ELPL Embedded Low-Power Laboratory

Embedded System Application

4190.303C

2010 Spring Semester

Power Supply Regulators

Naehyuck Chang
Dept. of EECS/CSE
Seoul National University
naehyuck@snu.ac.kr

Power Supply Overview

- Voltage regulation
  - Remove input noise
    - Ripple voltage
    - IR and inductive drop
  - Device protection
    - Surge protection
  - Maintain operating condition
    - Keep the legal operating range
- Lossless power conversion
  - Change the voltage and the current of power into useful range

Output / Source	AC	DC
AC	Transformer	Rectifier
DC	Inverter	Switching mode DC-DC converter

Power Supply Overview

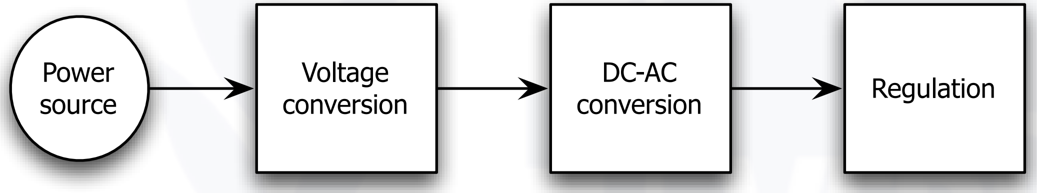
- Purpose of power supply
  - Voltage and current requirement of digital systems
    - Voltage ranges from 0.8 V to 5 V
    - Digital circuits need DC supply
    - Some devices requires 12 V or negative voltages
    - Current ranges from a few mili-amperes to hundreds of amperes
    - Multiple voltages are required in most cases
      - Power supplies supply multiple voltages
      - Onboard power supply circuits generate multiple voltages
- Power sources
  - DC sources
    - Batteries, solar panels, fuel cells, super capacitors, etc.
  - AC sources
    - Outlets, generators (before rectification), etc.

Power Supply Overview

- Power sources
  - Regulated
    - Voltage is constant and does not change by the load current
  - Unregulated
    - Voltage changes by itself and/or changes by the load current
  - Voltage source
    - Typical power source
    - Voltage is fixed, but the current varies by the load resistance according to the Ohm's Law
  - Current source
    - Not a typical power source
    - Current is fixed, but the voltage varies by the load resistance according to the Ohm's Law

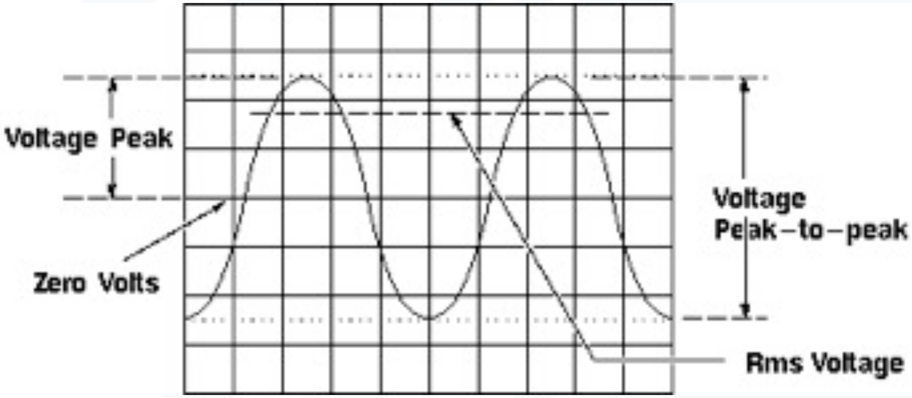
Power Supply Overview

- Typical legacy power supply architecture
  - Use of a linear regulator
  - Switching power supply has a different architecture, but beyond the scope
    - Computer Systems Design course will cover it



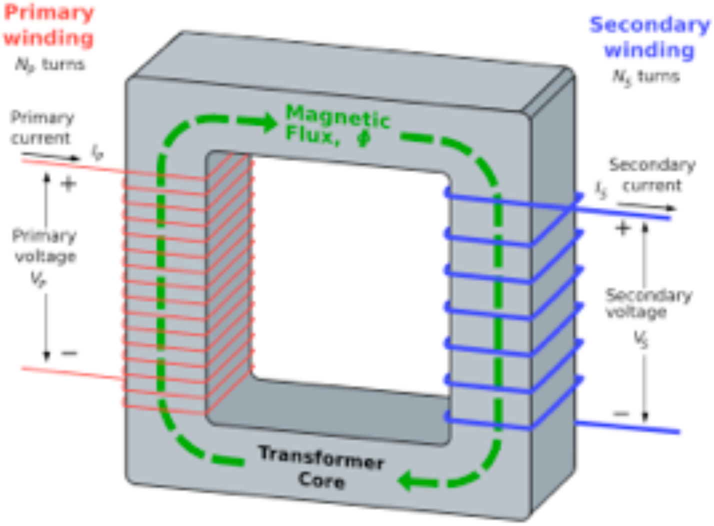
Power Supply Overview

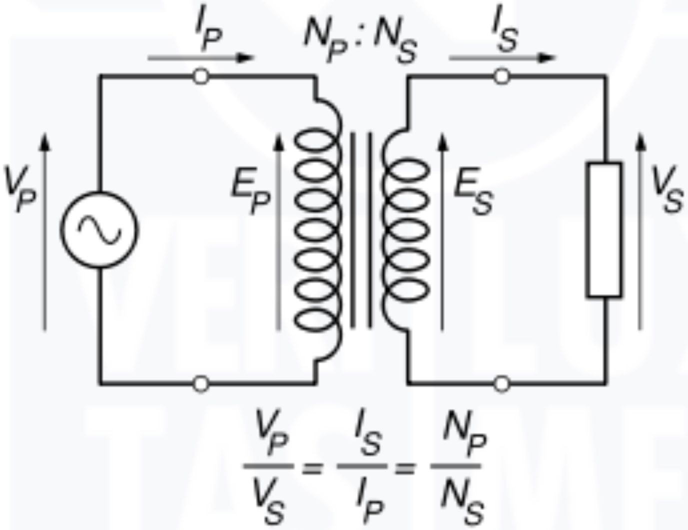
- Power Source
  - Typical power source for indoor applications
    - AC outlet
    - 110 to 220 V depending on the location
    - 60 Hz in general, but 50 Hz is also used
    - 110 and 220 V means the RMS (root mean square) voltage
    - Sinusoidal waveform
    - Peak to peak voltage



Power Supply Overview

- Voltage conversion of an AC power source
  - Use of a transformer

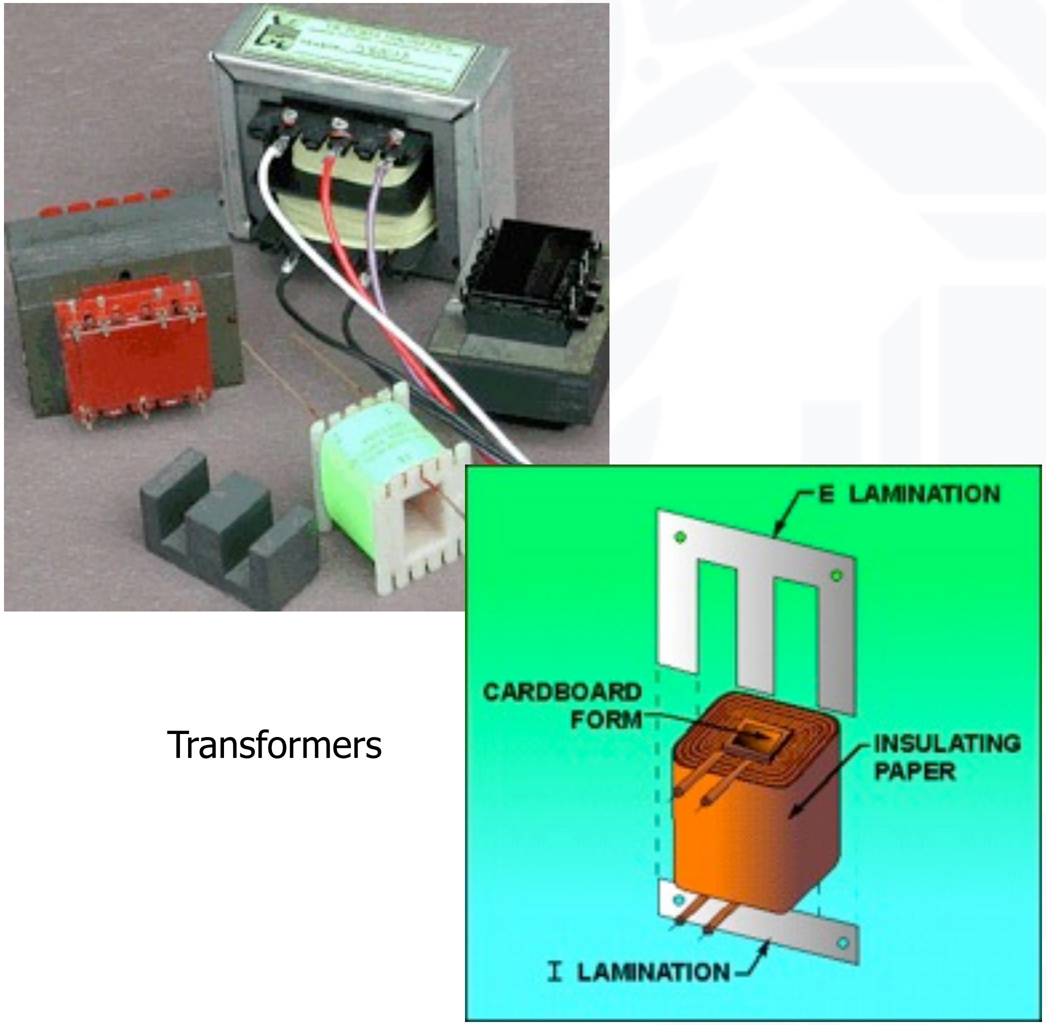




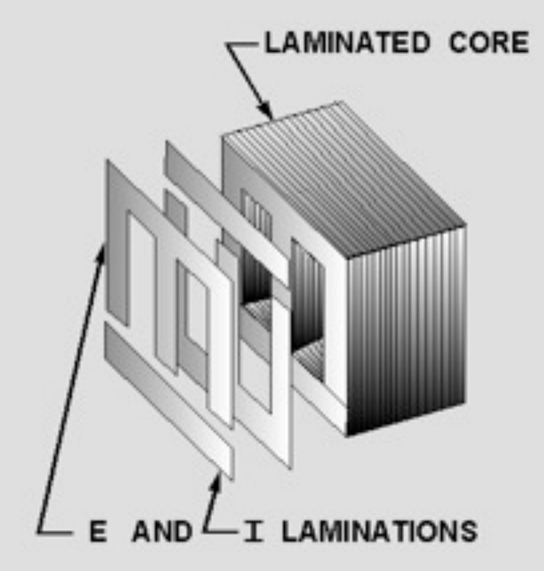
$$\frac{V_P}{V_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S}$$

Power Supply Overview

- Typical EI core transformers



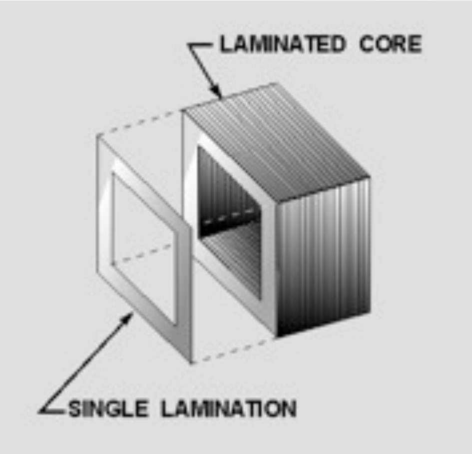
Transformers



EI cores

Power Supply Overview

- Transformer cores
  - Iron: low frequency (audio frequency, below 20 KHz)
  - Ferrite: high frequency
  - Air: very high frequency
- Types
  - EI
  - Hollow
  - Ring



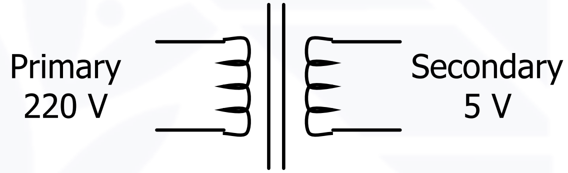
Hollow core

Power Supply Overview

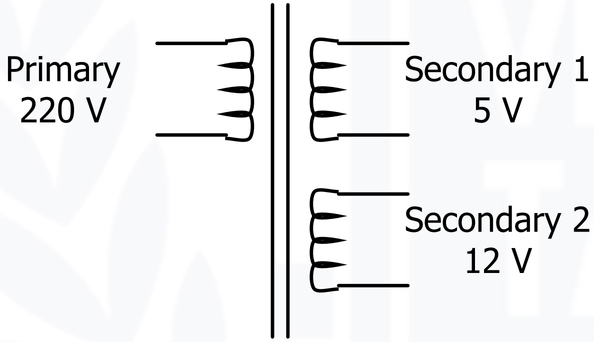
- Toroidal-core transformer
  - Ideal design for a transformer
    - Faraday designed and wound the first transformer on a toroidal core
  - Very low loss levels and high induction saturation
  - Magnetic flow is evenly spread in the core and due to the absence of intermediate metal parts, vibrations are eliminated
  - All the wound coils are spread over the surface of the core
  - Noise caused by magnetostriction practically disappear
    - a property of ferromagnetic materials that causes them to change their shape when subjected to a magnetic field

Power Supply Overview

- Basic power transformer

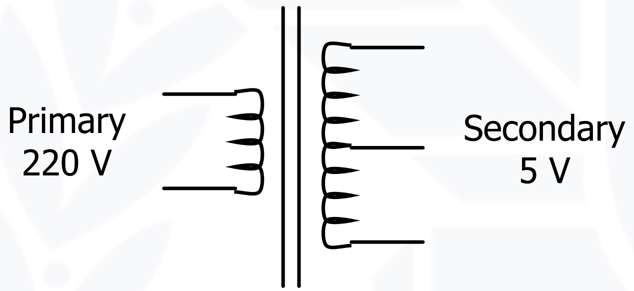


- Multiple secondary windings

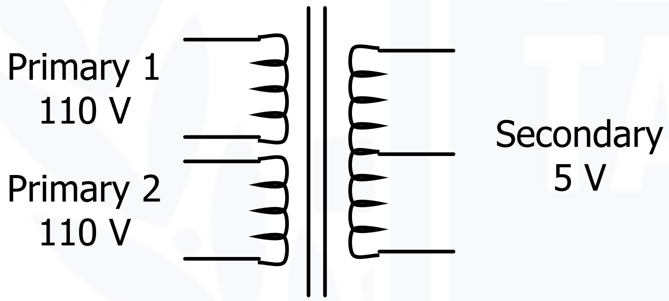


Voltage Conversion

- Center-tapped secondary winding

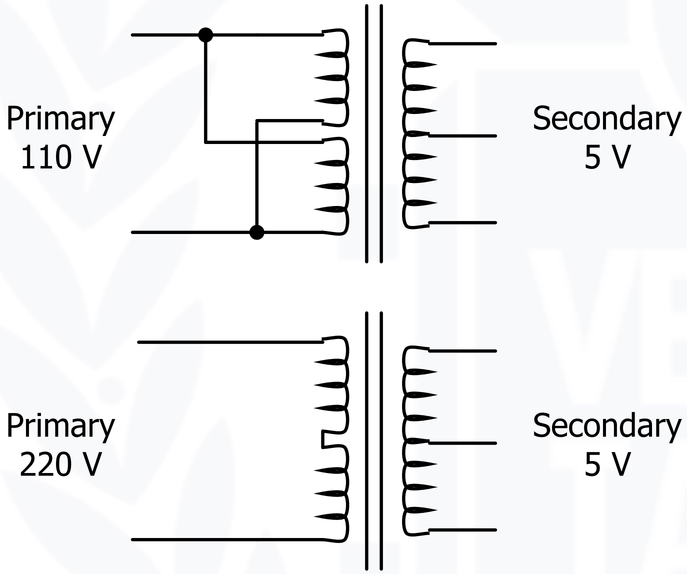


- Split dual primary windings



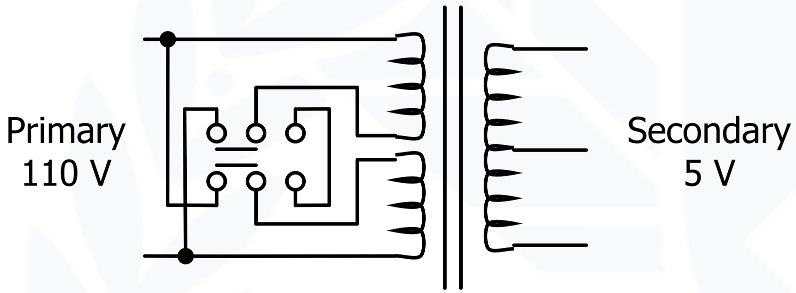
Voltage Conversion

- 110 V and 220 V dual input
  - Use of a selection switch to configure both wiring
  - Should be careful for the winding direction

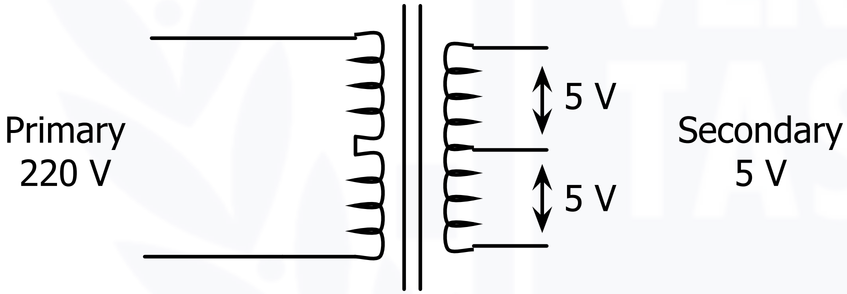


Voltage Conversion

- How to make a switch configuration for the dual primary winding?



- How to use the center-tapped secondary winding?



Voltage Conversion

- Transformers on the market

9V AC 500 mA with Center Tap
Power / Filament Transformer
Philmore # TR034

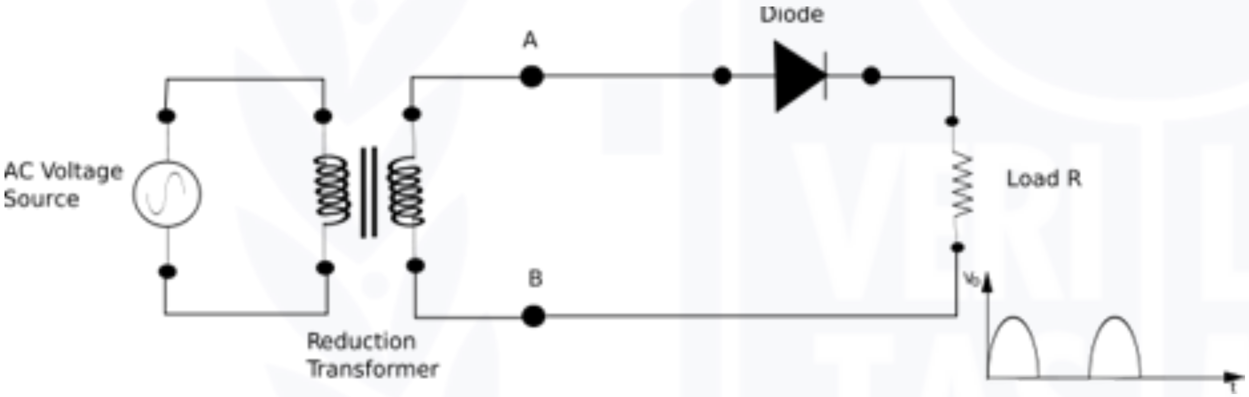
Output voltage given are across the entire secondary. Center tapped leads provide 1/2 that voltage from the center to either lead wire. Classic style with metal bracket with mounting holes.

- With Wire Leads
- Input Voltage: 110-120 VAC 60Hz
- Nominal Output at full load, 9 VAC
- Center Tap Voltage at full load: 4.5 VAC

Price: $4.79

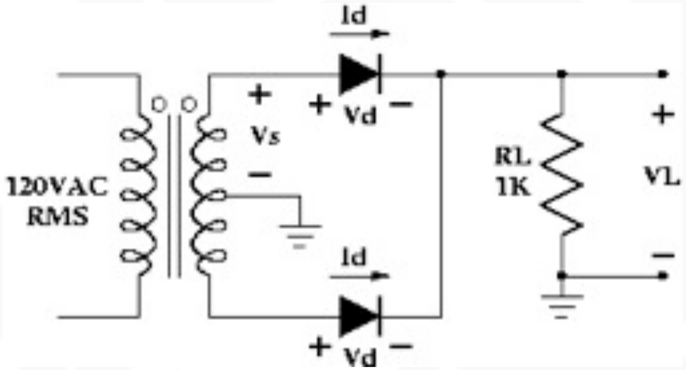
AC-DC Conversion

- Half-wave rectifier
  - Use of one diode
  - Very simple but high ripple

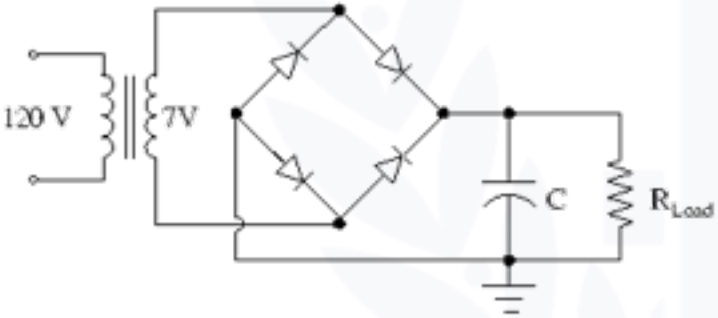


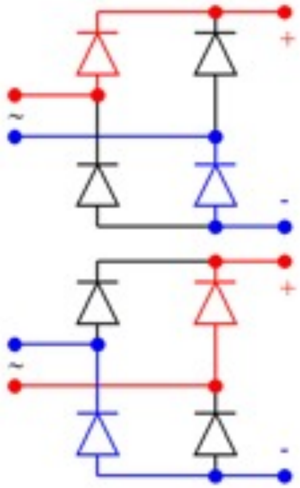
AC-DC Conversion

- Full-wave rectifiers
  - Use of a center-tapped transformer



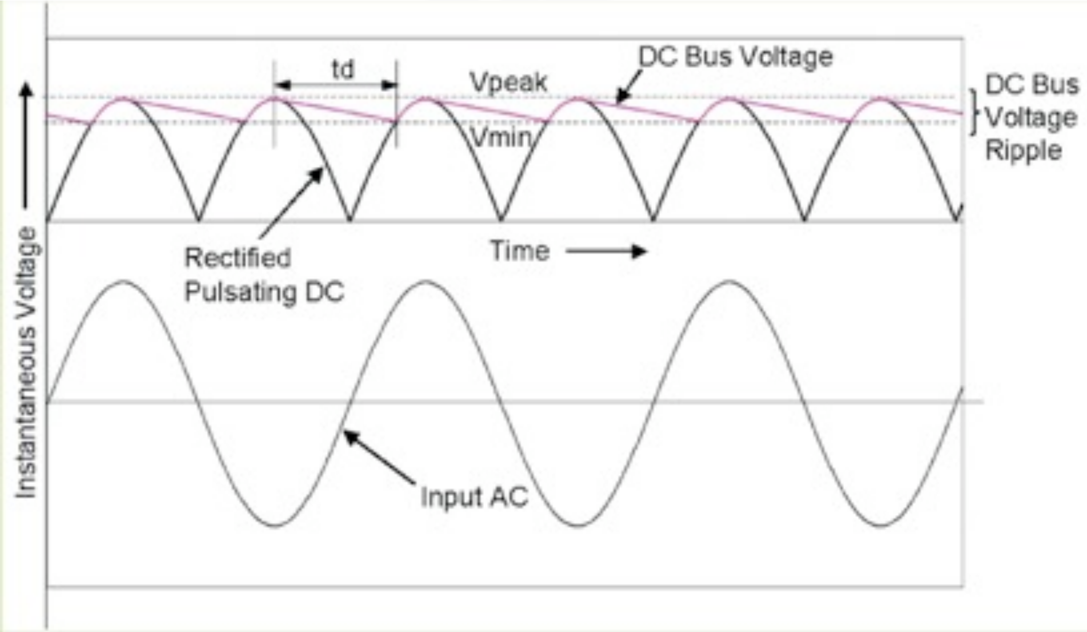
  - Use if a bridge diode

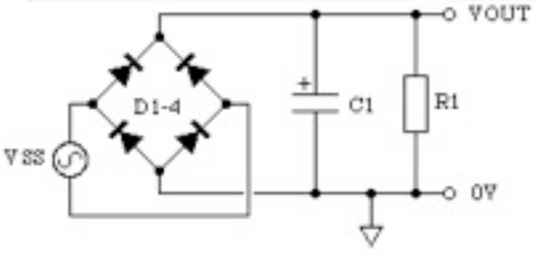




AC-DC Conversion

- Reducing the ripple voltage
  - The diode rectifier generates a DC output with ripple
  - Should be flatten by a bulk capacitor
  - Typically 4,700 uF to 22,000 uF aluminum electrolytic capacitor
    - Use of 2X or higher voltage ratings

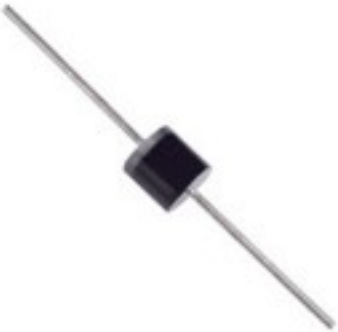




Circuit 14.2 Full-wave rectifier

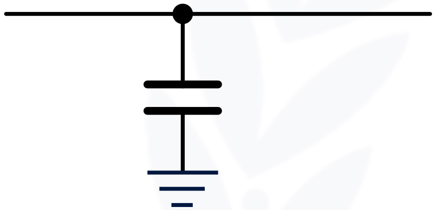
AC-DC Conversion

- Typically 3X rating
  - Minimum 50 V
  - 2 to 6 A
  - Single, dual and bridge



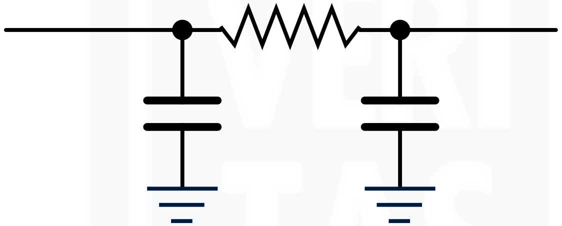
AC-DC Conversion

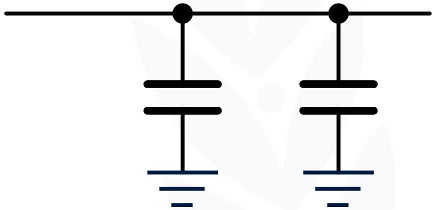
- Why parallel multiple electrolytic capacitors rather than a single capacitor?



Single 10,000 uF

Pi filter





Dual 4,700 uF

Dual 4,700 uF

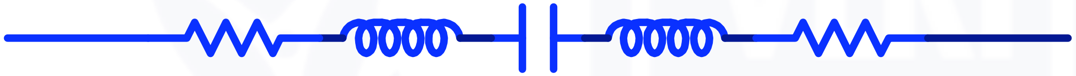
AC-DC Conversion

- For digital systems
  - Low equivalent series inductance (ESL) and low equivalent series resistance (ESR) capacitors

AC-DC Conversion

- For digital systems
  - Low equivalent series inductance (ESL) and low equivalent series resistance (ESR) capacitors

a) Ideal



b) real condition

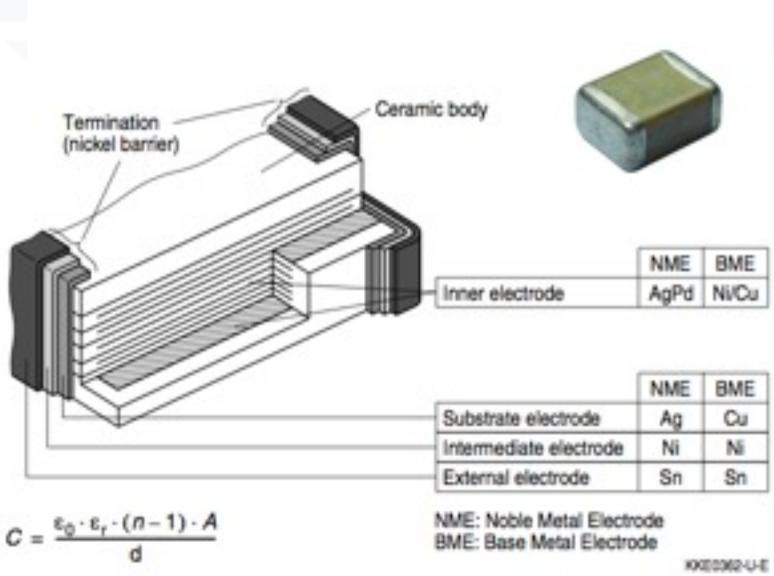
AC-DC Conversion

- Aluminum electrolytic capacitors
  - Polarity
    - Negative marking
    - Long wire is positive
  - Tolerance
    - +100%
  - Rating
    - 6.3 V to high voltages
  - High capacity over 100,000 uF
- Tantalum capacitors
  - Polarity
    - Positive marking
    - Long wire is positive
  - Better frequency response
  - Larger than 100 uF is not cost effective

AC-DC Conversion

- Monolithic capacitors
  - No polarity
  - Very good frequency response
  - Smaller than 1 uF

- Multilayer ceramic capacitor
  - Extremely low ESR
  - High capacitance such as 22 μF



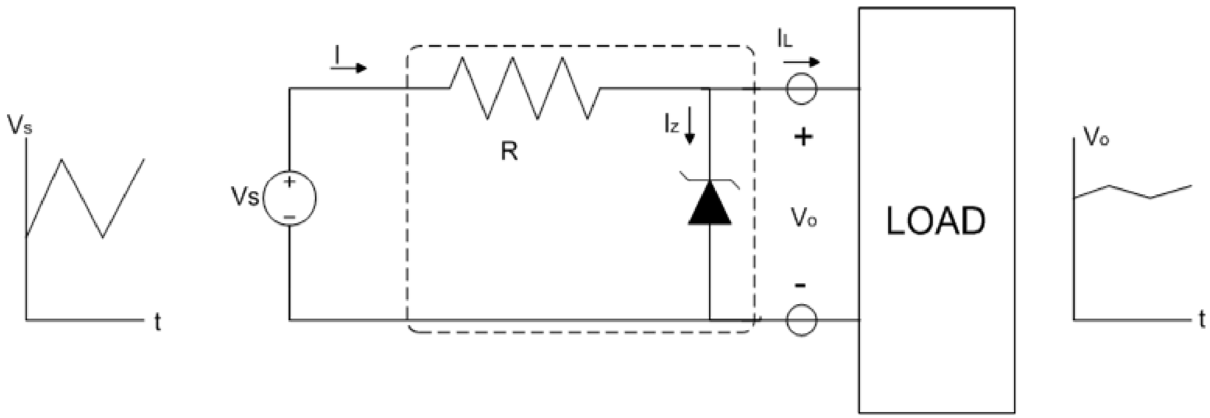
- Parallel connection of two or more different capacitors are desirable
  - Not for the capacity, but for the frequency response

Linear Voltage Regulators

- Voltage divider structure
  - Input current is the same to the output current
  - Only step down is feasible
- Inherently low efficiency
  - Efficiency = output power/input power
    - Input current = output current
  - Voltage difference means power loss!
    - Efficiency = output voltage/input voltage
- True DC output
  - Very low ripple
  - No switching noise
  - Suitable for
    - low-cost systems
    - Analog circuits
    - Low-power systems

Zener Diode Regulator

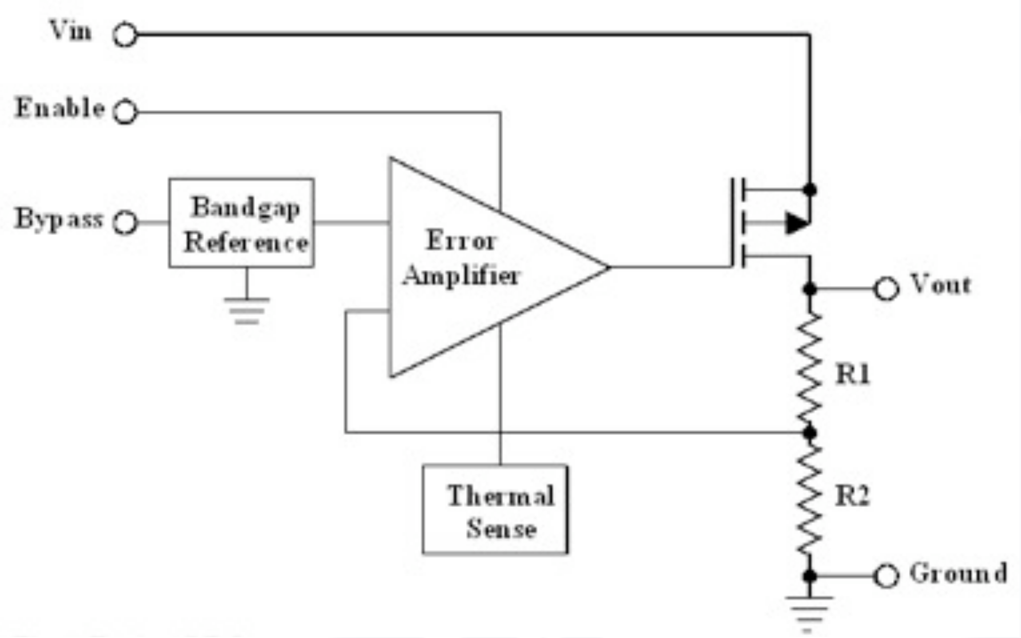
- Output voltage regulation using the breakdown voltage of a zener diode
  - Applicable to a very small load
  - Loss through the zener diode is very large



A zener shunt regulator

Voltage regulator using OP-amp

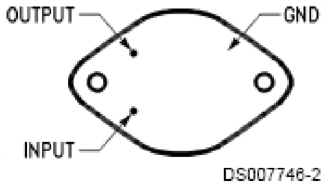
- The essential circuit elements
  - A zener reference, a pass or shunt transistor, a sensing circuit, and an error/amplifier circuit
- V_{out} depends on the feedback resistors
  - V_{out} is determined by R_1 and R_2
  - V_{in} must be greater than V_{out}



Three Terminal Voltage Regulator

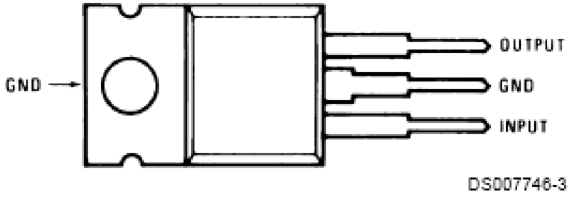
- Less flexible, but extremely simple to use
- Come in standard TO-3 (20 W) or TO-220 (15 W) transistor packages
- 78/79XX series regulators are commonly available with 5, 6, 8, 12, 15, 18, or 24 V output
  - Maximum output current with heat sink is 1 A
  - Built-in thermal shutdown protection
  - 3-V dropout voltage; maximum input of 37 V

Metal Can Package
TO-3 (K)
Aluminum



Bottom View

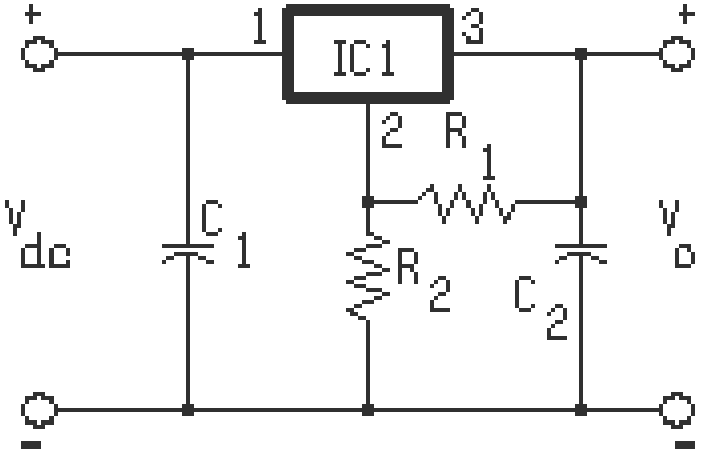
Plastic Package
TO-220 (T)



Top View

Three Terminal Voltage Regulator

- 3-terminal variable regulator

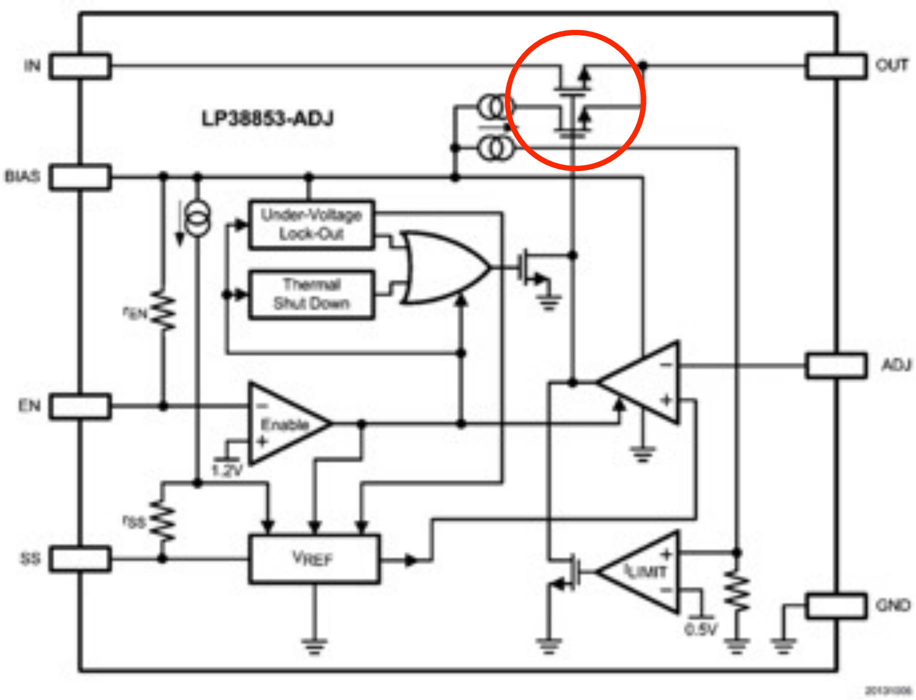


$$V_o = V_{reg} + \left(\frac{V_{reg}}{R_1} + I_Q \right) R_2$$

- 3-terminal regulator could be made into a variable regulator with feedback resistors
- Power dissipation in Resistors can in some cases be quite large resulting in bulky and expensive equipment
- A variety of 3-terminal variable regulators are available, e.g. LM317 (for +V_{EE} output) or LM 337 (for -V_{EE} output)

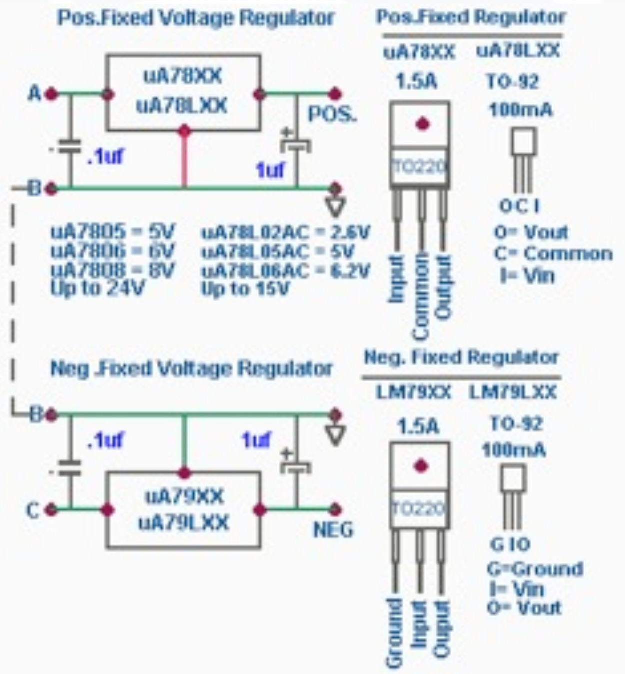
Low Dropout Regulator (LDO)

- Low dropout due to PMOS output
  - Dropout is typically less than 250 mV (2V dropout for LM78xx)
  - (Potentially) much more efficient than normal NMOS linear regulators
    - If the input and output voltages are the same, an LDO and a regular linear regulator efficiency is the same!



Dual Power Supply

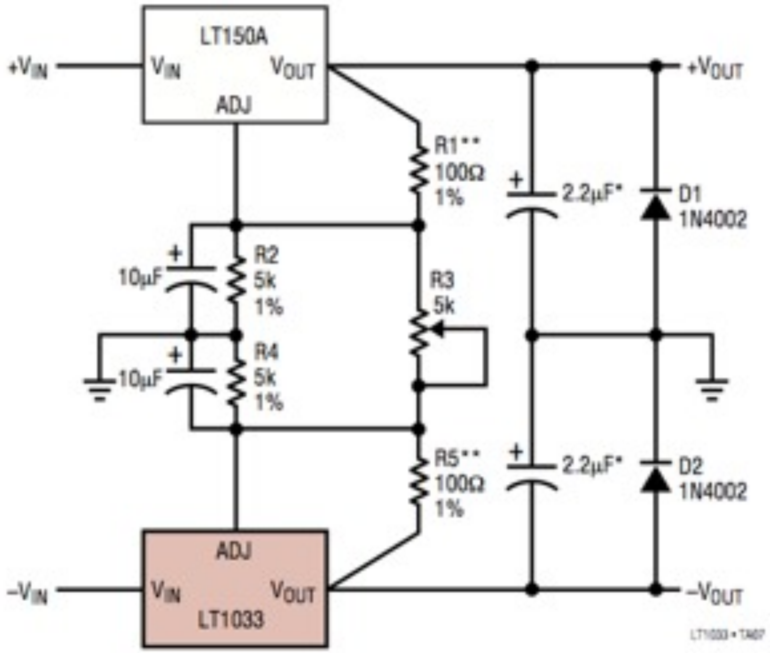
- Provide +V_{EE} or -V_{EE} output voltages
  - Common in direct coupled amplifiers
  - Can be implemented by two independent opposite polarity linear regulators



Dual Power Supply

- Dual tracking power supply
  - Symmetrical voltage output regardless of V+ and V- output current
  - If V+ output drops due to IR drop, V- output also drops

Dual Tracking 3A Supply ± 1.25V to ± 20V

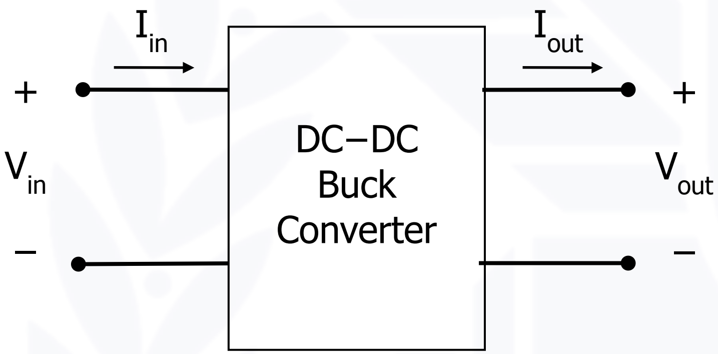


*SOLID TANTALUM

**R1 OR R5 MAY BE TRIMMED SLIGHTLY TO IMPROVE TRACKING

Switching Mode DC-DC Converter

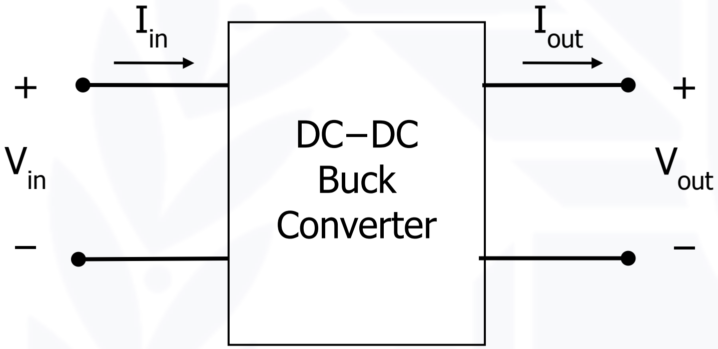
- Objective: to efficiently reduce DC voltage



- The DC equivalent of an AC transformer
- Lossless objective: $P_{in} = P_{out}$

Switching Mode DC-DC Converter

- Objective: to efficiently reduce DC voltage

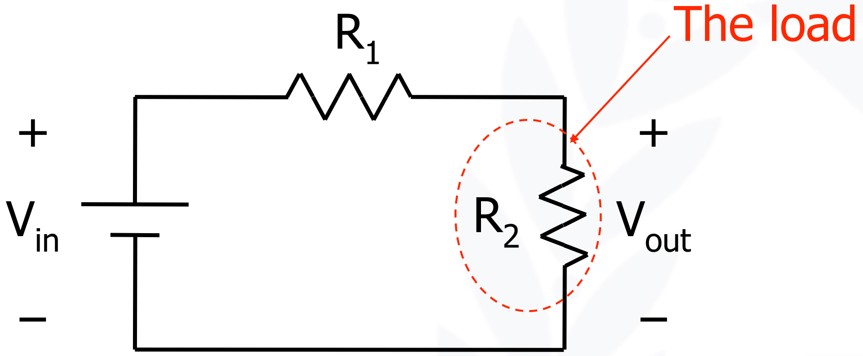


- The DC equivalent of an AC transformer
- Lossless objective: $P_{in} = P_{out}$

$$\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}}$$

Switching Mode DC-DC Converter

- Voltage divider



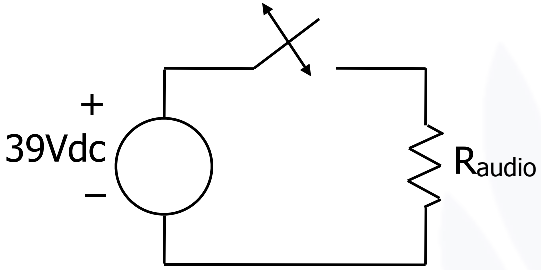
$$V_{out} = V_{in} \bullet \frac{R_2}{R_1 + R_2}$$

$$\eta = \frac{R_2}{R_1 + R_2} = \frac{V_{out}}{V_{in}}$$

- The most naive approach
- If Vin = 39V, and Vout = 13V, efficiency η is only 0.33
- Unacceptable except in very low power applications

Switching Mode DC-DC Converter

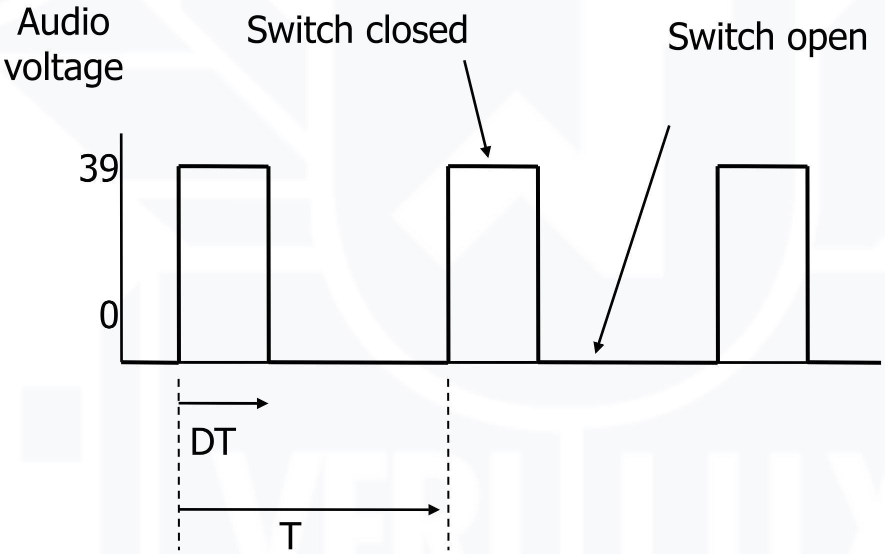
- Convert voltage by switching: 39V to 13V for a car audio



Switch state, Stereo voltage

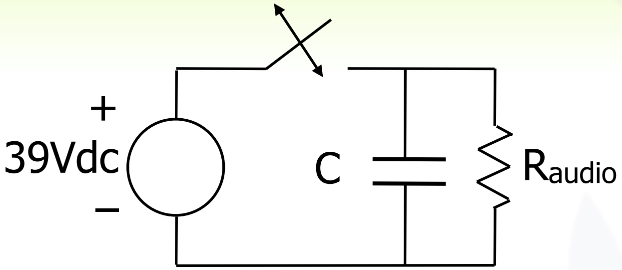
Closed, 39Vdc

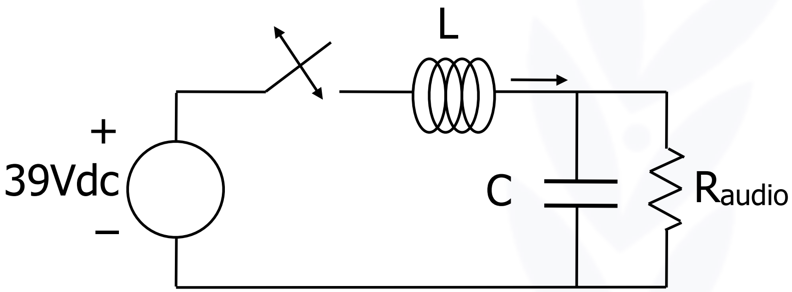
Open, 0Vdc

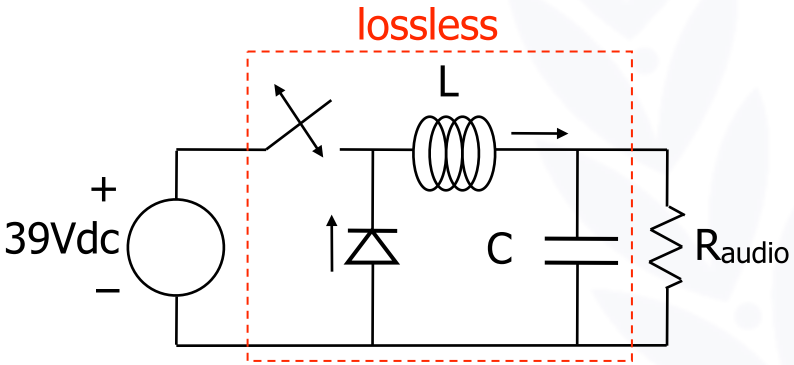


- The DC equivalent of an AC transformer
- If the duty cycle D of the switch is 0.33, then the average voltage to the expensive car stereo is 39 • 0.33 = 13Vdc
- This is lossless conversion, but is it acceptable?
  - If it is a light bulb or a heater, it is acceptable

Switching Mode DC-DC Converter

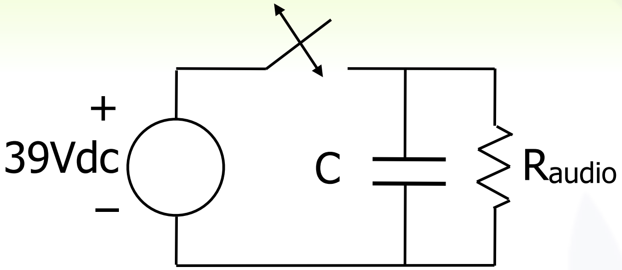




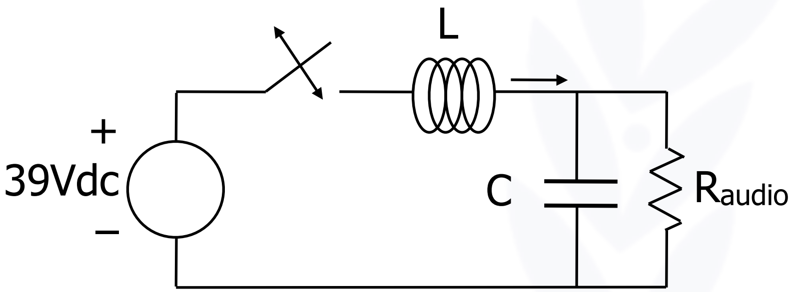


A DC-DC Buck Converter

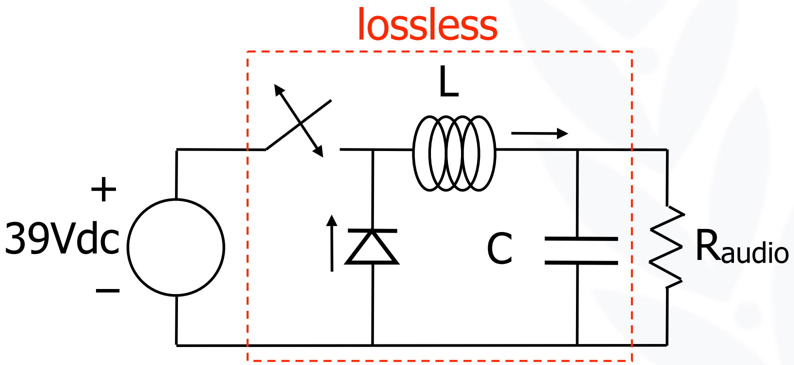
Switching Mode DC-DC Converter



Try adding a large C in parallel with the load to control ripple. But if the C has 13Vdc, then when the switch closes, the source current spikes to a huge value and burns out the switch.



Try adding an L to prevent the huge current spike. But now, if the L has current when the switch attempts to open, the inductor's current momentum and resulting Ldi/dt burns out the switch.



A DC-DC Buck Converter

By adding a "free wheeling" diode, the switch can open and the inductor current can continue to flow. With high-frequency switching, the load voltage ripple can be reduced to a small value.

Switching Mode DC-DC Converter

- In capacitors: The voltage cannot change instantaneously

- Capacitors tend to keep the voltage constant (voltage “inertia”)
  - An ideal capacitor with infinite capacitance acts as a constant voltage source
  - A capacitor cannot be connected in parallel with a voltage source or a switch (otherwise KVL would be violated, i.e. there will be a short-circuit)

- In inductors:
  - The current cannot change instantaneously
- Inductors tend to keep the current constant (current “inertia”)
  - An ideal inductor with infinite inductance acts as a constant current source
- **Thus, an inductor cannot be connected in series with a current source or a switch (otherwise KCL would be violated)**

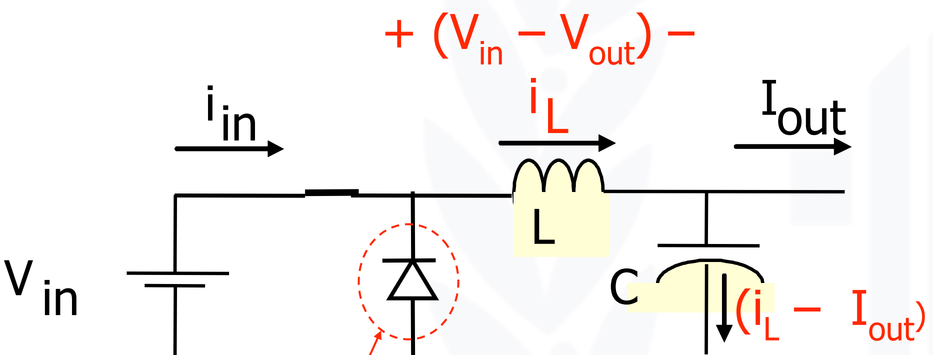
Switching Mode DC-DC Converter

- In capacitors: $i(t) = C\frac{dv(t)}{dt}$ The voltage cannot change instantaneously
- Capacitors tend to keep the voltage constant (voltage “inertia”)
  - An ideal capacitor with infinite capacitance acts as a constant voltage source
  - A capacitor cannot be connected in parallel with a voltage source or a switch (otherwise KVL would be violated, i.e. there will be a short-circuit)
- In inductors: $v(t) = L\frac{di(t)}{dt}$
  - The current cannot change instantaneously
- Inductors tend to keep the current constant (current “inertia”)
  - An ideal inductor with infinite inductance acts as a constant current source
- **Thus, an inductor cannot be connected in series with a current source or a switch (otherwise KCL would be violated)**

Buck Converter

- The input/output equation for DC-DC converters usually comes by examining inductor voltages

- Switch closed for DT seconds



Reverse biased, thus the diode is open

$$\boxed{v_L = V_{in} - V_{out},}$$

for DT seconds

Buck Converter

- The input/output equation for DC-DC converters usually comes by examining inductor voltages

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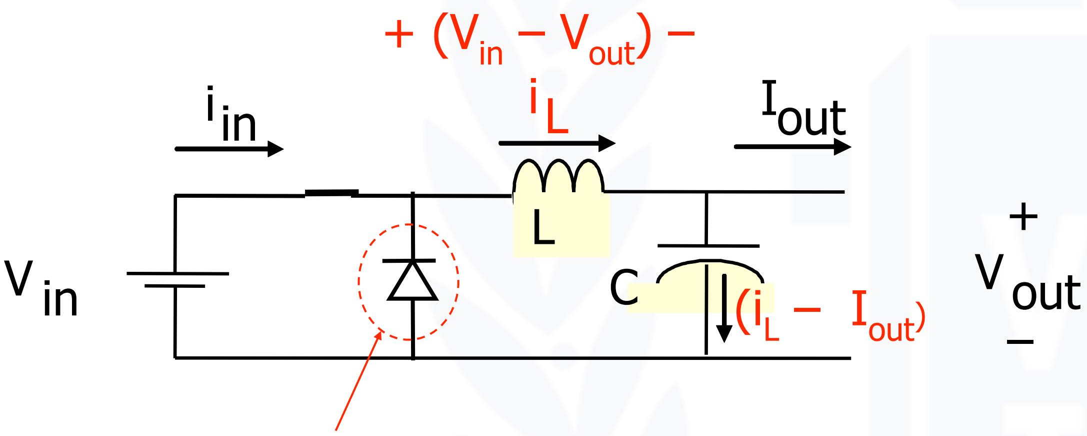


Reverse biased, thus the diode is open

$$v_L = L\frac{di_L}{dt},$$

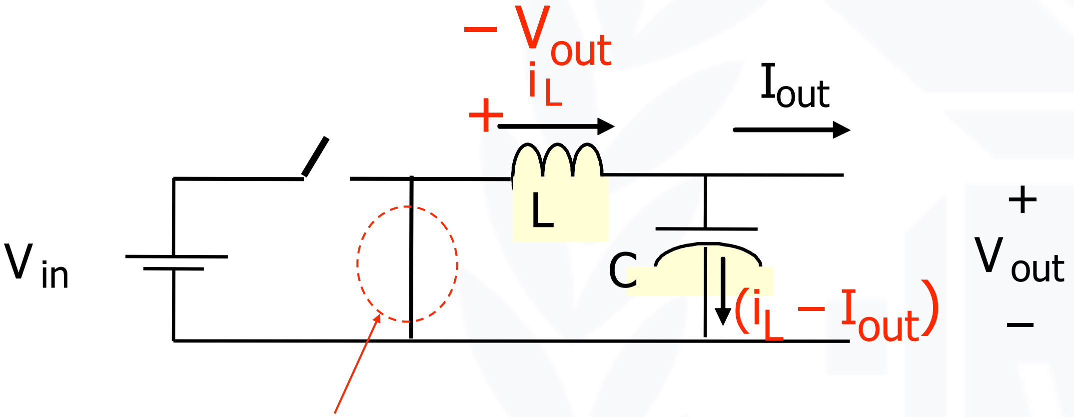
$$\boxed{v_L = V_{in} - V_{out},}$$

for DT seconds

$$\frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L}$$

Buck Converter

- Switch open for (1 – D)T seconds



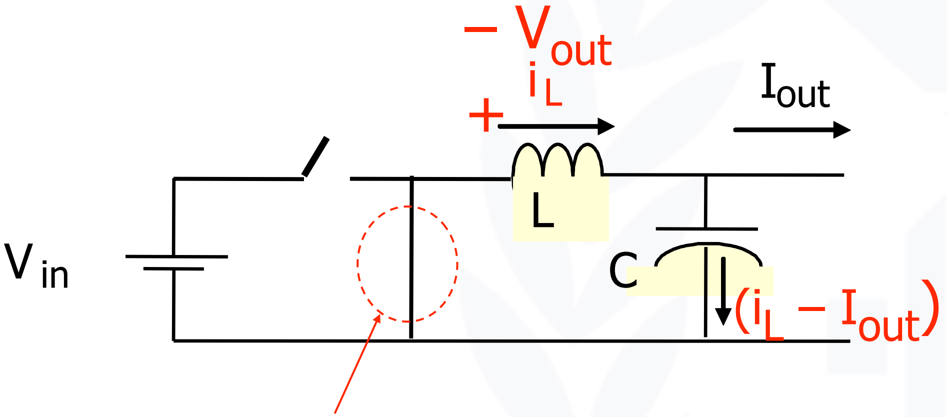
$$\boxed{v_L = -V_{out},}$$

for (1–D)T seconds

i_L continues to flow, thus the diode is closed. This is the assumption of “continuous conduction” in the inductor which is the normal operating condition.

Buck Converter

- Switch open for (1 – D)T seconds



i_L continues to flow, thus the diode is closed. This is the assumption of “continuous conduction” in the inductor which is the normal operating condition.

$$v_L = L\frac{di_L}{dt},$$

$$\boxed{v_L = -V_{out},}$$

for (1–D)T seconds

$$\frac{di_L}{dt} = \frac{-V_{out}}{L}$$

Buck Converter

- Since the average voltage across L is zero,

$$V_{Lavg} = D \bullet (V_{in} - V_{out}) + (1 - D) \bullet (-V_{out}) = 0$$

- From power balance,

- Output voltage and current become

$$\boxed{I_{out} = \frac{I_{in}}{D}} \qquad \boxed{V_{out} = DV_{in}}$$

Buck Converter

- Since the average voltage across L is zero,

$$V_{Lavg} = D \bullet (V_{in} - V_{out}) + (1 - D) \bullet (-V_{out}) = 0$$

- From power balance,

$$V_{in} I_{in} = V_{out} I_{out}$$

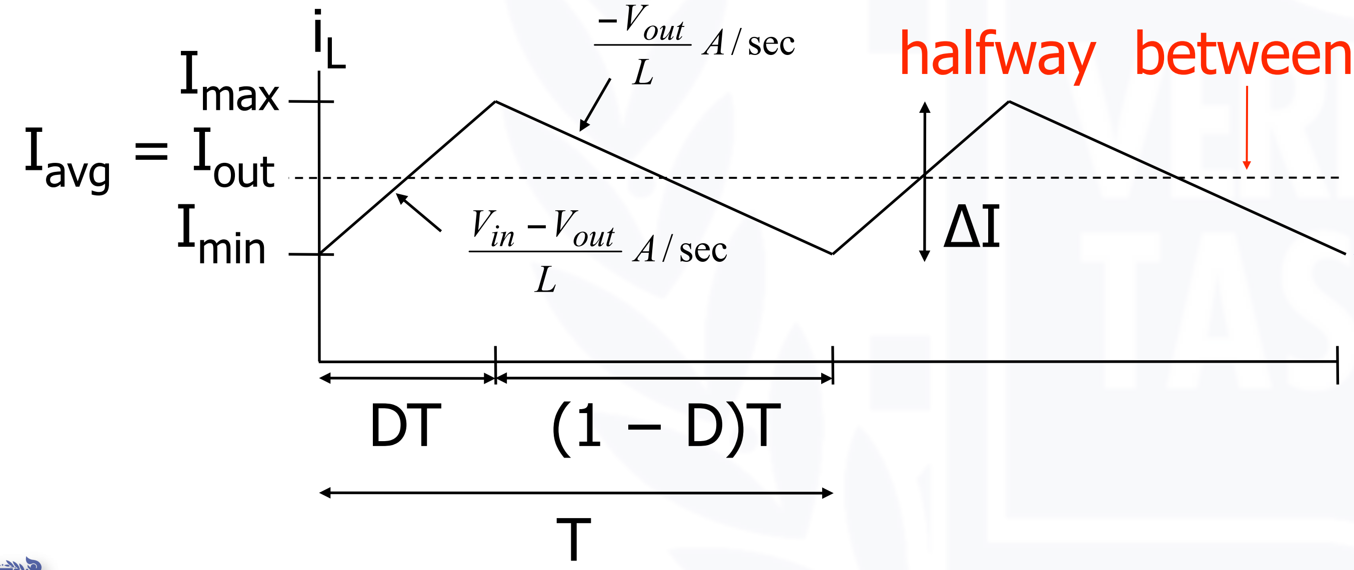
- Output voltage and current become

$$\boxed{I_{out} = \frac{I_{in}}{D}} \qquad \boxed{V_{out} = DV_{in}}$$

Buck Converter

- Examine the inductor current
- Switch closed

- Switch open



From geometry, $I_{avg} = I_{out}$ is halfway between I_{max} and I_{min}

Periodic – finishes a period where it started

Buck Converter

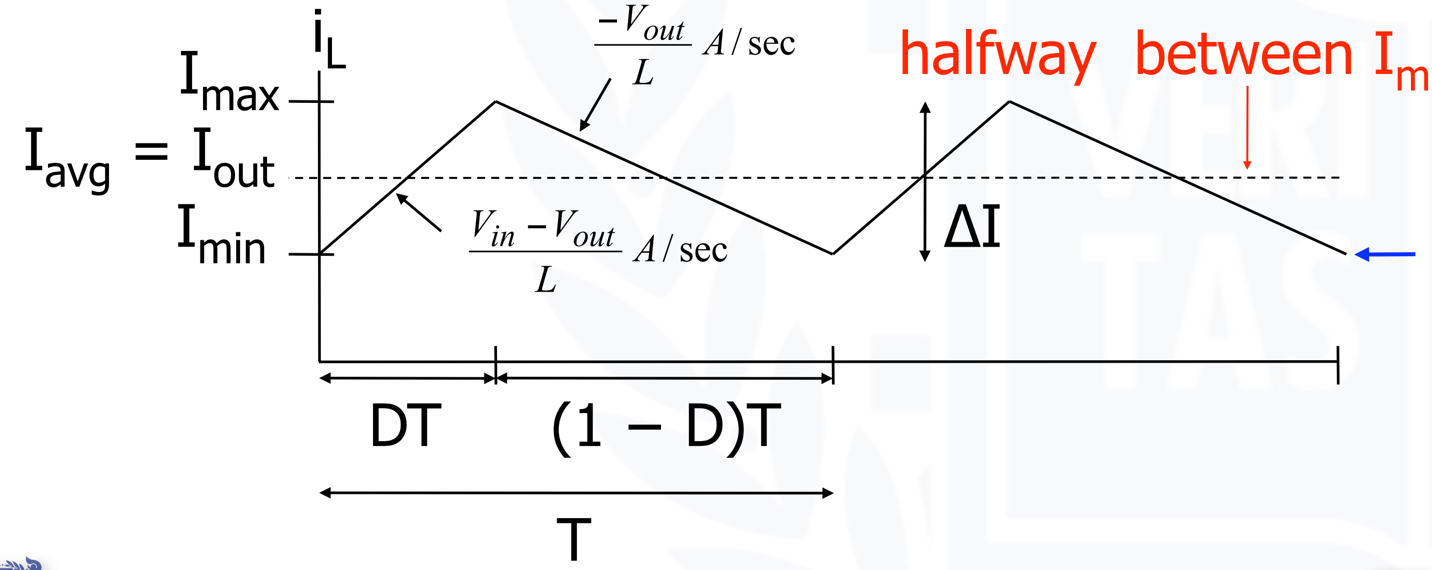
- Examine the inductor current
- Switch closed

$$v_L = V_{in} - V_{out}, \quad \frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L}$$

- Switch open

$$v_L = -V_{out}, \quad \frac{di_L}{dt} = \frac{-V_{out}}{L}$$

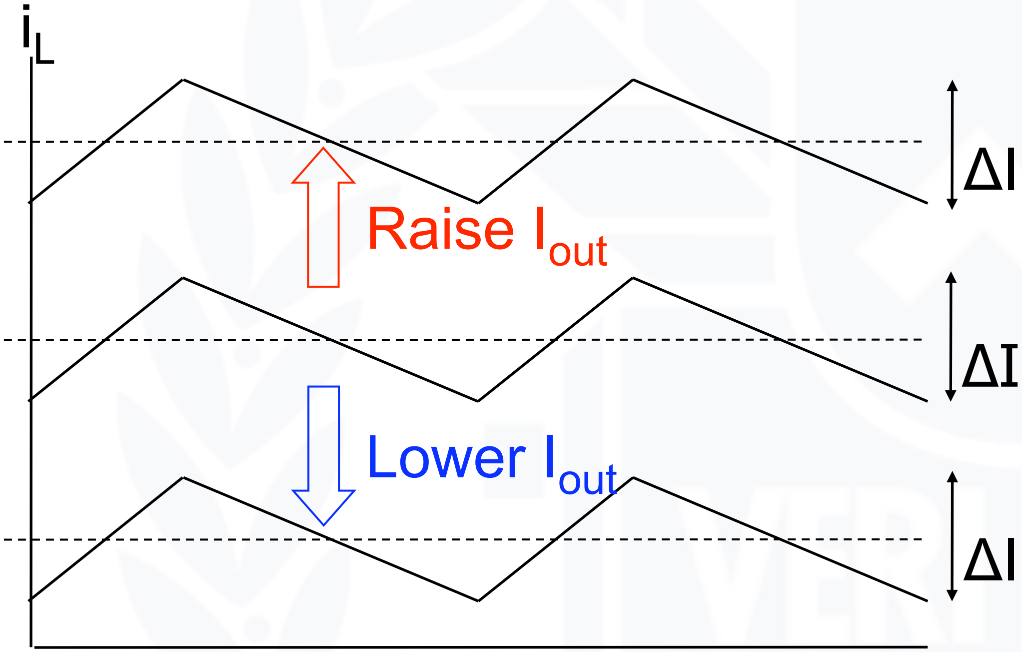
From geometry, $I_{avg} = I_{out}$ is halfway between I_{max} and I_{min}



Periodic – finishes a period where it started

Buck Converter

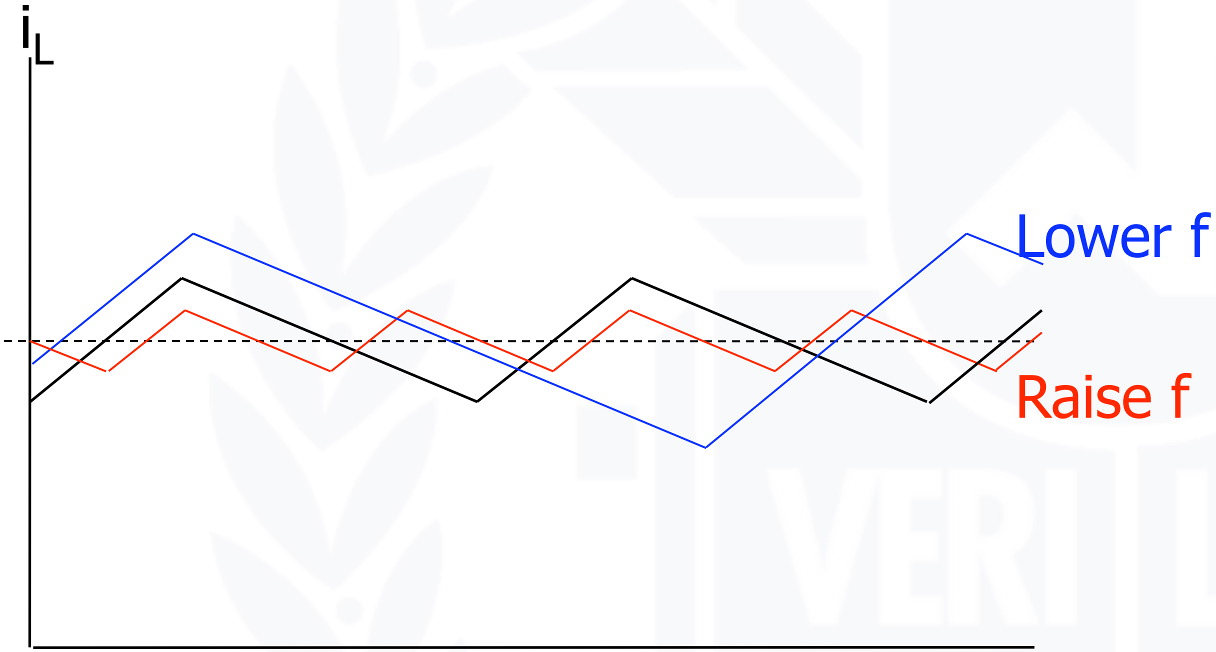
- Effect of raising and lowering Iout while holding Vin, Vout, f, and L constant



- ΔI is unchanged
- Lowering Iout (and, therefore, Pout) moves the circuit toward discontinuous operation

Buck Converter

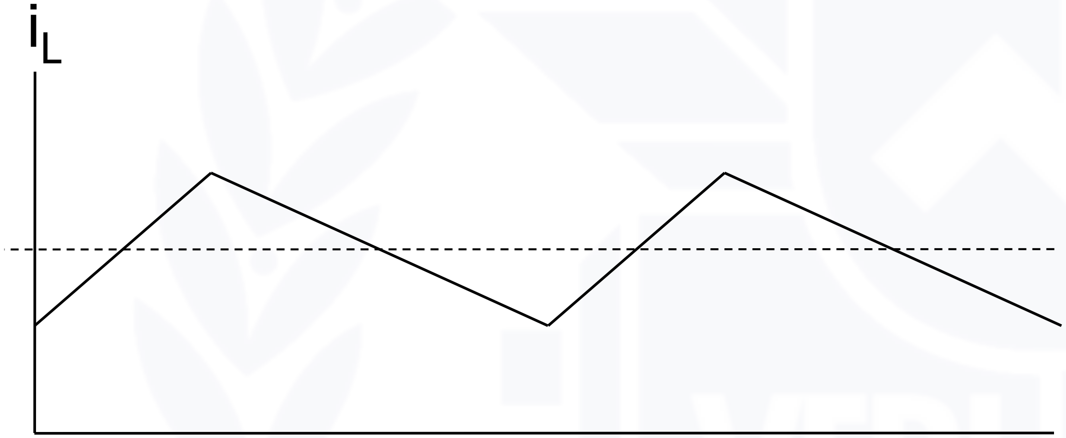
- Effect of raising and lowering f while holding V_{in}, V_{out}, I_{out}, and L constant



- Slopes of i_L are unchanged
- Lowering f increases ΔI and moves the circuit toward discontinuous operation

Buck Converter

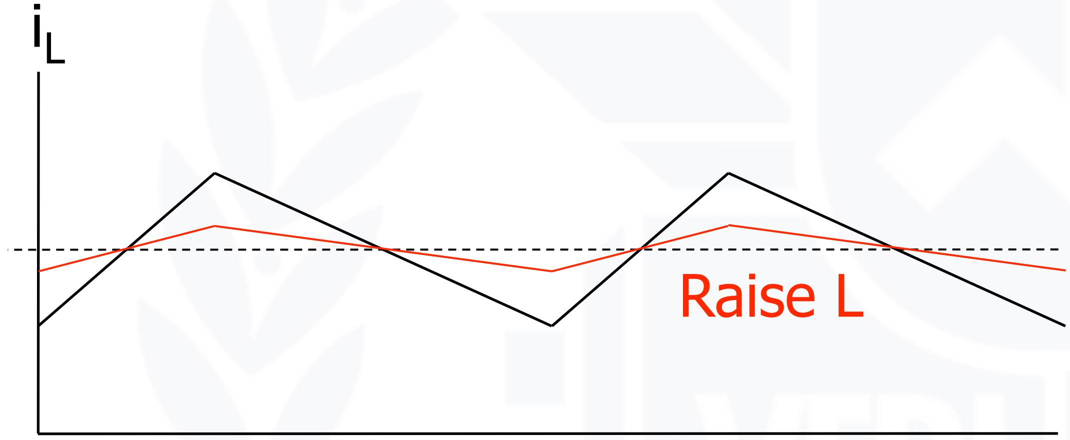
- Effect of raising and lowering L while holding V_{in}, V_{out}, I_{out} and f constant



- Lowering L increases ΔI and moves the circuit toward discontinuous operation

Buck Converter

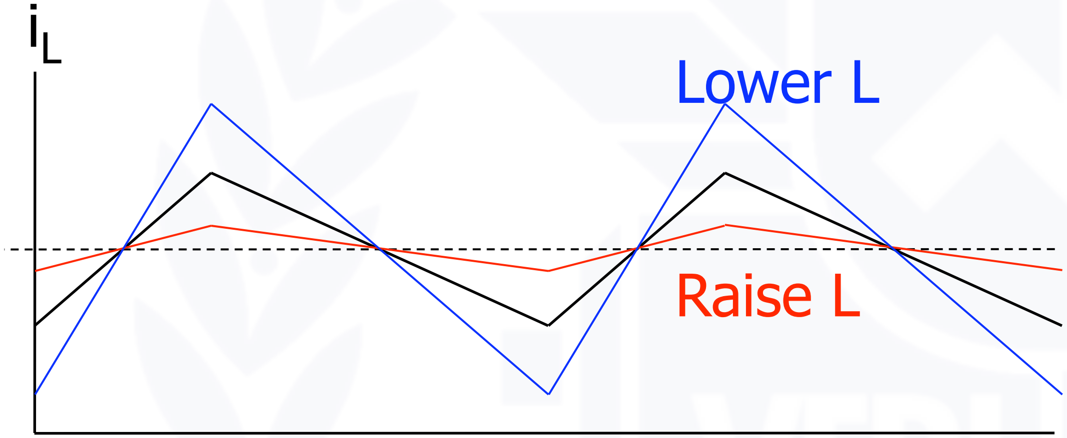
- Effect of raising and lowering L while holding V_{in}, V_{out}, I_{out} and f constant



- Lowering L increases ΔI and moves the circuit toward discontinuous operation

Buck Converter

- Effect of raising and lowering L while holding V_{in}, V_{out}, I_{out} and f constant

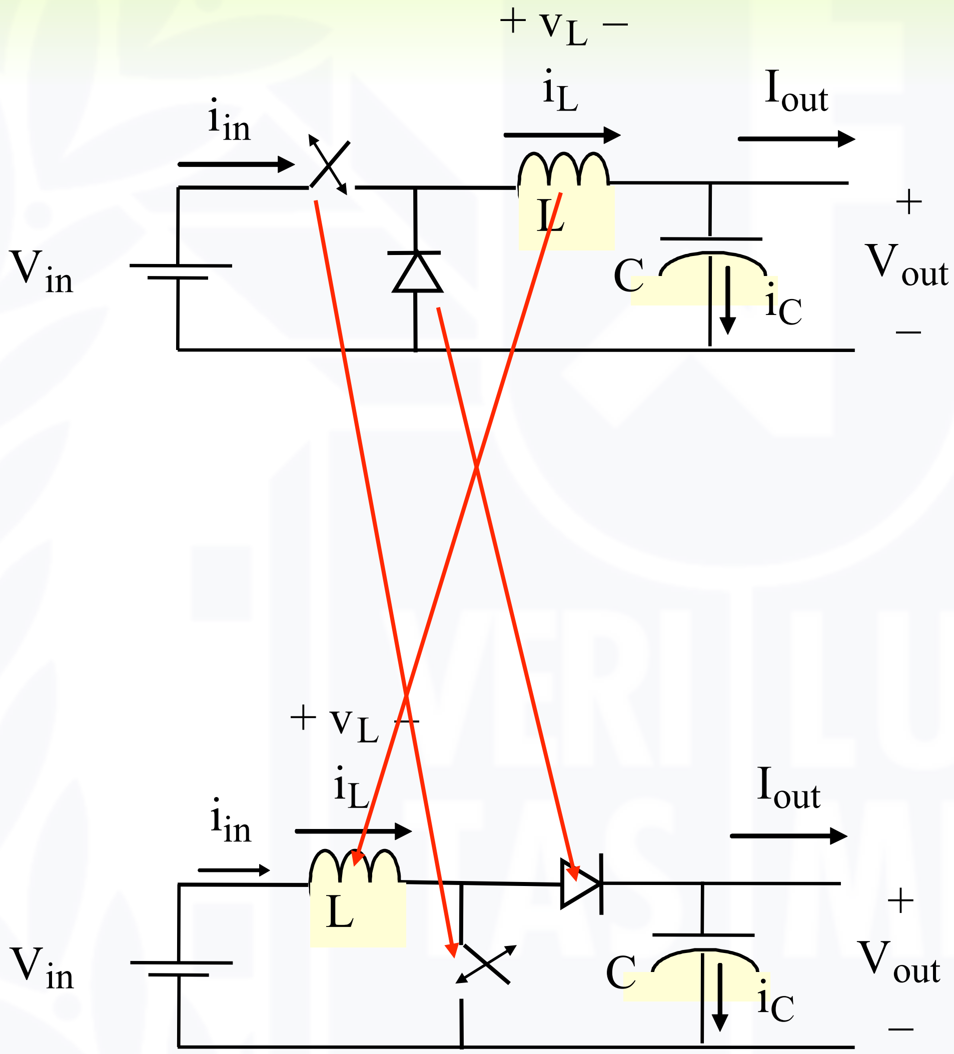


- Lowering L increases ΔI and moves the circuit toward discontinuous operation

Boost Converter

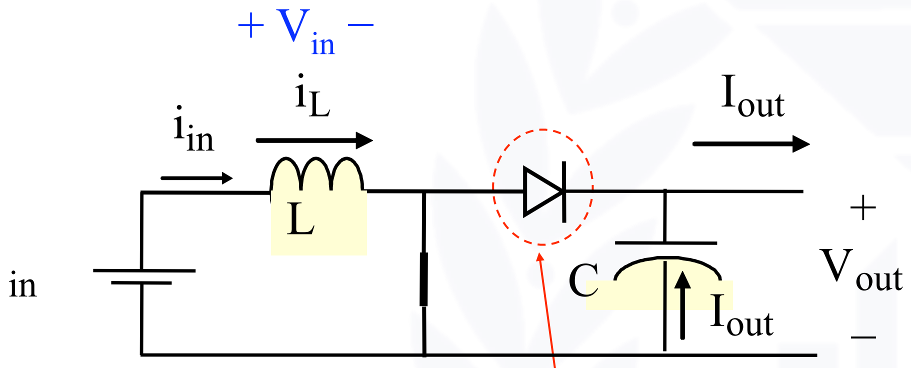
- Buck converter

- Boost converter



Boost Converter

- Switch closed for DT seconds



$$\boxed{\frac{di_L}{dt} = \frac{V_{in}}{L}}$$

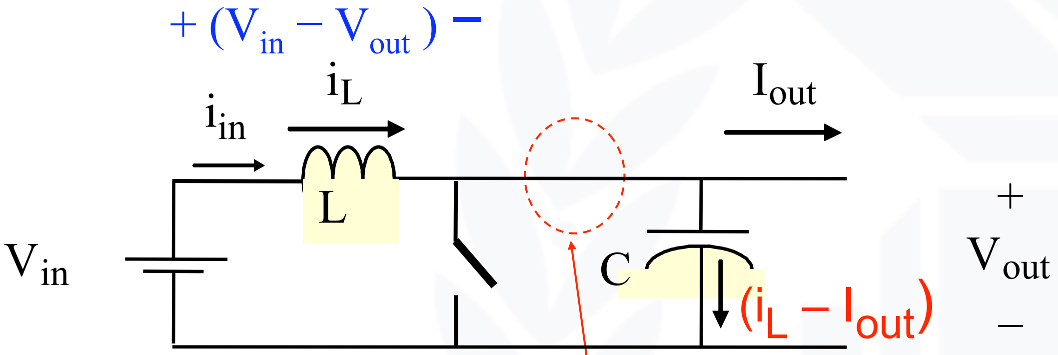
for DT seconds

Reverse biased, thus the diode is open

- If the switch stays closed, the input is short circuited!

Boost Converter

- Switch open for (1 – D)T seconds



$$\boxed{\frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L}}$$

for (1−D)T seconds

Diode closed. Assume continuous conduction.

Boost Converter

- Since the average voltage across L is zero

$$V_{Lavg} = D \bullet V_{in} + (1 - D) \bullet (V_{in} - V_{out}) = 0$$

- The input/output equation becomes

Boost Converter

- Since the average voltage across L is zero

$$V_{Lavg} = D \bullet V_{in} + (1 - D) \bullet (V_{in} - V_{out}) = 0$$

$$V_{out} \bullet (1 - D) = V_{in} + D \cancel{\bullet} V_{in} - D \cancel{\bullet} V_{in}$$

- The input/output equation becomes

Boost Converter

- Since the average voltage across L is zero

$$V_{Lavg} = D \bullet V_{in} + (1 - D) \bullet (V_{in} - V_{out}) = 0$$

$$V_{out} \bullet (1 - D) = V_{in} + \cancel{D \bullet V_{in}} - \cancel{D \bullet V_{in}}$$

- The input/output equation becomes

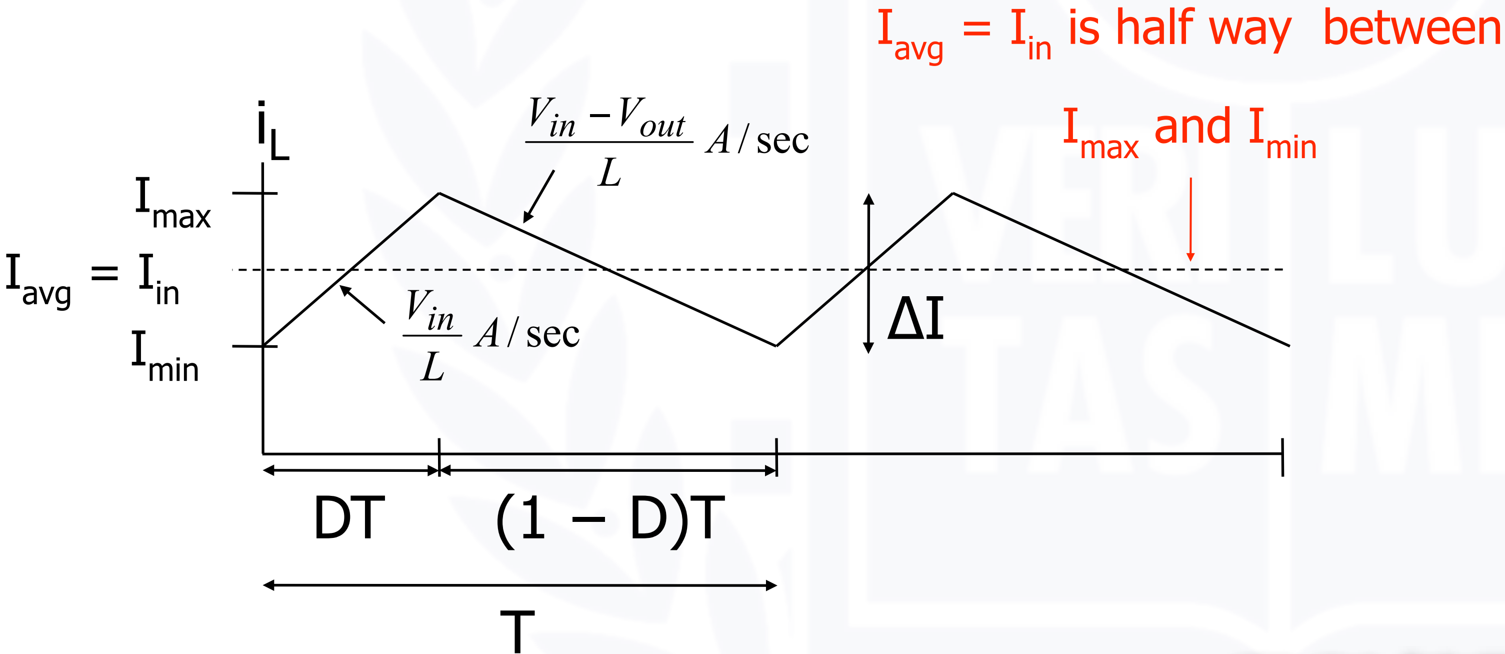
$$\boxed{V_{out} = \frac{V_{in}}{1 - D}}$$

A realistic upper limit on boost is 5 times

Boost Converter

- Examine the inductor current
- Switch closed

- Switch open



I_{avg} = I_{in} is half way between I_{max} and I_{min}

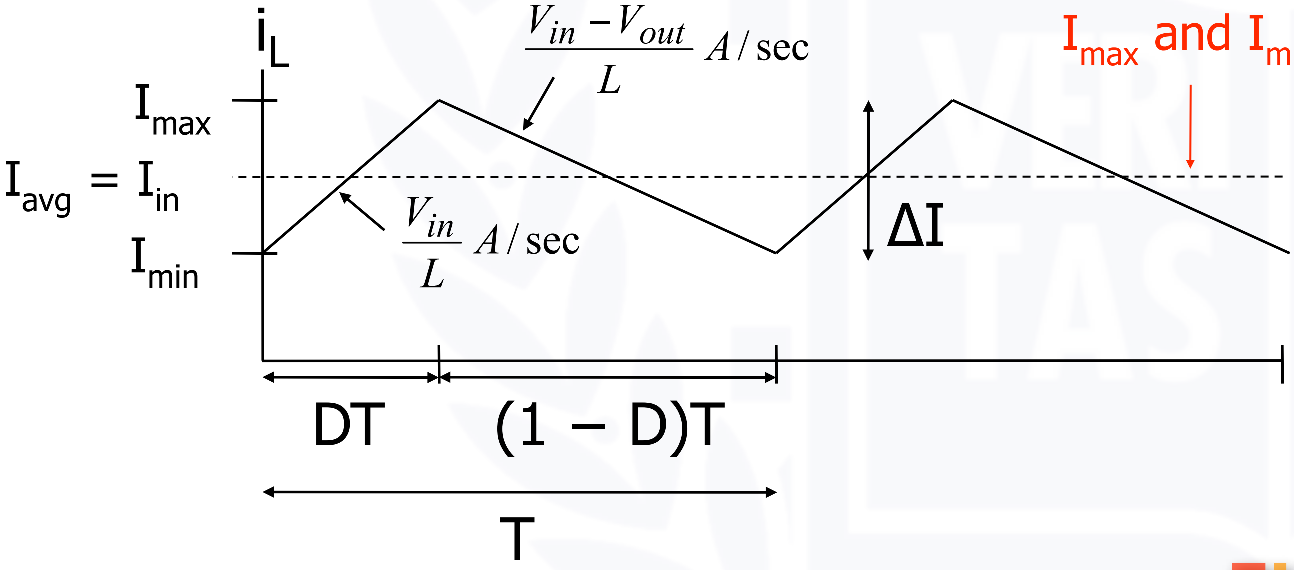
Boost Converter

- Examine the inductor current
- Switch closed

$$v_L = V_{in}, \frac{di_L}{dt} = \frac{V_{in}}{L}$$

- Switch open

$$v_L = V_{in} - V_{out}, \frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L}$$



$I_{avg} = I_{in}$ is half way between I_{max} and I_{min}

Embedded System Application

4190.303C

2010 Spring Semester

Simultaneous Optimization of Battery-aware Voltage Regulator Scheduling with Dynamic Voltage and Frequency Scaling

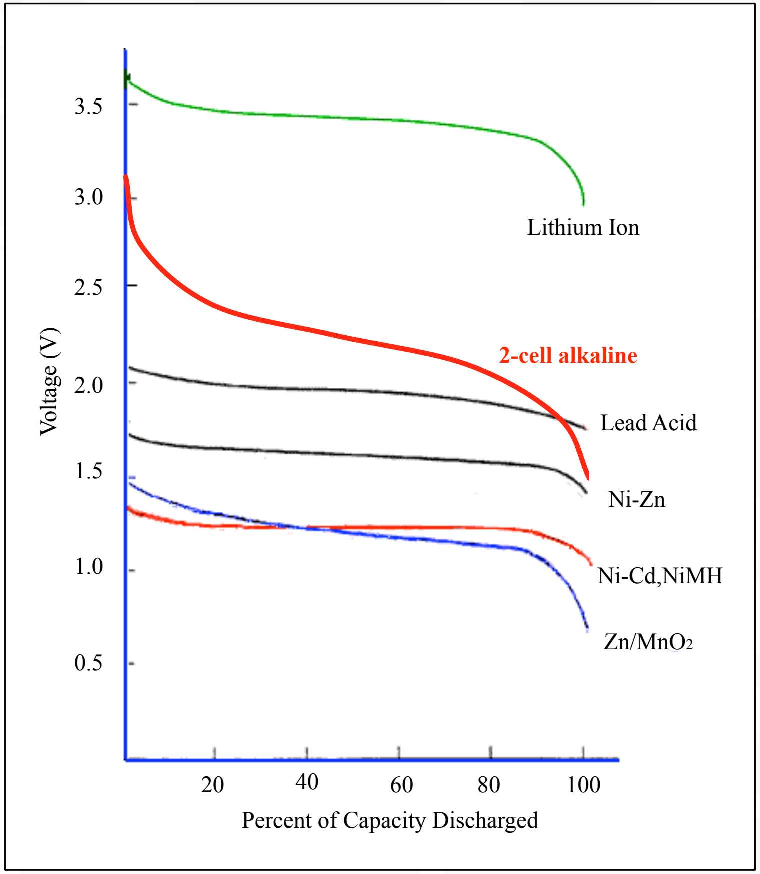
Naehyuck Chang
Dept. of EECS/CSE
Seoul National University
naehyuck@snu.ac.kr

Contents

- Motivation
- Paper contribution
- Problem statement
- Real device modeling
- DRS cost function
- Solution method
- Experimental results
- Conclusions

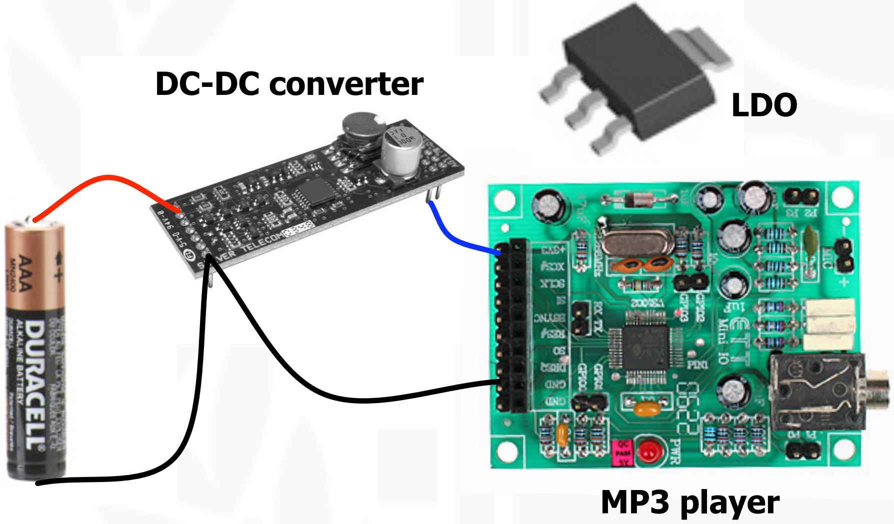
Motivation

- Why voltage regulators?
  - To obtain a proper supply voltage level
    - Battery cell voltages do not always match with the CPU VDD
  - To compensate the IR drop of the battery
    - Battery internal resistance
    - Power delivery network
  - To compensate the terminal voltage drop due to the state of charge loss



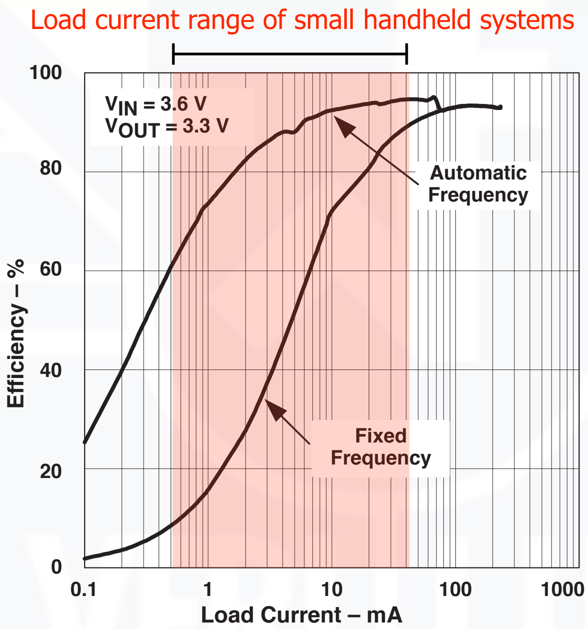
Motivation

- Typical power supply and management systems
  - Voltage regulation is not free
    - 10% to 40% system energy loss from voltage regulators, typically DC-DC converters or LDOs

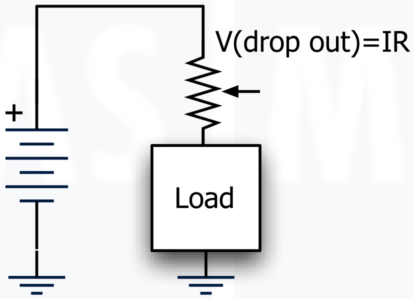


Motivation

- DC-DC converter
  - Buck, boost and flyback
  - DC →AC → voltage change → AC → DC
  - Voltage regulator loss becomes significant in light load applications
- Linear regulator
  - High drop out
    - VIN > VOUT + 2 V (7805)
  - Low drop out
    - VIN > VOUT + 150 mV
  - Power loss
    - Load current × drop out voltage
  - Naturally the loss is high



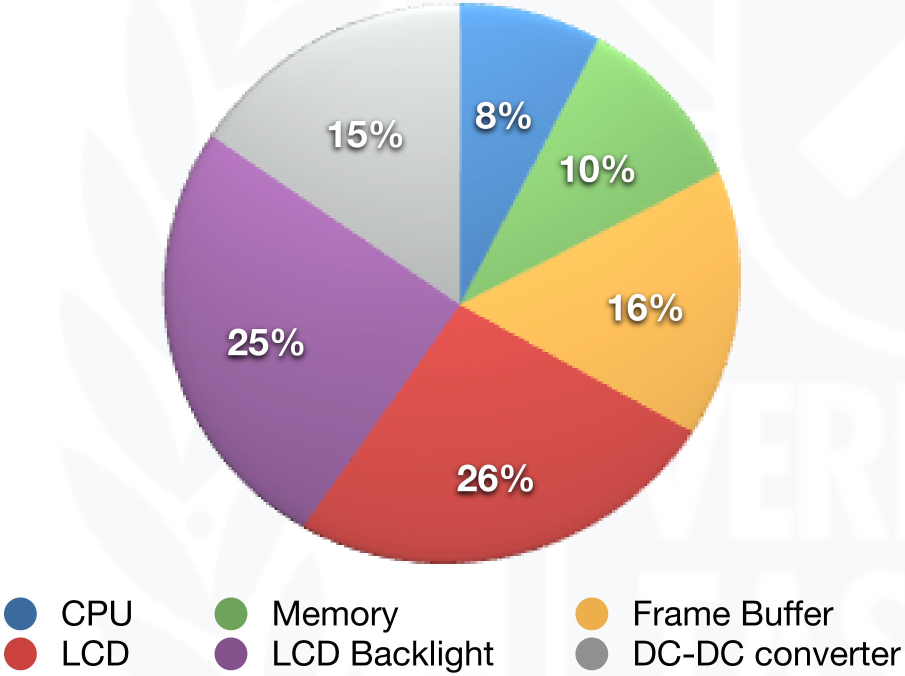
DC-DC converter



LDO

Motivation

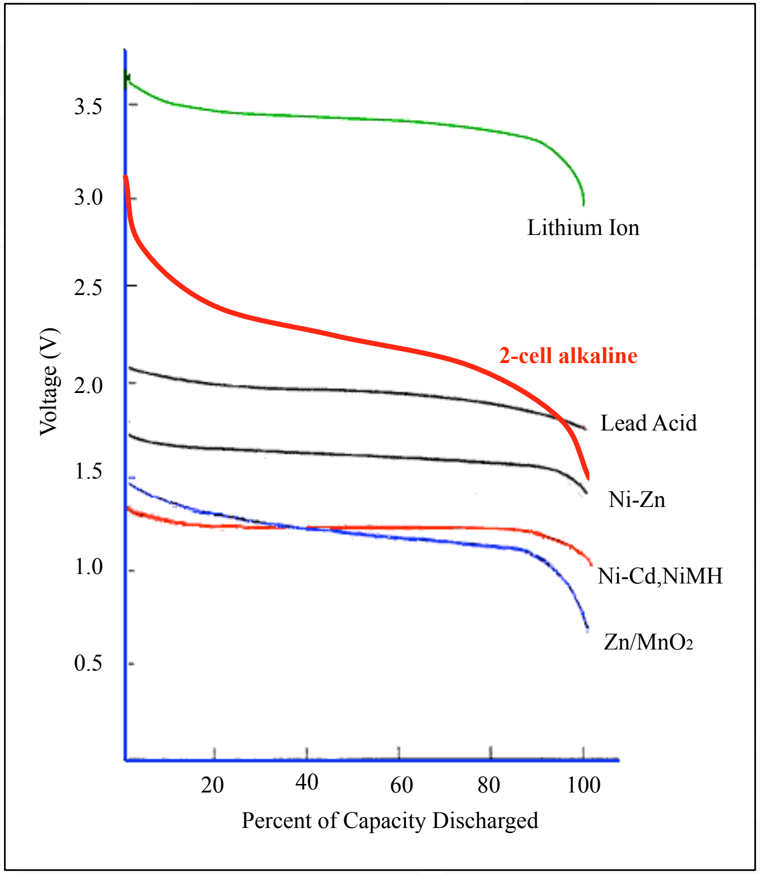
- Where does the power go?
  - Power breakdown of a portable MPEG4 player



- Hojun Shim, Youngjin Cho and Naehyuck Chang, "Power Saving in Hand-held Multimedia Systems Using MPEG-21 Digital Item Adaptation," in ESTIMedia, 2004

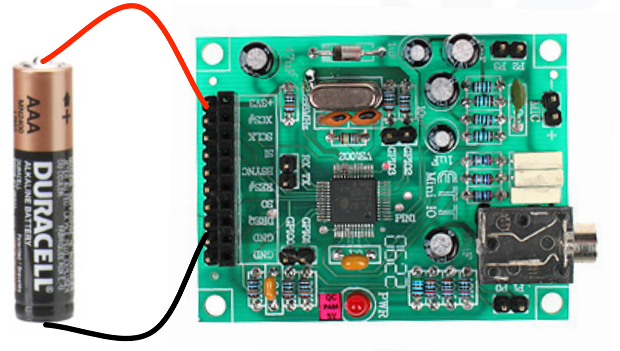
Motivation

- Question: why voltage regulators?
  - To obtain a proper supply voltage level
  - To compensate the IR drop of the battery
  - To compensate the terminal voltage drop due to the state of charge loss
- Alkaline battery discharge characteristics
  - Battery voltage may match with V_{DD} of the microprocessor
  - IR drop is tolerable for low-power applications
  - Wide voltage range while alive (3.0 to 1.7 V)
  - Direct battery drive is feasible



Motivation

- Previous direct battery drive methods
  - Voltage regulator elimination



Direct drive without a voltage regulator

Telos

IPSN 2005

- Operation of the CPU at the lowest clock frequency w/o clock scaling
- Guaranteed constant performance
- Waste of potential CPU performance

PVS

ISLPED 2007

- CPU clock frequency decreases as the battery voltage decreases in a passive manner
- Performance decreases as the battery voltage decreases
- Networked operation maintain a guaranteed performance

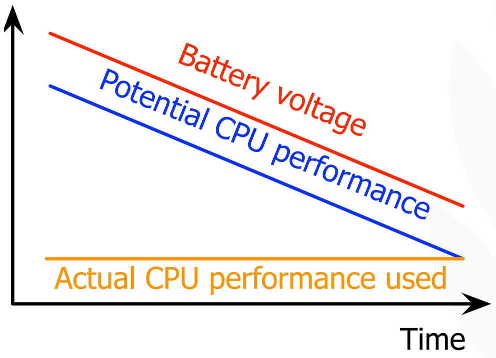
Multi-core

CODES+ISSS 2007

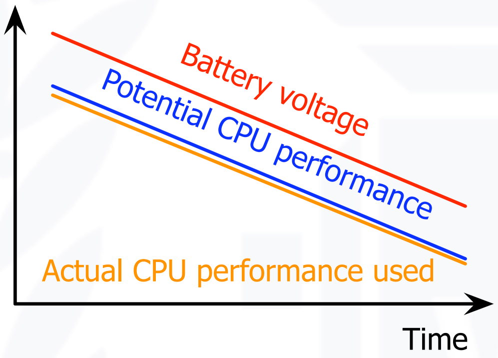
- Frequency scaling in a passive manner
- Progressive wake-up of a multi-core CPU to maintain a guaranteed performance

Motivation

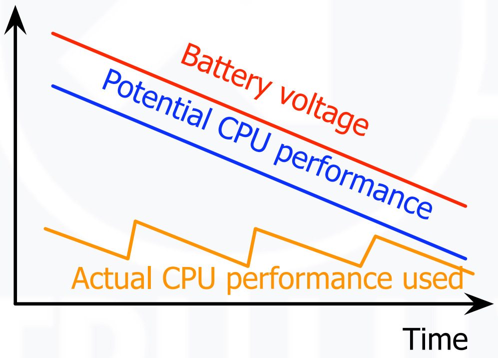
- Comparison among previous direct battery drive methods
  - It is not a good idea to waste potential CPU performance to provide a guaranteed performance to the end



ISPN 2005



ISLPED 2007



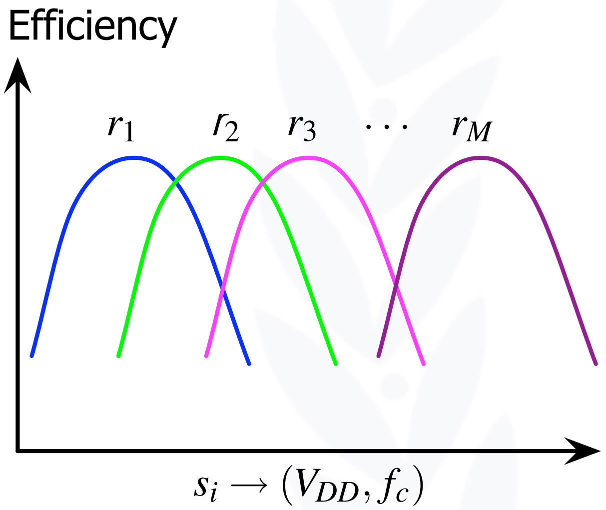
CODES+ISSS 2007

Motivation

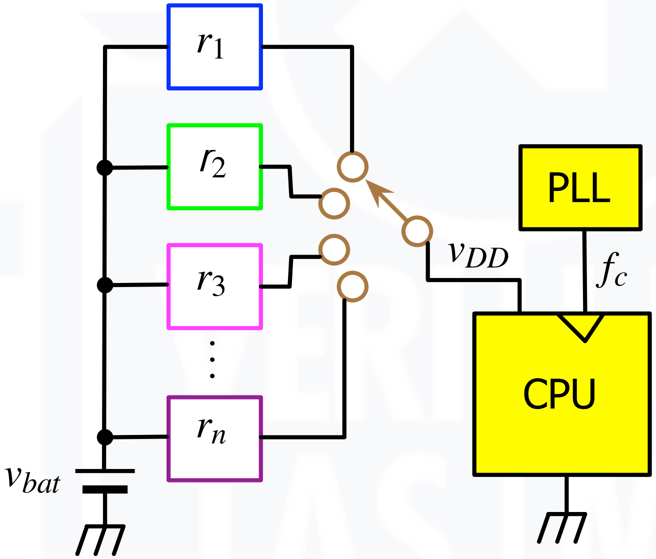
- Which voltage regulation is the best?
  - DC-DC converter
    - Can be applicable w/o limitation
    - Best when the battery voltage and V_{DD} difference is big
    - Inefficient when the load current is light
    - When the battery voltage < V_{DD}, this is the only feasible method
  - LDO (low-dropout linear regulator)
    - Applicable only when the battery voltage < V_{DD} + dropout
    - In general inefficient when the load current is large and the battery voltage and V_{DD} difference is big
    - Sometimes more efficient than DC-DC converter when the load current is very light and the battery voltage and V_{DD} difference is appropriate
  - Direct battery drive
    - Applicable only when the battery voltage is similar to V_{DD}
    - The most efficient when it is feasible (zero loss)
  - No single voltage regulation method is always the best!

Paper Contribution

- DRS: Dynamic regulator scheduling
  - Switch among heterogeneous voltage regulators dynamically for the best efficiency



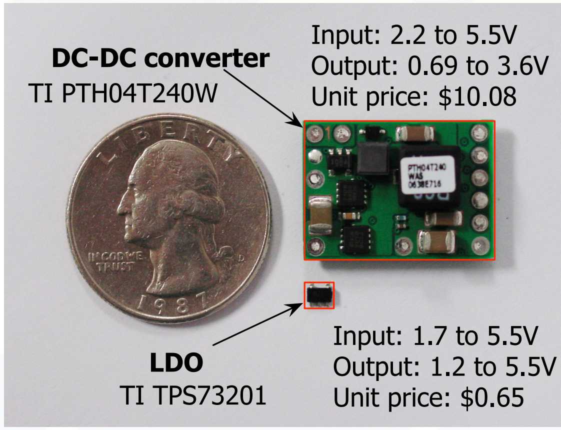
(a) Heterogeneous voltage regulators



(b) DRS

Problem Statement

- Is DRS a practical approach?
  - YES!
  - Adding an LDO and a voltage switch is not that expensive
  - DRS is an affordable method

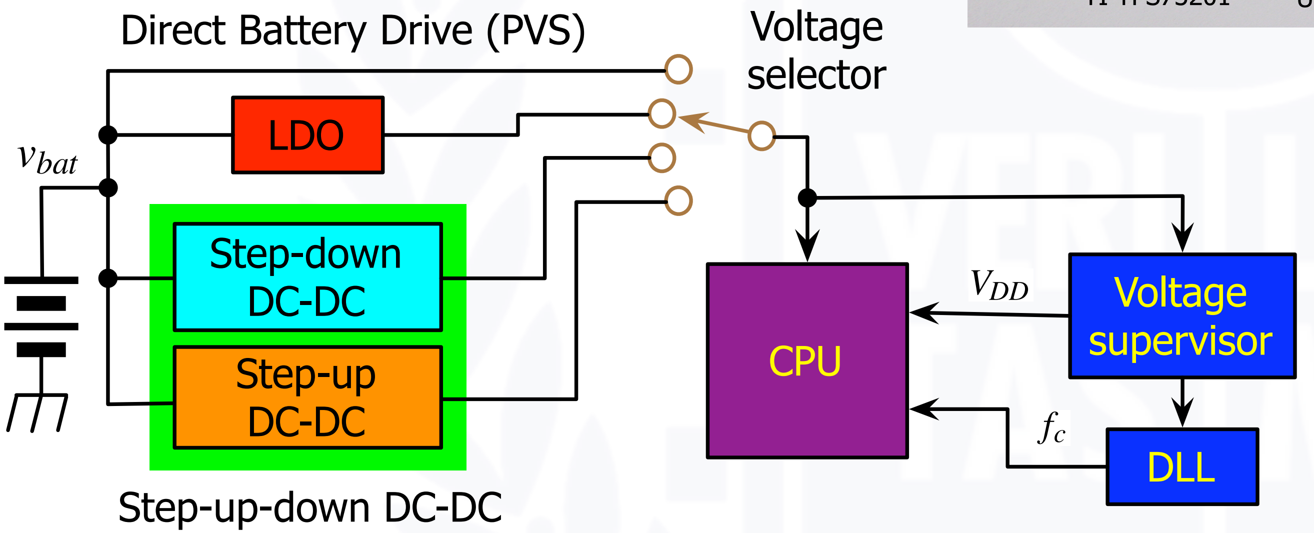


DC-DC converter
TI PTH04T240W

Input: 2.2 to 5.5V
Output: 0.69 to 3.6V
Unit price: $10.08

LDO
TI TPS73201

Input: 1.7 to 5.5V
Output: 1.2 to 5.5V
Unit price: $0.65



Direct Battery Drive (PVS)

Voltage selector

v_{bat}

LDO

Step-down DC-DC

Step-up DC-DC

Step-up-down DC-DC

CPU

V_{DD}

Voltage supervisor

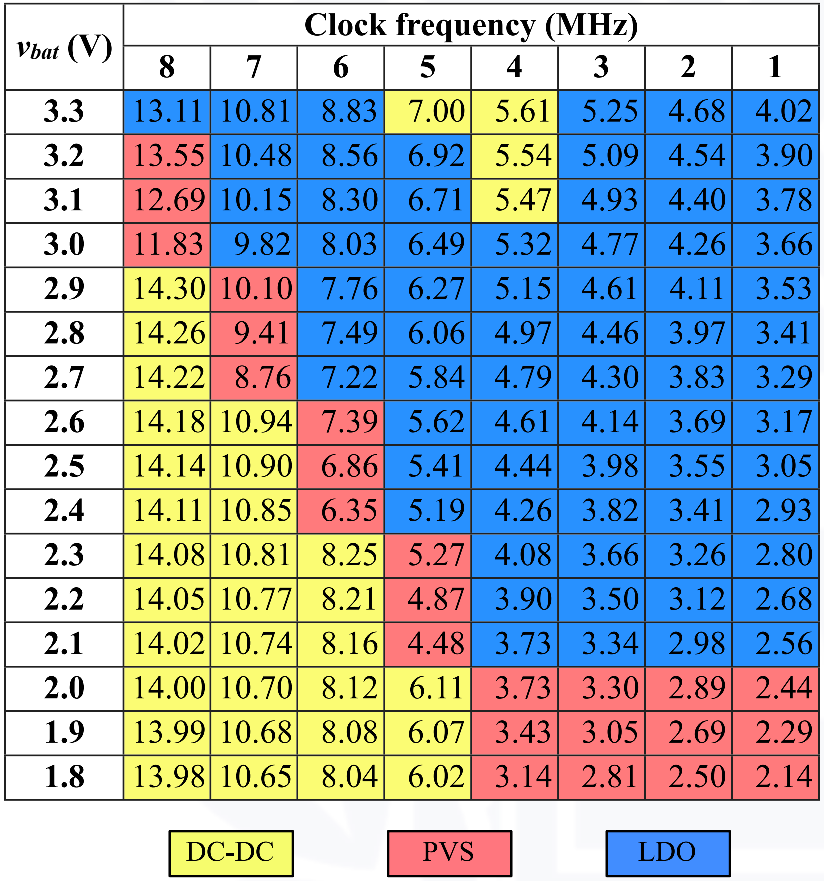
f_c

DLL

DRS Cost Function

- Characterization of the cost function of the power consumption of the system:

$$P(V_{bat}, s_j)$$



v_{bat} (V)	Clock frequency (MHz)							
	8	**7**	**6**	**5**	**4**	**3**	**2**	**1**
3.3	13.11	10.81	8.83	7.00	5.61	5.25	4.68	4.02
3.2	13.55	10.48	8.56	6.92	5.54	5.09	4.54	3.90
3.1	12.69	10.15	8.30	6.71	5.47	4.93	4.40	3.78
3.0	11.83	9.82	8.03	6.49	5.32	4.77	4.26	3.66
2.9	14.30	10.10	7.76	6.27	5.15	4.61	4.11	3.53
2.8	14.26	9.41	7.49	6.06	4.97	4.46	3.97	3.41
2.7	14.22	8.76	7.22	5.84	4.79	4.30	3.83	3.29
2.6	14.18	10.94	7.39	5.62	4.61	4.14	3.69	3.17
2.5	14.14	10.90	6.86	5.41	4.44	3.98	3.55	3.05
2.4	14.11	10.85	6.35	5.19	4.26	3.82	3.41	2.93
2.3	14.08	10.81	8.25	5.27	4.08	3.66	3.26	2.80
2.2	14.05	10.77	8.21	4.87	3.90	3.50	3.12	2.68
2.1	14.02	10.74	8.16	4.48	3.73	3.34	2.98	2.56
2.0	14.00	10.70	8.12	6.11	3.73	3.30	2.89	2.44
1.9	13.99	10.68	8.08	6.07	3.43	3.05	2.69	2.29
1.8	13.98	10.65	8.04	6.02	3.14	2.81	2.50	2.14

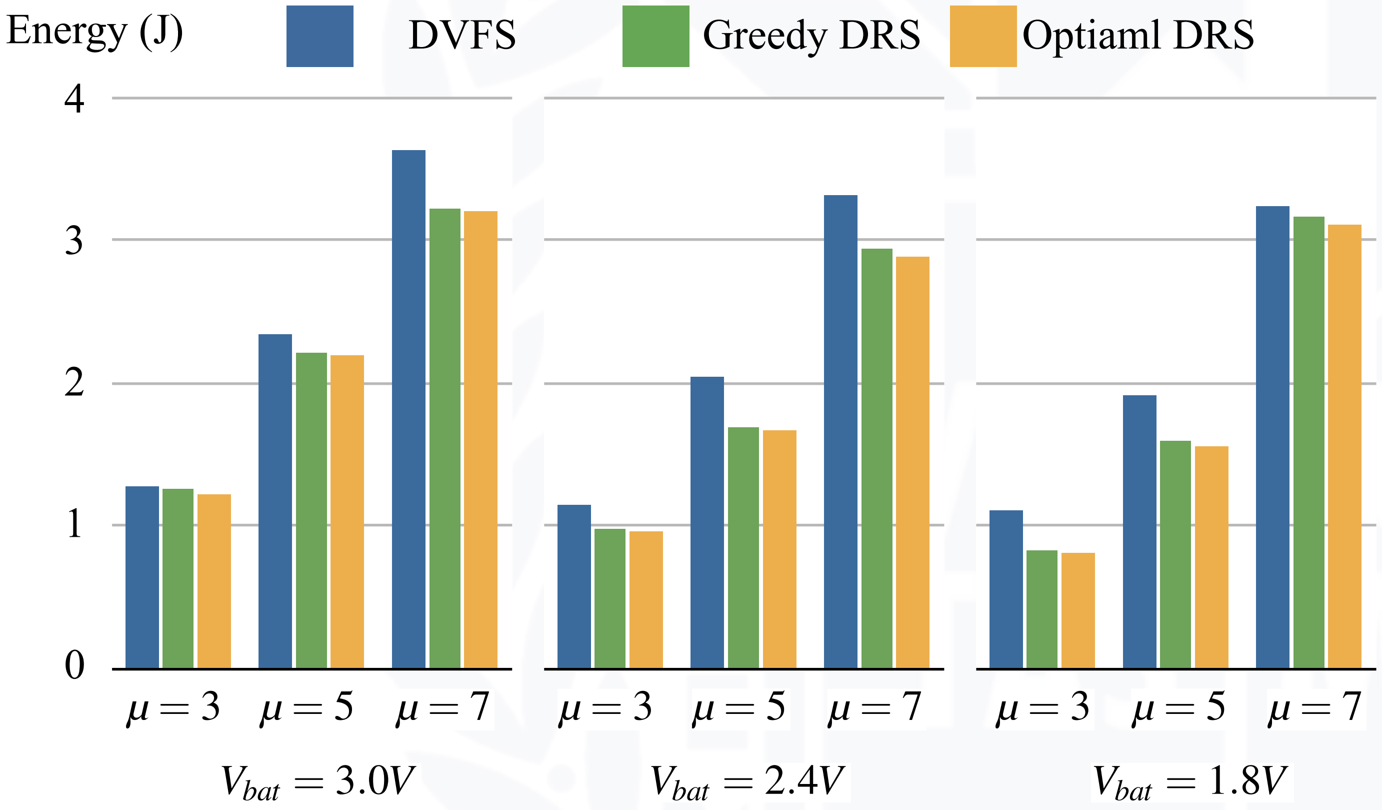
DC-DC

PVS

LDO

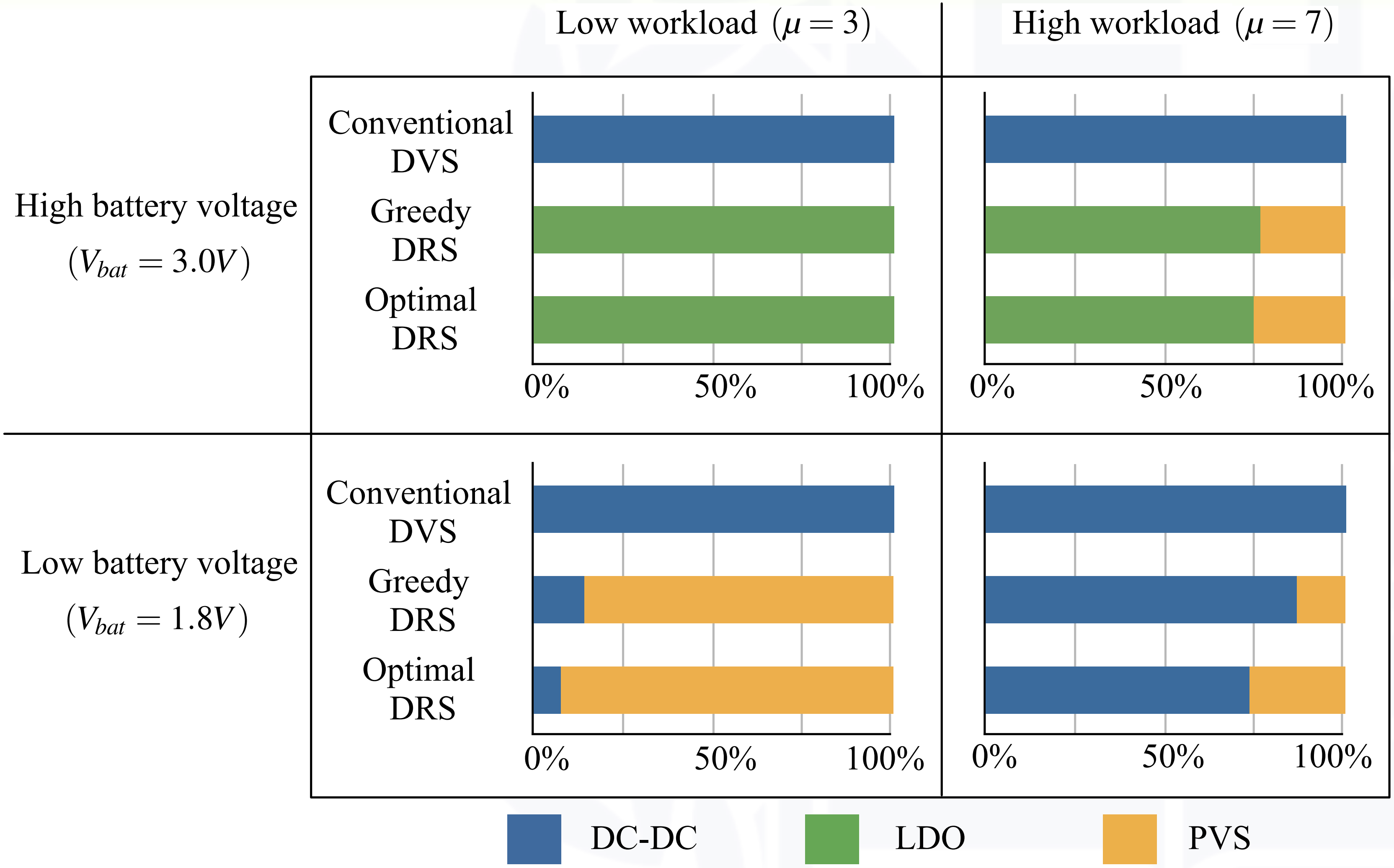
Experimental Results

- Energy consumption of optimal DRS, greedy DRS and conventional DVFS with $N = 40$ and $\lambda^{-1} = 10$ sec



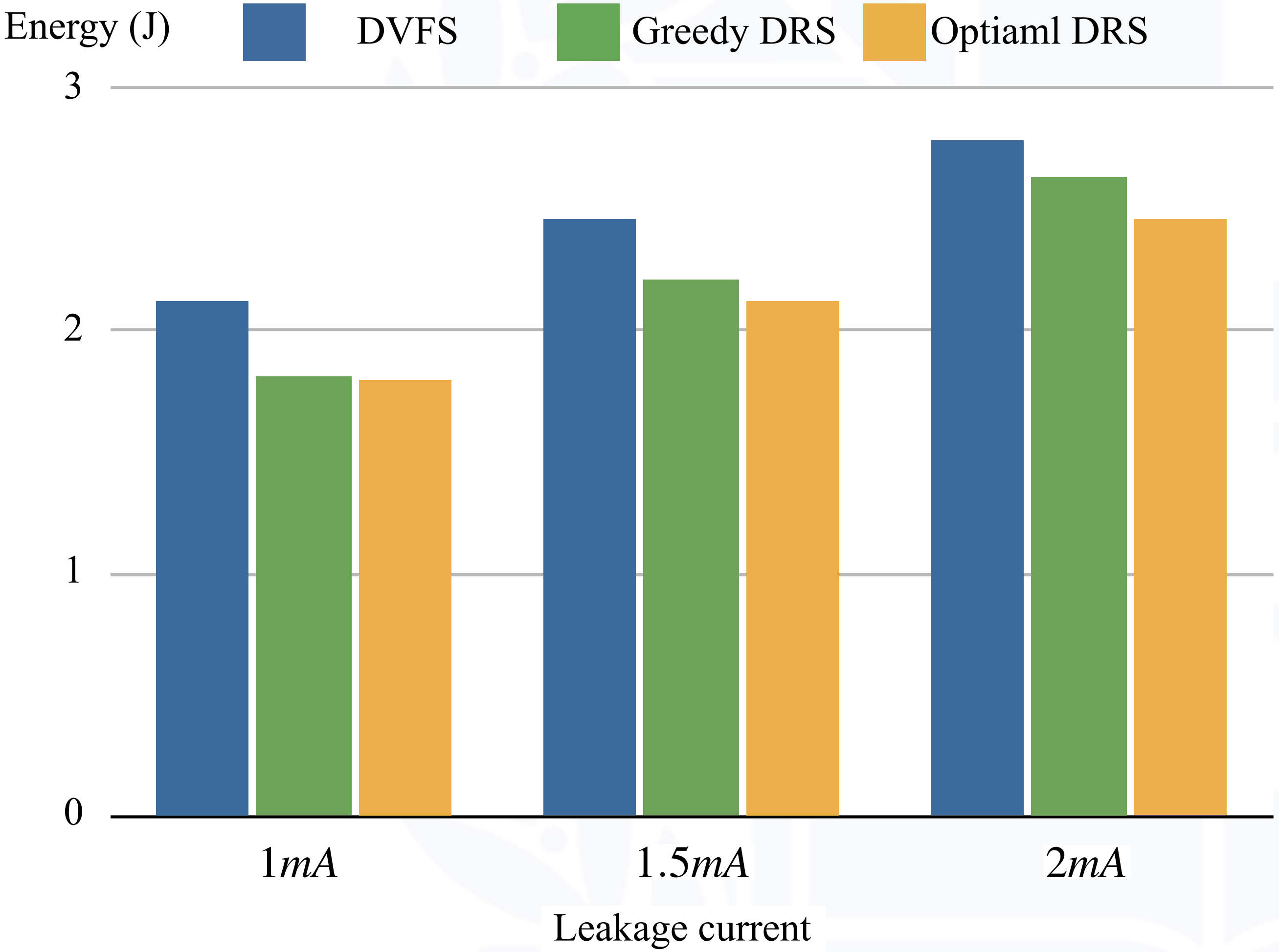
Experimental Results

- Relative utilization of DC-DC and LDO regulators and PVS



Experimental Results

- Energy consumption by the leakage power portion when $N = 40$, $\mu = 5$ sec and $\lambda^{-1} = 10$ sec.



Conclusions

- We introduced a new high-level low-power technique called DRS (Dynamic voltage regulator scheduling)
  - Joint regulator scheduling and the DVS scaling factor decision
- Load drive from multiple heterogeneous voltage regulators including the direct drive method (PVS)
- The greedy DRS:
  - Additional final regulator selection
  - 5.4% to 14.6% energy reduction
- The optimal DRS:
  - Simultaneous optimization of DVFS and regulator selection
  - 11.5% to 15.5% energy reduction
- DRS continues to perform well with a CPU with more leakage power consumption