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Ripple Compensation for LLC Resonant Converter with Spectrum Spread EMI Reduction

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Abstract. This paper describes a voltage ripple reduction method for the LLC current resonance converter. Conventionally, inserting a filter for input / output and covering the entire converter circuit with a shield has been used as an electromagnetic interference (EMI) reduction method. However, this approach has problems of large size and high cost. Noise spectrum spread techniques are widely used as an EMI reduction method to alleviate these problems. We investigated the spectrum spread technique for the LLC resonant converter as an EMI reduction method. The output voltage of the LLC resonant converter is controlled by the switching frequency, and therefore, the spectrum spread technique causes increase of the output voltage ripple. In this study, we examine the suppression of the voltage ripple increase, and our simulation shows that our method reduces the output voltage ripple from 95 mV to 15 mV, while keeping the same or better EMI noise reduction.

1. Introduction

In recent years, power consumption has been increasing more and more as electronic devices have become more functional and faster. Electromagnetic interference (EMI) is a serious problem of switching converter used for these devices. There are many regulations around the world for EMI noise [1-8]. Conventionally, EMI reduction methods such as using a filter and a shield have been used. However, these approaches have problems of large size and high cost. The spectrum spread technique is proposed as an EMI reduction method to solve these problems. The switching frequency modulation spreads the noise spectrum [4-8].

In the conventional capacitor input type switching converter where a large smoothing capacitor is connected to a diode bridge, the input current waveform is distorted significantly and the power factor decreases. The power factor reduction becomes a cause of harmonic current, while its related regulation is now increasingly stringent. One approach for the power factor improvement is the employment of the power factor correction (PFC) circuit. A PFC circuit configured with a boost converter and a switching converter used in the subsequent stage can have a high step-down ratio. The LLC resonant converter is one of the configurations which has a high step-down ratio. Previously, we proposed to apply a spectrum spread technique to the LLC resonant converter. However, there its output voltage is controlled by the switching frequency and hence the spectrum spread technique causes the output voltage ripple increase [9]. Hence in this study, we investigate a compensation method for the voltage ripple increase.

2. LLC Resonant Converter with Spectrum Spread EMI Reduction

2.1 Conventional LLC Resonant Converter

Figure 1 shows the basic configuration of the LLC resonance converter. The circuit consists of two MOSFETs connected in series (Q_1, Q_2), a resonance capacitor C_R, a transformer, a diode bridge and a smoothing capacitor C. On the primary side of the transformer, the resonance capacitor C_R and the primary winding of the transformer are connected in series between the connection points of MOSFETs (Q_1, Q_2) and GND [10, 11]. A full-wave rectifier circuit realized by the diode bridge is connected to the secondary side of the transformer. A smoothing capacitor C and a load R_{Load} are connected to the subsequent stage of the diode bridge. The transformer with a small coupling coefficient is used in the LLC resonant converter. The leakage inductance of transformer is used as the resonance inductor L_R. Since this method causes relatively large ripple, the smoothing capacitor C with an element value of several mF is often used. "LLC" is named after a resonance circuit consisting of two inductors and one capacitor: a resonance inductance L_R, an excitation inductance L_M and a resonance capacitor C_R.

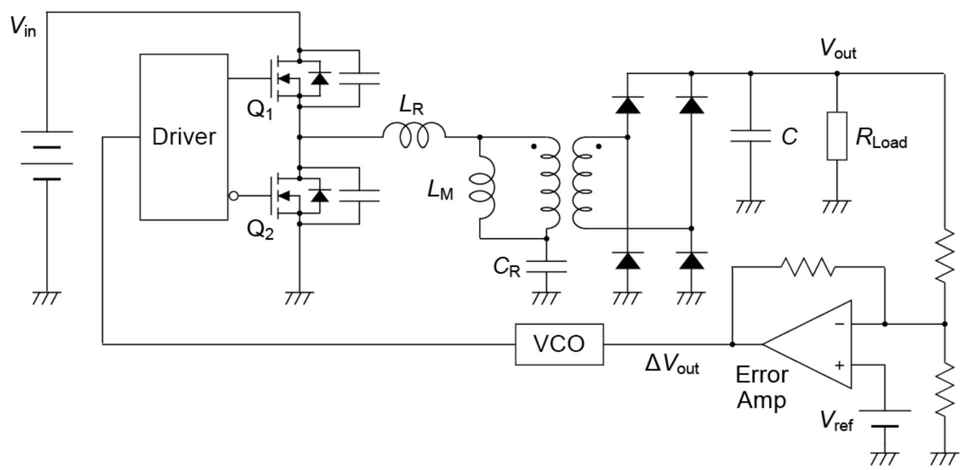
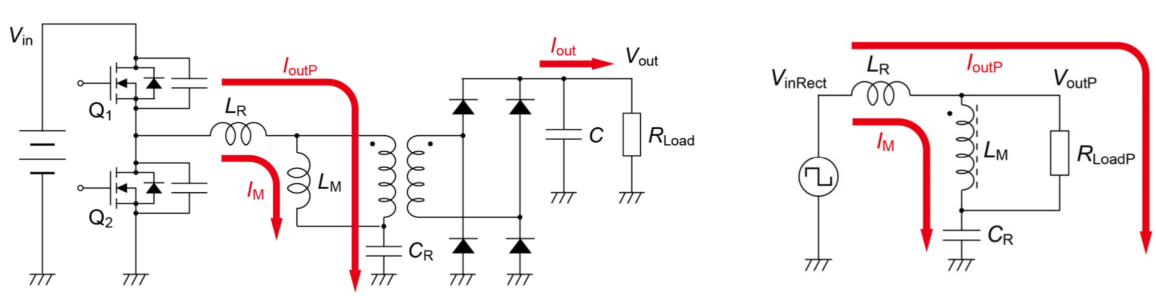


Fig. 1. Basic configuration of the LLC resonant converter.

The operating principle of the LLC resonance converter is now explained. Figure 2 (a) shows the path of the current flow through the LLC resonant converter. Figure 2 (b) is its equivalent circuit in which the load resistor R_{Load} is converted to the primary side shown as R_{LoadP}. There are two current paths in the LLC resonant converter. One is I_M flowing through the exciting inductance L_M, and the other is I_{outP}. Then the output current I_{out} is converted to the primary side.



(a) Basic circuit (b) Equivalent circuit

Fig. 2. Current flowing through the LLC resonant Converter.

The resonant frequency of the LLC resonant converter varies between the resonant frequency f_{RL} when R_{LoadP} is unloaded and the resonant frequency f_{RH} when R_{LoadP} is shorted. Since the resonance frequency f_{RL} in the case of unloading is resonance by L_R, L_M and C_R, it is given by the following [10, 11]:

$$f_{\mathrm{RL}} = \frac{1}{2\pi\sqrt{(L_{\mathrm{R}} + L_{\mathrm{M}})C_{\mathrm{R}}}} \tag{1}$$

The resonance frequency f_{RH} in the case of the short-circuit load is provided by the resonance by L_R and C_R since L_M is shorted by R_{LoadP}.

$$f_{\mathrm{RH}} = \frac{1}{2\pi\sqrt{L_{\mathrm{R}} C_{\mathrm{R}}}} \tag{2}$$

Figure 3 shows the frequency characteristics of the voltage gain G_P with R_{LoadAC}, which is obtained by converting the load resistance R_{Load} to the primary side. The resonance frequency varies from the resonance frequency f_{RL} for unloading to the resonance frequency f_{RH} for shorted load according to the change in R_{LoadAC}. The output voltage is controlled by switching frequency f_{SW} with various voltage gain G_P. Duty ratio of the switching pulse is fixed to 50%. Here the switching frequency f_{SW} is used the this range from the unload resonance frequency f_{RL} to the short-circuited load resonance frequency f_{RH}. In this range, the change direction of the voltage gain is constant with respect to change in the switching frequency, and circuit design is easy.

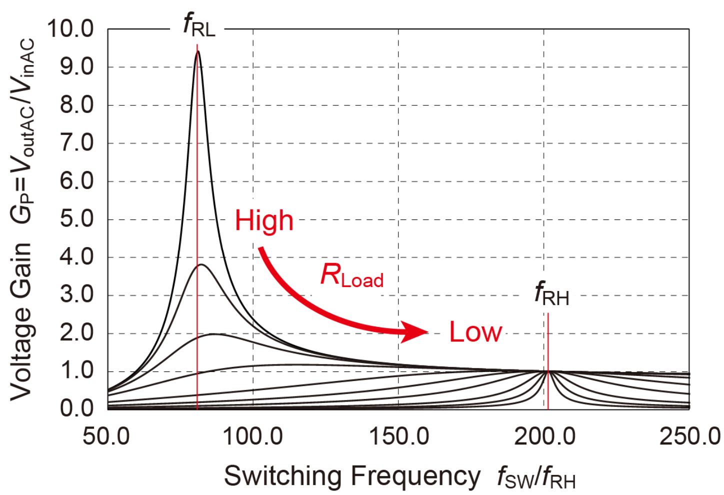


Fig. 3. Frequency characteristics of the voltage gain G_P.

2.2 LLC Resonant Converter with Noise Spectrum Spread

Conventional LLC resonant converter is controlled by frequency of the switching pulse that drives MOSFETs Q_1 and Q_2. In the steady state, the switching frequency is kept constant and EMI noise at specific frequency is caused by the switching. The LLC resonant converter has the characteristic of small EMI noise as compared to other switching converter methods. However, further EMI noise reduction is required for strict regulations.

In this study, the spectrum spreading technique is used as an EMI noise reduction method for the LLC resonant converter. This method is for frequency controlled switching converter. An error signal is fed-back to the control voltage input of the voltage controlled oscillator (VCO) for generating the switching pulse. Spectrum spreading is realized by modulating the switching pulse that is generated by an error signal with a low-frequency triangular wave.

Simulation verification is carried out with the circuit where the VCO is composed of a saw-tooth wave generation circuit using a relaxation oscillator and the current source controlled by a control signal. Figure 4 shows the VCO circuit with the frequency modulation by the triangular wave. The VCO consists of a reset switch S, a capacitor C, two current sources I_1 and I_2, a comparator and a reference voltage V_{ref}. The current source I_1 generates the current proportional to the output voltage error, and the current source I_2 generates the current proportional to the modulation signal. When switch S is turned off from on, the capacitor C is charged by the currents generated by two current sources. The capacitor voltage V_C and the reference voltage V_{ref} are compared by the comparator and the switch S is turned on when V_C becomes larger than V_{ref}. There the amplitude of the saw-tooth wave becomes V_{ref} and the frequency f is expressed by the following equation:

$$f = \frac{1}{CV_{\mathrm{ref}}}(I_1 + I_2) \tag{3}$$

We see from Eq. (3) the output frequency f of the VCO is proportional to the current sources I_1 and I_2.

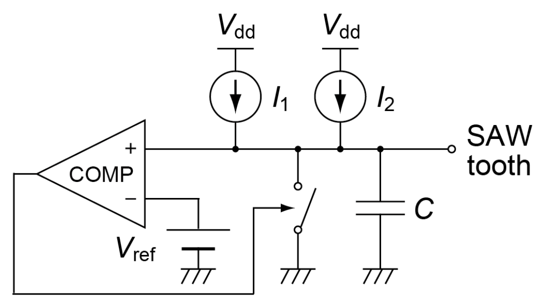


Fig. 4. Saw-tooth wave generator with frequency modulation.

3. Ripple Compensation Method

Since the LLC resonant converter is controlled by the switching frequency, the output voltage ripple is caused by the noise spectrum spread technique. In this study, we propose a compensation circuit that suppresses the voltage ripple by the spectrum spread. As mentioned in Section 1.1, the output voltage of the LLC resonant converter is controlled by the switching frequency f_{sw}, and this time the duty ratio of the switching pulse is fixed to 50%. The amplitude A_1 in the fundamental frequency of the rectangular wave is changed according to the following equation of amplitude A, frequency f and variable duty ratio D.

$$A_1 = \frac{2A}{\pi}\sin(\pi D)\cos(2\pi f - \pi D) \tag{4}$$

Figure 5 shows amplitude in the fundamental frequency of the rectangular wave when changing duty ratio. The amplitude of the fundamental wave component of the rectangular wave becomes maximum when the duty ratio is 50%, it decreases when the duty ratio is deviated from 50%.

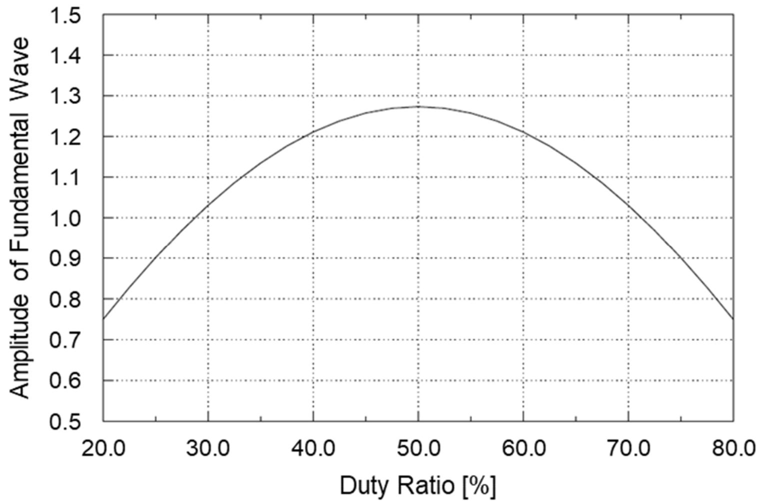


Fig. 5. Fundamental wave of switching pulse vs duty ratio.

The resonance voltage applied to the primary side of the transformer has a waveform close to a sine wave with the same frequency as the switching frequency. As a result, the output voltage of the LLC resonant converter is changed by the duty ratio (Fig. 6).

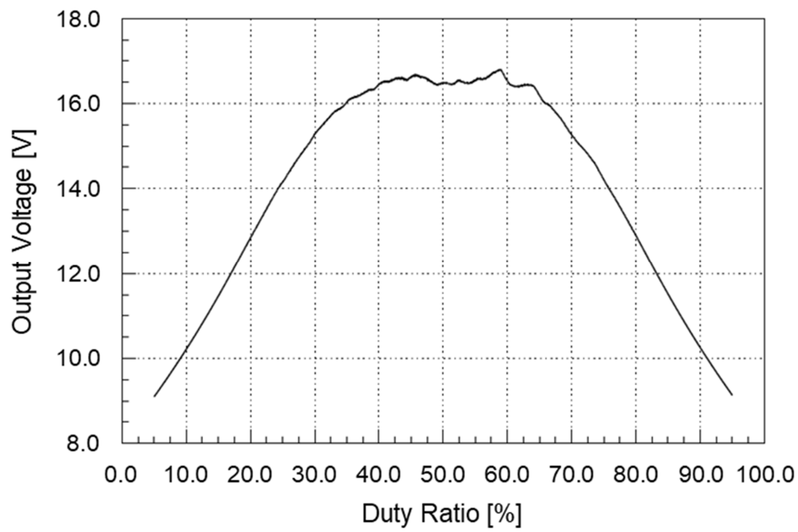


Fig. 6. Output voltage vs duty ratio.

The graph shape is symmetrical with respect to 50% duty ratio that is almost the same as the fundamental amplitude shown in Fig. 5. More precisely, it shows M-shaped characteristics; that is, the output voltage drops when the duty ratio is 40% to 50%.

The procedure of this proposal is as follows: first, duty ratio is set to 30% in the steady state. Second, the switching frequency is modulated in the negative direction from the steady state. At the same time, the duty ratio is reduced from 30%. In other words, the voltage rise due to the decrease in the switching frequency is offset by the voltage drop due to the decrease in the duty ratio, and the output voltage is kept to a constant value. A duty ratio modulation signal is generated based on the switching frequency modulation signal with the aim of compensating for the output voltage to the target value. An equation for realizing this is obtained from the relationship between the switching frequency and the duty ratio where the output voltage is kept to the target value. The current waveform of the LLC resonant converter is close to a sine wave. However, it is difficult to analyze the actual operation. Therefore, the relationship between the switching frequency and the duty ratio is obtained by simulation where the load is fixed and the LLC resonant converter operates at the steady state. Their relationship is expressed by a polynomial approximation. The compensation circuit generates the switching pulse so that the duty ratio follows their relationship.

4. Simulation results

4.1 LLC Resonant Converter with EMI reduction

Characteristics of the proposed LLC resonant converter with EMI reduction by spectrum spread was verified by simulation using the LTspice. Table 1 shows the simulation conditions. The frequency modulation signal input to the VCO is a triangular wave with an amplitude of 0 V to -1 V and a frequency of 20 Hz. The modulation sensitivity of the VCO is set to 10 kHz / V.

Table 1. Simulation conditions.

Input voltage V_{in}	100.0 V DC
Output voltage V_{out}	12.0 V
Excitation inductance L_M	198.0 μH
Resonance inductance L_R	22.0 μH
Resonance capacitance C_R	68.0 nF
Transformer turns ratio	9.89 : 1
Load R_{Load}	24.0 Ω

Simulation results with and without the noise spectrum spreading are shown in Figs. 7 and 8. Figure 7 shows the switching noise spectrum, while figure 8 shows the switching frequency and the output voltage.

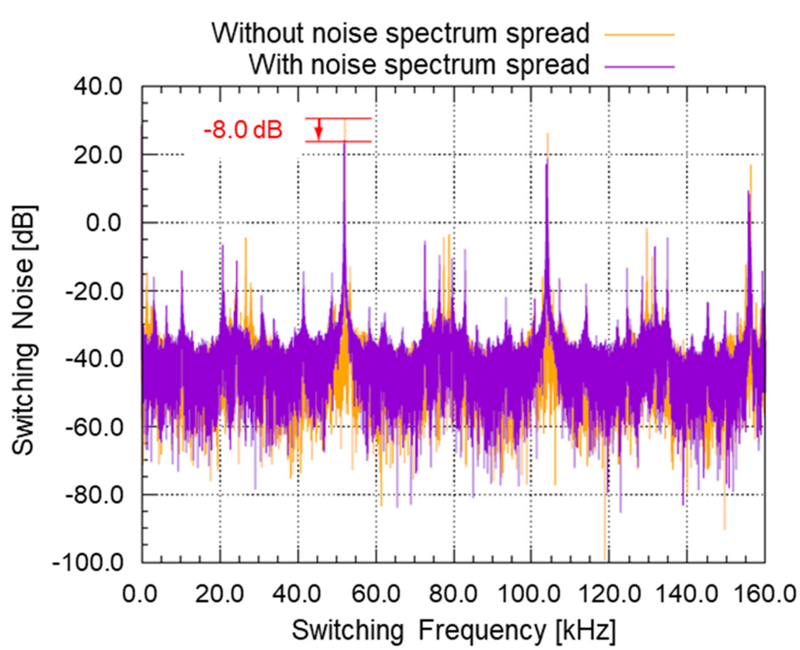


Fig. 7. Switching noise spectrum.

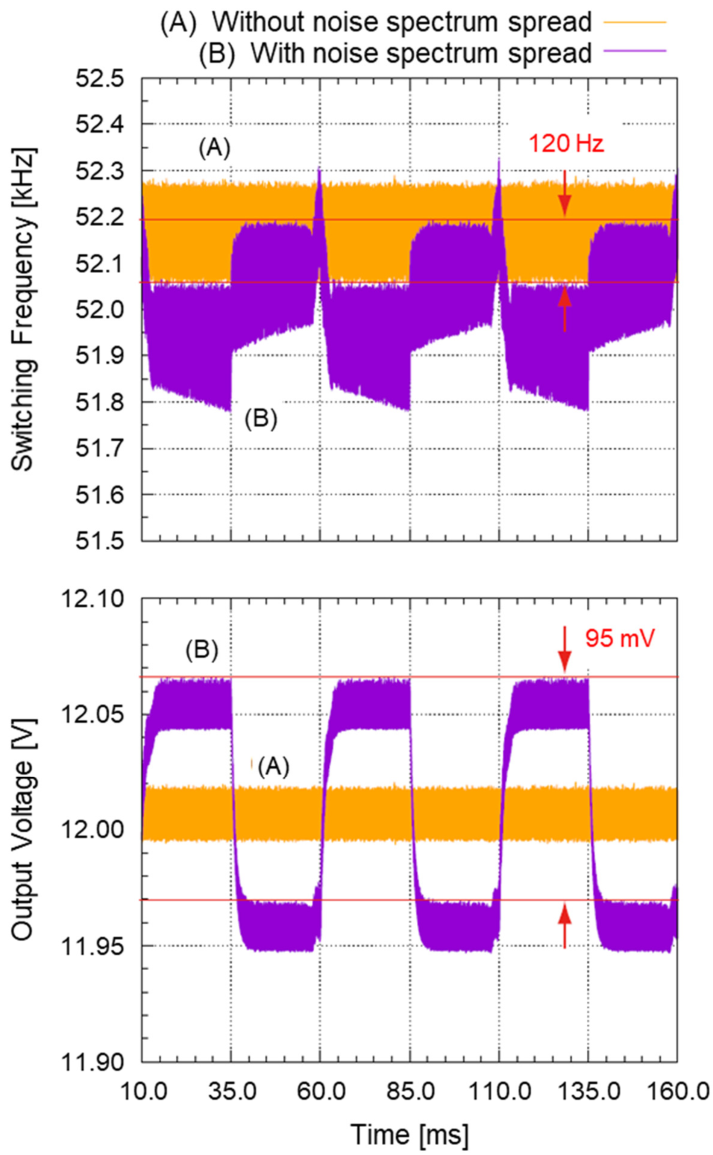


Fig. 8. Switching frequency transition and output voltage waveform.

We see from Fig. 7, that the peak value of switching noise was reduced by about 8 dB by applying spectrum spreading, and a noise reduction effect was obtained.

As shown in Fig. 8, the switching frequency changes by about 120 Hz due to spectrum spreading. As mentioned above, the amplitude of the modulation signal is 1 V, and the modulation sensitivity is 10 kHz / V, therefore the modulation efficiency is about 1.2%. 95 mV modulation ripple is occurred due to spectrum spread; it can reduce a noise but generate a large modulation ripple. In addition, in the control loop of the LLC resonant converter, the modulation of the switching frequency works as a disturbance. Since the disturbance is removed by the feed-back loop, the effect of modulation of the switching frequency becomes very small. The spread spectrum effect confirmed in this simulation is considered that the modulated signal that cannot be removed by the feedback loop and remains. The remaining modulated signal is also the main cause of modulated ripple.

4.2 Ripple Compensation with EMI Reduction LLC Resonant Converter

The characteristics of the circuit in which the voltage ripple suppression method proposed in Section 3 was added to the simulation circuit in Section 4.1 were verified by simulation. The element values of the power stage section are the same as the simulation circuit carried out in section 5.1. The parameters are as follows: The modulation signal is a triangular wave with an amplitude of 1 V and a frequency of 20 Hz, the modulation sensitivity is 2 kHz / V. The duty characteristic formula in this simulation circuit is obtained from our preliminary simulation:

$$0.355 \times \left(\frac{f_{SW}}{1000}\right)^2 - 31.8487 \times \left(\frac{f_{SW}}{1000}\right) + 722.5697\ [\%] \tag{5}$$

We performed preliminary simulations without the spectrum spreading using the duty ratio as a parameter. The switching frequency at the steady state is changed depending on the set value of the duty ratio. The duty characteristic formula uses an approximation curve of the switching frequency-to-duty ratio characteristics.

Figures 9 and 10 show the simulation results of the circuit with the voltage ripple suppression method added. For comparison, the simulation results without the voltage ripple suppression method and the results without noise spread spectrum, which were discussed in Figs. 7 and 8, are also shown.

Figure 9 shows the switching noise spectrum, Fig. 10 shows the switching frequency and output voltage, respectively.

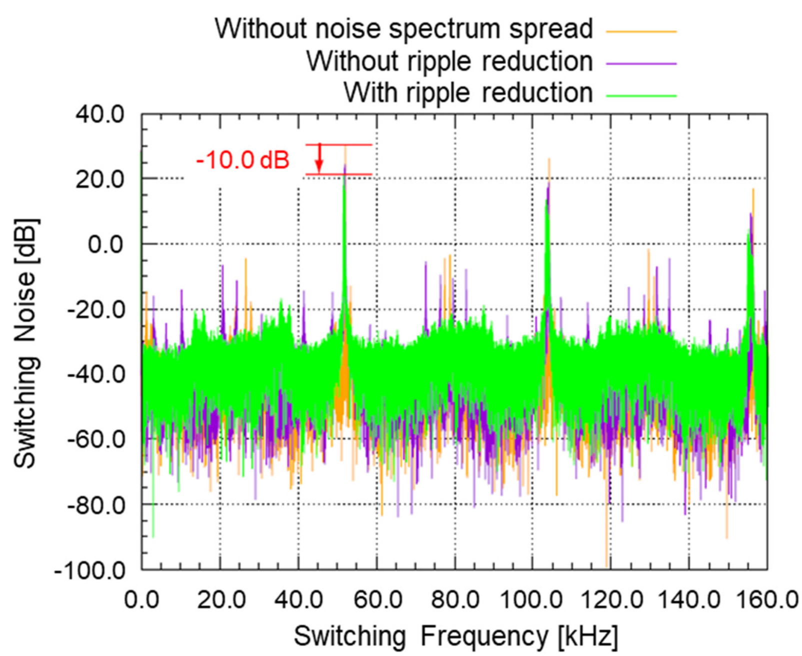


Fig. 9. Switching noise spectrum.

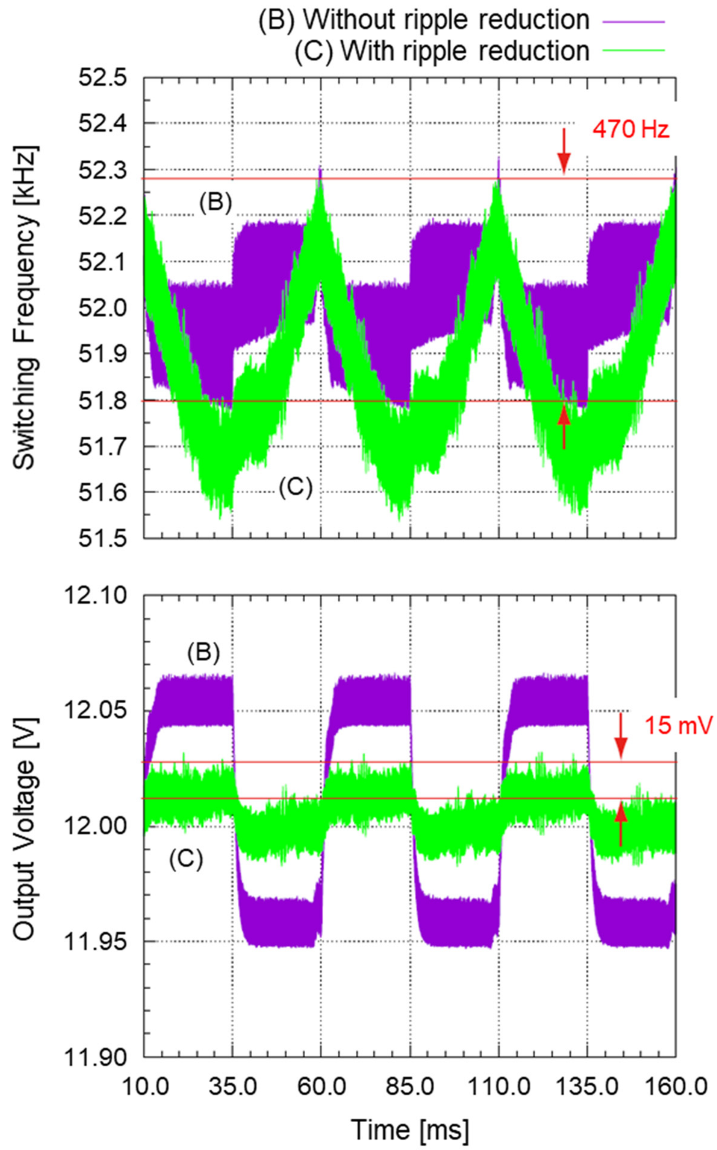


Fig. 10. Switching frequency transition and output voltage waveform.

According to Fig. 9, the switching frequency changed by 470 Hz. It increased 3.9 times by applying the ripple reduction method. According to Fig. 10, the output voltage ripple was 15 mV, which was reduced by 84% by the proposed method. The modulation sensitivity before ripple reduction was 10 kHz / V, and the modulation efficiency increased 19.6 times. According to Fig. 9, the peak value of switching noise with ripple reduction is reduced by 10 dB from that without spread spectrum. That is, it was confirmed that the output voltage ripple was suppressed while maintaining the noise reduction effect.

5. Conclusion

In this paper a compensating method for the output voltage ripple increase in the LLC resonant converter with the EMI noise reduction by a spectrum spread technique has been investigated. There, a low frequency signal of several dozens of Hz is superimposed on the input of the VCO to modulate the switching frequency in order to spread the noise spectrum. It was confirmed that the peak value of switching noise was reduced by about 8 dB; however, a large modulation ripple is generated, and in the control loop, the modulation of the switching frequency is treated as a disturbance. Then we propose a modulation ripple suppression method caused by the spectrum spread. The modulation ripple reduction was realized by changing the duty ratio (which was fixed to 50% in conventional LLC resonant converter, though); changing the duty ratio changes the output voltage. The simulation verifications were carried out with the following three cases; without the spectrum spread method, with only the spectrum spread method, with the modulated ripple reduction method. The modulated ripple reduction method reduces 85% of the output voltage ripple while keeping EMI noise reduction.

Since it is difficult to analyze the actual operation of the LLC resonant converter, we use simulation to obtain the relationship between the switching frequency and the duty ratio. As the next step, we will study the theoretical analysis for the operation in the case of the duty ratio change and modulation ripple reduction.

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