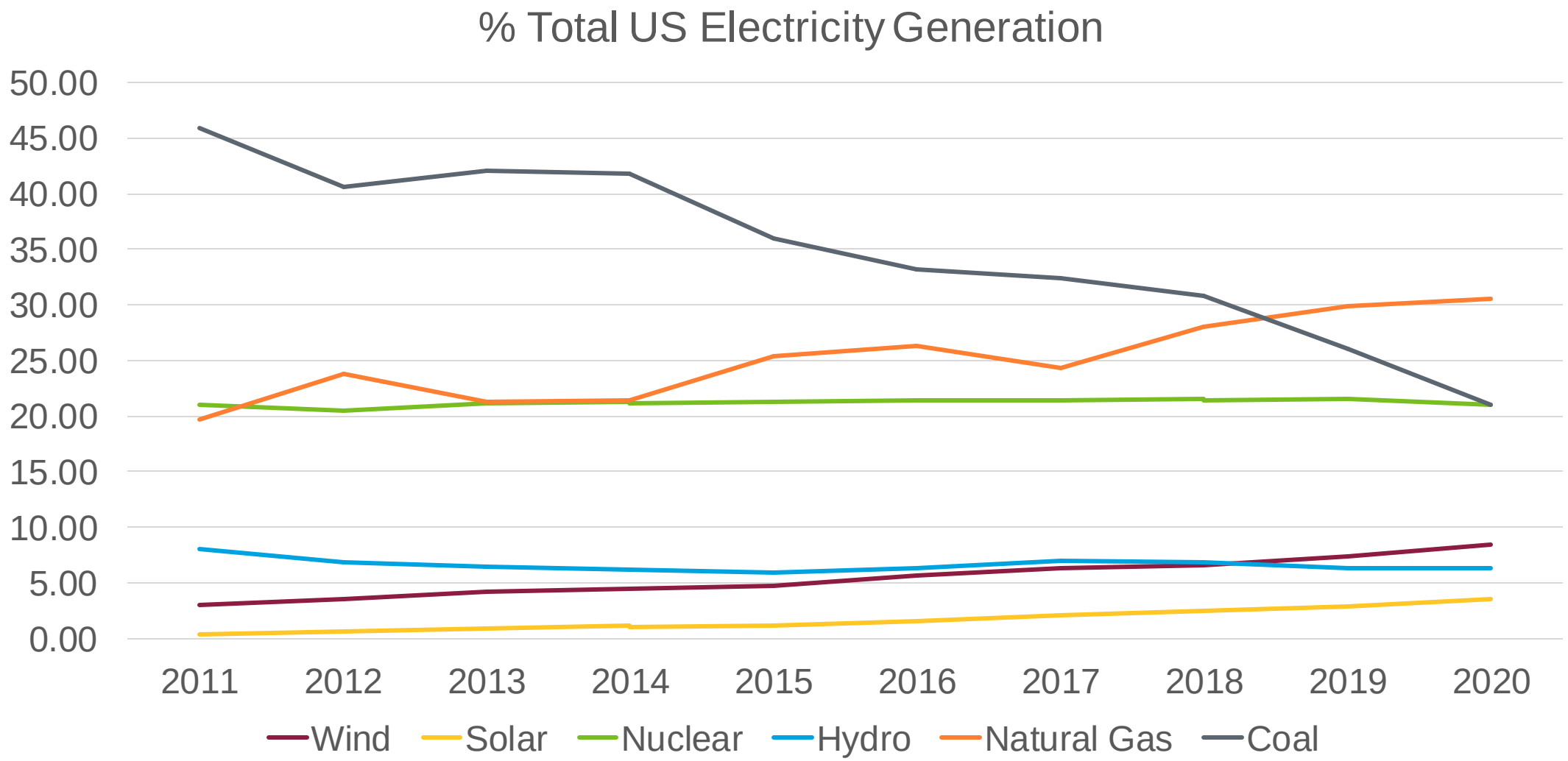
Module 2

Solar, Wind, and Power Electronics

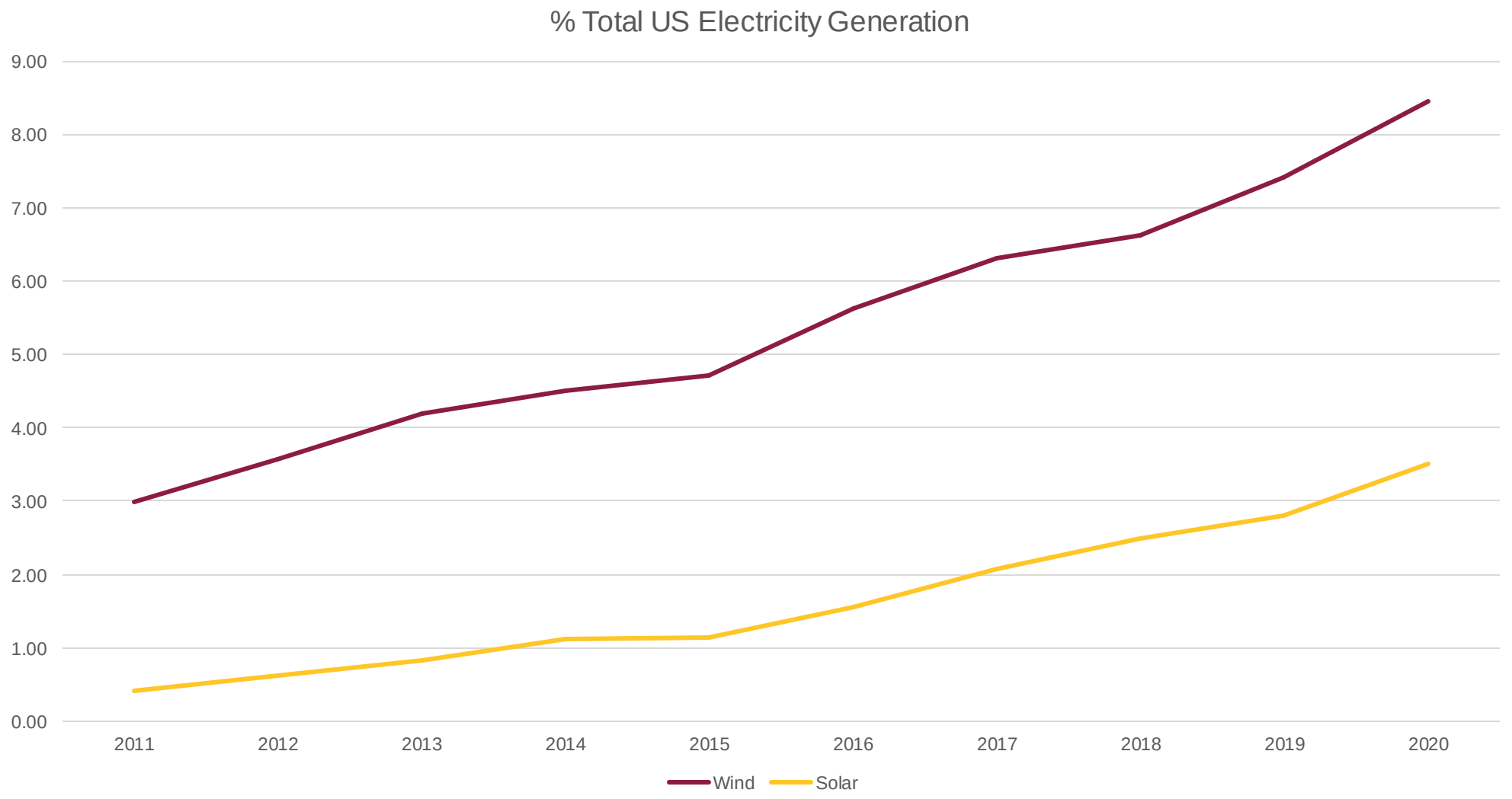
How do we interface renewable resources to the grid?

Arizona State University

Evolution of Electricity Generation



Solar and Wind are Making Huge Gains



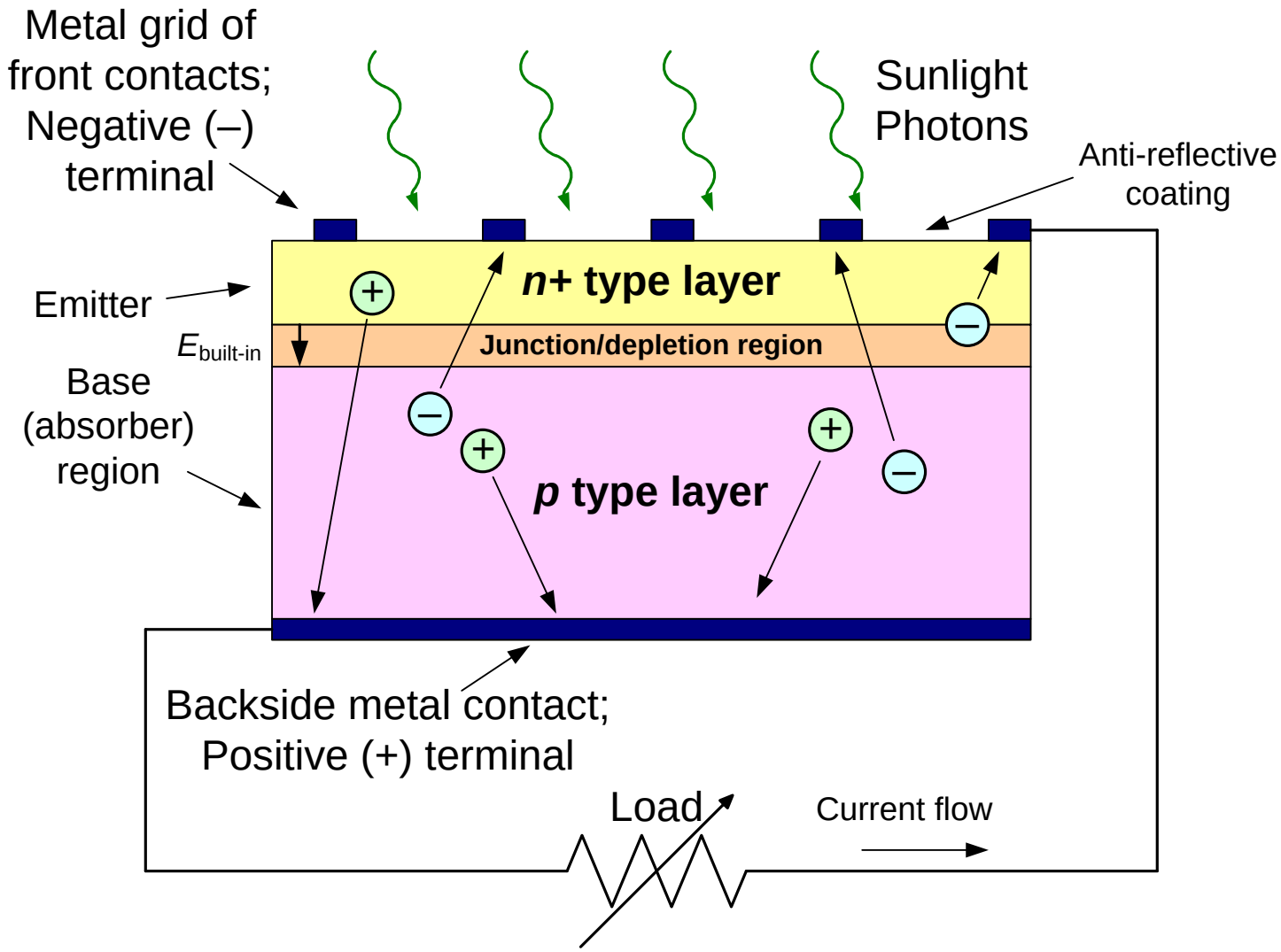
Module 2a

Solar Energy

How does it work and how do we connect it to the power system?

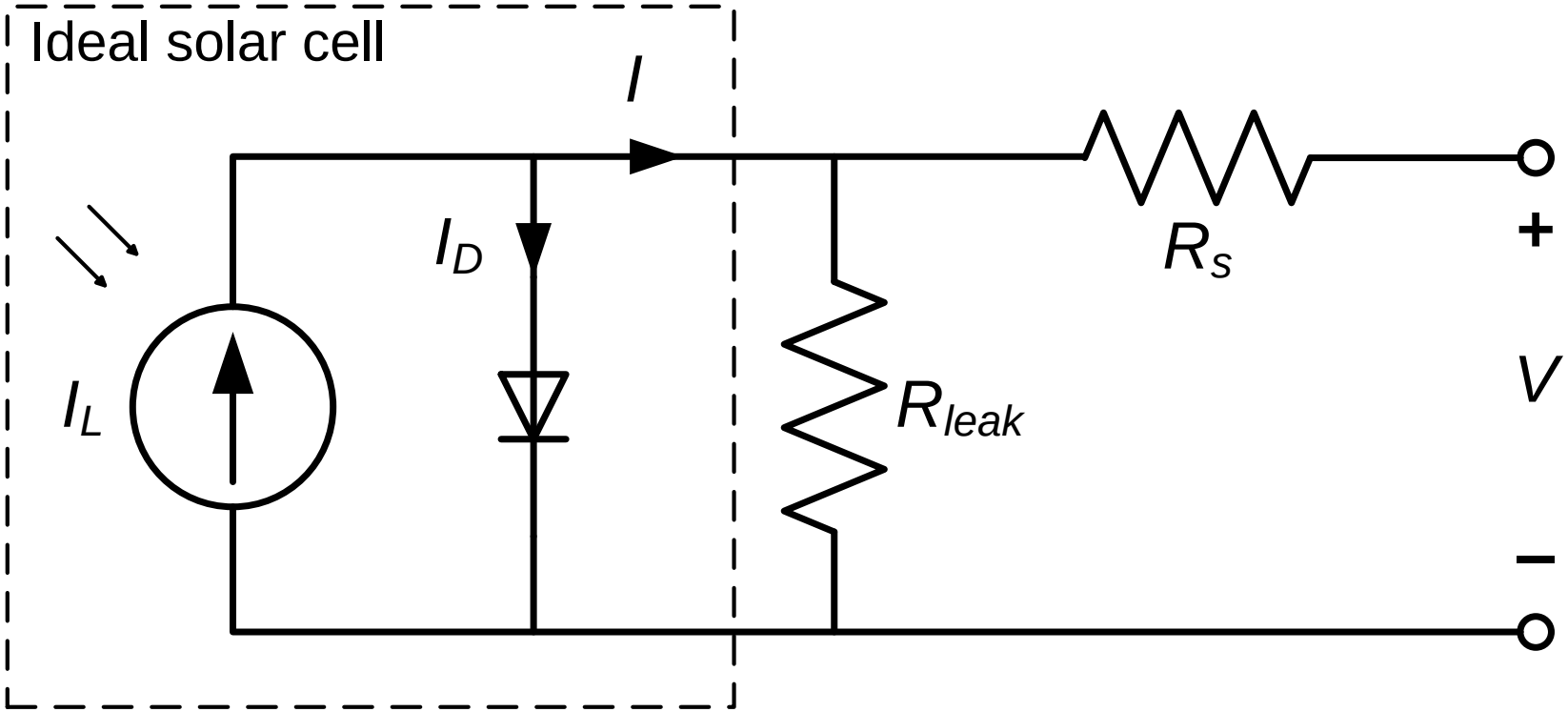
Arizona State University

Solar PV Employs the Photoelectric Effect



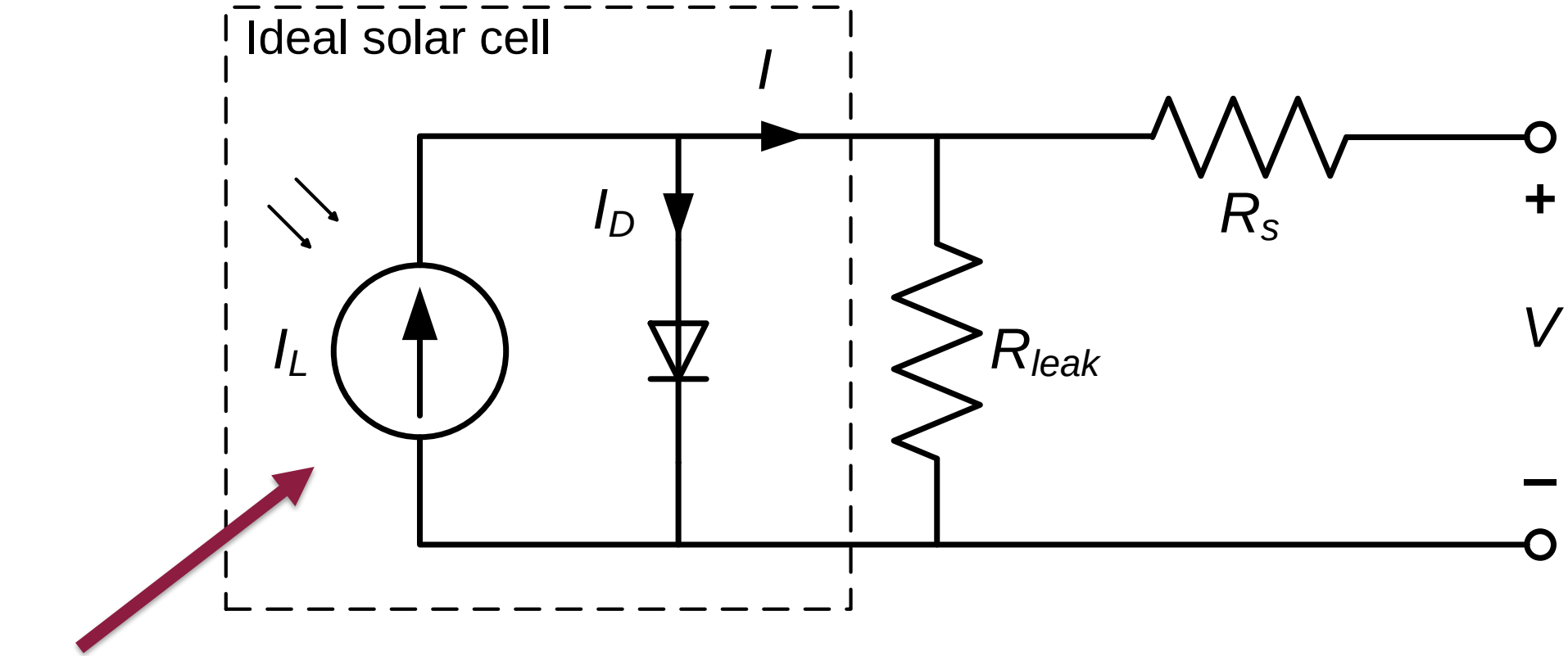
Karady and Holbert, “Electrical Energy Conversion and Transport”, 2nd Ed., Hoboken, NJ, 2005

Solar Cell Model



Karady and Holbert, “Electrical Energy Conversion and Transport”, 2nd Ed., Hoboken, NJ, 2005. Fig. 2.37

Solar Cell Model



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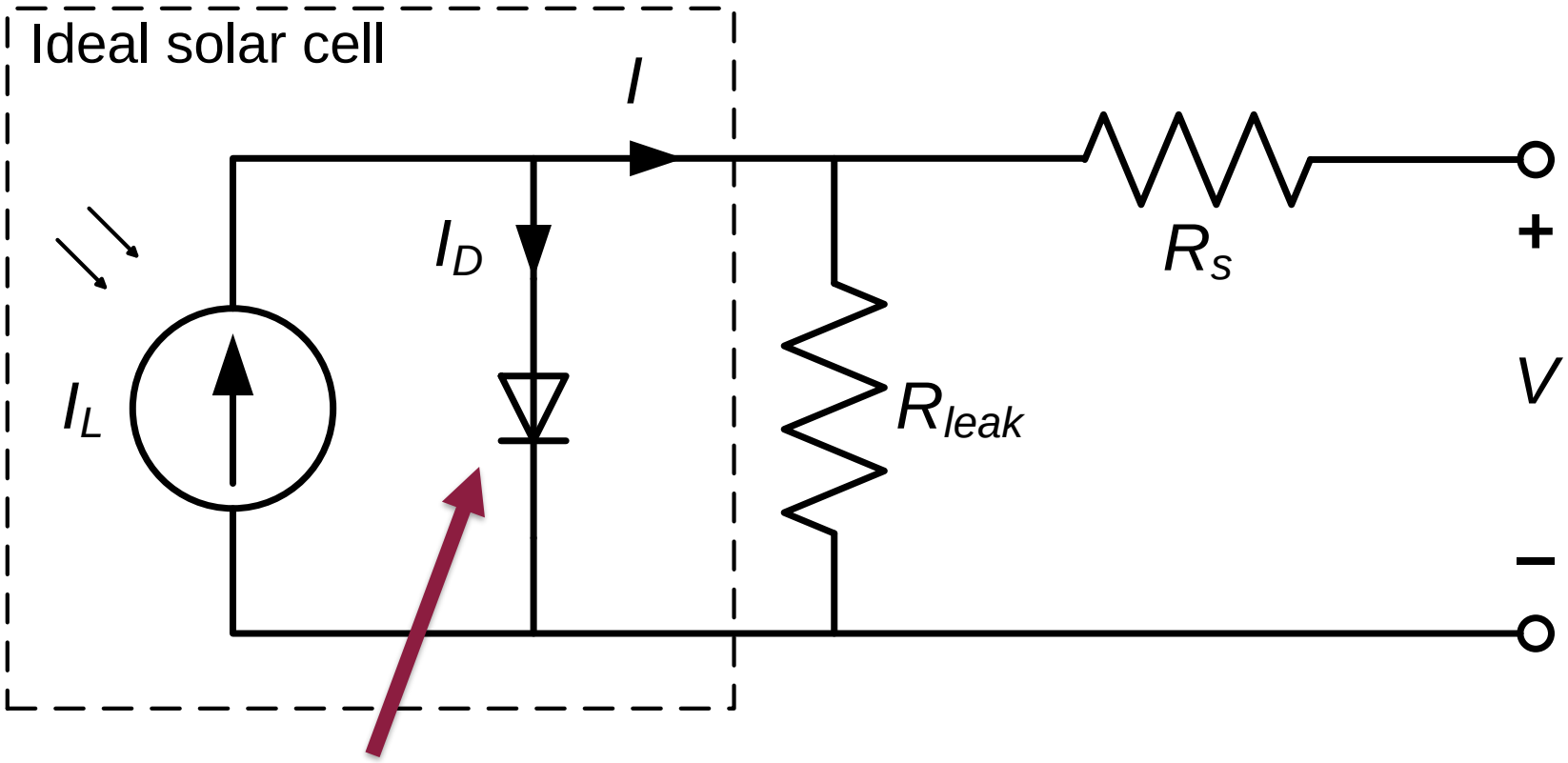
Solar Cell Model



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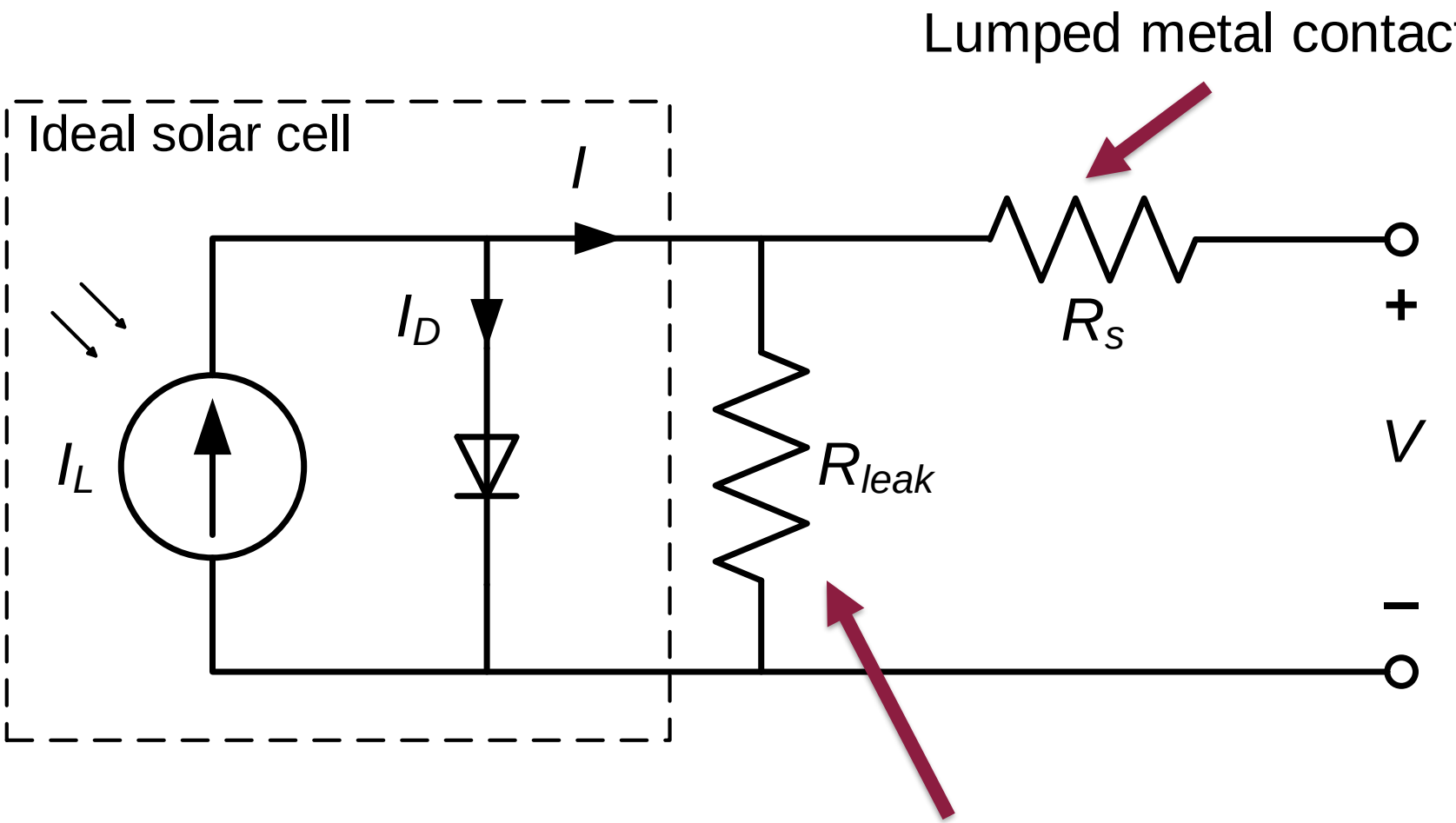
Solar Cell Model



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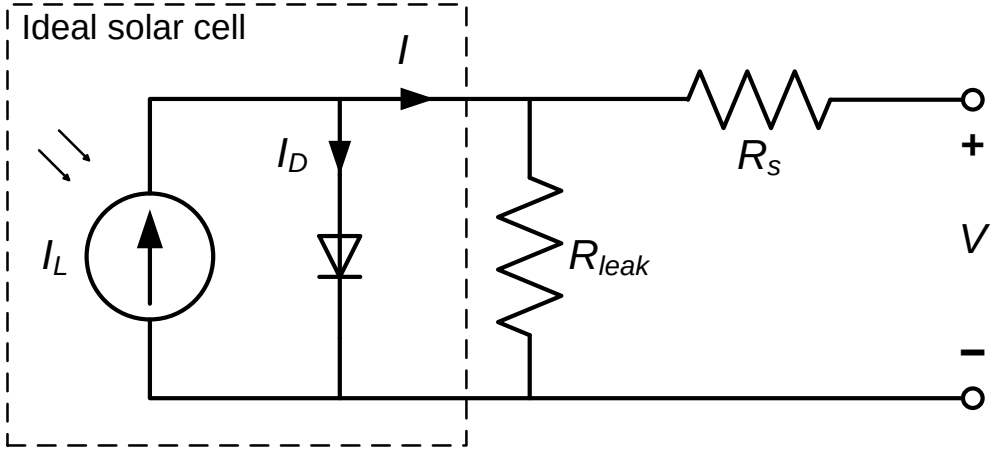
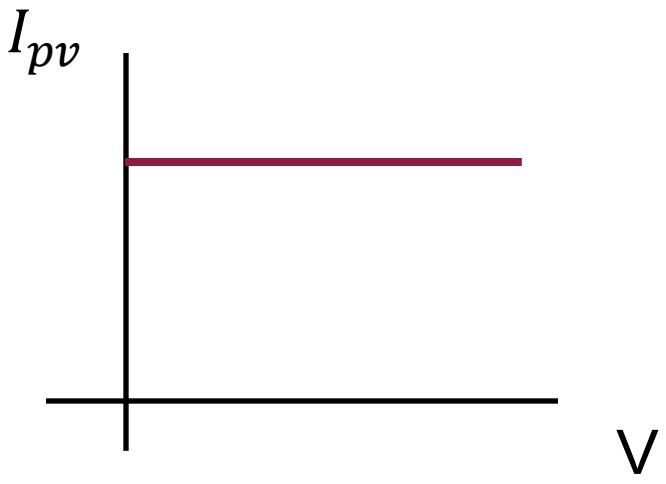
Solar Cell I-V Characteristic





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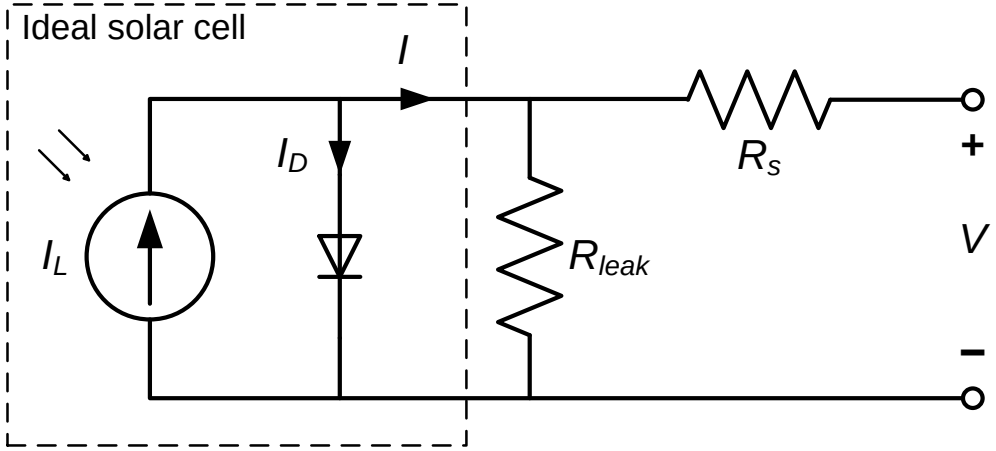
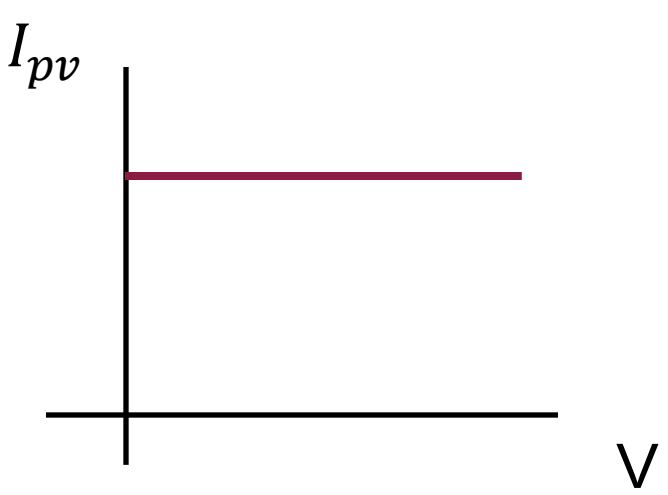
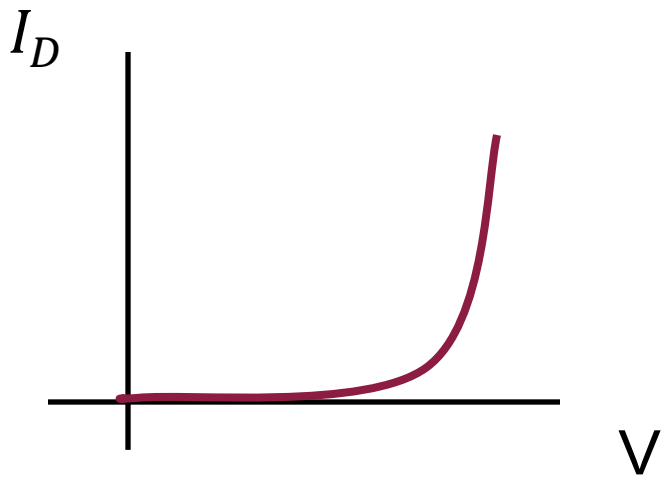
Solar Cell I-V Characteristic







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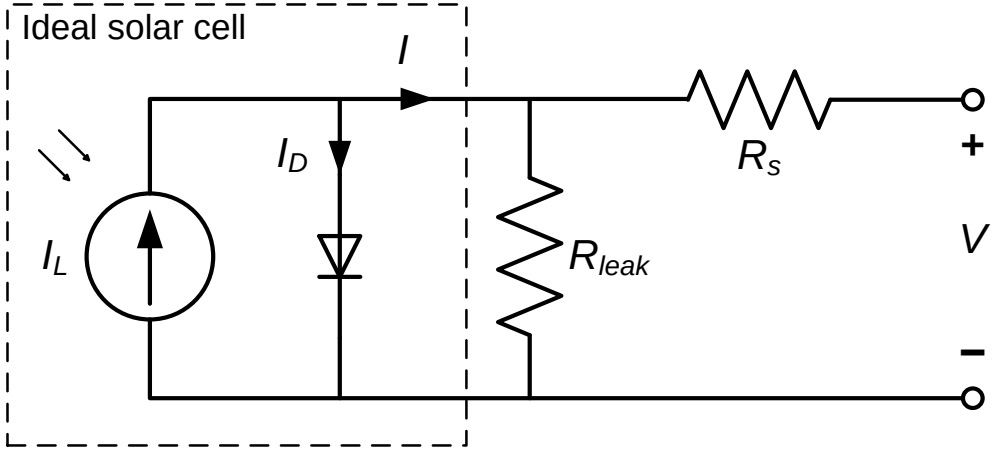
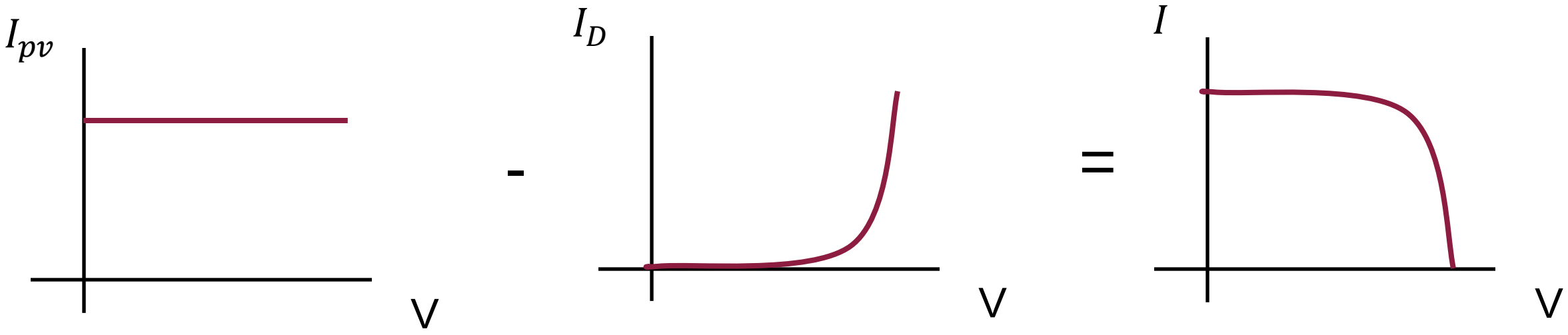
Solar Cell I-V Characteristic





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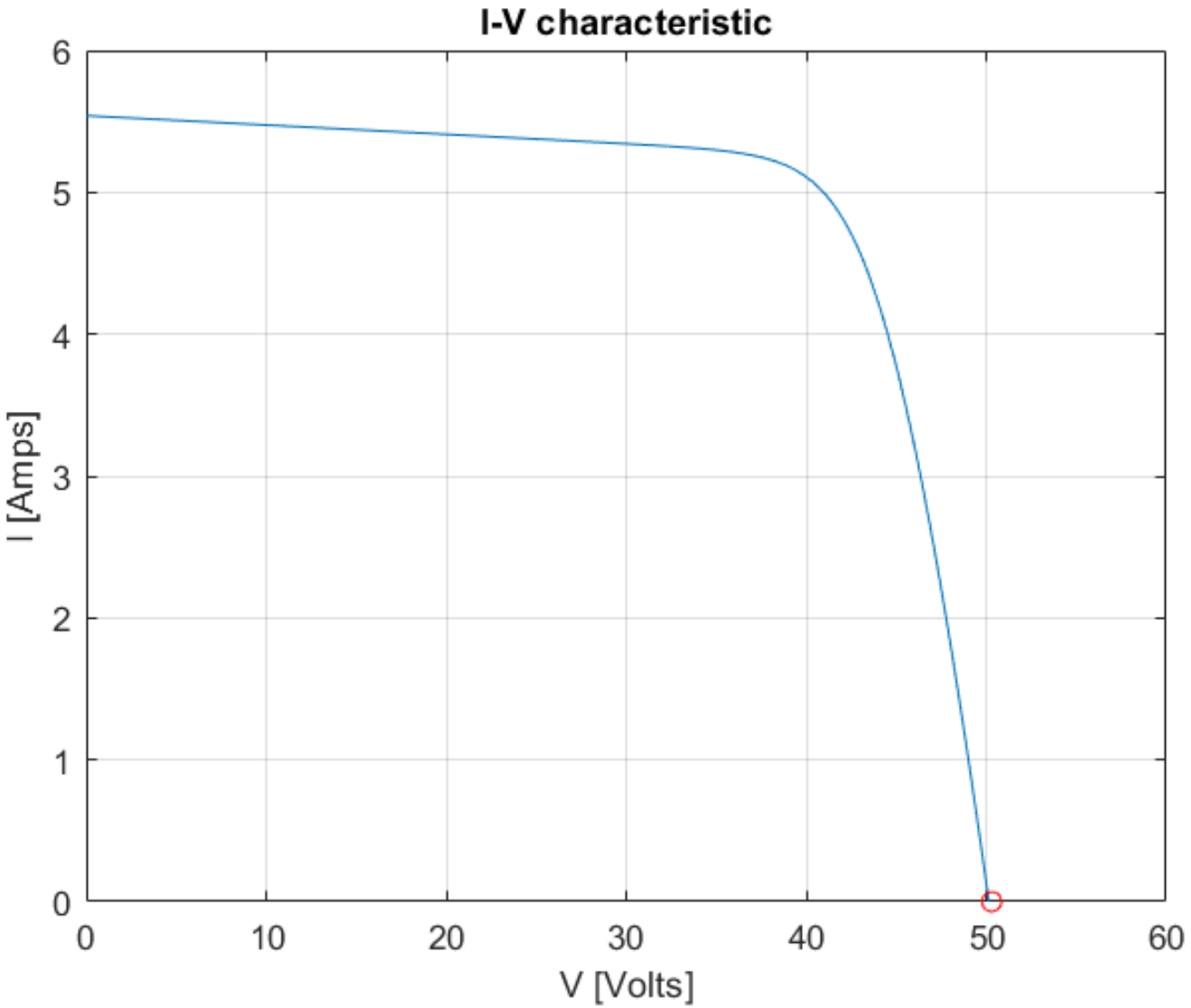
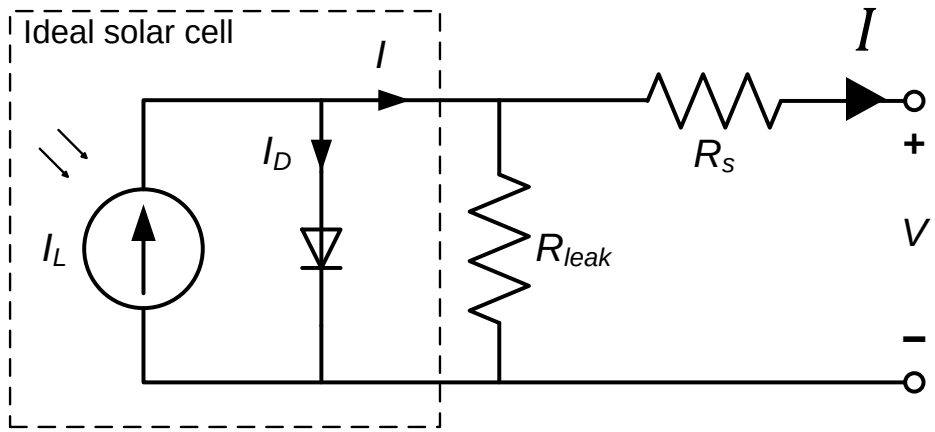
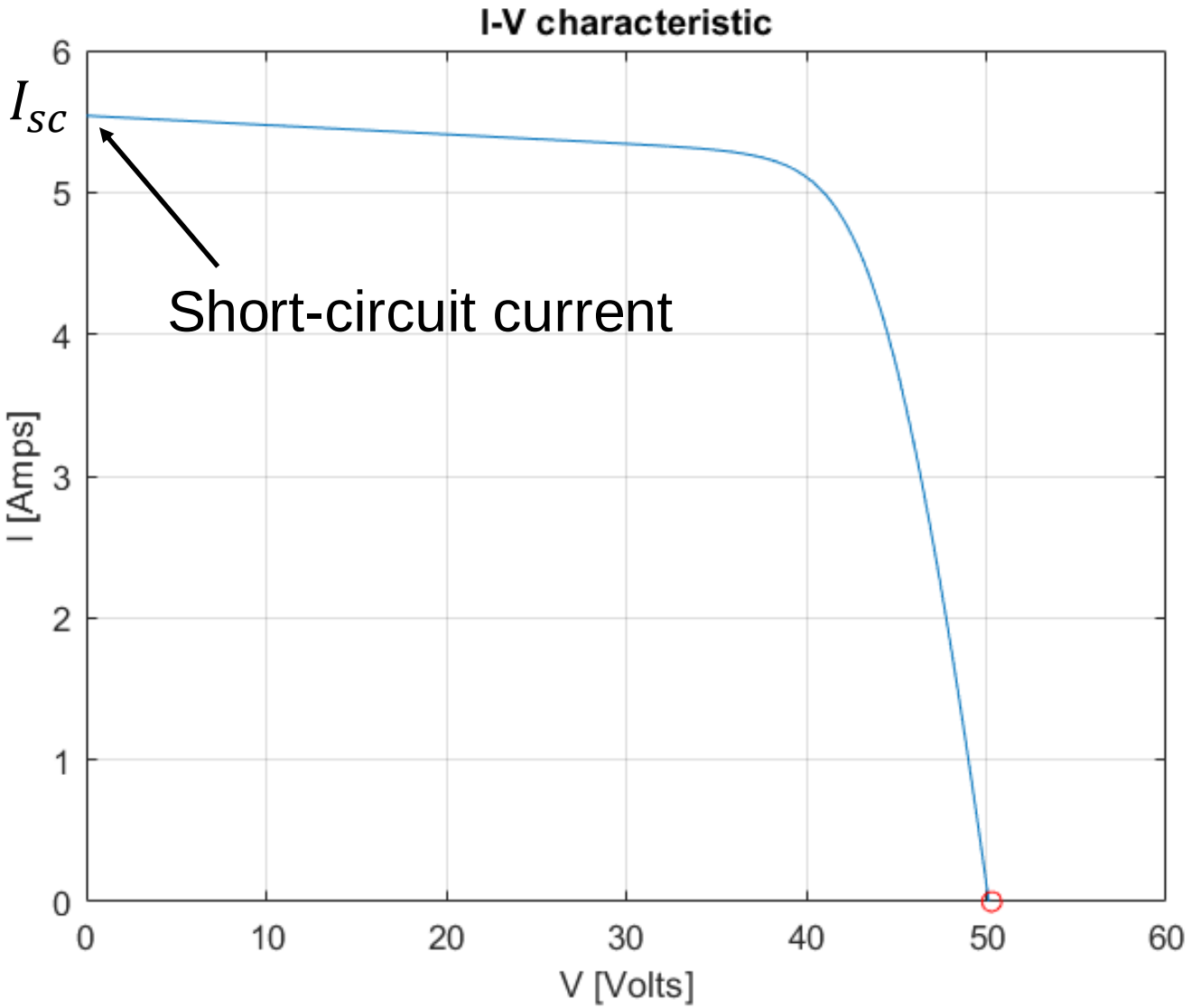
Key IV Curve Parameters

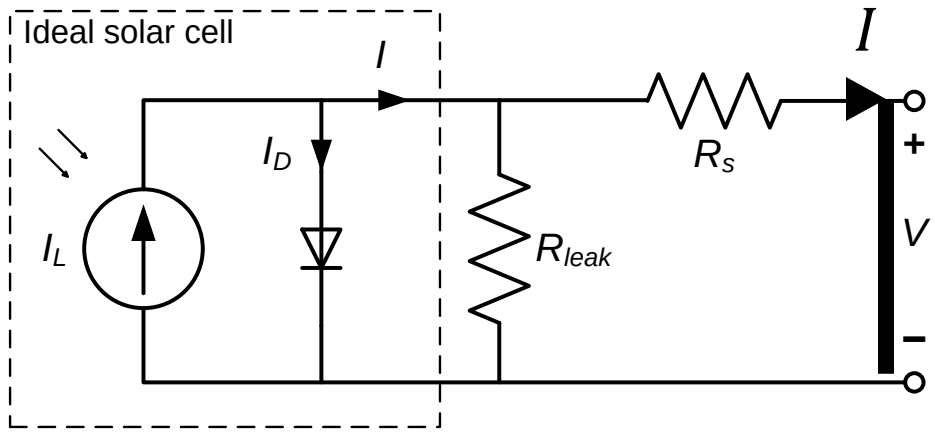




$$I = I_{pv} - I_0 \left[\exp\left(\frac{V}{V_t a} \right) - 1 \right]$$

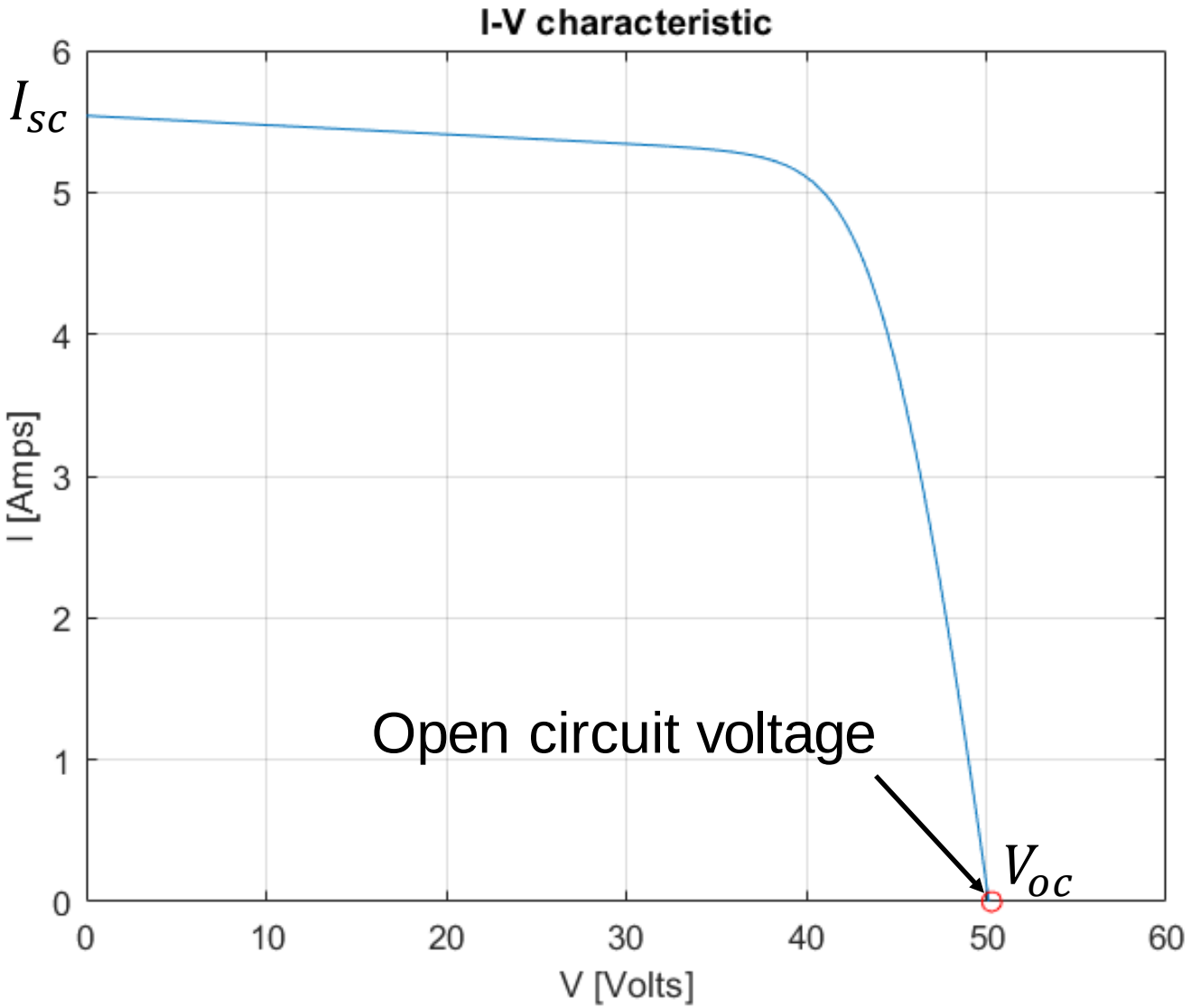
Short-circuit Current

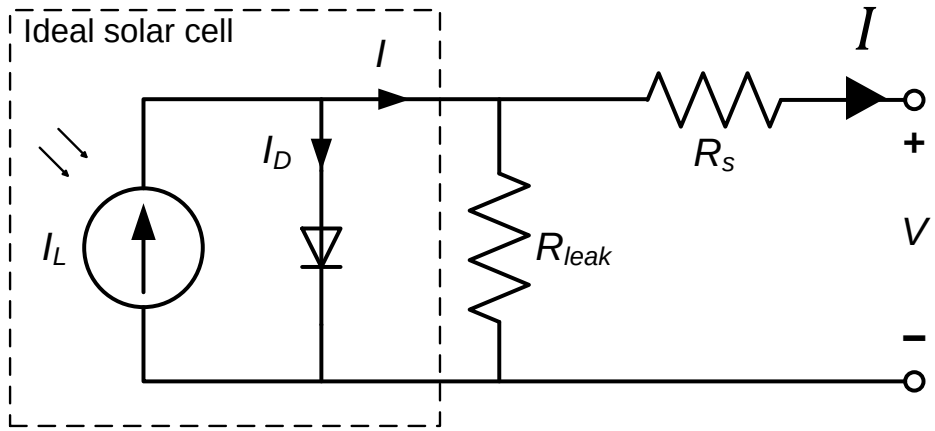




$$I = I_{pv} - I_0 \left[\exp\left(\frac{V}{V_t a} \right) - 1 \right]$$

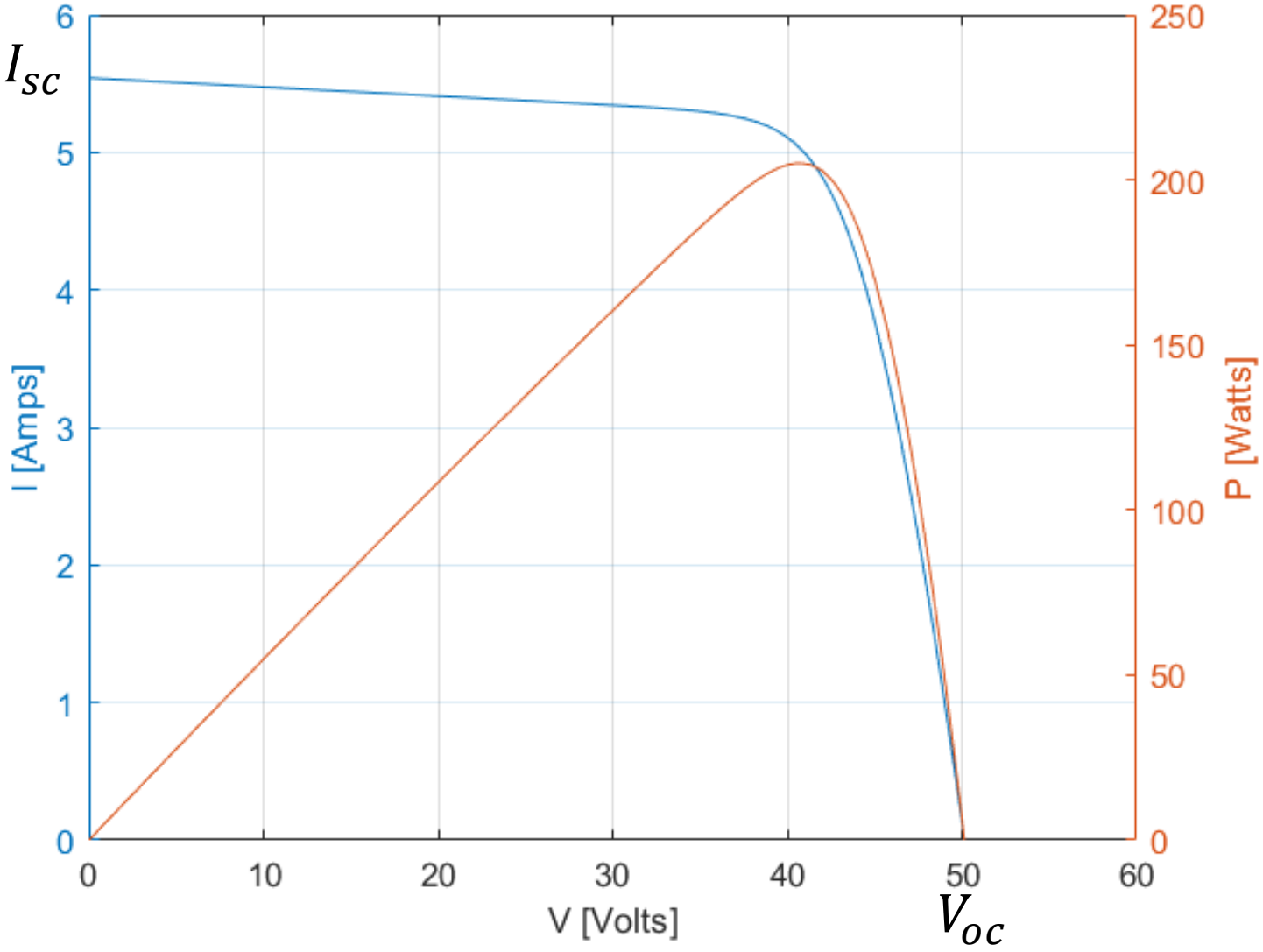
Open Circuit Voltage

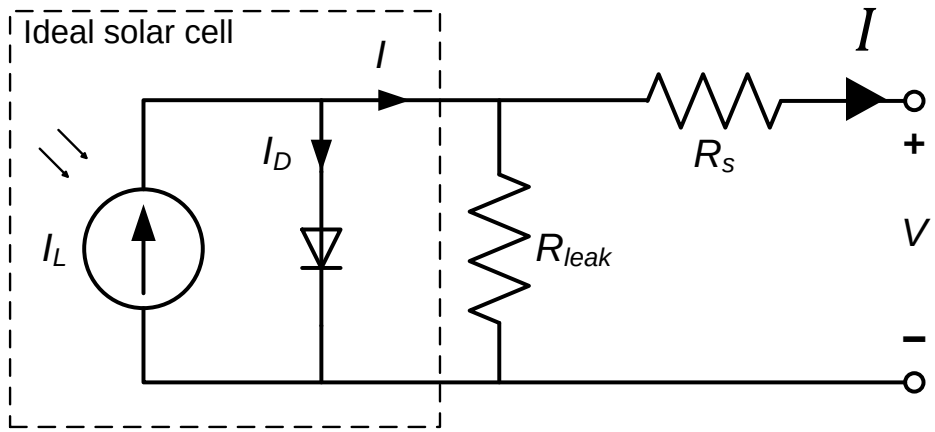




$$I = I_{pv} - I_0 \left[\exp\left(\frac{V}{V_t a} \right) - 1 \right]$$

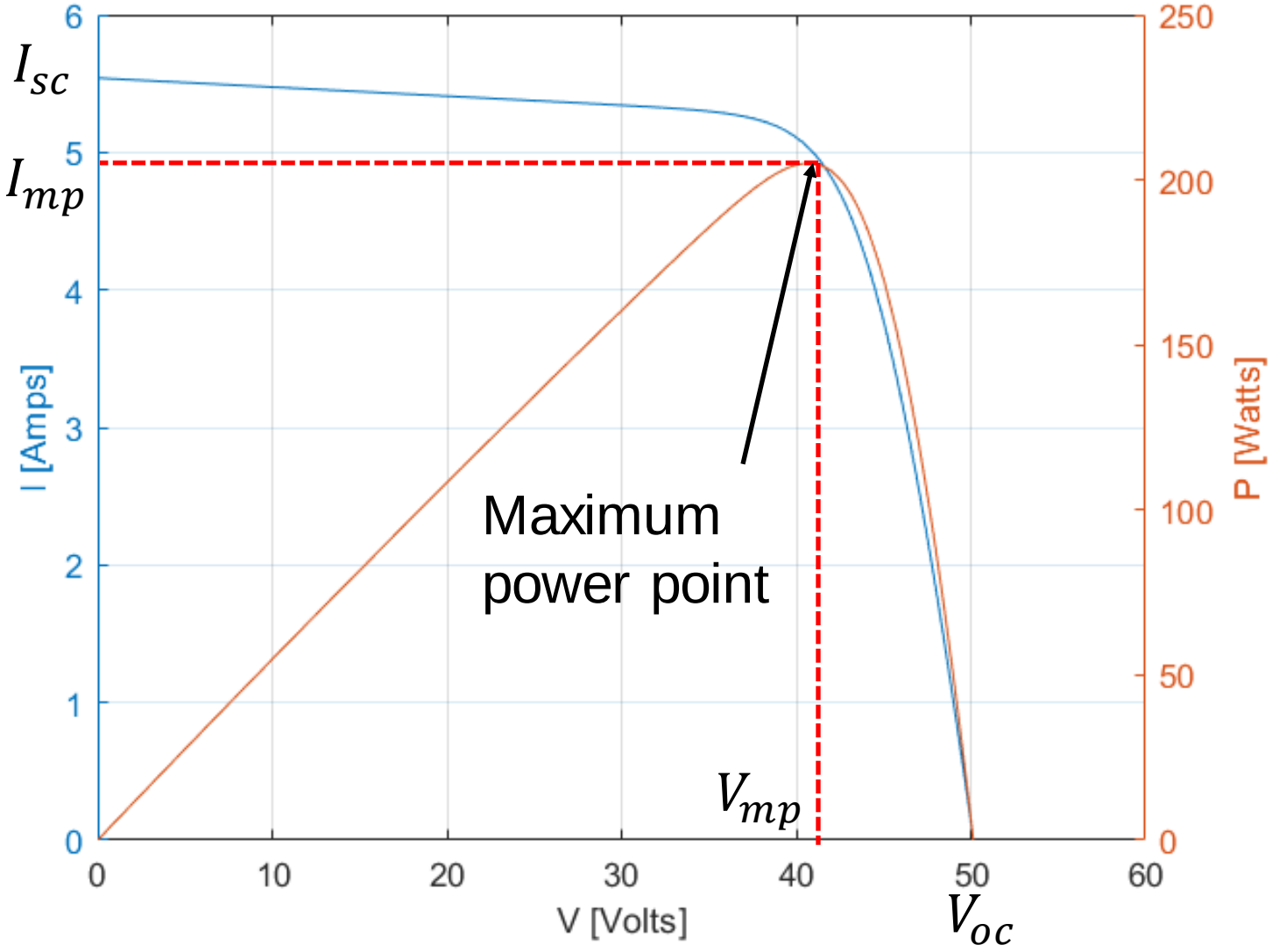
Power Produced by a PV Cell

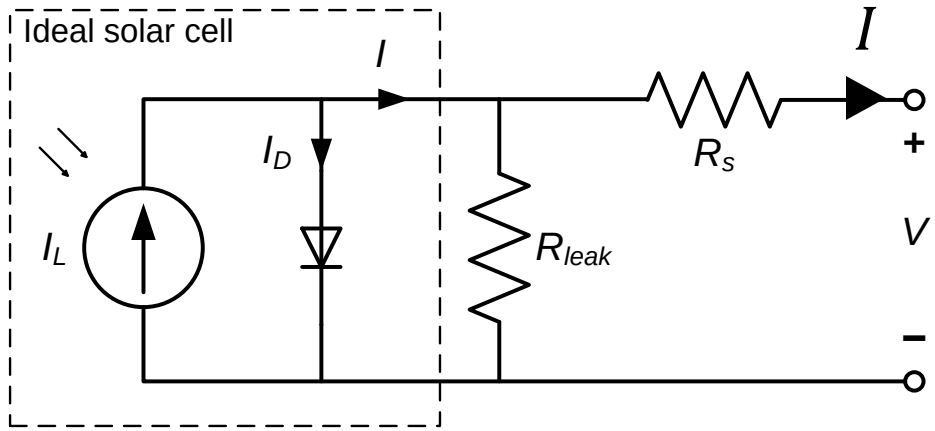




$$I = I_{pv} - I_0 \left[\exp\left(\frac{V}{V_t a} \right) - 1 \right]$$

Maximum Power Point





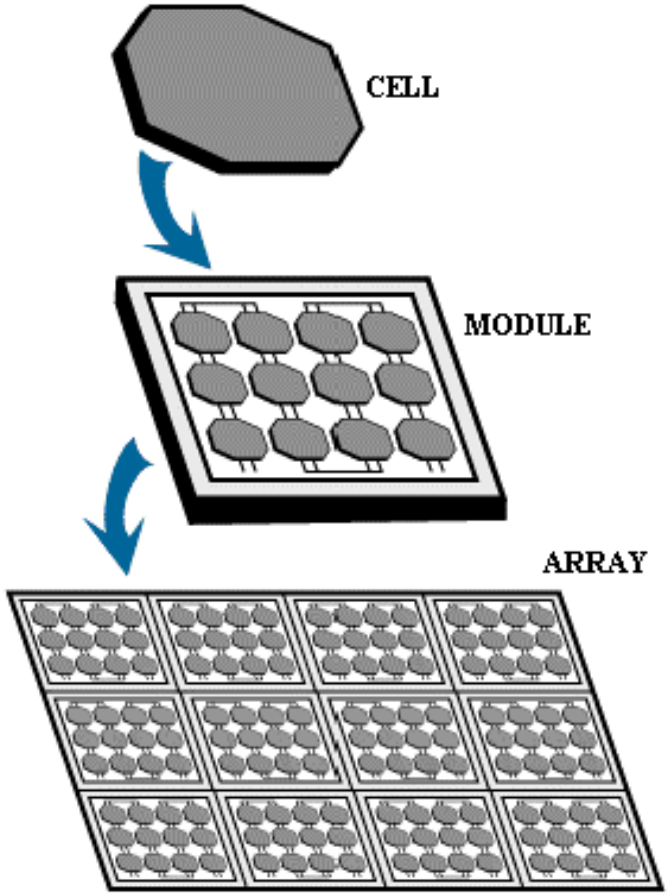
$$I = I_{pv} - I_0 \left[\exp\left(\frac{V}{V_t a}\right) - 1 \right]$$

Typical Silicon PV Cell Characteristics

- Open circuit voltage V_{oc}: 0.55 – 0.76V (@ $25^{\circ}C$)
- Max power voltage V_{MP}: 0.45-0.58V
- Short-circuit current I_{sc}
  - 4x4” : 3 – 3.8 A
  - 5x5” : 4.6 – 6 A
  - 6x6” : 6.8 – 8.5 A
  - 8x8”: 13 – 15 A
- Typical efficiency: ~15-20%
- Maximum theoretical efficiency: ~32%

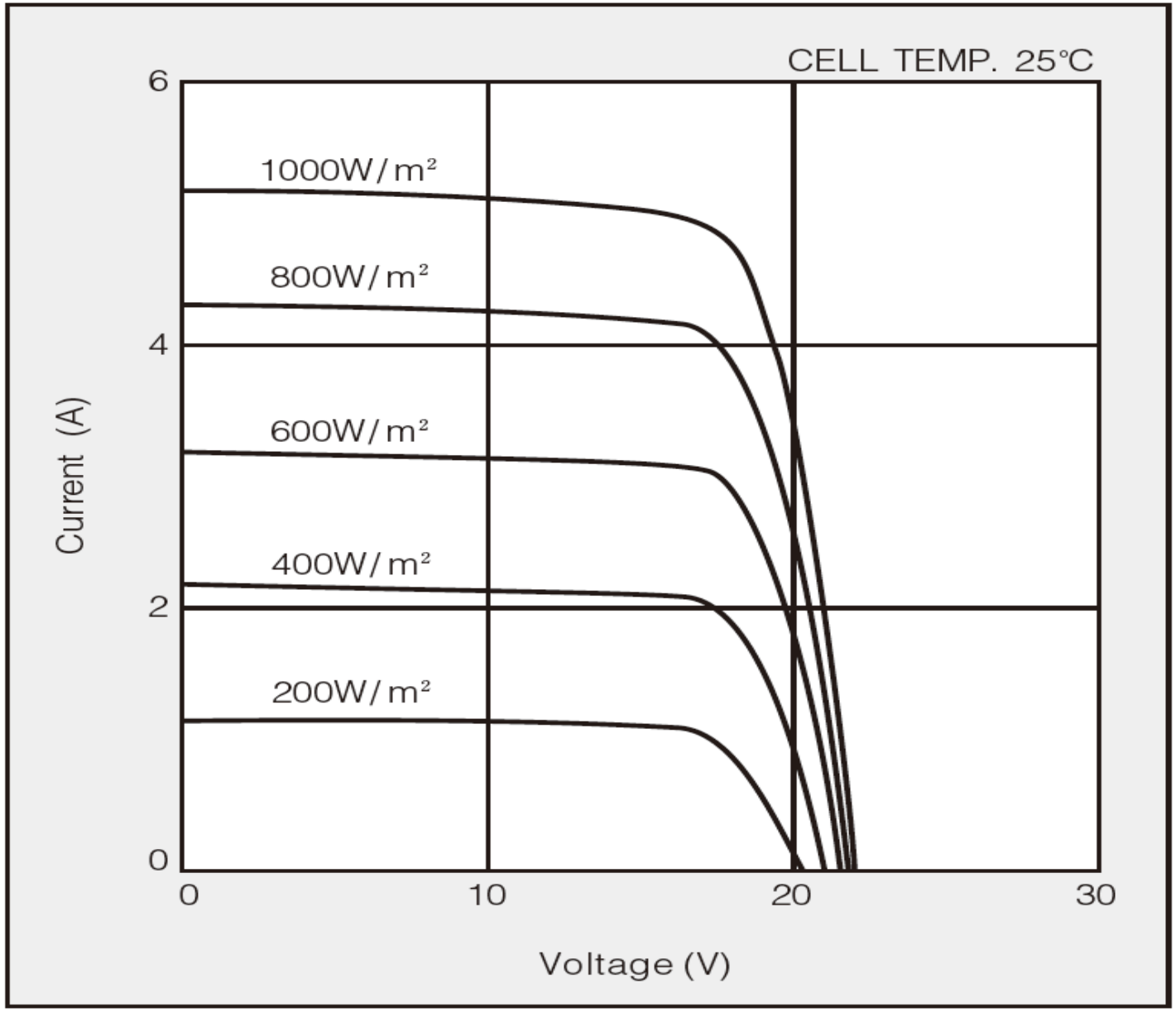
Cells, Modules, Arrays

- Typically connect many cells in series to increase operating voltage



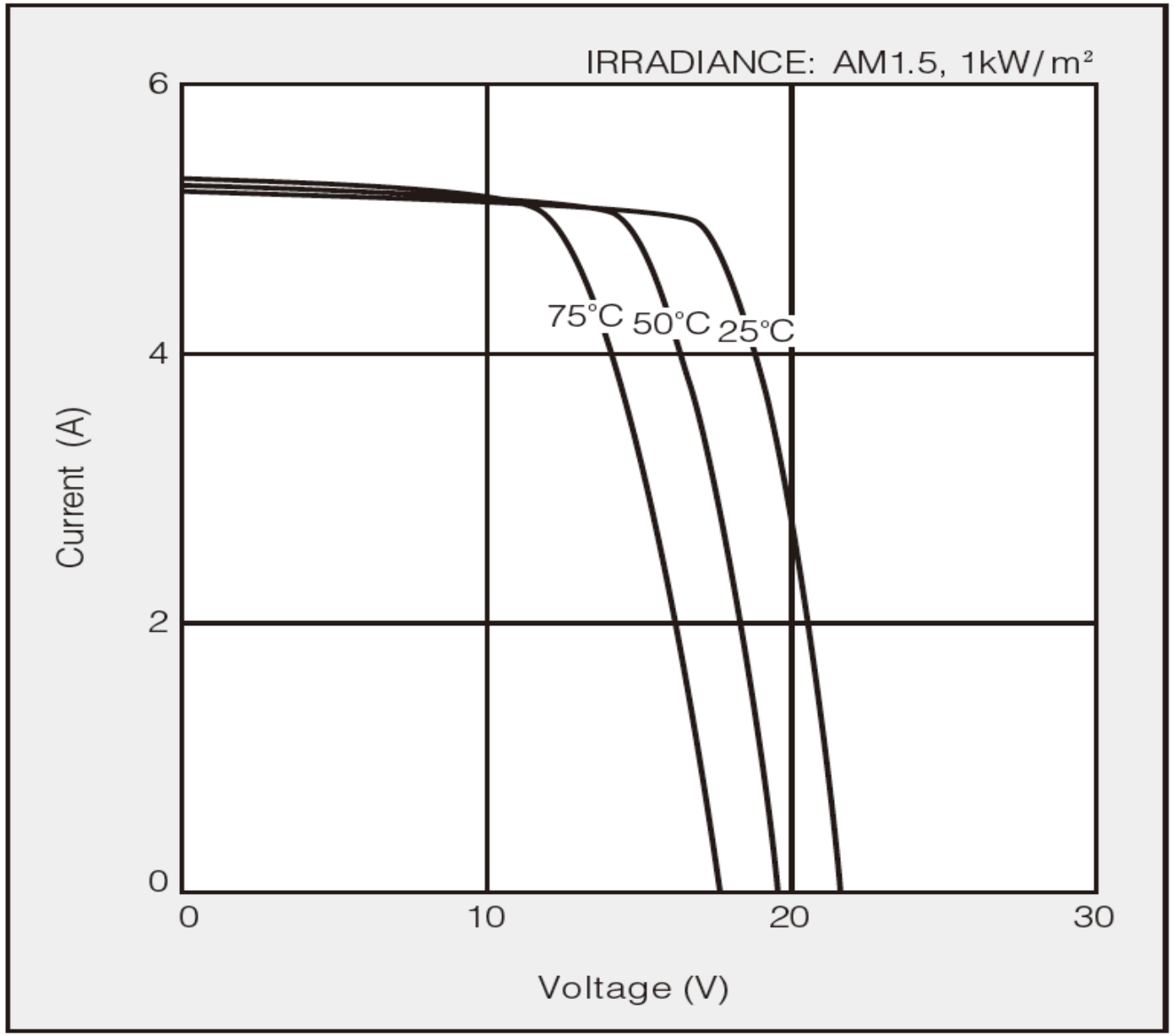
- Then connect modules in parallel/series for desired overall IV characteristic

Solar Panel I-V Characteristic with Irradiance



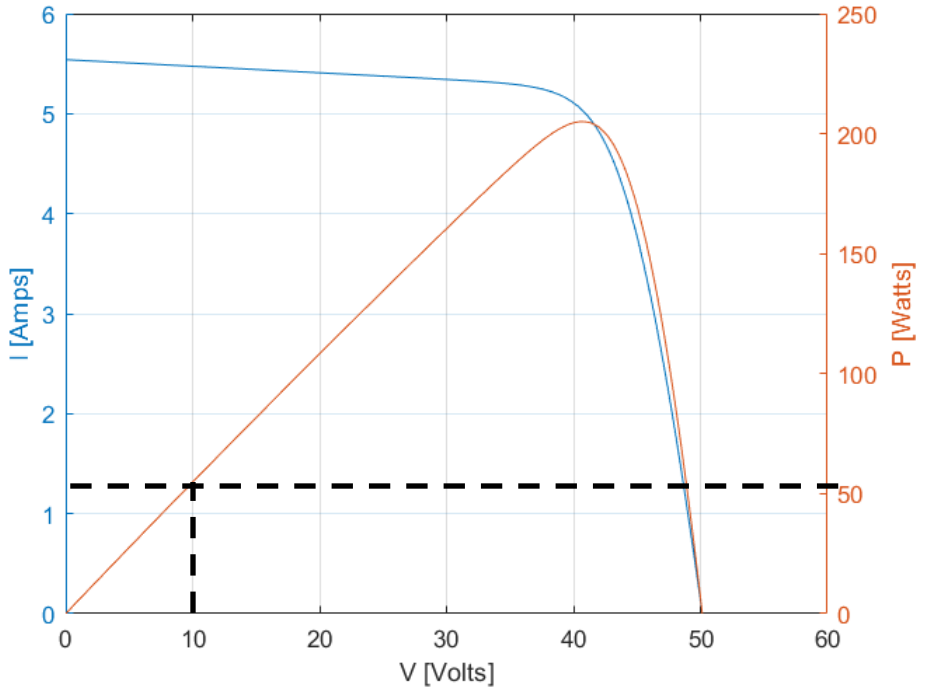
$$I = I_{pv} - I_0 \left[\exp\left(\frac{V}{V_t a}\right) - 1 \right]$$

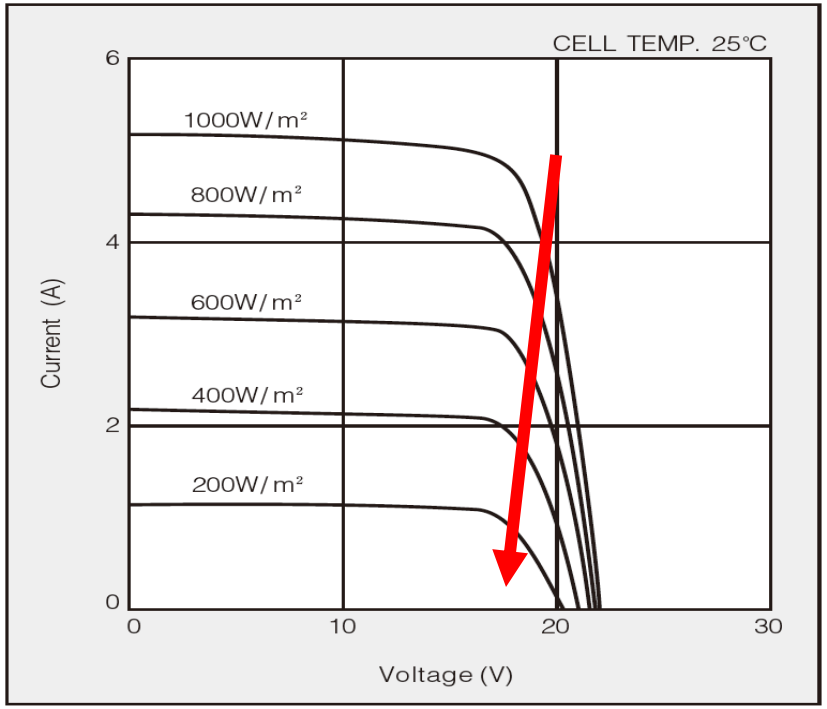
Solar Panel I-V Characteristic w/ Temperature

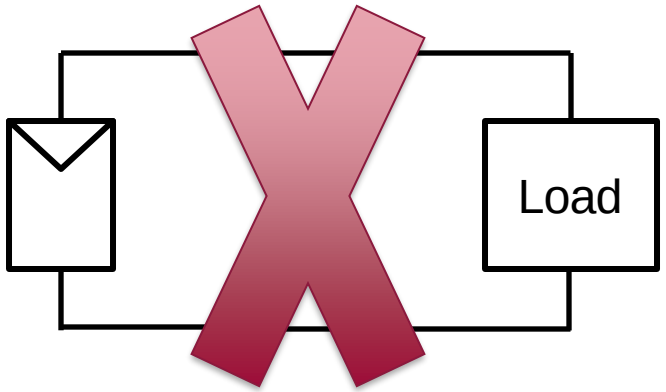


$$I = I_{pv} - I_0 \left[\exp\left(\frac{V}{V_t a}\right) - 1 \right]$$

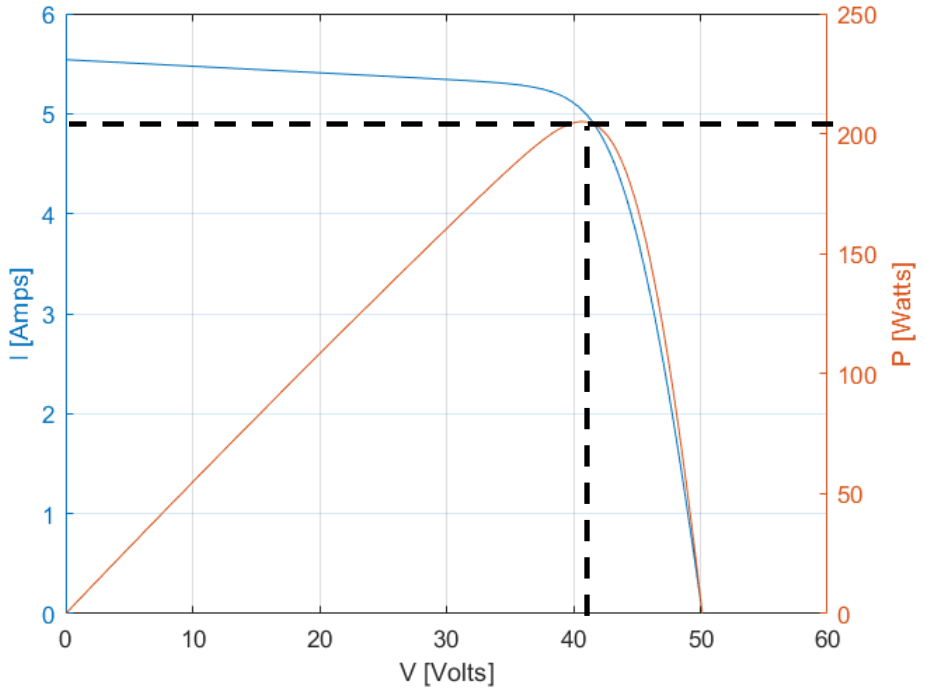
Direct Load Connection is Poor

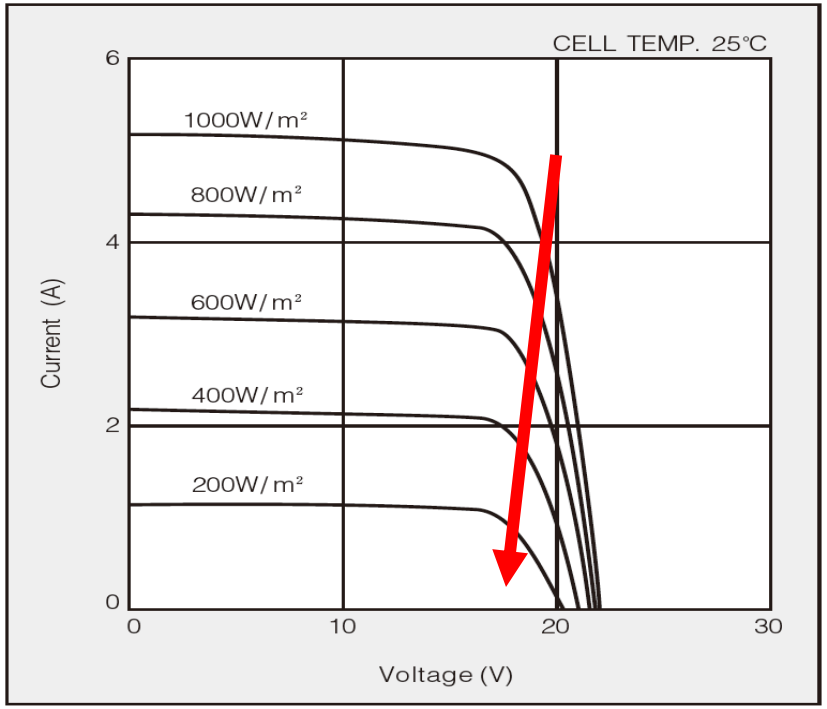


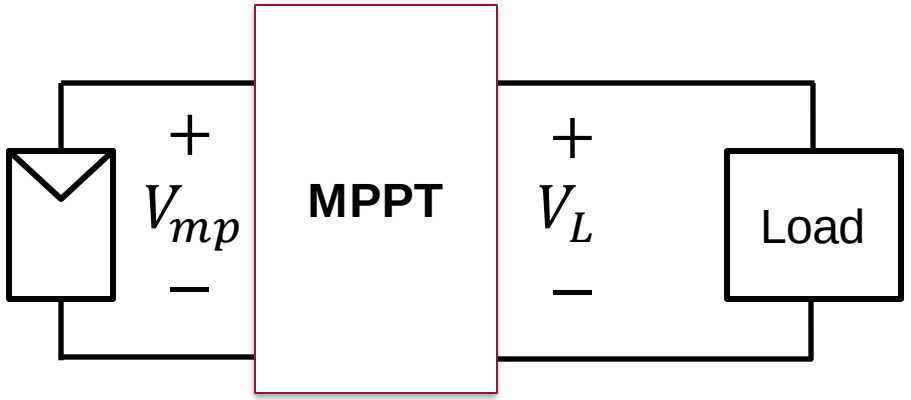




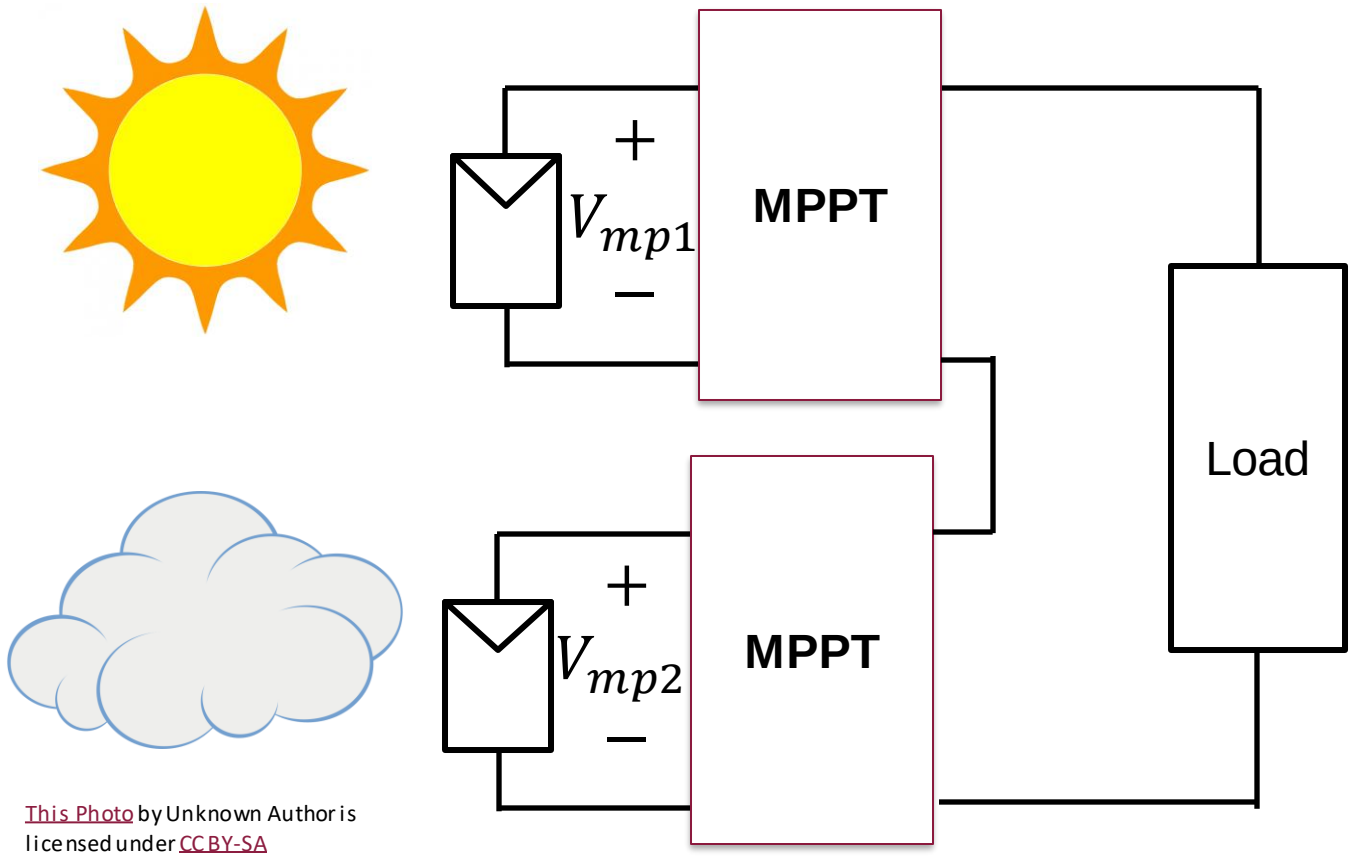
Need a “Smart Block” to Track MPP







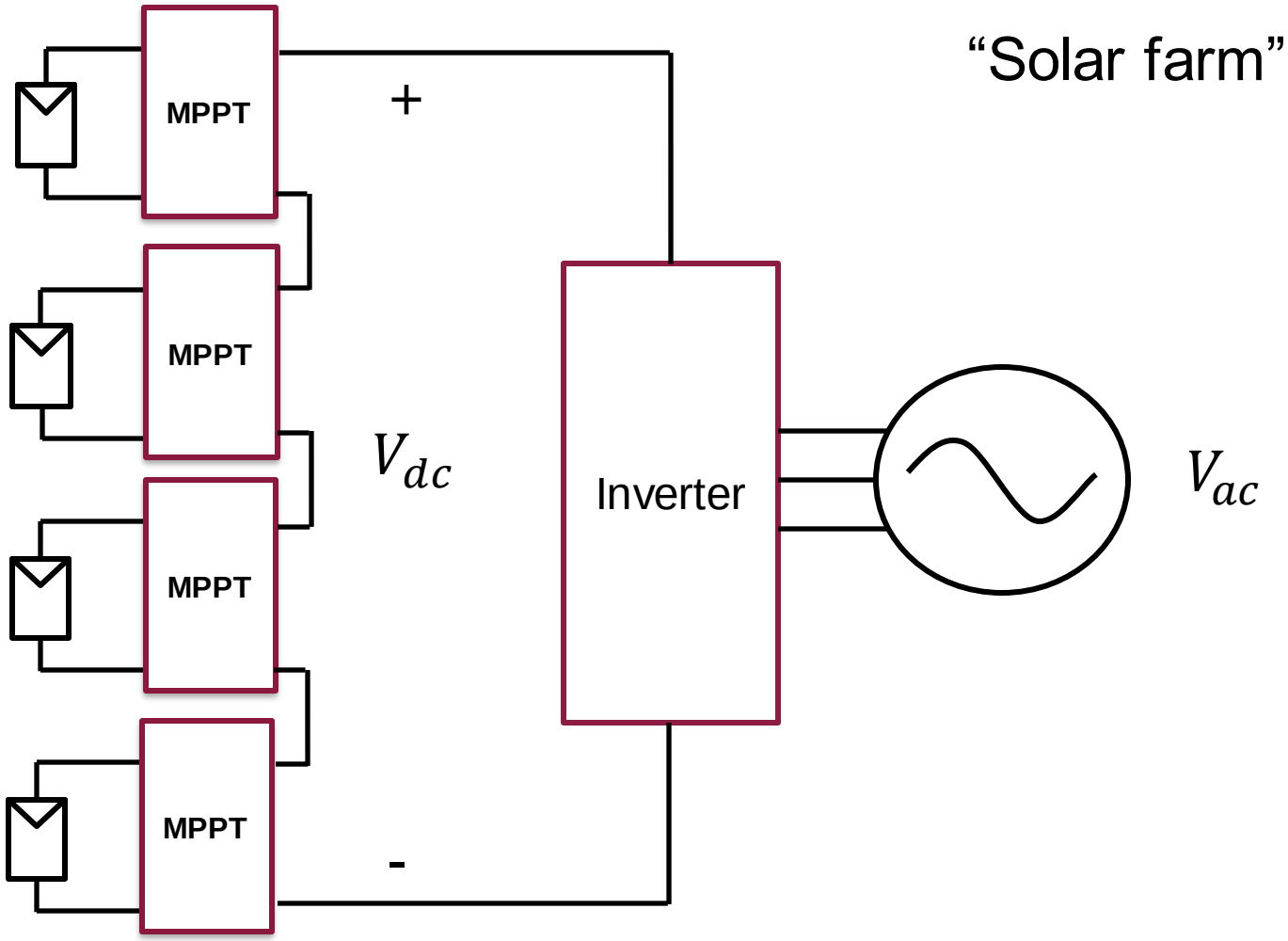
Distributed MPPT Common to Accommodate Different Weather



Inverter Converts dc to ac

These blocks are implemented via power electronics

No rotating masses, no inertia



Conclusions

- Solar PV cells convert sunlight to electrical energy
- Characterized by short-circuit current, open-circuit voltage, and maximum power point
- Highly variable output, MPPT must be employed
- Output is dc, must be converted to ac for grid connection
- No rotating masses, so no contribution to system inertia

Module 2b

Wind Energy

How does it work and how do we connect it to the power system?

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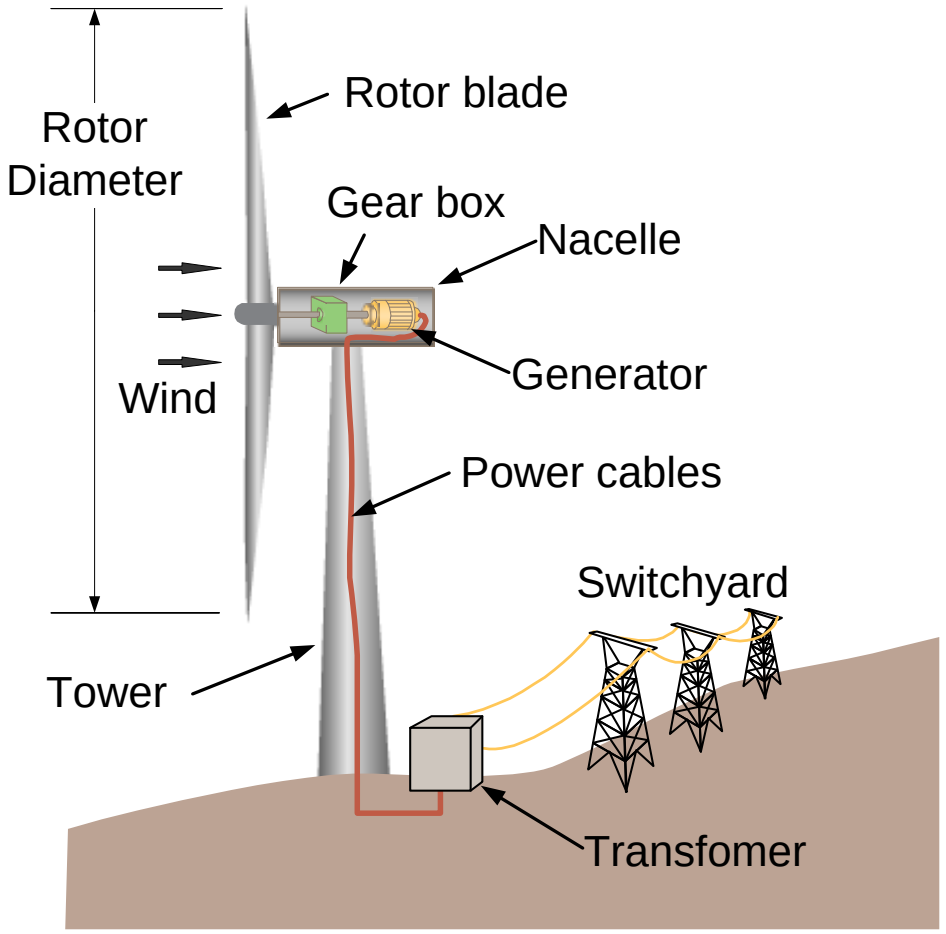
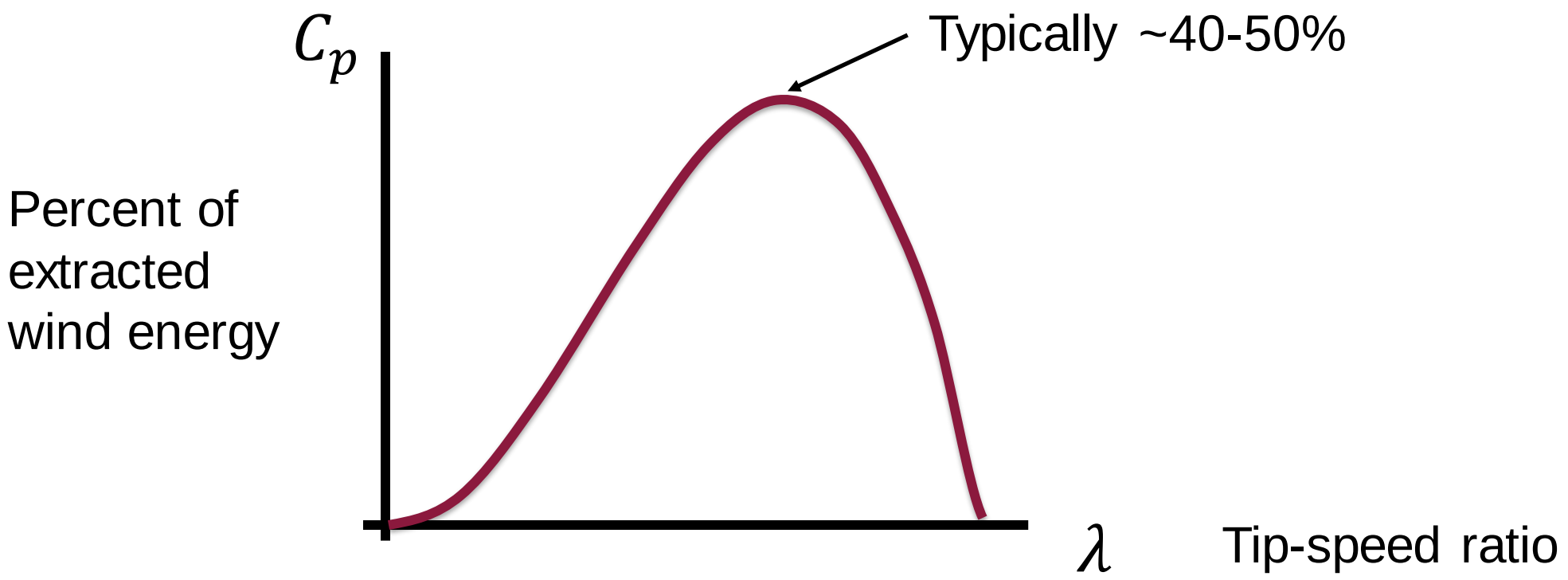
Extract Kinetic Energy of Wind

- Instead of hot high pressure gas in turbine, free flowing wind lifts blades, spins shaft
- ac machine converts motion to electricity



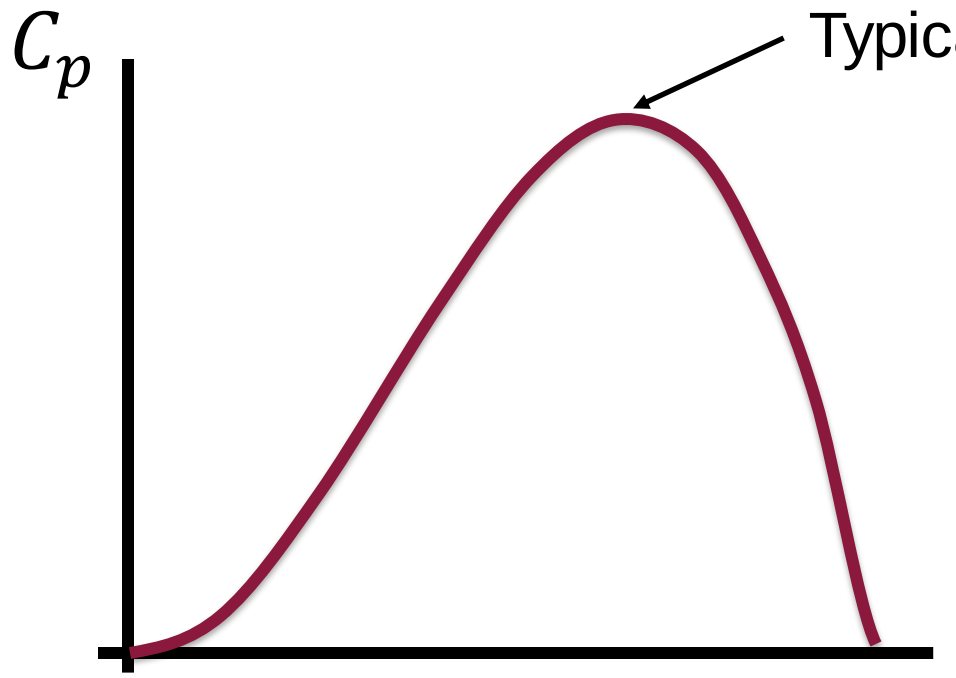
Karady and Holbert, “Electrical Energy Conversion and Transport”, 2nd Ed., Hoboken, NJ, 2005

Turbine Performance Coefficient



Jaffe and Taylor, *The Physics of Energy*, 1st ed.

Turbine Performance Coefficient



Percent of extracted wind energy

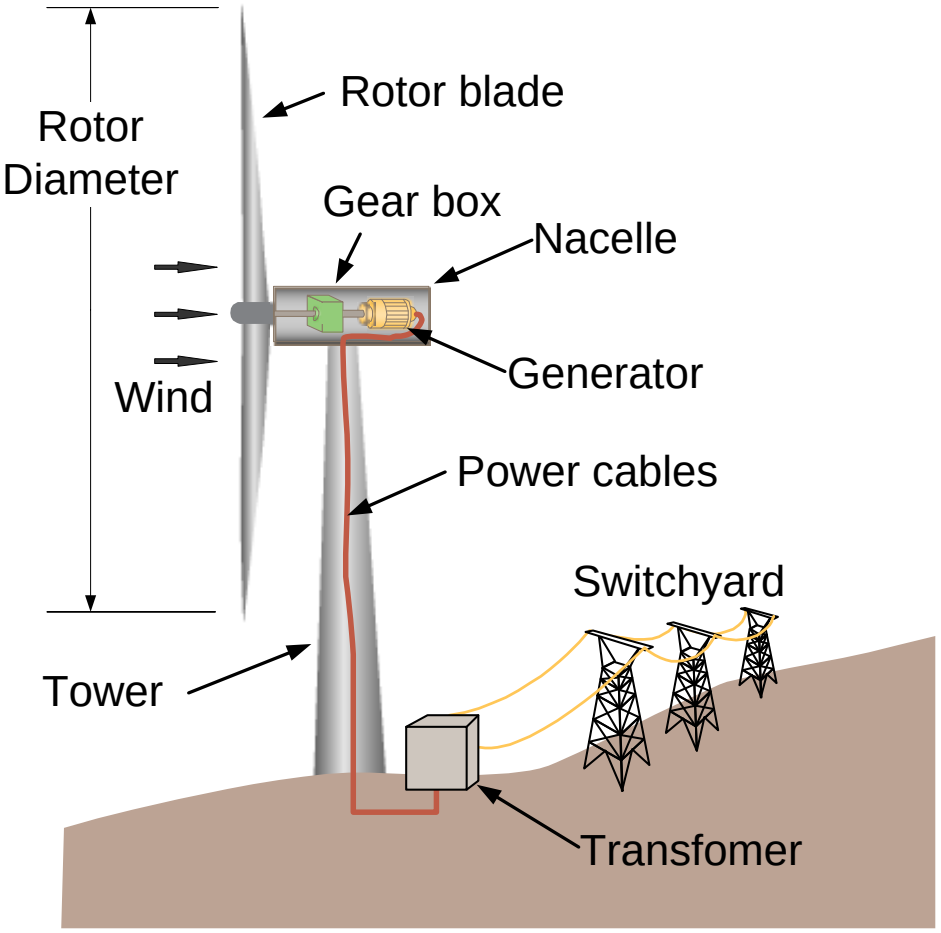
Tip-speed ratio $\lambda = \frac{\Omega R}{v}$

- Ω: Blade angular velocity
- R: Blade radius
- v: Incoming wind speed

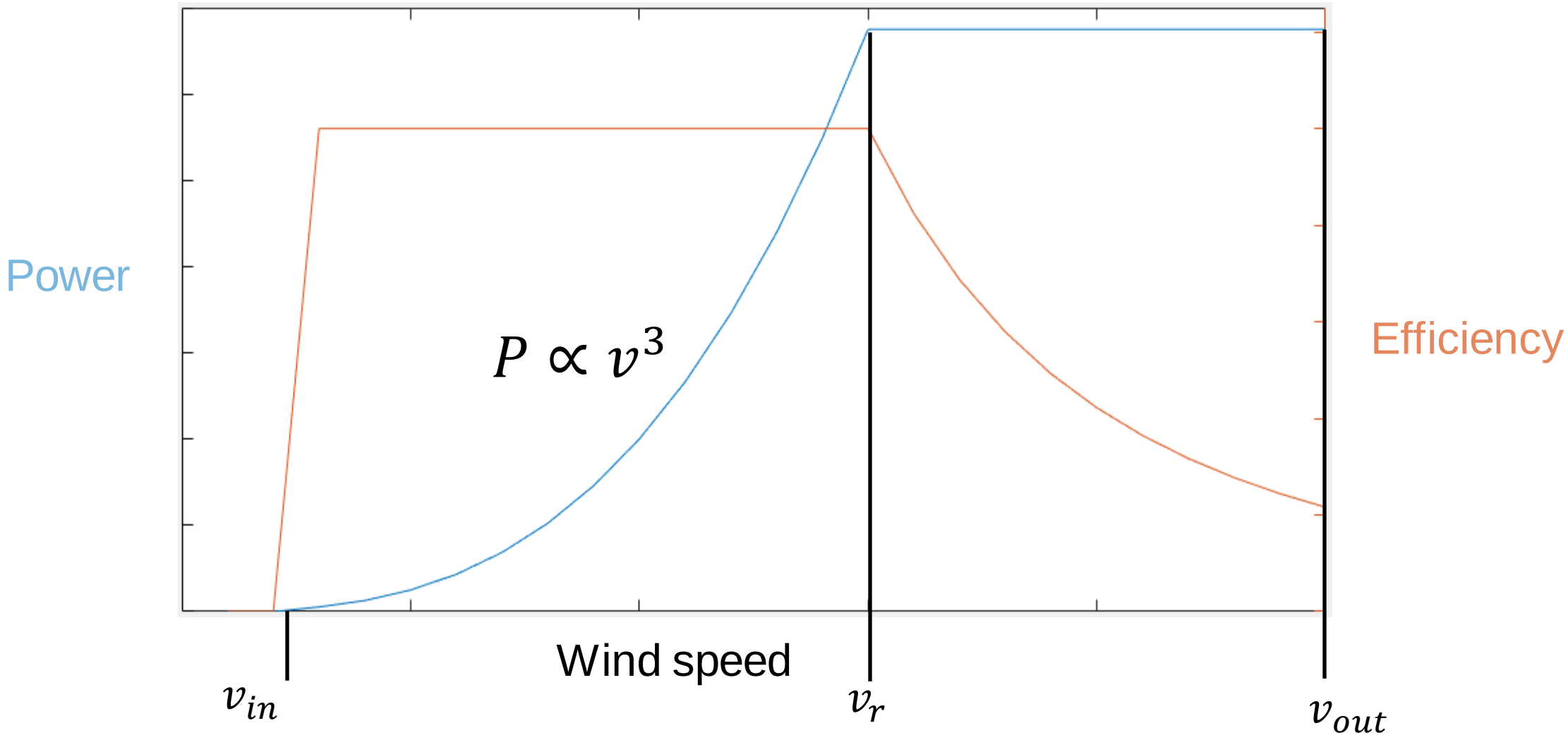
Jaffe and Taylor, *The Physics of Energy*, 1st ed.

Fixed-Speed Wind Turbines (Type 1 and 2)

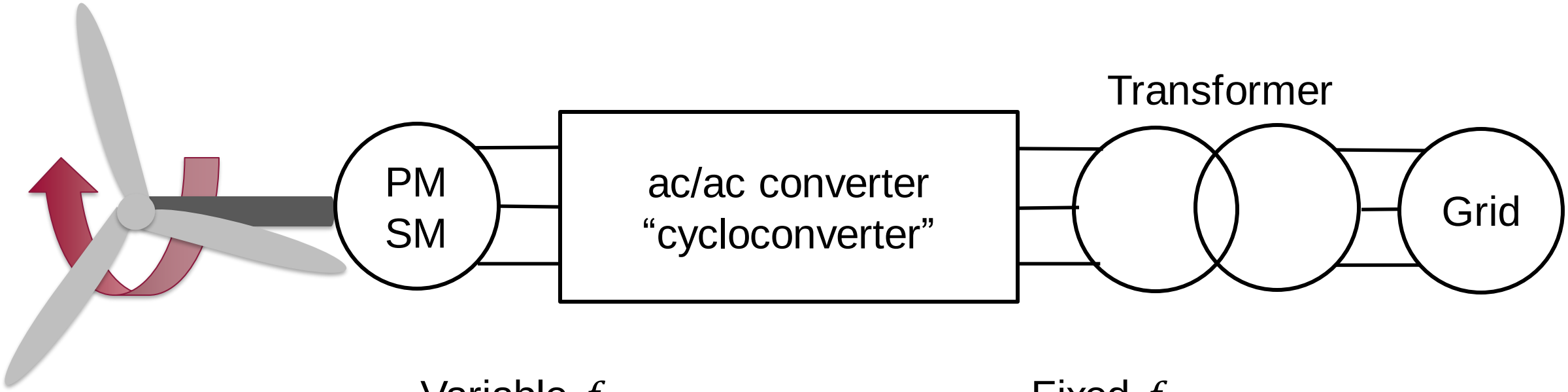
- Induction generator
- Direct power system connection
- Fixed speed (set by grid)
- Historically popular
- Only extract max. power at one wind speed
- Type 2: additional rotor resistors for improved gusting response
- Contribute inertia



Ideal Variable Speed Power Characteristic

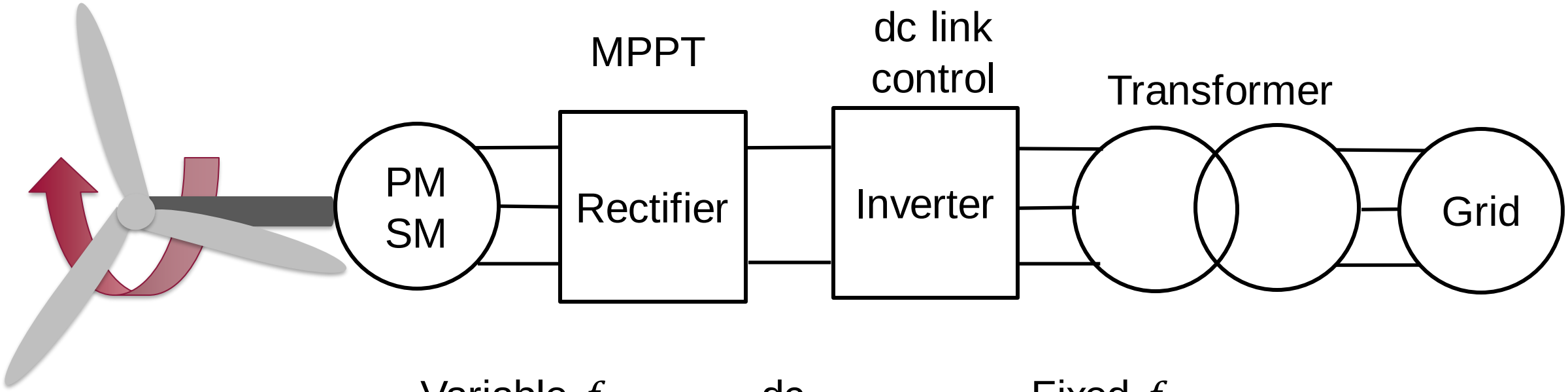


Variable Speed Turbine (Type 4)



Variable Ω for max. power

Variable Speed Turbine (Type 4)



Variable Ω for max. power

Turbine inertia does not contribute to system inertia!

Conclusion

- Wind turbines convert kinetic energy of wind to electrical energy
- Turbine generators have inertia, but only fixed-speed turbines contribute inertia to power system
- Today, most generators are variable-speed to extract maximum power
- Power electronics connect turbines to grid, decoupling their inertia

Module 2c

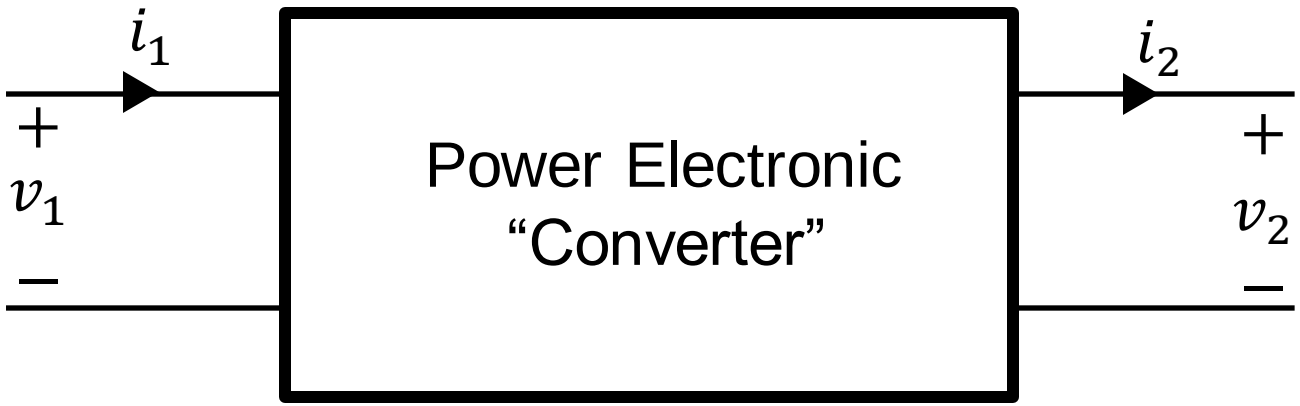
Introduction to Power Electronics: dc/dc conversion

How do we transform and control the flow of electrical energy between dc ports?

Arizona State University

General Idea of Power Electronics

Combine **active** electronic devices
and **passive** energy storage components to
efficiently transform and control the flow of energy
between **dissimilar** electrical ports



Four Classes of Power Conversion

	dc input	ac input
dc output	dc/dc	Rectifier
ac output	Inverter	Cycloconverter

Conversion doesn’t always happen directly. E.g. ac-dc-ac or dc-ac-dc

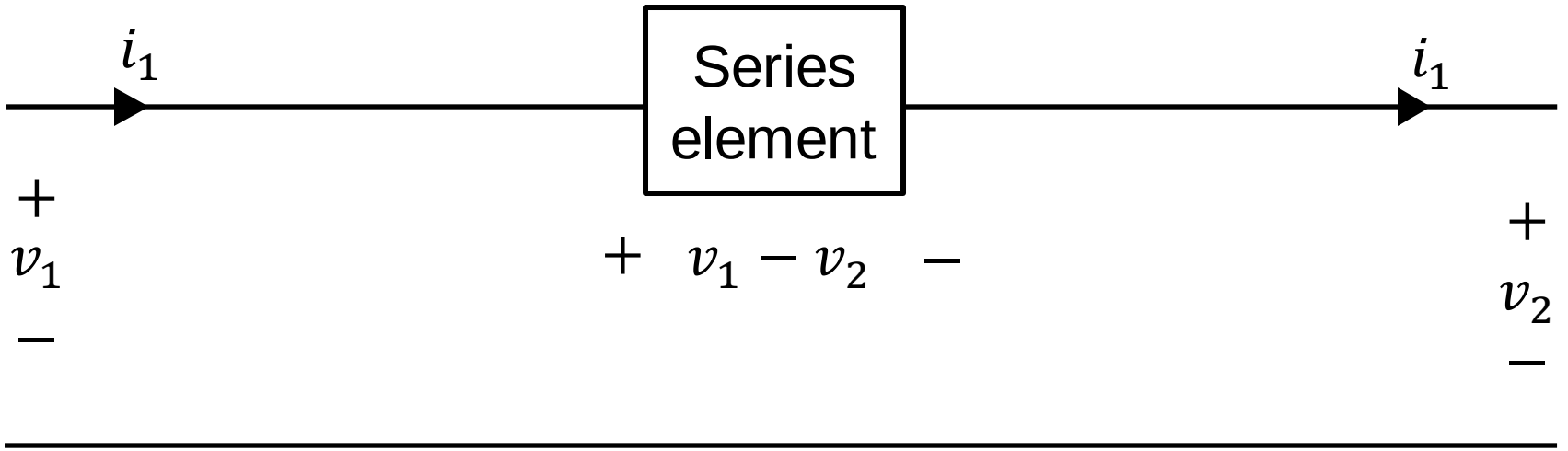
Four Classes of Power Conversion

	dc input	ac input
dc output	dc/dc	Rectifier
ac output	Inverter	Cycloconverter

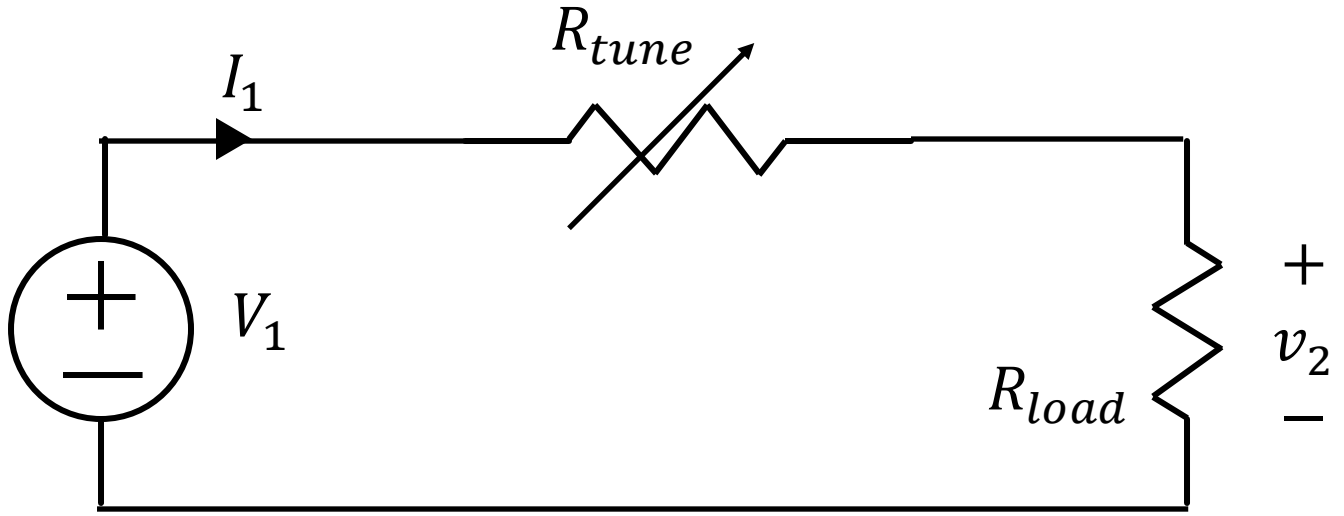
“Input” port is supplied power, “Output” port extracts power

Conversion doesn’t always happen directly. E.g. ac-dc-ac or dc-ac-dc

Simplest Conversion Between dc Voltages



Using a Tunable Series Resistor



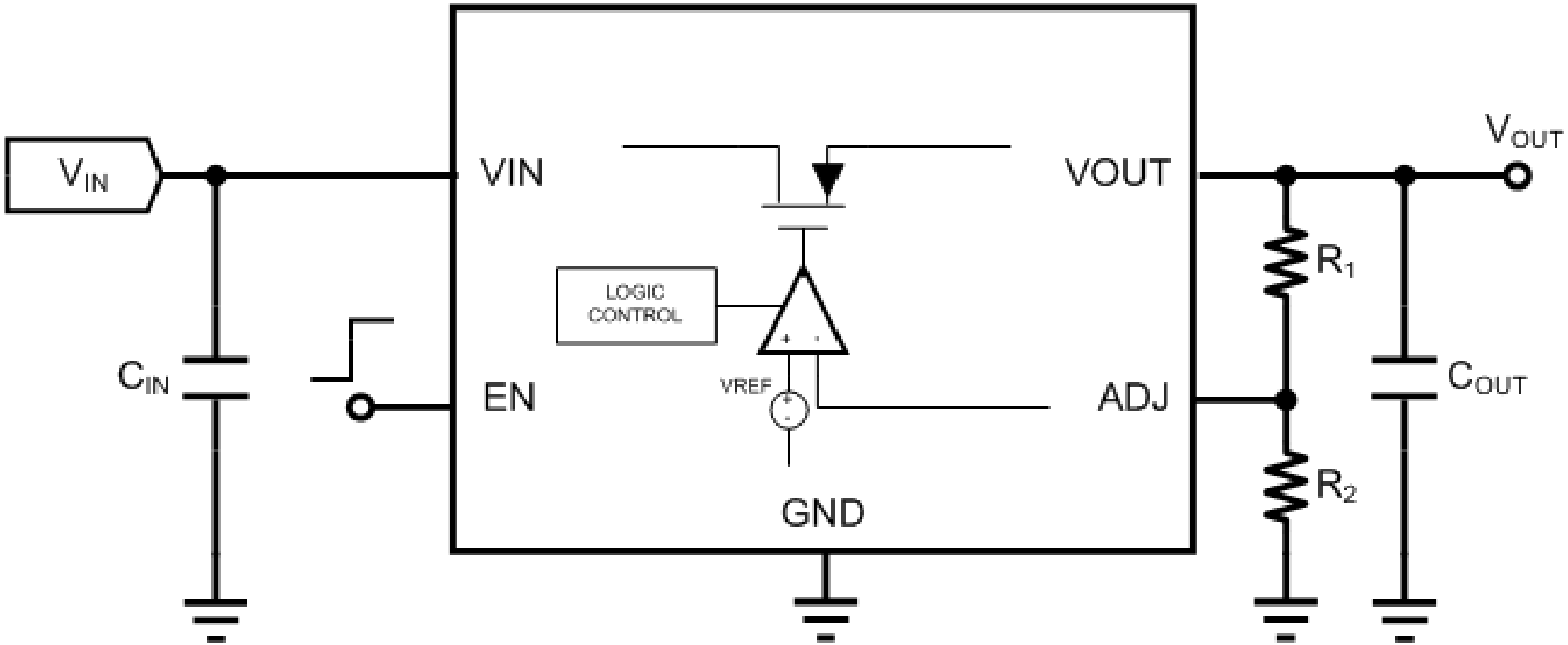
$$v_2 = \frac{R_{load}}{R_{load} + R_{tune}} v_1$$

$$\eta = \frac{V_2 I_1}{V_1 I_1} = \frac{V_2}{V_1}$$

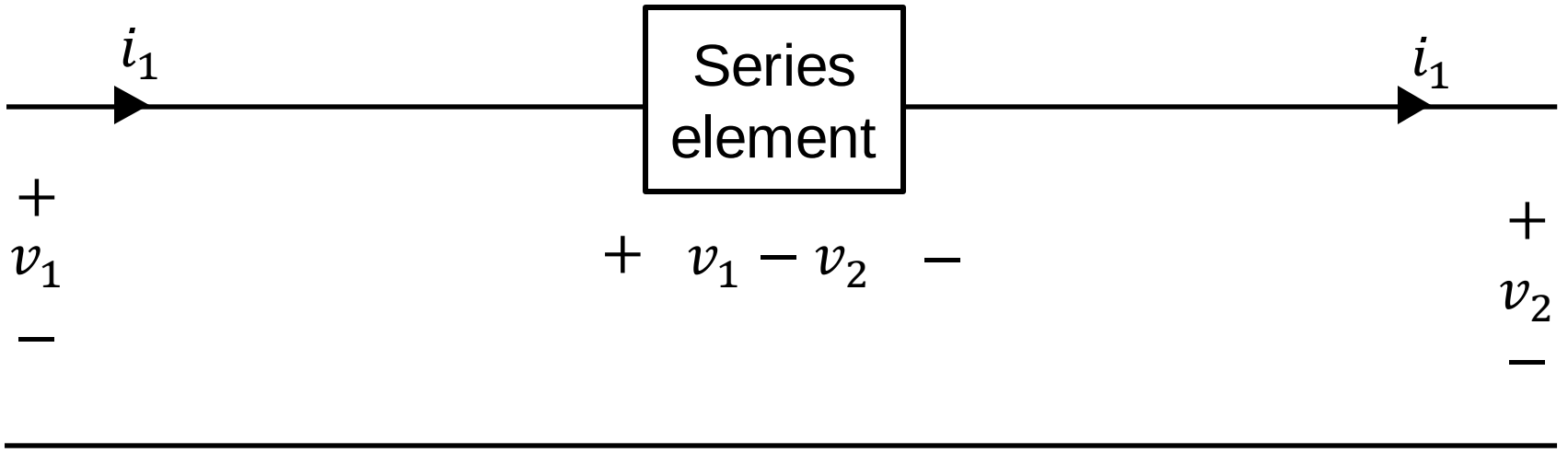
If $V_2 = 5V$, $V_1 = 10V$, $\eta = 50\%$!

Using a Regulated Current Source – “LDO”

$$\eta = V_{out}/V_{in}$$



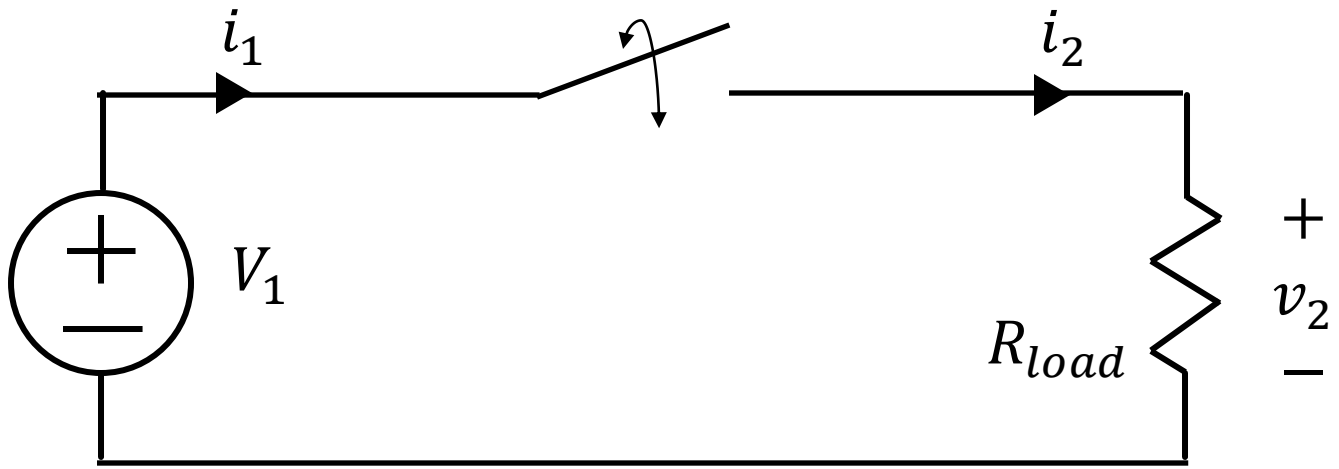
Simplest Conversion Between dc Voltages



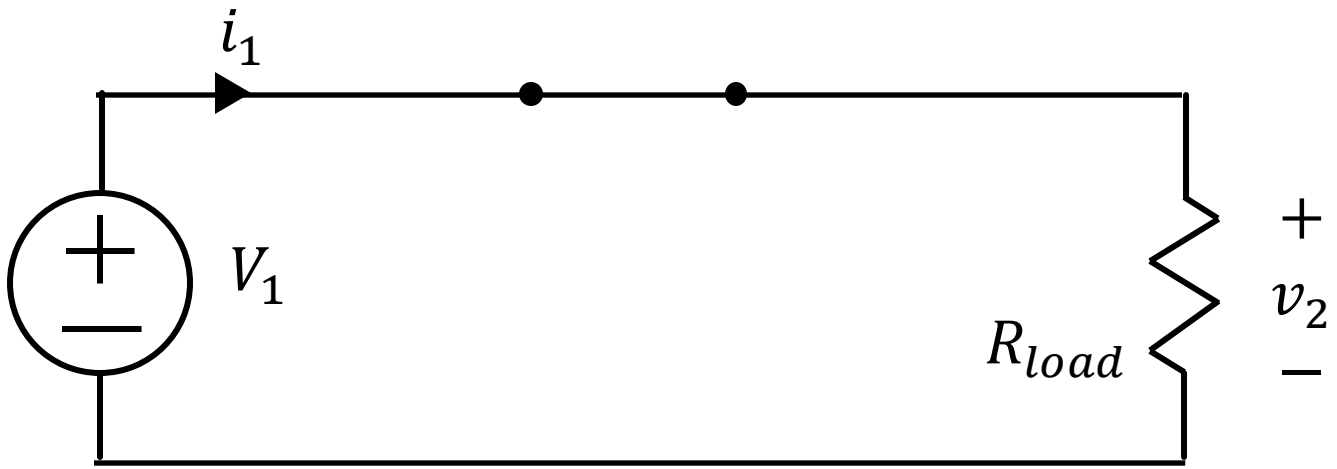
$$\eta = \frac{V_2 I_1}{V_1 I_1} = \frac{V_2}{V_1}$$

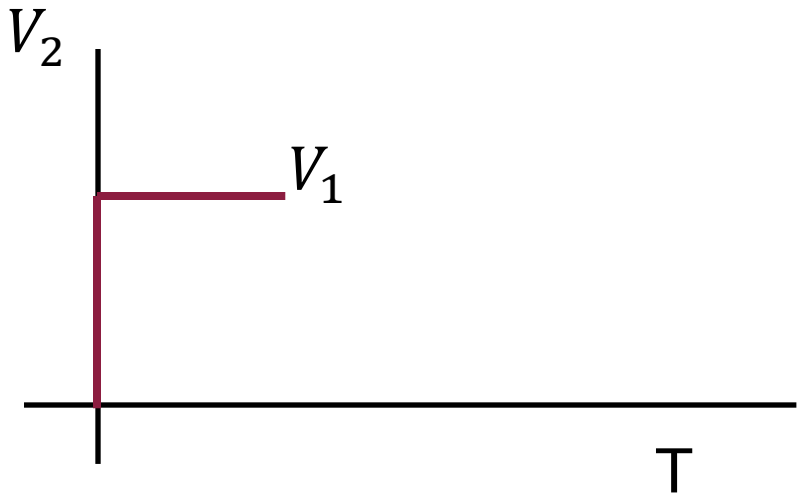
If $V_2 = 5V$, $V_1 = 10V$, $\eta = 50\%$!

What if Series Element was a Switch?



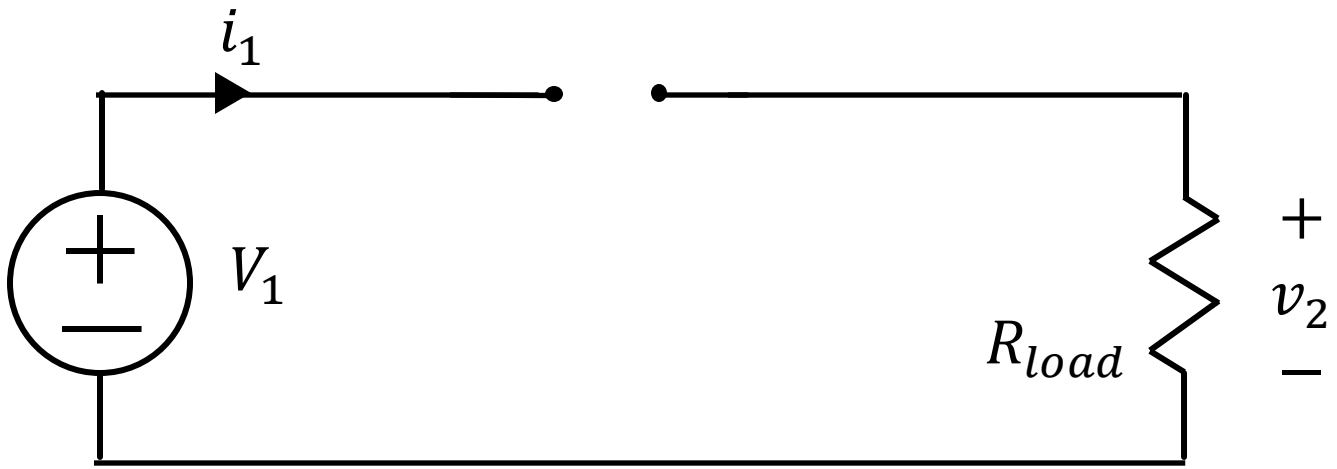
Switch Closed, No Voltage Drop

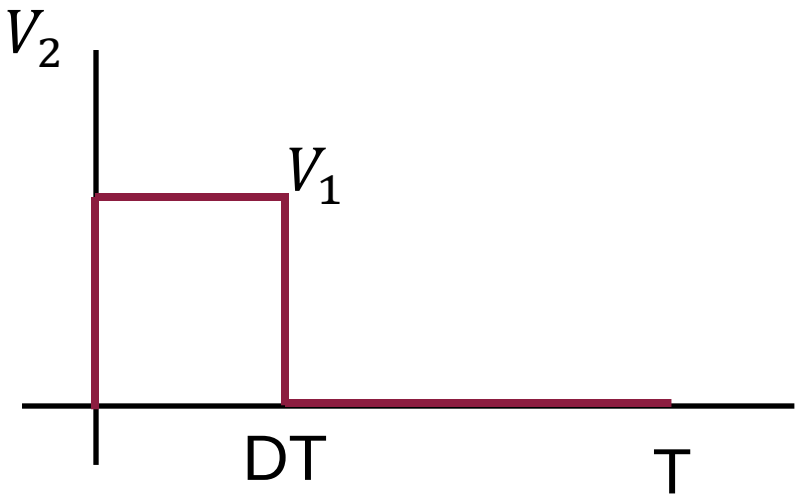




Ideal switch has zero voltage drop, no power loss

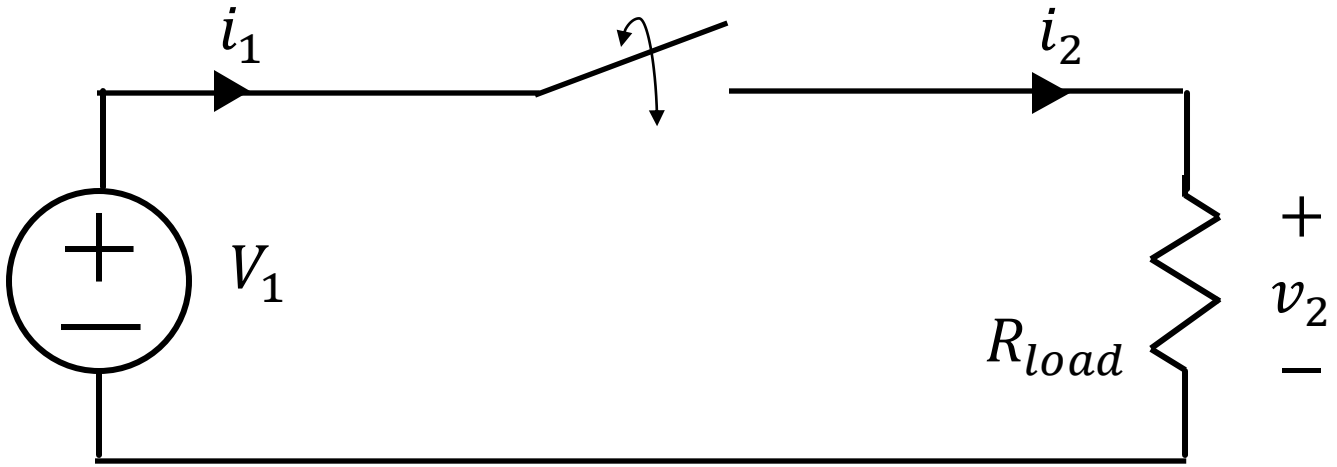
Switch Open, No Current Flow

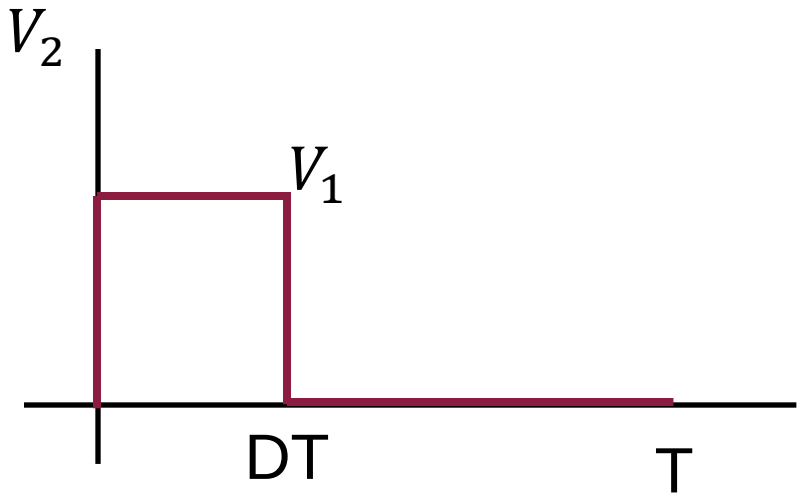




Ideal switch has zero current flow, no power loss

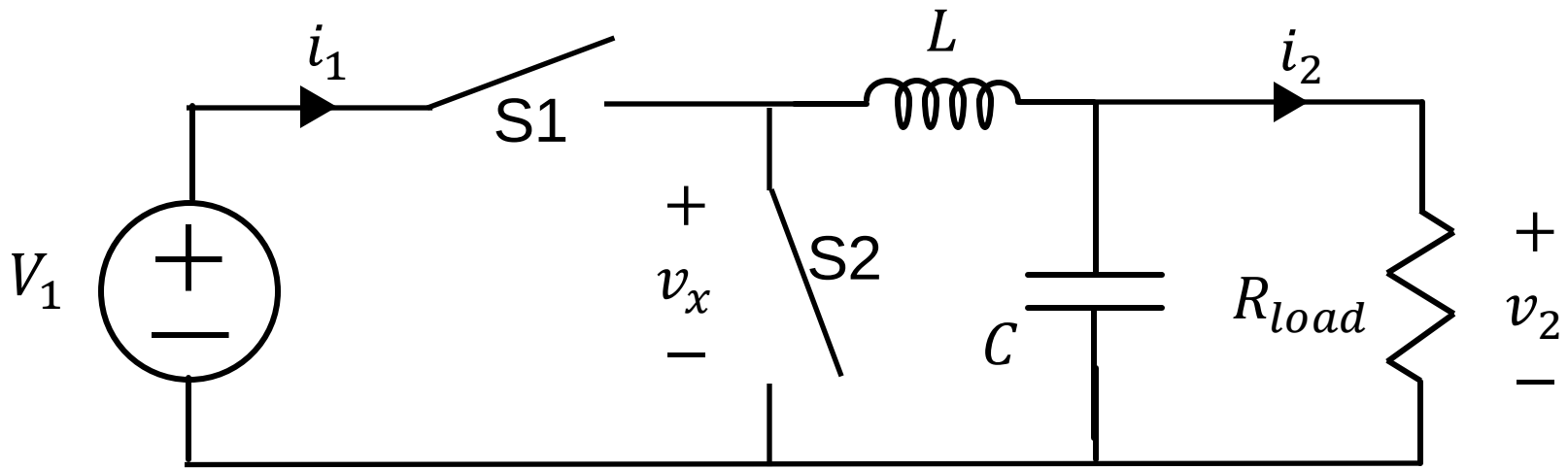
An Efficient but Noisy dc/dc Converter



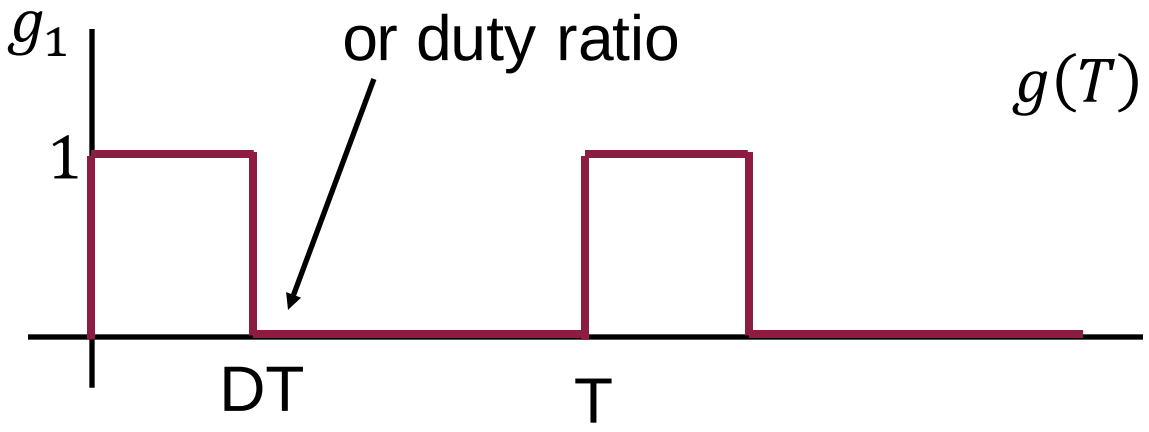


1. Conversion is lossless
2. Average output voltage is DV_1 -- controllable!
3. Output voltage is ac (we've made an inverter)
4. Input current is ac

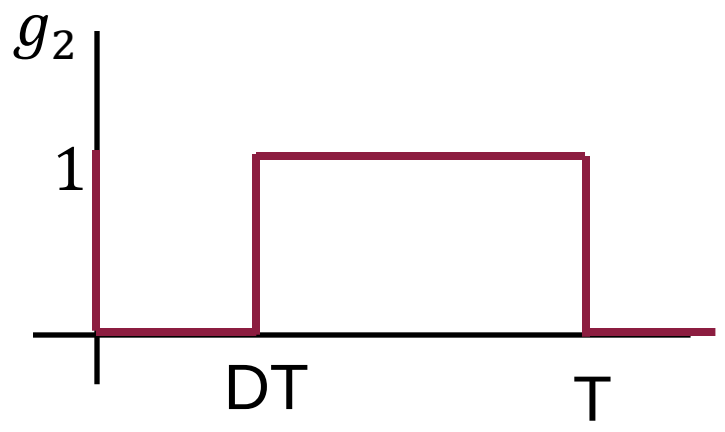
The “Buck” Converter



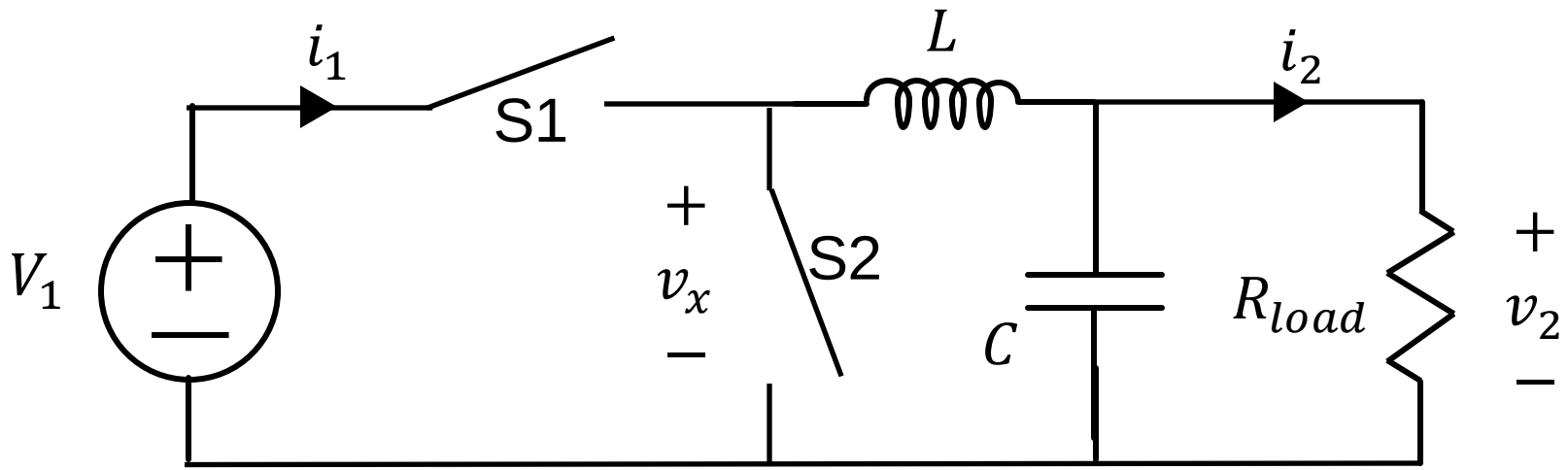
Duty cycle
or duty ratio

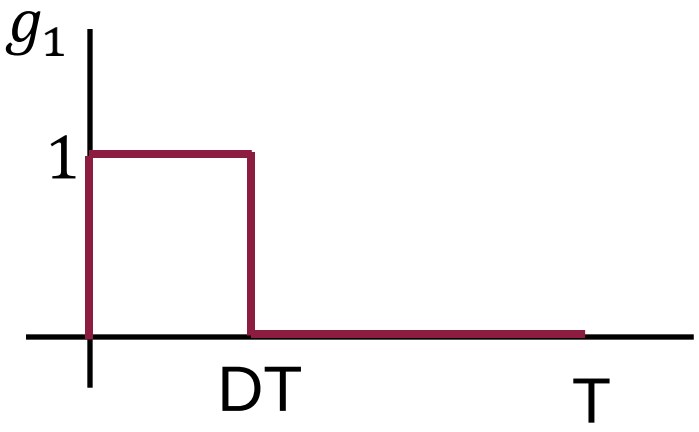


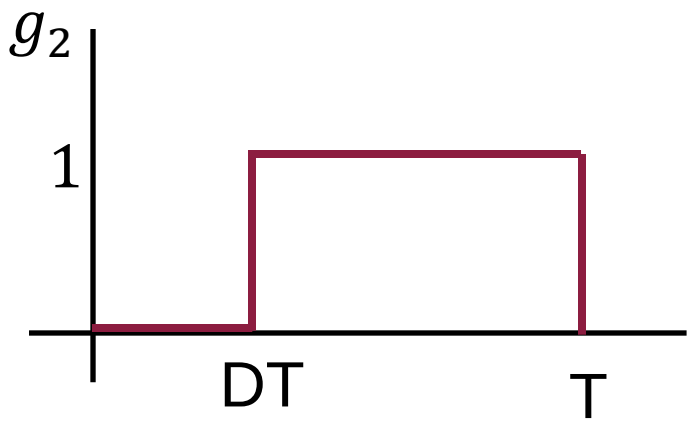
$$g(T) = g(0)$$

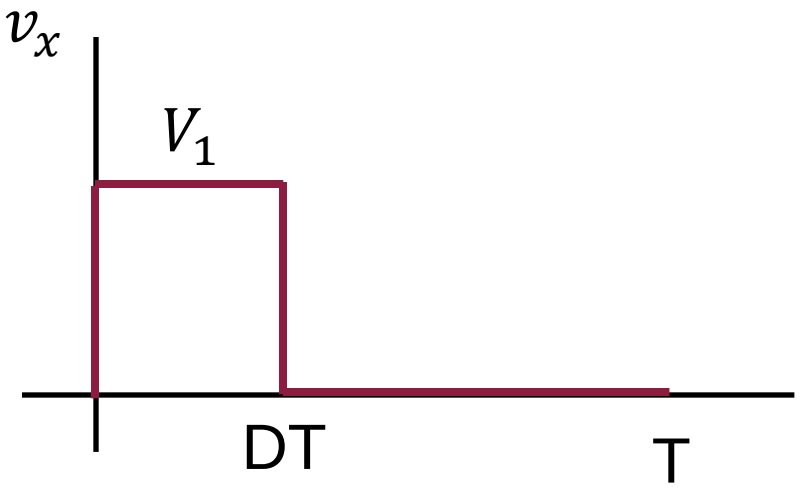


The “Buck” Converter

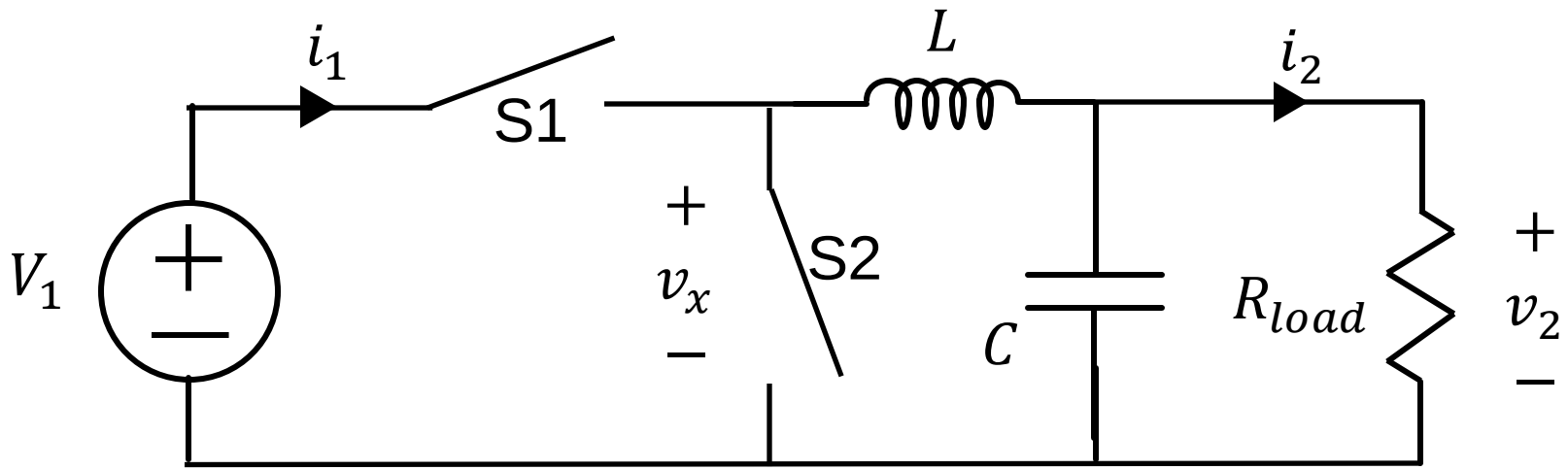


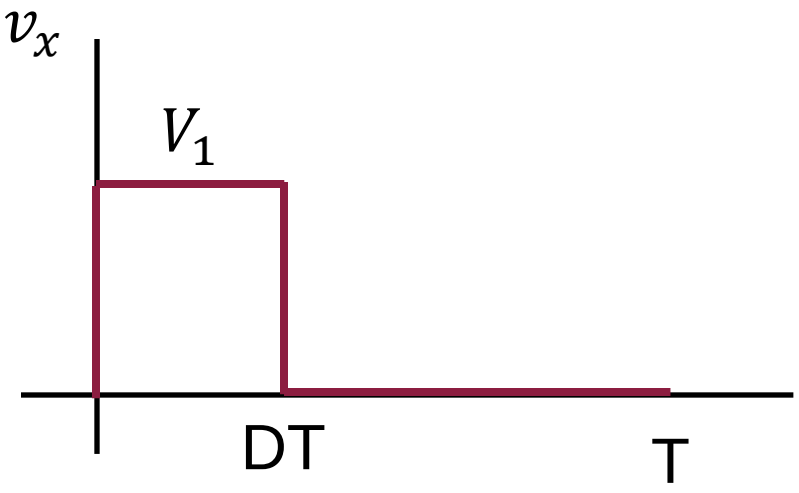




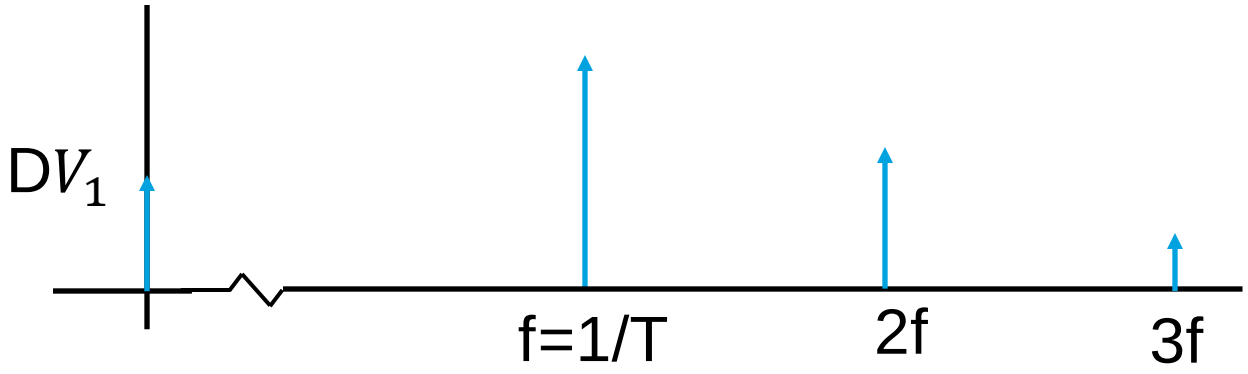


Harmonic Content of Switch Voltage

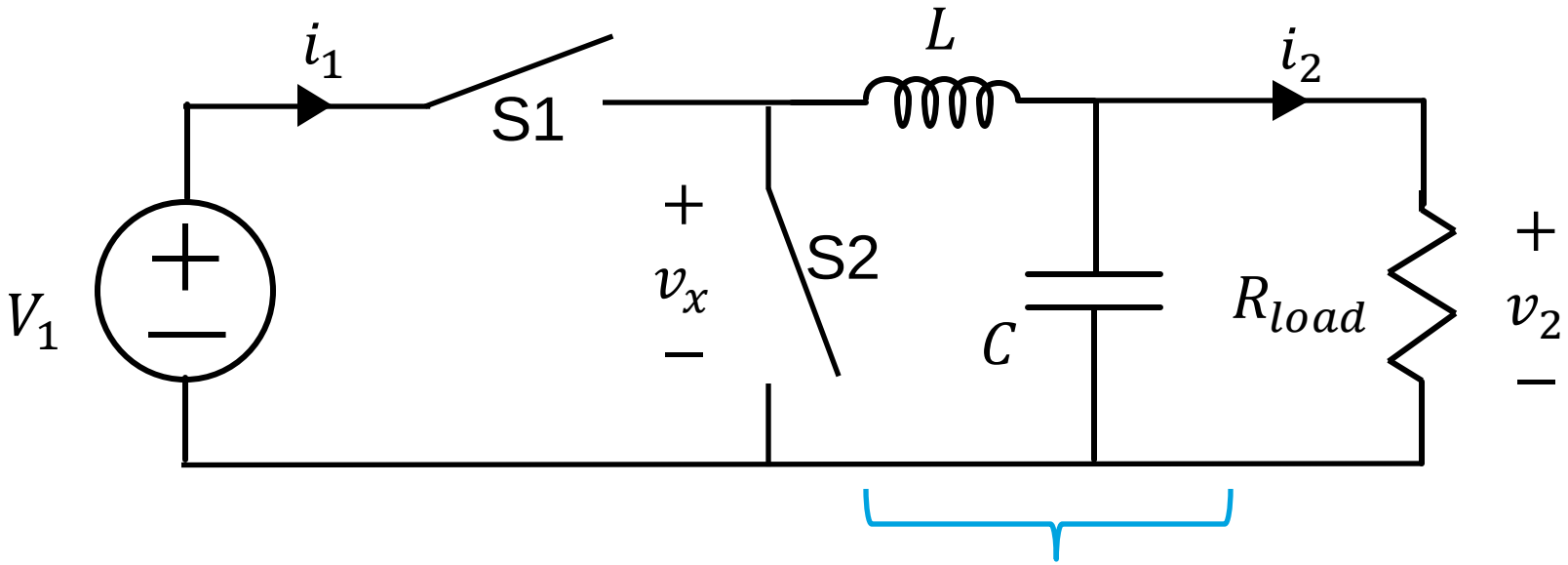


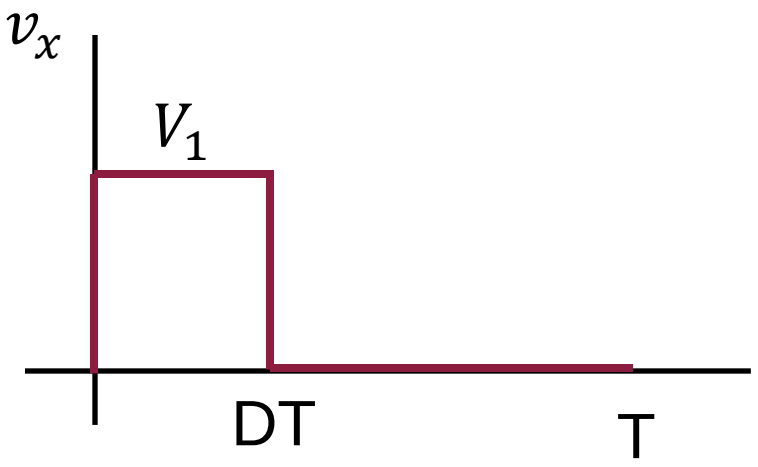


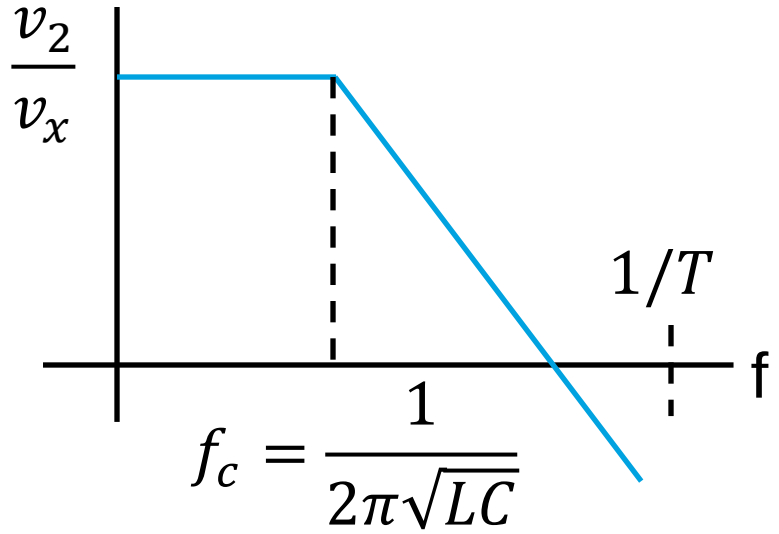
Harmonic amplitude

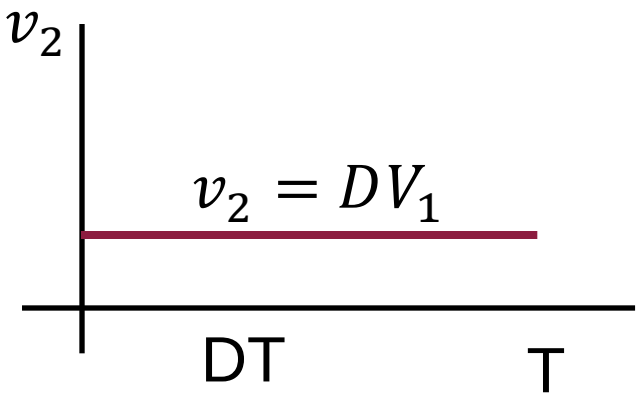


LC Branch Filters Harmonics

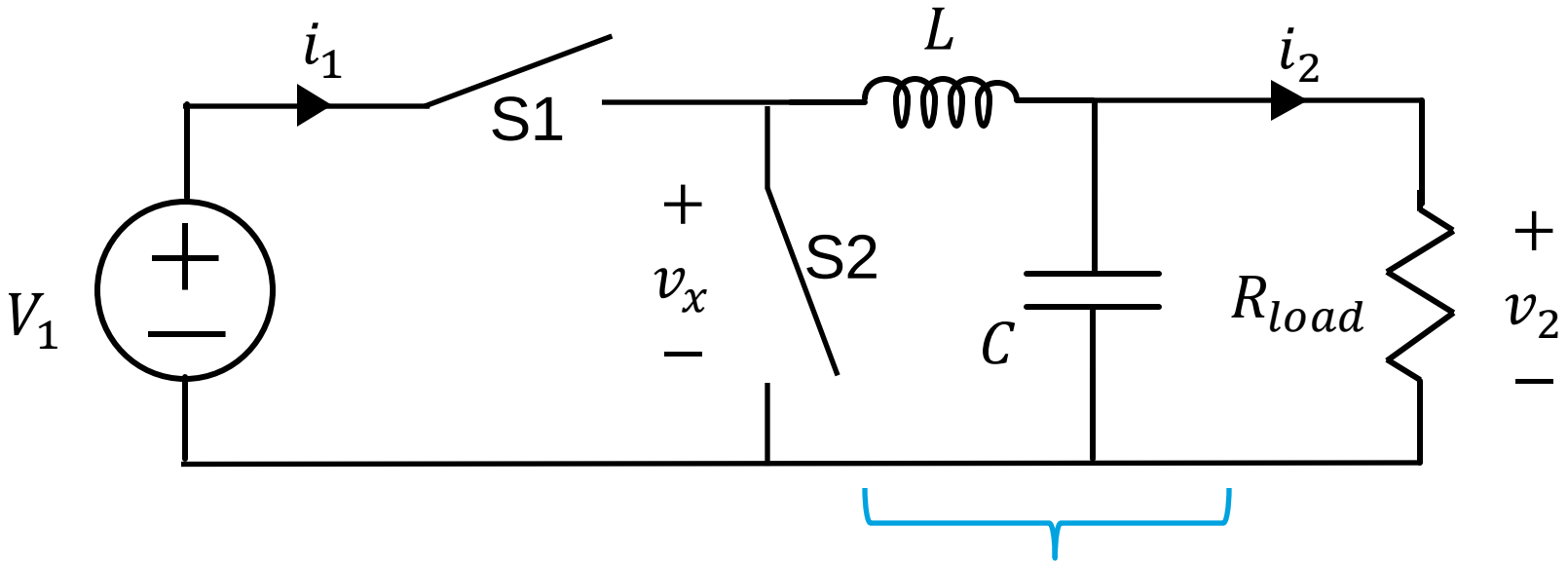






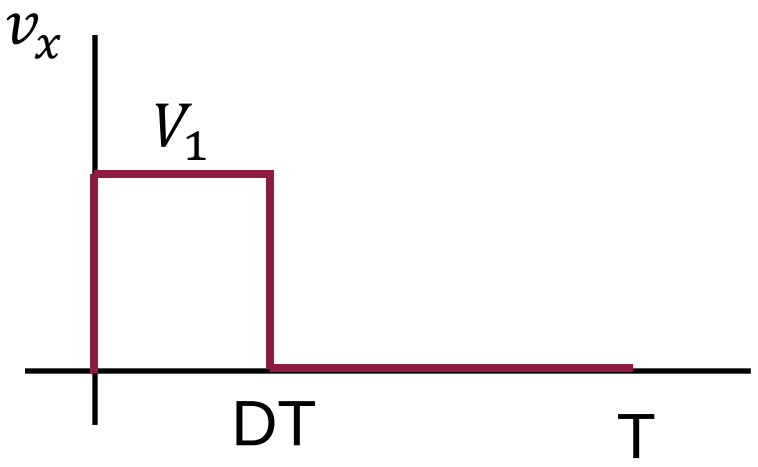


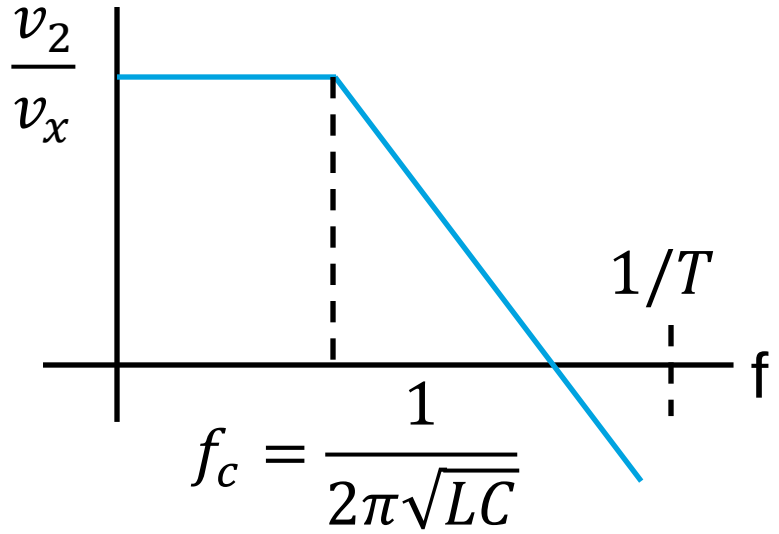
Very High Efficiency Achievable

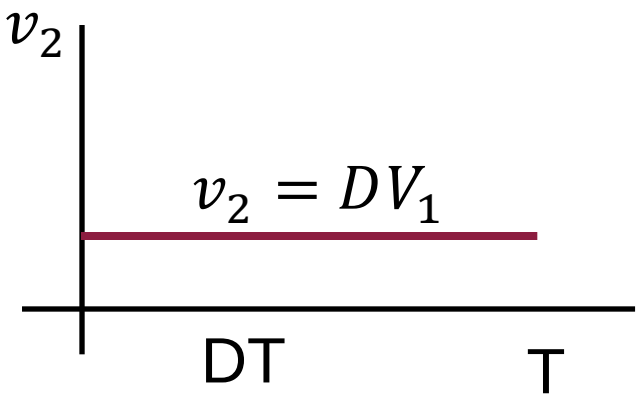


$\eta > 80\%$ typical

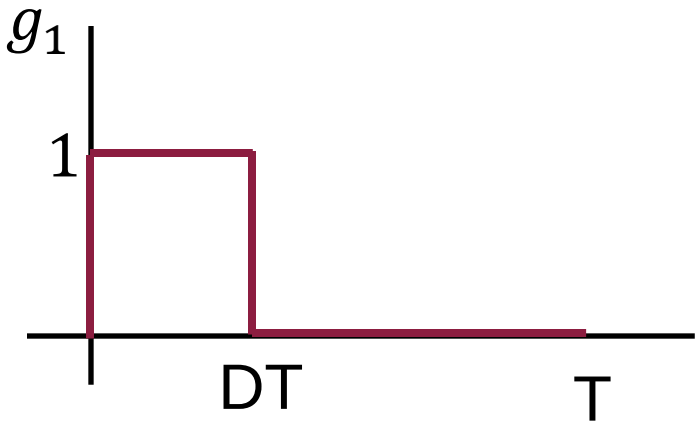
$\eta > 99\%$ achievable

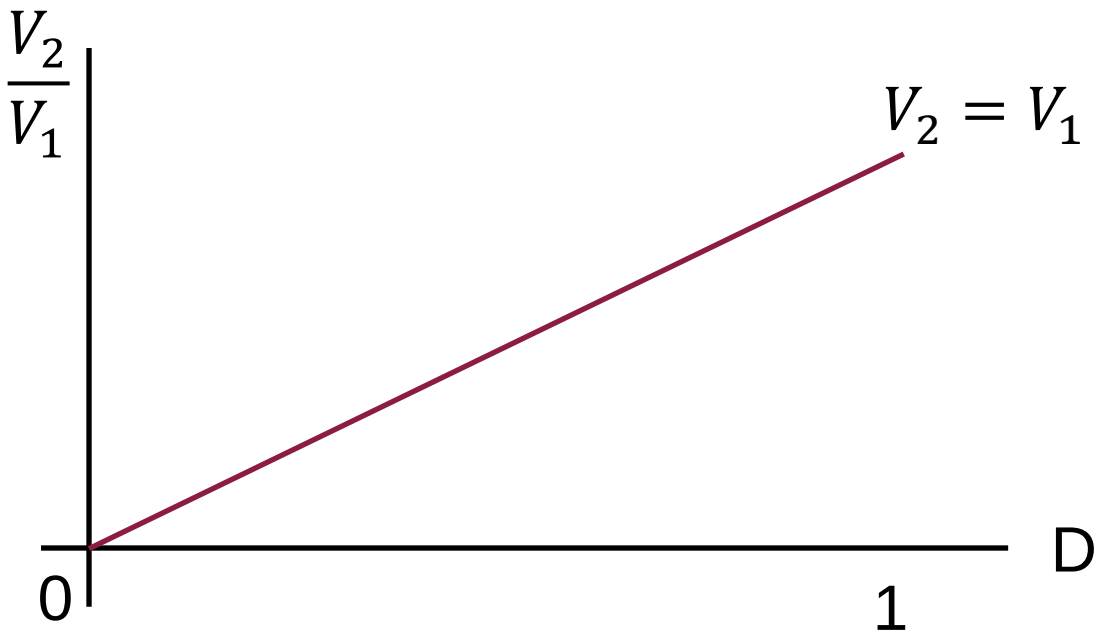






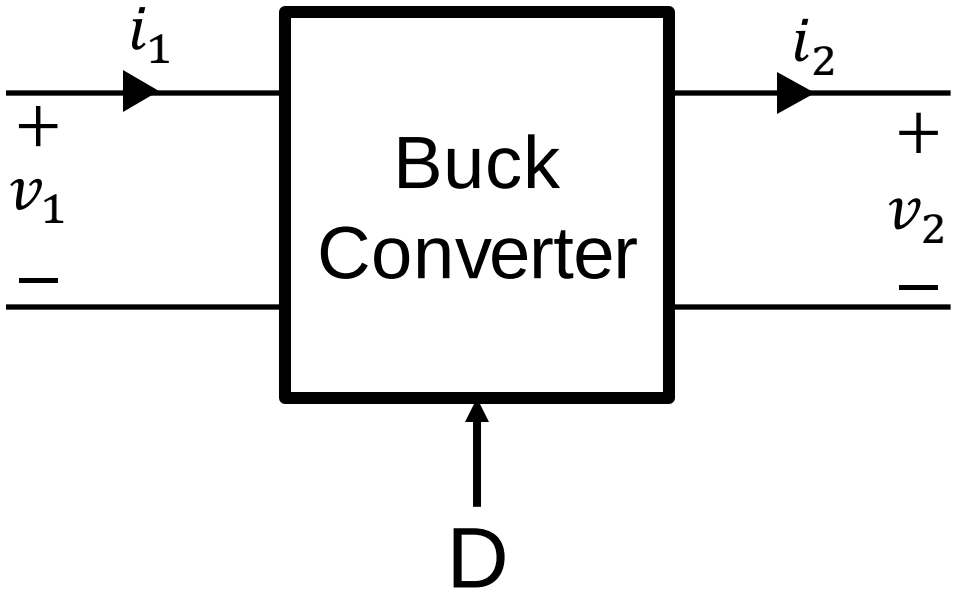
“Pulse Width Modulation” (PWM)

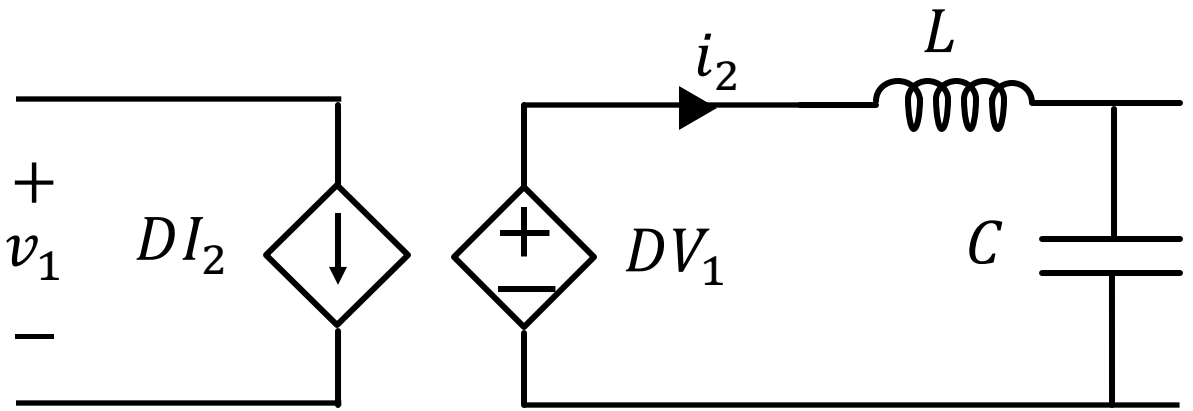




D is either constant or varied **much** more slowly than the switching period

Averaged Buck Converter Model

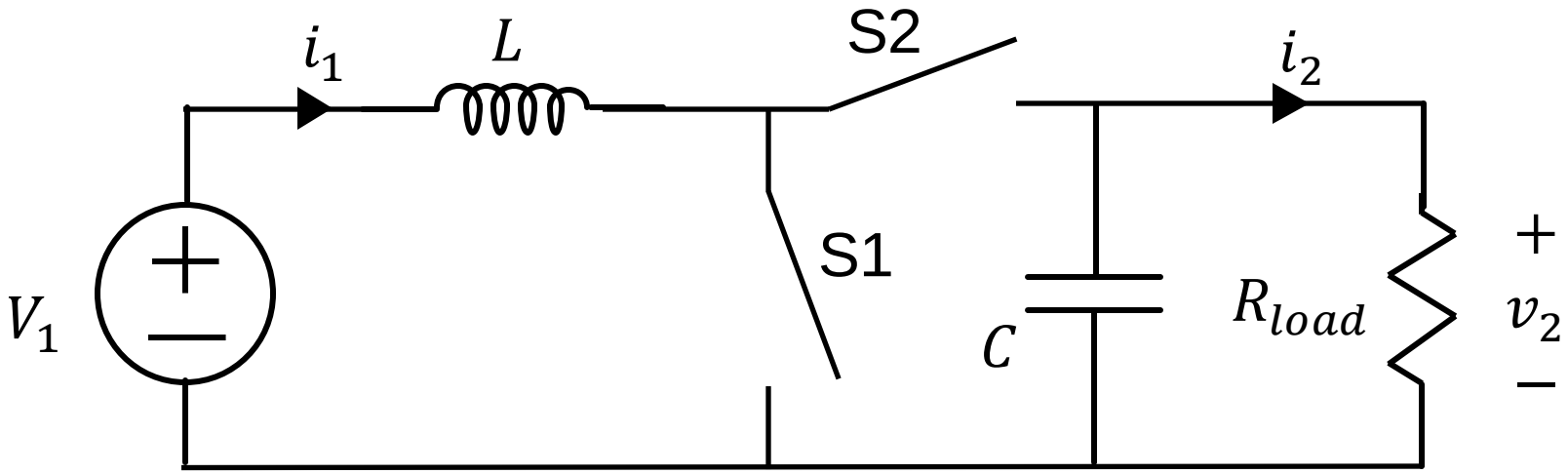


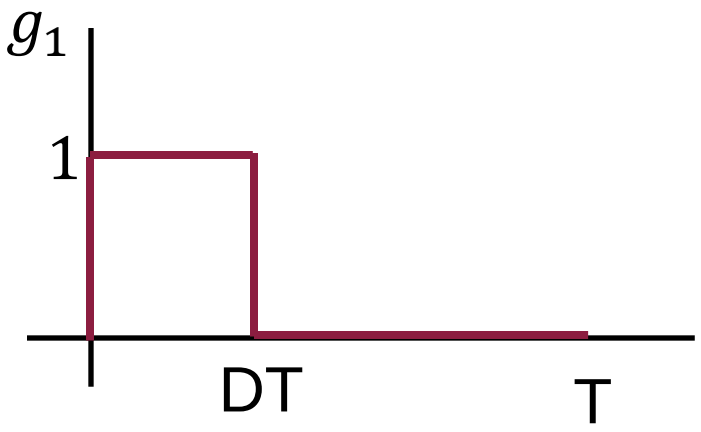


Typically $D \in [0.05, 1]$

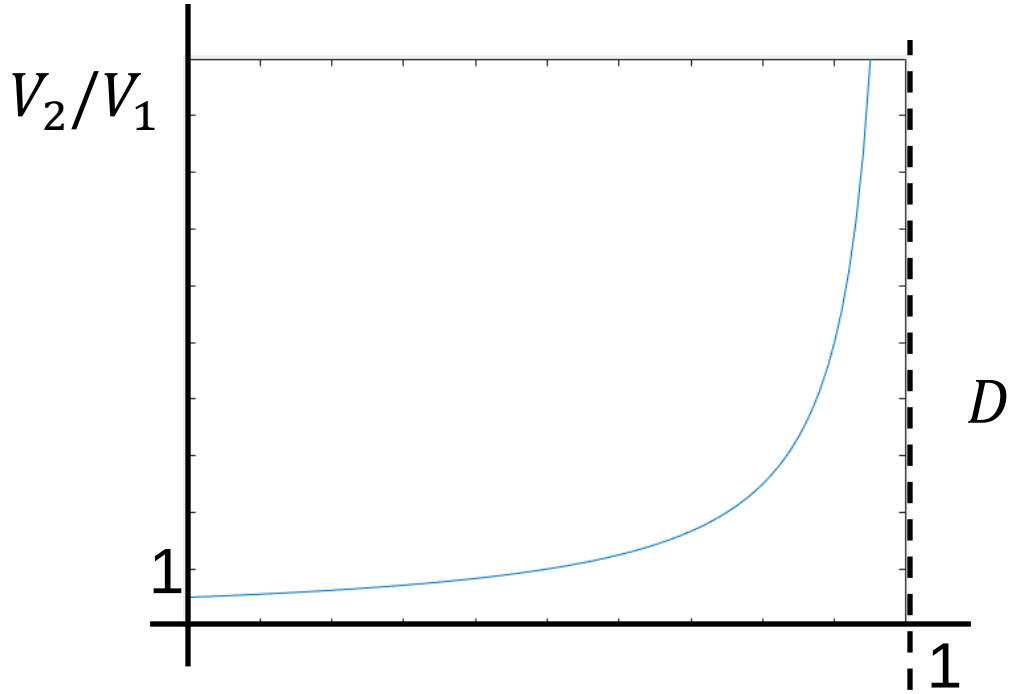
Reduces or “bucks” or “chops” input voltage

The “Boost” Converter

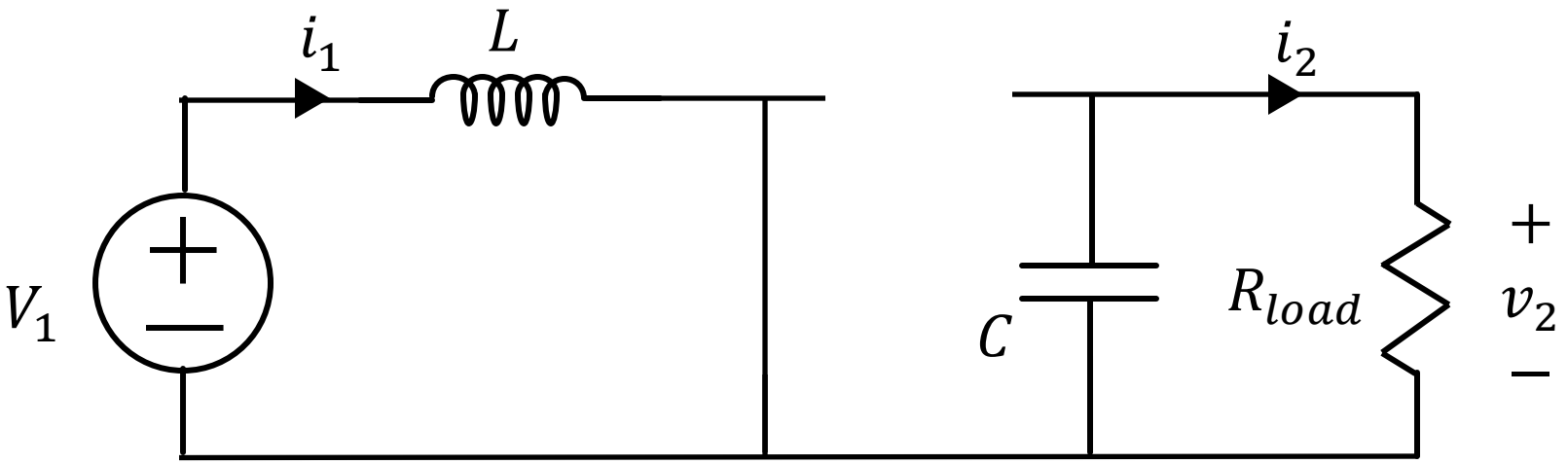




$$V_2 = \frac{V_1}{1 - D}$$

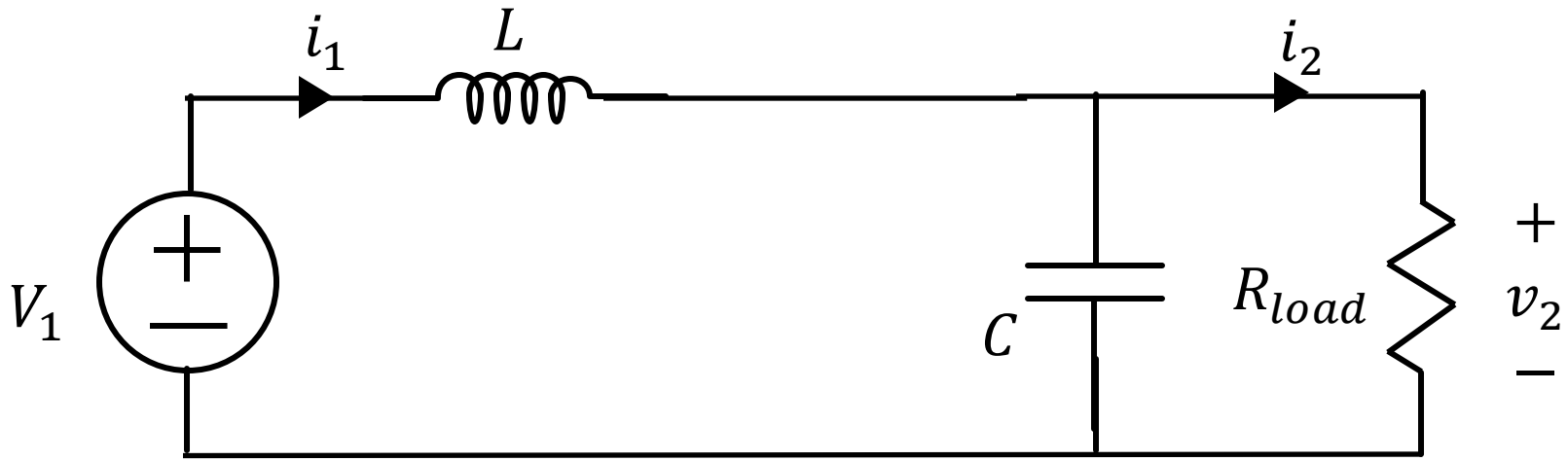


The “Boost” Converter



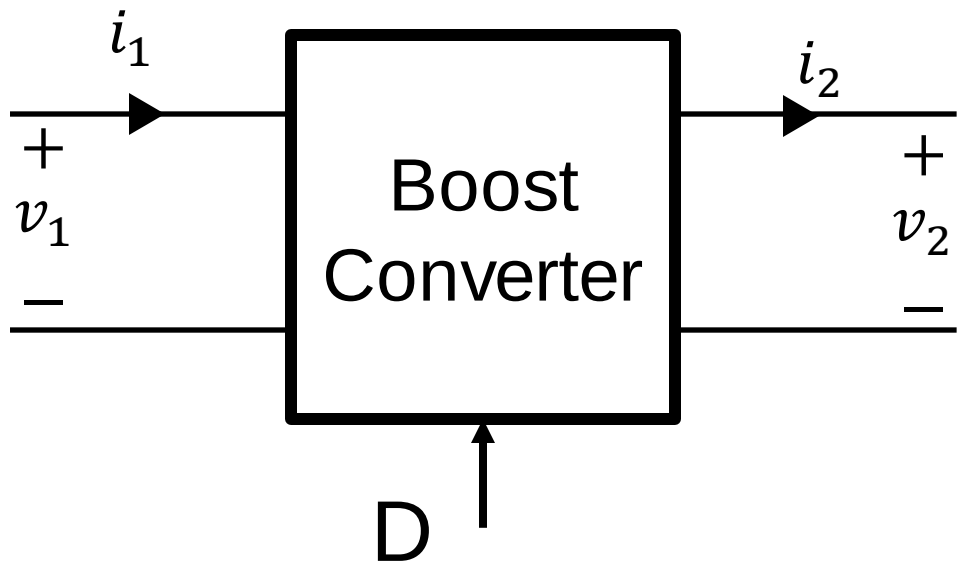
Energy transferred from V_1 into L

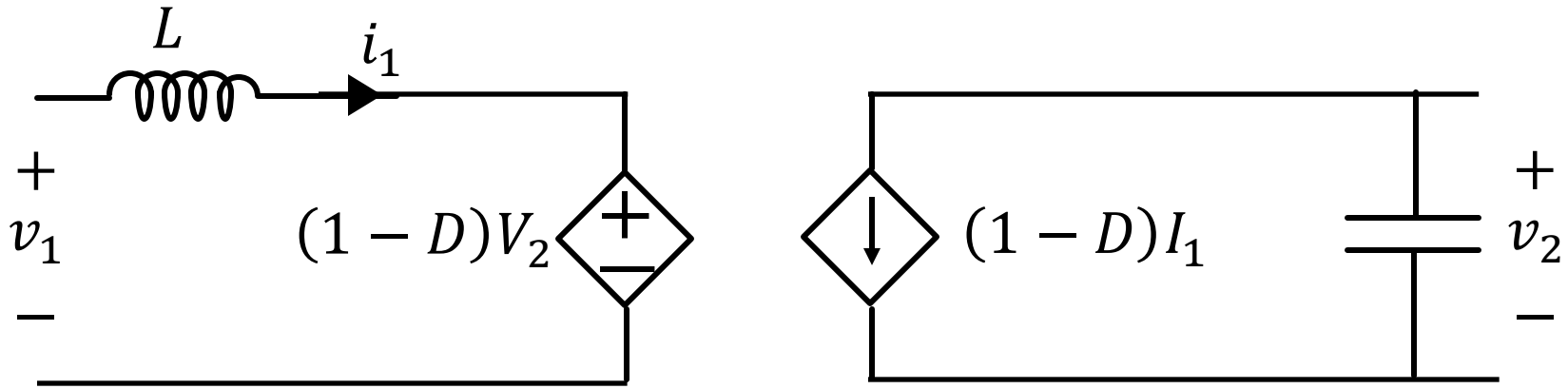
The “Boost” Converter



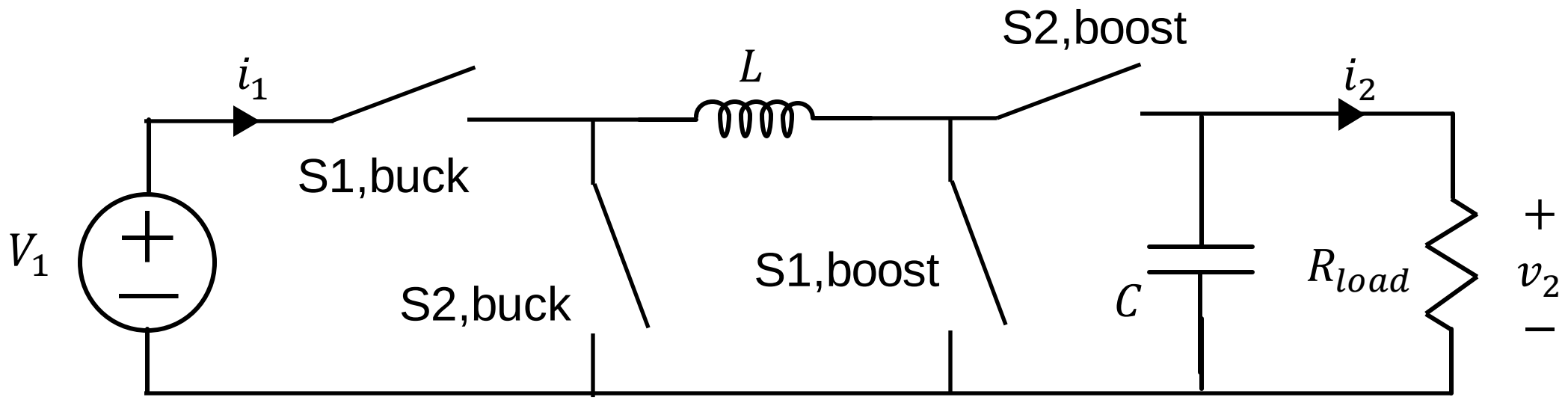
Energy transferred from V_1 and L into output

Averaged Boost Converter Model

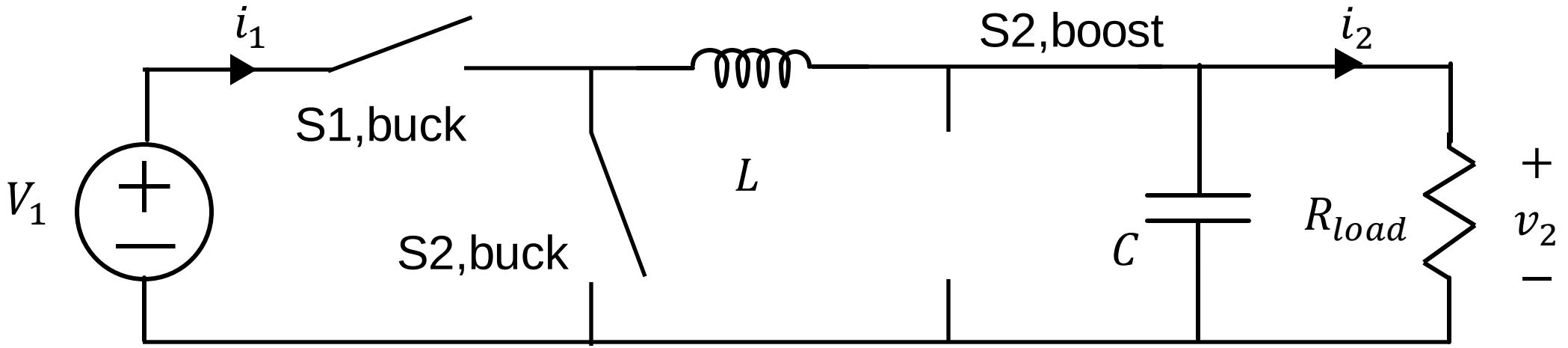




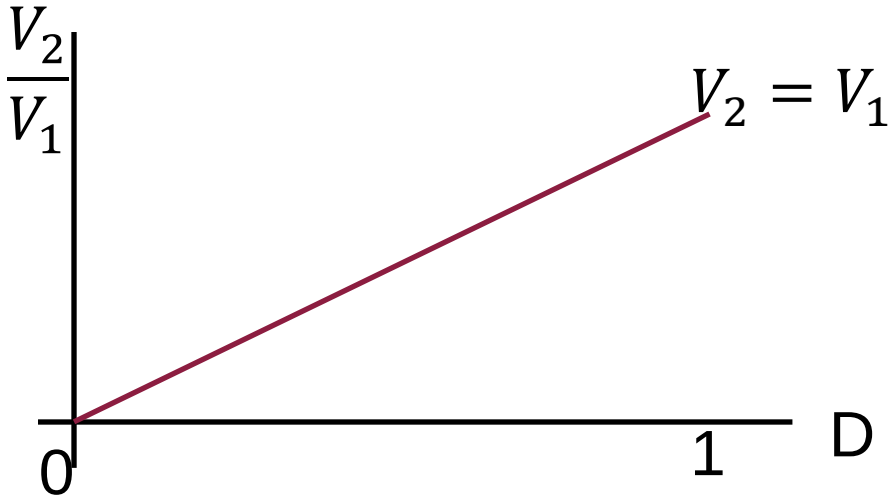
Non-inverting Buck-Boost



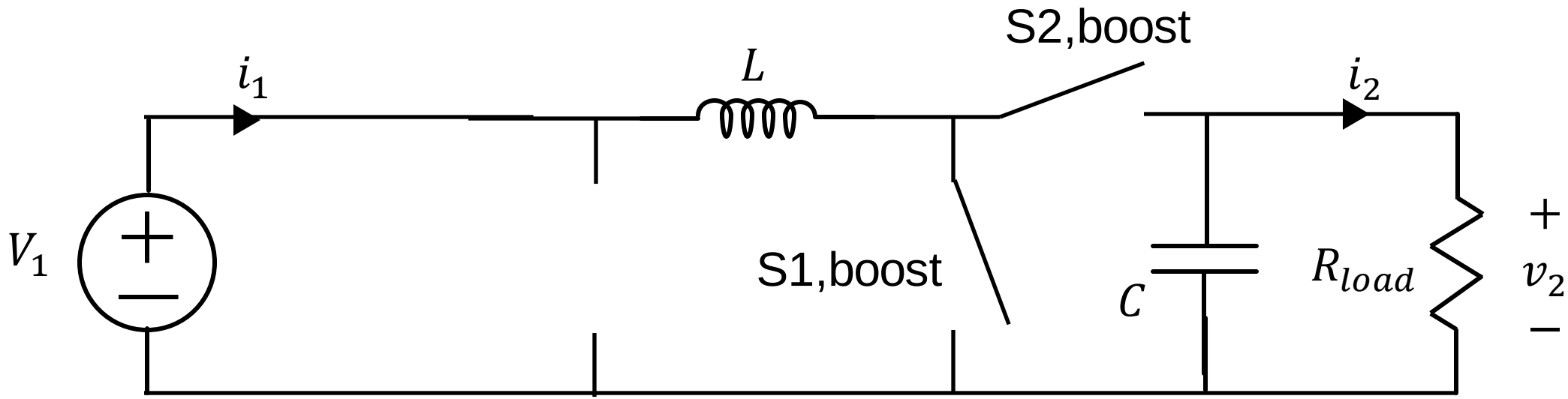
Non-inverting Buck-Boost – Buck Operation



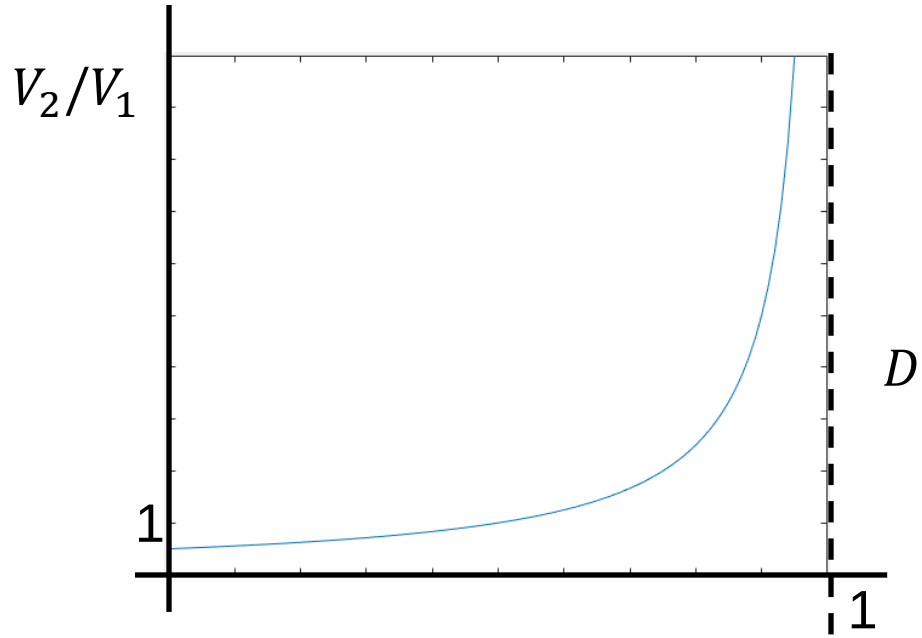
Hold S2,boost on,
PWM buck switches



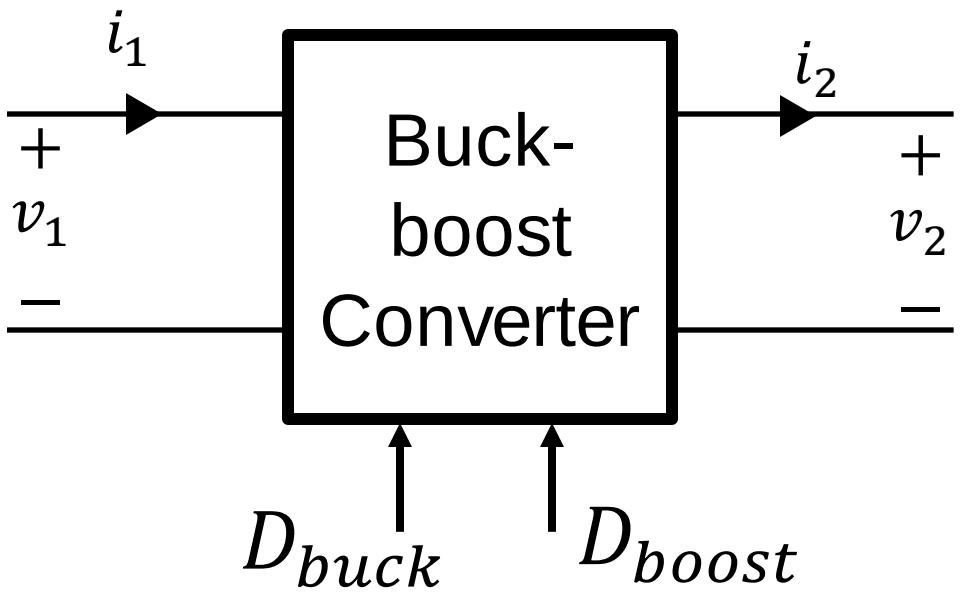
Non-inverting Buck-Boost – Boost Operation

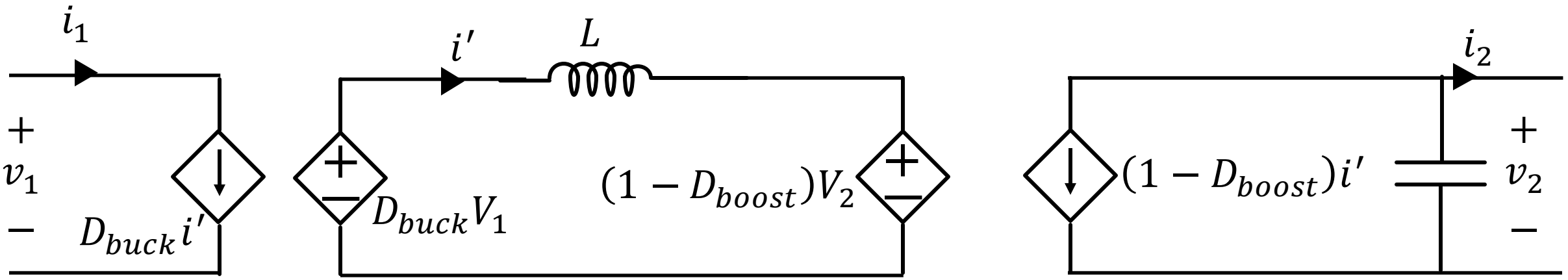


Hold S1,buck on,
PWM boost switches

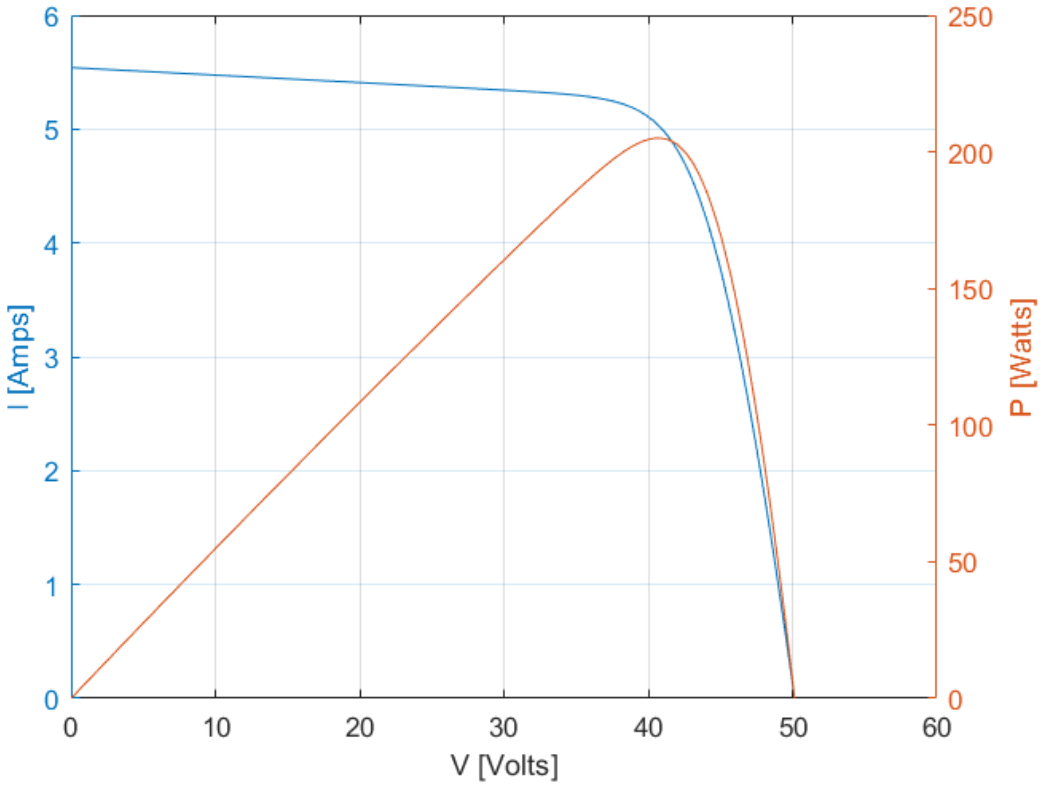


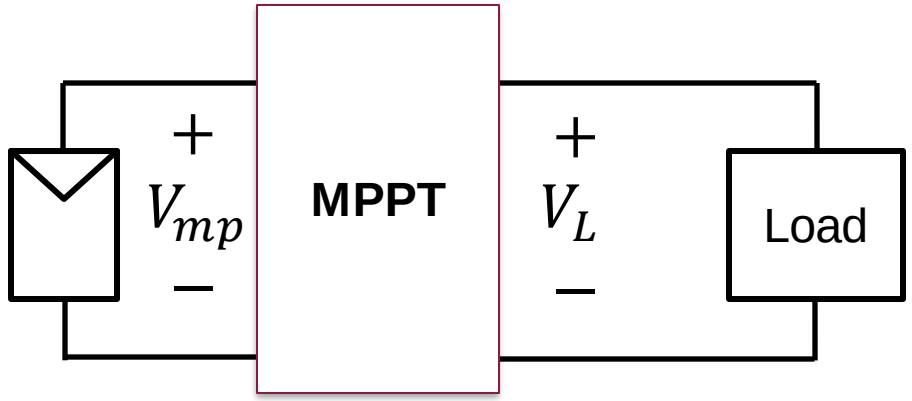
Averaged Buck-Boost Converter Model





Application: Solar PV MPPT





$$V_{mp} = 40V$$
$$V_L = 100V$$

Use boost converter, $D = 0.6$

Conclusion

- Power electronics combine active electronic switches with passive energy storage components
- Very high efficiency dc/dc conversion is achievable
- The buck, boost, and non-inverting buck-boost are popular dc/dc conversion topologies
- These are widely used for solar PV MPPT.

Module 2d

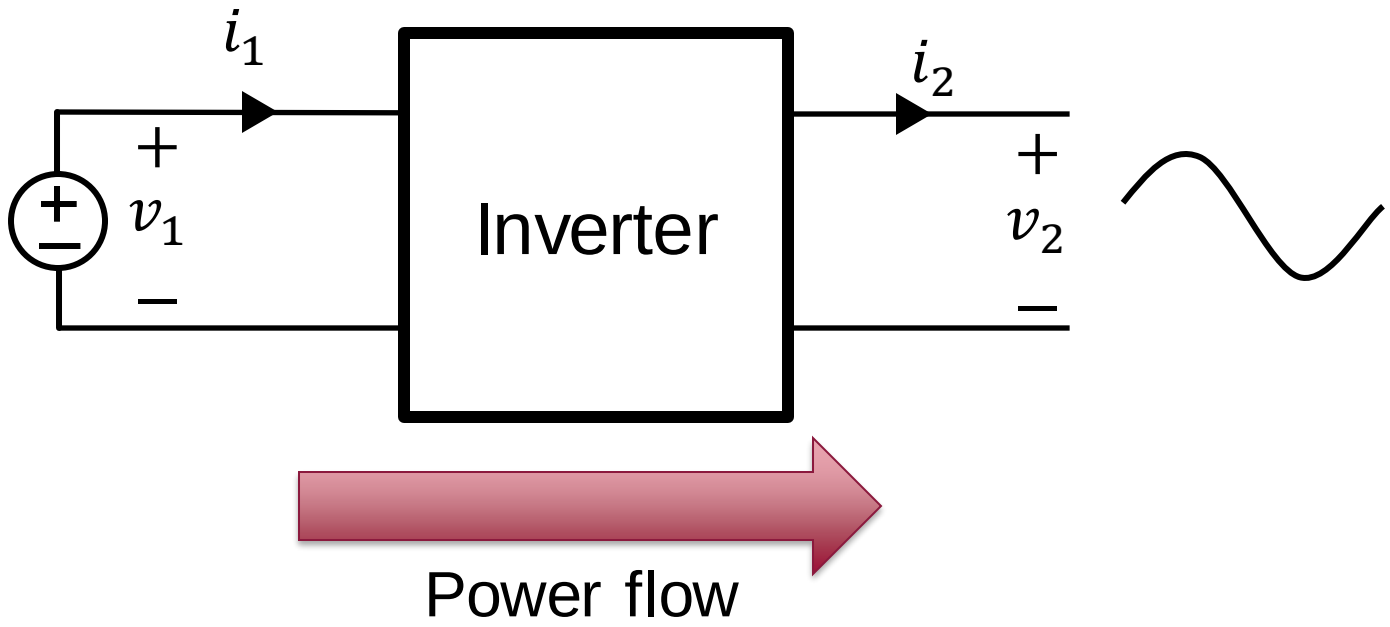
Introduction to Power Electronics: Inverters

How do we transform and control the flow of electrical energy between a dc port and an ac port?

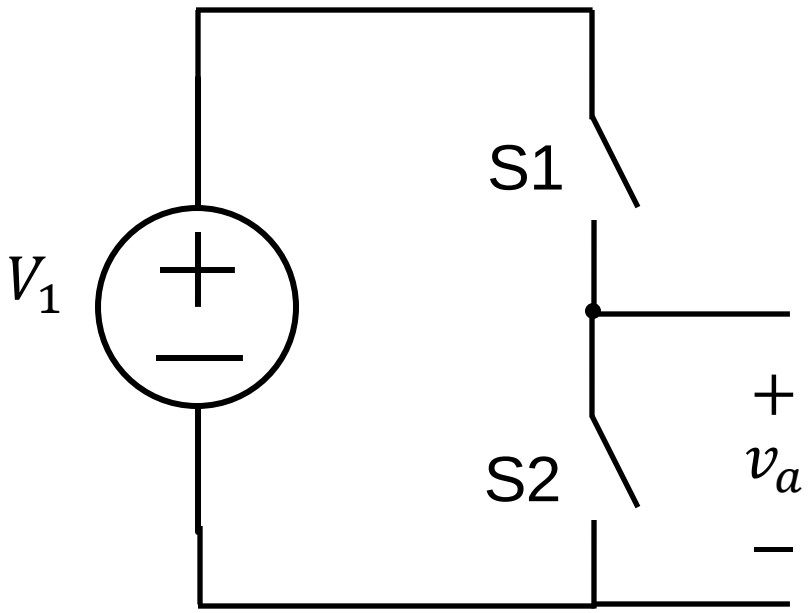
Arizona State University

dc/ac Conversion: PWM Inverters

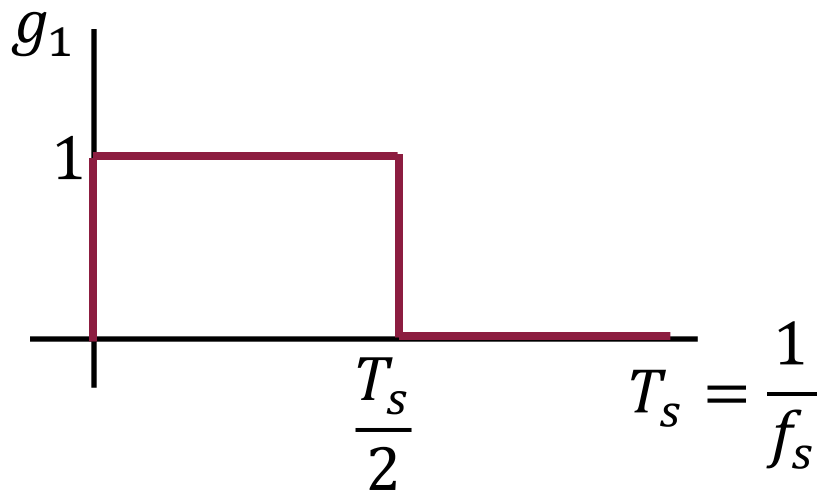
- Objective: produce a low-distortion sinusoidal voltage from a dc source

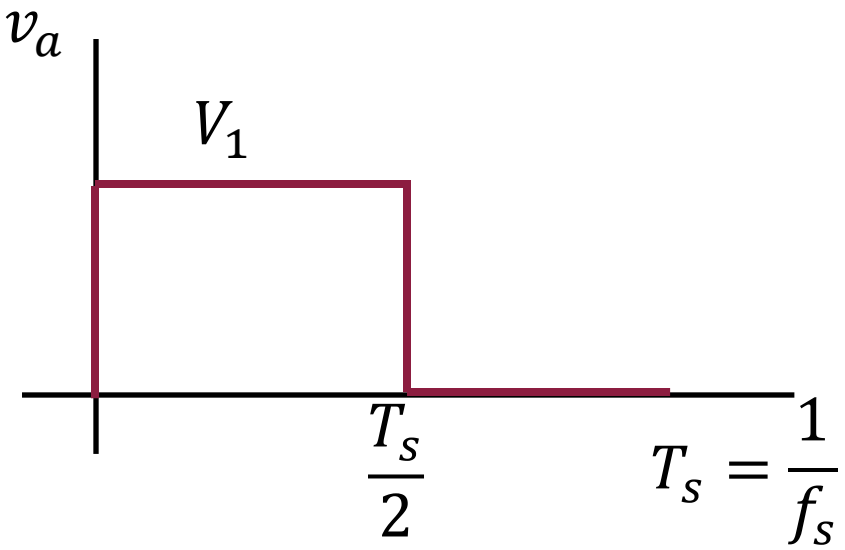


Half-Bridge Switching Cell

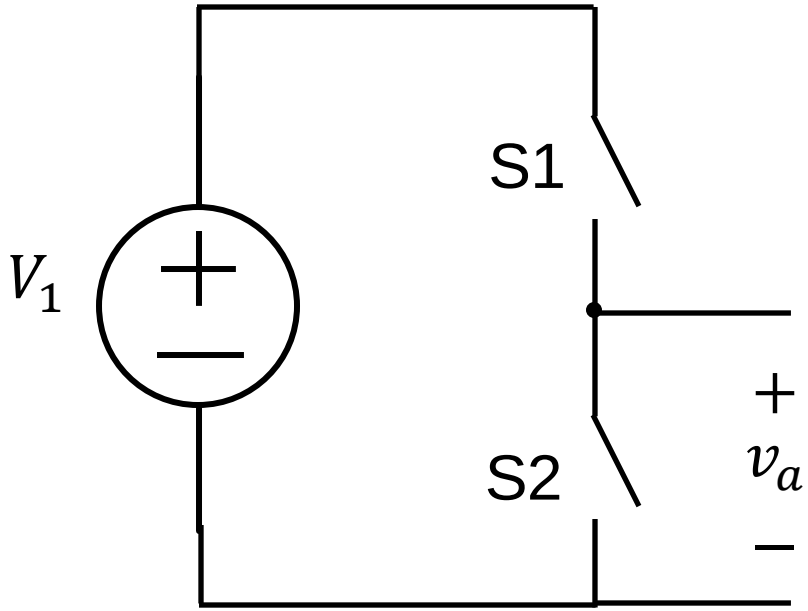


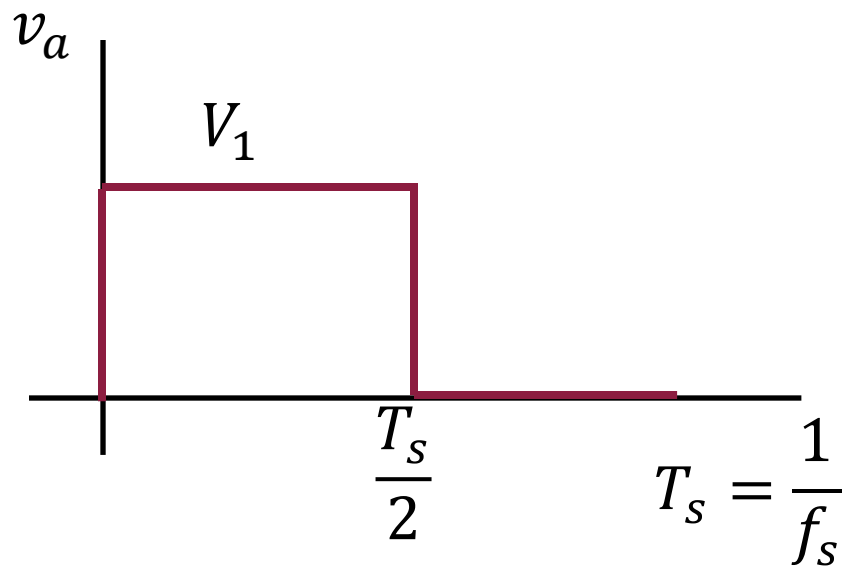
$$v_x = g_1 . V_1$$

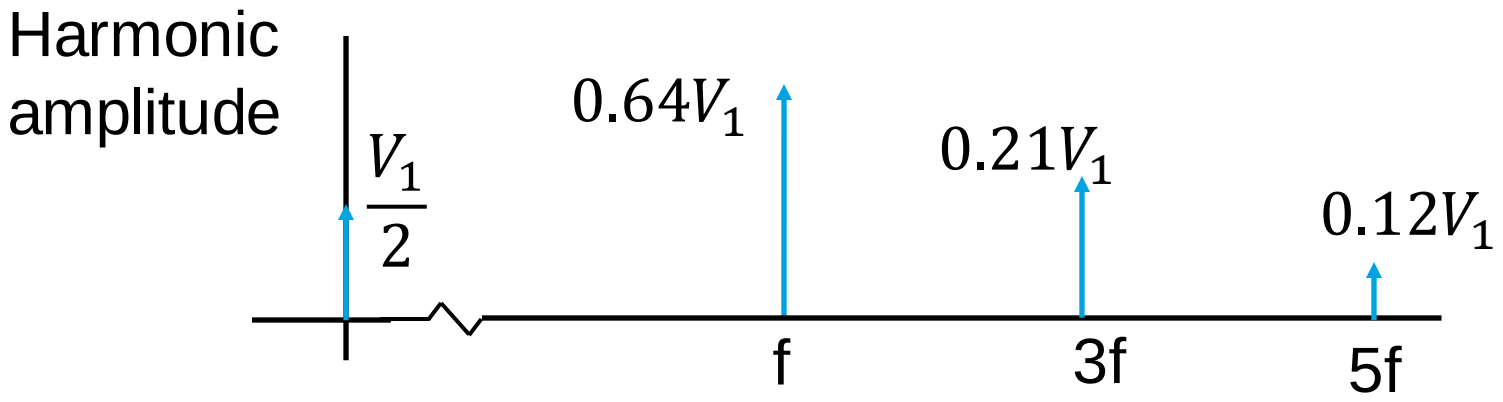




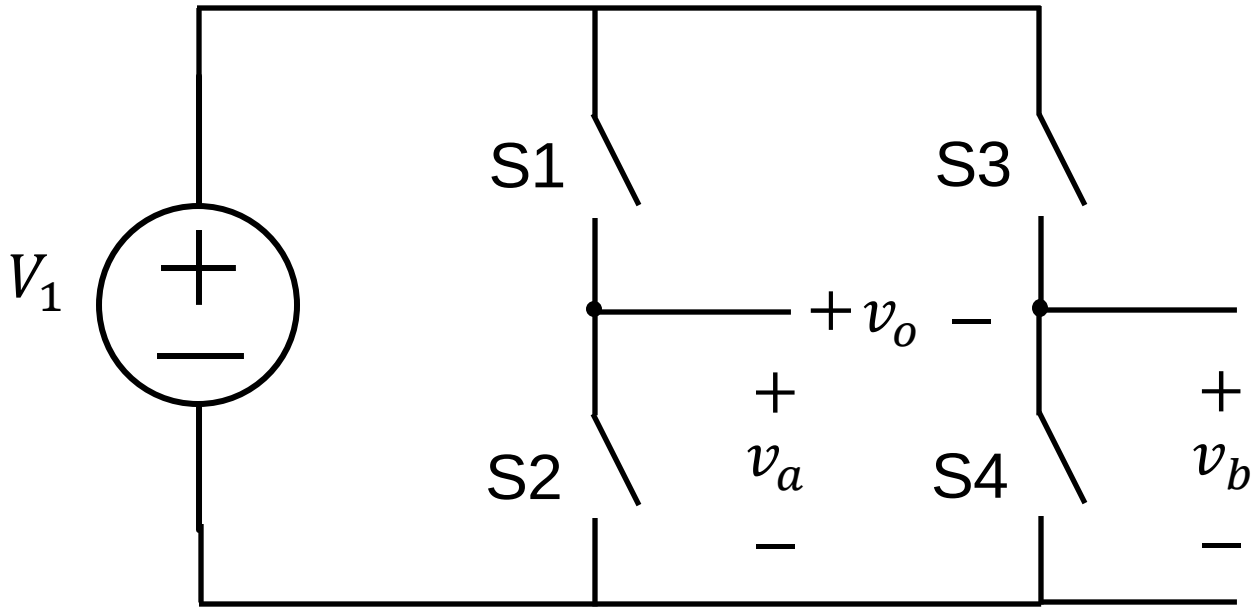
Half-Bridge Harmonics



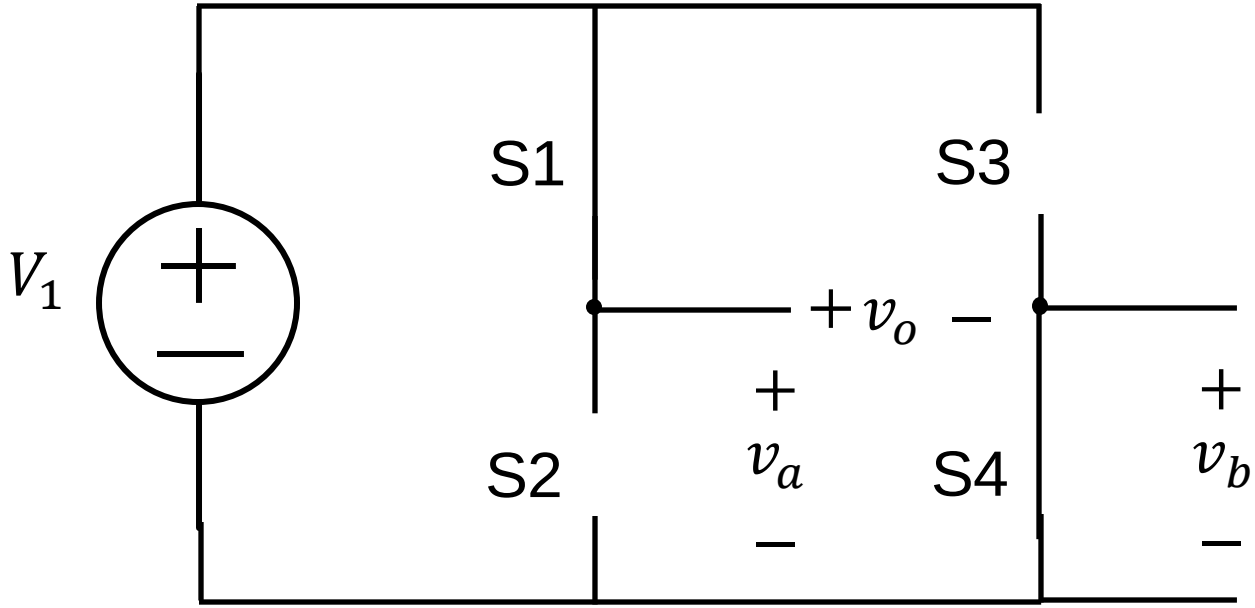


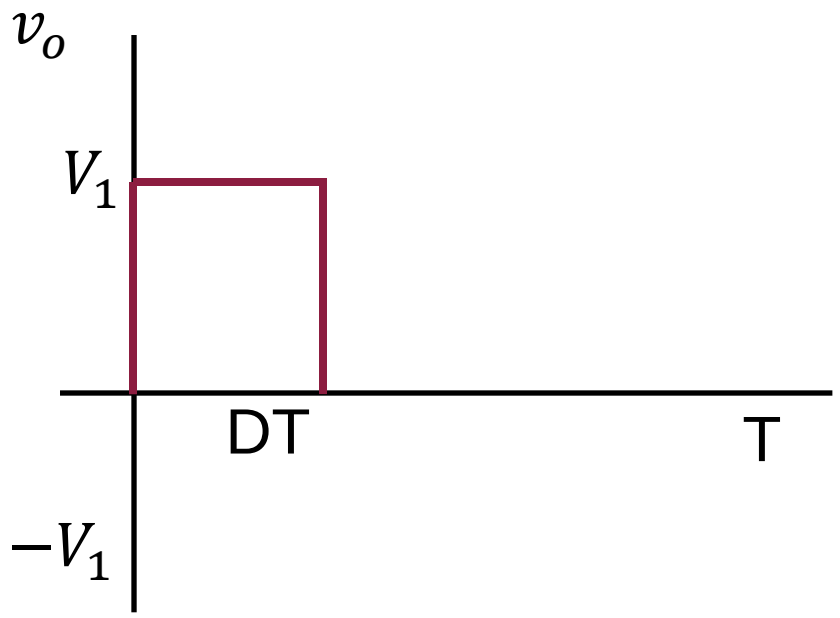


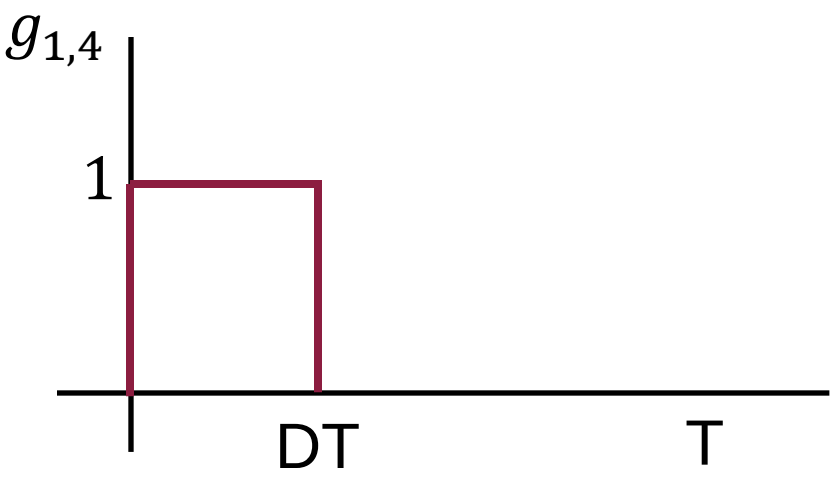
More Common: Full-Bridge Inverter

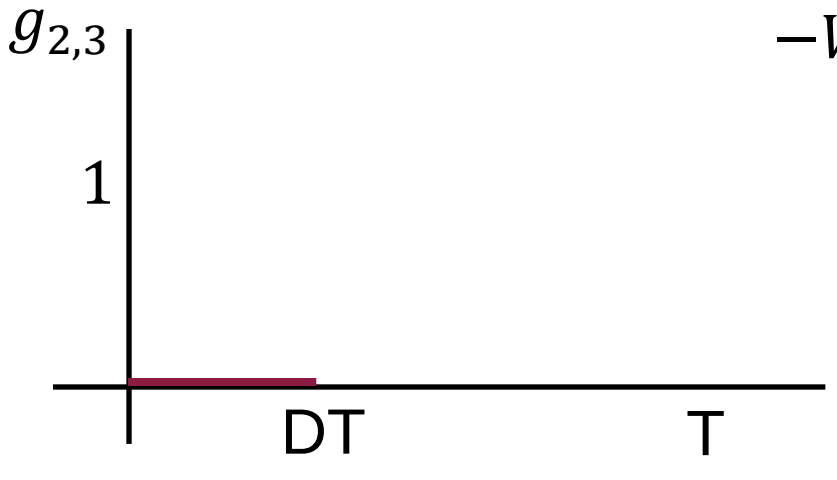


State 1: Positive Output Voltage

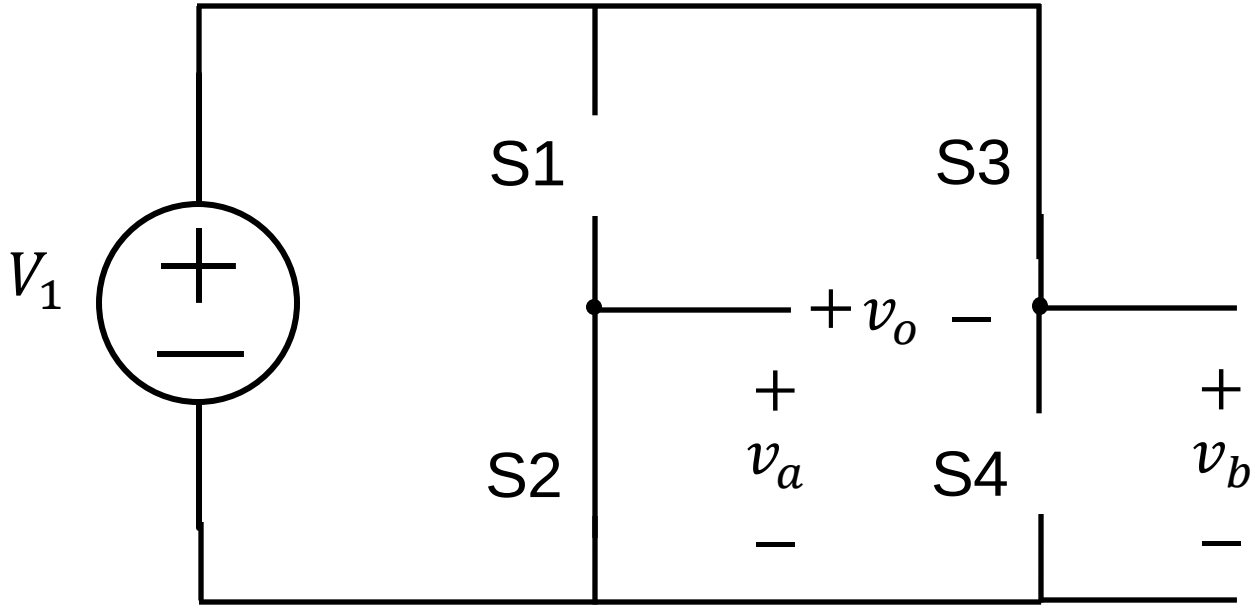


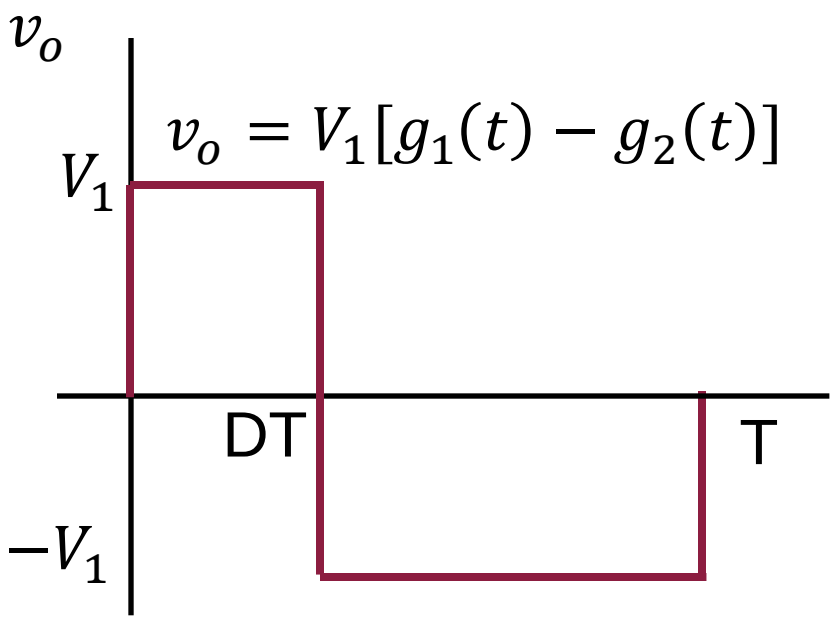


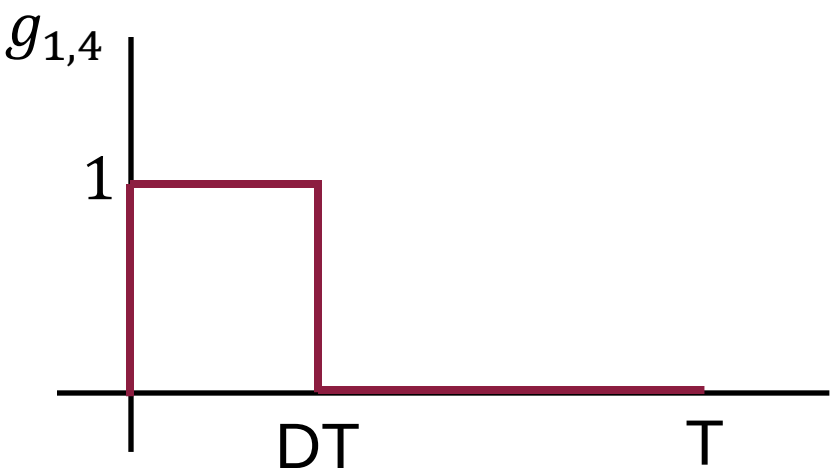


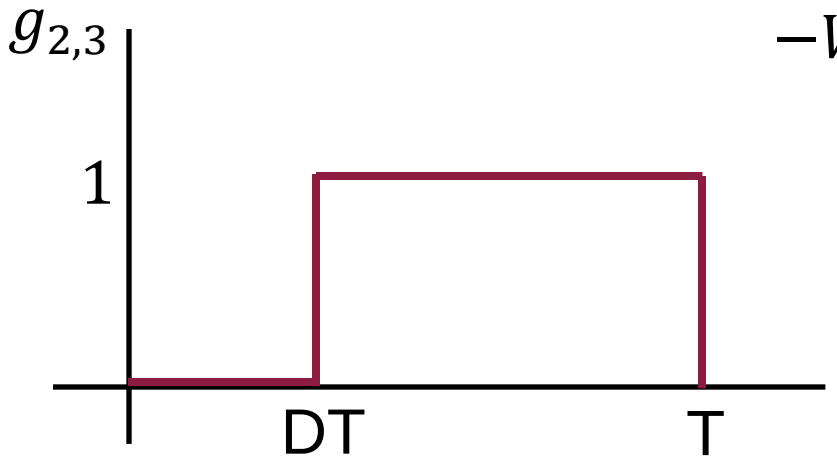


State 2: Negative Output Voltage

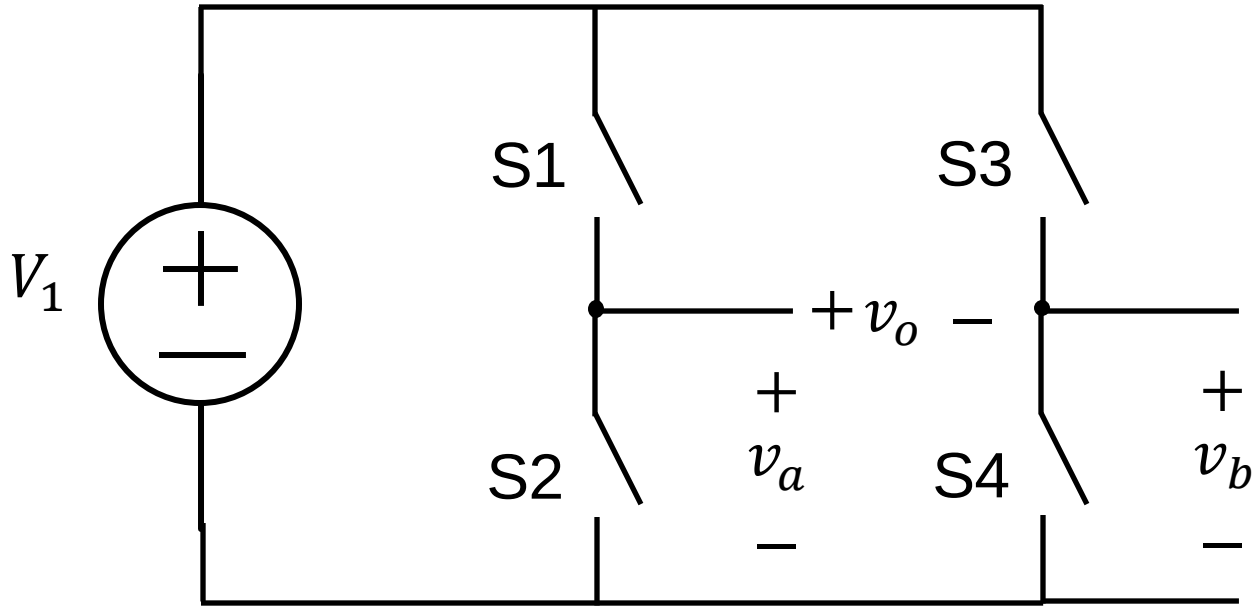


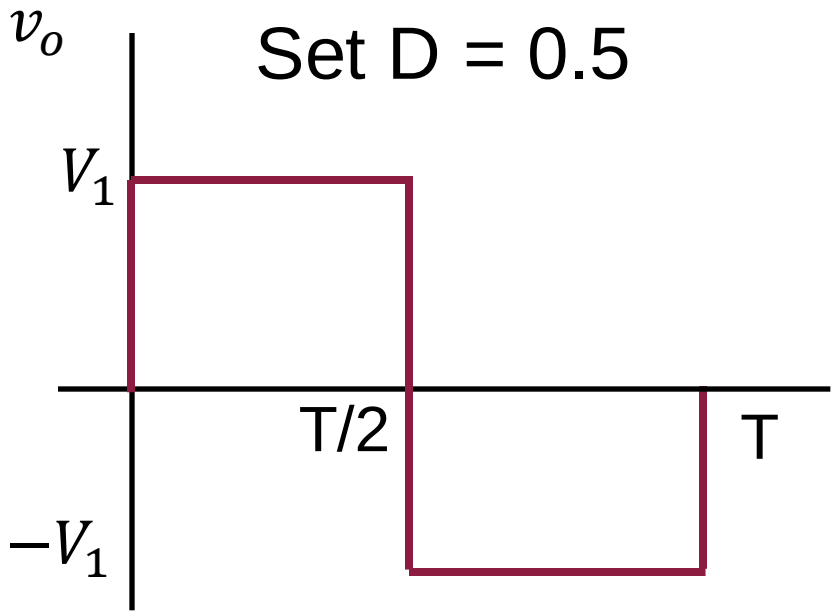


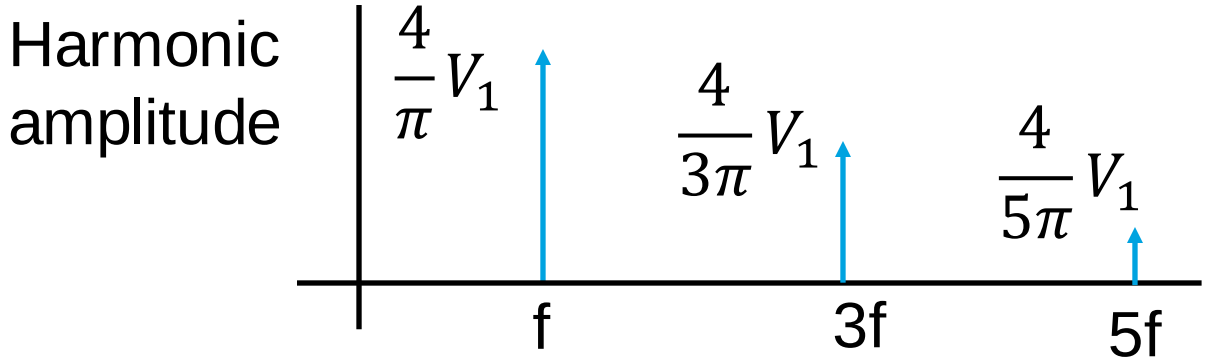




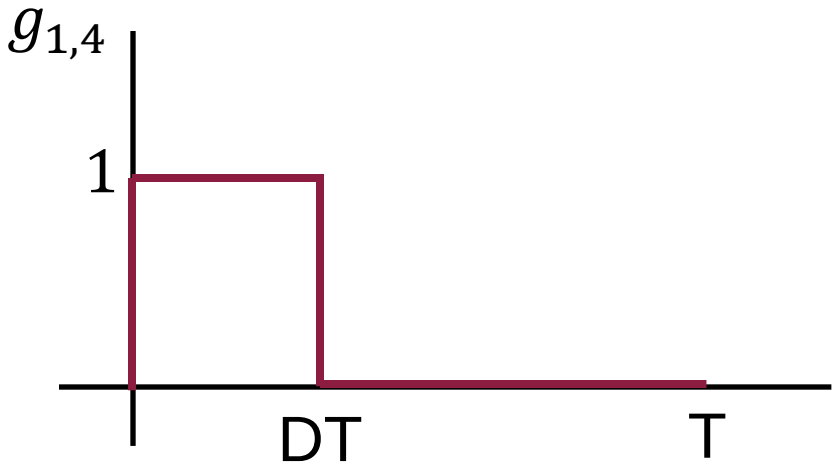
Simplest Operation: Square Wave



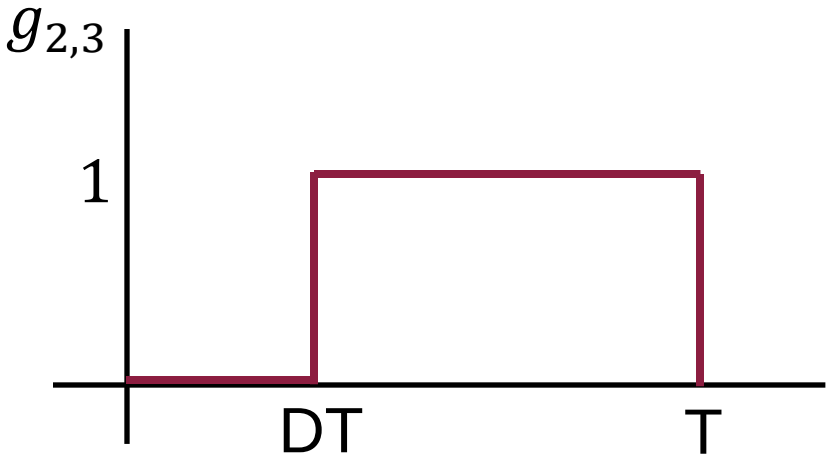




Interesting Duty Cycle Relationship



$$v_a = D + H.F.harmonics$$



$$v_b = 1 - D + H.F.harmonics$$

$$v_o = V_{dc}[2D - 1 + H.F.Harmonics]$$

Make “D” Vary Sinusoidally, Slowly

$$v_o = V_{dc}[(2D-1) + H.F.Harmonics]$$

Set $D(t) = \frac{1}{2} + \frac{m_a}{2}\cos(2\pi f_o t + \phi)$

Choose $f_o \ll f_s$

Make "D" Vary Sinusoidally, Slowly

$$v_o = V_{dc}[(2D-1) + H.F.Harmonics]$$

Set $D(t) = \frac{1}{2} + \frac{m_a}{2}\sin(2\pi f_o t + \phi)$

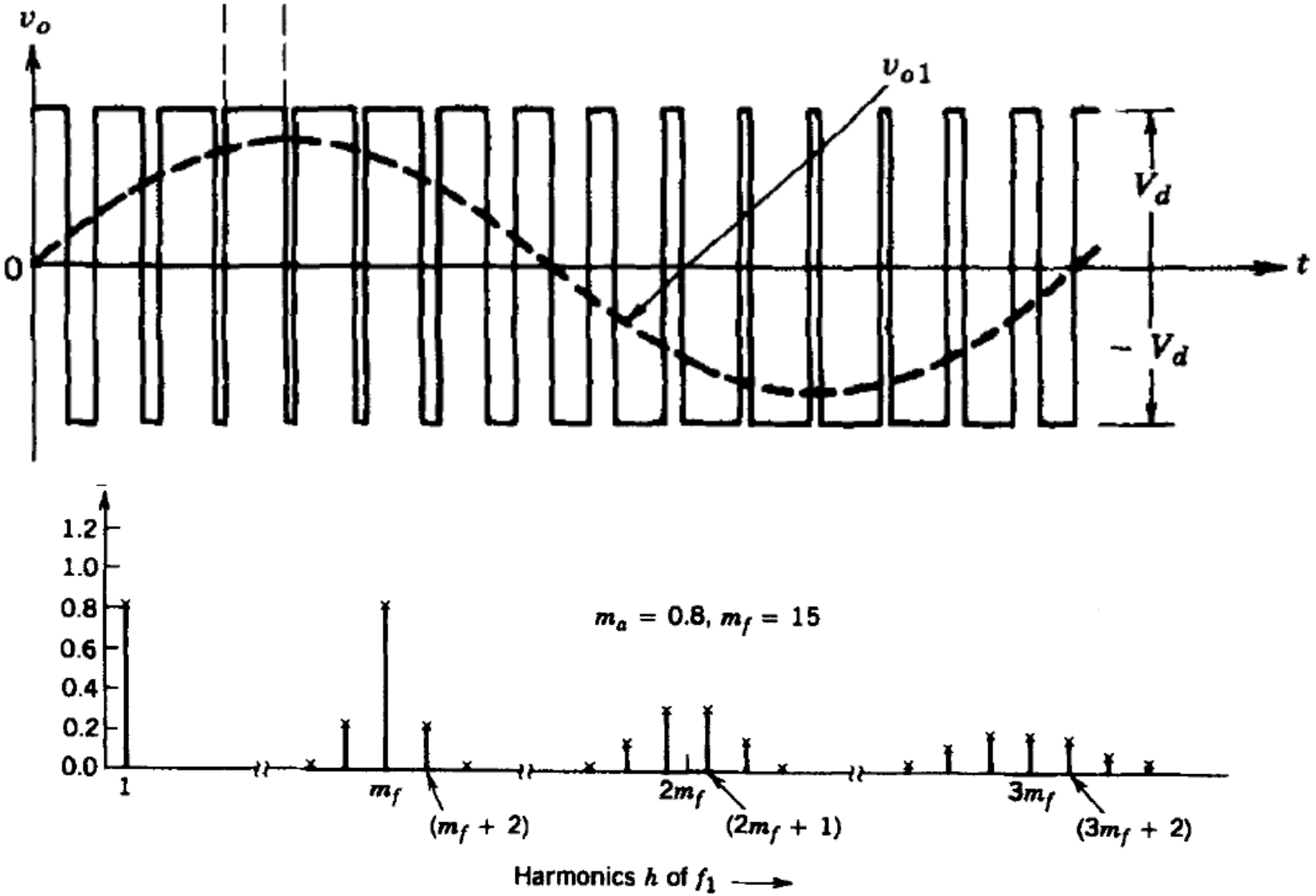
$m_A \in [0,1]$

Choose $f_o \ll f_s$

$$v_o = \underbrace{V_o m_a \sin(2\pi f_o t + \phi)} + H.F.harmonics$$

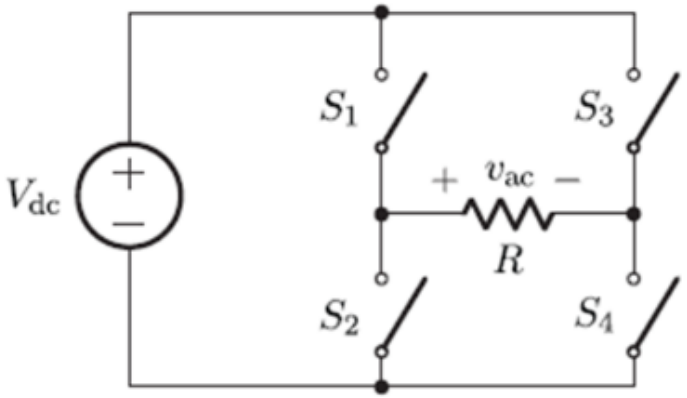
Low frequency sinusoid

SPWM Waveform and Harmonics

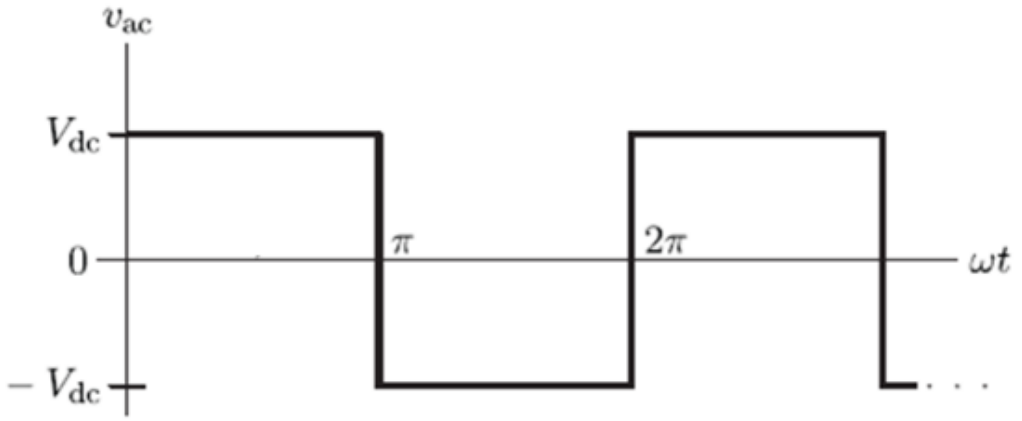


Mohan, Undeland, and Robbins, "Power Electronics - Converters, Applications, and Design", Wiley 2002. Fig. 8-5, 8-12

Simpler Inverter Control

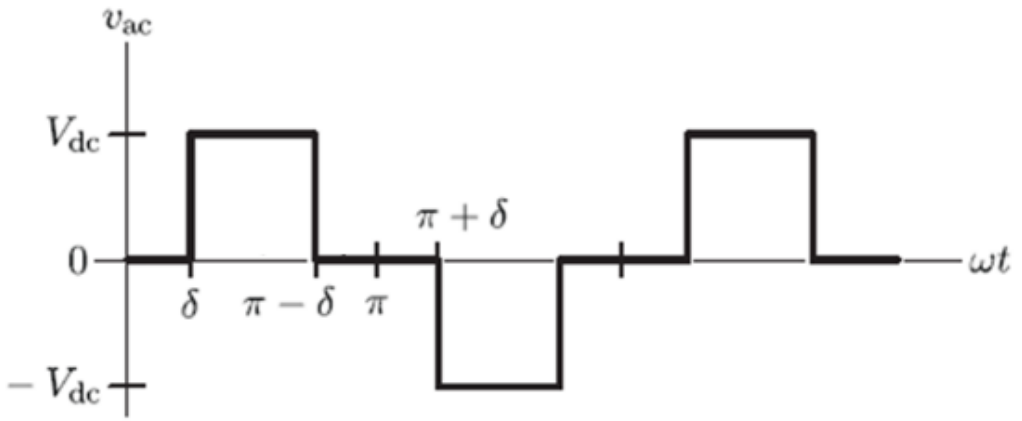


Full-bridge inverter



Square wave modulation

$$\frac{4V_{dc}}{\pi}\sin(\omega t)$$



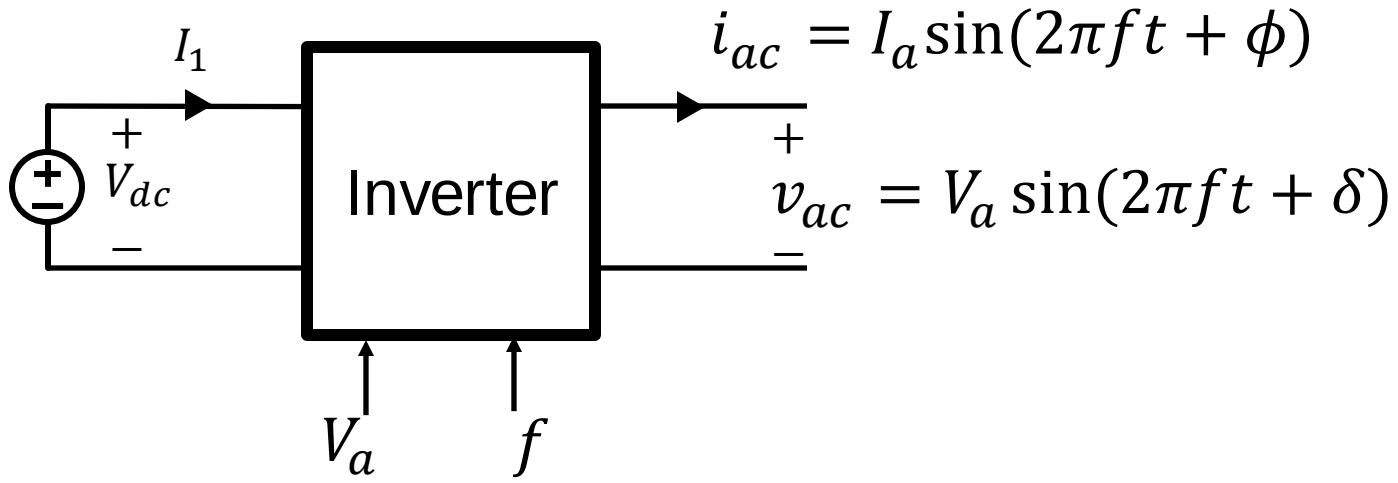
"Voltage cancellation" modulation

$$\frac{4V_{dc}}{\pi}\cos\delta\sin(\omega t)$$

$\delta = 30°$ eliminates all "triple-n" harmonics

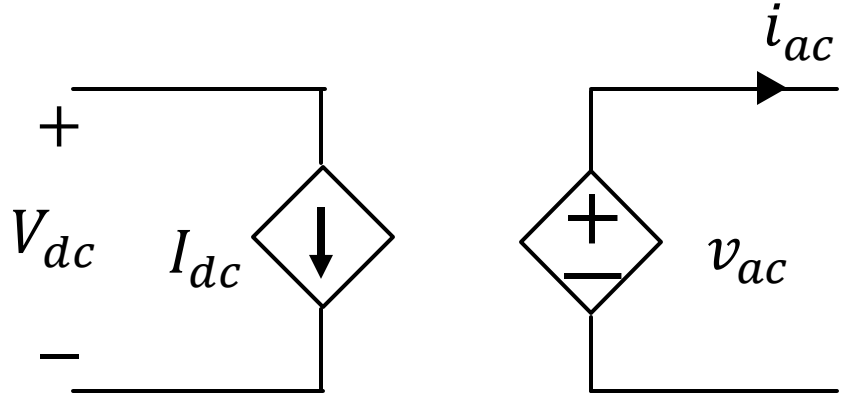
Averaged SPWM Inverter

Power equivalent model

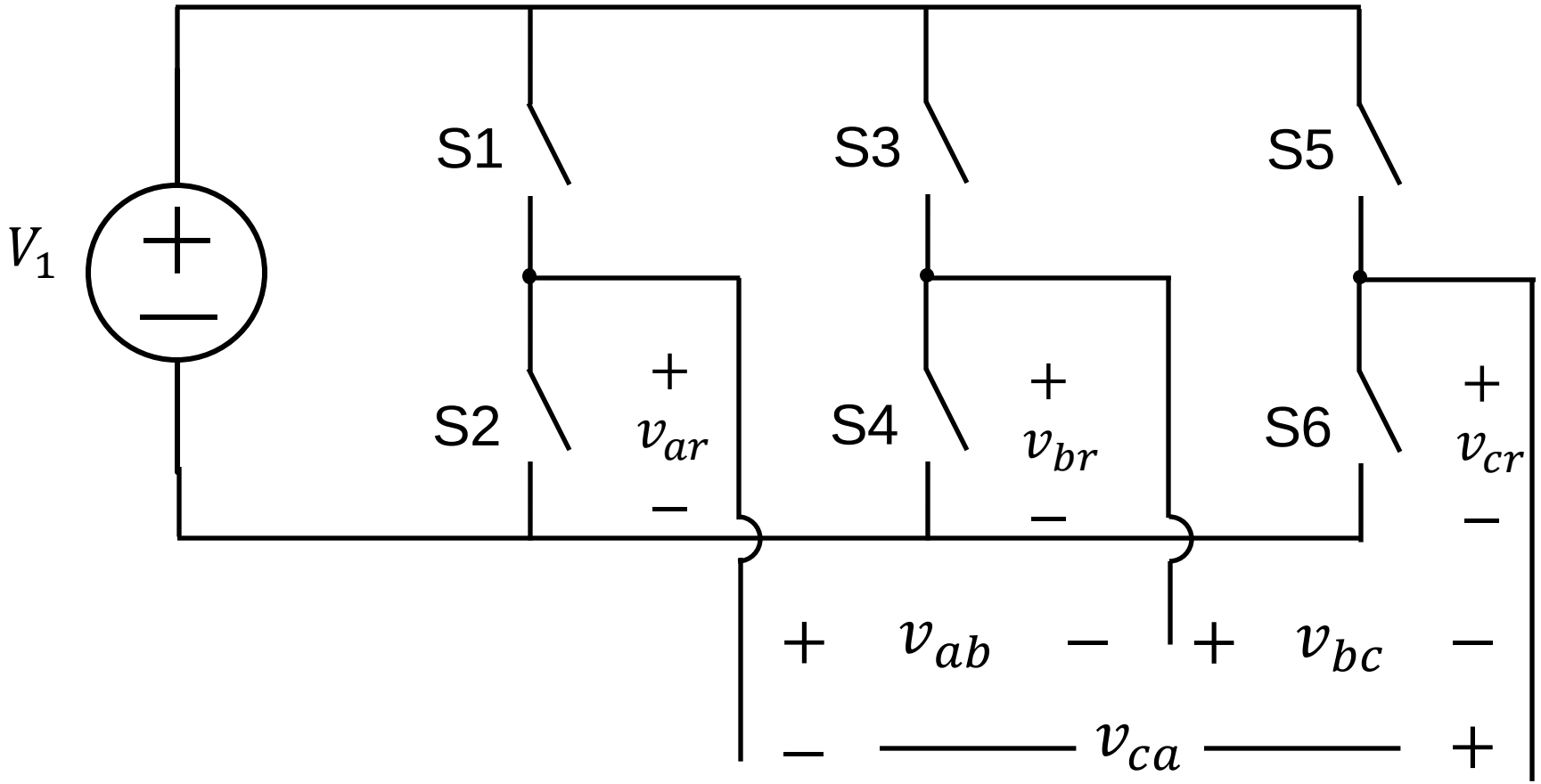


$$P_{in} = P_{out}$$

$$I_1 V_{dc} = \frac{\mathrm{V_a I_a}}{2} \cos(\delta - \phi)$$



Three-Phase PWM Inverter



SPWM Operation

- Operate each half-bridge 120 degrees out-of-phase

S1: $$D_1(t) = \frac{1}{2} + \frac{m_a}{2}\sin(2\pi f t)$$

S3: $$D_3(t) = \frac{1}{2} + \frac{m_a}{2}\sin(2\pi f t + 120^\circ)$$

S5: $$D_5(t) = \frac{1}{2} + \frac{m_a}{2}\sin(2\pi f t + 240^\circ)$$

SPWM Voltages

$$v_{ar} = \frac{V_{dc}}{2} + \frac{V_{dc} m_a}{2} \sin(2\pi f t) + H.F.harmonics$$

$$v_{br} = \frac{V_{dc}}{2} + \frac{V_{dc} m_a}{2} \sin(2\pi f t + 120^\circ) + H.F.harmonics$$

$$v_{cr} = \frac{V_{dc}}{2} + \frac{V_{dc} m_a}{2} \sin(2\pi f t + 240^\circ) + H.F.harmonics$$

Filtered SPWM Voltages

$$v_{ar} = \frac{V_{dc}}{2} + \frac{V_{dc} m_a}{2} \sin(2\pi f t) + H.F.harmonics$$

$$v_{br} = \frac{V_{dc}}{2} + \frac{V_{dc} m_a}{2} \sin(2\pi f t + 120°) + H.F.harmonics$$

$$v_{cr} = \frac{V_{dc}}{2} + \frac{V_{dc} m_a}{2} \sin(2\pi f t + 240°) + H.F.harmonics$$

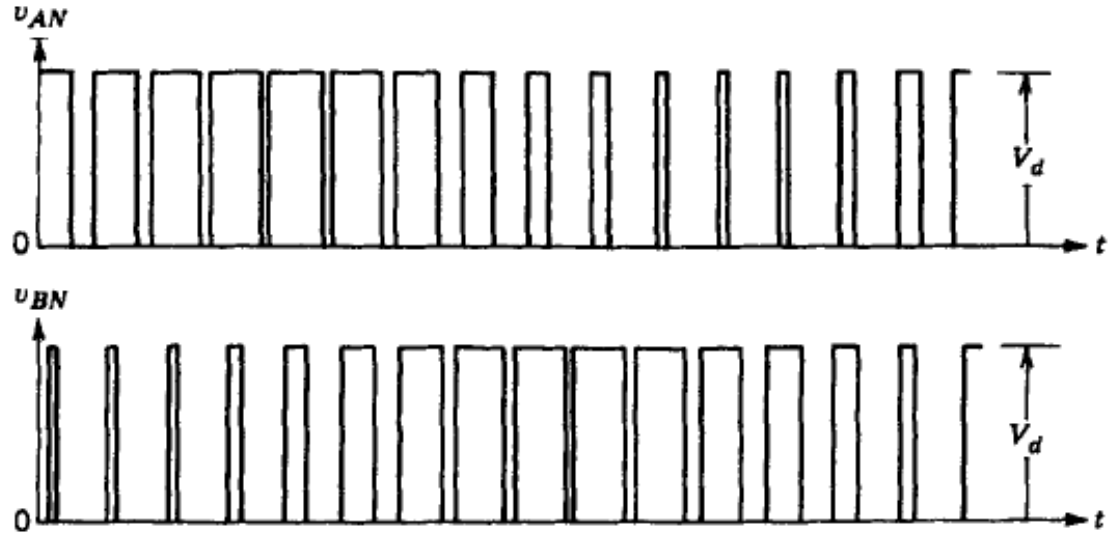
Filtered line-line voltages

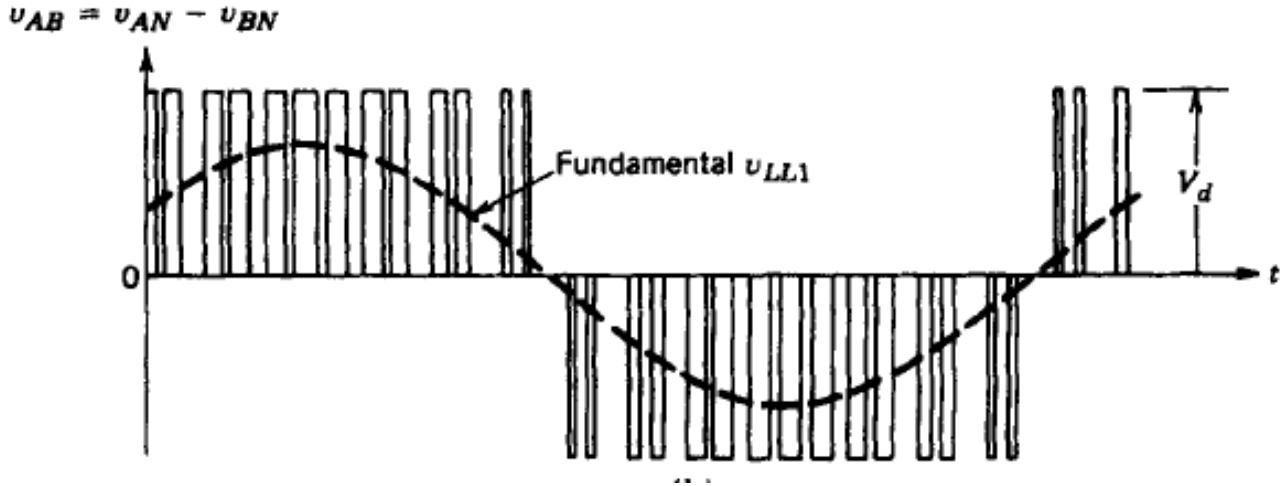
$$v_{ab} = \frac{\sqrt{3}V_{dc}m_a}{2}\sin(2\pi ft + 30^\circ)$$

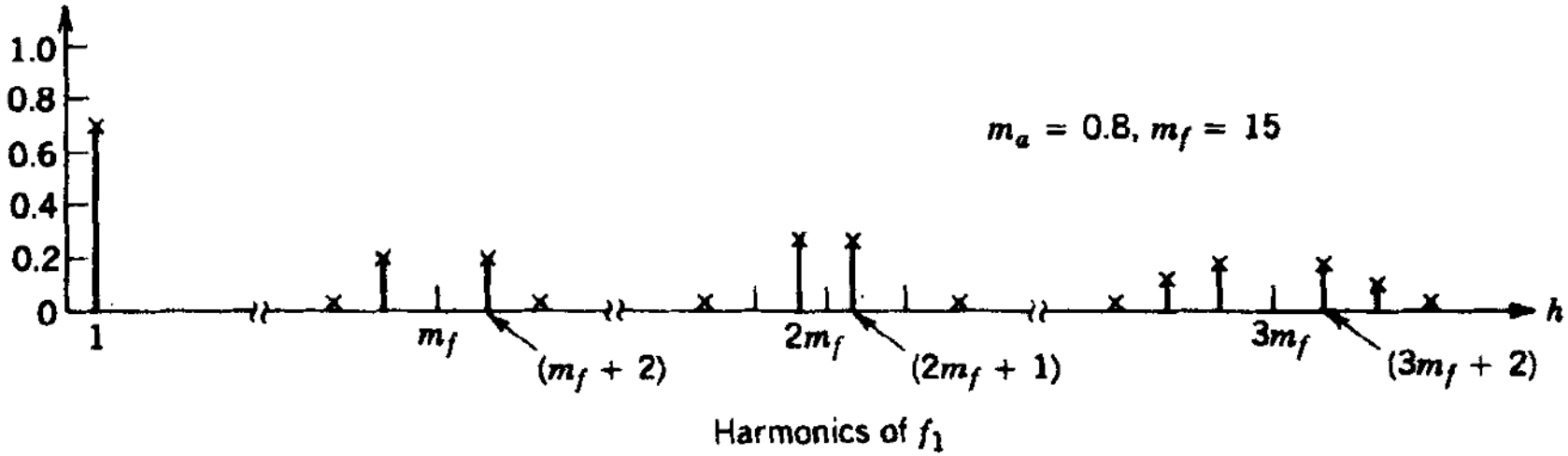
$$v_{bc} = \frac{\sqrt{3}V_{dc}m_a}{2}\sin(2\pi ft - 90^\circ)$$

$$v_{ca} = \frac{\sqrt{3}V_{dc}m_a}{2}\sin(2\pi ft - 210^\circ)$$

Waveforms and Harmonics

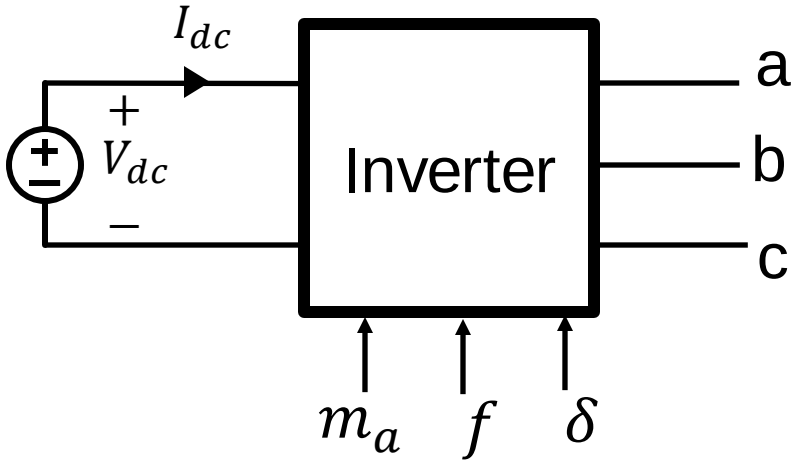


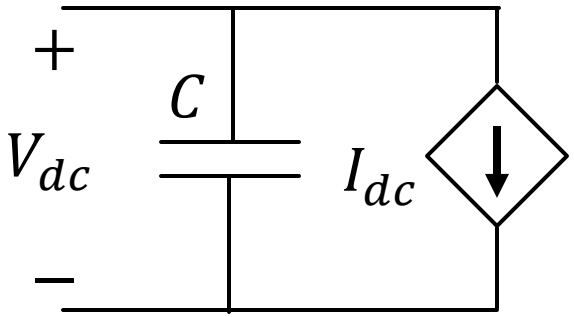


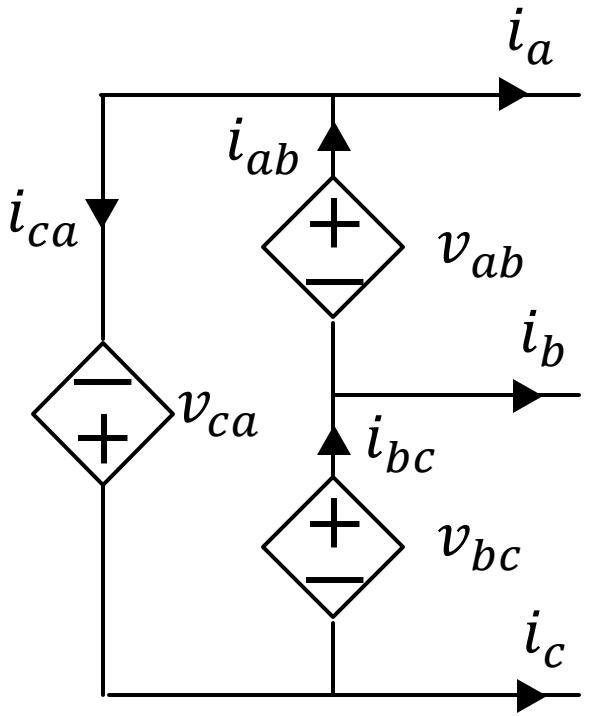


Mohan, Undeland, and Robbins, "Power Electronics - Converters, Applications, and Design", Wiley 2002. Fig. 8-22

Averaged SPWM Three-Phase Inverter







Enforce power balance

$$P_{in} = P_{out}$$

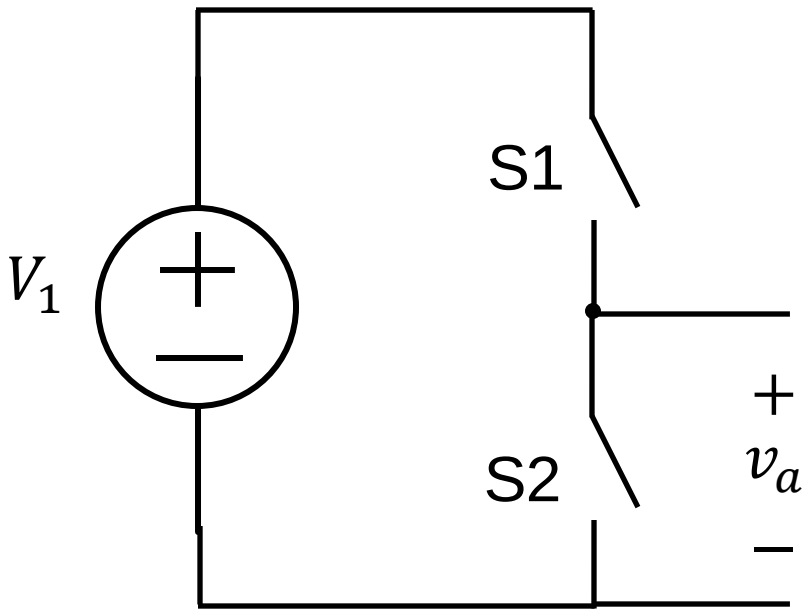
$$I_{dc}V_{dc} = P_{ac}$$

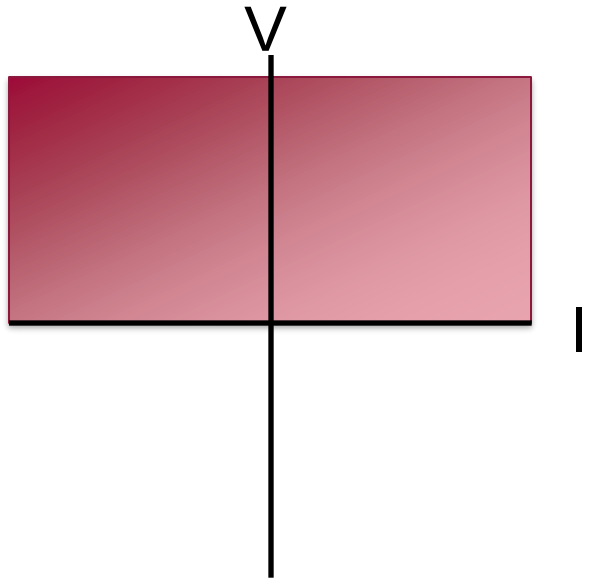
$$v_{ab} = \frac{\sqrt{3}V_{dc}m_a}{2}\sin(2\pi ft + 30^\circ + \delta)$$

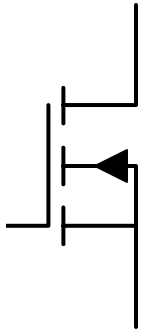
$$v_{bc} = \frac{\sqrt{3}V_{dc}m_a}{2}\sin(2\pi ft - 90^\circ + \delta)$$

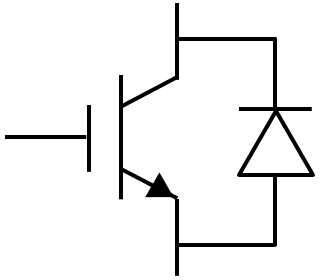
$$v_{ca} = \frac{\sqrt{3}V_{dc}m_a}{2}\sin(2\pi ft - 210^\circ + \delta)$$

Switches: IGBTs or MOSFETs









Conclusion

- The half-bridge is a key inverter component
- A single-phase full-bridge converter comprises two half-bridges
- Three-phase inverter comprises three half-bridges
- Averaged models allow us to more simply analyze inverter at the system-level

- Higher power inverters switch at lower frequencies (e.g. 100MW, 5kHz vs. 100W, 1MHz owing to switch limitations)