PCIM 2011 Presentation

by

Dr. Slobodan Ćuk

35 Years Anniversary also of:

1. State-Space Averaging *
2. Ćuk Converter*
3. Coupled Inductors*
4. Integrated Magnetics*
5. Duality in Switching Converters*

*Slobodan Ćuk: “Modelling, Analysis and Design of switching Converters” Ph.D. Thesis, Caltech, November 1976

31 Years Anniversary of Presentation at PCIM 1980:

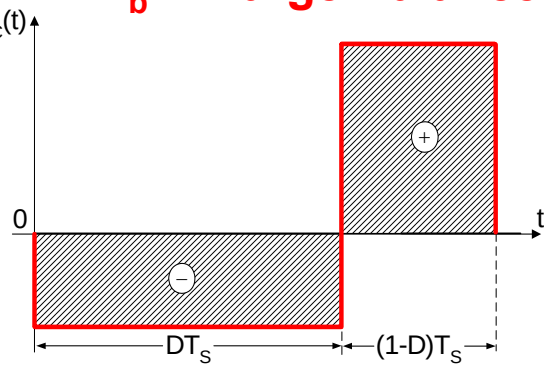
1. Ćuk Converter*
2. Coupled Inductors*
3. Integrated Magnetics*
4. Duality in Switching Converters*

*Slobodan Ćuk: "Modelling, Analysis and Design of switching Converters" Ph.D. Thesis, Caltech, November 1976

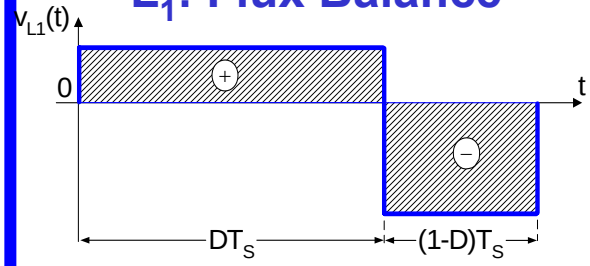
The State-space Averaging Uses Different Criteria

1. Flux Balance on All Inductors
2. Charge Balance on All Capacitors

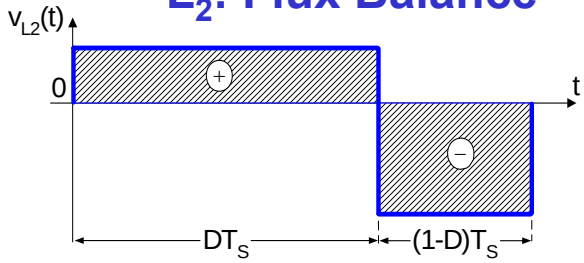
C_b: Charge Balance

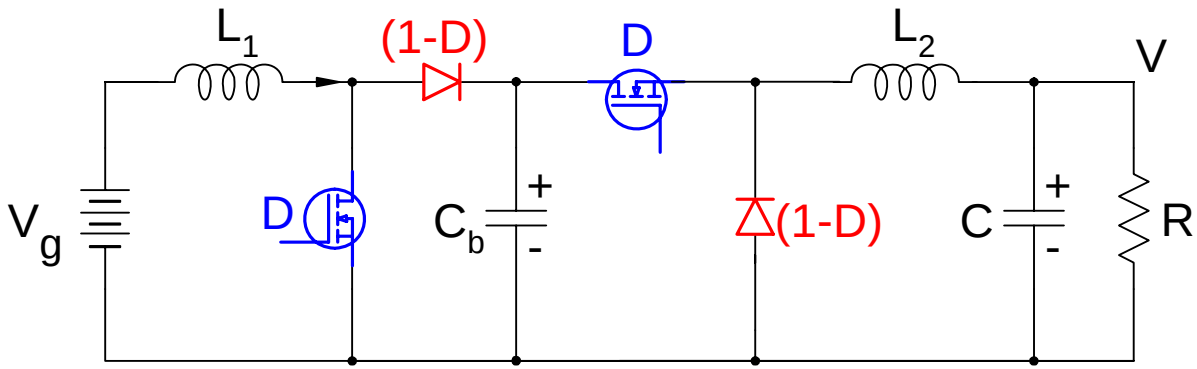


L_1: Flux Balance



L_2: Flux Balance



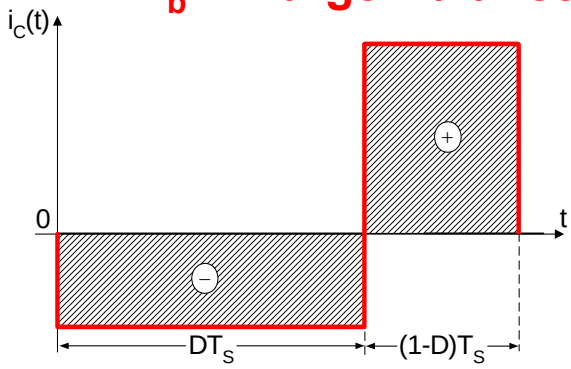


Boost-Buck Converter

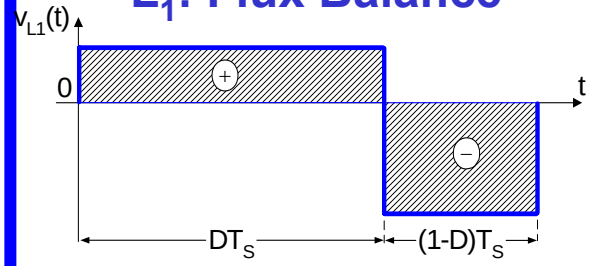
Ćuk Converter

1. Flux Balance on All Inductors
2. Charge Balance on All Capacitors

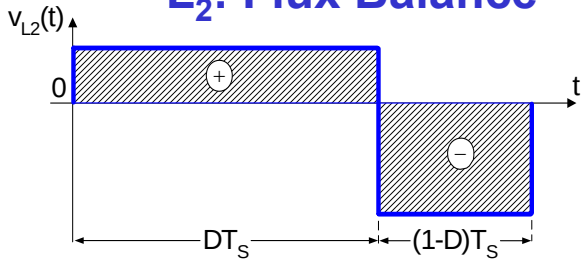
C_b: Charge Balance

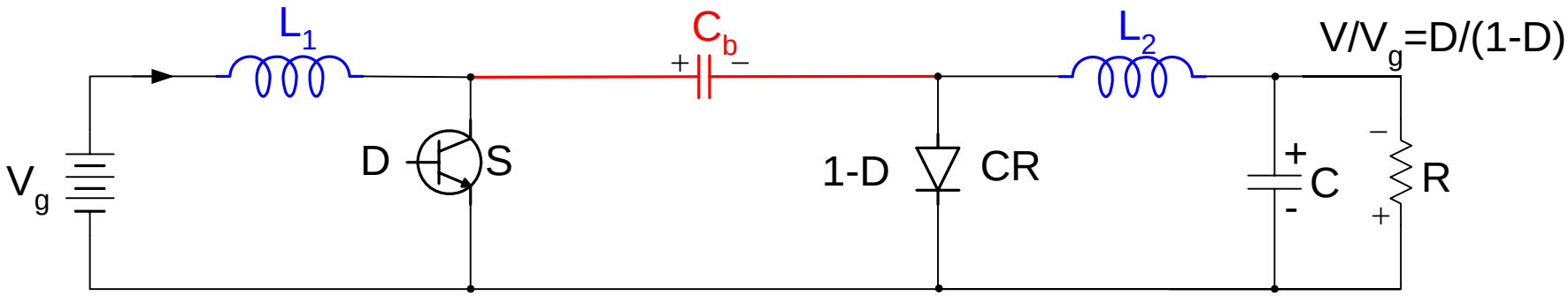


L_1: Flux Balance



L_2: Flux Balance

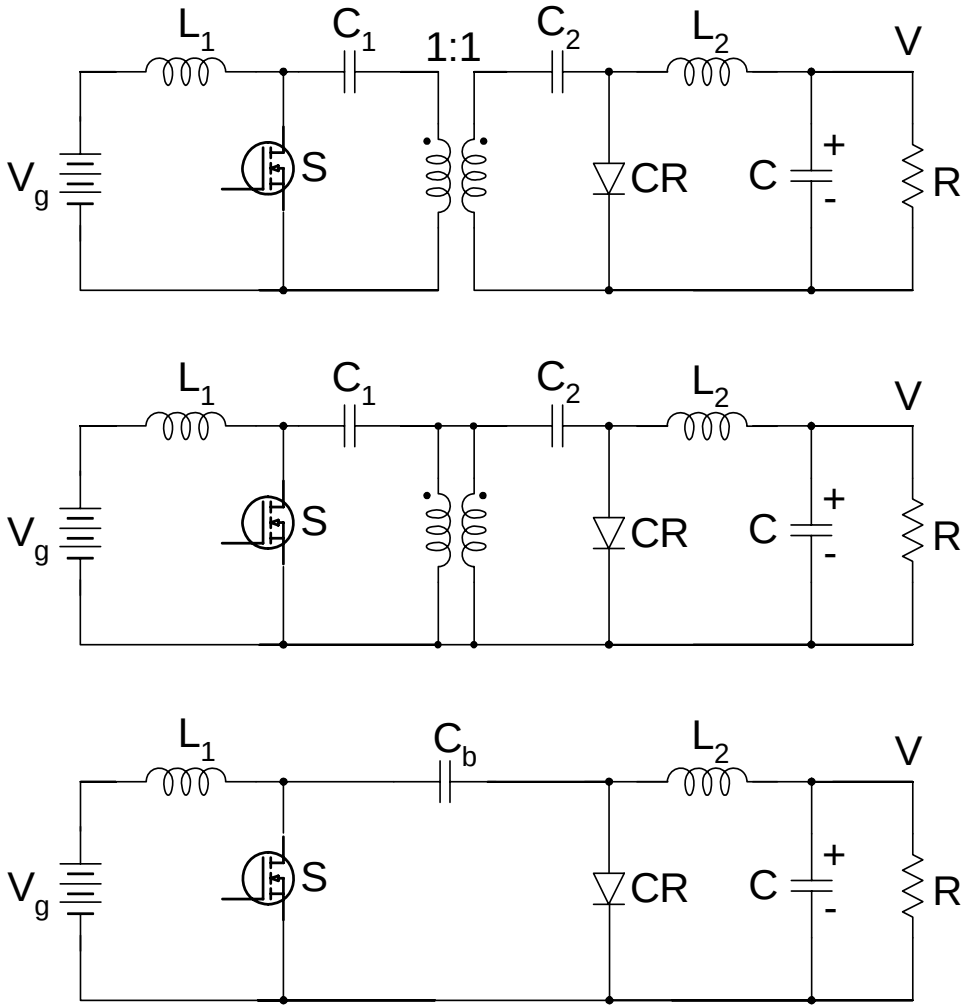




Ćuk Converter*

*US Patents: 4,184,197; 4,257,087; 4,274,133

From Isolated to Non-isolated Ćuk Converter



Square-wave Switching:

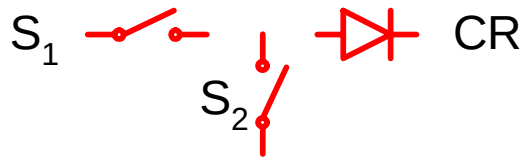
No 3 switches allowed
Eight needed for isolation
No capacitors

Hybrid-Switching Method:

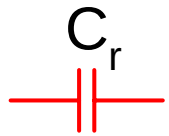
3 switches only
Resonant capacitor
Resonant inductor

What about converters with 3 switches

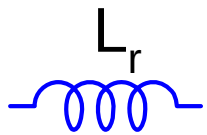
1. Three Switches



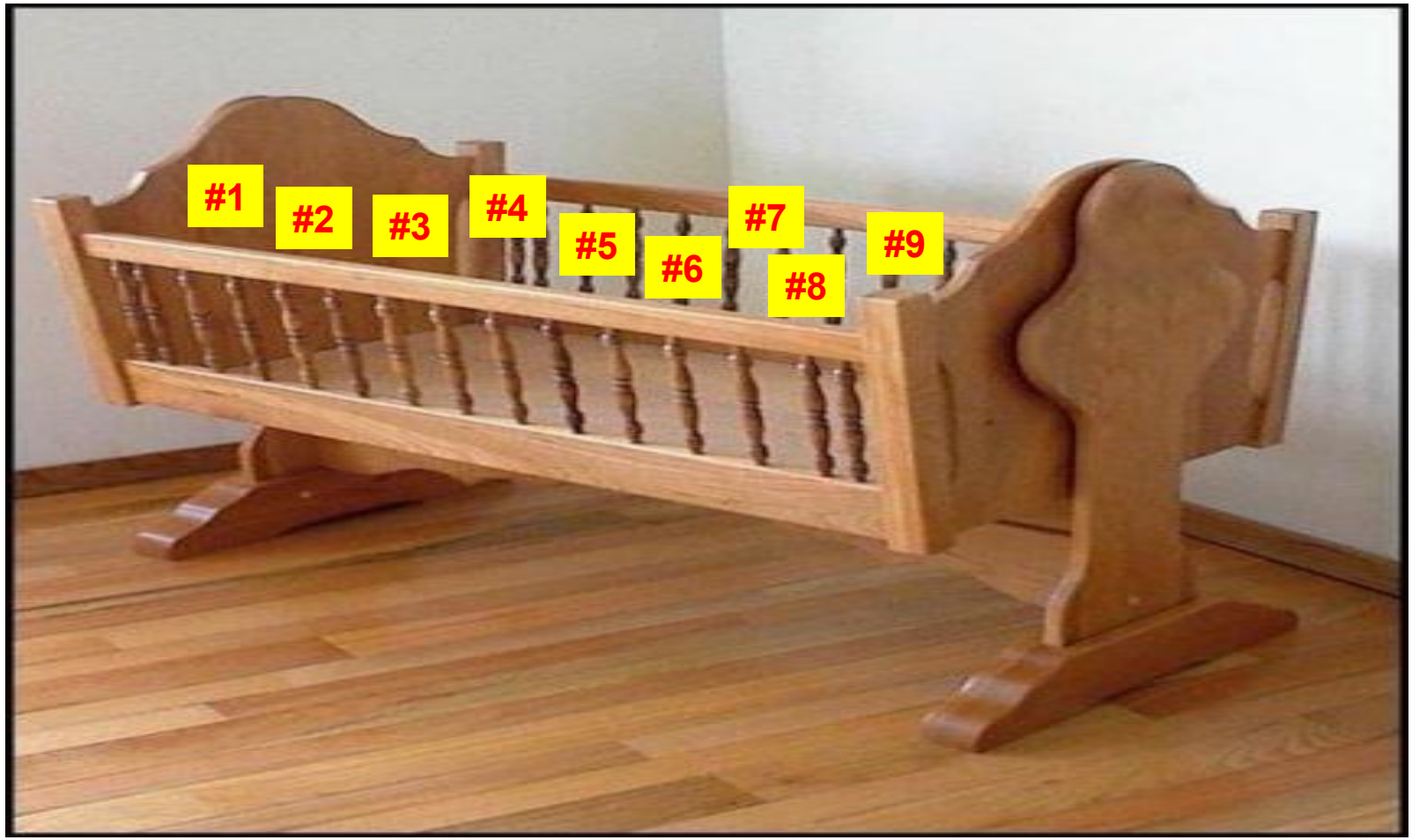
2. A Resonant Capacitor



3. A Resonant Inductor



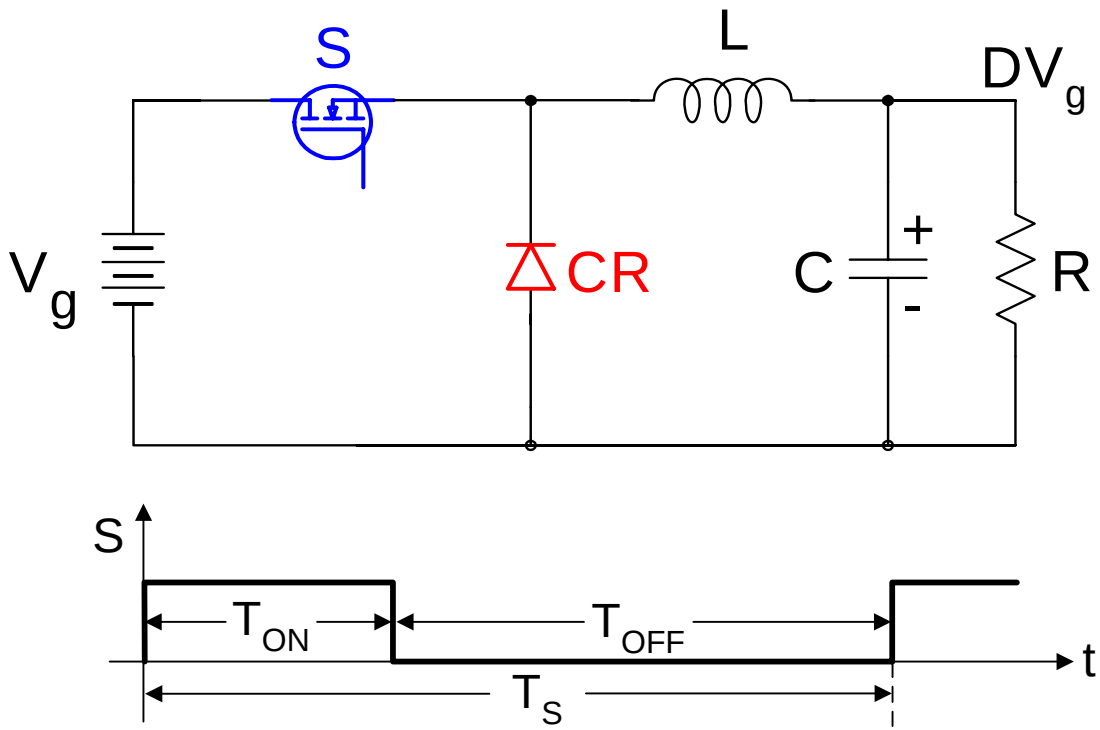
“Birth ” of Hybrid-Switching Method and Related Converter Topologies



DC-DC

Converter Comparison

Buck Converter

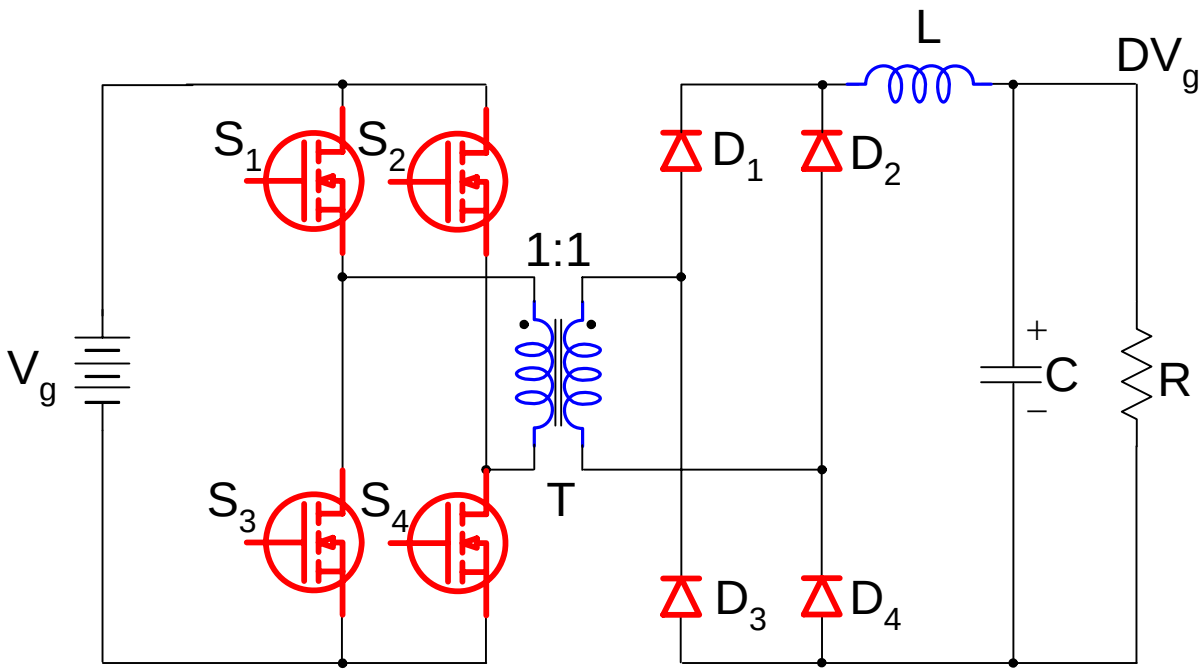


Problem

How to insert AC Isolation Transformer by using additional switches

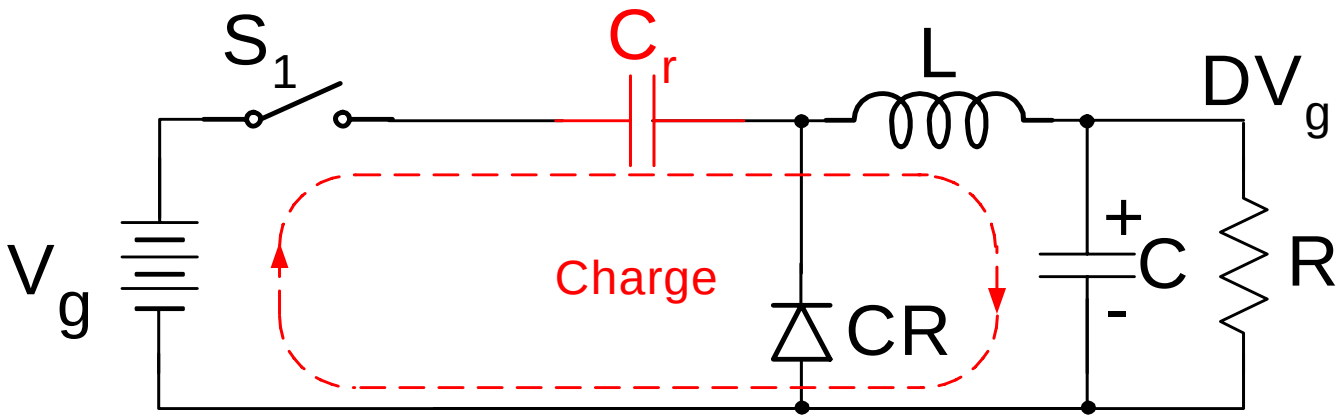
Isolated Full-bridge Buck Converter

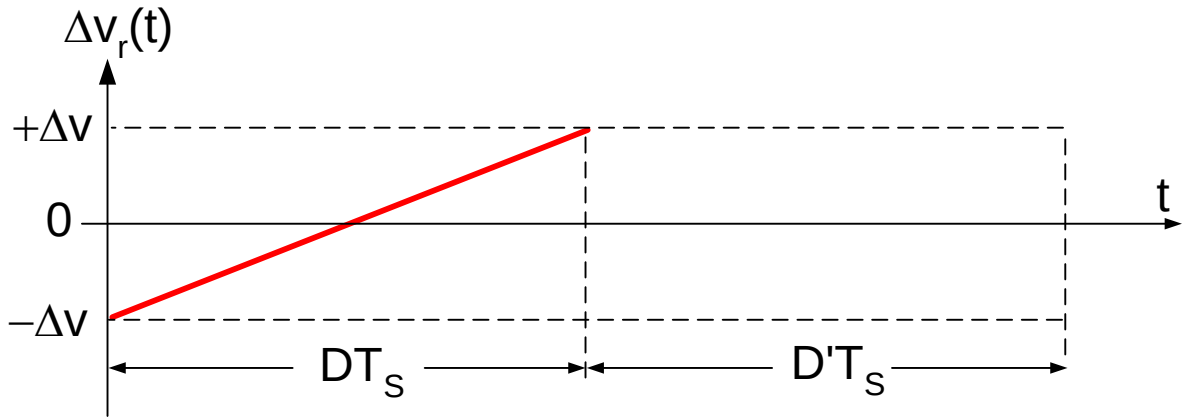
Two magnetic components



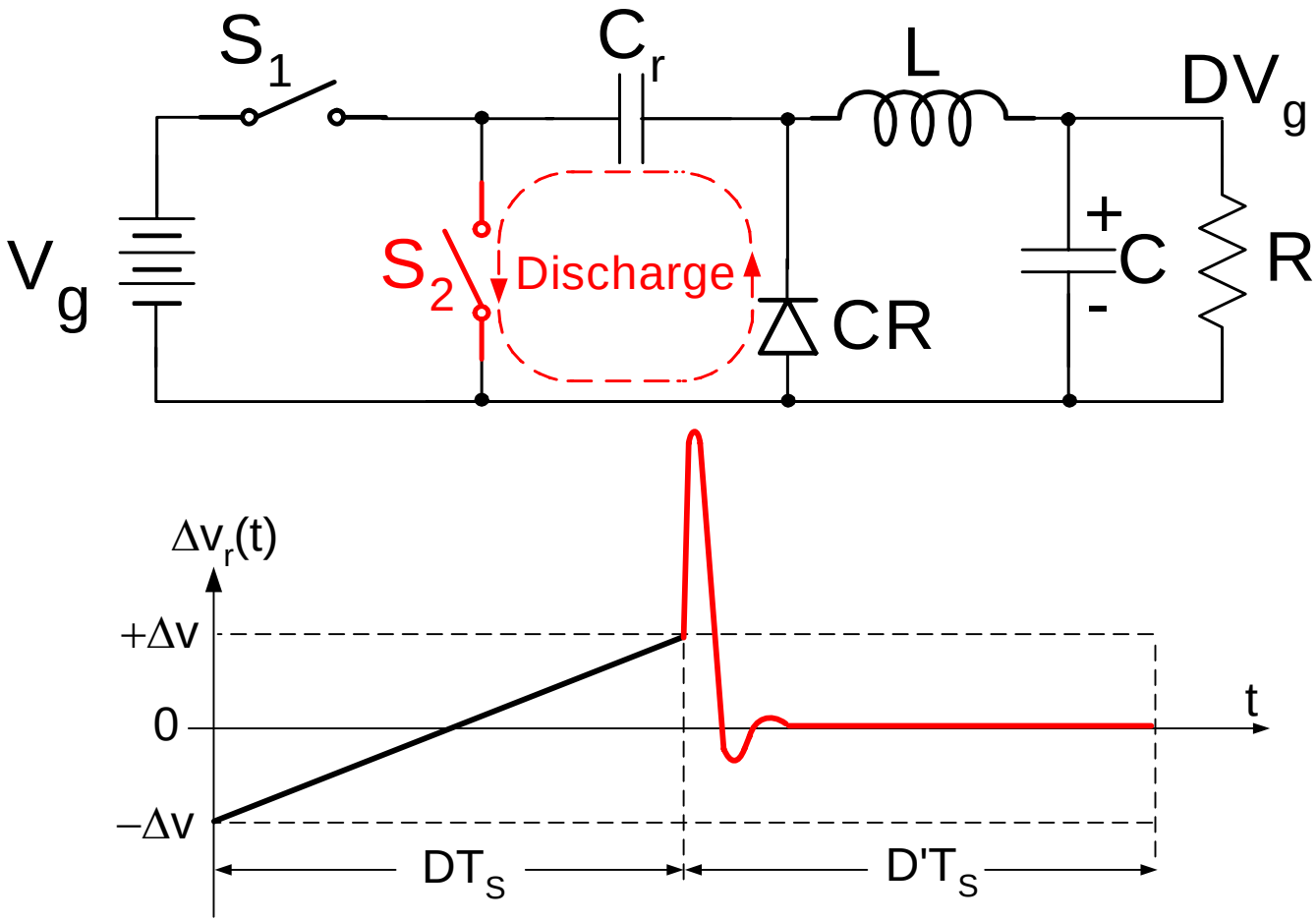
Total of 8 Switches

Step 1 – Insert Resonant Capacitor C_r

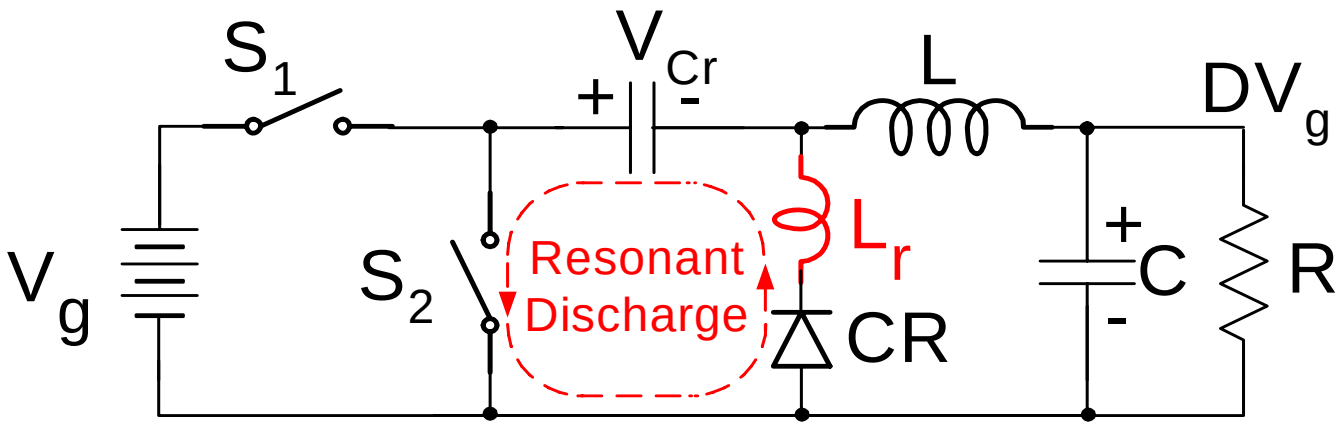


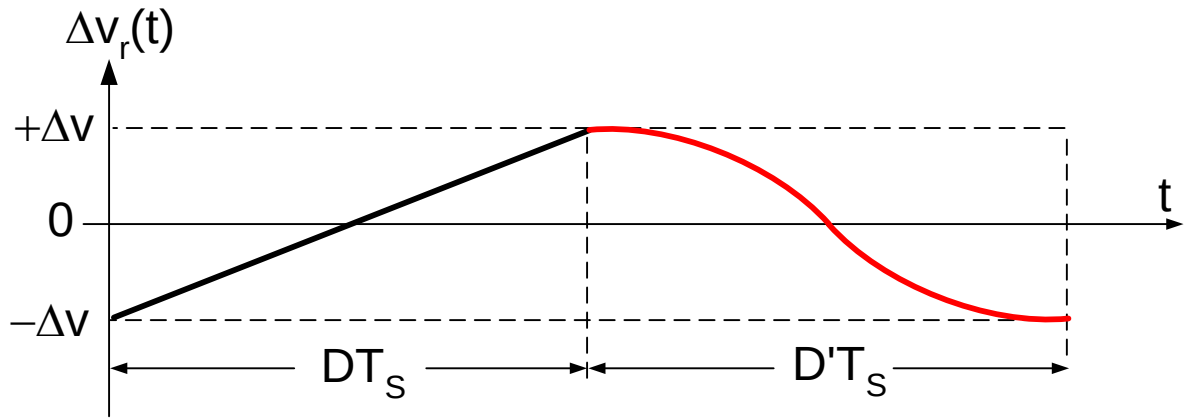


Step 2 – Insert Switch S_2



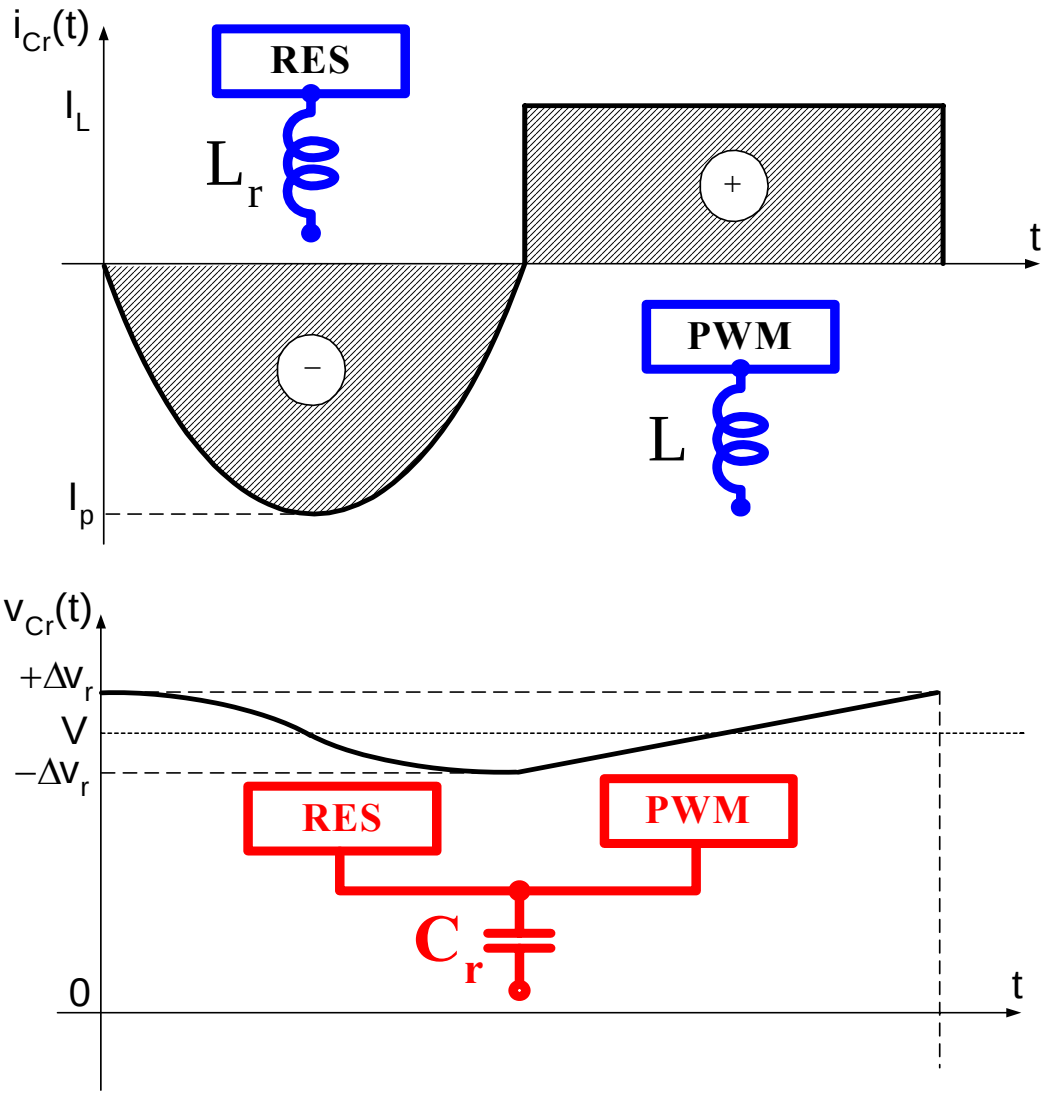
Step 3 – Insert Resonant Inductor L_r





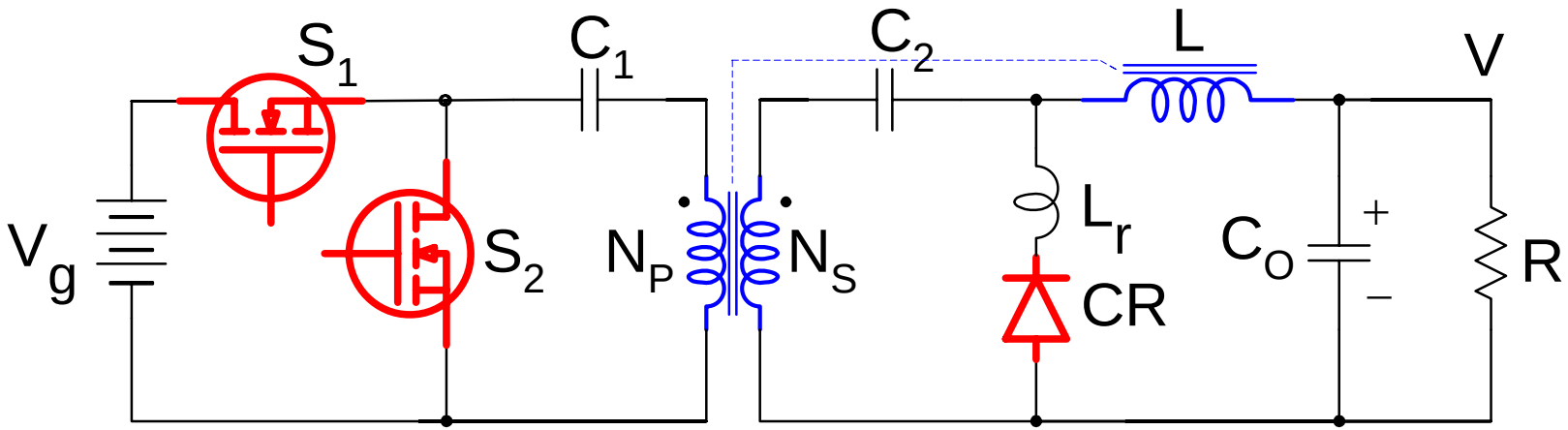
Flux Balance Resonant Inductor $L_r \Rightarrow V_{Cr}=0$

Hybrid-switching



Hybrid-Switching Buck Converter*

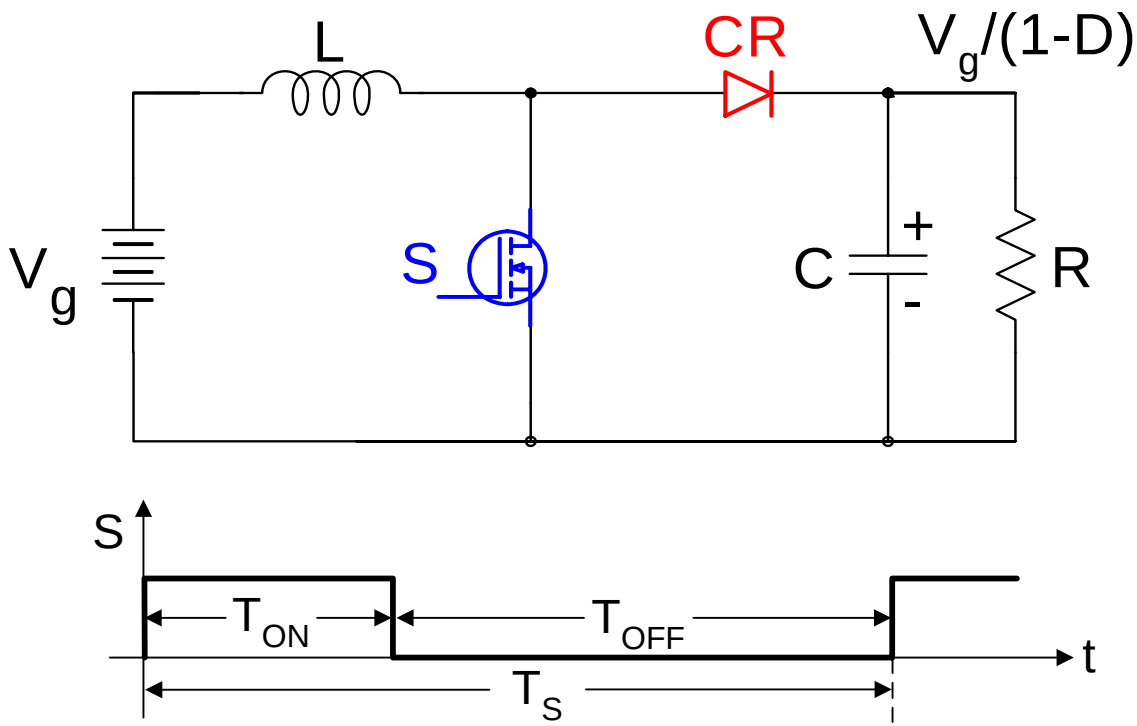
One Integrated Magnetics Component



Total of 3 Switches

*US and foreign patents pending

Boost Converter

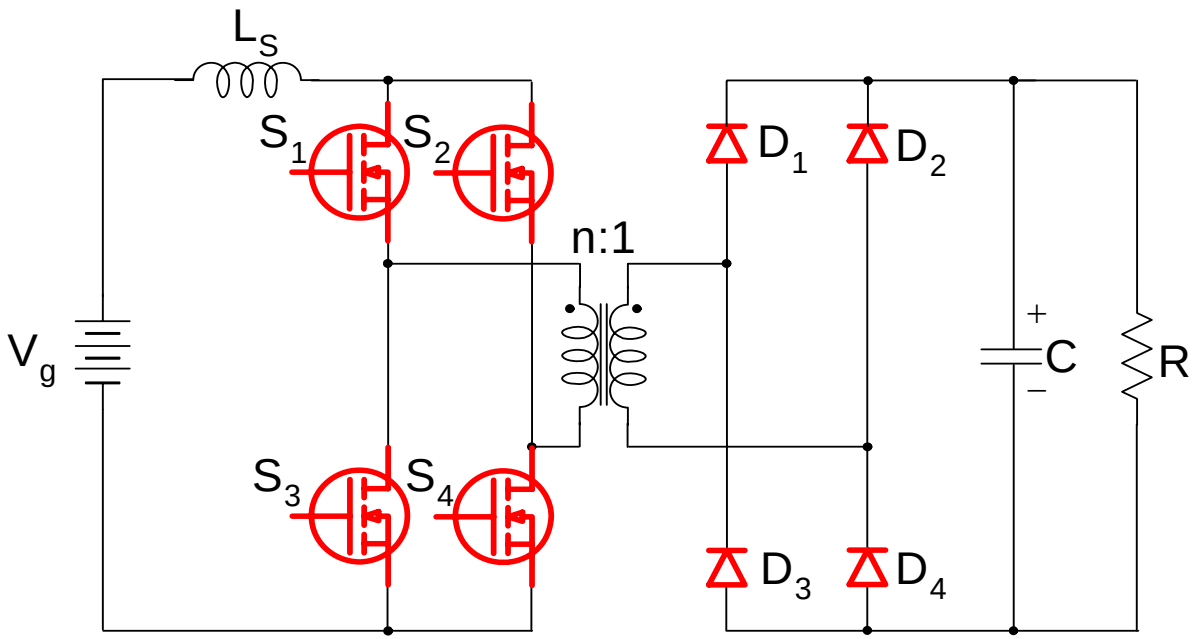


Problem

How to insert AC Isolation Transformer by using additional switches

Isolated Full-bridge Boost Converter

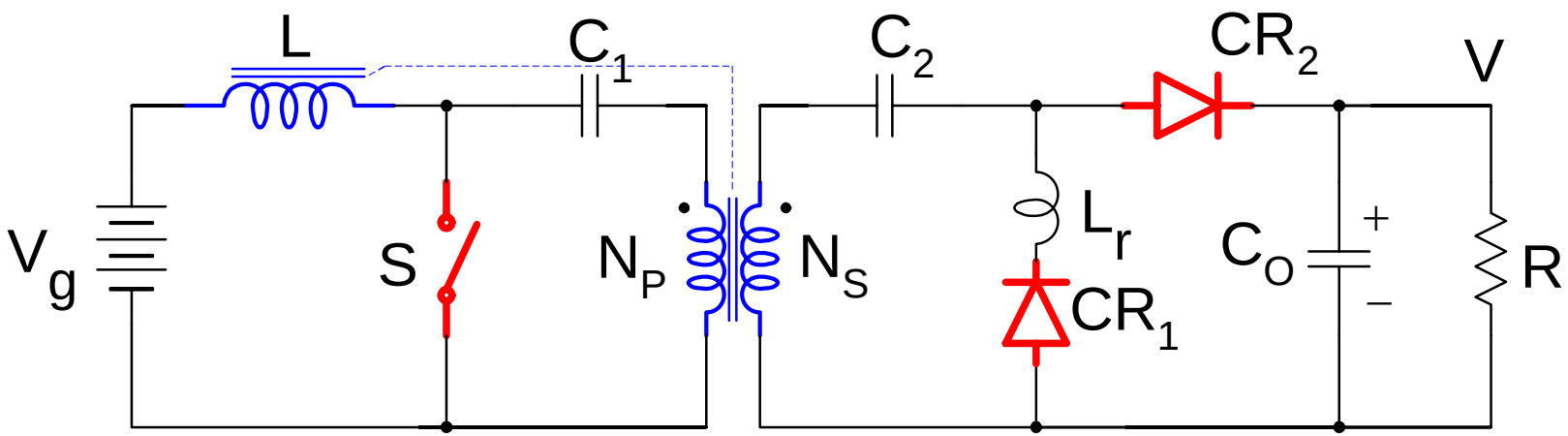
Two Magnetic Components



Total of 8 Switches

Hybrid-Switching Boost Converter*

One Integrated magnetic Component

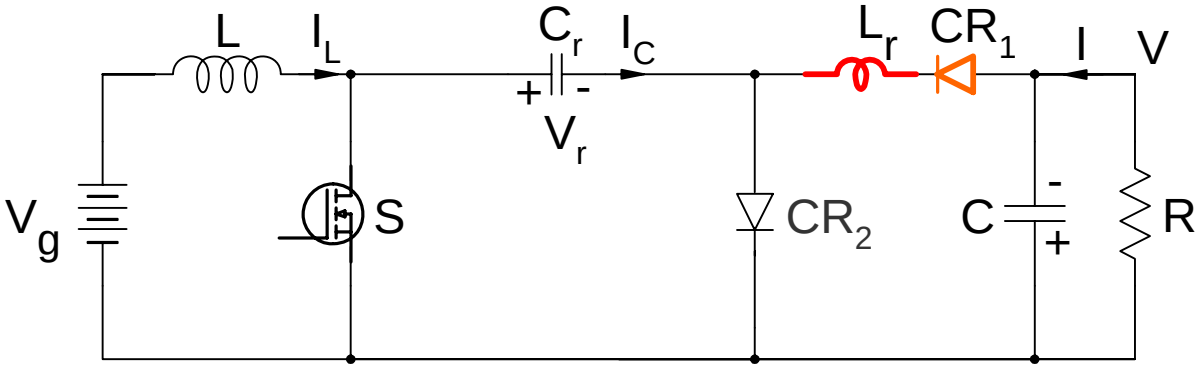


Total of 3 Switches

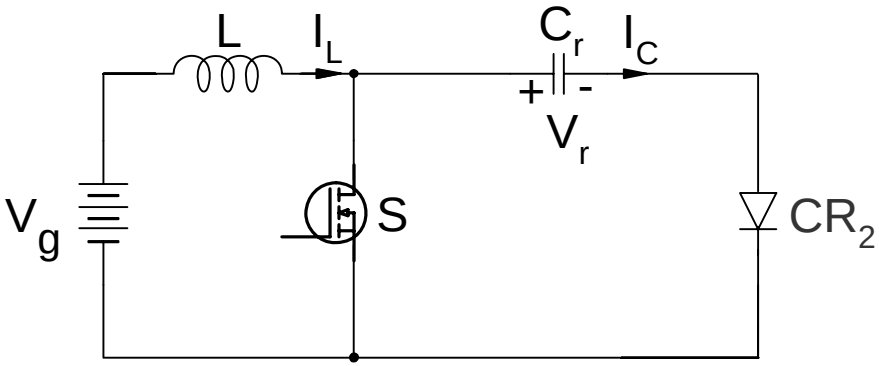
*US Patent No. 7,778,046

Polarity Inverting DC-DC Converter

Polarity Inverting 3 Switch Boost Converter*

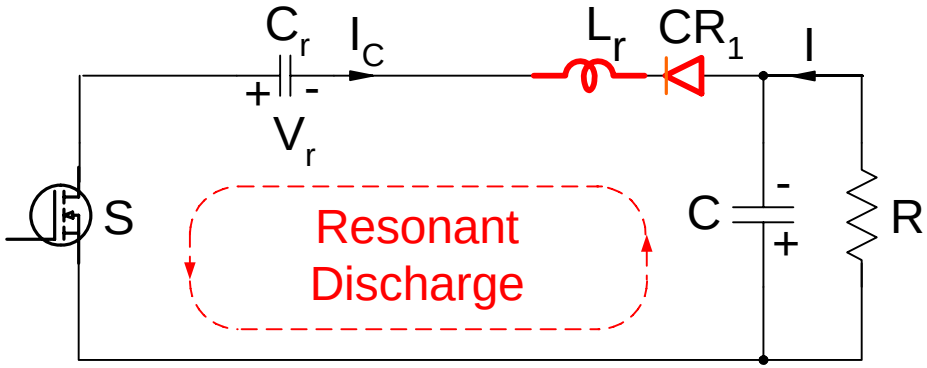


$V=V_g/(1-D)$



Boost Converter

$V_r=V_g/(1-D)$



$V=V_r$

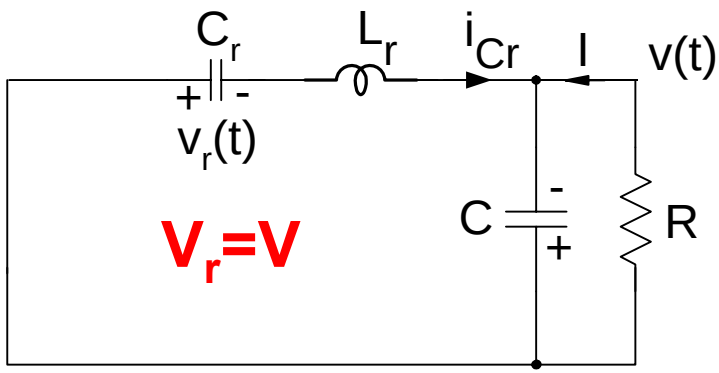
OFF-time Interval $(1-D)T_S$

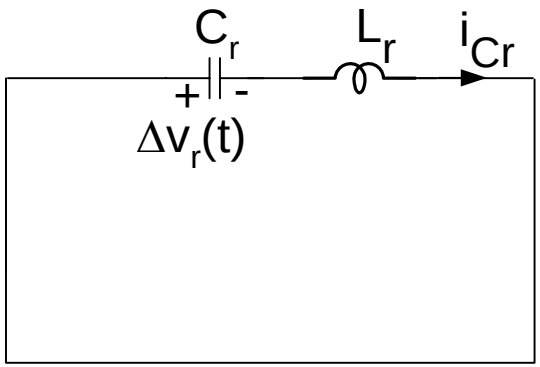
*US Patent No. 7,778,046

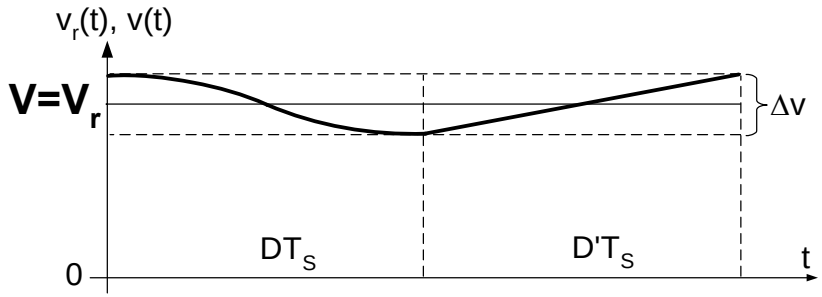
State-space Averaging Extension

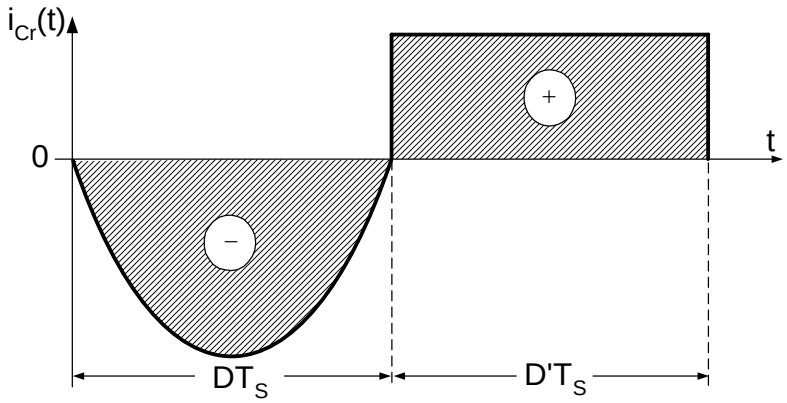
Flux Balance on Resonant Inductor During ON-time Interval Only

$V=V_r=V_g/(1-D)$









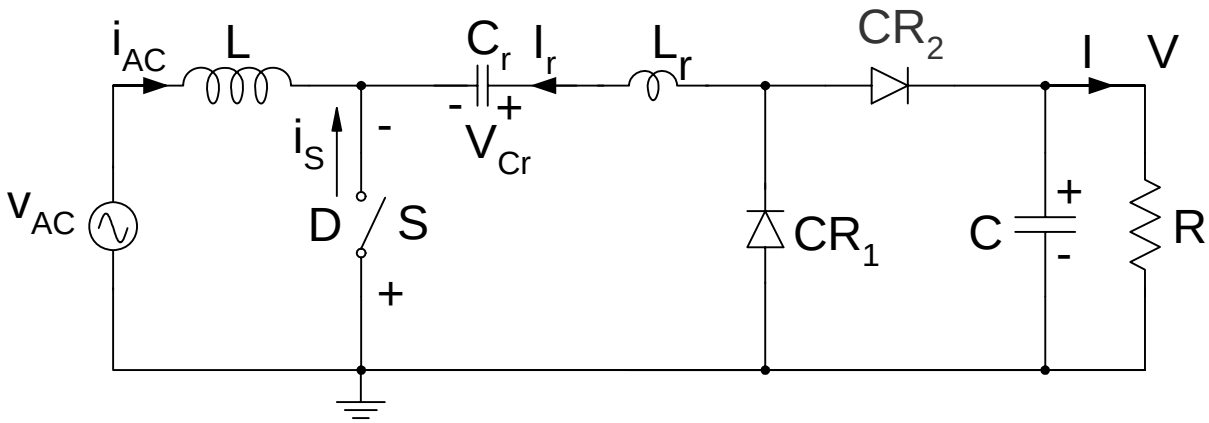
Resonant Inductor Excited by Small Ripple Δv_r Voltage Only on Resonant Capacitor

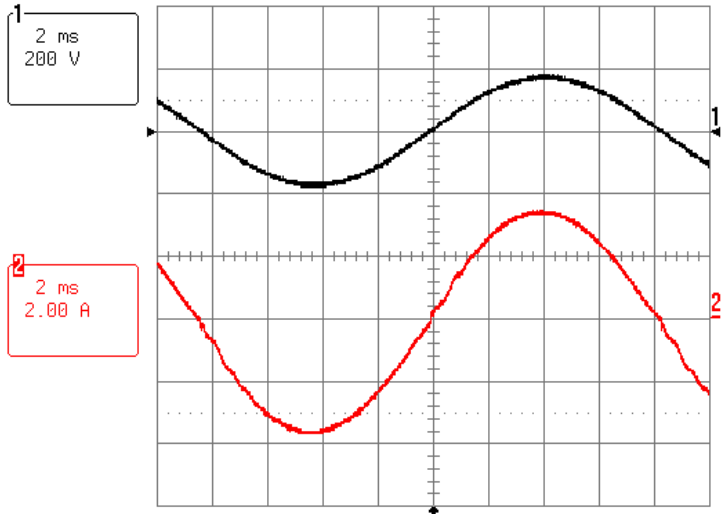
AC-DC

Converter Comparison

True Bridgeless PFC Converter

True Bridgeless PFC Converter*



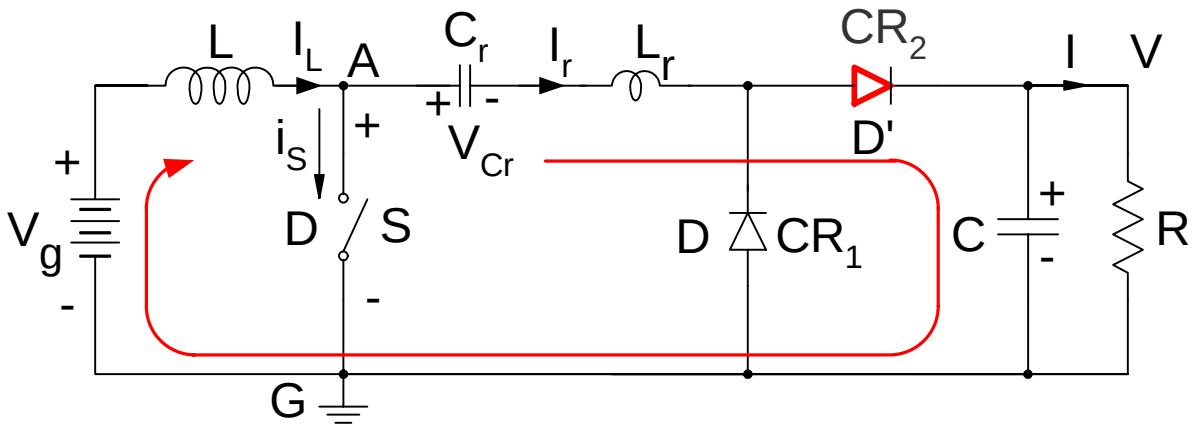


Input Voltage
110V

THD=1.7%
PF=0.999

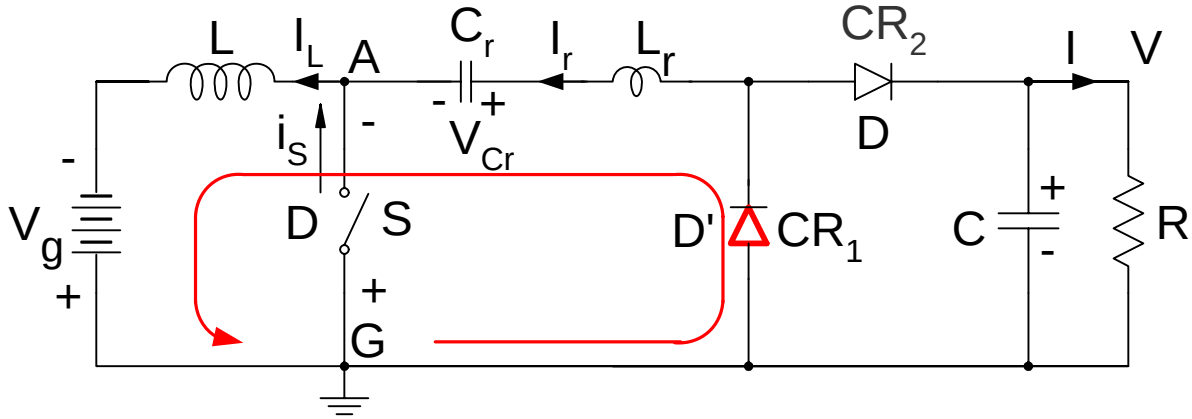
***US and foreign patents pending**

Positive and Negative Half-cycle of Input Voltage



$V_{Cr}=0$

$V=V_g/(1-D)$

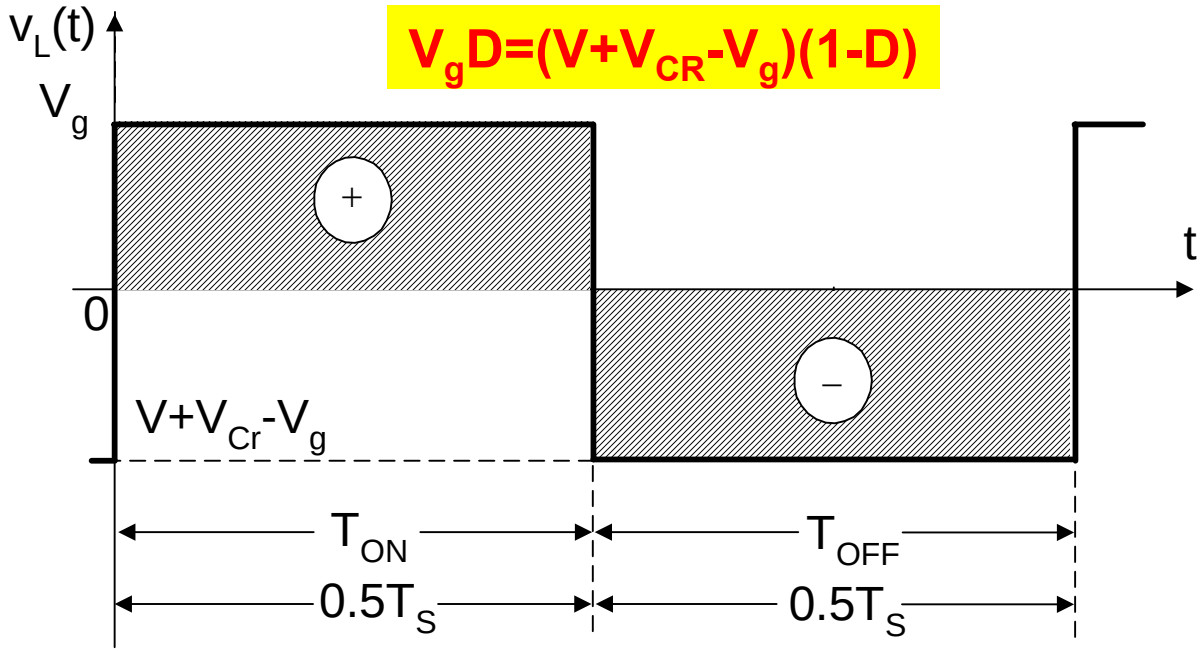


$V_{Cr}=V$

Source Polarity Controls Conduction Interval of Two Diodes:

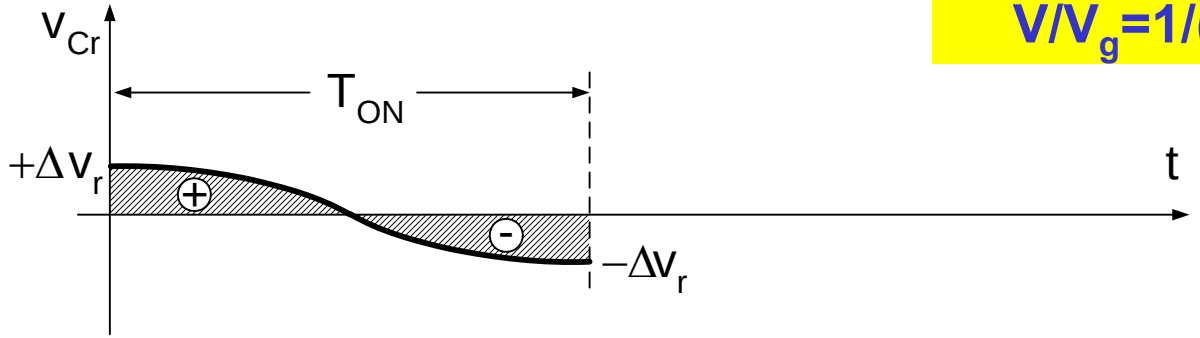
Full-Bridge Eliminated

Flux Balance for Positive Input



$V_gD=(V+V_{CR}-V_g)(1-D)$

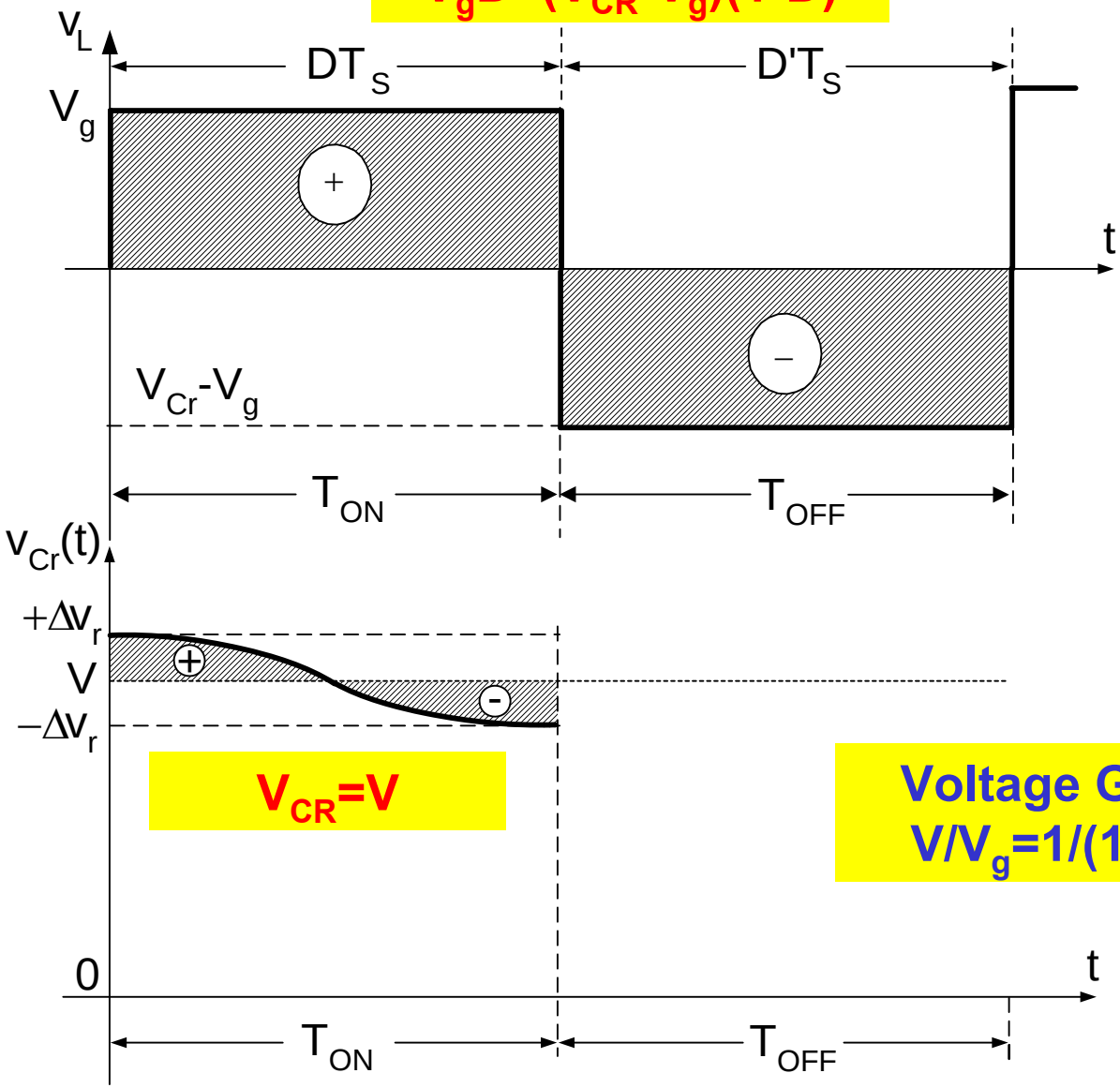
$V_{CR}=0$



Voltage Gain
$V/V_g=1/(1-D)$

Flux Balance for Negative Input

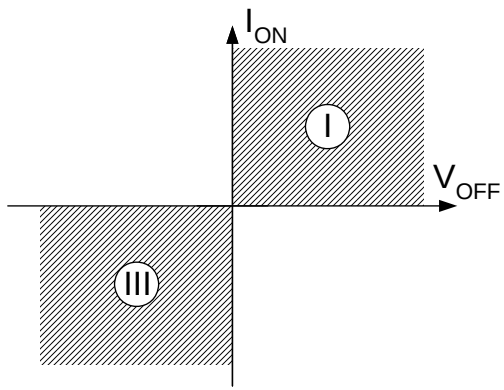
$V_g D=(V_{CR}-V_g)(1-D)$

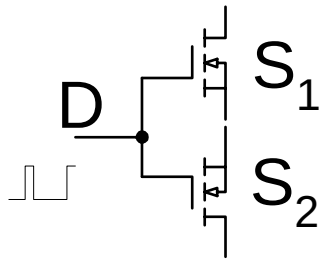


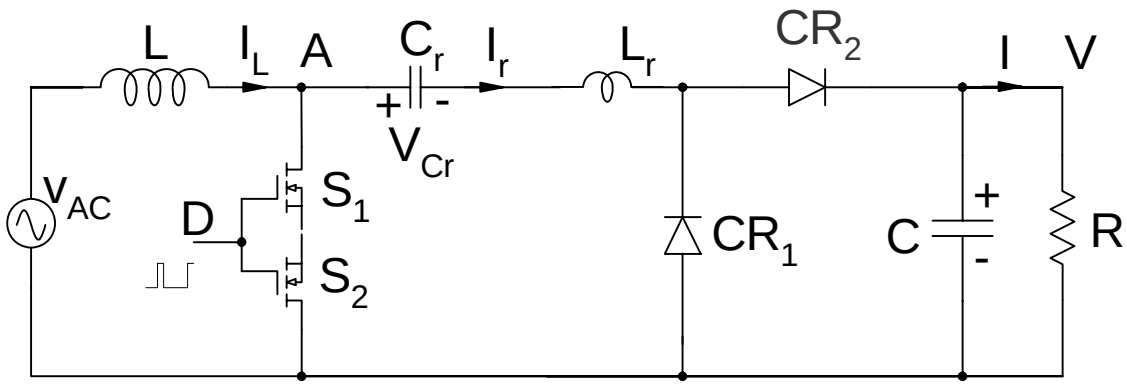
$V_{CR}=V$

Voltage Gain
$V/V_g=1/(1-D)$

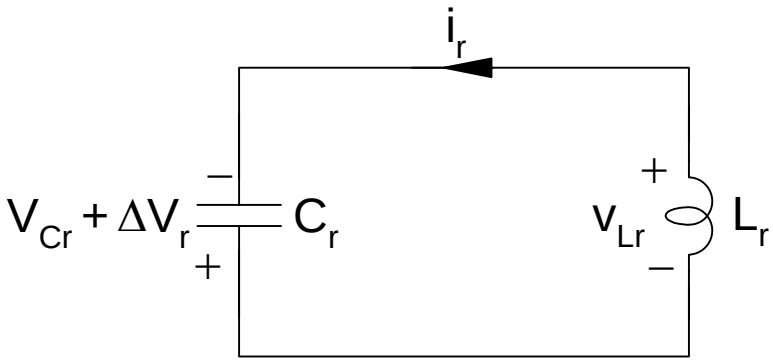
One Implementation of the Controlling Switch

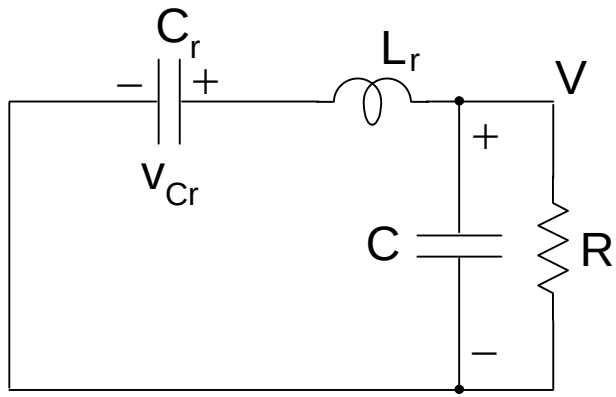


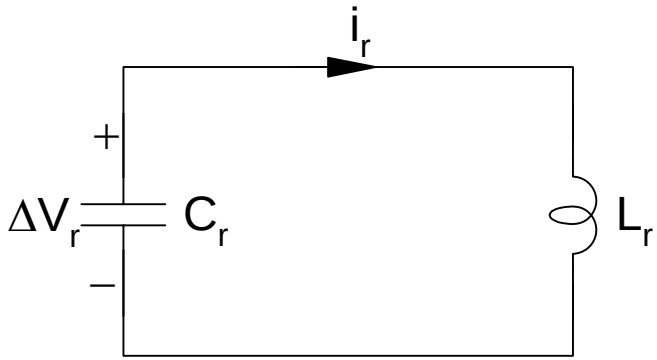




Resonant Equivalent Circuit Models







Solutions of Resonant Circuit Equations

$$i_r(t) = I_P \times \sin(\omega_r t)$$

$$v_{Cr}(t) = \Delta v_r \times \cos(\omega_r t)$$

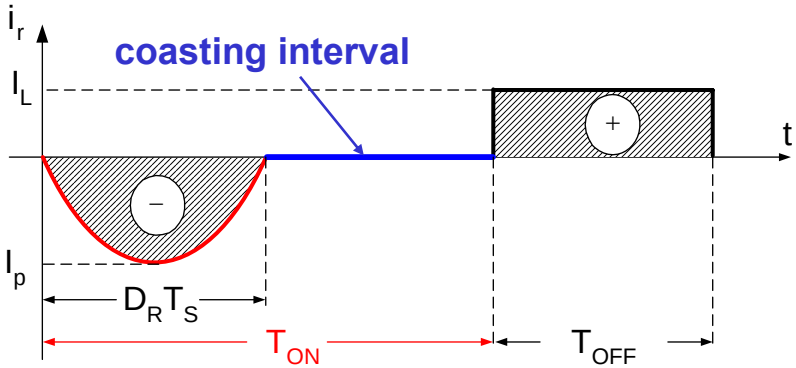
$$\Delta v_r = R_N \times I_P$$

$$R_N = \sqrt{L_r / C_r}$$

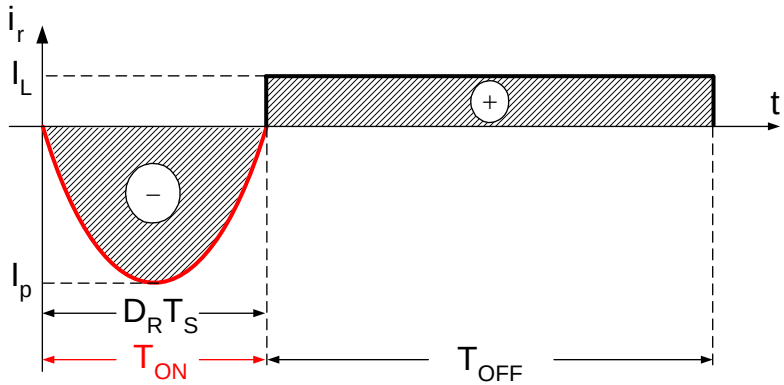
$$\omega_r = 1/\sqrt{L_r C_r}$$

$$f_r = \omega_r / 2\pi$$

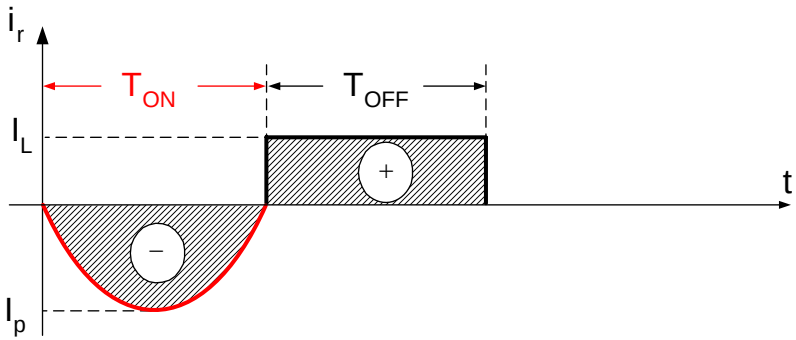
Resonant Inductor Current Waveforms



Variable ON-time
Constant f_S

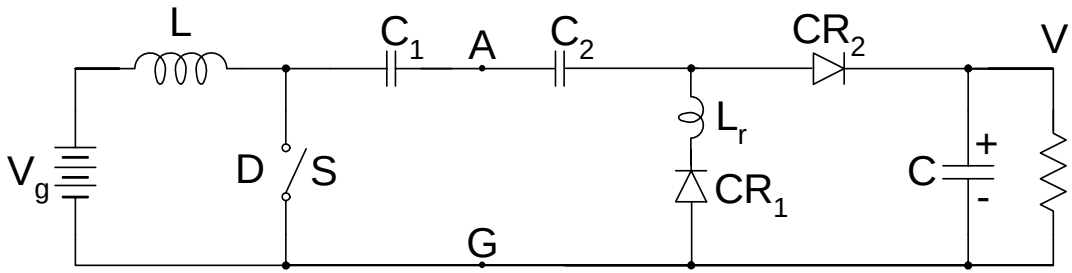


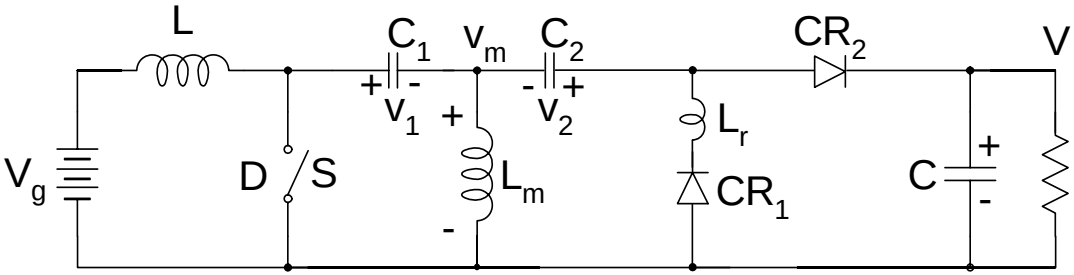
Constant ON-time
Variable OFF-time

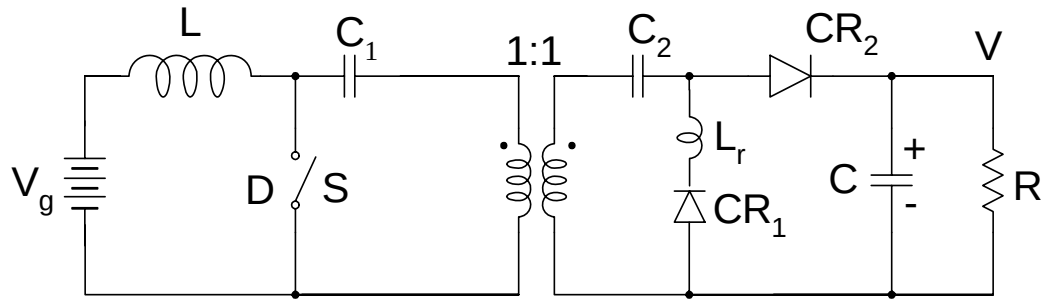


Constant ON-time
Variable f_S

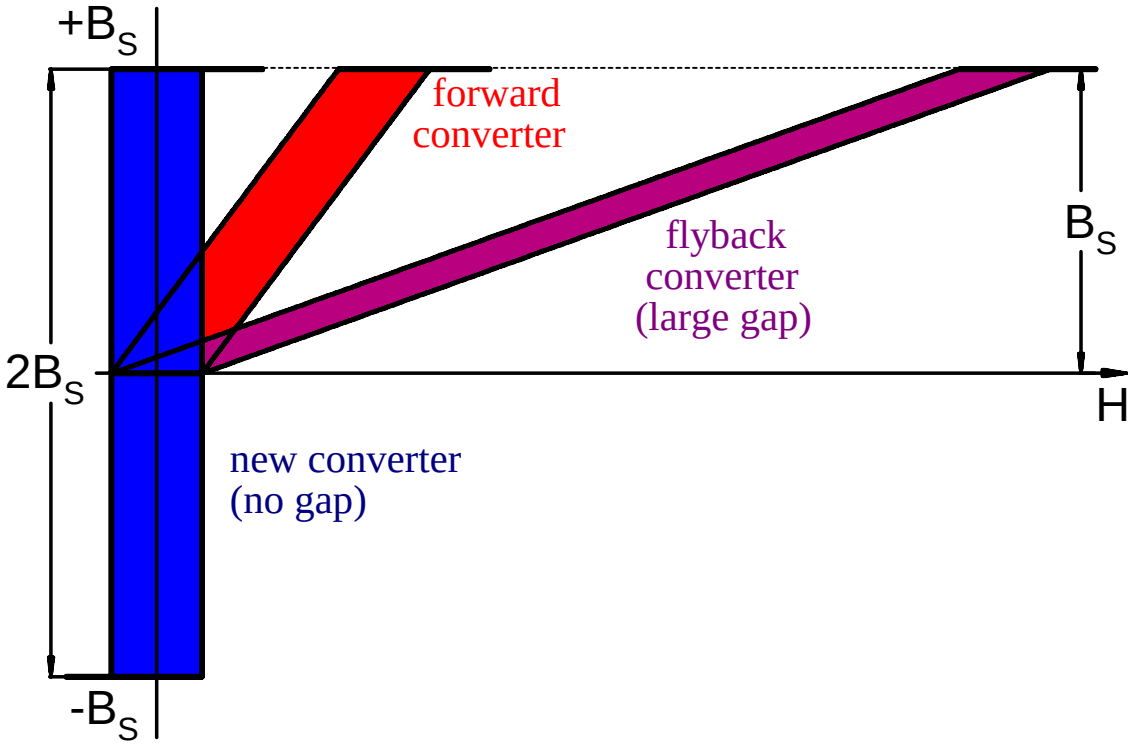
Insertion of the Isolation Transformer



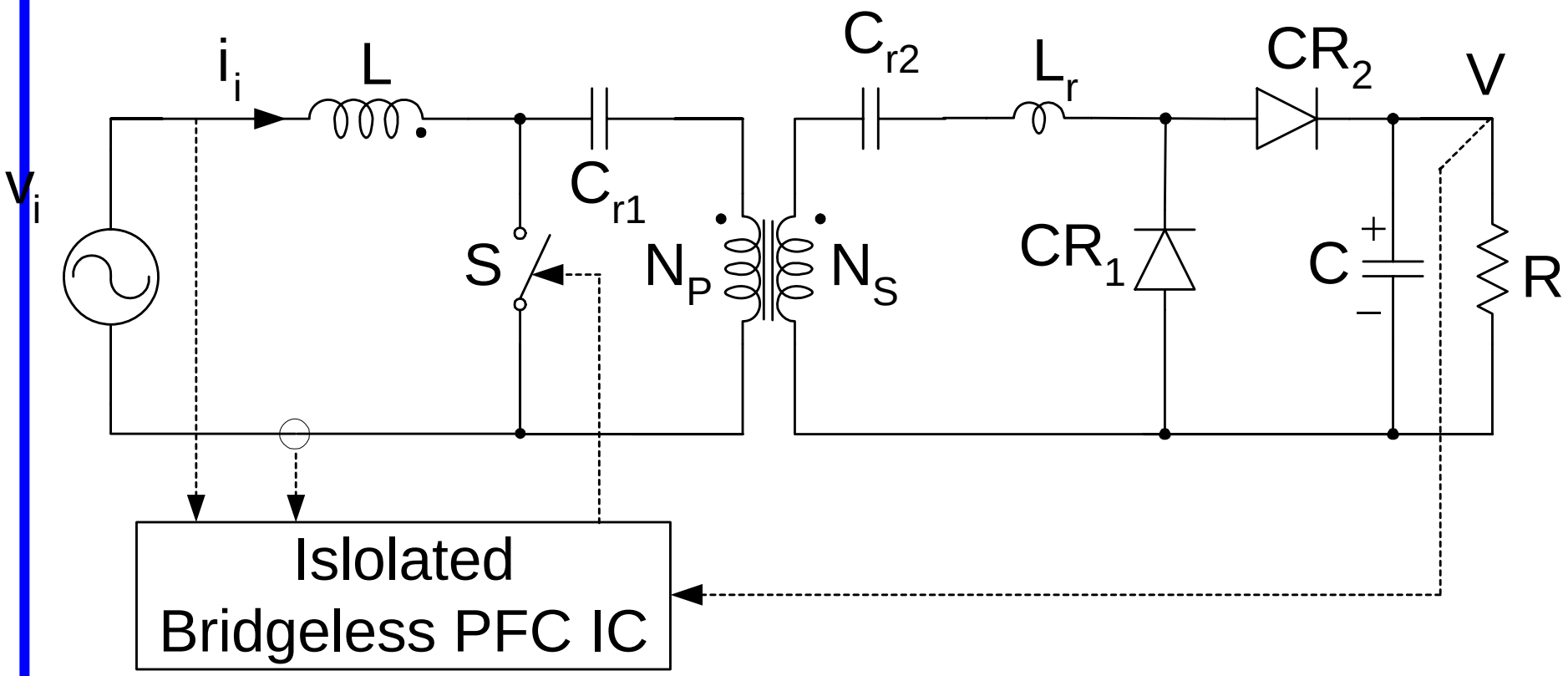




Comparison of Three Transformers Types



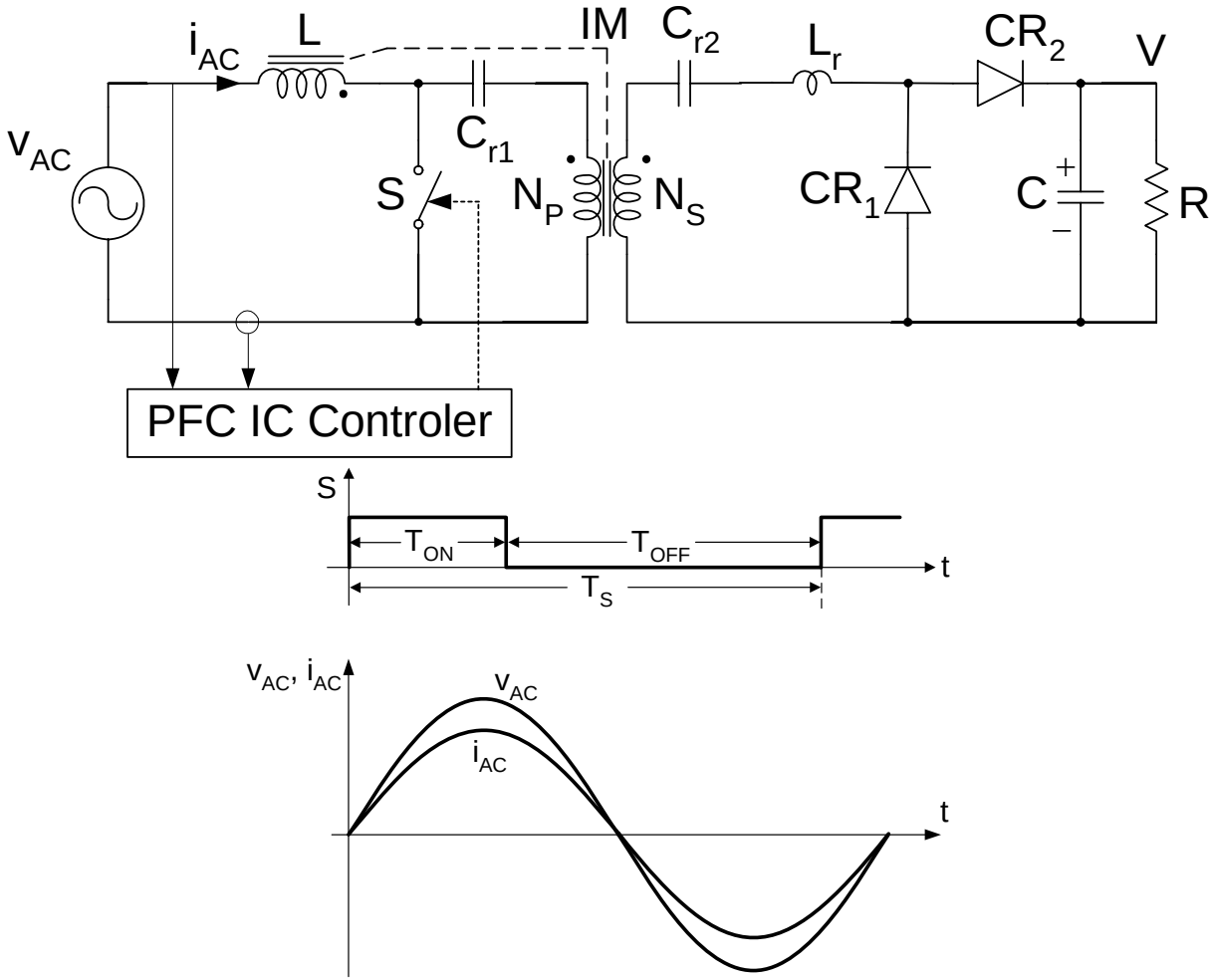
Hybrid-Switching AC-DC Rectifer*



Three Switches Only

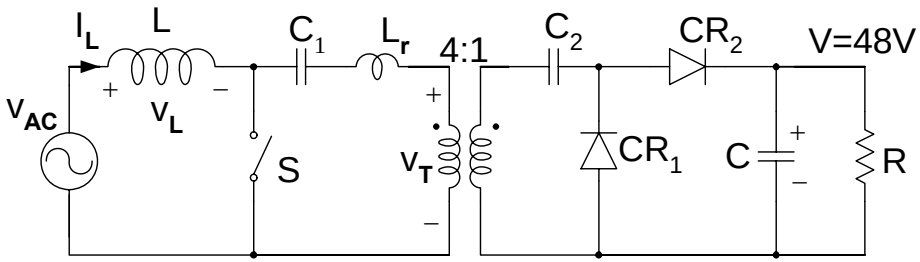
*US and foreign patents pending

True Bridgeless PFC Converter with Isolation*

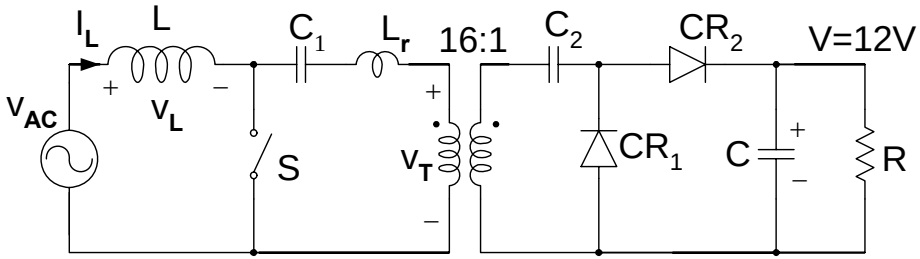


*US and foreign patents pending

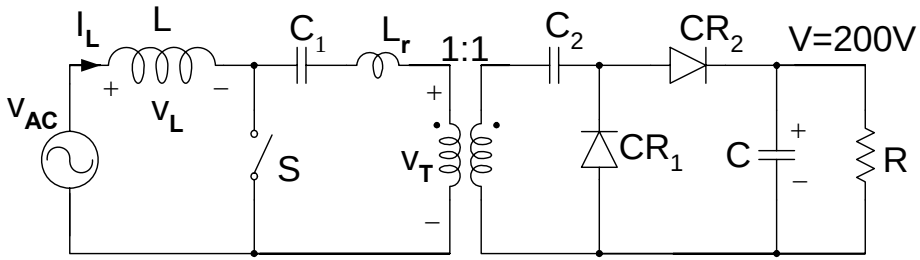
Variety of Output Voltages and Applications



Telecom



Data Centers

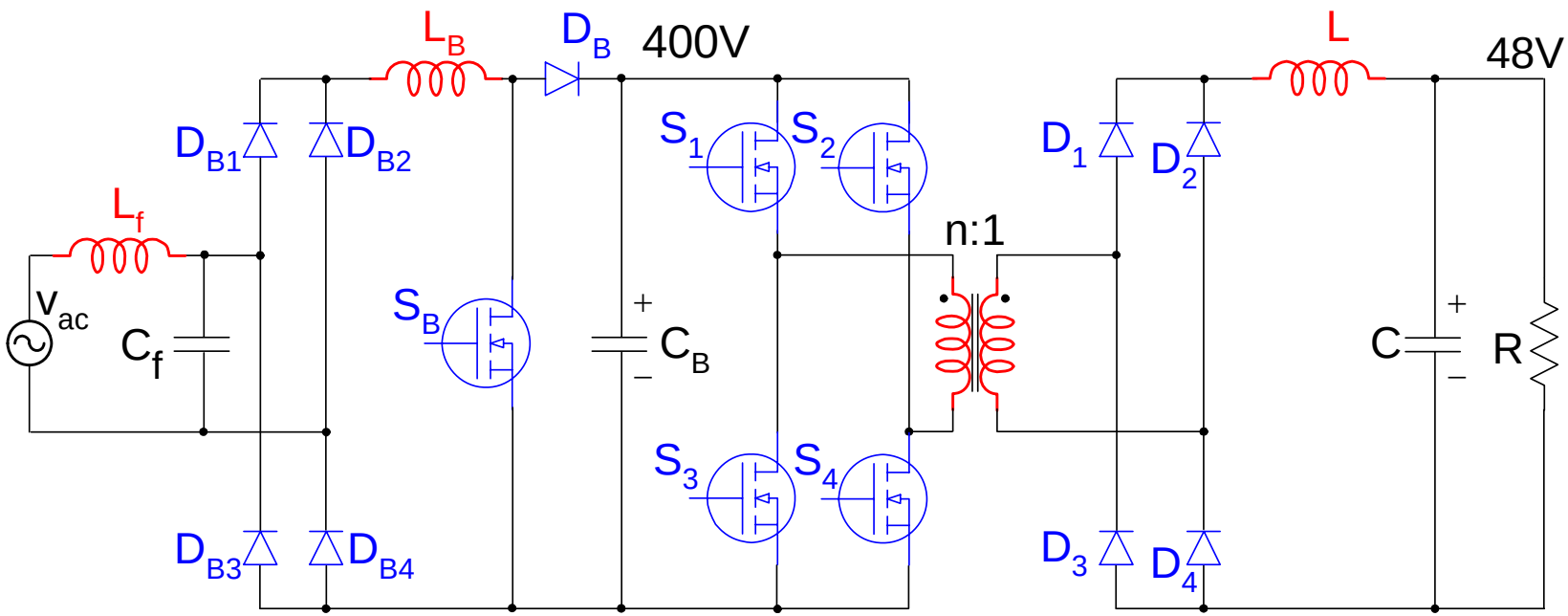


Battery Chargers

AC-DC

Converter Comparison

Conventional Three Power Processing Stage Approach



Comparison

Power Processing	Single-stage	Three-stage
Type of Converter	Isolated Bridgeless PFC	Bridge-Boost PFC-Full-bridge
Switching Method	HYBRID	Square-wave
Number of switches	3	14
Switch-voltage Stress	Low	High
Lossless-switching	YES	NO
Control	Simple	Complex
Magnetics pieces	1	4
Power Losses	3%	10%
Efficiency	>97%	88% to 90%
Size	Small	Big
Weight	Light	Heavy
Cost	Low	High

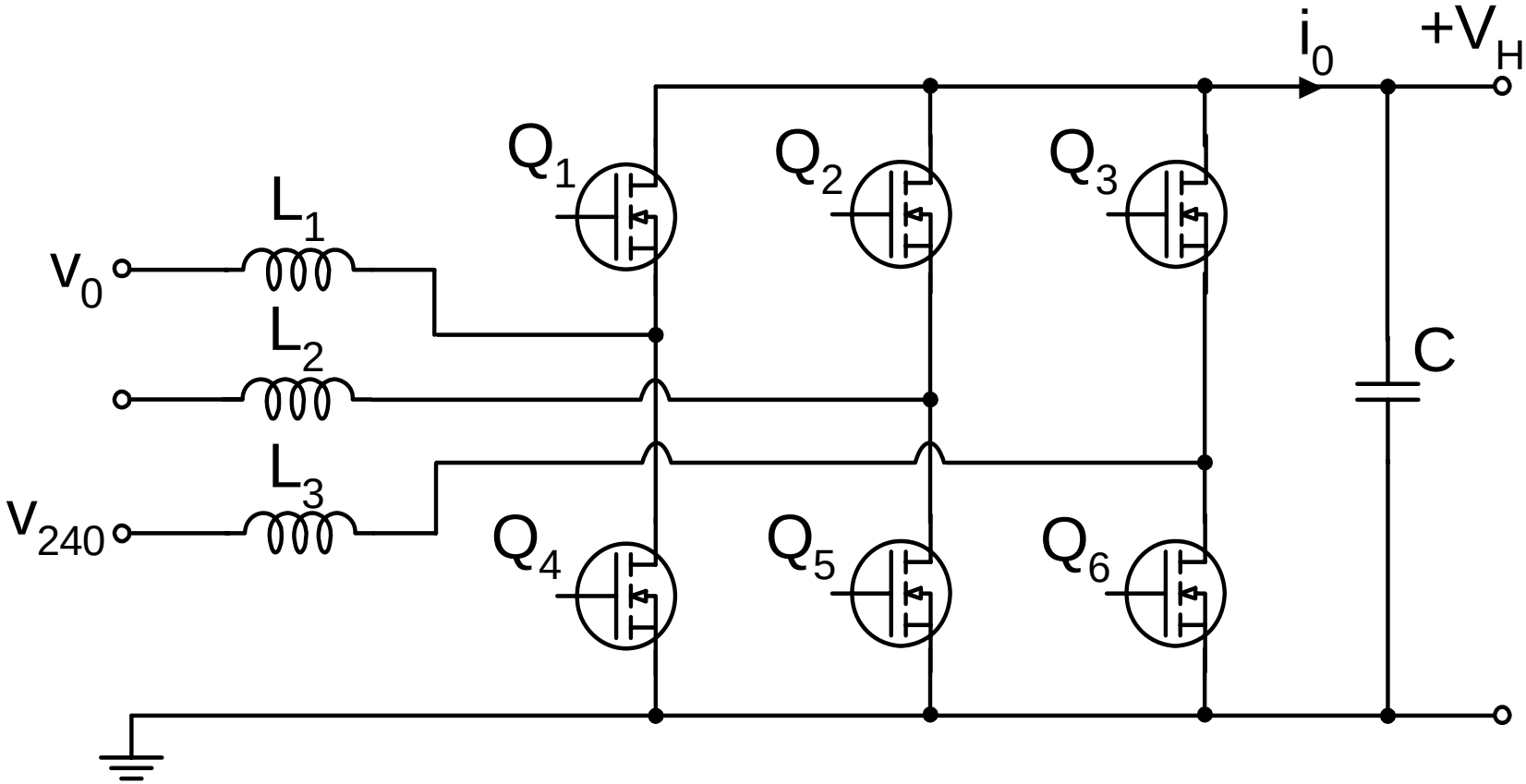
AC-DC conversion Summary

- Single stage power processing
- Efficiency greater than 97%
- Power factor greater than 0.99
- Meets IEC 1000-3-2 regulations
- Galvanic isolation
- Low weight and size
- NO CUSTOM COMPONENTS
- LOW COST

Three-Phase AC-DC

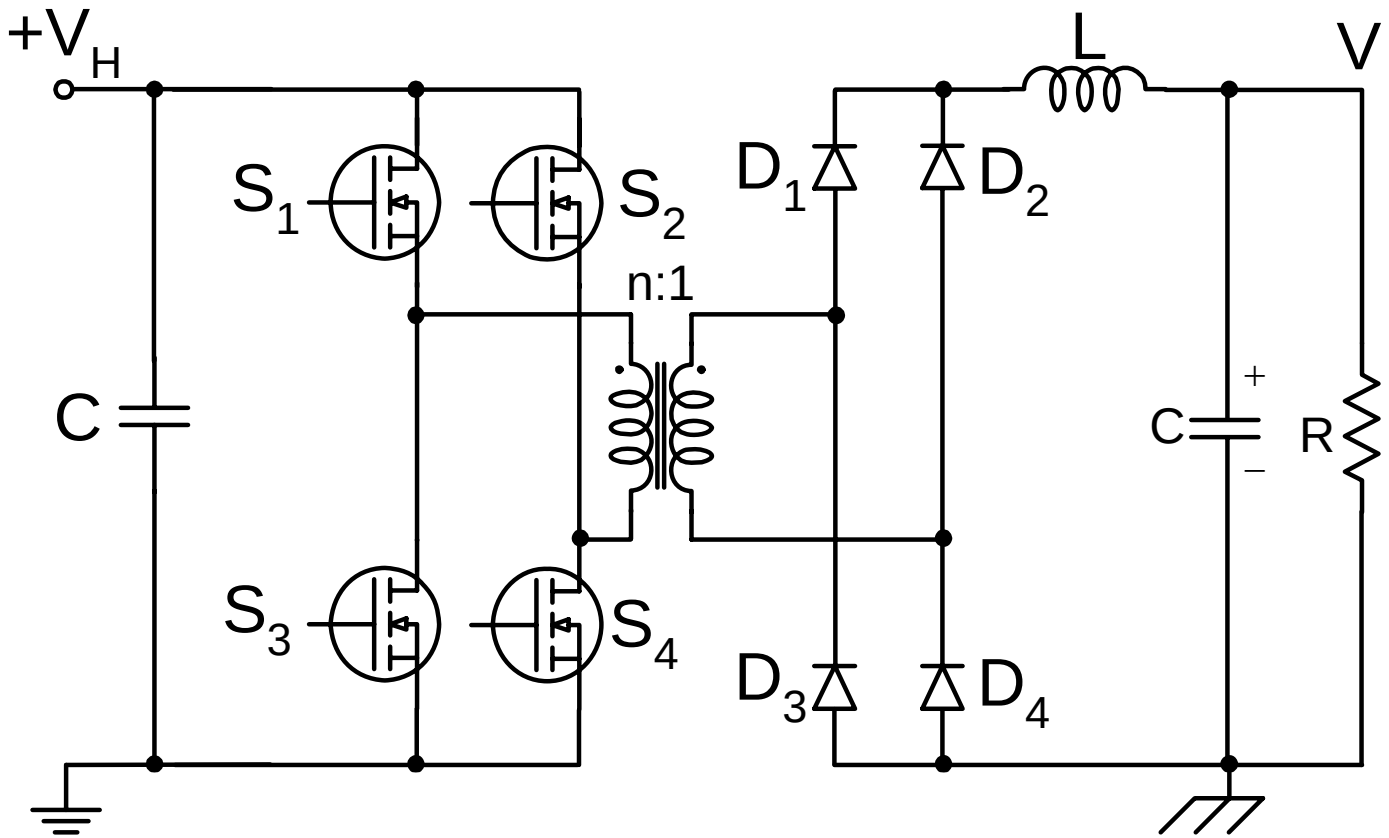
Converter Comparison

Conventional PFC Three-phase to DC Rectification without Isolation Transformer



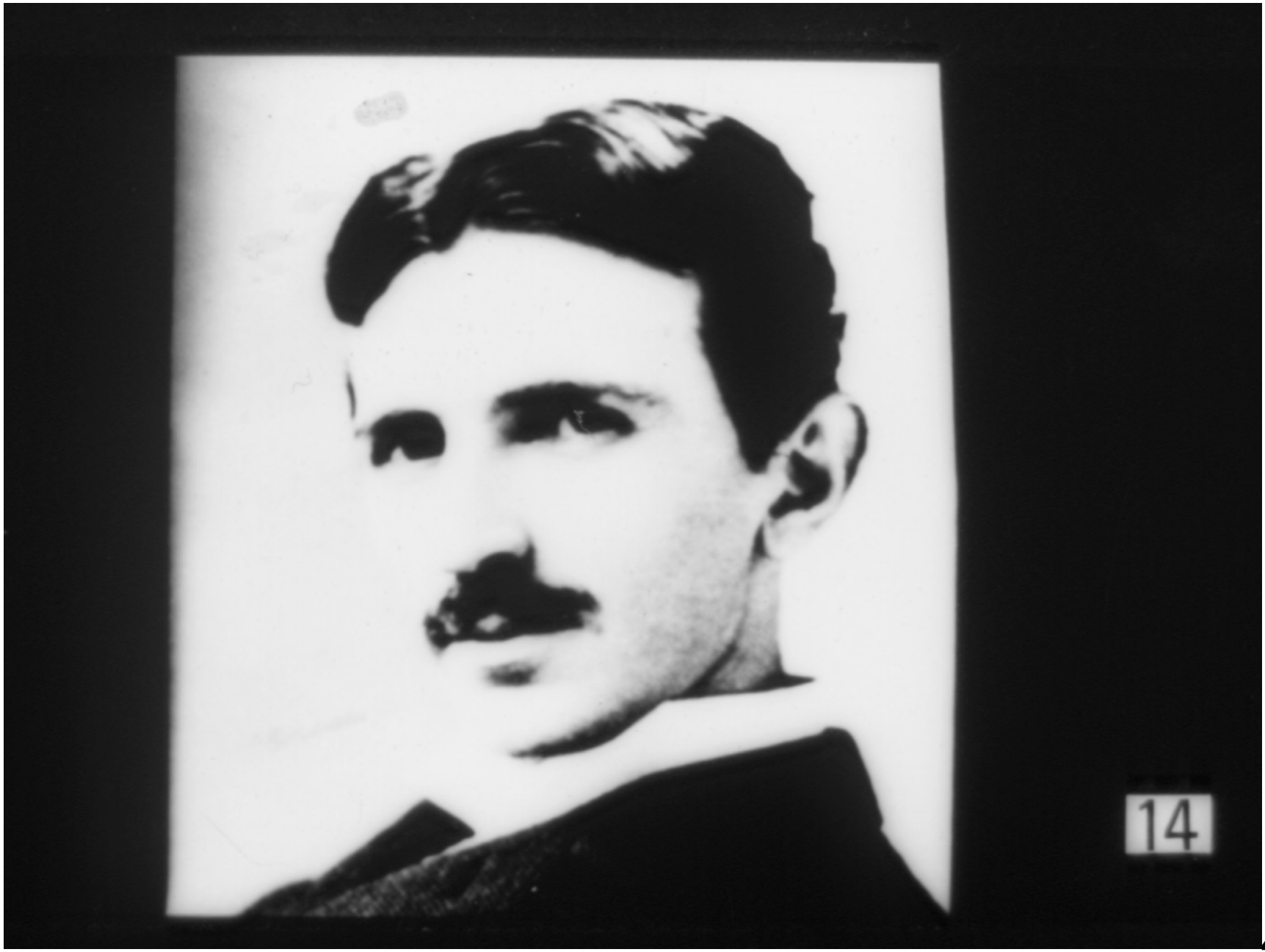
Three-phase properties prematurely lost after rectification

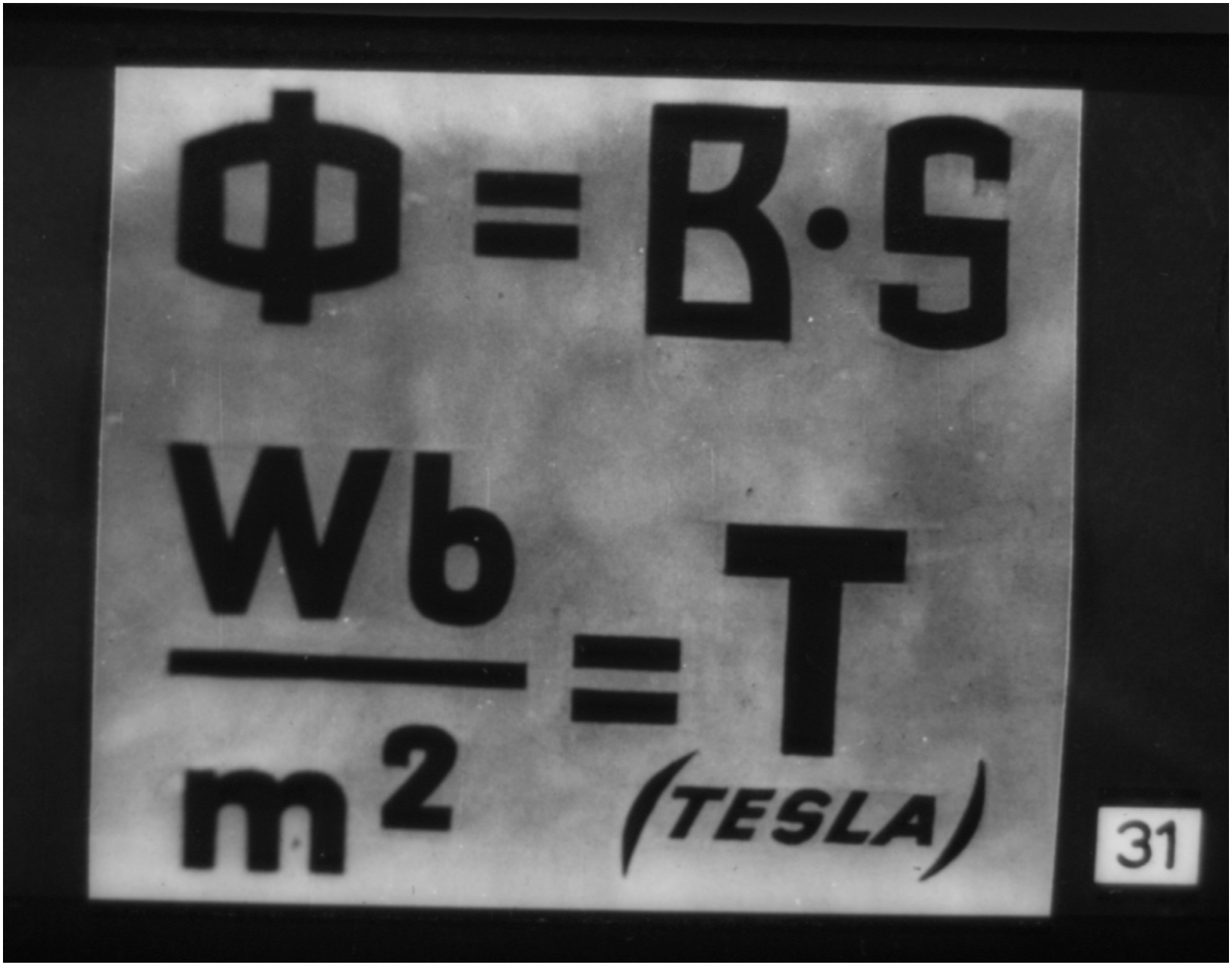
Second Stage: Isolated DC-to-DC Converter



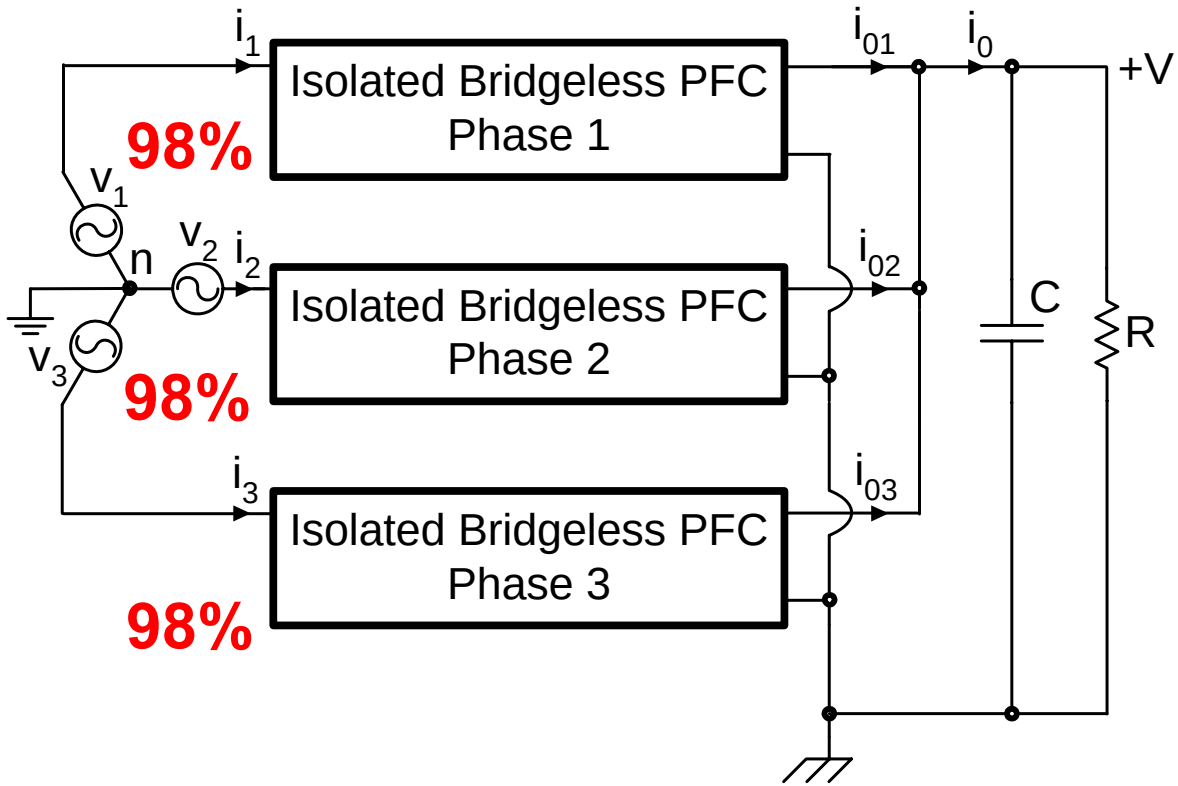
DC Storage in output inductor

New Single-stage Three-phase Rectifier




Φ = B·S
Wb / m² = T
(TESLA)
31

New Direct Three-Phase to DC Conversion with PFC and Isolation in a Single Stage

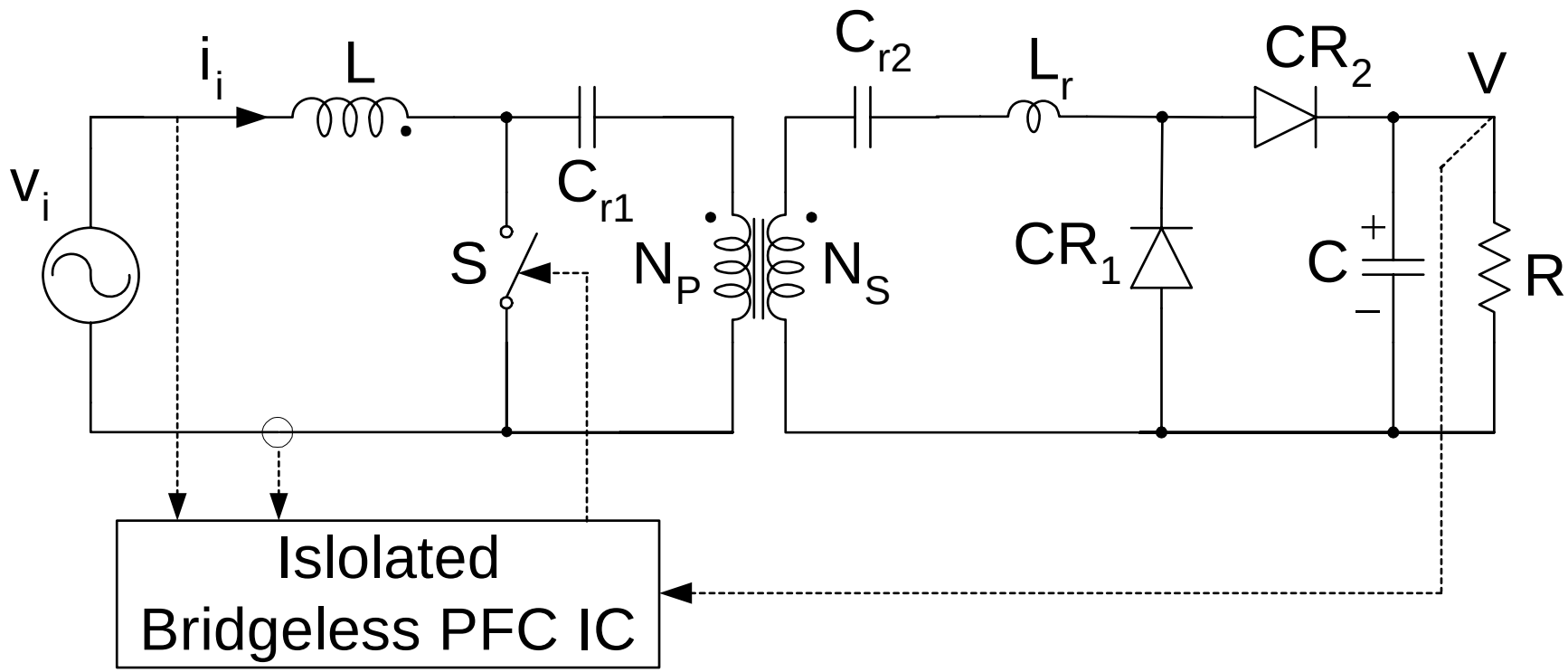


Power processed in parallel and not in series

Each Phase Efficiency 98%; TOTAL Efficiency 98%

*US and foreign patents pending

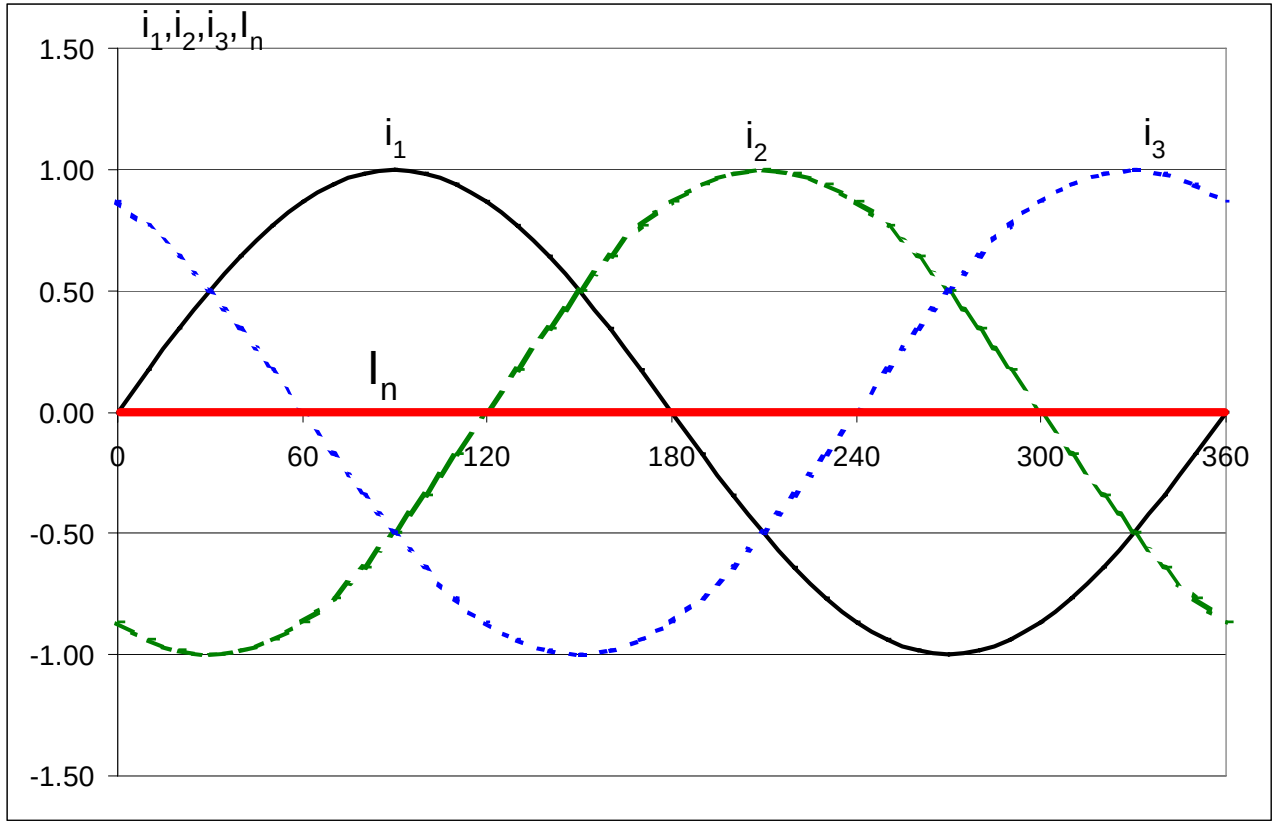
AC-DC Converter for Each Phase with PFC and Isolation*



Three Switches Only

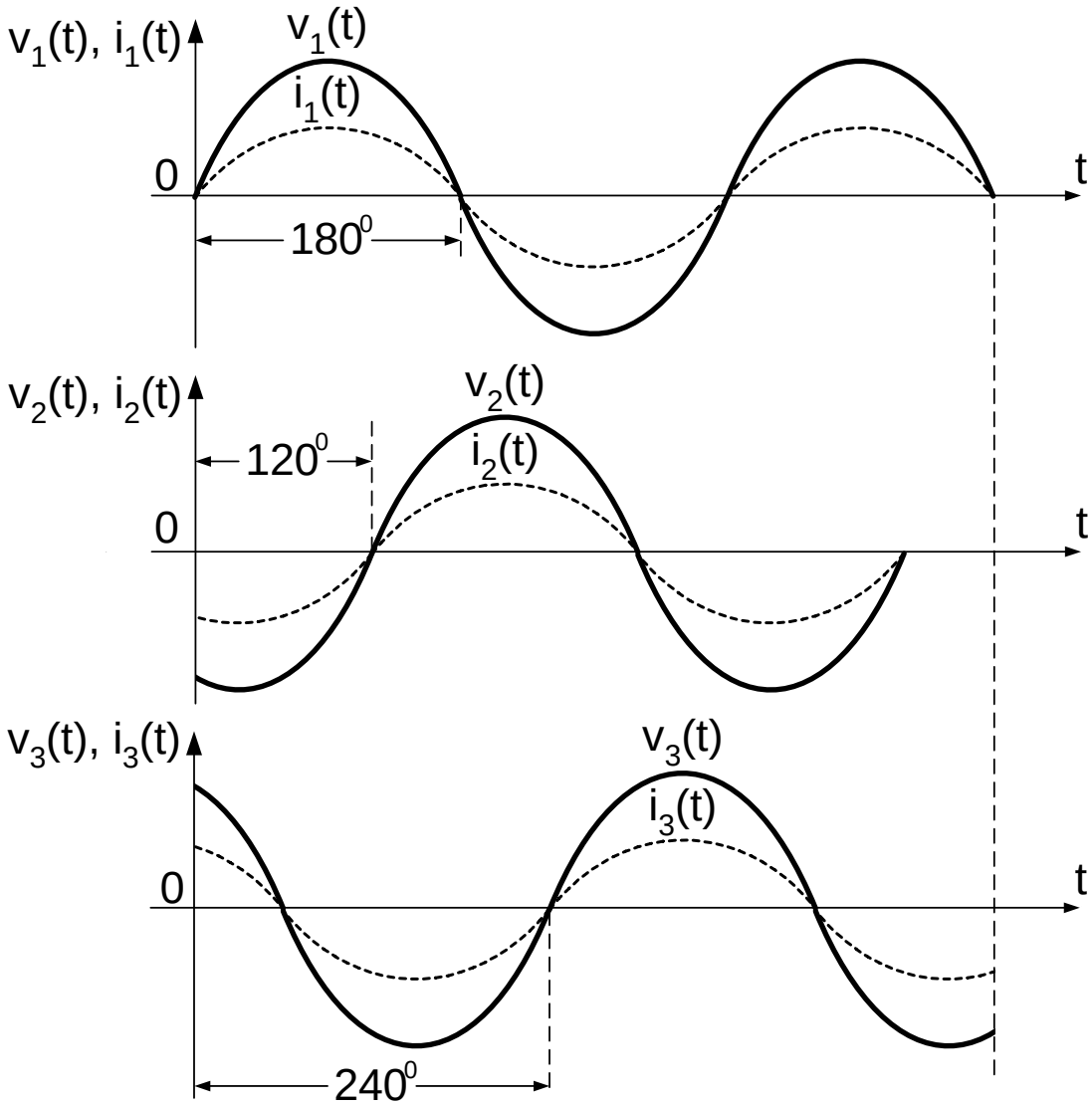
*US Patent No. 7,778,046

Input Currents of Three-phase Input

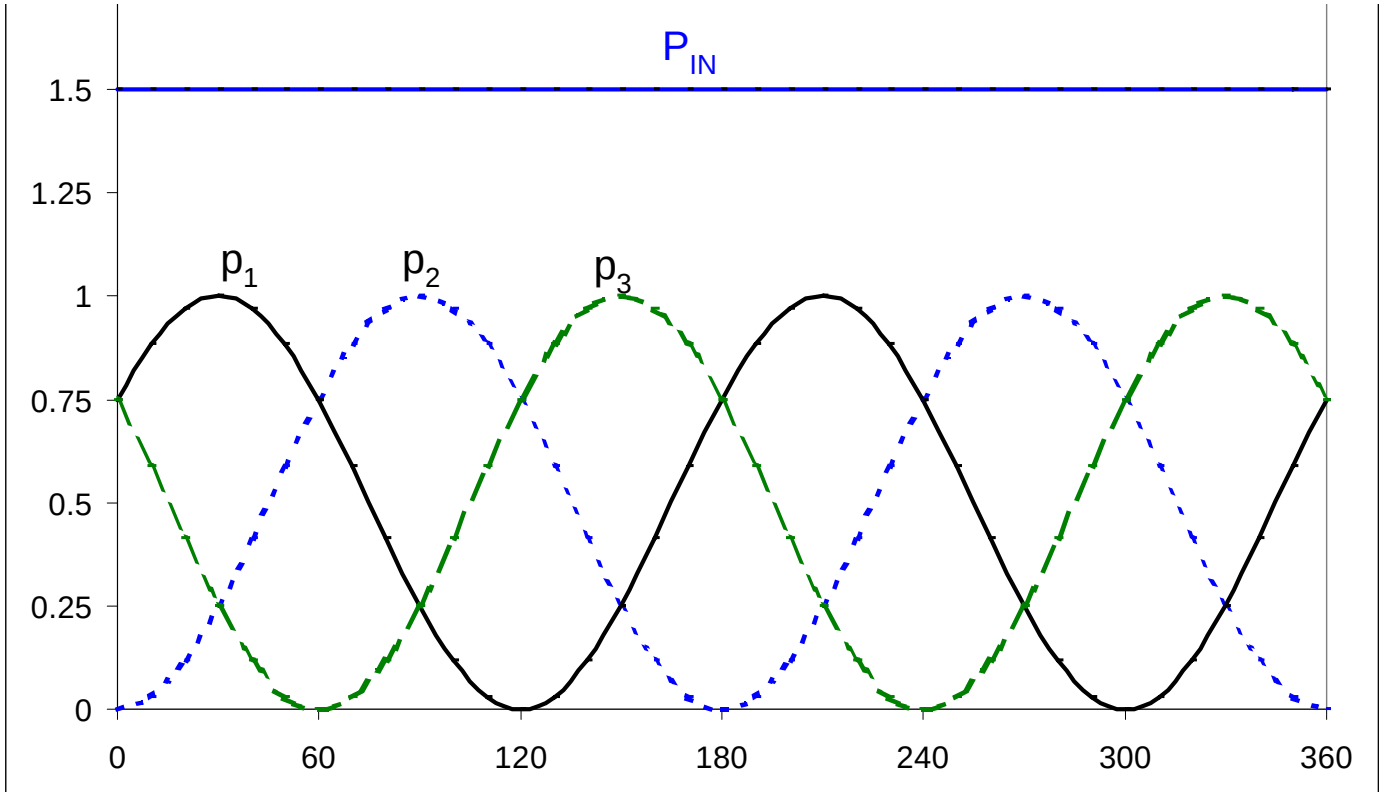


Neutral current is zero

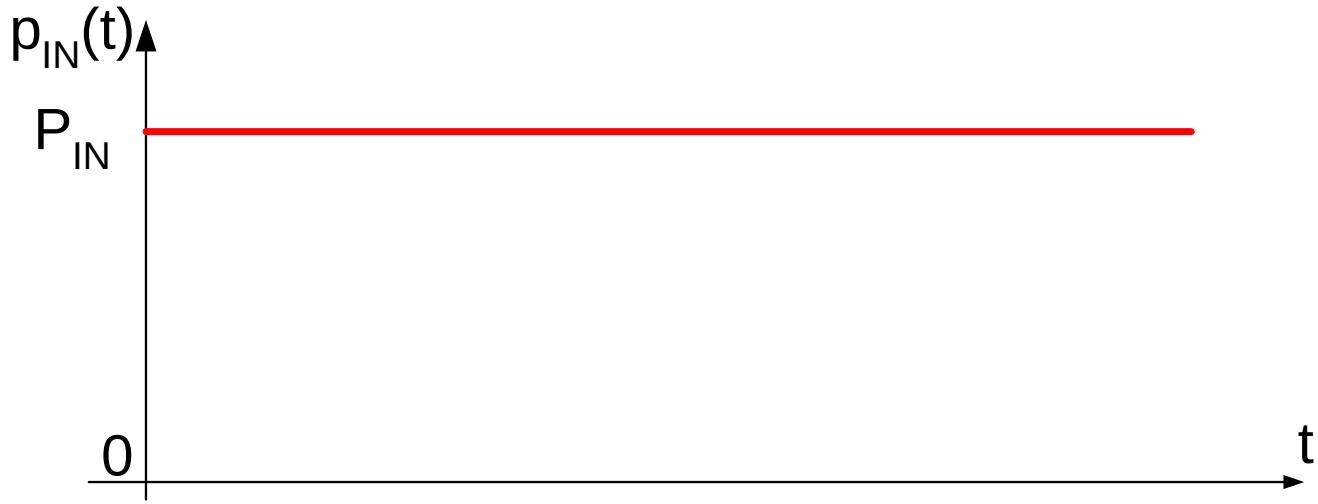
Input Voltages and Input Currents for Unity Power Factor



Sum of Instantaneous Input Powers of Three Phases is Constant

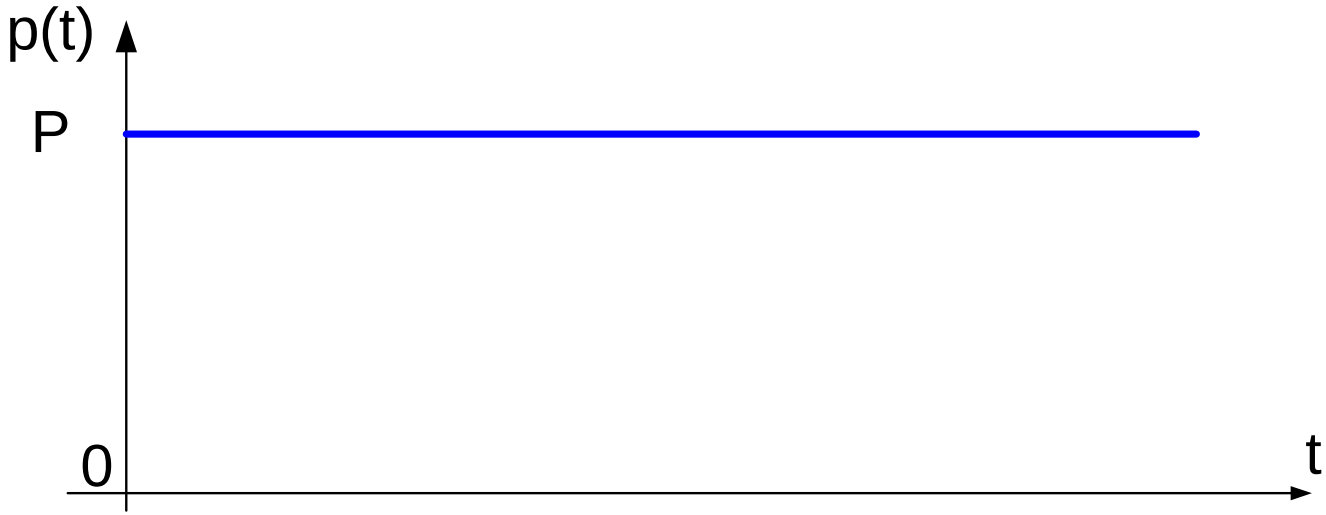


Instantaneous Input Power is Constant



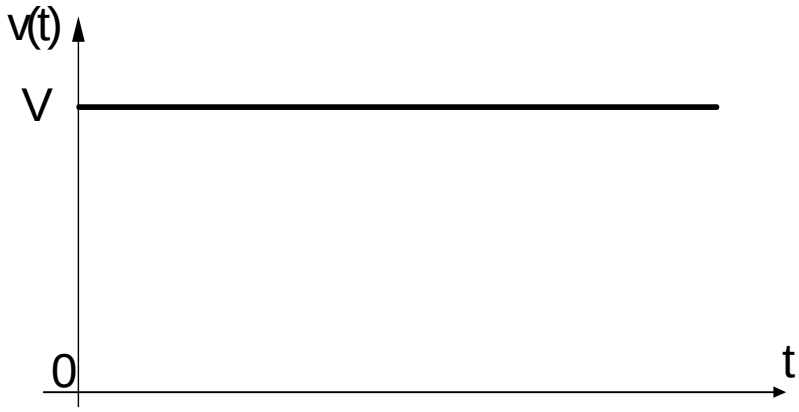
P_{IN}= constant

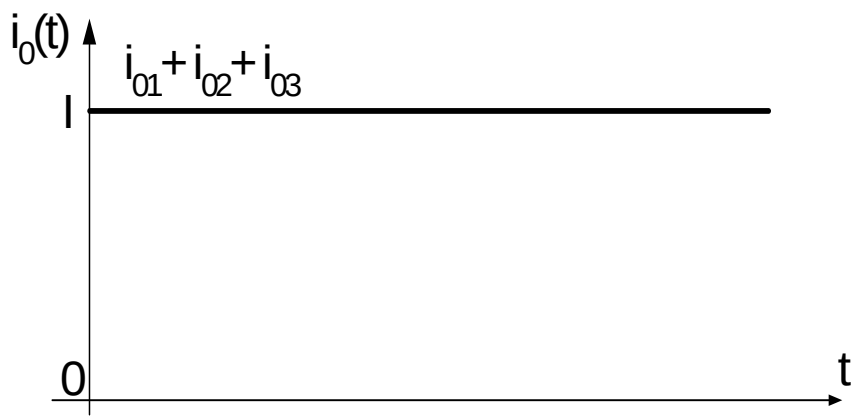
Instantaneous Output Power is Constant



P = constant

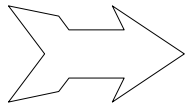
Constant Output Power and Constant Output Voltage Lead to Constant Output Current





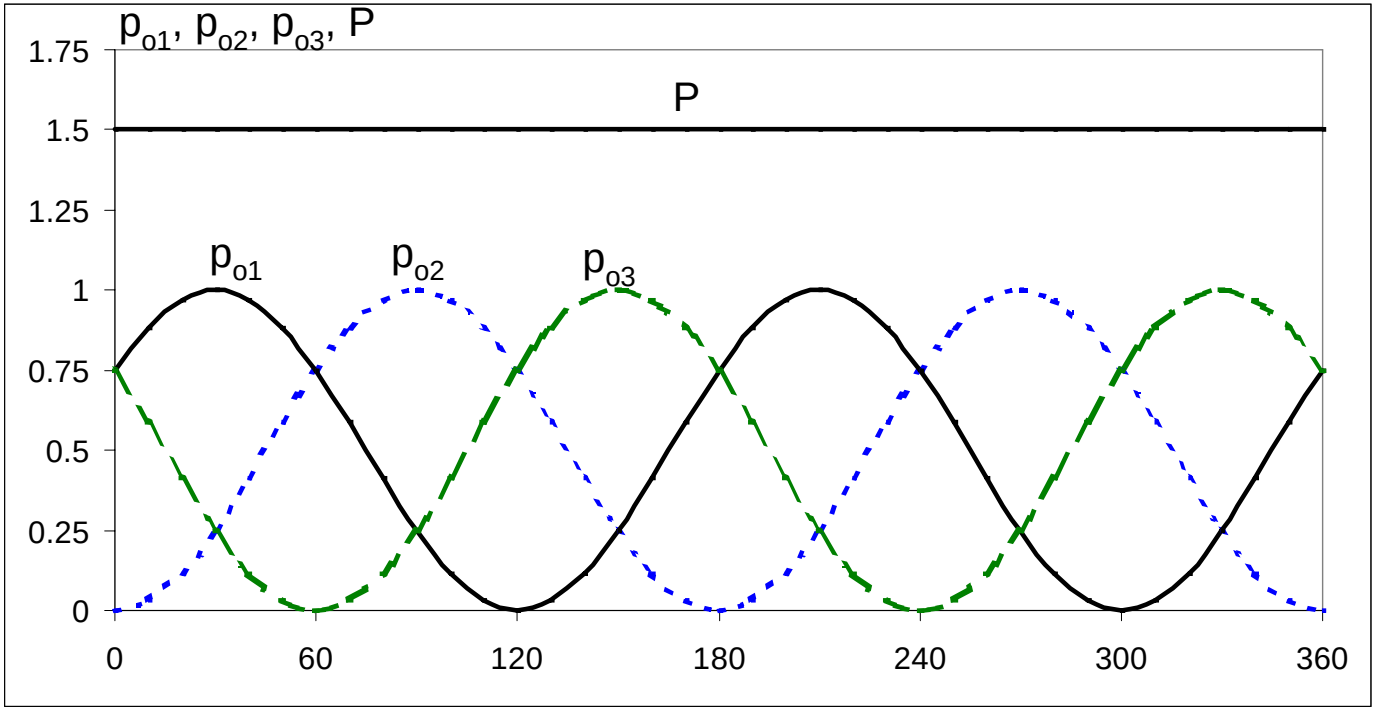
P = constant

V = constant

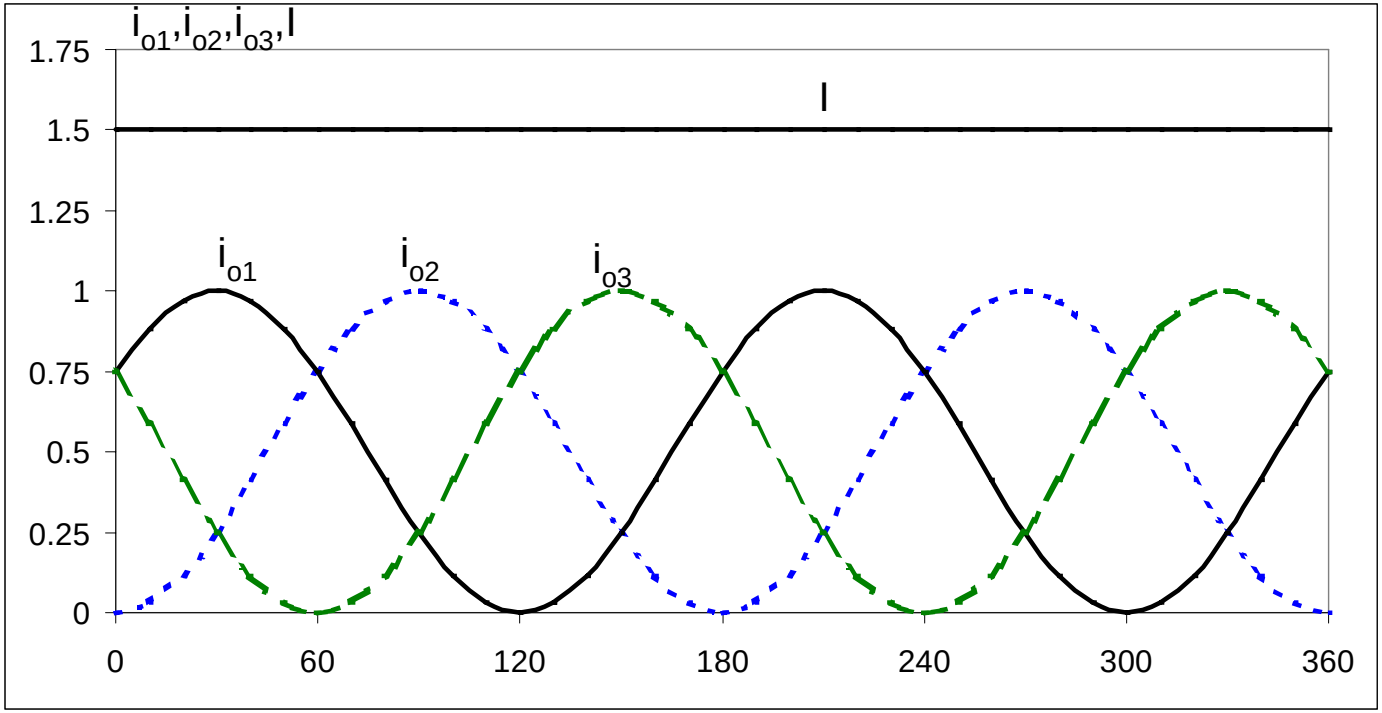


I = constant

Sum of Instantaneous Output Powers of Three Phases is Constant



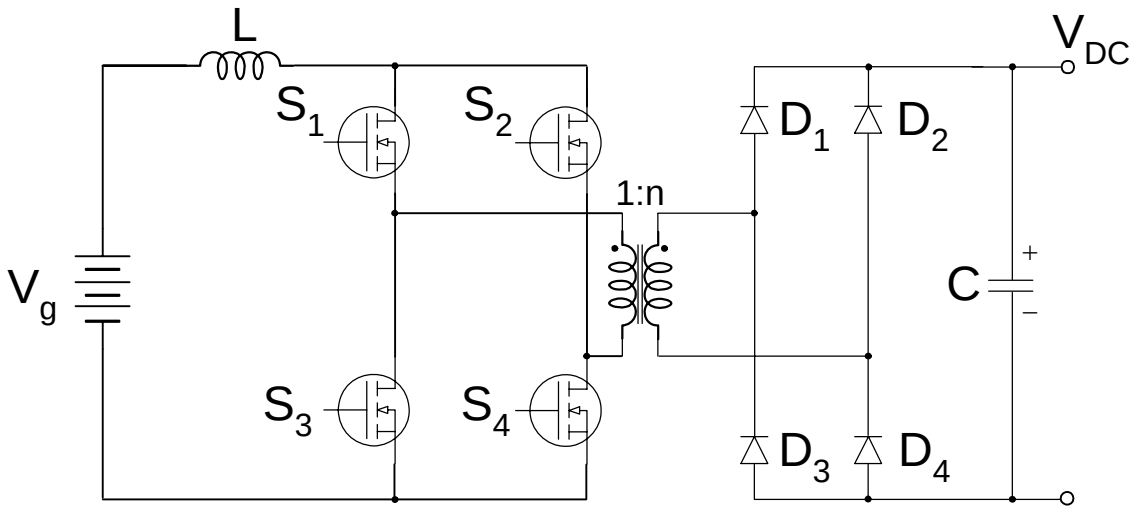
Sum of Instantaneous Output Currents of Each Phase is Constant

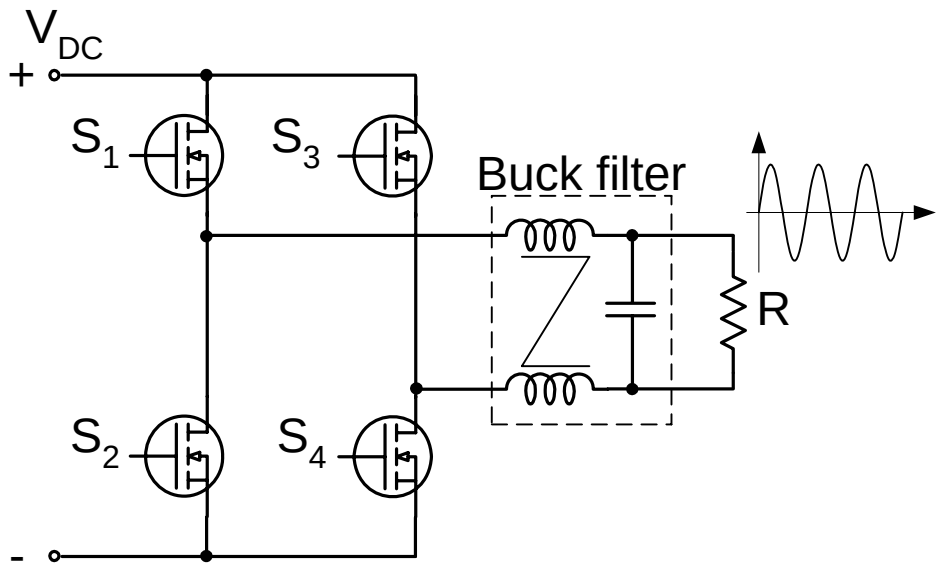


DC-AC

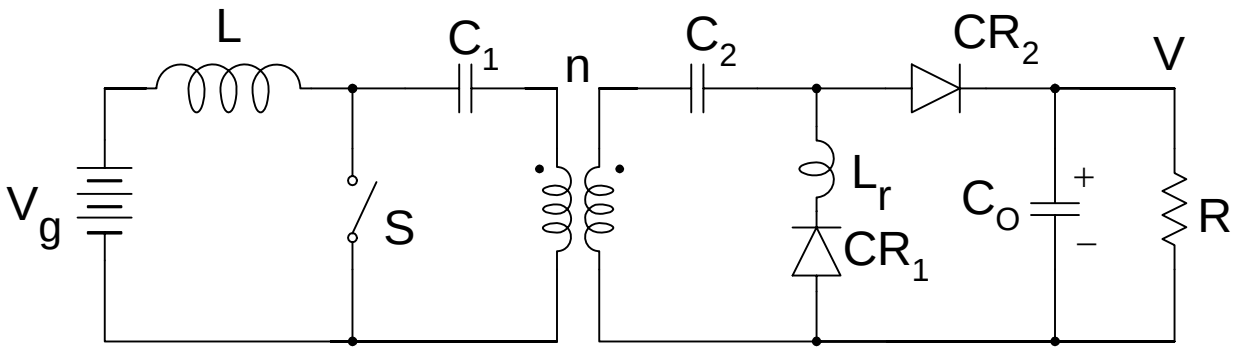
Inverter Comparison

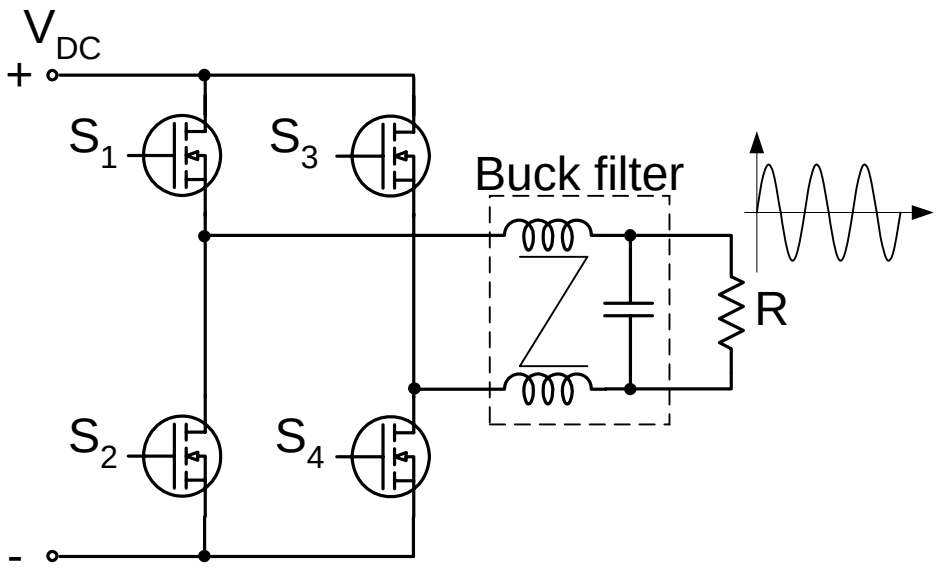
DC-AC Inverter with Full-Bridge Boost Converter





DC-AC Inverter with Three switch-boost Converter





Comparison Table

Type of Converter	Ćuk-boost Converter	Full-bridge Converter
Switching Method	HYBRID	Square-wave
Number of switches	3	8
Transistors	1	4
Diodes	2	4
Control	Simple	Complex
Magnetics pieces	1	2
Power Losses	2.5%	6.5%
Efficiency	>97.5%	94%

Hybrid-Switching Converters

1. DC-DC converters with high-frequency isolation and 3 switches only

2. Single-stage AC-DC conversion with PFC and high-frequency isolation

3. Single-Stage, Three-Phase AC-DC Rectification with high-frequency isolation

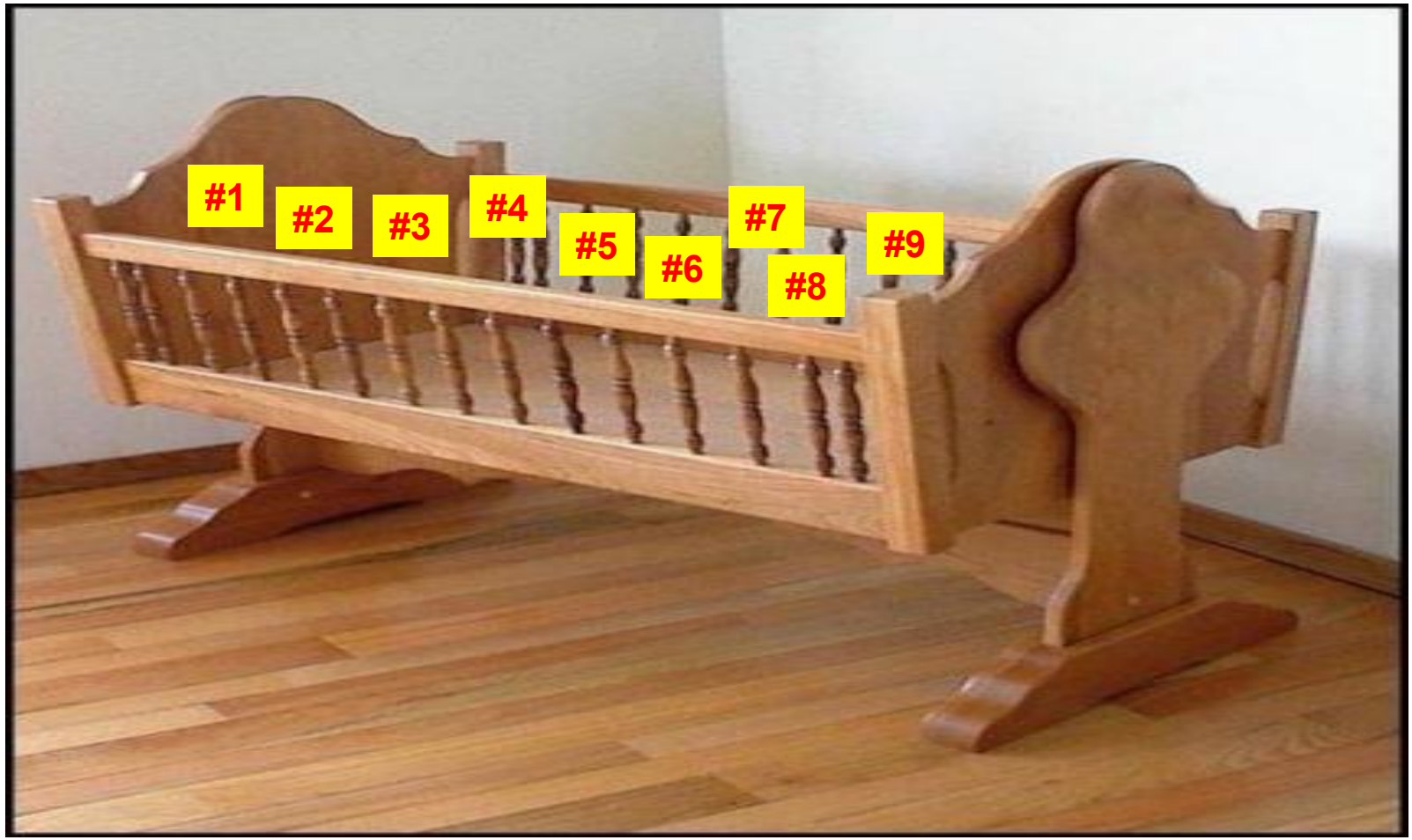
4. Single-stage DC-AC inversion with high-frequency isolation

5. Duty ratio control and high efficiency

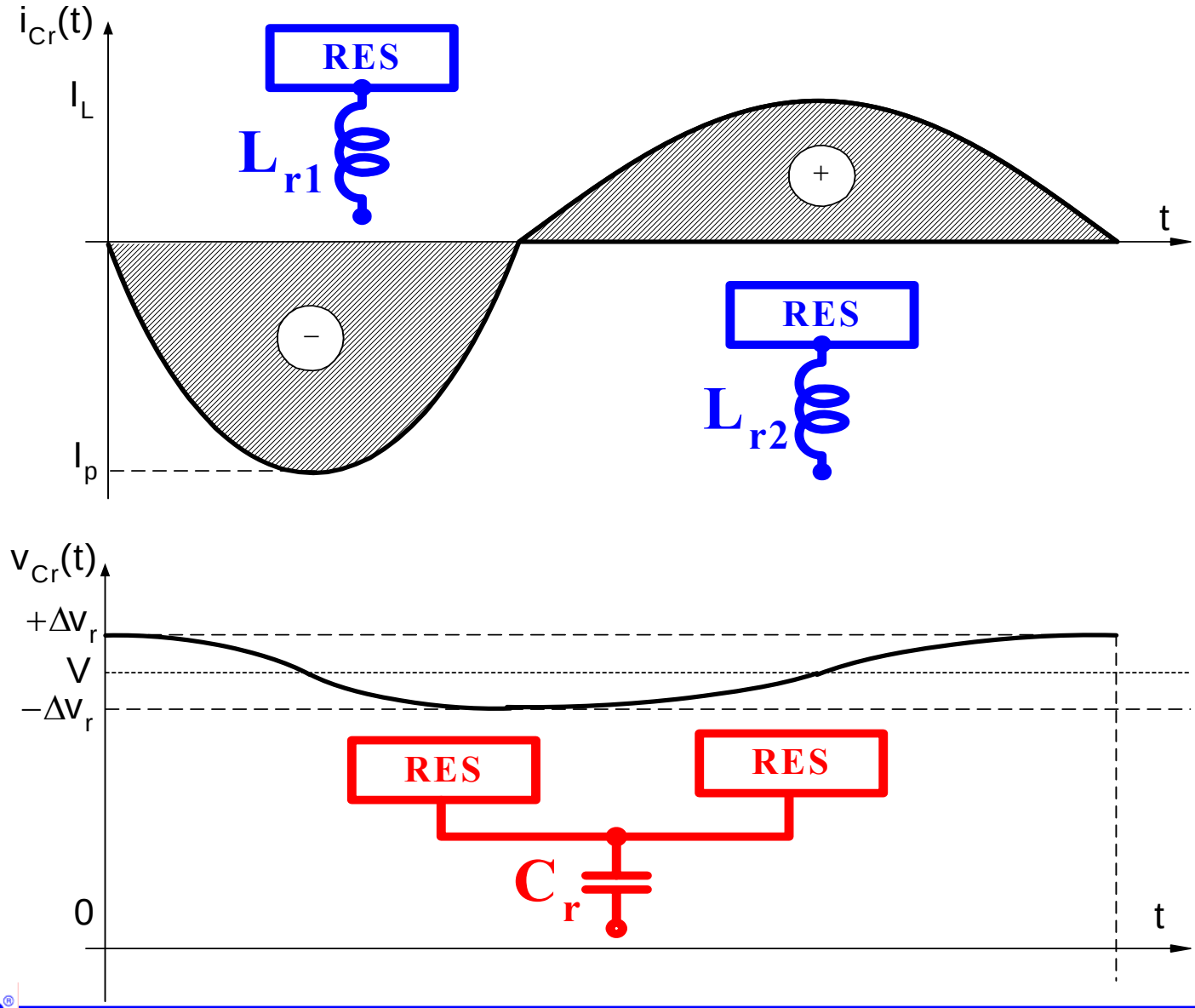
New Storageless-Switching Method for DC-DC Converter

Non-isolated and Isolated Converter Topologies

“Birth ” of Storageless Switching Method and Related Converter Topologies



Storageless Switching Method



Storageless-Switching Method:

1. Two separate resonant inductors define two independent resonances:
   a) during ON-time interval
   b) during OFF-time interval

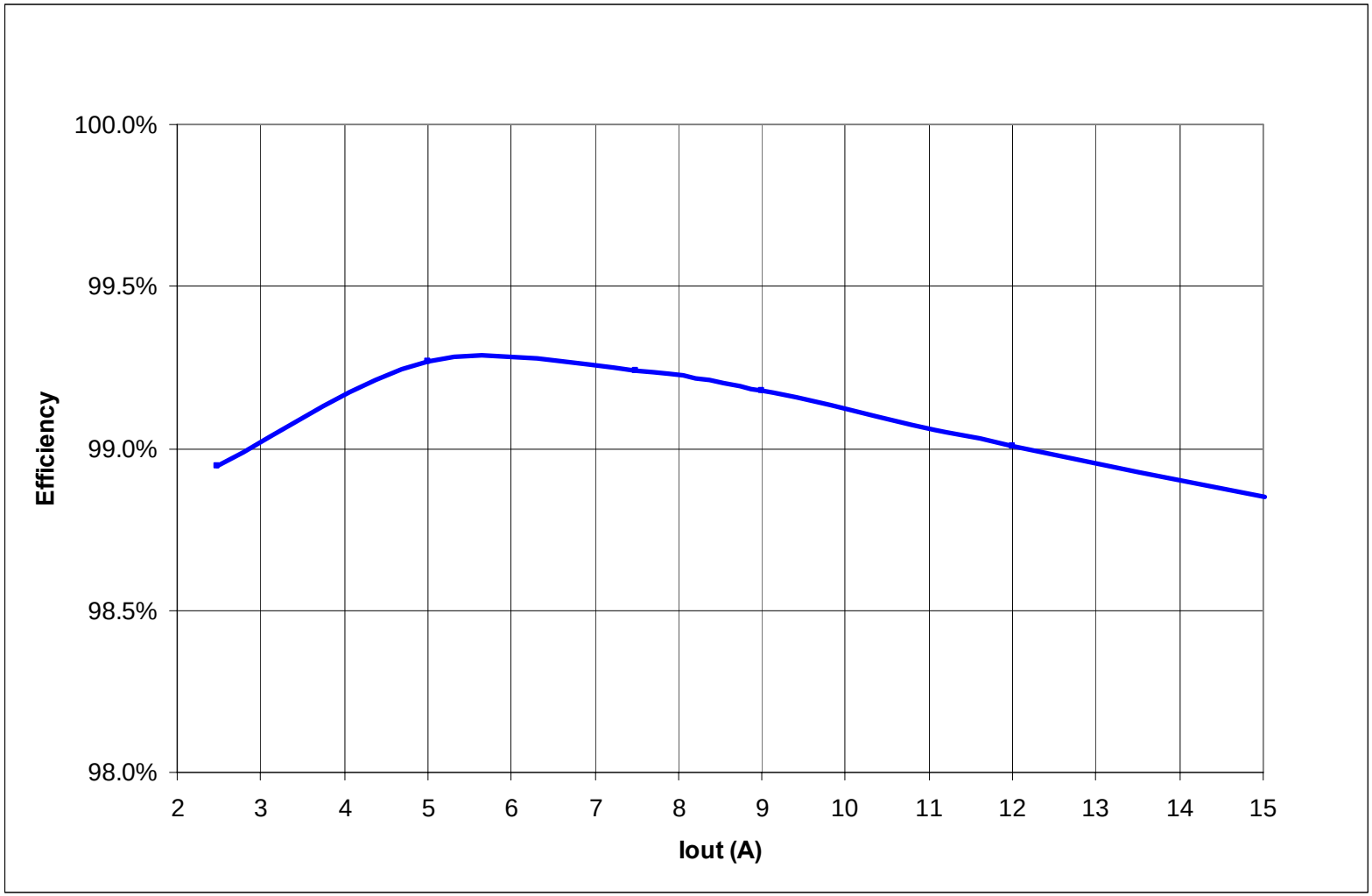
2. Common resonant capacitor

3. Duty ratio control of output voltage

Power Stage of 750W, 48V Prototype*

*US and foreign patents pending

Efficiency of 750W, 100V to 48V Converter

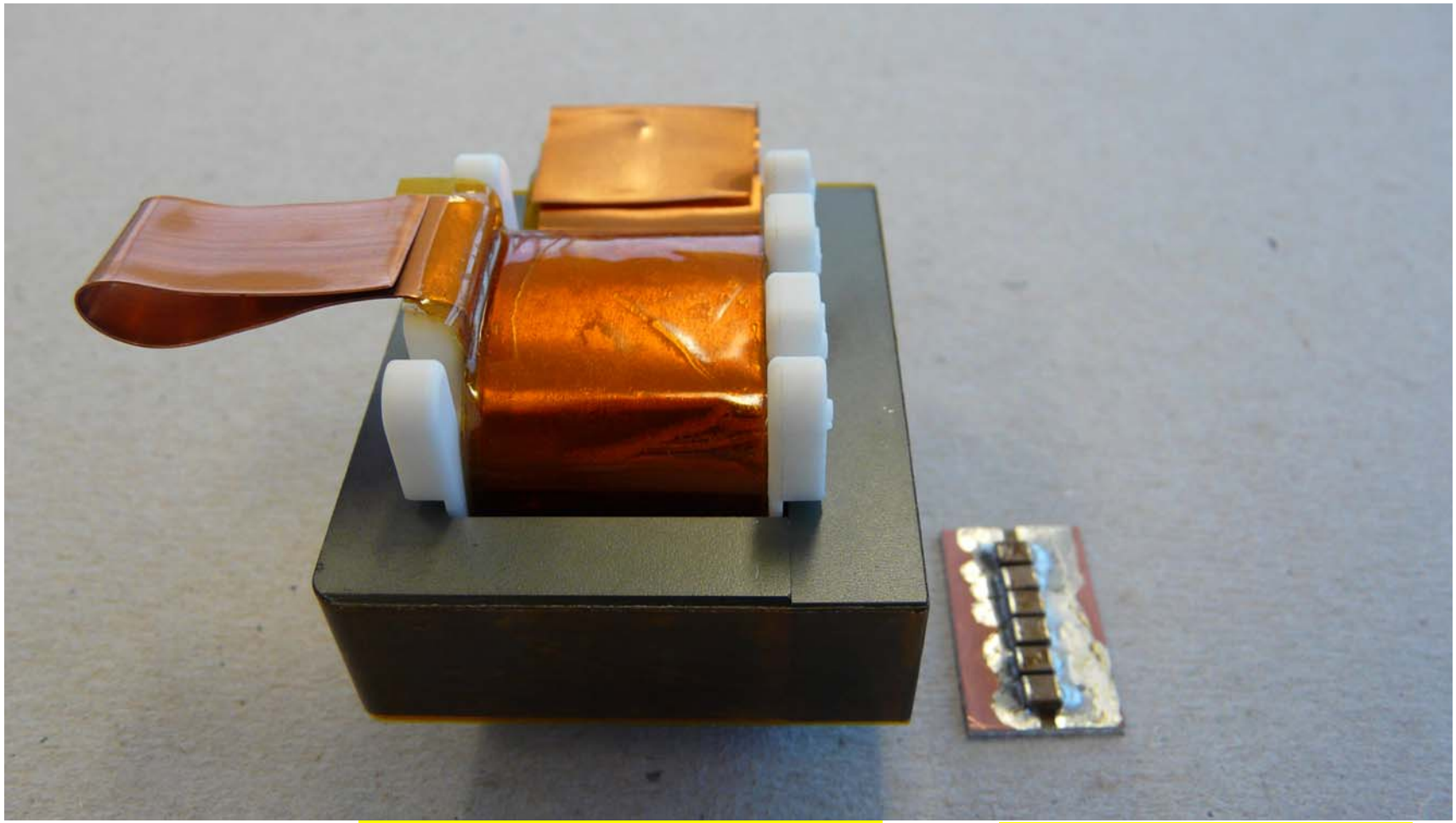


750W, 100V to 48V Converter
Energy Storage and Transfer

Inductive Only
Buck

Resonant
Storageless

750W, 48V, 16A Energy Storage



Inductive

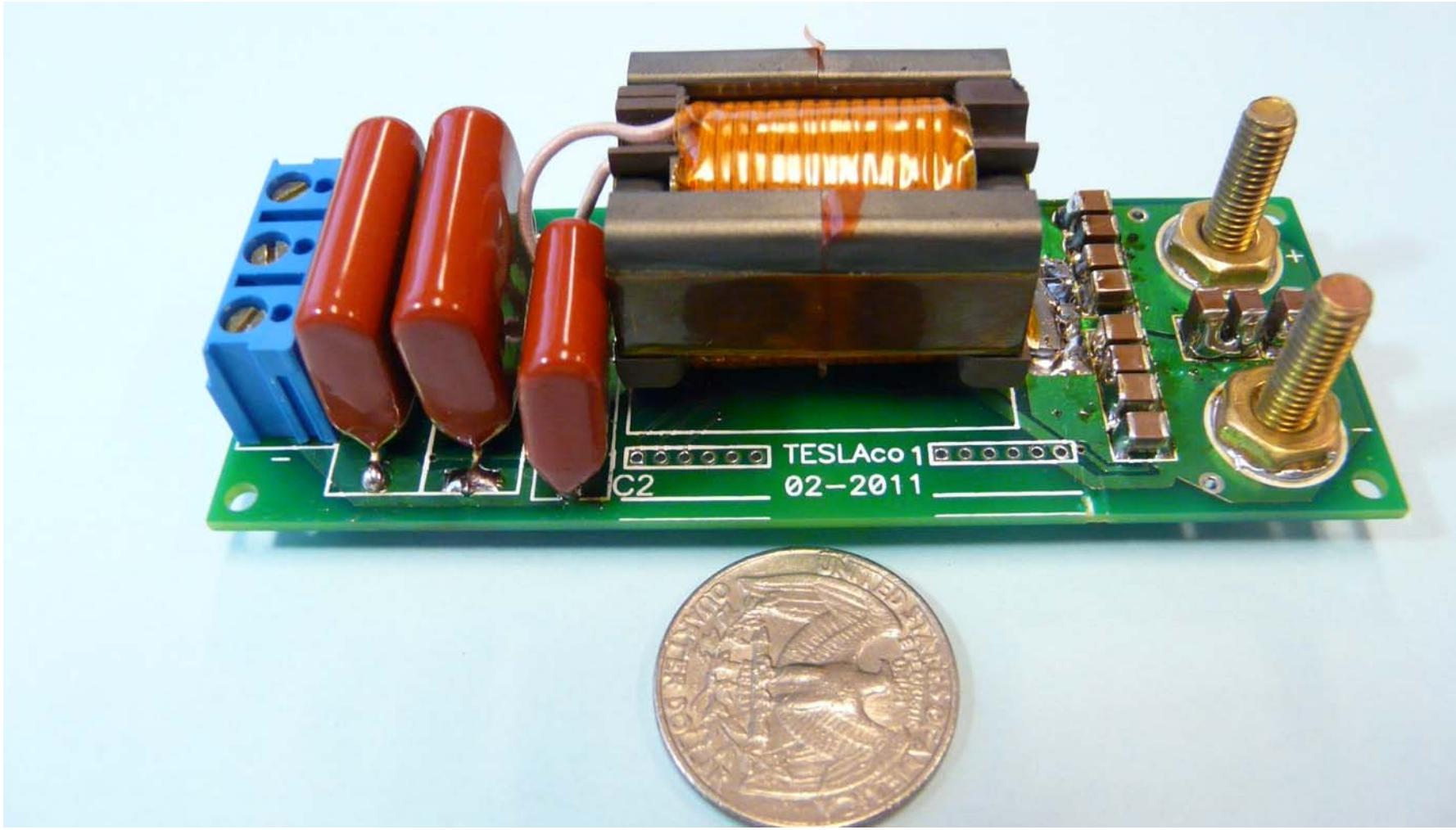
Capacitive

750W, 100V to 48V Converter
Energy Storage and Transfer

Inductive Only
Buck

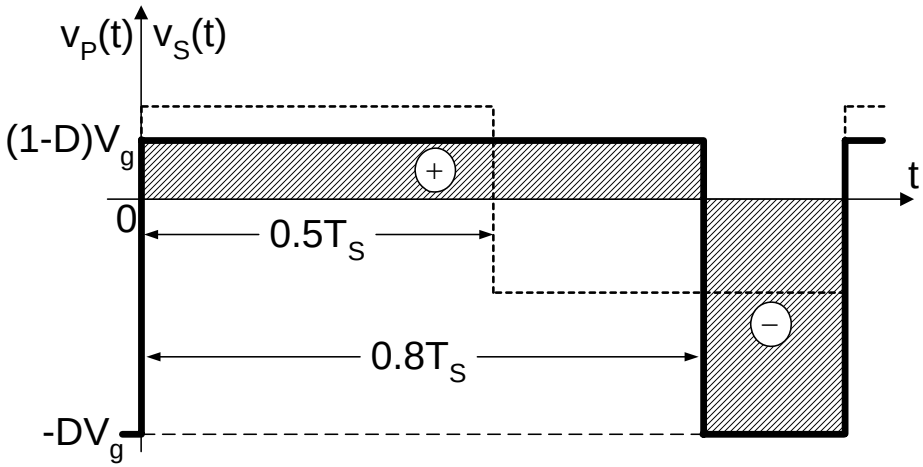
Resonant
Storageless

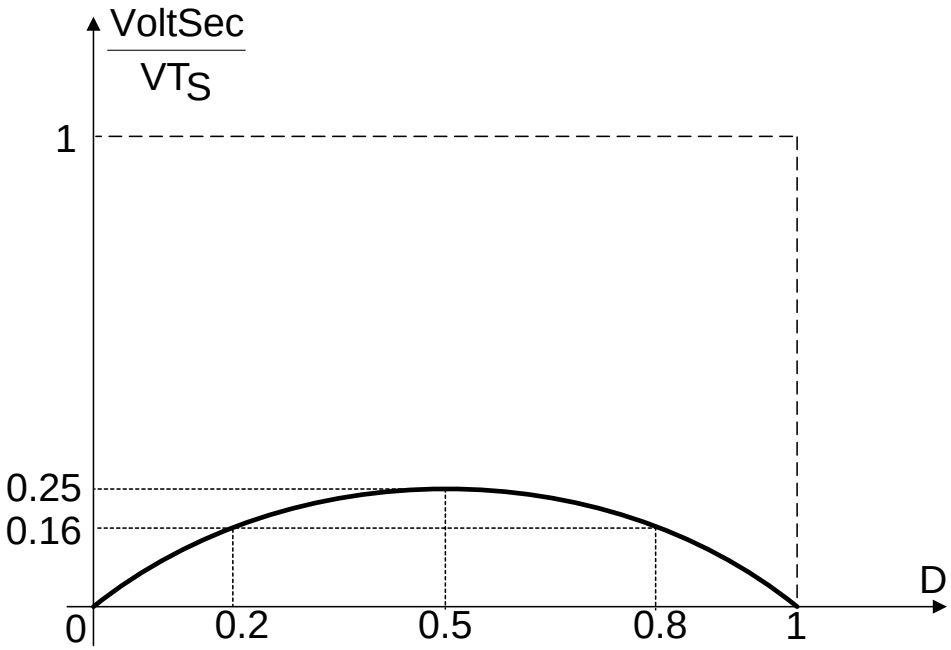
Isolated Storageless Converter*



*US and foreign patents pending

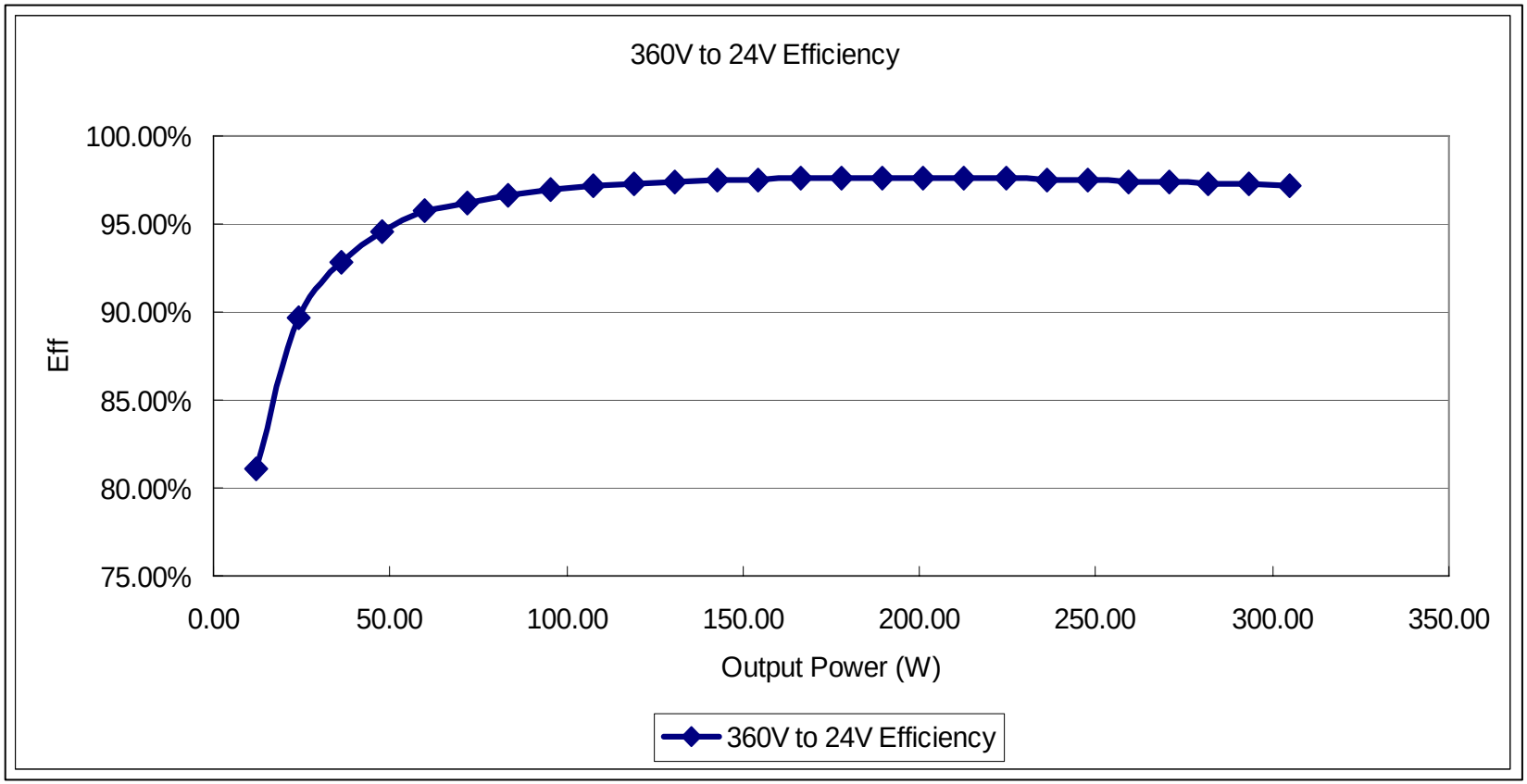
Storageless Transformer Flux



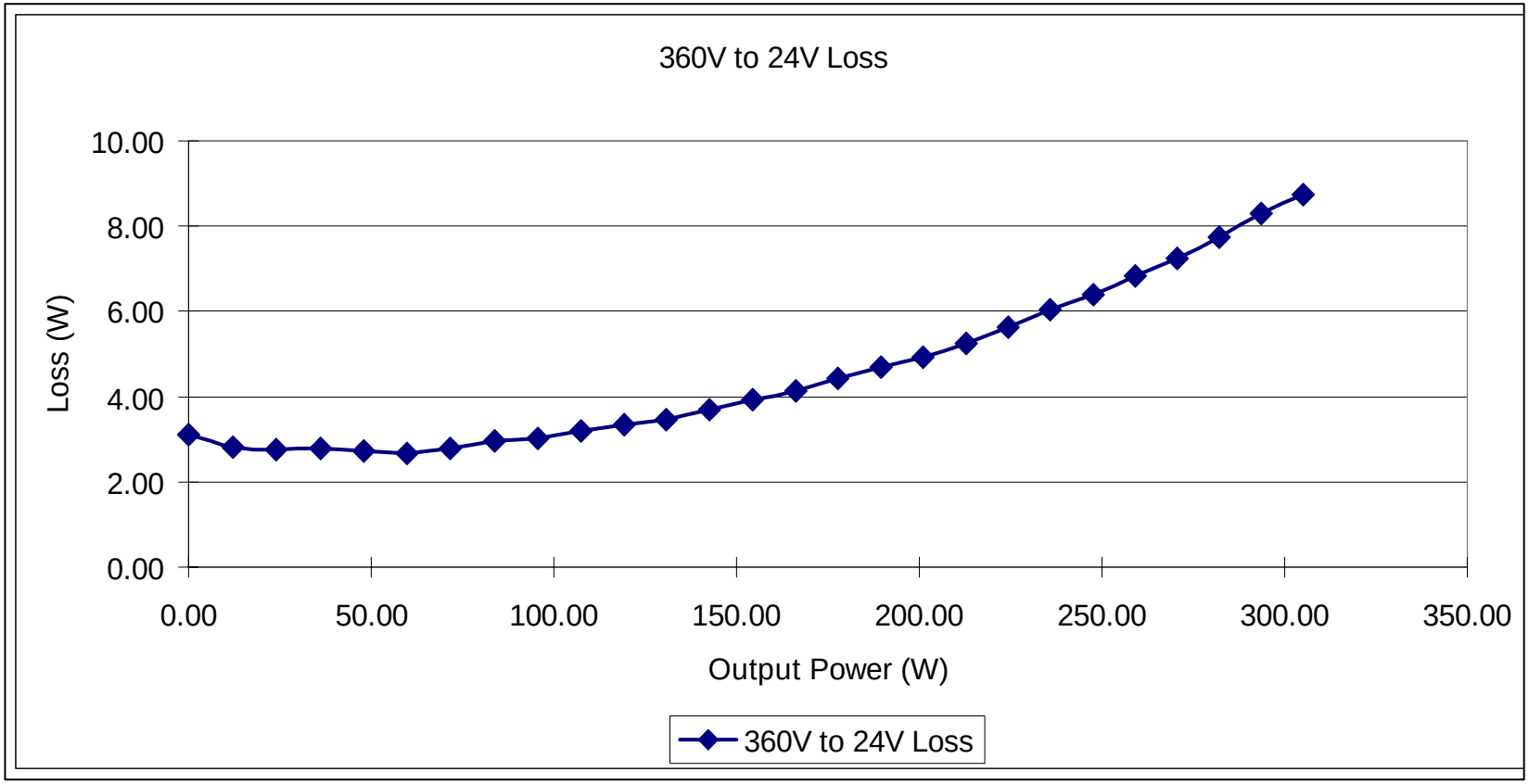


Efficiency of Isolated Storageless Converter

98.2% efficiency



Losses of Isolated Storageless Converter



Storageless-switching Converters

1. DC-DC non-isolated converters with efficiency over 99% and 10 times reduction of size

2. DC-DC Isolated converters with efficiency over 98%, 4 times size reduction and minimum voltage stresses of the switches

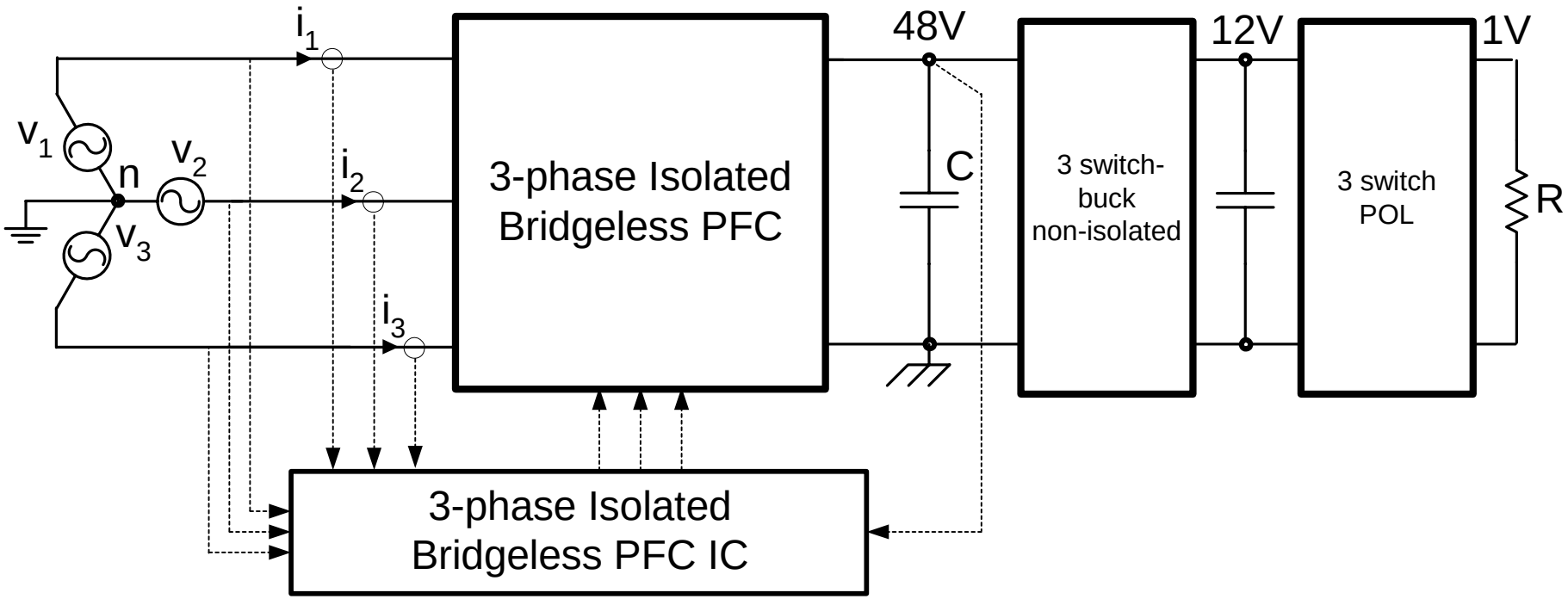
3. Duty ratio control

Applications Summary

- Wide range of applications:
- Computer servers
- Battery chargers
- Desktop computers
- AC Adapters, projectors, etc.
- Solar photovoltaic conversion

Green Dream Power Technology™

Efficiency	98%	99%	97%

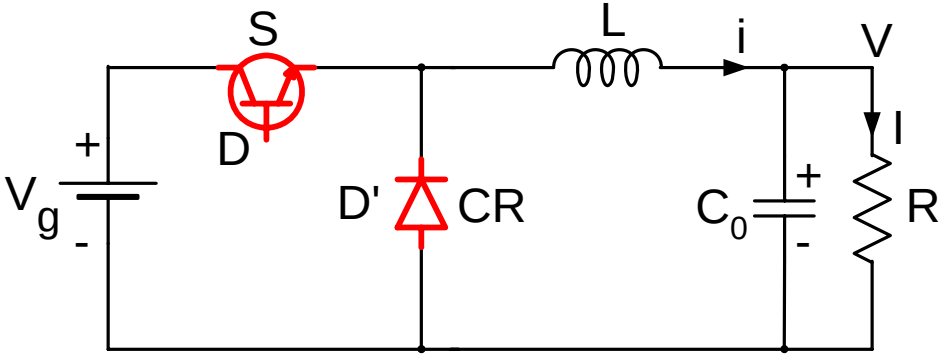


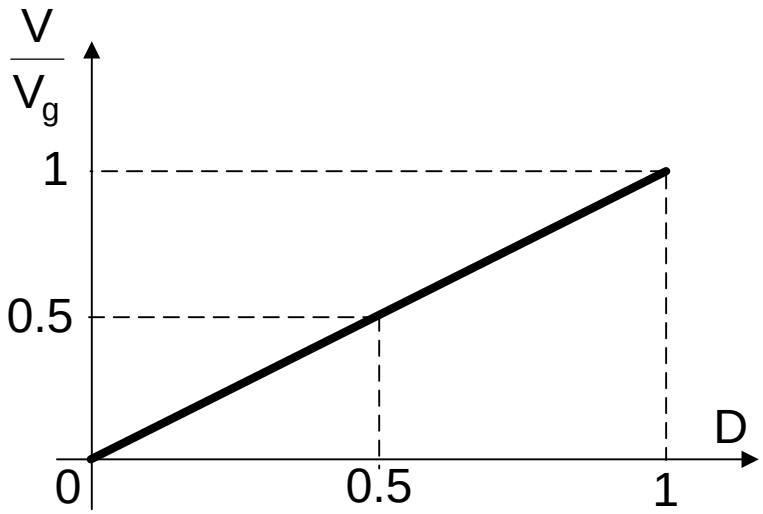
Switching method	Hybrid	Storageless	POL

Appendix

Hybrid-Switching Step-down Converter 48V to 1V nonisolated

Two-switch Buck Converter





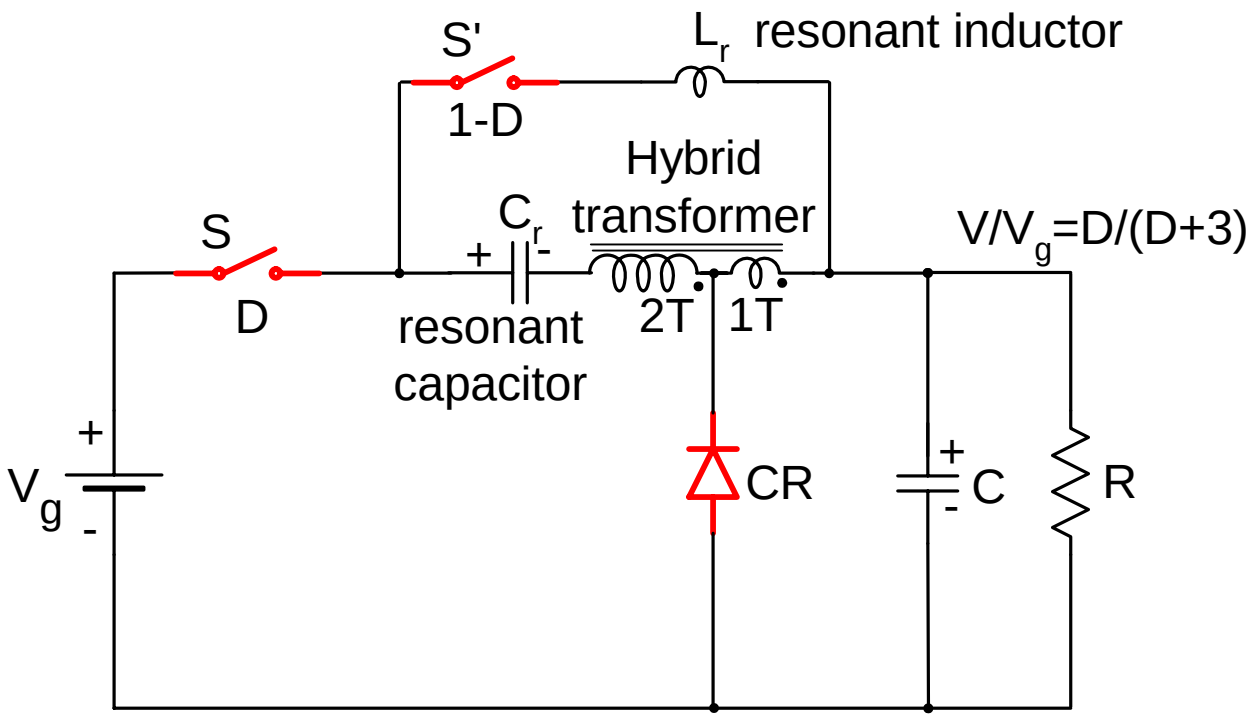
V_g=12V **V=6V at D=0.5**

Switches 25V rating

Could Converter with More Switches be More Efficient and at Lower Cost?

Alternative to 2 Switch Buck Converter

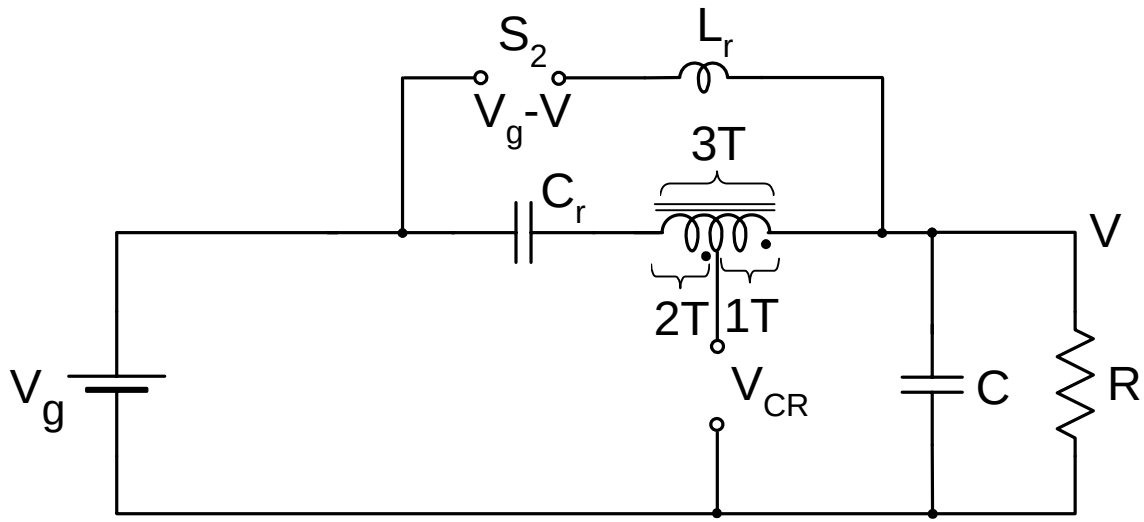
New Converter with 3 Switches*



Three Switches: Two Transistors and Diode

*US Patent No. 7,915,874

Voltage Stress on Diode

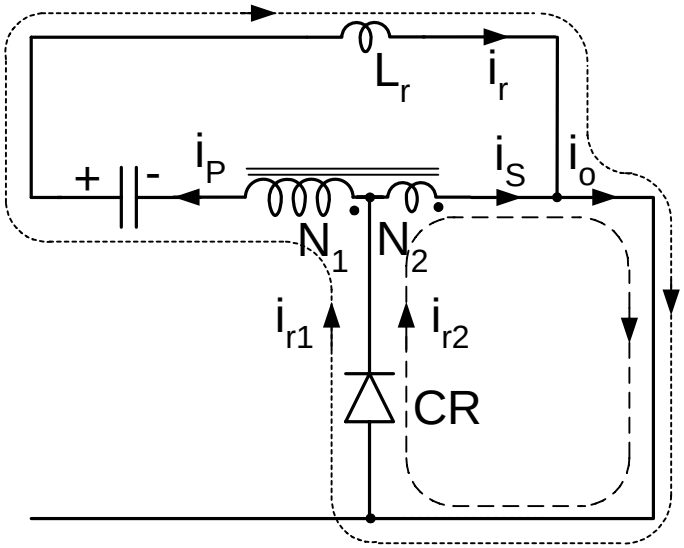


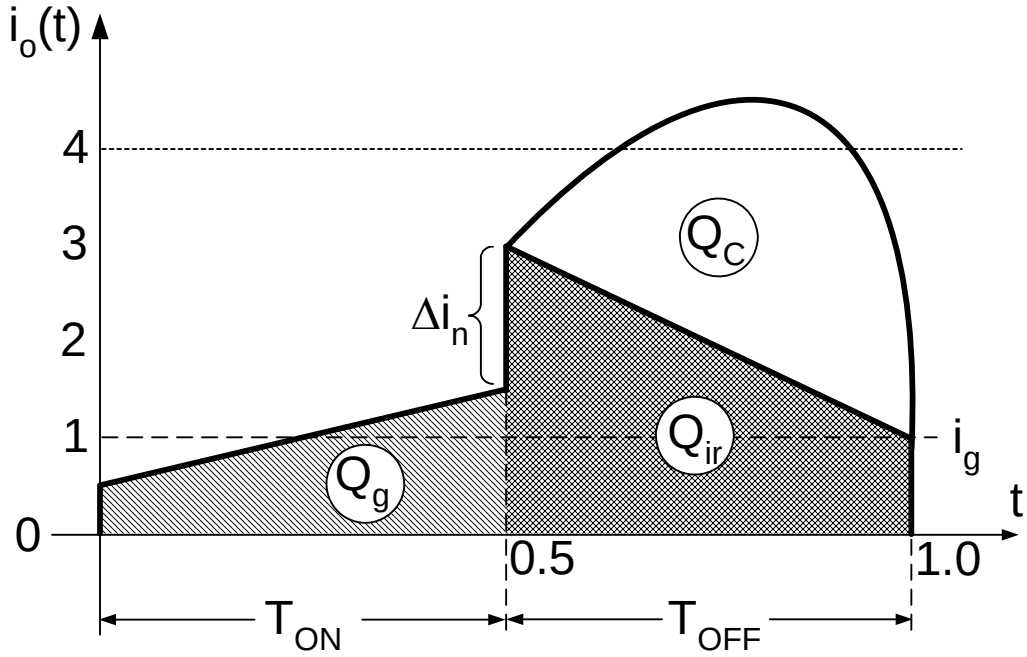
Diode Blocking Voltage $V_{CR}<V_g/3=4V$

Diode 5V rating

Silicon needed 20% or less than for Synchronous Buck Converter

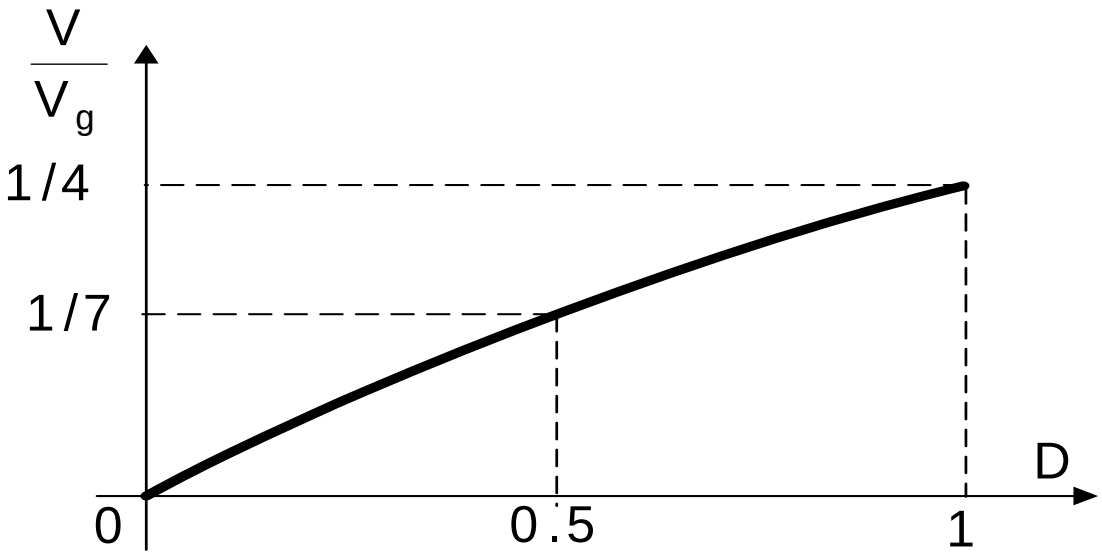
Hybrid Transformer and Its Current Multiplication





$I_r=I_L/5$ $I_L=30A$ $I_{r(cap)}=6A$ (2 chip capacitors in parallel)

Large Step-down at D=0.5



$V/V_g=D/(D+3)=1/7$

Vg=12V V=1.7V for D=0.5