

Power electronics

Slobodan Cuk came to Caltech in 1974 and obtained his PhD degree in Power Electronics in 1976. From 1977 until December, 1999 he was at the California Institute of Technology where he conducted research and taught courses in Power Electronics and Fundamentals of Energy Processing. During his 23 years at Caltech, more than 35 students obtained Ph.D. degree in Power Electronics under his guidance. From 2000 until present, Dr. Cuk continued his research contributions through TESLAcO, the company he founded. Dr. Cuk is Fellow of IEEE and is the inventor of numerous switching converter circuits such as the Cuk converter, the TESLAcO converter and many others.

Dr. Cuk is also the originator of the State-Space Averaging Method and more recently new switching methods: Hybrid Switching and Storageless Switching methods, which resulted in a number of ultra efficient, very compact and low cost switching converters for solar inverters, AC-DC battery chargers, data center power supplies and many other Power Electronics applications.

USC *Power Research* Workshop:

Power Electronics

Dr. Slobodan Čuk

November 18, 2011

What is in the name:

PCSC '70 and PCSC'71

Power Conditioning Specialists

PPESC'72

Power Processing and Electronics

PESC'73

Power Electronics Specialists

Electrical Engineering at Caltech

Sept. 2010: celebration of 100 years of Electrical Engineering at Caltech

1910-1956: High Voltage Laboratory of Prof. Sorensen

1970- 1999 Power Electronics Laboratory (Profs. Middlebrook and Cuk)

Power Electronics at Caltech :

**Started in 1970 by Prof. Middlebrook
as second in nation after Duke 1968**

**Both academic courses and research
program on a PhD level**

PCSC'71 at Jet Propulsion Laboratory

PESC'73 at Caltech

Power Electronics Group (PEG)

From 1970 – 1999

36 PhD students

**1998: 11 PhD in Electrical Engineering out of
which 5 in Power Electronics**

Prof. Middlebrook retired in 1998

Prof. Cuk semi-retired in 1999

First Sponsors 1974 and on

NASA (subcontract from TRW)

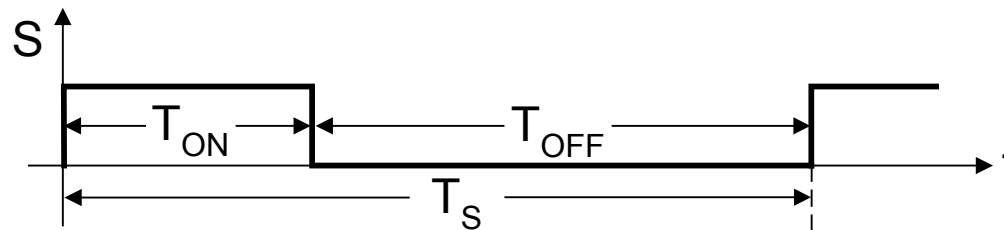
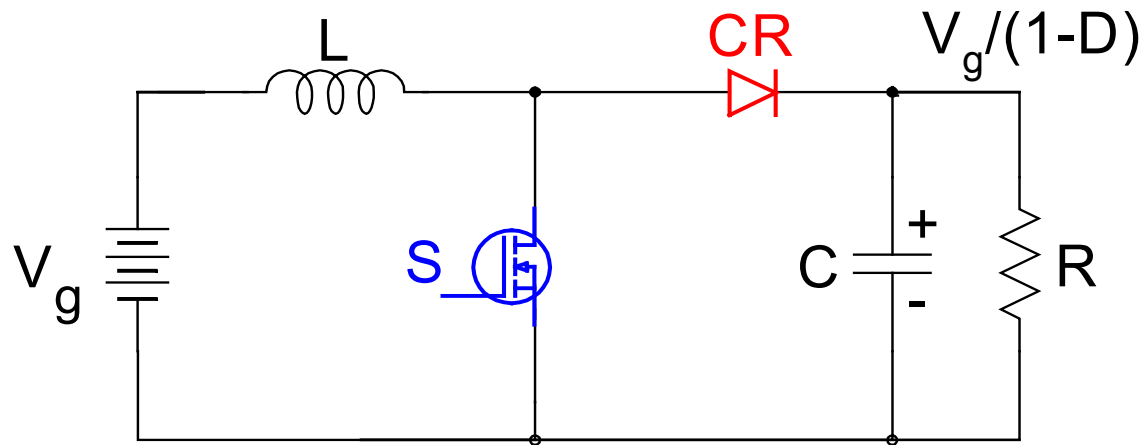
**NOSC (Naval Ocean System Center
(San Diego)**

ONR- Office of Naval Research

IBM

Other companies

Boost Converter



1973: Prof. Middlebrook sent me an article with boost converter

Power Electronics-Emerging from Limbo 1973 keynote by W.E. Newell, Westinghouse

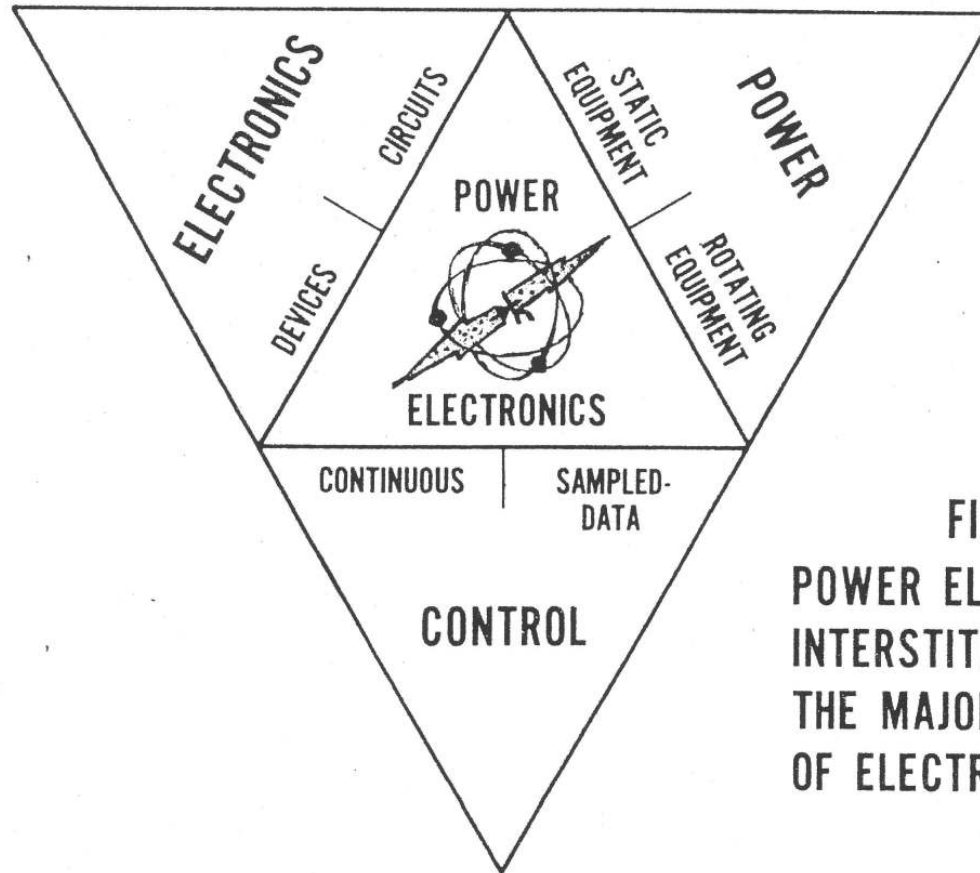


FIG. 1
POWER ELECTRONICS...
INTERSTITIAL TO ALL OF
THE MAJOR DISCIPLINES
OF ELECTRICAL ENGINEERING

35 Years Anniversary

State-space Averaging

***Slobodan Ćuk; “MODELING, ANALYSIS, AND DESIGN OF SWITCHING CONVERTERS”**

Ph.D. Thesis, Caltech, November 1976

***R.D.Middlebrook and Slobodan Ćuk; “A general Unified Approach to Modeling Switching-Converter Power Stages, IEEE PESC, 1976**

35 Years Anniversary

State-space Averaging

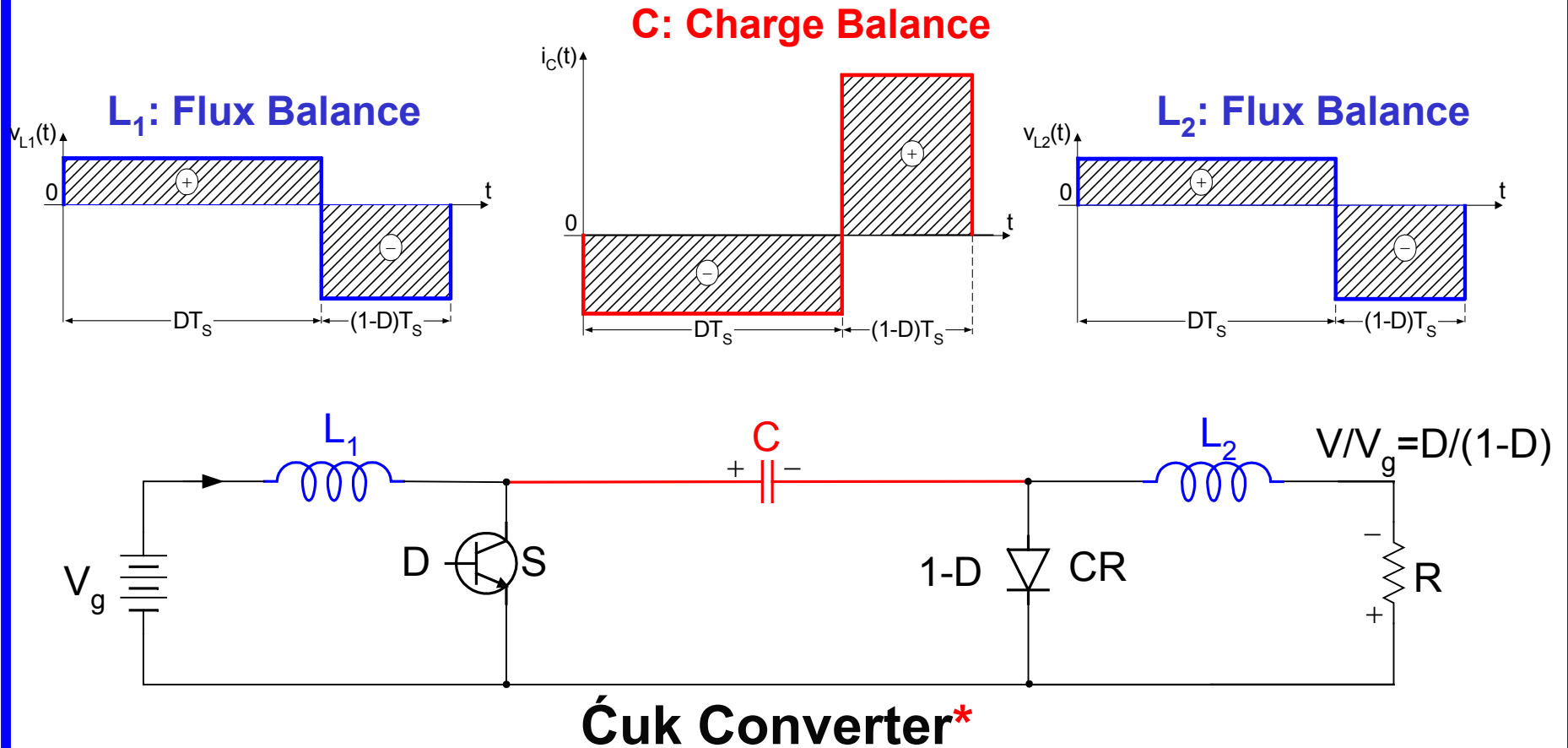
***Slobodan Ćuk; “MODELING, ANALYSIS, AND DESIGN OF SWITCHING CONVERTERS”**

Ph.D. Thesis, Caltech, November 1976

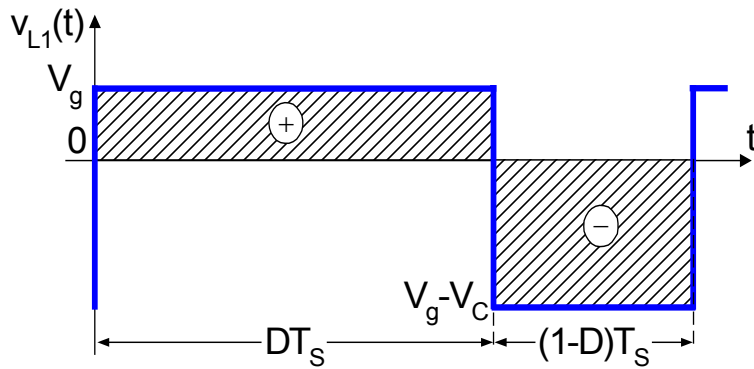
***R.D.Middlebrook and Slobodan Ćuk; “A general Unified Approach to Modeling Switching-Converter Power Stages, IEEE PESC, 1976**

The State-space Averaging Uses Different Criteria

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

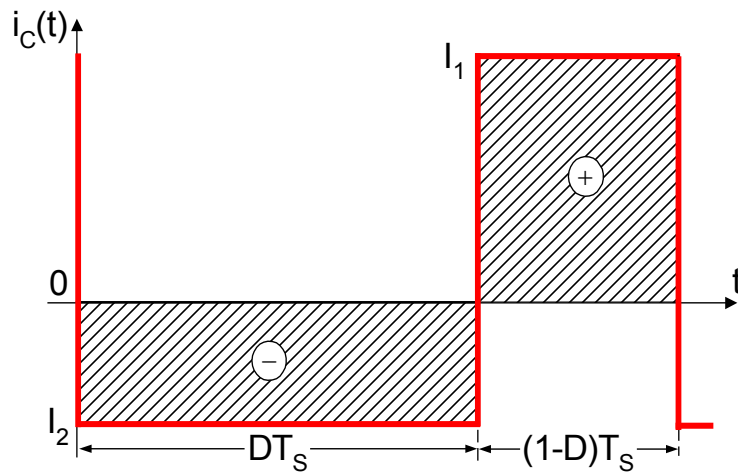


*US Patents: 4,184,197; 4,257,087; 4,274,133



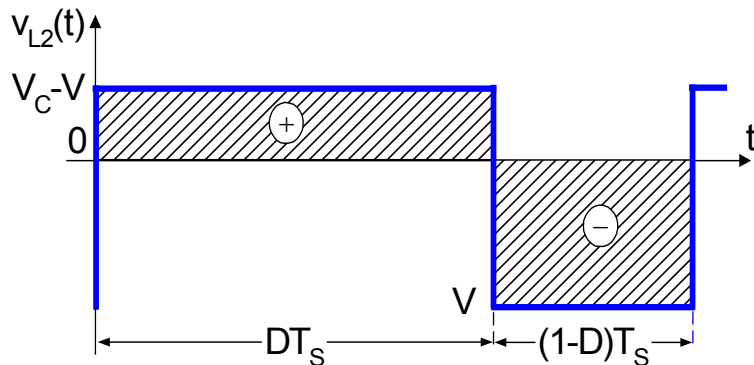
Flux Balance on L_1

$$v_{L1} = DV_g + (1-D)(V_g - V_C)$$



Charge Balance on C_r

$$i_c = D(-I_2) + (1-D)(I_1)$$



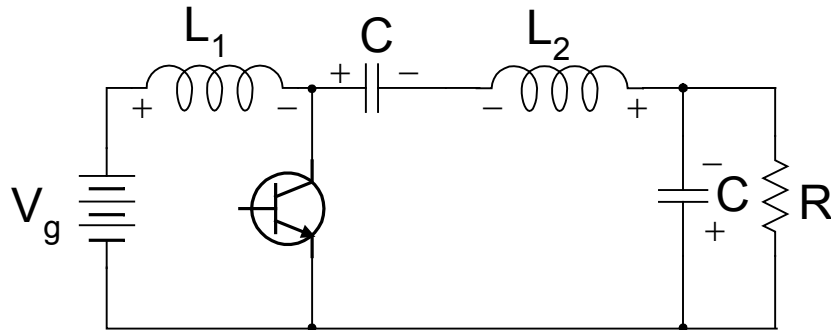
Flux Balance on L_2

$$v_{L2} = D(V_C - V) + (1-D)(-V)$$

$$\text{DC Solution: } v_{L1} = 0; \quad i_c = 0; \quad v_{L2} = 0$$

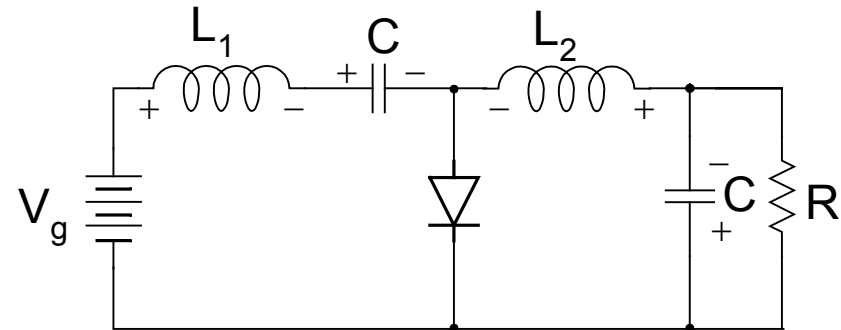
State-space Formulation of Flux and Charge Balances

ON-time Interval:



$$D \times \begin{cases} V_{L1} = V_g \\ i_C = -I_2 \\ V_{L2} = V_C - V \end{cases}$$

OFF-time Interval:



$$(1-D) \times \begin{cases} V_{L1} = V_g - V_C \\ i_C = I_1 \\ V_{L2} = -V \end{cases}$$

State-space Averaging DC Model:

1. Multiply equations for ON-time by D
2. Multiply equations for OFF-time by (1-D)
3. Add together and set $V_{L1}=0, I_C=0, V_{L2}=0$

Steady-State

$$\mathbf{A}\mathbf{X} + \mathbf{b}\mathbf{V}_g = \mathbf{0}$$

$$\mathbf{A} = \mathbf{D}\mathbf{A}_1 + \mathbf{D}'\mathbf{A}_2$$

$$\mathbf{b} = \mathbf{D}\mathbf{b}_1 + \mathbf{D}'\mathbf{b}_2$$

Dynamic (Small Signal AC) Response

$$\mathbf{v}_g = \mathbf{V}_g + \hat{\mathbf{v}}_g \quad ; \quad \mathbf{x} = \mathbf{X} + \hat{\mathbf{x}}$$

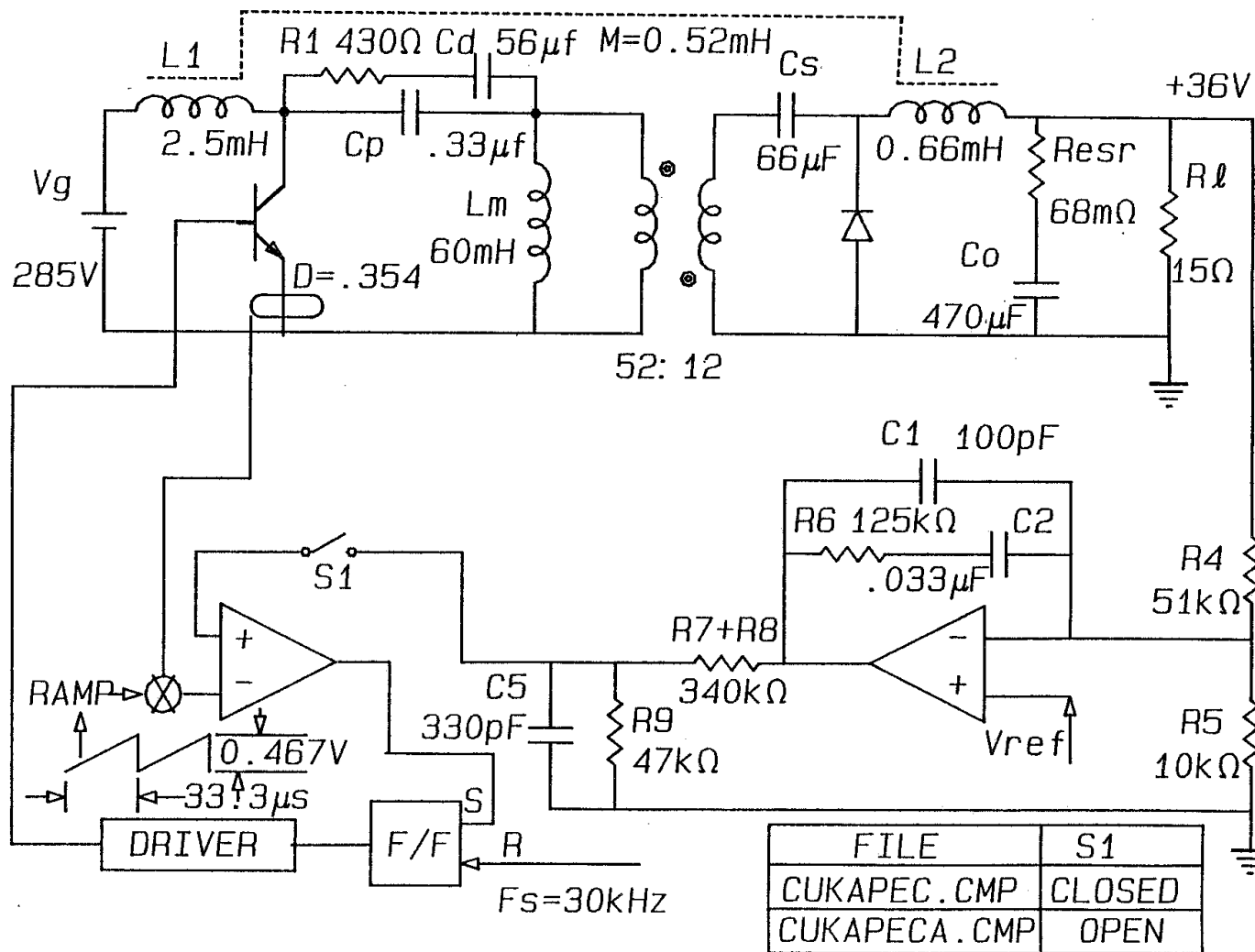
$$\mathbf{d} = \mathbf{D} + \hat{\mathbf{d}} \quad ; \quad \mathbf{d}' = \mathbf{D}' - \hat{\mathbf{d}}$$

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{b}\hat{\mathbf{v}}_g + \left[\left(\mathbf{A}_1 - \mathbf{A}_2 \right) \mathbf{X} + \left(\mathbf{b}_1 - \mathbf{b}_2 \right) \mathbf{V}_g \right] \hat{\mathbf{d}}$$

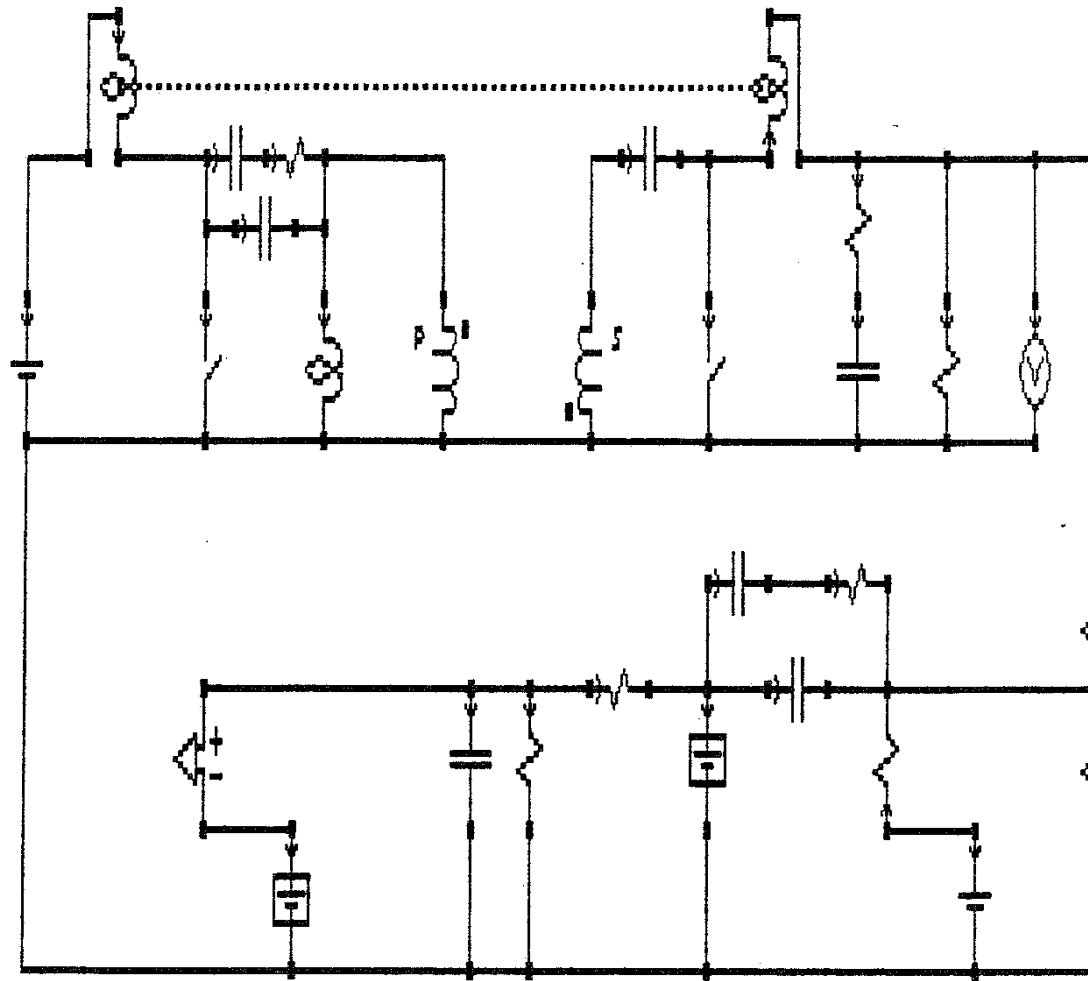
SCAMP

Switching
Converter
Analysis and
Measurement
Program

Coupled-Inductor Isolated Ćuk Converter



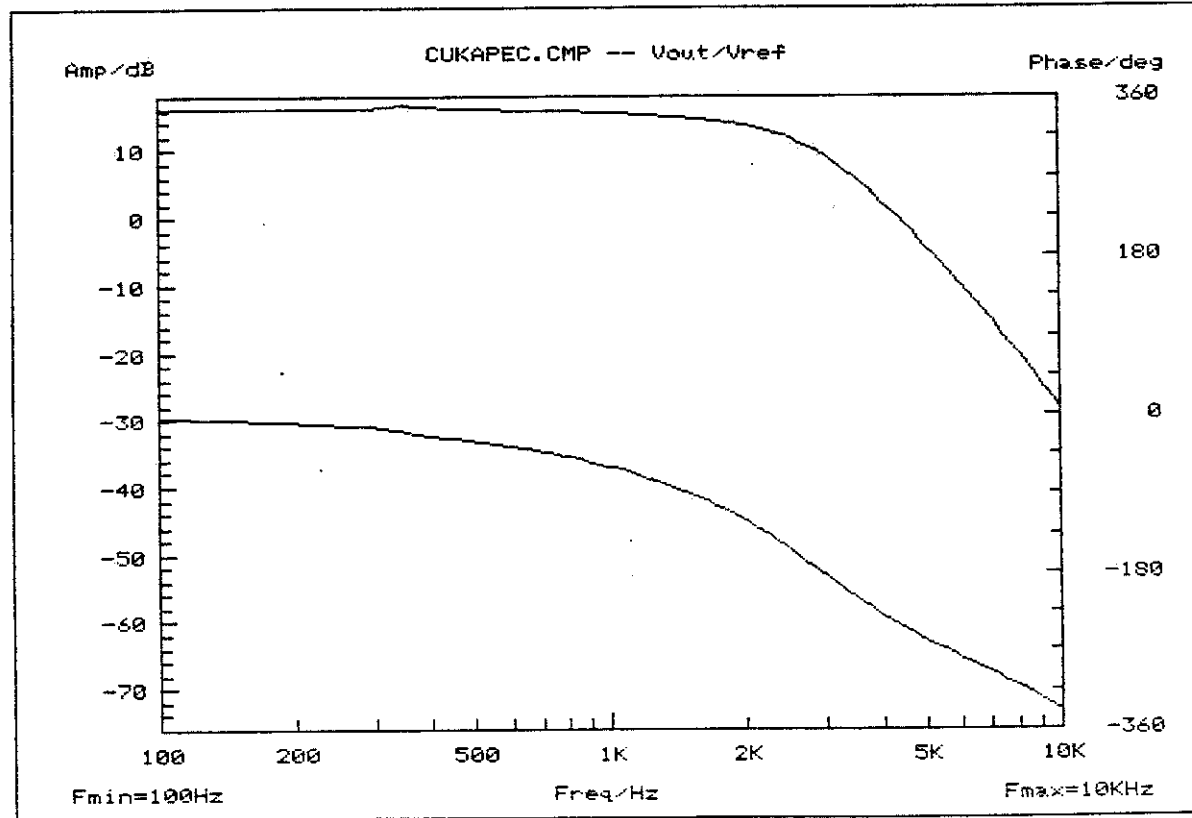
Manu Driven Graphics on First IBM-PC



CUKAPEC.CMP

From Paper at APEC Conference

Frequency Response – Loop Gain



Power Electronics Group exhibit at 1983 conference in San Diego



Question asked:

Can your SCAMP program do this:

Enter desired frequency plot then

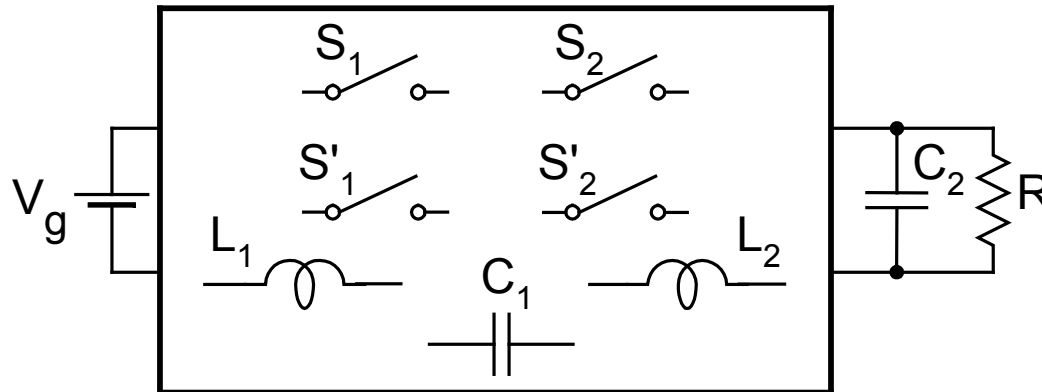
Draw the converter topology?

Related question:

Can you enter desired DC voltage gain such as $V/V_g = D \times D$ and:

DRAW ALL SUCH CONVERTERS:
Both known converters and
NEW (!!!) converter topologies?

Computer Generated Converters*



If Solution to:
 $AX + bVg = 0$
 exists, than:
 Valid DC-DC Converters:

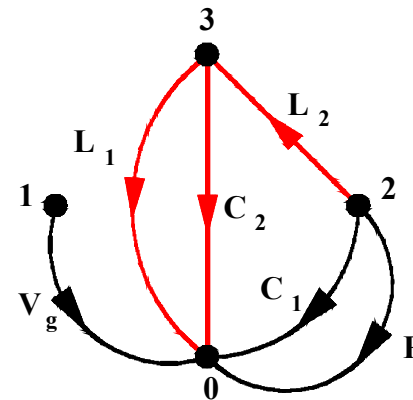
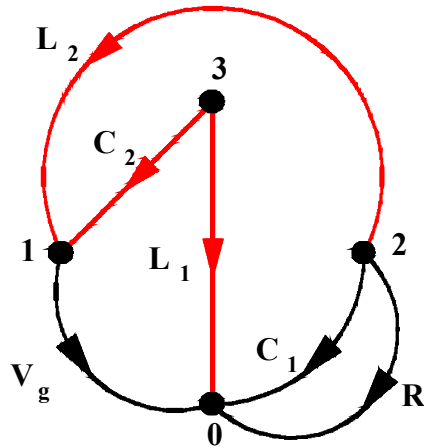
2 Inductors
 1 Capacitor
 2 States: ON&OFF } 1 million possibilities

Only 30 Working
 (Ćuk converter was there too !)

*Dragan Maksimovic, "Synthesis of PWM and Quasi-resonant DC-to-DC Power Converters", Ph.D. Thesis, January 12, 1989, Caltech, Pasadena

Enumeration via Incidence Matrices

AN EXAMPLE: (243, 146.2)



	V_g	C_1	C_2	L_1	L_2
0	-1	-1	0	-1	0
1	1	0	-1	0	-1
2	0	1	0	0	+1
3	0	0	1	1	0

\uparrow

T_1

E_1

H_1

	V_g	C_1	C_2	L_1	L_2
0	-1	-1	-1	-1	0
1	1	0	0	0	0
2	0	1	0	0	1
3	0	0	1	1	-1

\uparrow

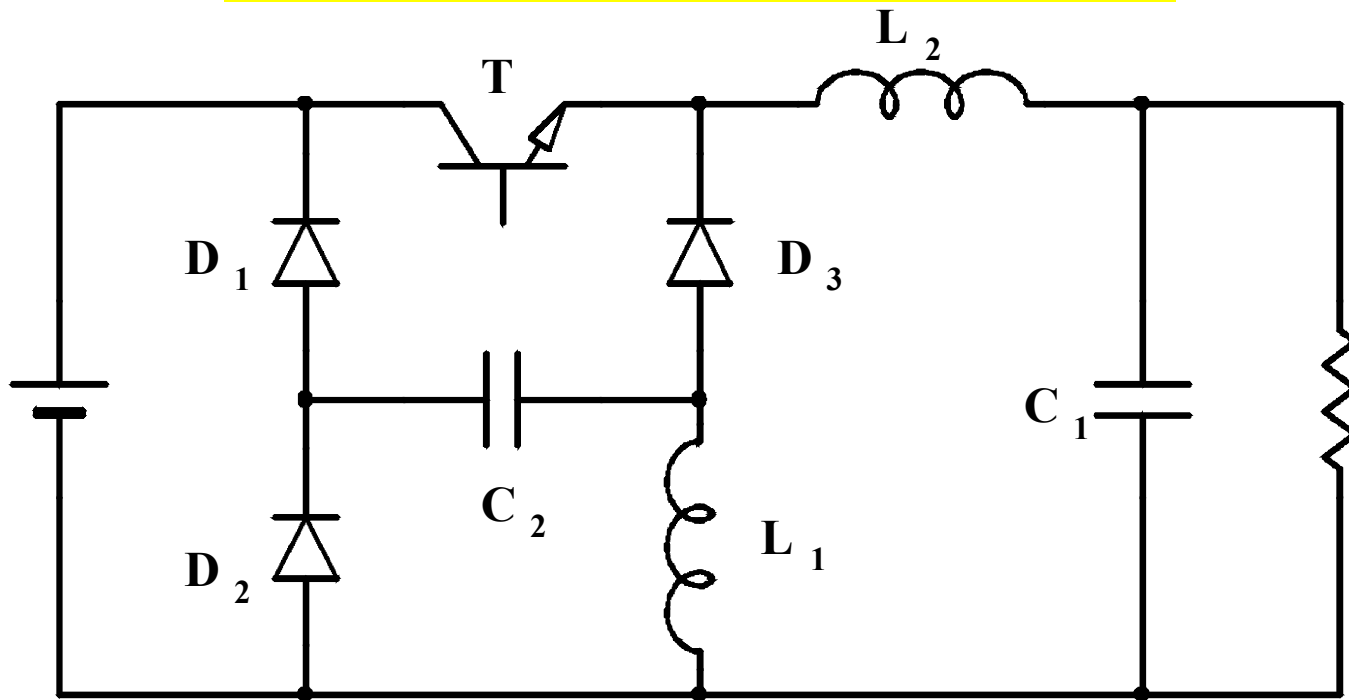
T_2

E_2

H_2

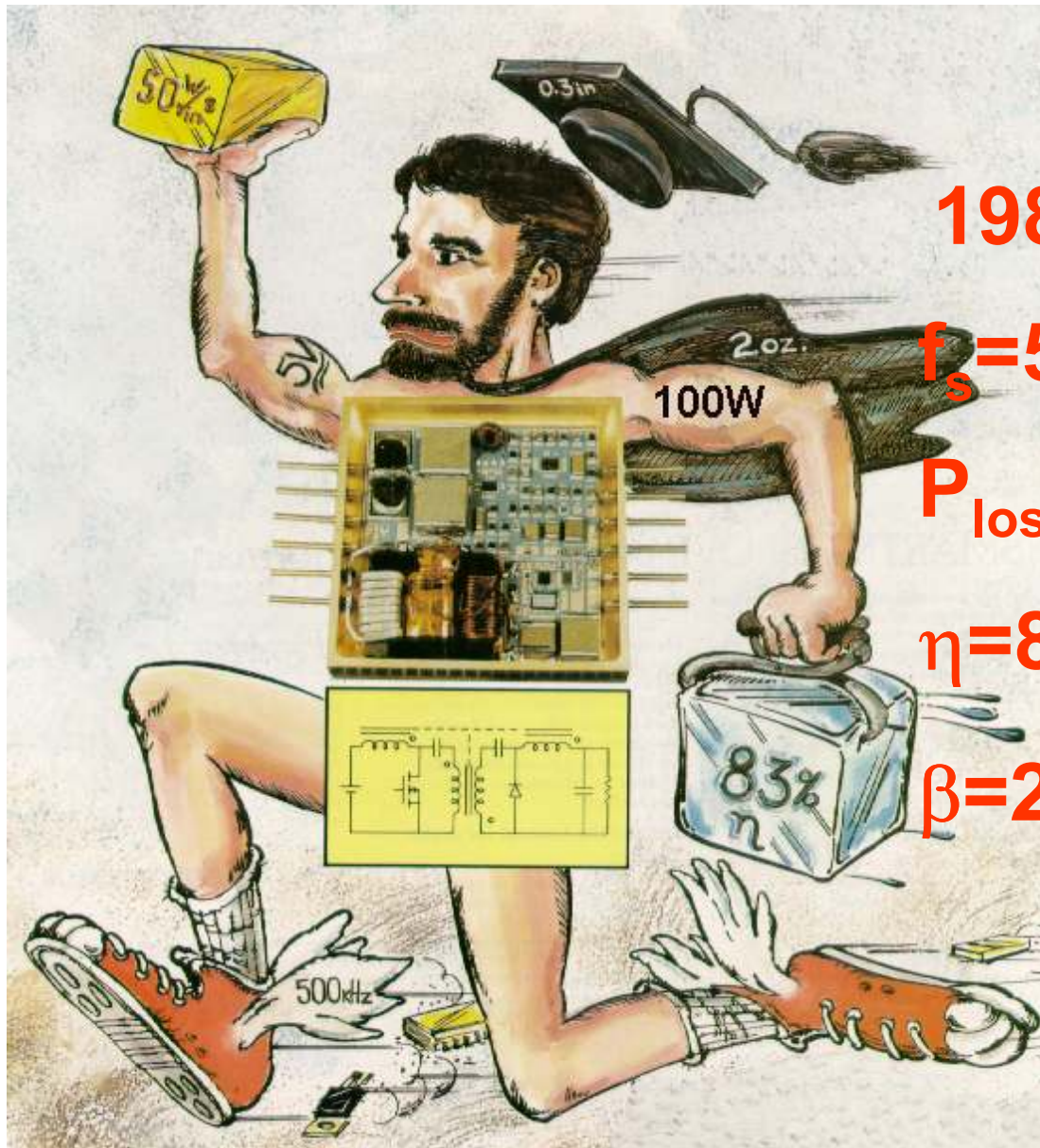
NEW CONVERTER

One Transistor, Three Diodes



$$M(D) = D^2$$
$$(243, 146.2)$$

Dr. Čuk's Power Technics 1988 cover



1988

$f_s = 500\text{kHz}$

$P_{\text{loss}} = 20.5\text{W}$

$\eta = 83\%$

$\beta = 20.5\%$

Power Electronics 117 class of 1998: TESLA temple prank



TESLAcO years: 1999- present

TESLAcO converter

NCT converter

Hybrid Switching Method

Storageless Switching Method

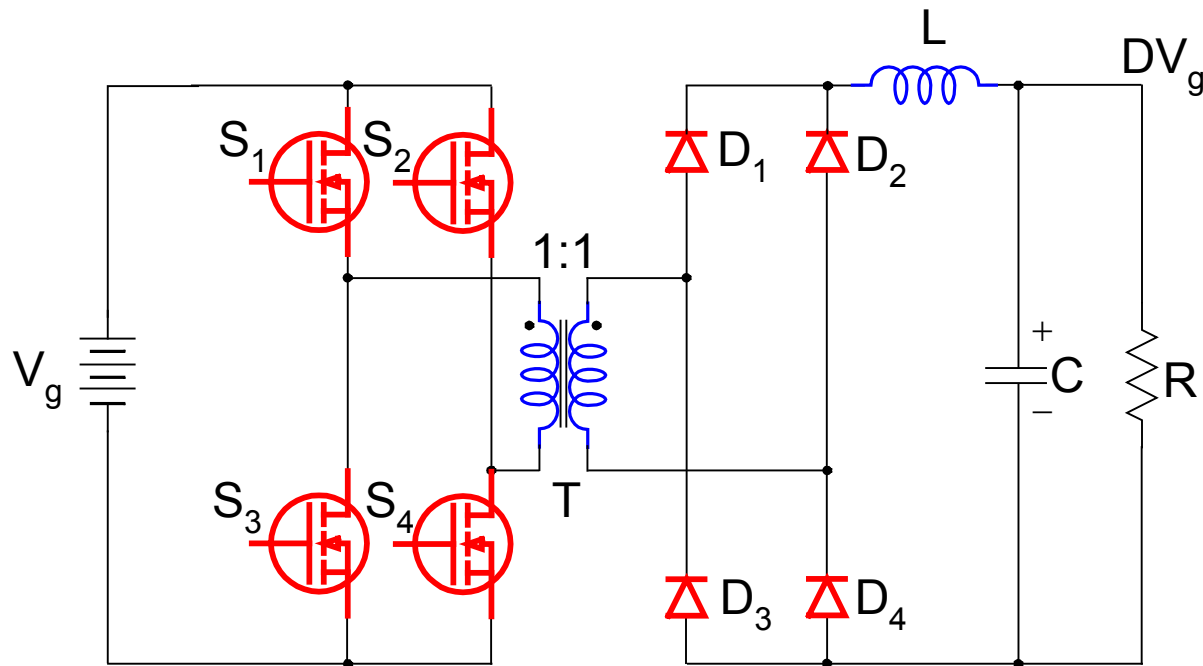
Bridgeless PFC converters

Single-stage converters

Solar inverters

Isolated Full-bridge Buck Converter

Two magnetic components



Total of 8 Switches

Square-wave Switching:

No 3 switches allowed

Eight needed for isolation

No capacitors

Hybrid-Switching Method:

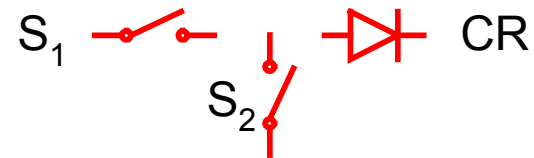
3 switches only

Resonant capacitor

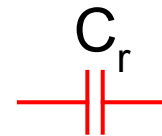
Resonant inductor

What about converters with 3 switches

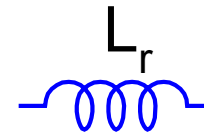
1. Three Switches



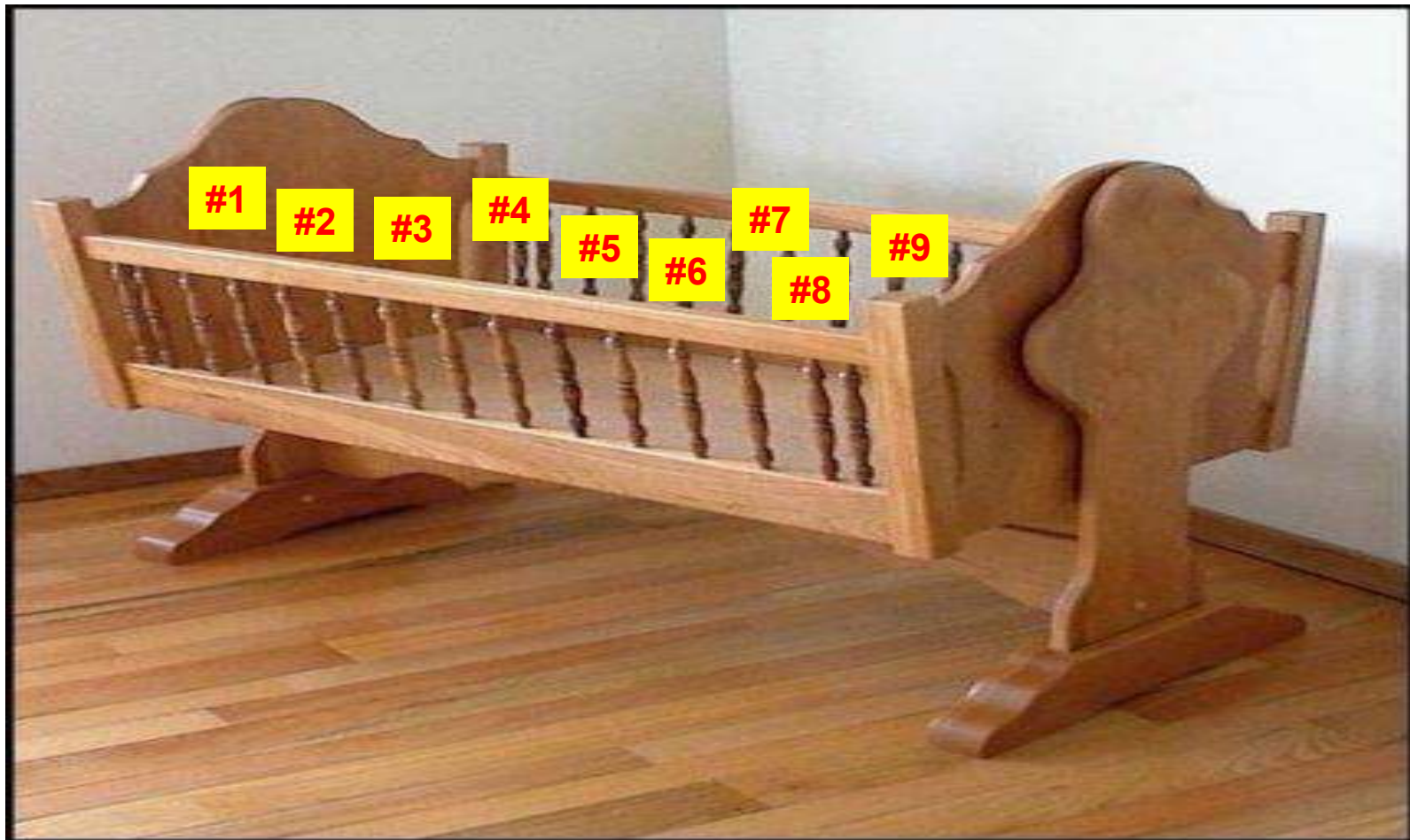
2. A Resonant Capacitor



3. A Resonant Inductor



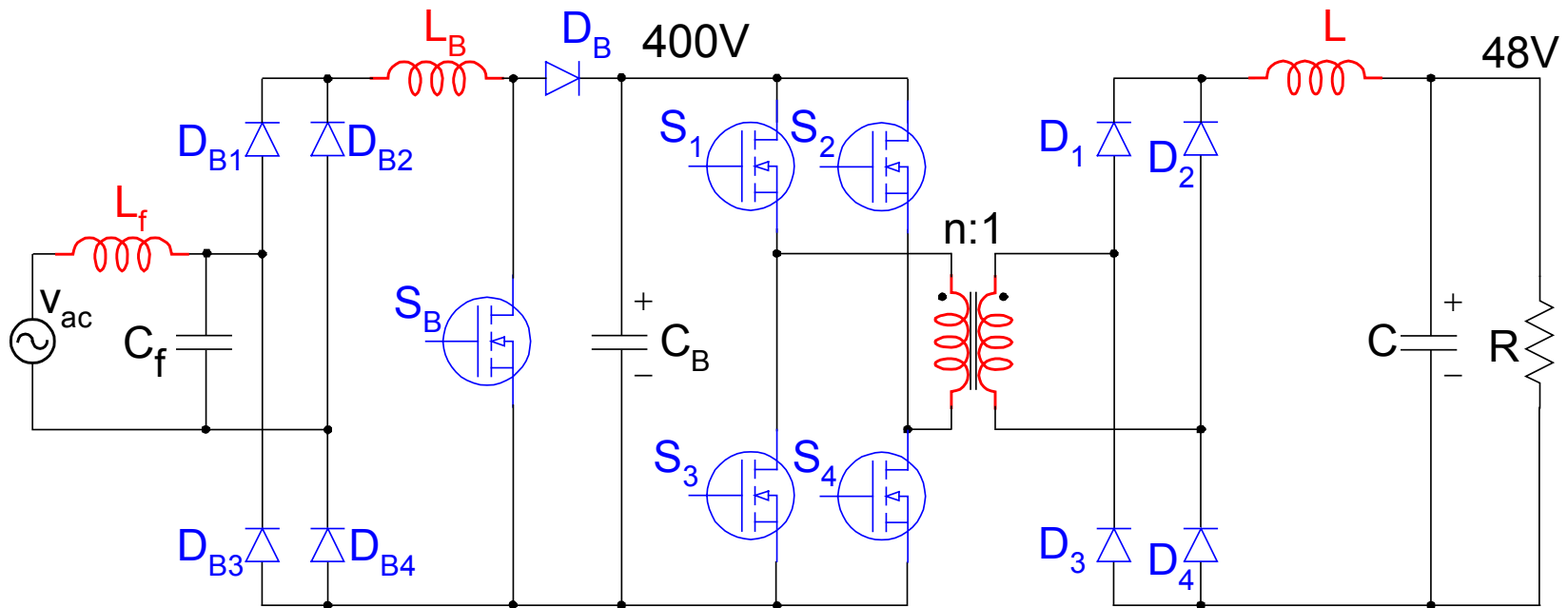
“Birth ” of Hybrid-Switching Method and Related Converter Topologies



AC-DC

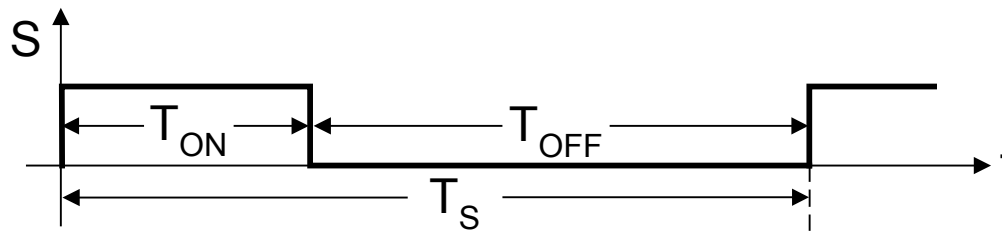
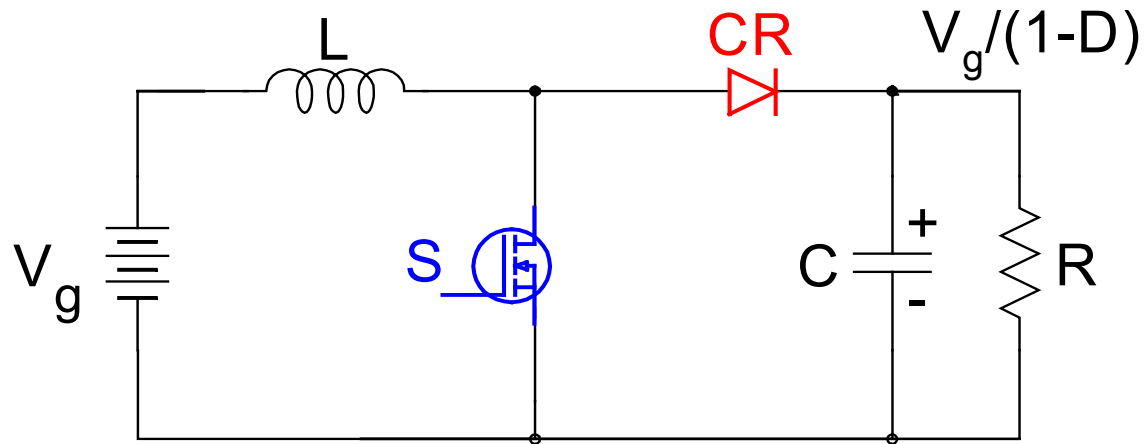
Converter Comparison

Conventional Three Power Processing Stage Approach



Polarity Inverting DC-DC Converter

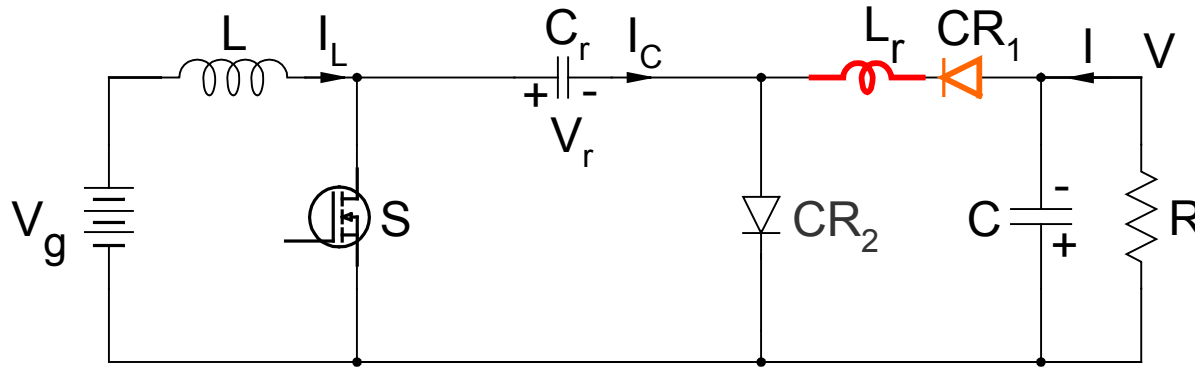
Boost Converter



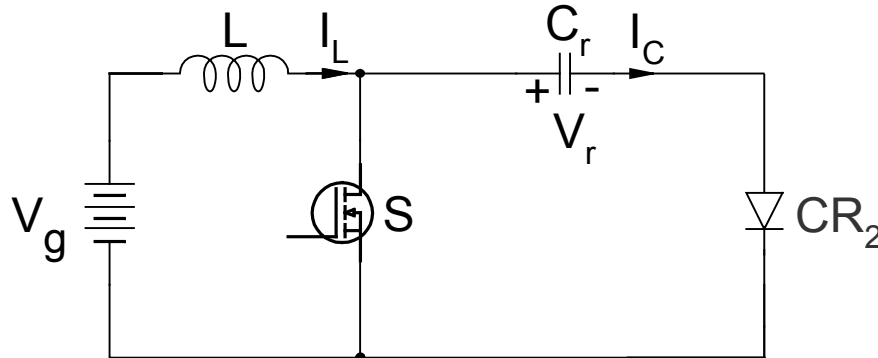
Problem

How to make a polarity inverting boost converter

Polarity Inverting 3 Switch Boost Converter*

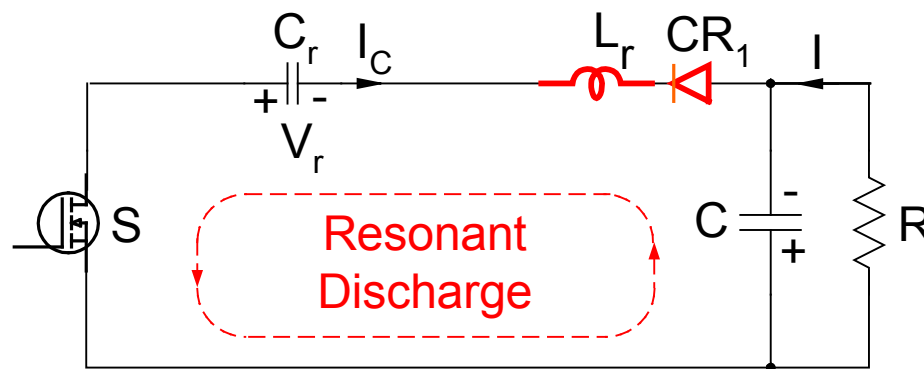


$$V = V_g / (1 - D)$$



Boost Converter

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

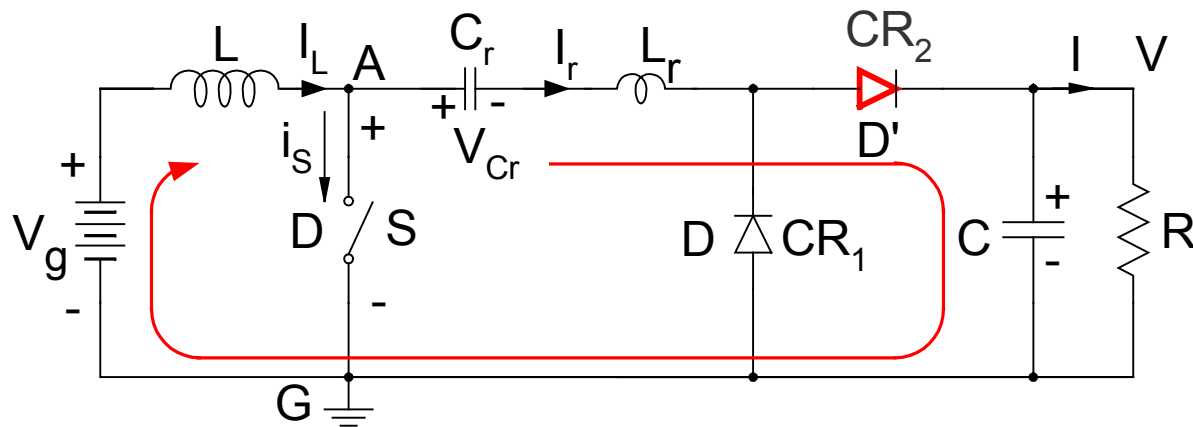


$$V = V_r$$

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

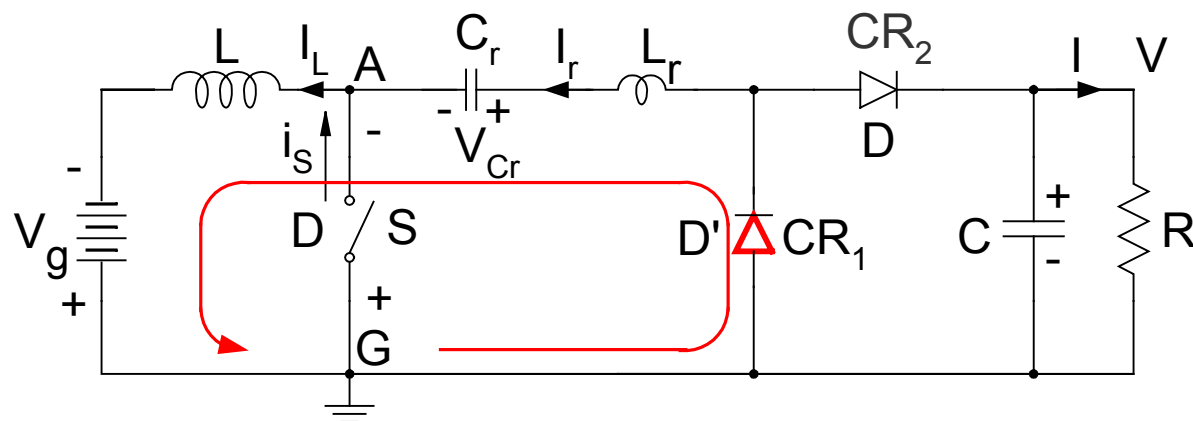
*US Patent No. 7,778,046

Positive and Negative Half-cycle of Input Voltage



$$V_{Cr} = 0$$

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



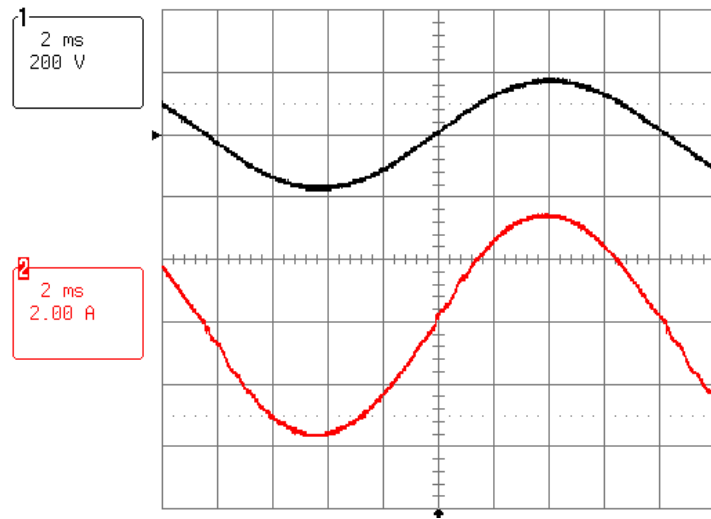
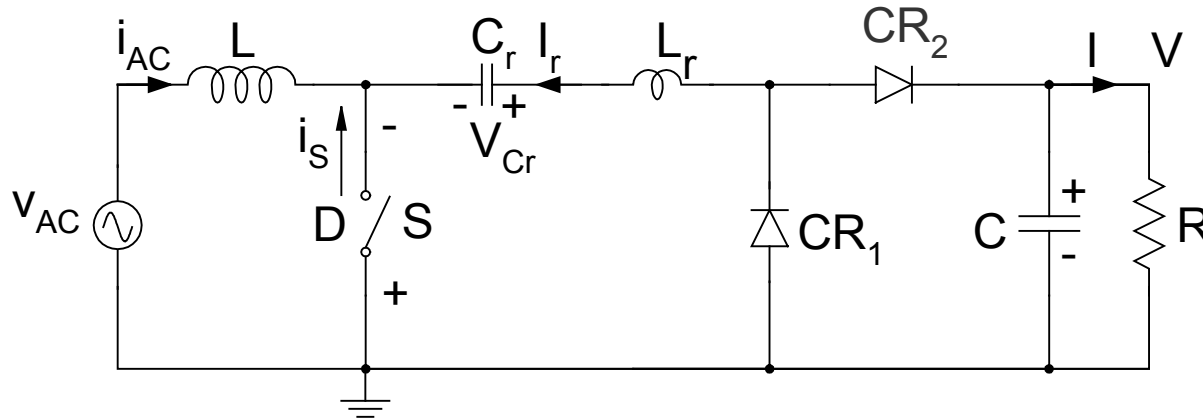
$$V_{Cr} = V$$

Source Polarity Controls Conduction Interval of Two Diodes:

Full-Bridge Eliminated

True Bridgeless PFC Converter

True Bridgeless PFC Converter*

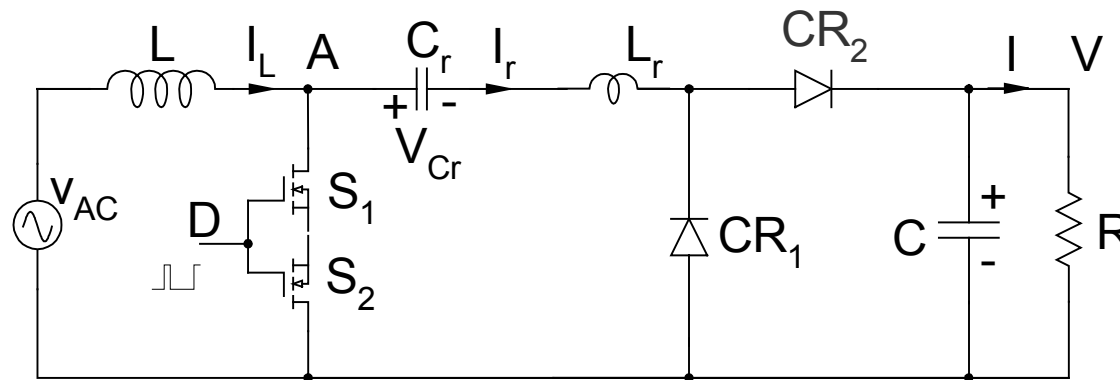
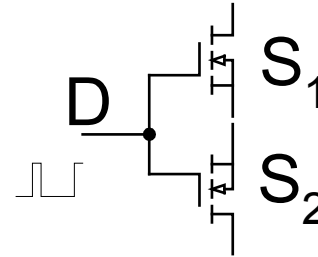
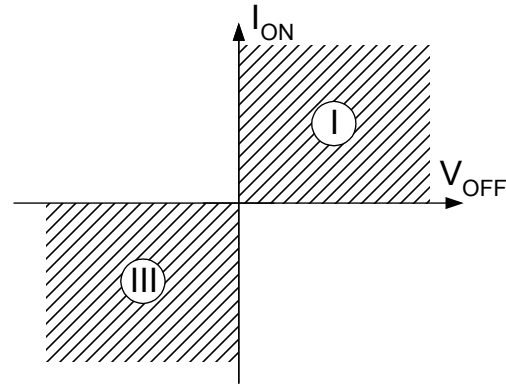


Input Voltage
110V

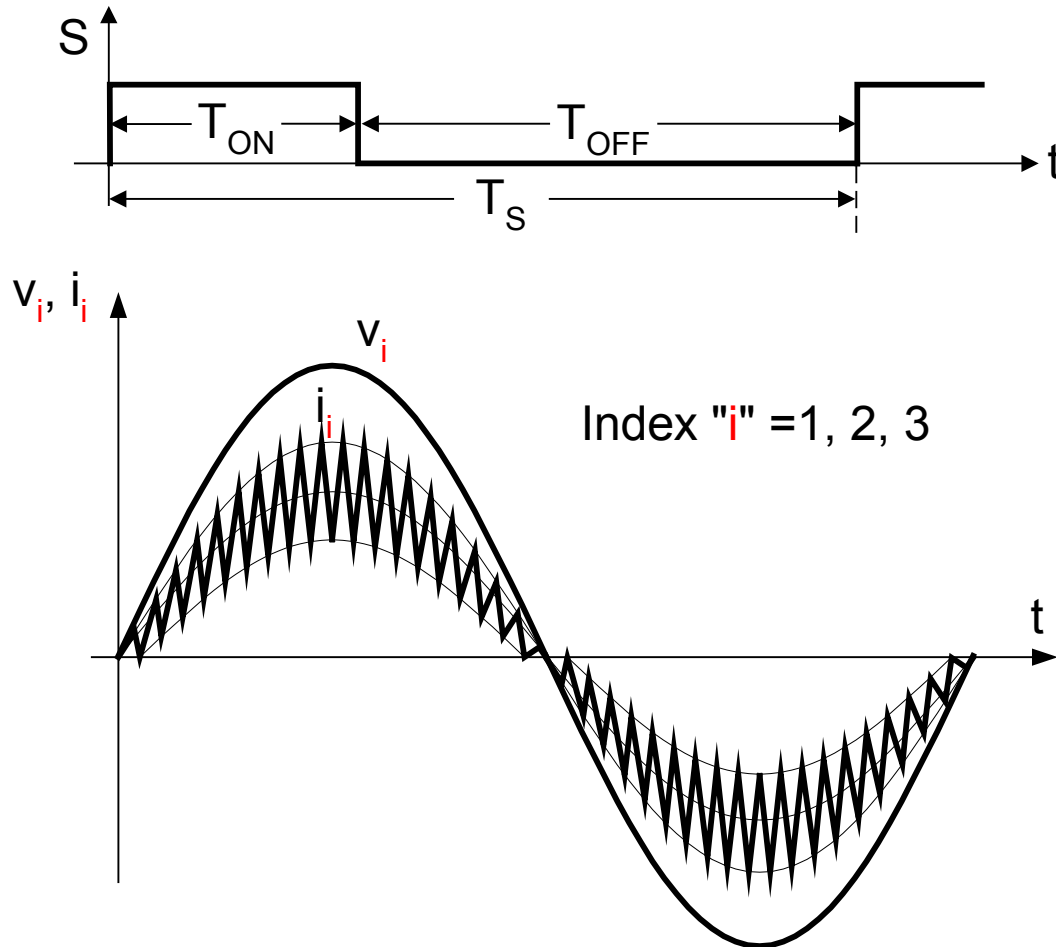
THD=1.7%
PF=0.999

*US and foreign patents pending

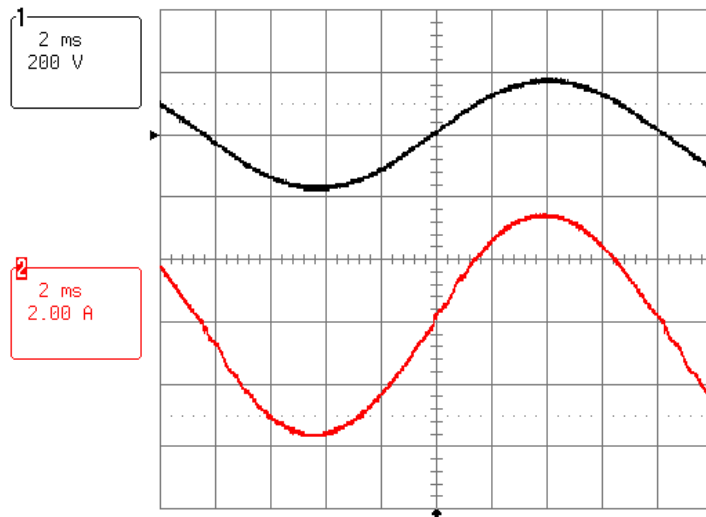
One Implementation of the Controlling Switch



Input Current Modulation for Each Phase at High Switching Frequency

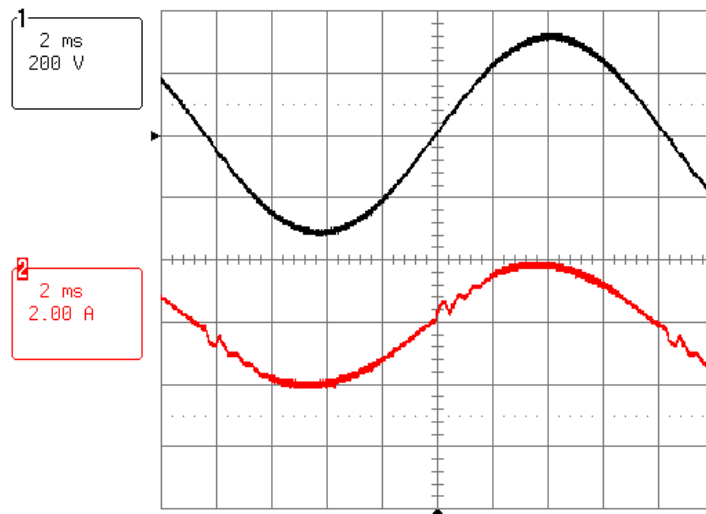


Voltage and Current Waveforms in Ćuk-rectifier™ with Integrated Magnetics Implemented



**Input Voltage
110V**

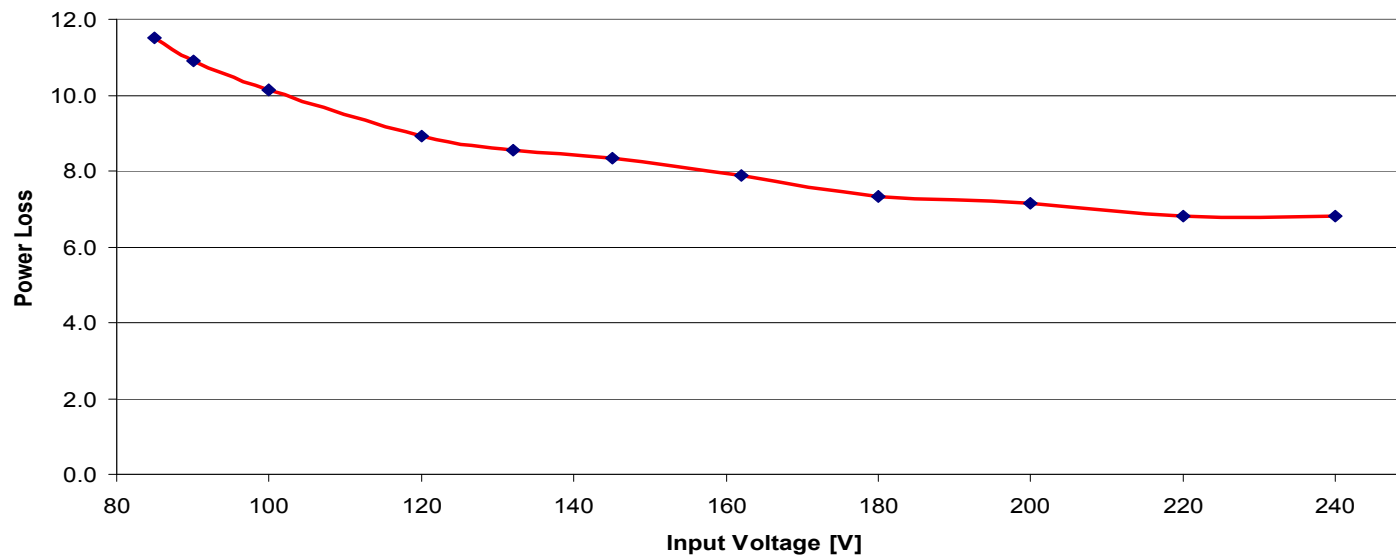
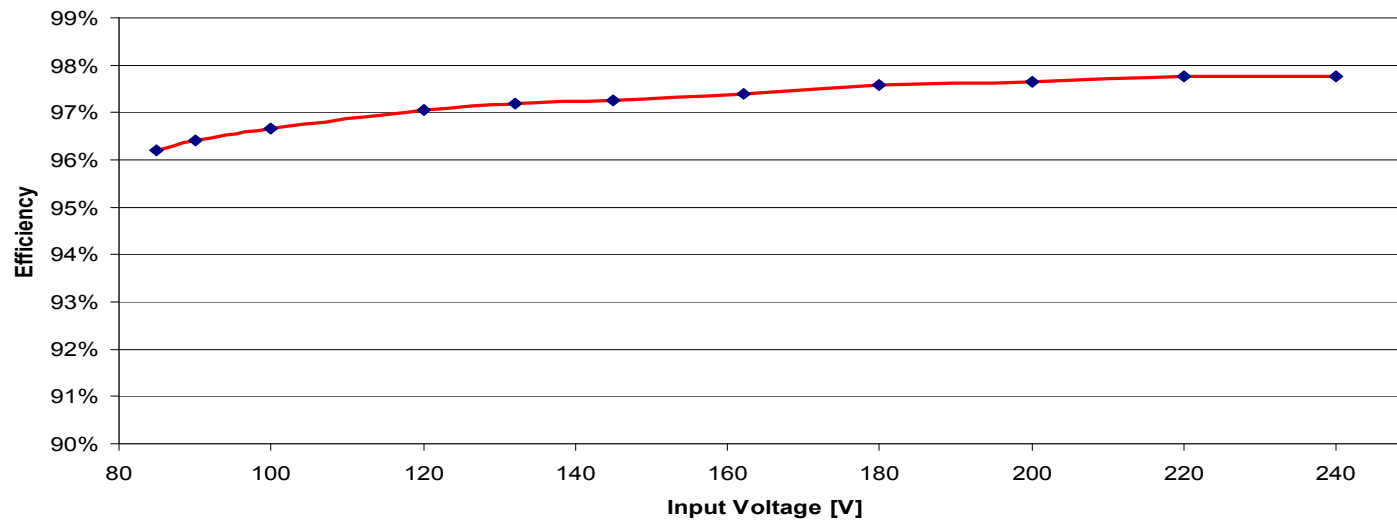
**THD=1.7%
PF=0.999**



**Input Voltage
220V**

**THD=2.0%
PF=0.991**

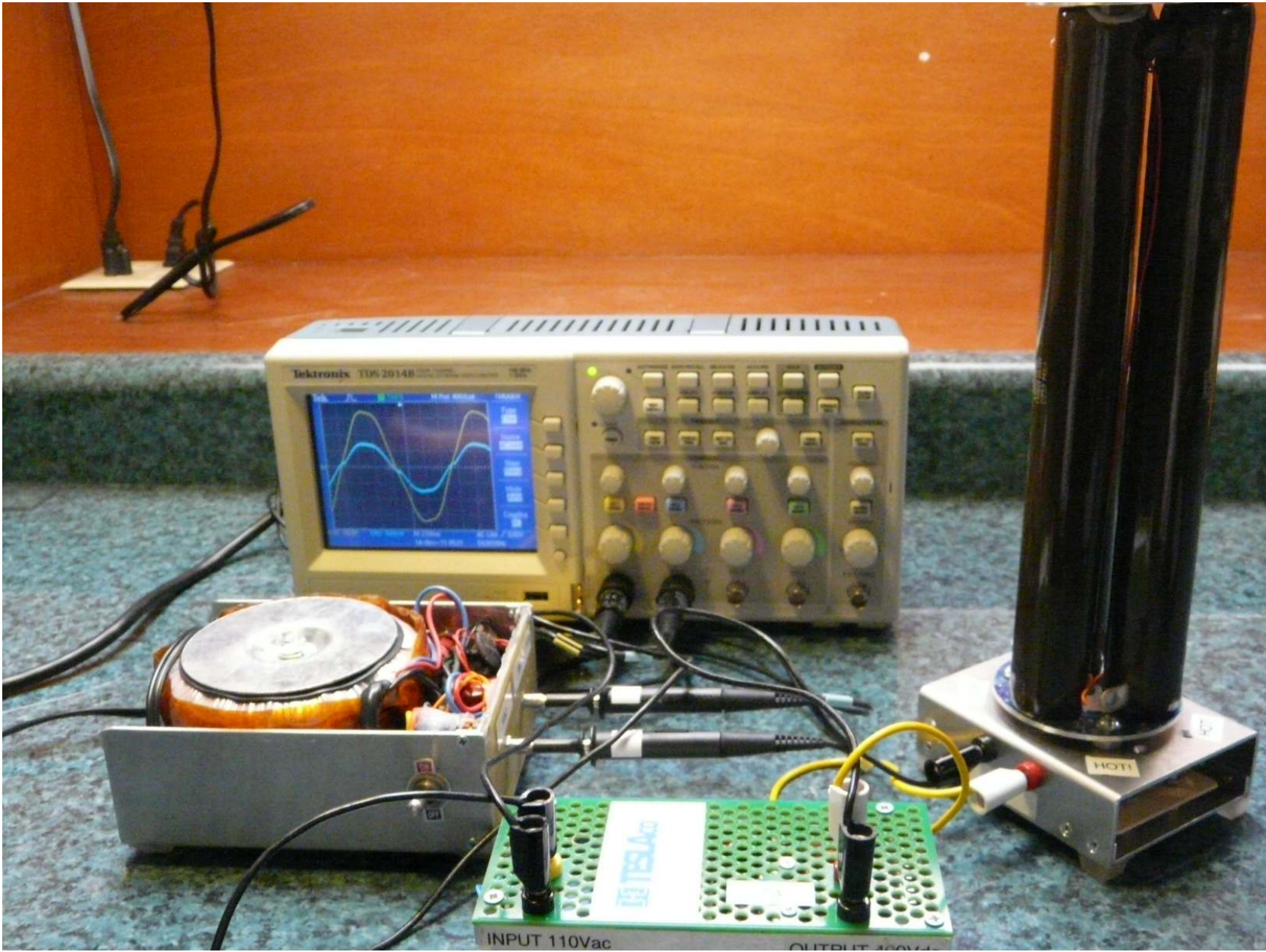
Efficiency and Power Loss of Ćuk-rectifier™

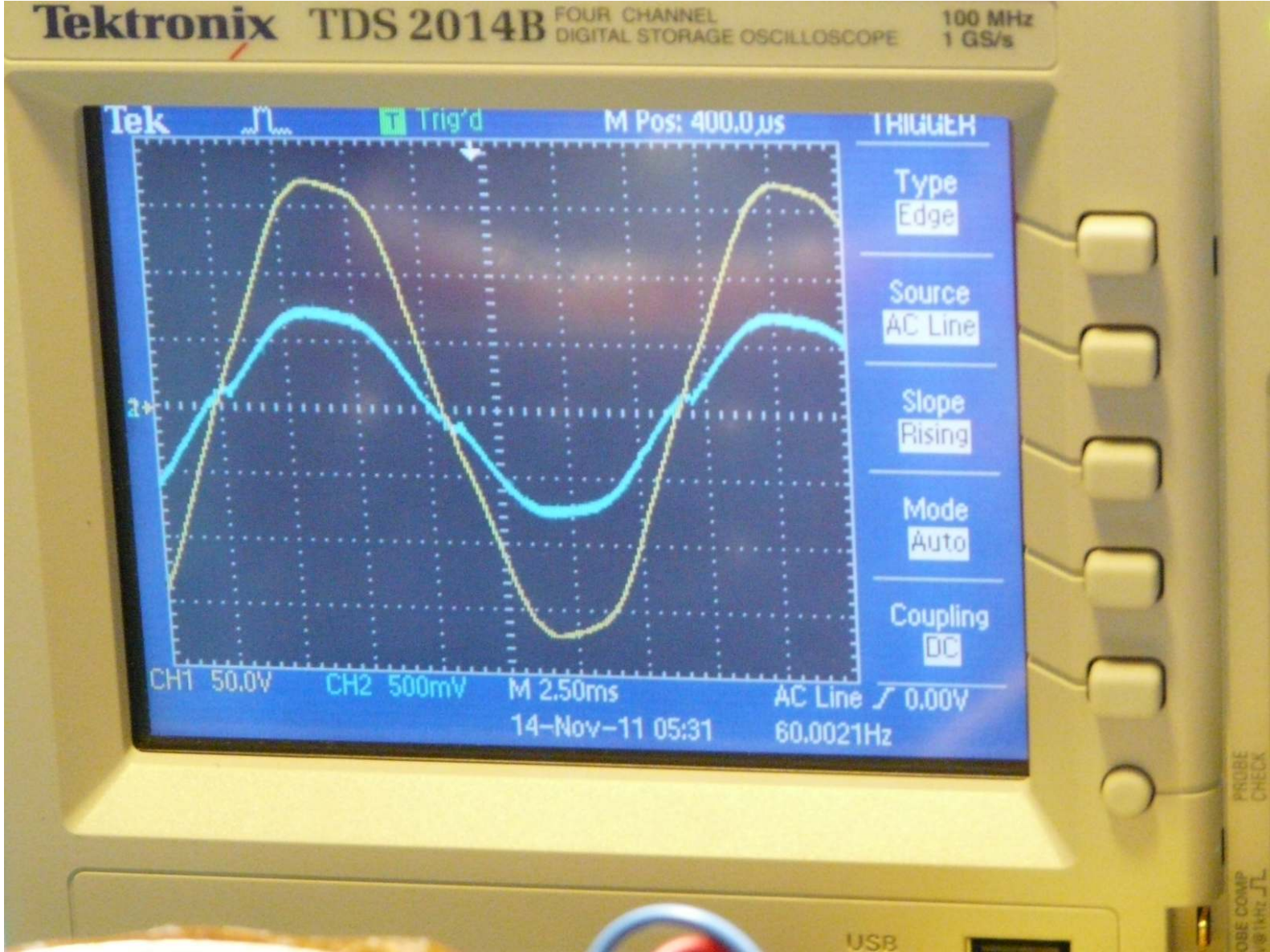


Demo #1:

400W Bridgeless

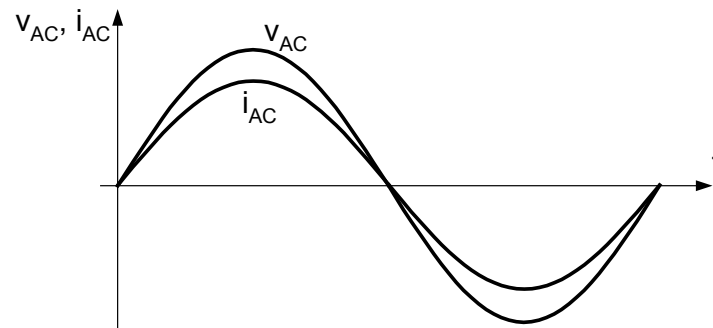
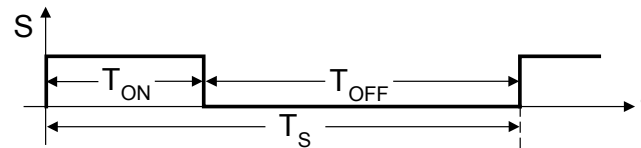
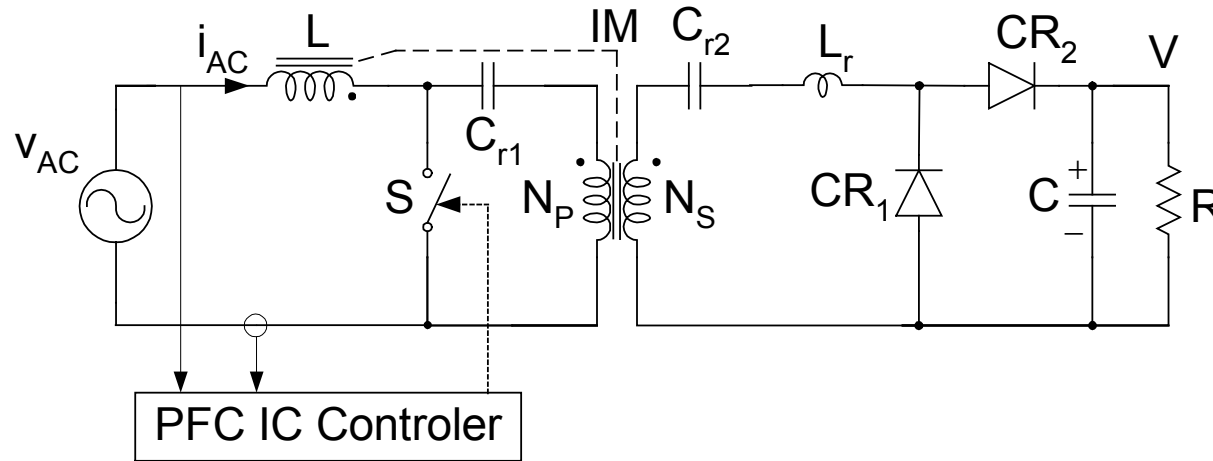
PFC converter





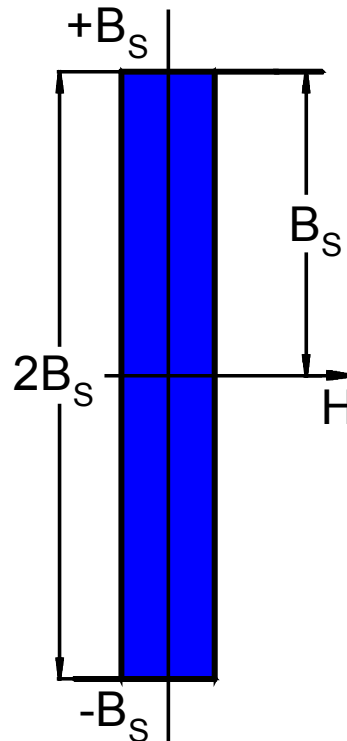
True Isolated Bridgeless PFC Converter

True Bridgeless PFC Converter with Isolation*



***US and foreign patents pending**

True AC Transformer



No Air-gap
No Energy Storage
Automatic Reset
Scalable to High Power

Comparison

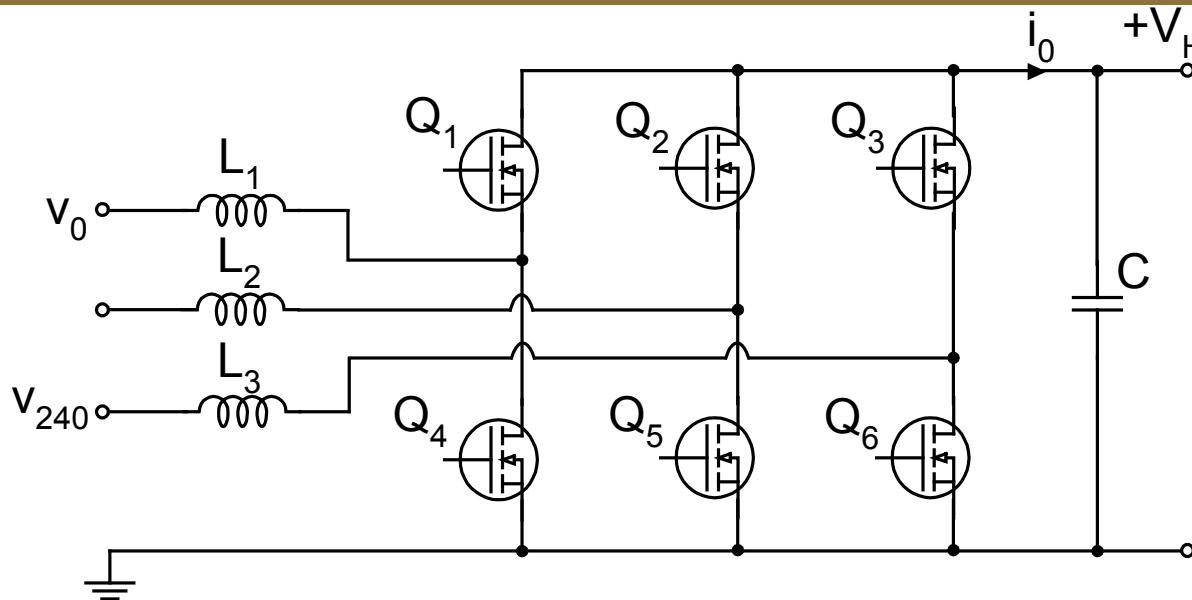
Power Processing	Single-stage	Three-stage
Type of Converter	Isolated Bridgeless PFC	Bridge-Boost PFC-Full-bridge
Switching Method	HYBRID	Square-wave
Number of switches	3	14
Switch-voltage Stress	Low	High
Lossless-switching	YES	NO
Control	Simple	Complex
Magnetics pieces	1	4
Power Losses	3%	10%
Efficiency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

Three-Phase AC-DC

Converter Comparison

Present Approach: Two Stages

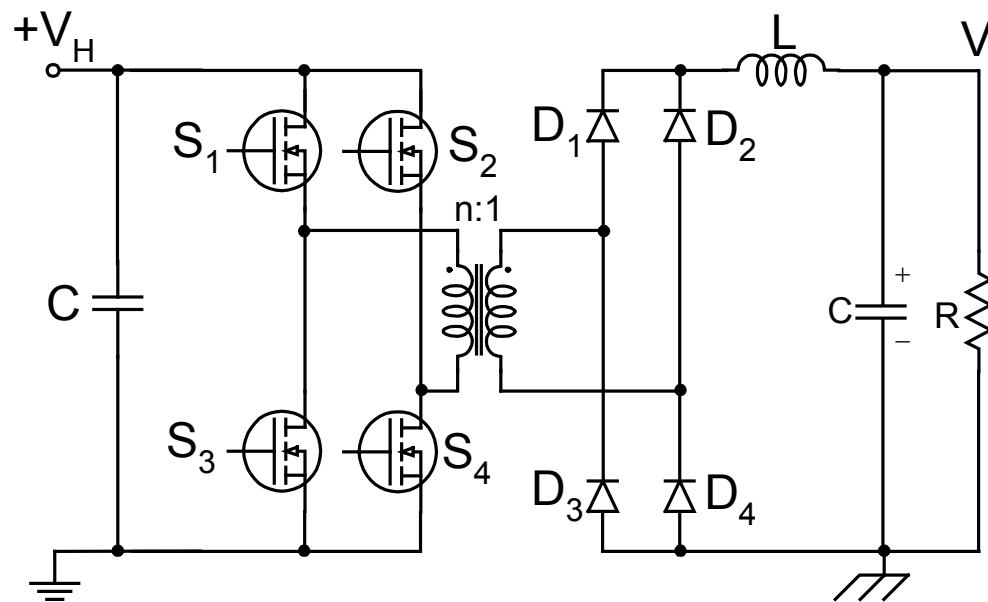
First Stage: Rectification and PFC
Efficiency = 98%



Three-phase properties prematurely
lost after rectification and PFC control

Second Stage: Isolated DC-to-DC converter

Second Stage: DC Isolation
Efficiency = 95%



Power processed sequentially in **Two** stages so
Low Total Efficiency of 92%

New Single-stage Three-phase Rectifier



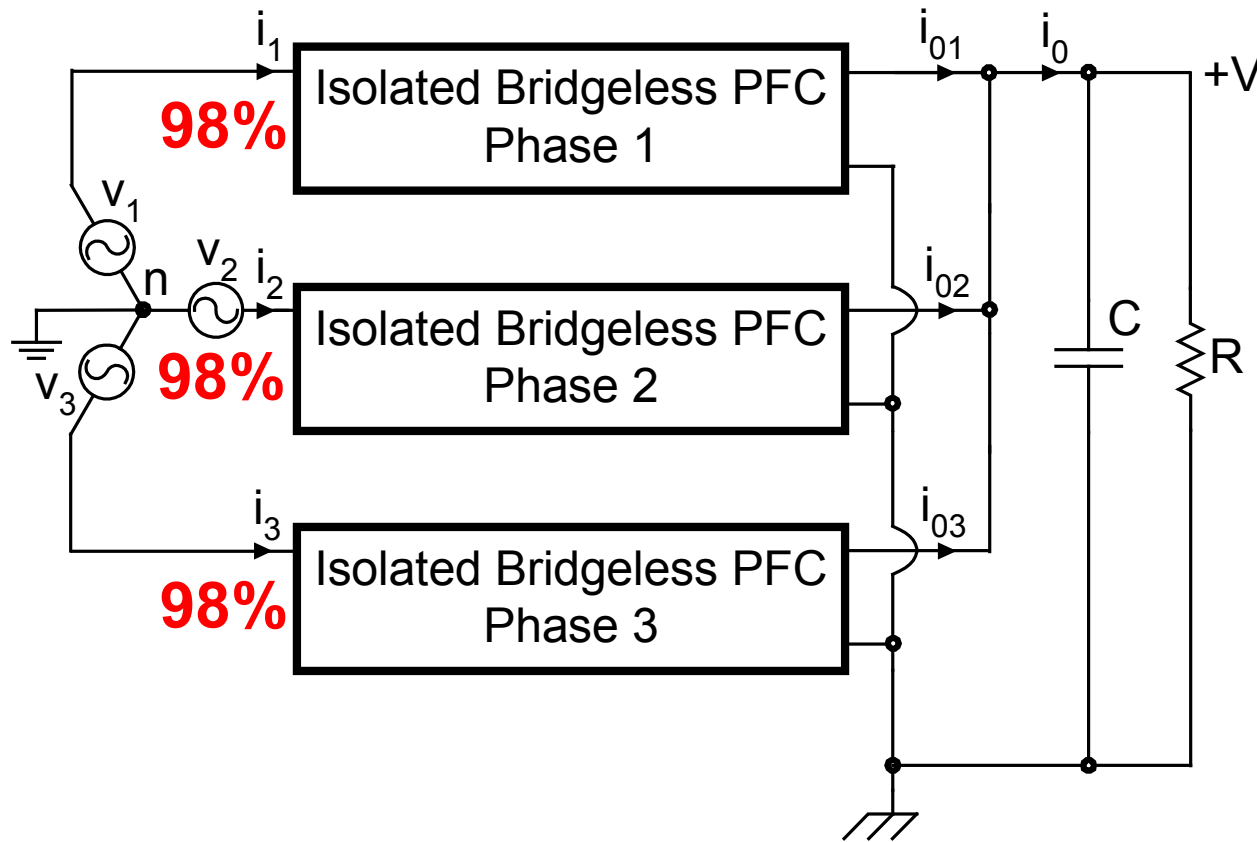
$$\Phi = B \cdot S$$

$$\frac{\text{Wb}}{\text{m}^2} = \text{T}$$

(TESLA)

31

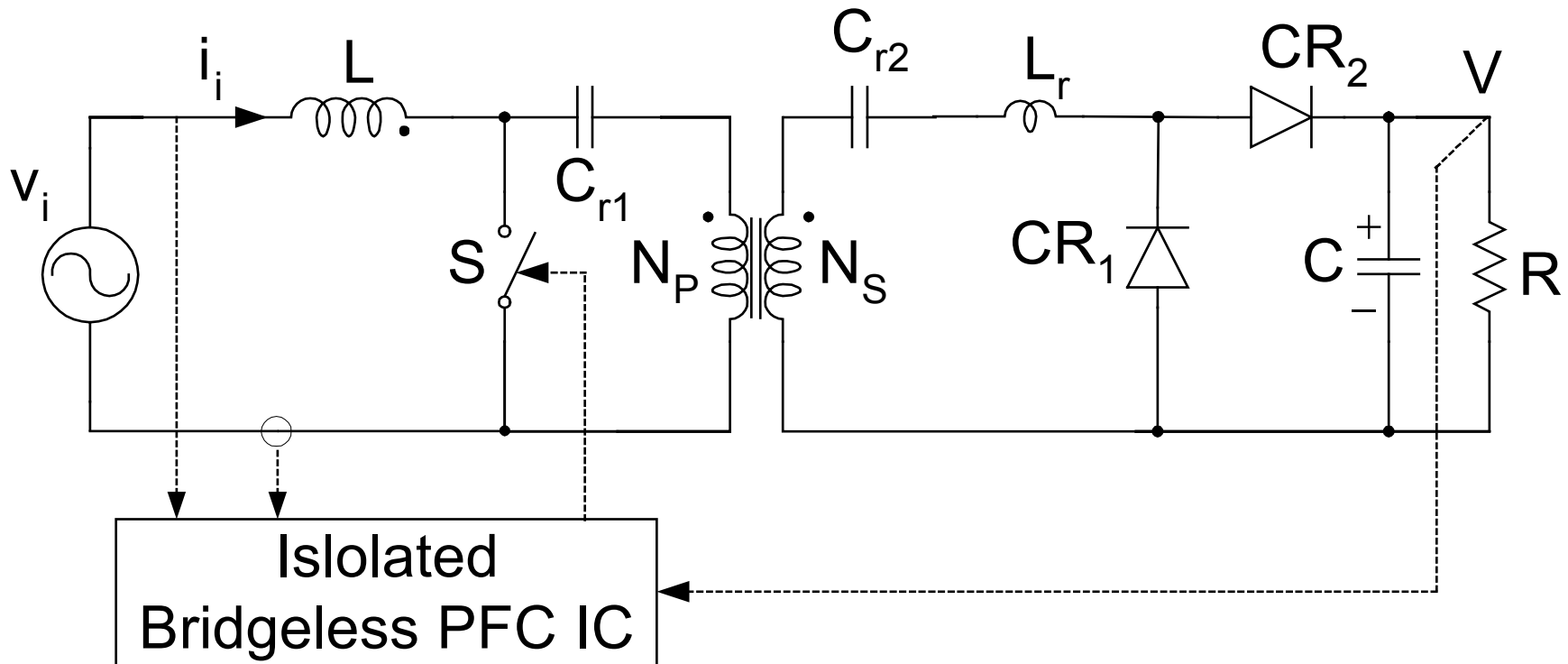
New Direct Three-Phase to DC Conversion with PFC and Isolation in a Single Stage



Power processed in parallel and not in series

Each Phase Efficiency 98%; TOTAL Efficiency 98%

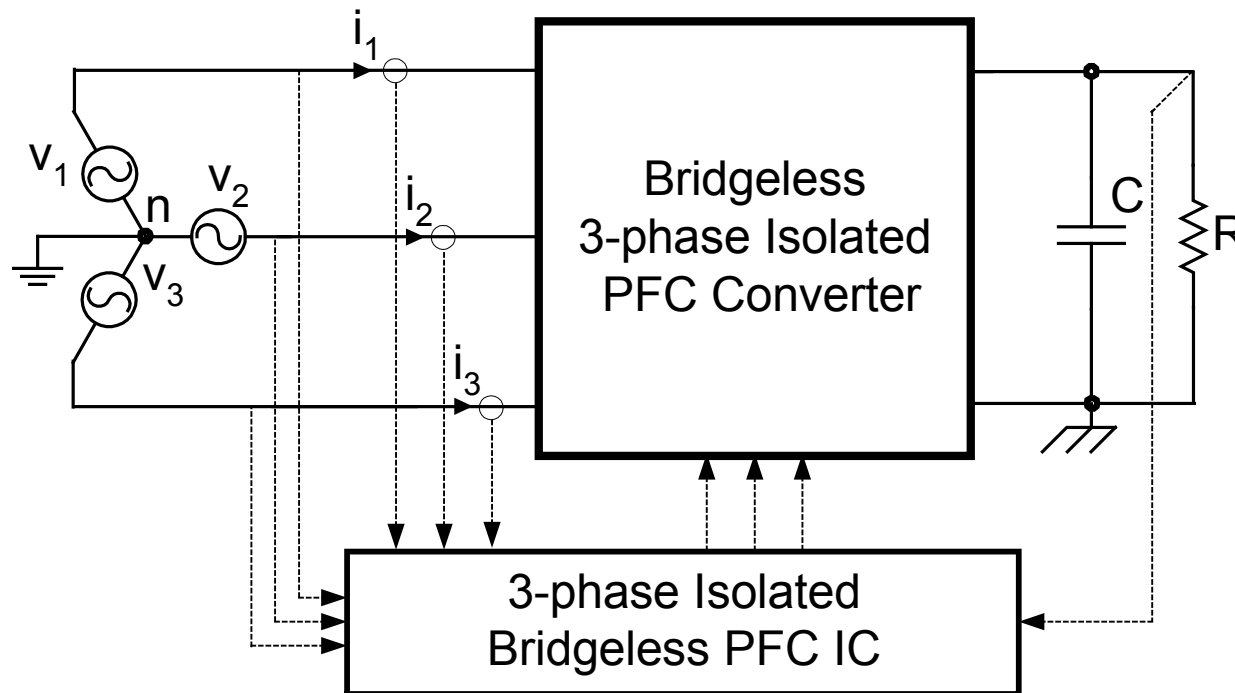
AC-DC Converter for Each Phase with PFC and Isolation*



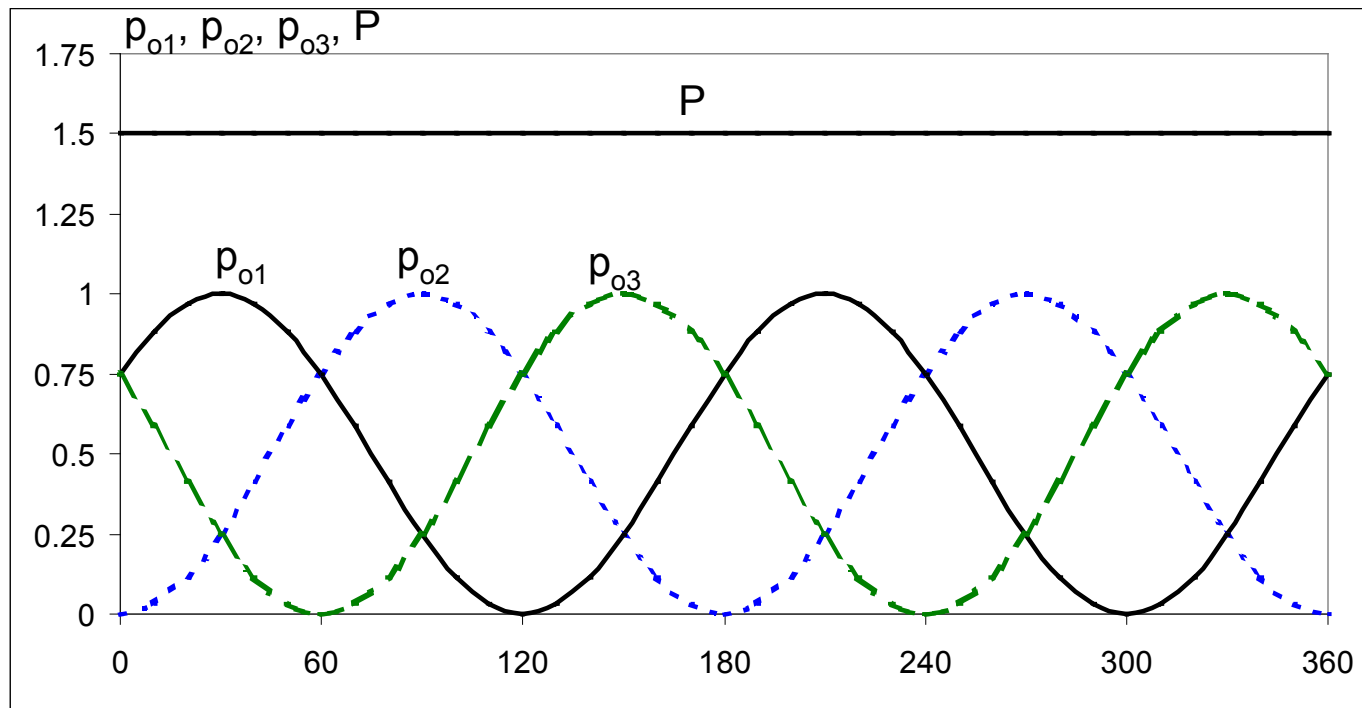
Three Switches Only

***US Patent No. 7,778,046**

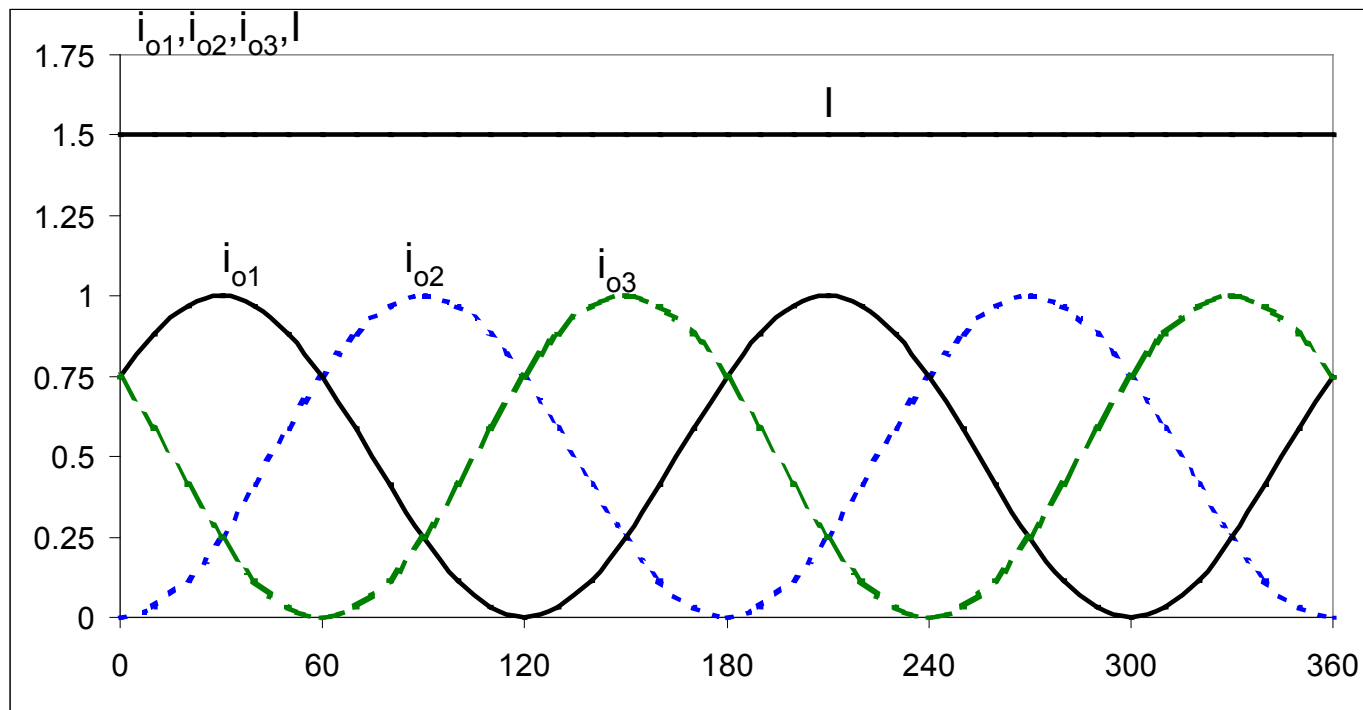
Three-Phase Ćuk-rectifier with PFC IC Control



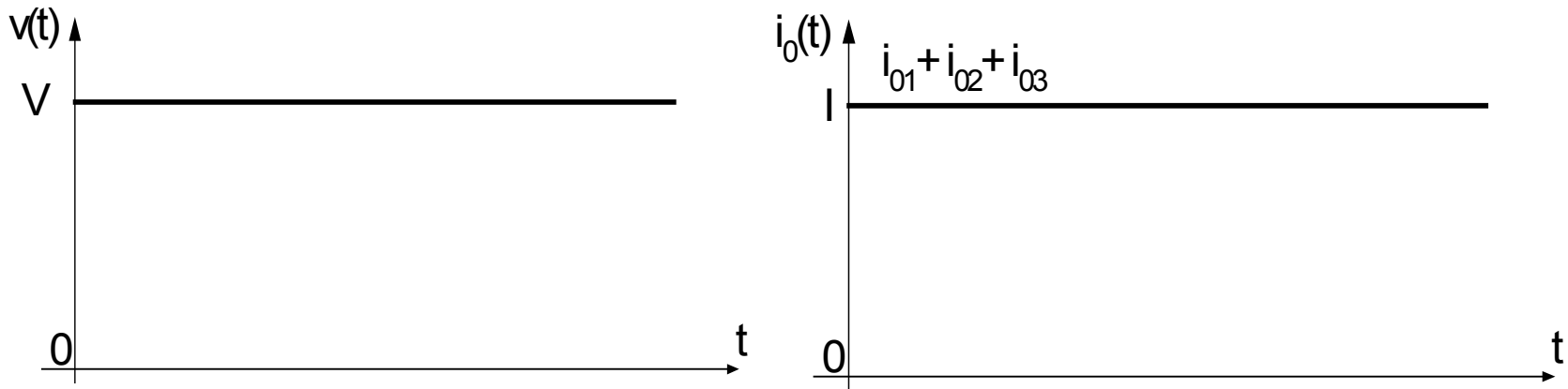
Sum of Instantaneous Output Powers of Three Phases is Constant



Sum of Instantaneous Output Currents of Each Phase is Constant



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



$P = \text{constant}$
 $V = \text{constant}$ \Rightarrow $I = \text{constant}$

“Birth ” of Storageless Switching Method and Related Converter Topologies



Demo #2:

200W DC-DC converter

48V to 24V

Power Stage of 200W Storageless Converter



Bi-directional Specifications

Switching Frequency: 50kHz

Input Voltage: 48V

Output Voltage: 24V

Output Current: 4A

Power: 200W

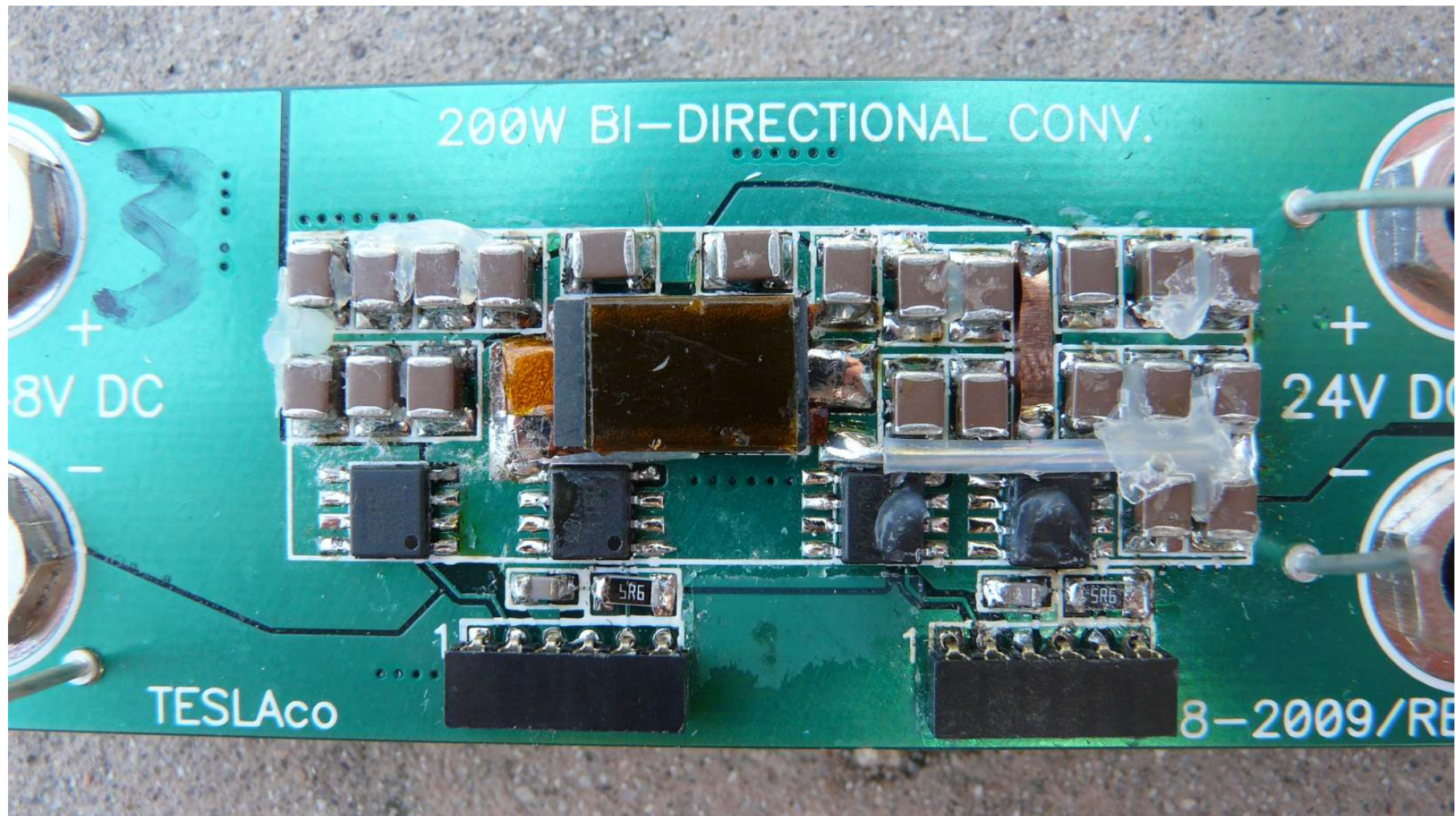
Volume : 0.2in³

Power Density: 1kW/in³

No Heat Sink

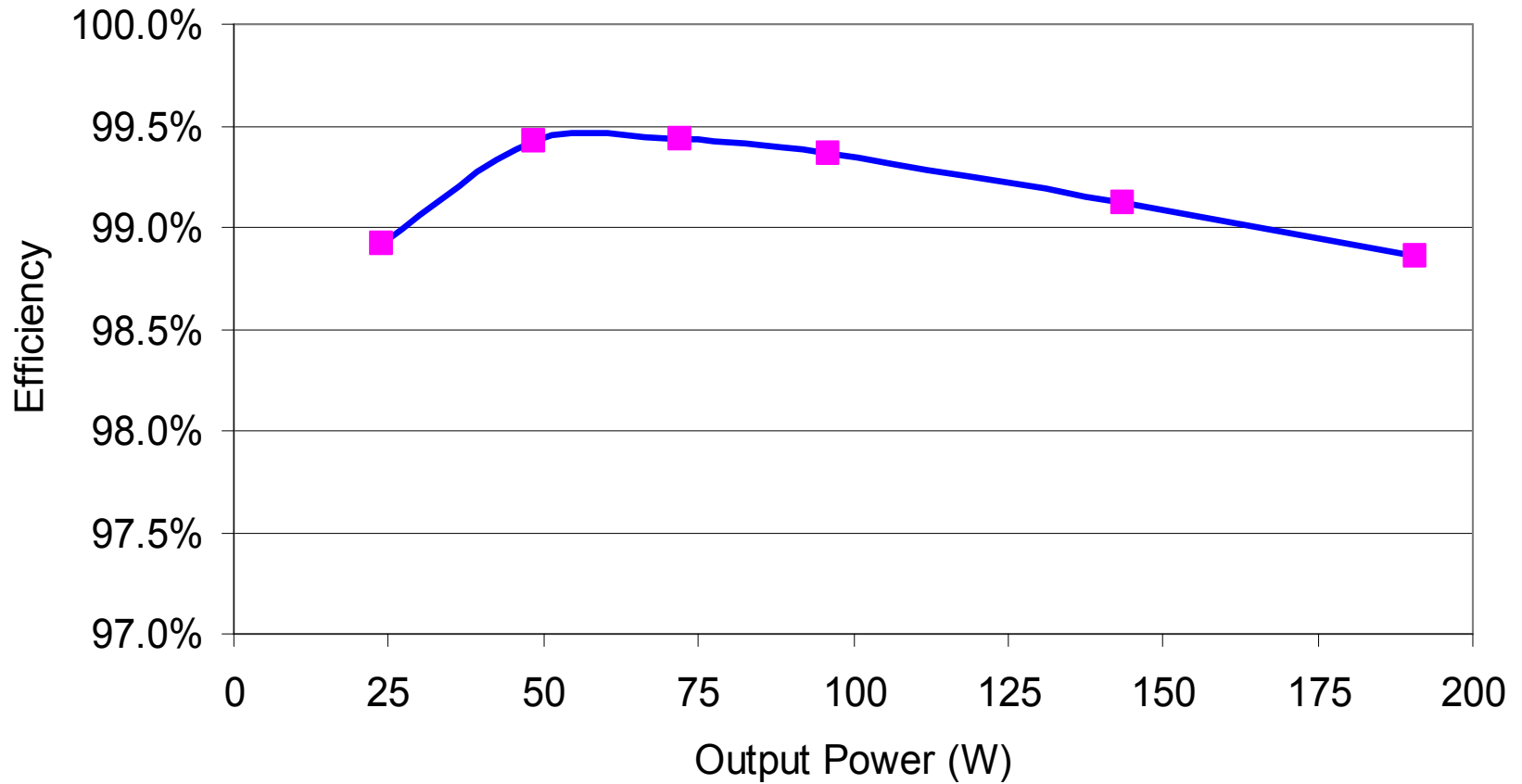
No Forced Air Cooling

200W, 48V/24V Storageless Ćuk-buck Converter



Efficiency of 200W Storageless Converter

Efficiency vs Output Power



Power Stage of 750W, 48V Prototype*

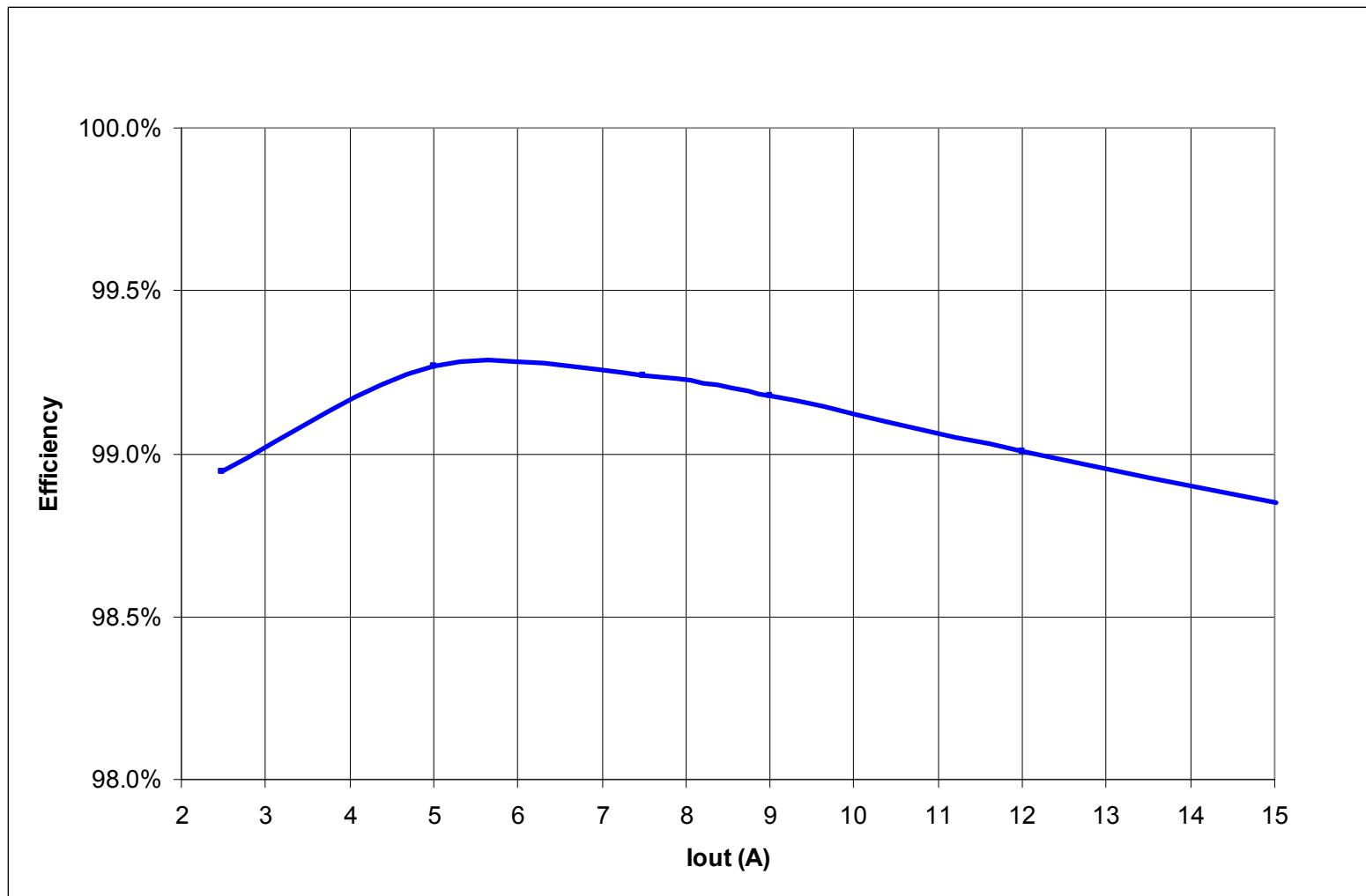
Storageless Buck Converter™



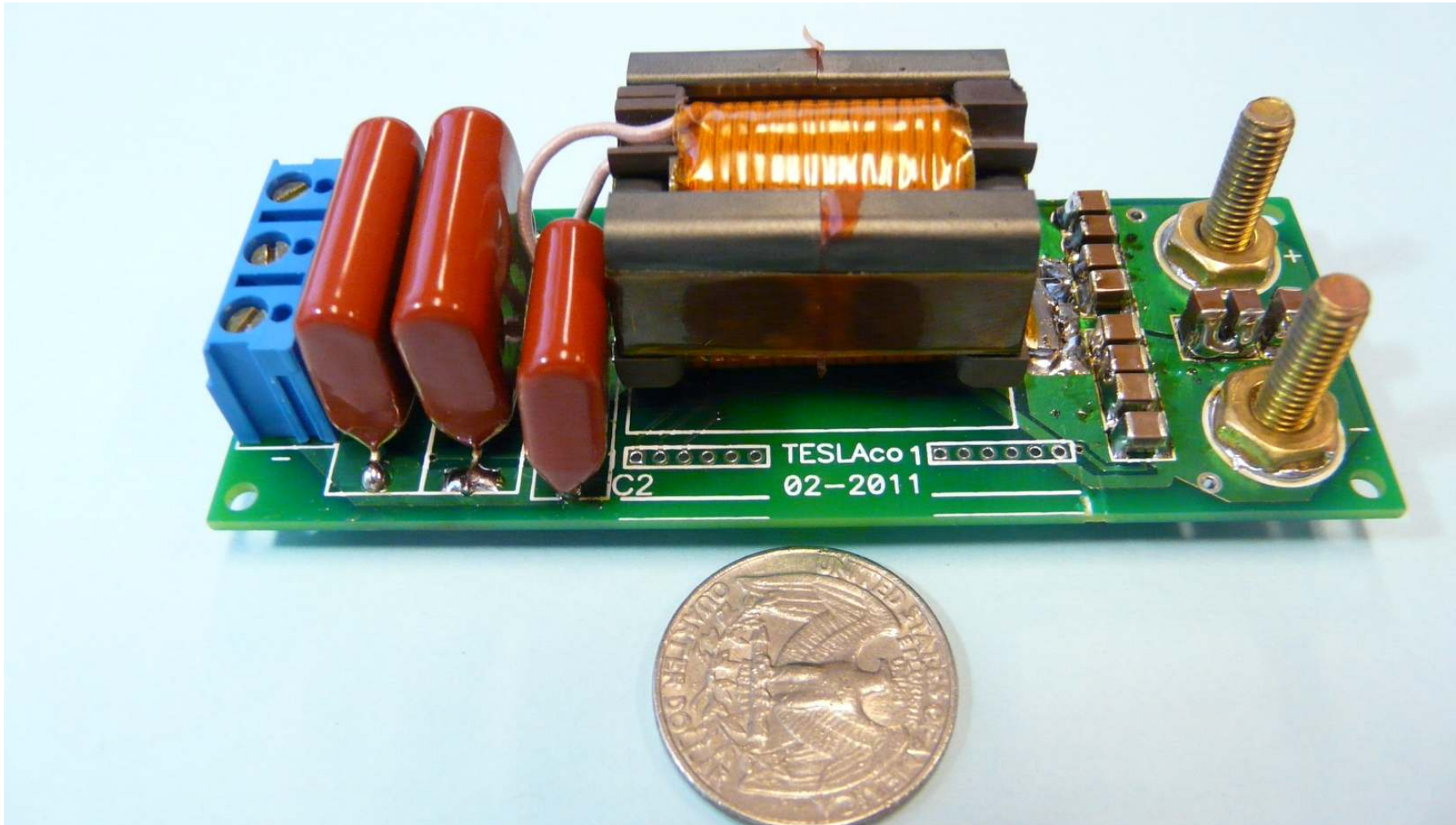
Efficiency over 99%

*US and foreign patents pending

Efficiency of 750W, 100V to 48V Converter



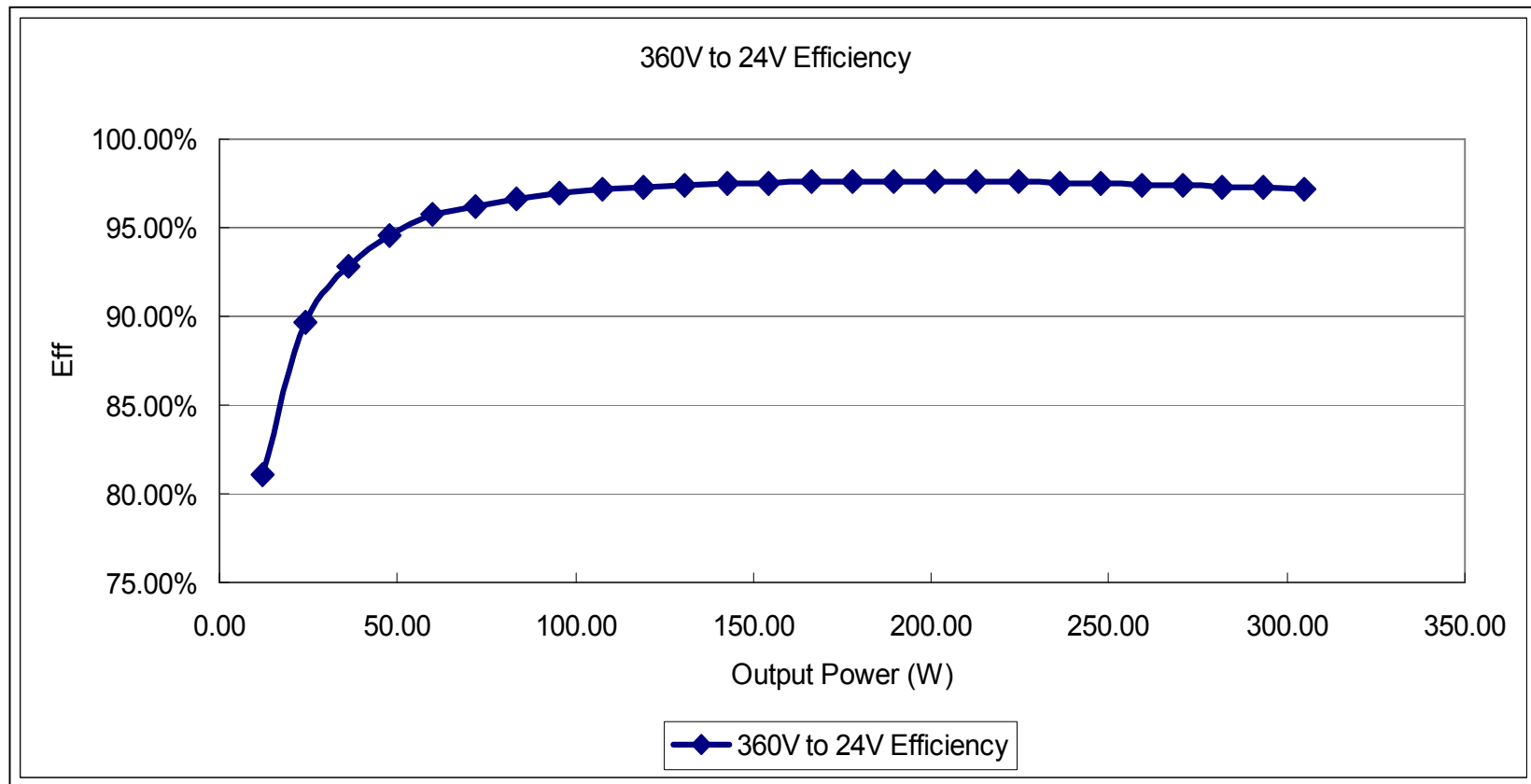
Isolated Storageless Converter*



*US and foreign patents pending

Efficiency of Isolated Storageless Converter

98.2% efficiency



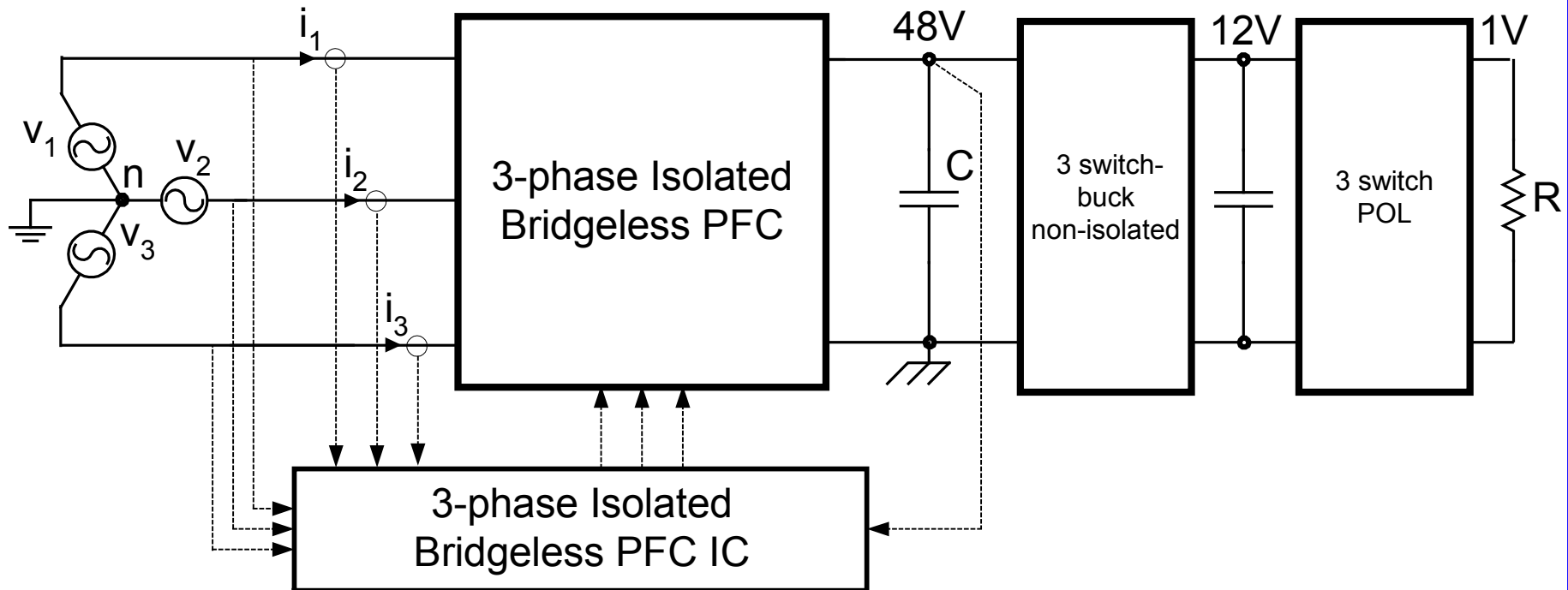
Green Dream Power Technology™

Efficiency

98%

99%

97%



Switching method

Hybrid

Storageless

POL

Applications Summary

- Computer servers

Battery chargers for electric cars and bicycles

- Desktop computers

- AC Adapters, projectors, etc.

- Solar photovoltaic conversion

- LED lighting

VRM (12V to 1V regulators)

Applications Summary

- Wide range of power
- From cell phones and under a one 1 Watt to 100kW for electric drive for motors, etc.

July 10, 2010 : Memorial for Professor Middlebrook



July 10, 2010 : Power Electronics Group Members and their relatives

