Ripple Compensation for LLC Resonant Converter with Spectrum Spread EMI Reduction

Shogo Katayama, Yasunori Kobori,
Anna Kuwana, Haruo Kobayashi
Division of Electronics and Informatics, Gunma University
E-mail: t15304906@gunma-u.ac.jp

Outline

1. Research Background
2. EMI Reduction Method for LLC Resonant Converter
3. Modulation Ripple Reduction Method
4. Simulation Verification
5. Conclusion

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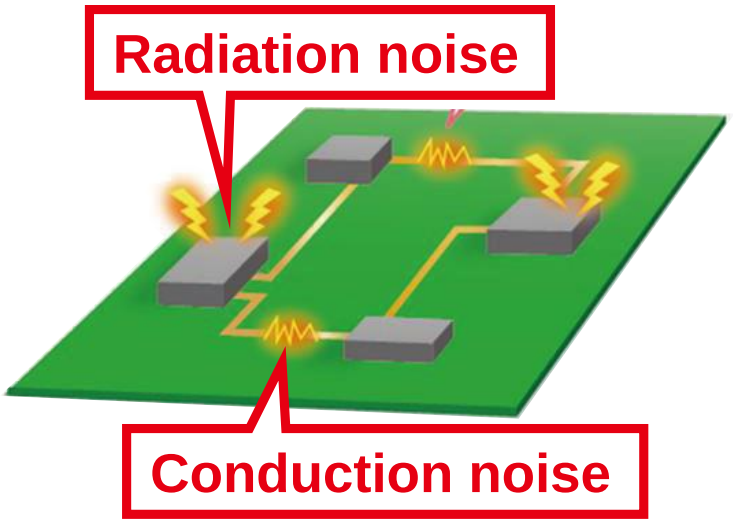
Research Background



EMI: Electro-Magnetic Interference

Output current: Increase
Switching frequency: Increase

EMI noise occur
at switching circuit

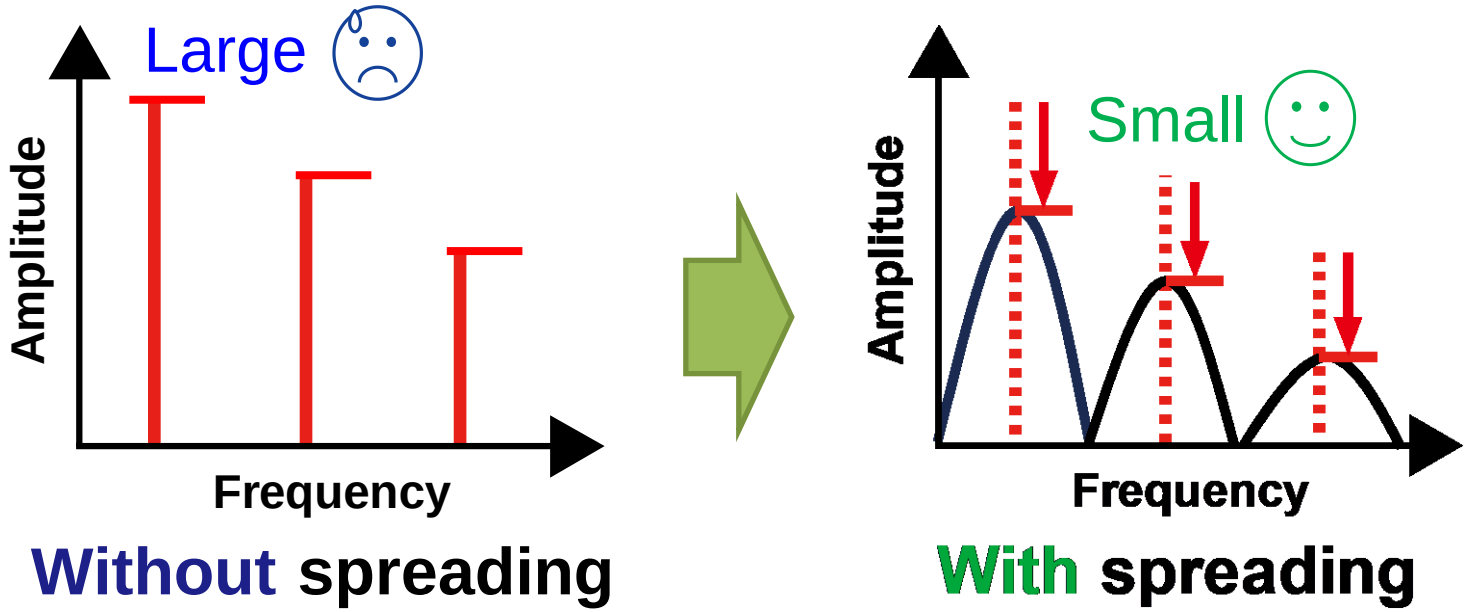
Conventional EMI noise reduction

Analog filter
Shield case

Large scale circuit
High cost

EMI Reduction by Spectrum Spreading

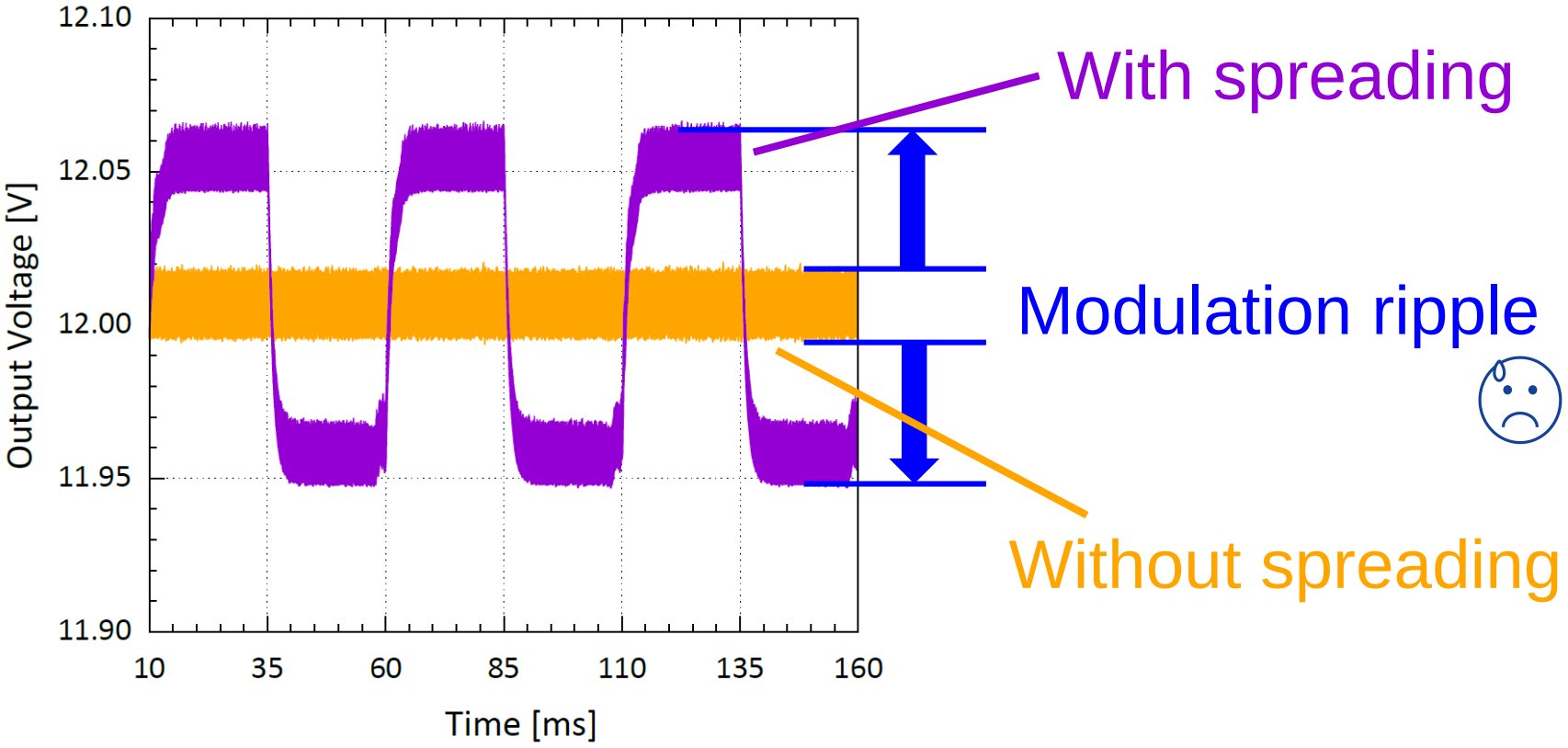
EMI reduction method in this work
Noise spectrum spreading



Modulating switching frequency

Noise spectrum peak ⇨ Decrease

Problem of Spectrum Spreading



Modulating switching frequency

Output voltage ripple ➡ Increase

Proposing ripple reduction

Research Overview

Conventional

Noise reduction method:
Spectrum spreading

Conventional

Switching converter method:
LLC resonant converter

Spectrum spreading
LLC resonant converter

Our proposal

Reduction
Output voltage ripple

Duty compensation

Our proposal

Spectrum spreading
LLC resonant converter
with duty compensation

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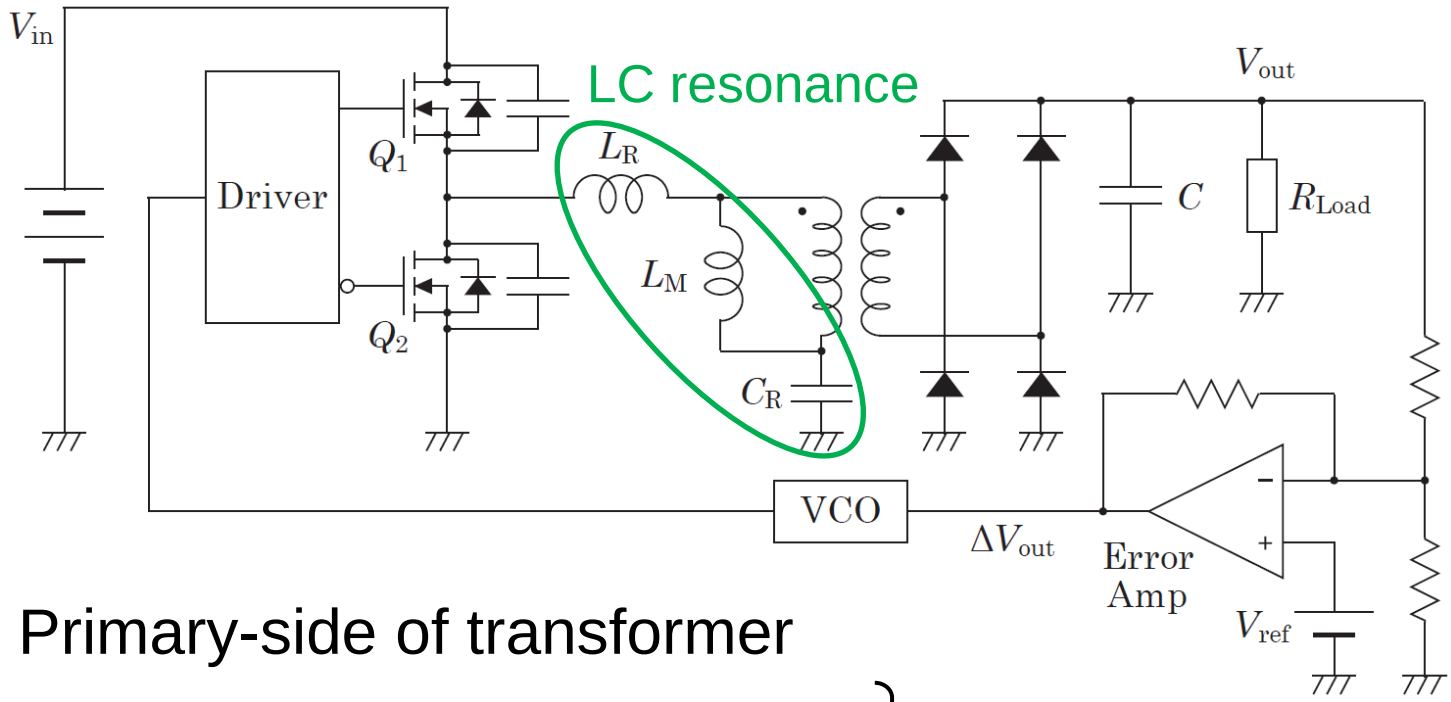
Configuration of LLC Resonant Converter



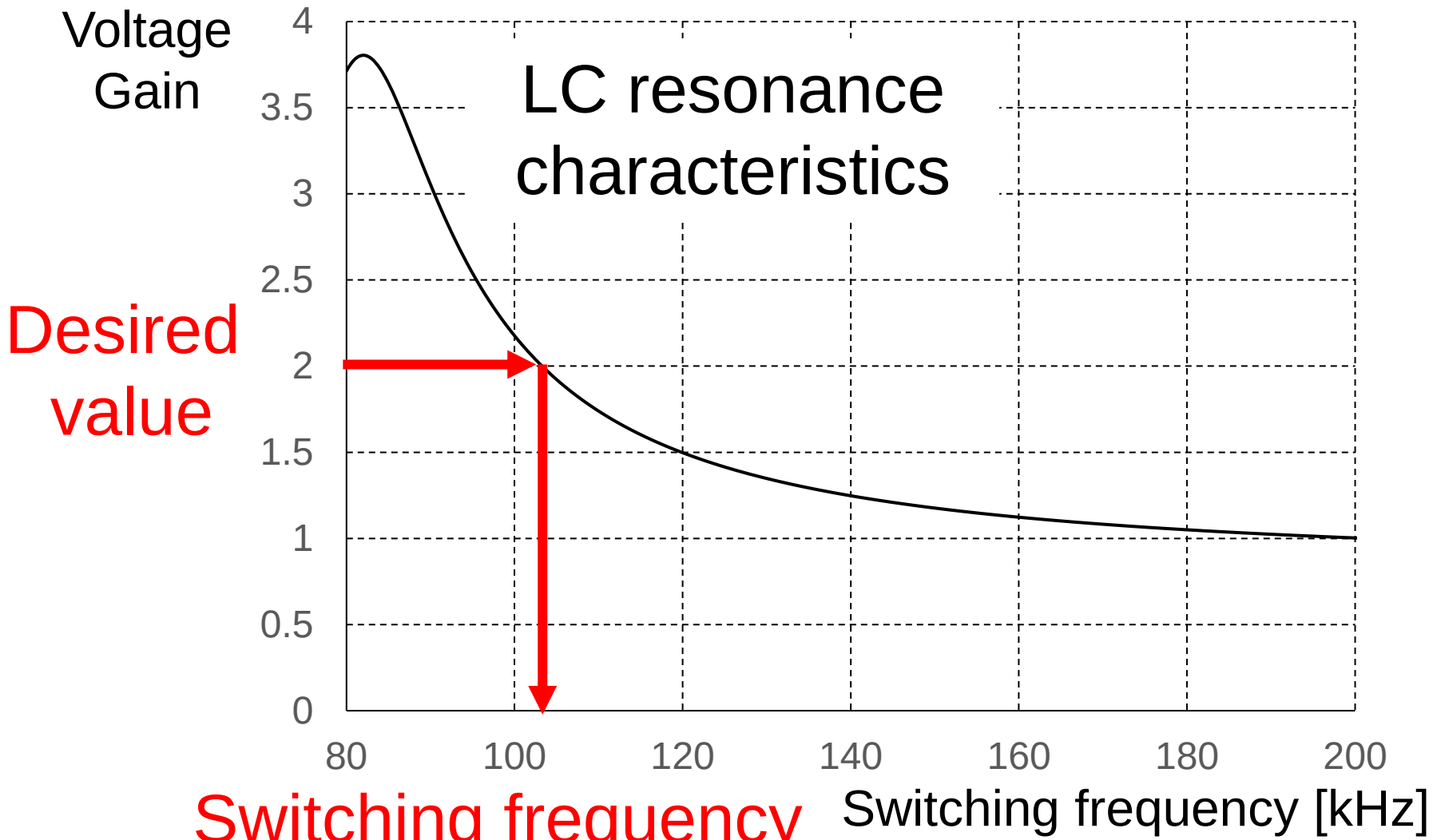
Primary-side of transformer

Resonance inductance L_R
Excitation inductance L_M
Resonance capacitor C_R
} LC resonance

Current waveform: Similar to sine wave ➡ EMI noise: Small

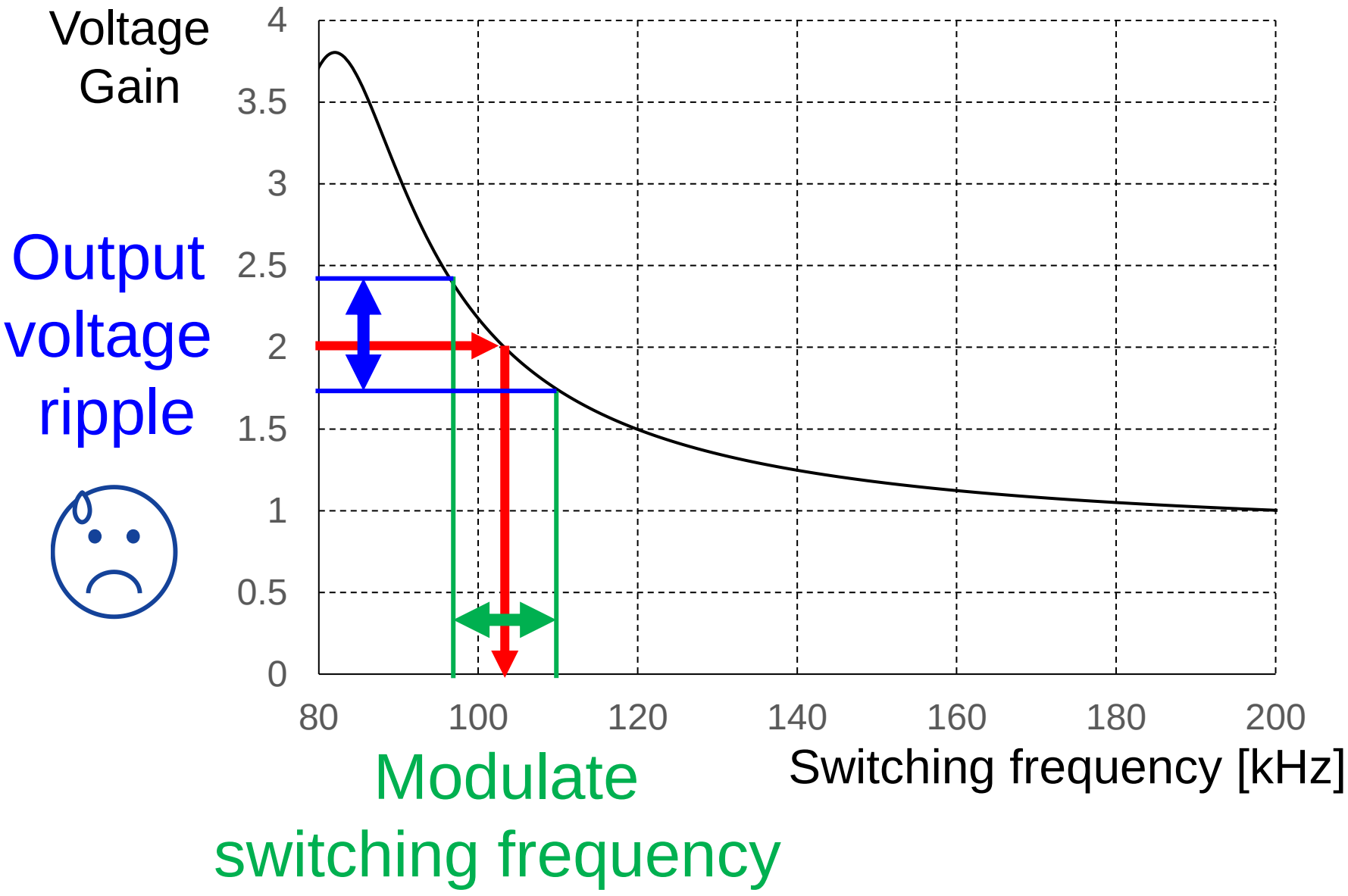
Further EMI noise reduction with spectrum spreading

Voltage Gain of LLC Resonant Converter



Switching frequency control value: Constant

Output Voltage Ripple Occur by Spectrum Spreading



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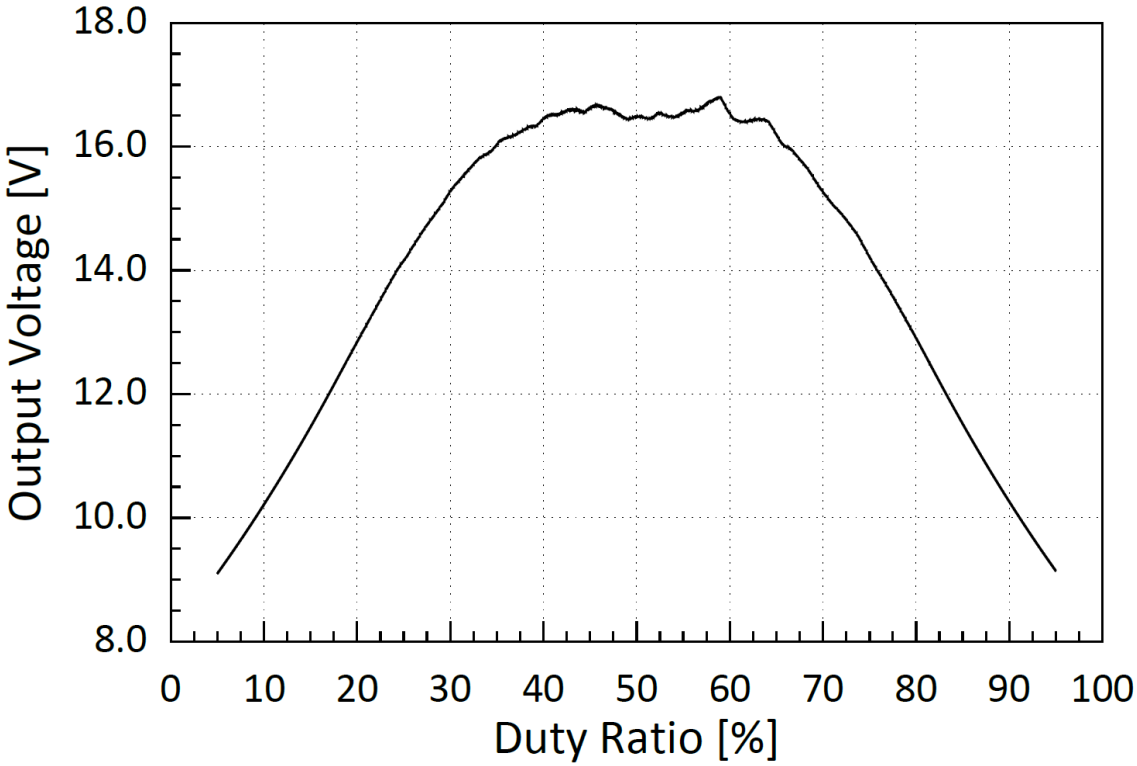
Voltage Ripple Reduction Method

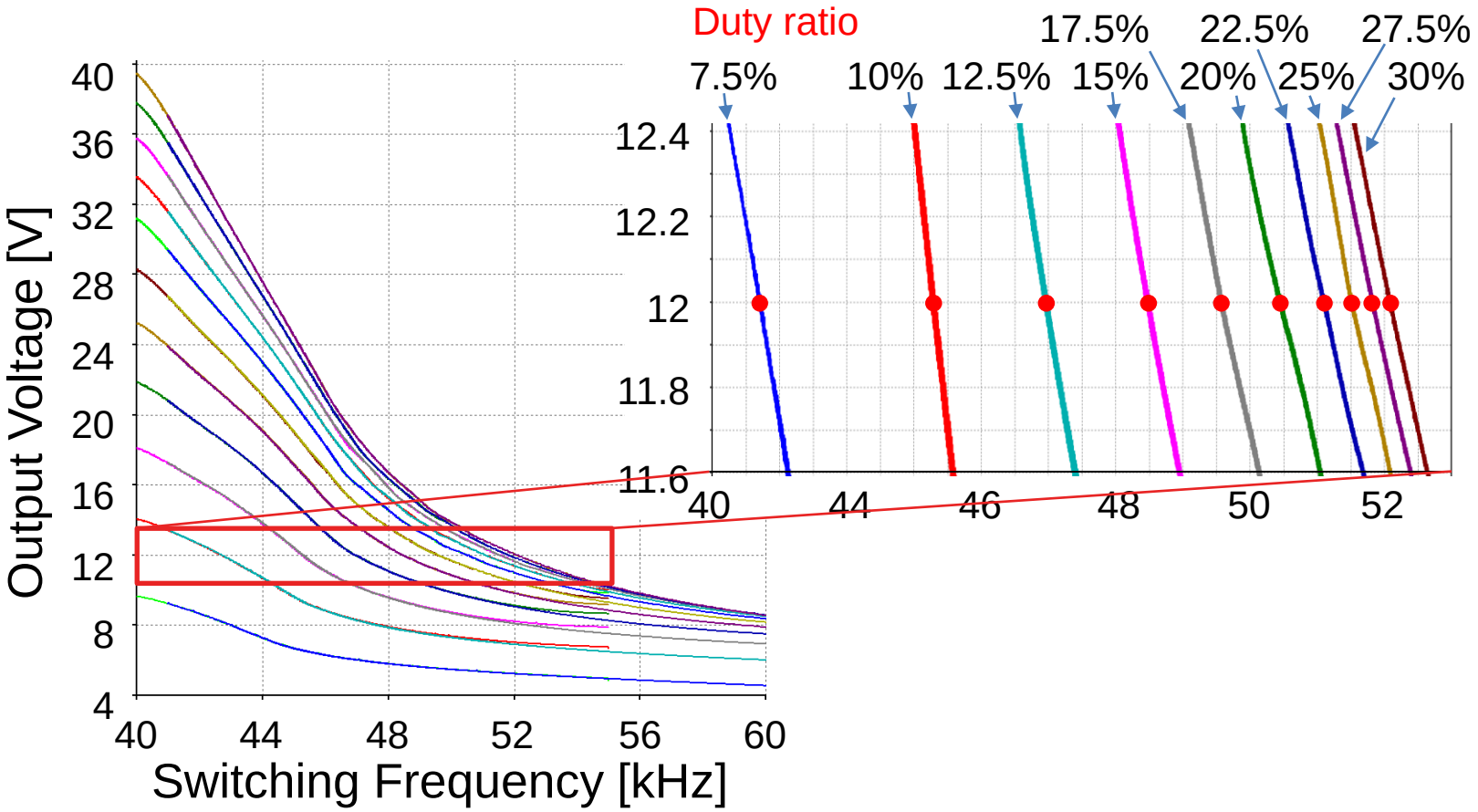


Changes duty ratio

Changed output voltage: Symmetrical 50%

Duty ratio change follows frequency modulation

Obtain Duty Compensating Equation



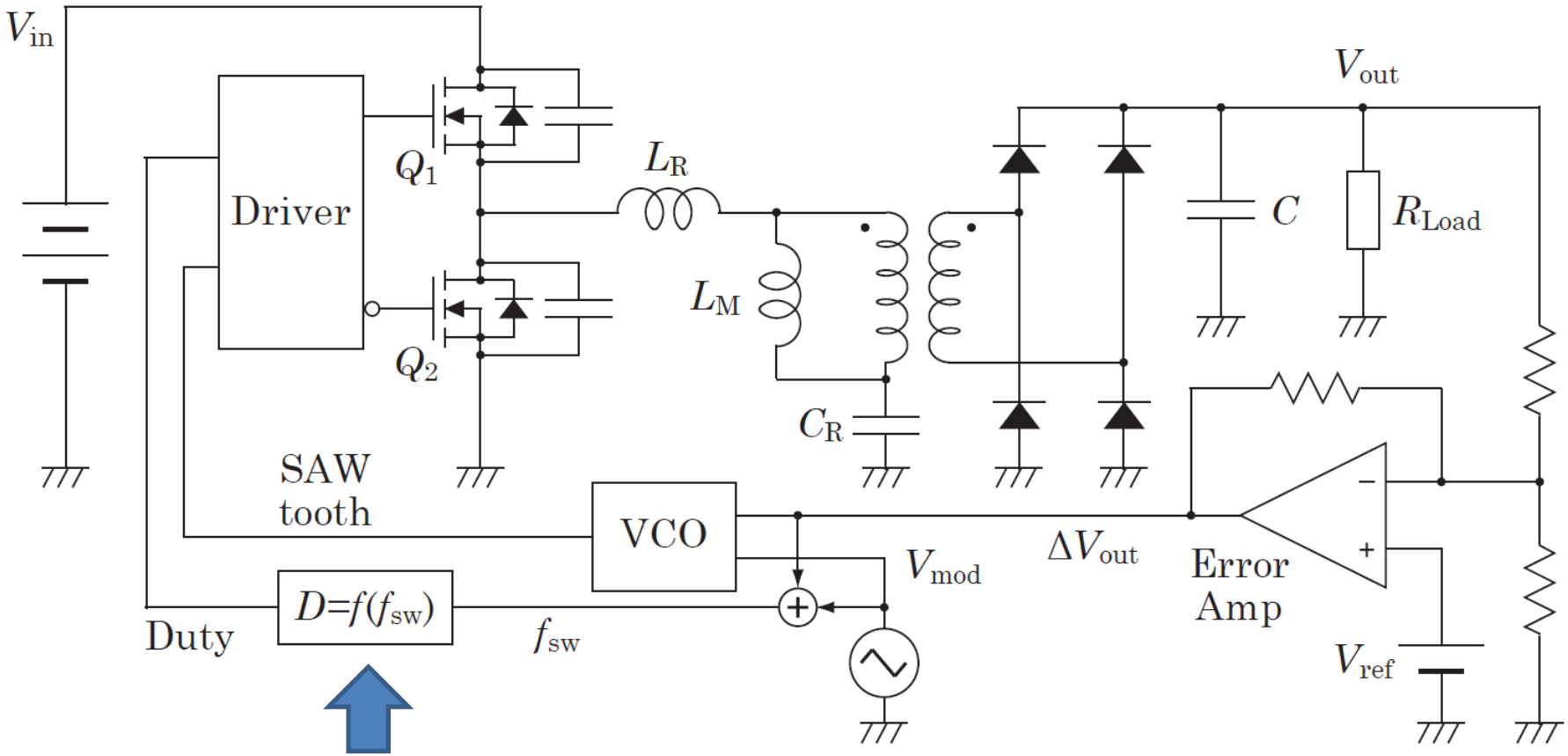
Simulation: Duty ratio ➡ Parameters

SW Frequency: Output voltage ➡ Constant

⬇

Duty ratio characteristic formula

Spectrum Spread LLC Converter with Duty Ratio Compensation



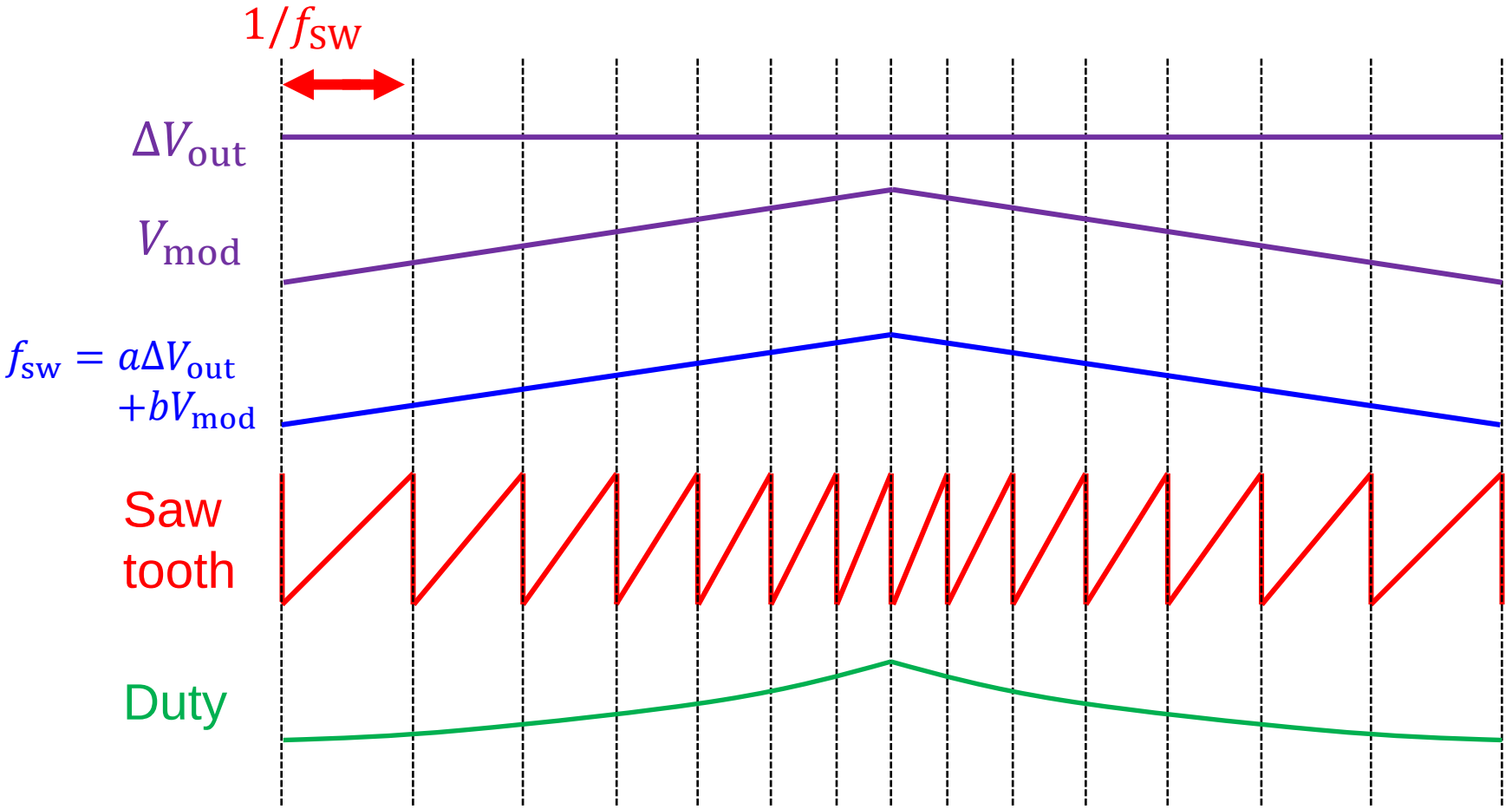
Duty ratio compensation formula

$$D = 0.355 \times 10^{-6} f_{sw}^{2} - 31.85 \times 10^{-3} f_{sw} + 722.57 \ [\%]$$

Control Signal Wave Form

Duty ratio compensation formula

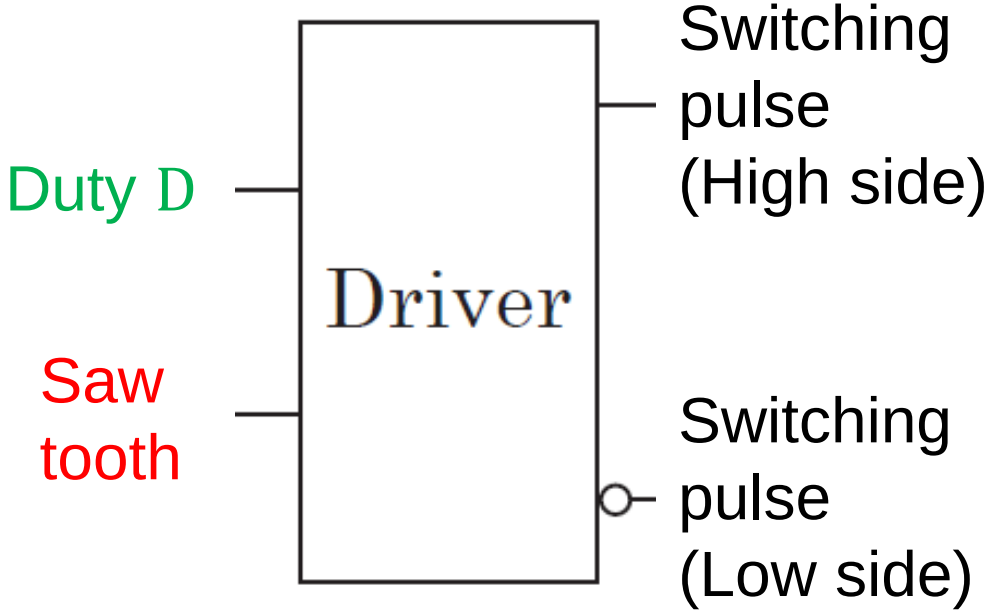
$$\mathrm{D} = 0.355 \times 10^{-6} f_{\mathrm{sw}}^{\ 2} - 31.85 \times 10^{-3} f_{\mathrm{sw}} + 722.57 \ \ [\%]$$

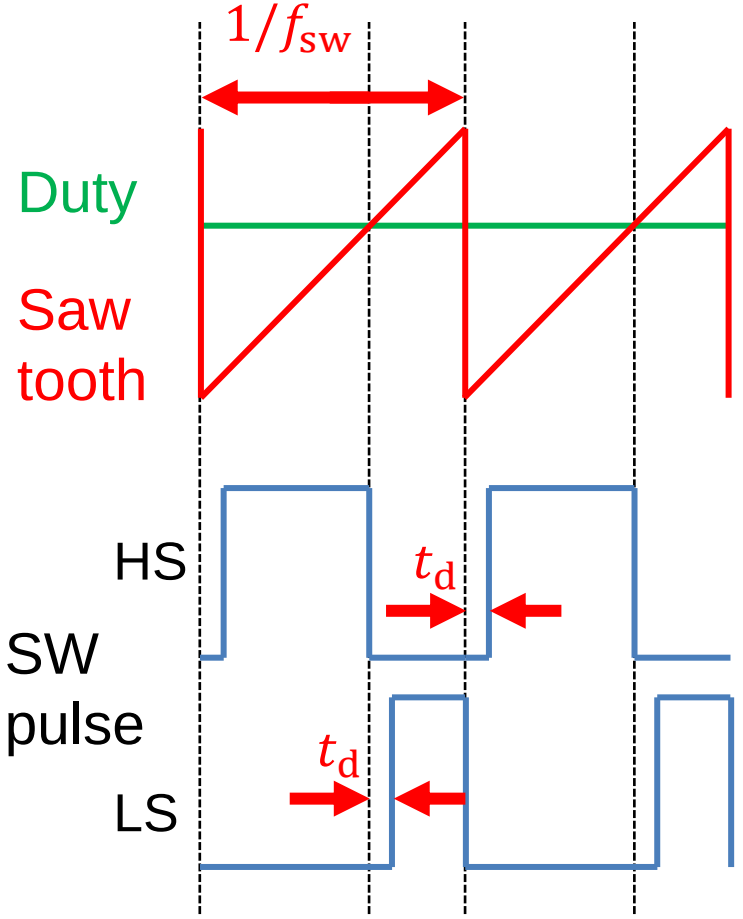


Driver Input / Output Wave Form

Duty ratio compensation formula

$$\mathrm{D} = 0.355 \times 10^{-6} f_{\mathrm{sw}}^{\ 2} - 31.85 \times 10^{-3} f_{\mathrm{sw}} + 722.57 \ [\%]$$





t_{d}: Dead time

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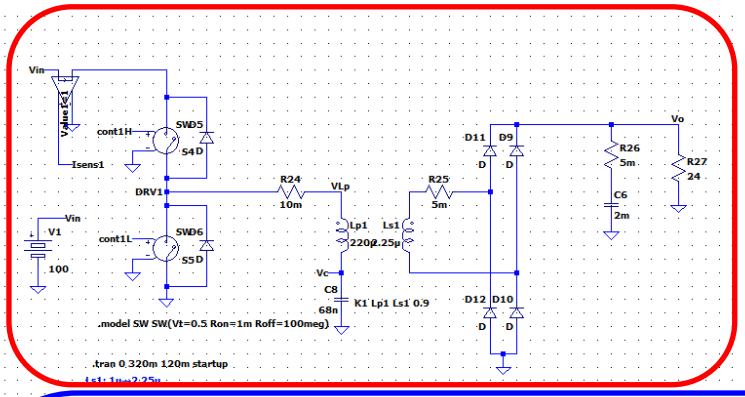
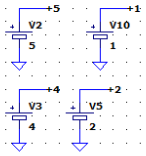
Simulation Conditions

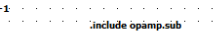
Parameters	Values
Input voltage V_{in}	100V DC
Output voltage V_{out}	12V
Excitation inductance L_{M}	$198\mu\mathrm{H}$
Resonance inductance L_{R}	$22\mu\mathrm{H}$
Resonance capacitance C_{R}	$68\mathrm{nF}$
Transformer turns ratio	$9.89:1$
Load R_{Load}	24Ω

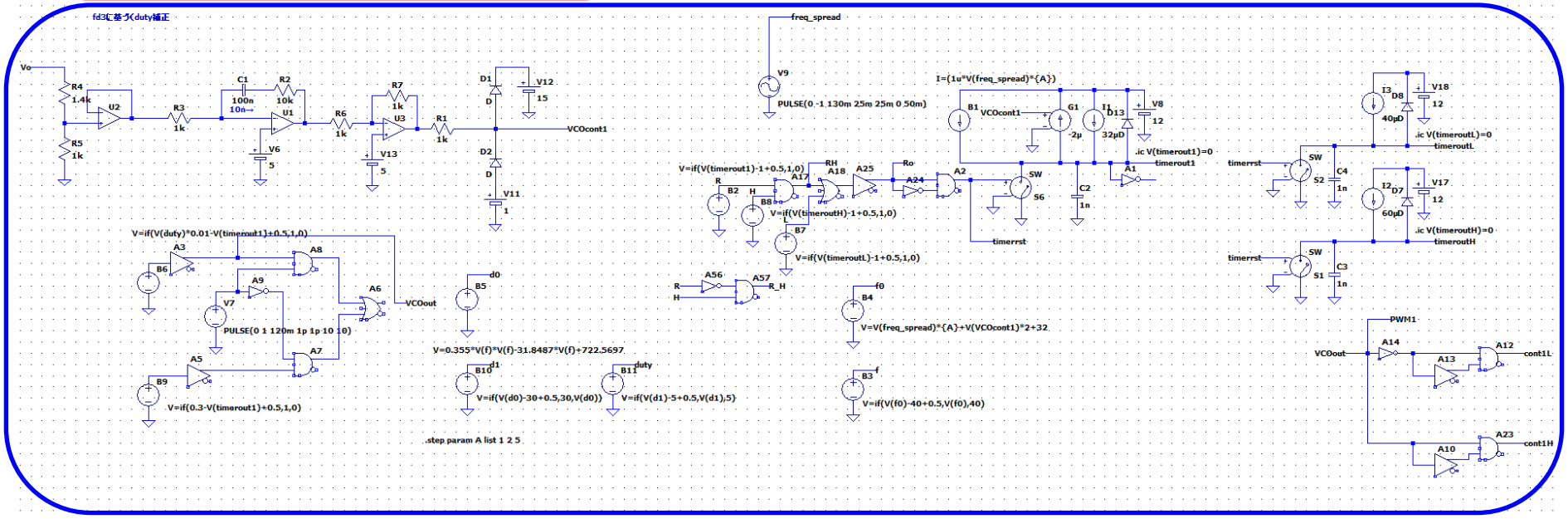
Simulation Schematic

Power stage









Control circuit

Correspondence between Research Overview and Simulation

Noise reduction method:
Spectrum spreading

Switching converter method:
LLC resonant converter

(A) Without spectrum spreading

Spectrum spreading
LLC resonant converter

(B) With spectrum spreading

Duty compensation

Spectrum spreading
LLC resonant converter
with duty compensation

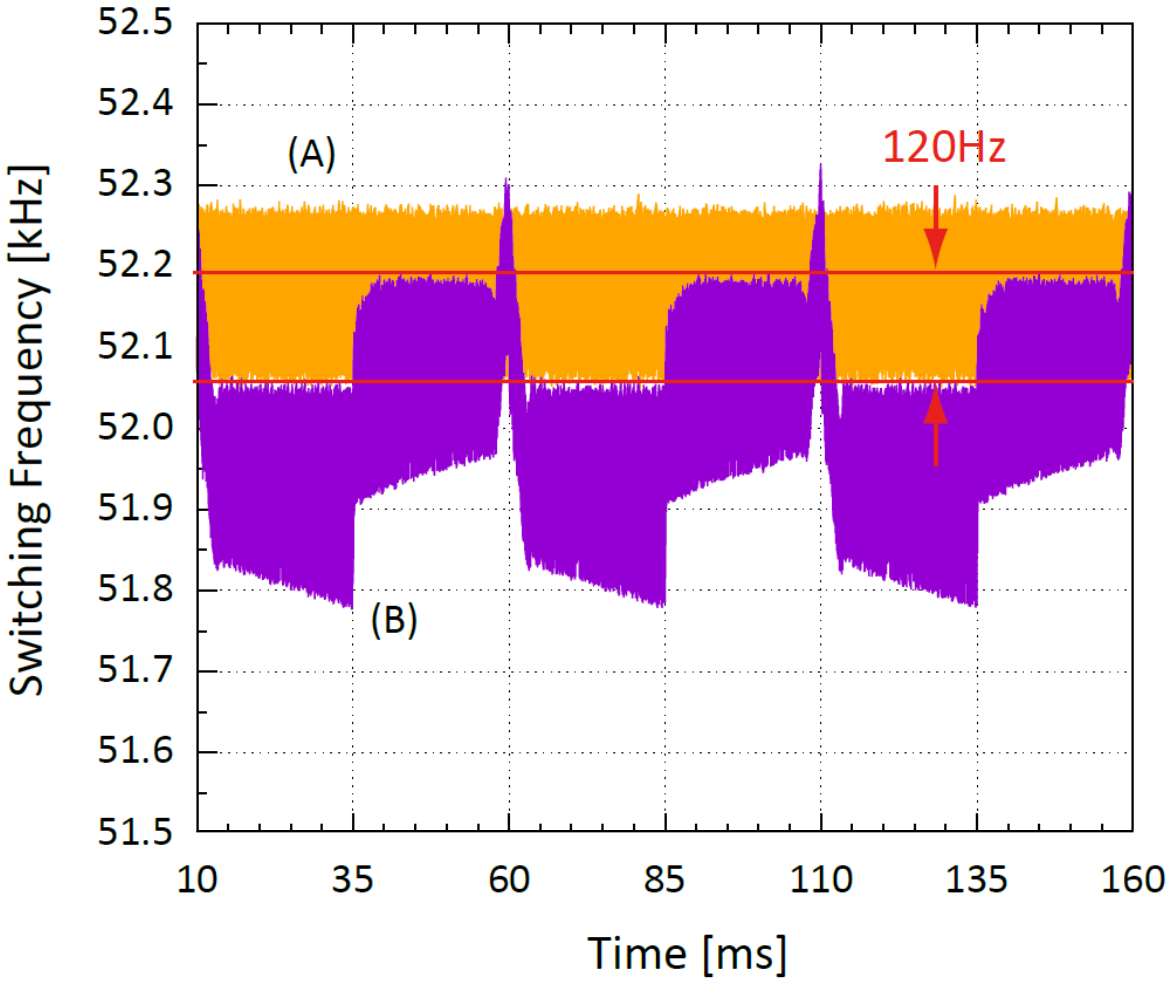
(C) Spectrum spreading & Duty compensation

Simulation Result: Spectrum Spreading (f_{sw})

Switching frequency modulation signal

Triangular: $20\ \mathrm{Hz}$, $1\ \mathrm{V_{P-P}}$ $(-1\ \mathrm{V}$ - $0\ \mathrm{V})$

Mod. sensitivity: $10\ \mathrm{kHz/V}$



(A) Without spectrum spreading

(B) With spectrum spreading

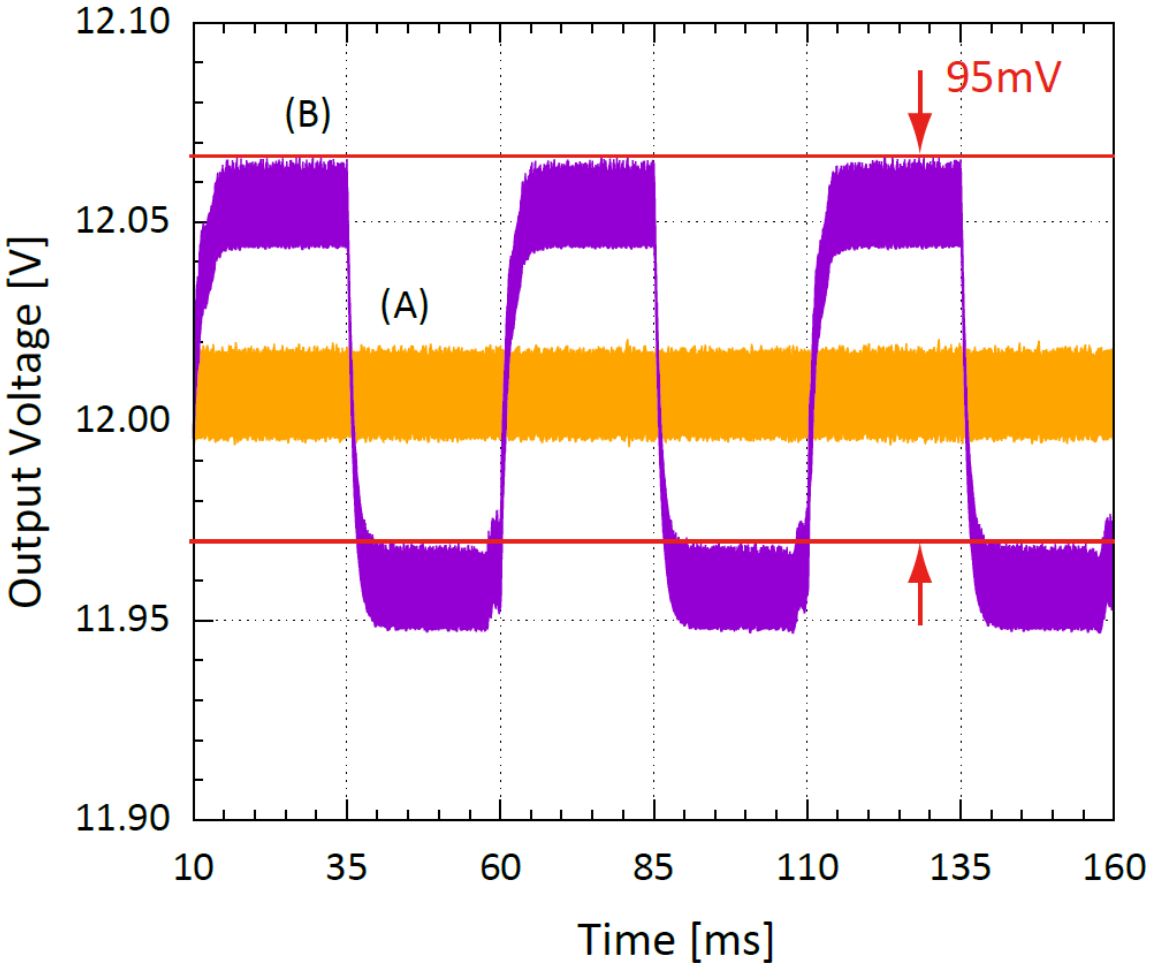
Frequency spreading: 120 Hz

Simulation Result: Spectrum Spreading (V_{out})

Switching frequency modulation signal

Triangular: 20 Hz, 1 V_{P-P} (−1 V - 0 V)

Mod. sensitivity: 10 kHz/V



(A) Without spectrum spreading

(B) With spectrum spreading

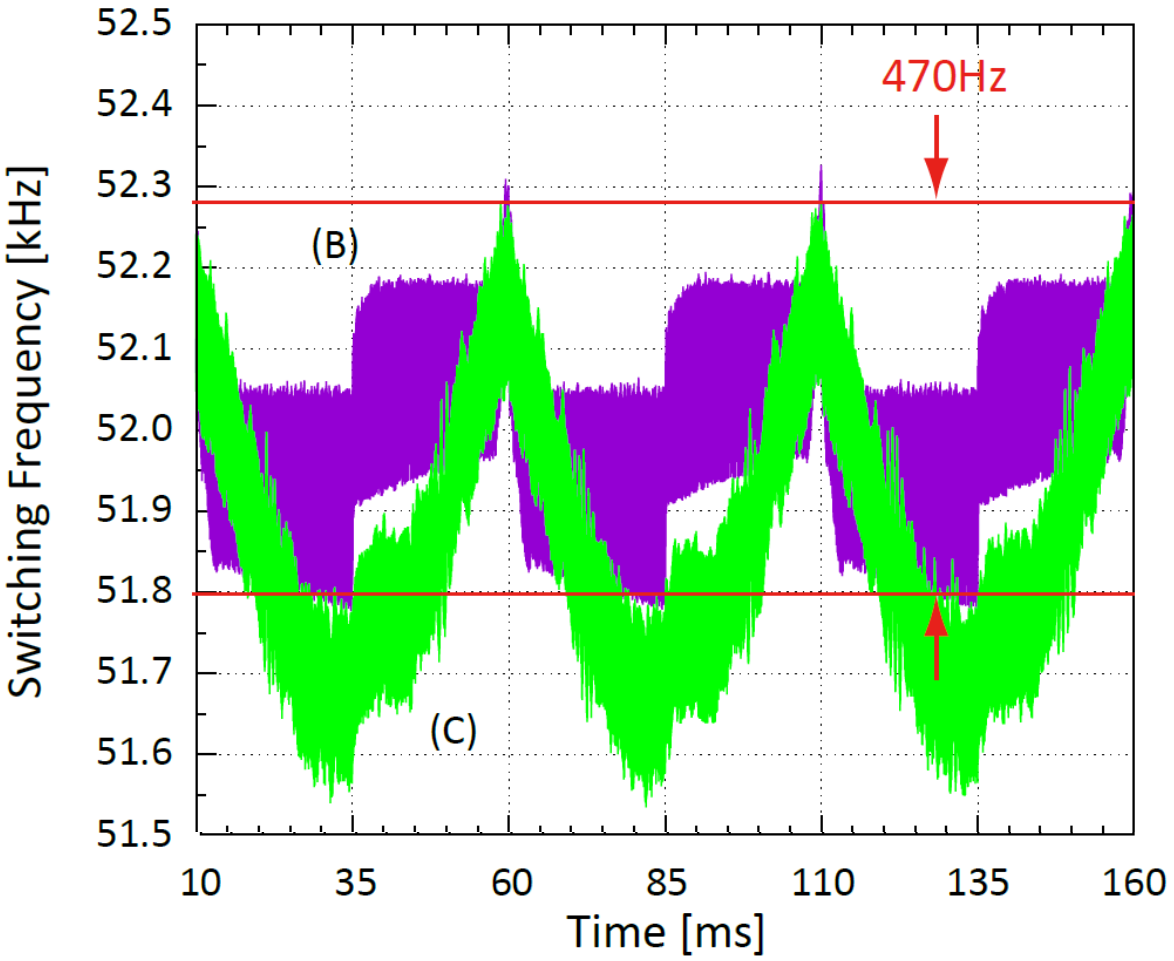
Modulation ripple: 95mV ☹

Simulation Result: Spectrum Spreading & Duty Compensation (f_{sw})

Switching frequency modulation signal

Triangular: 20 Hz, 1 V_{P-P} (-0.5 V - 0.5 V)

Mod. sensitivity: 2 kHz/V



(B) With spectrum spreading

(C) Spectrum spreading & Duty compensation

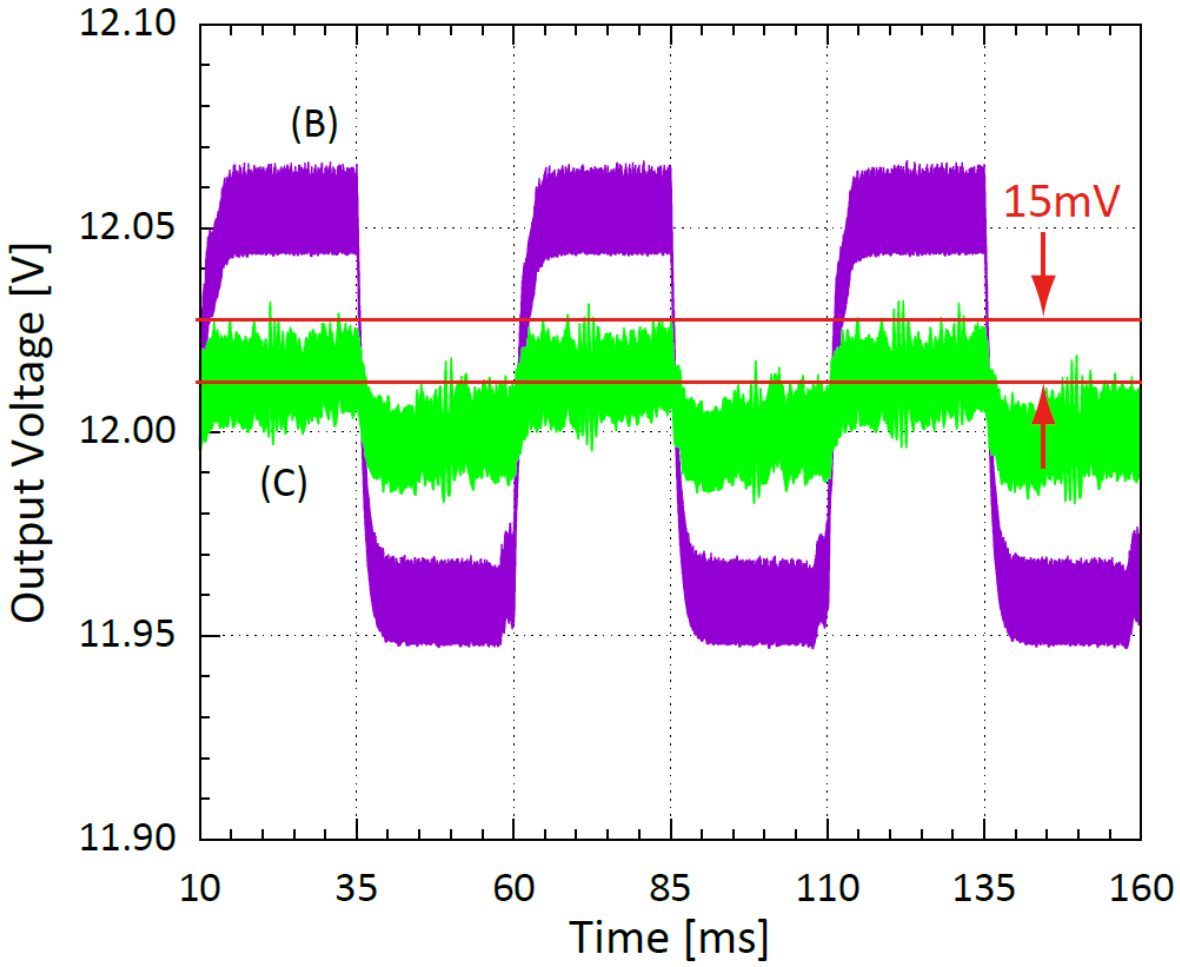
Frequency spreading: 470 Hz

Simulation Result: Spectrum Spreading & Duty Compensation (V_{out})

Switching frequency modulation signal

Triangular: 20 Hz, 1 V_{P-P} (-0.5 V - 0.5 V)

Mod. sensitivity: 2 kHz/V



(B) With spectrum spreading

(C) Spectrum spreading & Duty compensation

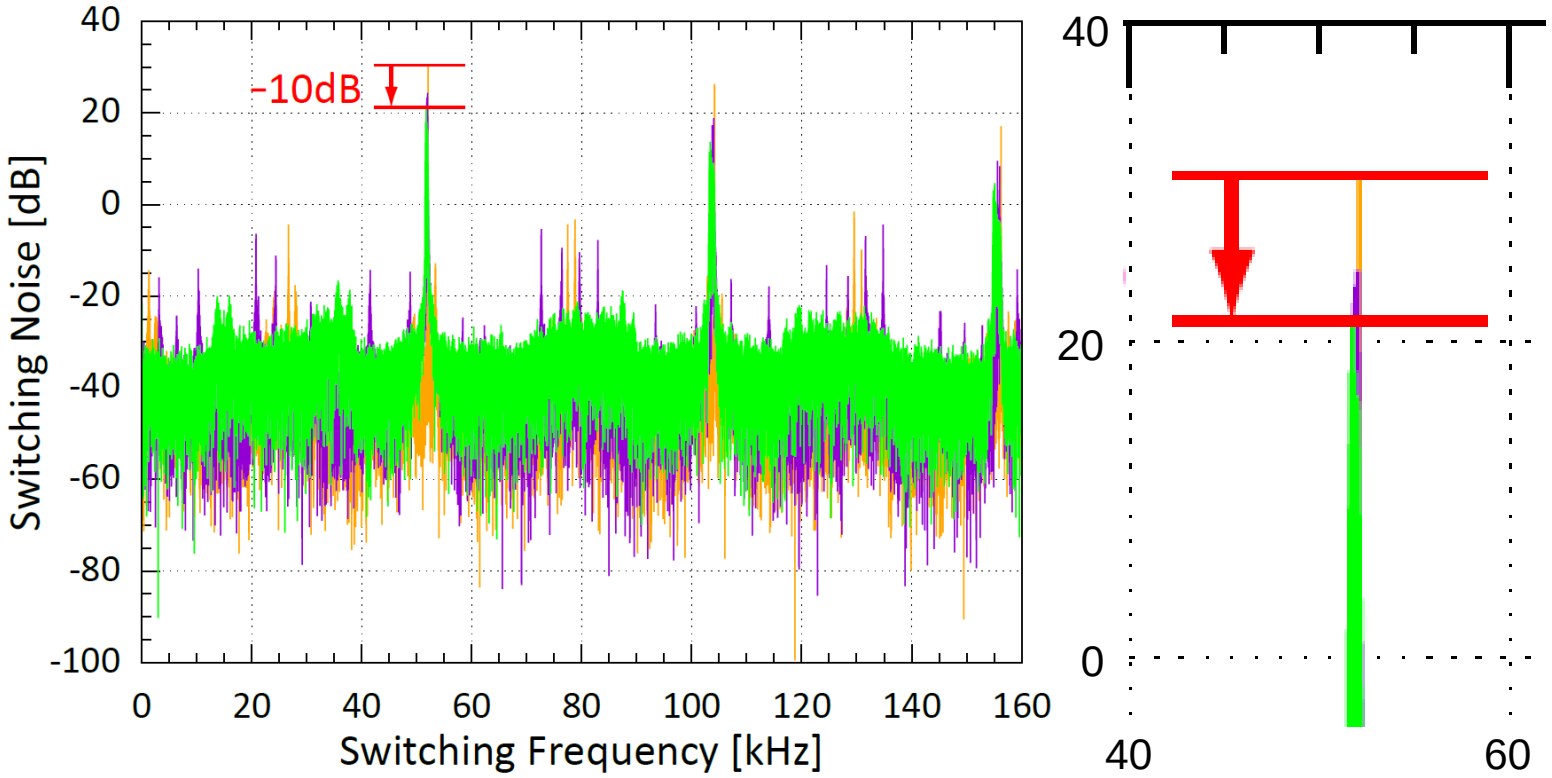
Modulation ripple: 15mV

Simulation Result (Noise Spectrum)

(A) Without spectrum spreading

(B) With spectrum spreading

(C) Spectrum spreading & Duty compensation



Switching noise spectrum: −10 dB

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Conclusion

EMI reduction LLC resonant converter by spectrum spreading

- Voltage ripple reduction method
  - Using duty ratio characteristics:
    - Changes output voltage

  ⇩

  Propose: **Duty compensation**

- Simulation verification
  - Spectrum spread: **−10 dB**
  - Modulation ripple: **95 mV** ➡ **15 mV**

Future works

	These works	Future works
Verification	Simulation	Experiment circuit
Output voltage ripple reduction	Duty ratio compensation	Dead time compensation