# The Basics of
# Linear Regulator and Switching Regulator

# AGENDA

## 1. Linear Regulator Basics

- Operating Principles
- Types and Circuit Configuration
- Advantages vs Disadvantages, and Applications
- Important Specifications
- Efficiency and Thermal Calculation

## 2. Switching Regulator Basics

- Types of Switching Regulator
- Advantages vs Disadvantages, and Comparison with Linear Regulator
- Operating Principles of Buck Converter
- Differences between Synchronous and Nonsynchronous Rectifying
- Efficiency Improvements at Light Load for the Synchronous Converter
- Control Methods (Voltage Mode, Current Mode, Hysteresis Control)
- Protective and Sequencing Functions
- Considerations on Switching Frequencies

# 1. Linear Regulator Basics

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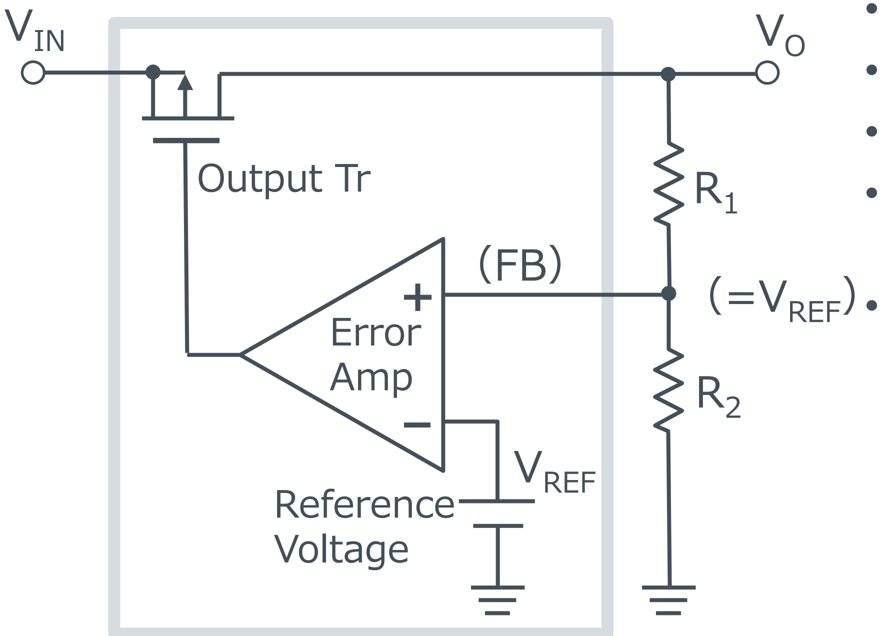
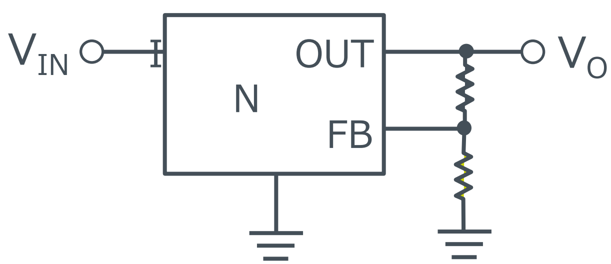
# Operating Principles of Linear Regulator




- Composed of an error amp, a voltage
- reference, and an output transistor
- Same operation as an inverting amp
- $V_{OUT}$ is set by the ratio between $R_1$ and $R_2$, because the voltage of non-inverting input
- is equal to $V_{REF}$

$$V_O = \frac{V_{REF}}{R_2} \times (R_1 + R_2)$$

$$= \frac{R_1 + R_2}{R_2} \times V_{REF}$$




EX: $V_{REF} = 1.0V$、$V_O = 3.3V$、$R_2 = 10k\Omega$

$$3.3V = \underbrace{\frac{1.0V}{10k\Omega}}_{100\mu A} \times (R_1 + 10k\Omega)$$

100μA×33kΩ = 3.3V Therefor R1 = 23kΩ

# Types of Linear Regulator

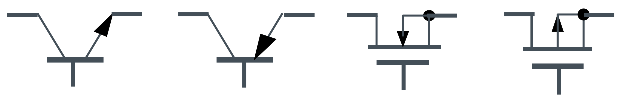
## Linear Regulators

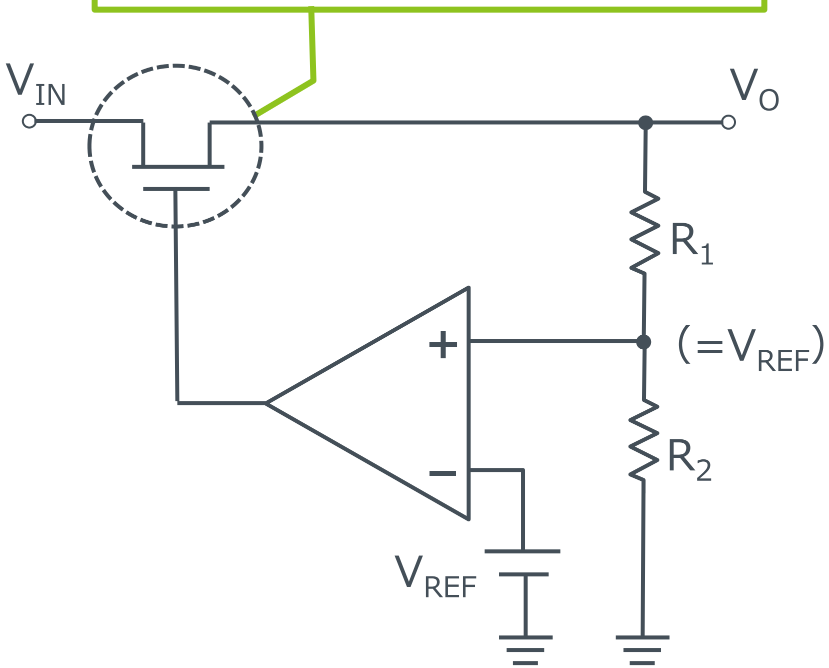
| | |
|---|---|
| ・Positive Voltage (Fixed/Adjustable) | - Conventional<br>- LDO |
| ・Negative Voltage (Fixed/Adjustable) | - Conventional<br>- LDO |


- Naming of linear regulator: Series regulator, 3-terminal regulator,
- Dropper, or LDO
- LDO is a modification to 1V or less of a conventional dropout
- Adjustable types require the output setting resistors, as opposed to that fixed output types include the resistors
- Generally, bipolar process linear regulators have higher voltage tolerant than CMOS, but the supply current is larger than CMOS
- Package type is various and low-thermal-resistance is required

# Circuit Configuration of Linear Regulator

For the control transistor, bipolar NPN/PNP transistor or Pch/Nch MOSFET with varying dropout voltages and performance characteristics is used.






- Dropout voltages vary with the type of the control transistor
- But operating principles as basically same
- NPN conventional configuration is used for 0.5A to 1A regulators like 78xx/79xx
- NPN LDO can supply larger Iout than 5A.
- PNP LDO is a standard of LDO
- Pch/Nch MOSFET achieves lower dropout voltage than PNP LDO

| Control Transistor | Dropout Voltage |
|---|---|
| NPN Conventional | Approx. 3V |
| NPN LDO | 1V～2V |
| PNP LDO | 0.5V or less |
| MOSFET LDO | 0.5V or less |

# Advantages vs Disadvantages, and Applications

## Advantages

- ✓ Simplicity of design
- ✓ Lower parts count
- ✓ Space savings (unless a heat sink is used)
- ✓ Low noise
- ✓ Fast transient response
- ✓ Low cost

## Disadvantages

- ✓ Low efficiency if input-output difference is large
- ✓ Low efficiency = significant heat dissipation
- ✓ May require a heat sink
- ✓ Capable exclusively of step-down operations

## Applications

- AV devices
- RF, radio, communication devices
- Medical equipment
- Measurement devices
- Small-power supply

# Important Specifications of Linear Regulator

- ✓ Input voltage range
- ✓ Output voltage range
- ✓ Output (VREF) accuracy
- ✓ Output current
- ✓ Dropout voltage
- ✓ Transient response characteristics
- ✓ Ripple rejection ratio

### Basic Verification Points in a Data Sheet

- Always check the absolute maximum rating
- Verify temperature and voltage conditions (Do they represent real-life conditions?)
- Using a graph, verify continuous characteristics beyond guaranteed values
- Determine which value, Typ, Min, or Max, must be used as a starting point

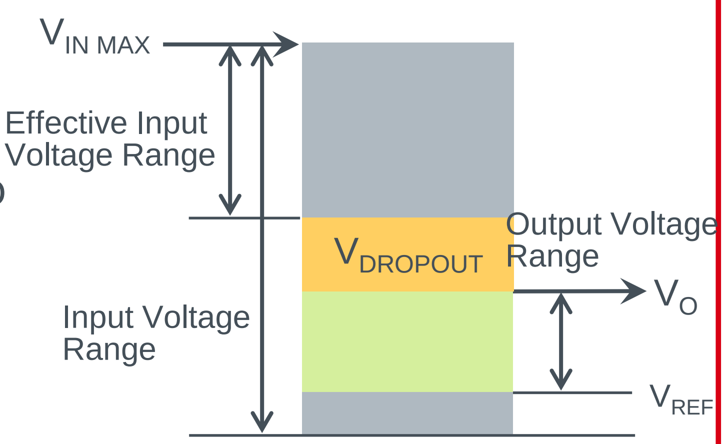
**Example table of specifications**

● **Electrical Characteristics** (Unless otherwise noted, Ta=25℃, EN=3V, $V_{CC}$=3.3V, $R_1$=16kΩ, $R_2$=7.5kΩ)

| Parameter | Symbol | Limits | | | Unit | Conditions |
|---|---|---|---|---|---|---|
| | | Min. | Typ. | Max. | | |
| Circuit current at shutdown mode | $I_{SD}$ | - | 0 | 5 | μA | $V_{EN}$=0V, OFF mode |
| Bias current | $I_{CC}$ | - | 250 | 500 | μA | |
| Line regulation | Reg.I | -1 | - | 1 | % | $V_{CC}$ =( $V_O$+0.6V )→5.5V |
| Load regulation | Reg $I_O$ | -1.5 | - | 1.5 | % | $I_O$=0→0.5A |
| Minimum dropout voltage1 | $V_{CO1}$ | - | 0.1 | 0.15 | V | $V_{CC}$ =3.3V, $I_O$ =125mA |
| Minimum dropout voltage2 | $V_{CO2}$ | - | 0.2 | 0.30 | V | $V_{CC}$ =3.3V, $I_O$ =250mA |
| Minimum dropout voltage3 | $V_{CO3}$ | - | 0.3 | 0.45 | V | $V_{CC}$ =3.3V, $I_O$ =375mA |
| Minimum dropout voltage4 | $V_{CO4}$ | - | 0.4 | 0.60 | V | $V_{CC}$ =3.3V, $I_O$ =500mA |
| Output reference voltage(Variable type) | $V_{FB}$ | 0.792 | 0.800 | 0.808 | V | $I_O$=0A |

# Important Specifications of Linear Regulator

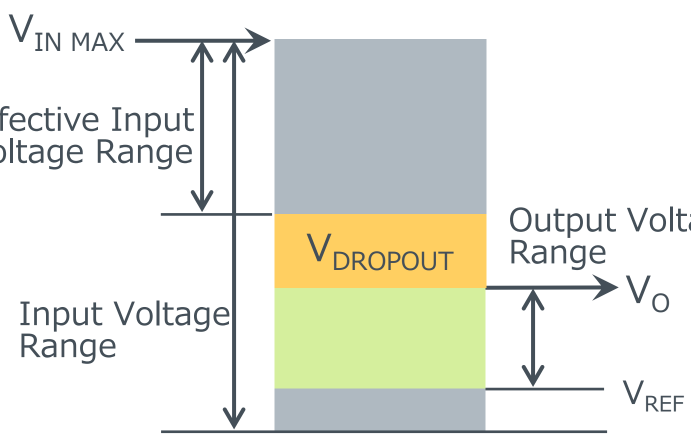
- Input Voltage Range
  - Meaning: A voltage that may be applied to the input terminal
  - Check if input voltage range guarantees adequate operation or fulfillment of specifications, or if it is a maximum rating value
  - Normally comply with the recommended conditions
  - Minimum operating input voltage is *Vo + dropout voltage* or higher.
  - Due to $Tj_{MAX}$ factor, the input voltage range is limited by Vo, Io, and Ta conditions
- Output Voltage Range
  - Meaning: Range of output voltages (a fixed value for the fixed type)
  - $V_{REF}$ to ($V_{INMAX}$ – $V_{DROPOUT}$)
  - Normally comply with the recommended range
  - Due to $Tj_{MAX}$ factor, the output range is subject to limits by Vo, Io, and Ta conditions
- Output accuracy ($V_{REF}$ accuracy)
  - Meaning: the extent of error indicated by +/- %
  - For the fixed type, a fixed value ($V_O$); for the adjustable type, $V_{REF}$



# Important Specifications of Linear Regulator

## Output Current

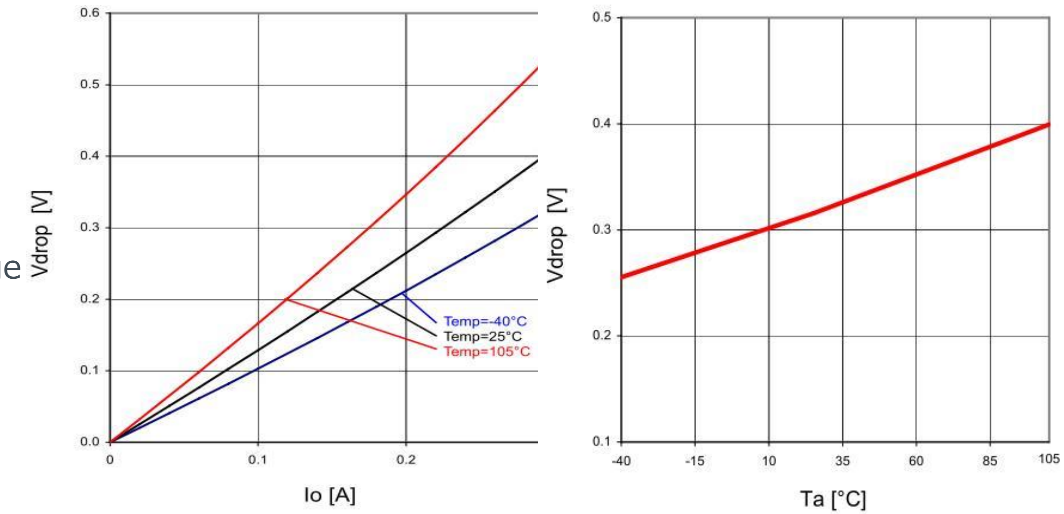
- Meaning: A current that can be output (capability)
- The expression current limit is also used in some cases
- Caution: Make sure if the term refers to a maximum or minimum value
- Any specifications on short-circuit current should also be considered
- Due to $Tj_{MAX}$, output current is subject to limits by $V_O$, $I_O$, and Ta




## Dropout Voltage

- Meaning: Voltage difference between input and output necessary to regulate the output
- Also referred to as input/output voltage difference or loss voltage
- If the difference is further reduced, the regulator ceases to operate
- The LDO has a small dropout voltage

**VDROPOUT vs $I_O$, Ta**

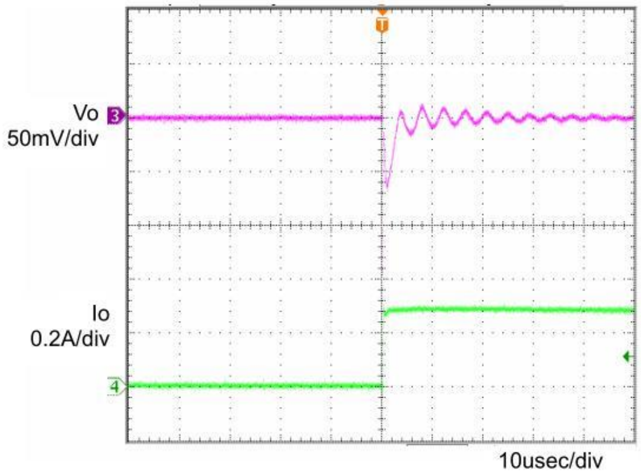


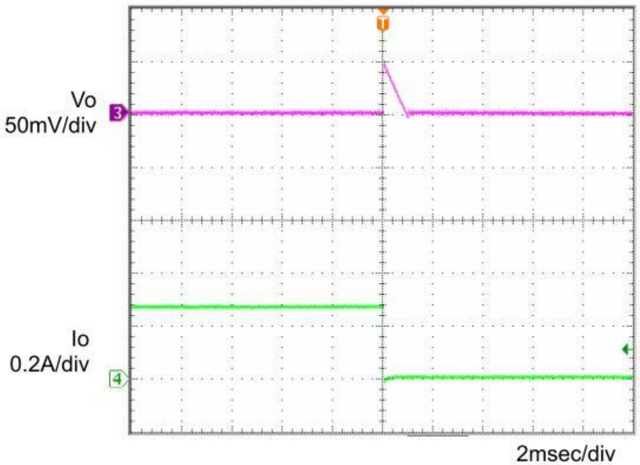
# Important Specifications of Linear Regulator

## Transient Response Characteristics

- Meaning: Time to settle the fluctuations of an $V_{OUT}$ by rapid load current changes
- Load current changes occur such when a large-power load (ex CPU) wakes up
- Must be considered separately from a shift in output voltage due to continuous increase and decrease in load.
- Basically there are no specification values; transient response characteristics must be verified in terms of a graph.
- Transient response characteristics are affected not only by the IC performance but also by the output capacitance (of the capacitor).

**Example of Transient Response Characteristics**

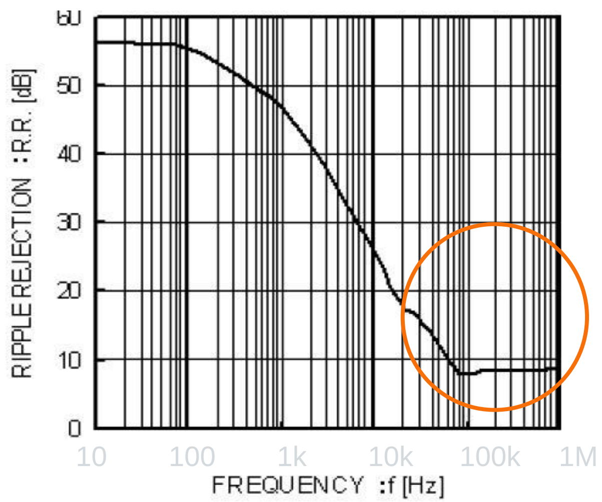


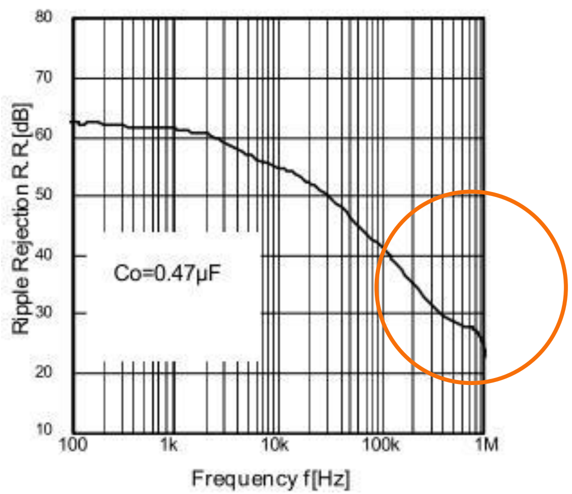



# Important Specifications of Linear Regulator

- Ripple Rejection Ratio
  - Meaning: The percentage of ripples (pulsation) contained in the input voltage that is rejected from the output voltage. Expressed as dB in most cases
  - Also called PSRR (power supply voltage ripple rejection) or input voltage ripple rejection, they refer to the same thing
  - Note that the rejection ratio depends on the ripple frequency
  - If the linear regulator is used as a post regulator of the switching regulator, the ripple rejection capability can reduce the output ripple of switching regulator when rectification and smoothing of the switching regulator are not sufficient

**Example of Ripple Rejection Ratio**



# Efficiency and Thermal Calculation

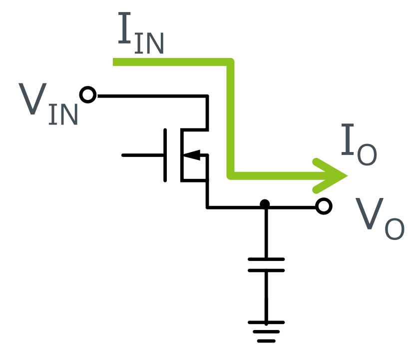
## ◆ Definition for Efficiency

- $\text{Efficiency} = \dfrac{\text{Output Power}}{\text{Input Power}} \times 100\ (\%)$
    - $\text{Input Power} = V_{IN} \times I_{IN}$ Where: $I_{IN} = I_O + I_{CC}$
    - $\text{Output Power} = V_O \times I_O$

EX: $V_{IN} = 5V$、$V_O = 3.3V$、$I_O = 0.2A$、$I_{CC} = 5mA$

$$\frac{3.3V \times 0.2A}{5V \times (0.2A + 5mA)} \times 100 = 64\%$$

- Factor: The smaller the input/output voltage ratio, the lower is efficiency




**Is the efficiency of LDO really low?**

If $V_{IN} = 3.6V$ at the left conditions,

$$\frac{3.3V \times 0.2A}{3.6V \times 0.205A} \times 100 = 89\%$$

*Almost Same as Switching Regulators!*

## ◆ Thermal calculation

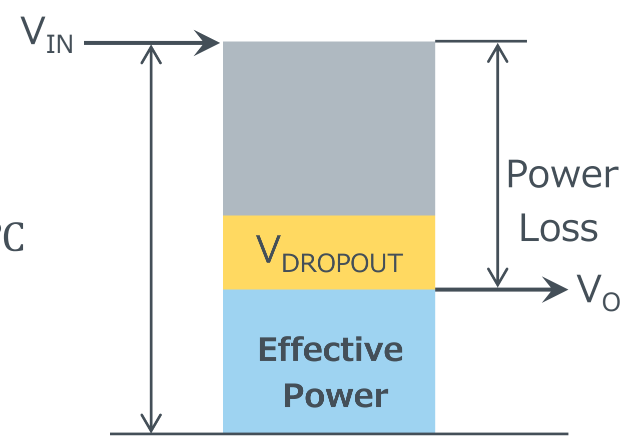
- $T_j = \text{Power Loss} \times \text{Thermal Resistance } \theta_{ja} + T_a$
    - $\text{Power Loss} = (V_{IN} - V_O) \times I_{IN}$

EX: Above condition, $\theta_{ja} = 50°C/W$、$T_a = 40°C$

$$\{(5V - 3.3V) \times (0.2A + 5mA)\} \times 50°C/W + 40°C = 57°C$$

At $T_{jmax} = 125°C$, 68°C margin is given

- Make sure Tjmax is not exceeded
- Factor: Heating increases as input/output voltage difference and $I_O$ rise.



# 2. Switching Regulator Basics

- Types of Switching Regulators
- Advantages vs Disadvantages, and Comparison with Linear Regulator
- Operating Principles of Buck Converter
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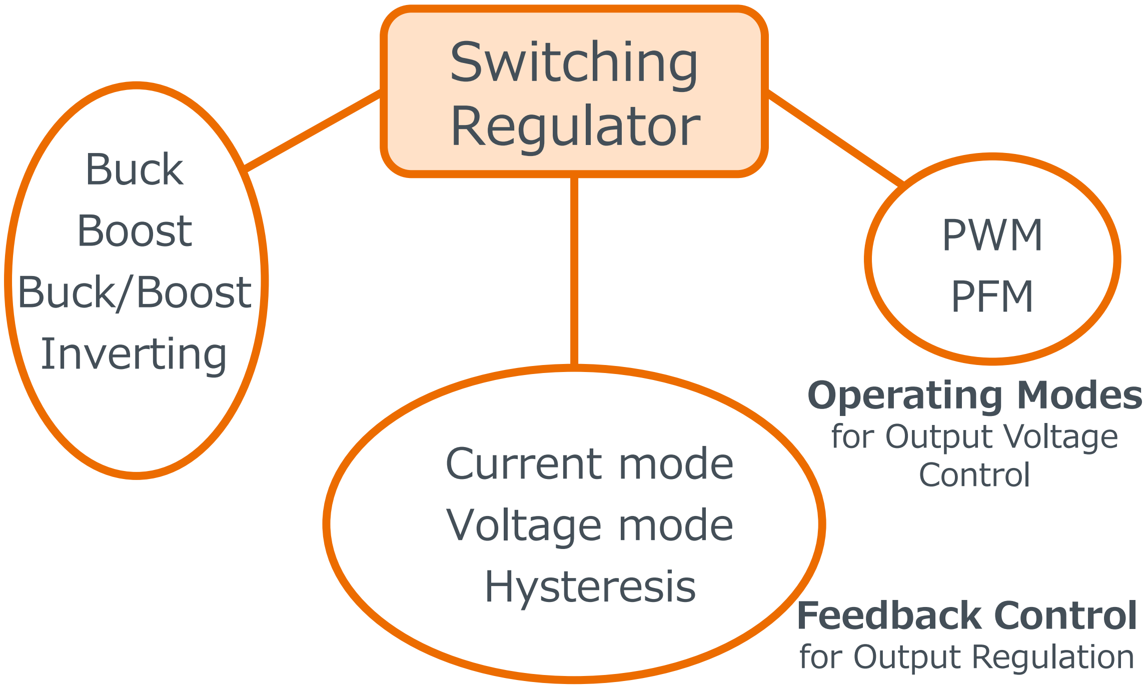
# Types of Switching Regulators

<u>DC/DC Converter</u>

- **Non Isolated**
  - Non-synchronous
  - Synchronous
- **Isolated**
  - Flyback
  - Forward
  - Push-Pull
  - Half/Full bridge




<u>AC/DC Converter</u>

- **Non isolated**
- **Isolated**

- **Application**: consumer, industrial, domestic, overseas. . .
- **Input/Output Conditions**: AC, DC, battery. . .
- **Requirements**: power, efficiency, accuracy. . .
- **Limitations**: size, cost, restrictions. . .

# Advantages vs Disadvantages, & Comparison

## Advantages

- ✓ Capable of Boost, Buck, Inverting and Buck/Boost
- ✓ High efficiency
- ✓ Low thermal dissipation
- ✓ Can handle a large output current

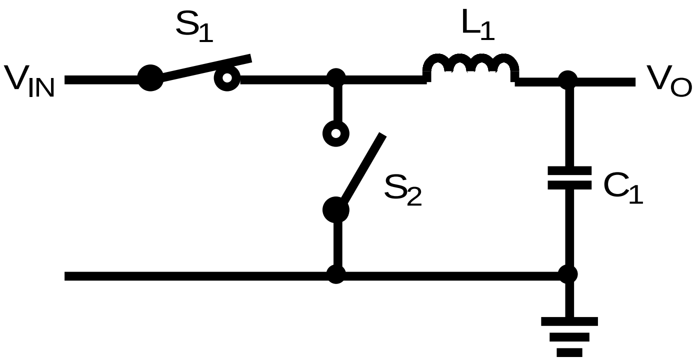
- ✓ Complicated design
- ✓ High parts count
- ✓ Switching noise and ripple exist
- ✓ Cost factor

## Comparison with Linear Regulator

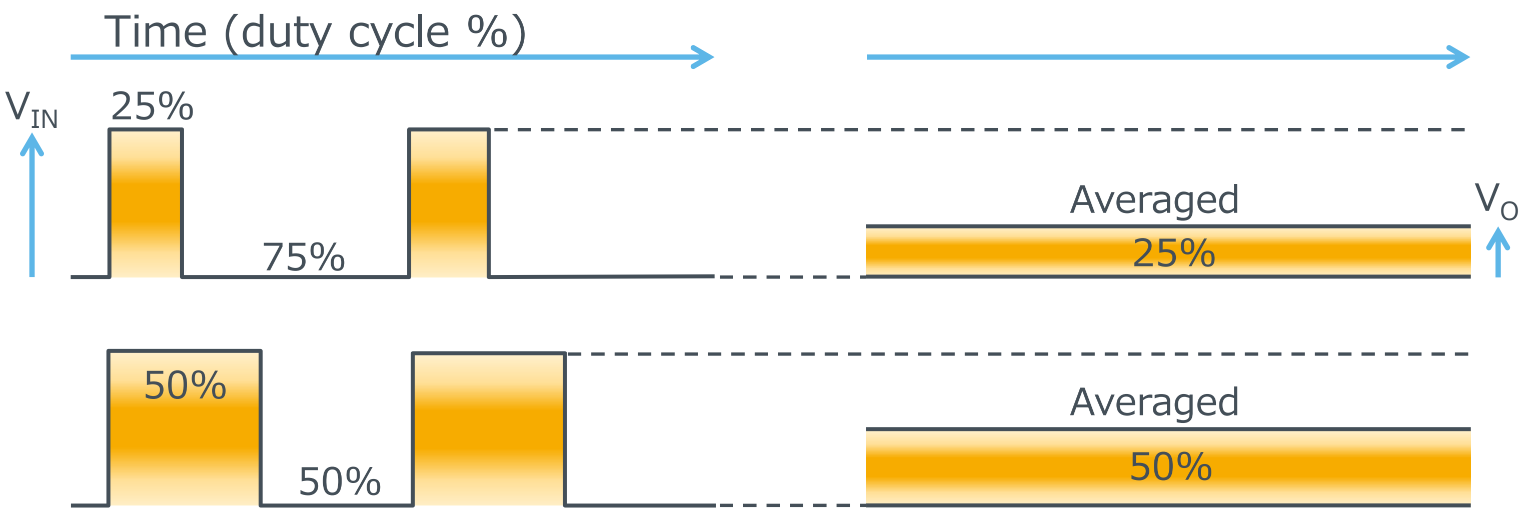
| | **Linear Regulator** | **Switching Regulator** |
|---|---|---|
| Buck<br>Boost<br>Buck/Boost<br>Inverting | Possible<br>Impossible<br>Impossible<br>Impossible | Possible<br>Possible<br>Possible<br>Possible |
| Efficiency | $V_O/V_{IN}$<br>Mostly low | Approx. 95%<br>Usually high |
| Output Power | Generally several watts Depending on thermal design | Large power possible |
| Noise | Low | Switching noise exists |
| Design | Simple | Complicated |
| BOM | Low count | High count |
| Cost | Low | Relatively high |

# Operating Principles of Buck Converter

## Buck Conversion Operating Principles



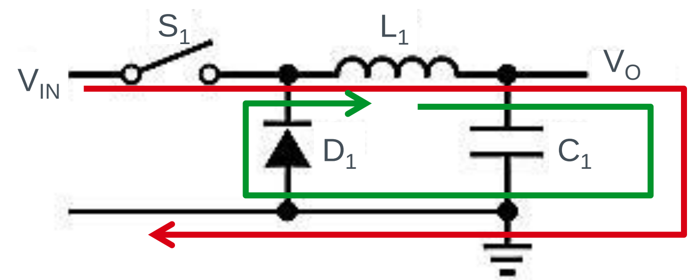

- When S1 is on and S2 off, VIN is applied to L1.
- When S1 is off and S2 on, L1 is connected to GND.
- VIN (DC) is converted to VIN/GND level pulses.
- The voltage is averaged in C1 and converted to DC.

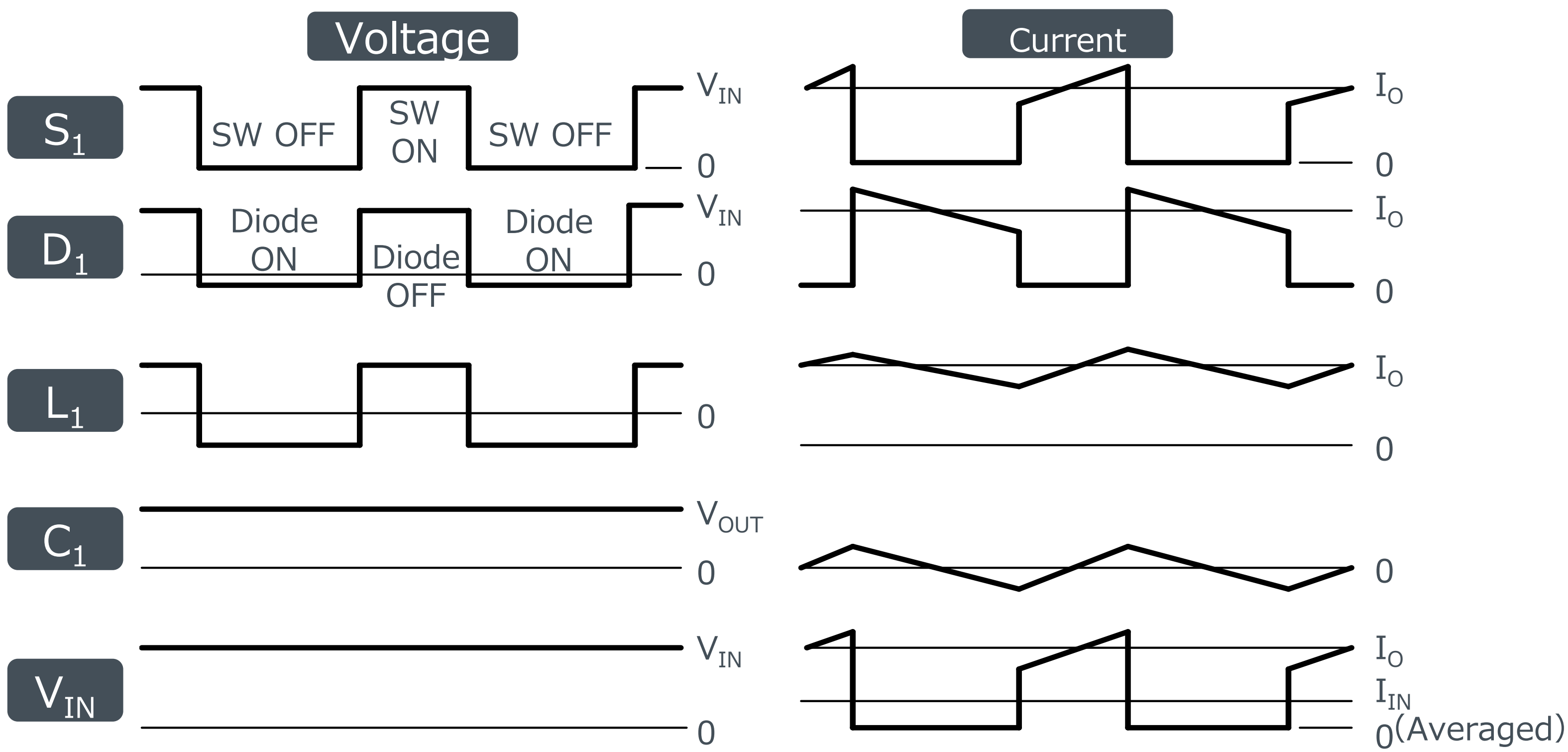


# Operating Principles of Buck Converter

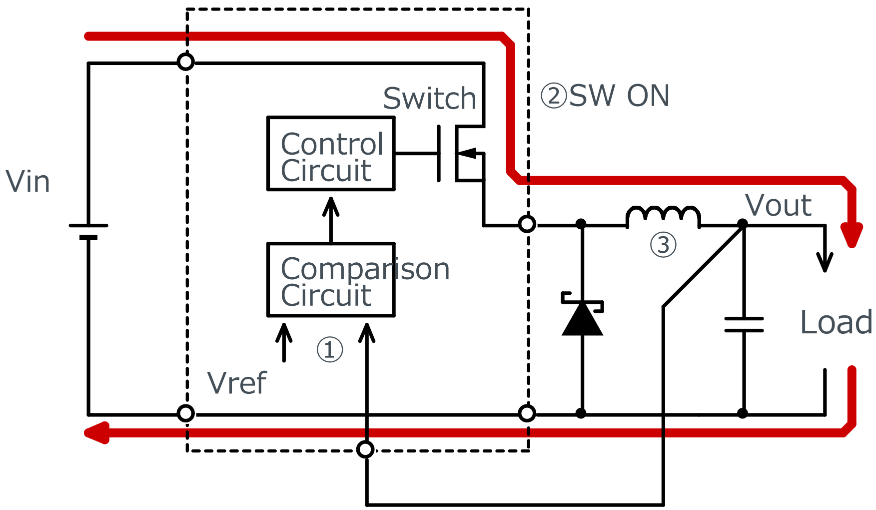
**Basic Circuit for Nonsynchronous (diode) DC/DC Conversion**

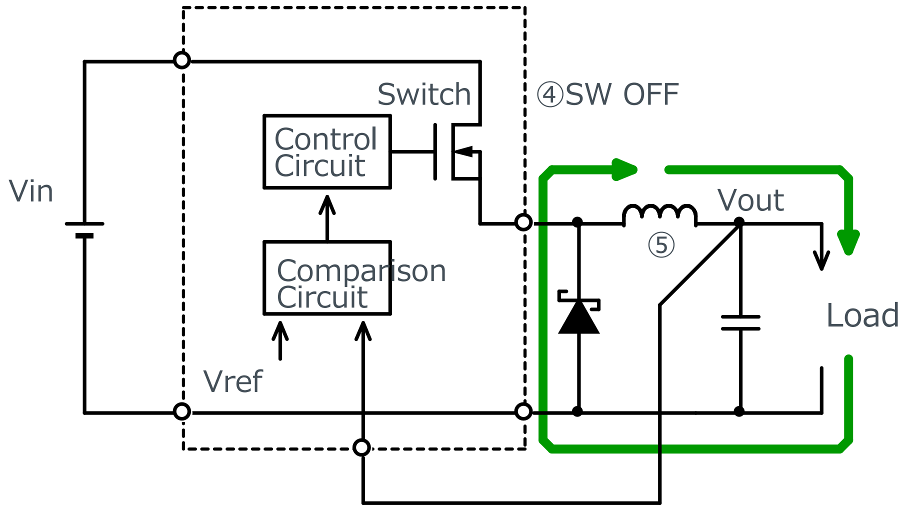
- S1: normal transistor element
- D1: denotes as S2 in the preceding page
- Red line: a current path when S1 is on; green line, when S1 is off



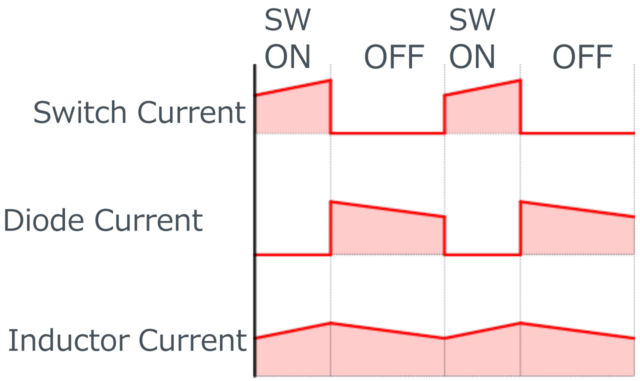



# Operating Principles of Buck Converter



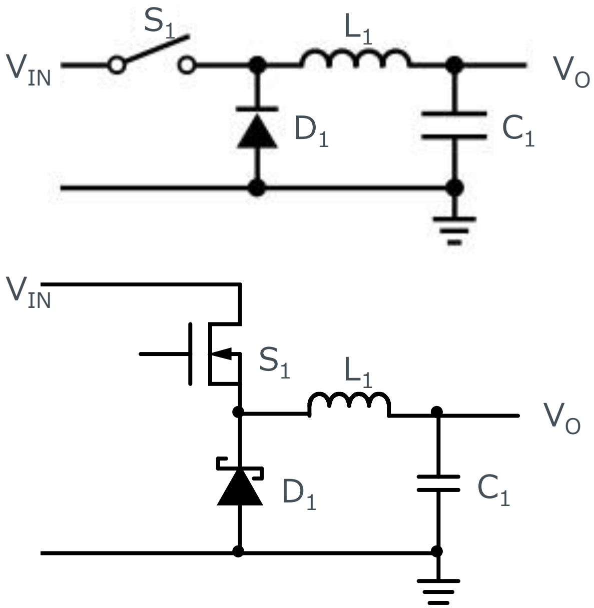




① The comparison circuit (error amp) compares the output voltage with the reference voltage to determine if it is equal to a set voltage.
② If the output voltage is less than the set voltage, the switch (MOSFET) is turned on, supplying power from the input to the output.
③ In this case, magnetic energy is accumulated in the inductor.
④ When the output voltage exceeds the set voltage, the switch is turned off.
⑤ The magnetic energy stored in the inductor is supplied to the output load in the form of current, and it returns to the inductor.
⑥ When the magnetic energy in the inductor is depleted and the output voltage declines, the switch turns on again.

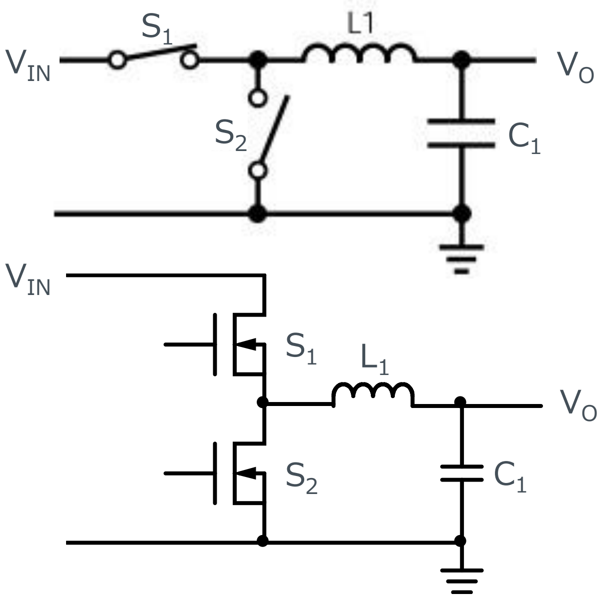


# Differences between Synchronous & Nonsynchronous

## Nonsynchronous (diode) Rectifying




## Synchronous rectifying

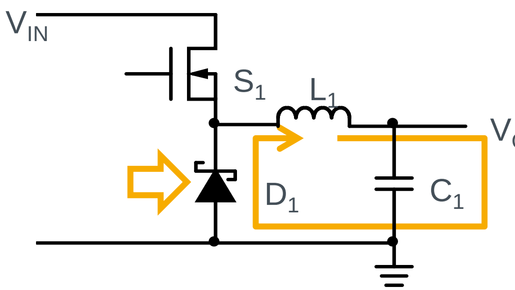



- When S1 is on, no current flows to D1 (off)
- When S1 is off, a forward current flows to D1 (on)
- In an actual circuit, S1 comprises a transistor, and D1 a Schottky diode
- In efficiency, the nonsynchronous rectifying type trails the synchronous type
- The circuit is relatively simple

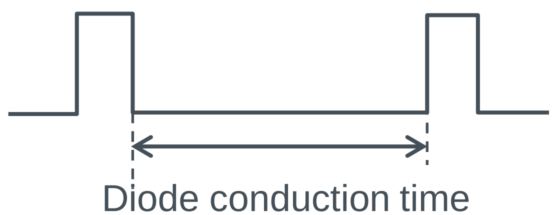
- When S1 is on, S2 is turned off
- When S1 is off, S2 is turned on
- Same current path as nonsynchronous, but the switches are controlled by the control circuit
- A transistor is actually used for the switch
- High efficiency, but it requires special provisions to boost its efficiency at low load
- More complex circuitry to the nonsynchronous

# Differences between Synchronous & Nonsynchronous

## Nonsynchronous (diode) Rectifying

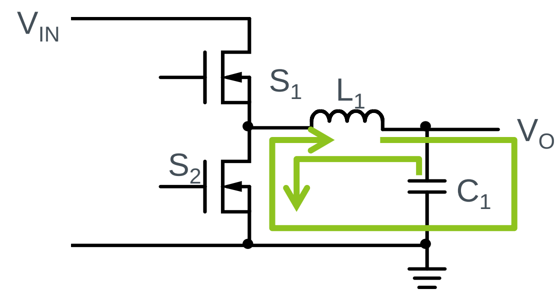


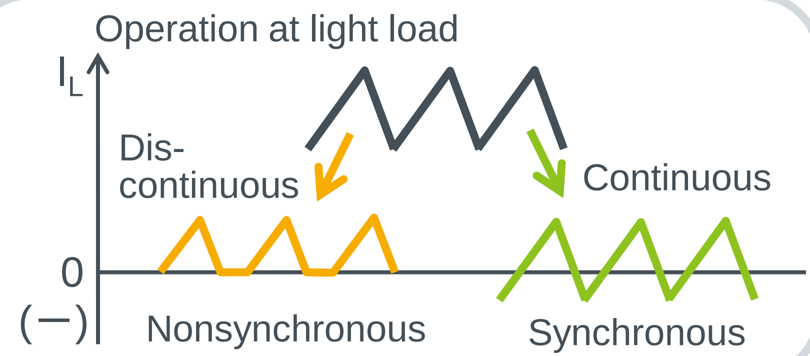

$V_F$ of D1 presents a problem when step-down ratio is high




- When the step-down ratio is high, D1 has a long conduction time
- A low Vo value increases dropout by $V_F$ of D1

## Synchronous rectifying




- Under light load, the inductor current remains at 0A for some time
- In the nonsynchronous, a current flows through the diode only in one direction, resulting in a discontinuous operation and a ringing condition
- In the synchronous, a current can flow in a reverse direction in the transistor, for a continuously regulation, but lower efficiency

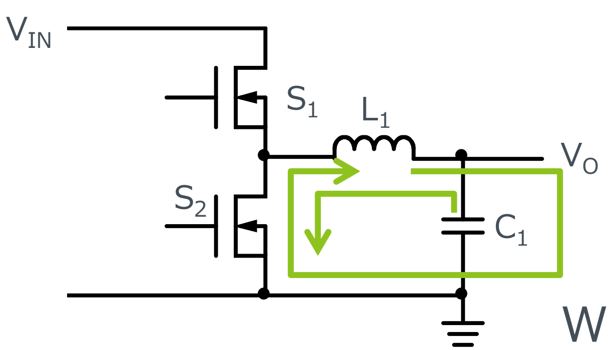
# Efficiency Improvements at Light Load

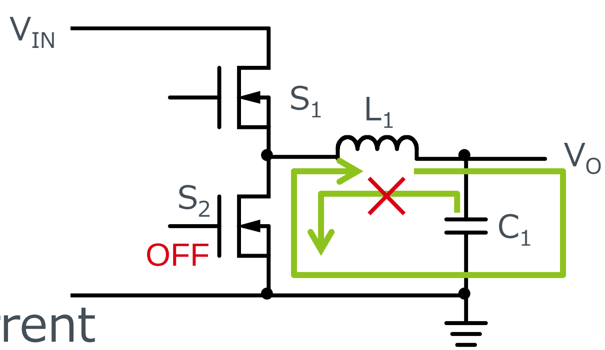
## 1. Addition of a Discontinuous Mode

Improving the efficiency of the synchronous rectifying involves the addition of a function that operates in discontinuous mode during the light load state.

i. Detect the inductor current falling to almost zero
ii. Turned off the low-side transistor
iii. Prevent any reverse current flow

During discontinuous mode at light load, it makes the switching speed reduce and increases the ripple voltage in some cases.



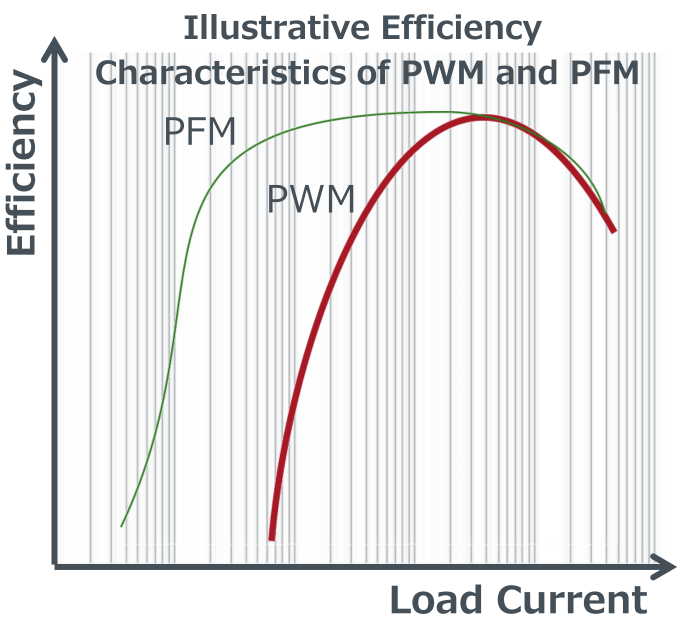



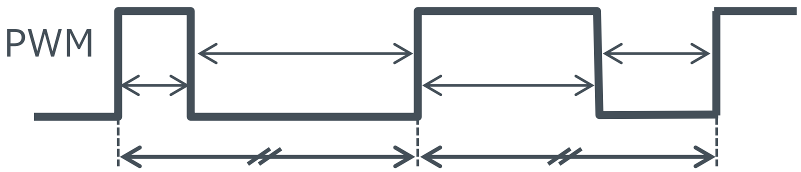

When inductor current
near zero level is detected

# Efficiency Improvements at Light Load

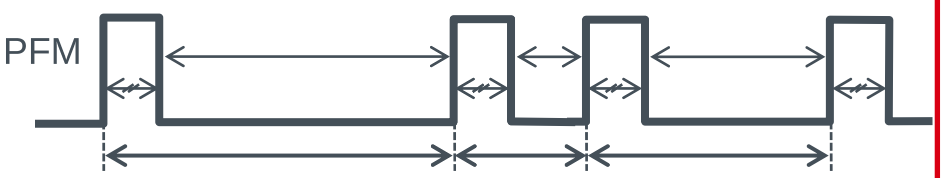
## 2. Switching from PWM mode to PFM mode

- In pulse-width modulation (PWM), the frequency is constant, and duty cycles are adjusted
  - ✓ Because the frequency remains fixed even during light load conditions, switching loss reduces the efficiency
  - ✓ The fixed frequency facilitates the noise filtering
- In pulse-frequency modulation (PFM), the on- (or off-time) is fixed, and the off- (or on-) time is adjusted
  - ✓ Reduced-frequency operations cut switching loss
  - ✓ The unknown frequency makes noise-filtering difficult, with the result that some noise ends up in an audible band




The cycle remains constant with a variable on/off time ratio

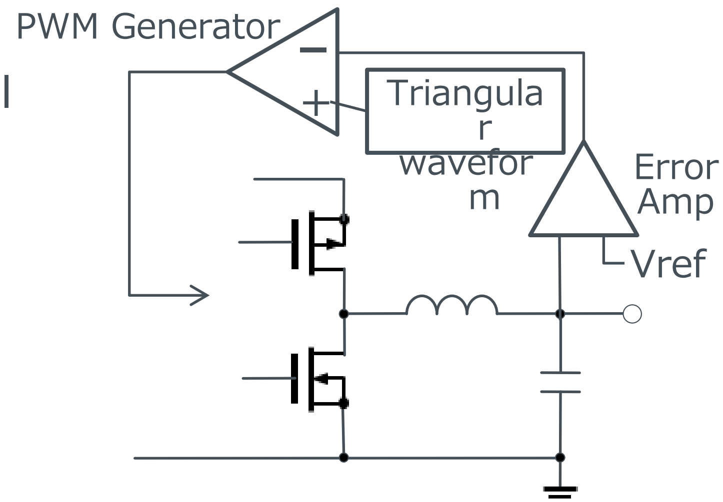



The on-time is constant with a variable off-time = cycle also fluctuates

# Control Methods

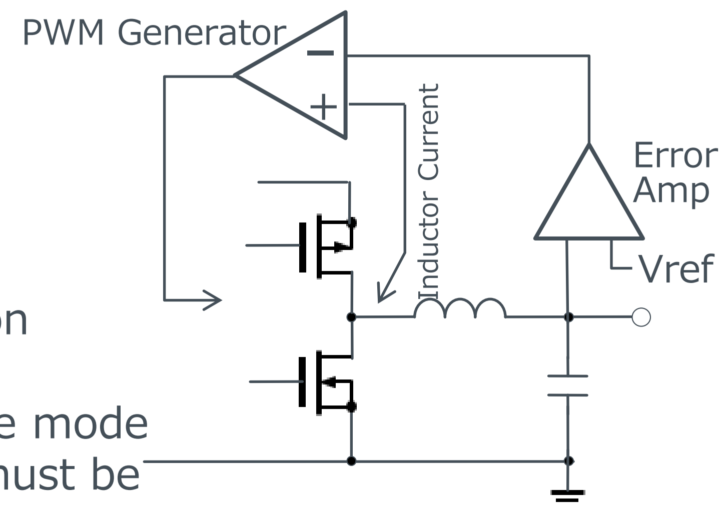
## Voltage Mode Control

- ✓ A voltage-only feedback loop makes control simple
- ✓ The ability to control shorter on-time
- ✓ High noise tolerance
- ✓ Complex phase compensation circuitry




## Current mode control

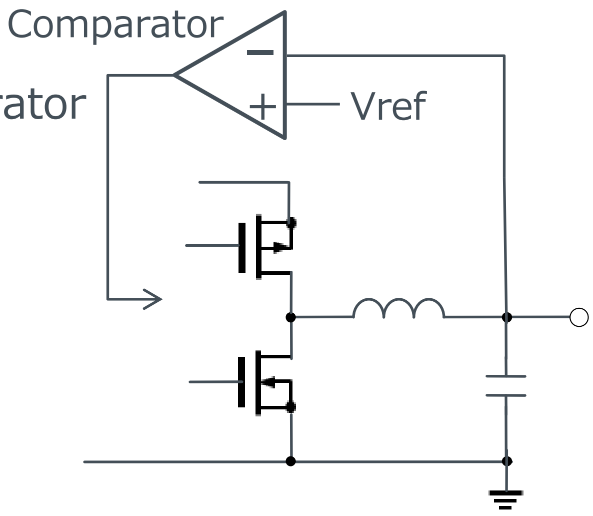
- ✓ Modified voltage mode control
- ✓ Detects and uses circuit inductor current instead of triangular waves
- ✓ High stability of the feedback loop
- ✓ Substantially simplified phase compensation circuit design
- ✓ Faster load transient response than voltage mode
- ✓ Noise to current detection feedback loop must be addressed



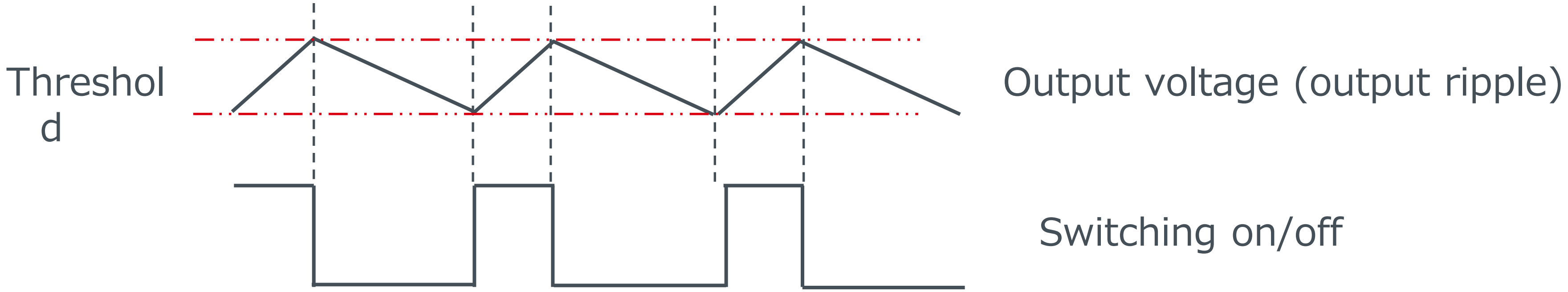
# Control Methods

## Hysteresis (ripple) Control

- ✓ Directly monitors output voltage with a comparator
- ✓ Extremely fast load transient response
- ✓ Highly stable feedback loop
- ✓ Eliminates the need for phase compensation
- ✓ Variable switching frequencies
- ✓ Large jitter
- ✓ Requires a capacitor with a large ESR value to detect ripples



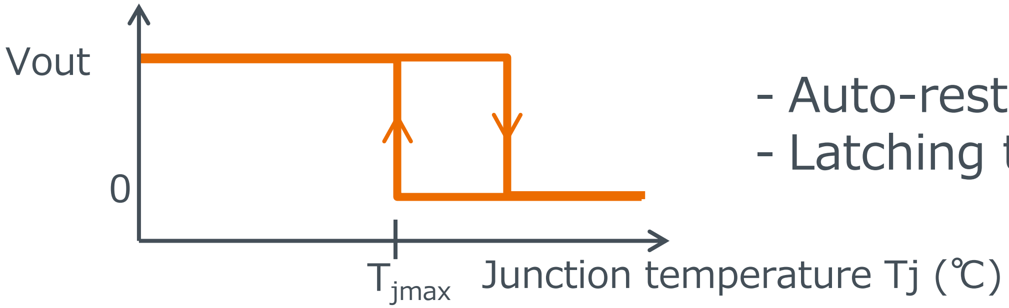

### Illustration of Hysteresis Control



# Protective Functions

## ◆ Thermal Shut Down (TSD)

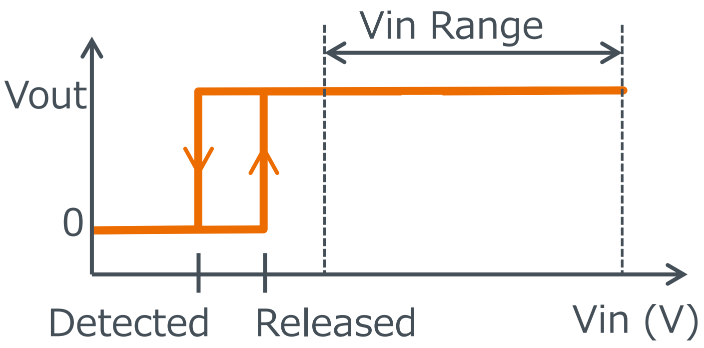
Operation ceases when IC junction temperature Tj reaches the maximum rating Tjmax±α




- Auto-restart type
- Latching type

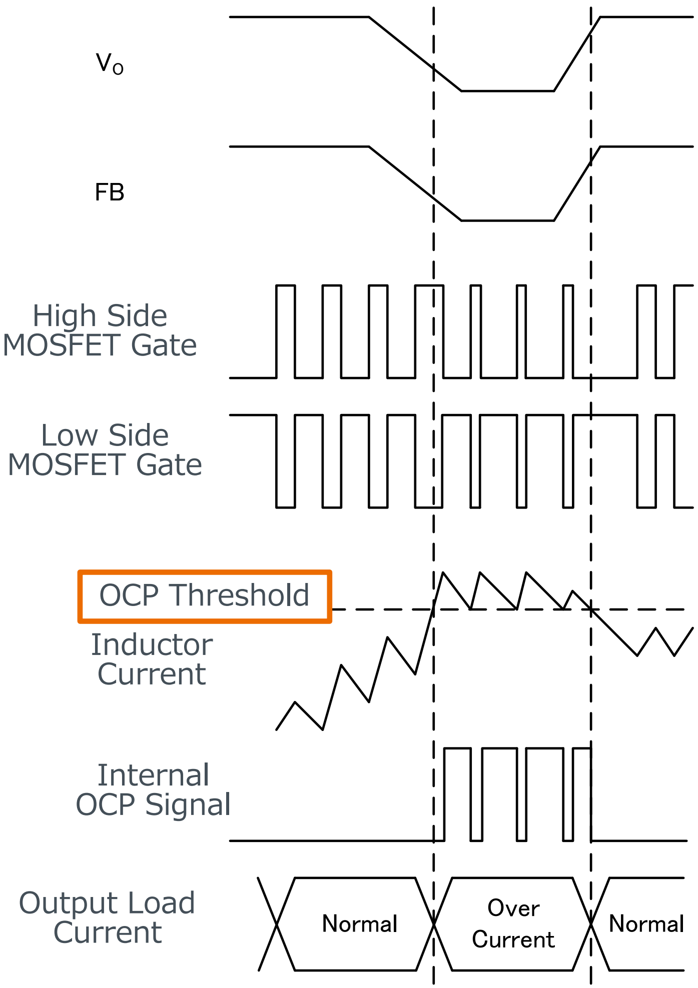
## ◆ Under Voltage Lock Out (UVLO)

Shuts down when input voltage falls below a preset level



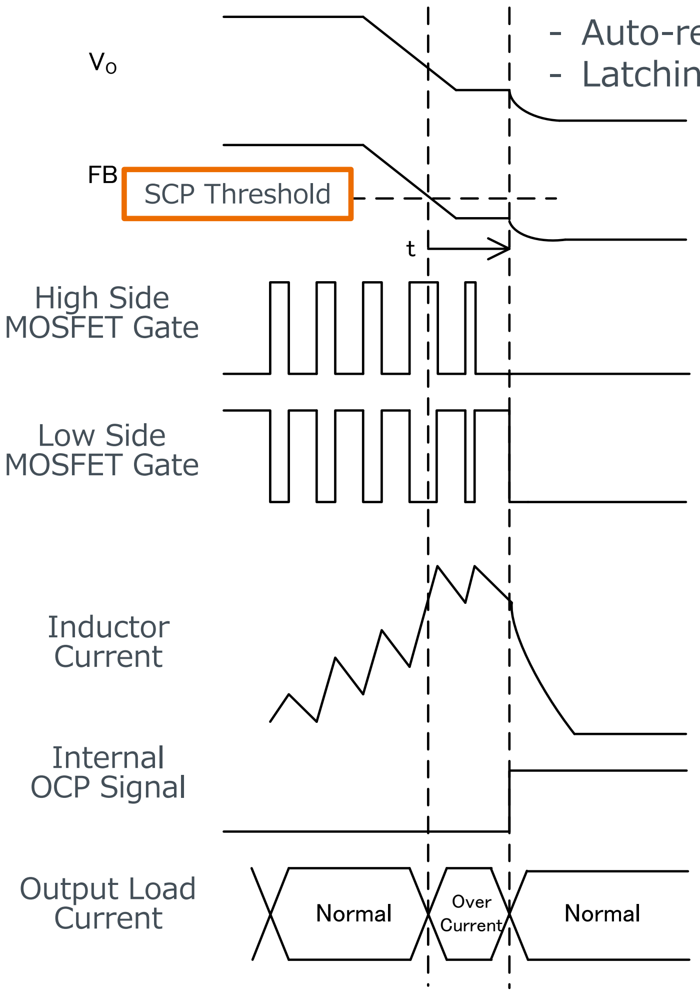
# Protective Functions

◆ **Over Current Protection (OCP)**
Limit the current when output current exceeds a limit value




◆ **Short Circuit Protection (SCP)**
Shuts off operation when output voltage falls below a set level

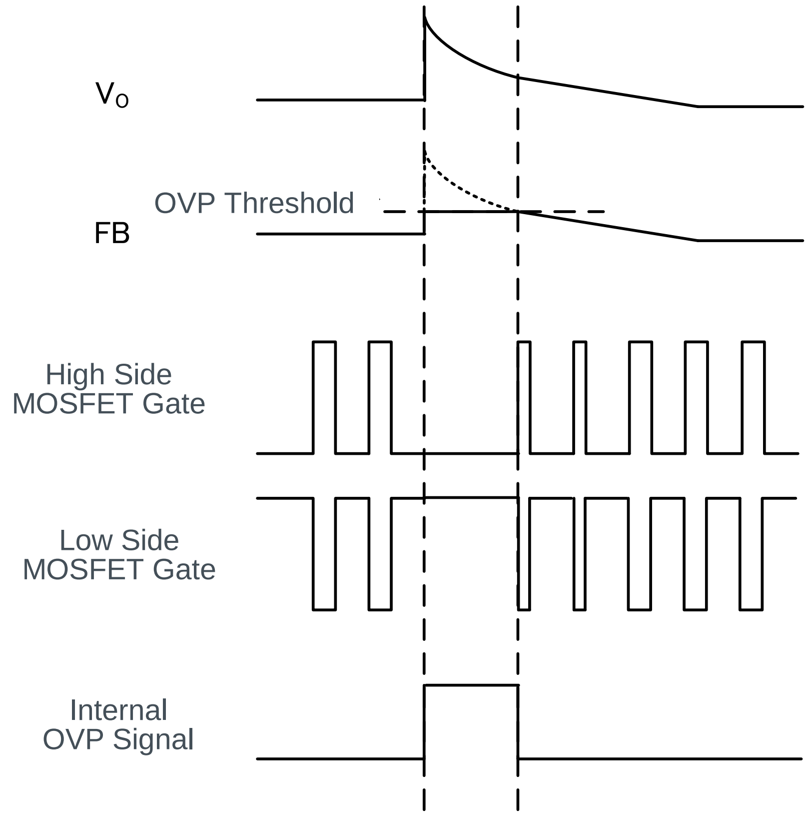
- Auto-restart type
- Latching type

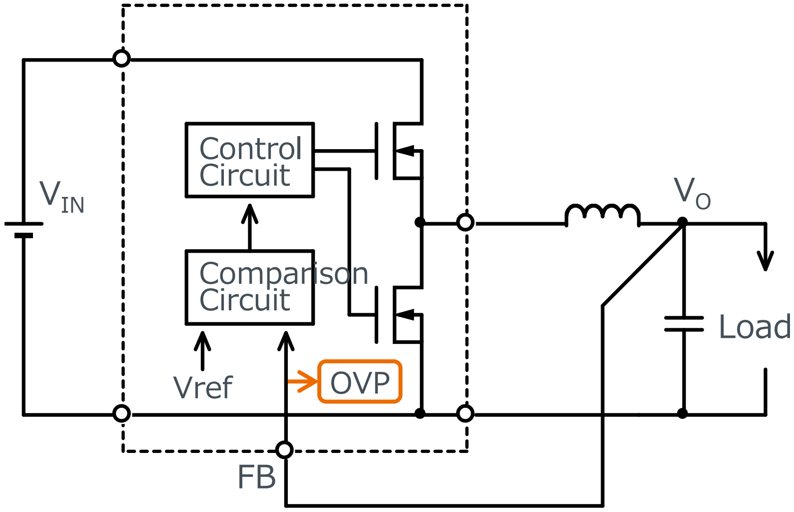


# Protective Functions

◆ Over-Voltage Protection (OVP)

Operation stops when a voltage on output exceeds a set level

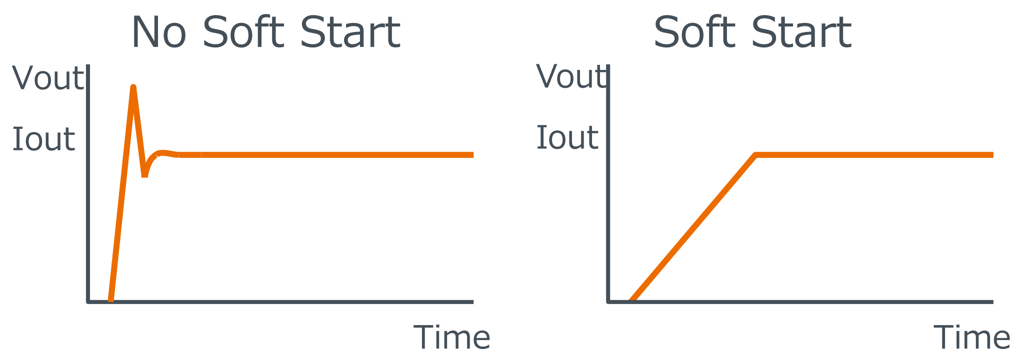


# Sequencing Functions

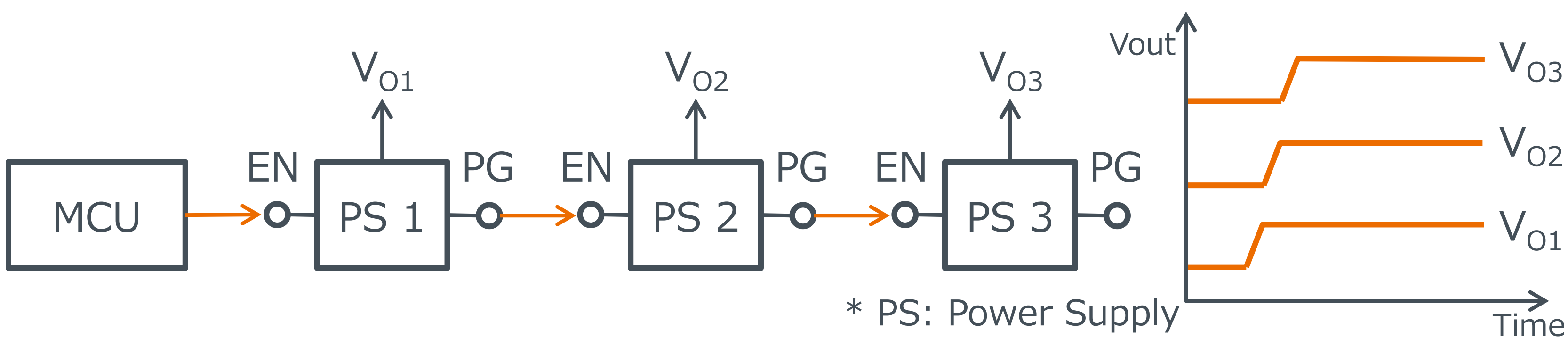
Shutdown: On/off the operation of internal control circuit (same as "Enable" function)

Soft start: Prevent inrush current at startup slowly to rise Vout



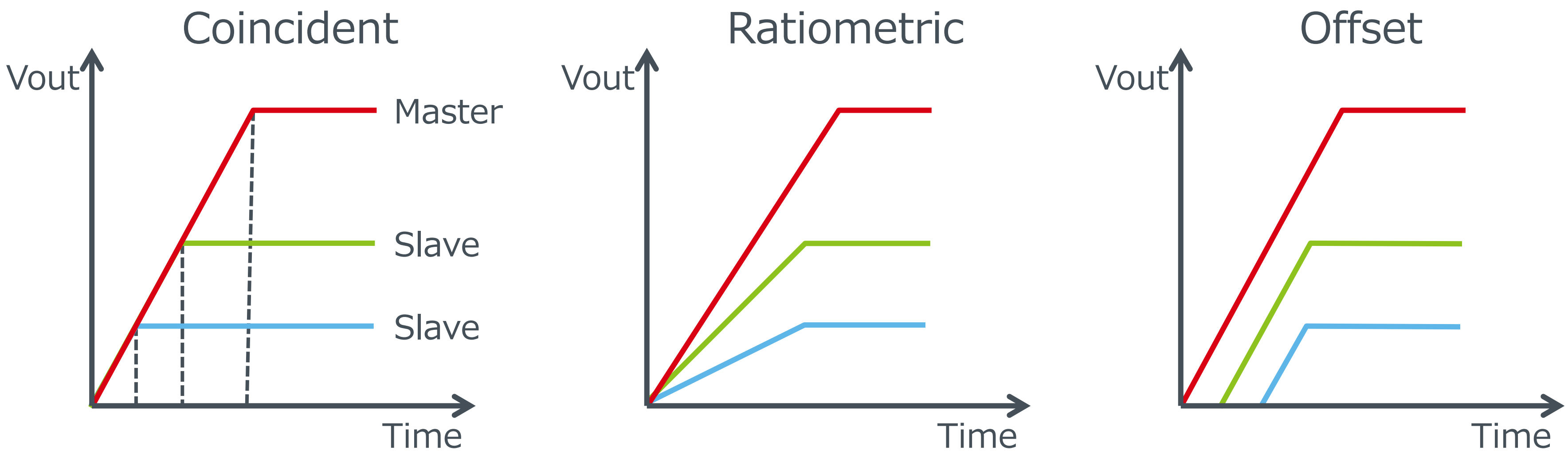

Power-good output: Raise a flag when the output reaches a set voltage level
Notify other devices the power supply has started up

Construct a startup sequence for multiple power supply with the enable function



# Sequencing Functions

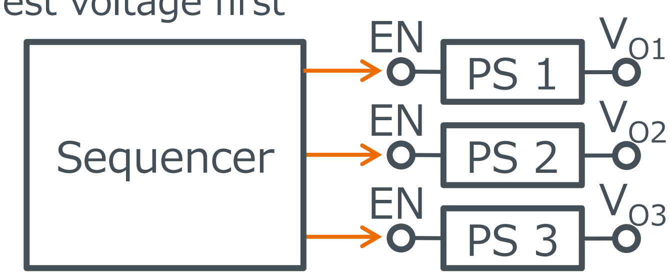
Tracking: Set the sequence and timing of multiple power supplies at start up
There are 3 types

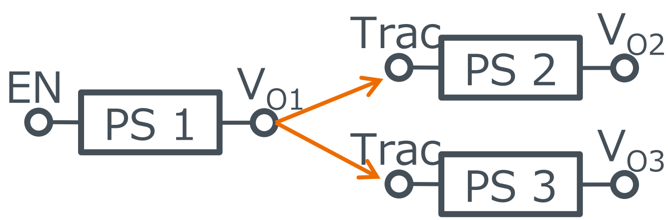



Power supply voltages are applied in sequence, the lowest voltage first

Power supplies start at different slew-rates

Fixed offset voltage between power supplies




＊ PS: Power Supply

# Considerations on Switching Frequencies

## Tradeoff between Efficiency and Size

Increasing the switching frequency:

permits a reduction in size of external inductor and capacitor
reduces efficiency due to switching loss
reduces ripples, and tends to cut noise as well, and
improves transient response.

| Switching Frequency | Up to hundreds kHz | 1 MHz or higher |
|---|---|---|
| Parts Size | Large | Small |
| Efficiency | Increases | Diminishes |
| Noise | Large | Small |
| Ripple | Large | Small |
| Transient Response | Slow | Fast |

# AGENDA

## 1. Linear Regulator Basics

- Operating Principles
- Types and Circuit Configuration
- Advantages vs Disadvantages, and Applications
- Important Specifications
- Efficiency and Thermal Calculation

## 2. Switching Regulator Basics

- Types of Switching Regulator
- Advantages vs Disadvantages, and Comparison with Linear Regulator
- Operating Principles of Buck Converter
- Differences between Synchronous and Nonsynchronous Rectifying
- Efficiency Improvements at Light Load for the Synchronous Converter
- Control Methods (Voltage Mode, Current Mode, Hysteresis Control)
- Protective and Sequencing Functions
- Considerations on Switching Frequencies

# Web Site for Linear Regulator & Switching Regulator


**http://www.rohm.com/**

ROHM SEMICONDUCTOR