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Estimation of Circuit Component Values in Buck Converter using Efficiency Curve

S. Sakurai, N. Tsukiji,
Y. Kobori, H. Kobayashi
Gunma University

Outline

1. Purpose of this work

2. Background

3. Estimation principle

4. Estimation result

5. Summary

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1. Purpose of this work
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4. Estimation result
5. Summary

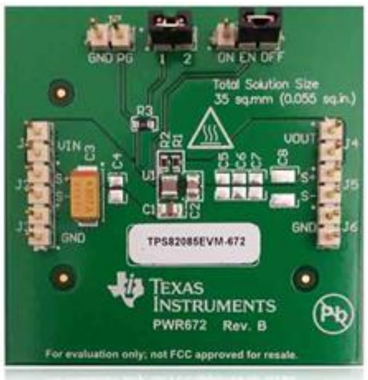
Purpose of this work

- Development of an estimation method for component values in DC-DC converter from its measured efficiency curve

- Validation of its transfer function estimation for phase compensation design with estimated component values

Outline

Background

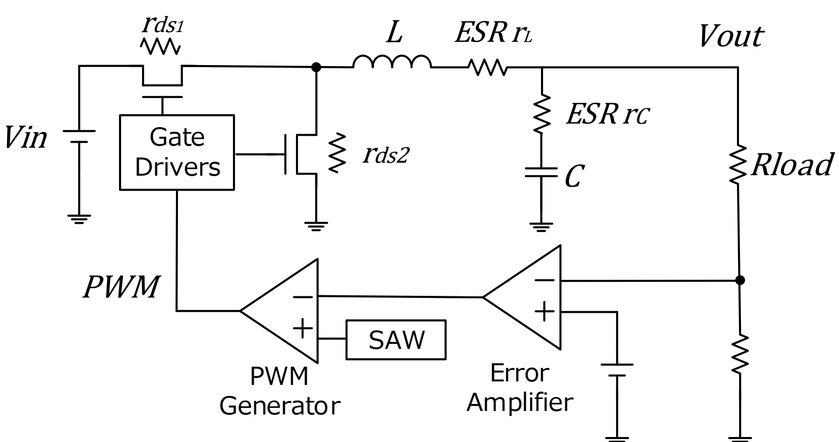


Switching converter

Electronic Devices

IoT Device

Information Device



Demands

Smaller
Lighter
Higher efficiency

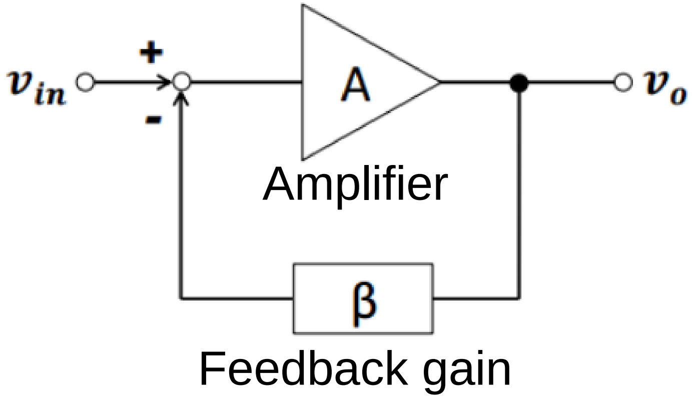
Negative Feedback Circuit

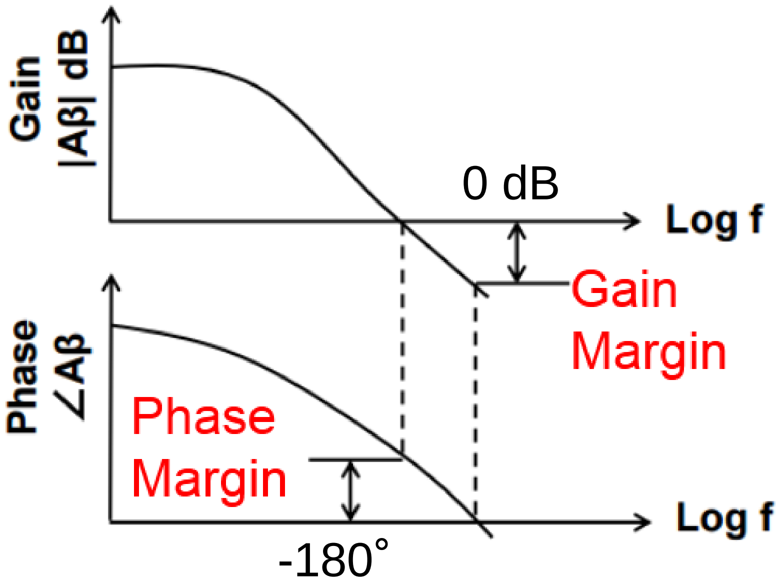
Switching converter use negative feedback control

When loop gain $A\beta = -1$, circuit oscillates.

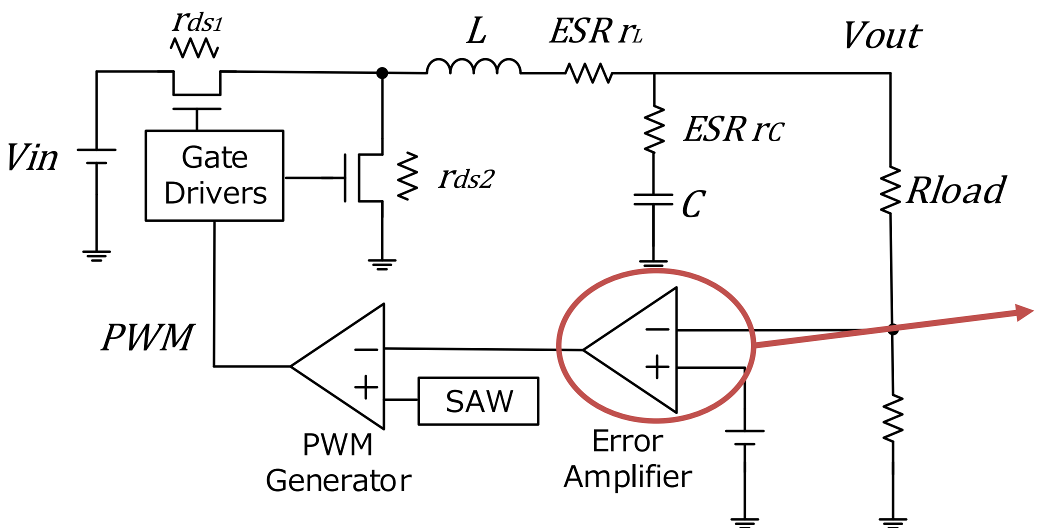
Need suitable phase compensation.

$$\frac{v_o}{v_{in}} = \frac{A}{1 + A\beta}$$

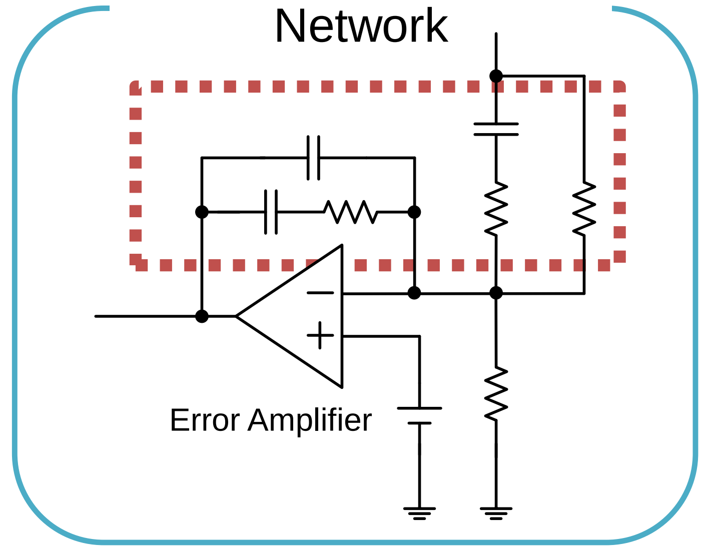


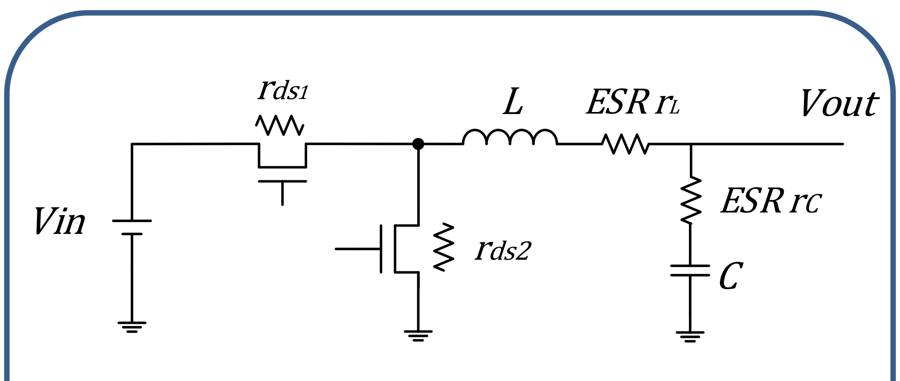


Phase Compensation Design



Phase Compensation Network





Power stage

$$G_{dv}(s)\Big|_{\substack{\Delta V_i=0\\ \Delta I_o=0}} = \frac{\Delta V_o}{\Delta D} \rightarrow \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Transfer function of power stage

is necessity

Power-Stage Transfer Function and Component Values

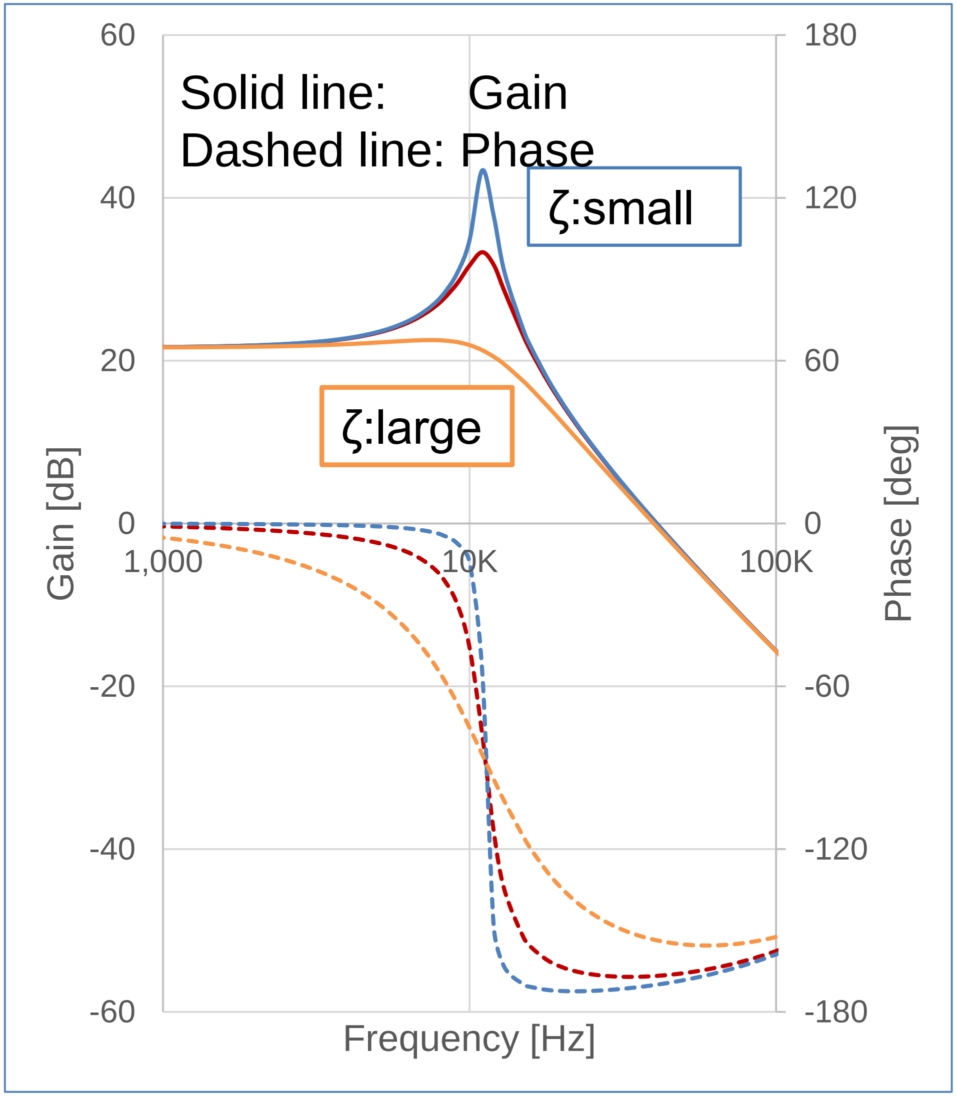
$$G_{dv}(s)\Big|_{\substack{\Delta V_i=0\\ \Delta I_o=0}} = \frac{\Delta V_o}{\Delta D} \rightarrow \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$= \frac{V_i \cdot \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}\left(1 + \frac{s}{\omega_{esr}}\right)$$

$$\zeta = \frac{r_L + r_C + r_{ds}}{2}\sqrt{\frac{C}{L}},\quad \omega_n = \frac{1}{\sqrt{LC}},\quad \omega_{esr} = \frac{1}{Cr_c}$$

Damping factor ζ

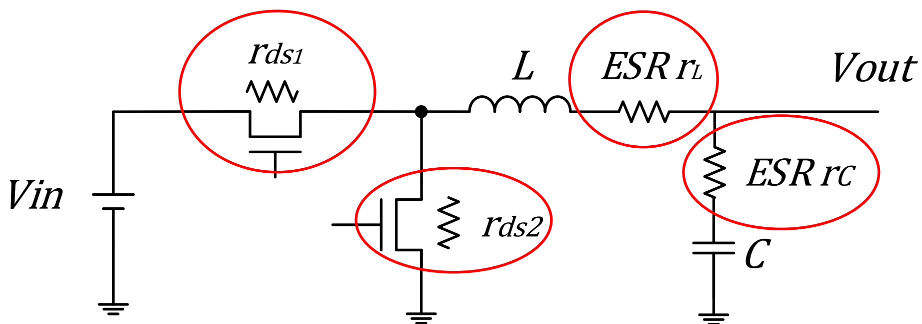
ζ	Gain	Phase
Larger	Peak	Looser
Smaller	No peak	Steeper



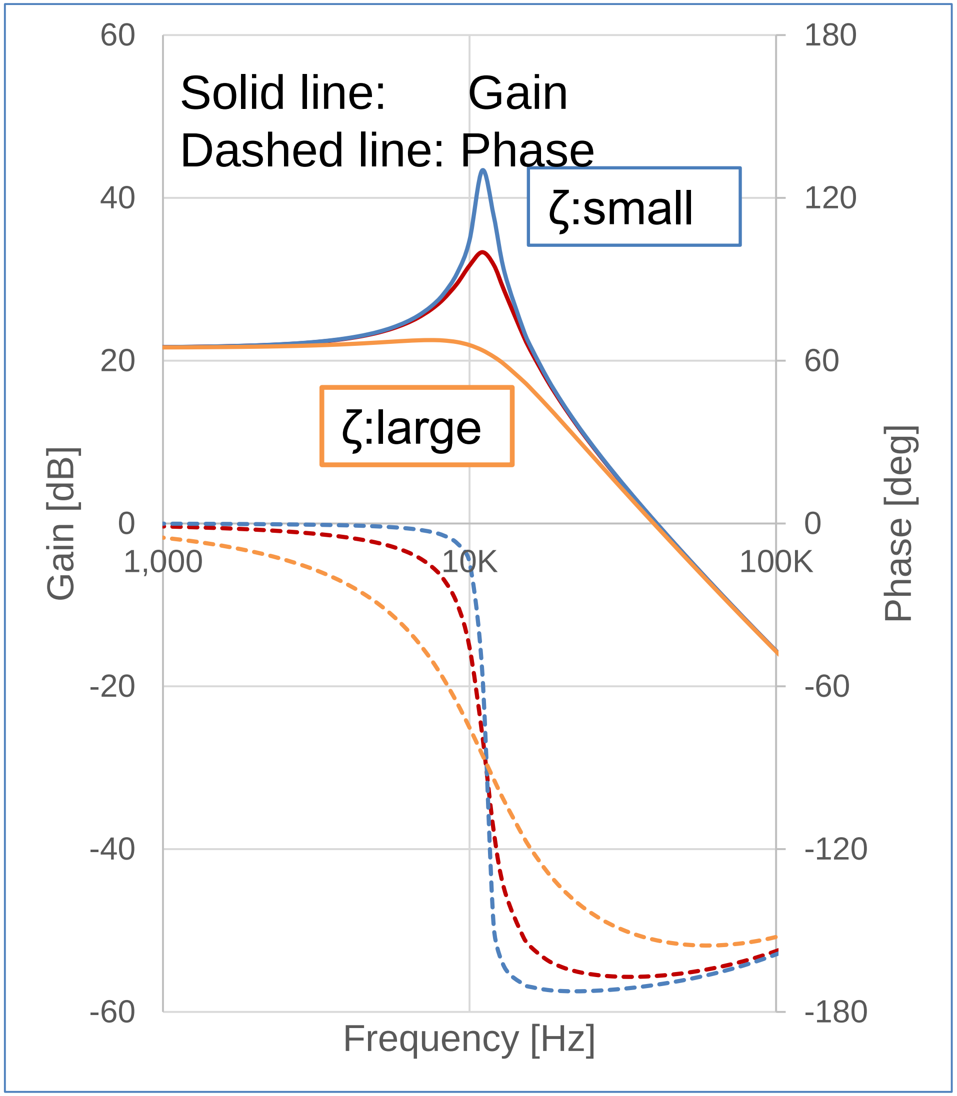
Importance of Component Values

ζ depends on
circuit component values

$$\zeta = \frac{r_L + r_{ds} + r_C}{2}\sqrt{\frac{C}{L}}$$

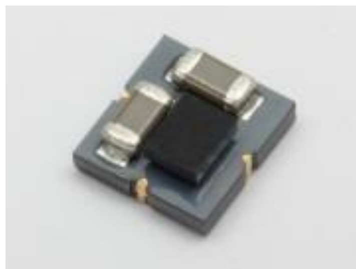


Necessary for
phase compensation
design

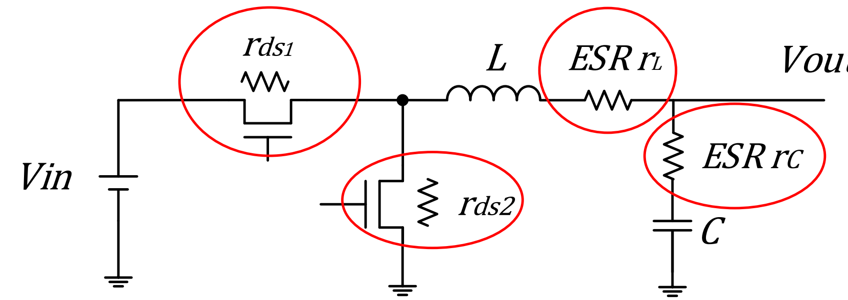


Problems

Implemented power supply



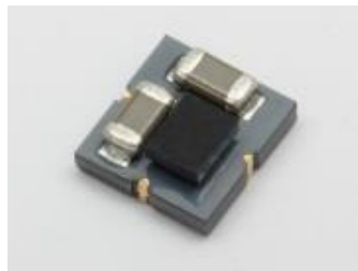
Component values



Difficult to measure

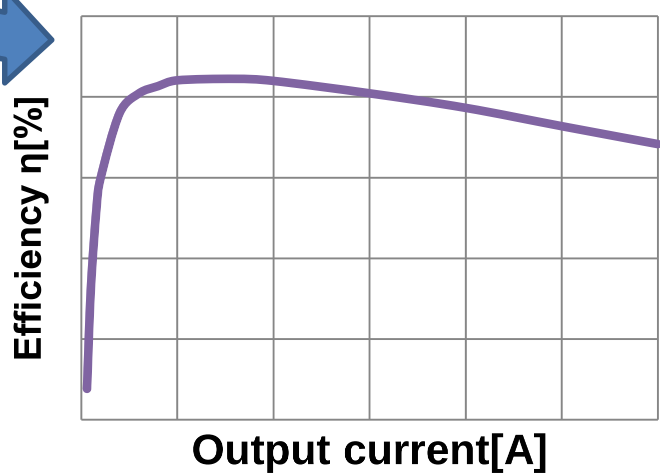
Proposed method

Implemented power supply

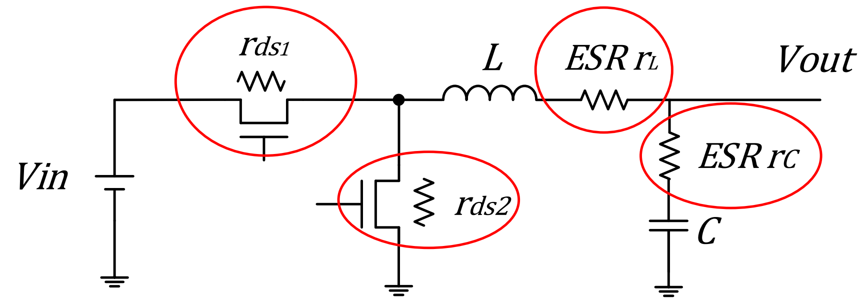


Easy

Measure efficiency curve



Component values



Estimate

Our proposal

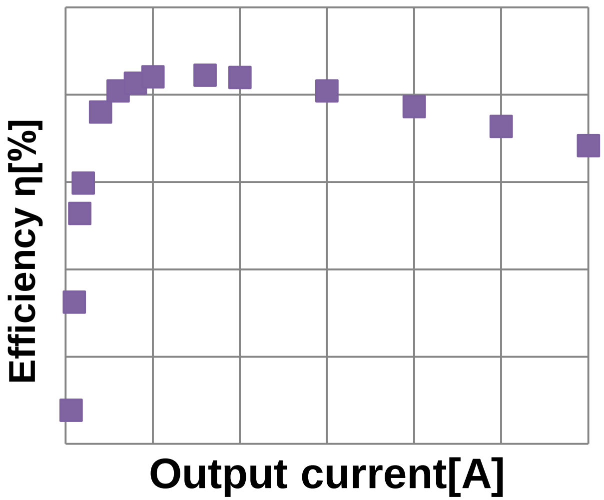
Not directly measure.

Estimation from measured efficiency curve.

Outline

Estimation Principle

Measured efficiency



Theoretical formula of losses

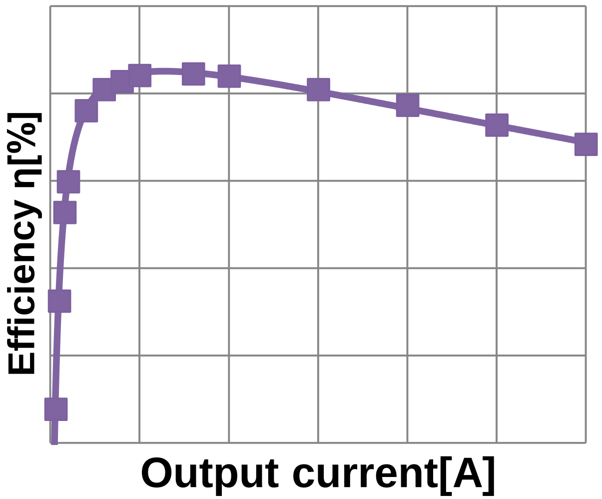
$$P_{sw\ loss} = \frac{1}{6} V_i I_o (\Delta T_{ON} + \Delta T_{OFF}) \cdot f_{sw}$$

$$P_L = R_L \cdot I_o^2 \qquad P_C = R_C \cdot I_C^2$$

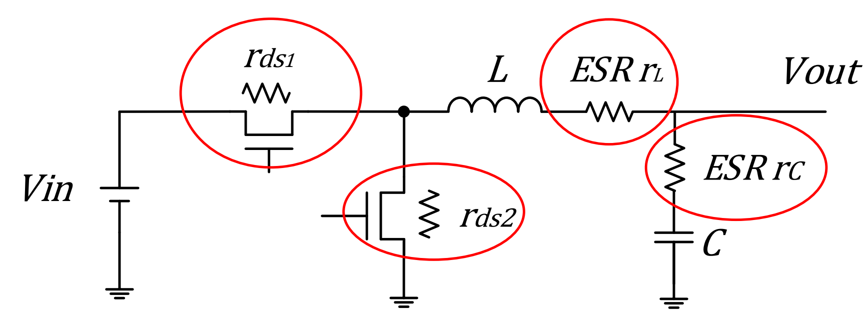
$$\eta = \frac{V_{out} \cdot I_o}{V_{out} \cdot I_o + P_{loss}}$$

Fitting

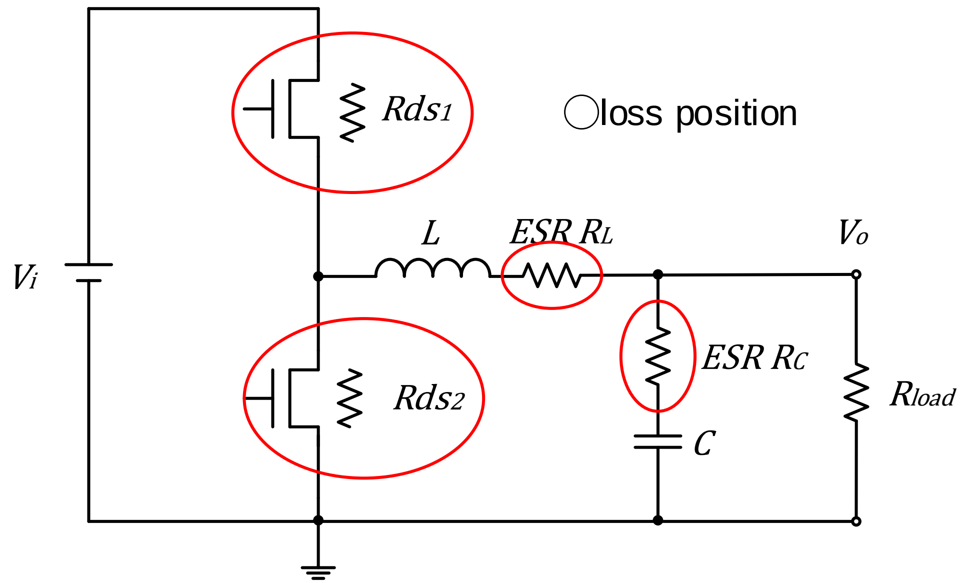
Fitted efficiency curve



Component values



Loss Classification of Switching Regulator



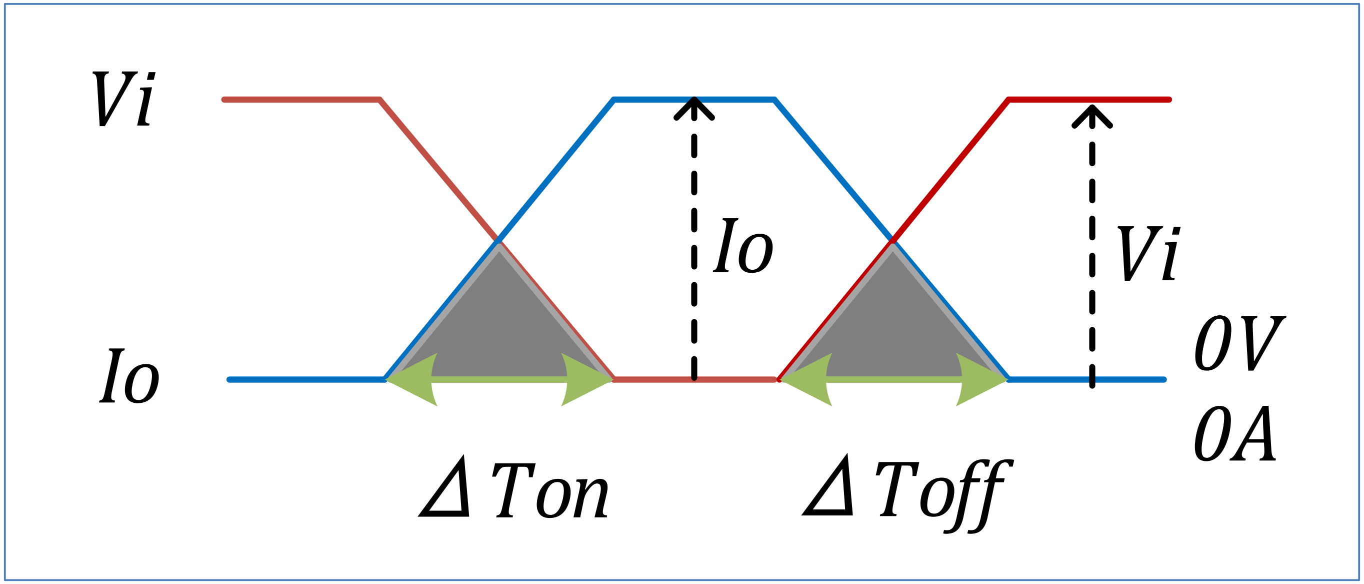
1. Proportional to the load current $: P_1[W]$
   Switching loss

2. Proportional to square of the load current $: P_2[W]$
   Conduction loss

3. Constant loss $: P_{const}[W]$

Switching Loss (P_1)

First loss



$$P_{sw\ loss} = f_{sw}\left[\int_0^{\Delta T_{on}} v_{tr}(t)\cdot i_{tr}(t)dt + \int_0^{\Delta T_{off}} v_{tr}(t)\cdot i_{tr}(t)dt\right]$$

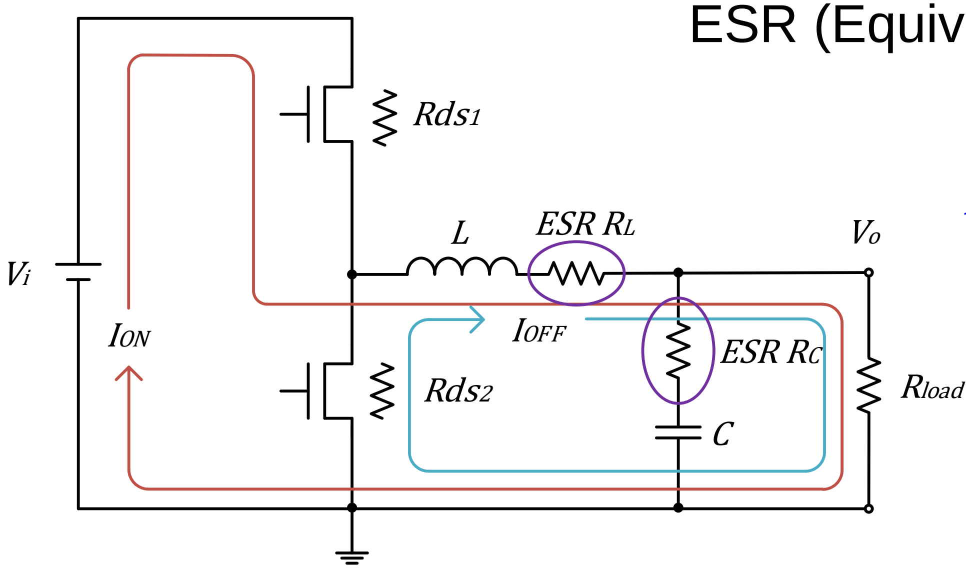
$$= \frac{1}{6}V_i\cdot I_o(\Delta T_{ON} + \Delta T_{OFF})\cdot f_{sw}$$

V_i : Drain-source voltage [V]

I_o : Load current [A]

Conduction Loss of L , C (P_2)

Second loss



ESR (Equivalent Series Resistance)

I^2R drop by lead, metal coating

Caused by
resistances of cable, metal

- Inductor loss

$$P_L = R_L \cdot I_o^2$$

R_L : Inductor ESR
I_o : Load current

- Capacitor loss

$$P_C = R_C \cdot I_C^2$$

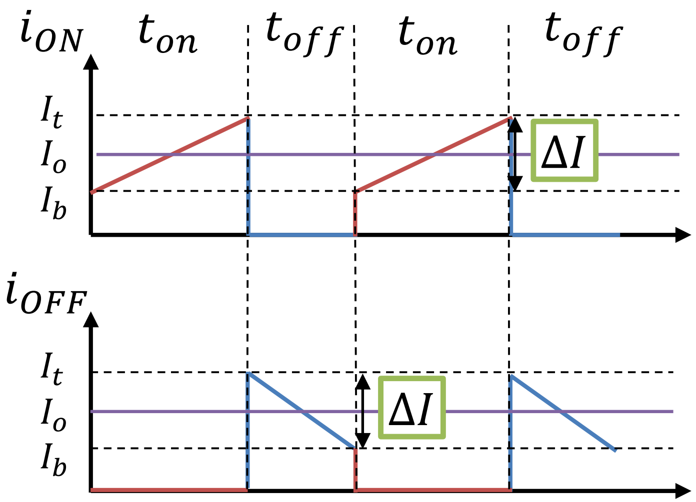
※$I_C \propto I_o$

R_C : Capacitor ESR
I_c : Ripple current

MOSFET Conduction Loss (P_2)

Second loss

MOSFET Conduction loss

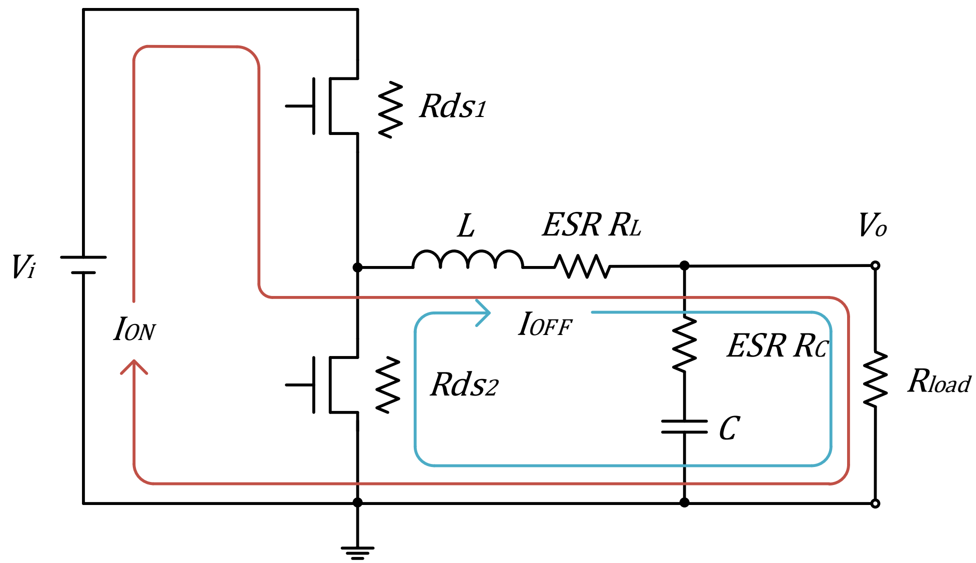


P_{cond1}

$$\frac{V_o}{V_{in}}\left(I_o^2 + \frac{\Delta I^2}{12}\right) \cdot R_{ds1}$$

P_{cond2}

$$\left(1 - \frac{V_o}{V_{in}}\right)\left(I_o^2 + \frac{\Delta I^2}{12}\right) \cdot R_{ds2}$$



$$P_{cond} = I_o^2\left[\frac{V_o}{V_{in}}(R_{ds1} - R_{ds2}) + R_{ds2}\right]$$

I_o : Load current
ΔI : Ripple current
R_{DS1} : High-side MOS resistance
R_{DS2} : Low-side MOS resistance

Loss Equations

First loss : P_1

$$P_{sw\ loss} = \frac{1}{6} V_i I_o (\Delta T_{ON} + \Delta T_{OFF}) \cdot f_{sw}$$

Second losses : P_2

$P_L = R_L \cdot I_o^2$ $\qquad$ $P_C = R_C \cdot I_C^2$ $\qquad$ ※$I_C \propto I_o$

$$P_{cond} = I_o^2 \left[\frac{V_o}{V_{in}} \left(R_{ds1(on)} - R_{ds2(on)} \right) + R_{ds2(on)} \right]$$

Constant loss : P_{const}

Control stage

Error amp
Comparator
Gate driver

Quiescent current

Given as constant

Loss Equations - Highlight

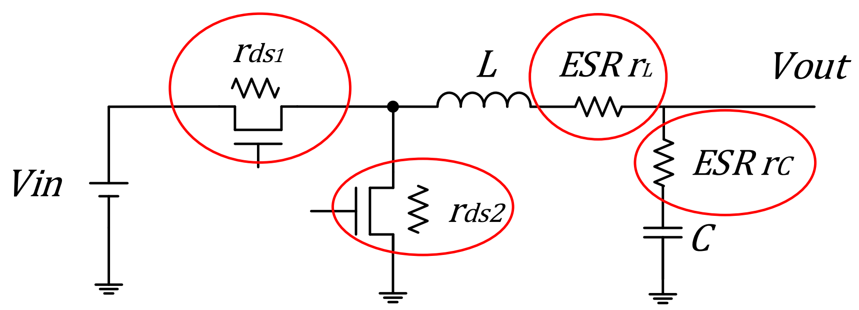
Most important!

Second order losses : P_2

$$P_L = R_L \cdot I_o^2 \qquad P_C = R_C \cdot I_C^2 \qquad ※ I_C \propto I_o$$

$$P_{cond} = I_o^2 \left[\frac{V_o}{V_{in}} \left(R_{ds1(on)} - R_{ds2(on)} \right) + R_{ds2(on)} \right]$$

Component values



Losses and Efficiency

$$P_2 = P_{MOS} + P_L + P_C = K_2 \cdot I_o^2$$

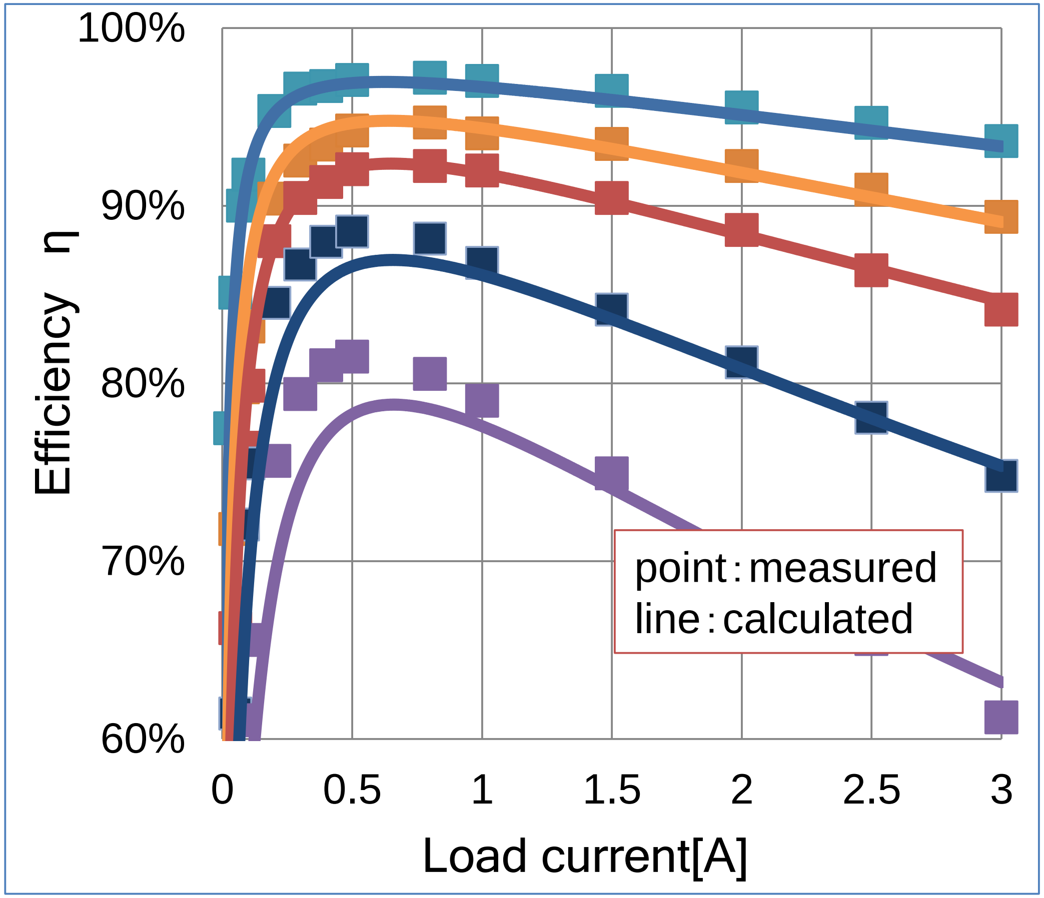
$$P_1 = P_{sw} = K_1 \cdot I_o$$

$$P_{const}$$

$$P_{loss} = P_2 + P_1 + P_{const}$$

Efficiency

$$\eta = \frac{V_{out} \cdot I_o}{V_{out} \cdot I_o + P_{loss}}$$

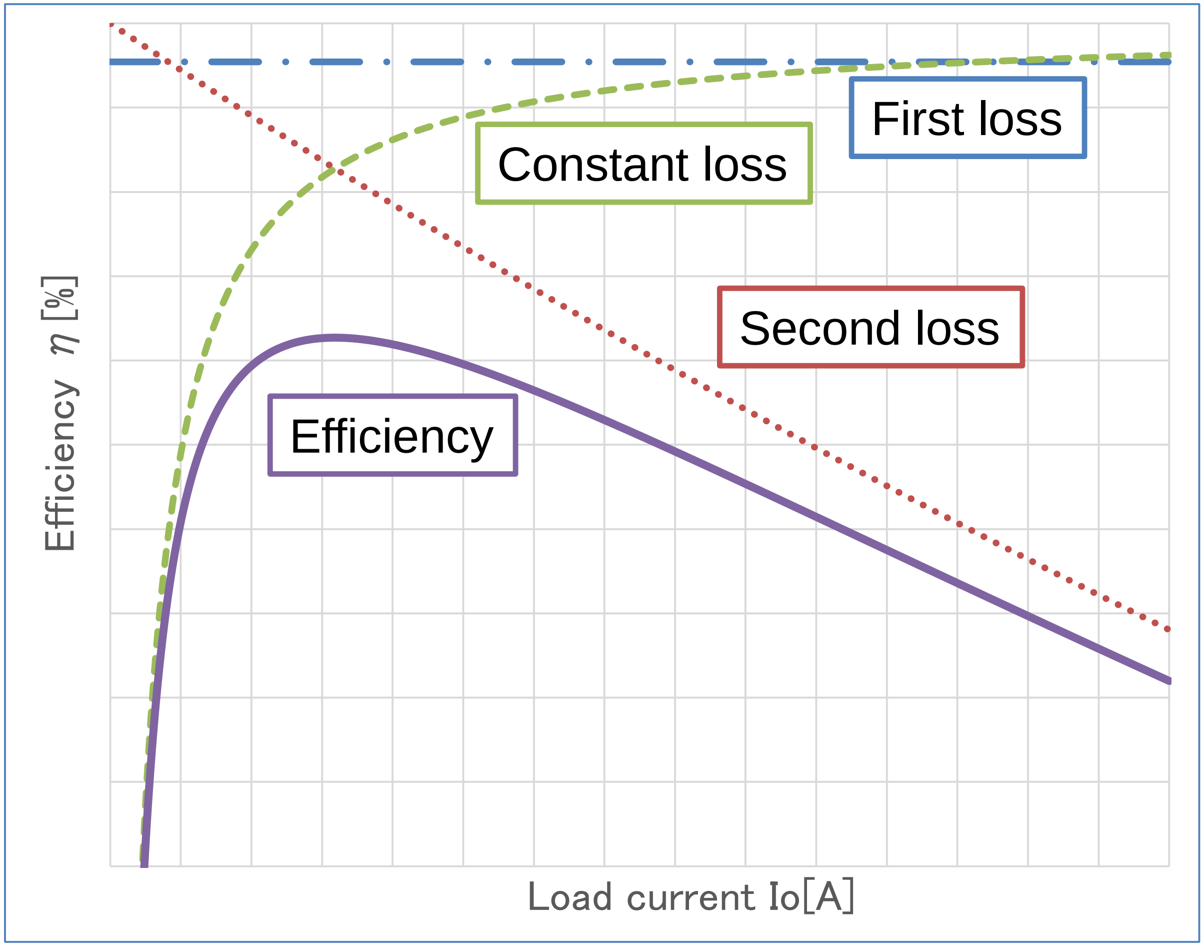


Fitting between calculation and measurement

Effect of Each Loss to Efficiency

For load current increase

- First loss →constant
- Second loss →decrease
- Constant loss →log increase



Outline

Experiment Conditions

- Synchronous step-down DC/DC converter (TPS54317 Texas Instruments)
- Only measured efficiency curve used

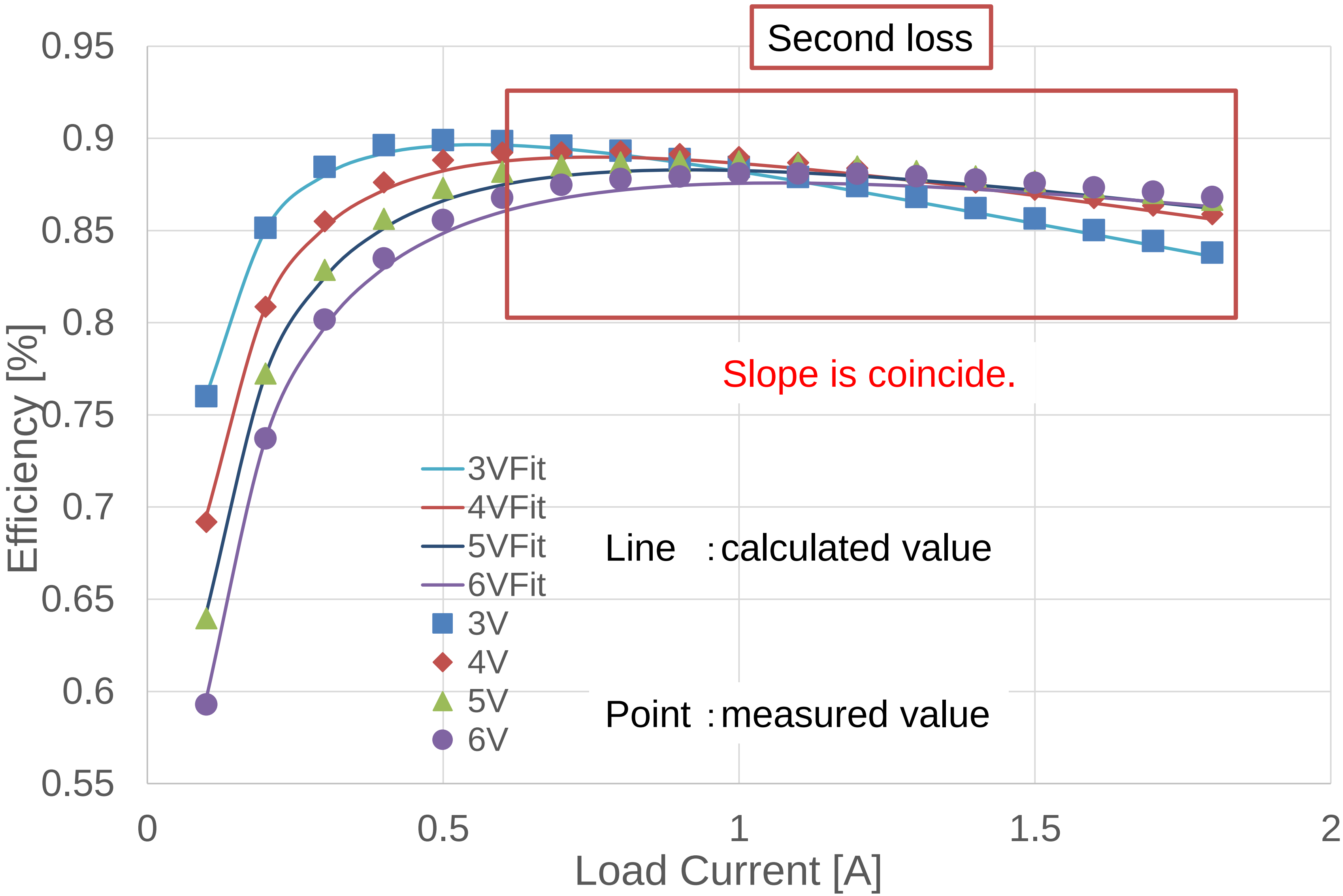
Estimation parameters

- ☐ Inductor ESR
- ☐ High side MOS DC resistance
- ☐ MOSFET Turn on time
- ☐ Constant loss
- ☐ Capacitor ESR
- ☐ Low side MOS DC resistance
- ☐ MOSFET Turn off time

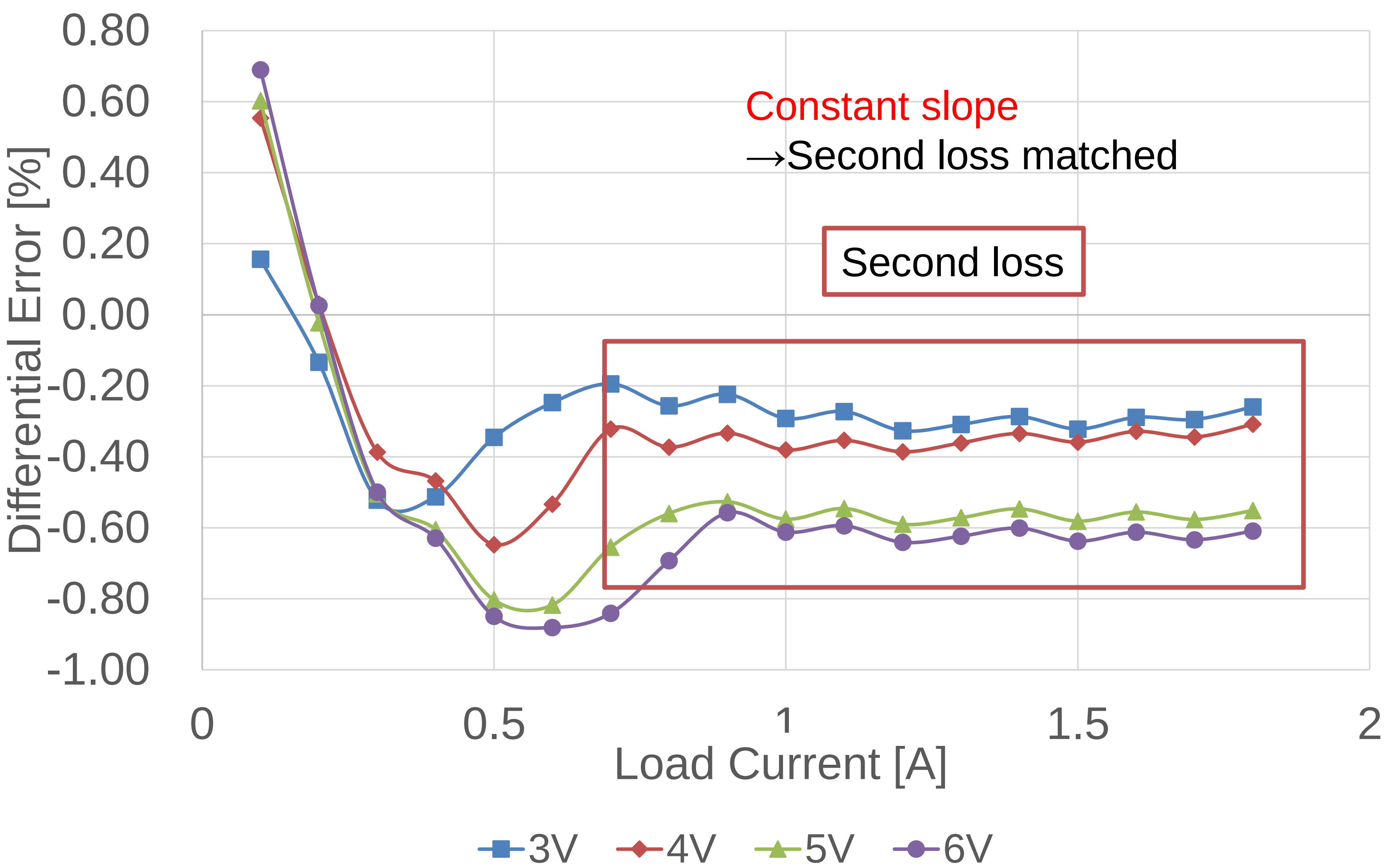
Setting parameter

Input Voltage V_i	3.0V/4.0V/5.0V/6.0V
Output Voltage V_o	1.8V
Switching frequency f_{sw}	550kHz
Inductor L	1μH
Capacitor C	200μF(100uF*2+1.0nF)

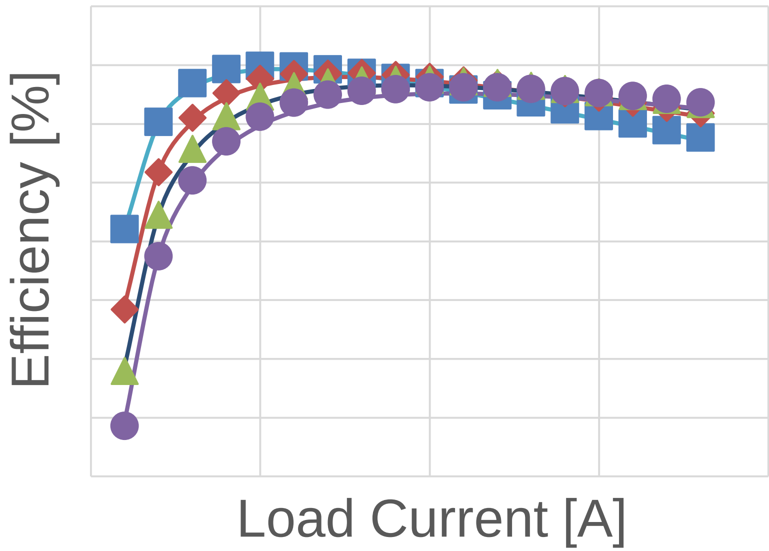
Fitting Result



Fitting Result – Error



Component Value Estimation Result



Turn-on time of MOSFET T_{on}	2nsec
Turn-off time of MOSFET T_{off}	4nsec

Estimation result

Inductor ESR	10mΩ
Capacitor ESR	1mΩ
High side ON resistor of MOSFET R_{ds1}	30mΩ at 3V 20mΩ at 4V 15mΩ at 5V 10mΩ at 6V
Low side ON resistor of MOSFET R_{ds2}	45mΩ at 3V 30mΩ at 4V 24mΩ at 5V 20mΩ at 6V
Quiescent current of IC I_{IC}.	4.8mA at 3V 5.1mA at 4V 5.2mA at 5V 5.3mA at 6V

Transfer Function Calculation

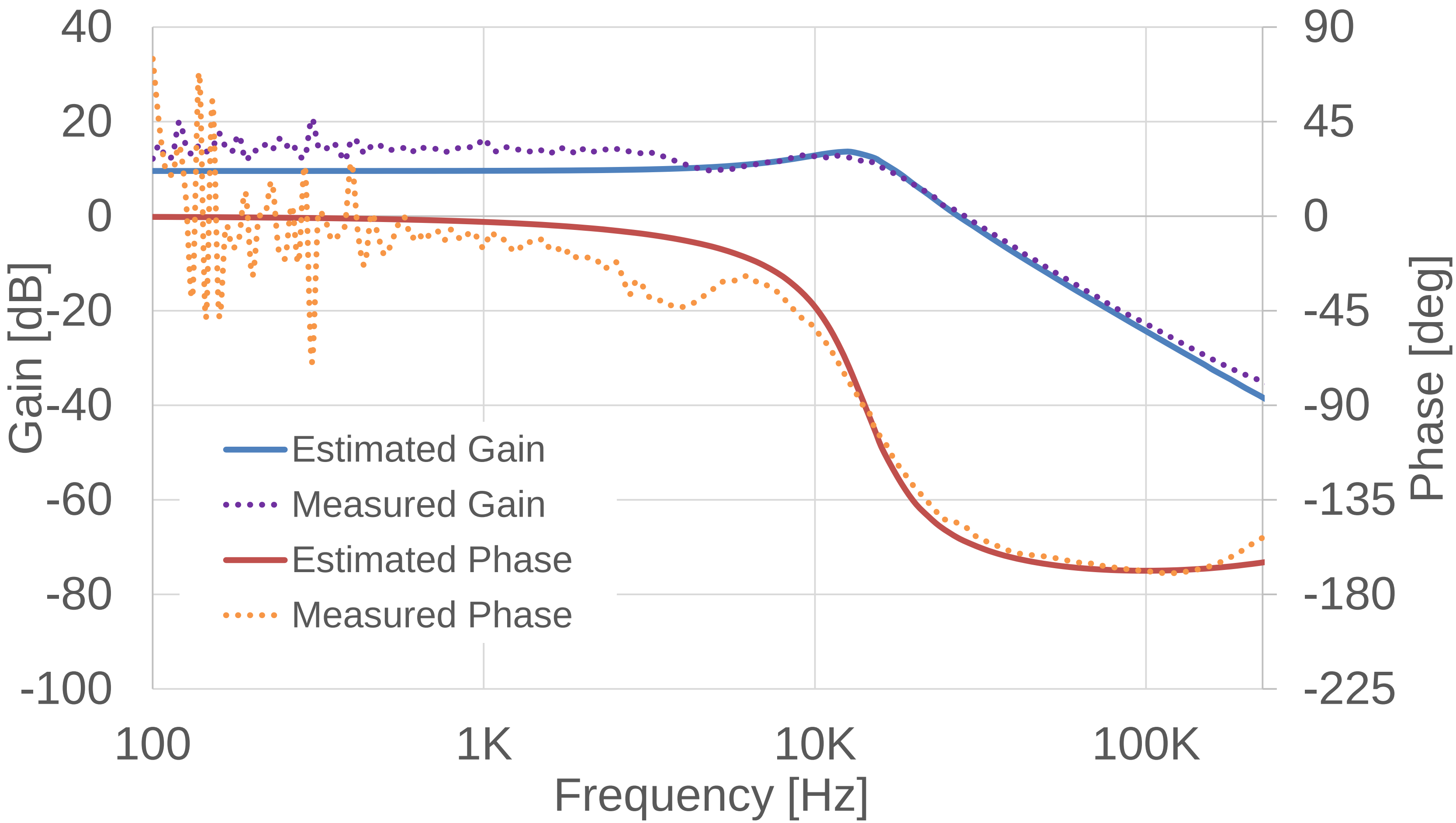
Transfer function of power stage is necessary for phase compensation

Possible to use estimated values

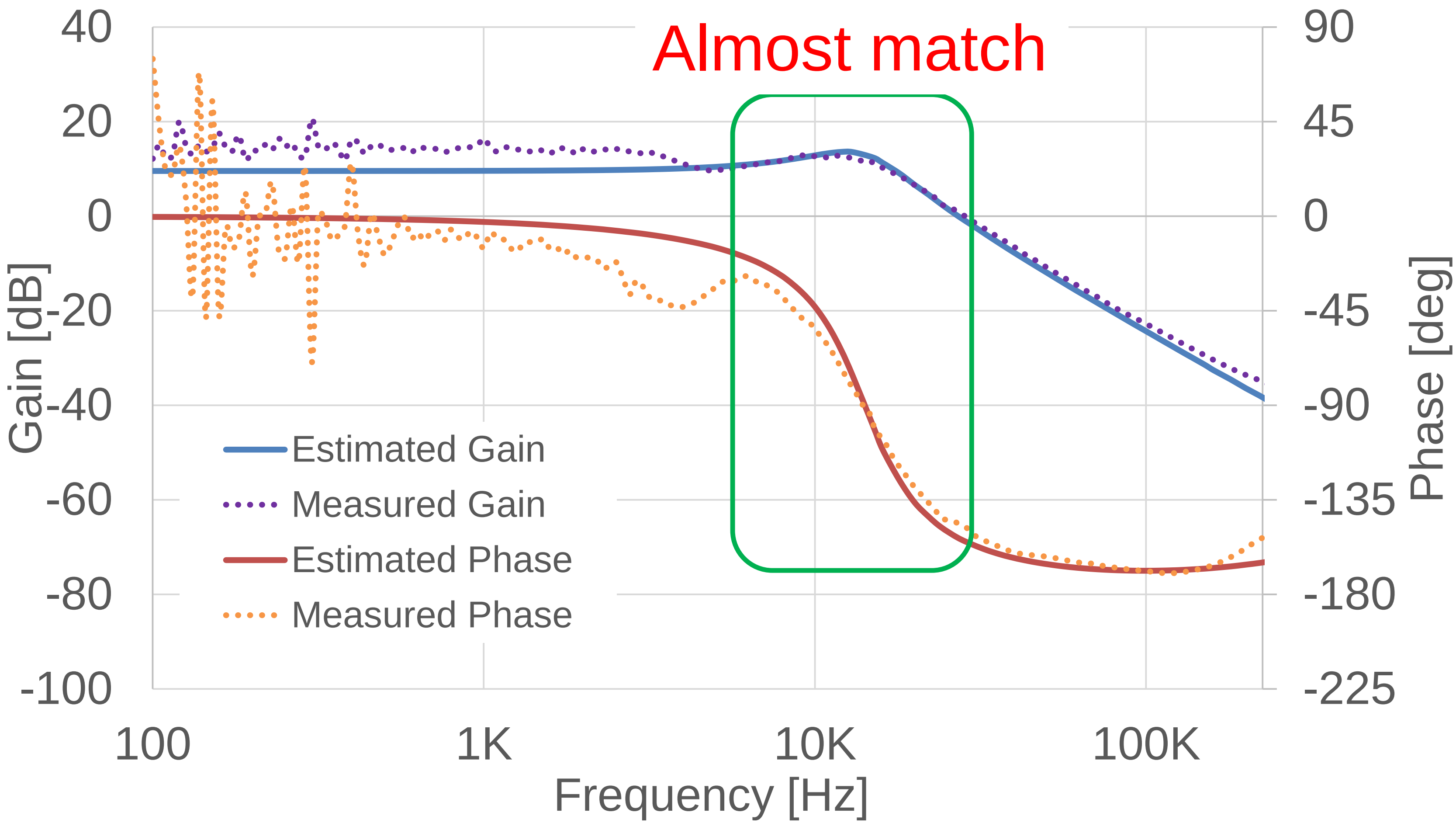
Parameters of G_{dv} at 3.0V

Switching Frequency f_{sw}	550kHz	Input Voltage V_i	3.0V
Inductor L	0.8μH	Capacitor C	160μF
Inductor ESR r_L	10mΩ	Capacitor ESR r_C	1mΩ
High side MOSFET DC resistance r_{ds1}	30mΩ	Low side MOSFET DC resistance r_{ds2}	45mΩ

Transfer Function Comparison



Transfer Function Comparison



Estimation result can be used for phase compensation

Outline

Summary

- Proposed a method to derive DC-DC converter component values from measured efficiency curve.

- Calculated the transfer function of power stage using estimation result.

- Measured and estimated results are well matched.

Future Research

- More experiment for validation
- Design of phase compensation using estimation result.
- More accurate fitting incorporate losses not considered.

Back Up

Power stage transfer function

Power stage transfer function at open loop

$$G_{dv}(s)\Big|_{\substack{\Delta V_i=0\\ \Delta I_o=0}} = \frac{\Delta V_o}{\Delta D} = \frac{V_i \cdot \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}\left(1 + \frac{s}{\omega_{esr}}\right)$$

$$= \frac{V_i(1 + j\omega C r_c)}{1 - \omega^2 LC + j\omega C(r_L + r_c + r_{ds})}$$

$$\zeta = \frac{r_L + r_C + r_{ds}}{2}\sqrt{\frac{C}{L}},\ \omega_n = \frac{1}{\sqrt{LC}},\ \omega_{esr} = \frac{1}{Cr_c}$$

Parameter of G_{dv} at 3.0V

Switching Frequency f_{sw}	550kHz	Input Voltage V_i	3.0V
Inductor L	0.8µH	Capacitor C	160µF
Inductor ESR r_L	10mΩ	Capacitor ESR r_C	1mΩ
High side MOSFET DC resistance r_{ds1}	30mΩ	Low side MOSFET DC resistance r_{ds2}	45mΩ