Overshoot Cancelation Based on Balanced Charge-Discharge Time Condition for Buck Converter in Mobile Applications

Minh Tri Tran*, Yifei Sun, Yasunori Kobori,
Anna Kuwana, Haruo Kobayashi

群馬大学
GUNMA UNIVERSITY

Gunma University, Japan

Outline

1. Research Background
   - Applications of Switching Power Supply
   - Basic Switching Converter Architecture
2. Analysis of Step-down Switching Converter
   - Conventional Classical Technique
   - Superposition Principle
3. Proposed Design of Buck Converter
   - Overshoot Improvement with Parallel RLC Network
   - Experimental Results
4. Conclusions

1. Research Background

Research Objective & Approach

Objective

Development of switching power supply with

- Fast response & high efficiency
- Low EMI noise
- Small output ripple

Approach

- Analysis of buck converter system based on classical technique and superposition principle
- Overshoot reduction using parallel RLC network

1. Research Background

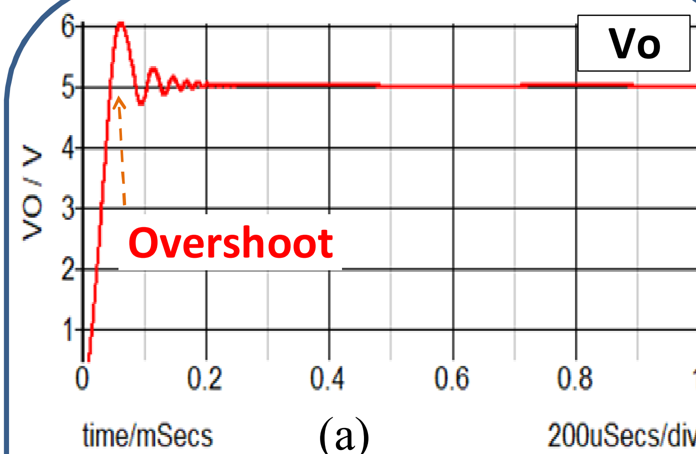
Design Achievements of This Work

Condition for overshoot cancelation

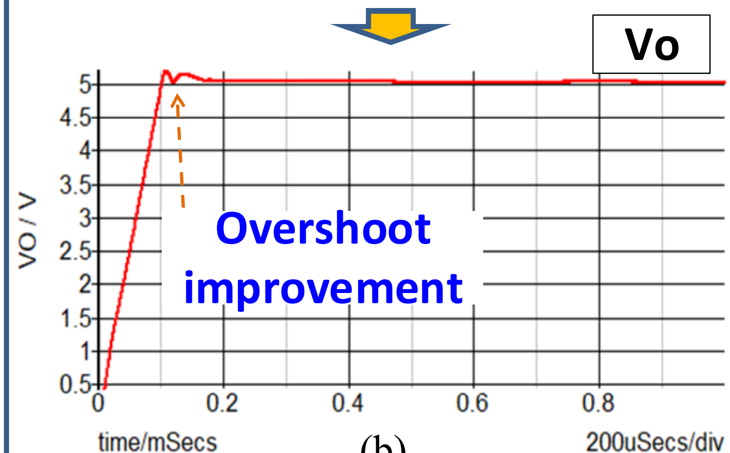
Balanced charge-discharge time

$$|Z_L| = |Z_C| = 2R \Rightarrow \omega L = \frac{1}{\omega C} = 2R$$

Here, $\omega = \frac{1}{\sqrt{LC}} = \frac{1}{2RC}$



(a)



(b)

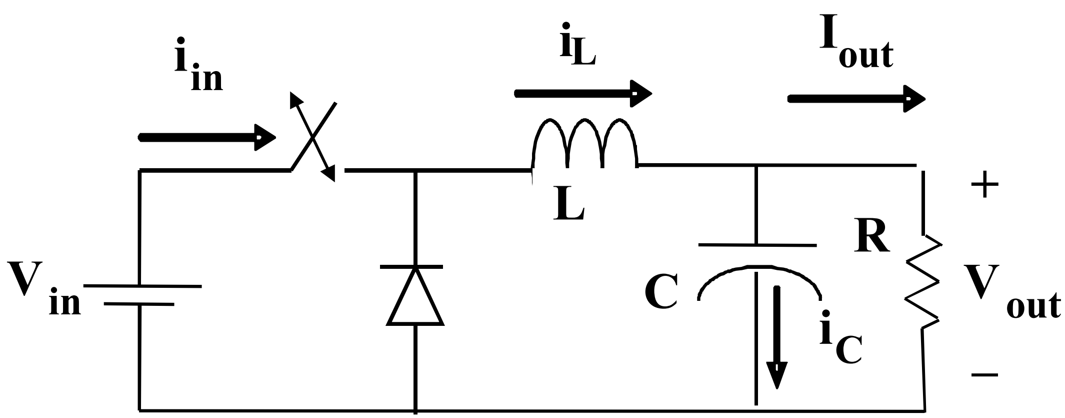
Overshoot improvement from 1Vpp into 0.1Vpp

Imbalance of charge-discharge time

Overshoot improvement with parallel RLC

1. Research Background

Basic Switching Converter Architecture



Basic Switching Converter

Merits

- Downsizing
- Light Weight
- High Efficiency

High Efficiency Switching

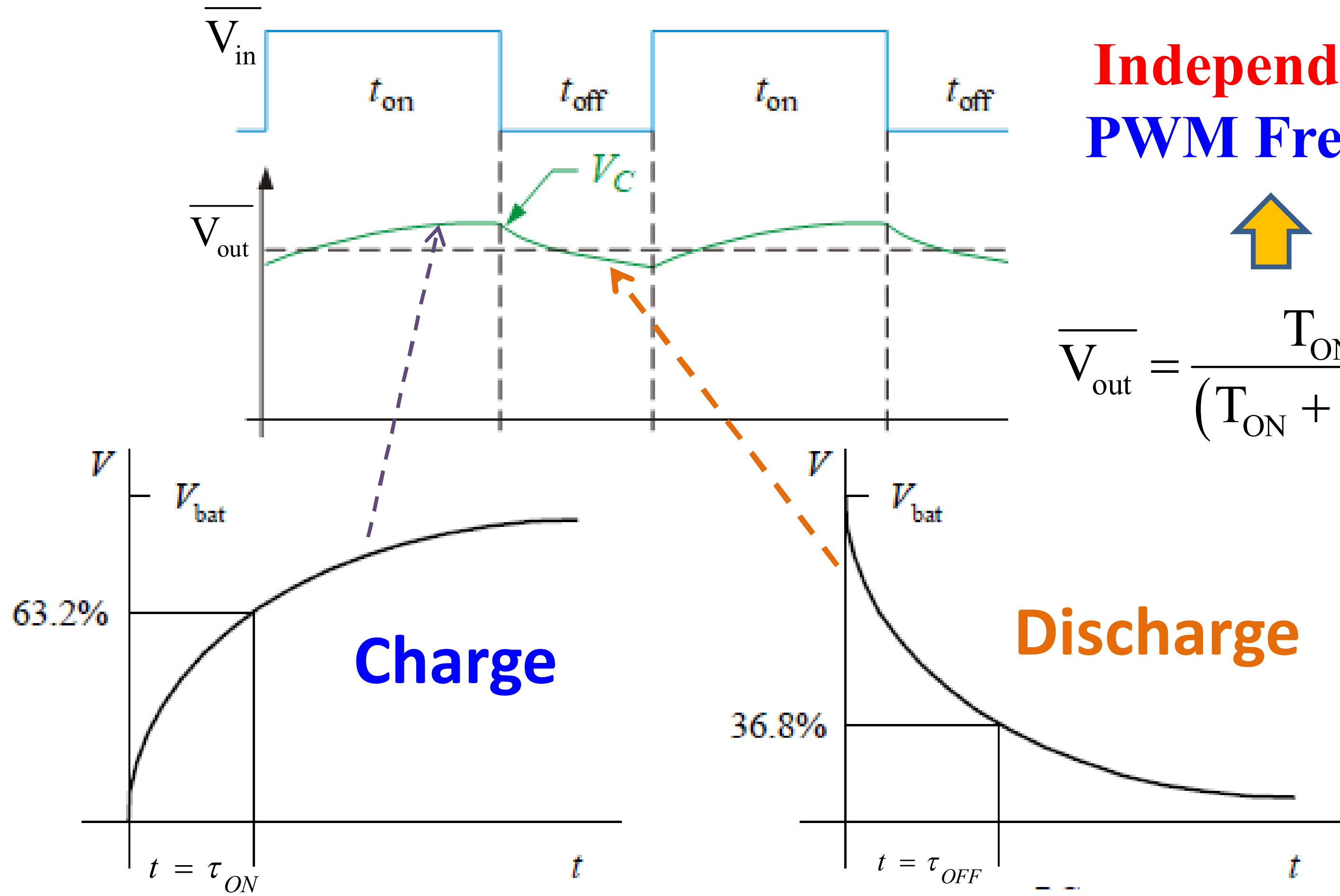
➔Reduce energy consumption
➔Extend battery operating time
➔Minimize costs of systems

Demerits

- Output Ripple
- Switching noise
- Harmonic noise

1. Research Background

Switching Regulator



Independence of PWM Frequency

$$\overline{V_{out}} = \frac{T_{ON}}{\left(T_{ON} + T_{OFF}\right)}\overline{V_{in}}$$

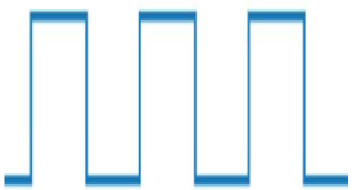
$$V_{Charge}(t_i) = \overline{V_{discharge}(t_{i-1})}\left(1 - e^{\frac{-t}{\tau_{ON}}}\right)$$

$$V_{discharge}(t_i) = \overline{V_{charge}(t_i)}\, e^{\frac{-t}{\tau_{OFF}}}$$

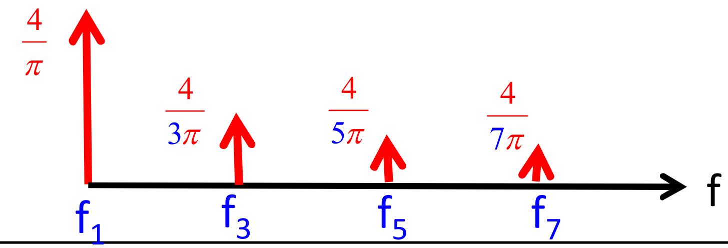
1. Research Background

Harmonics of PWM Signals

50% Duty Cycle

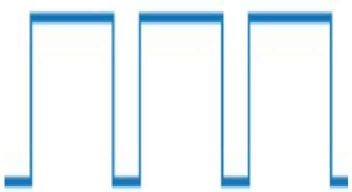


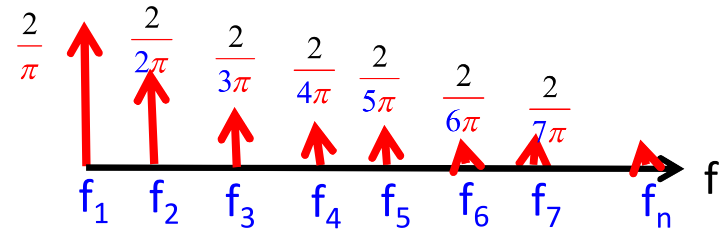
$$S_{PWM}(t)=\frac{4}{\pi}\left(\sin(2\pi ft)+\frac{1}{3}\sin(3*2\pi ft)+\frac{1}{5}\sin(5*2\pi ft)+\ldots\right)$$



75% Duty Cycle

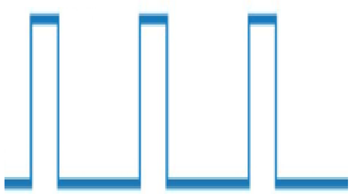
$$S_{PWM}(t)=\frac{4}{\pi}\left(\sin(2\pi ft)+\frac{1}{2}\sin(2*2\pi ft)+\frac{1}{3}\sin(3*2\pi ft)+\frac{1}{4}\sin(4*2\pi ft)+\frac{1}{5}\sin(5*2\pi ft)+\ldots\right)$$

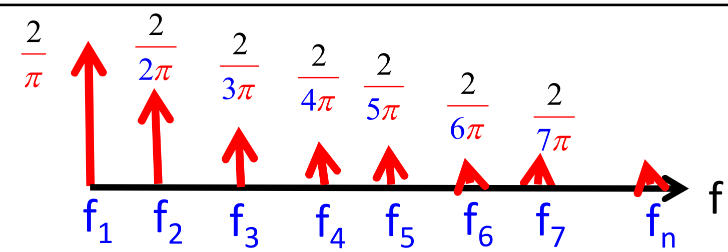




$$S_{PWM}(t)=\frac{4}{\pi}\left(\sin(2\pi ft)-\frac{1}{2}\sin(2*2\pi ft)+\frac{1}{3}\sin(3*2\pi ft)-\frac{1}{4}\sin(4*2\pi ft)+\frac{1}{5}\sin(5*2\pi ft)+\ldots\right)$$

25% Duty Cycle

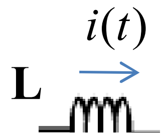




2. Analysis of Step-down Switching Converter

Conventional Classical Technique

Inductor

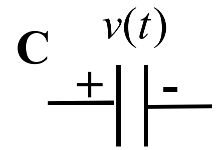


Magnetic energy

$$i(t) = \frac{1}{L}\int_{-\infty}^{t_0} v(\tau)d\tau + \frac{1}{L}\int_{t_0}^{t} v(\tau)d\tau$$

$$= i(t_0^-) + \frac{1}{L}\int_{t_0}^{t} v(\tau)d\tau$$

Capacitor



Electric energy

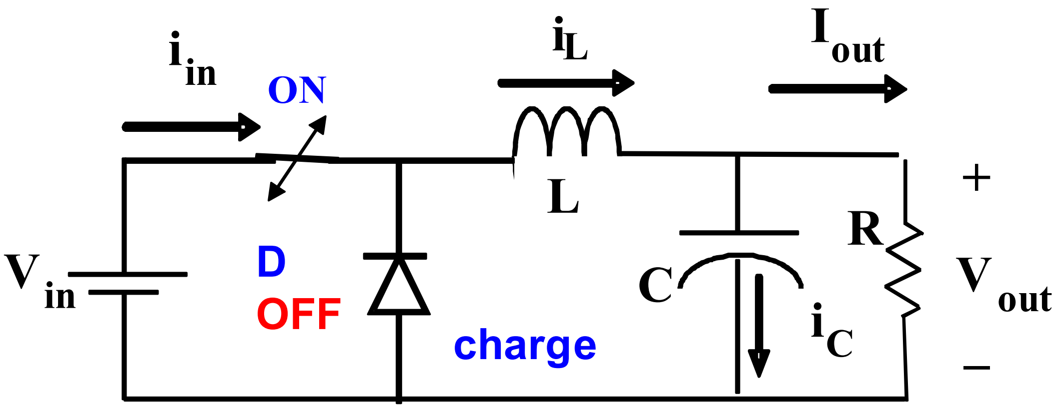
$$v(t) = \frac{1}{c}\int_{-\infty}^{t_0} i(\tau)d\tau + \frac{1}{c}\int_{t_0}^{t} i(\tau)d\tau$$

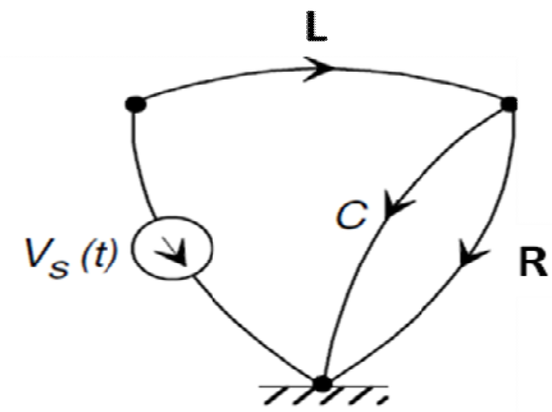
$$= v(t_0^-) + \frac{1}{c}\int_{t_0}^{t} i(\tau)d\tau$$

- **Advantages**
  - **Converts differential equation into algebraic equation.**
  - **Rapidly provides stability & transient response.**
- **Disadvantages**
  - **Applicable only to Linear, Time-Invariant (LTI) systems**

2. Analysis of Step-down Switching Converter

Linear Graph of Buck Converter (Switch ON)





$$\begin{bmatrix} \dot{i}_L(t) \\ \dot{v}_C(t) \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_i(t) \qquad y(t) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + [0] v_i(t)$$

$$\begin{cases} \frac{1}{L}V_C(s) + sC\left(s + \frac{1}{RC}\right)V_C(s) = \frac{1}{L}V_i(s) \\ I_L(s) = C\left(s + \frac{1}{RC}\right)V_C(s) \end{cases}$$

2. Analysis of Step-down Switching Converter

Analysis of Buck Converter (Switch ON)

$$V_C(s) = \frac{\frac{1}{LC}}{\left(s^2 + \frac{s}{RC} + \frac{1}{LC}\right)} V_i(s)$$

$$s^2 + \frac{1}{RC}s + \frac{1}{LC} = 0$$

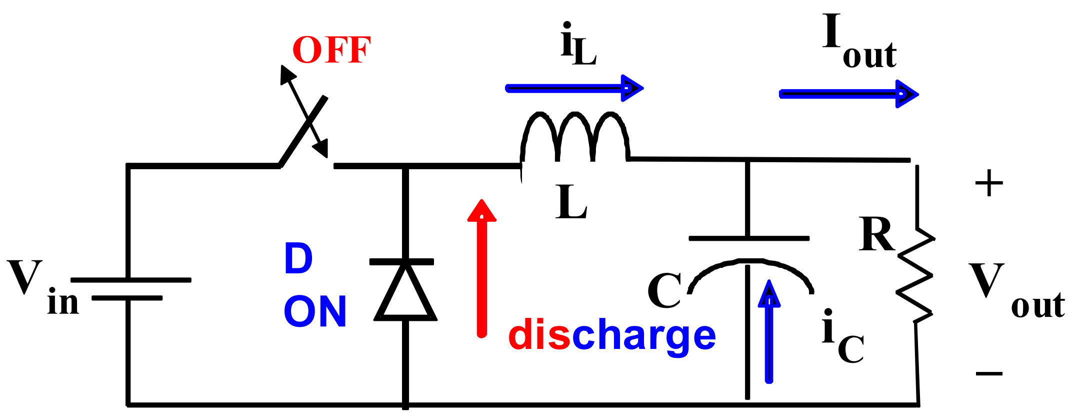
$$s_1 = -\frac{1}{2RC} + \sqrt{\left(\frac{1}{2RC}\right)^2 - \frac{1}{LC}} \quad \vee \quad s_2 = -\frac{1}{2RC} - \sqrt{\left(\frac{1}{2RC}\right)^2 - \frac{1}{LC}}$$

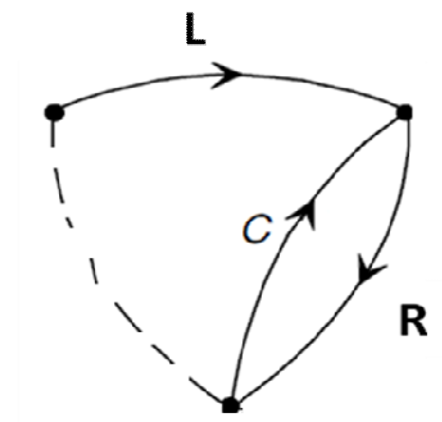
$$\omega_{2RC} = \frac{1}{2RC}; \omega_{LC} = \frac{1}{\sqrt{LC}};$$

$$V_{charge}(t) = A_{ch1} e^{\left(-\omega_{2RC} + \sqrt{(\omega_{2RC})^2 - \omega_{LC}^2}\right)t} + A_{ch2} e^{\left(-\omega_{2RC} - \sqrt{(\omega_{2RC})^2 - \omega_{LC}^2}\right)t}$$

2. Analysis of Step-down Switching Converter

Linear Graph of Buck Converter (Switch OFF)





$$\begin{bmatrix} \dot{i}_L(t) \\ \dot{v}_C(t) \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ -\frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} v_i(t)$$

$$y(t) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} v_i(t)$$

$$\begin{cases} \frac{1}{L} V_C(s) - sC\left(s + \frac{1}{RC}\right) V_C(s) = 0 \\ I_L(s) = -C\left(s + \frac{1}{RC}\right) V_C(s) \end{cases}$$

2. Analysis of Step-down Switching Converter

Analysis of Buck Converter (Switch OFF)

$$\left(s^2 - \frac{s}{RC} + \frac{1}{LC}\right)V_C(s) = 0$$

$$s^2 - \frac{1}{RC}s + \frac{1}{LC} = 0$$

$$s_{dis1} = \frac{1}{2RC} + \sqrt{\left(\frac{1}{2RC}\right)^2 - \frac{1}{LC}} \quad \vee \quad s_{dis2} = \frac{1}{2RC} - \sqrt{\left(\frac{1}{2RC}\right)^2 - \frac{1}{LC}}$$

$$\omega_{2RC} = \frac{1}{2RC}; \omega_{LC} = \frac{1}{\sqrt{LC}};$$

$$V_{discharge}(t) = A_{dis1}e^{\left(\omega_{2RC} + \sqrt{(\omega_{2RC})^2 - \omega_{LC}^2}\right)t} + A_{dis2}e^{\left(\omega_{2RC} + \sqrt{(\omega_{2RC})^2 - \omega_{LC}^2}\right)t}$$

2. Analysis of Step-down Switching Converter

Balanced Charge-Discharge Time Condition

$$\overline{V_{out}} = \frac{1}{(T_{ON}+T_{OFF})}\left(\begin{aligned} &\int_0^{T_{ON}} \left(A_{ch1} e^{\left(-\omega_{2RC}+\sqrt{(\omega_{2RC})^2-\omega_{LC}^2}\right)t} + A_{ch2} e^{\left(-\omega_{2RC}-\sqrt{(\omega_{2RC})^2-\omega_{LC}^2}\right)t} \right) dt \\ &+ \int_{T_{ON}}^{T_{OFF}} \left\{ A_{dis1} e^{\left(\omega_{2RC}+\sqrt{(\omega_{2RC})^2-\omega_{LC}^2}\right)t} + A_{dis2} e^{\left(\omega_{2RC}-\sqrt{(\omega_{2RC})^2-\omega_{LC}^2}\right)t} \right\} dt \end{aligned} \right)$$

$$\omega_{2RC} = \omega_{LC} \Leftrightarrow \omega = \frac{1}{\sqrt{LC}} = \frac{1}{2RC}$$

$$|Z_L| = |Z_C| = 2R$$

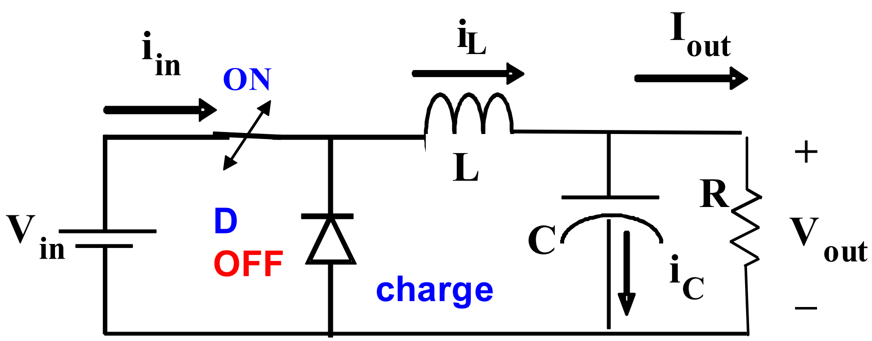
Balanced Charge-Discharge Time Condition

$$\omega L = \frac{1}{\omega C} = 2R$$

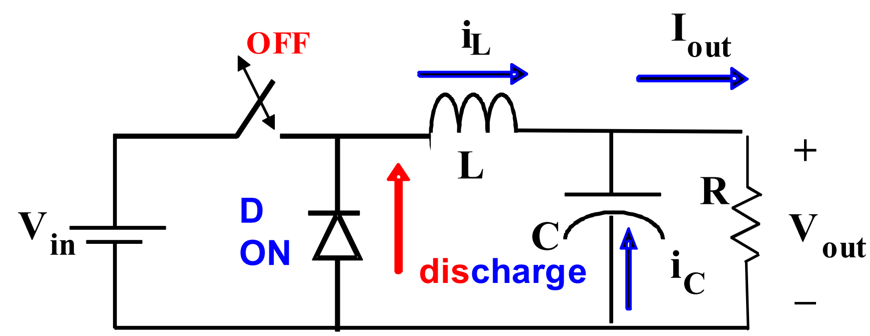
$$\overline{V_{out}} = \frac{1}{(T_{ON}+T_{OFF})}\left(\int_0^{T_{ON}} A_{ch} e^{-\omega t} dt + \int_{T_{ON}}^{T_{OFF}} A_{dis} e^{\omega t} dt \right)$$

2. Analysis of Step-down Switching Converter

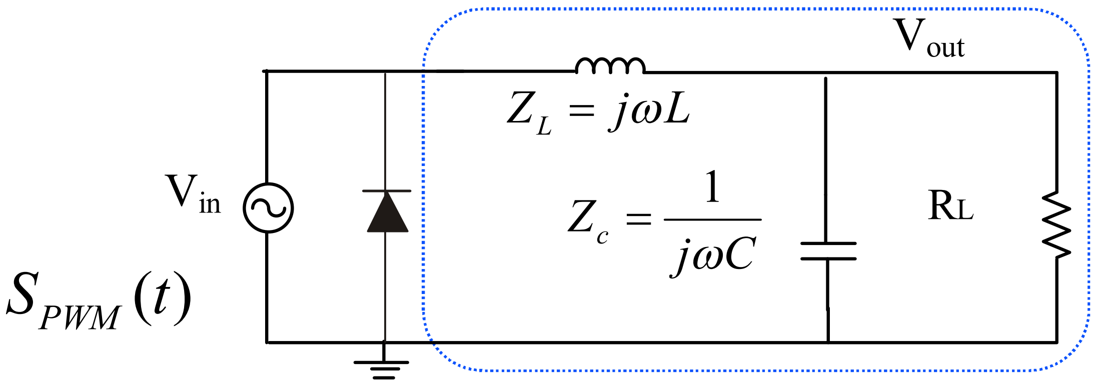
Proposed Analysis Model of Buck Converter



Switch ON



Switch OFF



Model of Buck Converter

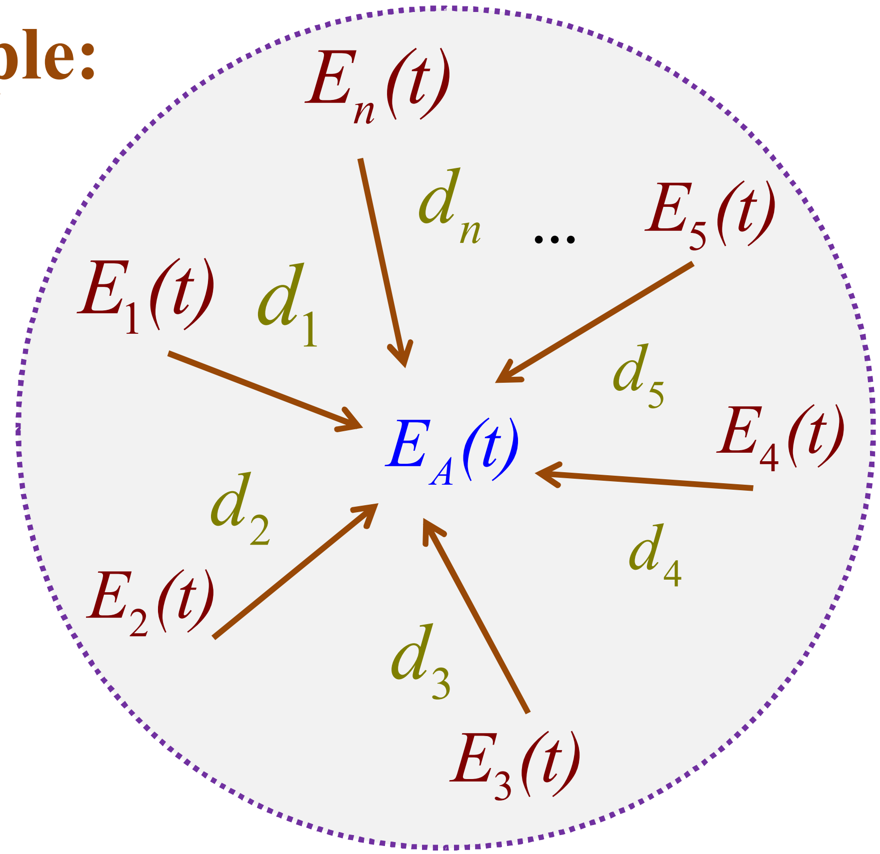
2. Analysis of Step-down Switching Converter

Definition of Widened Superposition Principle

A superposition of energy at *one place* is proportional with their *input sources* and *resistance distances of transmission spaces*.

Widened Superposition Principle:

$$E_A(t)\sum_{i=1}^{n}\frac{1}{d_i}=\sum_{i=1}^{n}\frac{E_i(t)}{d_i}$$



$E_A(t)$: ***energy at one place***

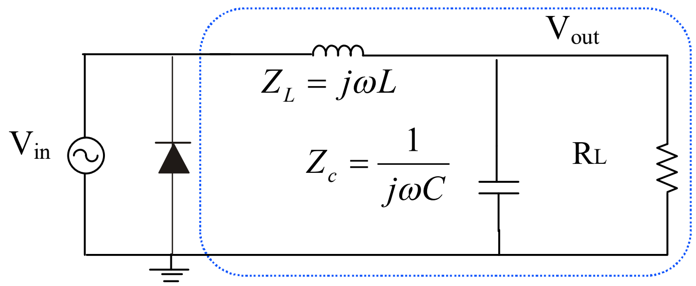
$E_i(t)$: ***input sources***

$d_i(t)$: ***resistance distances***

2. Analysis of Step-down Switching Converter

Transfer Function of Proposed Analysis Model

Proposed analysis model



$$E_A(t)\sum_{i=1}^{n}\frac{1}{d_i} = \sum_{i=1}^{n}\frac{E_i(t)}{d_i}$$

Superposition principle

$$V_o\left(\frac{1}{Z_L}+\frac{1}{Z_C}+\frac{1}{R}\right)=\frac{V_{in}}{Z_L}$$

Output Voltage

$$V_o = V_{in}\frac{RZ_C}{R\left(Z_L+Z_C\right)+Z_L Z_C}$$

Transfer Function

$$H=\frac{V_o}{V_{in}}=\frac{RZ_C}{R\left(Z_L+Z_C\right)+Z_L Z_C}$$

$$H\left(j\omega\right)=\frac{\frac{1}{LC}}{\left(j\omega\right)^2+j\omega\frac{1}{RC}+\frac{1}{LC}}$$

2. Analysis of Step-down Switching Converter

Condition for Max Power Propagation

Transfer Function

$$H(j\omega) = \frac{\frac{1}{LC}}{(j\omega)^2 + j\omega\frac{1}{RC} + \frac{1}{LC}}$$

$$H(j2\pi f) = \frac{\frac{1}{(2\pi)^2 LC}}{(j*f)^2 + j*f\frac{1}{2\pi RC} + \frac{1}{(2\pi)^2 LC}}$$

$$|H(f)| = \frac{\frac{1}{(2\pi)^2 LC}}{\sqrt{\left(\frac{1}{(2\pi)^2 LC} - f^2\right)^2 + \left(\frac{f}{2\pi RC}\right)^2}}$$

$$|Z_L| = |Z_C| = 2R$$

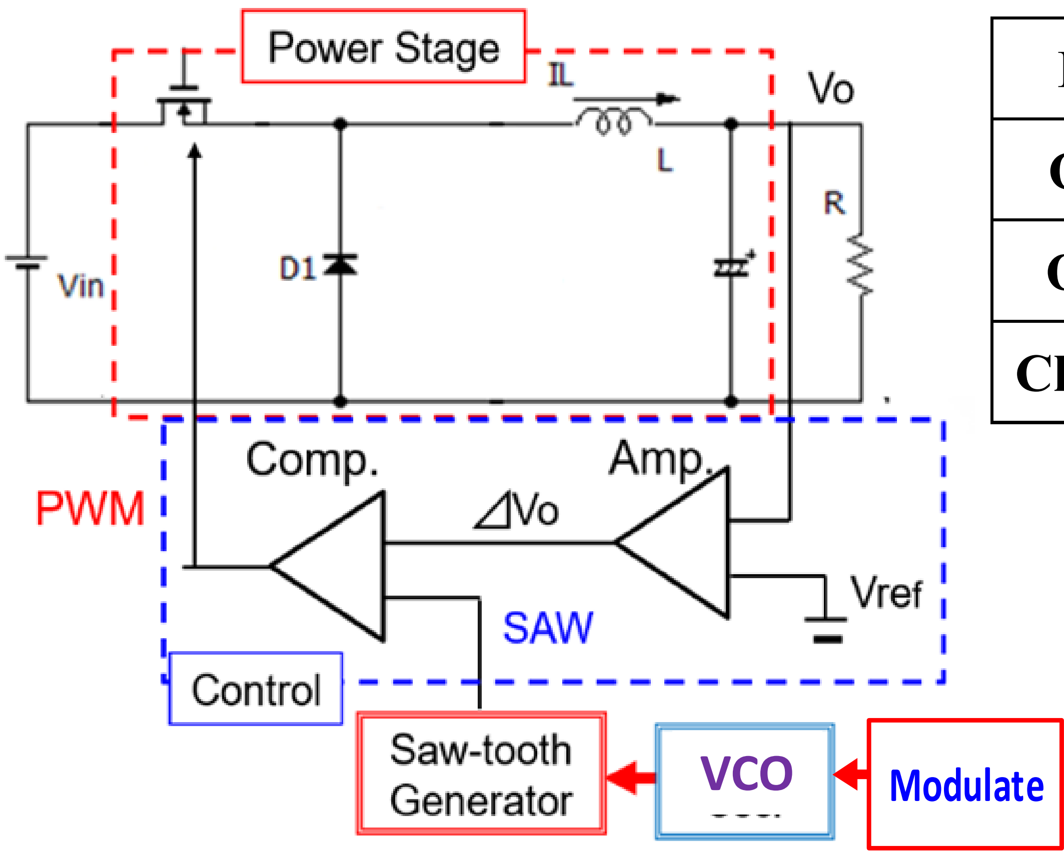
Balanced Charge-Discharge Time Condition

$$|H(f)| = \frac{\frac{1}{(2\pi)^2 LC}}{\left(\frac{1}{4\pi RC}\right)^2 + f^2} \Rightarrow |H(f)| = \frac{1}{2} \qquad when \quad f = \frac{1}{4\pi RC} = \frac{1}{2\pi\sqrt{LC}}$$

3. Proposed Design of Buck Converter

Conventional Step-down Switching Converter

VCO : Voltage Controlled Oscillator



Circuit with Frequency Modulation

Input Voltage (Vin)	12V
Output Voltage (Vo)	5.0V
Output Current (Io)	1.0A
Clock Frequency (Fck)	200kHz

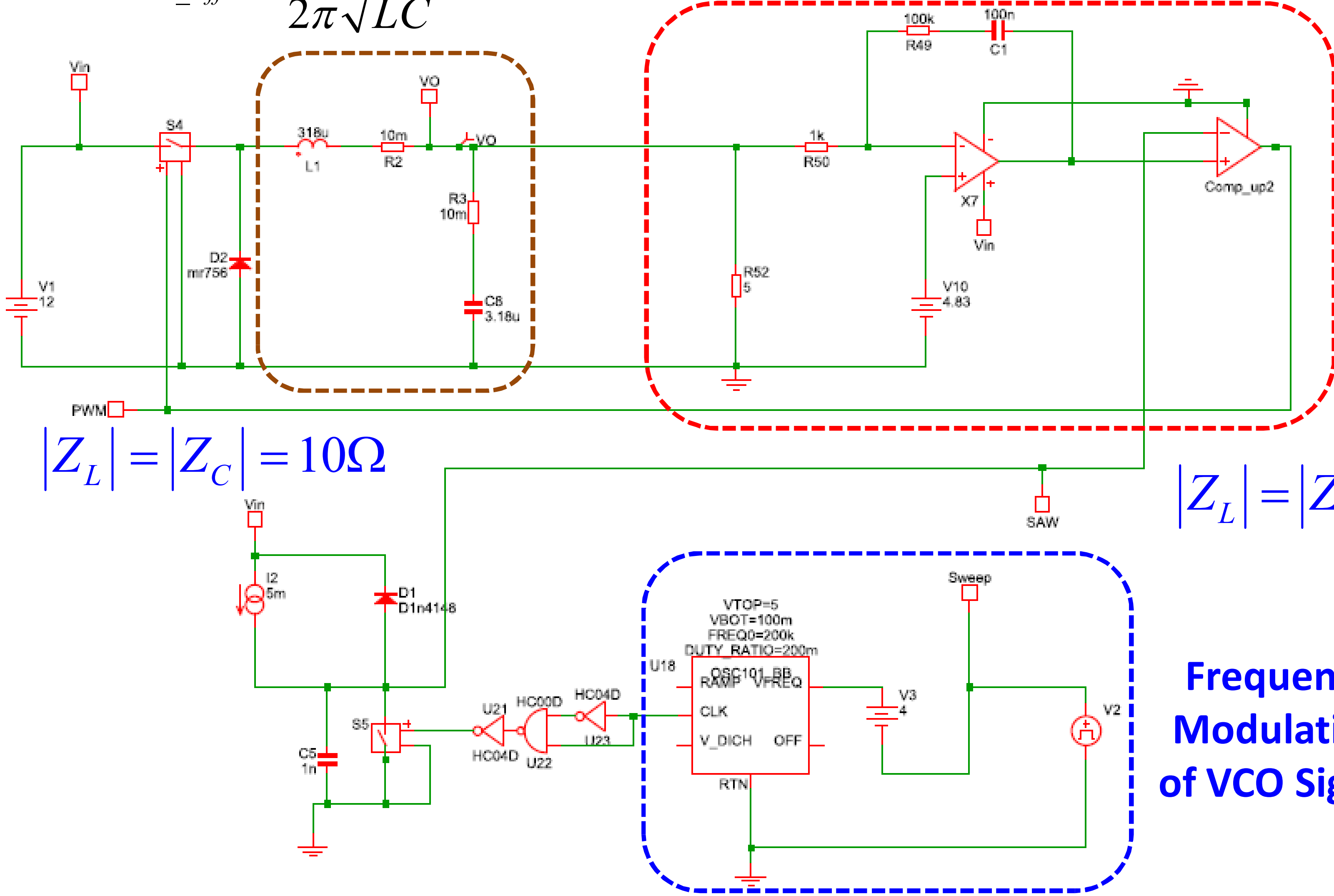
EMI Reduction using Spread Spectrum of VCO

3. Proposed Design of Buck Converter

Simulation of Conventional Buck Converter

$$f_{cut\_off} = \frac{1}{2\pi\sqrt{LC}} = 5kHz$$

$$R_{total} > 5\Omega$$



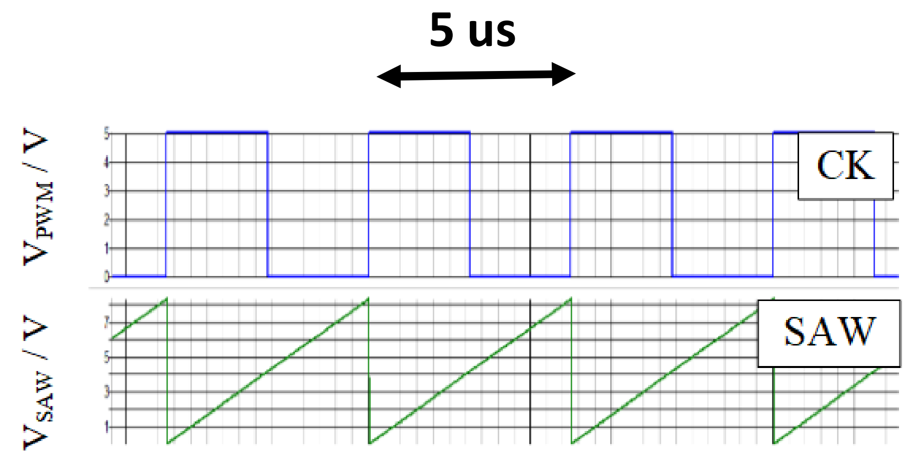
$$|Z_L| = |Z_C| = 10\Omega$$

$$|Z_L| = |Z_C| < 2R$$

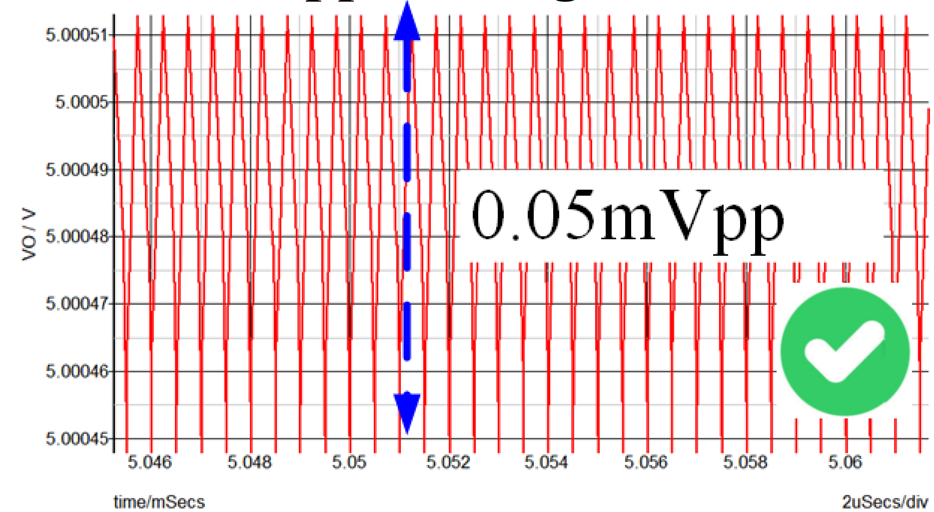
Frequency Modulation of VCO Signal

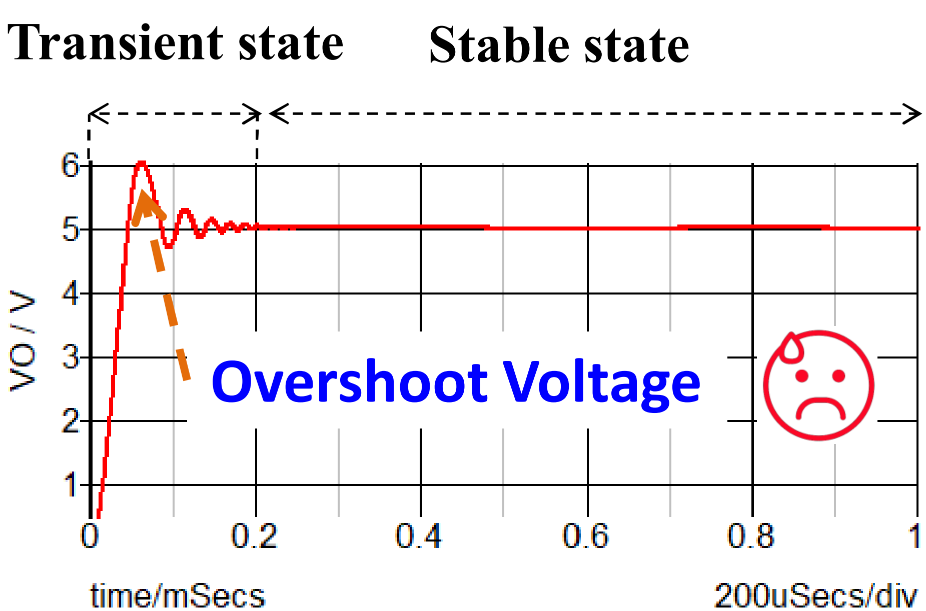
3. Proposed Design of Buck Converter

Waveforms of Conventional Buck Converter

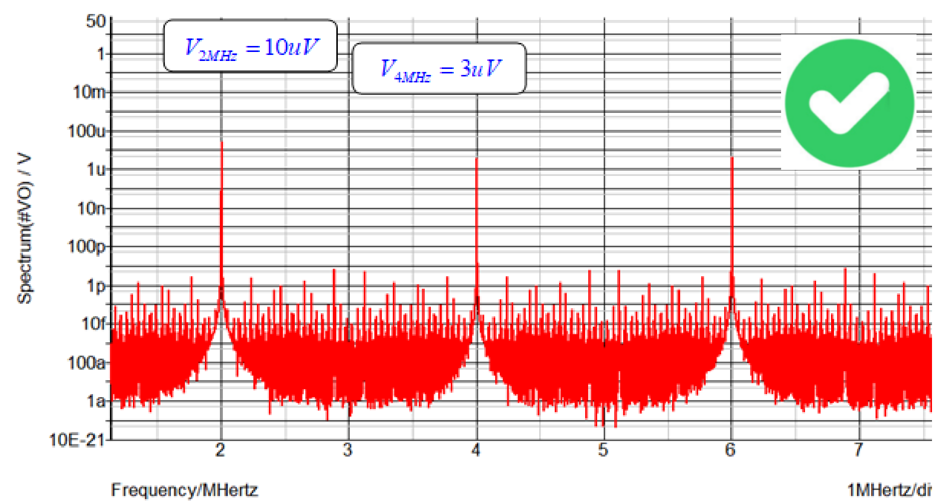


Ripple voltages



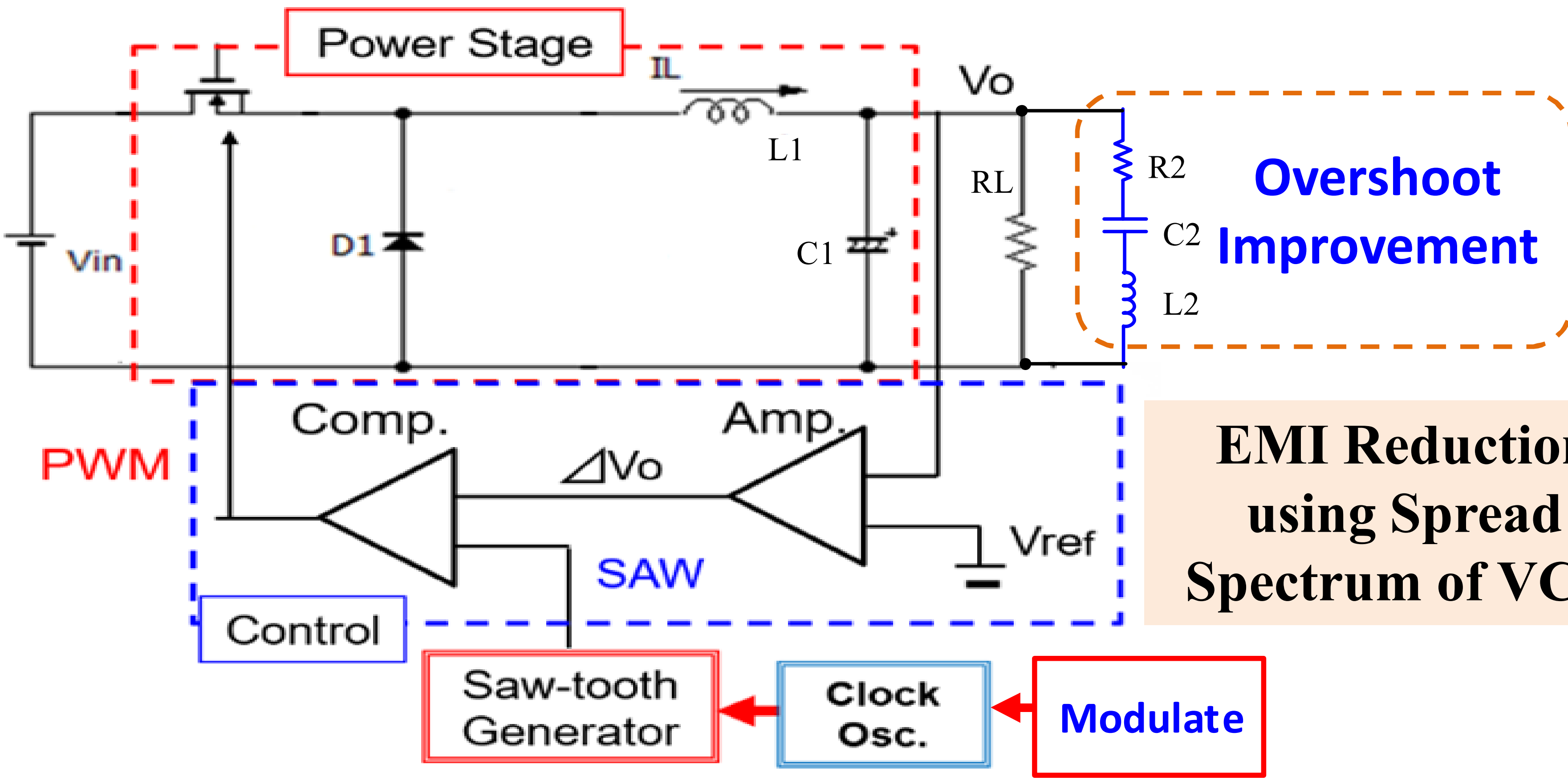


Spectrum of ripple voltages



3. Proposed Design of Buck Converter

Proposed Design of Step-down Switching Converter



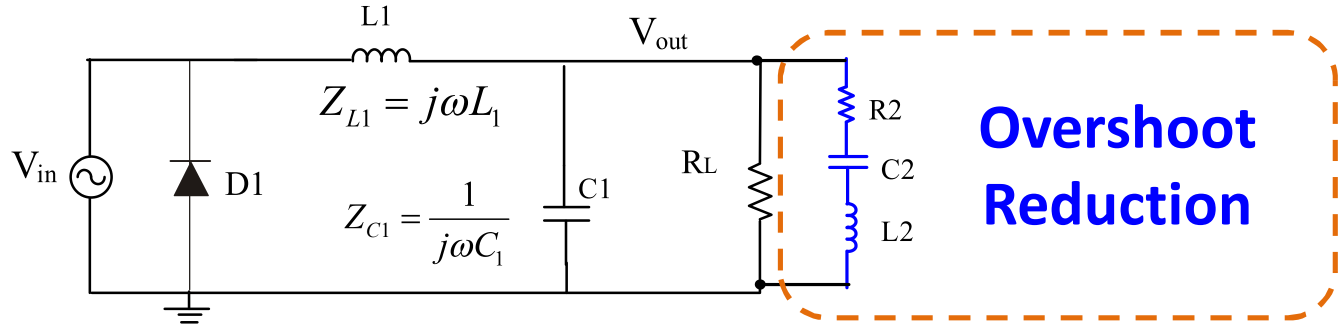
EMI Reduction using Spread Spectrum of VCO

Overshoot improvement with parallel RLC

3. Proposed Design of Buck Converter

Overshoot Improvement with Parallel RLC Network

Proposed model



Superposition principle

$$V_o\left(\frac{1}{Z_{L1}}+\frac{1}{Z_{C1}}+\frac{1}{R_L}+\frac{1}{R_2+Z_{L2}+Z_{C2}}\right)=\frac{V_{in}}{Z_{L1}}$$

Output Voltage

$$V_o=V_{in}\frac{\left(Z_{L2}+Z_{C2}+R_2\right)Z_{L1}R_L}{\left(Z_{L2}+Z_{C2}+R_2\right)\left[R_L\left(Z_{L1}+Z_{C1}\right)+Z_{L1}Z_{C1}\right]+Z_{L1}Z_{C1}R_L}$$

Transfer Function

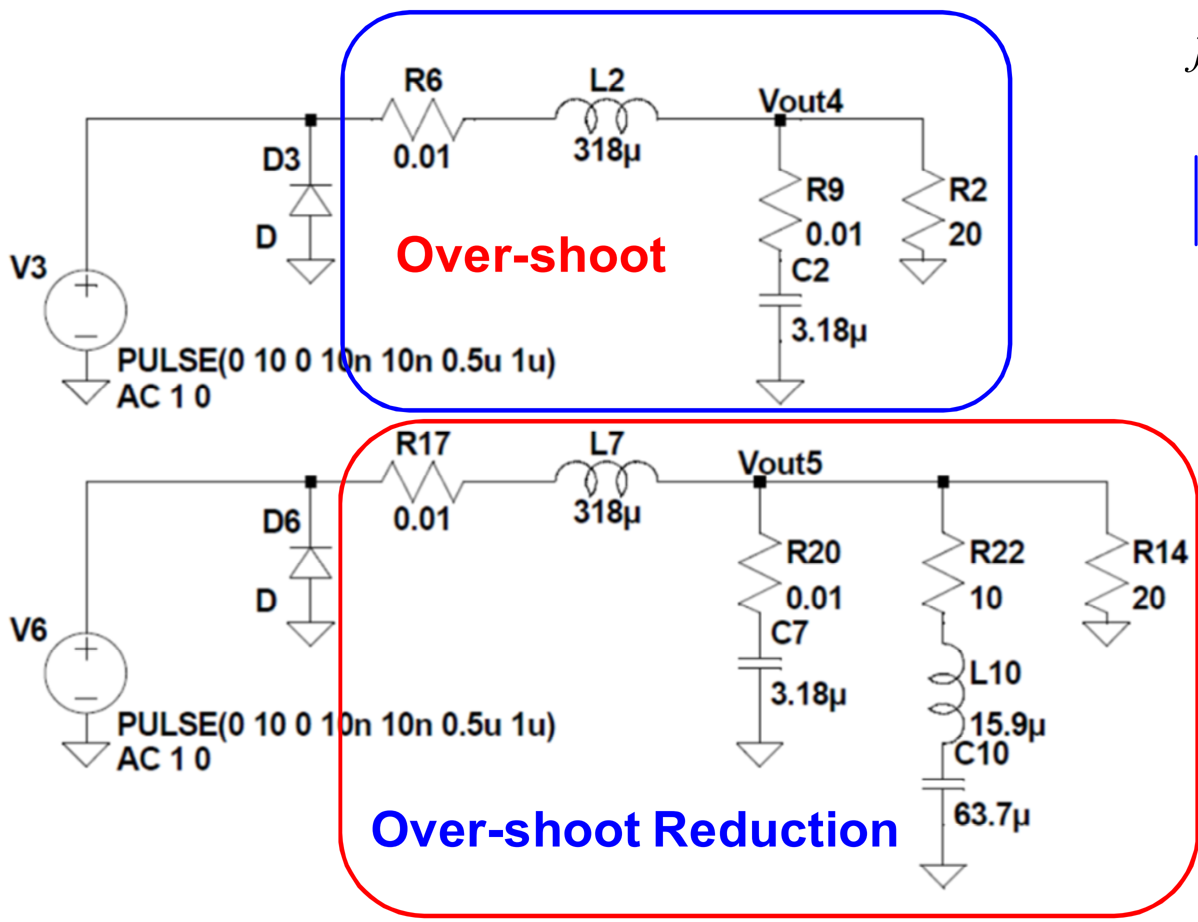
$$H=\frac{V_o}{V_{in}}=\frac{\left(Z_{L2}+Z_{C2}++R_2\right)Z_{L1}R_L}{\left(Z_{L2}+Z_{C2}+R_2\right)\left[R_L\left(Z_{L1}+Z_{C1}\right)+Z_{L1}Z_{C1}\right]+Z_{L1}Z_{C1}R_L}$$

$$H(j\omega)=\frac{\frac{1}{L_1C_1}\left((j\omega)^2+j\omega\frac{R_2}{L_2}+\frac{1}{L_2C_2}\right)}{\left((j\omega)^2+j\omega\frac{R_2}{L_2}+\frac{1}{L_2C_2}\right)\left((j\omega)^2+j\omega\frac{1}{R_LC_1}+\frac{1}{L_1C_1}\right)+\frac{(j\omega)^2}{L_2C_1}}$$

3. Proposed Design of Buck Converter

Simulation of Parallel RLC Network

$$|Z_L| = |Z_C| = 10\Omega < 2R = 40\Omega$$



Cutoff frequency

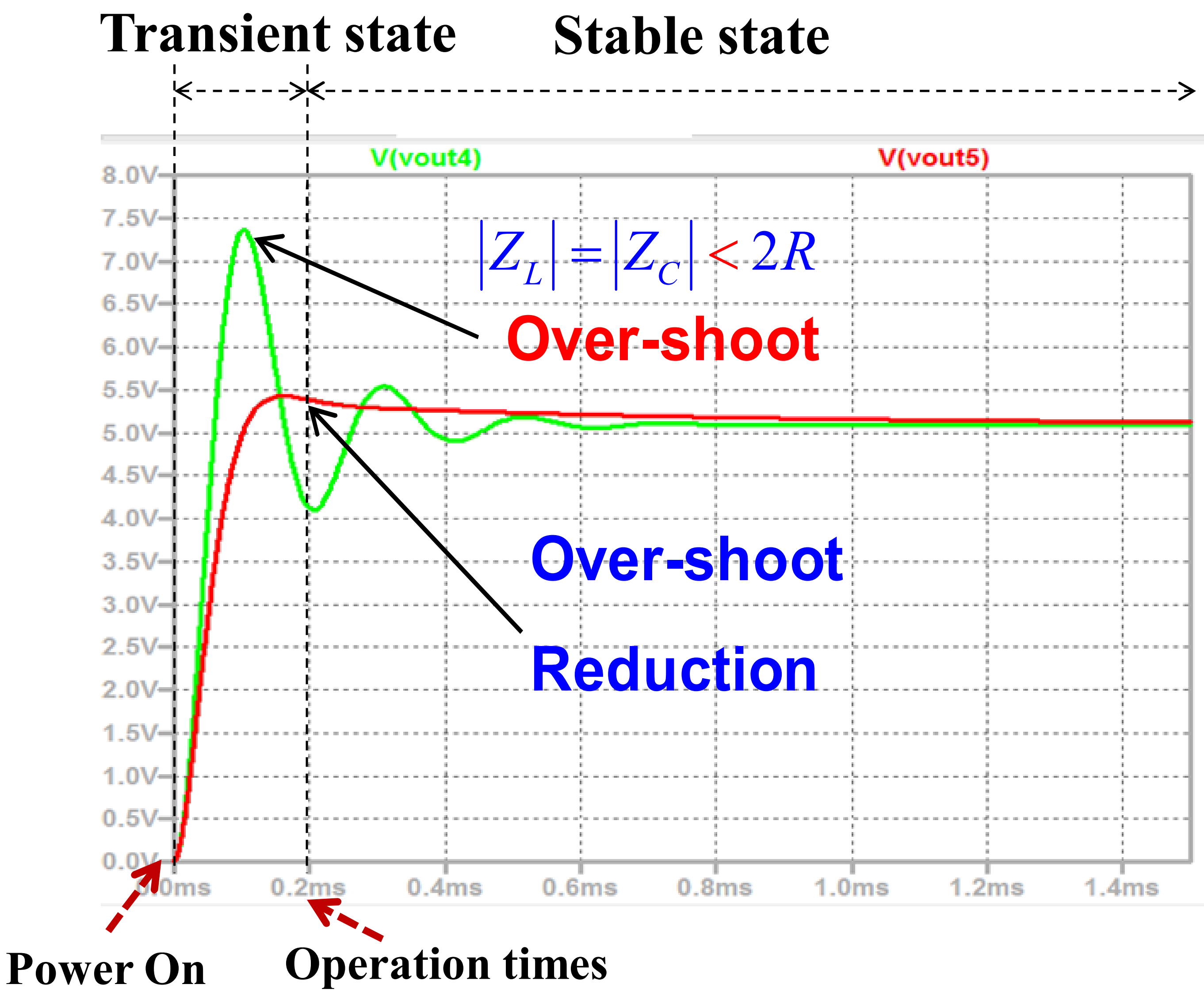
$$f_{cut\_off} = \frac{1}{2\pi\sqrt{LC}} = 5kHz$$

$$|Z_L| = |Z_C| = 10\Omega;$$

$$2R = 40\Omega$$

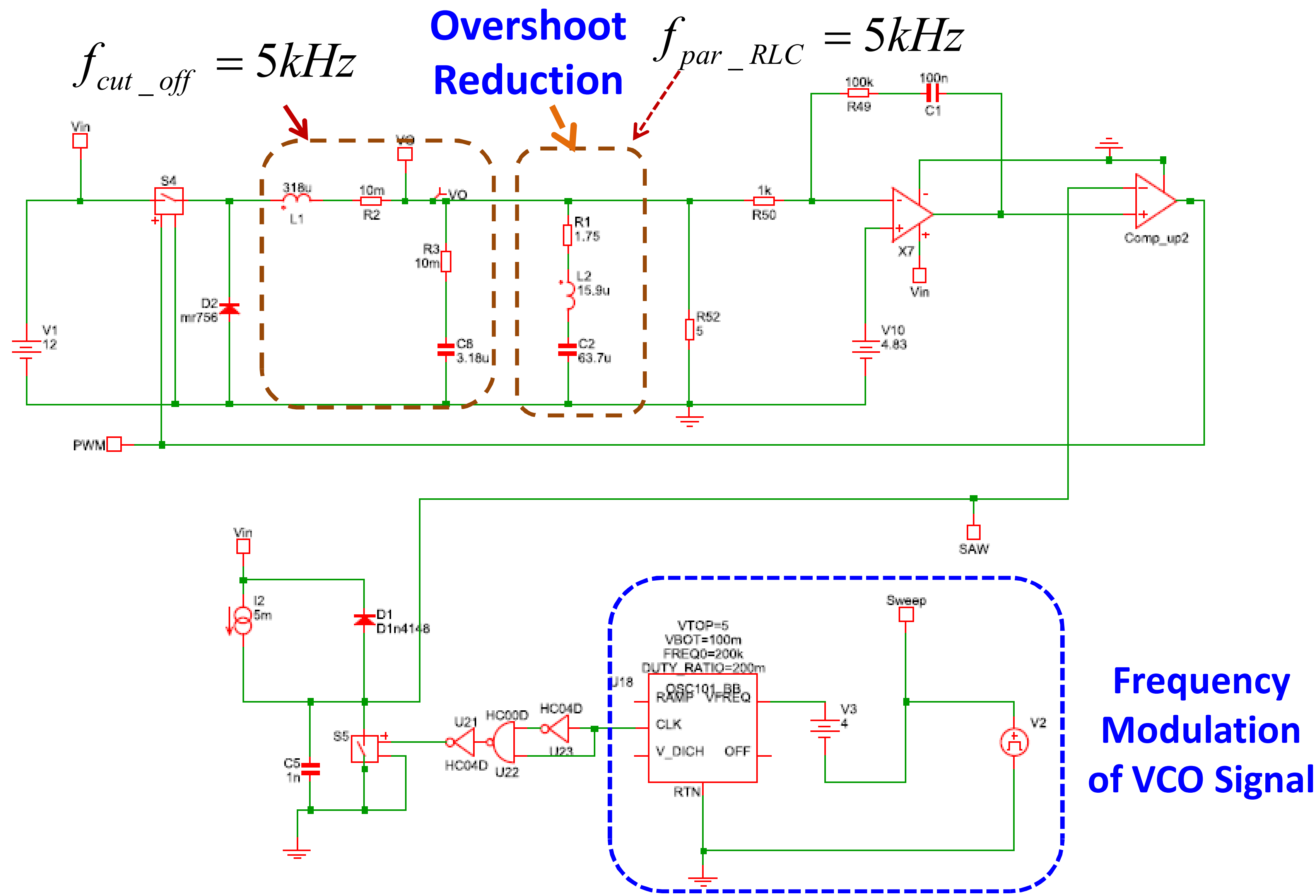
3. Proposed Design of Buck Converter

Transient Response of Parallel RLC Network



3. Proposed Design of Buck Converter

Proposed Design of Step-down Switching Converter



3. Proposed Design of Buck Converter

Overshoot Reduction Waveforms

without parallel RLC network

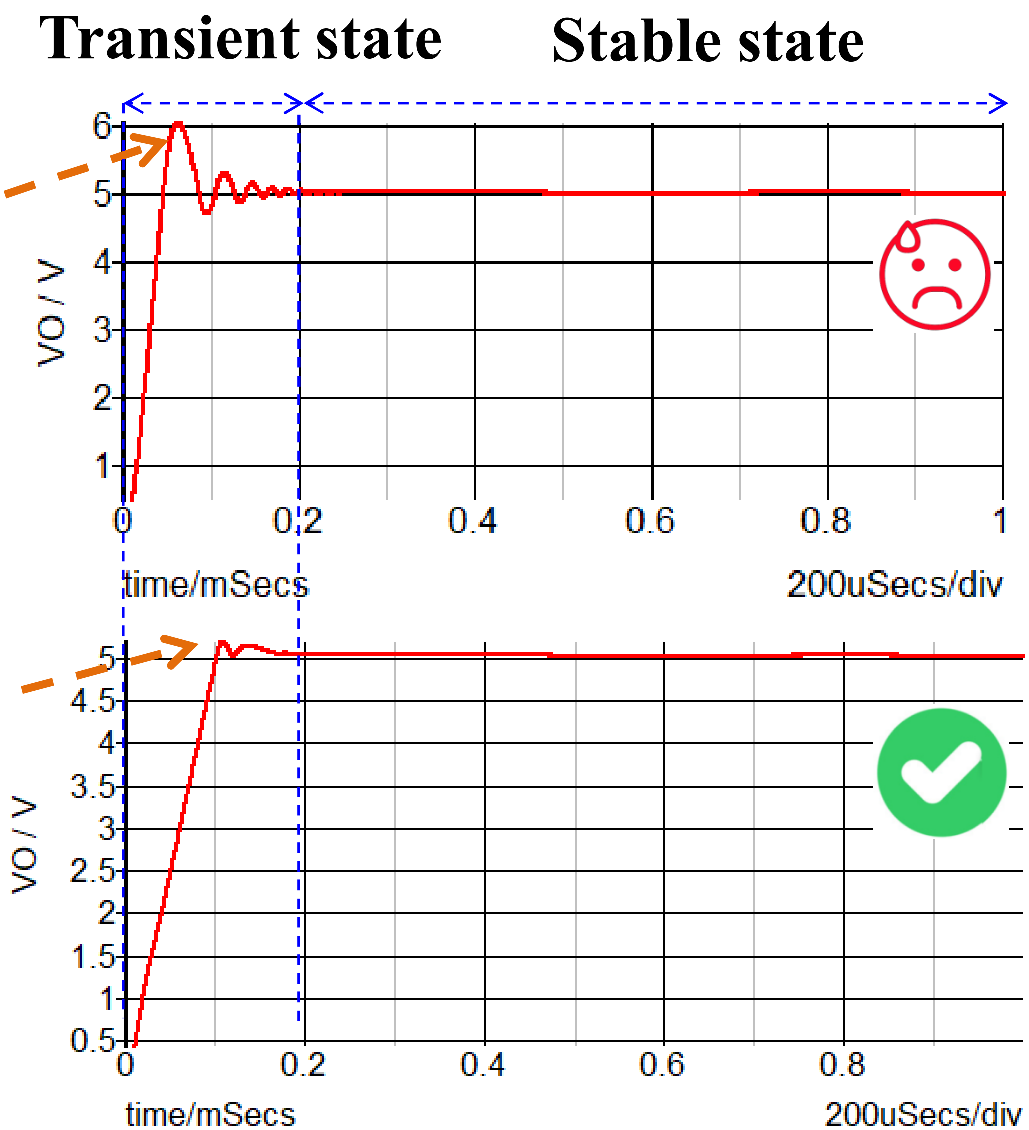
Overshoot Voltage

>1 Vpp

with parallel RLC network

Overshoot Voltage Reduction

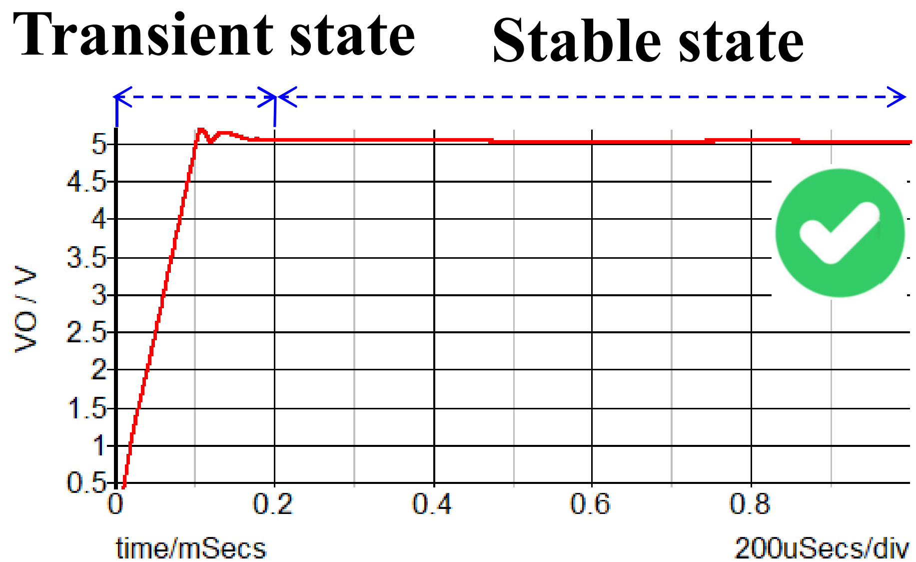
< 0.1 Vpp

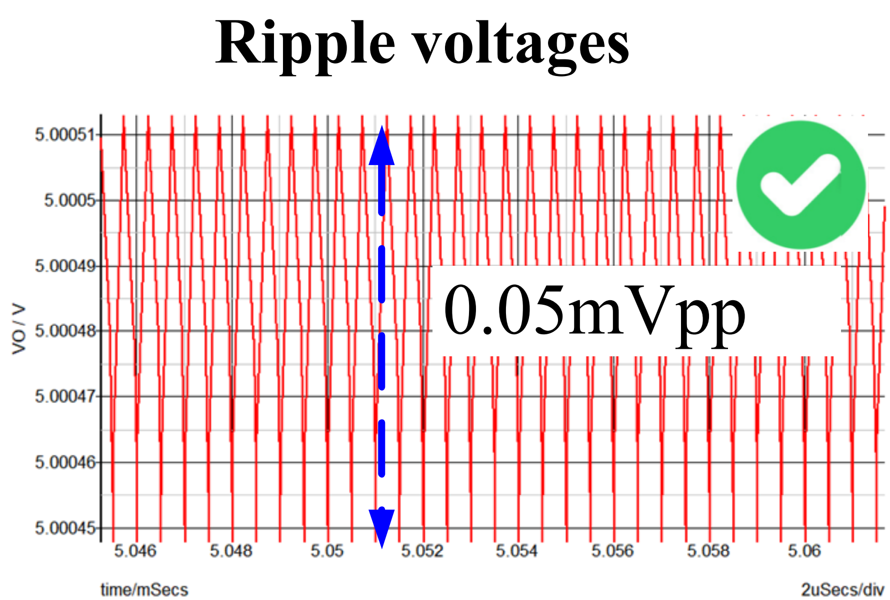


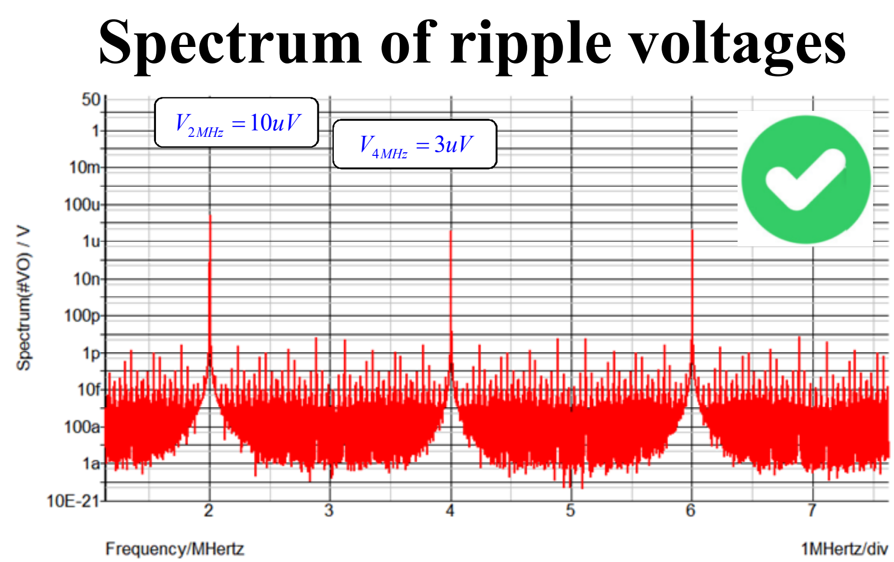
3. Proposed Design of Buck Converter

Waveforms of Proposed Buck Converter

- Input Voltage (Vin): 12V
- Output Voltage (Vo): 5.0V
- Output Current (Io): 1A
- Clock Frequency (Fck): 200kHz
- Overshoot: 0.1V
- Ripple Voltage: 0.05mVpp







4. Conclusions

This work:

- **Balanced charge-discharge time condition**

$$|Z_L| = |Z_C| = 2R \Rightarrow \omega L = \frac{1}{\omega C} = 2R \qquad \omega = \frac{1}{\sqrt{LC}} = \frac{1}{2RC}$$

- **Analysis model of Buck converter system based on classical technique and superposition principle**
- **Overshoot improvement with parallel RLC network**

  → Overshoot reduction from 1Vpp into 0.1Vpp

Future of Work

- **Analysis of parasitic of RLC and other components**

Thanks for your kind attention!

谢 谢