Abstract—This study examined the step-down DC-DC converter with high-efficiency appropriate for hybrid vehicles. The above described converter supplies power to electronic components such as headlights and air conditioners by replacing an electric generator of an internal combustion engine and converting the high voltage of a main battery to low voltage (12 V). In this study, the development specification was selected through benchmarking to design a 1 kW DC-DC converter. Subsequently, more than 94% efficiency was confirmed through performance test, and the stability was analyzed by measuring the load and line regulation.

Keywords—Step-down DC-DC converter, LDC(Low DC-DC Converter), Active-clamp, Current-doubler, HEV(Hybrid electric vehicles)

I. INTRODUCTION

Currently, in the automobile market, there is an increasing demand for low-cost and high-efficiency automobiles due to the depletion of fossil fuels and environmental pollution, and environmentally friendly vehicles have spread rapidly according to government regulations and supporting policies of each country. Electric vehicles as a representative environmentally friendly vehicle are divided into battery electric vehicles (BEVs) powered only by a battery, hybrid electric vehicles (HEVs) powered by a mixture of an internal combustion engine and a battery, and fuel cell electric vehicles (FCEVs). The vehicles are equipped with a step-down DC-DC converter replacing an electric generator of an internal combustion engine. Currently, the phase shifted full-bridge is applied to the topology of converters for HEVs and is at an efficiency of approximately 90%. Further studies are required to improve the efficiency. This study developed a high-efficiency 1 kW step-down DC-DC converter appropriate for HEVs and examined the excellence of products through performance test.

II. CIRCUIT DESIGN

A. Performance Specifications

This study performed about benchmarking a product of a step-down converter for C-segment mild HEVs and selected the development specifications as shown in Table 1 [1]. Although the mounting position of converters vary depending on the vehicle type and volumes, this study aimed to attach them between trunk and life space and was based on the assumption of the forced air cooling by a blower. In addition, stable system operation was guaranteed by providing a protective function, and the converter was designed to communicate with a host controller by providing controller area network (CAN).

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>130 VDC ~ 200 VDC</td>
</tr>
<tr>
<td>Output voltage</td>
<td>14.3 VDC</td>
</tr>
<tr>
<td>Output current</td>
<td>&gt; 70 A</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt; 94% (Max.)</td>
</tr>
<tr>
<td>Frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Cooling</td>
<td>Forced air</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt; 2.5 kg</td>
</tr>
<tr>
<td>Communication</td>
<td>CAN 2.0B</td>
</tr>
</tbody>
</table>

B. Circuit configuration and design

As shown in Figure 1, the developed converter consisted of an input filter circuit for noise reduction of input power, a power conversion circuit for converting the high input voltage to low...
voltage of 12 V, an auxiliary power circuit for providing electricity to the components of the circuits such as IC, a PWM circuit for modulating the output by duty-cycle control, and a communication and system control circuit.

As shown in Figure 2, a phase shifted full-bridge topology is generally applied to converters at more than 1 kW, and the above circuit is characterized by zero-voltage switching in order to minimize the switching losses. However, it is difficult to apply a synchronous rectifier because the control system is complex and the section where voltage is not induced to the secondary winding exists, and there is a problem that the inductor added in series to the transformer for zero-voltage switching of the primary winding reduces the overall power efficiency.

![Fig. 2 The phase-shifted full bridge of topology](image)

Thus, as shown in Figure 3, this study applied an active-clamp circuit for zero-voltage switching to the primary winding and a current-doubler circuit to the secondary winding with the used of the leakage inductance of the transformer. The active-clamp circuit consisting of an auxiliary switch (S2) and a clamp capacitor (Cc) can increase the power conversion efficiency operates when eliminating the primary switch (S1) by preventing overvoltage of the switching elements due to the energy stored in the leakage and magnetizing inductance and reusing the energy [2]-[4]. Moreover, it has the advantage that it is possible to create a driving waveform of the synchronous rectifier by using only simple auxiliary windings not only because the control method is simple but also because voltage is always generated in the secondary winding. The secondary current-doubler circuit can reduce the filter inductor and achieve high power density by loosely combining two inductors with a core [5]-[6].

![Fig. 3 Power conversion topology adopted to this study](image)

The operating principle of the circuit is as follows: When applying current to the primary switch (S1), the current in the primary switch (S1) flows from negative to positive by the leakage inductance of the transformer (T). In other words, it transfers energy to the secondary side by charging the inductor (L2) of the secondary rectifier with zero-voltage switching. In this process, the current through the primary switch (S1) and Synchronous rectifier (SR1) flows in a form similar to a rectangular waveform, minimizes the peak current of the diode and reduces conduction losses. When eliminating the primary switch (S1), the current in the auxiliary switch (S2) flows from negative to positive by the current flowing in the magnetizing and leakage inductance of the transformer (T). In other words, it transfers energy to the secondary side by charging the inductor (L1) of the secondary rectifier with zero-voltage switching. While the auxiliary switch (S2) applies current, the current flowing the leakage inductance charges and discharges the clamp capacitor (Cc), and the energy stored in the leakage inductance is reused.

In this study, Fairchild's 600 V MOSFET were applied to the primary side, and International Rectifier's 100 A MOSFET was used in the secondary side in consideration of the output current. In addition, TDK's PQ 50 series was used as a core of the transformer in consideration of the output capacity and frequency, and TI's UCC2894 was applied as a PWM controller. Also ATmel's 8-bit processor was used for the overall system control and transmitted control signals via photo-coupler and pulse trans in order to maintain electrical insulation of the primary and secondary side.

III. EXPERIMENT AND RESULTS

A. Prototype fabrication

The components were arranged in reference to the designed circuit diagram. The major component, a switching element, increased the heat diffusion efficiency by being arranged directly in the housing. On the other hand, the input and output terminals were placed on the other side in consideration of the effect of electromagnetic waves, and the upper case was designed to protect the circuit from external contamination.

![Fig. 5 Images of 3D model and developed converter](image)

Al 6xxx materials were used for the lower case, and the heat sinks were arranged at appropriate intervals. Then, the interference between components was checked by 3D modeling, and the converter was fabricated by reflecting the modifications as shown in Figure 5. The converter weighed approximately 2.4 kg and was heavy for its output capacity. However, if some
components such as magnetic materials and housing are optimized, it is considered possible to additionally reduce the weight by more than 20%.

B. Performance test

As shown in Figure 6, this study created a test environment for the performance analysis of the developed product. The high voltage battery of the vehicle was replaced by NF's ES6000W power supply device, and various electrical loads were replaced by KIKUSI's PCZ600R. In addition, in order to measure the output capacity and power conversion efficiency, Yokogawa's WT-1800 was used, and current transformers were used to measure the high current of the output side.

![Performance test condition of the developed converter](image)

Fig. 6 Performance test condition of the developed converter

Figure 7 is a graph measuring the capacity and efficiency of the developed product. According to this, the capacity was output up to approximately 1.1 kW. The efficiency of power conversion within the normal input voltage range, 130 to 200 V, was on average at approximately 92.9% and in the rated input voltage, 180 V, was on average at approximately 94.6%.

![The graph of conversion efficiency for developed converter](image)

Fig. 7 The graph of conversion efficiency for developed converter

Figure 8 is a graph measuring the efficiency of the benchmarked product [1]. The performance specifications except the capacity were the same as those of the developed product. The average and maximum efficiencies were approximately 89.4 and 90.4%, respectively. The results showed that the developed product was superior to the benchmarked product.

![The graph of conversion efficiency for competitive product](image)

Fig. 8 The graph of conversion efficiency for competitive product

Figures 9 and 10 are graphs measuring load and line regulation for stability assessment of the developed product. The load regulation was measured at rated input voltage.

![Load regulation graph of the developed converter](image)

Fig. 9 Load regulation graph of the developed converter

![Line regulation graph of the developed converter](image)

Fig. 10 Line regulation graph of the developed converter
The load regulation was within 1%, and the line regulation was also excellent, within 1%.

The developed product was designed by reflecting 20% of margin in the input voltage range. Figure 11 is a graph showing the protective function of the input voltage. Output interruption was found at approximately 240 V with overvoltage, and at approximately 110 V with low voltage.

![Graph showing protective function test by input condition](image)

(a) Over voltage mode  (b) Under voltage mode

Fig. 11 Protection function test by input condition

Figure 12 is a graph showing that the protective function according to overvoltage and over current works. The output stopped at 16 V and immediately interrupted at approximately 85 A in over current.

![Graph showing protective function test by output condition](image)

(a) Over voltage mode  (b) Over current mode

Fig. 12 Protection function test by output condition

IV. CONCLUSION

This study developed a 1 kW step-down DC-DC converter with high-efficiency for hybrid electric vehicles and conducted performance testing through experiments. In order to achieve high efficiency, active-clamp and current-doubler circuit topologies were applied instead of the existing phase shifted full bridge. As a result, this study achieved an average efficiency of approximately 92.9% and up to 94.6%. The stability of the developed product was confirmed by the performance tests. Based on the results of this study, it is planned to improve the completeness through the development of a mass-produced converter prototype with more than 1.5 kW. For this purpose, we will conduct research as follows:

- Performance optimization by customizing the main components and size reduction
- Improvement of the heat diffusion efficiency by module packaging of the switching elements

ACKNOWLEDGMENT

This research was financially supported by the Ministry of Trade, Industry & Energy (MOTIE), Korea Institute for Advancement of Technology (KIAT) and DaeGyeong Institute for Regional Program Evaluation (DGIRPE) through the Leading Industry Development for Economic Region.

REFERENCES


