

# A Study on High Efficiency Bidirectional LVDC for Vehicle ISG System

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## Abstract

**Background/Objectives:** As recently, they have installed modules with various features related to the field of vehicles in the future, including hybrid vehicle and intelligent vehicle, it came to be difficult for the existing power supply to cover those sufficiently. In addition, judging from the recent intelligent keynote and hybrid development direction, a high-power converter becomes essential. Thus, research on the technology that achieves high efficiency is urgently needed.

**Methods/Statistical analysis:** As recently, the need of high mileages of vehicle systems has come to the fore, studies for energy saving are actively conducted by applying the Idle Stop & Go (ISG) System technology that stops the engine running while idling. In general, the fuel consumed in the vehicle while idling takes up 5-8% of the total fuel consumption, so a Stop-Start System in the hybrid vehicle is considered one of the essential features.

**Findings:** To maximize the efficiency of a Stop-Start system, it is essential to employ a maneuvering engine motor run at high voltage, and for this, it becomes generalized to build up a 48 [V] voltage system in the Stop-Start system. In the vehicle power system, for small capacity power, such as light and stereo systems, the existing 12 [V] voltage system is constructed, while in high-capacity systems such as start system, power steering, air conditioning and heating system, a binary system is applied, in which the 48 [V] voltage system is constructed, and in this binary system, the DC/DC converter for power supply between two power sources comes to have a four times higher boosting ratio. Because of this high boosting ratio, the non-isolated general DC/DC converter is not enough for the promotion of efficiency, so studies are conducted on various charging pumps for efficiency improvement. In this paper, propose a new topology and a construction method for 3kW class bidirectional DC / DC converters suitable for automotive systems with redundant power supplies. The proposed resonant charge pump uses input and output grounds in common, enables soft switching in a full load region, and has a very small inductor size.

**Improvements/Applications:** In this paper, designed a controller of a DC/DC converter that could improve power quality and increase reliability, and as a result, the following conclusions could be drawn.

**Keywords:** ISG System (Idle Stop & Go system), Charge pump, High power converters, DC / DC converter, Hybrid vehicle

## 1. Introduction

Today, electric/electronic structures inside vehicles become gradually more complex, according to various factors such as consumers' requirements for safety and convenience, technological innovation, competition, product differentiation and regulation. As recently, they have installed modules with various features related to the field of vehicles in the future, including hybrid vehicle and intelligent vehicle, it came to be difficult for the existing power supply to cover those sufficiently. In addition, judging from the recent intelligent keynote and hybrid development direction, a high-power converter becomes essential. Thus, research on the technology that achieves high efficiency is urgently needed. As recently, the need of high mileages of vehicle systems has come to the fore, studies for energy saving are actively conducted by applying the Idle Stop & Go (ISG) System technology that stops the engine running while idling. In general, the fuel consumed in the vehicle while idling takes up 5-8% of the total fuel consumption, so a Stop-Start System in the hybrid vehicle is considered one of the essential features. Also, to the general internal combustion engine vehicles, its application tends to gradually expand[1-3]. And yet, the ISG system has many

advantages, but in starting mode, a large amount of current momentarily flows to run the engine, so an instant drop of voltage takes place, and the technology that controls this is the core of the DC/DC converter technology on the electronic circuit. To maximize the efficiency of a Stop-Start system, it is essential to employ a maneuvering engine motor run at high voltage, and for this, it becomes generalized to build up a 48 [V] voltage system in the Stop-Start system. In the vehicle power system, for small capacity power, such as light and stereo systems, the existing 12 [V] voltage system is constructed, while in high-capacity systems such as start system, power steering, air conditioning and heating system, a binary system is applied, in which the 48 [V] voltage system is constructed, and in this binary system, the DC/DC converter for power supply between two power sources comes to have a four times higher boosting ratio. Because of this high boosting ratio, the non-isolated general DC/DC converter is not enough for the promotion of efficiency, so studies are conducted on various charging pumps for efficiency improvement[4,5]. This study proposes a new topology and a method for constructing a 3kW class bi-directional DC/DC converter appropriate for the in-vehicle system with redundant power. The proposed resonant charging pump commonly uses input/output grounding. It is

characterized by soft switching in the entire load area and very small inductor size, while the proposed resonant charging pump has an advantage that the resonant circuit is not affected in tandem drive by constructing it so that in the delivery of power to the output side, the inductor is constructed in series with the input power source[6,7].

## 2. Materials and Methods

### 2.1 DC / DC Converter Topology Analysis for ISG

Figure 1 shows a bidirectional DC / DC converter with conventional I / O common ground. The converter operates as a step-up converter from the input side to the output side, and operates as a reduced-pressure converter to the input side from the output side.

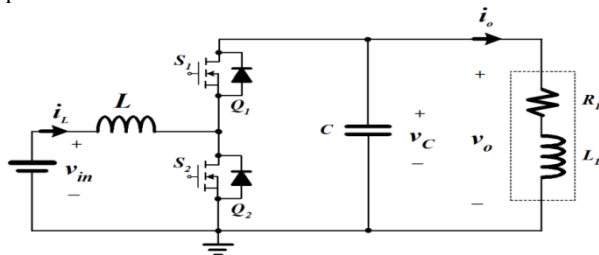


Figure 1: Conventional bi-directional DC / DC converter

When a MOSFET switch device is used in this converter, it is generally used as a synchronous DC / DC converter which lowers the saturation voltage of the diode for the purpose of increasing the efficiency. When the converter is operated with a booster of 4 times or more, the output current peak value becomes large due to a high duty ratio, which limits the construction of the high efficiency power converter. Figure 2 shows a conventional double-boost soft-switching bidirectional charge pump with heterogeneous ground. Figure 3 shows the operating waveform of the charge pump. This converter is a DC / DC converter whose output voltage is twice the input voltage, operating as a charge pump for C1, C2 connected in series with the input voltage.

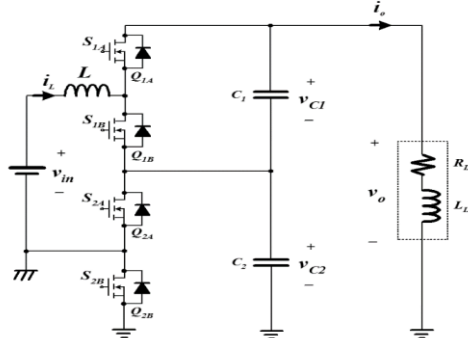


Figure 2: Heterojunction Ground Charge Pump

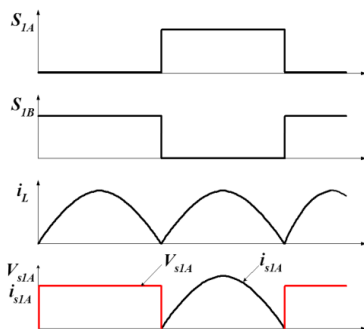


Figure 3: Operation Waveform of Heterojunction Ground Charge Pump

As for the operation of the converter, an arm switch mounted on a

capacitor connected in series switches interlocked with a duty ratio of 0.5. In this switching operation, the capacitor C1 is charged by the ZCS (zero current switching) method while the inductor current is serially resonated by the switches Q1A and Q2A, and the capacitor C2 is also charged by the switches Q1B and Q2B. Therefore, the output voltage acts as a voltage doubler which doubles the input voltage by the voltage of the capacitors C1 and C2 connected in series on the output side. This method is a high-efficiency and integrated topology by forming an output voltage with a resonant charge pump capable of high soft switching[8-9]. However, this method is different from the reference potential of input and output as shown in figure 2, which is a topology which cannot be used when all the power sources such as the vehicle are grounded to the vehicle frame. In particular, this converter structure has resonance and load current by connecting two resonance capacitors in series on the output side, so resonance is broken due to interference of capacitor currents of each converter during parallel operation. It is a structure that parallel operation is difficult.

Figure 4 shows a bi-directional voltage reference charge pump capable of double boosting.

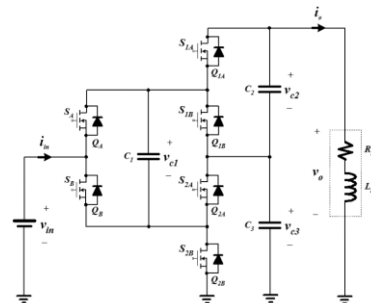


Figure 4: Same ground type charge pump

This converter has a structure in which the switches QA, QB and the capacitor C1 are added to form the same reference potential in the input power and the output power in the charge pump of FIG. That is, the input voltage is charged to C1 by the charge pump circuit by the switches Q1A and Q2A, and the capacitor C2 is charged to the C1 voltage by the Q1B and Q2B switches, and the capacitor C2 is also charged by the C1 voltage by the Q2A and Q2B switches. Therefore, this method is a structure in which the input voltage is transferred to the output voltage by charging the capacitor two stages[10-12].

### 2.2. The Proposed Resonant Charge Pump Topology

Figure 5 shows a new bidirectional equivalent grounded charge pump capable of double boosting. The proposed grounded resonant charge pump has fewer switching elements and two condenser elements than the conventional grounded type charge pump shown in figure 4.

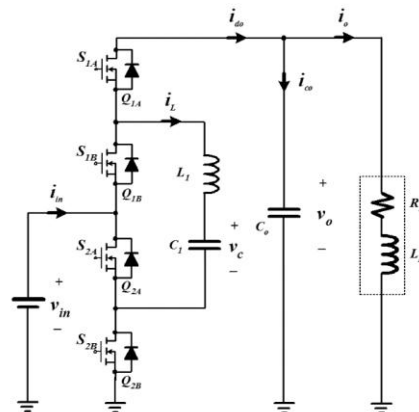


Figure 5: The proposed charge pump

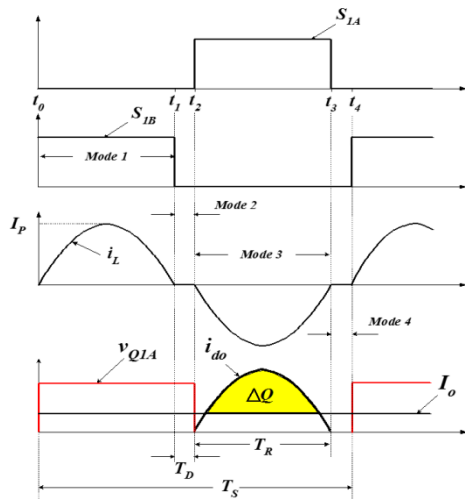


Figure 6: The proposed charge pump resonant waveform

The resonant current waveform and the output current waveform according to the switching signal in the proposed charge pump are shown in figure 6 and the operating mode is shown in figure 7.

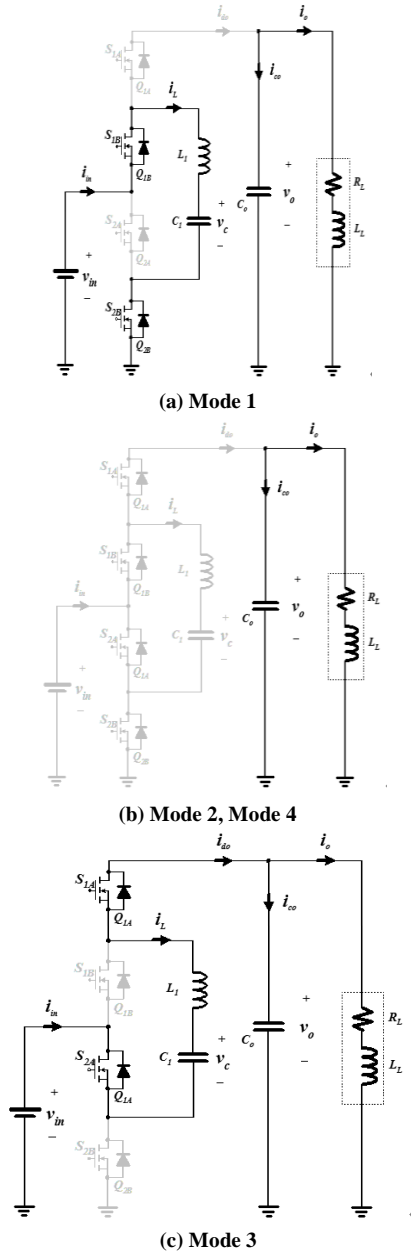


Figure 7: Schematic of operation mode of proposed charge pump

In figure 7, the switching period is defined as  $T_s$ , the resonance half period is defined as  $T_R$ , and the dead time is defined as  $T_D$ . Therefore, the above time relation is given as follows.

$$T_s = 2(T_R + T_D) \quad (1)$$

Figure 7(a) starts from the moment the switches  $S_{1B}$  and  $S_{2B}$  are turned on in Mode 1. By the  $Q_{1B}$  and  $Q_{2B}$  switches, the input voltage and the L-C series resonant circuit are energized to the capacitor  $C_1$  by the ZCS. When the resonant capacitor voltage  $V_c(0)$  is less than the input voltage  $v_{in}$  at the start of this mode, energy is transferred from the input side to the capacitor side. When the capacitor voltage is larger than the input voltage, energy is transferred from the capacitor side to the input side. The voltage equation of the resonant circuit from the equivalent circuit of figure 7(a) is as follows.

$$V_{in} = L_1 \frac{di_L}{dt} + V_c \quad (2)$$

The current of the resonant capacitor is given by the following equation.

$$i_c = C_1 \frac{dV_c}{dt} = i_L \quad (3)$$

Since the initial value of current in this resonance circuit is zero, the above equation can be simplified as follows.

$$V_c(t) = V_{in} - [V_{in} - V_c(t_0)] \cos[\omega_r(t - t_0)] \quad (4)$$

Since the initial value is zero, the above formula can be simplified as follows.

$$i_L(t) = \frac{V_{in} - V_c(0)}{z} \sin[\omega_r(t - t_0)] \quad (5)$$

In this mode, the output current ( $i_o$ ) is taken over by the capacitor  $C_o$ . If the ripple of the output voltage is small or the load inductor is large, the value can be treated as a constant value.

$$i_0 = \frac{I_p T_s - 2T_D}{\pi T_s} = \frac{V_0}{R} \quad (6)$$

As can be seen from equation (6), when the dead time is large, the load current is reduced for the same resonance peak current. Therefore, in order to reduce the current peak value of the switch, it is desirable to set the value as small as possible so as to allow the dead time. From the equation (6), the resonance peak current is given by the following equation.

$$I_p = \frac{\pi T_s V_0}{R(T_s - 2T_D)} \quad (7)$$

If the power converter is in a steady state, the resonant capacitor voltage is a periodic function. Therefore, the initial capacitor voltage of Mode 1 is given by equation (5) and (7) as follows.

$$V_c(0) = V_{in} \left(1 - \frac{2\pi T_s}{R(T_s - 2T_D)} \sqrt{\frac{L_1}{C_1}}\right) \quad (8)$$

In Mode 1, the switches  $S_{1B}$  and  $S_{2B}$  are turned off when the direction of the resonance current is changed. Figure 7(b) shows that the mode 2 and mode 4 are maintained for the dead time period when all switches are off, and the resonance current is zero and the load current is transferred from the capacitor. Figure 7(c) starts from the moment the switches  $S_{1A}$  and  $S_{2A}$  are turned on in Mode 3. The difference between the output voltage and the input voltage is applied to the L-C series resonant circuit by the switches  $Q_{1A}$  and  $Q_{2A}$ . At this time, the resonance current is received by the ZCS from the capacitor  $C_1$  to the output side. When the sum of the resonant capacitor voltage  $V_c(0)$  and the input voltage  $v_{in}$  is greater than the output voltage at the start of this mode, energy is transferred from the capacitor side to the output side. If the sum of the capacitor voltage and the input voltage is less than the output voltage, Energy is transferred to the capacitor side. At this time, the inductor current and the capacitor

voltage are given by the following equations.

$$i_{L1}(t) = \frac{(V_0 - V_{in}) - V_c(t_2)}{z} \sin[\omega_r(t - t_2)] \quad (9)$$

$$V_c(t) = (V_0 - V_{in}) - [(V_0 - V_{in}) - V_c(t_2)] \cos[\omega_r(t - t_2)] \quad (10)$$

The average voltage of the resonant capacitor becomes the input voltage.

$$V_{c\_ave} = V_{in} \quad (11)$$

If the capacitor ripple is defined as  $V_c$  by equation (11), the maximum voltage and minimum voltage of the capacitor are given by the following equations.

$$V_{c\_max} = V_{in} + \Delta V_c / 2$$

$$V_{c\_min} = V_{in} - \Delta V_c / 2 \quad (12)$$

Therefore, the variation of the energy when the capacitor is charged or discharged is given as follows.

$$\Delta E_c = C_1 V_{in} \Delta V_c [\text{joule}] \quad (13)$$

The capacitors energized by the switches Q1B and Q2B are resonated with the input voltage so that the Q1A and Q2A switches are turned on and become equal to the received energy. Therefore, the power delivered from the capacitor to the output side can be defined as follows.

$$P_c = f_s C_1 V_{in} \Delta V_c [\text{W}] \quad (14)$$

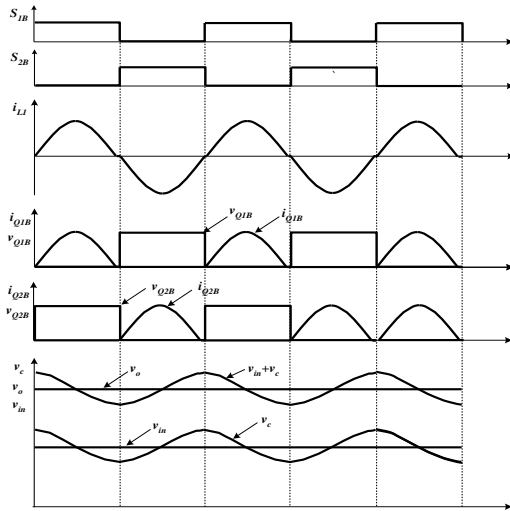


Figure 8:. Operation waveform of proposed charge pump

The power delivered from the capacitor to the output side is determined by  $V_c$ . However, if the input voltage is constant,  $V_c$  is determined by the load. Therefore, it is necessary to derive a relational expression for the  $V_c$  value depending on the load. Figure 8 shows the operation waveform of the proposed charge pump. As shown in the figure, the resonant tank capacitor voltage ( $V_c$ ) is symmetrical up and down with respect to the input voltage. Therefore,  $V_c$  is given by equations (8) and equations (12) as follows.

$$\Delta V_c = 2V_{in} \left(1 - \frac{2\pi T_s}{R(T_s - 2T_D)} \sqrt{\frac{L_1}{C_1}}\right) \quad (15)$$

As can be seen from equation (15), if the hardware of the resonant charge pump is determined, the resonant tank capacitor voltage ripple is determined only by the load ( $R$ ). Therefore, if the

maximum load is determined, the ripple of the capacitor can be determined. The condition that the minimum voltage of the resonant tank becomes zero at rated load by setting the resonant tank capacitor voltage ripple rate to 100 [%] is as follows.

$$C_1 = \left[\frac{2\pi T_s}{R(T_s - 2T_D)}\right]^2 L_1 \quad (16)$$

In a vehicle system with a redundant power supply, when two voltage boost pumps are connected to form a voltage system of 12[V] and 48[V], only if one of the two power systems is equipped with an energy storage device, Power is available. However, when both systems are equipped with energy storage devices, if the two system voltages are not exactly four times the voltage is transmitted to infinitely lower voltage, causing the power converter to burn out. Therefore, it is essential to install a power converter that can control the amount of power. In a vehicle system with a redundant power supply, when connecting two double booster charge pumps, bidirectional power regulation converters must be used depending on the power state of the system, resulting in a reduction in efficiency. In this paper, considering this situation, we used one double - boost pump and two - way booster converter. In order to reduce the current size of the resonant circuit, the step-up converter is used to boost to 24 [V] at the 12[V] stage and the 48[V] .

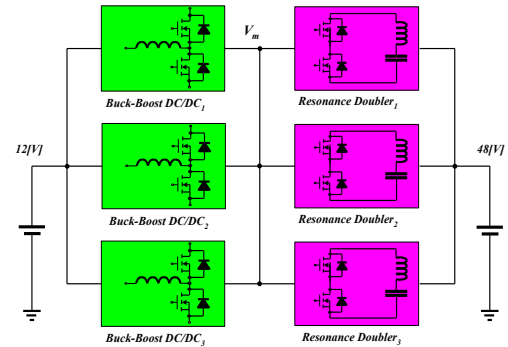


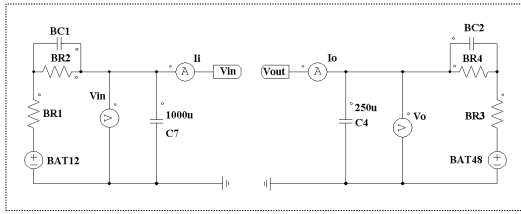
Figure 9:. Proposed dual system configuration diagram

As shown in figure 9, three bidirectional step-up converters are used on the 12[V] side to form a  $V_m$  voltage of 24[V] and boosted to 48[V] by a resonant charge pump. Each step-up converter and charge pump adopts interleaved switching method with 120 ° phase difference to reduce ripple of input / output current.

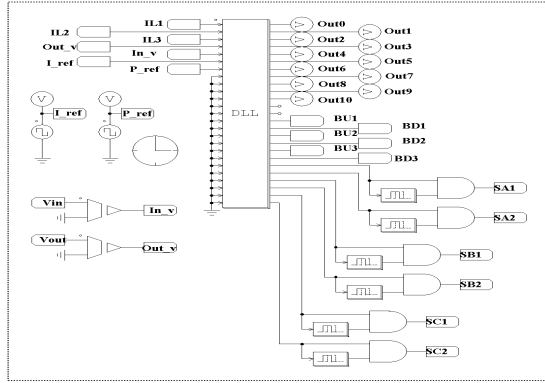
### 3. Simulation and Experimental Results

#### 3.1. Simulation Results

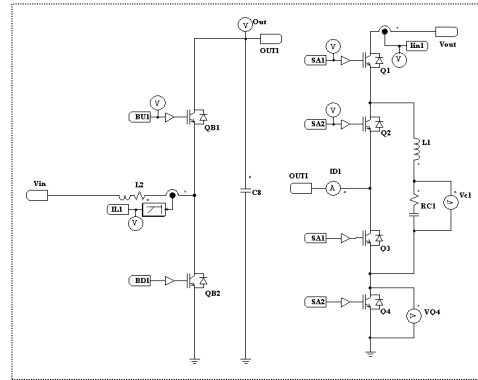
Figure 10 is a simulation circuit diagram for analyzing the feasibility of the proposed redundant power system. The simulation circuit is largely divided into a battery equivalent circuit, a power conversion part using the proposed resonance type charge pump, and a dll part for controlling power conversion. The RCR equivalent circuit is used for the battery part, and the power conversion part is composed of the charge pump and the boost converter. The dll section consists of signals for observing input and output voltage currents, switching signals of three sets of interleaved boost converters, resonant charge pump switching signals and control variables.



Battery equivalent circuit



Control DLL Block



Bidirectional DC/DC<sub>1</sub>

Bidirectional DC/DC<sub>2</sub>

Bidirectional DC/DC<sub>3</sub>

Figure 10: Simulation circuit diagram of the proposed charging circuit

Figure 11 shows the simulated results at 3[kW] rated load to analyze the interleaving characteristics of the charge pump. The three sets of resonant circuit current ( $i_L$ ) resonates at a phase difference of  $120^\circ$ , and the capacitor voltage is  $90^\circ$  out of phase with the current, and the minimum value is zero and the average value is about 24[V]. It can be seen that the charge pump input current ( $i_{DT}$ ) is the sum of the full-wave rectification of the three-phase resonant current, which has a ripple current six times that of the resonant frequency, and the ripple rate is significantly improved. It can be seen that the ripple current of the charge pump output side ( $Lin_T$ ) is the sum of the half-wave rectification of the resonance current, which is 6 times the resonance frequency, and the ripple rate is significantly improved compared with the input

side ripple improving effect. Thus, it can be seen that the capacitance of the input / output capacitors can be reduced.

Figure 12 shows the doubler & DC / DC circuit schematic. In this design, the system is designed as a one-board system, ACS758ECB current sensor for single power control board is adopted, and copper bus-bar system is adopted for PCB pattern reinforcement.

Figure 13 shows the experimental waveform of a doubler & DC / DC circuit. As can be seen from the waveforms, the soft-switching characteristics of the doubler and the DC / DC converter are good

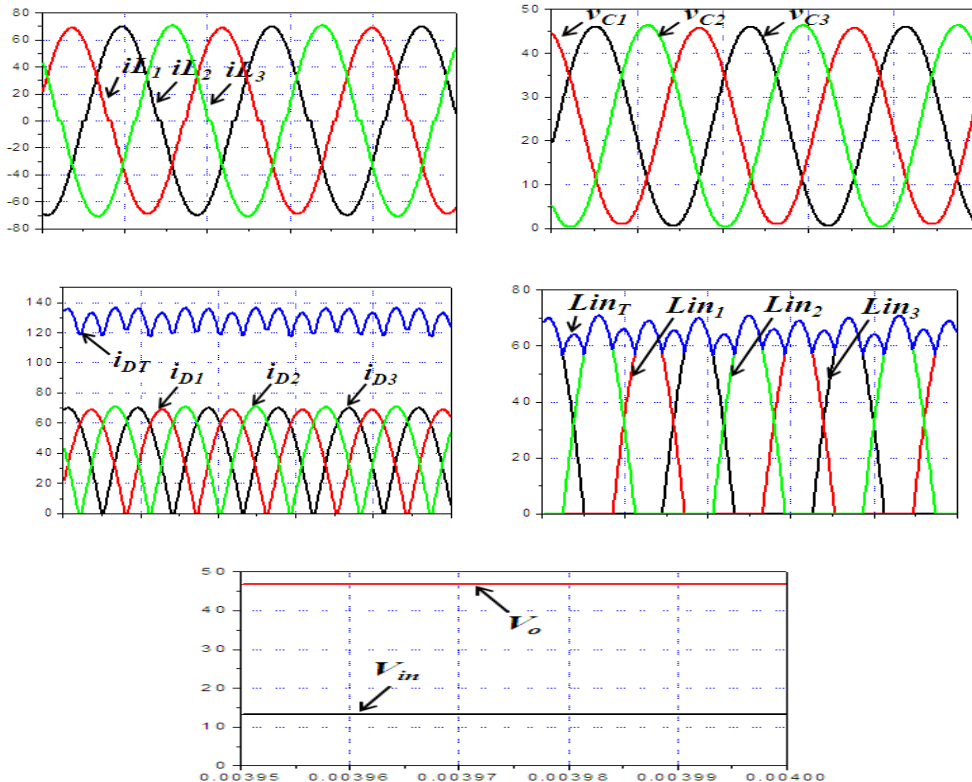


Figure 11: Interleaving Characteristics of Charge Pump

3.2. Experimental Results

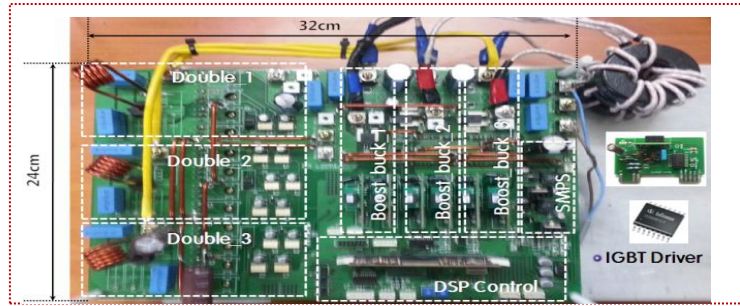
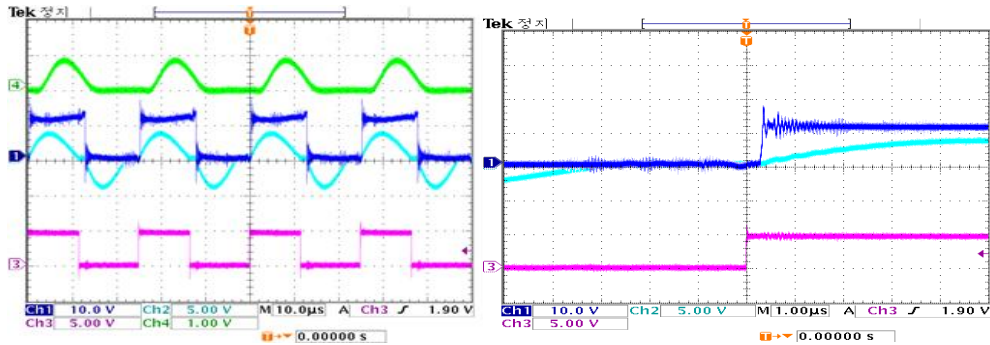
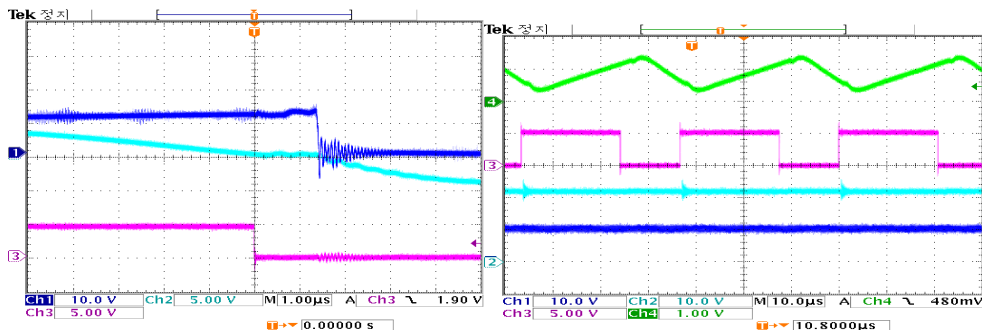


Figure 12: Manufacture of doubler & DC / DC circuit PCB



(a) Resonance characteristics of doubler (b) ZCS characteristics of doubler on



(c) ZCS characteristics when the doubler is off (d) DC / DC characteristic waveform

Figure 13: Experimental waveform of doubler & DC / DC circuit

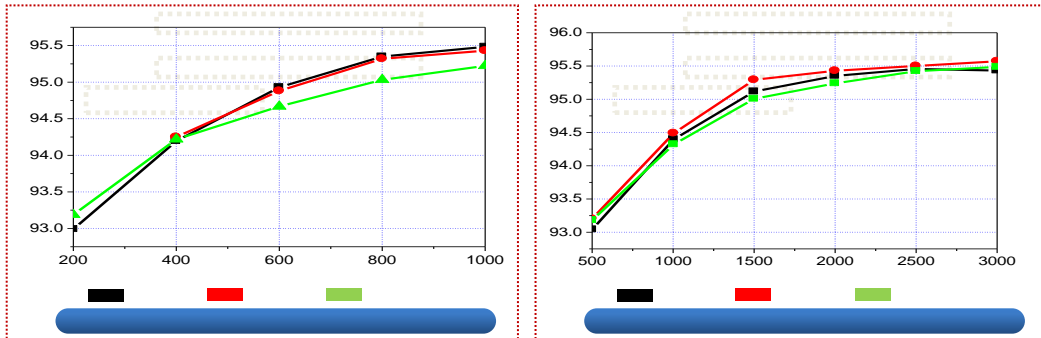


Figure 14: Efficiency characteristics according to switching frequency in IPM Type DC / DC decompression mode

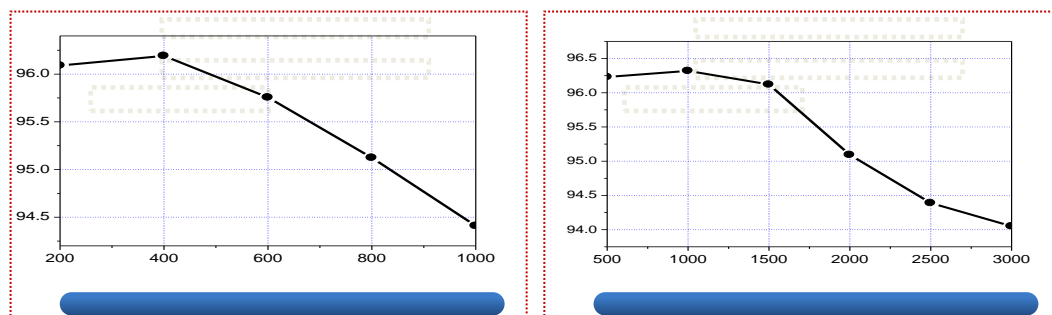


Figure 15: IPM Type Efficiency Characteristics in DC / DC Decompression Mode

Figure 14 shows the result of analysis of the efficiency characteristics in the third IPM type DC / DC decompression mode. The 3-phase interleaving method is superior to the single-module driving due to the reduction of the switch loss in light load, but the 3-phase interleaving method is superior in driving with a single module as the conduction loss increases under the rated load. Figure 15 shows the results of the efficiency

measurement of the IPM Type DC / DC in the reduced mode, and figure 16 shows the efficiency analysis results of the IPM Type DC / DC in the reduced mode. As can be seen in figure 17, the maximum efficiency was the maximum efficiency point at 96.69% at 1kW. Switching loss was the main cause of the decrease in efficiency of light load.

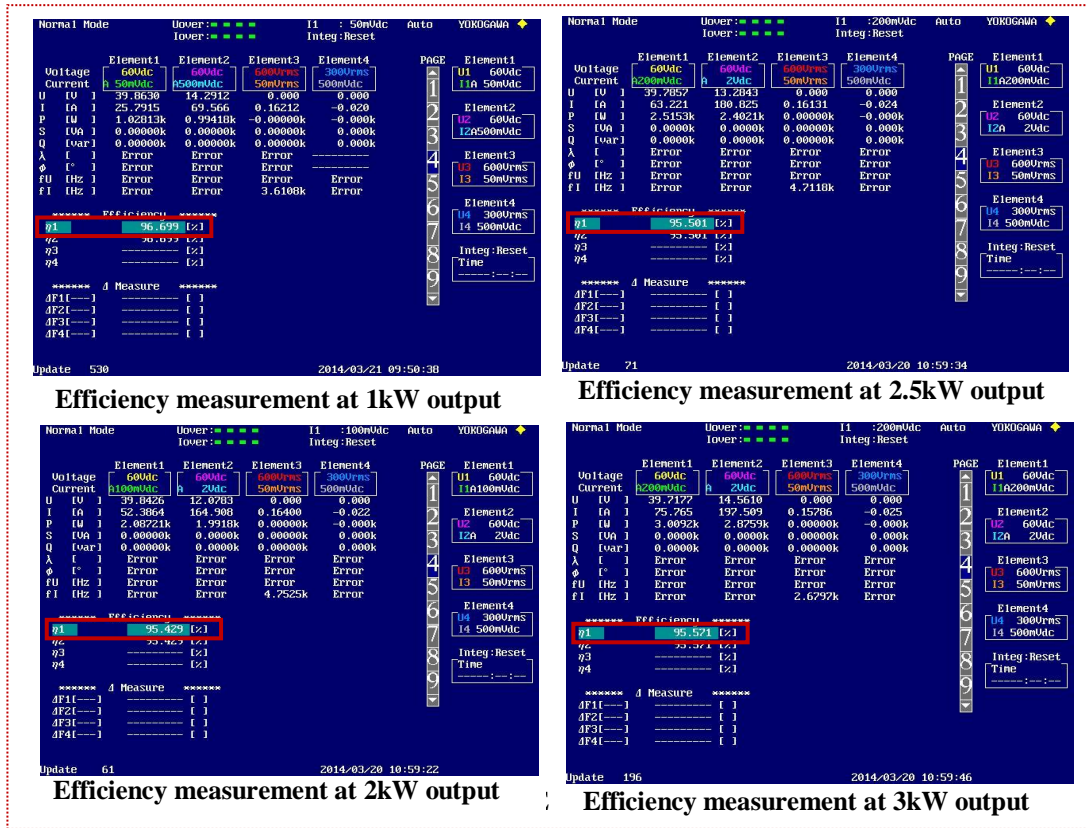


Figure 16: IPM Type DC / DC Decompression Mode Efficiency Measurement Results

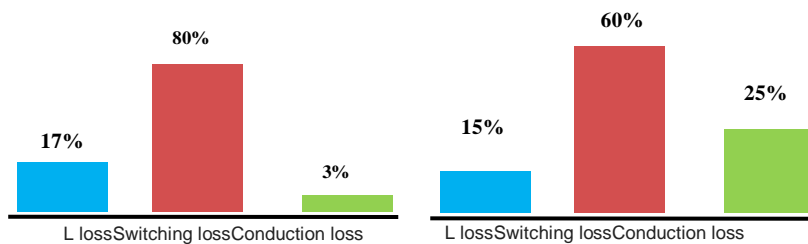


Figure 17: IPM Type DC / DC Decompression Mode Efficiency Analysis by Load

#### 4. Conclusion

The general high mileage in-vehicle electrical system is a binary voltage system, which commonly uses the grounding of both power sources through a chassis. In such a binary system, since the general DC/DC converter for the power supply between two power sources has a limitation in promoting the efficiency with a PCB pattern because of the boosting ratio with a four times higher boosting ratio, so studies of various topologies and PCB patterns for efficiency improvement are actively conducted. This development proposed a new topology and its composition method of a bi-directional DC/DC converter suitable for the in-vehicle system with redundant power and conducted a study of the optimum topology and PCB pattern, measuring the efficiency of various methods. In addition, this study designed a controller of a

DC/DC converter that could improve power quality and increase reliability, and as a result, the following conclusions could be drawn.

- The maximum efficiency at depressurization was 96.69% and the maximum efficiency at depressurization was 95.57% when the maximum efficiency was 95% or more and the maximum efficiency was 93 [%] or more.
- The maximum efficiency at depressurization was 96.69% and the maximum efficiency at depressurization was 95.57% when the maximum efficiency was 95% or more and the maximum efficiency was 93 [%] or more.
- In the discrete type 4-phase interleave method, the maximum efficiency and the maximum efficiency were 95.29 [%] and 93.10[%], 95.29[%] and 92.23 [%] .

출력	효율
1kW	96.69%
2kW	95.43%
2.5kW	95.50%
3kW	95.57%

○In the resonance-type 3-phase interleaved method, the maximum efficiency and the maximum efficiency were 93.34 [%] and 92.28 [%] for the decompression, 88.40 [%] and 87.22[%] Respectively.

## References

- [1] Sejun Kim, Jiyong Yu, ChongahGwon, Hyungjoon Kim, Idle Stop & Go System Development for Automatic-Transmission Vehicle, The Korean Society Of Automotive Engineer, 2011.May:647-52 , Available from:<http://www.dbpia.co.kr/Article/NODE01755397>
- [2] Sung Chul Kim, Soo Youn Kim, Thermal Analysis and Design of an ISG Motor System for a Hybrid Electric Vehicle, The Society Of Air-Conditioning And Refrigerating Engineers Of Korea, 2015.Jun:1026-27 , Available from:<http://www.dbpia.co.kr/Article/NODE06365861>
- [3] Dae Geon Kim, Sung Chul Kim, An Analysis Study for Thermal Design of ISG (Integrated Starter & Generator) for Hybrid Electric Vehicle, Transaction of the Korean Society of Automotive Engineers, 21(4):2013.Jul;120-27, Available from:<http://www.dbpia.co.kr/Article/NODE02200423>
- [4] Jun-Sung Park, Min-Ho Kwon, Se-Wan Choi, Design and Control Strategy for Autonomous and Seamless Mode Transition of High Efficiency Bidirectional DC-DC Converter for ISG Systems, Transactions of Korean Institute of Power Electronics, 21(1): 2016. Feb;19-26 , Available from: <http://www.dbpia.co.kr/Article/NODE06612035>
- [5] Seungwoo Choi, Seoyun Han, taeho Park, Hyeongcheol Lee, A Study on the Validation Environment of the Control Algorithm for the ISG System, The Korean Society Of Automotive Engineers, 2014.May; 1224-32, Available from:<http://www.dbpia.co.kr/Article/NODE02432264>.
- [6] Seung-Ryong Kim, Han-Geol Sun, Man-Seung Han, Sung-Jun Park, Novel ZVS Switching Method of Full-bridge Converter, Transactions of Korean Institute of Power Electronics 16(5), pp. 477-483 , 2011.10, Available from:<http://www.dbpia.co.kr/Article/NODE01700347>
- [7] Sang-Hyeok Lee, Min-Ho Heo, Sung-Jun Park, Feel-Soon Kang, Su-Eog Cho, A Low-Cost ZCS Switched DC/DC Converter Employing Bidirectional Energy Flows, Power Electronics Annual Conference, 2009.Jul;402-404, Available from:<http://www.dbpia.co.kr/Article/NODE01246851>
- [8] Young-Ju Kim, Jung-Goo Hwang, Sun-Pil Kim, Sung-Jun Park, Sung-geun Song, Isolated Step-up DC/DC Converter applied Soft-switching Method, Journal of the Korean Institute of Illuminating and Electrical Installation Engineers ,29(7): 2015.7;87-94, Available from: <http://www.dbpia.co.kr/Article/NODE06387665>
- [9] Nak-Yoon Kim, Hyun-Chil Choi, A New High Efficiency Interleaved Buck Converter with Soft-switching Scheme, The Transactions of Korean Institute of Power Electronics, 19(2): 2014. Apr; 116-23, Available from:<http://www.dbpia.co.kr/Article/NODE02391464>
- [10] E. C. Lee and H. C. Choi, A Zero-Current-Transition Synchronous Buck Converter Using Auxiliary Circuit with Soft-Switching, Transactions of Korean Institute of Power Electronics , 18(4):2013, Aug ; 359-366,.
- [11] Sung-Geun Song, Sung-Jun Park, Dae-Kyong Kim, Duck-Shick Shin, High Efficiency DC/DC Converter for Neighborhood Electric Vehicle, Power Electronics Annual Conference, 2009.Jul;693-95, Available from:<http://www.dbpia.co.kr/Article/NODE01246957>
- [12] I.A. Khan, DC-to-DC Converters for Electric and Hybrid Vehicles, Power Electronics in Transportation, 20(22):1994, Oct; 113-22.