Switched Mode Power Conversion

Prior Art

How was Power Conversion Done before the Introduction of Electronic Switches?
Switched Mode Power Conversion

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DC-DC Converters

A DC Voltage Source of $V_{IN}$ is Available

$V_{IN}$
Switched Mode Power Conversion
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DC-DC Converters

A Resistive Load Requires a Voltage of $V_O$
Switched Mode Power Conversion
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DC-DC Converters

How to Deliver $V_O$ to the Load from a Source Voltage of $V_{IN}$?
Switched Mode Power Conversion

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DC-DC Converters

Conceptual Solution

Drop the Excess Voltage in a Series Element
Switched Mode Power Conversion

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DC-DC Converters

A DC Current Source of $I_{IN}$ is Available
Switched Mode Power Conversion
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DC-DC Converters

A Resistive Load Requires a Current of $I_o$
Switched Mode Power Conversion
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DC-DC Converters

How to Deliver $I_O$ to the Load from A Source Current of $I_{IN}$?
Switched Mode Power Conversion

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DC-DC Converters

Conceptual Solution

Divert the Excess Current in a Shunt Element
Switched Mode Power Conversion

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Conceptual Solution

Drop the Excess Voltage in a Series Element
Switched Mode Power Conversion

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DC-DC Converters

Circuit Model

Drop the Excess Voltage in a Series Resistor
Switched Mode Power Conversion

**Prior Art**

**Selection of $R_S$**

\[
V_O = V_{IN} \frac{R}{R + R_S} \quad R_S = R \left( \frac{V_{IN}}{V_O} - 1 \right)
\]
Switched Mode Power Conversion

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Efficiency of Power Conversion

\[ \eta = \frac{P_O}{P_{IN}} = \frac{V_O I_O}{V_{IN} I_O} = \frac{V_O}{V_{IN}} \]

At Low Ratio of Conversion \( \eta \) is very Poor
Switched Mode Power Conversion

Prior Art
DC-DC Converters
Conceptual Solution

Divert the Excess Current in a Shunt Element
Switched Mode Power Conversion

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DC-DC Converters

Circuit Model

Divert the Excess Current in a Shunt Resistance
Switched Mode Power Conversion

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Selection of $R_{SH}$

\[ I_O = I_{IN} \frac{R_{SH}}{R + R_{SH}} \]

\[ R_{SH} = \frac{R}{((I_{IN}/I_O) - 1)} \]
Switched Mode Power Conversion

Prior Art

Efficiency of Power Conversion

\[ \eta = \frac{P_o}{P_{in}} = \frac{V_o I_o}{V_{in} I_{in}} = \frac{I_o}{I_{in}} \]

At Low Ratio of Conversion \( \eta \) is very Poor
Switched Mode Power Conversion

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General Linear Power Converter

![Diagram of a linear power converter with labeled components: Source, $V_{IN}$, $R_S$, $R_{SH}$, $I_O$, $V_O$, and $R$.]
Switched Mode Power Conversion
Prior Art

Shunt Controlled Converter

Source

\[ V_{IN} \]

\[ R_S \]

\[ R_{SH} \]

\[ I_o \]

\[ V_o \]

\[ R \]
Switched Mode Power Conversion
Prior Art

Series Controlled Converter

Source

\[ V_{IN} \]

\[ R_S \]

\[ I_O \]

\[ V_O \]

\[ R \]
Shunt Controlled Converter

Sample Design

Zener Regulator
Shunt Controlled Converter
Sample Design
Zener Regulator

\[ V_{IN} \quad R_S \quad V_O \quad R \]
Shunt Controlled Converter
Sample Design
Zener Regulator
Shunt Controlled Converter

Load Line

Zener Regulator

\[ \text{Load Line} \]

\[ V \]

\[ I \]
Shunt Controlled Converter

Output Voltage

Zener Regulator

\[ \begin{align*}
V_{IN} &\rightarrow R_S \rightarrow V_O \\
R &\rightarrow VO
\end{align*} \]
Shunt Controlled Converter

Load Variation

Zener Regulator

![Diagram of a shunt controlled converter with symbols and variables: VIN, RS, VO, R, IO, V, and I. Various resistors and voltages are indicated with lines and annotations.]

- **VIN**: Input Voltage
- **RS**: Shunt Resistance
- **VO**: Output Voltage
- **R**: Resistor
- **IO**: Output Current
- **V**: Voltage
- **I**: Current
Shunt Controlled Converter

No Load & Full Load Lines

Zener Regulator

![Diagram of shunt controlled converter with voltage and current axes showing no load and full load lines.]
Shunt Controlled Converter

**Source Line**

**Zener Regulator**

![Circuit Diagram](image)

- **$V_{IN}$**
- **$R_S$**
- **$V_O$**
- **$R$**

- **$V_{IN}$**
- **$V_O$**
- **$I_Z$**
- **$R_S$**

**No Load**
Shunt Controlled Converter
Minimum Zener Current
Zener Regulator

VIN
RS
VO
R

V

V_{IN}
V_O

I_Z
I_O
I_{IN}

Full Load
Shunt Controlled Converter

Zener Current Variation

Zener Regulator

\[ \text{VIN} \rightarrow R \rightarrow V_O \rightarrow I_O \]

\[ \text{RS} \]

\[ \text{No Load} \quad \text{Full Load} \]

\[ \text{V} \]

\[ \text{I} \]
Shunt Controlled Converter

Typical Operating Point

Zener Regulator

![Diagram of shunt controlled converter with labels for $V_{IN}$, $R_S$, $V_O$, $R$, $I_Z$, $I_O$, $I_{IN}$, and part load](image)
Shunt Controlled Converter

Output Power

Zener Regulator

\[ V_{IN} \]
\[ V_{O} \]
\[ R_{S} \]
\[ I_{IN} \]
\[ I_{Z} \]
\[ I_{O} \]
Shunt Controlled Converter

Input Power
Zener Regulator

\[ \text{VIN} \rightarrow R_S \rightarrow V_O \rightarrow \text{Zener Diode} \rightarrow V_O \]

\[ V_{IN}, V_O, R_S, I_{IN}, I_Z, I_O \]
Shunt Controlled Converter

Efficiency

Zener Regulator
Shunt Controlled Converter

Design Sequence

Zener Regulator

Vin

Rs

V0

R

Vin(min), V0

Iz(min)

IO

V

I

Vin

VO

Iz(max), Vmax

Iz(min)

IO, V0

No Load

Full Load
Switched Mode Power Conversion

Prior Art
DC-DC Converters
Series Controlled Converter
Prior art
Circuit Diagram
Series Controlled Converter
Prior Art

Load Line

Series Controlled Converter

\[ R_S \quad V_O \quad V_{IN} \quad R \]
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Source Line
Series Controlled Converter

\[ V_{IN} \]

\[ V \]

\[ I \]
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Output Voltage
Series Controlled Converter
 Prior Art

Control Strategy

Series Controlled Converter
Prior Art

Output Power

Series Controlled Converter

\[ R_S \quad V_O \]

\[ V_{IN} \quad R \]

\[ V_{IN} \]

\[ V \]

\[ V_O \]

\[ I_O \]

\[ I \]
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Input Power

Series Controlled Converter
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Efficiency

Series Controlled Converter

\[ \eta = \frac{V_O}{V_{IN}} \]
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Losses

Series Controlled Converter

\[ \eta = \frac{V_O}{V_{IN}} \]
Prior Art

Losses

Series Controlled Converter

\[ \eta = \frac{V_O}{V_{IN}} \]
Prior Art

Losses

Series Controlled Converter

\[ \eta = \frac{V_O}{V_{IN}} \]
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Two Low-Loss Conditions
Series Controlled Converter
Prior Art

Central Idea of Switch Mode Power Conversion

Series Controlled Converter

\[ R_S = \propto \]
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Another Version
Series Controlled Converter
Prior Art
Closed Loop Control
Series Controlled Converter
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Output Voltage

Series Controlled Converter

\[ (g(V_o^* - V_o) - J_B) \beta R = V_o \]

\[ V_o = V_o^* \frac{g \beta R}{1 + g \beta R} + J_B \frac{\beta R}{1 + g \beta R} \]

\[ V_o \approx V_o^* \text{ for } g \gg 1 \]
Shunt Controlled Power Converter
Zener Regulated Power Converter
A Sample Exercise
Shunt Controlled Power Converter
A Sample Exercise

\[ V_O = 10 \text{ V} ; \quad P_O = 10 \text{ W} ; \]
\[ R = 10 \Omega \text{ to } 100 \Omega ; \]
\[ V_{IN} = 15 \text{ V} \text{ to } 18 \text{ V} ; \]
\[ V_Z = 10 \text{ V}, 7 \Omega, 1 \text{ W Zener} ; \]
\[ \beta = 20 ; \]
\[ R_B = ? ; \eta = ? ; \]
\[ \Delta V_O = ? ; \]
Shunt Controlled Power Converter

Load Current

\[
\begin{align*}
V_{IN} &\quad I_{IN} \\
R_B &\quad I_Z \\
\beta &\quad I_O \\
V_O &\quad R
\end{align*}
\]

Load Current

\begin{align*}
10 \text{ V} &\quad 0.1 \text{ A} \\
&\quad 1 \text{ A}
\end{align*}
Shunt Controlled Power Converter

Base Current
Shunt Controlled Power Converter

**Base Current**

![Circuit Diagram]

- $V_{IN}$
- $I_{IN}$
- $R_B$
- $I_Z$
- $I_O$
- $V_O$
- $R$

**Graph:**

- 10 V
- 0.1 A
- 1 A

**Load Current**
Shunt Controlled Power Converter

Selection of $R_S$

$V_{IN} \quad I_{IN} \quad R_B \quad I_Z \quad I_O \quad V_O$

$R_S = \frac{5}{0.06} = 83 \ \Omega$

$V_{IN(min)} = 10 \ \text{V}$

$I_Z(min) = 10 \ \text{mA}$

$I_B$ = 50 mA

$V = 15 \ \text{V}$

Load Current

$I = 0.1 \ \text{A}$ to 1 A
Shunt Controlled Power Converter

Spread of Zener Current

\[ V_{IN} \rightarrow I_{IN} \rightarrow R_B \rightarrow I_Z \rightarrow I_O \rightarrow V_O \]

Load Current

- \[ V_{IN}^{(max)} = 15 V \]
- \[ V_{IN}^{(min)} = 10 V \]
- \[ I_Z^{(max)} \]
- \[ I_Z^{(min)} \]

\[ R_S = \frac{5}{0.06} = 83 \, \Omega \]
Shunt Controlled Power Converter

Output Power

\[ V_{IN} \rightarrow I_{IN} \rightarrow R_B \rightarrow I_Z \rightarrow I_O \rightarrow V_O \]

\[ R_S = \frac{5}{0.06} = 83 \, \Omega \]

Load Current

Graph showing voltage and current ranges:
- \( V_{IN}^{(max)} = 18 \, V \)
- \( V_{IN}^{(min)} = 15 \, V \)
- \( V_{IN}^{(max)} = 10 \, V \)
- \( I_Z^{(max)} \)
- \( I_Z^{(min)} \)

Current ranges:
- 0.1 A to 1 A
Shunt Controlled Power Converter

**Input Power**

\[ V_{IN} \rightarrow I_{IN} \rightarrow R_B \rightarrow I_Z \rightarrow I_O \rightarrow V_O \]

\[ R_S = \frac{5}{0.06} = 83 \, \Omega \]

- \( V_{IN}(\text{max}) = 18 \, V \)
- \( V_{IN}(\text{min}) = 15 \, V \)
- \( I_{Z}(\text{max}) \)
- \( I_{Z}(\text{min}) \)
- \( I_B \)
- Load Current

V vs I graph:

- \( 0.1 \, A \) to \( 1 \, A \)

Input Power Range:

- \( 10 \, V \) to \( 15 \, V \)

Power Conversion Range:

- \( 0.1 \, A \) to \( 1 \, A \)
Shunt Controlled Power Converter

Efficiency

\[ R_S = \frac{5}{0.06} = 83 \, \Omega \]

\[ \eta = \frac{10 \times 1.0}{15 \times 1.1} = 61\% \]
Shunt Controlled Power Converter

Load Regulation

\[ \Delta V_O = \Delta I_Z R_Z = \frac{0.9}{21} \times 7 = 0.3 \text{ V} \]
Shunt Controlled Power Converter

Line Regulation

\[ \Delta V_o = \Delta I_Z R_Z = \frac{3.0}{83} \times 7 = 0.25 \text{ V} \]
Shunt Controlled Power Converter
Line & Load Regulation

\[ \Delta V_O = \Delta I_Z R_Z = \left( \frac{0.9}{21} + \frac{3.0}{83} \right) \times 7 = 0.55 \text{ V} \]
Shunt Controlled Power Converter

Output Voltage Band

\[ V_{IN} \rightarrow I_{IN} \rightarrow R_B \rightarrow I_Z \rightarrow I_O \rightarrow V_O \]

\[ V_{IN}(max) = 18 \text{ V} \]
\[ V_{IN}(min) = 15 \text{ V} \]
\[ V_{out} = 10 \text{ V} \]

\[ I_Z(max) \]
\[ I_Z(min) \]

Load Current

0.1 A to 1 A
Prior Art

Summary

Series & Shunt Controlled Converters

General Linear Power Converter

![Diagram of a general linear power converter with components labeled: Source, \( V_{IN} \), \( R_S \), \( R_{SH} \), \( I_O \), \( V_O \), and \( R \).]
Prior Art

Summary

Series & Shunt Controlled Converters

Simple in Design
Poor Efficiency

Loss is Low if $R_S$ and $R_{SH}$ are Replaced with Switches
Switched Mode Power Conversion
Central Idea of Loss-less Power Conversion
Switching Converter
Switched Mode Power Conversion
Central Idea of Loss-less Power Conversion
Switching Converter

\[ \text{Source} \quad I_{IN} \rightarrow \quad I_{O} \rightarrow \quad V_{O} \quad R \]
Switched Mode Power Conversion

What Next?

Devices for Efficient Power Conversion

Switches
Inductors
Transformers
Capacitors