Chapter 6. Converter Circuits

6.1. Circuit manipulations

6.2. A short list of converters

6.3. Transformer isolation

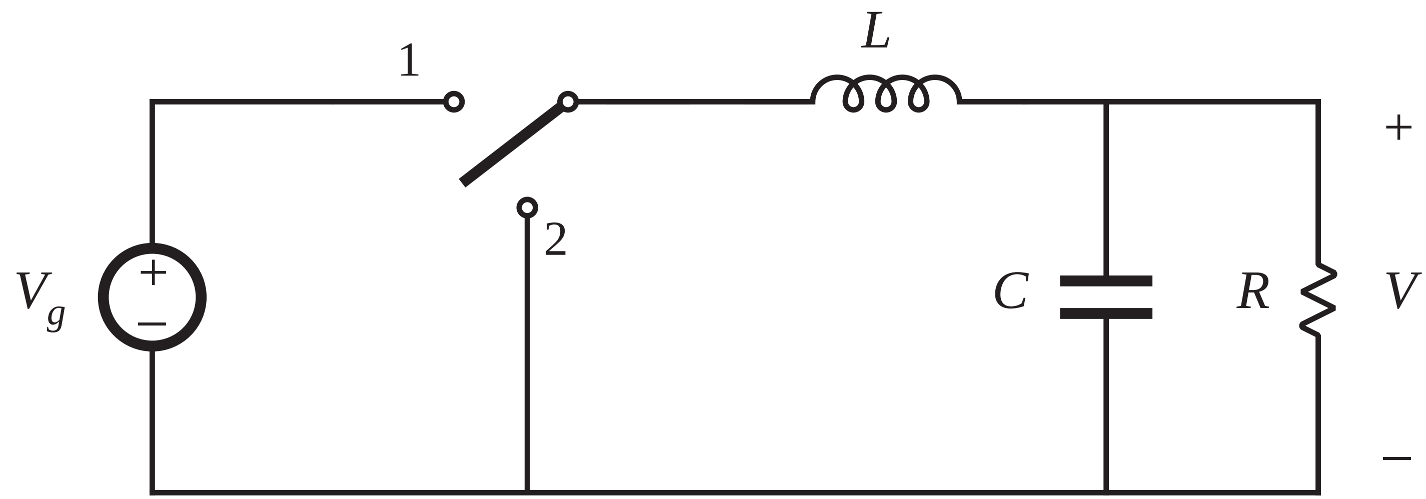
6.4. Converter evaluation and design

6.5. Summary of key points

5 Questions

- 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

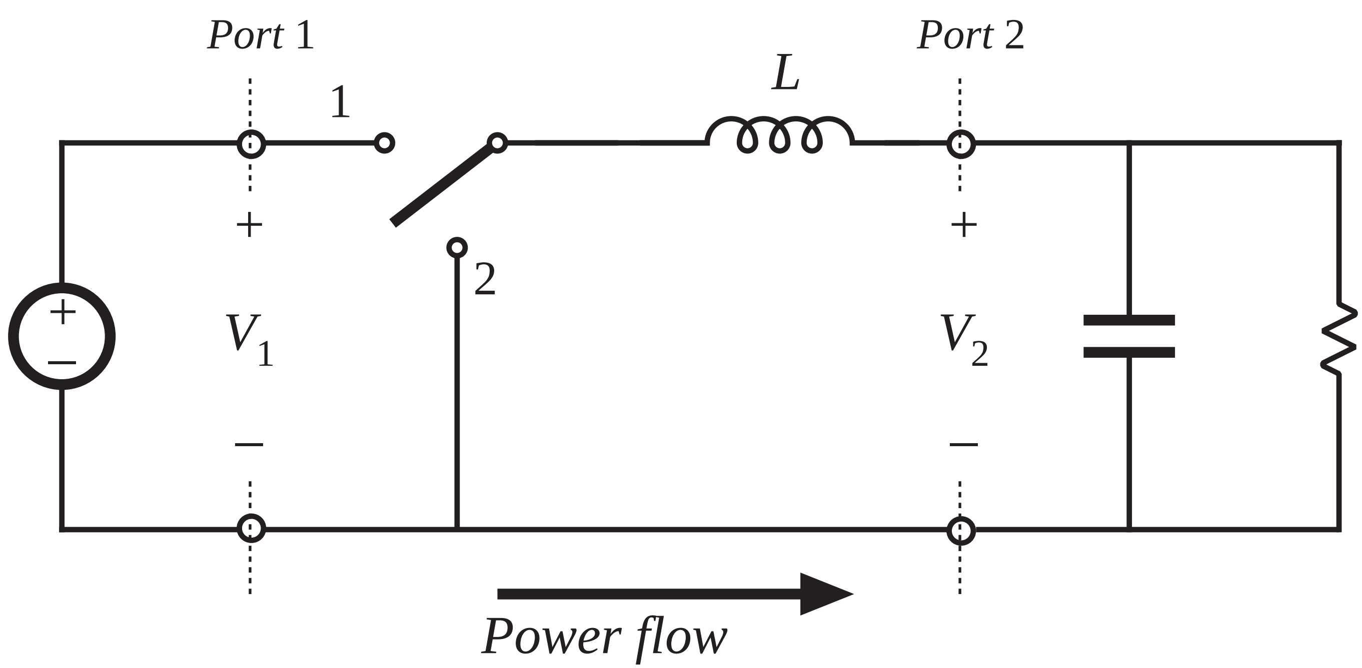
- Switch changes dc component, low-pass filter removes switching harmonics
- Conversion ratio is $M = D$

6.1.1. Inversion of source and load

Interchange power input and output ports of a converter

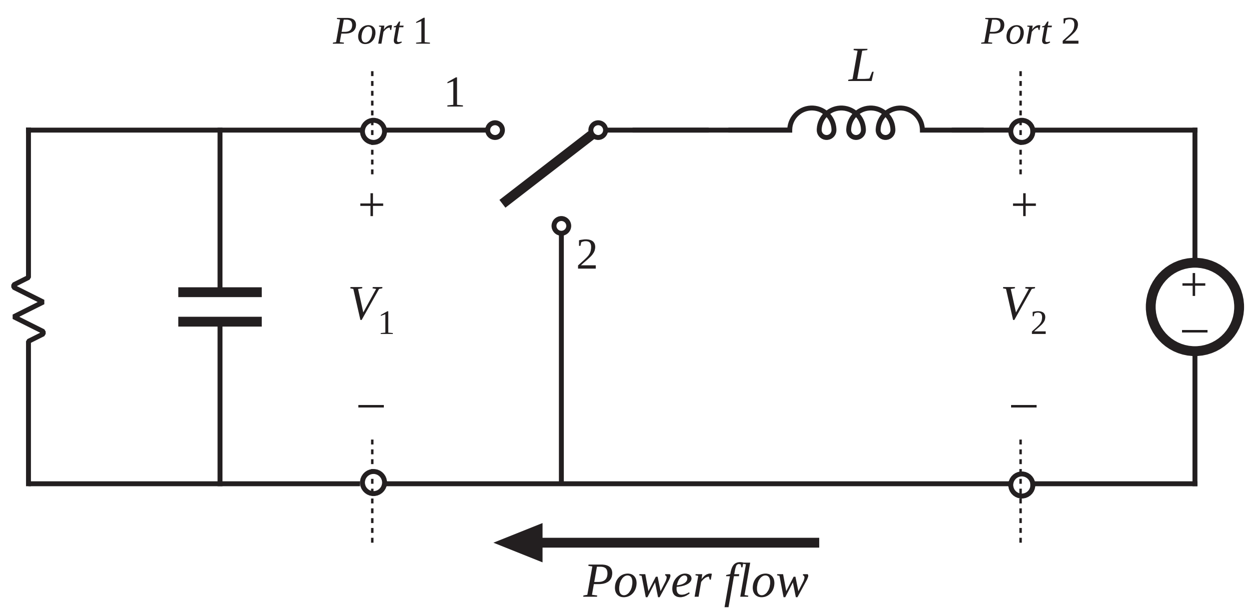
Buck converter example

$$V_2 = DV_1$$



Inversion of source and load

Interchange power source and load:

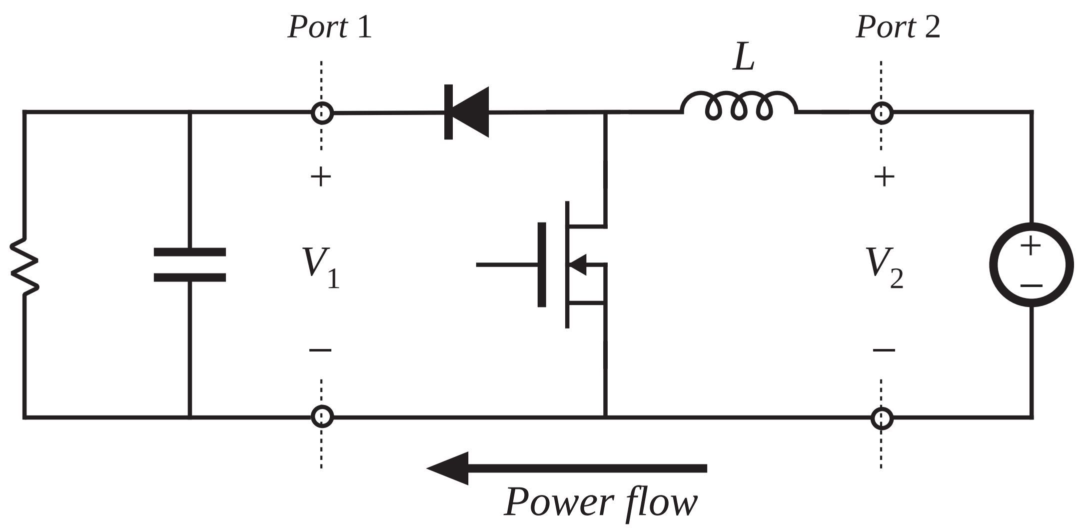


$$V_2 = DV_1$$

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

Realization of switches as in Chapter 4

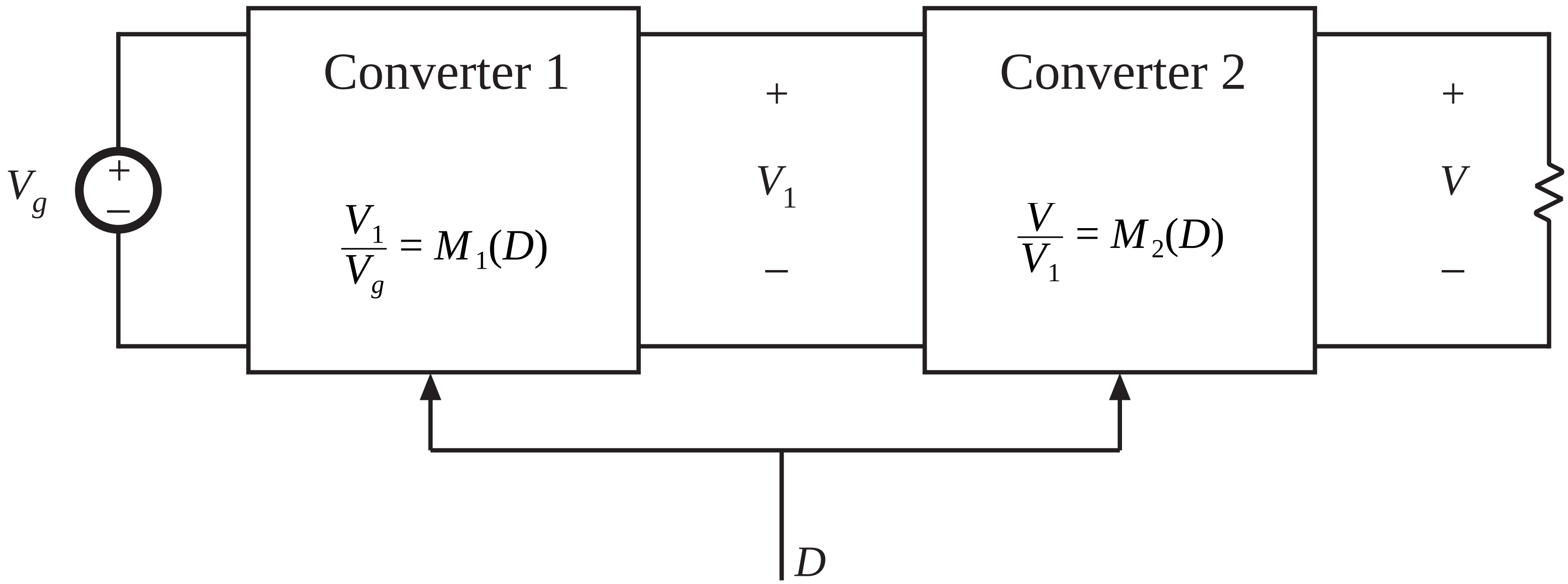
- Reversal of power flow requires new realization of switches
- Transistor conducts when switch is in position 2
- Interchange of D and D'



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

Inversion of buck converter yields boost converter

6.1.2. Cascade connection of converters

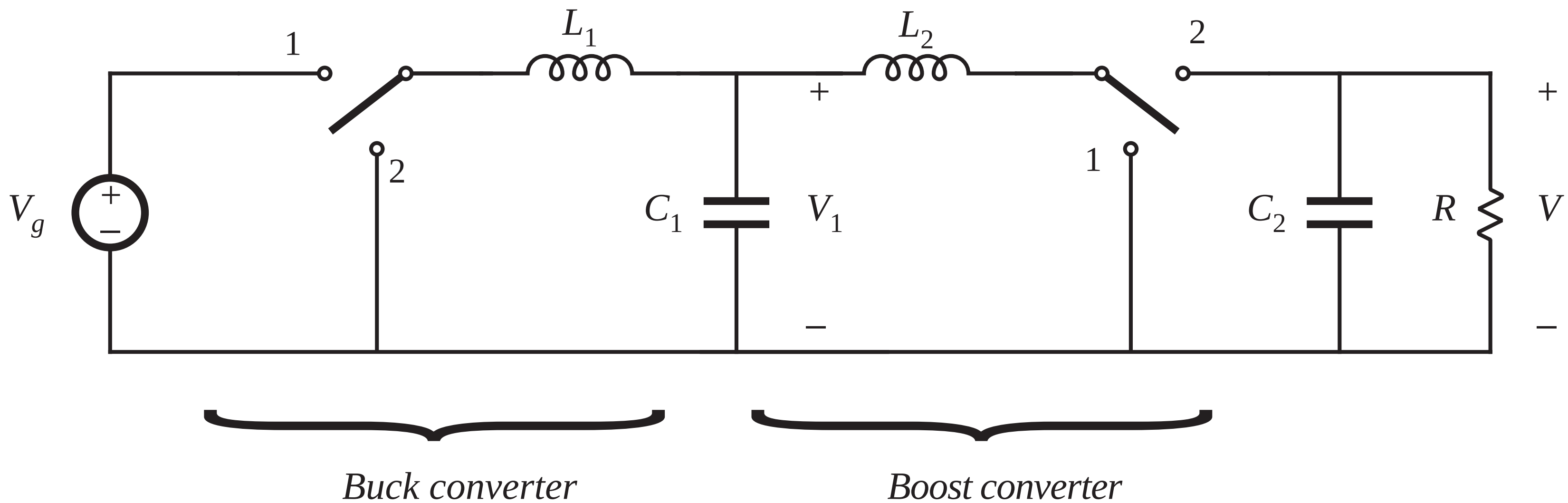


$$V_1 = M_1(D)V_g$$

$$V = M_2(D)V_1$$

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

Example: buck cascaded by boost



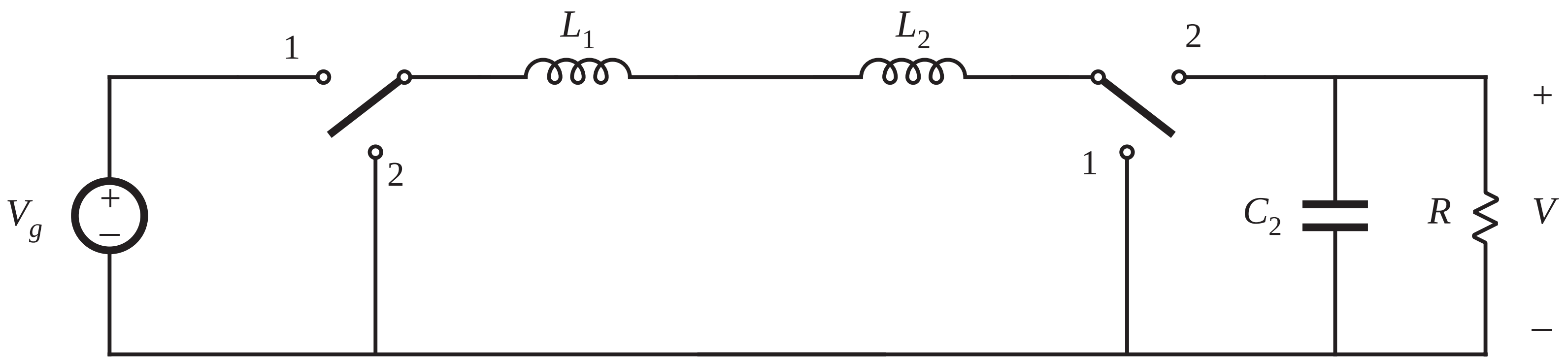
$$\frac{V_1}{V_g} = D$$

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

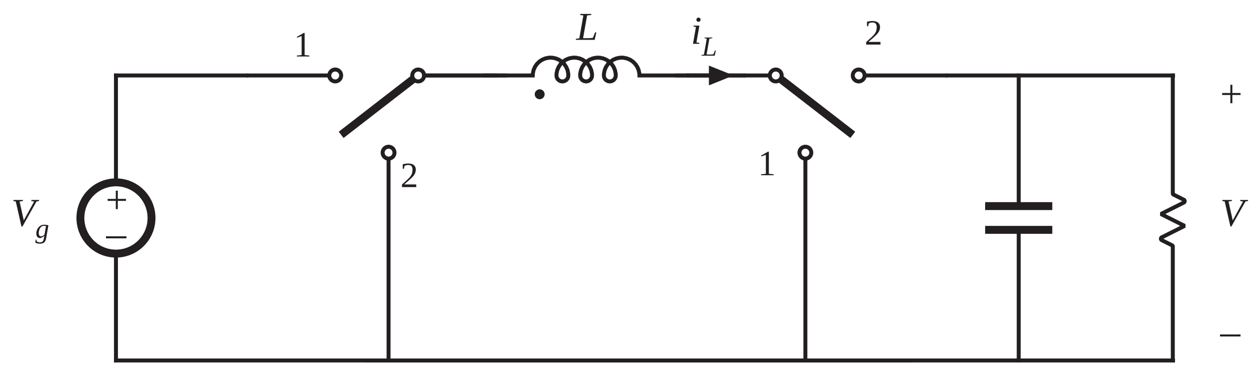
$$\longrightarrow \quad \frac{V}{V_g} = \frac{D}{1-D}$$

Buck cascaded by boost: simplification of internal filter

Remove capacitor C_1

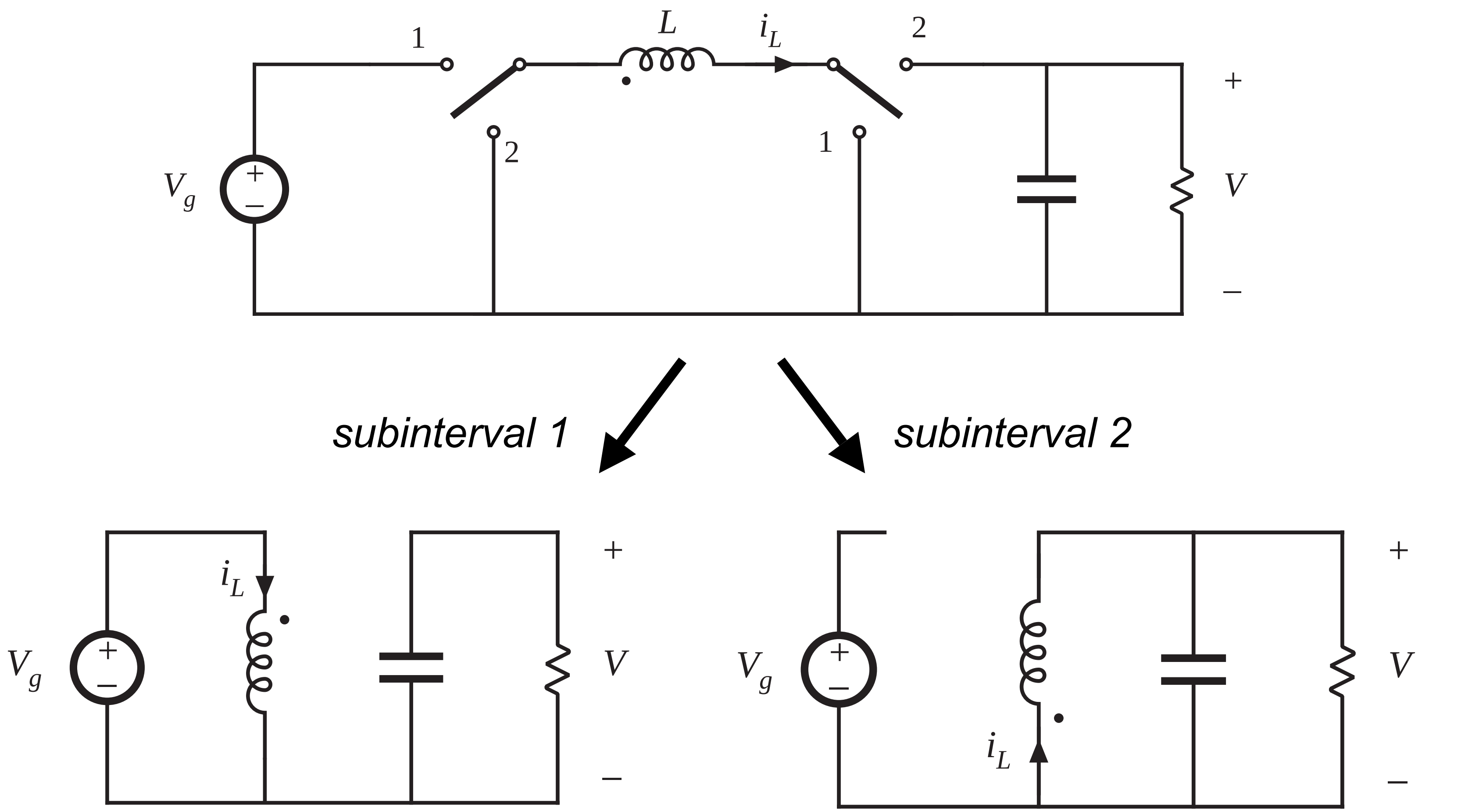


Combine inductors L_1 and L_2



Noninverting buck-boost converter

Noninverting buck-boost converter

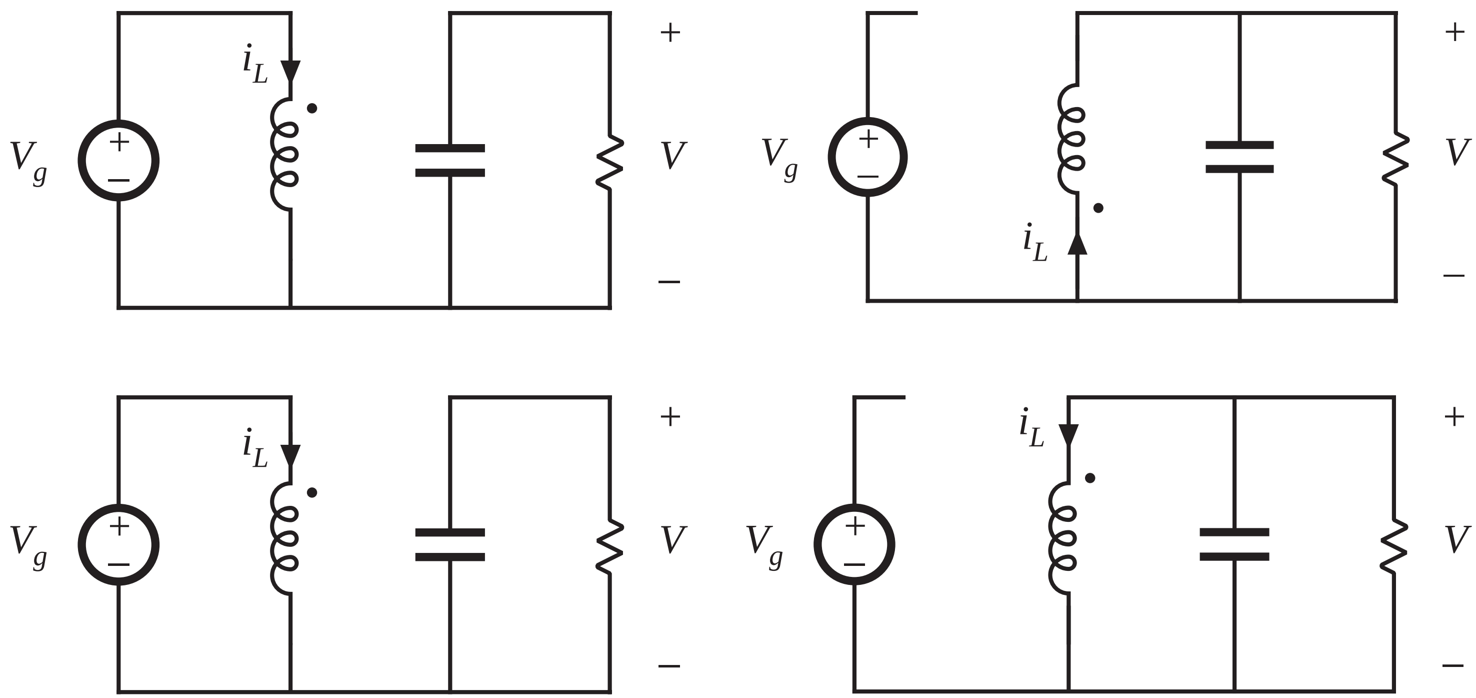


Reversal of output voltage polarity

subinterval 1 | subinterval 2

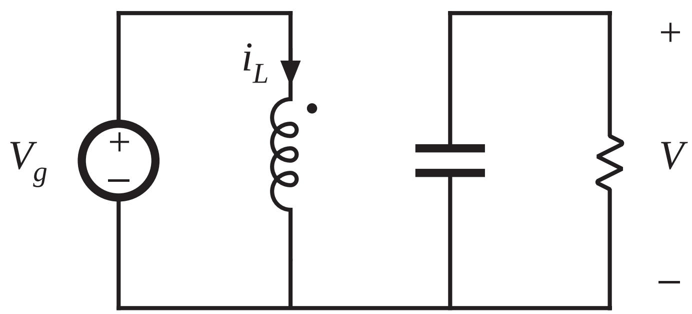
noninverting buck-boost

inverting buck-boost

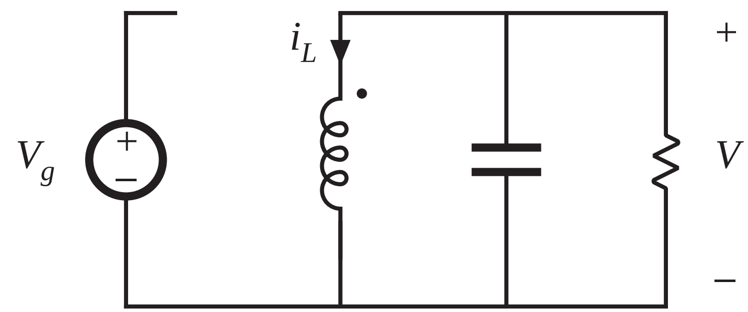


Reduction of number of switches: inverting buck-boost

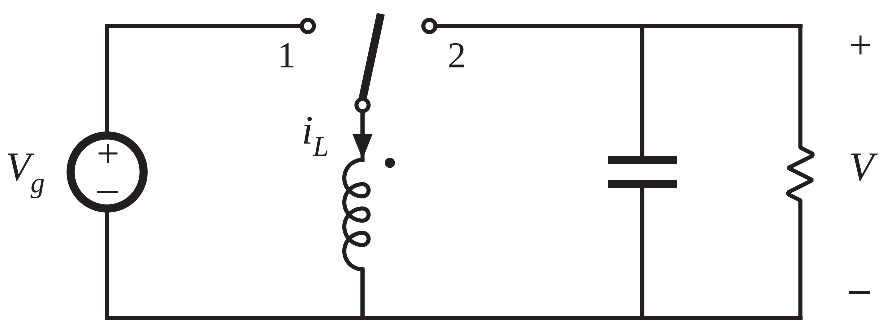
Subinterval 1



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

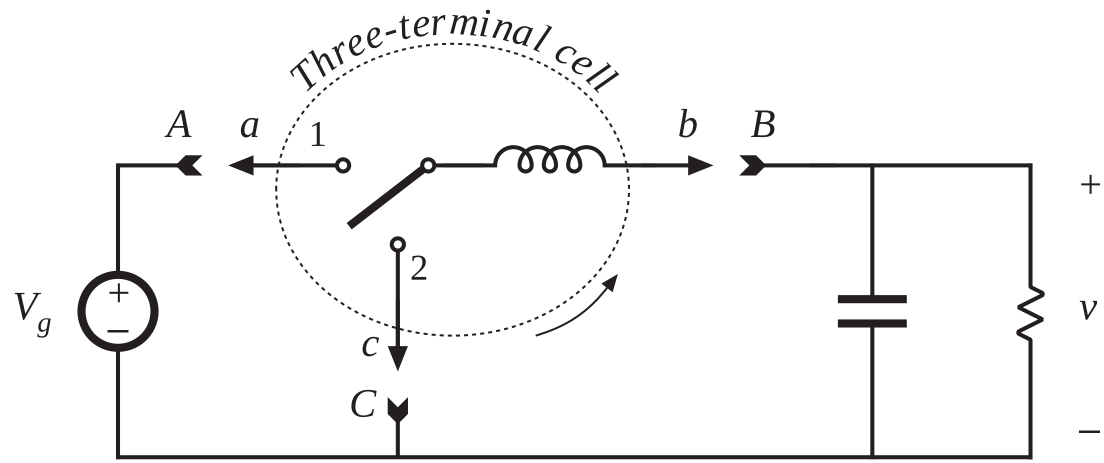
  Pulsating output current of boost converter

- 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:

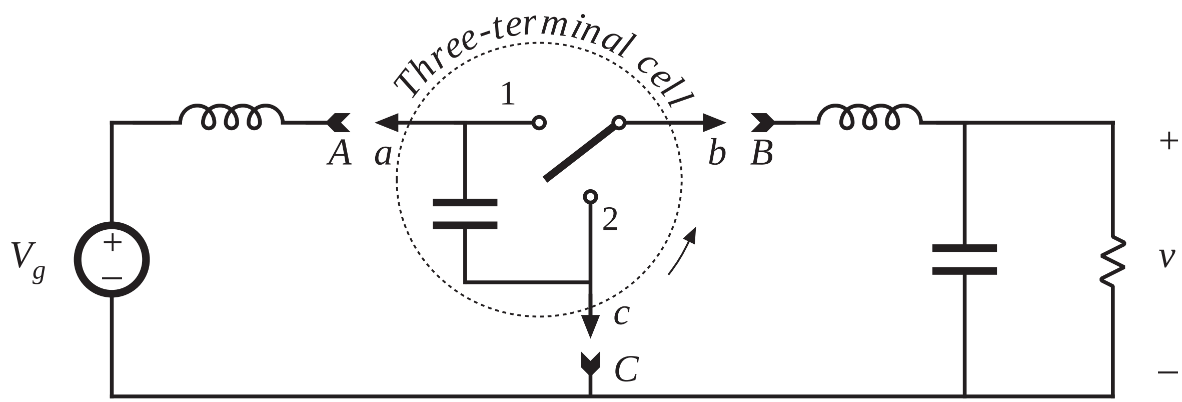


Three-terminal cell can be connected between source and load in three nontrivial distinct ways:

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

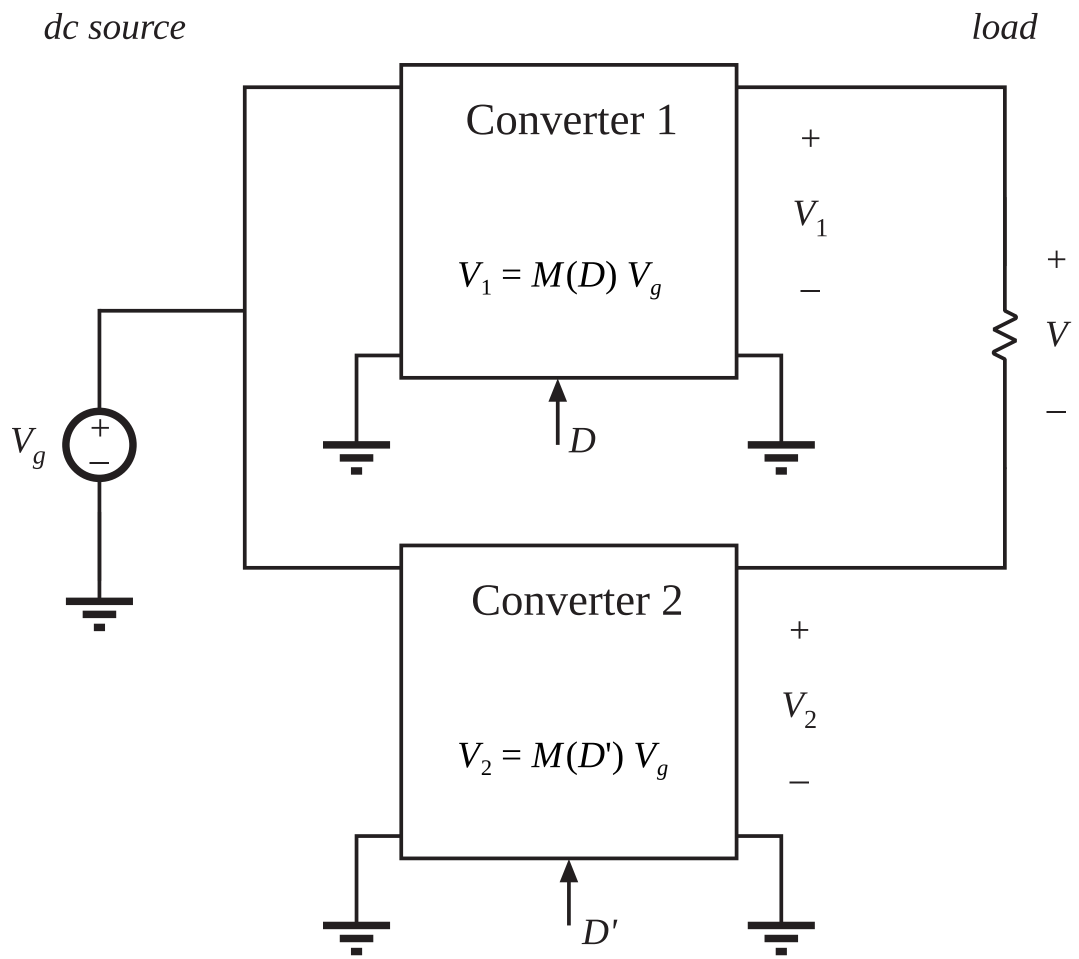
A capacitor and SPDT switch as a three-terminal cell:



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

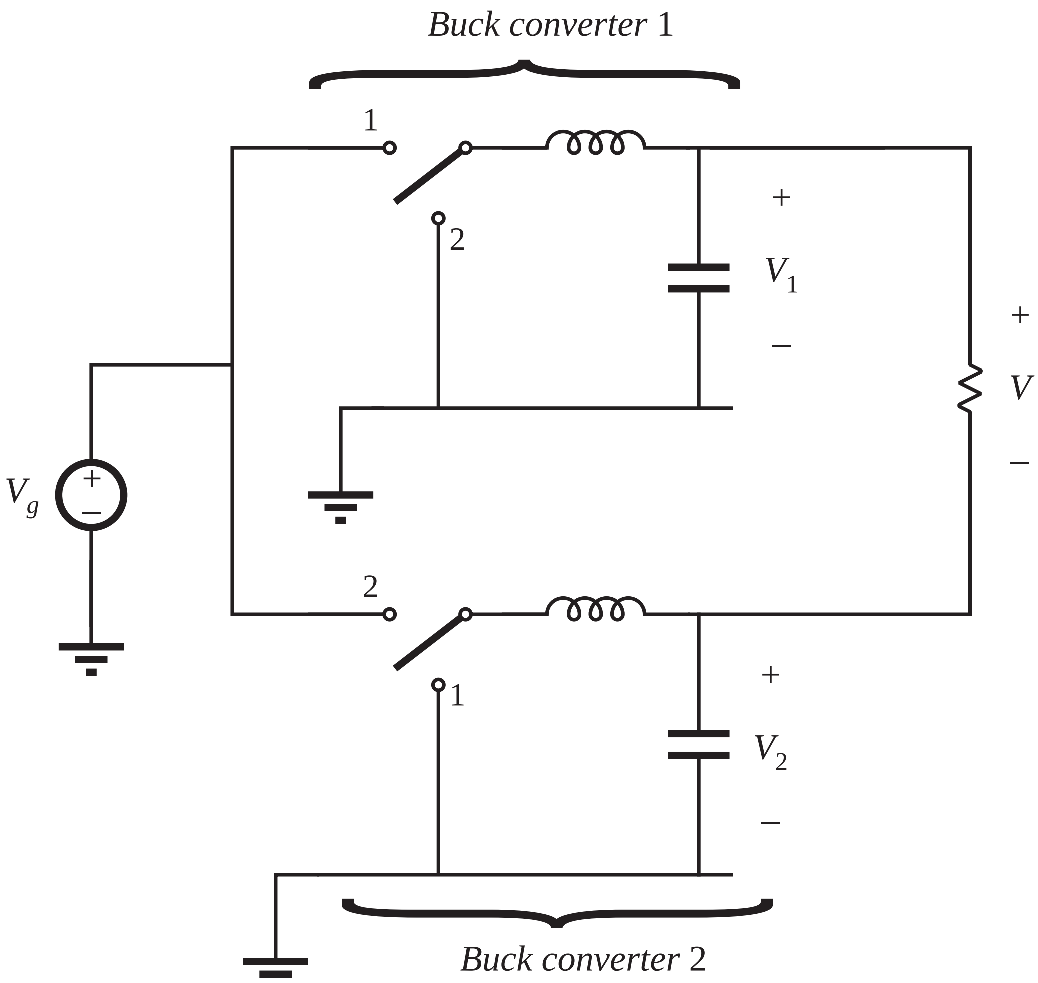


Differential load voltage is

$$V = V_1 - V_2$$

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

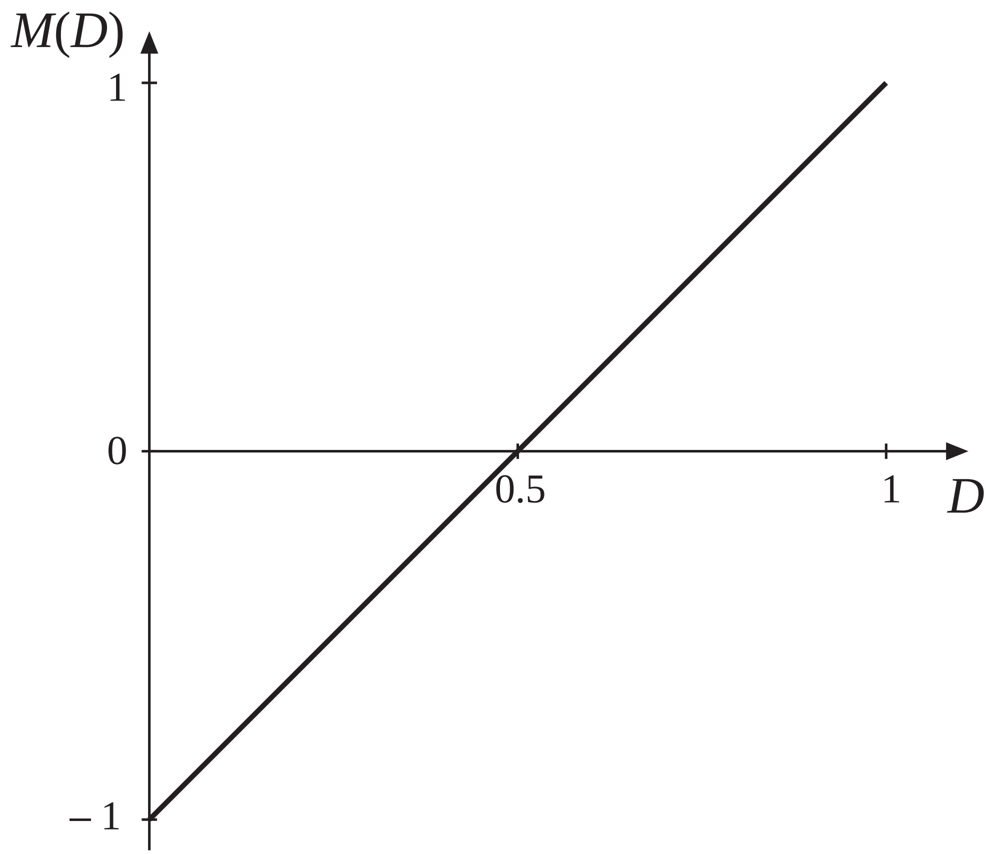
$$V = DV_g - D'V_g$$

Simplify:

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

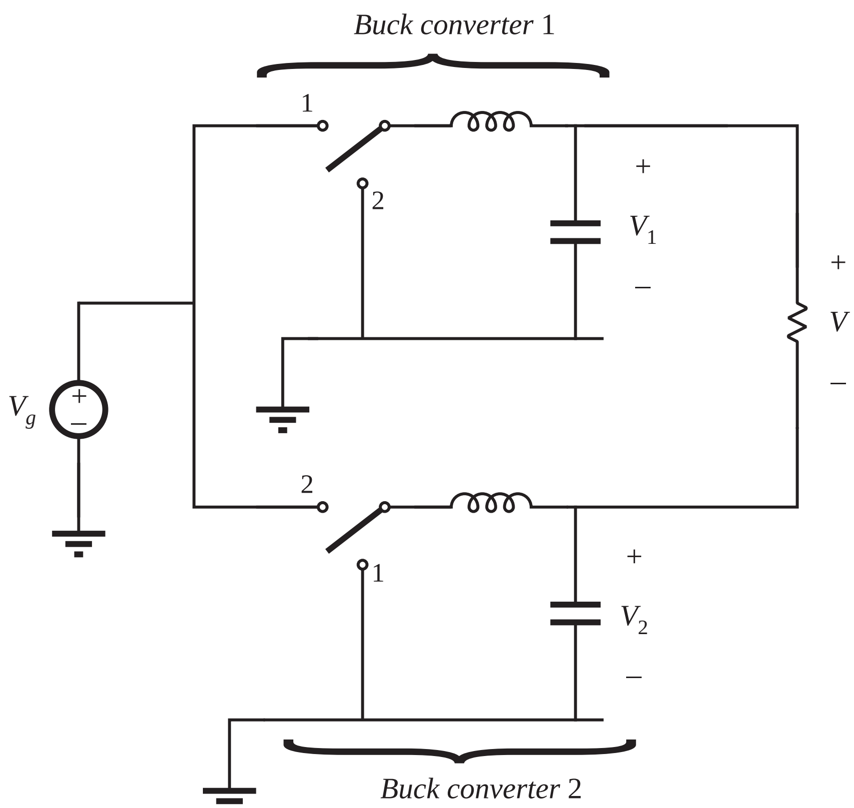
Conversion ratio $M(D)$, differentially-connected buck converters

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

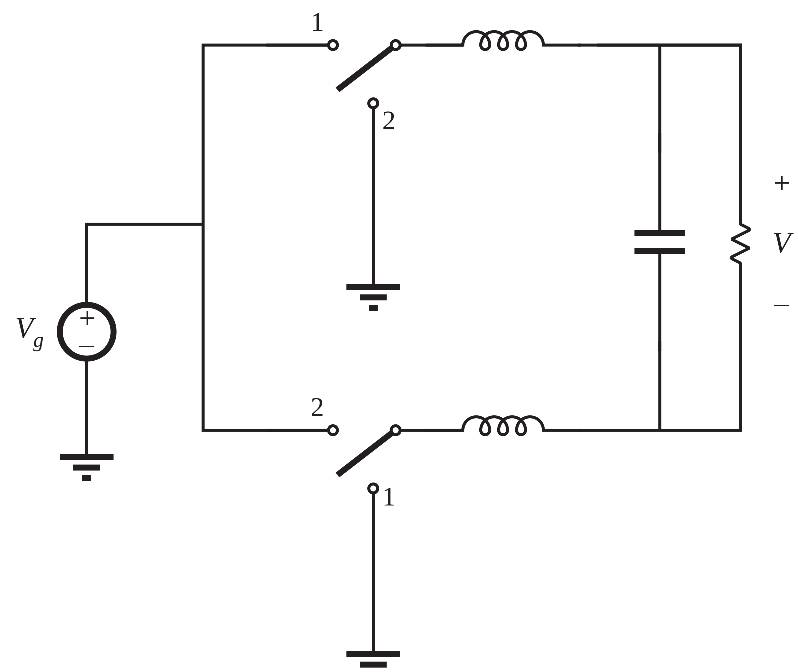


Simplification of filter circuit, differentially-connected buck converters

Original circuit

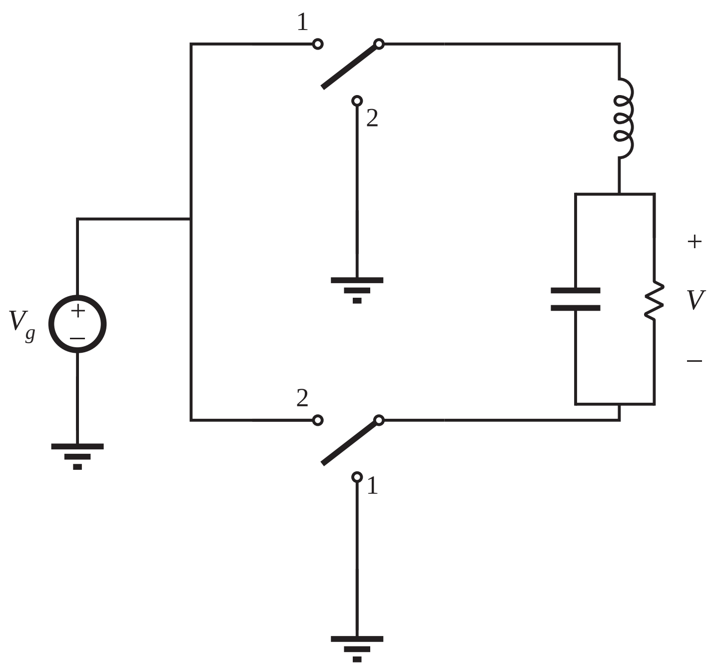


Bypass load directly with capacitor

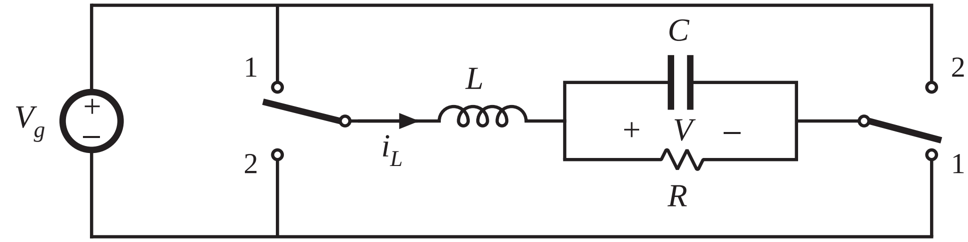


Simplification of filter circuit, differentially-connected buck converters

Combine series-connected inductors



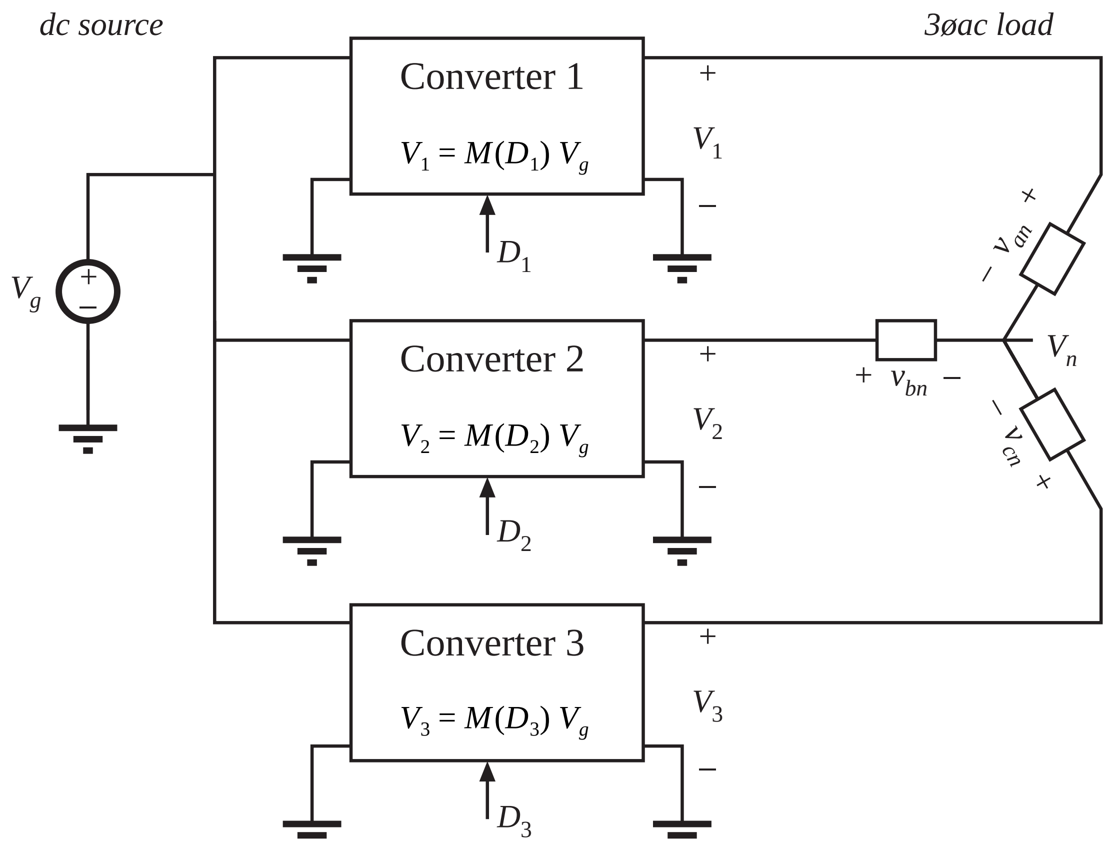
Re-draw for clarity



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

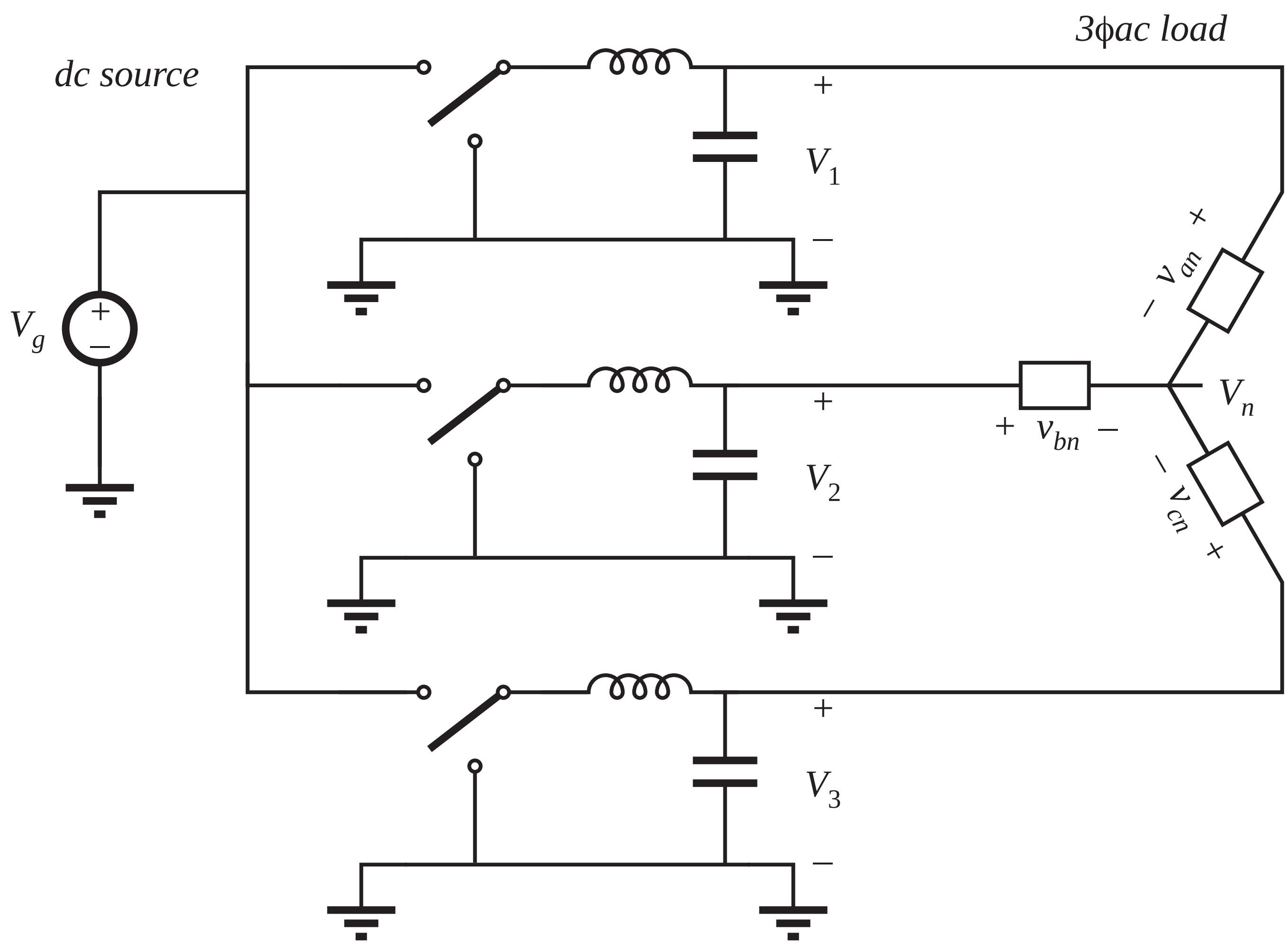
$$V_n = \frac{1}{3}\left(V_1 + V_2 + V_3\right)$$

Phase voltages are

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

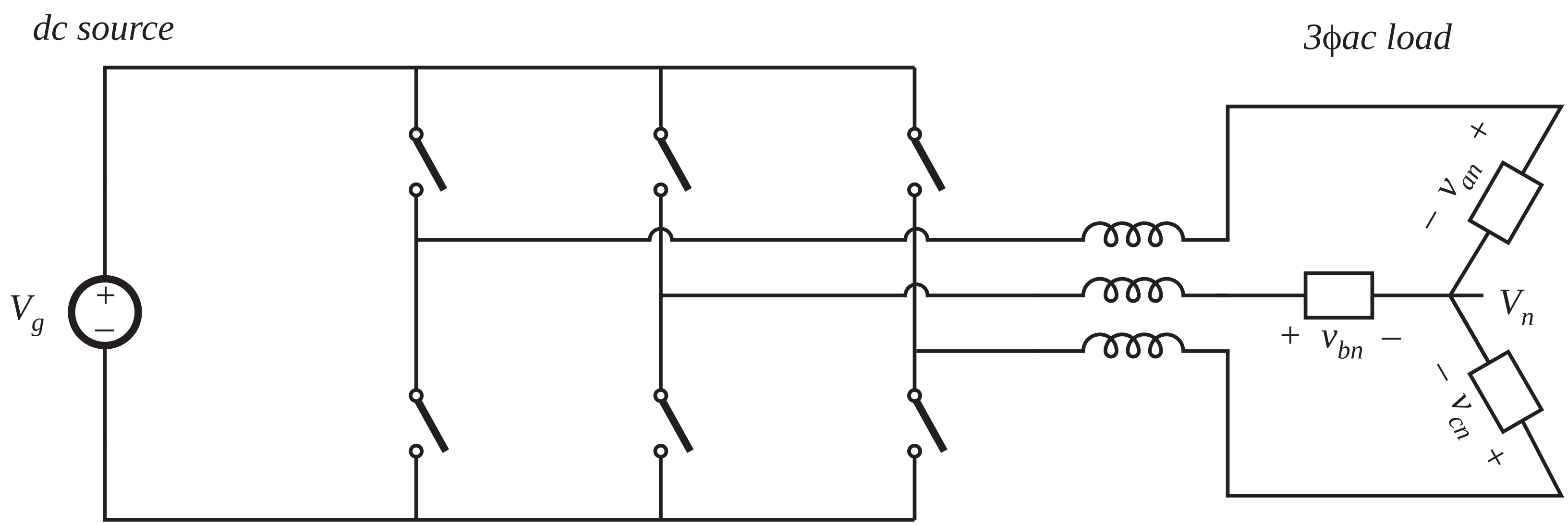
Control converters such that their output voltages contain the same dc biases. This dc bias will appear at the neutral point V_n. It then cancels out, so phase voltages contain no dc bias.

3ø differential connection of three buck converters



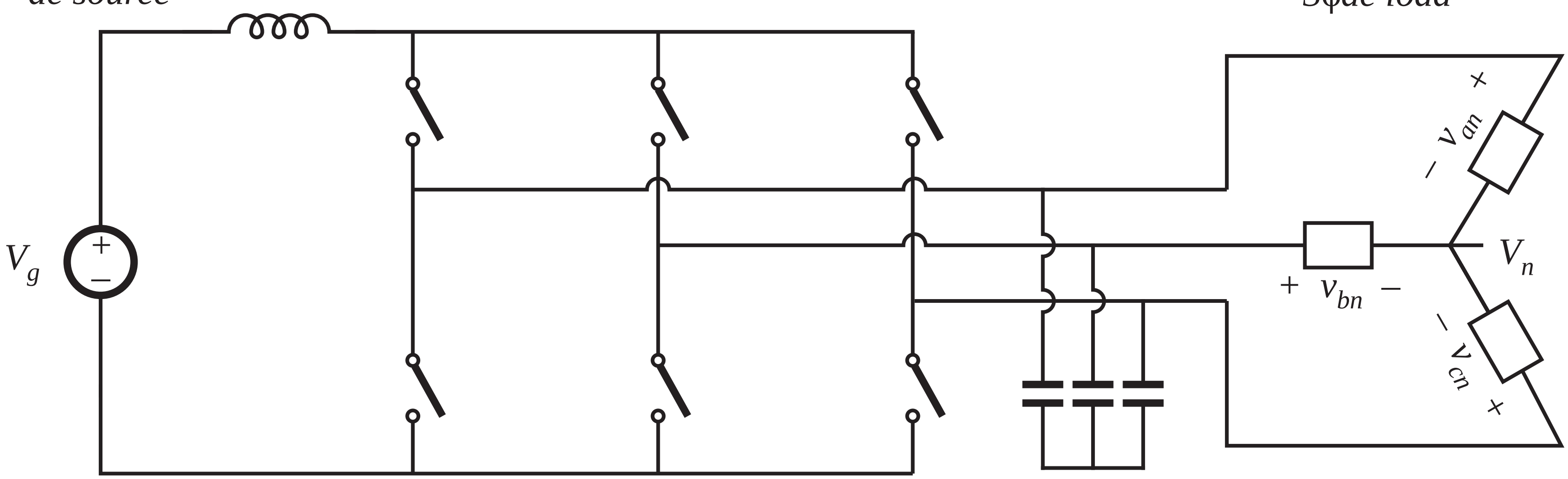
3ø differential connection of three buck converters

Re-draw for clarity:



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

The 3ø current-source inverter



- Exhibits a boost-type conversion characteristic

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

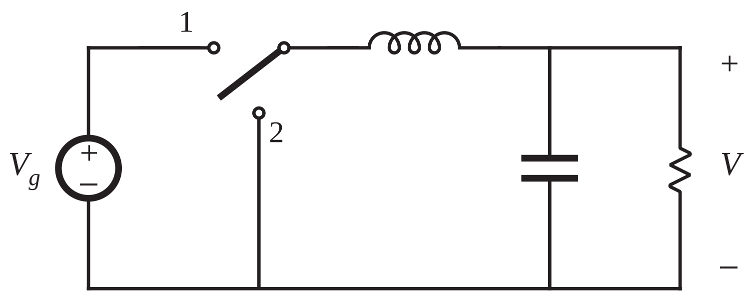
ac-dc converters

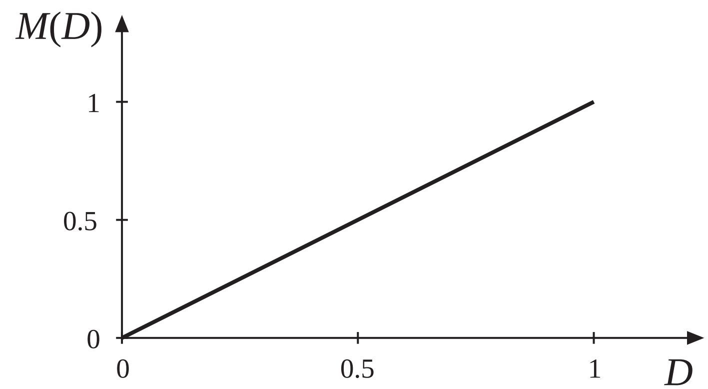
current-fed bridge inverse of Watkins-Johnson

Converters producing a unipolar output voltage

1. *Buck*

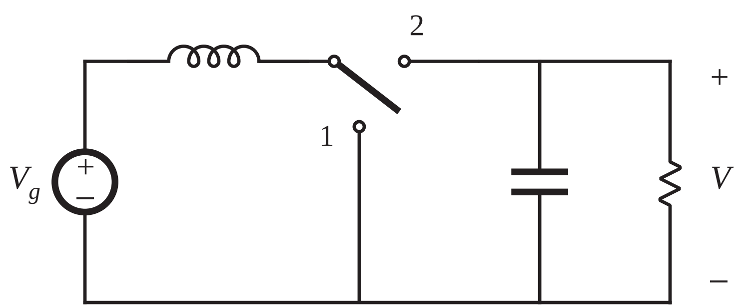
$$M(D) = D$$

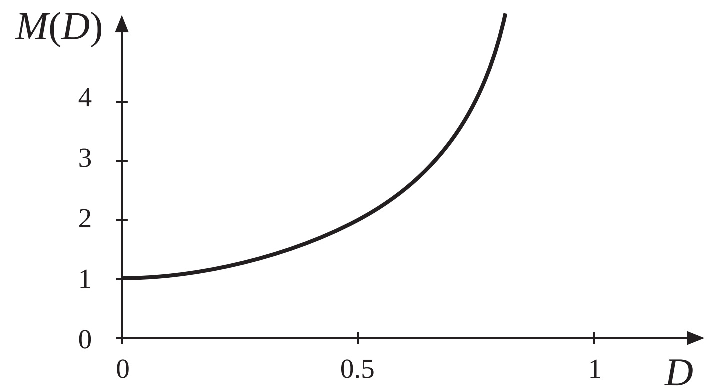




2. *Boost*

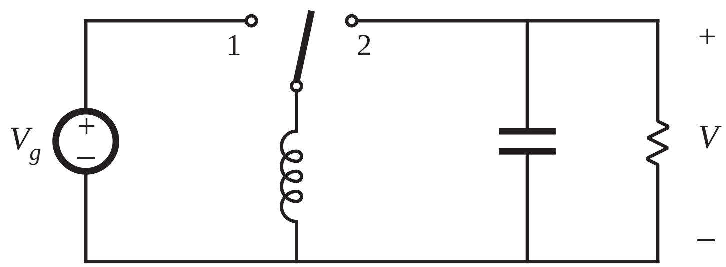
$$M(D) = \frac{1}{1 - D}$$

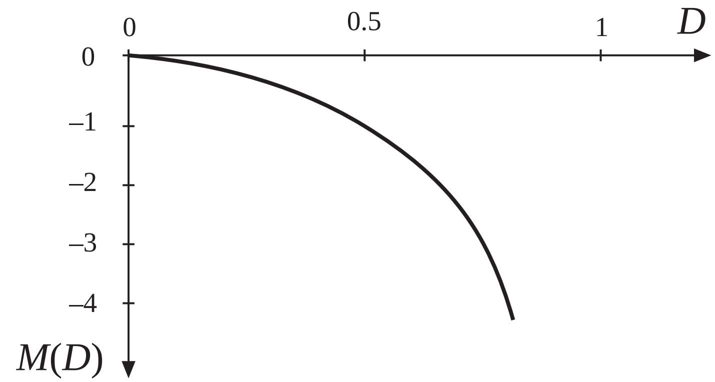




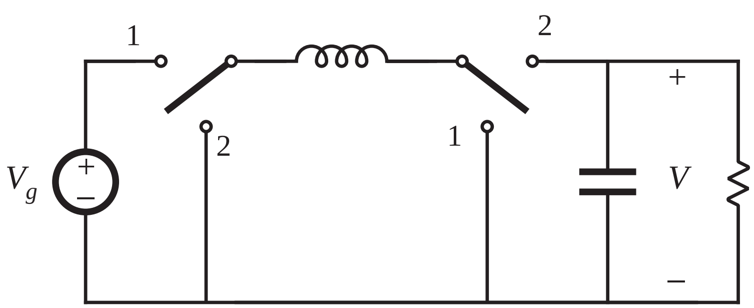
Converters producing a unipolar output voltage

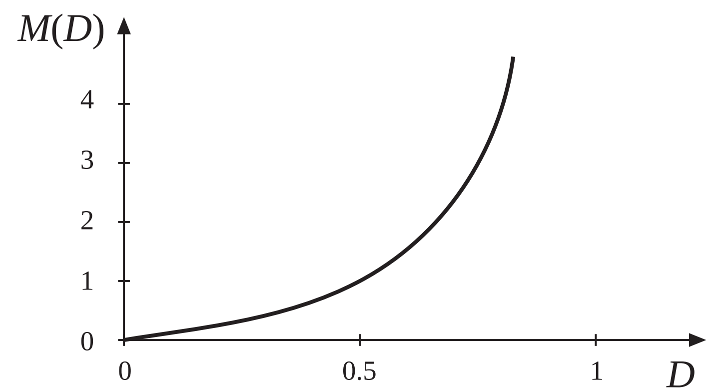
3. *Buck-boost* $M(D) = -\dfrac{D}{1-D}$





4. *Noninverting buck-boost* $M(D) = \dfrac{D}{1-D}$

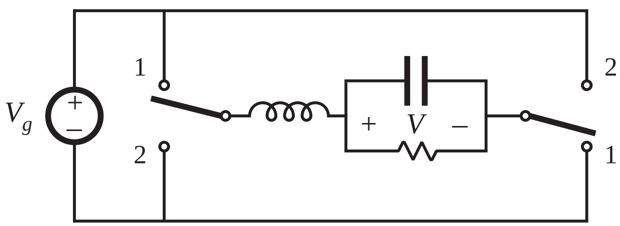


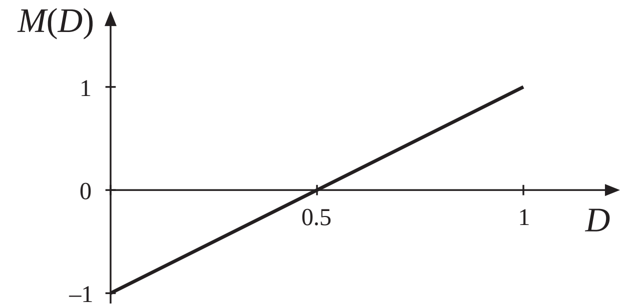


Converters producing a bipolar output voltage suitable as dc-ac inverters

5. *Bridge*

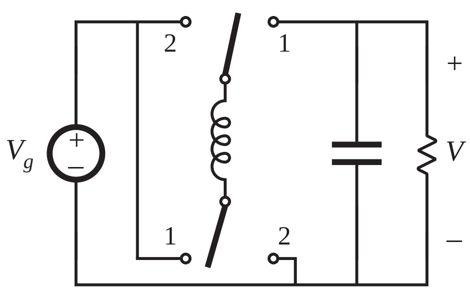
$$M(D) = 2D - 1$$



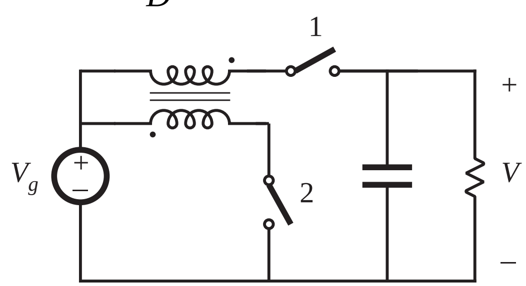


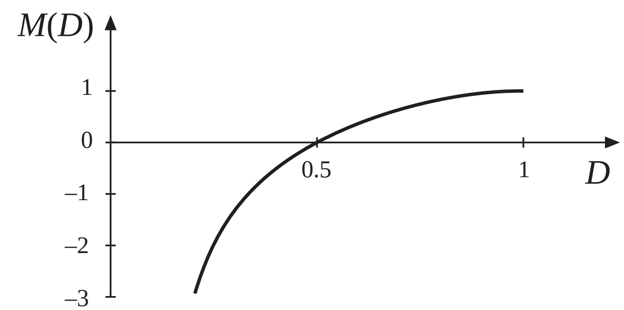
6. *Watkins-Johnson*

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



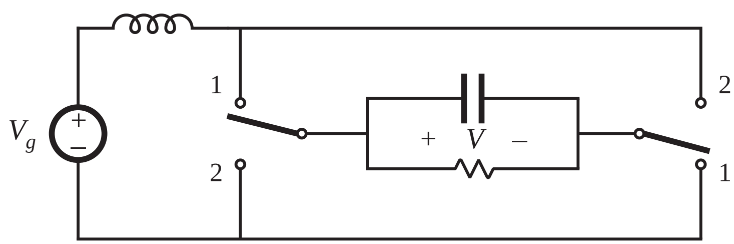
or

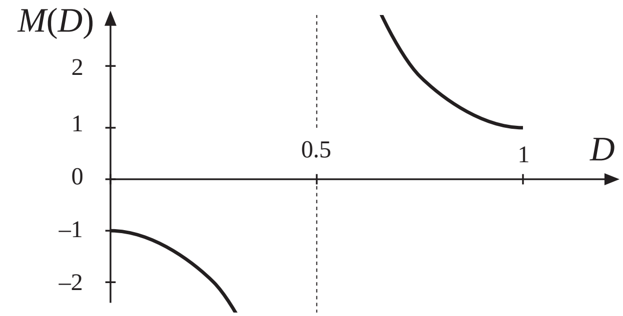




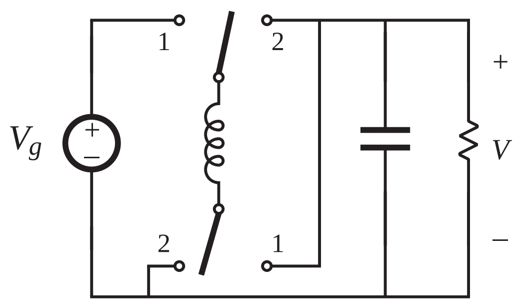
Converters producing a bipolar output voltage suitable as ac-dc rectifiers

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





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



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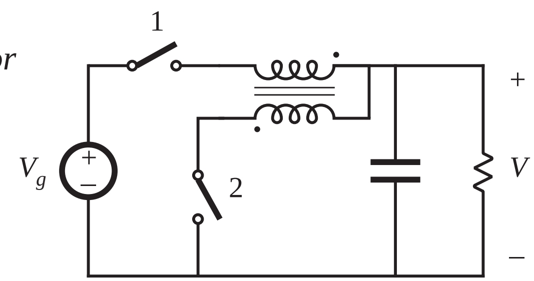
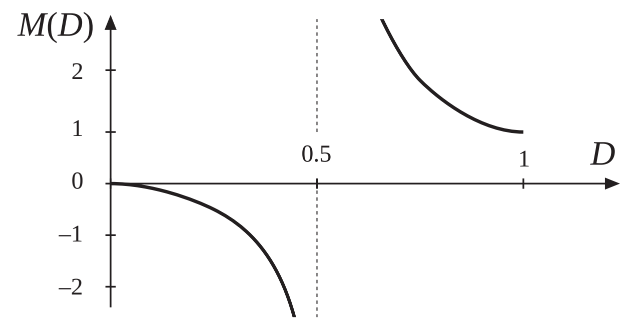
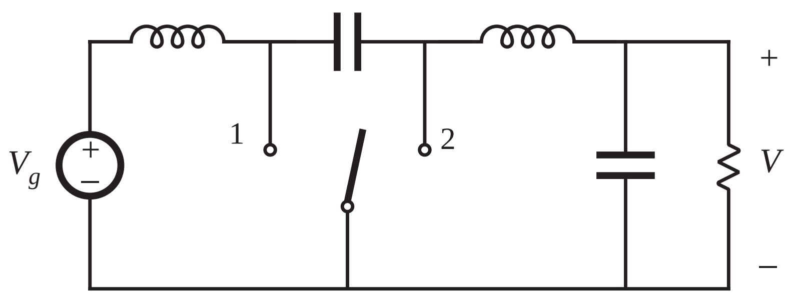
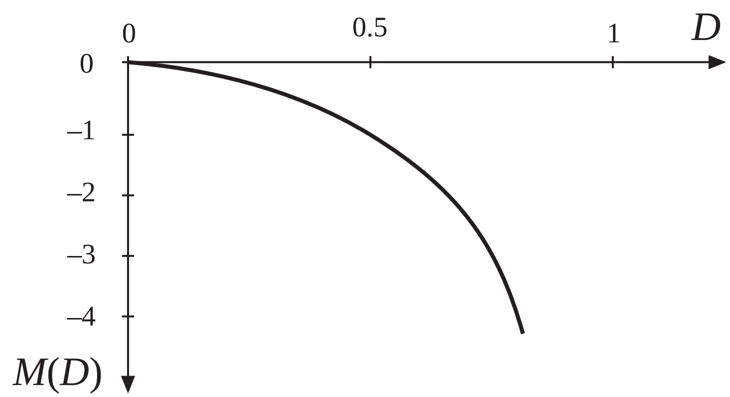




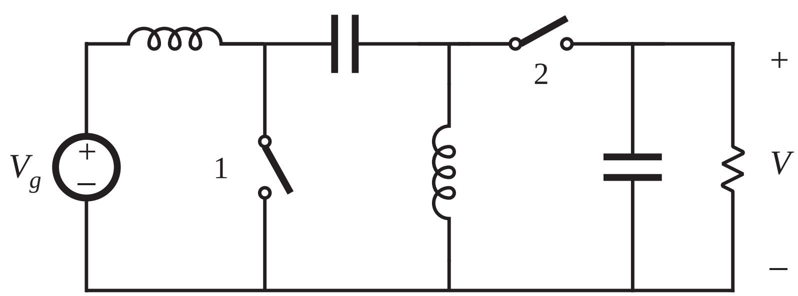
Several members of the class of two-inductor converters

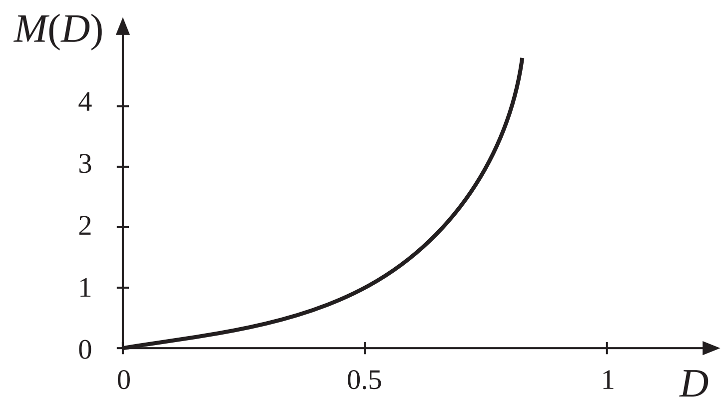
1. *Ćuk* $M(D) = -\frac{D}{1-D}$





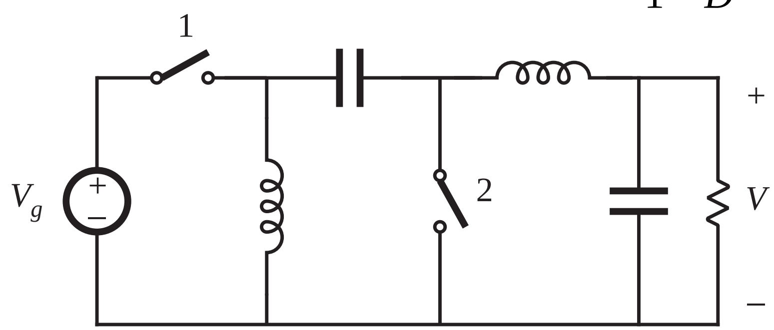
2. *SEPIC* $M(D) = \frac{D}{1-D}$

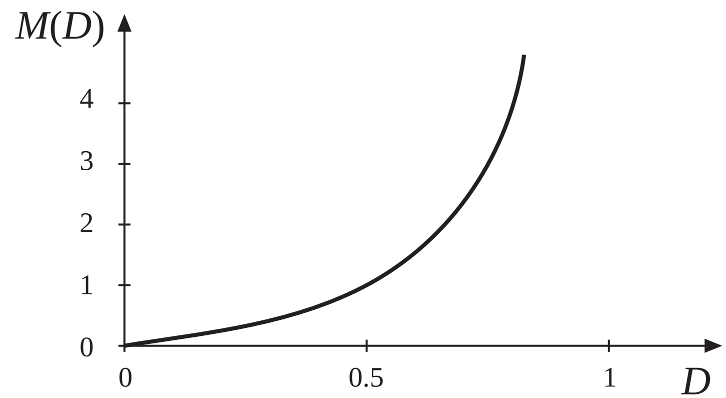




Several members of the class of two-inductor converters

3. *Inverse of SEPIC* $M(D) = \dfrac{D}{1-D}$





4. *Buck* [2] $M(D) = D^2$