# Chapter 6. Converter Circuits

6.1. Circuit manipulations

6.2. A short list of converters

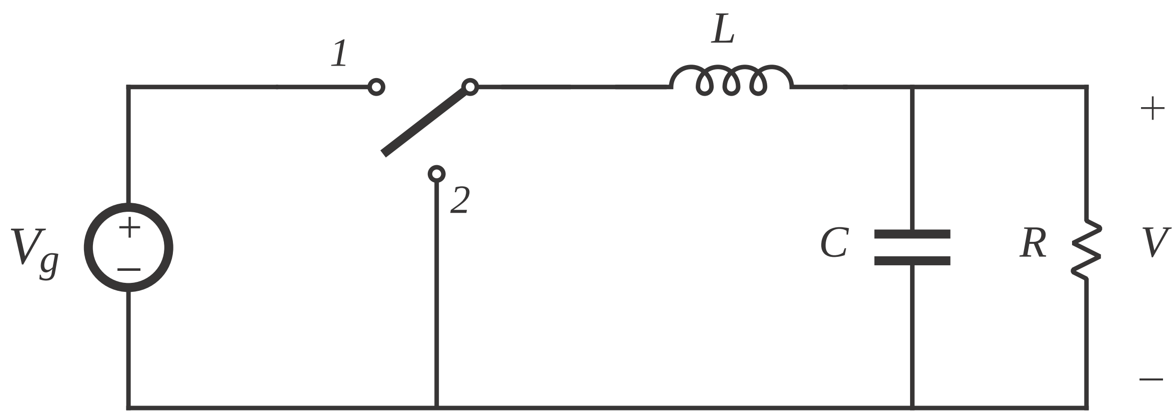
6.3. Transformer isolation

6.4. Converter evaluation and design

6.5. Summary of key points

- Where do the boost, buck-boost, and other converters originate?
- How can we obtain a converter having given desired properties?
- What converters are possible?
- How can we obtain transformer isolation in a converter?
- For a given application, which converter is best?

# 6.1. Circuit manipulations



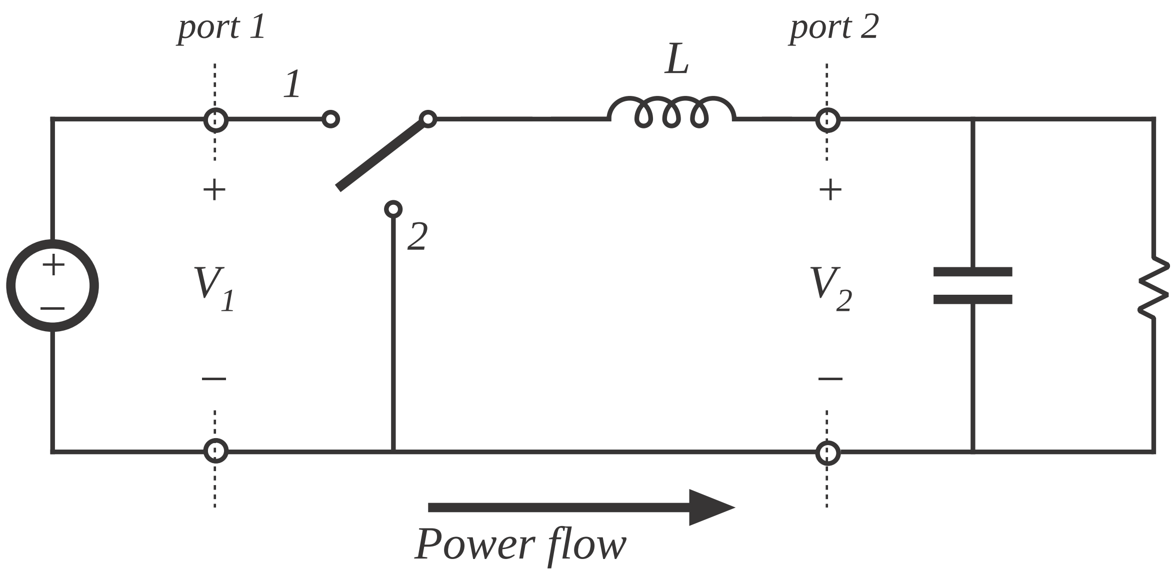

Begin with buck converter: derived in chapter 1 from first principles

- Switch changes dc component, low-pass filter removes switching harmonics
- Conversion ratio is $M = D$

# 6.1.1. Inversion of source and load

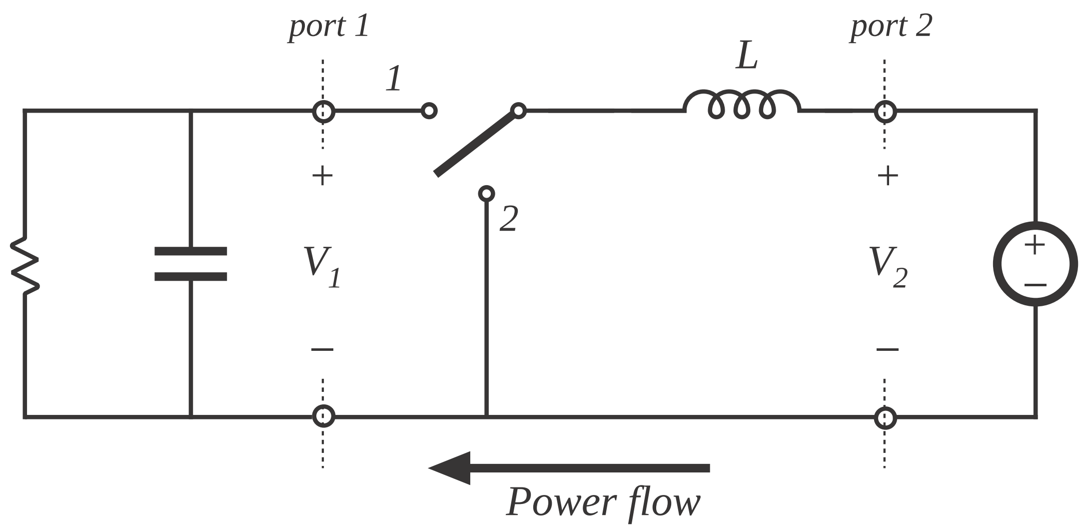
Interchange power input and output ports of a converter

Buck converter example $$V_2 = DV_1$$



# Inversion of source and load

Interchange power source and load:

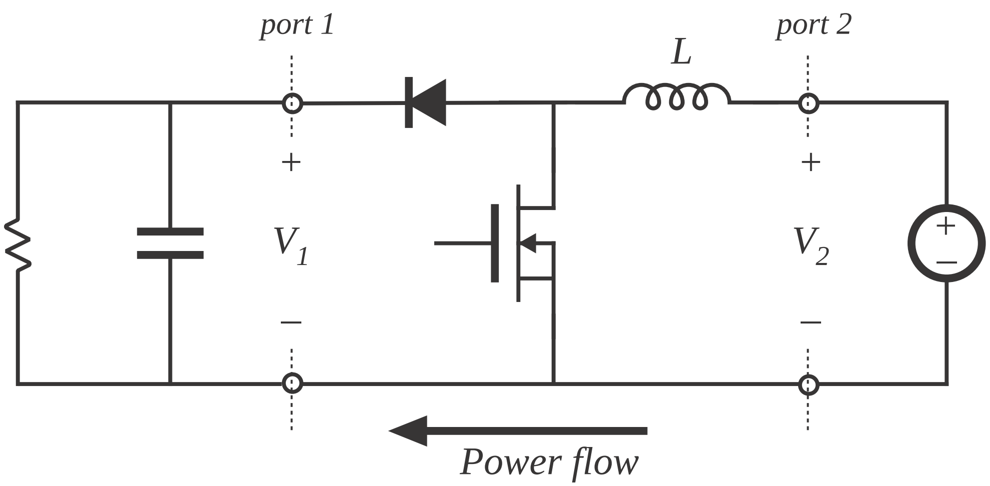



$$V_2 = DV_1 \qquad V_1 = \frac{1}{D} V_2$$

# Realization of switches as in chapter 4

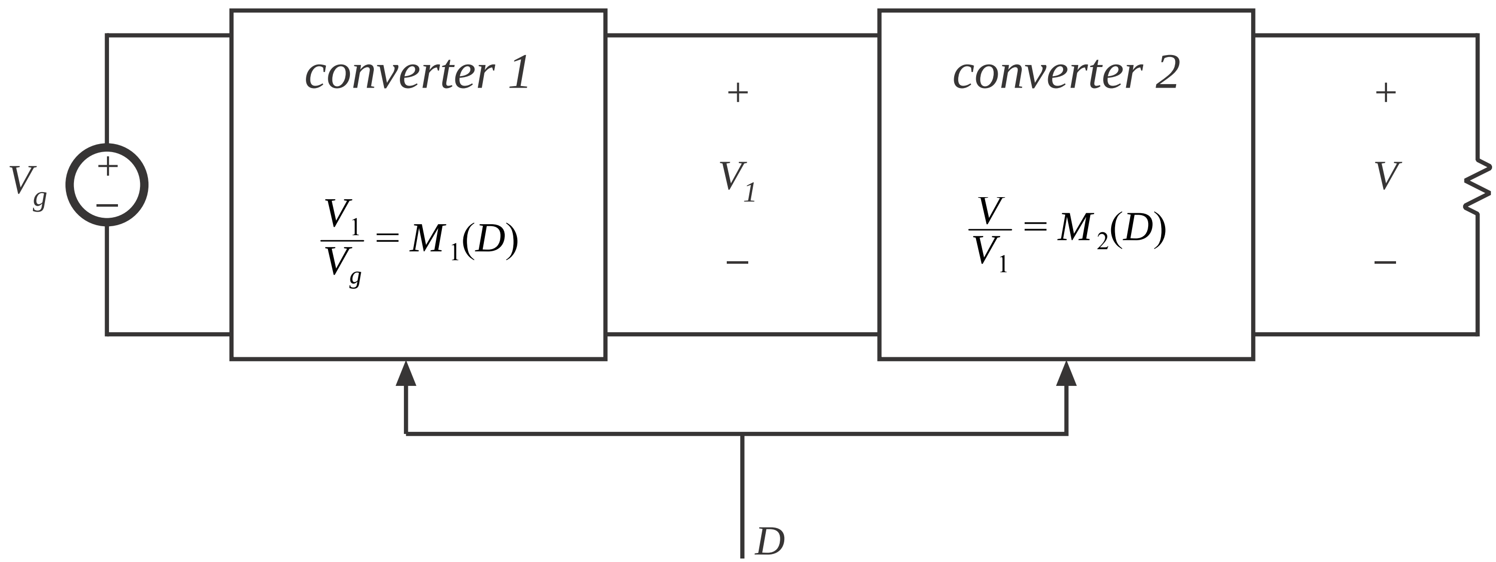
- Reversal of power flow requires new realization of switches
- Transistor conducts when switch is in position 2
- Interchange of $D$ and $D'$

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




Inversion of buck converter yields boost converter

# 6.1.2. Cascade connection of converters

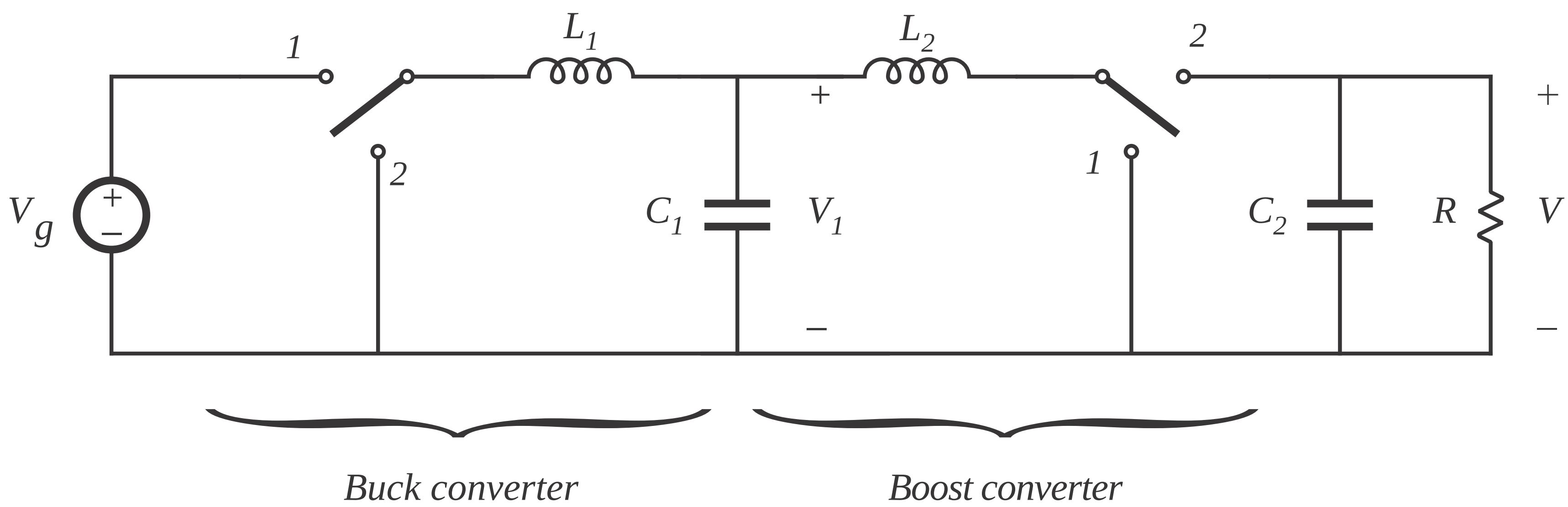



$$V_1 = M_1(D)\, V_g$$

$$V = M_2(D)\, V_1$$

$$\frac{V}{V_g} = M(D) = M_1(D)\, M_2(D)$$

# Example: buck cascaded by boost



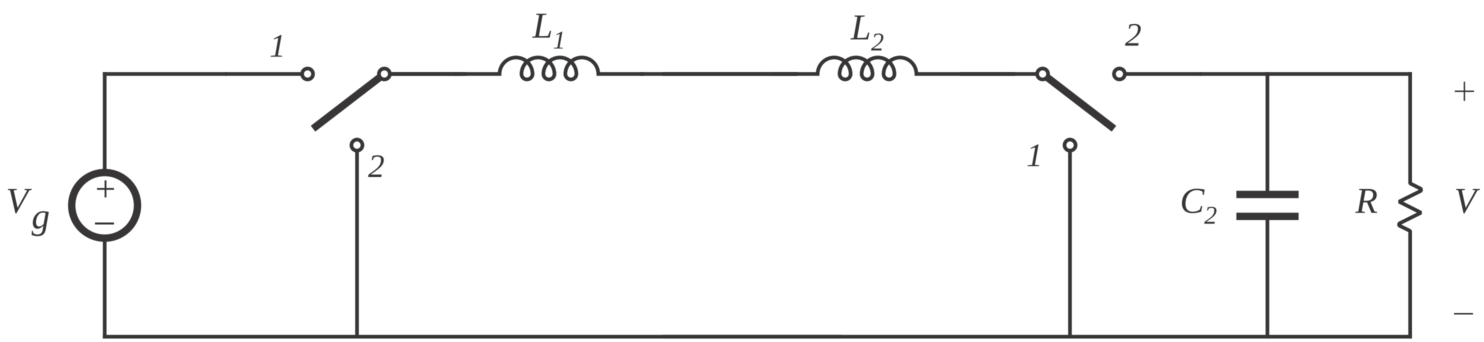

$$\frac{V_1}{V_g} = D$$

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

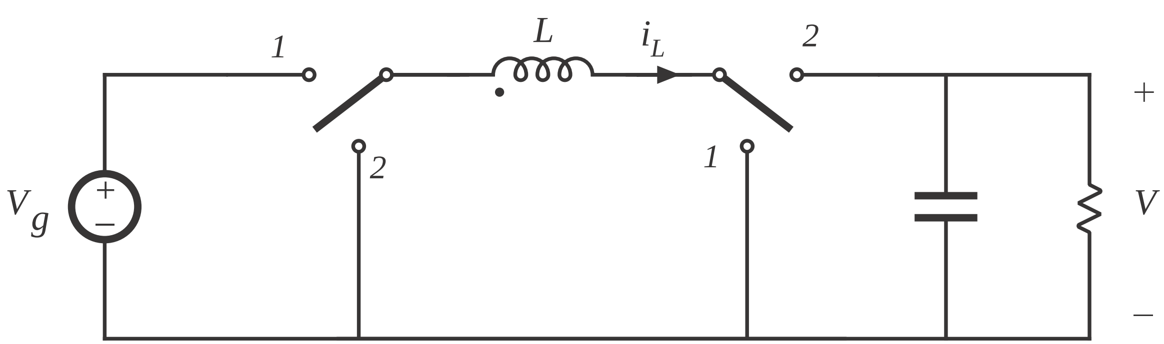
$$\longrightarrow \quad \frac{V}{V_g} = \frac{D}{1-D}$$

# Buck cascaded by boost: simplification of internal filter

remove capacitor $C_1$

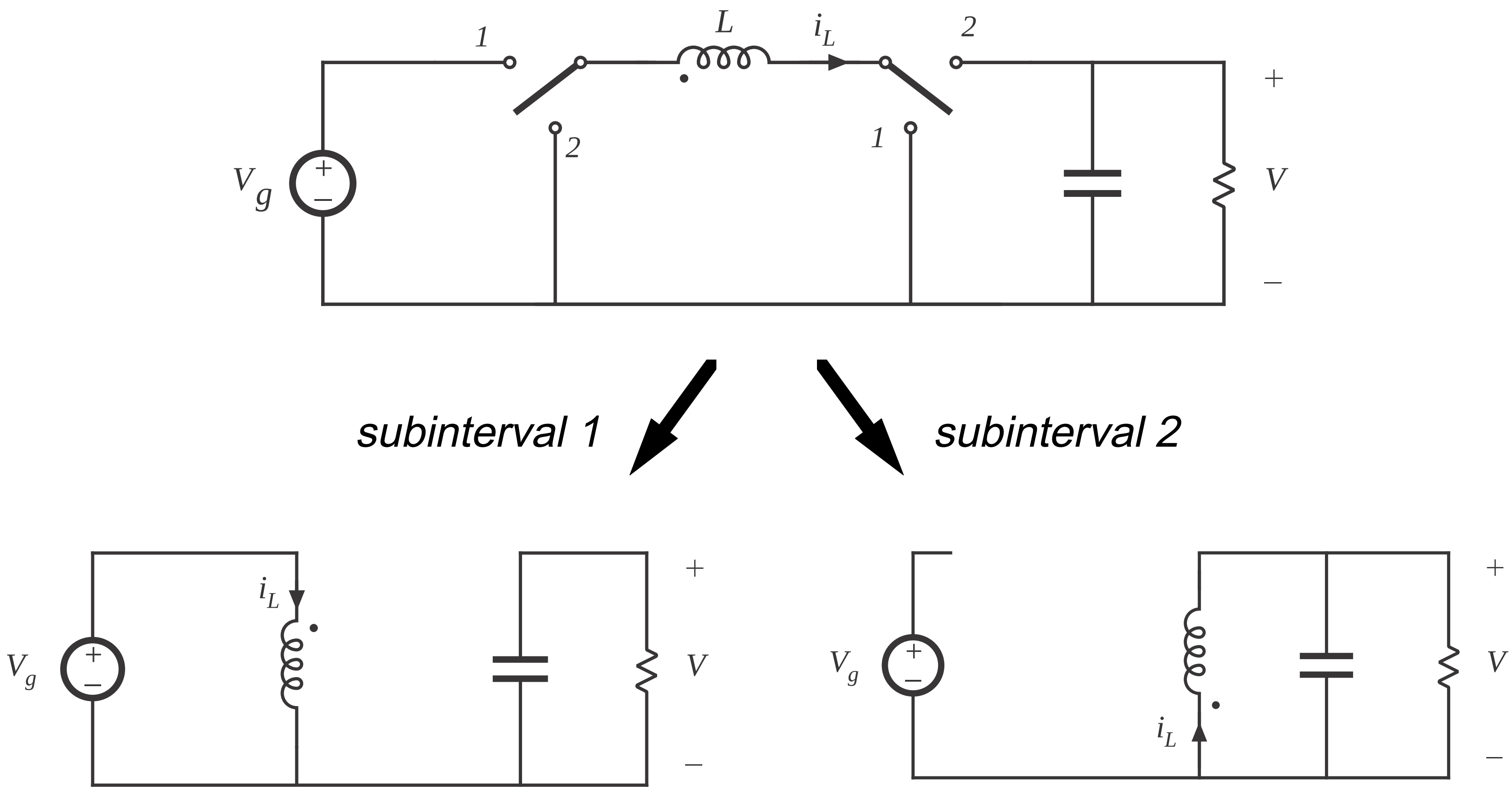



combine inductors $L_1$ and $L_2$




*Noninverting buck-boost converter*

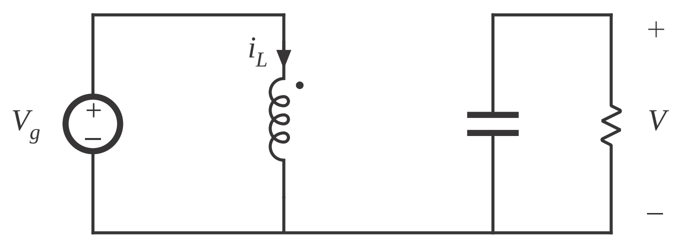
# Noninverting buck-boost converter

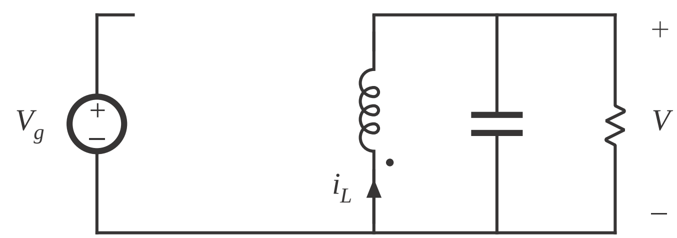


# Reversal of output voltage polarity

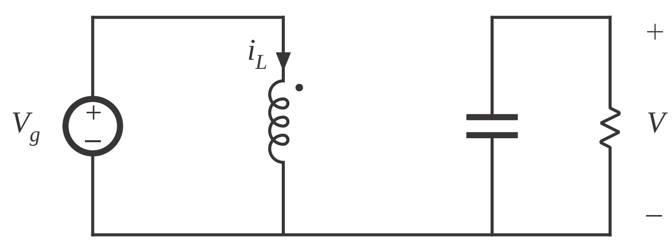
*subinterval 1* | *subinterval 2*

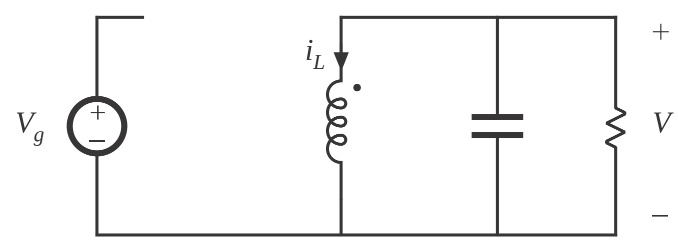
*noninverting buck-boost*



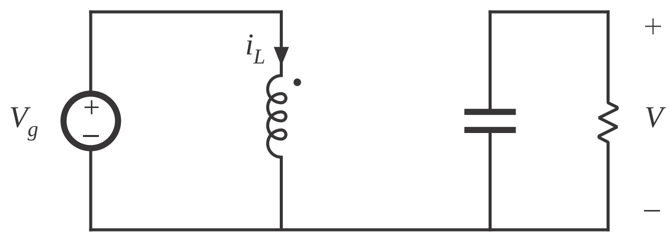

*inverting buck-boost*



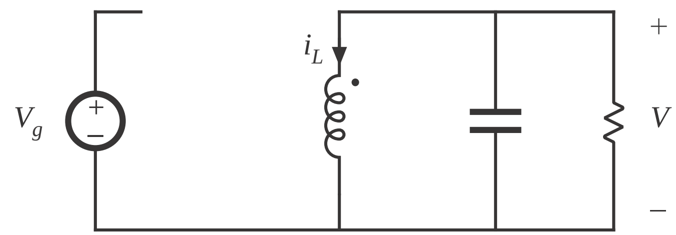



# Reduction of number of switches: inverting buck-boost

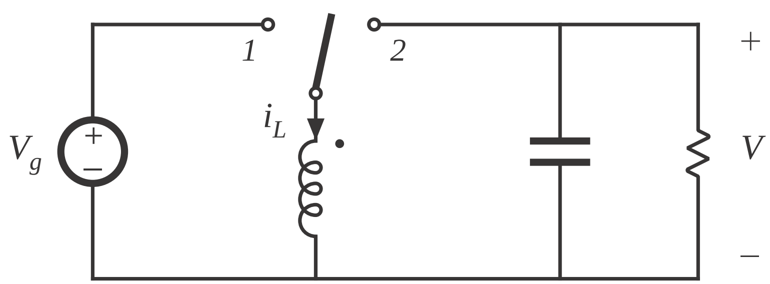
*subinterval 1*




*subinterval 2*




One side of inductor always connected to ground — hence, only one SPDT switch needed:




$$\frac{V}{V_g} = -\frac{D}{1-D}$$

# Discussion: cascade connections

- Properties of buck-boost converter follow from its derivation as buck cascaded by boost

  Equivalent circuit model: buck 1:$D$ transformer cascaded by boost $D'$:1 transformer

  Pulsating input current of buck converter

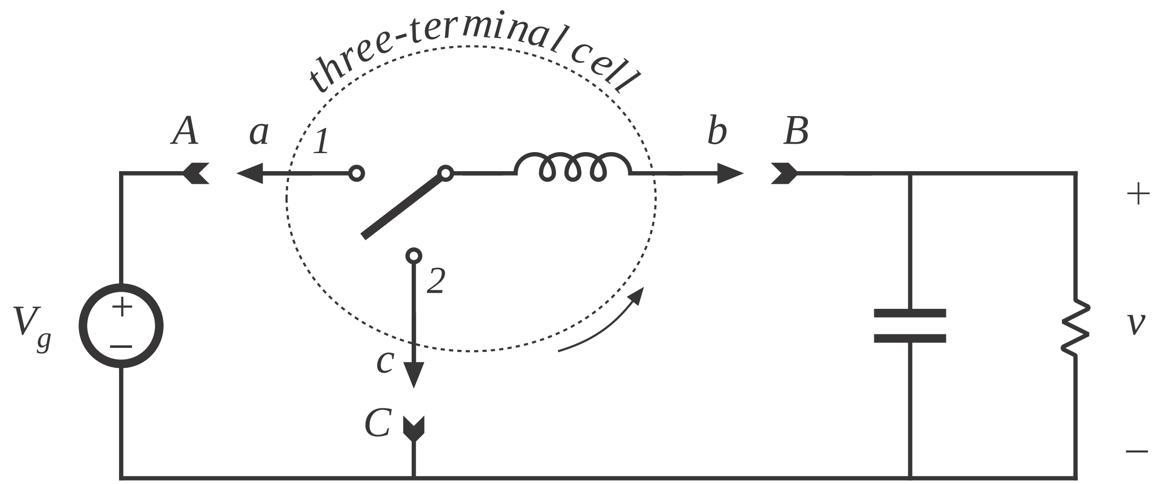
  Pulsating output current of boost converter

- Other cascade connections are possible

  Cuk converter: boost cascaded by buck

# 6.1.3. Rotation of three-terminal cell

Treat inductor and SPDT switch as three-terminal cell:

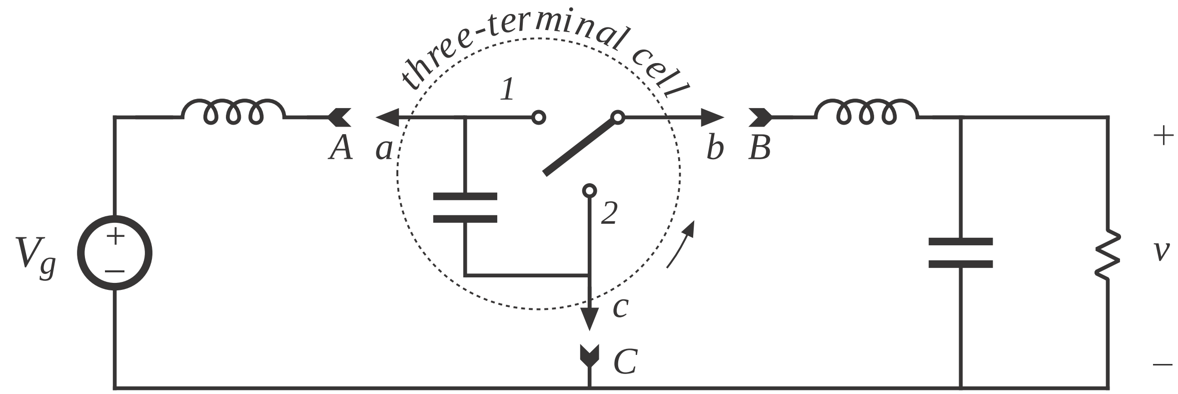



Three-terminal cell can be connected between source and load in three nontrivial distinct ways:

| | |
|---|---|
| a-A b-B c-C | buck converter |
| a-C b-A c-B | boost converter |
| a-A b-C c-B | buck-boost converter |

# Rotation of a dual three-terminal network

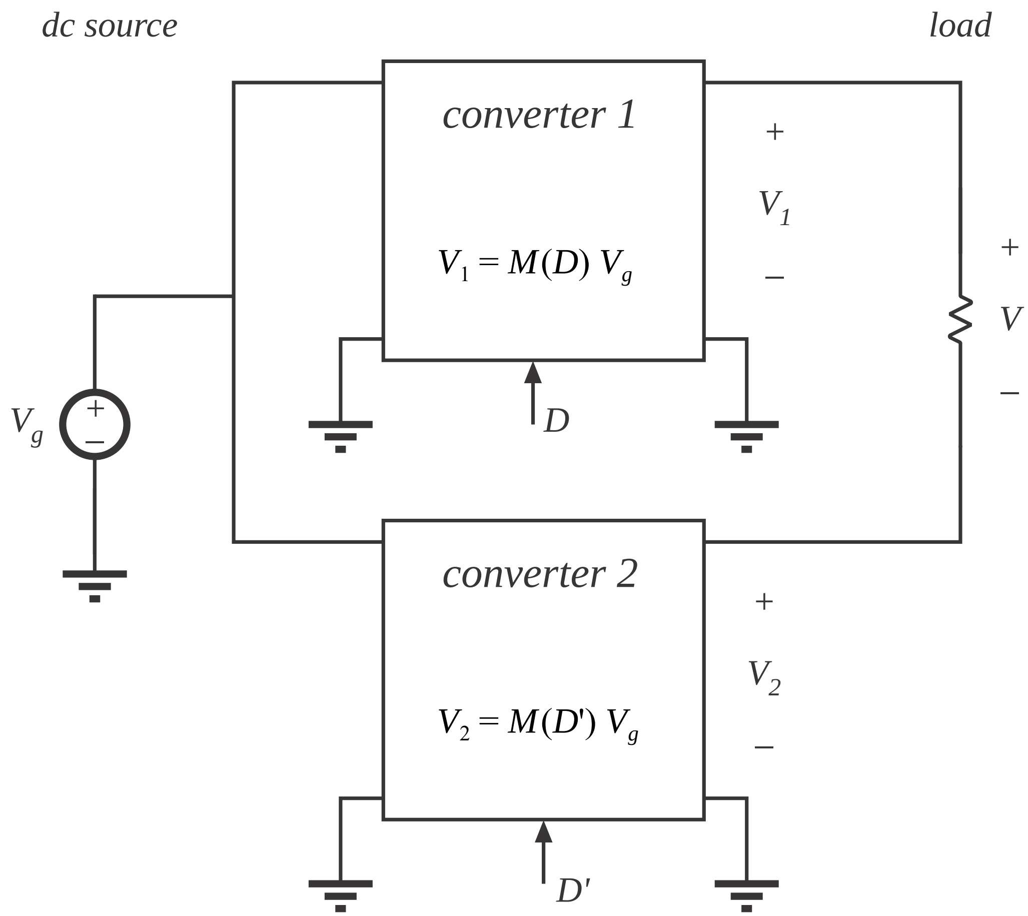
A capacitor and SPDT switch as a three-terminal cell:




Three-terminal cell can be connected between source and load in three nontrivial distinct ways:

| | |
|---|---|
| a-A b-B c-C | buck converter with L-C input filter |
| a-C b-A c-B | boost converter with L-C output filter |
| a-A b-C c-B | Cuk converter |

# 6.1.4. Differential connection of load to obtain bipolar output voltage

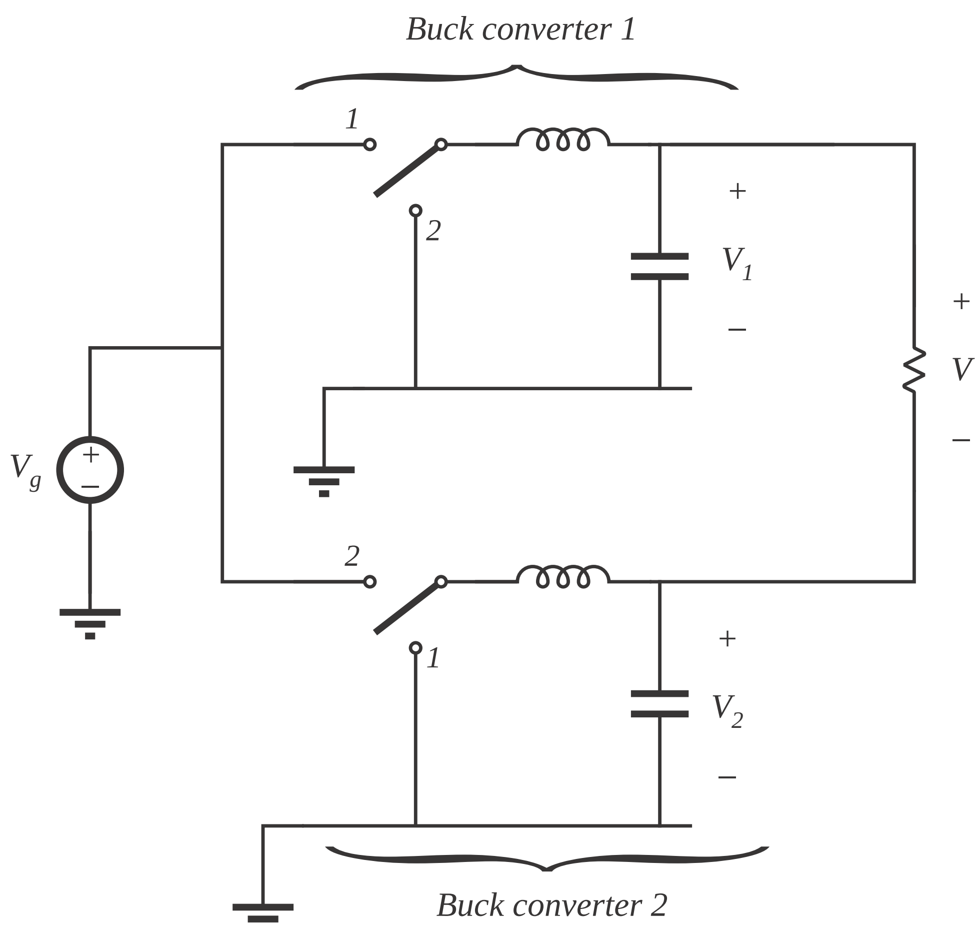



Differential load voltage is

$$V = V_1 - V_2$$

The outputs $V_1$ and $V_2$ may both be positive, but the differential output voltage $V$ can be positive or negative.

# Differential connection using two buck converters




Converter #1 transistor driven with duty cycle $D$

Converter #2 transistor driven with duty cycle complement $D'$

Differential load voltage is

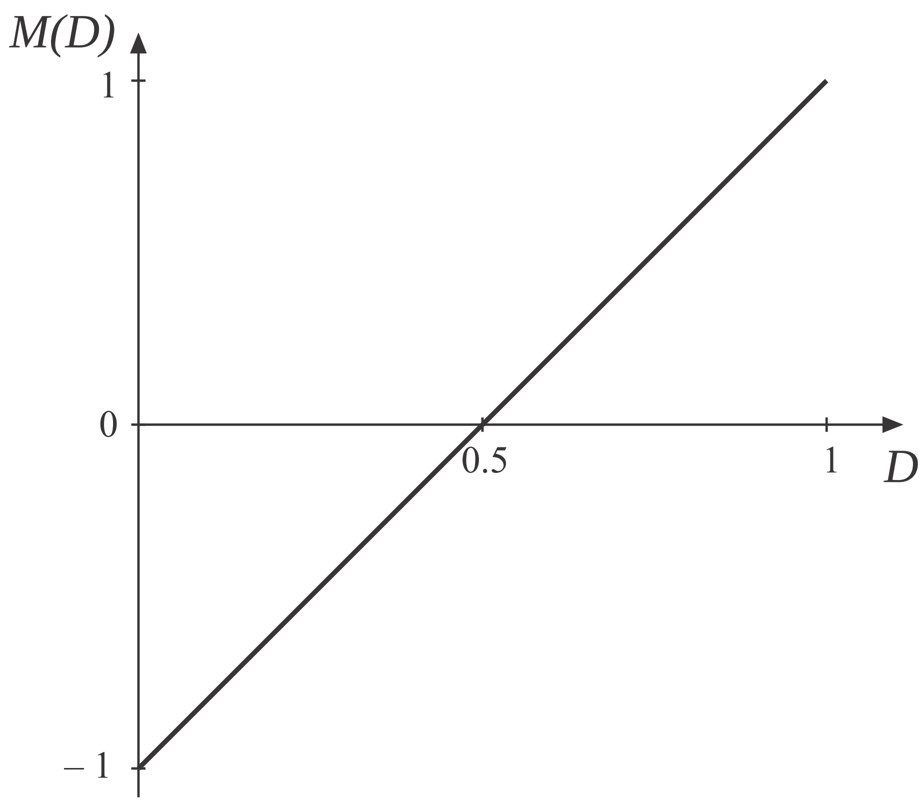
$$V = DV_g - D'V_g$$

Simplify:

$$V = (2D - 1)\, V_g$$

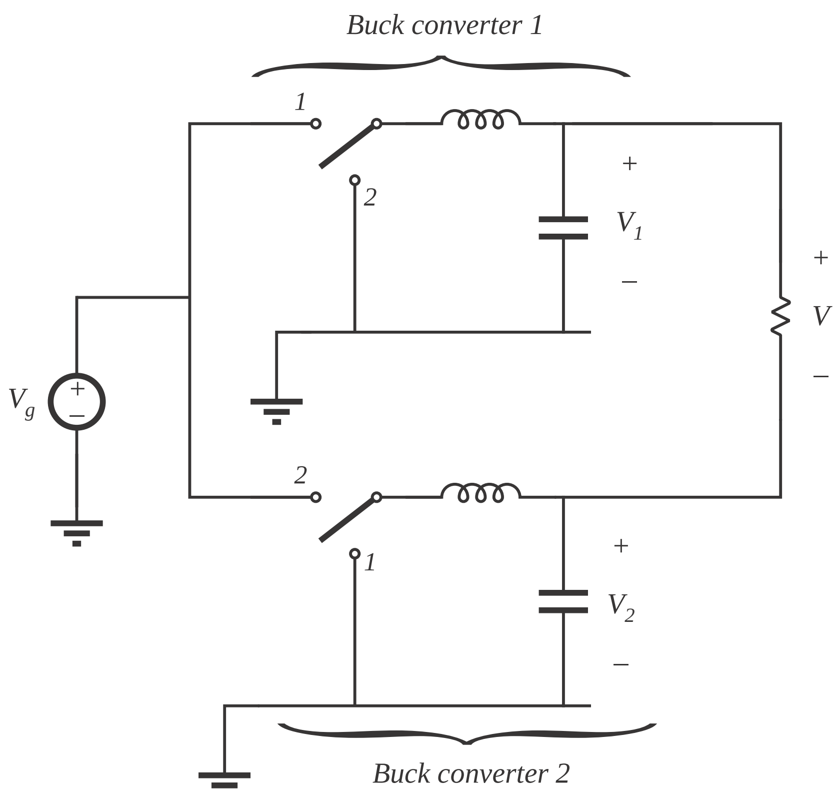
# Conversion ratio *M(D)*, differentially-connected buck converters

$$V = (2D - 1)\, V_g$$

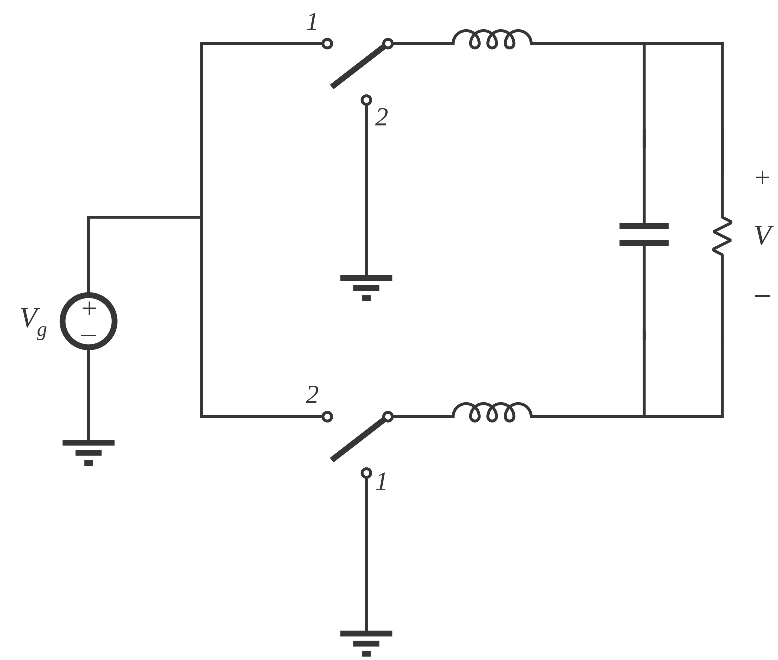


# Simplification of filter circuit, differentially-connected buck converters

Original circuit

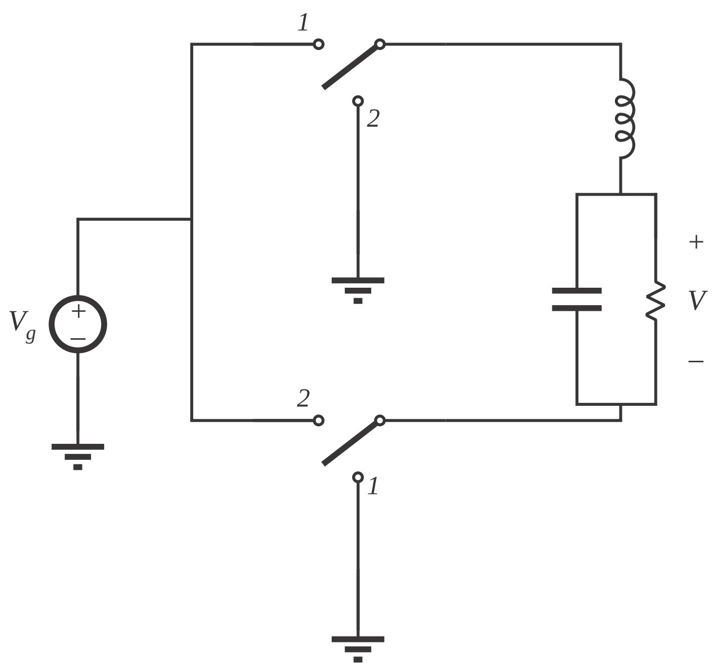



Bypass load directly with capacitor

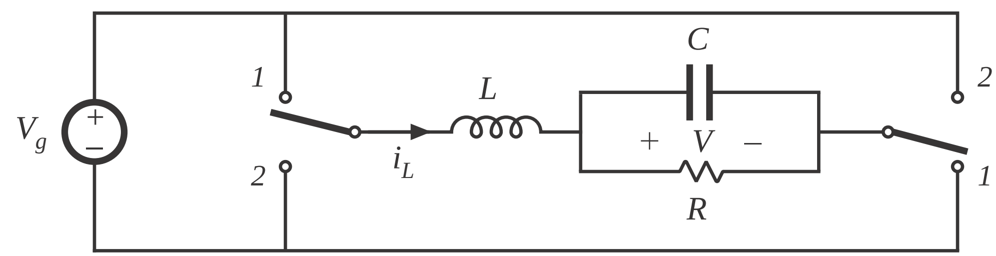


# Simplification of filter circuit, differentially-connected buck converters

Combine series-connected inductors



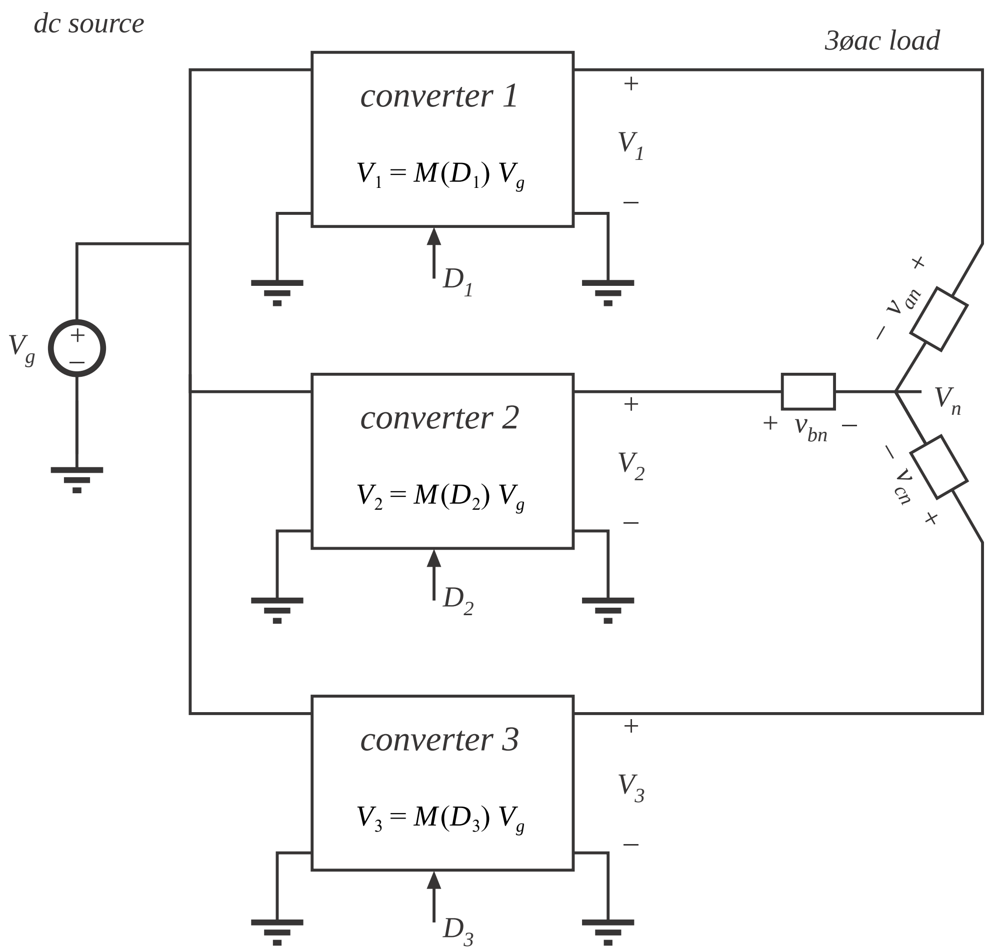

Re-draw for clarity




H-bridge, or bridge inverter

Commonly used in single-phase inverter applications and in servo amplifier applications

# Differential connection to obtain 3ø inverter




With balanced 3ø load, neutral voltage is

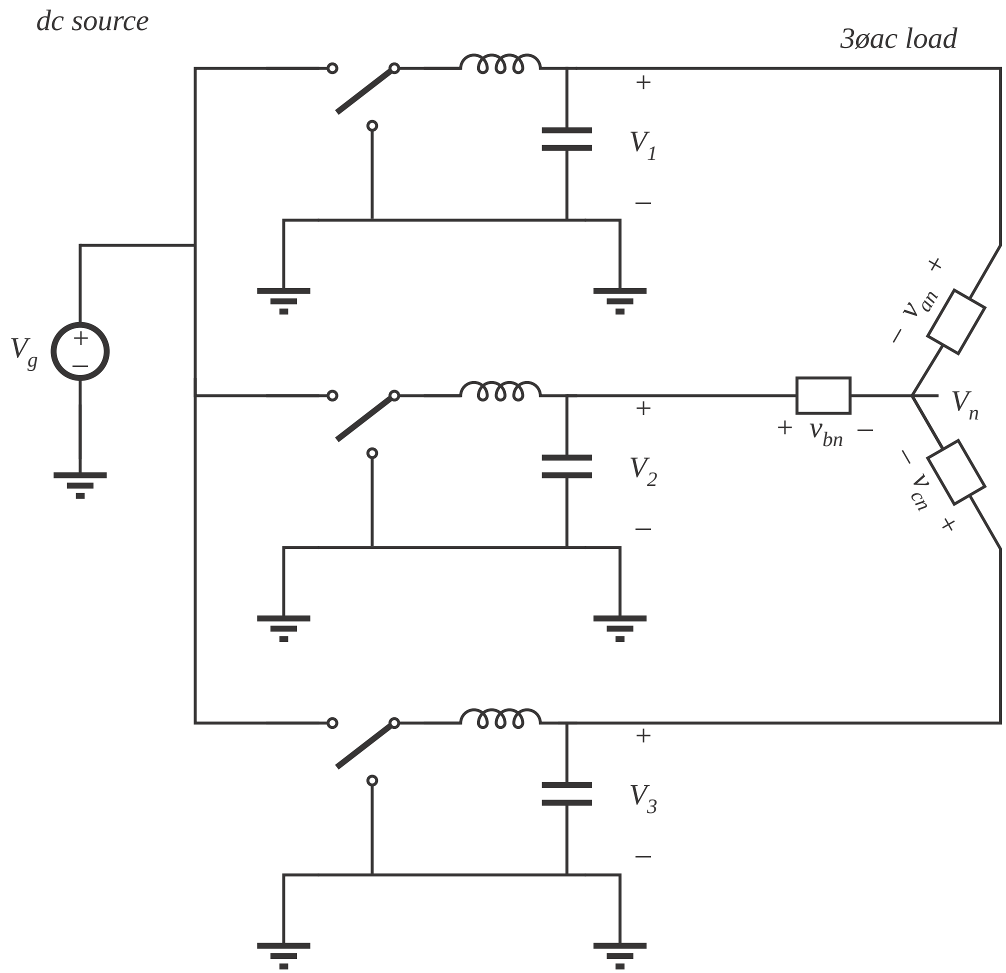
$$V_n = \frac{1}{3}\,(V_1 + V_2 + V_3)$$

Phase voltages are

$$V_{an} = V_1 - V_n$$
$$V_{bn} = V_2 - V_n$$
$$V_{cn} = V_3 - V_n$$

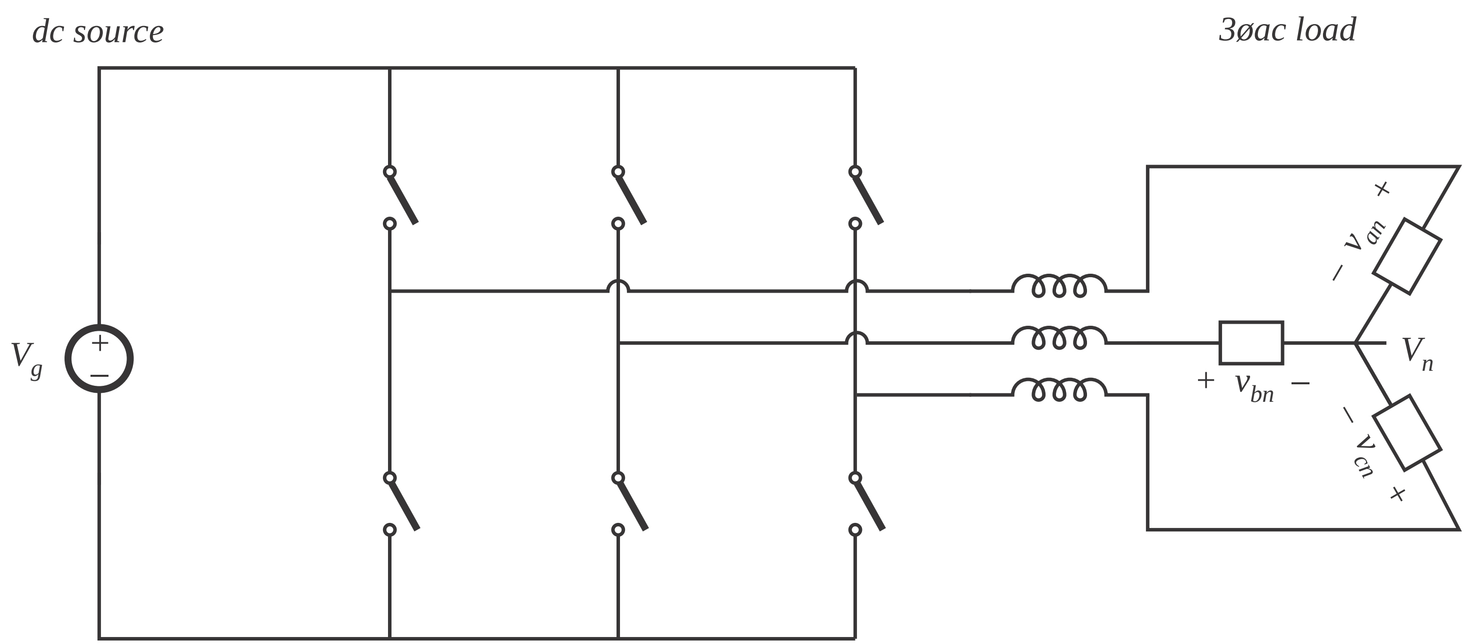
Control converters such that their output voltages contain the same dc biases. This dc bias will appear at the neutral point Vn. It then cancels out, so phase voltages contain no dc bias.

# 3ø differential connection of three buck converters



# 3ø differential connection of three buck converters

Re-draw for clarity:




"Voltage-source inverter" or buck-derived three-phase inverter

# 6.2. A short list of converters

An infinite number of converters are possible, which contain switches embedded in a network of inductors and capacitors

Two simple classes of converters are listed here:

- Single-input single-output converters containing a single inductor. The switching period is divided into two subintervals. This class contains eight converters.
- Single-input single-output converters containing two inductors. The switching period is divided into two subintervals. Several of the more interesting members of this class are listed.

# Single-input single-output converters containing one inductor

- Use switches to connect inductor between source and load, in one manner during first subinterval and in another during second subinterval
- There are a limited number of ways to do this, so all possible combinations can be found
- After elimination of degenerate and redundant cases, eight converters are found:

*dc-dc converters*

buck boost buck-boost noninverting buck-boost

*dc-ac converters*

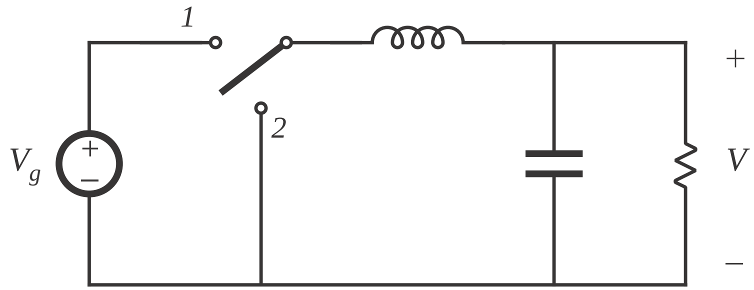
bridge Watkins-Johnson

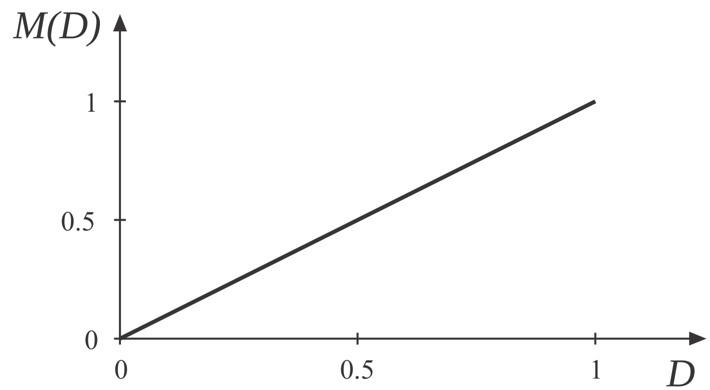
*ac-dc converters*

current-fed bridge inverse of Watkins-Johnson

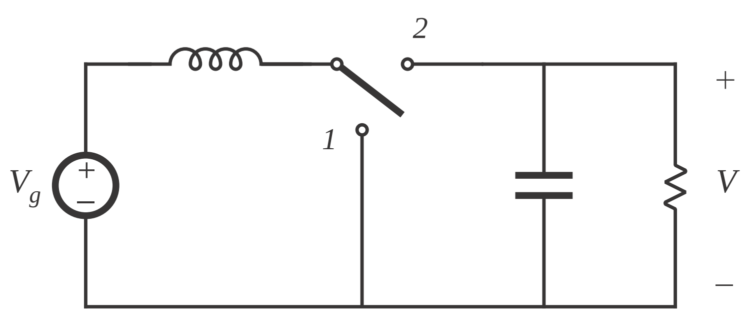
# Converters producing a unipolar output voltage

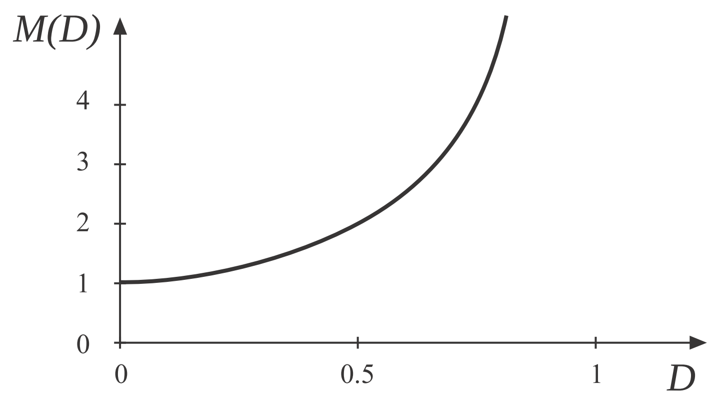
1. *Buck* $M(D) = D$




2. *Boost* $M(D) = \frac{1}{1-D}$

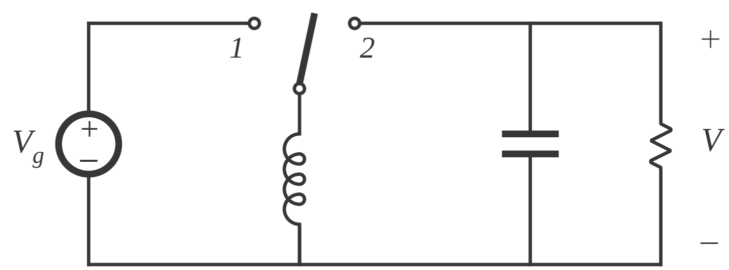


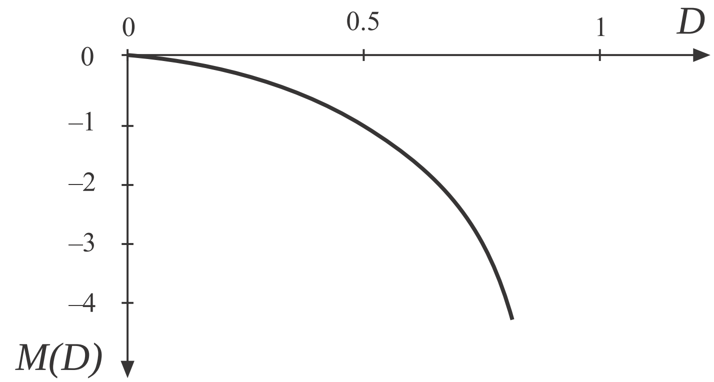



# Converters producing a unipolar output voltage

*3. Buck-boost*

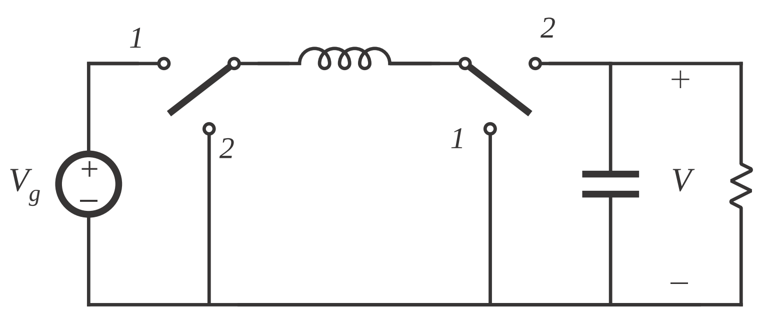
$$M(D) = -\frac{D}{1-D}$$

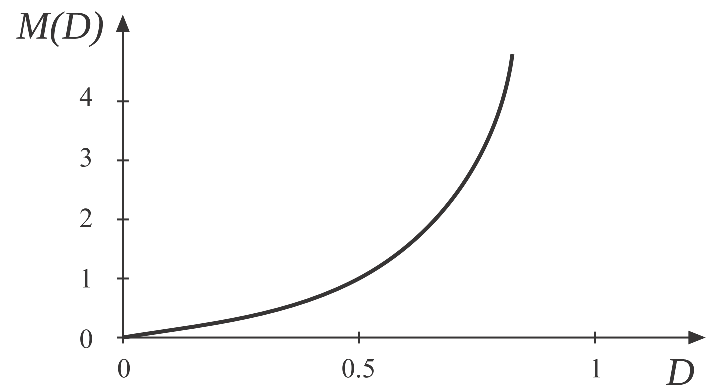



*4. Noninverting buck-boost*

$$M(D) = \frac{D}{1-D}$$

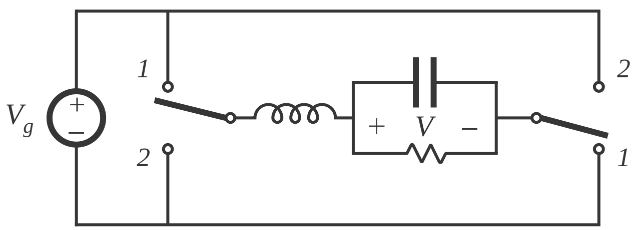


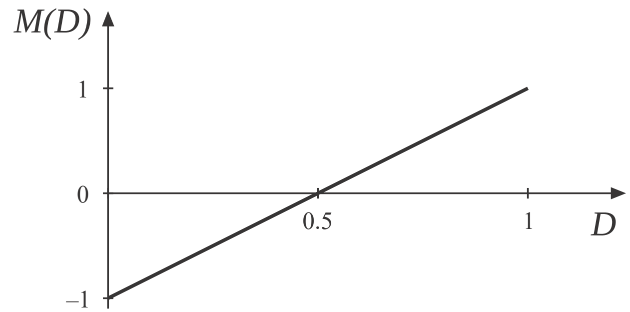



# Converters producing a bipolar output voltage suitable as dc-ac inverters

*5. Bridge*

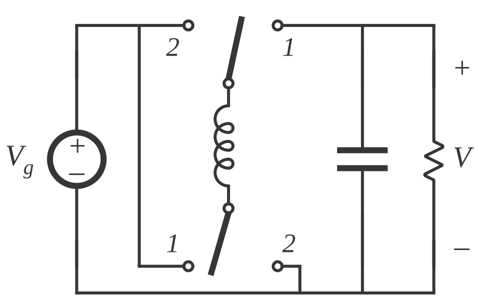
$$M(D) = 2D - 1$$



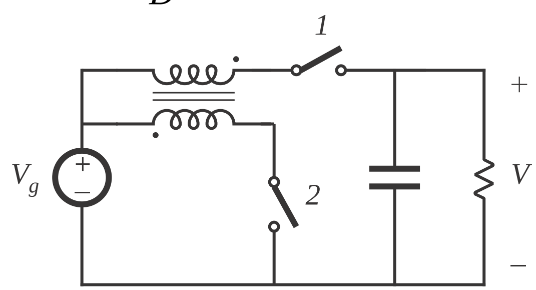



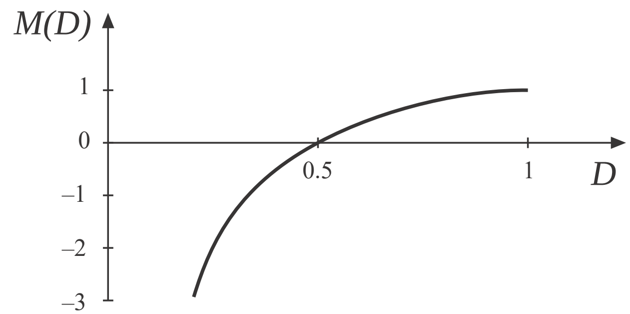

*6. Watkins-Johnson*

$$M(D) = \frac{2D-1}{D}$$



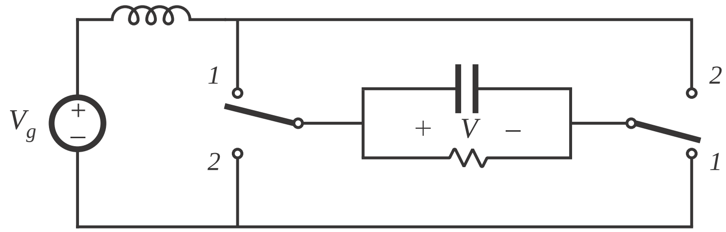

*or*

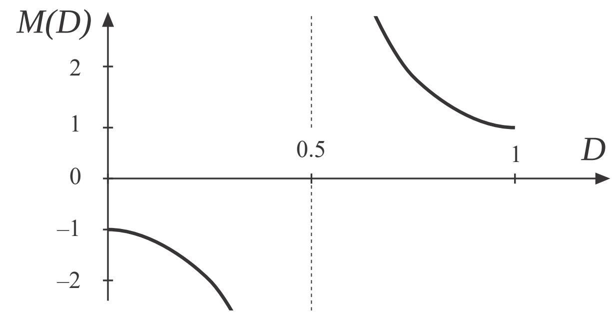


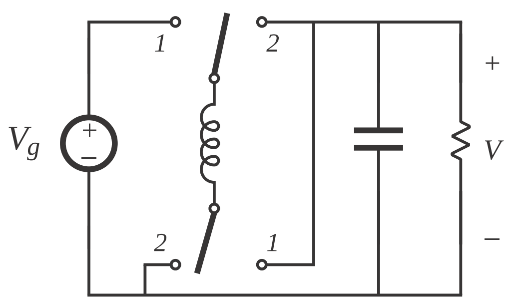
# Converters producing a bipolar output voltage suitable as ac-dc rectifiers

*7. Current-fed bridge* $M(D) = \dfrac{1}{2D-1}$

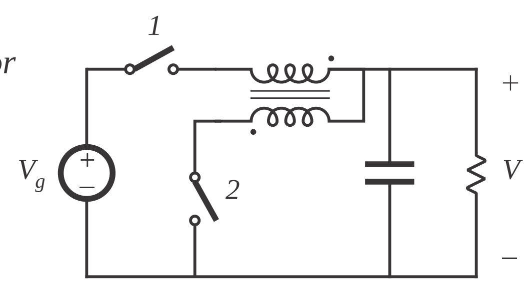


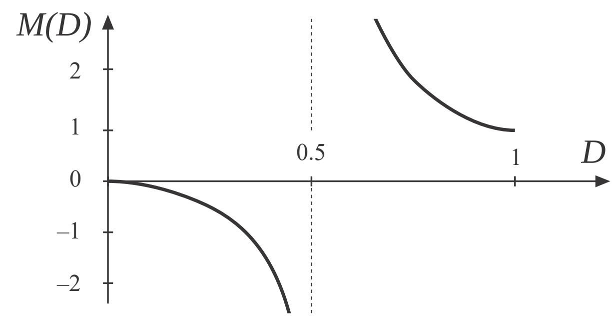




*8. Inverse of Watkins-Johnson* $M(D) = \dfrac{D}{2D-1}$




*or*

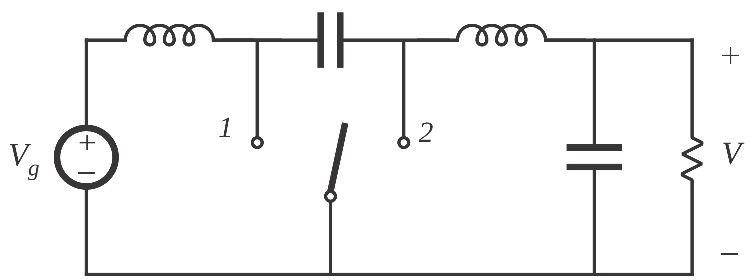


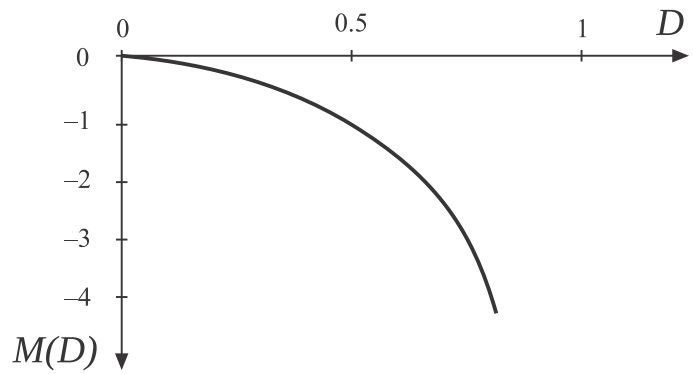



# Several members of the class of two-inductor converters

*1. Cuk*

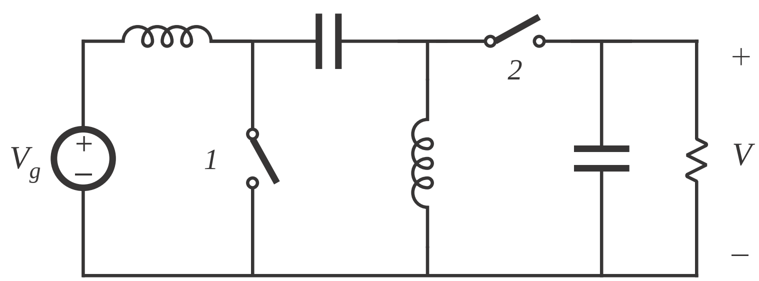
$$M(D) = -\frac{D}{1-D}$$

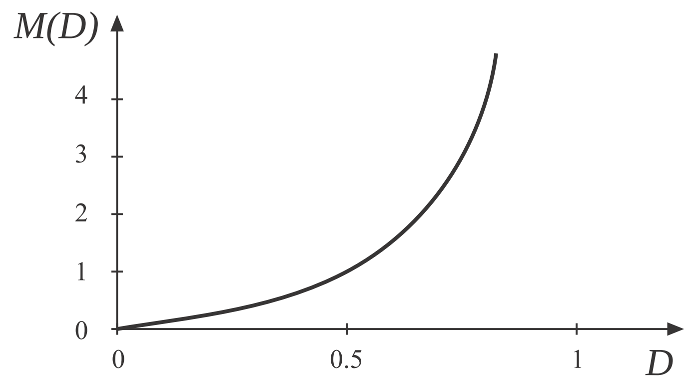



*2. SEPIC*

$$M(D) = \frac{D}{1-D}$$

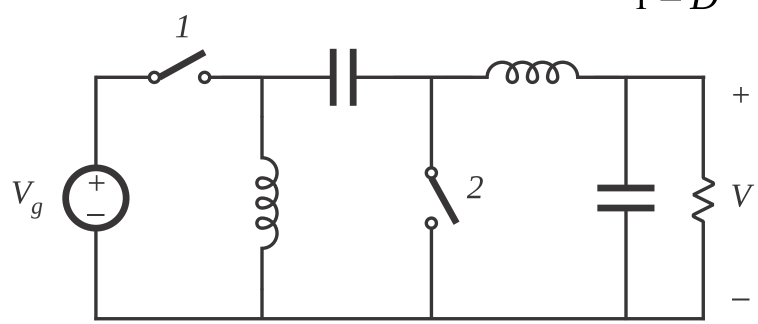


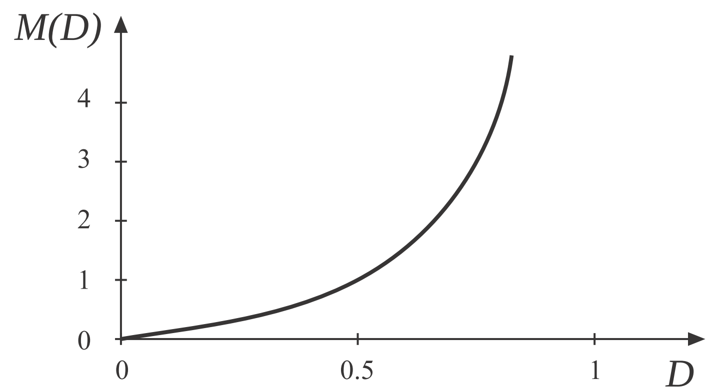



# Several members of the class of two-inductor converters

*3. Inverse of SEPIC*

$$M(D) = \frac{D}{1-D}$$




*4. Buck [2]*

$$M(D) = D^2$$