3MHz GaN DC-DC 48Vin direct to 0.6Vout realized by ultra-short pulse(5ns) using Virtual Peak Current Mode control technique

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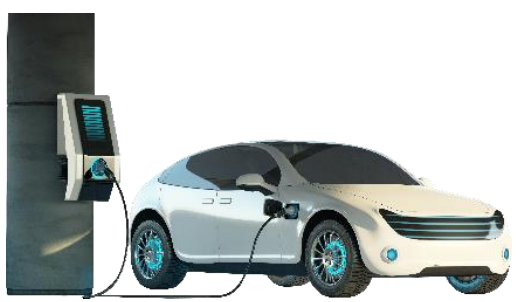
Introduction
Power Supply Market Trends

- **Increasingly high-capacity applications such as EV, data center, base station, etc.**
- **Increased applications for mobility (EV, E-bike, Drone, etc.)**

Reduce power loss with higher bus voltage



Introduction
Changes in Buck DCDC Converter Configurations

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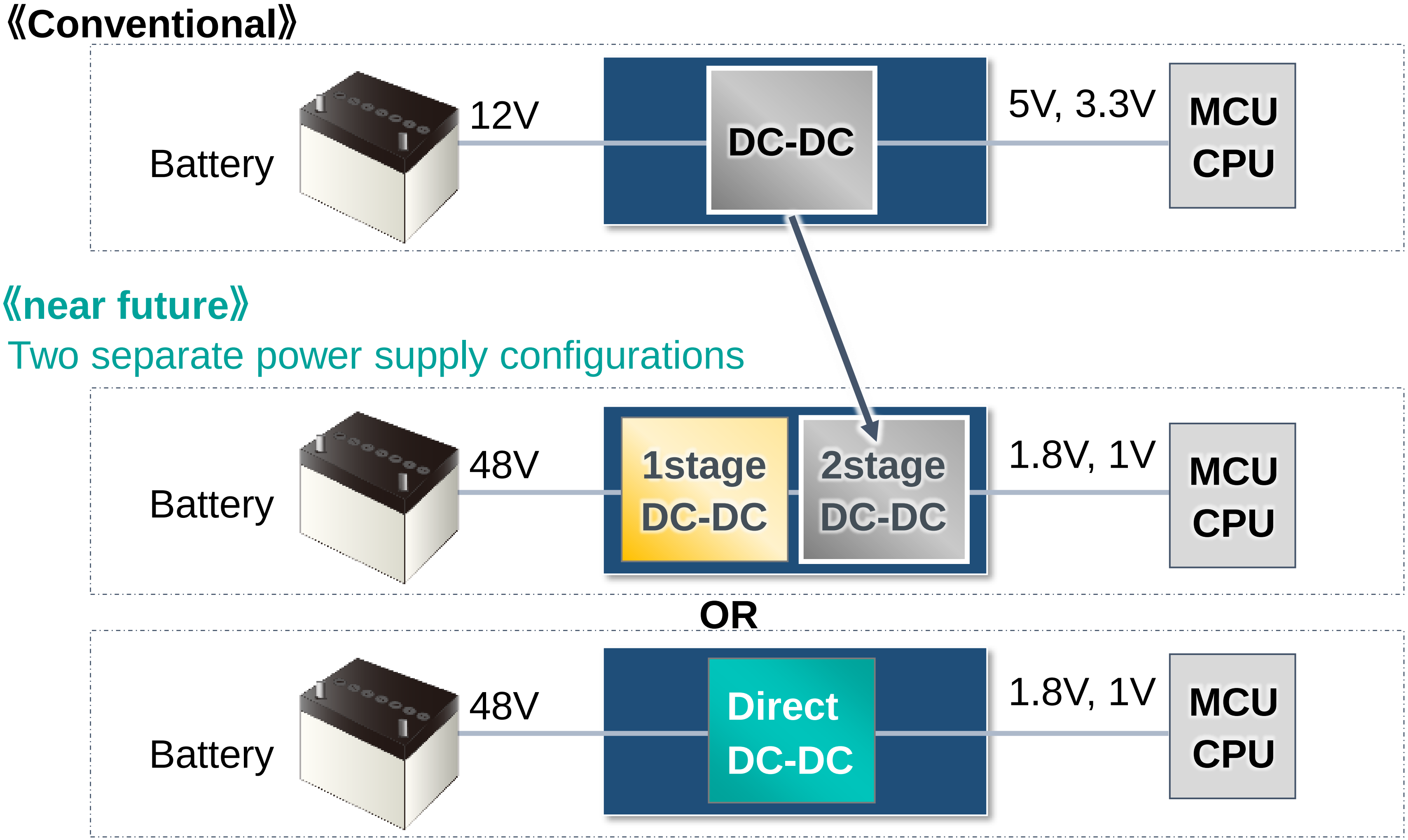
- **Higher bus voltage and battery voltage**
- **Lower supply voltage for MCU and CPU**



Introduction
48V Solution Configuration and Characteristics

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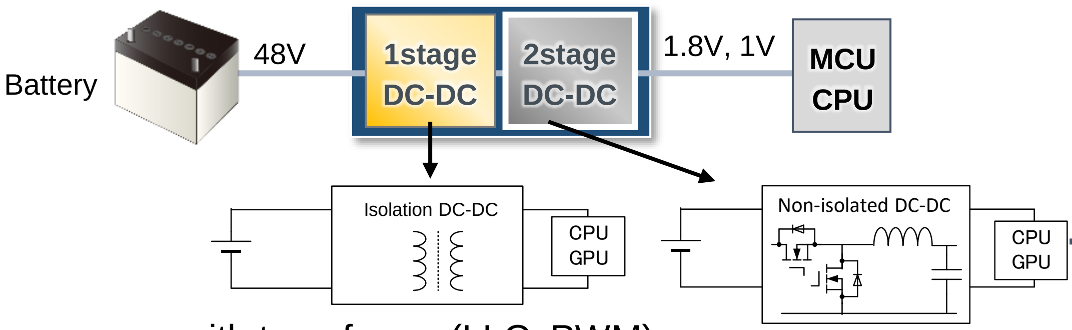
《2-stage configuration》

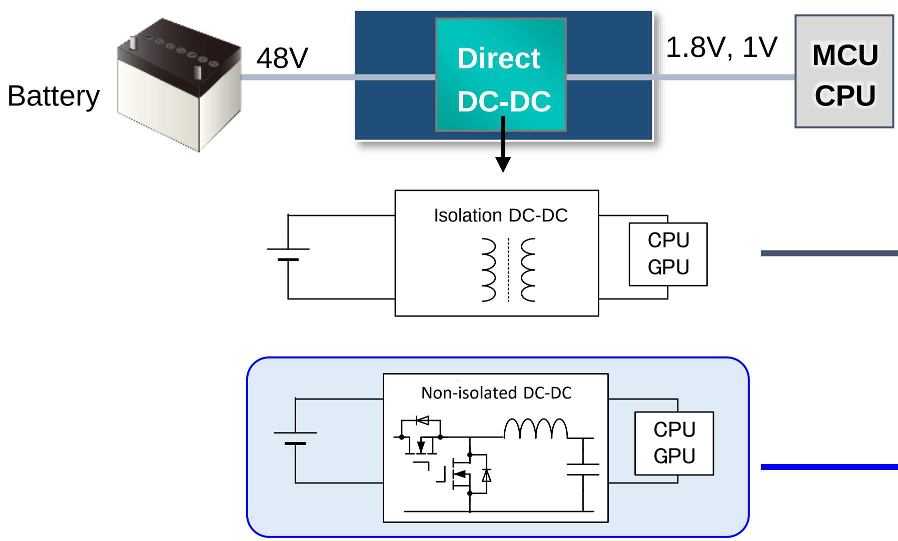


with transformer(LLC, PWM)
without transformer(Buck)

POLs

characteristic
- Existing DC-DC (actual results)
- Efficiency is surprisingly good (96%×90%=86%)
- Issues with area and cost

《1-stage configuration》



48V direct of this work

characteristic
- simple configuration
- Low flexibility
- Issues with cost

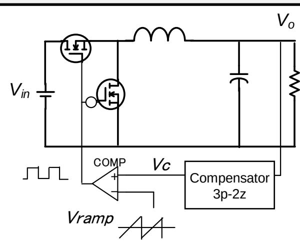
characteristic
- Advantages in area and cost due to reduced number of parts
- Efficiency is a little lower than 2-stage

Power control system list

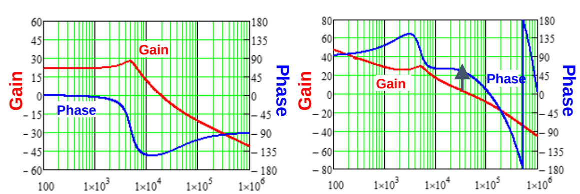
(tutorial) Voltage mode control, Peak current mode control, Nonlinear control (hysteresis, COT, etc.), with the easiest to use generally being peak current mode

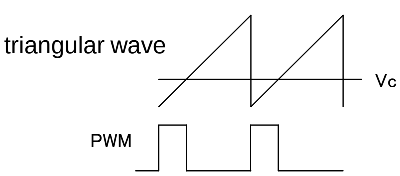
Voltage mode control	Peak current mode control	Nonlinear control (hysteresis, COT, etc.)

Voltage mode control

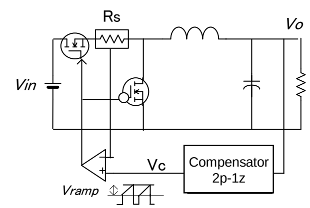


Plant(2nd-order delay) — open-loop transfer function

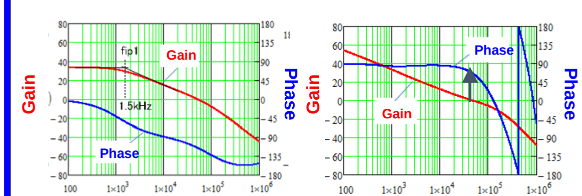


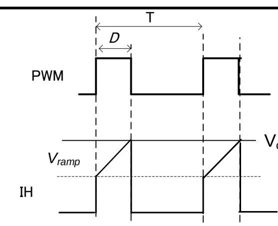


Peak current mode control

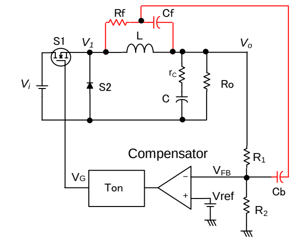


Plant(1st-order delay) — open-loop transfer function

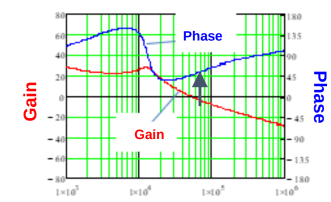


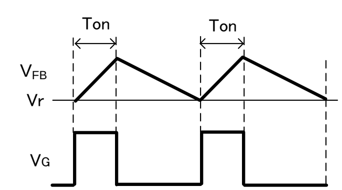


Nonlinear control (hysteresis, COT, etc.)



open-loop transfer function(2nd-order delay + 1st order advance)



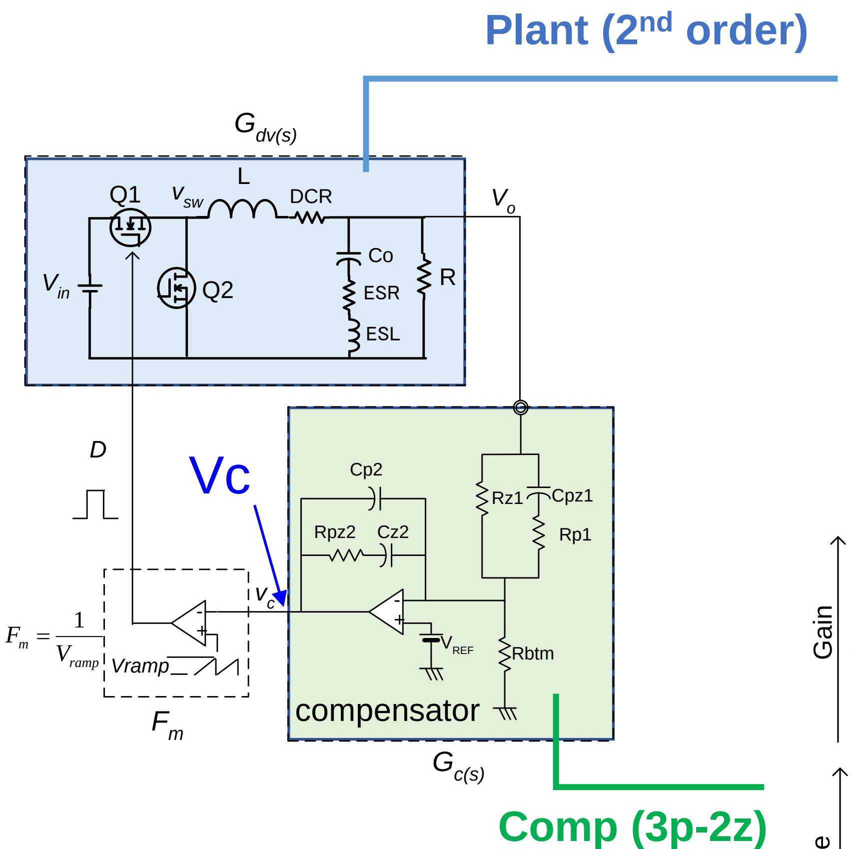


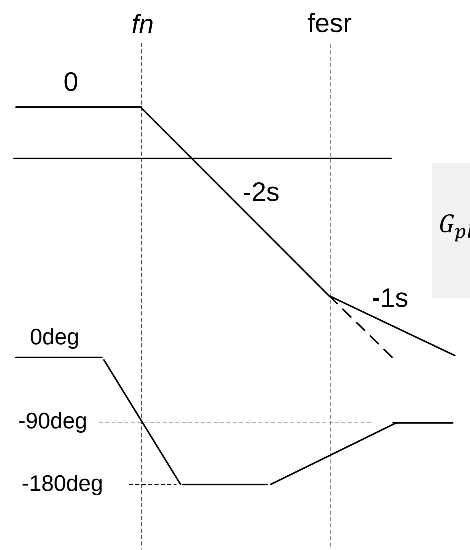
Easy to get stability, constant frequency, available in parallel

Voltage-mode (2nd order)

Pros: Traditional and lot of knowledge.   Good for high-voltage application
Cons: 2nd order need careful design of complex 3pole-2zero compensator)

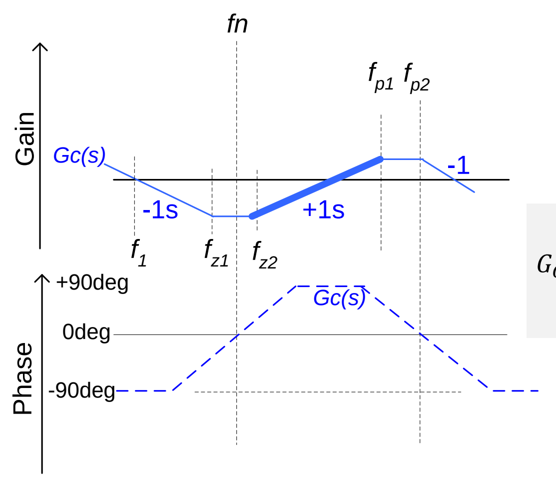
(Relatively low-bandwidth)





Equation

$$G_{plant}(s) = F_m \cdot V_{in} \cdot \frac{\left(1 + \frac{s}{\omega_{esr}}\right)}{\left\{1 + 2\delta \cdot \frac{s}{\omega_n} + \left(\frac{s}{\omega_n}\right)^2\right\}}$$

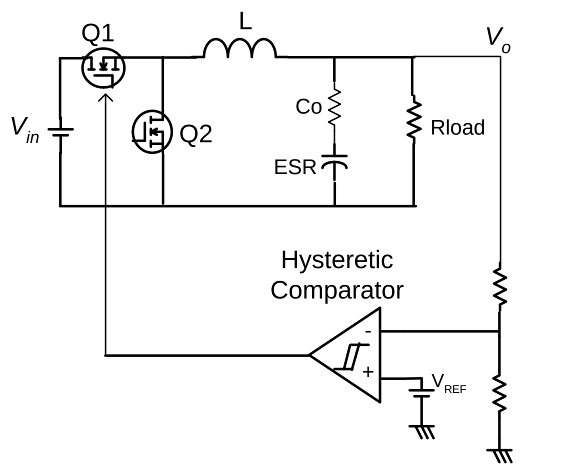
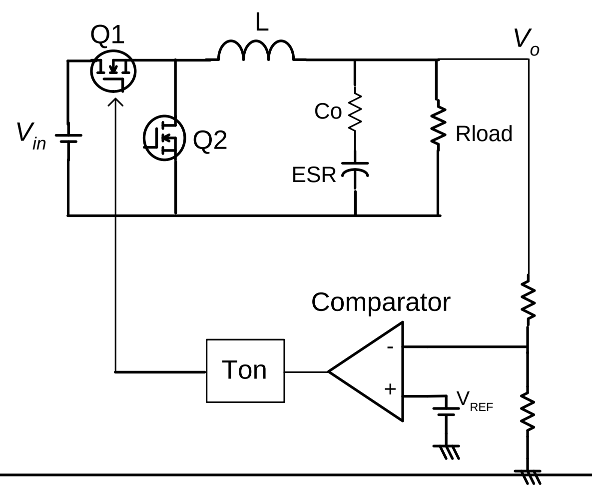
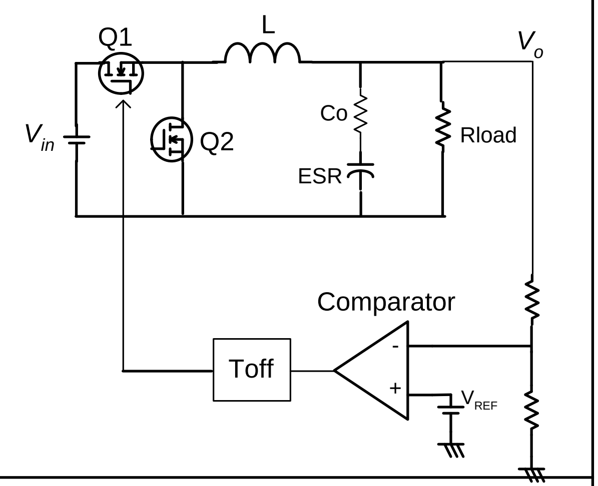
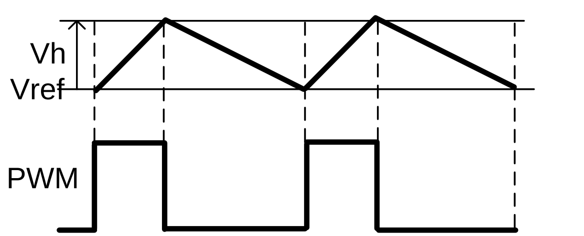
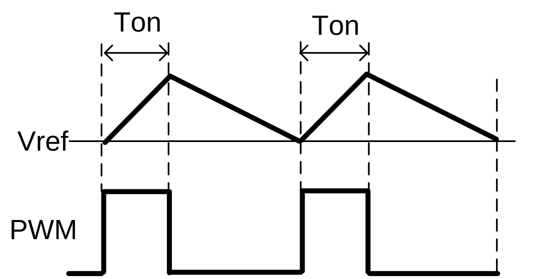
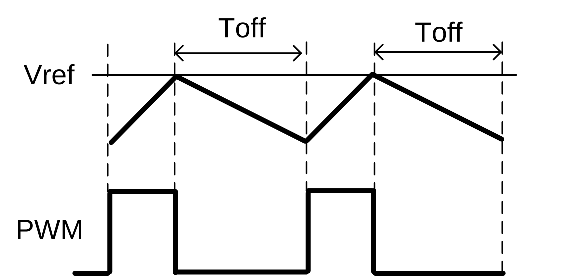


Equation

$$G_C(s) = \frac{\omega_1}{s} \cdot \frac{\left(1 + \frac{s}{\omega_{z1}}\right)\left(1 + \frac{s}{\omega_{z2}}\right)}{\left(1 + \frac{s}{\omega_{p1}}\right)\left(1 + \frac{s}{\omega_{p2}}\right)}$$

Hysteresis family

Pros: first response (intra-cycle response) because no clock
Cons: Frequency changes, difficult of parallel operation

Basic Hysteretic window	**COT (Constant On-Time)**	**Constant Off-Time**
		
		
No delay for both load step up and down transient.	No delay for load step up. Delay exist for load step down.	No delay for load step down. Delay exist for load step up.

Peak-current mode(PCM) (1st order)

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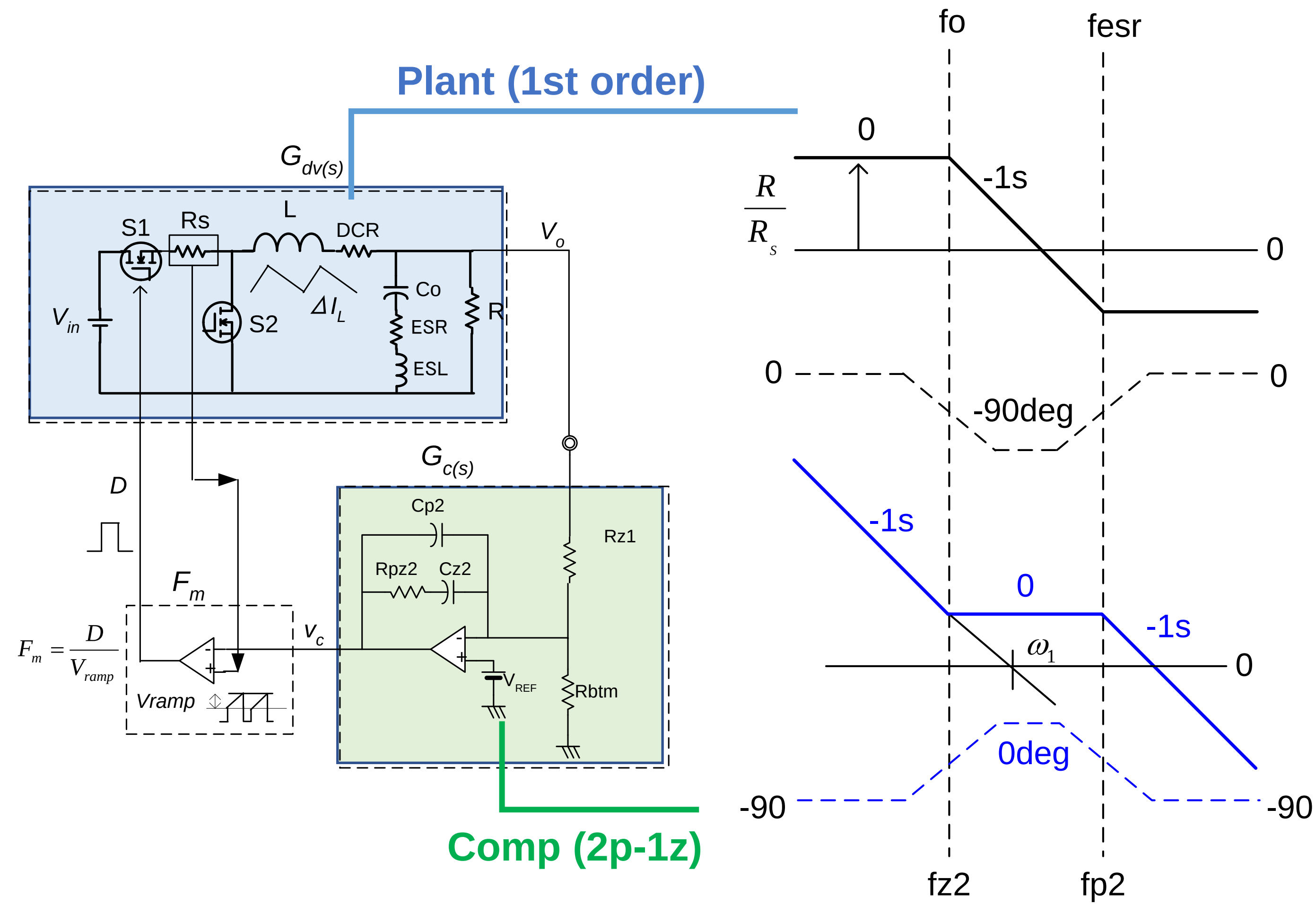
Pros: 1st order is stable, easy to design compensator, high–bandwidth.
Cons: Difficult of Short Ton (such high voltage ratio, high frequency)



Equation

$$G_{plant}(s) \approx \frac{R}{R_s} \cdot \frac{1+\frac{s}{\omega_{esr}}}{1+\frac{s}{\omega_0}}$$

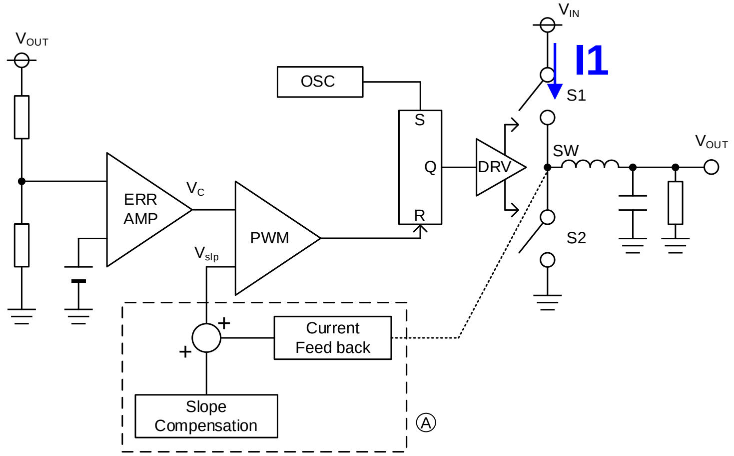
Equation

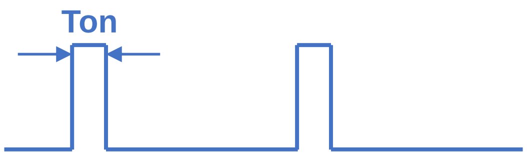
$$G_c(s) = \frac{\omega_1}{s} \cdot \frac{1+\frac{s}{\omega_{z2}}}{1+\frac{s}{\omega_{p2}}}$$

Conventional Peak-current mode (PCM) control

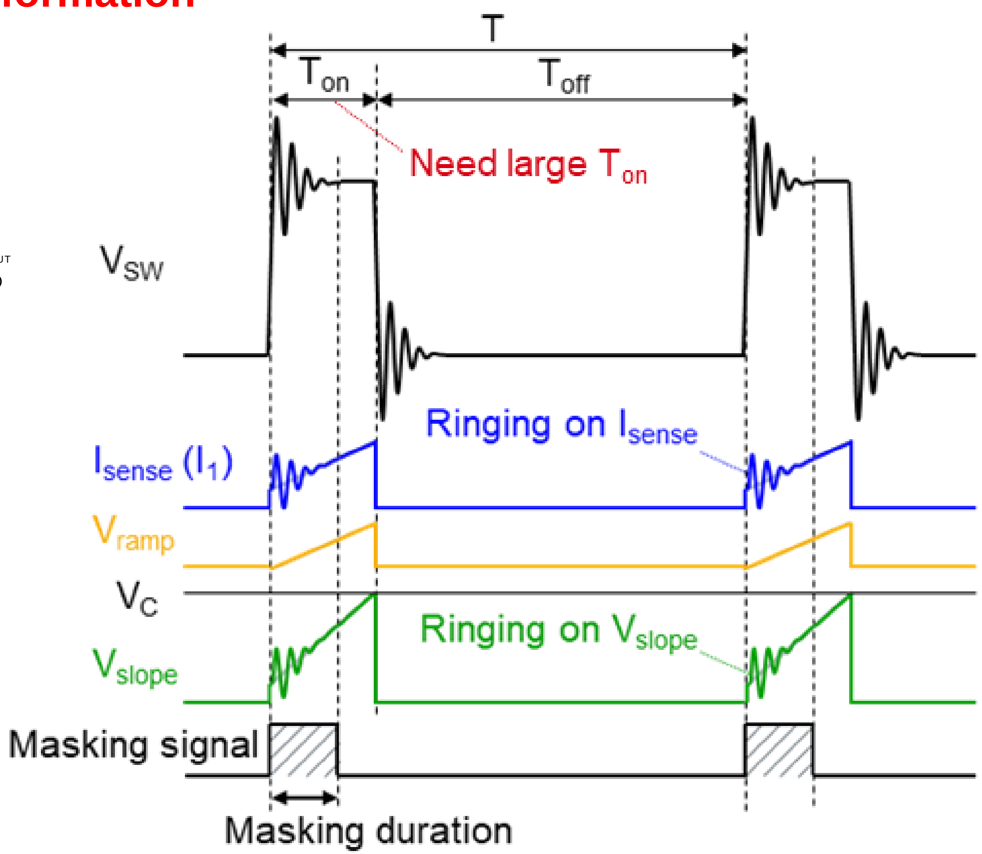
2 factors make it difficult to achieve narrow pulse

- Ringing at rise
- Finite delay time to process current information





At 48V/0.6V/3MHz, Ton≒5ns



$V_{slope} = I_{sense} + V_{ramp}$

Masking duration is required

Virtual PCM control
Peak Current-sense method for ultra-short pulse

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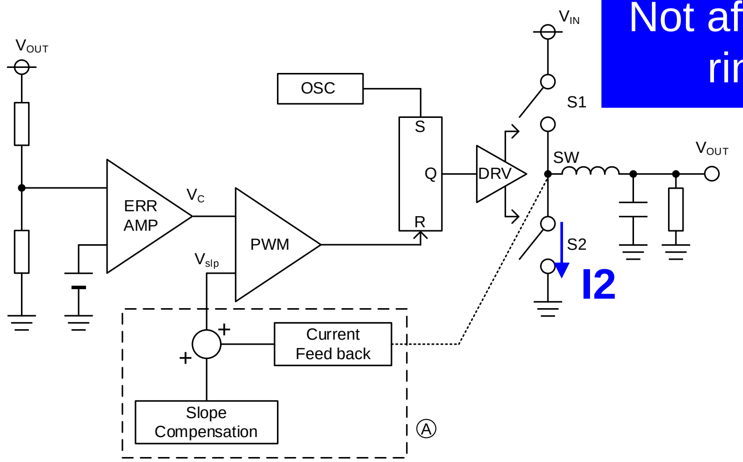
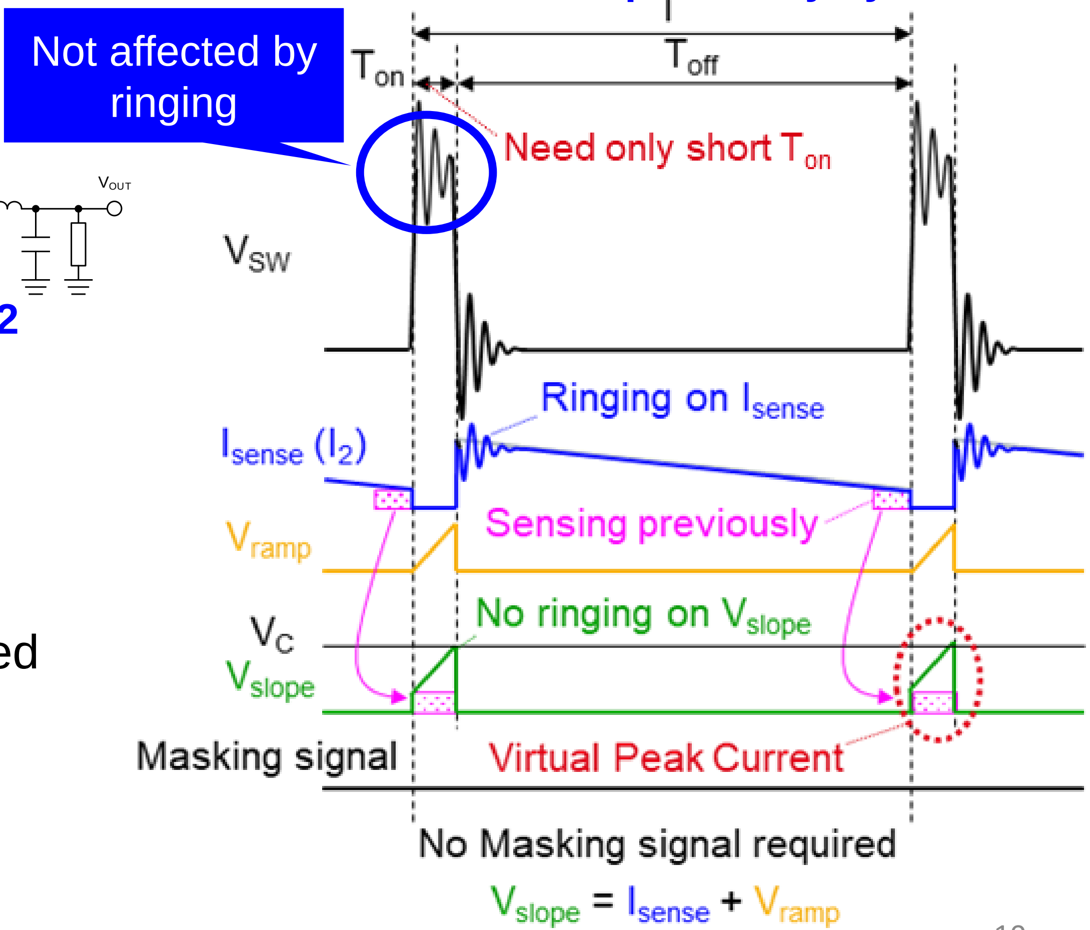
2 conditions necessary for problem solving

1. **That provides robust and reliable information that is directly proportional to the inductor current**
2. **Holds the feedback current information for use in the subsequent duty cycle**



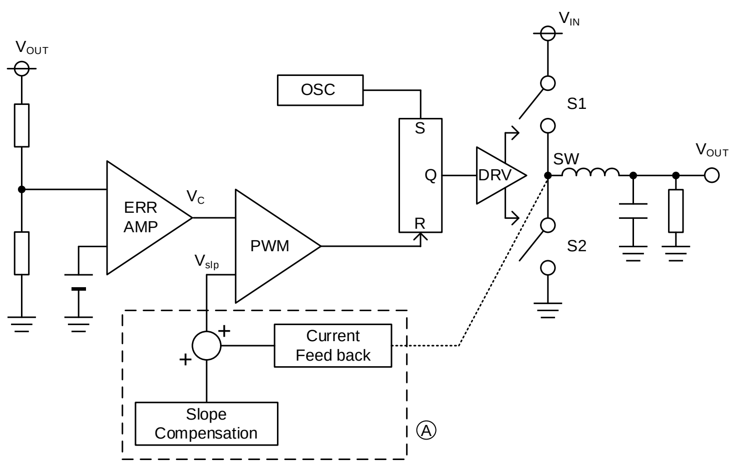


feed back current information internally without being affected by noise

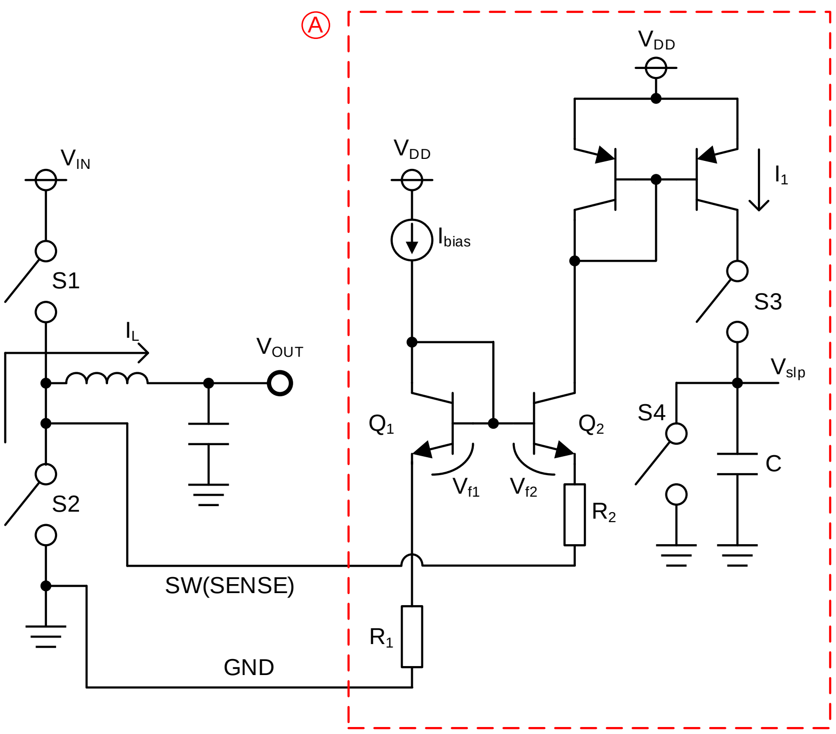
Virtual PCM control
Current feedback circuit

Stable current information monitoring with sample/hold

The basic configuration is the same as the conventional S1 detection, but the Ⓐ part is different.



Sample/hold circuit to avoid noise effects



$$R_S = \frac{\beta}{CR_2}\Delta t_{on}$$

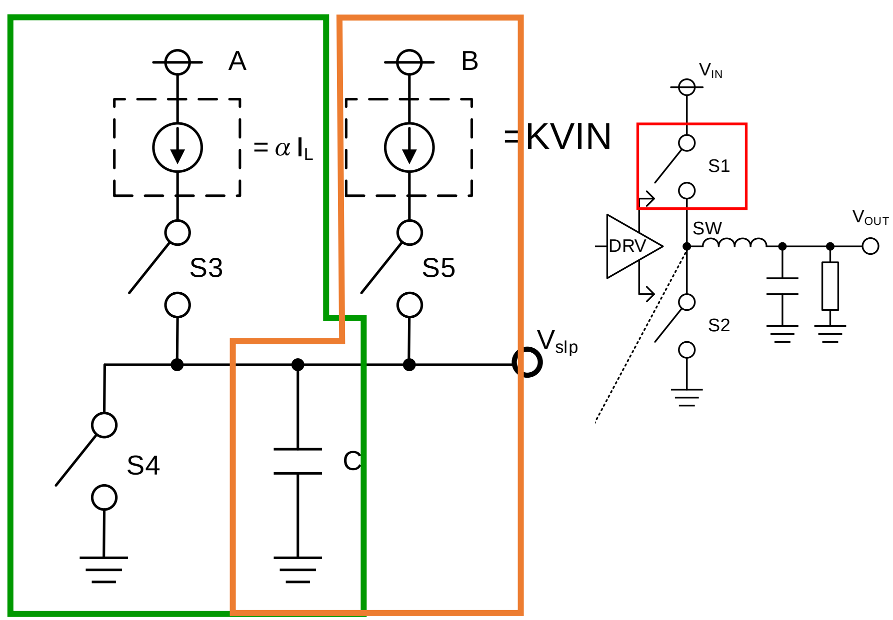
β:S2 Ron

Δton:fixed time

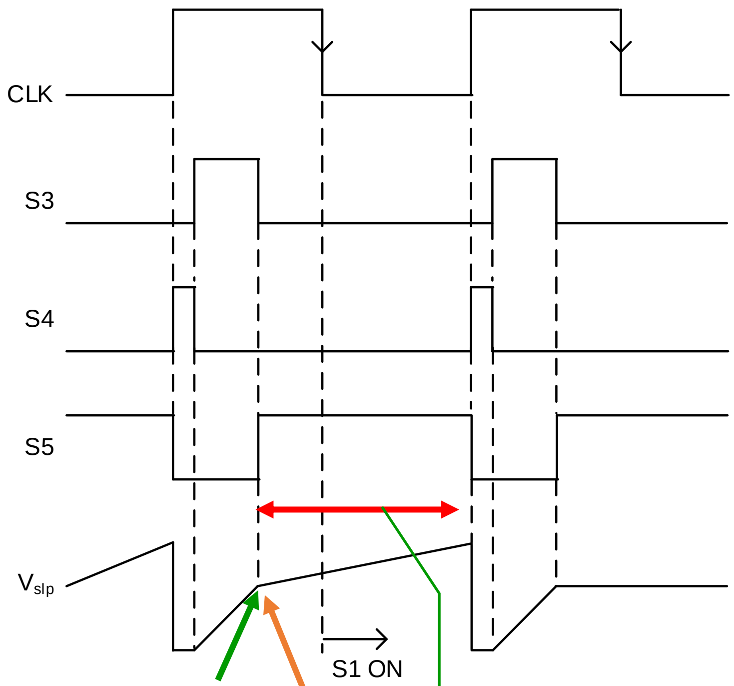
Virtual PCM control
Slope compensation circuit

Timing chart to avoid noise effects

Sample/hold circuit



Slope compensation circuit



Get current information

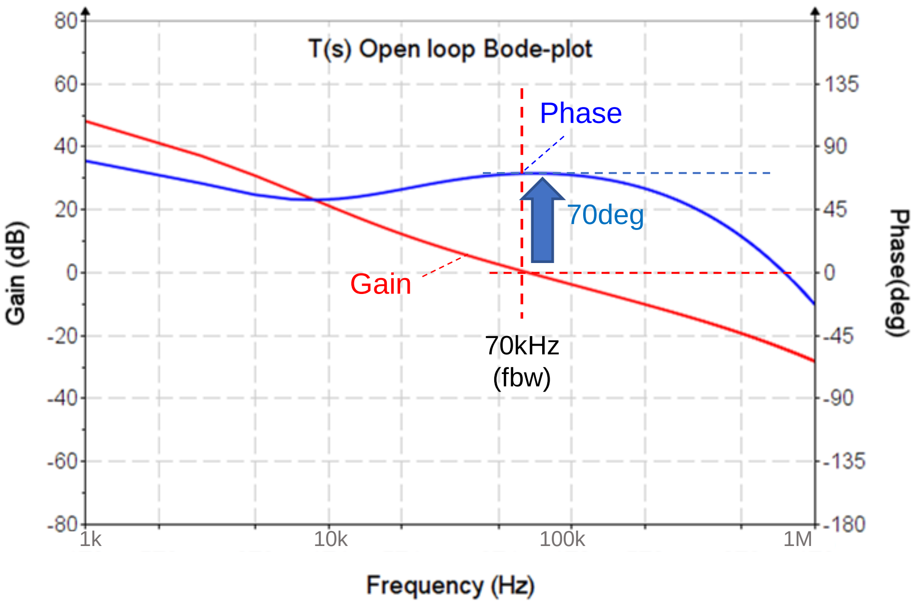
Operating regardless of noise and delay

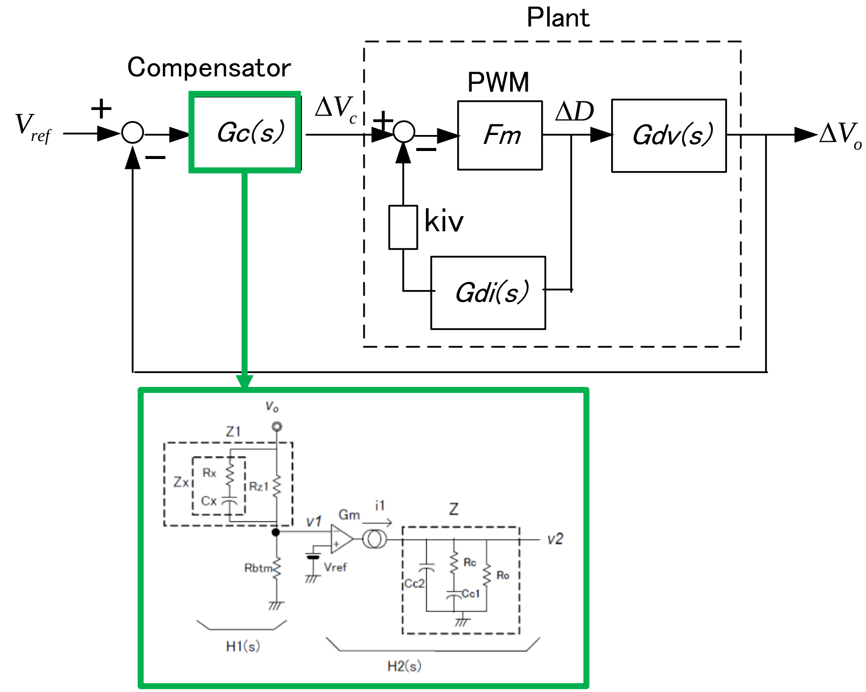
Start of slope compensation

This method can operate in current mode, no matter how narrow the pulse

Transfer function of the Virtual PCM

Calculated bode-plot of Open-loop Transfer function T(s) at Target fbw=70kHz with 2pole-1zero compensator





Gplant(s)

$$Pdi(s,R_0) := \frac{Vin}{R_0}\cdot\left(1+\frac{s}{\omega_o(R_0)}\right) \quad Pdv(s) := Vin\cdot\left(1+\frac{s}{\omega_{esr}}\right)$$

$$P(s,R_0) := 1 + 2\cdot\delta(R_0)\cdot\left(\frac{s}{\omega_n(R_0)}\right) + \left(\frac{s}{\omega_n(R_0)}\right)^2$$

$$Gplant(s,R_0) := \frac{Fm}{1+\frac{R_S\cdot Pdi(s,R_0)\cdot Fm}{P(s,R_0)}}\cdot\frac{Pdv(s)}{P(s,R_0)}$$

Gc(s): 2pole-1zero

$$Gc\_2plz(s) := \frac{R_{btm}}{R_{z1}+R_{btm}}\cdot\frac{1}{\frac{s}{\omega_1}}\cdot\frac{\left(1+\frac{s}{\omega_{z2}}\right)}{1+\frac{s}{\omega_{p2}}}$$

T(s): Open loop

$$T\_2pz(s,R_0) := Gplant(s,R_0)\cdot Gc\_2plz(s)\cdot e^{-s\cdot\frac{Ts}{2}}$$

Experimental Results of the prototype
Switching operation

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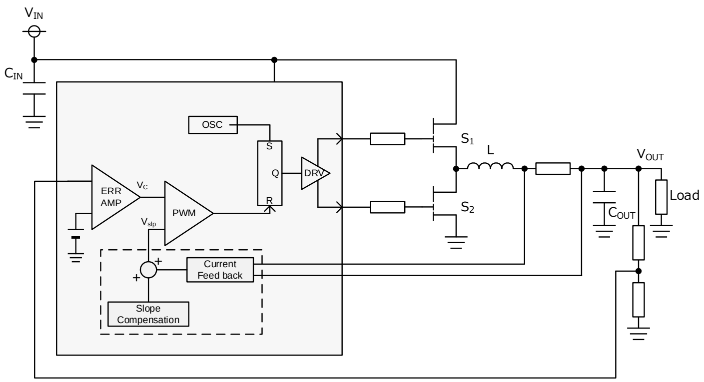
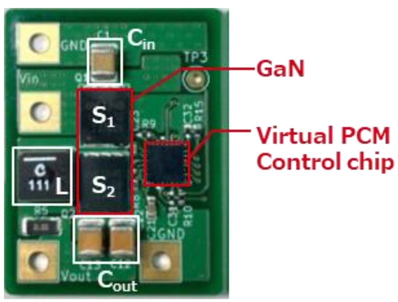
Schematic of prototype board



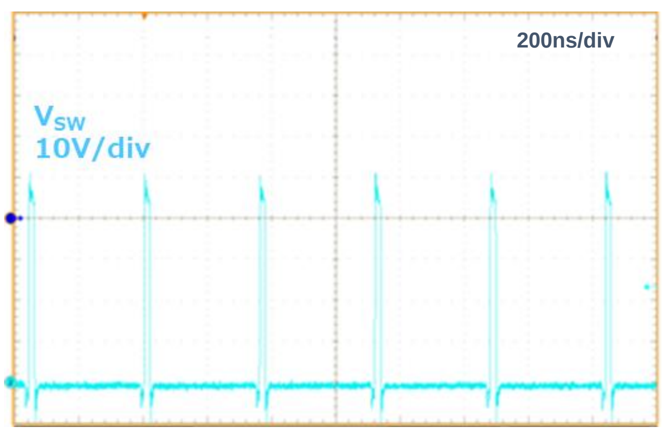
prototype board



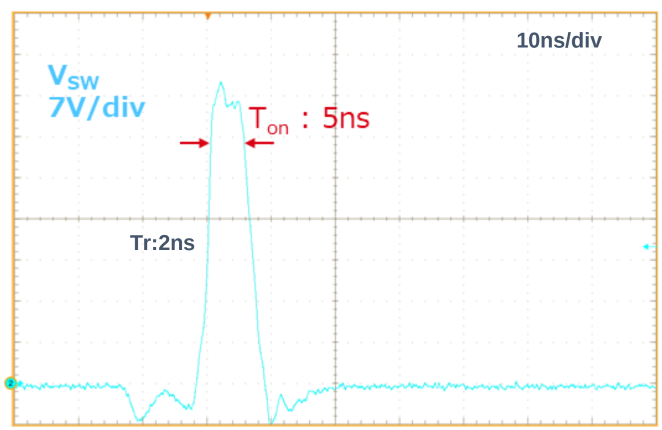
The specification of the board

Input voltage	48V
Output voltage	0.6V
Output load	5A
Switching frequency	3MHz
Inductor	110nH
Output Capacitor	400uF
High side Switch (S1)	GNE1040TB(150V/40m)
Low side Switch (S2)	GNE1040TB(150V/40m)
Controller	BD9JZ00TL

Switching waveform



Switching waveform(zoom)



Switching operation at 3MHz with input voltage (Vin) of 48V and output voltage (Vout) of 0.6V with ultra-short pulse (at Ton around 5ns) was confirmed.

Experimental Results of the prototype
Bode-Plot

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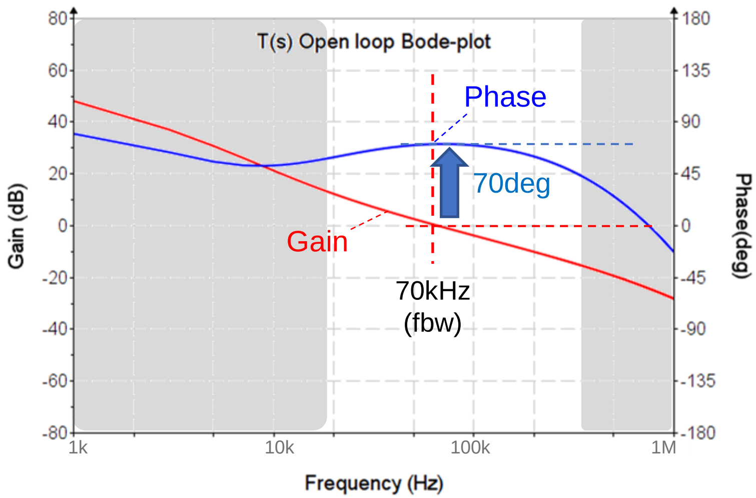
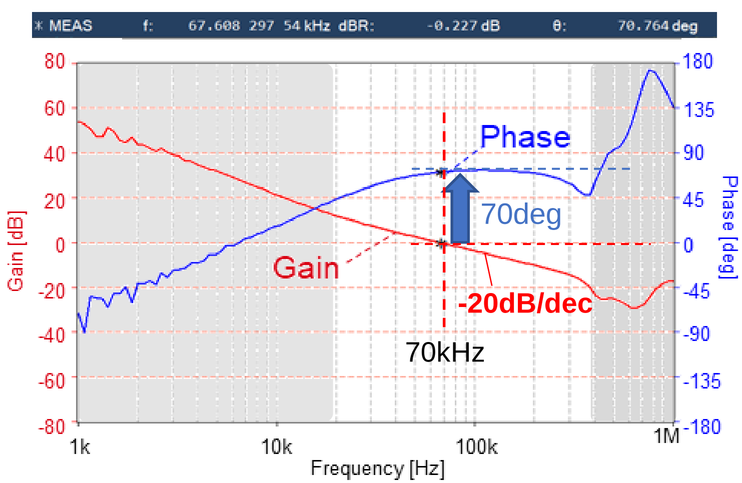
Calculated bode-plot

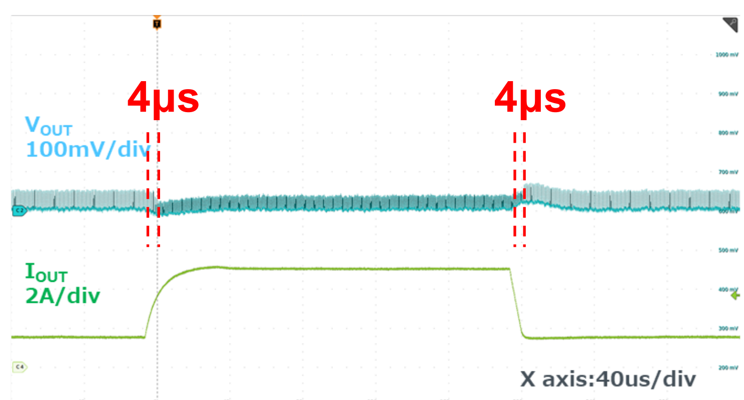


It is confirmed that the open-loop transfer function shows a typical 1st-order system that successfully uses a Type II (2pole, 1zero) compensator common to conventional PCM control.
The measured load transient response waveform verified the results of the bode-plot

Measured of bode-plot



Measured of load transient response waveforms



1/70kHz×1/4≒4μs

Conclusion

Developed virtual PCM (peak current mode) control chip

High-frequency and high-buck conversion

Using 150V/40mΩ high-speed GaN on high side and low side,
Confirms stable operation at 3MHz, 48Vin, 0.6Vout, 5A, Ton=5ns

Avoids current ringing during turn-on and enables PCM operation even with ultra-short pulses

- ✓ Bode plot measurements confirm that the open-loop transfer function shows a typical 1st-order system with a type II (2pole,1zero) compensator
- ✓ Load transient test confirms that the transfer function works properly

This technology is promising for high-frequency, high-buck conversions such as 48V direct converters