Introduction to Power Electronics
Buck DC-DC Converter

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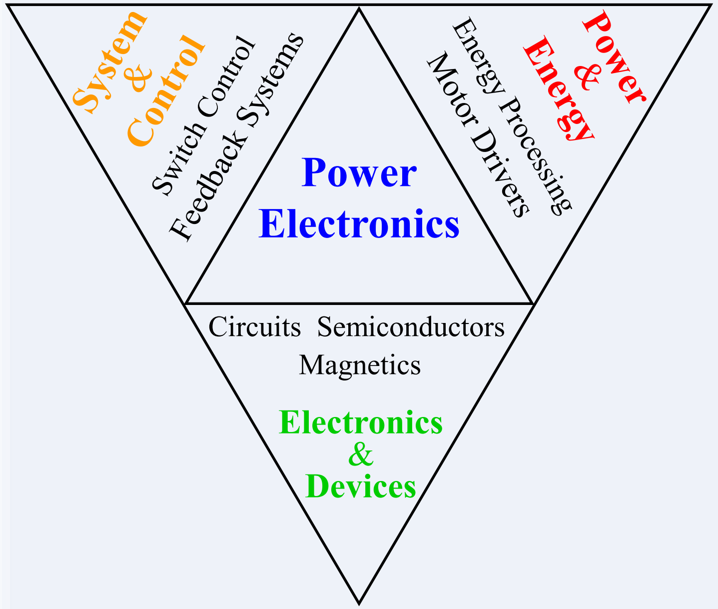
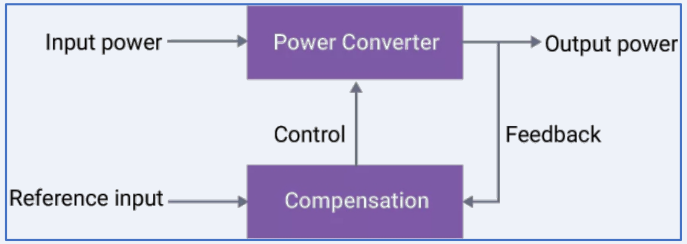
Date: Thur., Sept. 05, 2024

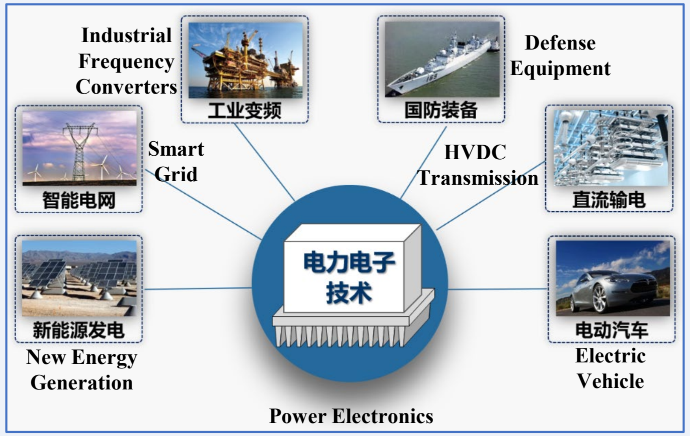
Introduction to Power Electronics

What is Power Electronics?

William E. Newell's Description



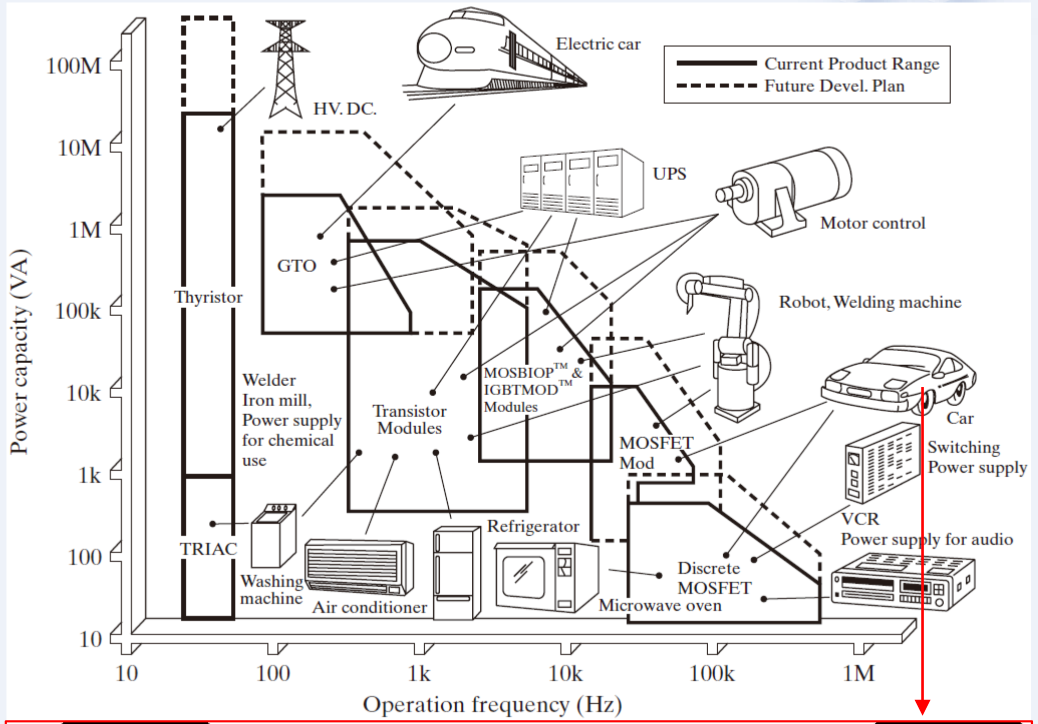


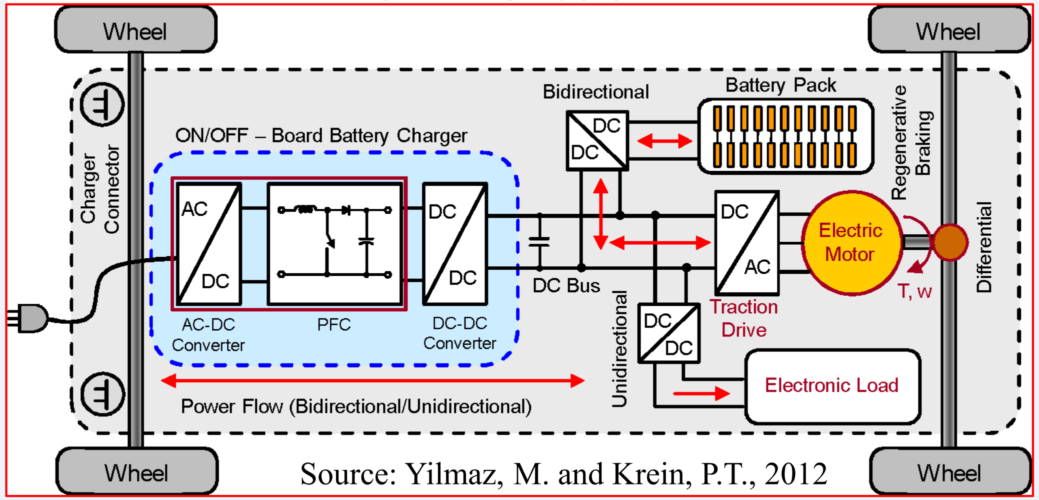


Source: https://sicpower.fudan.edu.cn/26999/list.htm

The ***Power Electronics Technology*** consists of a cross-section of the disciplines of ***electricity***, ***electronics*** and ***control theory***. It uses power semiconductor devices as switching elements, thereby controlling or modifying the voltages or currents for energy conversion.

Related Courses for Bachelor of Science in Automation and Systems Engineering [DES]: *Circuit Analysis*, *Analog Circuits*, *Digital Circuits*, *Principles of Automatic Control*, etc.

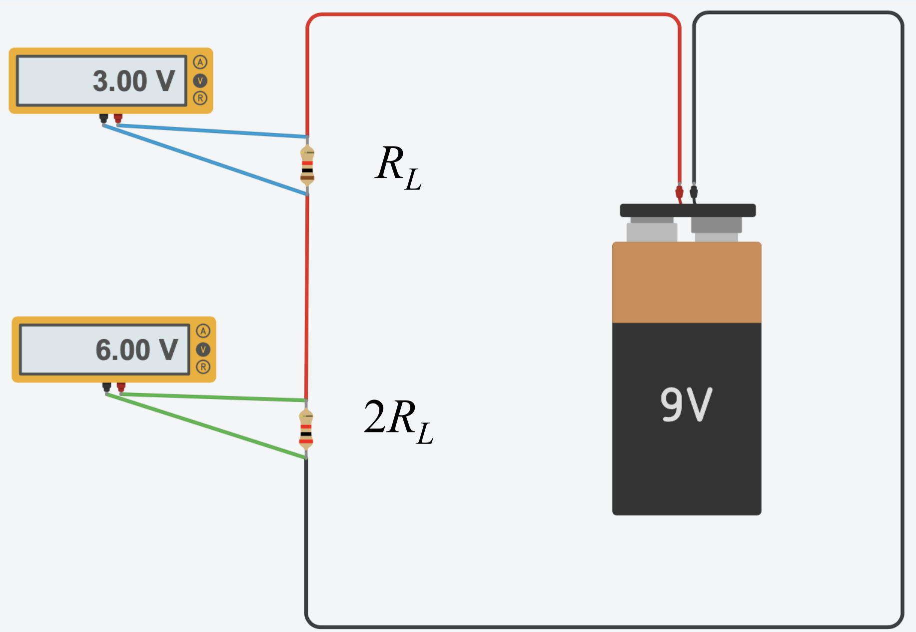




Source: Yilmaz, M. and Krein, P.T., 2012

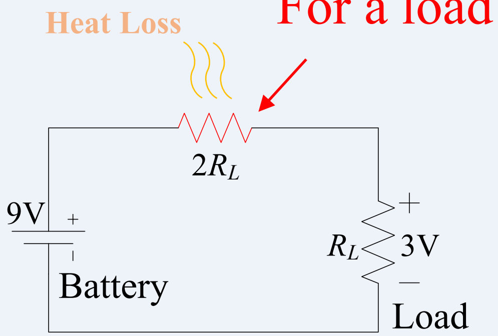
Conventional Solution

How to get a 3-V dc voltage from a 9-V battery?



One simple solution is to use a **Voltage Divider**.

For a load resistor R_L, inserting a series resistor $2R_L$.



$$V_o = V_{in} \times \frac{R_L}{R_L + 2R_L}$$
$$= 9\text{V} \times \frac{1}{3} = \mathbf{3V}$$

Tips:

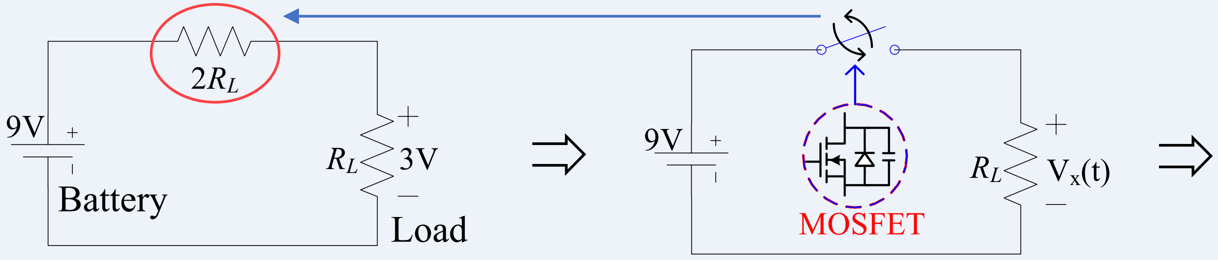
- Using Ohm's Law for Series Circuits With Multiple Resistors
- The total voltage drop is equal to the sum of the individual voltage drops across all resistors.

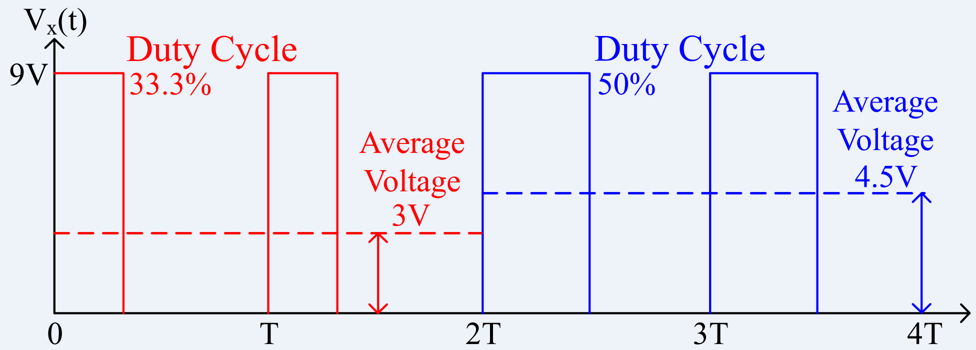
Problems with the Voltage Divider

- ☹ **Low Efficiency:** The power absorbed by the $2R_L$ resistor is twice as much as delivered to the load and is lost as heat, making the circuit only 33.3 percent efficient.
- ☹ If the value of the load resistance changes, the output voltage will change unless the $2R_L$ resistance changes proportionally.

Power Electronics Solution

To use a MOSFET in place of the $2R_L$ resistance

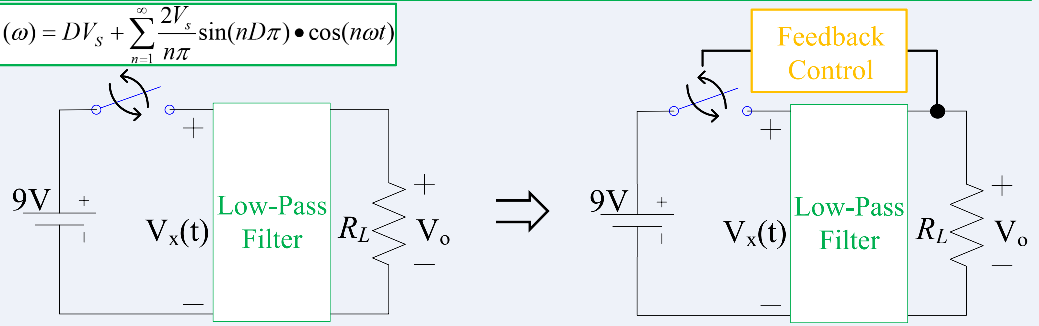




The switch is opened and closed periodically. When it is closed $V_x = 9\text{V}$, and when it is opened $V_x = 0\text{V}$.

NOTE: The square waveform V_x can be expressed as a **Fourier series** containing a **dc term** (i.e., average value) plus sinusoidal terms.

$$V_{EO}(\omega) = DV_s + \sum_{n=1}^{\infty} \frac{2V_s}{n\pi} \sin(nD\pi) \bullet \cos(n\omega t)$$



- A low-pass filter can remove the ac terms of V_x
- A feedback control system can detect the output voltage and adjust the switch's duty cycle to maintain the desired output.

The average value of V_x: $avg(V_x) = \frac{1}{T}\int_0^T V_x(t)dt = 9D$

Duty Cycle → D

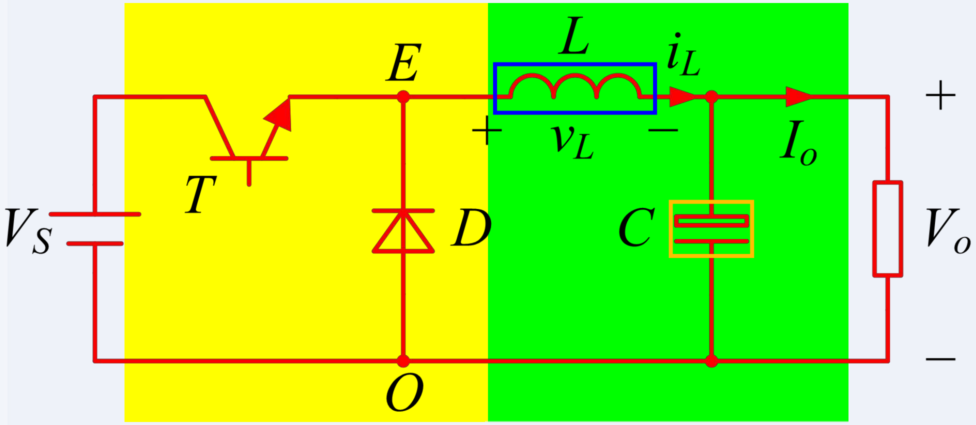
If D=33.3%, $avg(V_x)$ = 3V

If D=50%, $avg(V_x)$ = 4.5V

Advantages of Power Electronics Circuit

- **High Efficiency:** Ideally, the power absorbed by the switch is zero, making the circuit 100 percent efficient.
- **Easy for Use:** The load voltage can be changed easily by adjusting the duty cycle. With feedback control, the output voltage can be maintained regardless of R_L.

A Practical Buck Converter



Switch Network   Filter network

LC Second-Order Low-Pass Filter

$$V_L = L\frac{di_L}{dt} \rightarrow i_L = \frac{1}{L}\int V_L dt + I_{L0}$$

L can control current and store energy

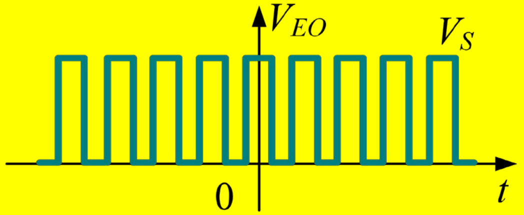
$$i_C = C\frac{dv_C}{dt} \rightarrow v_C = \frac{1}{C}\int i_C dt + V_{C0}$$

C can smooth voltage and store energy

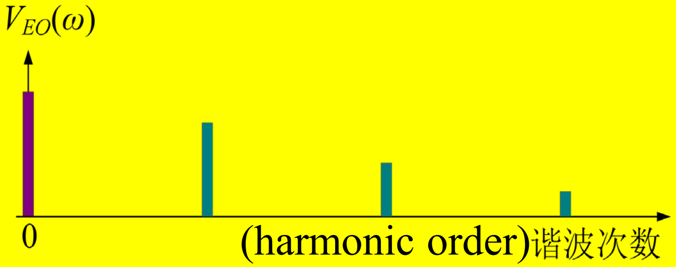
Why is diode necessary in a practical buck converter?

Inductor's current cannot suddenly change!

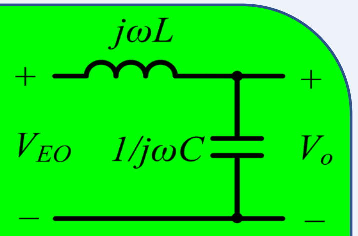
When switch is turned off, the diode can take over the inductor's current.

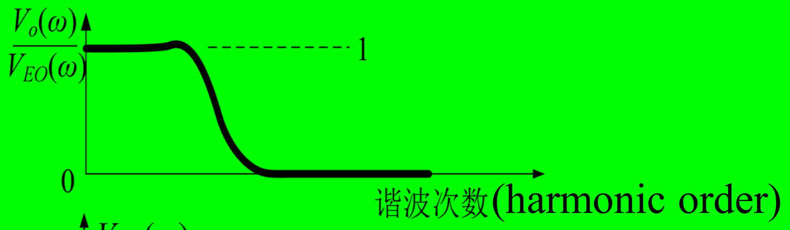


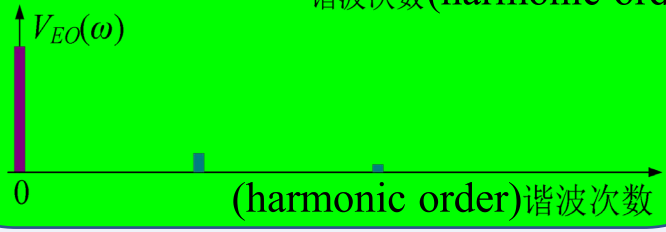
$$V_{EO}(\omega) = DV_S + \sum_{n=1}^{\infty}\frac{2V_s}{n\pi}\sin(nD\pi)\bullet\cos(n\omega t)$$

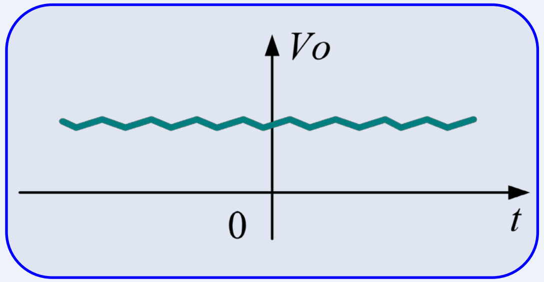


$$V_o(\omega) = \frac{1}{1-\omega^2 LC}V_{EO}(\omega)$$





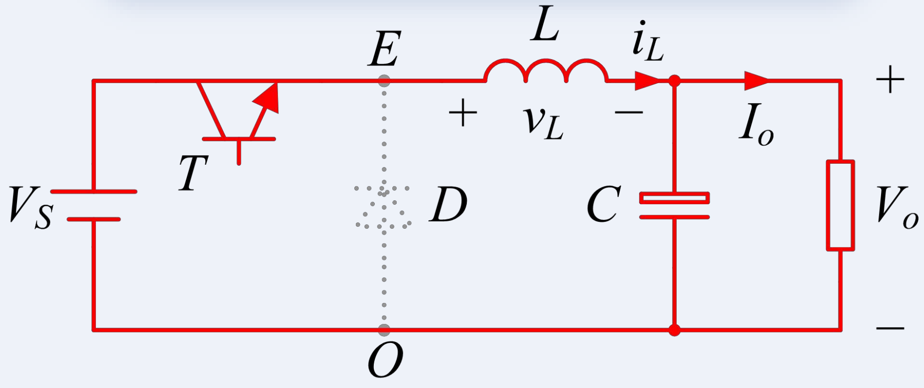




Output Voltage with Ripples

Buck Converter: Continuous Conduction Mode (CCM)

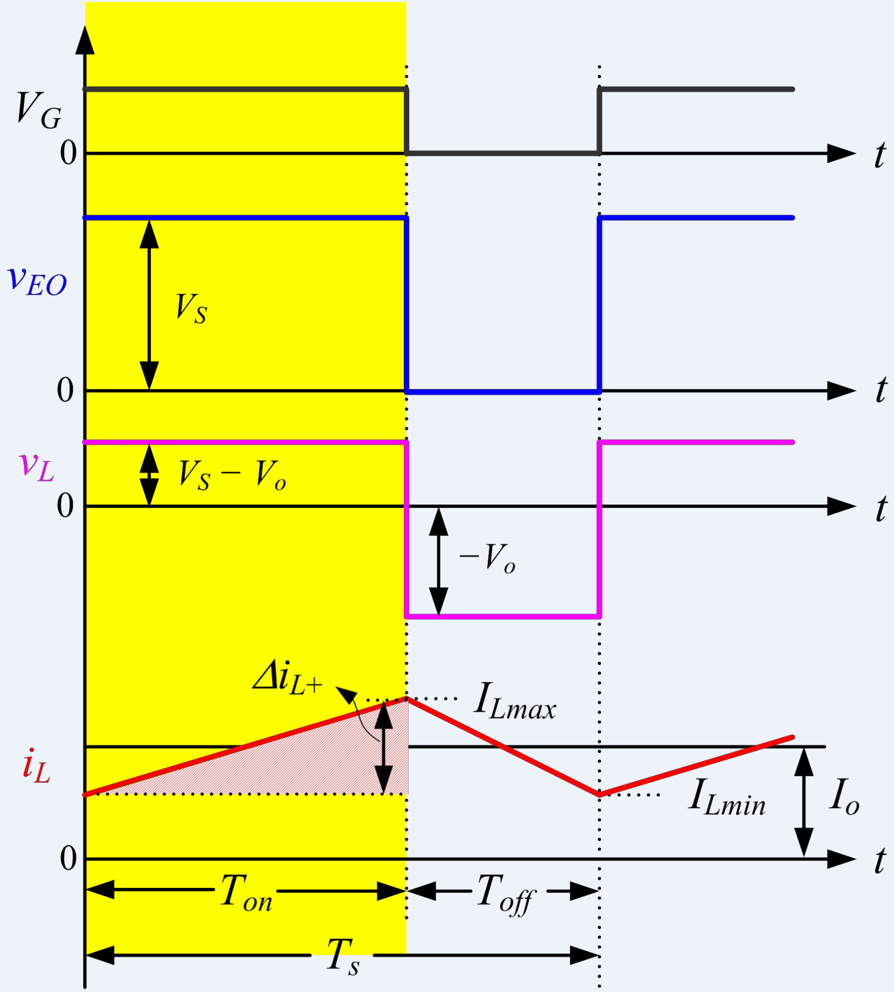
Switch T is Turned on



$$v_L = V_S - V_o = L\frac{di_L}{dt}$$

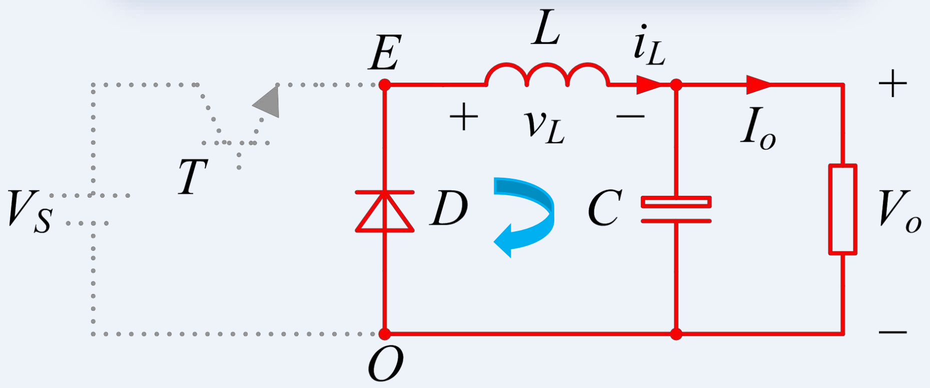
$$\frac{di_L}{dt} = \frac{V_S - V_o}{L}$$

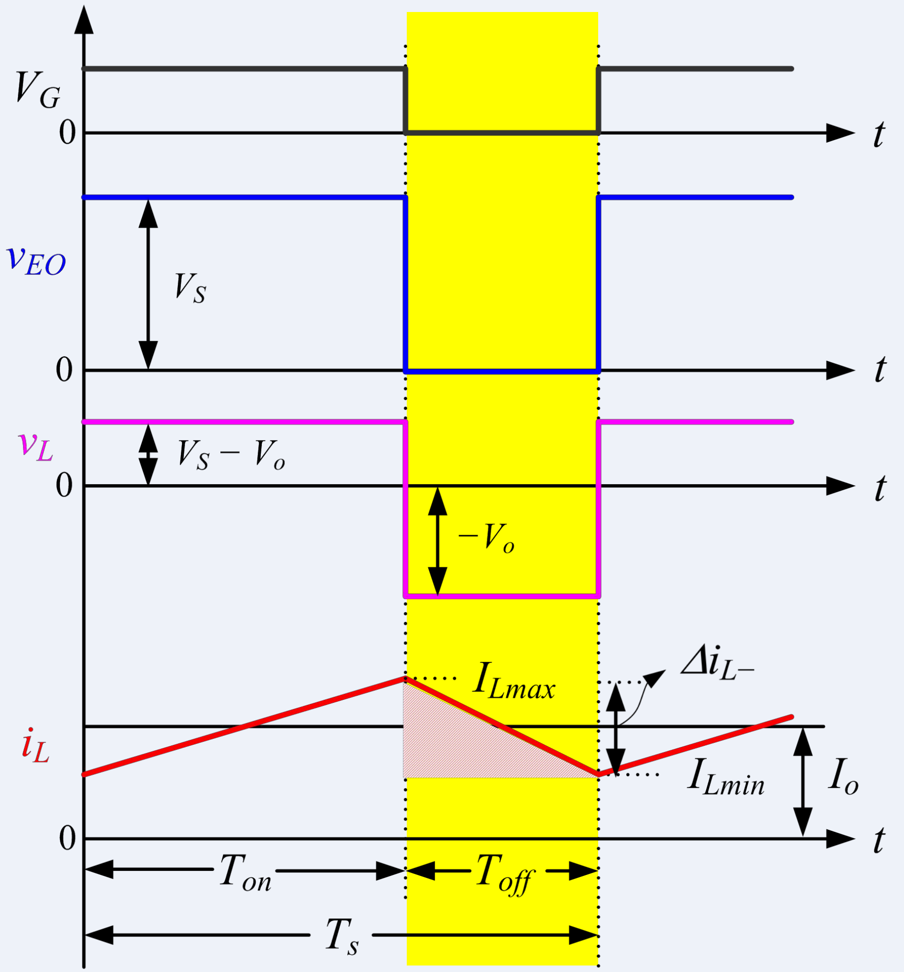
$$\Delta i_{L+} = \frac{V_S - V_o}{L}\cdot T_{on}$$



Buck Converter: Continuous Conduction Mode (CCM)

Switch T is Turned off





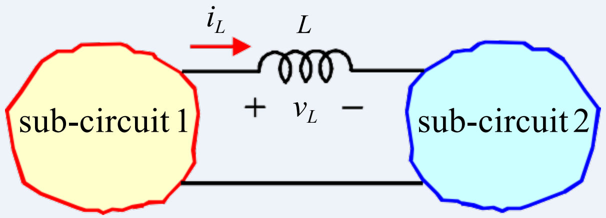
$$v_L = -V_o = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{-V_o}{L}$$

$$\Delta i_{L-} = -\frac{V_o}{L} \cdot T_{off}$$

Buck Converter: Principal of Volt-Second Balance

Principal of Inductor Volt-Second Balance

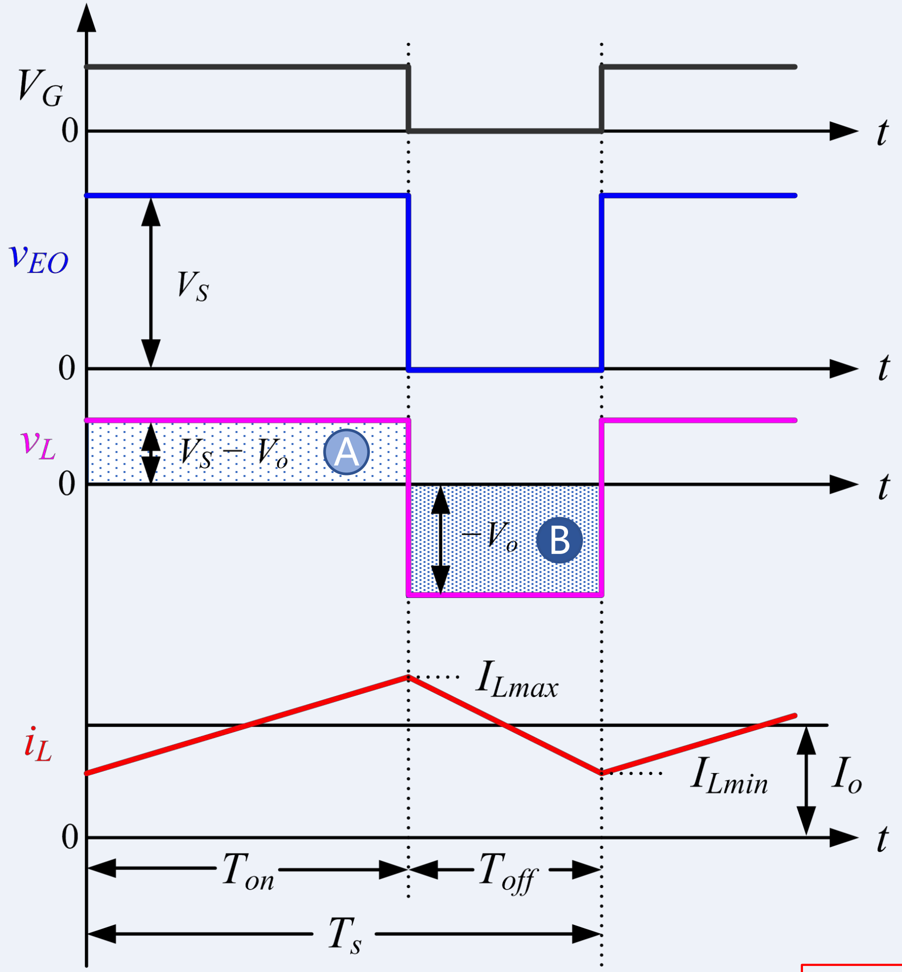


$$i(t_0+T)-i(t_0)=\frac{1}{L}\int_{t_0}^{t_0+T} v_L(t)\,dt=0$$

$$\text{avg}[v_L(t)]=V_L=\frac{1}{T}\int_{t_0}^{t_0+T} v_L(t)\,dt=0$$

- For periodic currents, the average voltage across an inductor is zero.

Otherwise, the average current will increase or decrease continuously, thus damaging the inductor.



Step-by-Step Derivations:

$$\Delta i_{L+}+\Delta i_{L-}=0$$

$$\Delta i_{L+}=\frac{V_s-V_o}{L}\cdot T_{on}$$

$$\Delta i_{L-}=-\frac{V_o}{L}\cdot T_{off}$$

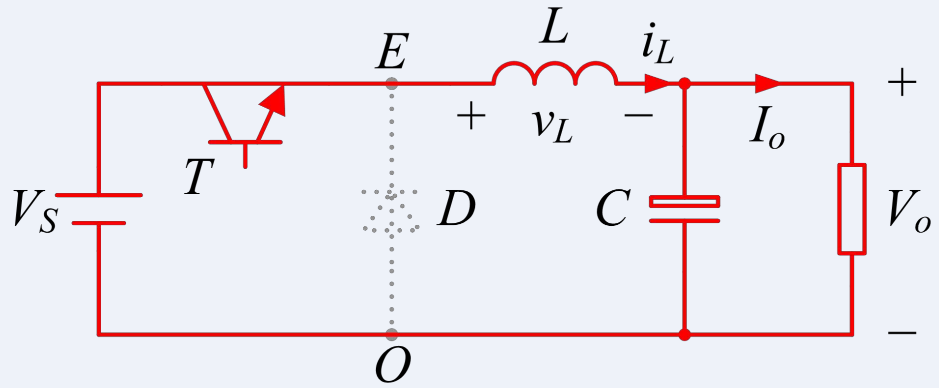
$$\frac{V_s-V_o}{L}\cdot T_{on}-\frac{V_o}{L}\cdot T_{off}=0$$

$$\frac{V_o}{V_s}=\frac{T_{on}}{T_{on}+T_{off}}=\frac{T_{on}}{T_s}=D$$

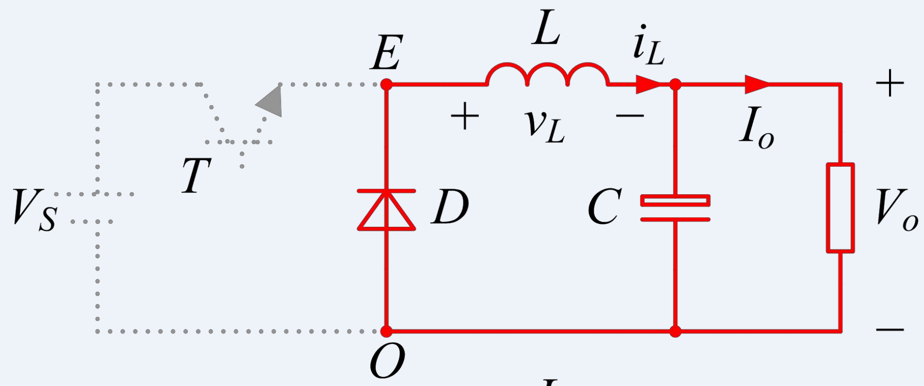
For a Buck converter: Controlling V_o by D

Buck Converter: Discontinuous Conduction Mode (DCM)

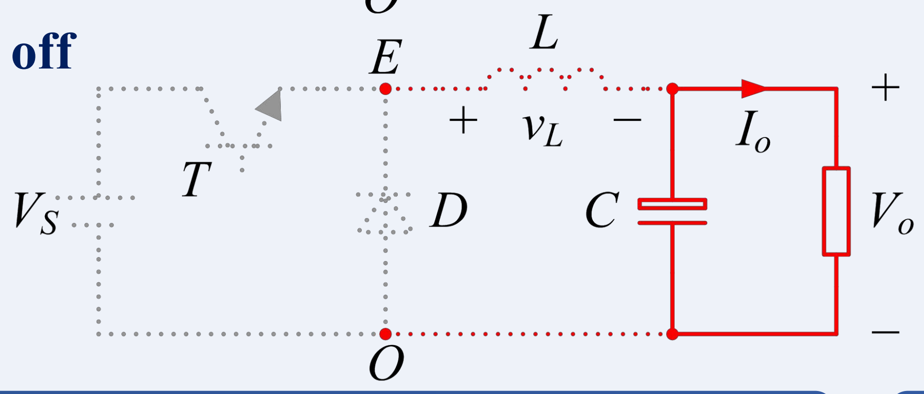
T on



T off

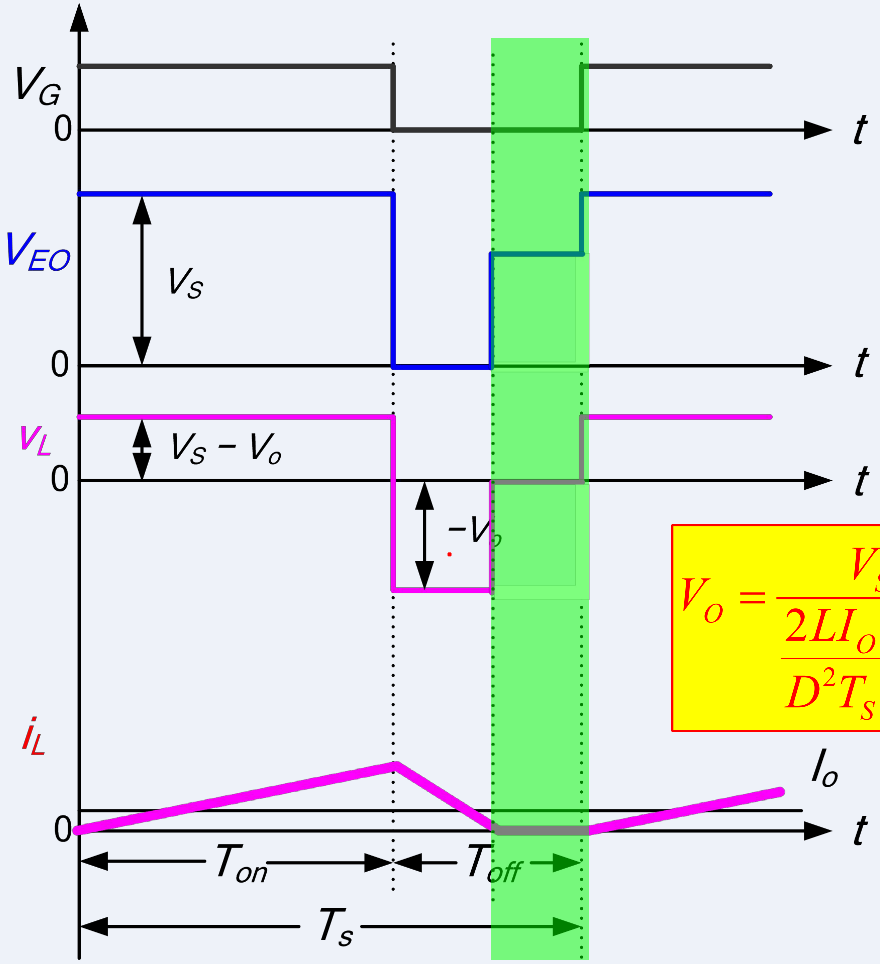


i_L cut off



Classroom Test

Try to calculate the relationship between input and output voltages under DCM mode.

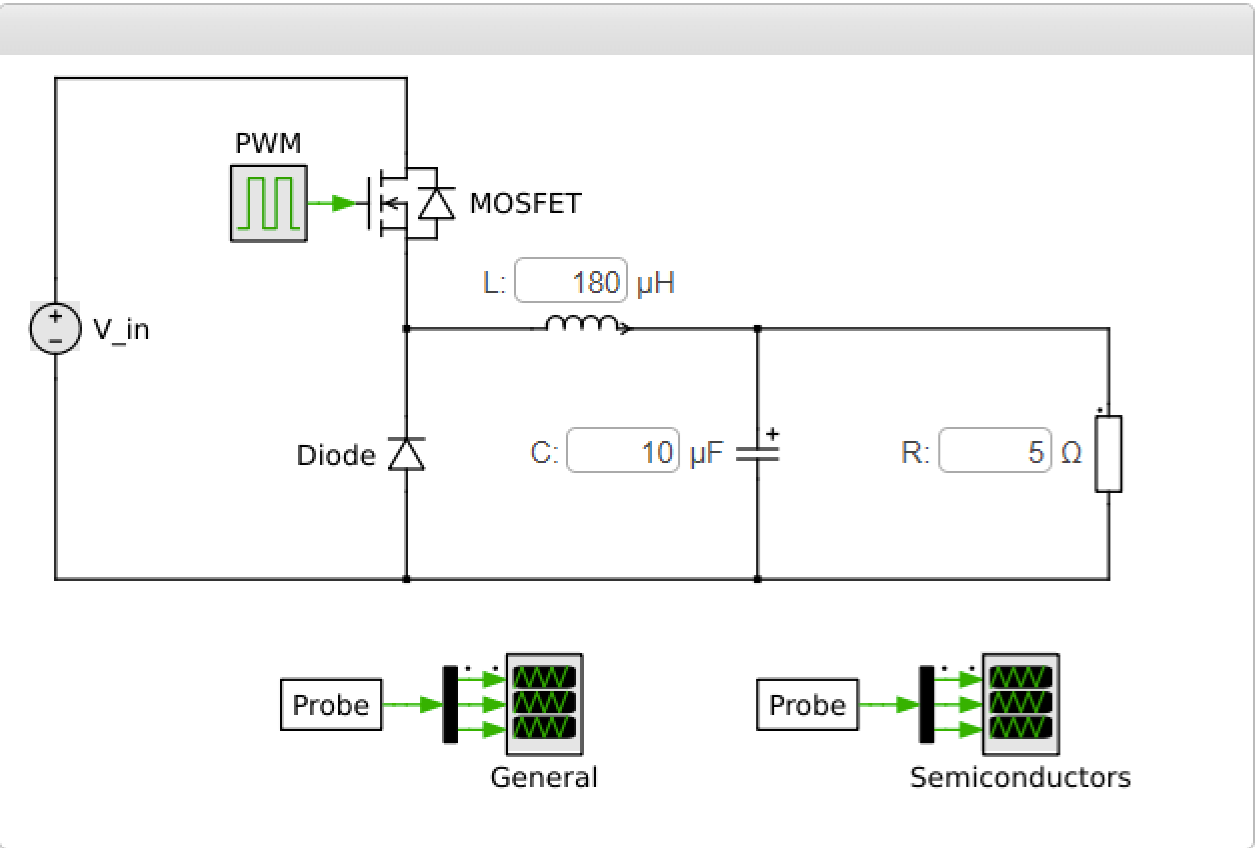


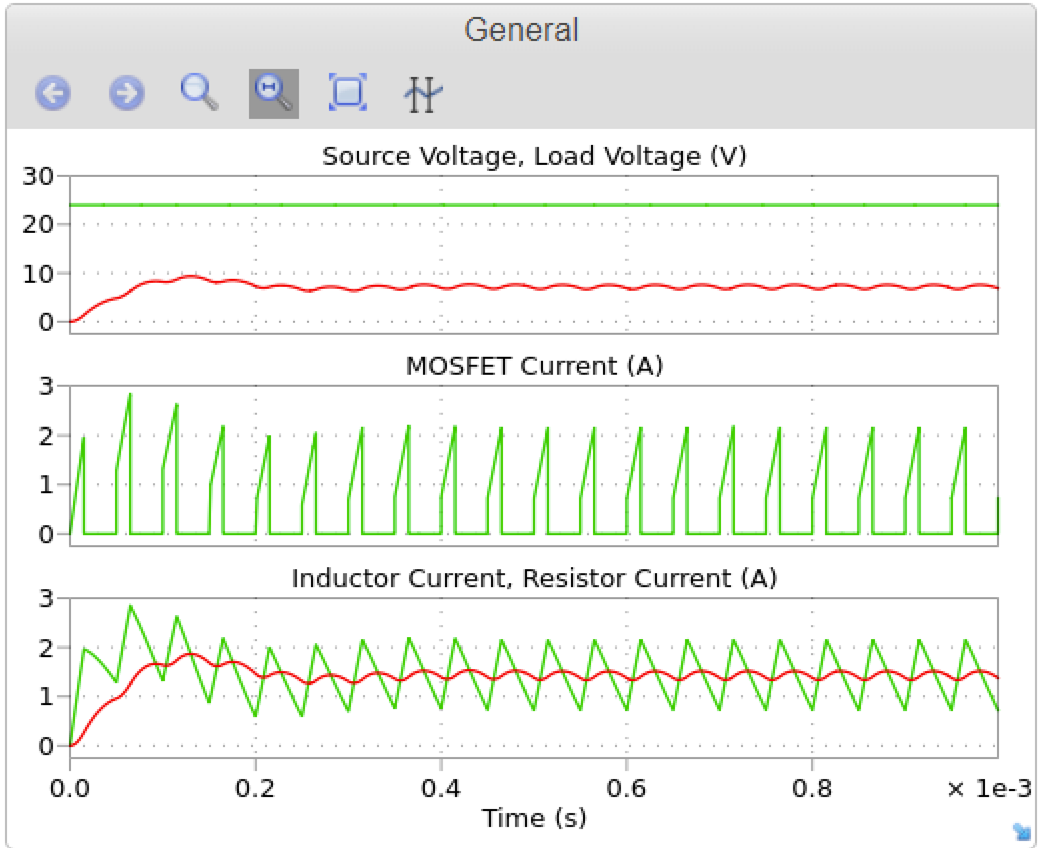
$$V_O = \frac{V_S^2}{\frac{2LI_O}{D^2T_S} + V_S}$$

Buck Converter: Summary

- A switched-mode dc-dc converter is much more efficient than a voltage divider because of reduced losses in the switch.
- A buck converter has an output voltage less than the input.
- Practical buck converters typically contain two semiconductors (a diode and a MOSFET) and two energy storage elements (a capacitor and an inductor in combination).
- The output voltage of a buck converter can be adjusted by the duty cycle.
- The principle of inductor volt-second balance states that the average value, or dc component, of voltage applied across an ideal inductor winding must be zero.
- Through appropriate parameter design, a buck converter can always work in CCM.

Buck Converter Simulation in PLECS®



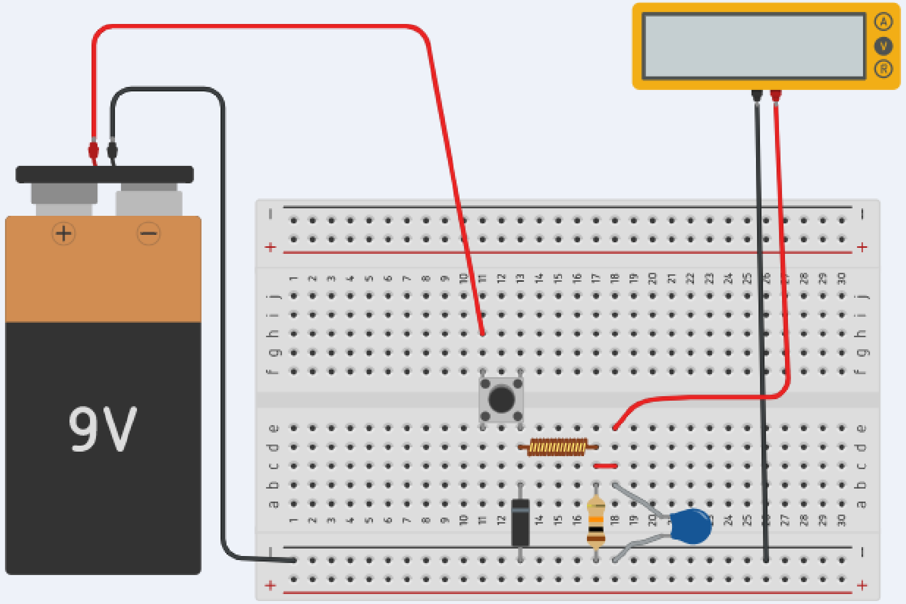


Simulation powered by **PLECS** using WebSIM patented technology
https://www.plexim.com/de/academy/power-electronics/buck-conv

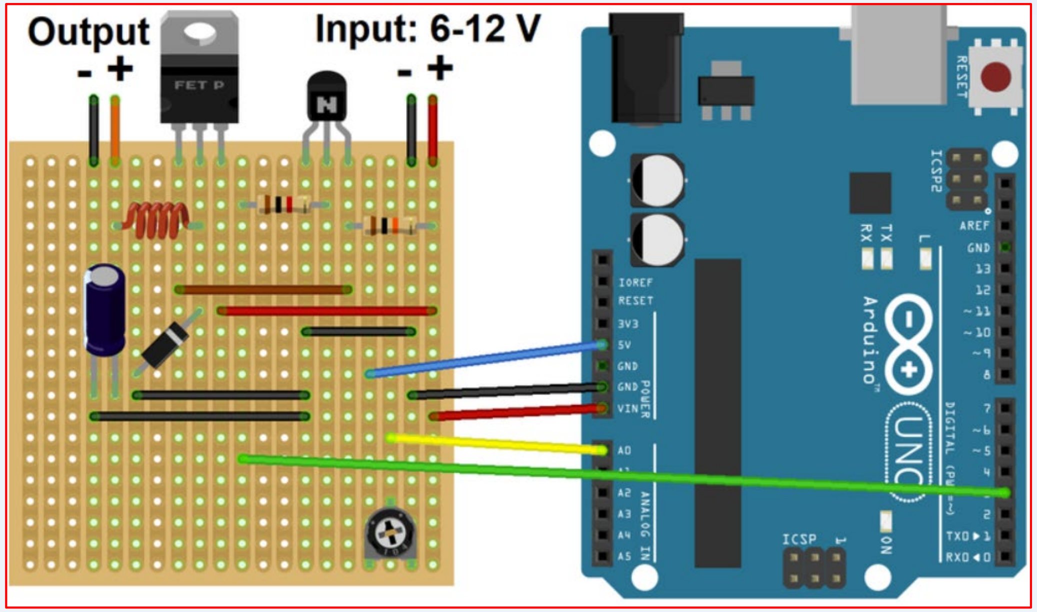
Exercises:

- ☐ Change the PWM duty cycle of the converter from 0.3 to 0.5 and observe how the average output voltage changes from 7.2 V to 12 V.
- ☐ Change the resistance value from 5 Ω to 50 Ω and observe how the converter goes into discontinuous conduction mode.

Experiments of Buck Converter



Buck Converter With Push Button



Buck converter using Arduino for PWM Generation

Source: https://samiralavi.github.io/blog/buck_coverter/buck_converter_arduino/

Report in Groups

Your hand-written report must include the following:

a) A short introduction to Buck DC-DC converters

b) Detailed steady-state analysis calculation of the Buck converter

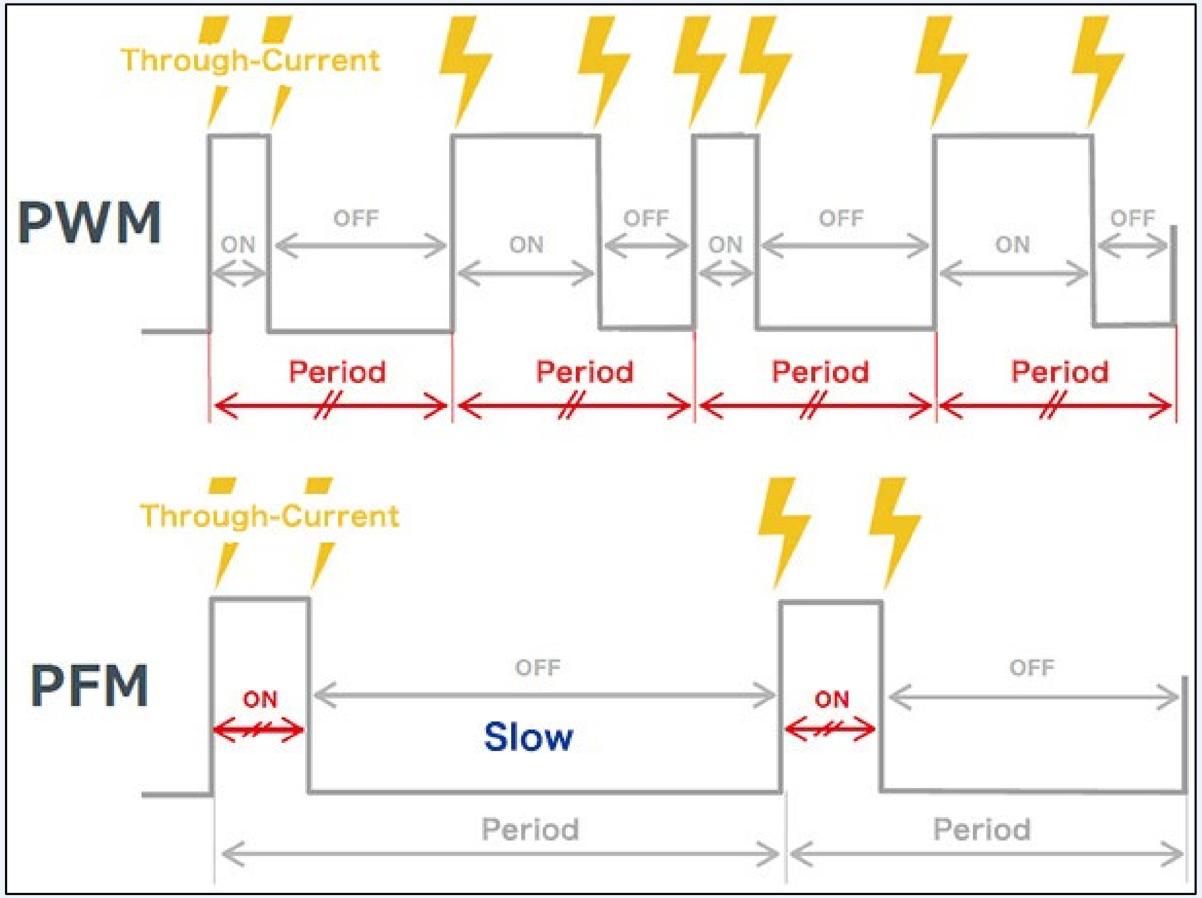
c) Experimental results (plots and tabulated data) and discussion

d) Simulation results (plots and tabulated data) and discussion

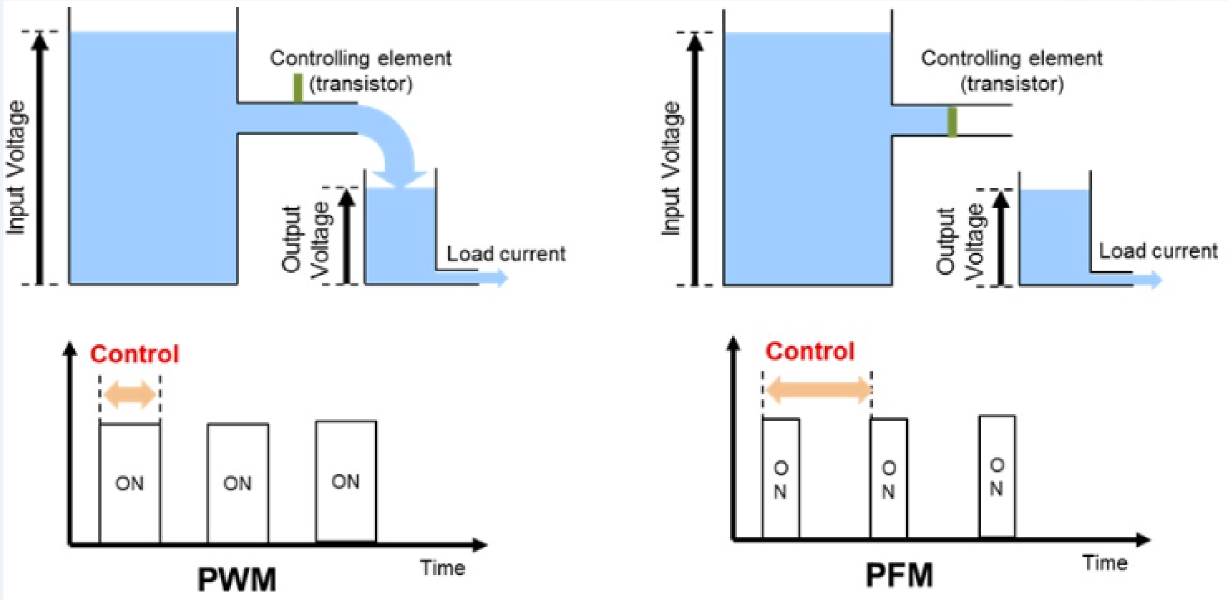
e) Conclusions

Duty Cycle	Output Voltage		Output Current		Inductor Current	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
10%						
20%						
30%						
40%						
50%						

Other Modulation Schemes for Buck Converter



■ **PWM (Pulse Width Modulation)**
A control method that produces the output equivalent from the input voltage at a constant frequency by turning the switch ON.



■ **PFM (Pulse Frequency Modulation)**
A method for generating the equivalent output by changing the frequency (OFF time) while keeping the ON time constant. There is also a type that varies the ON time while keeping the OFF time constant.

Extracurricular Reading Materials

[1] W. -R. Liou, M. -L. Yeh and Y. L. Kuo, "A High Efficiency Dual-Mode Buck Converter IC For Portable Applications," in IEEE Transactions on Power Electronics, vol. 23, no. 2, pp. 667-677, March 2008.
[2] A. Morra, M. Piselli, M. Flaibani and A. Gola, "A buck converter operating in PFM mode, mathematical model and simulation analysis," INTELEC 07 - 29th International Telecommunications Energy Conference, Rome, Italy, 2007, pp. 23-26.

THANK YOU VERY MUCH FOR YOUR TIME AND ATTENTION !

Questions and Answers