High Efficiency Isolated AC/DC Converter with Gradationally Controlled Voltage Inverter for On-board Charger

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We have developed a new isolated AC/DC converter for electric vehicle on-board chargers. It consists of an AC/DC converter with Gradationally Controlled Voltage Inverter (GCVI AC/DC converter) and an isolated Zero-Voltage-Switching (ZVS) DC/DC converter, each of which is optimally controlled to convert in a highly efficient means. As a result, the new on-board charger has achieved a power conversion efficiency of over 94%.

1. Introduction

Generally, an Electric Vehicle (EV) is equipped with an on-board charger to charge its large-capacity battery from an Alternating Current (AC) power outlet. The rate of consumption of AC electric energy, which is defined as the ratio of the driving distance to the electric energy charged from the grid power, is one of a key factor for an EV; to improve it, the on-board charger is required higher efficiency of conversion. This paper describes technologies for improving the efficiency of the isolated AC/DC converter and the application examples to the on-board charger.

Figure 1 shows the converter configuration and technologies of the new on-board charger. The AC/DC converter circuit employs a Gradationally Controlled Voltage Inverter (GCVI) technology, which is based on our original multi-level inverter technology that can reduce both power loss and electromagnetic noise. While the GCVI has already been applied to the voltage sag compensator(1) and other inverter devices, we newly applied this technology to the converter circuit(2) and have developed a new on-board charger. The isolated DC/DC converter employs the Zero-Voltage-Switching (ZVS)(3), which is soft switching method with low switching loss. In addition, we have developed an optimized converter control technology(4) to achieve high efficiency of conversion in a wide range of input/output voltages.

2. Employed Technologies

2.1 GCVI AC/DC converter

2.1.1 Gradationally controlled voltage inverter (GCVI)

Figure 2 shows a schematic circuit diagram of the GCVI AC/DC converter. This circuit is configured with a general AC/DC step-up converter being connected to a GCVI circuit, which consists of series-connected inverter units. By controlling these inverter units so that A capacitor C2 has twice as much voltage as C1, e.g., 2V0 and V0, the output voltage of GCVI Vinv can have seven different values from -3V0 to +3V0 according to the combination of switching pattern. The GCVI can also selects charge/discharge of C1 to C2 voltage ratio to be two.

2.1.2 Operation principle of AC/DC converter

For the Power Factor Correction (PFC), the GCVI AC/DC converter controls the AC input current to be a sinusoidal wave in phase with the AC input voltage VAC. By controlling the GCVI so that the amplitude of Vinv in the Pulse Width Modulation (PWM) period equals V0, an input current ripple due to switching can be reduced and controllability of the input current is improved, which also enables the size of the PFC reactor to be reduced and the switching frequency to be lowered. In
addition, since the voltage required for the current control is distributed to each inverter unit, the switching voltage for the current control is lower than that of a general AC/DC step-up converter. As a result, the switching loss can be reduced, and the electromagnetic noise can be also suppressed.

Figure 3 shows the gate waveform of the switching devices Q1 and Q2 with the AC input voltage. During the ON period of Q1 and Q2, the GCVI controls AC current by outputting against the AC voltage V_ac, and C1, C2 are charged. While the OFF period of Q1 and Q2, the GCVI controls AC current by adding to V_ac, and C1, C2 are discharged. Therefore, by controlling the ON period (phase $\theta_1$) of Q1 and Q2, the voltages of C1 and C2 can be controlled. The switching voltages of Q1, Q2 is equal to the output voltage of the AC/DC converter V_link, but the switching frequency is just four times an AC period, so the switching losses of Q1, Q2 are very low.

![Fig. 3 Gate waveform of switching devices Q1, Q2 with AC input voltage](image)

As shown in Fig. 3, the GCVI AC/DC converter can control V_link at a lower voltage than the AC peak voltage, Vp. As a result, the GCVI AC/DC converter allows the use of an output device with a lower withstand voltage compared to the conventional converter, and the loss can also be reduced. While the GCVI AC/DC converter works stably, the charge and discharge energy of C1, C2 during one period of the AC input voltage are equal, and then the relationship between V_link and phase $\theta_1$ is given by the following equation:

$$V_{\text{link}} = V_p \cdot \frac{\pi}{4}\cos\theta_1$$

(1)

The lowest voltage is given at phase $\theta_1 = 0$, which gives “$V_{\text{link}} = V_p \cdot \frac{\pi}{4}$.”

### 2.2 Isolated ZVS DC/DC converter

Figure 4 shows the schematic diagram of the isolated ZVS DC/DC converter. It is based on a full-bridge isolated DC/DC converter circuit, resonant capacitors are connected to switching devices for ZVS in parallel, and a resonant reactor is connected to the high frequency transformer in series. While the period of freewheeling, the primary current flows through the loop between the switching devices and the transformer, and power is not transferred to secondary side, so the conduction losses increase. Thus, shortening the freewheeling period causes higher efficiency in the ZVS DC/DC converter.

![Fig. 4 Schematic diagram of the isolated ZVS DC/DC converter](image)

### 2.3 Optimized converter control

The optimized converter control is our original technology, which controls V_link as low as possible to reduce the power loss of the isolated ZVS DC/DC converter.

With this technology, the freewheeling period of the DC/DC converter is shortened and the conduction loss can be reduced. In addition, because of its low V_link, the resonance energy for the ZVS operation is reduced. Therefore, it expands the range of ZVS operation and enables the switching energy to be reduced. Furthermore, the GCVI AC/DC converter allows step-down operation and thus further expands the range of ZVS operation compared to the conventional AC/DC converter.

### 3. Performance

Figure 5 shows the external appearance and specifications of the newly developed on-board charger.

As shown in Fig. 6, the input/output waveforms of this on-board charger operated with a supply voltage of AC 200 V and battery voltage of DC 370 V. The input current is controlled well with a power factor of over 99%. In addition, as shown in Fig. 7, when operated at the maximum power with the battery voltage ranging from DC 200 to 370 V, the power conversion efficiency is over 92% and the maximum efficiency exceeds 94%.
4. Conclusion

We have developed a high-efficiency isolated AC/DC converter for on-board chargers, which employs our original Gradationally Controlled Voltage Inverter (GCVI) technology and optimized converter control technology. The newly developed on-board charger provides a high power conversion efficiency of over 92% over a wide voltage range and the maximum efficiency exceeds 94%.

The newly developed technologies are also applicable to other on-board chargers with different power ratings, as well as to other products consisting of an AC/DC converter and an isolated DC/DC converter.

References