

Proton Exchange Membrane fuel cell stack with interleaved boost converter for vehicular applications

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Abstract— A fuel cell is a clean and green way of generating electricity from the chemical energy. In a normal vehicle, fuel is combusted in internal combustion engines releasing many harmful emissions. But in a fuel cell vehicle hydrogen is made to react with oxygen to produce electricity and hence will be used to curb the pollution. This paper discusses the modeling of a proton exchange membrane fuel cell when used in transportation applications. To reduce the cost of testing, a simulation was done in MICROSIM PSPICE by modeling a fuel cell that generates 100 KW of power at a constant voltage of 300 V. The output of fuel cell will be coupled to a boost converter that regulates the output voltage to the required level. A boost converter however can inject current harmonics into the fuel cell which might otherwise damage the durability of fuel cell. Therefore an interleaved boost converter making use of two switch mode power supplies with varying duty cycles and same switching frequency was investigated to reduce current harmonics. With an interleaved boost converter, the current harmonics on fuel cells can be reduced and the output voltage levels can be increased. Further recommendations of the circuit have also been suggested that could lead to development of an efficient and an economical fuel cell vehicle.

I. INTRODUCTION

According to the statistics from the U.S. government pollution board, most ozone pollution is caused by motor vehicles. Cars which are very common in United States emit 20.4 lbs of Carbon Dioxide for every gallon of diesel and in 2002 around 314 metric tones of Carbon Dioxide were released from motor vehicles. Hence it is high time that measures must be taken to curb the vehicular pollution. Fuel cell vehicles are one of the best solutions available today to decrease huge amounts of Carbon dioxide being released.

The output of a fuel cell is typically connected to regulate the output voltage. The boost converter however injects current harmonics into the fuel cell. Such current harmonics can cause long term damage to the fuel cell. To reduce the harmonics several boost converters can be connected in parallel with staggered switching times. Such an arrangement is called interleaving.

This paper discusses the method of reduction of harmonics caused in a fuel cell vehicle by using the concept of interleaving. A comparison was made between two fuel cell circuits built in PSPICE simulation software from MICROSIM and the results are discussed

II. FUEL CELL VEHICLE

This portion of the paper describes the working of a fuel cell and its use in a vehicle. A fuel cell is used to generate electricity from the chemical energy. Depending on the components used, there are different types of fuel cells. This paper deals with Proton Exchange Membrane Fuel cells (PEMFC) which is the most commonly used fuel cell in different applications including transportation, military and other commercial products. The working of the PEMFC can be understood from the figure below [1]

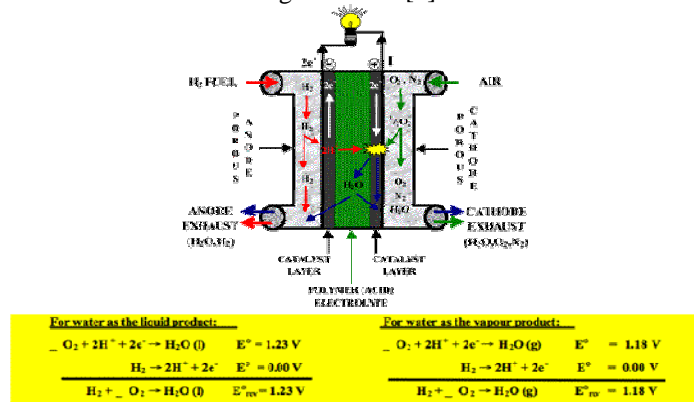


Figure 1. Proton Exchange Membrane fuel cell [1]

Ideally each fuel cell produces a voltage of 1.2 V. When placed in a fuel cell vehicle, many fuel cells are stacked together to produce large voltages in the range of 300 V that would in turn run an electric motor to drive the wheels of vehicle. But due to the V-I characteristics of a fuel cell, the voltage varies a lot with a small change in current. Hence bidirectional converter will be used to maintain a constant voltage at the output side. A lithium ion battery will be used to store the voltage when the output level increases the constant bus level and it delivers power when the output voltage level is low than required. This set up is known as Auxiliary power unit (APU).

III. MODELING OF FUEL CELL

A fuel cell was modeled using MICROSIM PSPICE software to resemble the electrical terminal characteristics of a real cell. Since much research is going on fuel cells still, the cost of a fuel cell is very high. Especially in case of a vehicle where the power output is in the range of hundred of watts, simulating a fuel cell would be very advantageous to observe the characteristics and improvements with a new model.

This paper discusses the application of a proton exchange membrane fuel cell in transportation. A HONDA FCX clarity vehicle was taken into consideration and according to the technical specifications [2]; the output power of fuel cell vehicle was 100 KW. Assuming that the voltage is expected to be 300v, the output current rating is 333 A.

The first task was to model a fuel cell such that it delivers 333 A of current at a voltage of 300 V. The basis for designing the simulation was taken from a paper on electronic circuit model [3] where all the characteristics of a fuel cell were modeled using simple circuit components like resistors, capacitors, inductors, transistors and diodes. Voltage drops inside the fuel cell, referred to as polarization losses, are important characteristics to be modeled. There are three kinds of polarization or losses in any kind of fuel cell which are namely activation polarization, ohmic polarization and concentration polarization.

Activation polarization occurs at low current densities due to sluggish electrode kinetics and is given by Tafel equation $V=A \ln(i/i_0)$ [4]. Thus this characterization is represented by a diode whose emission coefficient is adjusted to match the V-I characteristics of the fuel cell stack.

The ohmic loss is due to the resistance of the membrane to the protons and also of the electrodes. It is modeled using a linear resistance and can be included as an internal resistance of a diode.

The third kind of polarization which is known as concentration polarization arises due to different concentrations at different points of the gas channels and is more evident at higher current densities. This is developed using the PSPICE model of a current limiting circuit consisting of two transistors and a current sensing resistor [3]. Since the current of the order of 300 amperes is expected to flow in the fuel cell, the areas of the transistors have been modified in the PSPICE's BJT model. The circuit model developed looked like the figure below

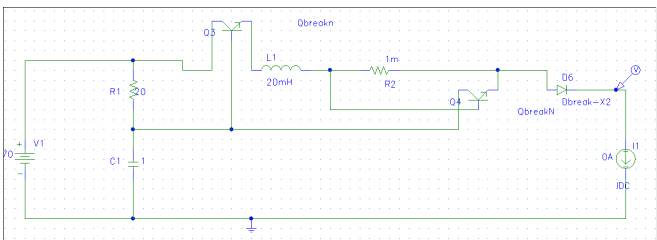


Figure 2. 100 KW Fuel cell stack model developed in Microsim PSPICE

IV. FUEL CELL WITH INTERLEAVED BOOST CONVERTER

The department of energy set a target that if 500,000 units were produced, the fuel cell stack must cost a \$30 per net kilowatt of power produced. In transportation applications few hundreds of kilowatts of power is required and since the fuel cells are still in the development stage, it would be practical enough if we use a smaller size fuel cell stack and then boost the output voltage to 300v using a boost converter. However, using a boost converter would possibly introduce current harmonics when operated at higher switching frequencies which may eventually damage the fuel cells. Hence this paper focuses on the use of interleaving concept to reduce the harmonics caused on the fuel cell stack.

Interleaving boost converter consists of two boost converters which are 180° out of phase with each other. This will result in canceling out the ripple currents caused in each inductor and hence produce a minimum ripple and hence tend to decrease the harmonic content on the input current. There are other advantages of interleaving boost converter like the reduction of stress on the capacitor, reduction of size of components and improved voltage [5]. A typical interleaved boost converter is shown in the figure below

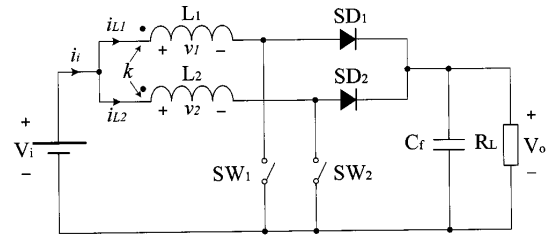


Figure 3. Interleaved boost converter [5]

In the consequent sections, the results of the simulation have been described and important conclusions on fuel cell coupled with interleaved boost converter have been deduced. A comparison study has been made between the existing boost converter coupled fuel cell with the new model and its advantages have been shown.

V. SIMULATION-RESULTS

A. Fuel Cell Model

As mentioned above, fuel cell has been modeled in PSPICE to generate the Voltage-Current (V-I) characteristics of a 100 KW fuel cell stack along with the three kinds of polarization. The diode model was modified in terms of its area and parasitic resistance to accommodate for the activation polarization and ohmic polarizations. The two transistor models were also modified in terms of its area to include large currents. After many trial and error values for the current sensing resistor, it was found to be 1milli ohm. The V-I characteristics obtained are shown in figure below

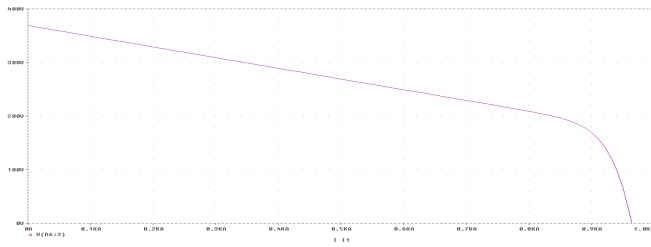


Figure 4. V-I characteristics of 100 KW fuel cell stack model

B. Fuel cell with a Boost converter and with an interleaved boost converter

A fuel cell stack generating 200 V of output was coupled to a boost converter and analysis was made in terms of output voltage of the boost, the harmonic content by means of Total Harmonic Distortion (THD) with respect to the current on the diode used for modeling the stack and the stresses on the capacitor used to filter out the ripple on the output of boost converter. Later the same fuel cell was coupled to an interleaved boost converter and a comparison study was made analyzing the advantages of interleaving. The figure below is the schematic diagram of the proposed model of fuel cell with interleaved boost converter

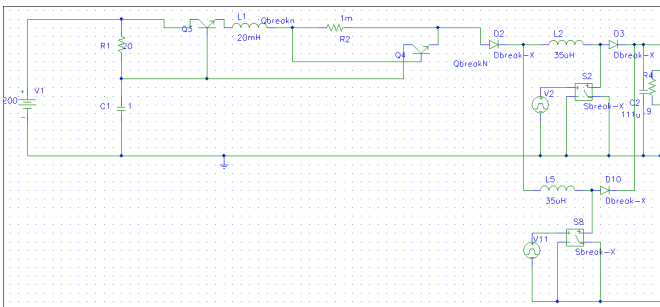


Figure 5. PSPICE schematic of a fuel cell stack coupled to interleaved boost converter

The comparison between a normal boost converter and an interleaved boost converter coupled fuel cell is tabulated as given below.

TABLE 1. COMPARISON BETWEEN FUEL CELL COUPLED TO BOOST CONVERTER AND COUPLED TO INTERLEAVED BOOST CONVERTER

Parameter	Fuel cell/Boost	Fuelcell/Interleaved boost
Vin	200 V	200 V
L	7uH	4 uH
C	1110uF	1110 uF
Duty cycle	0.4	0.4
Time period	50 us	50us
Output voltage	253 V	297.3 V
Output current	281 A	330 A
Average input inductor current	577.57A	629.346 A
RMS input inductor current	591.32A	642.306 A

THD on the current side on input inductor	21.9%	20.3%
Average current on the diode after fuel cell	473.442 A	579.153 A
RMS current on the diode after fuel cell	501.31A	598.26 A
THD on the current side on the diode	34.8%	25.8%

As seen from the table, the THD with respect to the current on the diode representing the fuel cell has decreased around 10% by using interleaved boost converter. Also the output current levels have boosted up using the proposed model. When analysis was made on the voltage ripple on the output capacitor, it was observed that by using two boost converter circuits operating out of phase with each other, the stresses on the capacitor decrease as well. Also it could be observed that in the new model, the inductors used are of small size compared to the circuit consisting of a normal boost converter.

C. Fuel cell with an interleaved boost converter and a Auxiliary Power Unit (APU)

Auxiliary power unit will be used to maintain the output voltage to a constant value irrespective of changes in the load value. An attempt was made to design the APU system to maintain a constant voltage of 300 v irrespective of changes in the load; by means of using two voltage controlled voltage switches, battery and a huge capacitor.

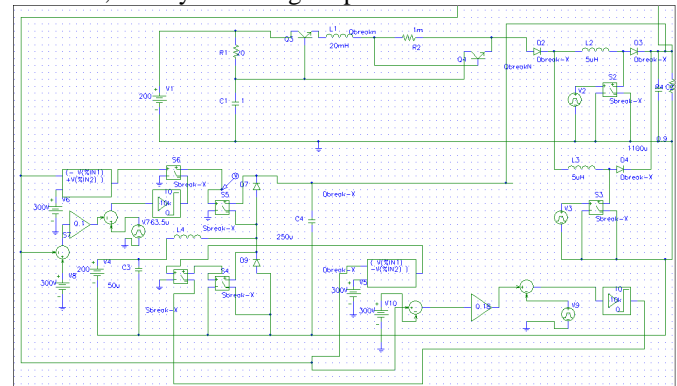


Figure 6. PSPICE schematic of a fuel cell stack coupled to interleaved boost converter with APU

In the figure, the 200 V source acts as a battery. If the diode D7 is turned on, the battery acts as a source and the current flows through the inductor L4 and then through the diode acting as a boost converter directing the power flow from the battery to the output. On the other hand if the diode D8 is turned on, the power flow will be from the fuel cell to the battery and hence charging it. If the output voltage from the fuel cell stack is less than 300 V, the switch S6 is turned on which in turn turns on the diode D7 invoking a boost converter operation. If the output voltage is more than 300v, the switch S7 turns on, turning on the diode D9 and a buck converter operation takes place.

The circuit was simulated and it was observed that by using APU though the THD has increased on the diode represented in the fuel cell model, the THD on the input inductor decreased drastically. Also it was observed that the output voltage reached steady state quickly by using the interleaved boost converter along with the APU.

VI. CONCLUSION

On the whole, the research on proton exchange membrane fuel cell stack coupled to an interleaved boost converter led to some improvements in terms of the reduction of total harmonic distortion on fuel cells which might otherwise damage the fuel cell and reduce its durability. Future work on the modifications of this model might result in further reduction of harmonics and boost the voltage levels higher which could be advantageous both in terms of energy efficiency and cost reduction.

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