Implementation of DC-DC Boost Converter for Fuel Cell System

A.Inba Rexy [#1], **Jayarama Pradeep** [*2]
[#1]*Department of Electrical & Electronics Engineering, Loyola ICAM College of Engineering and Technology, Chennai, India*
[*2]*Department of Electrical & Electronics Engineering, St. Joseph's College of Engineering, Chennai, India*
[1]inbacruz@gmail.com
[2]jaya_7pradeep@yahoo.co.in

***Abstract* – Fuel cell powered systems are considered attractive because of their various advantages, such as high efficiency, low pollution and low noise. A DC-DC converter having a high turn ratio transformer is needed in such a system, to boost the low voltage battery to a high level, to enable the DC-AC conversion and to provide isolation. The high turn's ratio of the transformer causes a high leakage inductance, and therefore, reduces efficiency, and increases difficulty in control of the DC-DC converter. In this project a new DC-DC converter for low voltage residential power generation system is presented. The converter uses the leakage inductance for energy conversion, which not only reduces the problems of low efficiency and difficulty of control, caused by leakage inductance, but also eliminates the need for a separate inductor. Lack of a separate inductor reduces the cost the DC-DC converter. Also, soft switching is employed for some of the switches to reduce the switching losses. Consequently, the DC-DC converter has low cost and high efficiency. Simulation results are presented here.**

***Index Terms* – DC-DC converter, Solid oxide fuel cell (SOFC), Distributed Generation (DG), zero current switching (ZCS).**

I. INTRODUCTION

The interest in distributed generation has increased significantly in recent years. It is believed that the distributed generation market will be between U.S.$10 and 30 billion by 2010 [1]. Due to environmental concerns, more effort is now being put in to the clean distributed power like geothermal, solar thermal, photovoltaic, and wind generation, as well as fuel cells that use hydrogen, propane natural gas, or other fuels to generate electricity without increasing pollution[2].

Among the other fuel cell technologies Solid oxide fuel cell (SOFC) are considered more suitable for residential power generation, due to their characteristics of high power density and high efficiency [3]. Fuel cells are electrochemical devices that convert the chemical energy of a fuel (hydrogen) and an oxidant (oxygen) directly to electrical energy and heat, without combustion [4]. Therefore they are efficient, clean and noise –free sources of power [5,6].

The configuration of a typical distributed fuel cell powered residential power generation systems is shown in Fig.1. A DC-DC converter is used to boost the low voltage of the fuel cell to make a high voltage DC link. According to the specifications of 2003 International Future Energy Challenge for such an application, the fuel cell output voltage is 22V-41V and the AC load is 120/240V at 5KW continuous and 10KW peak. For these specifications a high DC link voltage (>350V) is required, to enable the DC-AC conversion to provide the required AC output voltage.

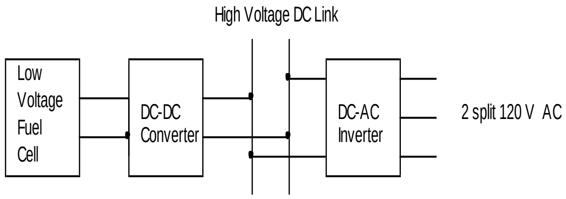


Fig.1. Typical layout of fuel cell converter system

Conventional DC-DC converters, such as push-pull, half-bridge and full-bridge converters, can be used to boost the low voltage of the fuel cell to the required level [7] while also providing isolation. However, the transformers in these converters have large turns ratios (such as 1:20), and hence, large leakage inductances. These large leakage inductances cause low energy efficiency and difficulty in control of the DC-DC converter [8].

Cost and efficiency are critical evaluation factors for distributed fuel cell residential power generation systems, and low cost and high efficiency are imperative for commercialization [9]. Continued efforts are being made to optimize the cost and efficiency of the fuel cells themselves and also the accompanying power converters in such systems, to enable commer-cialization.

In [10], a new DC-DC converter has been proposed, in which a three phase rectifier at the secondary side of a set of isolation transformers, is used to enable reduction of the transformer turns ratio and therefore the leakage inductance. Moreover the converter utilizes soft switching to reduce the switching loses. In [8], a DC-DC converter is proposed, which uses a voltage doubler on the secondary side to reduce the transformer turns ratio and hence the leakage inductance. The converter also has a low number of switches and achieves high efficiency.

In this project a new DC-DC converter for fuel cell powered distributed residential power generation systems is designed. The designed converter uses the leakage inductance for energy conversion, which not only mitigates the leakage inductance resultant low efficiency and difficulty in control problem but also eliminates the need for a separate filter inductor. Lack of a separate inductance helps to reduce the cost of the DC- DC converter. Soft switching is also achieved for some of the switches in the DC-DC converter.

II. TOPOLOGY ANALYSIS

Fig.2 shows the fuel cell converter systems, which consist of a full bridge inverter whose output is given to a half bridge diode rectifier through a transformer. The transformer is capable of boosting the output voltage without increasing the transformer turns ratio. Here S_1 – S_6 are the active switches; D_1 – D_6 are the body diodes of switches S_1 – S_6 respectively, D_7 and D_8 are power diodes; C is the filter capacitor; T is the transformer; R is the load of the DC – DC converter.

III. MODES OF OPERATION

The transformer primary side referred equivalent circuits of the converter are shown in Fig.3 and are used to explain the different modes of the converter operation. The magnetizing inductance of the transformer is ignored and only the leakage inductance is considered in the derivation of the equivalent circuits. The waveforms of the key components of the converter in one complete cycle are shown in Fig.4.

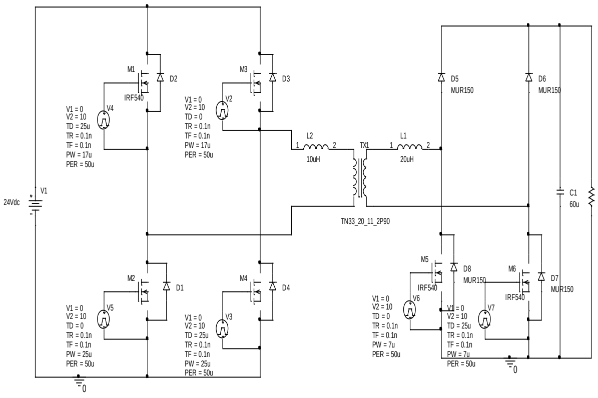


Fig 2. DC – DC converter topology

In Fig.3, and Fig.4, V_1, V_{Or}, V_p, V_{Sr}, V_L and I_L stand for the input voltage of the converter, output voltage of the converter (primary side referred), primary side voltage of the transformer, secondary side voltage of the transformer (primary side referred), voltage across the leakage inductance of the transformer (primary side referred), and primary side current of the transformer, respectively.

In Fig.4, G_1 – G_6 represent the gating signals to switches S_1 – S_6 respectively and the time period from t_0 - t_8 represents one complete operating cycle of the converter. As shown in Fig.4, the operation of the converter in the second half cycle, from t_4 - t_8, is similar to that in the first half cycle, from t_0 - t_4, except being in the opposite direction. Therefore only the operation of the converter in the first half cycle, from t_0 - t_4 is detailed and illustrated in Fig.3.a-Fig.3.d. The operation of the converter during different time periods in the first half cycle is explained as follows;

Mode 1 (t_0 - t_1): In this mode switches S_2, S_3 and S_5 are gated. A closed current path is created as shown in Fig.3.a, We can derive that

$V_p = V_i$, $V_{Sr} = 0$ and

$V_L = (V_p - V_{Sr}) = (Vi - 0) = Vi$

Using $V_L = V_i$ and $V_L = L\dfrac{dI_L}{dt}$, where L is the leakage inductance of the transformer

Primary side current of the transformer I_L is given by;

$$I_L = \frac{I_{T1}}{L}\, t \qquad (1)$$

It should be noted that S_2, S_3 and S_5 are turned on at zero current condition.

Mode 2 (t_1 - t_2): In this mode switches S_2 and S_3 are kept on while switch S_5 is turned off. D_7 conducts to carry the inductor current as the result of the turn-off of S_5. A closed current path is created as shown in Fig.3.b. We can derive that

$V_p = V_i$, $V_{Sr} = V_{Or}$ and

$V_L = V_p - V_{Sr} = V_1 - V_{Or}$

Similar to (1) we can derive that,

$$I_L = \frac{V_1 - V_{Or}}{L} t + I_{T1} \qquad (2)$$

Where I_{T1} is the current through the transformer at time instant t_1, and it can be calculated using (1). V_L is still positive but decreases from its previous value. As a result, the current in the transformer continues to rise linearly, but now at the slower rate, as shown in Fig.4.

Mode 3 (t_2 - t_3): In this mode switch S_2 is turned off while S_3 is kept on. D_4 conducts to carry the inductor current as a result of the turn-off of S_2. The inductor current flows as shown in Fig.3.c. and is given as;

$$I_L = I_{T2} - \frac{V_{Or}}{L} t \qquad (3)$$

Where I_{T2} is the current through the transformer at the time instant t_2, and can be calculated using (2).

Mode 4 (t_3 - t_4): No current flows through the switches of the converter. S_3 is turned off at $t = t_4$. It should be noted that S_3 is turned off at zero current condition.

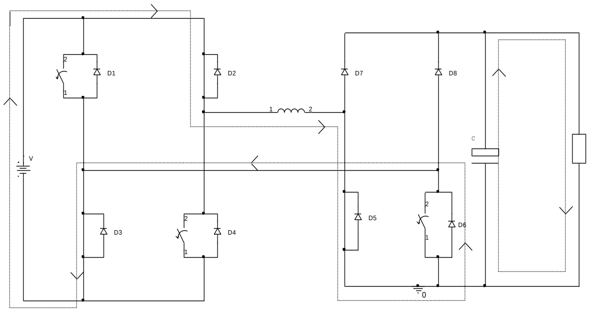


Fig.3.a Mode 1 (t_0 - t_1)

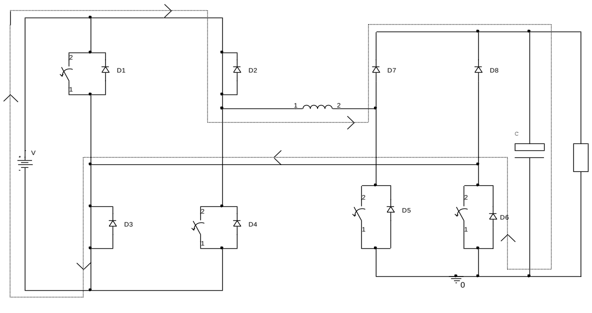


Fig.3.b Mode 2 (t_1 - t_2)

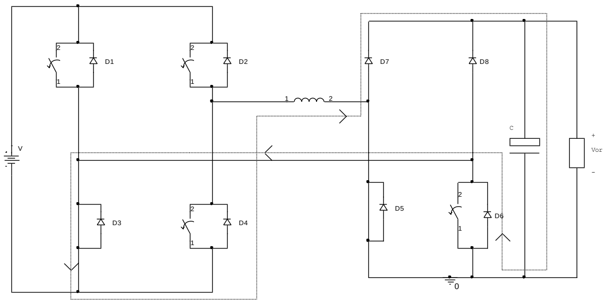


Fig.3.c Mode 3 (t_2 - t_3)

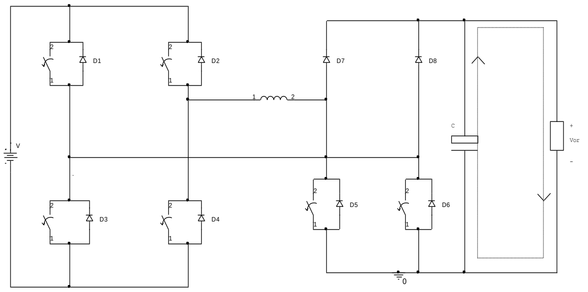


Fig.3.d Mode 4 (t_3 - t_4)

Fig 3. Transformer primary side referred equivalent circuits of the converter during different time periodsin the first half cycle

The converter is operated at a fixed switching frequency. This can be seen from the description of the working of the converter. Time periods T_1 and T_2 control the current through the transformer and hence the power of the converter. It can be seen that switches S_5 and S_6 are turned on for time period T_1, with 180 degree phase difference. Switches S_1 and S_2 are turned on for a time period equal to $T_1 + T_2$, with 180 degree phase difference. And switches S_3 and S_4 are turned on for half the switching time period (T/2), with 180 degree phase difference.

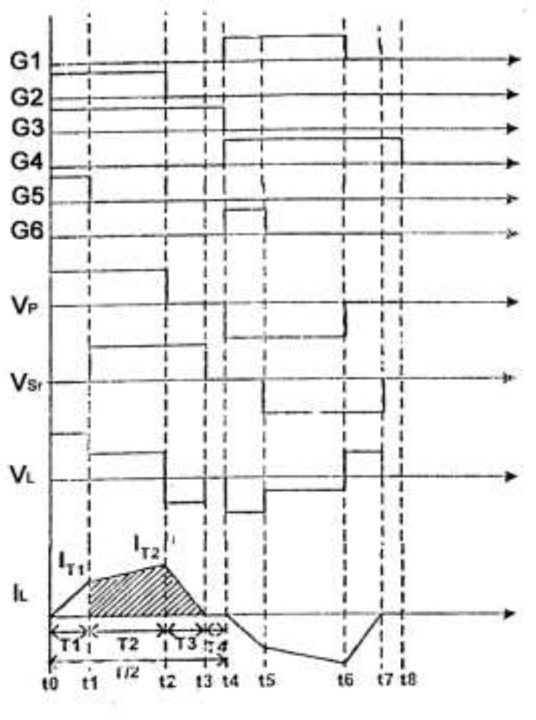


Fig. 4. Key waveforms of the converter

IV. CONTROL STRATERGY

The control strategy of the converter is shown in Fig.5 The output voltage of the converter is sensed and compared to the reference voltage (V_{Oref}). The voltage error thus obtained is passed through a PI (proportional – Integral) controller to obtain the reference output current (I_{Oref}). The output current I_O is sensed and compared to the $I_{Oref.}$ The current error thus obtained is passed through two different PI circuits. The signals thus obtained are compared to a high frequency saw tooth signal to generate PWM control signals with pulse widths T_1 and $T_1 + T_2$. A constant value signal is also compared to the same saw tooth signal to generate PWM control signal with pulse width T/2. These three PWM control signals of pulse width T_1 , $T_1 + T_2$ and T/2 are individually phase delayed by 180 degrees to obtain 3 more PWM control signals. Thus a total of 6 PWM control signals are obtained which are used to control the 6 active switches of the converter, as indicated in Fig.5.

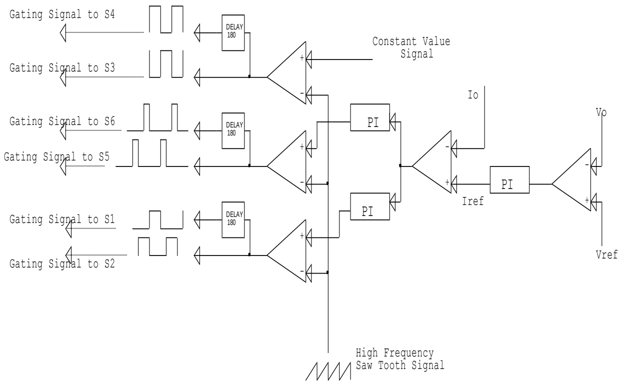
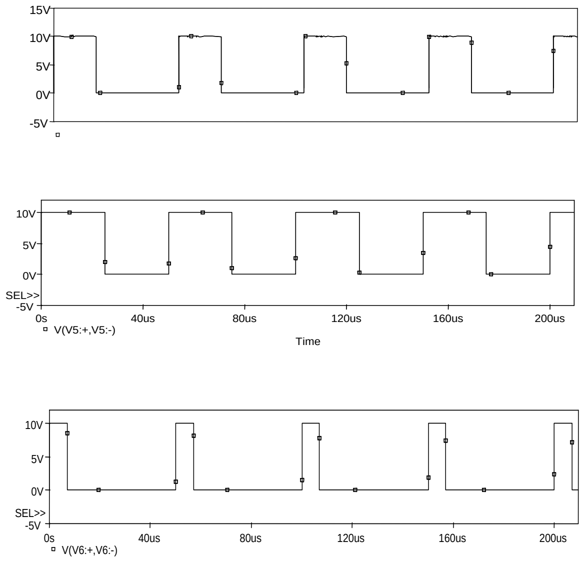


Fig.5. Control circuit of the DC - DC converter

V. SIMULATION RESULTS

The performance of the converter is simulated. The simulation results are shown in Fig.6, where from top to bottom is the gating signal (G_2) of switch S_2, gating signal (G_3) of switch S_3, gating signal (G_5) of switch S_5, primary side voltage (V_p), secondary side voltage (V_s), and transformer primary current (I (L)). As shown in Fig.6, during time period T_1, all the three switches S_2, S_3 and S_5 are on. During time period T_2, S_2 and S_3 are kept on while switch S_5 is turned off. During time period T_3, switch S_2 is turned off while S_3 is kept on.

Thus by comparing Fig.6 to Fig.4, it is seen that the simulated results match the designed waveforms, and thus the converter working is verified by simulation.



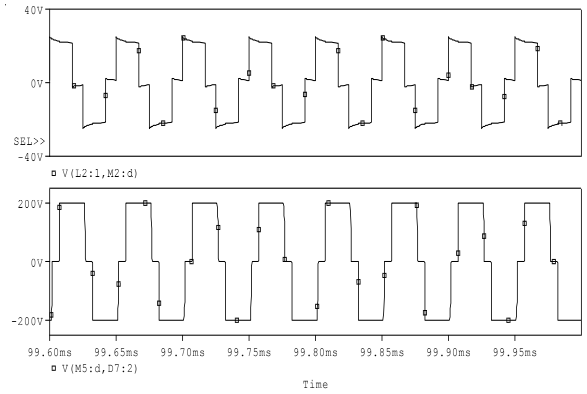


Fig.6. Simulation results of: gating signal of switch S2, gating signal of switch S3, gating signal of switch S5, primary side voltage, secondary side voltage of the transformer

VI. CONCLUSION

The DC – DC converter for fuel cell powered distributed residential power system is presented. The leakage inductance of the transformer is used for energy conversion. This not only mitigates the low efficiency and difficulty in control problem resulting from the leakage inductance but also eliminates the need for a separate filter inductor. Soft switching is achieved for some of the switches to reduce the switching losses. As a result the achieved low cost and high efficiency make the boost converter suitable for fuel cell powered distributed residential power system application. The simulation was done using orcad pspice.

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