A Frequency Controlled Bi-directional Synchronous Rectifier Converter for HEV Using Super-Capacitor

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***Abstract*- In this paper, a control method of a bi-directional zero-voltage-switching (ZVS) DC-DC converter for HEV power system is presented. By controlling the minimum and maximum values of the inductor current, the ZVS condition is achieved. Also employing the variable frequency control with respect to the variation of the DC-link current and the super-capacitor voltage, the circulating energy loss at the light load condition is minimized. A 1.25kW experimental hardware prototype module is built to verity the efficiency improvement, especially at the light load condition. It shows about 34% efficiency improvement compared to the fixed frequency control at the light load condition.**

I. INTRODUCTION

In hybrid electric vehicle (HEV) systems, a bi-directional DC-DC converter is required to process the power between the energy storing device and the DC-link capacitor (Fig. 1) [1]. When the vehicle accelerate the super-capacitor delivers amount of the current the motor needs. In the regenerative braking operation, the motor works as a generator delivering the recovered energy into the super-capacitor as shown in Fig. 1. Thus operations must be controlled by the fast and sudden discharging or charging [1].

For the energy storing device, the battery has some limitations on life cycle, abrupt storage and consumption of stored energy. Super-capacitor has a longer life cycle and higher power density, which can be a crucial factor to absorb the regenerative energy in the braking mode and to discharge in the acceleration mode [2].

In this paper, design and control of the bi-directional zero-voltage-switching (ZVS) synchronous rectifier (SR) DC-DC converter of the HEV system employing the super-capacitor are presented.

An adaptive control scheme for the wide variation of load and super-capacitor voltage for both charging and discharging mode employing a variable frequency control are presented to improve the overall efficiency of the converter especially for the light load condition. The following sections explain the control strategies and design guidelines. A 1.25kW prototype converter is designed and built for the hardware verification.

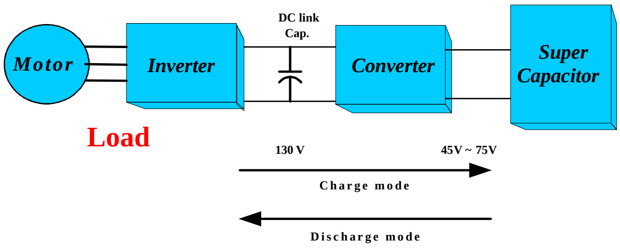

Fig. 1. HEV system using Super-Capacitor

II. PROPOSED CONTROL OF THE BI-DIRECTIONAL ZVS BUCK/BOOST

Among various possible topologies for the dc-dc converter power stage, a zero-voltage-switching (ZVS) synchronous rectifier (SR) converter shown in Fig.2 is selected, due to its fast transient response and high power density [3],[4],[6].

In this scheme, the inductor current flows bi-directionally and the direction of its average value represents either the charge or the discharge mode. The anti-parallel diodes of the MOSFET conducts before the MOSFET turns on, thus ZVS is achieved. However, HEV operates in wide load range, and the synchronous rectifier has a poor efficiency at light load condition because of its circulating energy [1],[2],[5]. To minimize the circulating energy loss, the switching frequency is controlled to high frequency at the light load condition as shown in Fig.2.

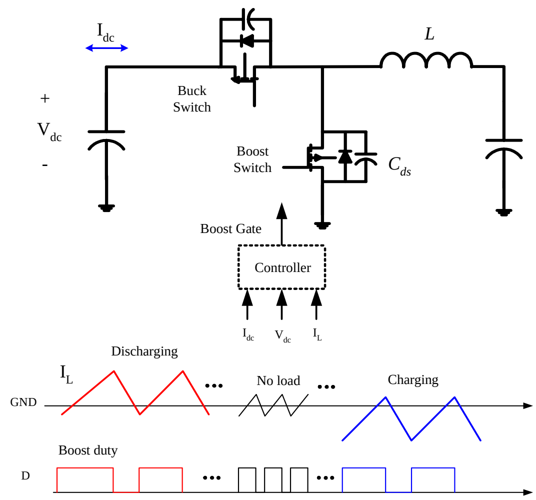

Fig. 2. Basic idea of the control method (Boost duty cycle control)

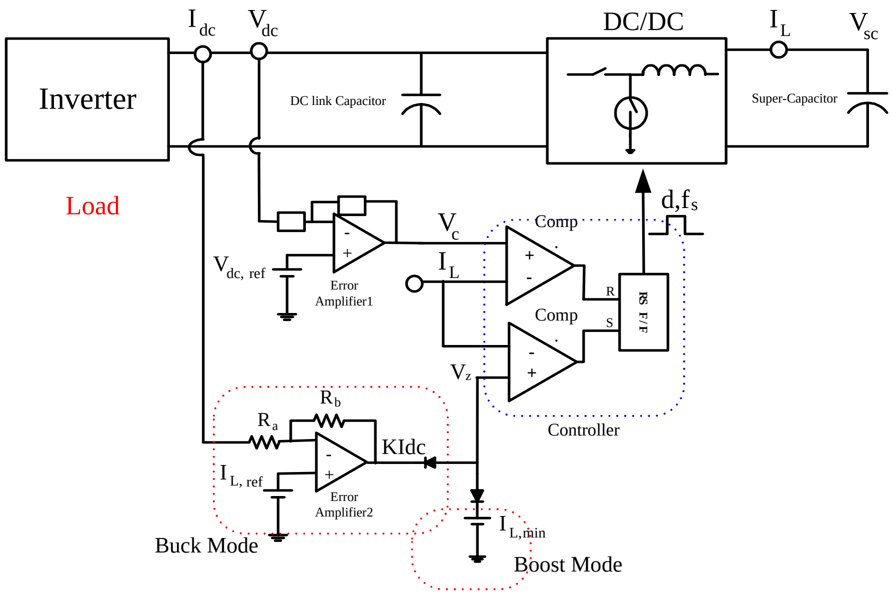

Fig. 3. The proposed control scheme

I_{dc} : DC-link current, V_{dc}: DC-link voltage, V_{sc} : super-capacitor voltage, V_c : Error voltage of voltage feedback

Figure 3 shows the control scheme for the converter. The main function of the controller is to regulate the DC-link capacitor voltage for both the charging and discharging mode by controlling the duty cycle of the boost switch. Thus, as far as the controller is concerned, it is a bi-directional boost converter and the charging and discharging converter are determined by the HEV system operation modes.

When the inverter draws the current from the DC-link capacitor during the motoring, the voltage loop maintain the DC-link capacitor voltage by discharging energy from the super-capacitor. During the regeneration period, the super-capacitor is charged by simply maintaining the DC-link voltage by the voltage loop.

Beside the main voltage loop, the inductor current is sensed to control the switching frequency as the load current varies. It also offers the current sharing for the parallel module operation.

In order to overcome the sensitivity problem of the current sensing in the small positive current in the buck mode, the positive DC offset voltage is added to the sensed current.

A. Discharging Operation (Boost Mode)

During the discharge mode, a negative direction of the DC-link current, I_{dc} makes *KIdc* high, thus V_z in Fig.3 becomes the reference value of the minimum inductor value for the boost mode.

The maximum value of the inductor current is set by the control voltage, V_c , which controls the duty cycle of the boost switch. As the load changes, V_c changes from V_{c1} (for heavy load) to V_{c2} (for light load) as shown in Fig. 4.

As the load current decreases the switching frequency of the converter increases and the circulation energy is reduced.

Figure 5 shows the case when the super-capacitor voltage, V_{sc} varies. When the V_{sc} has a low value, V_c becomes higher to increase the average value of the inductor current. This results in decrease of the switching frequency and shorter the interval T_x.

$I_{L,\min}$ in Fig. 4 and Fig. 5 is selected as a constant value from the Eq.(2), so that the converter has a minimum circulation loss and satisfies ZVS condition. In order to obtain ZVS operation, the inductor current at the turn on, I_{L_crit} should be negative satisfying the condition in Eq.(1) [8].

$$I_{L\_crit} < \sqrt{\frac{2 \cdot C_{ds}}{L}} \cdot V_{dc} \qquad (1)$$

$$I_{L,\min} = I_{L\_crit} \cdot K_{cs} \qquad (2)$$

$$T_x = \frac{V_{dc}}{V_{dc} - V_{sc}} \sqrt{2 \cdot C_{ds} \cdot L} \qquad (3)$$

Where, T_x denotes the interval to obtain I_{L_crit} from the Eq.(3), K_{cs} is the sensing gain of the inductor current and C_{ds} is the capacitance of the MOSFET.

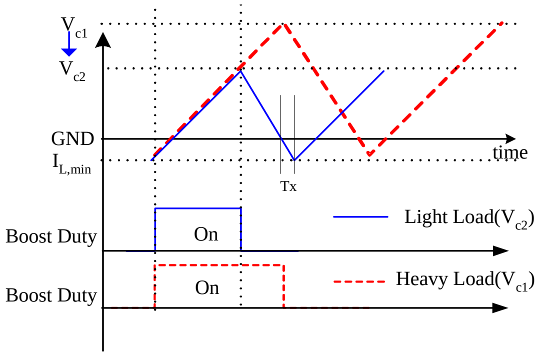

Fig. 4. Discharging operation for the load variation

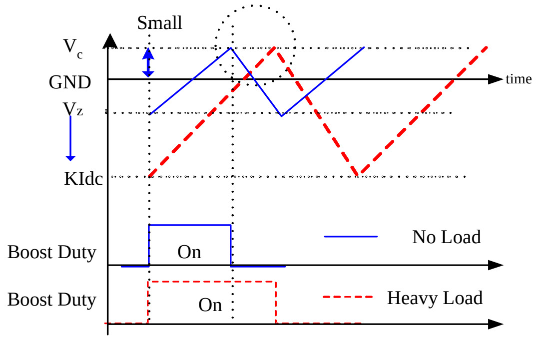

Fig. 6. Charging operation for the load variation

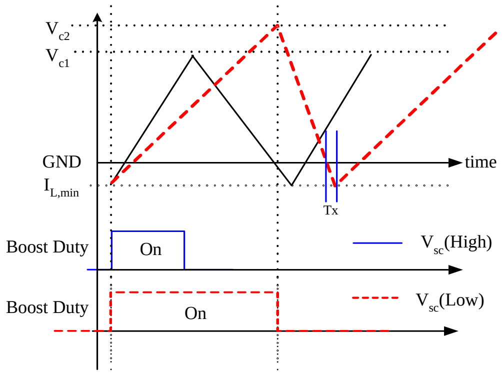

Fig. 5. Discharging operation for the input voltage, V_{sc} variation

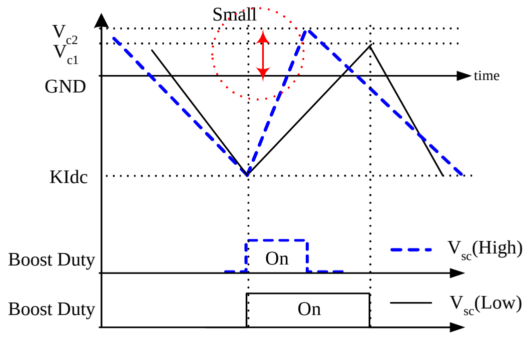

Fig. 7. Charging operation for input voltage, V_{sc} variation

B. *Charging Operation (Buck Mode)*

In the charging mode, the inductor current goes below $I_{L,\min}$ and reaches the $KIdc$ (reference of the average current), V_z becomes $KIdc$. As the DC-link current increases, the $KIdc$ becomes a negatively larger value as shown in Fig.6. As magnitude of the $KIdc$ decreases for the light load, the switching frequency increases and the peak to peak inductor current becomes small.

The value $KIdc$ is determined by the following equations.

$$I_{L\_avg} = \frac{I_{dc}}{D} \text{ , } I_{LS\_avg} = I_{L\_avg} \cdot K_{cs} \tag{4}$$

$$KIdc = I_{LS\_avg} \cdot (1 + \frac{R_b}{R_a}) \text{ , } KIdc > 2 \cdot I_{LS\_avg} \tag{5}$$

$$R_b > R_a$$

where, I_{L_avg} is the average value of the inductor current and I_{LS_avg} is the average value of the sensed inductor current and K_{cs} is the sensing gain of the inductor.

Figure 7 shows the case when the super-capacitor voltage, V_{sc} varies. When V_{sc} increases the control voltage, V_c changes from V_{c1}(low V_{sc}) to V_{c2}(high V_{sc}), and the charging current to the super-capacitor(average value of the inductor current) decreases. Since the control voltage V_c is always positive the ZVS operation is guaranteed for all V_{sc}.

C. *The control of the mode change between buck and boost*

As the voltage loop regulates the DC-link voltage, the direction of the DC-link current is determined by the vehicle's operation mode. The direction of the current is sensed by the I_{dc} loop and the diode-OR circuit chooses the reference value either $I_{L,\min}$ (boost mode) or $KIdc$ (buck mode) accordingly. Thus the transition between the buck and the boost mode can be controlled automatically.

III. HARDWARE EXPERIMENTAL RESULTS

TABLE I
THE MAJOR COMPONENT USED FOR THE HARDWARE PROTOTYPE

Components	Parameters
Main L	10uH, PQ5050, TDK
MOSFET	IXFN180N20, Rdson ($10\,m\Omega$)
Switching frequency f_{sw}	40kHz~80kHz
Super-capacitor	PC2500, 2700F, 2.7V/cell, 35cell

A 1.25kW bi-directional ZVS SR converter module is implemented for the hardware experiment. The range of the super-capacitor voltage is 45~80 V_{DC} , and the DC-link voltage is 130 V_{DC} . The major components used for the hardware prototype are listed in TABLE I.

A. Current sensing

In the boost operation, it is very easy to sense the inductor current. However, in the buck mode operation, this is not the case. In order to overcome the sensitivity problem, the positive DC offset voltage is added to the sensed current as shown in Fig.8. The sensed inductor current (I_{LS}) can be calculated as follows:

$$I_{LS} = I_L \cdot K_{cs} + K_{DC} \quad , \quad I_{LS} > 0 \tag{6}$$

$$V_z = K_{DC} - I_{L\_crit} \cdot K_{cs} \quad , \quad V_z > 0 \, , \tag{7}$$

where, K_{DC} is the DC offset voltage and V_z is selected as the above Eq.(6) and (7).

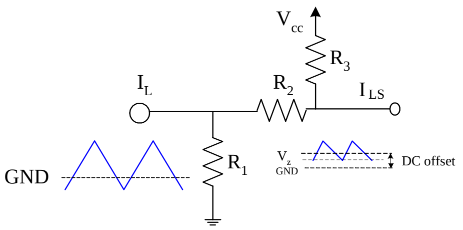

Fig. 8. Current sensing network

B. Determining the peak value of the inductor current

In Fig. 9, the DC-link voltage is sensed and fed to the negative input of Error Amplifier (EA) and compared with the reference voltage. The error signal is compensated to ensure the loop stability and optimum dynamic performances [7]. The output of EA (V_c) is fed to a comparator as the reference of the peak value of the inductor current.

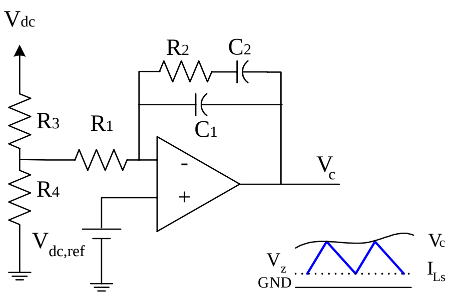

Fig. 9. Peak value of the inductor current

C. Waveforms of the inductor current by the load

At the no load condition, the peak to peak value of the inductor current is decreased to 40A compared to 72A at the full load condition and the switching frequency of the converter is increased to 79kHz as shown in Fig 10.

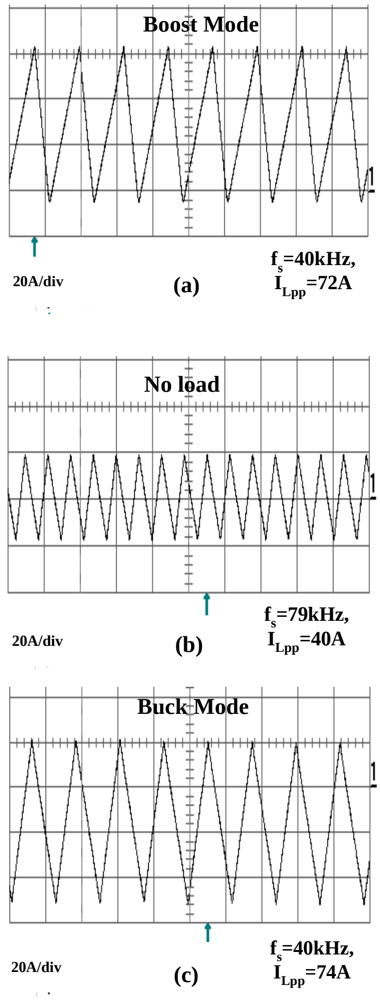

Fig. 10. Waveforms of the inductor current by the load condition. Switching frequency is increased to 79kHz at the no load condition. (a) Boost mode (b) No load (c) Buck mode

D. Efficiency of the proposed converter

The efficiency of the converter is improved by the frequency control compared to the fixed frequency control as shown in Fig. 11 and Fig. 12 for the case of $V_{sc}=50V_{DC}$, $V_{dc}=130V_{DC}$. The efficiency is increased both the buck and the boost mode at all load condition.

For the no load condition, the loss of the fixed frequency controlled converter is 71W and that of the proposed converter is 48W. As a result, the power loss reduced about 34% at no load condition.

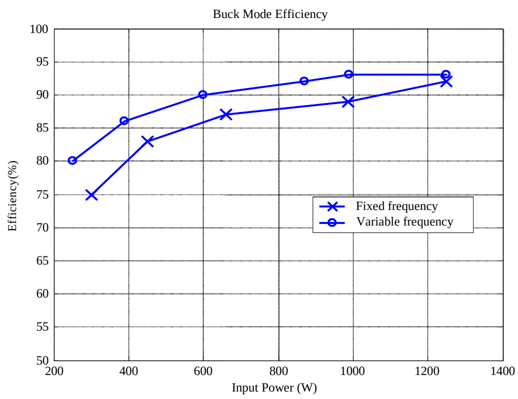

Fig. 11. Efficiency for the proposed converter at the buck mode

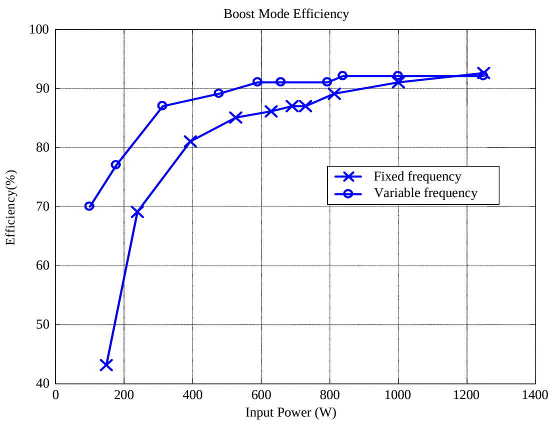

Fig. 12. Efficiency for the proposed converter at the boost mode

E. Step response of the boost mode

Fig. 13 shows the experimental results of the step response at the discharging mode. In this results, the DC-link voltage clamps 130 V_{DC} and the step load changes from 500W to 1kW.

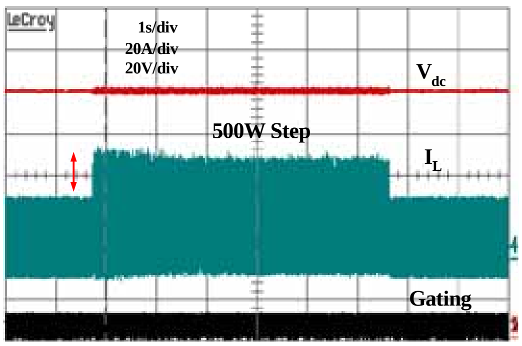

Fig. 13 Step response of the discharging mode

F. Mode change between buck and boost

Fig. 14 shows the experimental results of the mode change between the charging and discharging. The DC-link voltage clamps 130 V_{DC} and the average value of the inductor current changes negative and positive automatically while regulating the DC-link voltage.

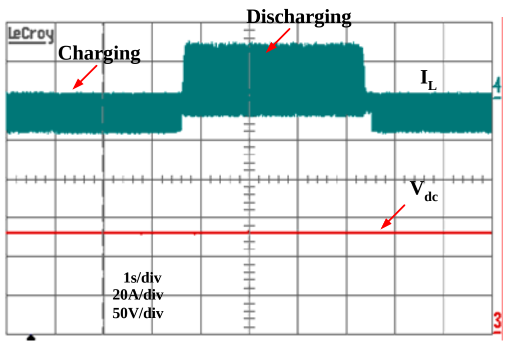

Fig. 14. Mode change between the charging and discharging

IV. CONCLUSION

In this paper, a control method of a bi-directional zero-voltage-switching (ZVS) DC-DC converter for HEV power system is presented. The charging and discharging of the super-capacitor bank is controlled by simply regulating the DC-link capacitor voltage and the charging and discharging currents are determined by the vehicle's operating modes. By controlling the minimum and maximum values of the inductor current, the ZVS condition is achieved. Also employing the variable frequency control with respect to the variation of the DC-link current and the super-capacitor voltage, the circulating energy loss at the light load condition is minimized. A 1.25kW experimental hardware prototype module is built to verity the efficiency improvement, especially at the light load condition. It shows about 34% efficiency improvement compared to the fixed frequency control at the light load condition.

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