Switched Mode
One-Quadrant Power Converters

R. Petrocelli
Summary

- Power Electronics. Basics definitions and rules
- Basic DC-DC Power Converters
- Control of DC-DC Power Converters
- Derived Topologies
- Other Issues
Power converter Definition

- Electrical Energy Source
- Power Converter
- Electrical Load
Clasification of Power converters

Source

DC

Load

DC

AC

DC/DC

Rectifier

Inverter

Cycloconverter
Matrix converter

AC

One-Quadrant Definition

Energy flow
One-Quadrant Power Converter in Particle Accelerators

- 2n-pole:
  - dipole
  - quadrupole
  - sextupole
  - octupole ...

n:
1 2 3 4 ...

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Power Electronics
Basic Definition and Rules

- Sources Definition
- Basic Rules
- Interconnection Rules
Type of Sources

Voltage Source

- A voltage source is able to impose a voltage regardless of the current flowing through it.

- In a more open sense, if the voltage across and element can not have discontinuities in time due to the current flowing through it.
Source Type

Current Sources

A current are able to impose current regardless the voltage across its terminals.

Similar to the voltage sources this can be extended to elements which current can not have discontinuities.
Basic Rules

• Rule 1: A voltage source must never be short-circuited
Basic Rules

• Rule 2: A current source must never be open-circuited

\[ I \rightarrow \infty \]

\[ V \rightarrow \infty \]
Basic Rules

• Interconection Rules

\[ S \text{ must not be closed} \quad \text{Unless} \quad V_1 = V_2 \]

\[ S \text{ must not be open} \quad \text{Unless} \quad I_1 = -I_2 \]
Interconnection Rules

Basic Commutation Cell

<table>
<thead>
<tr>
<th>$S_1$</th>
<th>$S_2$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>open</td>
<td>open</td>
<td>Not allowed</td>
</tr>
<tr>
<td>open</td>
<td>closed</td>
<td>Allowed</td>
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<tr>
<td>closed</td>
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</tbody>
</table>
Basic DC-DC Converter

- Chopper
- Buck Converter
- Boost Converter
- Buck-Boost Converter
DC Chopper

• Resistive Load
DC Chopper

- Inductive Load

Application: Motor control
Chopper Waveforms

\[ I_L = \frac{V_S D}{R_L} \]
Buck Converter

\[ \text{Diagram of Buck Converter} \]

\[ V_S \quad D \quad L \quad C \quad R \quad V_O \]
Buck Converter

Faraday Law:
volt-second product of the inductor voltage should be zero for steady-state operation

\[
(V_S - V_O) DT = V_O (1 - D) T
\]
Output-Input Voltage Ratio

\[ M_v \equiv \frac{V_o}{V_s} = D \]
\[ L_b = \frac{(1 - D)R}{2f} \]  
Inductance for boundary between CCM and DCM

\[ C_{\text{min}} = \frac{(1 - D)V_o}{8V_rLf^2} \]  
Minimum capacitance for an output voltage ripple \( V_r \),
Continuous and Dis-Continuous Mode

\[ V_s - V_o \]

\[ i_l \]

\[ DT \]

\[ T \]
CCM and DCM Boundary

\[
i_{OB} = \frac{D T}{2 L} (V_s - V_o) = \frac{T V_s}{2 L} (D - D^2)
\]

\[
I_{OB_{\text{max}}} = \frac{T V_s}{8 L}
\]
\[(V_S - V_O)DT = V_O \Delta T\]

\[\frac{V_O}{V_S} = \frac{D}{(D + \Delta)}\]

\[I_O = \frac{I_{L\text{ peak}}(D + \Delta)T}{2T}\]

\[I_{L\text{ peak}} = \frac{V_O \Delta T}{L}\]

\[I_O = 4I_{O\text{B MAX}} D \Delta\]
Output-Input Voltage Ratio in DCM

\[
\frac{V_O}{V_S} = \frac{D^2}{D^2 + \frac{1}{4} \frac{I_O}{I_{OB_{MAX}}}}
\]

Graph showing the relationship between \(\frac{V_O}{V_S}\) and \(\frac{I_{OB}}{I_{OB_{MAX}}\) for different values of \(D\): 0.90, 0.75, 0.50, 0.25, and 0.10.
Buck Converter

• Widely used. Even for high power converters

• Advantages:
  • Simple
  • Linear output-input voltage ratio. It makes easier the control.
  • Smooth output current.

• Disadvantages:
  • Discontinuous input current
  • No isolation.
Boost Converter

![Boost Converter Diagram]

- $V_S$: Input voltage
- $L$: Inductor
- $D$: Diode
- $S$: Switch
- $C$: Capacitor
- $R$: Resistor
- $V_L$: Inductor voltage
- $i_L$: Inductor current
- $i_S$: Switch current
- $i_D$: Diode current
- $i_C$: Capacitor current
- $i_O$: Output current
- $V_O$: Output voltage
Boost Converter

Faraday Law:

\[ V_S D T = (V_O - V_S)(1 - D)T \]

\[ M_v \equiv \frac{V_O}{V_S} = \frac{1}{(1 - D)} \]

\[ L_b = \frac{(1 - D)^2 DR}{2f} \]

\[ C_{min} = \frac{DV_O}{V_r RF} \]
Boost Converter: Output-Input Voltage Ratio

\[ M_v \equiv \frac{V_o}{V_s} = \frac{1}{(1 - D)} \]
Boost Converter

- Output voltage higher than input voltage

Advantages:
- Simple
- Smooth input current.

Disadvantages:
- Discontinuous output current. Stress the output capacitor
- No isolation.
Buck-Boost Power Converter

\[ V_S \rightarrow L \rightarrow C \rightarrow R \rightarrow V_O \]

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\[ V_S T D = -V_O (1-D) T \]

\[ M_V \equiv \frac{V_O}{V_S} = -\frac{D}{(1-D)} \]

\[ L_b = \frac{(1-D)^2 D R}{2 f} \]
Buck-Boost Converter: Output-Input Voltage Ratio

\[ M_v \equiv \frac{V_o}{V_s} = -\frac{D}{(1-D)} \]
Buck-Boost Converter

Reverse voltage polarity

• Advantages:
  • Simple
  • Step-down and step-up

• Disadvantages:
  • Discontinuous input and output current.
  • No isolation.
Control of DC-DC Power Converters

- Regulation
- Pulse-Width Modulation (PWM)
- Current Mode
- Variable Structure Control
Control of Switched Mode DC-DC Power Converter

Switching function.

Definition:

The switching function, $S(t)$, has a value of 1 when the corresponding physical switch is on and 0 when it is off.

Switching functions are discrete-valued functions of time, and control of switching devices can be represented with them.

$$s(t) = \begin{cases} 1 & \text{when the switch is on} \\ 0 & \text{when the switch is off} \end{cases}$$
Power Converter Block Diagram

\[ V_S \rightarrow \text{Power Converter} \rightarrow V_O \]

\[ S(t) \rightarrow \text{Modulator} \]

\[ V_D \]
Regulation – Feedback

- Close loop, the output voltage is sensed and the feedback controller acts to get the wished value.
- Stability issues
Regulation – Feed-Forward

- It is very fast. Perturbations do not have to reach the output in order to be compensated.
- It needs a good model of the converter in order to design the controller.
- Usually is used together with a feedback loop.
Constant Frequency PWM
Variable Frequency PWM

constant off-time, variable on-time

constant on-time, variable off-time
Current Mode Control (CMC)

\[ V_s \]

\[ L \]

\[ C \]

\[ R \]

\[ S \]

\[ D \]

\[ S(t) \]

\[ Q \]

\[ R \]

\[ S \]

\[ v_D \]

\[ i_L(t) \]

\[ T \]

\[ S(t) \]
Current Mode Control

The CMC controls the inductor current. An outer control loop is needed for output voltage regulation.

Advantages:
- Simple
- Low cost
- Easy input voltage feed-forward

Disadvantages:
- Sub-harmonic oscillation for $D>0.5$. An slope compensation solves this problem.
Variable Structure Control

It is a nonlinear control which generates the switching function according to the state-space variables of the system.

Advantages:

- Low sensitivity to plant parameter uncertainty
- Robustness

Disadvantages

- Chattering
- Variable frequency
Variable Structure Control

Hysteresis control

\[ V_S \]

\[ D \]

\[ C \]

\[ R \]

\[ L \]

\[ i_L \]

\[ S_{(t)} \]

\[ v_D \]

\[ S_{(t)} \]

\[ V_R \]

\[ v_D \]

\[ t \]
Derived Topologies

- Half Bridge Converter
- Push-Pull Converter
- Full Bridge Converter
- Forward Converter
- Flyback Converter
- Ćuk Converter
Derived Topologies

Half Bridge Converter
Transformer Input Waveform

- Volt-second product over a period must be zero to avoid transformer saturation
Derived Topologies

Push-Pull Converter

\[ M_v \equiv \frac{V_o}{V_s} = 2D \frac{n_2}{n_1} \]
Derived Topologies

Full Bridge Converter

\[ M_v \equiv \frac{V_o}{V_s} = 2D \frac{n_2}{n_1} \]
Derived Topologies

Forward Converter

\[ M_V \equiv \frac{V_O}{V_S} = D \frac{n_2}{n_1} \]

\[ n_1 D \leq n_3 (1 - D) \]
Derived Topologies

Flyback Converter

\[ M_V \equiv \frac{V_O}{V_S} = \frac{n_2}{n_1} \frac{D}{1 - D} \]
Derived Topologies

Čuk Converter

\[ I_{L_2} DT = I_{L_1}(1 - D)T \]

\[ P_{IN} = V_S I_{L_1} = -V_O I_{L_2} = P_{OUT} \]

\[ M_V \equiv \frac{V_O}{V_S} = \frac{D}{(1 - D)} \]
Derived Topologies

Ćuk Converter

There is also an isolated version.
The inductors can be integrated using only one magnetic core

Advantage:
- Smooth input and output current

Disadvantage:
- More components
Other Issues

- Synchronous Rectification
- Interleaved Converters
- Hard Switching, Snubbers and Soft Switching
- DC-DC Resonant Converters
- References and Further Readings
Synchronous Rectification

Conduction losses

\[ P_D = V_F I_O (1 - D) \]

\[ \eta = \frac{V_O I_O}{V_O I_O + V_F I_O (1 - D)} = \frac{V_O}{V_O + V_F (1 - D)} \]

Efficiency is low for low output voltage power converters
Power Losses in Diode and MOSFET

\[ P[W] \]

\[ I_o[A] \]
Interleaved Converters

\[ V_s \]

\[ C_{IN} \]

\[ 2\pi \frac{0}{N} \]

\[ D_{IN} \]

\[ L_{IN} \]

\[ S_{IN} \]

\[ 2\pi \frac{1}{N} \]

\[ L_{I1} \]

\[ S_{I1} \]

\[ D_{I1} \]

\[ 2\pi \frac{(N-1)}{N} \]

\[ L_{I2} \]

\[ S_{I2} \]

\[ D_{I2} \]

\[ C_{OUT} \]

\[ R \]

\[ V_o \]

\[ i_{O1} \]

\[ i_o \]

\[ i_{O2} \]

\[ i_{ON} \]
Interleaved Converters: Output Current
Normalized Output Current Ripple

\[ \frac{I_{o_{pk-pk}}}{I_{o_{pk-pk}[N=1]}} \]

Graph showing normalized output current ripple for different values of \( N \): \( N=1, 2, 3, 4, 5 \).
Normalized Input Capacitor RMS Current

\[ I_{C(RMS)} \]

\[ I_O = 1 \text{ A.} \]

\[ \Delta I_{ON} = 0.30 I_{ON}. \]
Hard Switching

Switch off

Switch on

$V_{SW}$

$I_{SW}$

$E_{SW}$
Snubbers

When the switch is turned off, energy is transferred to the snubber. When the switch is turned on, energy is transferred from the snubber.

\[ V_{SW} \]
\[ I_{SW} \]

\[ V_{SW} \]
\[ I_{SW} \]

\[ t \]
Soft Switching
Soft Switching

\[ V_S \]

\[ M_1 \]

\[ D_1 \]

\[ C_1 \]

\[ L \]

\[ M_2 \]

\[ D_2 \]

\[ C_2 \]

\[ C_O \]

\[ R_O \]

\[ v_A \]

\[ i_L \]

\[ t \]

\[ V_{GS1} \]

\[ V_{GS2} \]
Resonant Converters operates by applying a square voltage or current generated by switches to a resonant circuit.

- **Series resonant converter**

- **Parallel resonant converter**

The converters operate at frequencies close to the resonant frequency.

The energy transferred to the load is controlled by changing the operating frequency.
LCC and LLC Resonant Converters

- LCC resonant converter
  - Disadvantages: two capacitors

- LLC resonant converter
  - Advantage: the two inductances can be integrates into one magnetic component
LLC Resonant Converters
LLC Converter Waveforms. ZVS
DC-DC Resonant Converters

- High Efficiency – Soft switching operation
- High operating frequency – small reactive components
- High power density
- More complex control
- Stress in semiconductors (large voltages and currents)
References and Further Reading


Thank You!