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PART A

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Praise Worthy Prize

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High Voltage Ratio Interleaved Boost DC-DC Converter for High Power Fuel Cell Application

A. S. Samosir, M. Anwari, A. H. M. Yatim

Abstract – *The application of fuel cell is increasing in the last years mainly due to the possibility of high efficient decentralized clean energy generation. Fuel cells are a potential power source for electric vehicle or distributed power generation system. In electric vehicle application, a high power boost dc-dc converter is adopted to adjust the output voltage, current and power of fuel cell engine to meet the vehicle requirements. The major challenge of designing a boost converter for high power application is how to handle the high current at the input and high voltage at the output. In this paper, a high voltage ratio interleaved boost dc-dc converter is proposed for stepping-up the voltage on high power application. A prototype of converter system was built. The experimental waveforms of the high voltage ratio interleaved boost converter are presented.*

***Keywords**: Interleaved Boost Converter, Fuel Cell Electric Vehicle, High Voltage Ratio, High Power Application*

Nomenclature

D	Duty cycle
L	Inductor
C	Capacitor
V_L	Inductor Voltage
V_C	Capacitor Voltage
V_{in}	Input Voltage
V_O	Output Voltage
I_L	Inductor Current
I_O	Output Current
M	Voltage Gain ratio
n	Turn ratio
Y	Dynamic characteristic of system
Y_0	Initial value of Y
m	Speed of error decrease rate
V_{err}	Error voltage
V_{ref}	Reference voltage
V_t	Repetitive triangle voltage

I. Introduction

Recently, the use of fuel cells has increased. Fuel cells are a potential power source for electric vehicle or distributed power generation system. Fuel cells have several advantages such as low emission, direct energy conversion, quiet operation, and size flexibility. Fuel cell has higher energy storage capability thus enhancing the range of operation for automobile and is a clean energy source [1]-[4]. An electric vehicle powered by the fuel cells called Fuel Cell Electric Vehicles (FCEV) has higher efficiency and lower emissions compared with the internal combustion engine vehicles [1].

So, FCEV is promising a much better performance [4]. A common FCEV power supply system is shown in Fig. 1. Power supply system consists of Fuel Cell Engine (FCE), Boost DC-DC Converter, energy storage element, and bidirectional dc-dc converter [1]-[4]. In this system, the high power dc-dc converter is required to adjust the output voltage, current and power of FCE to supply the needs of vehicles [2].

Generally, the output voltage of fuel cell is rather low, while the motors are driven at higher voltages. Hence, a high voltage ratio boost dc-dc converter is required as interface to convert the low dc voltage of fuel cell into a sufficiently high voltage dc-link bus voltage. At the same time for high power applications such as electric vehicle, the low input voltage causes the input currents that flow becomes very large.

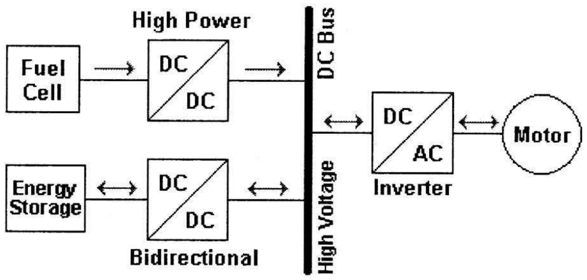

Fig. 1. Power supply system of FCEV

The major challenge of designing a boost converter for high power application is how to handle the high current at the input and high voltage at the output

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[5],[6],[7]. An effective way is to connect parallel the input sides of the boost converter in order to share the input currents and to connect series the output sides in order to raise the output voltage [8]-[14].

In this paper, a high voltage ratio interleaved boost converter for high power fuel cell application is presented. As an illustration, two-phase configuration is given for analysis, while this configuration can be upgraded to a three-phase, four-phase or more.

A converter prototype for circuit verification was built. The operation is evaluated and the experimental waveforms are presented.

II. Boost Converter Operation

II.1. Conventional Boost DC-DC Converter

The schematic diagram of the conventional boost dc-dc converter is shown in Fig. 2.

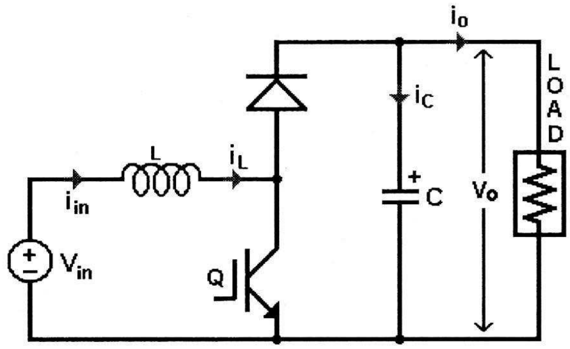

Fig. 2. Conventional Boost DC-DC Converter

The duty cycle, D, is defined as the time relationship that the switch is on relative to the total switching period. Based on the steady state analysis, the DC voltage in the inductor V_L can be expressed as (1) and is equal to zero:

$$V_L = D(V_{in}) - (1-D)(V_{in} - V_O) = 0 \qquad (1)$$

From (1) at steady state it can be verified that the gain ratio between output and input voltage becomes:

$$M = \frac{V_O}{V_{in}} = \frac{1}{1-D} \qquad (2)$$

The inductor current can be obtained by the input and output power:

$$V_{in} \cdot I_L = V_O \cdot I_O$$
$$I_L = \frac{V_O}{V_{in}} \cdot I_O \qquad (3)$$

Substituting (2) into (3), the inductor current can be expressed as:

$$I_L = M \cdot I_O \qquad (4)$$

From (3), the boost converter inductor current will increase proportional to the output power, while (4) says the boost converter inductor current also will increase with the increase of the voltage gain ratio M. These resulted in high inductor currents of boost converter at high power applications. This make the conventional boost converter is quite inefficient for high power applications.

II.2. High Voltage Ratio Interleaved Boost DC-DC Converter

Fig. 3 shows the schematic diagram of the proposed high voltage ratio interleaved boost dc-dc converter. This converter consists of a dc input voltage V_{in}, two power switches, two coupled inductors, six diodes and five capacitors. This converter is proposed to deal with the high input current problems and high output voltage requirement at high power applications.

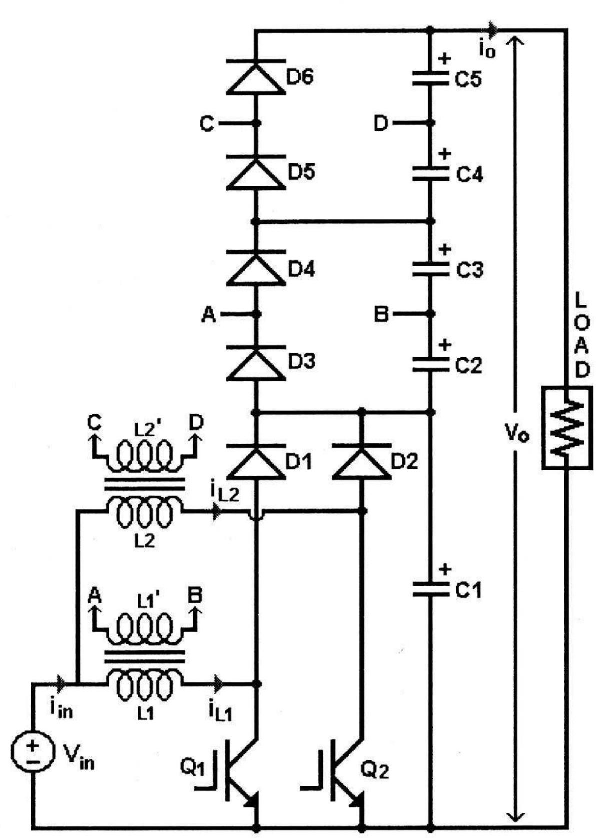

Fig. 3. High Voltage Gain Ratio Interleaved Boost DC-DC Converter Circuit Configuration

The converter has two boost units connected in parallel on the input side, which is working in interleaved operation mode. The dc input V_{in}, inductor L_1, Inductor L_2, power switch Q_1, power switch Q_2, diode d_1, diode d_2 and capacitor C_1 are operated as a conventional two-phase interleaved boost dc-dc converter. This section is useful to share the input current. The ability of current sharing is causing this converter can be used for handle the large input current in high power applications.

The converter has two voltage doublers connected in series on the output side. Inductor L_1', diode d_3, diode d_4, capacitor C_2, and capacitor C_3 build the first voltage doubler, while the second voltage doubler consist of inductor L_2', diode d_5, diode d_6, capacitor C_4, and capacitor C_5. Both of them are stacked with the conventional two-phase interleaved boost converter on the output side to increase the output voltage. This section is useful to increase the voltage gain. The two of two-winding coupled inductor is used to provide high step-up voltage gain by set up the suitable windings turn ratio.

With the above configuration, the proposed converter has good features such as current sharing on the input side and high step-up voltage gain. Further, the voltage across power switch Q_1 and Q_2 is clamped effectively to the voltage of capacitor C_1, hence the voltage stress on the power switch is low, thus a low voltage rating power switch can be used.

In order to simplify the circuit analysis, it is assumed that the capacitors C_1, C_2, C_3, C_4, and C_5 are large enough. The inductance value of both inductor are L_1 and L_2, where L_1=L_2=L. The turn ratios of the coupled inductor are: $n_1=N_1'/N_1$, $n_2=N_2'/N_2$. The duty cycle of Q_1 and Q_2 denoted as D_1 and D_2, with $D_1=D_2=D$.

According to Fig. 4 the operations of the converter are explained as follows:

1) State a:

At time t_0, Q_1 is closed and Q_2 is opened. d_2, d_3, and d6 are turn on, and d_1, d_4 and d_5 are turn off. The current of the inductor L_1 starts to rise, while L_2 release the stored energy to C_1 through d_2. The energy stored in L_1' is released to C_2 through d_3, and energy stored in L_2' is released to C_5 through d_6.

2) State b:

At time t_1, Q_1 and Q_2 are opened. d_1, d_2, d_4, and d_6 are turn on, and d_3 and d_5 are turn off. The inductors L_1 and L_2 continue release the stored energy to C_1 through d_1 and d_2 respectively. The energy stored in L_1' is released to C_3 through d_4, and energy stored in L_2' is released to C_5 through d_6.

3) State c:

At time t_2, Q_2 is closed and Q_1 is opened. d_1, d_4, and d_5 are turn on, and d_2, d_3 and d6 are turn off. The current of the inductor L_2 starts to rise, while L_1 continue release the stored energy to C_1 through d_1. The energy stored in L_1' is released to C_3 through d_4, and energy stored in L_2' is released to C_4 through d_5.

4) State d

At time t_3, Q_2 is opened and Q_1 still opened. The situation is same as state b. d_1, d_2, d_4, and d_6 are turn on, and d_3 and d_5 are turn off. The inductors L_1 and L_2 continue release the stored energy to C_1 through d_1 and d_2 respectively. The energy stored in L_1' is released to C_3 through d_4, and energy stored in L_2' is released to C_5 through d_6. This state is ended at time t_4, when switch Q_1 is closed. The next state is similar to the previous because of the symmetry of the circuit.

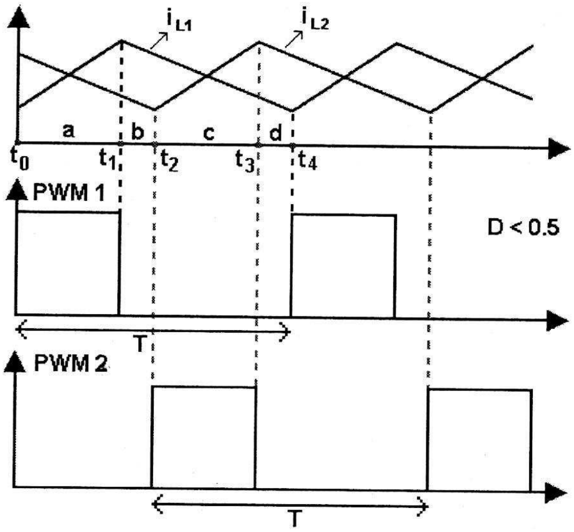

Fig. 4. Inductor Current and PWM Signals of Interleaved Boost DC-DC Converter

In order to simplify the steady state characteristics analysis, the leakage inductors of the coupled inductor windings are neglected. The coupling coefficients of both of coupled inductor are assumed 1.

During Q_1on period, V_{L1} and V_{C2} can be written as

$$V_{L1} = V_{in} \tag{5}$$

$$V_{C2} = n_1 \cdot V_{in} \tag{6}$$

During Q_1 off period, V_{L1} and V_{C3} can be written as:

$$V_{L1} = V_{C1} - V_{in} \tag{7}$$

$$V_{C3} = n_1 \cdot (V_{C1} - V_{in}) \tag{8}$$

Based on the steady state analysis, the average DC voltage in the inductor L_1 during one switching period is equal to zero and can be expressed as (9):

$$V_{L1} = D \cdot (V_{in}) + (1-D) \cdot (V_{C1} - V_{in}) = 0 \tag{9}$$

From (9), it can be verified that the voltage of capacitor C_1 at steady state can be written as:

$$V_{C1} = \frac{1}{1-D} V_{in} \tag{10}$$

From (8) and (10), the voltage of capacitor C_3 is:

$$V_{C3} = \frac{n_1 \cdot D}{1-D} V_{in} \tag{11}$$

Since the circuit is balanced, the voltage of capacitors C_4 and C_5 can be written as (12) and (13):

$$V_{C4} = n_2 \cdot V_{in} \tag{12}$$

$$V_{C5} = \frac{n_2 \cdot D}{1-D} V_{in} \tag{13}$$

From (6), (10), (11) and (12), the output V_O is expressed as:

$$V_O = V_{C1} + V_{C2} + V_3 + V_{C4} + V_{C5}$$
$$V_O = \left(\frac{1}{1-D} + n_1 + \frac{n_1 \cdot D}{1-D} + n_2 + \frac{n_2 \cdot D}{1-D} \right) \cdot V_{in} \tag{14}$$
$$V_O = \left(\frac{1 + n_1 + n_2}{1-D} \right) \cdot V_{in}$$

Fig, 5 shows the voltage gain of converter versus duty ratio under various turn ratios of the coupled inductors.

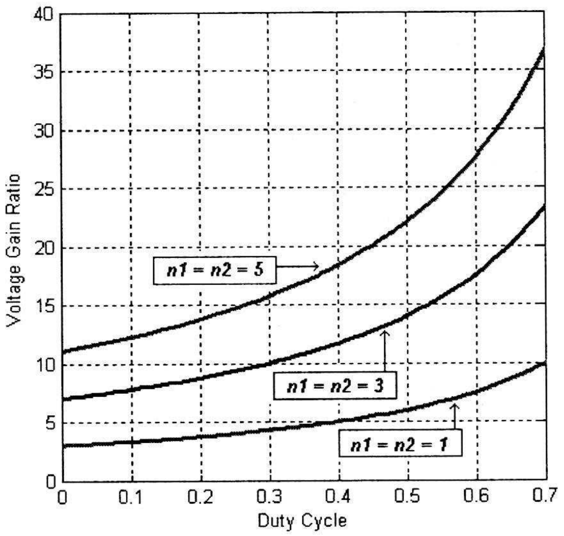

Fig. 5. Converter Voltage Gain Ratio versus Duty Cycle under various turn ratios of the coupled inductors

III. Dynamic Evolution Controller Design

Dynamic evolution Control is a new control technique in power electronics application. The dynamic evolution control has been utilized in reference [3] and [4]. The basic idea of the dynamic evolution control is to reduce the error state by forcing the error state to follow the specific path, that ensure the error state goes to zero in increase of time. This specific path is named Dynamic Evolution Path. By using dynamic evolution control, the dynamic characteristic of system is forced to make evolution by following an evolution path.

In this research, the selected evolution path is an exponential function. With this evolution path the value of the dynamic characteristic of system will decrease exponentially to zero by (15) and the dynamic evolution function of this controller can be written as (16):

$$Y = Y_O \cdot e^{-mt} \tag{15}$$

$$\frac{dY}{dt} + mY = 0, \quad m > 0 \tag{16}$$

The controlled converter in this research is the interleaved boost dc-dc converter. Since the interleaved boost converter basically works like two boost dc-dc converter in parallel, then the duty cycle analysis can be performed as a normal boost dc-dc converter.

Based on the state-space average model, the voltage and current dynamics of the boost dc-dc converter are given by:

$$v_{in} = L \frac{di_L}{dt} + v_O \cdot [1-D] \tag{17}$$

Rearranging (17), the output voltage of converter can be written as:

$$v_O = v_{in} + v_O \cdot D - L \frac{di_L}{dt} \tag{18}$$

By defining the state error function (Y) is a linear function of error voltage as (19), the obtained duty cycle formula for boost dc-dc converter operation is given in (21):

$$Y = k \cdot v_{err} \tag{19}$$

$$v_{err} = V_{ref} - v_o \tag{20}$$

$$D = \frac{\left[\begin{array}{l} k \cdot \frac{dv_{err}}{dt} + (m \cdot k - 1) \cdot v_{err} + \\ + L \frac{di_L}{dt} + V_{ref} - v_{in} \end{array} \right]}{v_O} \tag{21}$$

The expression for duty cycle D is the control action for the converter controller, with k is a positive coefficient

Duty cycle formula (21) forces the state error function (Y) to satisfy the dynamic evolution function (16). Consequently, the state error function (Y) is forced to make evolution by following equation (15) and decrease to zero ($Y = 0$) with a decrease rate m.

The PWM duty cycle signals are generated by comparing a level control signal with a constant peak repetitive triangle signal (V_{st}). The frequency of the repetitive triangle signal establishes the switching frequency. Since, this frequency is kept constant. Therefore, the dynamic evolution control is operated at constant switching frequency.

Since the interleaved boost converter requires two PWM signals to drive both of switches, the additional work necessary to generate two of PWM signals from single duty cycle formula. Fig. 6 shows the PWM signals generation technique. The first PWM signal is produce when the control signal V_1 is less than V_{st} and the second

PWM signal is produce when the control signal V_2 is greater than V_{st}.

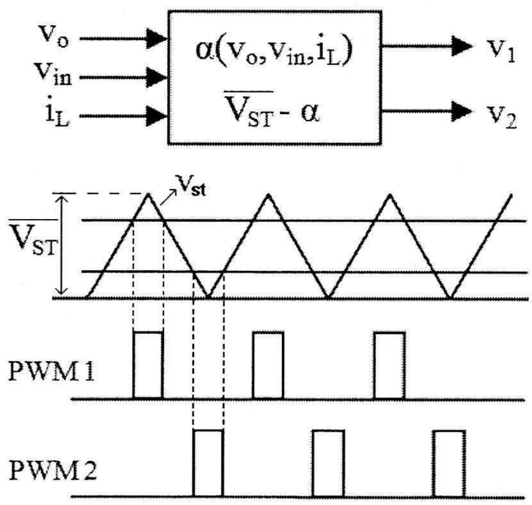

Fig. 6. PWM Signal Generation scheme

The values of the desired level control signals are got from the calculation used the duty cycle formula (21). The values of control signal V_1 and V_2 are given in (22) and (23), while the PWM signals are generated by (24):

$$v_1 = D \tag{22}$$

$$v_2 = \overline{V_{ST}} - D \tag{23}$$

$$\left.\begin{array}{lll} PWM1 & = & v_{st} > v_1 \\ PWM2 & = & v_2 > v_{st} \end{array}\right\rangle \tag{24}$$

where, V_{st} is the triangle signal and $\overline{V_{ST}}$ is the peak value of V_{st}.

IV. Experiment Results

In order to verify the analysis above, a prototype of high voltage gain ratio interleaved boost dc-dc converter has been built. With the turn ratios of both of coupled inductors are three, the converter is operated at duty cycle around 0.5. The waveforms of voltage and current from experiment results of interleaved boost dc-dc converter are shown in Figs. 7 – 9.

Fig. 7 shows the gate signals and current waveforms of the interleaved boost dc-dc converter. The gate signals operate at a duty cycle of about 0.5. The inductor currents flow every half of period. This waveform showed that the inductor current is not continuous. This means that the converter works in discontinuous mode.

Fig. 8 shows the current waveforms of the interleaved boost dc-dc converter. These waveforms show that although the inductor currents are not continuous, because of the inductor current has 180 degree phase-shift, the input current is continuous.

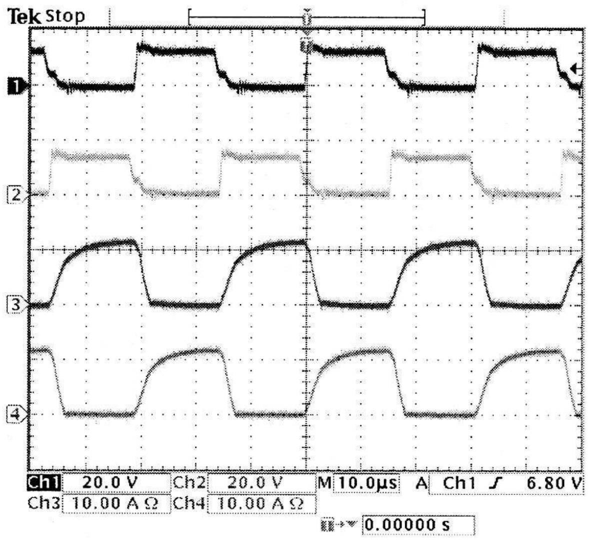

Fig. 7. Gate signal and Current Waveforms (1) Gate signal Q1 (2) Gate signal Q2 (3) L2 Current (4) L1 Current

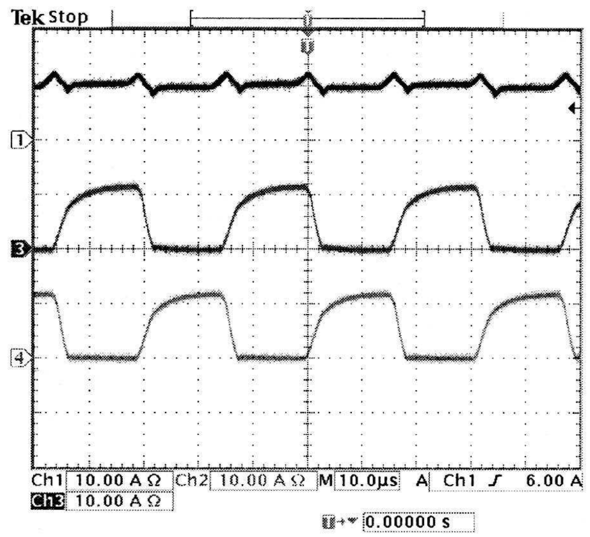

Fig. 8. Current Waveforms (1) Input Current (2) L1 Current (3) L2 Current

Fig. 9 shows the voltage waveforms of the proposed interleaved boost dc-dc converter. With a nominal input voltage is 20V, the voltage of capacitor C_1 is about 40V, and the voltage of capacitor C_2 is about 60V. This waveform shows that the output voltage is about 270V. This means that the converter boost the voltage with a gain ratio of 13.5.

This is much higher than the gain of the conventional converter, which boost the voltage with a gain ratio of 2 when operated at duty cycle around 0.5.

Fig. 10 shows the prototype of interleaved boost dc-dc converter. In this figure the prototype have three inductors and three IGBT switch because this prototype is designed to support three phase configuration.

For two phase configuration, one of inductor and IGBT switch is not used.

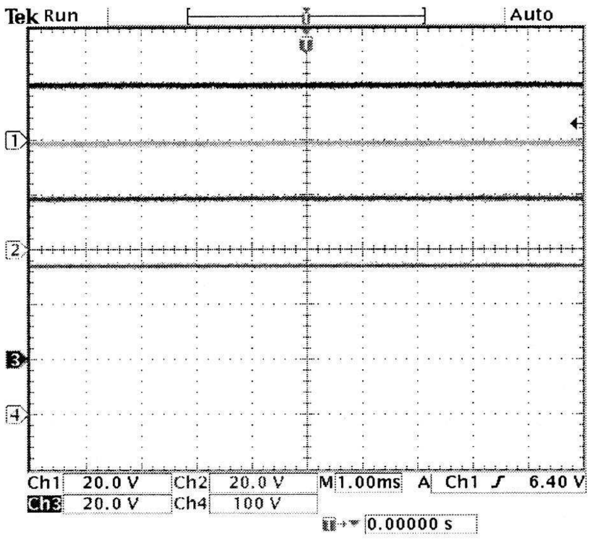

Fig. 9. Voltage Waveforms, (1) Input Voltage
(2) C1 Voltage (3) C2 Voltage (4) Output Voltage

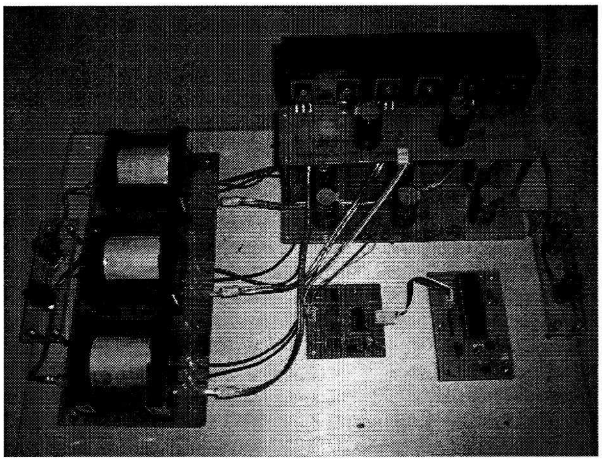

Fig. 10. Prototype of interleaved boost dc-dc converter

V. Conclusion

The high voltage gain ratio interleaved boost dc-dc converter is proposed. The performance of the interleaved boost converter system has been investigated. Experiment results shown the proposed high gain ratio interleaved boost converter have a load sharing capability and the gain voltage ratio of the converter is much higher than the conventional one. The input current flows continue, thus this converter suitable for fuel cell applications.

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