

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Performance Evaluation of Boost and Z-Source Converters for Fuel Cell Application

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Abstract—Z-source being an attractive option for buck-boost energy conversion in renewable system, this paper investigates the performances of the traditional boost converter and Z-source inverter fed by fuel cell as the dc source. The changes in the fuel cell utilization, stack consumption and efficiency of a 65kW fuel cell is studied by maintaining a constant fuel flow rate. The output voltage and current of the stack, dc output voltage, inverter output voltages and currents are evaluated for balanced and unbalanced load conditions. Simulations are carried out using Matlab/Simulink and the results are presented.

Index Terms—Proton Exchange Membrane Fuel Cell (PEMFC); Z-source inverter; Boost converter; Renewable energy; dc-dc/ac.

I. INTRODUCTION

The worldwide energy has grown leaps and bounds leading to more stress on the availability and sustainability of the natural energy sources. Even though fossil fuel contributes to major production of energy; there are various drawbacks associated with the processing of these energy sources, one of the main concern being the carbon-di-oxide emissions. The global carbon-di-oxide emissions has been increasing drastically as shown in Fig 1 [1], which motivates to look for an alternative, renewable way of energy conversion.

One of the renewable source making its way to the top regardless of the low power generation is the hydrogen technology. The electrical generators which makes use of hydrogen to deliver electricity are fuel cells. Fuel cells works on chemical reactions, the result of which is the production of electricity in the external circuit connected to it. In this paper, Proton Exchange Membrane Fuel Cell (PEMFC) is chosen because of its advantages like operating at relatively low temperature, high power density and the output of this fuel cell can be changed instantly to meet the shift in load demands. The output range of the fuel cells can vary from several watts to several kilowatts, thereby extending its usability to large scale applications [2]. To study the dynamic modelling, research has been done emphasizing more on the electrical terminal characteristics of the fuel cell [3]. As the output of the sources tends to vary, connecting it directly to the utility mains or grid is not advisable. So the required energy regulation can be achieved by using power converter which converts the magnitude, frequency and phase of the electrical

Figure 1. Carbon emissions all over the world

quantities for the smooth integration of renewable sources to the load.

In this paper, the Proton Exchange Membrane Fuel Cell is connected to the load by using boost converter and Z-source inverter as shown in Figs 2 and 3. Studies are carried out to evaluate the performances of both the converters and the changes in the fuel cell output are plotted. Simulations are carried out using Matlab/Simulink and the results are presented in the later section.

II. PEM FUEL CELL

PEMFC shows great performance when used as distributed generation sources. When compared with other distributed generation sources like solar and wind, fuel cell doesn't have any geographic limitations. Therefore it can be moved and placed at any site when best performance can be achieved. Fuel cells are good reliable source of energy when used in steady state. Due to the slow internal process, fuel cells are not found to be effective in responding to transients. So in order to operate effectively, several researches has been done on the steady-state modeling [4], [5] and dynamic modeling [6]-[8] of the fuel cell. PEMFC uses hydrogen as the fuel which is oxidized at the anode [9] and the oxygen is

Figure 2. Fuel cell stack with boost converter and conventional PWM inverter

Figure 3. Fuel cell stack with Z-source inverter

introduced at the cathode. The chemical reactions happening in the fuel cell are given by the following equations

The fuel cell output voltage is a combination of reversible voltage and the irreversible voltage. The irreversible voltage represents the losses in the fuel cell. The main losses that contribute in the output voltage of the fuel cell are activation losses, ohmic losses and concentration losses. The output of the fuel cell is given by (4) [10].

$$V = E_{rev} + E_{loss} \quad (4)$$

$$= E_{rev} + V_{act} + V_{ohmic} + V_{conc}$$

where,

E_{rev} –reversible cell potential.

$E_{loss} = V_{act} + V_{ohmic} + V_{conc}$ –irreversible cell potential or losses in the cell (V).

V_{act} – activation losses.

V_{ohmic} – ohmic losses.

V_{conc} – concentration losses.

The losses are contributed by rates of chemical reaction happening on the surface of the electrode (activation), electrical resistance of the electrodes (ohmic) and change in concentration of the reactants (concentration). The electrical characteristics of a fuel cell can be explained by the polarization curve which depicts the change in the fuel cell output voltage with respect to the current density. The typical

Figure 4. Polarization Curve of a PEM Fuel Cell

Figure 5. Maximum shoot-through boost control method waveforms

polarization curve for a fuel cell with all the losses is shown in Figure 4.

III. Z-SOURCE INVERTER WITH MAXIMUM BOOST CONTROL METHOD (MBC)

A. Maximum Boost Control Method

In renewable energy systems, inverters with voltage buck-boost capabilities play a vital role in energy conversion, as it rectifies the unexpected voltage fluctuations. The traditional dc-dc boost converter and Z-source inverter proposed in [11] are individually integrated with the fuel cell to meet the load demands. One of the main advantage of the Z-source inverter is its ability to boost the output voltage to any value between zero and infinity by introducing additional shoot-through states. Insertion of shoot-through states is achieved by different shoot-through methods proposed in [12]-[15]. In this paper, the insertion of additional states is achieved by using maximum boost control method [15]. This method provides a maximum operating region for the inverter. Whenever the triangular carrier wave is greater than or lesser than the maximum or minimum value of the reference curves (V_a , V_b , and V_c) respectively, the circuit enters into shoot-through state as shown in Figure 5.

B. Mathematical Expressions:

The shoot-through duty ratio varies each cycle. To obtain the voltage gain, the average value of the shoot-through duty ratio is measured. At every $\pi/3$, the shoot-through state repeats periodically. The shoot-through duty ratio for the interval $(\pi/6, \pi/2)$ is given by,

$$\frac{T_0(\theta)}{T} = \frac{2 - (M \sin \theta - M \sin(\theta - \frac{2\pi}{3}))}{2} \quad (5)$$

which on simplification gives,

$$\frac{\overline{T_0}}{T} = \frac{2\pi - 3\sqrt{3}M}{2\pi} \quad (6)$$

Boost factor B can be obtained using (6) as,

$$B = \frac{1}{1 - 2\frac{\overline{T_0}}{T}} = \frac{\pi}{3\sqrt{3}M - \pi} \quad (7)$$

Voltage gain G can be obtained using Modulation index M and is expressed as,

$$G = \frac{\widetilde{v}_{ac}}{V_0/2} = MB = \frac{\pi M}{3\sqrt{3}M - \pi} \quad (8)$$

Voltage stress across the switches is given by,

$$V_s = B \cdot V_0 = \frac{\pi V_0}{3\sqrt{3}M - \pi} \quad (9)$$

IV. SIMULATION RESULTS

The schematic diagram of the system under study is shown in Figures 2 and 3 respectively. The system consists of a fuel cell stack, a fuel regulator, a boost converter or a three phase Z-source converter controlled by SPWM and corresponding RL load.

A. Operation of fuel cell stack with boost converter under balanced load

The fuel flow rate which is expressed in liters per minute (lpm) is maintained constant at 5lpm. Even though the fuel flow is maintained constant, a fuel flow regulator is used to regulate the flow of hydrogen gas into PEMFC. The corresponding oxygen and hydrogen utilization are presented. In Figure 6, there is a drop in the oxygen utilization which is due to transient state of the voltage regulator. After that instant the utilization is back to normal operation and consumption of the air and fuels are plotted. The efficiency of the fuel cell system shown in Figure 6 is found to be 30% which is in the theoretical range of 30-50% for PEMFC.

Figure 6. Fuel Cell Characteristics

Figure 7. Output Waveforms of Fuel cell and DC-link

Figure 7 shows the fuel cell output voltage, current and the dc link voltage. At $t=0$ when the fuel cell voltage is low, the current is at its maximum. The voltage increases with time, the current decreases thereby proving the concept of a fuel cell. The boost converter does its operation by boosting the voltage to 100 V. The corresponding ac output pole voltage for one phase and three phase currents are shown in Figures 8 and 9 respectively. From Figure 9, the output currents of the inverter with the same magnitudes represents the balanced load condition of the system.

Figure 8. AC output pole voltage

Figure 9. Three phase Output current

Figure 10. Fuel cell Characteristics

B. Operation of fuel cell with Z-source inverter under balanced load

The schematic diagram of the fuel cell integrated with the Z-source converter is shown in Figure 3. The operation of the fuel cell stack with the Z-source implementing the maximum boost control method is investigated. The fuel flow rate is maintained constant. The oxygen utilization in Figure 10 shows the transient state effect of the regulator is eliminated. Also, there is a slight change in the utilization which results in the drop in the consumption. When compared to the efficiency of the fuel cell with boost converter, the efficiency of fuel cell with Z-source is slightly less. Even though there is

Figure 11. Output Waveforms of fuel cell and dc-link

Figure 12. AC output line voltage

Figure 13. Three phase AC output current

a drop in efficiency, the output voltage of the fuel cell remains the same.

The fuel cell output voltage, output current and the DC-link output voltage are shown in Figure 11. Also, the Z-source inverter does the boost operation and the dc-link voltage is reasonably around 95V which is maintained at a desired value to meet the load demand. The dc-link voltage can be further boosted by controlling the shoot-through states in the inverter. The ac output line voltage and the three phase currents are shown in Figures 12 and 13 respectively.

C. Operation of fuel cell with boost under unbalanced load

The operation of the system is evaluated under unbalanced load but still maintaining the constant fuel flow

figure 14. fuel Cell Characteristics

Figure 15. Output Waveforms of fuel cell and dc-link

rate. The load changes will causes the change in the output current thereby having an impact in the efficiency of the fuel cell. Thereby changes in the utilization and the consumption of the fuel cell are studied. The performance of the fuel cell stack for the unbalanced load condition is shown in Figure 14. The oxygen utilization is the maintained the same whereas the percentage of hydrogen utilization is slightly reduced when compared to the balanced load utilization. There are some drops at the initial stages of the utilization which is mainly due to the transient state of the voltage regulator. In few seconds, the fuel cell utilization is back to normal operation and the consumption of air and fuel in liters per minute are also shown.

Figure 15 shows the fuel cell output voltage, output current and the dc-link voltage. Even during unbalanced, the

Figure 16. AC output pole voltage

Figure 17. Three phase output current

Figure 18. Fuel Cell Characteristics

boost converter can deliver 100V. Figure 16 and 17 shows the ac output voltage and ac output current waveforms for the unbalanced load condition respectively.

D. Operation of fuel cell stack with Z-source converter under unbalanced load

In this case the fuel cell stack is operated with the Z-source inverter and the variations in the output of the fuel cell stack are studied.

The changes in the fuel cell stack with the Z-source inverter under unbalanced load condition is shown in Figure 18. The utilization of oxygen is maintained the same and due to unbalanced condition there is a change in the hydrogen

Figure 19. Output Waveforms of fuel cell and dc-link

Figure 20. AC output line voltage

Figure 21. Three phase output current

utilization. The air and fuel consumption for the unbalanced condition is also plotted. The fuel cell output voltage, fuel cell output current and dc-link voltage are shown in Figure 19. As mentioned earlier, the dc-link voltage can be further increased by adjusting the shoot through duty ratio of the Z-source converter. The ac output voltage and currents are shown in Figures 20 and 21 respectively.

V. CONCLUSION

In this paper the performance of the fuel cell stack with both the boost converter and the Z-source converter with a modulation index of 0.7 are evaluated. The fuel flow rate is constant and the input variables of the fuel cell, the output of the fuel cell, DC link voltage and the ac output voltage and current for both the converters are plotted. From the results, it can be seen that when the stack is used with Z-source converter, there are changes in the utilization of the fuels

when compared to that of boost converter. Regardless of the decrease in the fuel utilization, Z-source provided the required amount of dc link voltage. As utilization plays one of the roles in efficiency, the variation caused the efficiency of stack when used with Z-source to drop. In both cases of the boost converter, the dc link voltage is reaching a peak value at the beginning which is due to the transient state of the regulator. But in cases of Z-source this effect is eliminated in both balanced and unbalanced condition due to the network capacitors. Also, the output of the boost converter is static but as far as Z-source inverter is concerned, by adjusting the shoot-through duty ratio, the output of the dc link voltage can be further increased. Thus Z-source inverter can be considered as best alternatives for boost converters.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support provided by Energy Research Institute at NTU (ERI@N) for this work.

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