

Optimal Filter Design for Electromagnetic Noise Reduction in Resonant Tank of LLC Converter

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High-voltage power-converter reliability in electric vehicles (EVs) is becoming increasingly important due to their rapid popularization. The DC-DC converter is a core component of the EV power system, supplying voltage from high-voltage battery sources. It significantly influences electrical efficiency and performance. EMI-related reliability issues between electronic devices are critical, as are safety concerns from high-capacity batteries. High-voltage DC-DC converters can adopt various topologies, among which the LLC resonant topology enables zero-voltage and zero-current switching to minimize losses in high-speed switching. This study analyzes EMI-conducted emission characteristics under ZVS and presents key factors for optimal noise-reduction design.

Keyword - DC-DC power converters, Electromagnetic compatibility, Zero voltage switching.

I. INTRODUCTION

In an electric vehicle, the high voltage power conversion system affects charging efficiency and requires performance and reliability verification to ensure stable driving. At this stage, EMI becomes a critical issue, as electronic devices in EVs continuously generate EMI during operation. This EMI can interfere with other electronic equipment both inside and outside the vehicle, potentially causing malfunctions or disruptions.

The DC-DC converter is one of the most commonly used power conversion systems in EVs and can be designed with various topologies. Recently, the LLC resonant topology has gained attention for its ability to achieve stable zero-voltage switching (ZVS) and zero-current switching (ZCS) in high-frequency switching environments. Therefore, this study designed and fabricated an LLC resonant DC-DC converter to analyze the characteristics of EMI-conducted emissions (CE) generated under ZVS conditions in power semiconductors. Furthermore, the study identified and proposed key factors for the optimal design of high-voltage DC-DC converters in EVs, with a focus on mitigating EMI noise.

II. LLC RESONANT DC-DC CONVERTER

The LLC resonant topology can be composed of the connection of an inductor and a capacitor, and can be divided into three elements: the primary side, the secondary side, and the Resonant Tank. The primary side consists of a switching network utilizing a full-bridge circuit; the middle comprises an LLC circuit and a high-frequency transformer; the secondary side comprises an electrically isolated rectifier.

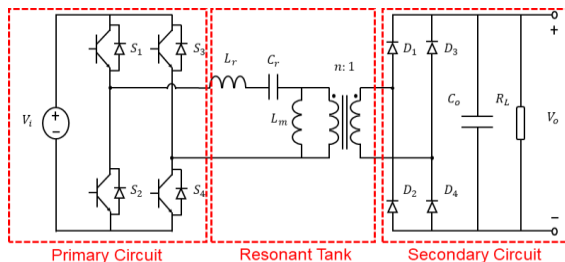


Fig. 1. Basic circuit model of an LLC resonant converter

The DC-DC converter controls power conversion through the switching operation of the power semiconductor, where conduction loss due to internal on-resistance components and switching loss due to on/off operations occur. In this case, the switching loss may be reduced by reducing the voltage and current overlapping sections using the ZVS and ZVC methods.

III. ANALYSIS OF EMI-CONDUCTED EMISSION NOISE ACCORDING TO ZVS

In this paper, an LLC resonant converter was designed and manufactured to analyze the change in EMI conduction emission noise when applying the aforementioned ZVS operation. The measurement was carried out according to the CISPR 25 standard, and two experiments were conducted: noise comparison according to the presence or absence of ZVS application under constant frequency operating conditions and noise comparison according to the presence or absence of ZVS application under constant output voltage conditions.

As a result of the experiment, it was confirmed that the noise in the mobile frequency band of 26 MHz to 54 MHz decreased when ZVS was applied under certain frequency operating conditions, as shown in Figure 2.

On the other hand, under constant output voltage conditions, the noise showed little change even with the application of ZVS.

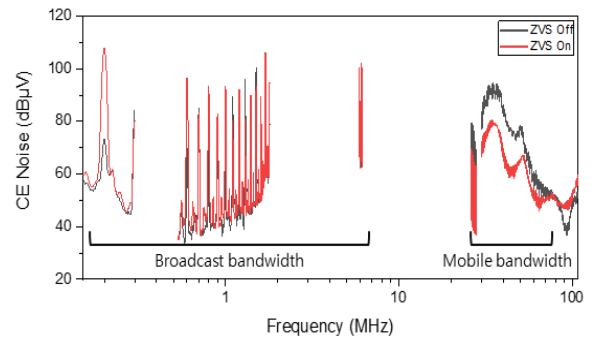


Fig. 2. CE noise with/without ZVS (constant frequency)

IV. OPTIMAL DESIGN OF THE LLC RESONANT CONVERTER FOR EMI CONDUCTED-NOISE REDUCTION

Two additional experiments were conducted to analyze the effects of frequency and filter capacitors as a design to reduce EMI conduction noise.

In the first experiment, EMI noise was measured by varying the operating frequency of the converter from 90 kHz to 120 kHz. The input and output voltage-gain characteristics of the LLC resonant converter vary around the resonant frequency. When the switching frequency of the converter is higher than the resonant frequency, the converter may operate in buck mode, reducing the output voltage. At this point, the output voltage decreases by approximately 5 V, which is sufficient to meet the power performance requirements of the electric vehicle. In buck mode, as the output voltage of the converter decreases, the ripple magnitude of the resonant current also decreases, resulting in an expected reduction in EMI noise.

The conducted emission noise was measured starting at 90 kHz and increasing the frequency in 10 kHz steps up to 120 kHz. As the operating frequency increased, the CE noise was observed to decrease, as shown in Figure 3.

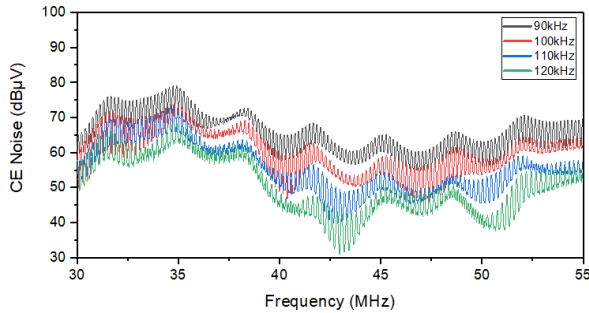


Fig. 3. CE noise by frequency change

In the second experiment, CE noise was analyzed based on the application of the filter capacitor. To examine the noise component in the mobile frequency band, where noise reduction was insufficient under constant voltage conditions, noise was measured by applying the capacitor to the converter in X-Cap and Y-Cap forms separately. The measurement results show that noise was further reduced when the Y-Cap was applied, as illustrated in Figure 4, indicating that the CM noise component is more significant in the mobile frequency band.

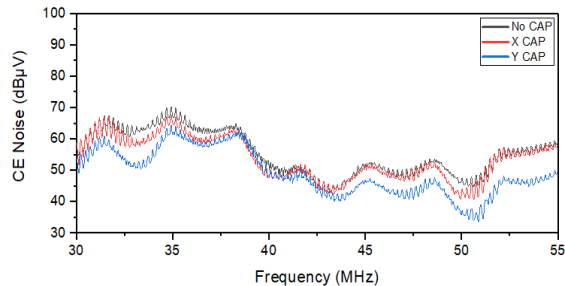


Fig. 4. CE noise by capacitor attachment

In addition, when the Y-Cap was installed, it was confirmed that the ripple magnitude of the resonant current did not change;

however, the harmonic component was significantly reduced. Furthermore, the voltage ringing component of the resonant inductor was also reduced, indicating that an EMI noise attenuation effect can be expected.

In the previous experiment, it was observed that applying ZVS under constant frequency conditions reduced noise in the mobile frequency band, whereas under constant output voltage conditions, no significant change in noise was observed. To address this, a 470 pF Y-Cap, with a resonant frequency corresponding to 35 MHz within the mobile frequency band, was installed and the noise was measured. As a result, it was observed that the noise in the mobile frequency band decreased by up to 55 dBμV, as shown in Figure 5.

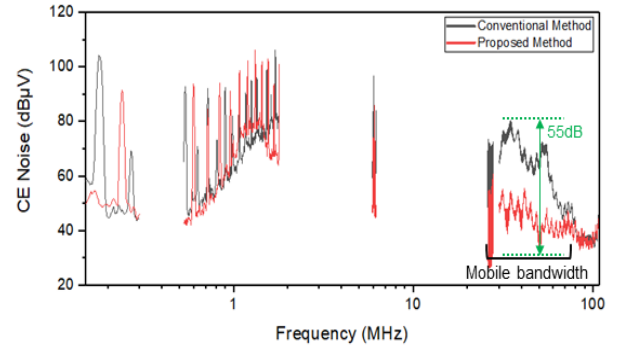


Fig. 5. CE noise of the conventional and proposed methods

The comparison results of the conducted emission noise measurement in Figure 5 show that noise exceeding the Class 3 criteria specified in the international standard document CISPR 25 was detected before the countermeasure design was applied. However, after applying the countermeasure, the noise was effectively reduced to meet the Class 3 criteria.

V. CONCLUSION

In this study, conducted EMI characteristics of LLC resonant converters for HV DC-DC applications were analyzed, and optimal design techniques were proposed to minimize EMI noise in the 26–54 MHz range. Increasing the converter's operating frequency under ZVS buck mode reduced current ripple-induced EMI noise. Additionally, incorporating a Y-Cap based on resonance tank capacitance effectively reduced CM noise.

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