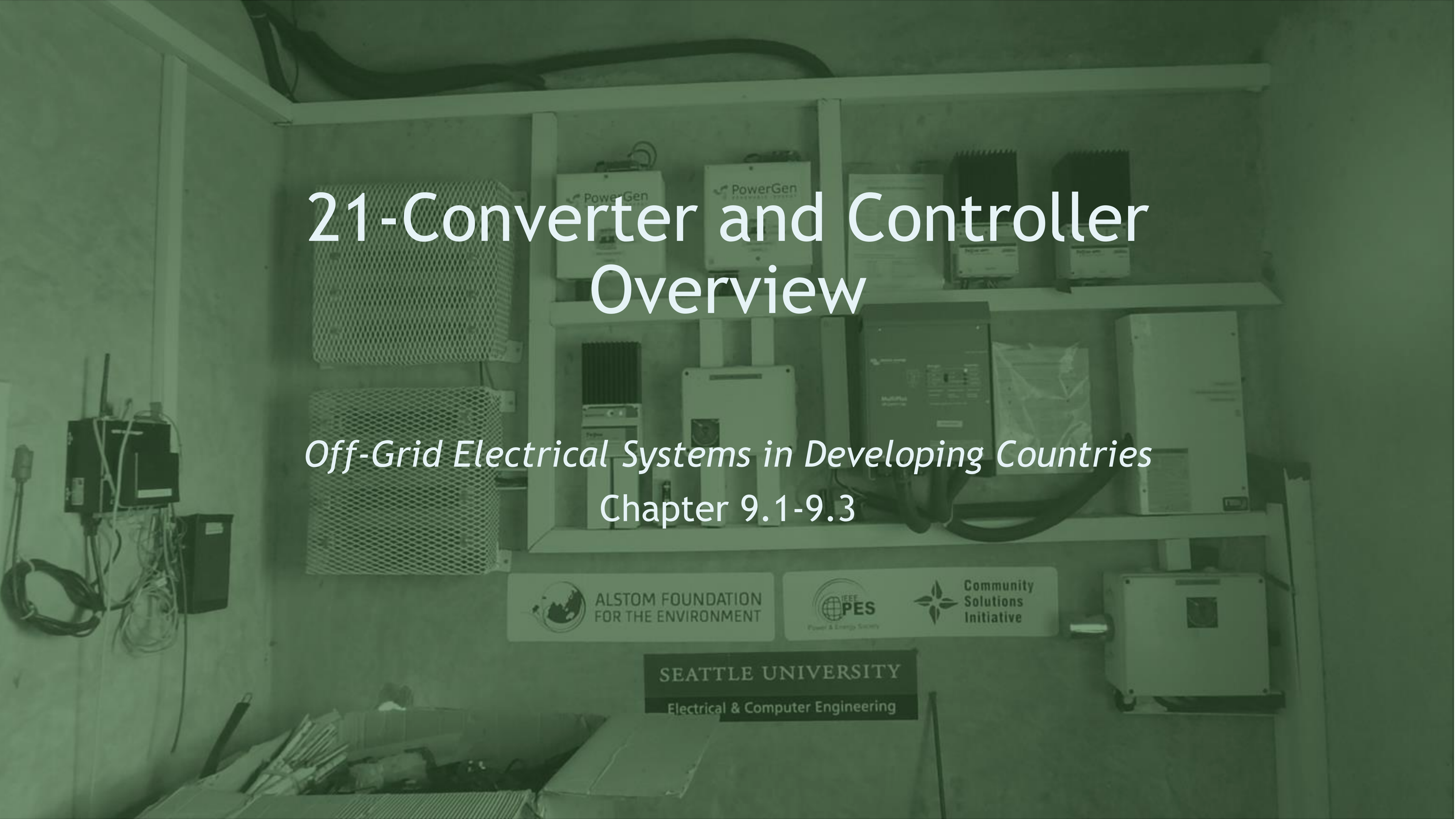
21-Converter and Controller Overview

Off-Grid Electrical Systems in Developing Countries

Chapter 9.1-9.3



Learning Outcomes

At the end of this lecture, you will be able to:

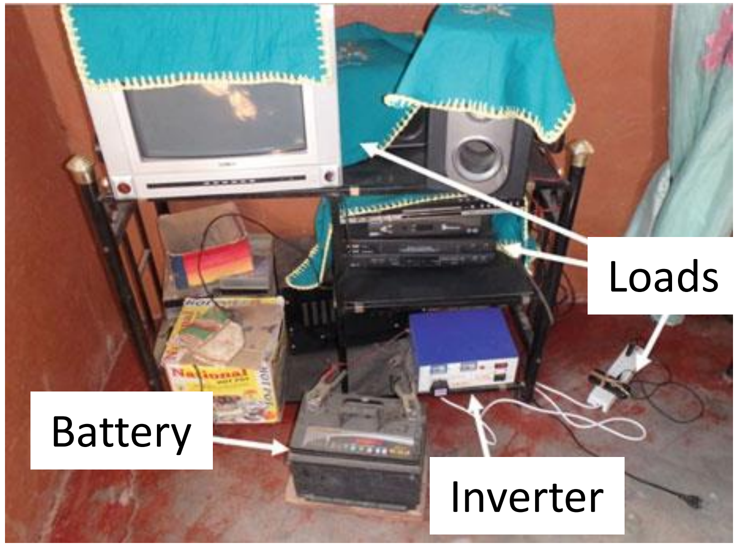
✓describe the role of converters and controllers in off-grid systems

✓understand the significance of distortion in off-grid systems

✓describe the operation of boost DC-DC converters

Why use converters and controllers?

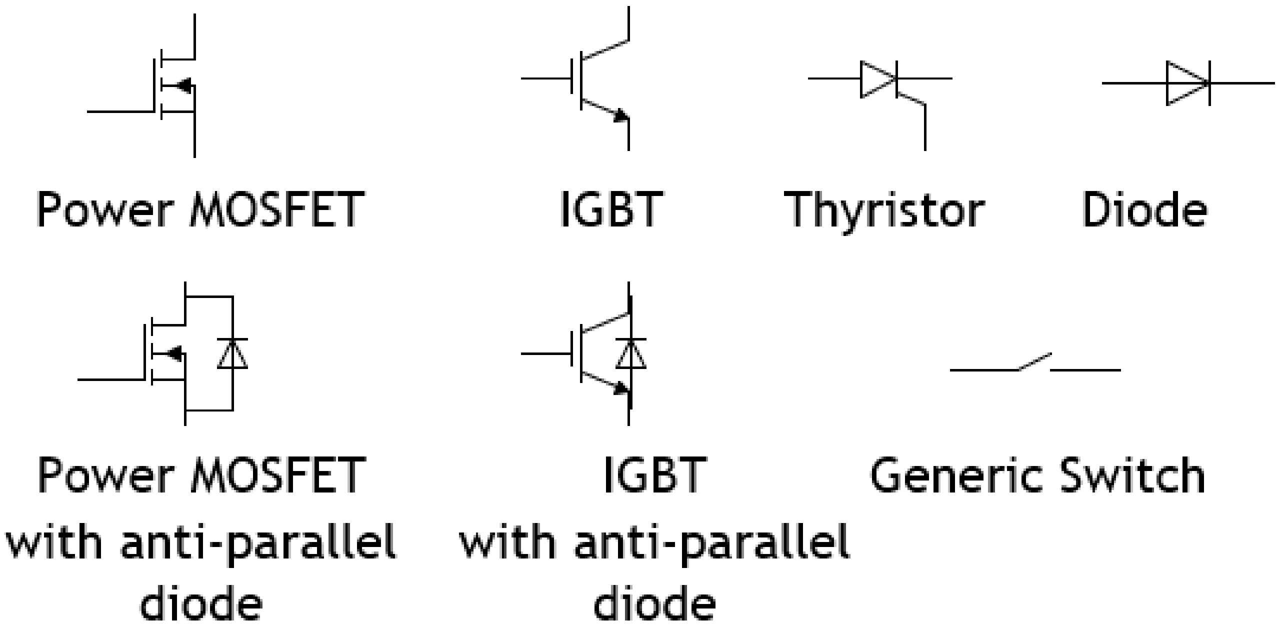
- Simple, improvised or non-engineered off-grid systems often do not use converters or controllers
- Converters and controllers can improve efficiency and utilization of components, and prolong their life



Converters & Controllers Found in Off-Grid Systems

Converter	Basic Function
DC-DC converter	Increases or decrease output voltage relative to input voltage
Maximum power point tracker (MPPT)	Increases the power produced by PV arrays or WECS
Solar battery charger	Charges batteries directly from PV sources
AC battery charger	Converters AC produced by generators or other sources to DC and manages battery charging
Rectifier	Converts AC to DC
Automatic voltage regulator (AVR)	Adjusts excitation to synchronous generators
Electronic load controller (ELC)	Controls power to ballast load to regulate frequency
Inverter	Converts DC to AC
Grid-tied inverter	Converts DC to AC and synchronizes with AC bus
Bi-directional inverter	Allows power to be exchanged between DC and AC buses

Solid-State Switching Elements



Some switches are operated by a control signal $q(t)$.
We will use the convention:

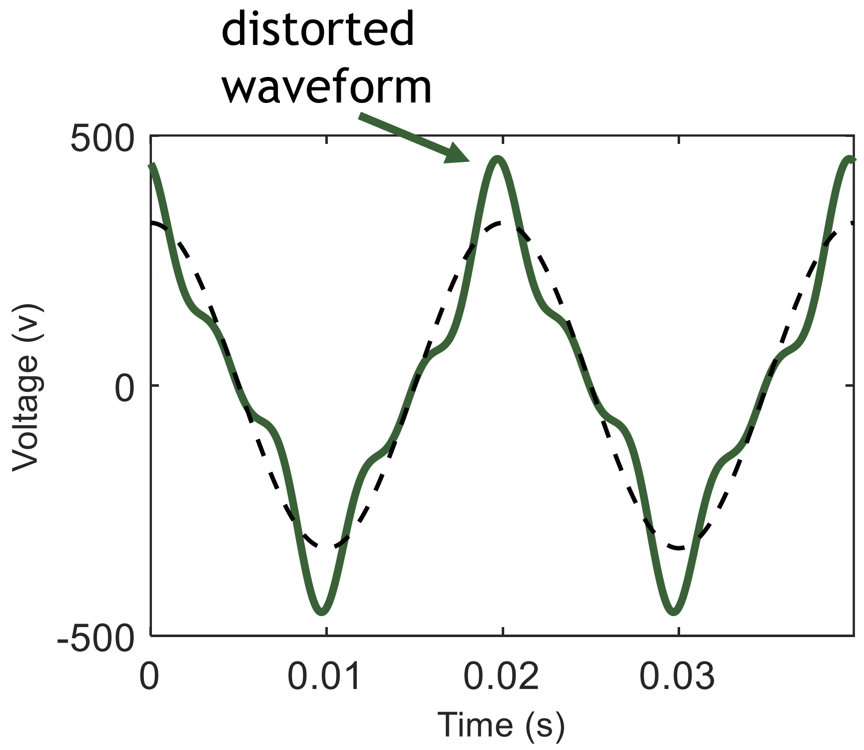
$q(t) = 1$: switch has received closed signal

$q(t) = 0$: switch has received open signal

Note: in some cases a switch will receive an open signal and remain closed, and vice-versa

Distortion

- Many converters have non-linear characteristics resulting in <u>distorted</u> waveforms
  - Time-varying, non-sinusoidal voltage and current
- Deleterious effects of distortion
  - Generators and conductors overheat
  - Humming
  - Visible flicker
  - Malfunction of sensitive electronic devices



Distortion

- Analysis of distorted waveforms is challenging in the time domain, and phasor analysis does not apply
- Basic approach:
  - Decompose distorted waveform into its harmonic components using Fourier Series
  - Analyze each harmonic separately, for example using phasor analysis
  - Combine results from each harmonic

Fourier Series

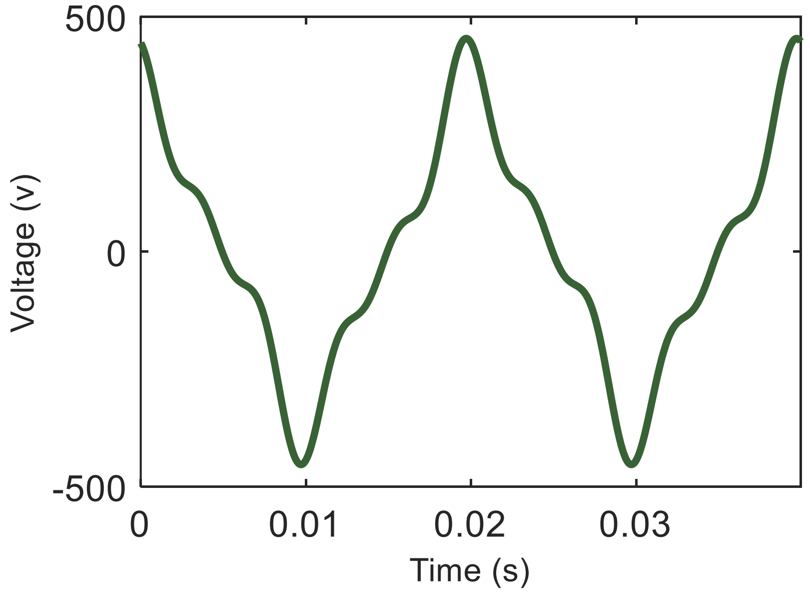
Recall that any periodical zero-mean signal $f(t)$ can be decomposed into its harmonic components as:

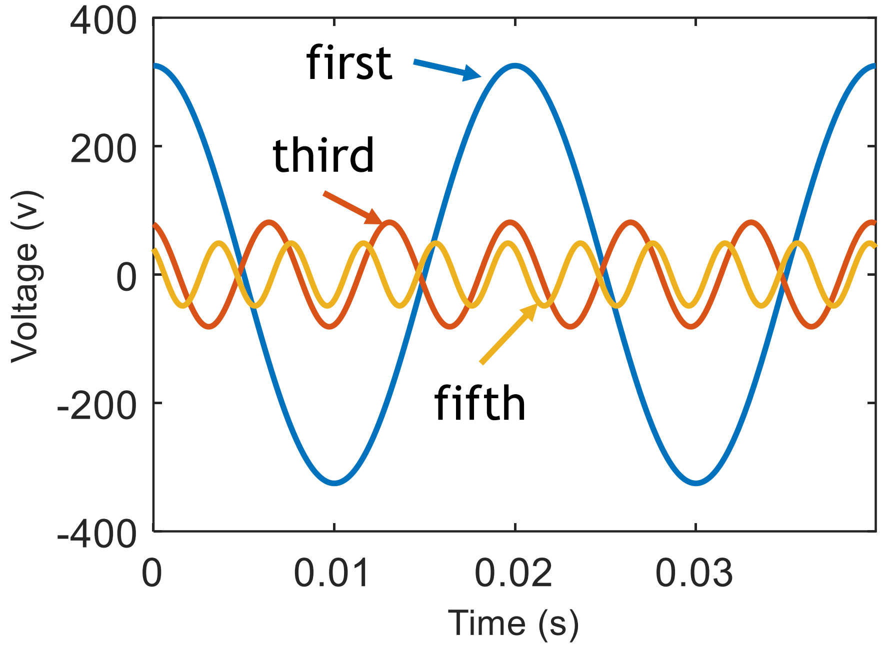
$$f(t) = \sum_{k=1}^{\infty} F_k \sin\left(k\omega_0 t + \delta_k\right)$$

ω_0: fundamental frequency of f(t), rad/s
k: harmonic number
F_k: magnitude of the kth harmonic
δ_k: angle of the kth harmonic

Waveforms with little distortion will have $F_1 >> F_2, \ldots, F_\infty$

Fourier Series





$F_1 = 325.3$ V $\delta_1 = 0^o$

$F_3 = 81.3$ V $\delta_3 = 15^o$

$F_5 = 48.8$ V $\delta_5 = 35^o$

Total Harmonic Distortion

- Distortion is commonly quantified using the Total Harmonic Distortion (THD) (commonly expressed as a percent)

$$THD = \frac{\sqrt{\sum_{k=2}^{\infty} F_k^2}}{F_1}$$

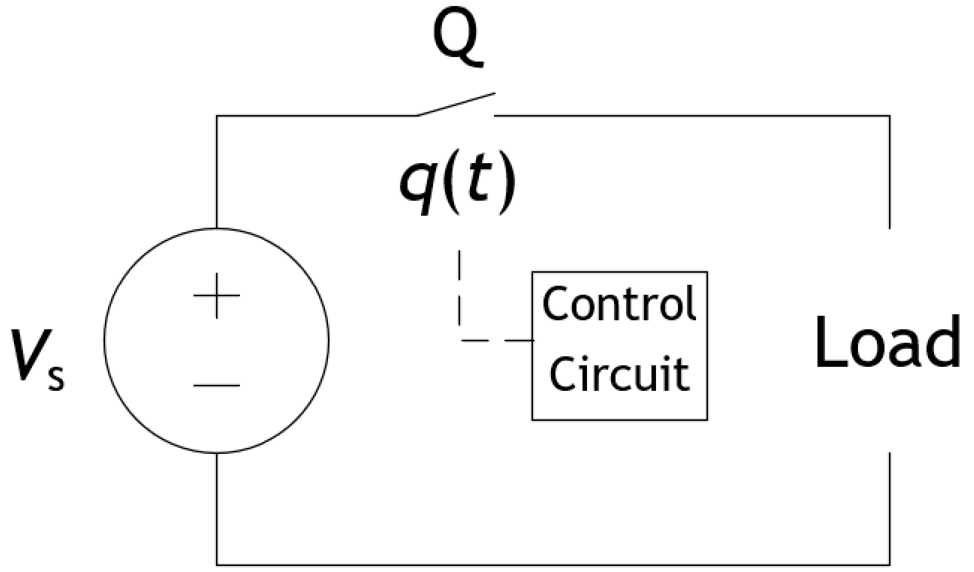
- THD usually reported by gen sets and inverters
- Higher quality gen sets and inverters will have a THD of less than 5%

Filtering

- Distortion can be reduced by using a passive filter at the output of a converter
- For example, use a low pass filter (capacitor) to filter out harmonics higher than the fundamental

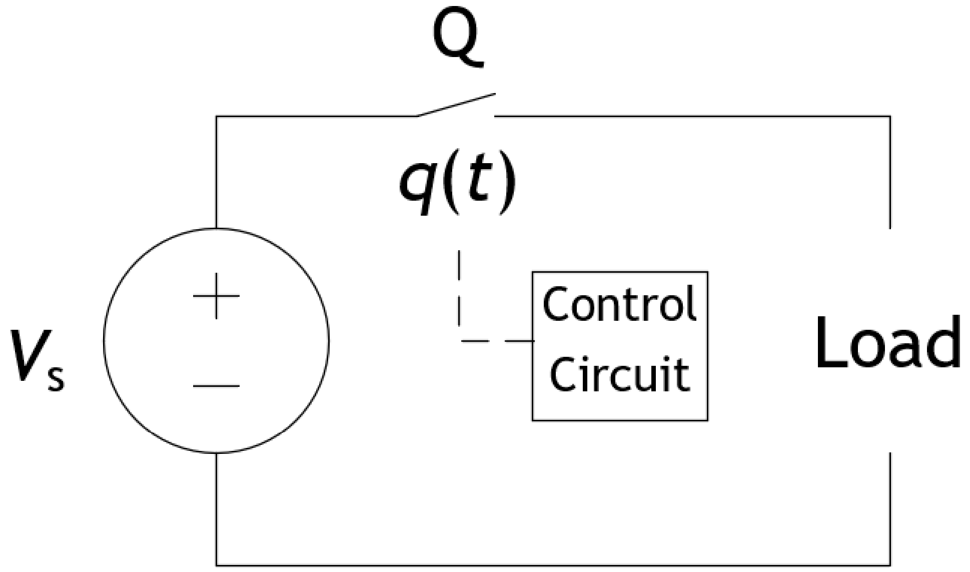
Pulse Width Modulation (PWM)

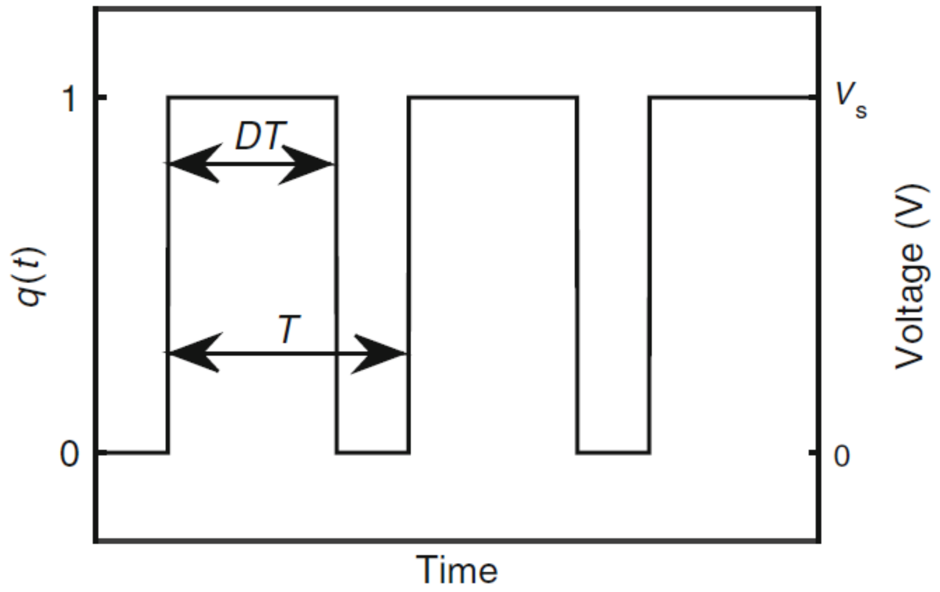
- Technique in which the width of a pulse is varied to achieve a desired average value
- Allows for control of an independent DC source



simple "chopper" circuit

Pulse Width Modulation (PWM)



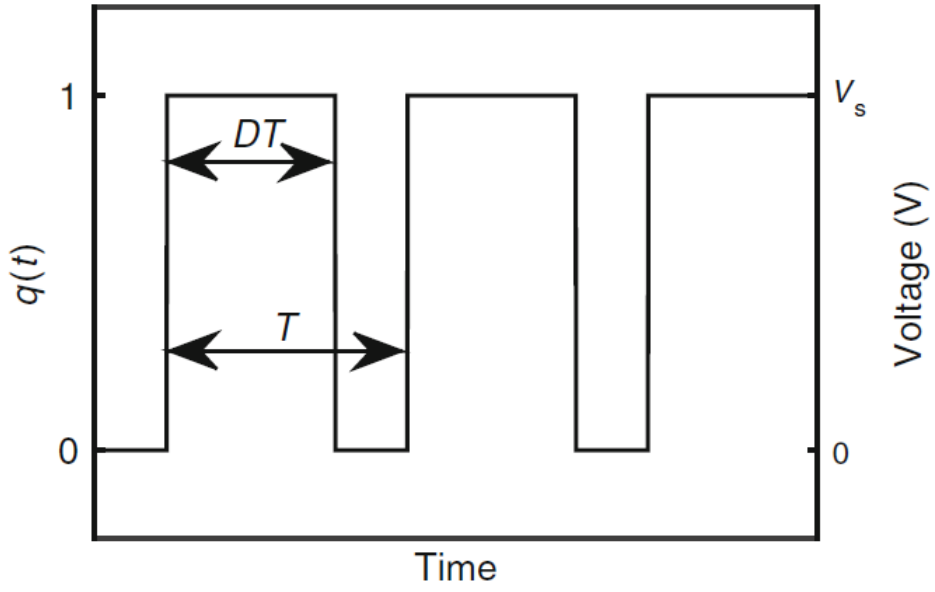


T: period, s
D: duty cycle, often expressed as proportion or percent

Average Value

- The average value of the voltage waveform applied to the load is:

$$\bar{V}_{Load} = \frac{1}{T}\int_0^T v(t)dt = \frac{1}{T}\int_0^{DT} V_s dt = DV_s$$



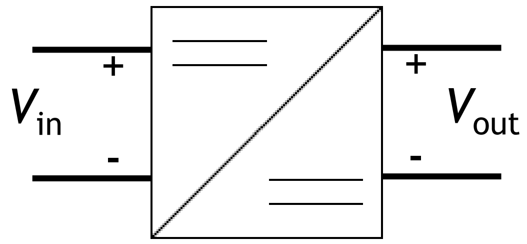
Pulse Width Modulation

- The voltage of a more general pulse train, which varies between a voltage $V_{\max}$ and $V_{\min}$ is:

$$\bar{V}_{Load} = \frac{1}{T}\int_0^T v(t)dt = \frac{1}{T}\left(\int_0^{DT} V_{\max}dt + \int_{DT}^{T} V_{\min}dt\right) = DV_{\max} + (1-D)V_{\min}$$

DC-DC Converters

- Conceptually similar to AC transformers, where the output voltage can be greater than, equal to, or less than the input voltage
- Unlike transformers, the ratio between output voltage and input can be easily adjusted by changing the duty cycle of a solid-state switch



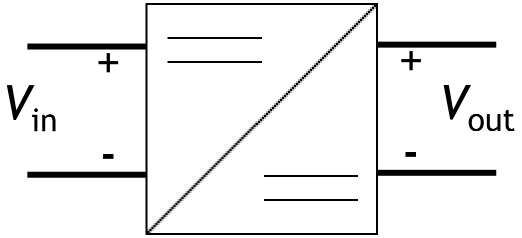
DC-DC Converters

- The input and output quantities are related to the power output as:

$$P = \eta_{\text{DC-DC}} V_{\text{in}} I_{\text{in}} = V_{\text{out}} I_{\text{out}}$$

$\eta_{\text{DC-DC}}$: efficiency of the converter

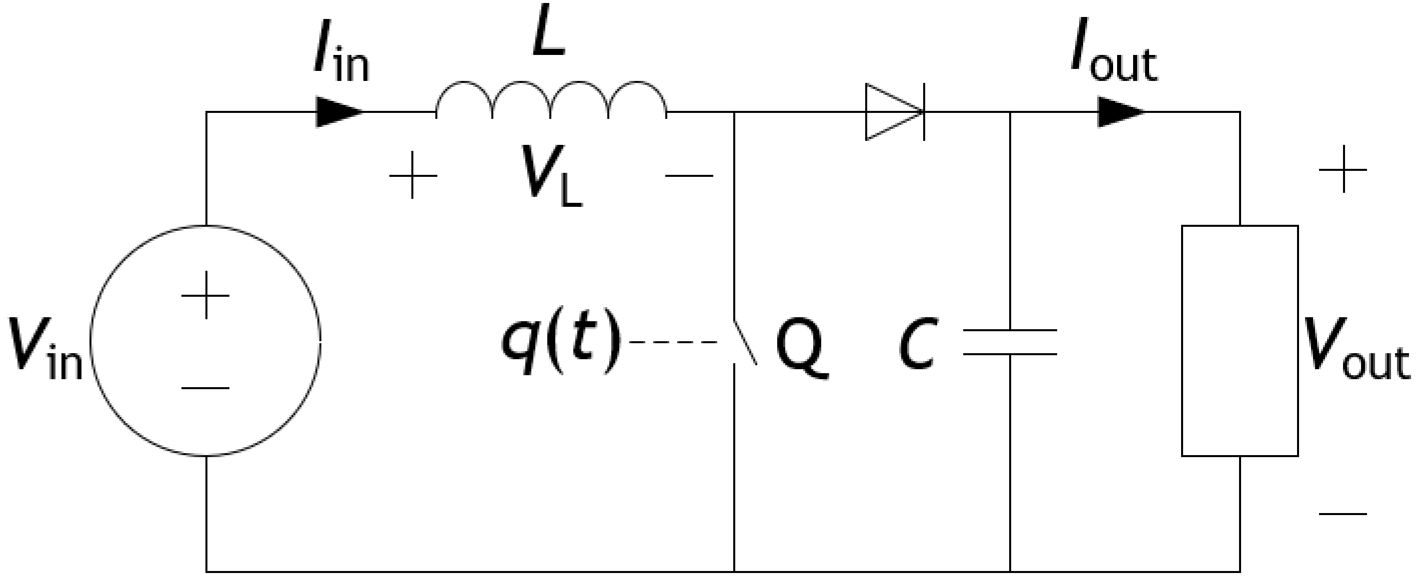
- Increasing the output voltage decreases the output current and vice versa
- DC-DC converters have efficiencies of approx. 90%



Boost Converter

- We will examine one type of DC-DC converter known as a "boost converter" to explain the general principles of DC-DC converter operation
- Boost converters are common DC-DC converters and are found internal to many off-grid converters and controls
- Boost converters increase the output voltage

Boost Converter Circuit

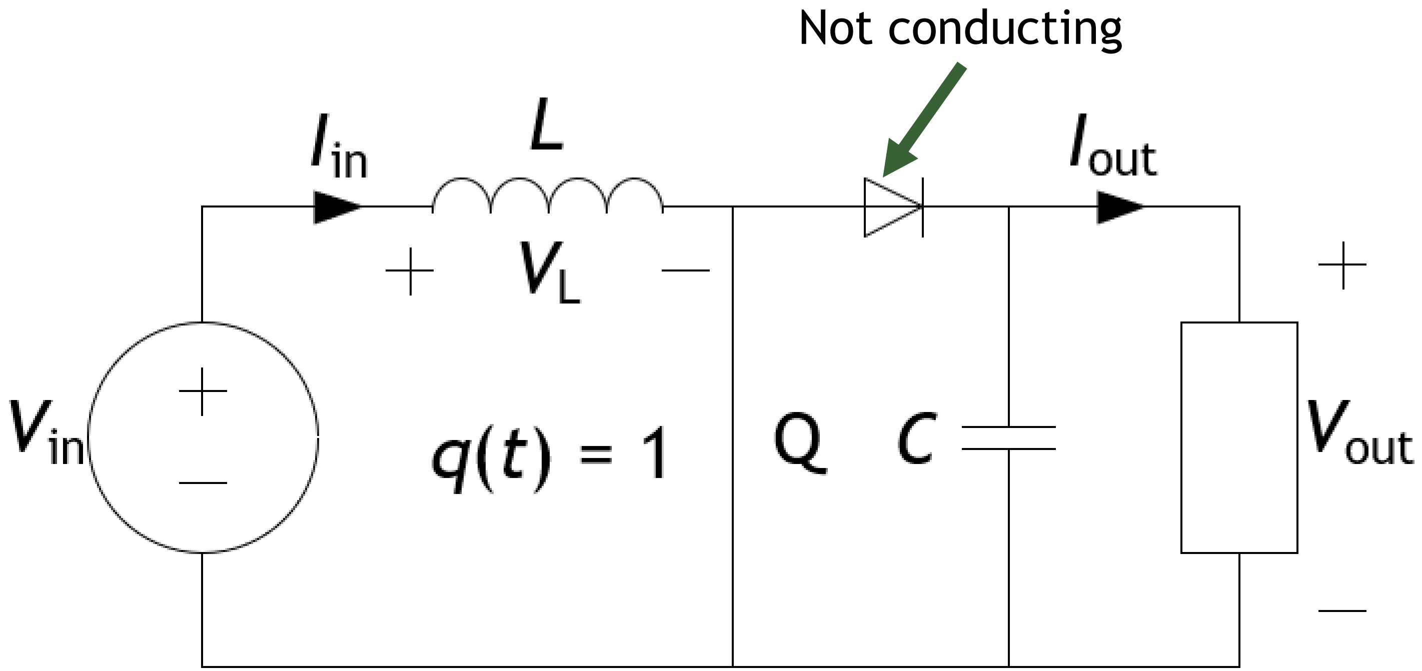


Boost Converter Circuit (Q = 1)

When switch is closed, the voltage across the inductor is V_{in}, and the current through it rises according to:

$$I_{in}(t) = \frac{1}{L}\int V_L \mathrm{d}t$$

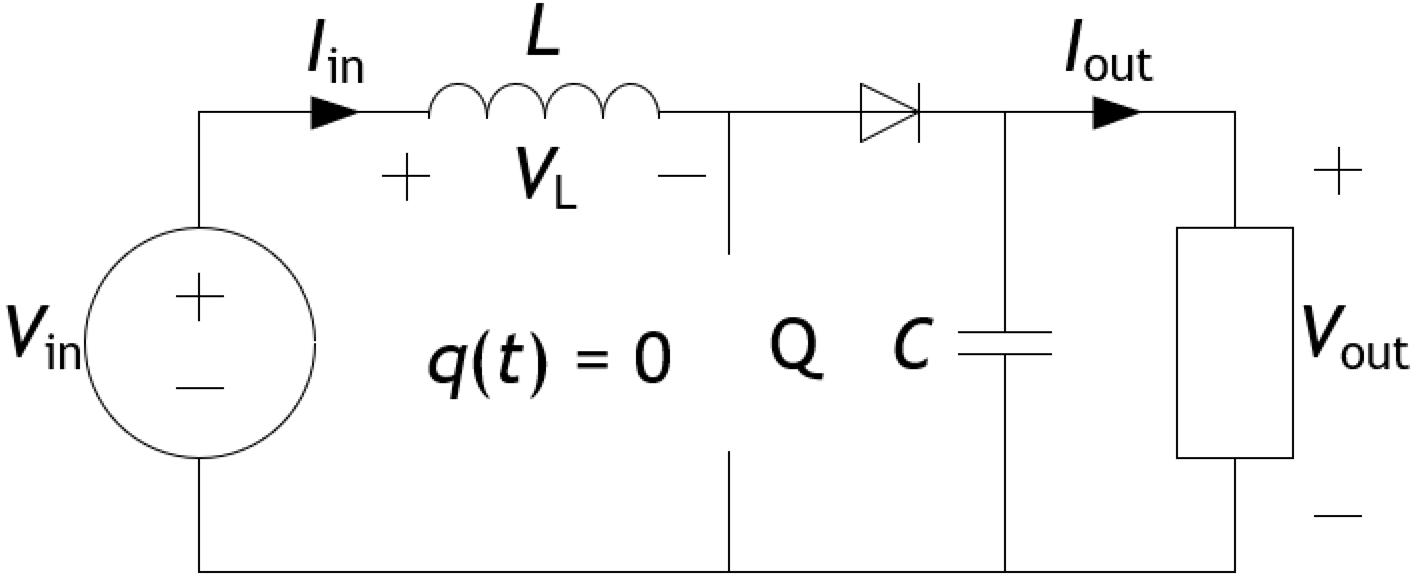
Energy stored in the inductor increases



Boost Converter Circuit (Q = 0)

- Now the switch opens
- Current through inductor cannot instantly drop to zero
- Diode must be conducting
- KVL shows that:

$$V_{\text{in}} = V_{\text{L}} + V_{\text{out}}$$



Ignoring the diode voltage drop

Boost Converter Circuit (Q = 0)

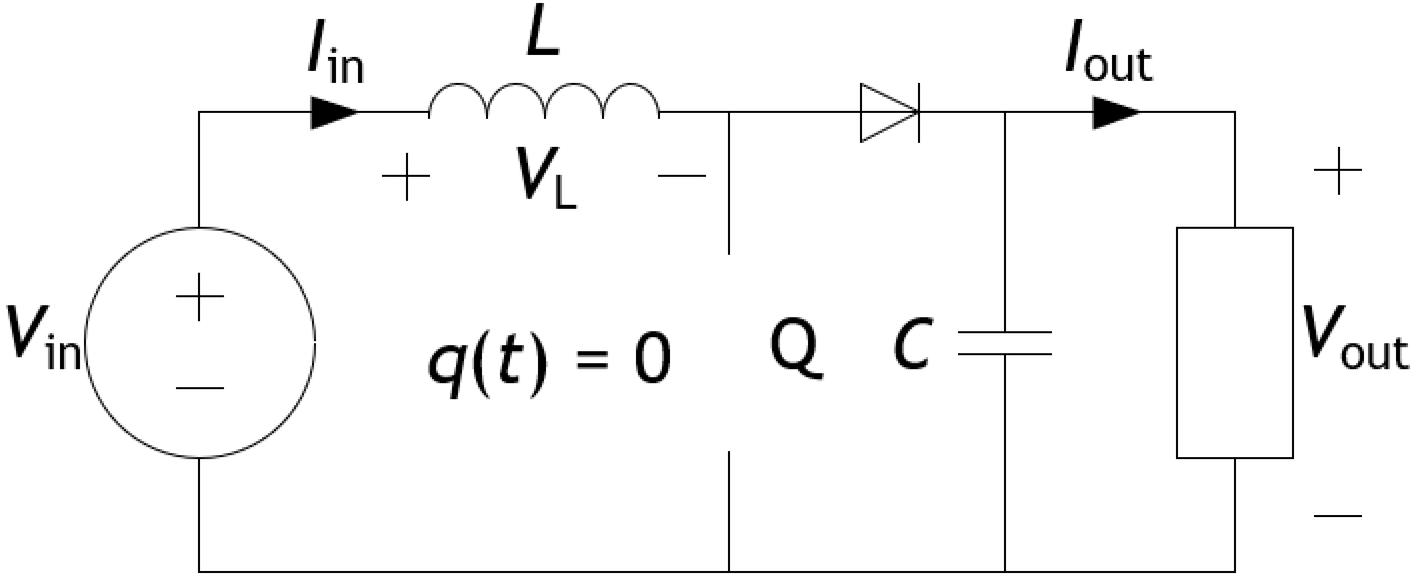
- Inductor current decreases (energy transferred to load)
- Inductor voltage becomes <u>negative</u> due to

$$V_L = L\frac{di_L}{dt}$$

- The output voltage is therefore:

$$V_{in} = V_L + V_{out}$$

$$V_{out} = V_{in} - V_L$$



The output voltage is therefore greater than the input

Boost Converter Output Voltage

- When Q = 0, the voltage across inductor is V_{in}
- When Q = 1, the voltage across inductor is $V_L = V_{in} - V_{out}$
- Since Q = 0 for *D* percent of the time, and Q = 1 for 1 – *D* percent of the time, the average is:

$$DV_{in} + (1 - D)(V_{in} - V_{out}) = \bar{V}_L$$

$$DV_{in} + (1 - D)(V_{in} - V_{out}) = 0$$

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

The average inductor voltage must be 0 (otherwise its energy would be increasing or decreasing on average over time)

DC-DC Converters

Other converters use different topologies to achieve voltage gain or reduction

Converter	Relationship
Boost	$V_{out} = \frac{1}{1-D} V_{in}$
Buck	$V_{out} = DV_{in}$
Buck–boost	$V_{out} = \frac{-D}{1-D} V_{in}$

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