Elements of Power Electronics
PART III: Topologies and applications

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PART III: Topologies and applications

- Chapter 6: Converter Circuits
- Applications

Chapter 6: Converter Circuits

- What is a topology? Why different topologies?
- The choice of a topology depends on the application:
  1. voltage/current range/direction,
  2. power direction,
  3. number of inputs/outputs,
  4. isolated vs. non-isolated,
  5. input and output current ripple,
  6. switches/transformer/inductor utilization,
  7. soft switching vs. hard switching,
  8. compactness (see Google interest https://en.wikipedia.org/wiki/Little_Box_Challenge),
  9. reliability (see European interest http://www.inrel-npower.eu/),
  10. EMC considerations...
- Today's optimum topologies are not tomorrow's better topologies because of semiconductors evolution (storageless example).
- Topology selection is an important decision.

Fundamentals of Power Electronics

Second edition

Robert W. Erickson

Dragan Maksimovic

University of Colorado, Boulder

Chapter 6. Converter Circuits

6.1. Circuit manipulations

6.2. A short list of converters

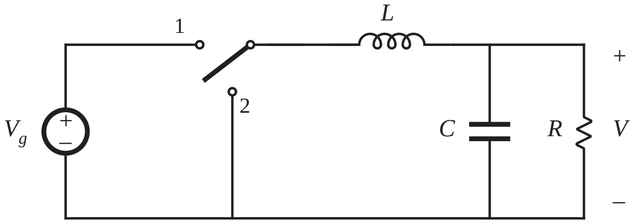
6.3. Transformer isolation

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

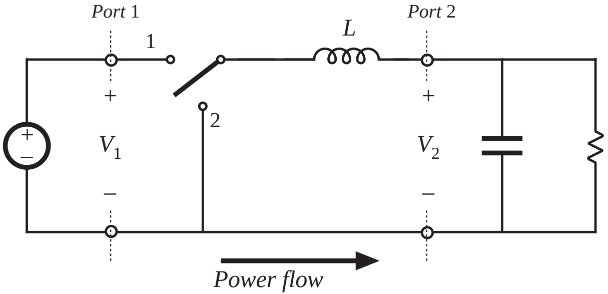
- Switch changes dc component, low-pass filter removes switching harmonics
- Conversion ratio is $M = D$

6.1.1. Inversion of source and load

Interchange power input and output ports of a converter

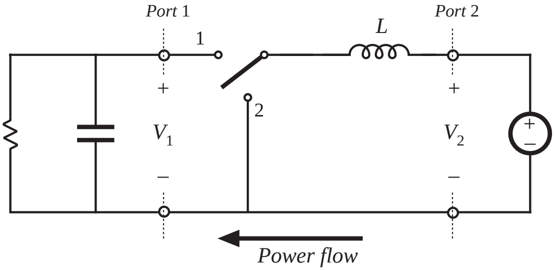
Buck converter example

$$V_2 = DV_1$$



Inversion of source and load

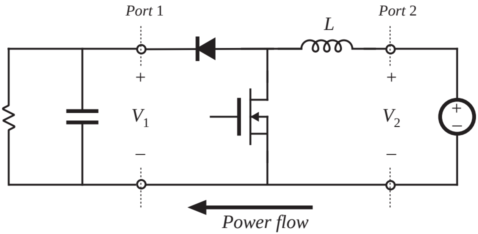
Interchange power source and load:



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

Realization of switches as in Chapter 4

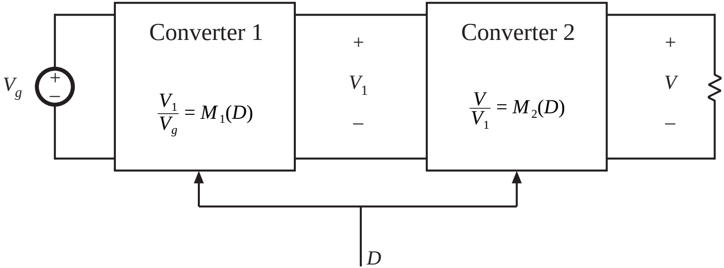
- Reversal of power flow requires new realization of switches
- Transistor conducts when switch is in position 2
- Interchange of D and D'



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

Inversion of buck converter yields boost converter

6.1.2. Cascade connection of converters

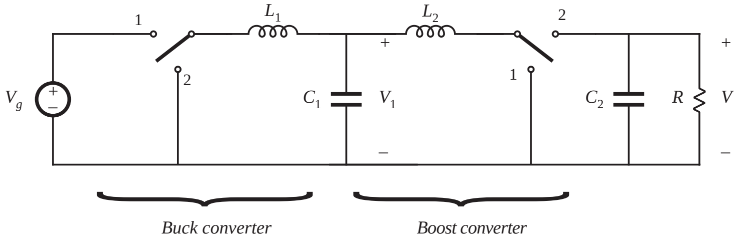


$$V_1 = M_1(D)V_g$$

$$V = M_2(D)V_1$$

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

Example: buck cascaded by boost



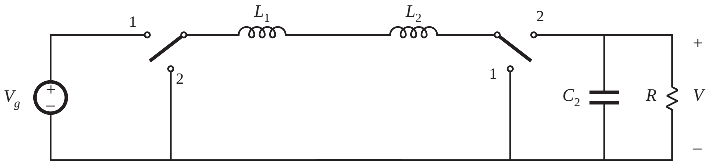
$$\frac{V_1}{V_g} = D$$

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

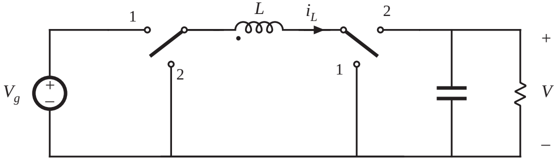
$$\longrightarrow \quad \frac{V}{V_g} = \frac{D}{1-D}$$

Buck cascaded by boost: simplification of internal filter

Remove capacitor C_1

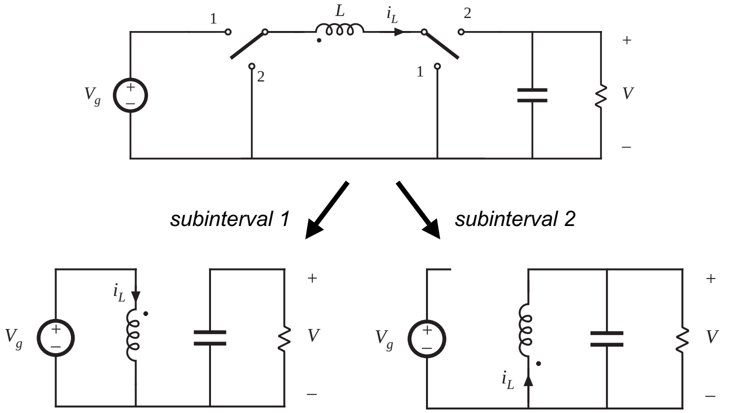


Combine inductors L_1 and L_2

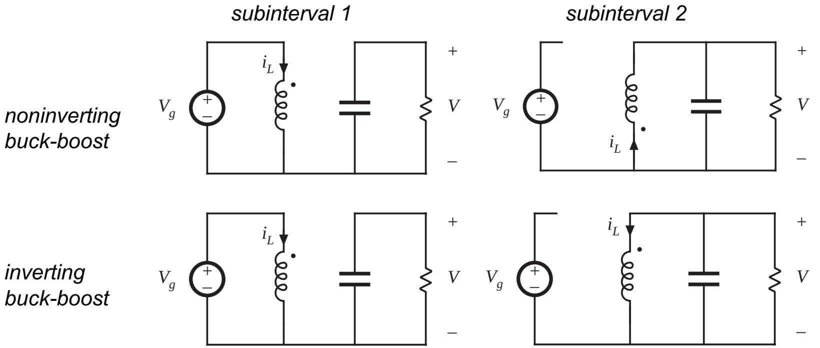


Noninverting buck-boost converter

Noninverting buck-boost converter

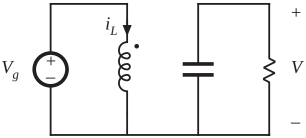


Reversal of output voltage polarity

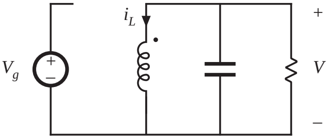


Reduction of number of switches: inverting buck-boost

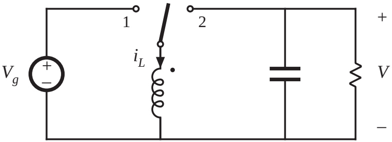
Subinterval 1



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

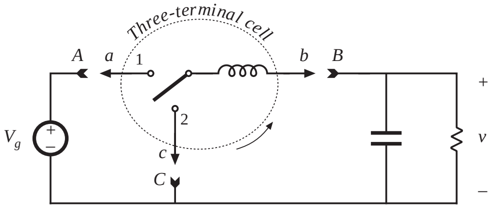
  Pulsating output current of boost converter

- 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:

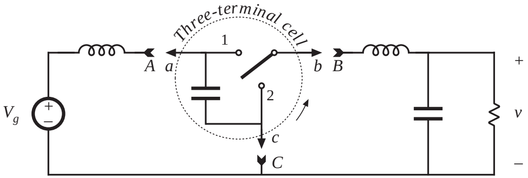


Three-terminal cell can be connected between source and load in three nontrivial distinct ways:

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

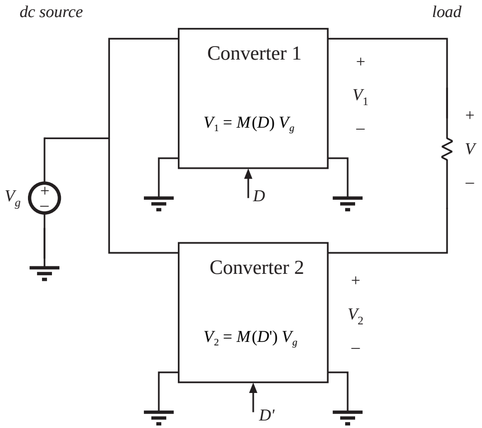
A capacitor and SPDT switch as a three-terminal cell:



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

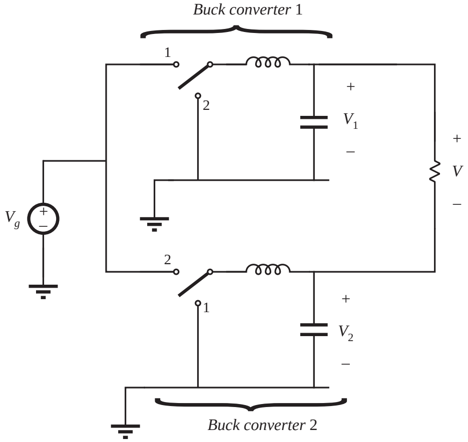


Differential load voltage is

$$V = V_1 - V_2$$

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

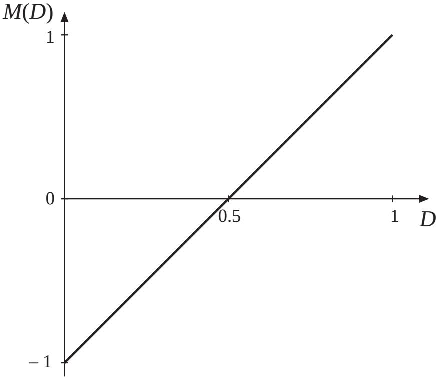
$$V = DV_g - D'V_g$$

Simplify:

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

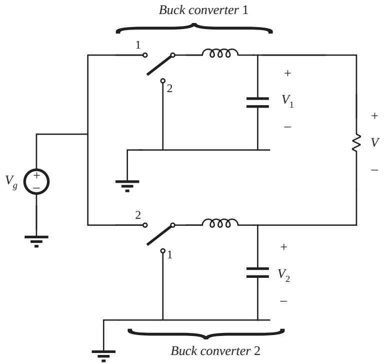
Conversion ratio $M(D)$, differentially-connected buck converters

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

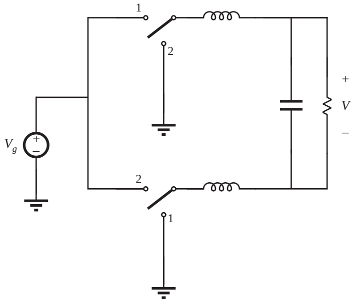


Simplification of filter circuit, differentially-connected buck converters

Original circuit

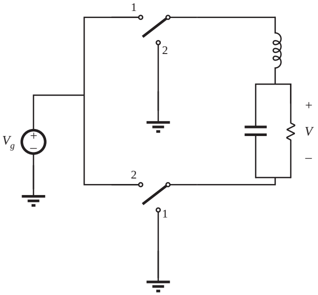


Bypass load directly with capacitor

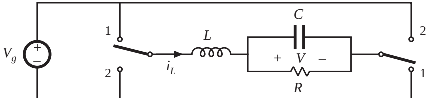


Simplification of filter circuit, differentially-connected buck converters

Combine series-connected inductors



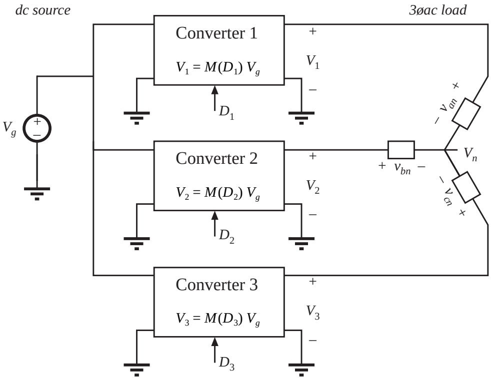
Re-draw for clarity



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

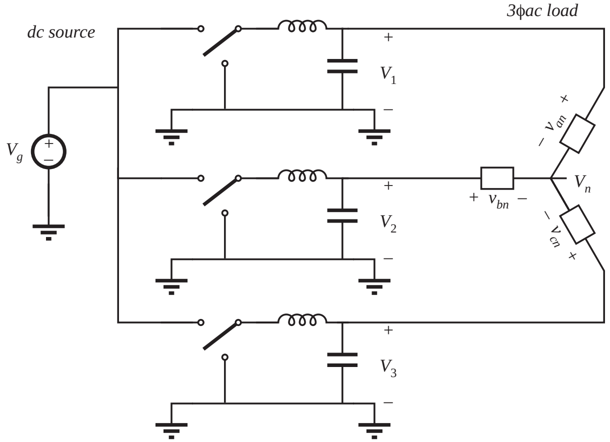
$$V_n = \frac{1}{3}\left(V_1 + V_2 + V_3\right)$$

Phase voltages are

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

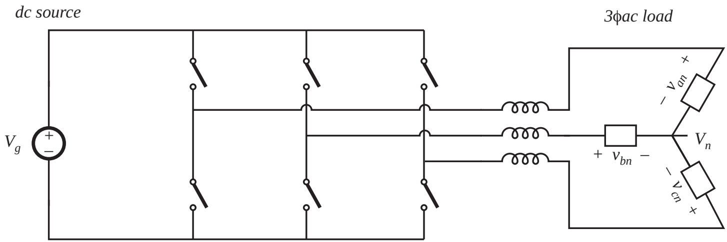
Control converters such that their output voltages contain the same dc biases. This dc bias will appear at the neutral point V_n. It then cancels out, so phase voltages contain no dc bias.

3ø differential connection of three buck converters



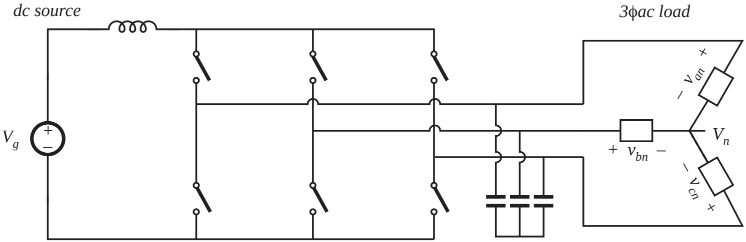
3ø differential connection of three buck converters

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

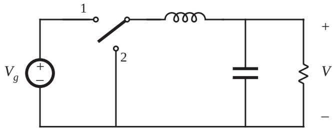
bridge   Watkins-Johnson

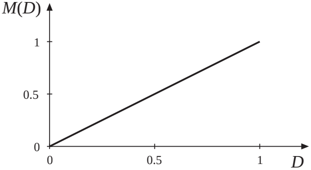
ac-dc converters

current-fed bridge   inverse of Watkins-Johnson

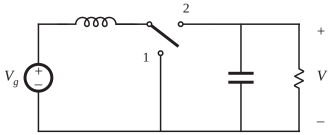
Converters producing a unipolar output voltage

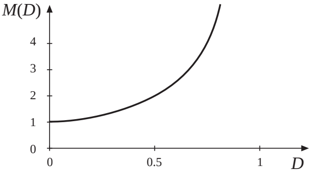
1. *Buck* $M(D) = D$





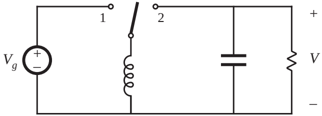
2. *Boost* $M(D) = \frac{1}{1-D}$

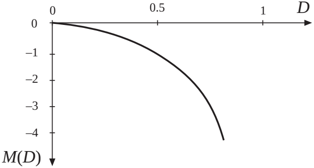




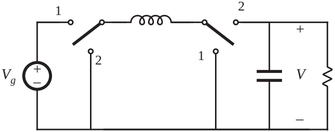
Converters producing a unipolar output voltage

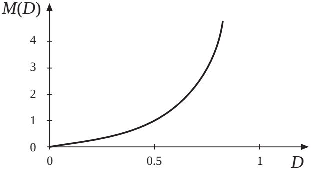
3. *Buck-boost* $M(D) = -\frac{D}{1-D}$





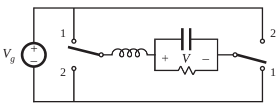
4. *Noninverting buck-boost* $M(D) = \frac{D}{1-D}$

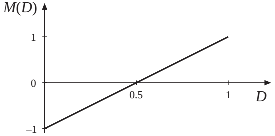




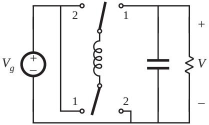
Converters producing a bipolar output voltage suitable as dc-ac inverters

5. *Bridge* $M(D) = 2D - 1$

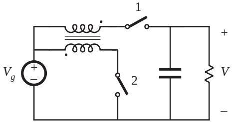


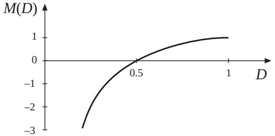


6. *Watkins-Johnson* $M(D) = \frac{2D-1}{D}$



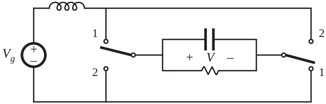
or

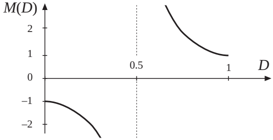




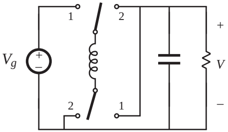
Converters producing a bipolar output voltage suitable as ac-dc rectifiers

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





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



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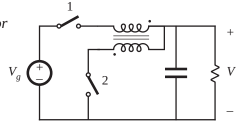
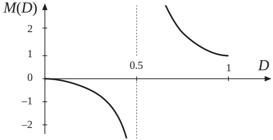
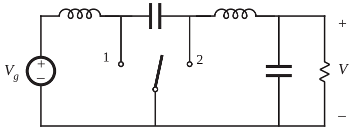
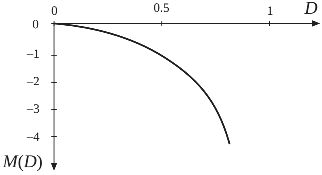




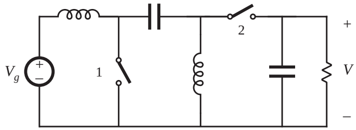
Several members of the class of two-inductor converters

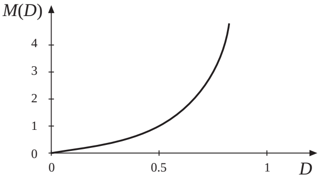
1. *Ćuk* $M(D) = -\dfrac{D}{1-D}$





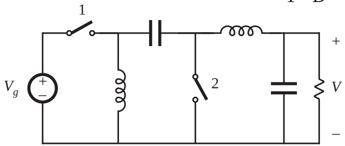
2. *SEPIC* $M(D) = \dfrac{D}{1-D}$

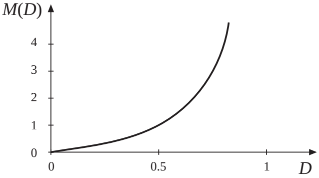




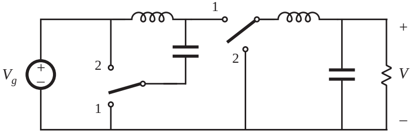
Several members of the class of two-inductor converters

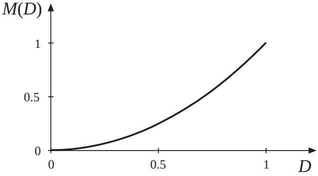
3. *Inverse of SEPIC* $\quad M(D) = \frac{D}{1-D}$





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





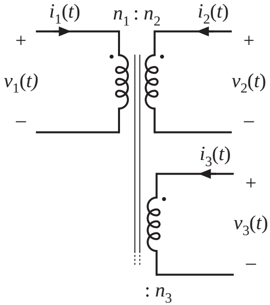
6.3. Transformer isolation

Objectives:

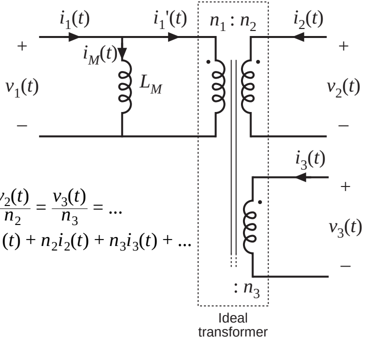
- Isolation of input and output ground connections, to meet safety requirements
- Reduction of transformer size by incorporating high frequency isolation transformer inside converter
- Minimization of current and voltage stresses when a large step-up or step-down conversion ratio is needed —use transformer turns ratio
- Obtain multiple output voltages via multiple transformer secondary windings and multiple converter secondary circuits

A simple transformer model

Multiple winding transformer



Equivalent circuit model



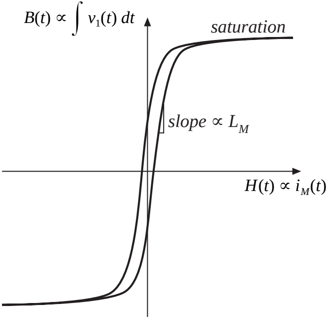
$$\frac{v_1(t)}{n_1} = \frac{v_2(t)}{n_2} = \frac{v_3(t)}{n_3} = \dots$$

$$0 = n_1 i_1'(t) + n_2 i_2(t) + n_3 i_3(t) + \dots$$

The magnetizing inductance L_M

- Models magnetization of transformer core material
- Appears effectively in parallel with windings
- If all secondary windings are disconnected, then primary winding behaves as an inductor, equal to the magnetizing inductance
- At dc: magnetizing inductance tends to short-circuit. Transformers cannot pass dc voltages
- Transformer saturates when magnetizing current i_M is too large

Transformer core B-H characteristic



Volt-second balance in L_M

The magnetizing inductance is a real inductor, obeying

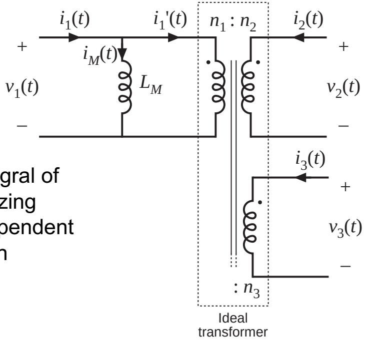
$$v_1(t) = L_M \frac{di_M(t)}{dt}$$

integrate:

$$i_M(t) - i_M(0) = \frac{1}{L_M} \int_0^t v_1(\tau) d\tau$$

Magnetizing current is determined by integral of the applied winding voltage. The magnetizing current and the winding currents are independent quantities. Volt-second balance applies: in steady-state, $i_M(T_s) = i_M(0)$, and hence

$$0 = \frac{1}{T_s} \int_0^{T_s} v_1(t) dt$$

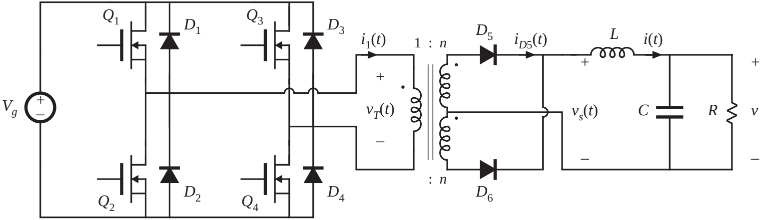


Transformer reset

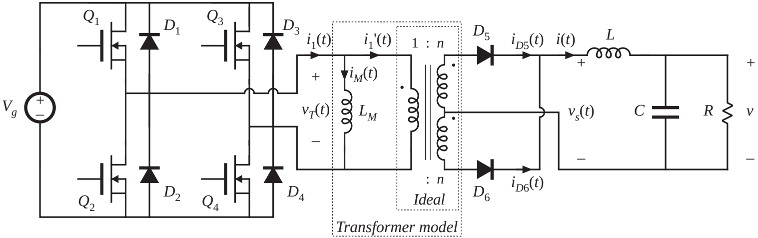
- "Transformer reset" is the mechanism by which magnetizing inductance volt-second balance is obtained
- The need to reset the transformer volt-seconds to zero by the end of each switching period adds considerable complexity to converters
- To understand operation of transformer-isolated converters:
  - replace transformer by equivalent circuit model containing magnetizing inductance
  - analyze converter as usual, treating magnetizing inductance as any other inductor
  - apply volt-second balance to all converter inductors, including magnetizing inductance

6.3.1. Full-bridge and half-bridge isolated buck converters

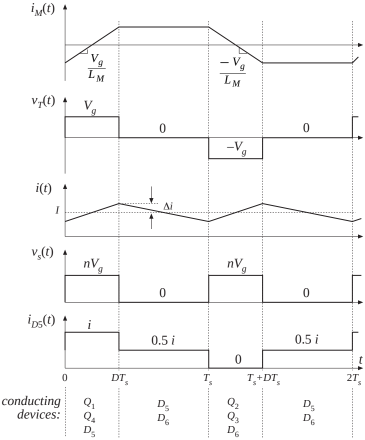
Full-bridge isolated buck converter



Full-bridge, with transformer equivalent circuit



Full-bridge: waveforms



- During first switching period: transistors Q_1 and Q_4 conduct for time DT_s , applying volt-seconds $V_g\,DT_s$ to primary winding
- During next switching period: transistors Q_2 and Q_3 conduct for time DT_s , applying volt-seconds $-V_g\,DT_s$ to primary winding
- Transformer volt-second balance is obtained over two switching periods
- Effect of nonidealities?

Effect of nonidealities on transformer volt-second balance

Volt-seconds applied to primary winding during first switching period:

$$(V_g - (Q_1 \text{ and } Q_4 \text{ forward voltage drops}))(Q_1 \text{ and } Q_4 \text{ conduction time})$$

Volt-seconds applied to primary winding during next switching period:

$$-(V_g - (Q_2 \text{ and } Q_3 \text{ forward voltage drops}))(Q_2 \text{ and } Q_3 \text{ conduction time})$$

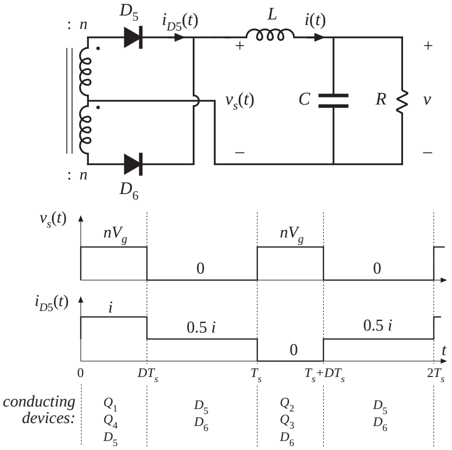
These volt-seconds never add to *exactly* zero.

Net volt-seconds are applied to primary winding

Magnetizing current slowly increases in magnitude

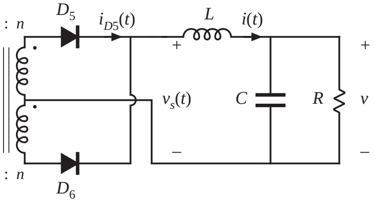
Saturation can be prevented by placing a capacitor in series with primary, or by use of current programmed mode (Chapter 12)

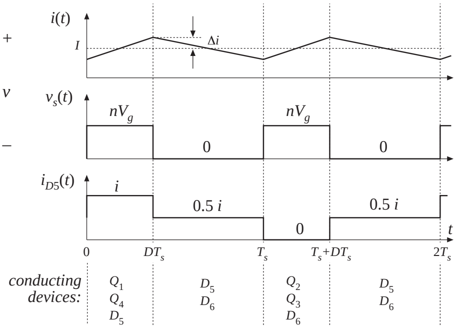
Operation of secondary-side diodes



- During second (D') subinterval, both secondary-side diodes conduct
- Output filter inductor current divides approximately equally between diodes
- Secondary amp-turns add to approximately zero
- Essentially no net magnetization of transformer core by secondary winding currents

Volt-second balance on output filter inductor



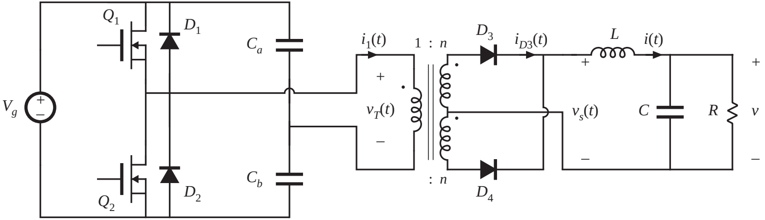


$$V = \langle v_s \rangle$$

$$V = nDV_g$$

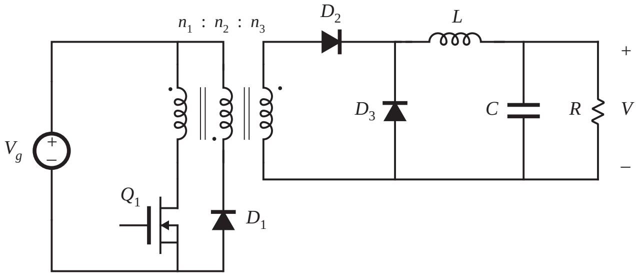
$M(D) = nD$ buck converter with turns ratio

Half-bridge isolated buck converter



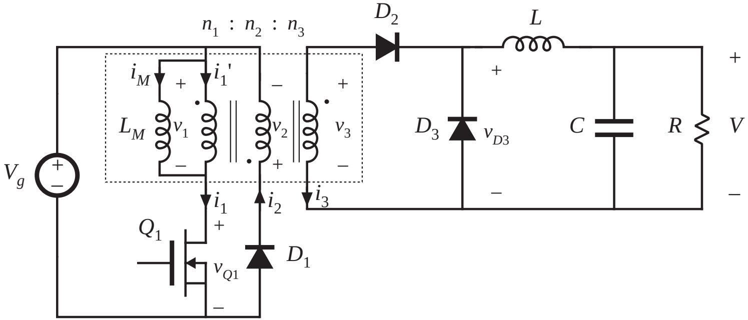
- Replace transistors Q_3 and Q_4 with large capacitors
- Voltage at capacitor centerpoint is $0.5V_g$
- $v_s(t)$ is reduced by a factor of two
- $M = 0.5\ nD$

6.3.2. Forward converter

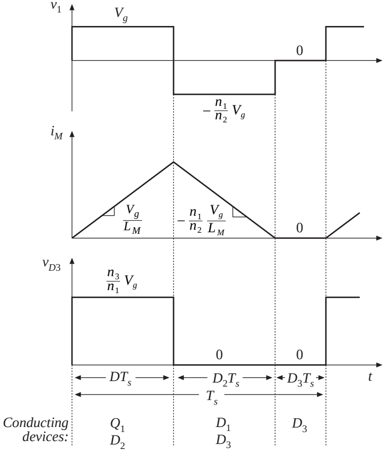


- Buck-derived transformer-isolated converter
- Single-transistor and two-transistor versions
- Maximum duty cycle is limited
- Transformer is reset while transistor is off

Forward converter with transformer equivalent circuit

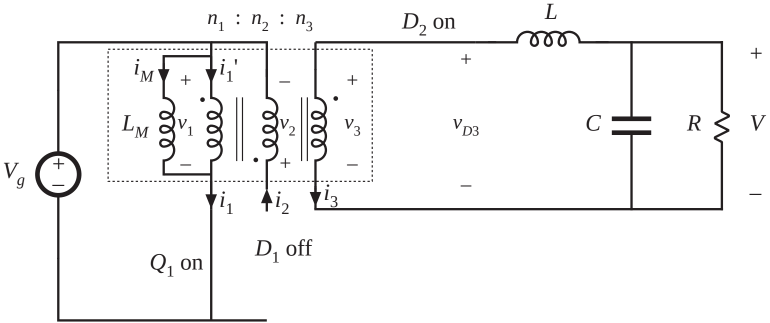


Forward converter: waveforms

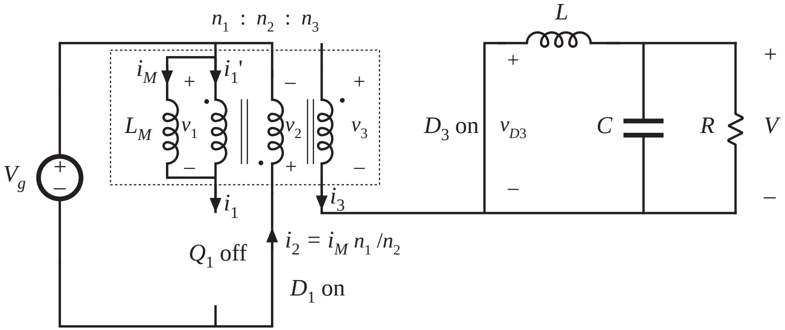


- Magnetizing current, in conjunction with diode D_1, operates in discontinuous conduction mode
- Output filter inductor, in conjunction with diode D_3, may operate in either CCM or DCM

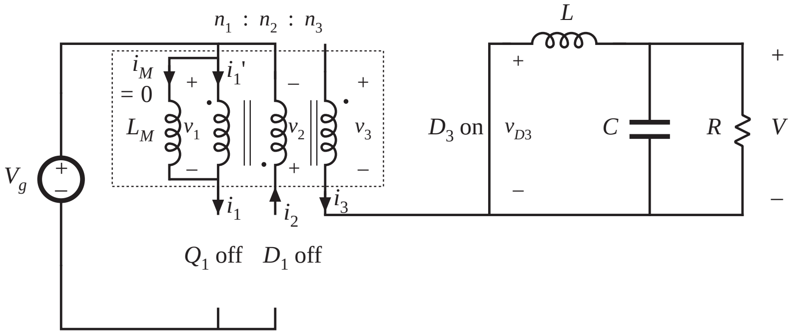
Subinterval 1: transistor conducts



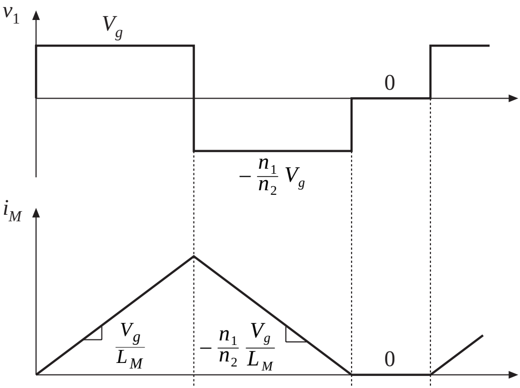
Subinterval 2: transformer reset



Subinterval 3



Magnetizing inductance volt-second balance



$$\langle v_1 \rangle = D(V_g) + D_2(-V_g n_1/n_2) + D_3(0) = 0$$

Transformer reset

From magnetizing current volt-second balance:

$$\left\langle v_1 \right\rangle = D\left(V_g\right) + D_2\left(-V_g n_1/n_2\right) + D_3\left(0\right) = 0$$

Solve for D_2:

$$D_2 = \frac{n_2}{n_1} D$$

D_3 cannot be negative. But $D_3 = 1 - D - D_2$. Hence

$$D_3 = 1 - D - D_2 \geq 0$$

$$D_3 = 1 - D\left(1 + \frac{n_2}{n_1}\right) \geq 0$$

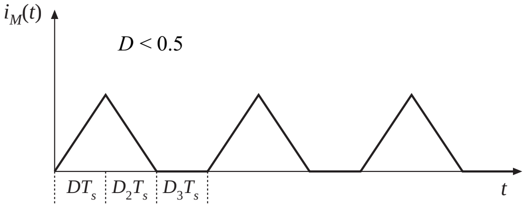
Solve for D

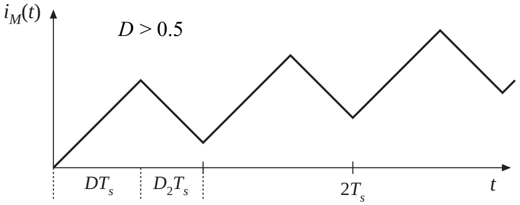
$$D \leq \frac{1}{1 + \frac{n_2}{n_1}}$$

for $n_1 = n_2$: $D \leq \frac{1}{2}$

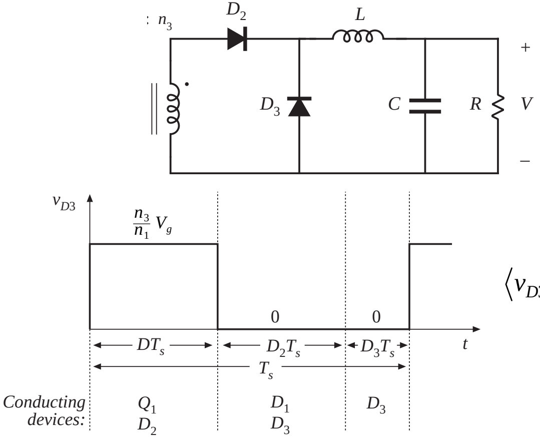
What happens when $D > 0.5$

magnetizing current waveforms,
for $n_1 = n_2$





Conversion ratio $M(D)$



$$\langle v_{D3} \rangle = V = \frac{n_3}{n_1} D V_g$$

Maximum duty cycle vs. transistor voltage stress

Maximum duty cycle limited to

$$D \le \frac{1}{1 + \frac{n_2}{n_1}}$$

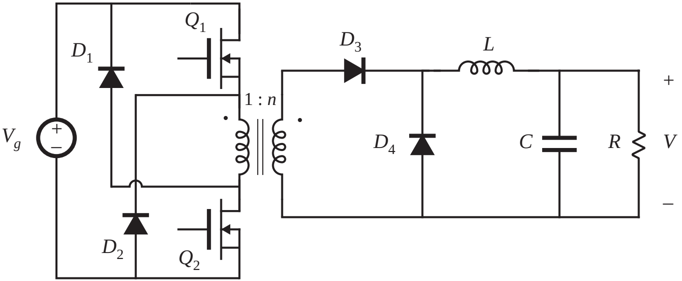
which can be increased by decreasing the turns ratio n_2 / n_1. But this increases the peak transistor voltage:

$$\max\left(v_{Q1}\right) = V_g\left(1 + \frac{n_1}{n_2}\right)$$

For $n_1 = n_2$

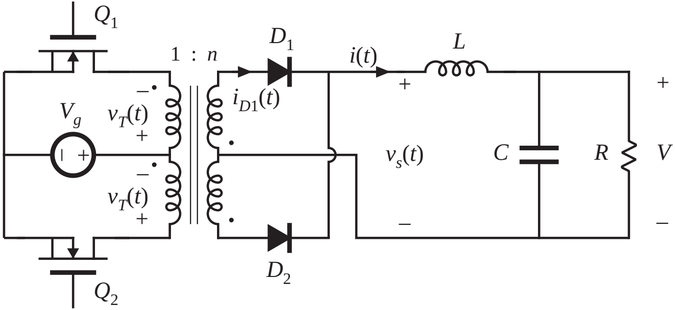
$$D \le \frac{1}{2}$$ and $$\max(v_{Q1}) = 2V_g$$

The two-transistor forward converter



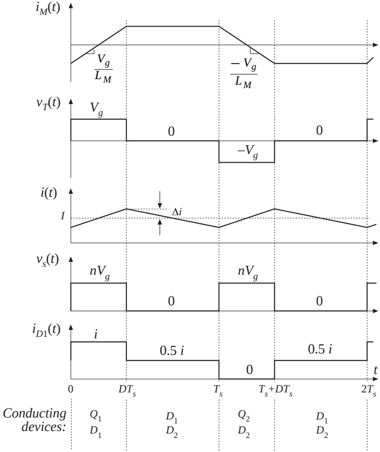
$$V = nDV_g \qquad D \leq \frac{1}{2} \qquad \max(v_{Q1}) = \max(v_{Q2}) = V_g$$

6.3.3. Push-pull isolated buck converter



$$V = nDV_g \qquad 0 \le D \le 1$$

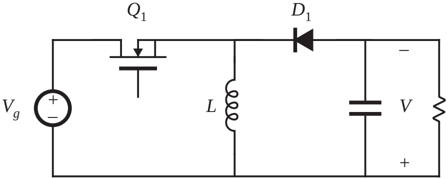
Waveforms: push-pull



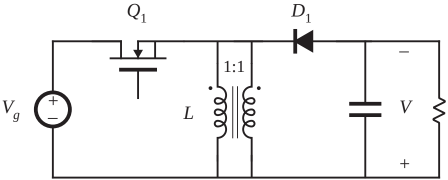
- Used with low-voltage inputs
- Secondary-side circuit identical to full bridge
- As in full bridge, transformer volt-second balance is obtained over two switching periods
- Effect of nonidealities on transformer volt-second balance?
- Current programmed control can be used to mitigate transformer saturation problems. Duty cycle control not recommended.

6.3.4. Flyback converter

buck-boost converter:

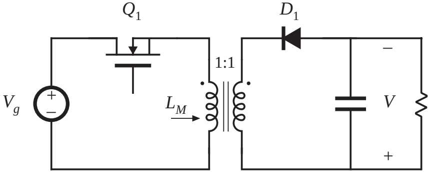


construct inductor winding using two parallel wires:

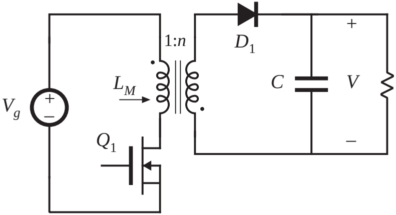


Derivation of flyback converter, cont.

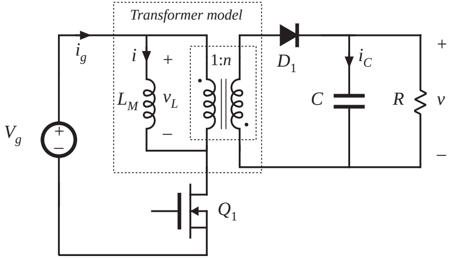
Isolate inductor windings: the flyback converter



Flyback converter having a $1{:}n$ *turns ratio and positive output:*



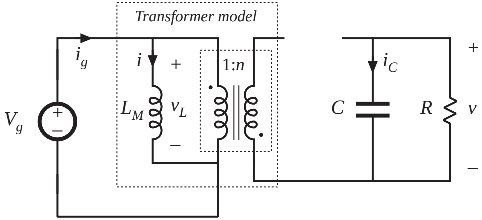
The "flyback transformer"



- A two-winding inductor
- Symbol is same as transformer, but function differs significantly from ideal transformer
- Energy is stored in magnetizing inductance
- Magnetizing inductance is relatively small

- Current does not simultaneously flow in primary and secondary windings
- Instantaneous winding voltages follow turns ratio
- Instantaneous (and rms) winding currents do not follow turns ratio
- Model as (small) magnetizing inductance in parallel with ideal transformer

Subinterval 1



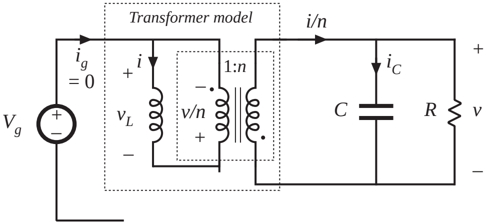
Q_1 on, D_1 off

$$v_L = V_g$$
$$i_C = -\frac{v}{R}$$
$$i_g = i$$

CCM: small ripple approximation leads to

$$v_L = V_g$$
$$i_C = -\frac{V}{R}$$
$$i_g = I$$

Subinterval 2



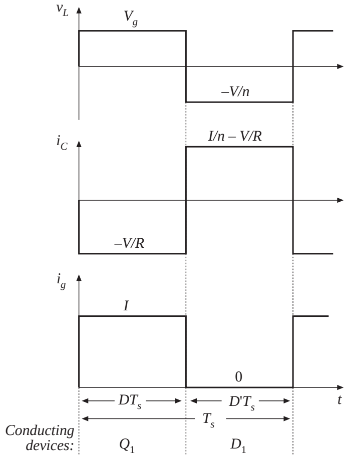
$$v_L = -\frac{v}{n}$$
$$i_C = \frac{i}{n} - \frac{v}{R}$$
$$i_g = 0$$

CCM: small ripple approximation leads to

Q_1 off, D_1 on

$$v_L = -\frac{V}{n}$$
$$i_C = \frac{I}{n} - \frac{V}{R}$$
$$i_g = 0$$

CCM Flyback waveforms and solution



Volt-second balance:

$$\langle v_L \rangle = D\left(V_g\right) + D'\left(-\frac{V}{n}\right) = 0$$

Conversion ratio is

$$M(D) = \frac{V}{V_g} = n\,\frac{D}{D'}$$

Charge balance:

$$\langle i_C \rangle = D\left(-\frac{V}{R}\right) + D'\left(\frac{I}{n} - \frac{V}{R}\right) = 0$$

Dc component of magnetizing current is

$$I = \frac{nV}{D'R}$$

Dc component of source current is

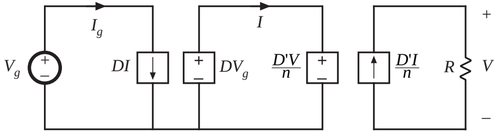
$$I_g = \langle i_g \rangle = D\left(I\right) + D'\left(0\right)$$

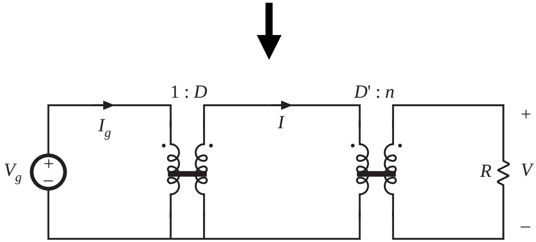
Equivalent circuit model: CCM Flyback

$$\langle v_L \rangle = D\left(V_g\right) + D'\left(-\frac{V}{n}\right) = 0$$

$$\langle i_C \rangle = D\left(-\frac{V}{R}\right) + D'\left(\frac{I}{n} - \frac{V}{R}\right) = 0$$

$$I_g = \langle i_g \rangle = D\left(I\right) + D'\left(0\right)$$



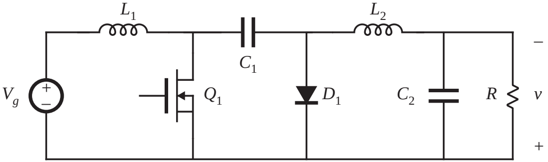


Discussion: Flyback converter

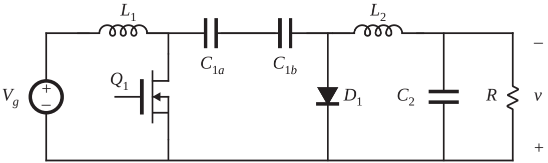
- Widely used in low power and/or high voltage applications
- Low parts count
- Multiple outputs are easily obtained, with minimum additional parts
- Cross regulation is inferior to buck-derived isolated converters
- Often operated in discontinuous conduction mode
- DCM analysis: DCM buck-boost with turns ratio

Obtaining isolation in the Cuk converter

Nonisolated Cuk converter



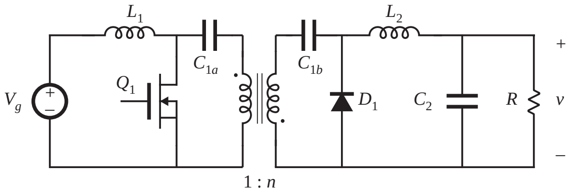
Split capacitor C_1 into series capacitors C_{1a} and C_{1b}



Isolated Cuk converter

Insert transformer between capacitors C_{1a} and C_{1b}

$$M(D) = \frac{V}{V_g} = \frac{nD}{D'}$$



Discussion

- Capacitors C_{1a} *and* C_{1b} ensure that no dc voltage is applied to transformer primary or secondary windings
- Transformer functions in conventional manner, with small magnetizing current and negligible energy storage within the magnetizing inductance

6.4. Converter evaluation and design

For a given application, which converter topology is best?

There is no ultimate converter, perfectly suited for all possible applications

Trade studies

- Rough designs of several converter topologies to meet the given specifications
- An unbiased quantitative comparison of worst-case transistor currents and voltages, transformer size, etc.

Comparison via switch stress, switch utilization, and semiconductor cost

Spreadsheet design

6.4.1. Switch stress and switch utilization

- Largest single cost in a converter is usually the cost of the active semiconductor devices
- Conduction and switching losses associated with the active semiconductor devices often dominate the other sources of loss

This suggests evaluating candidate converter approaches by comparing the voltage and current stresses imposed on the active semiconductor devices.

Minimization of total switch stresses leads to reduced loss, and to minimization of the total silicon area required to realize the power devices of the converter.

Total active switch stress S

In a converter having k active semiconductor devices, the total active switch stress S is defined as

$$S = \sum_{j=1}^{k} V_j I_j$$

where

V_j is the peak voltage applied to switch j,

I_j is the rms current applied to switch j (peak current is also sometimes used).

In a good design, the total active switch stress is minimized.

Active switch utilization U

It is desired to minimize the total active switch stress, while maximizing the output power P_{load}.

The active switch utilization U is defined as

$$U = \frac{P_{load}}{S}$$

The active switch utilization is the converter output power obtained per unit of active switch stress. It is a converter figure-of-merit, which measures how well a converter utilizes its semiconductor devices.

Active switch utilization is less than 1 in transformer-isolated converters, and is a quantity to be maximized.

Converters having low switch utilizations require extra active silicon area, and operate with relatively low efficiency.

Active switch utilization is a function of converter operating point.

Comparison of switch utilizations of some common converters

Table 6.1. Active switch utilizations of some common dc-dc converters, single operating point.

Converter	*U(D)*	max *U(D)*	max *U(D)* *occurs at D =*
Buck	$\sqrt{D}$	1	1
Boost	$\frac{D'}{\sqrt{D}}$	∞	0
Buck-boost, flyback, nonisolated SEPIC, isolated SEPIC, nonisolated Cuk, isolated Cuk	$D'\sqrt{D}$	$\frac{2}{3\sqrt{3}} = 0.385$	$\frac{1}{3}$
Forward, $n_1 = n_2$	$\frac{1}{2}\sqrt{D}$	$\frac{1}{2\sqrt{2}} = 0.353$	$\frac{1}{2}$
Other isolated buck-derived converters (full-bridge, half-bridge, push-pull)	$\frac{\sqrt{D}}{2\sqrt{2}}$	$\frac{1}{2\sqrt{2}} = 0.353$	1
Isolated boost-derived converters (full bridge, push-pull)	$\frac{D'}{2\sqrt{1+D}}$	$\frac{1}{2}$	0

Switch utilization : Discussion

- Increasing the range of operating points leads to reduced switch utilization
- Buck converter
  - can operate with high switch utilization (U approaching 1) when D is close to 1
- Boost converter
  - can operate with high switch utilization (U approaching ∞) when D is close to 1
- Transformer isolation leads to reduced switch utilization
- Buck-derived transformer-isolated converters
  - $U \leq 0.353$
  - should be designed to operate with D as large as other considerations allow
  - transformer turns ratio can be chosen to optimize design

Switch utilization: Discussion

- Nonisolated and isolated versions of buck-boost, SEPIC, and Cuk converters
  - $U \leq 0.385$
  - Single-operating-point optimum occurs at $D = 1/3$
  - Nonisolated converters have lower switch utilizations than buck or boost
  - Isolation can be obtained without penalizing switch utilization

Active semiconductor cost vs. switch utilization

$$\left(\begin{array}{c}\text{semiconductor cost}\\ \text{per kW output power}\end{array}\right) = \frac{\left(\begin{array}{c}\text{semiconductor device cost}\\ \text{per rated kVA}\end{array}\right)}{\left(\begin{array}{c}\text{voltage}\\ \text{derating}\\ \text{factor}\end{array}\right)\left(\begin{array}{c}\text{current}\\ \text{derating}\\ \text{factor}\end{array}\right)\left(\begin{array}{c}\text{converter}\\ \text{switch}\\ \text{utilization}\end{array}\right)}$$

(semiconductor device cost per rated kVA) = cost of device, divided by product of rated blocking voltage and rms current, in $\$/\mathrm{kVA}$. Typical values are less than $\$1/\mathrm{kVA}$

(voltage derating factor) and (current derating factor) are required to obtain reliable operation. Typical derating factors are 0.5 - 0.75

Typical cost of active semiconductor devices in an isolated dc-dc converter: \$1 - \$10 per kW of output power.

Summary of key points

1. The boost converter can be viewed as an inverse buck converter, while the buck-boost and Cuk converters arise from cascade connections of buck and boost converters. The properties of these converters are consistent with their origins. Ac outputs can be obtained by differential connection of the load. An infinite number of converters are possible, and several are listed in this chapter.

2. For understanding the operation of most converters containing transformers, the transformer can be modeled as a magnetizing inductance in parallel with an ideal transformer. The magnetizing inductance must obey all of the usual rules for inductors, including the principle of volt-second balance.

Summary of key points

3. The steady-state behavior of transformer-isolated converters may be understood by first replacing the transformer with the magnetizing-inductance-plus-ideal-transformer equivalent circuit. The techniques developed in the previous chapters can then be applied, including use of inductor volt-second balance and capacitor charge balance to find dc currents and voltages, use of equivalent circuits to model losses and efficiency, and analysis of the discontinuous conduction mode.

4. In the full-bridge, half-bridge, and push-pull isolated versions of the buck and/or boost converters, the transformer frequency is twice the output ripple frequency. The transformer is reset while it transfers energy: the applied voltage polarity alternates on successive switching periods.

Summary of key points

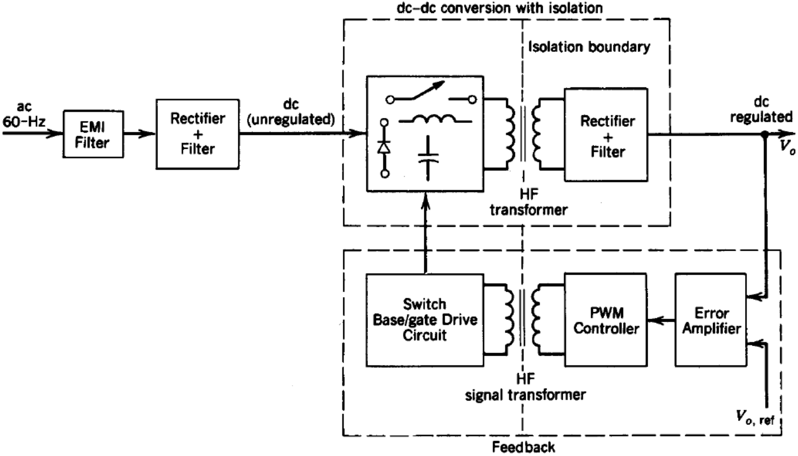
5. In the conventional forward converter, the transformer is reset while the transistor is off. The transformer magnetizing inductance operates in the discontinuous conduction mode, and the maximum duty cycle is limited.
6. The flyback converter is based on the buck-boost converter. The flyback transformer is actually a two-winding inductor, which stores and transfers energy.
7. The transformer turns ratio is an extra degree-of-freedom which the designer can choose to optimize the converter design. Use of a computer spreadsheet is an effective way to determine how the choice of turns ratio affects the component voltage and current stresses.
8. Total active switch stress, and active switch utilization, are two simplified figures-of-merit which can be used to compare the various converter circuits.

Applications

- Isolation
- Uninteruptible power supplies (UPS)
- Motor drive
- Heating, Welding
- Wireless power transfer
- Energy generation (solar, wind)
- Active filtering, power factor correction (PFC)
- Vehicles
- HVDC (1 GW and more)

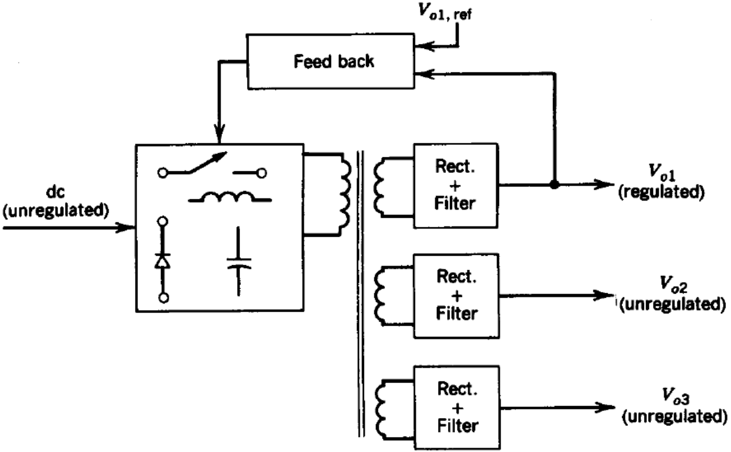
Utility grid adapter

Excerpt of [1] (fig 10-2), typical wall adapter with isolation, including feedback for proper DC regulated voltage.



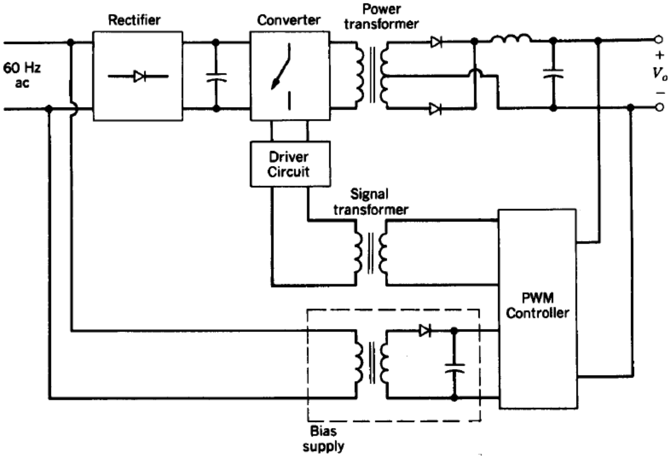
Multiple outputs power supply

Excerpt of [1] (fig 10-3), multiple outputs isolated power supply with cross-regulated outputs.



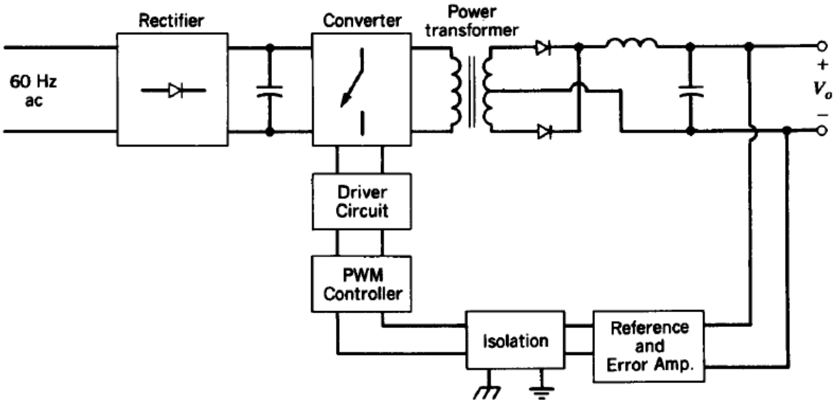
Isolating feedback (solution 1)

Excerpt of [1] (fig 10-34a), PWM controller on the output side.



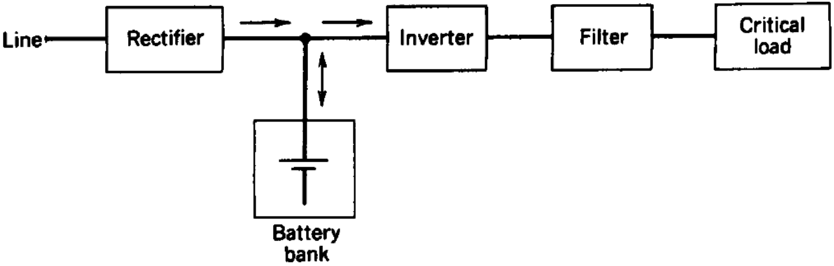
Isolating feedback (solution 2)

Excerpt of [1] (fig 10-34b), PWM controller on the input side.



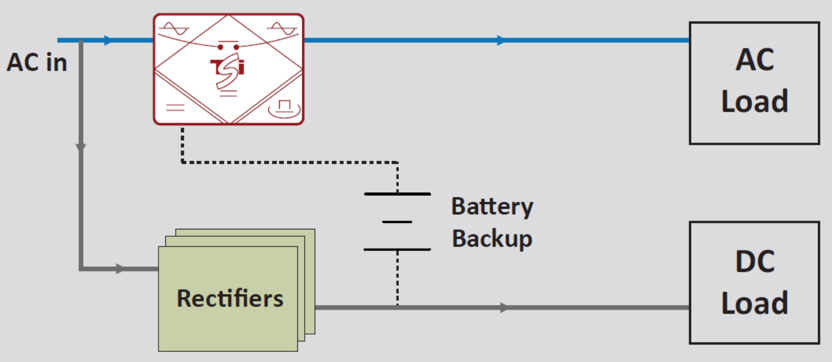
Uninterruptible power supply (classical solution)

Excerpt of [1] (fig 11-4), classical UPS for powering critical load.



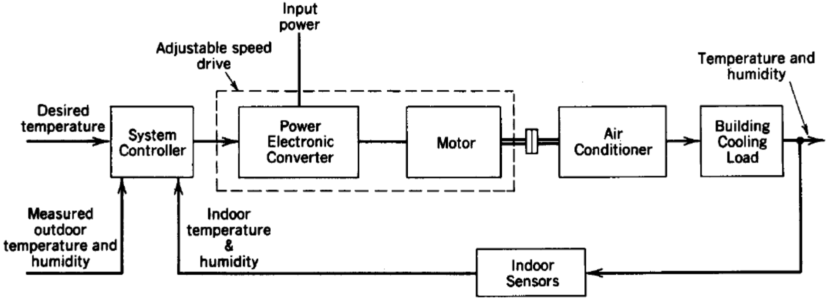
Uninterruptible power supply (optimized solution)

Excerpt of the CE+T web site, high efficiency UPS solution.



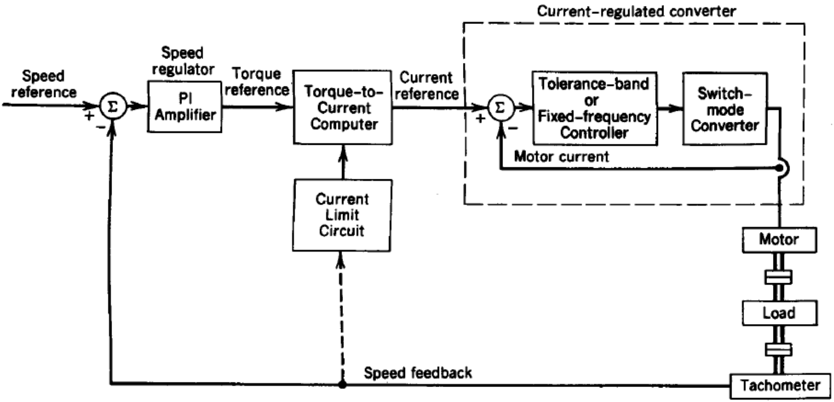
Motor drive application

Excerpt of [1] (fig 12-3), air conditioner that takes benefit of a converter (inverter) to control the temperature.



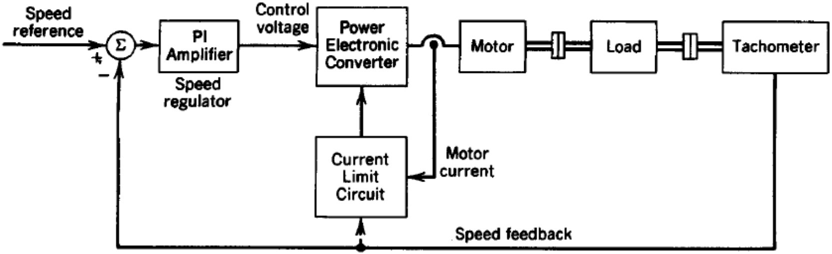
Servo drive control and current limiting

Excerpt of [1] (fig 12-8a), speed control block diagram (method a).

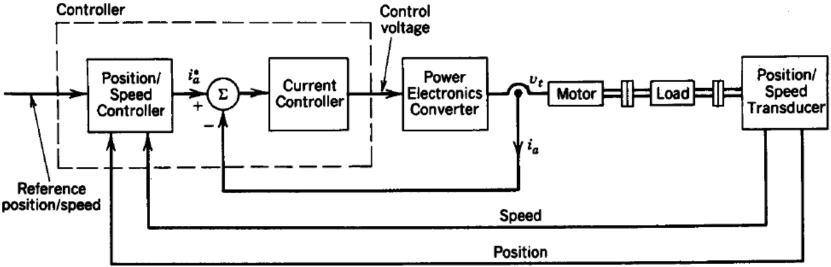


Servo drive control and current limiting

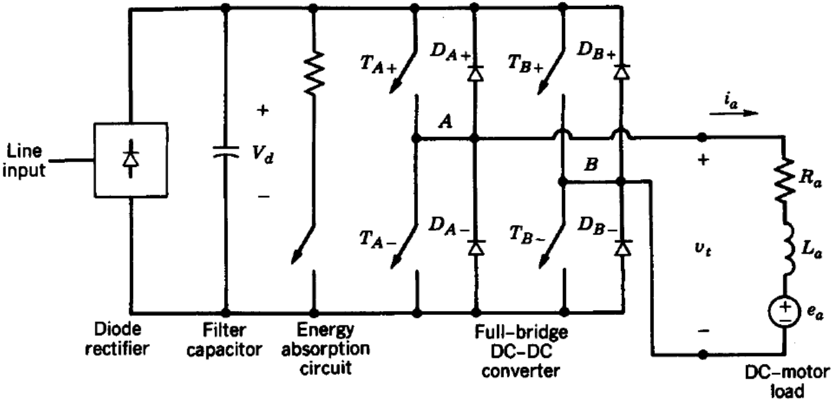
Excerpt of [1] (fig 12-8b), speed control block diagram (method b).



Excerpt of [1] (fig 13-6), closed loop position/speed DC servo drive.

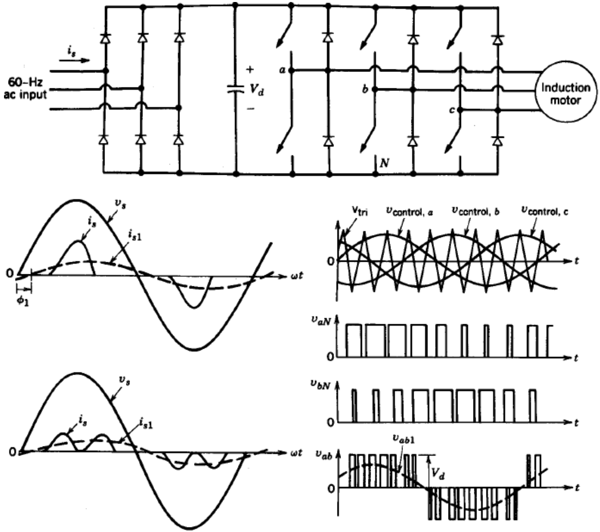


Excerpt of [1] (fig 13-10), drive with four-quadrant operation.



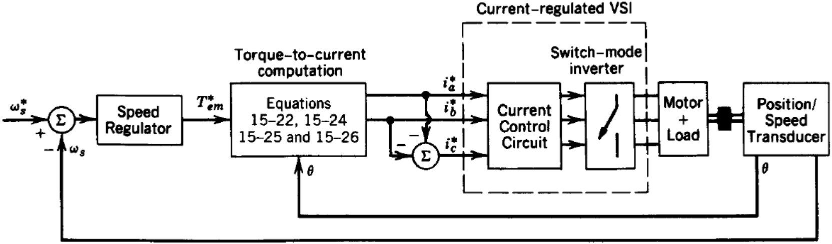
Induction motor drive

Excerpt of [1] (fig 14-19), PWM-VSI inverter.



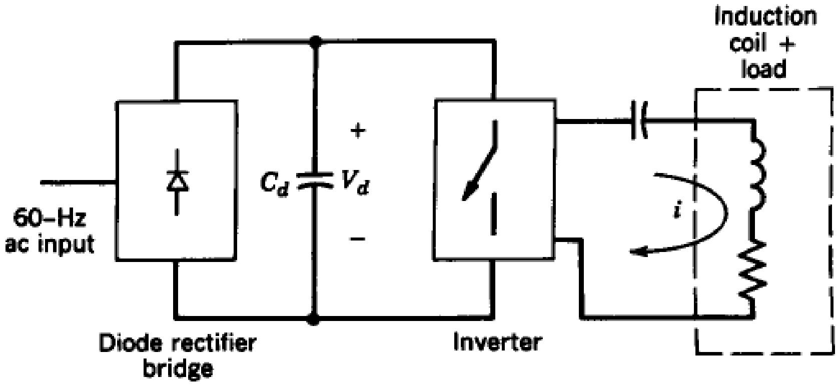
Synchronous motor servo drive

Excerpt of [1] (fig 15-5), synchronous motor servo drive.



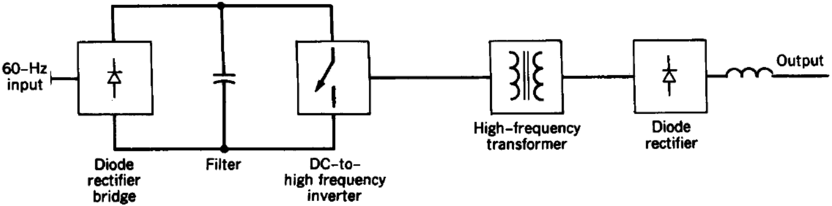
Induction heating

Excerpt of [1] (fig 16-7), voltage source resonant induction heating.



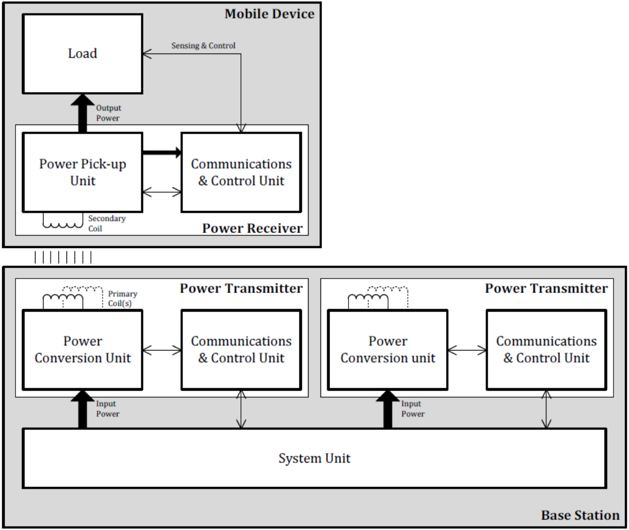
Electric welding

Excerpt of [1] (fig 16-9), switch-mode welder.



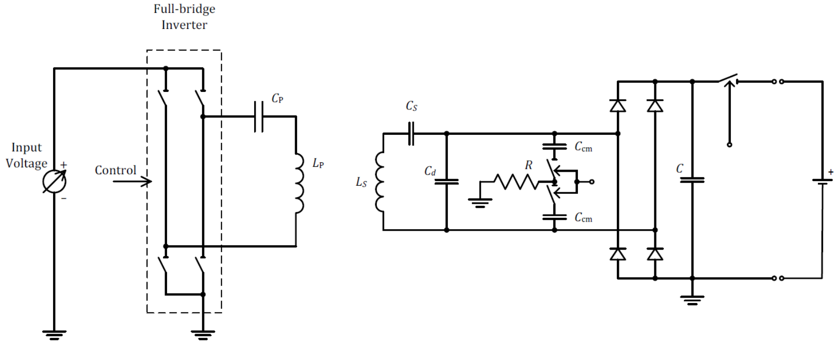
Wireless power transfer

Excerpt of the Qi standard, basic system overview.



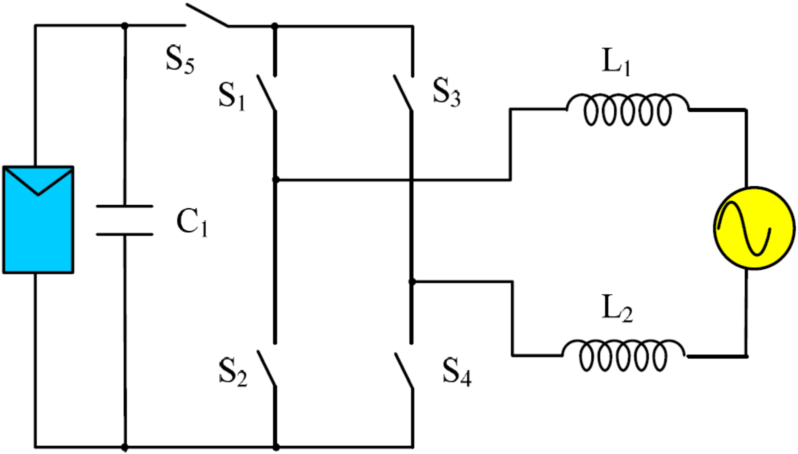
Wireless power transfer

Excerpt of the Qi standard, example of power TX and RX devices.



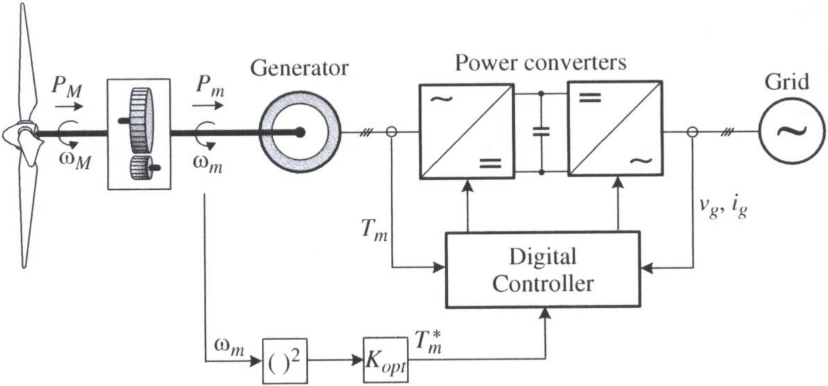
Solar inverter

Excerpt of [2], H5 topology from SMA (implemented in their commercial inverters).

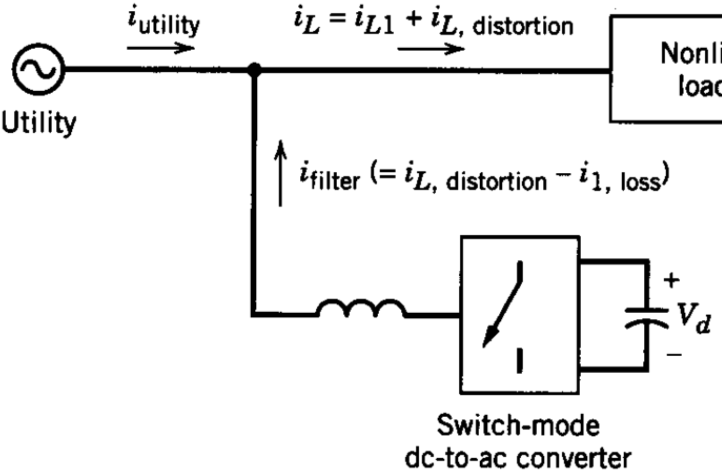


Wind inverter

Excerpt of [3], example of wind energy converter implementing MPPT with optimal torque control of wind turbines.

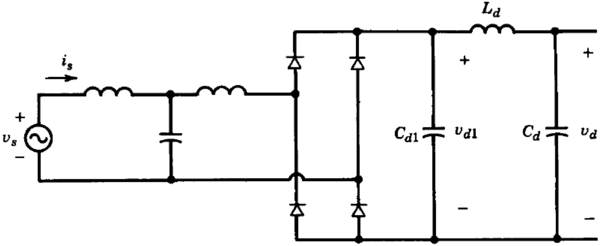


Excerpt of [1], utility grid parallel active filter.

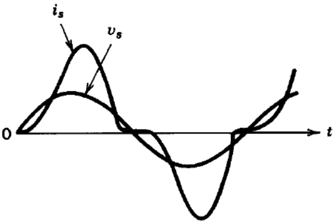


Power factor corrector

Excerpt of [1], power factor correction problem.

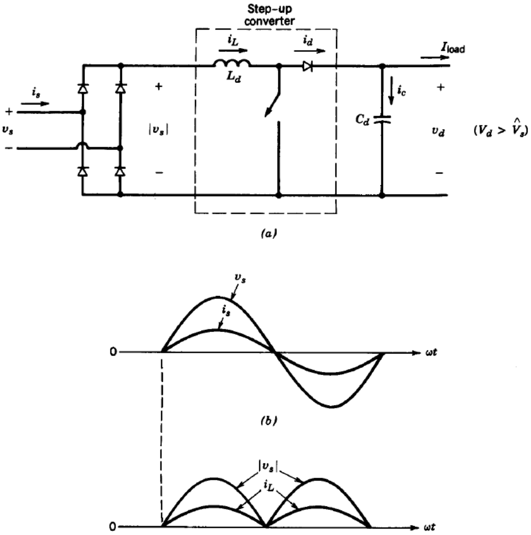


(a)



Power factor corrector

Excerpt of [1], the typical solution.



Maiden flight with a record-setting motor

2016-Jul-04

For the first time ever, a plane in the certification category CS23 flies with Permit-to-Fly purely electric. The plane is powered by a 260 kilowatt Siemens motor that weighs a mere 50 kilogramm – a record-setting power-to-weight ratio.

HVDC example: ALEGrO

- $1GW$ converter required (see flyer).
- https://www.elia.be/fr/infrastructure-et-projets/projets-infrastructure/alegro

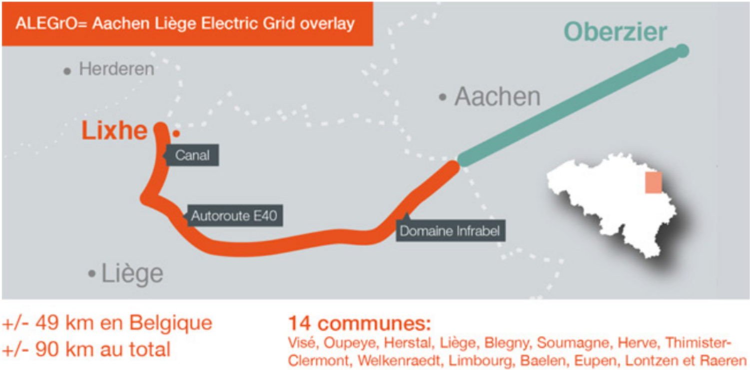


Figure reproduced from the *elia* website.

HVDC principle

- HVDC can interconnect asynchronous systems.
- HVDC transmission can be controlled faster $\Rightarrow$ AC system stability can be improved.

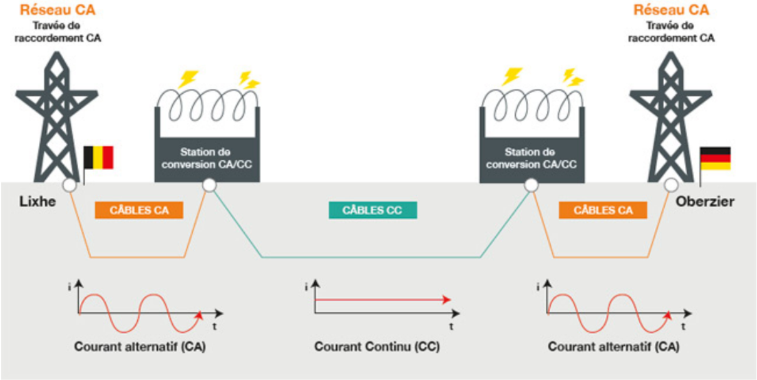


Figure reproduced from the *elia* website.

HVDC cost benefit

- HVDC vs HVAC

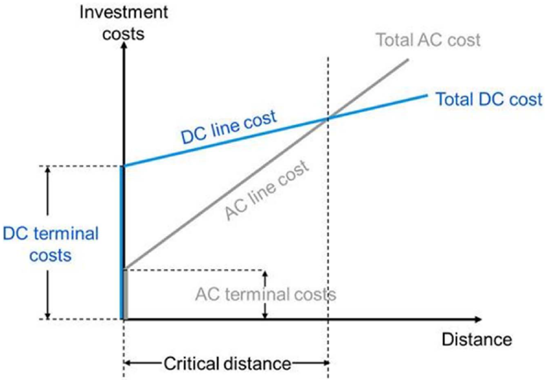


Figure reproduced from [4].

HVDC converter solution: MMC

- The modular multilevel converter (MMC) is the most advanced power converter topology for HVDC.
- IGBT example: high power IGBT

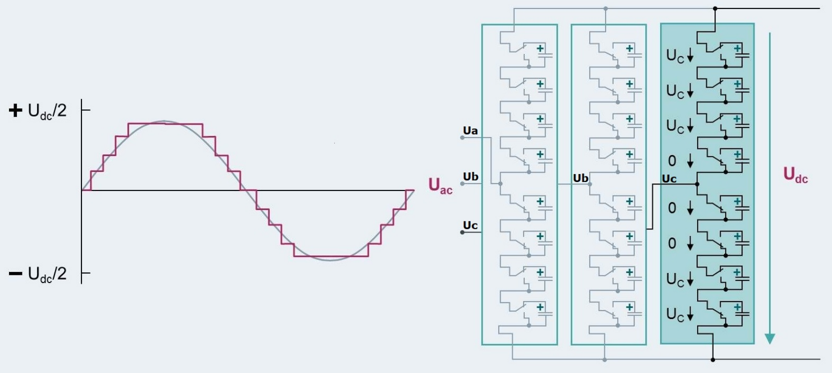
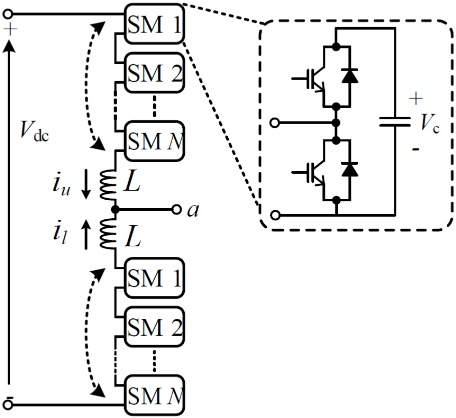


Figure reproduced from the *elia* website.

MMC: half bridge principle

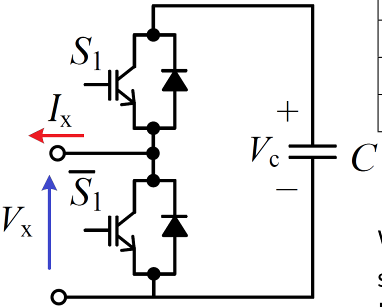
Excerpt of [4]:



- Cascaded connection cells (half or full-bridge)
- $2N$ cells in series to create the half bridge
- L are prevent excessive circulating currents

MMC: cell principle

Excerpt of [4]:



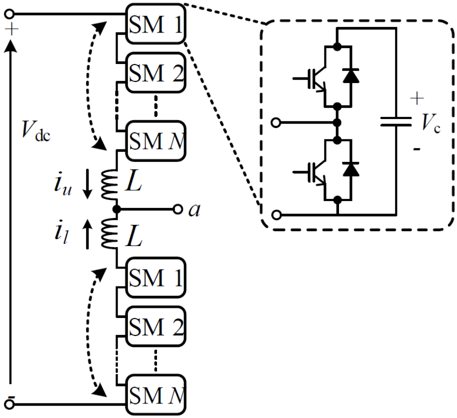
$S1$	$\overline{S1}$	I_x	V_x	C
ON	OFF	> 0	V_c	discharging
ON	OFF	< 0	V_c	charging
OFF	ON	> 0	$0V$	-
OFF	ON	< 0	$0V$	-

Table: Cell states

With a correct selection of the four states during a $50Hz$ sinewave, charge balance can be guaranteed over all the cells.

MMC: half bridge principle

Excerpt of [4]:



- Cell voltage: $V_c = \frac{V_dc}{N}$
- N cells have $S1 = ON$ and N cells have $S1 = OFF$
- The number of cells n with $S1 = ON$ in the low part of the bridge give the voltage generated at node a : $V_a = nV_C$
- There is however a degree of freedom when selecting cells state.

MMC: operation

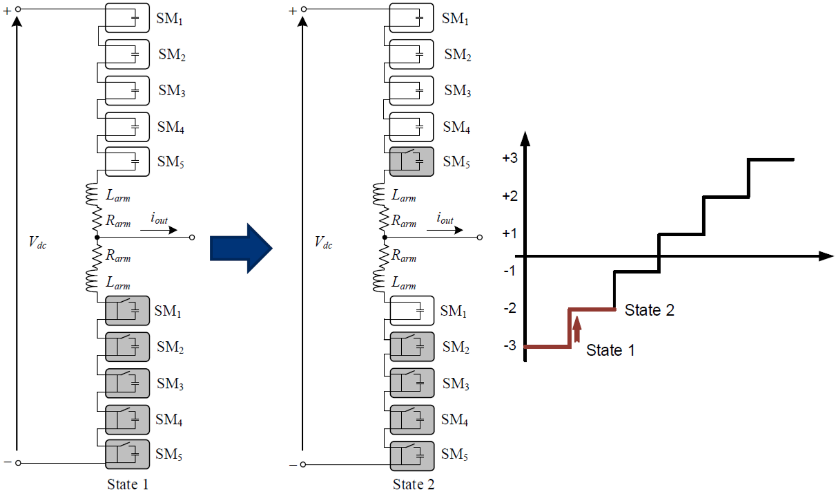


Figure reproduced [4].

MMC: operation

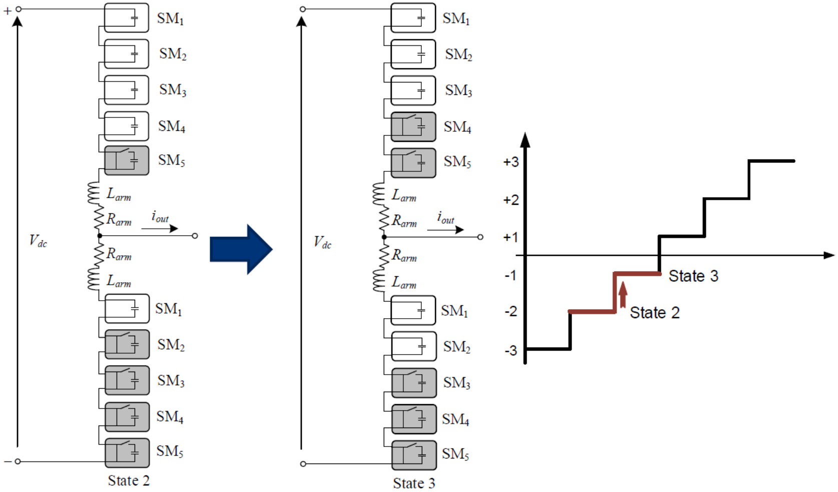


Figure reproduced [4].

MMC: operation

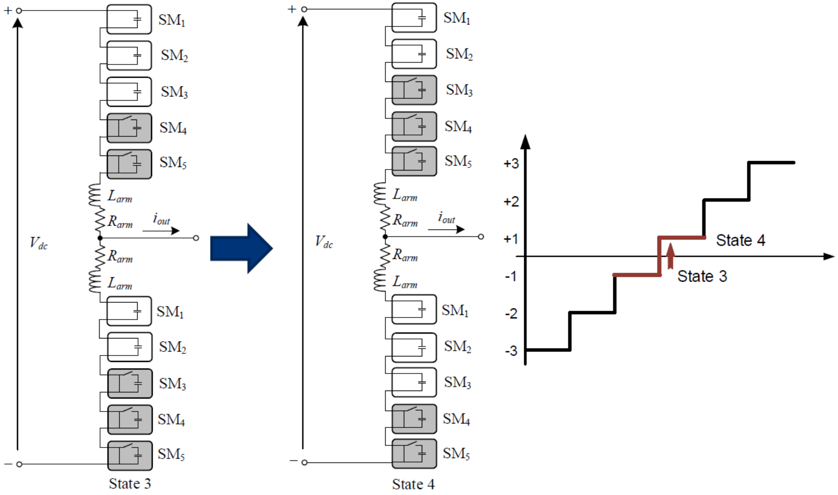


Figure reproduced [4].

MMC: operation

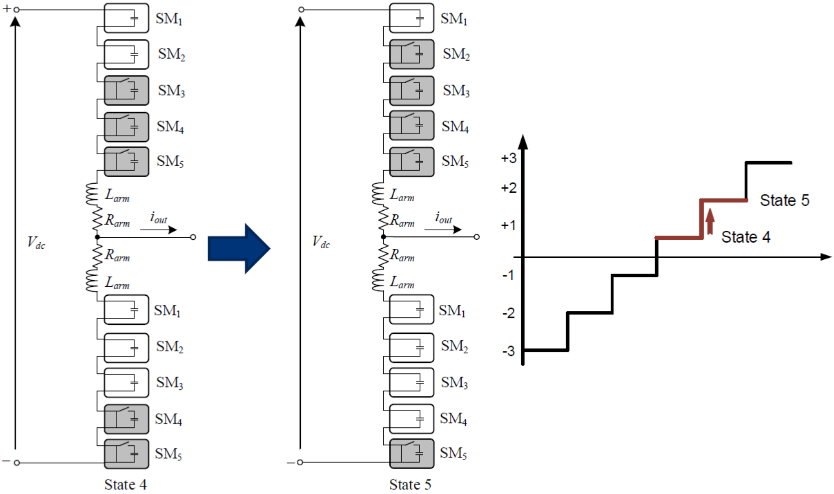


Figure reproduced [4].

MMC: operation

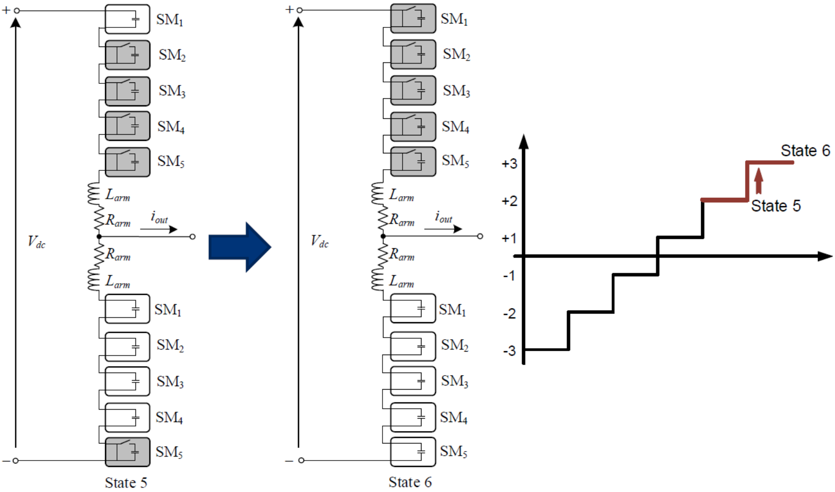


Figure reproduced [4].

MMC: capacitor charge balance

- During the operation of the MMC, the output current flows though the cells capacitors, which charge and discharge the capacitors.
- An active capacitor charge balance method is required for the operation of the MMC.
- The voltage balancing algorithm uses measurements from the cells capacitor voltages and half bridge currents to select the next cell to be connected or bypassed.
- Capacitor charge balance is possible because there is a degree of freedom on the selection of the cells.

References I

[1] Mohan, Undeland, and Robbins, *POWER ELECTRONICS: Converters, Applications and Design*.
Wiley, third ed., 2003.

[2] J. Wang, B. Ji, J. Zhao, and J. Yu, "From h4, h5 to h6 - standardization of full-bridge single phase photovoltaic inverter topologies without ground leakage current issue," in *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 2419–2425, Sept 2012.

[3] B. Wu, Y. Lang, N. Zargari, and S. Kouro, *Power Conversion and Control of Wind Energy Systems*.
Wiley-IEEE Press, first ed., 2011.

[4] J. Pou, "The modular multilevel converter," in *Southern Power Electronics Conference*, pp. 5–25 (slides), 2017.

References II

[5] R. W. Erickson and D. Maksimović, *Fundamentals of Power Electronics*.
Kluwer Academic Publishers, second ed., 2001.