Towards Highly Efficient Monolithic DC/DC Converter

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Guide: Prof. Heiner Ryssel
Towards Highly Efficient Monolithic DC/DC Converter

Outline

• Introduction
• Types of switching regulators
• Structure of monolithic converter
• Method of operation of various parts of the converter
• Integration of inductor on chip
• Integration of capacitor on chip
• Power losses in the converter
• Power flow analysis
• Issues in monolithic DC/DC converter
• Techniques to improve performance
  • Light load efficiency
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- Types of switching regulators
  - Buck converter
  - Boost converter
  - Buck-Boost converter
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Introduction

What is a DC/DC Converter?
- A device that accepts a DC input voltage and produces a DC output voltage

Used to provide:
- Noise isolation
- Power bus regulation etc.
- Output at different voltage level
- Wide input voltage range but a constant output voltage
Introduction

- Battery-operated portable electronic devices such as cellular phones, personal digital assistants (PDAs)
- Highly efficient low-voltage switch-mode DC–DC converters are mandatory in these devices
- Also used for hybrid vehicles, solar cells and underwater cables
- Main motive is to maximize system run time (high efficiency) and decrease the volume of the converters
- Trend is to focus on the CMOS implementation of low-power converters such that power management and mixed-signal circuitries can be fabricated on the same chip
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Linear Regulator

- Extremely inefficient (depending on voltage drop!)
- High heat dissipation
- Bulky and expensive heat sink
- Impossible for SOC design
- Reduce battery life
- No switching noise
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Switching Regulator

- Takes small chunk of energy from input & transfer to the output
- Uses electrical switch & controller to regulate rate of energy
- High efficiency
- Use in portable devices - cell phones, laptops, robots, etc.
- Smaller size
- Lower heat generation
- Suitable for on chip design

**Disadvantages**
- Complex system design
- High frequency electrical noise
- Ripple voltage at switching frequency
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Types of Switch Mode Regulators

- Buck converter-step-down converter
- Boost converter-step-up converter
- Buck Boost converter

Many other configurations also exist like:
- Cuk converter
- Isolated converters:
  - Flyback converter
  - Forward converter
  - Full-Half bridge converter
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Types of Switch Mode Regulators

Fig. Buck converter.

Fig. Boost converter.

Fig. Flyback converter.

Fig. Cuk converter.
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Buck Converter

- **When Transistor ‘ON’**
  - Inductor current rises

- **When Transistor ‘OFF’**
  - Current through inductor passes through the diode

- **Modes of operation:**
  - Continuous mode
  - Transition between continuous & discontinuous mode
  - Discontinuous mode

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Buck Converter

- **Continuous Mode**

\[
V_x - V_o = L \frac{di}{dt}
\]

- The change in current satisfies

\[
di = \int_{0^N} (V_x - V_o) \, dt + \int_{0^F} (V_x - V_o) \, dt
\]

- For steady state operation

\[
di = 0 = \int_{0^N} (V_x - V_o) \, dt + \int_{0^F} (V_x - V_o) \, dt
\]

- Hence,

\[
\frac{V_o}{V_{in}} = \frac{ton}{T}
\]
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Buck Converter

Transition between Continuous & Discontinuous Mode

- Inductor current just goes to zero

Now, during the ON time \(V_{in} - V_{out}\) is across the inductor thus

\[ I_L(\text{peak}) = (V_{in} - V_{out}) \frac{t_{ON}}{L} \]

The average current which must match the output current satisfies

\[ I_L(\text{average at transition}) = \frac{I_L(\text{peak})}{2} = (V_{in} - V_{out}) \frac{dT}{2L} \]

\[ = I_{out}(\text{transition}) \]

Where, duty ratio, \( d = \frac{t_{ON}}{T} \)

\[ I_{out}(\text{transition}) = V_{in} \frac{(1 - d)d}{2L} \]

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Buck Converter

Discontinuous Mode

- Transistor OFF time divided into:
  - segments of diode conduction $ddT$
  - zero conduction $doT$
- The inductor average voltage gives:
  \[
  (V_{in} - V_o)dt + (-V_o)\delta_d T = 0
  \]
  \[
  \frac{V_{out}}{V_{in}} = \frac{d}{d + \delta_d}
  \]
- To resolve the value of consider the output current:
  \[
  i_{out} = \frac{i_L(peak)}{2} d + \delta_d
  \]
Buck Converter

- **Discontinuous Mode**
  - Solving for the diode conduction
  - defining \( k^* = \frac{2L}{(VinT)} \)

- **Output voltage vs. Current**
  - At high Output current, voltage ratio depends on the duty ratio "d"
  - At low currents discontinuous operation tends to increase output voltage of the converter towards Vin

\[
\delta_d = \frac{2L I_{out}}{Vin d T}.
\]

\[
\frac{V_{out}}{V_{in}} = \frac{d^2}{d^2 + \left(\frac{2L I_{out}}{Vin T}\right)}.
\]

*Fig. Output voltage vs. current.*

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Boost converter

- When Transistor “ON”
  \[ V_x = 0 \]
- When Transistor “OFF”
  \[ V_x = V_o \]
- For Steady State
  Voltage across the inductor & average must be zero for the average current.
  \[
  \dot{V}_{in} t_{on} + (V_{in} - V_o) t_{off} = 0
  \]
  This can be rearranged to give,
  \[
  \frac{V_o}{V_{in}} = \frac{T}{t_{off}} = \frac{1}{(1-D)}
  \]
  - Since, the duty ratio "D" is b/w 0 and 1 thus the output voltage must always be higher than the input voltage in magnitude.
Buck Boost Converter

- When Transistor “ON”
  \[ V_x = V_{in} \]

- When Transistor “OFF”
  \[ V_x = V_o \]

- For Steady State Voltage across the inductor & average must be zero for the average current
  \[ V_{in} \cdot t_{ON} + V_o \cdot t_{OFF} = 0 \]

- This can be arranged to give voltage ration as
  \[ \frac{V_o}{V_{in}} = \frac{D}{(1 - D)} \]

- Since, the duty ratio "D" is between 0 and 1 hence the output voltage may be higher or lower than the input voltage in magnitude

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Comparison Of Different Converters

- Only the buck converter shows a linear relationship.
- The buck-boost can reduce or increase the voltage ratio with unit gain for a duty ratio of 50%.

**Buck converter:**
\[
\frac{V_o}{V_{in}} = \frac{ton}{T}
\]

**Boost converter:**
\[
\frac{V_o}{V_{in}} = \frac{T}{t_{off}} = \frac{1}{(1-D)}
\]

**Buck-boost converter:**
\[
\frac{V_o}{V_{in}} = \frac{D}{(1-D)}
\]
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• Techniques to improve performance
  • Light load efficiency
Monolithic integrated DC/DC converter

Why Monolithic DC/DC Converter?

- Decrease the size & weight of the portable devices.
- Miniaturization of the power modules.
  Integrating a DC-DC converter can potentially lower the parasitic losses as interconnect b/w DC-DC converter & microprocessor is reduced. Need for on chip, point-of-load (PoL) power conversion.

Challenges

- Tight area constraint for the on-chip integration of inductive & capacitive elements.
- Poor parasitic impedance characteristics.
- High frequency means low value & physical size of passive devices required.

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Monolithic integrated DC/DC converter

Applications

- Battery operated portable electronic devices like laptops, cell phones, PDAs (Personal digital assistants) & other palm
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Monolithic integrated DC/DC converter

- Structure of Current mode Buck Converter
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Power Stage: Inductors on chip

- MEMS based inductors.
  - Use iron-based alloy plated on Si substrate.
  - Spirals made of 1µm Al-Cu isolated from ground plane by 0.5 µm of SiO2.
  - The magnetic film surrounding metal is amorphous CoZrTa alloy that exhibits:
    - Small hysteresis losses.
    - Withstand temperature up to 450°C.
    - Cut off frequency of approx. 1.4GHz.
- Superior higher frequency & saturation characteristics.
- Reduces size & parasitic effects.
- Performs at frequency up to & beyond 10 MHz.
- Magnetic material below & above spirals reduces straying of magnetic flux.
- One layer of magnetic material increases inductance by 36-50% & two layers by 100-500%.

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Power Stage: Capacitors on chip

- Limited area overhead - Filter capacitance integrated on a microprocessor is limited.
- Ranges between 100nF –1nF.
- As capacitance decreased
  - Filter inductance & switching frequency both increased to satisfy output voltage & current.
  - Switching & conduction power dissipation of power MOSFETS & filter inductor increases.
  - Efficiency degrades.
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Monolithic integrated DC/DC converter

- Structure of Current mode Buck Converter

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Compensator

**Cascode OTA (Operational Trans-conductance Amplifier)**

- For Power stage of current mode converter
  - Control-to-output transfer function has real poles.
  - Pole from output filtering capacitor heavily dependent on equivalent resistance of load RL.
  - Poor frequency response.
- Pole Zero Cancellation preferred
  - Band width can be extended.
  - Speed up response time.
- Transfer function of Compensator is
  \[
  A(s) = \frac{V_a}{bV_o} \approx g_m R_o \frac{1 + sC_c R_Z}{1 + sC_c R_o}
  \]

- where, \(g_m\) - Trans-conductance of OTA
- \(R_o\) - Output resistance of the OTA.

![Schematic of Pole Zero Cancellation Compensator](image)
Compensator

\textbf{gm & Ro}

- Important for frequency compensation.
- Determine gain & phase margin of DC/DC converter.
- Depend on biasing current.

\textbf{Result}

- Average -20 dB/dec closed loop-gain.
- Sufficient phase margin below unity gain frequency.
- Two Stage OTA
  - Higher gain
  - Large output swing.
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Cascode OTA

- Circuit Implementation

- Single stage amplifier.
- High gain and only one dominant pole

Schematic for Cascode OTA

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Monolithic integrated DC/DC converter

- Structure of Current mode Buck Converter
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On Chip Current Sensing Technique

Schematic for on chip current sensing circuit

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On Chip Current Sensing Technique

- Aspect ratio of M2 << M1 in power stage.
- Op amp enforce same voltage at node A & B.
- Output current IO flows through M1.
- Switch MS1 is shorted.
- $V_{DS}(M1) = V_{DS}(M2)$.
- $I_{S}(\text{Sensing current}) << IO$.
- $I_2 << IS$.
- $V_{sense}$ in control feedback loop.
- Mrs should operate in saturation.
- The sensing scheme needs to be realized with high bandwidth and low power consumption.
On Chip Current Sensing Technique

Characteristics

- $V_{\text{sense}} = I_{\text{sense}}$ $R_{\text{sense}} = I_L/R_{\text{sense}}/1000$
- High gain amplifier required for accurate current sensing
- Accuracy of sensed current depend on
  - current mirror $M_1$ & $M_2$.
  - On-chip resistor $R_{\text{sense}}$.

Matching of $M_1$ & $M_2$ can be done by

- Common centroid technique
- $M_2$ is surrounded by 500 fingers of transistor $M_1$
On Chip Current Sensing Technique

- Advantages
  - $I_{\text{sense}}$ small hence, power loss reduced in the sensing circuit.
  - Improve efficiency of converter.
- On-chip current-sensing circuit can be extended to sense power NMOS transistor by building complementary circuit for other topologies – boost converter & buck-boost converter.
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Monolithic integrated DC/DC converter

- Structure of Current mode Buck Converter
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Modulator (comparator)

Needed in both

- modulator in feedback control (PWM control).
- hysteretic comparator in the Oscillator & ramp generator circuit.
- Implemented by a source-coupled differential pair with positive feedback to provide a high gain.
- Use of Inverter Chains

![Schematic of the comparator](image)
Oscillator and Ramp Generator

**Used to generate**
- The clock & ramp signals for PWM control.
- Compensation slope for current mode converter.

**Consists of**
- Voltage-to-current (V-I) converter.
- Hysteretic comparator.

**Clock freq and slope of compensation ramp**
- Synchronized with each other
- Depend on Vref, Ct, Rt, VH & VL.
- Rt & Ct can be off-chip components- Switching frequency can be adjusted for different applications.
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Oscillator and Ramp Generator

Schematic of oscillator and ramp generator
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Power Losses in DC/DC Converter

- Conduction Loss
- Switching Loss
- Shoot through current Loss (Related to design of buffer stage to drive transistors)
- Significant energy dissipated in parasitic impedances of circuit board interconnect & discrete components of the regulator.
- **Conduction Losses**: Caused by the parasitic resistive impedances.
- **Switching Losses**: Due to parasitic capacitive impedances of circuit components.
- Power consumed by PWM feedback circuit & integrated filter capacitor is small as compared to the power consumption of the power train (the power MOSFETs, MOSFET gate drivers, the filter inductor).
Power flow analysis

- Buck converter Output
  \[ V_{DD2}(t) = D \cdot V_{DD1} + V_{ripple}(t) \]
- Ripple Current
  \[ \Delta i = \frac{(V_{DD1} - V_{DD2}) \cdot D}{2L \cdot f_s} \]
- Amplitude of voltage ripple,
  \[ \Delta V_{DD2} = \frac{(V_{DD1} - V_{DD2}) \cdot D}{16LCf_s^2} = \frac{\Delta i}{8Cf_s} \]

where, L - Filter inductance.
C - Filter Capacitor.
fs - Switching frequency.

Fig. Inductor current \(i_L(t)\), output voltage \(V_{DD2}(t)\), capacitor current \(i_C(t)\) waveforms.
Power flow analysis

MOSEFETs Related Power

- Combination of conduction loss & dynamic switching loss.
- Conduction power - Dissipated in series resistance of transistor.
- Dynamic Power - Dissipated in each switching cycle of charging/discharging of gate oxide, gate-to-source/drain overlap & drain-to-body junction capacitance of MOSFET.
- MOSFET width optimized to minimize power dissipation.

Energy consumption also due to:

- Series resistance of filter inductor.
- Stray capacitance of filter inductor
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Power flow analysis

- **Total Power Consumption of Buck Converter**

\[
P_{\text{buck}} = P_{\text{tot,MOS (opt)}} + P_{\text{tot,inductor}} + P_{\text{tot,capacitor}}
\]

\[
P_{\text{buck}} = a \sqrt{(I^2 + \frac{i^2}{3}) f_s} + b \left( \frac{I^2}{\Delta i f_s} + \frac{\Delta i}{3 f_s} + \frac{C_{\text{Lo}} V_{\text{DDL}}^2}{R_{\text{Lo}} \Delta i} \right) + df_s \Delta i
\]

- Strongly function of switching frequency (fs) & ripple current (Δi).
- Ptot, capacitor increases as fs & Δi increases.
- Ptot, inductor decreases as fs & Δi increases.
- Ptot, capacitor-negligibly small (less than 1%) as compared to inductor & MOSFET power.

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Power flow analysis

- Efficiency

\[ \eta = 100 \times \frac{P_{\text{Load}}}{P_{\text{Load}} + P_{\text{buck}}} \]

\[ P_{\text{buck}} = a \sqrt{(I^2 + \frac{i^2}{3}) f_s + b \left( \frac{I^2}{\Delta i f_s} + \frac{\Delta i}{3 f_s} + \frac{C_{\text{Lo}} V_{\text{DDL}}^2}{R_{\text{Lo}} \Delta i} \right)} + df_s \Delta i \]

- Low \( f_s \) & \( \Delta i \) - Power dissipation mainly in the Inductor.

- As \( f_s \) & \( \Delta i \) increases - Inductor Loss decreases
  Parasitic Loss increases
  MOSFET Power Loss increases
Efficiency Analysis

As the filter capacitance decreases

- The filter inductance & switching frequency are both increasing to satisfy the output voltage and current requirements.
- Both the switching and conduction power dissipation of the power MOSFETs and the filter inductor increases.
- Thereby degrading the efficiency.

**Major challenges for a monolithic switching DC-DC converter**

- The area occupied by the integrated filter capacitor.
- The effect of the parasitic impedance characteristics of the integrated inductors on the overall efficiency characteristics of a switching DC-DC converter.
Light load efficiency (to improve efficiency)

- Full loading not present for prolonged periods.
- Rather devices run at light loads (stand-by mode) for most of the time.
- Region I
  - Conduction losses dominate.
- Region II
  - Switching losses proportional to load current, input voltage, switching frequency.
- Region III
  - Gate-drive losses while charging /discharging gate capacitances of power transistors during switching transition.

**Decreasing Switching Freq best way to Reduce Total Loss**
Issues with monolithic DC/DC converter

- High efficiency with large input voltage range.
- High performance system-on-chip (SOC) systems.
- Dynamic power management.
- Fast dynamic response.
- Low power consumption: low stand by power.
- Need to provide robust output voltage regulation.
- Maximum efficiency.
- Minimize ripple noise on input & output.
- Minimize cost.
- To have accurate sensed current for current mode PWM controller.
- Reduce supply voltage demand, greater amount of current from external power supplies.
- Voltage scaling capability.
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References

Books

Research Papers
IISB – Power Electronic Systems

Broad spectrum of competencies for system solutions from one source

- Development of novel devices
- Development of new materials and joining technologies
- Simulation
- Mechatronics, Electrical Eng.
- Construction
- Materials Science
- Circuit design
- Software
- Electrical Eng.

Nano-Ag sinter layer
DCB Chip
Key components for the cars of tomorrow

High power loads
- x-by-wire
- active suspension
- electromagnetic valves
- climate compressor

14V Battery

14V Powernet

Traction energy storage
UltraCaps, NiMH, Li-Ion,...

Fuel cell

Mobile power station

Hybrid drive

Backbone

AC

DC

200...500V

40...100kW

230V, 400V

120...400V

6...100kW

1...3 kW

IISB – Power Electronic Systems

Application focus on automotive power electronics
Hybrid motors:
Mechatronic integration of a 100kVA electric motor into a gearbox –
2nd generation of development

- Novel and structure-flexible devices
- New constructive approaches for the 3D integration of power electronics into complex mechanical structures
- Use of software tools for integrated 3D system design (concurrent engineering)
- Optimized thermal management

Power density record
75 kVA / dm$^3$
IISB – Power Electronic Systems

DC/DC converters for traction energy management

- 70 kW
- 0.15 kW/dm³
- 5 kW/dm³
- 70 kW
- Increase of power density
- Increase of switching frequency
- Optimized circuit topologies - »Silicon-instead-of-passives«
- New devices and materials
- Multifunctional integration
- 25 kW/dm³
- 100 kW in notebook format
IISB – Power Electronic Systems

High power density power convertors for fuel cell hybrid cars

Successful first test run:
Stuttgart, February 2005
IISB – Power Electronic Systems

70kW DC/DC converter for the energy management in hybrid and fuel cell vehicles

HyGenius F600
Thank You
Pulse Width Generator

- S=1, R=1 is a forbidden state for the SR latch.
- At startup, O/p of compensator Vc is low compared with sum of the ramp and sensed signal.
- Hence, R is always high.
- However, the given circuit ensures that RS latch do not reach forbidden state.
- R and S do not go high simultaneously.
Buffer

- Required for receiving and amplifying the signal produced by the control circuit.
- Poorly designed buffer will lead to shoot-through current will occur during each switching transition.
- Hence, buffer without short-circuit power consumption is needed.
- Power rails of the buffer should be laid-out carefully & resistances to be minimized so that the converter efficiency do not degrade.
Power flow analysis

Filter Inductor Power

Energy consumption due to:

• Series resistance of filter inductor.
• Stray capacitance of filter inductor.

Total power consumption in inductor is:

\[
P_{\text{tot, inductor}} = b \left( \frac{I^2}{\Delta f_s} + \frac{\Delta i}{3f_s} + \frac{C_{Lo} V_{DD1}^2}{R_{Lo} \Delta i} \right)
\]

\[
b = \frac{(V_{DD1} - V_{DD2}) D R_{Lo}}{2}
\]

Where, CLo - Parasitic stray capacitance per nH inductance.
RLo - Parasitic series resistance per nH inductance
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Power flow analysis

• **Filter Capacitor Related Power**

• Integrated Capacitor implemented utilizing Gate Oxide Capacitance of MOSFET

• Total Power dissipation of a filter Capacitor is:

\[ P_{\text{tot, capacitor}} = df_s \Delta i \]

\[ d = \frac{8R_{ocap}L_{cap}C_o \Delta V_{DD2}}{3} \]

Where  
- \( R_{ocap} \) - Series capacitance of MOSFET with 1\( \mu \)m width.
- \( C_o \) - Gate oxide capacitance per \( \mu \)m\(^2\).
- \( L_{cap} \) - Channel length of the MOSFET.
V-I Converter

- In current mode converters, compensation ramp add with inductor current signal to avoid sub harmonic oscillations.
- V-I designed to convert ramp signal and sensing inductor signal into current.

Schematic of V-I Converter

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V-I Converter

- Now, $VA = Vin + VSG1$
- For 2nd stage V-I converter
  - Trans-conductance, $G_{m2} = \frac{l_1}{V_A} \approx \frac{g_{m2}}{1 + g_{m2}R_s} \approx \frac{1}{R_s}$ for $g_{m2}R_s \gg 1$
  - Then, the output current is given by
    $$I_1 = \frac{V_A}{R_s} = \frac{Vin + V_{SG1}}{R_s}$$
- Need to eliminate non-ideal term, $V_{SG1}$
- Now, $$I_2 = \frac{V_{SG3}}{R_s}$$
- Hence, output current $I_{out}$,
  $$I_{out} = I_1 - I_2 = \left(\frac{Vin}{R_s} + \frac{V_{SG3}}{R_s}\right) - \frac{V_{SG1}}{R_s} = \frac{Vin}{R_s} \alpha Vin$$
V-I Converter

- Now, sensing voltage, $V_{sense} = Isense \times R_{sense}$.
- Hence, output current

$$I_{out} = \frac{V_{sense}}{R_s} = I_{sense} \left( \frac{R_{sense}}{R_s} \right)$$

- $I_{out}$ and $I_{sense}$ do not depend on value of $R_s$ and $R_{sense}$, rather on the ratio.
  - Can be easily controlled