Objective

Rapid, On-Board Charger for Fully Electric Vehicles

Ćuk 2 AC-DC charger only option

Ćuk 2 uses unique property of Ga N devices which no other device technology has.

POWER ELECTRONICS

DR. SLOBODAN ĆUK

VOL. 1

POWER ELECTRONICS:
TOPOLOGIES, MAGNETICS AND CONTROL

Power Electronics field is an interdisciplinary field started in 1960's requiring expertize in three key areas: converter topologies, magnetics and control. Converter topologies require the use of active and passive semiconductor switching devices to implement its ideal switches.

The invention of the *Ćuk converter* on April 1, 1975 highlighted the importance of the introduction of the fourth basic converter topology, which for the first time used additional capacitive energy storage and transfer. The other three known basic converters: the buck, the boost and the buck-boost relied solely on inductive energy storage and transfer. Ceramic chip capacitors now enable elimination of large, heavy and inefficient PWM inductors and result in simultaneous tenfold reduction of losses, sizes and costs of new switching converters based on novel *Resonant/PWM switching methods.* The advent of soft-switching alternatives to hard-switching revealed that new switching methods could be developed to either reduce or eliminate entirely the switching losses. The present four- volume edition provides the four pillars on which the new Power Electronics System Technology is being built upon. The subsequent volumes to this Power Electronics book series will provide complete re-evaluation of the converter topologies and switching methods used for the last 50 years. It will also introduce new Power Electronics System Technology based on the new *Resonant/PWM* switching methods and their related *novel converter topologies.*

DR. SLOBODAN ĆUK

Dr. Ćuk was a Professor of Electrical Engineering at Caltech for 25 years where he supervised 35 PhD students completing their PhD degrees in Power Electronics. Dr. Ćuk is also a founder and CEO of TESLAco. His key inventions: Ćuk converter, State- Space Averaging, Coupled Inductors/ Integrated Magnetics, Tesla converter, Hybrid and Storageless Switching, Single stage isolated Bridgeless PFC, Ćuk-buck and Ćuk-buck2 converters, Ćuk rectifier, Rapid On-board Charger for EVs, Isolated Storageless Ćuk converter,Ćuk ...

...Two volume 1981 paperback edition was responsible for my getting into Power Electronics as a young engineer. Since there were no courses then I learned from the two books and now enjoy a very rewarding, lifetime professional career.

...I received the three volume hardcover edition as a part of the Power Electronics Course Dr. Ćuk gave in Sweden in 1985. Dr. Ćuk is not only world recognized educator but also the leading Pioneer in the world of Power Electronics and the most exciting and relevant innovator in this field today, bar none!

ISBN 978-1-5191-6113-0

Four volumes books (vol.1 to vol. 4) Power Electronics published by Amazon .com and CreateSpace.com

Teslaco website www.teslaco.com has detailed description and 31 page article of Chapter 1 of Volume 1: Topologies, Magnetics and Control

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

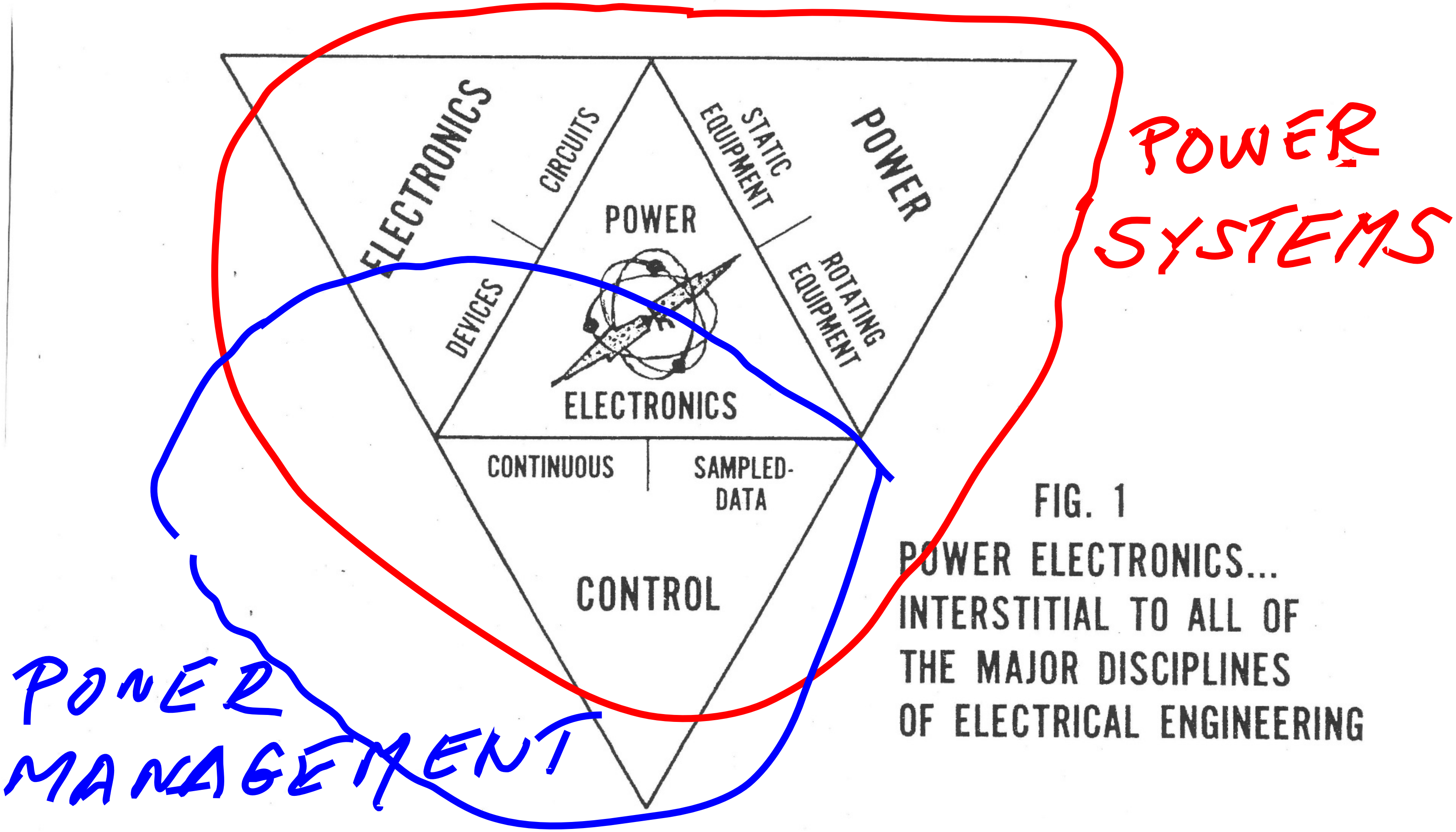


FIG. 1
POWER ELECTRONICS... INTERSTITIAL TO ALL OF THE MAJOR DISCIPLINES OF ELECTRICAL ENGINEERING

Fig.2a

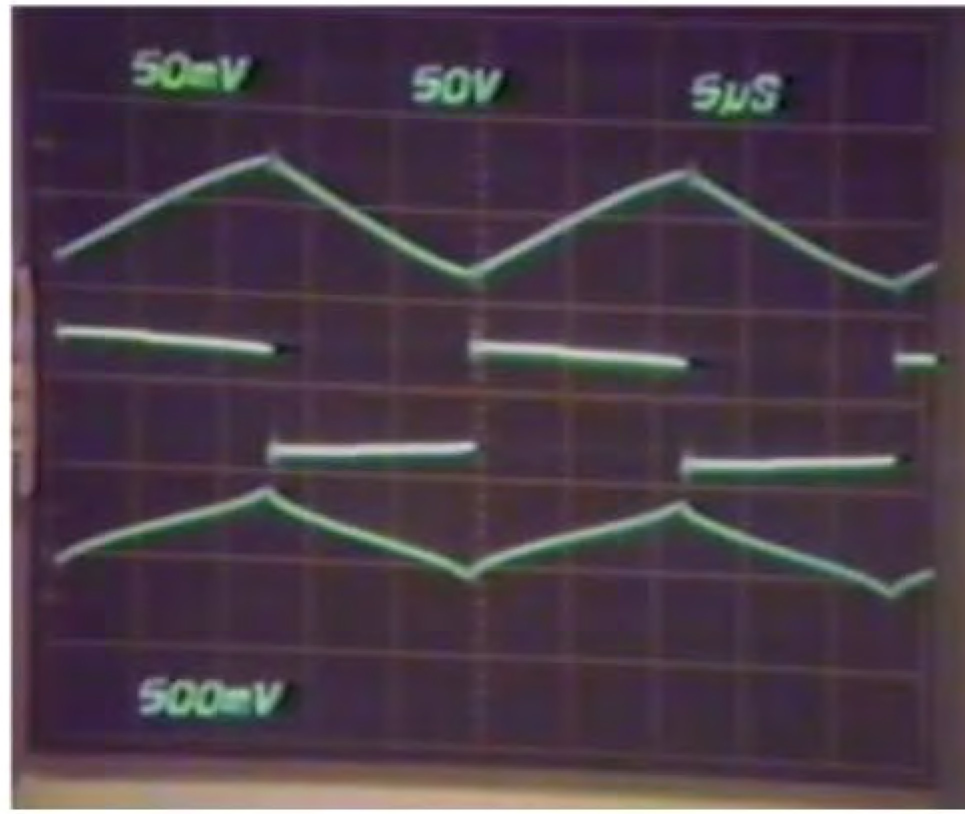
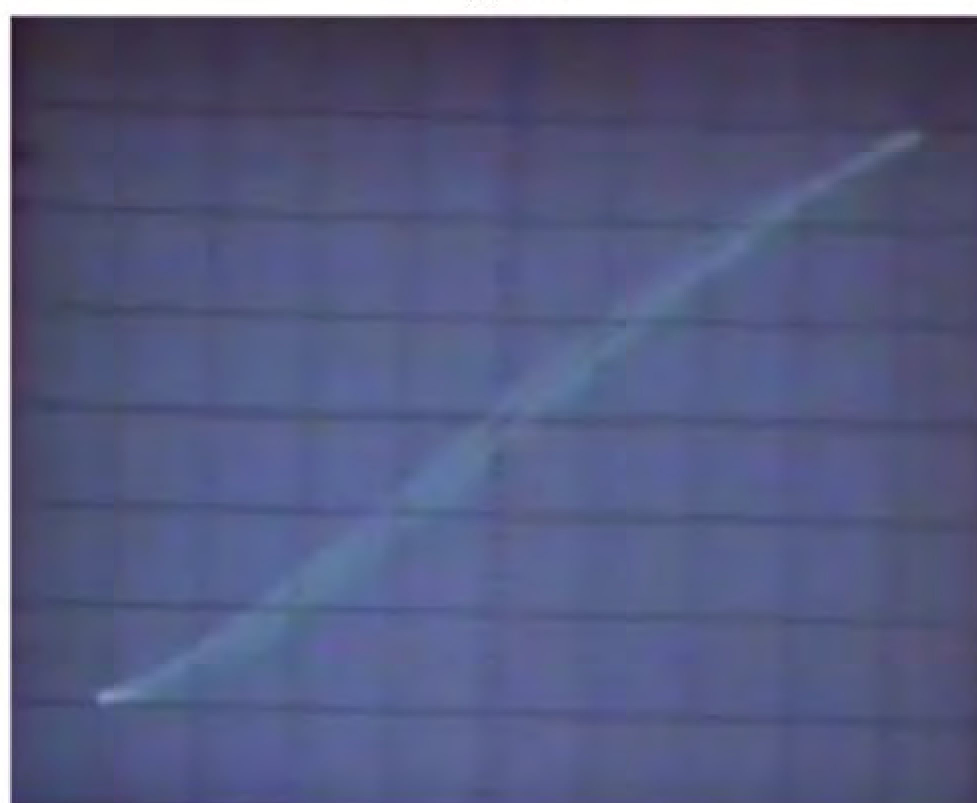


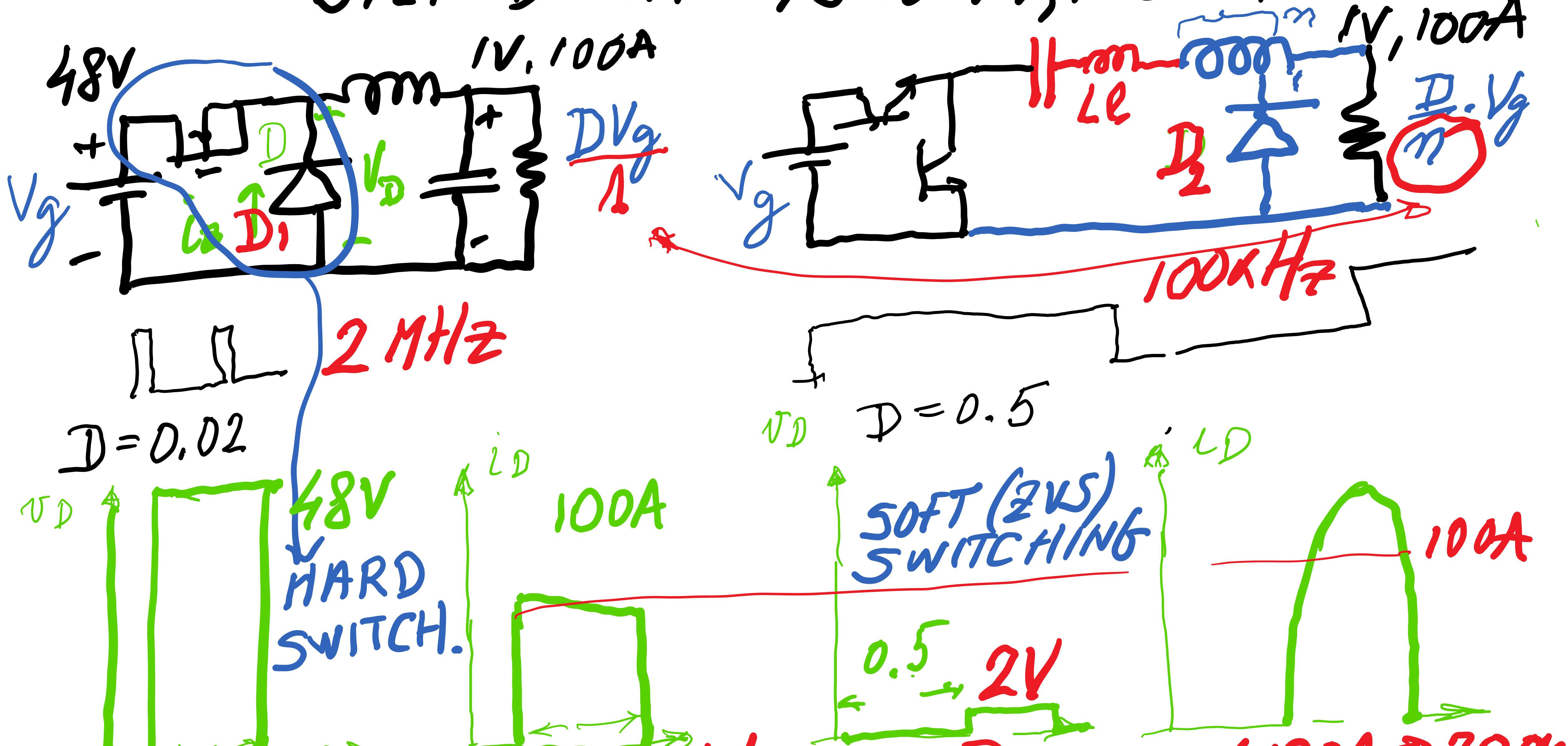
Fig.3a

Fig.2b

Fig.3b



STEP-DOWN 48 to 1V, 100A ⇒ 100W



D1 ⇒ 100V, 100A ⇒ 10kW

D2 ⇒ 2V, 100A ⇒ 200W

LARGE VOLTAGE STEP-DOWN

BUCK - SYNCH rectifier

PROBLEM

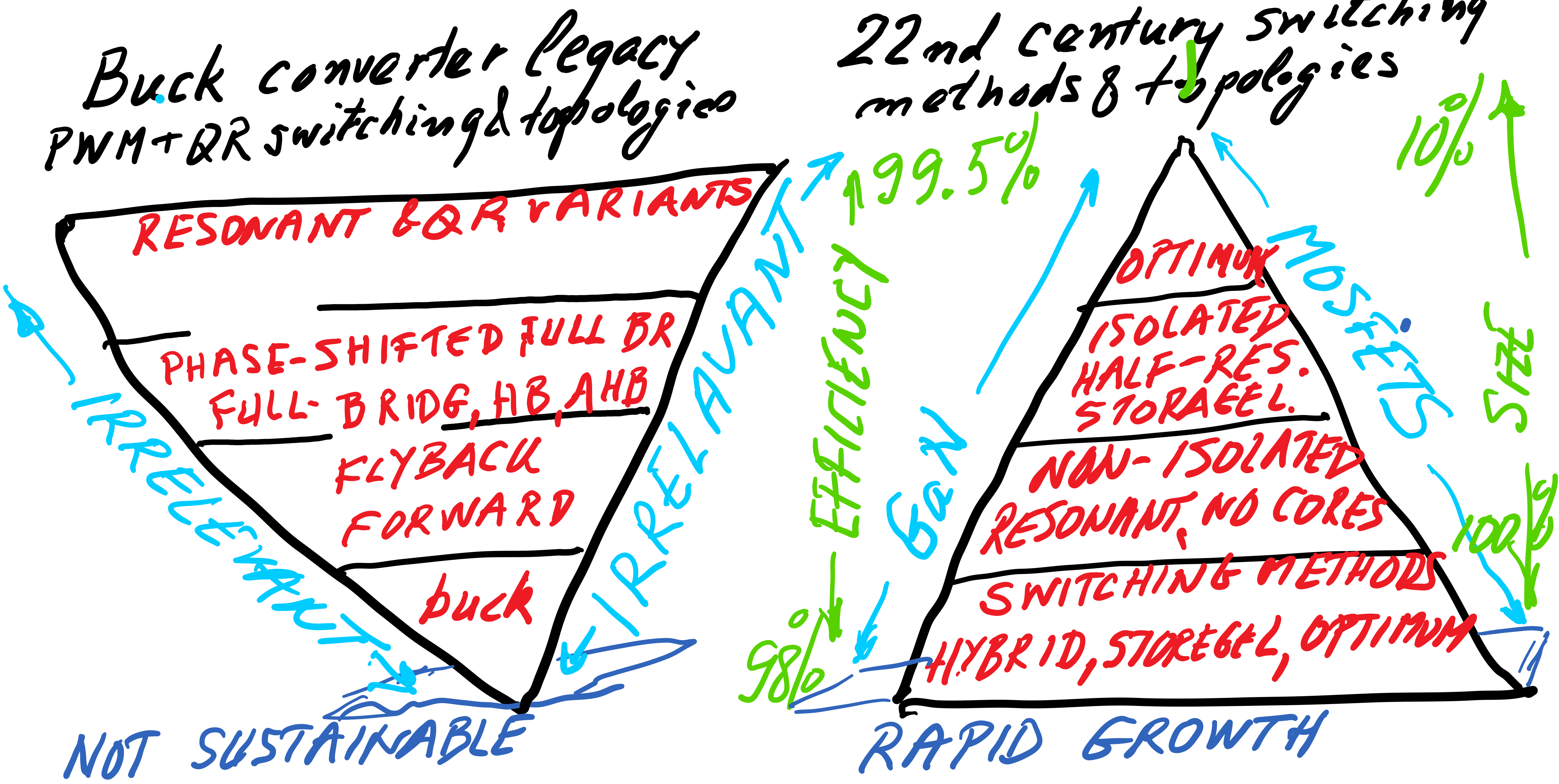
- HUGE VOLTAGE STRESS ⇒ 100 V_{out}
- MAXIMUM CURREN 100A @ SWITH
- HARD SWITCHING
- SIZE ⇒ BUCK 2 TIMES LAR.
- NO ISOLATION
- 400V - 1V ⇒ IMPOSSBLE

ĆUK - buck 2 - SYNCH.

SOLUTIONS

- LOW VOLTAGE ST. = 2 V_o
- ZERO CURRENT & SW.
- SOFT (ZVS) SWITCHING
- SIMLE ISOLATION
- 400V to 1 ⇒ EASY

TOPOLOGIES COMPARISON



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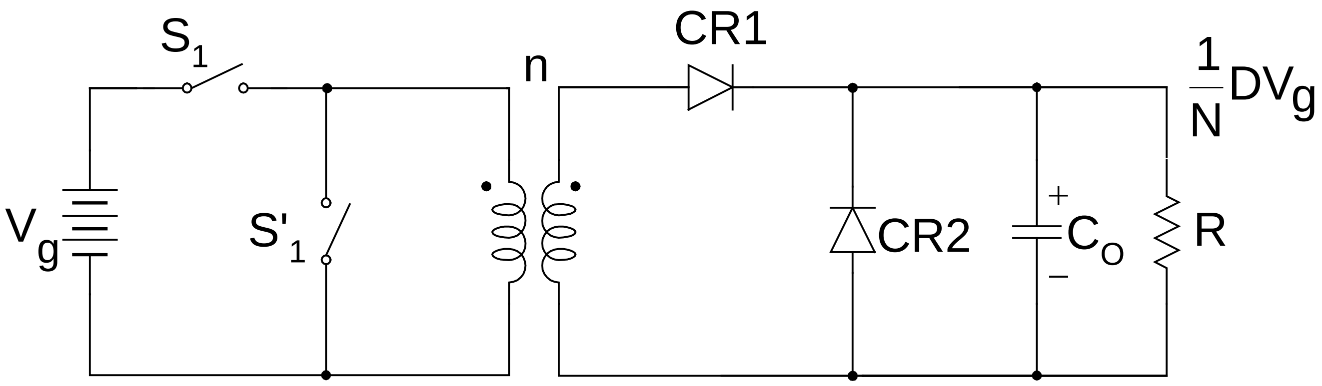
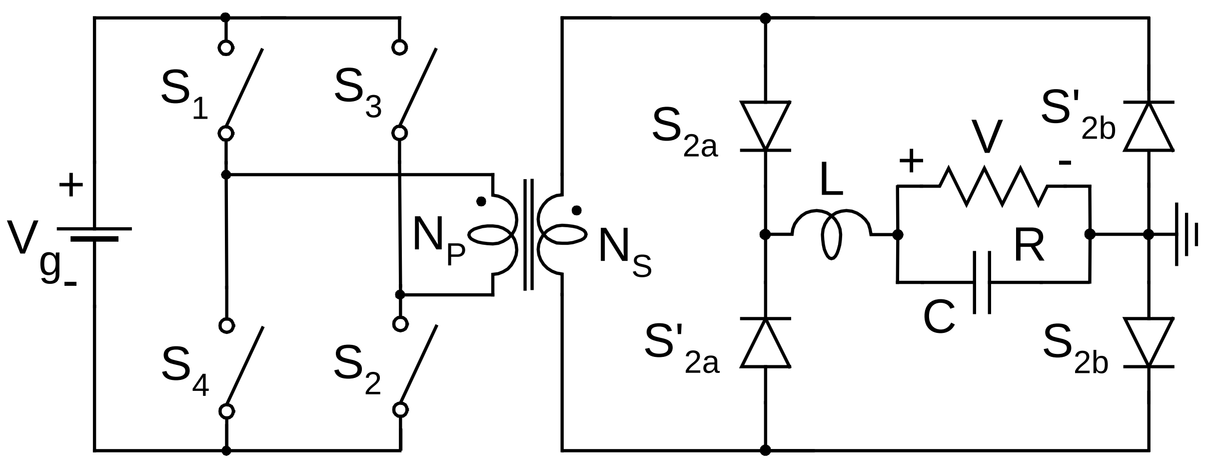
Forward and Full-bridge Converters





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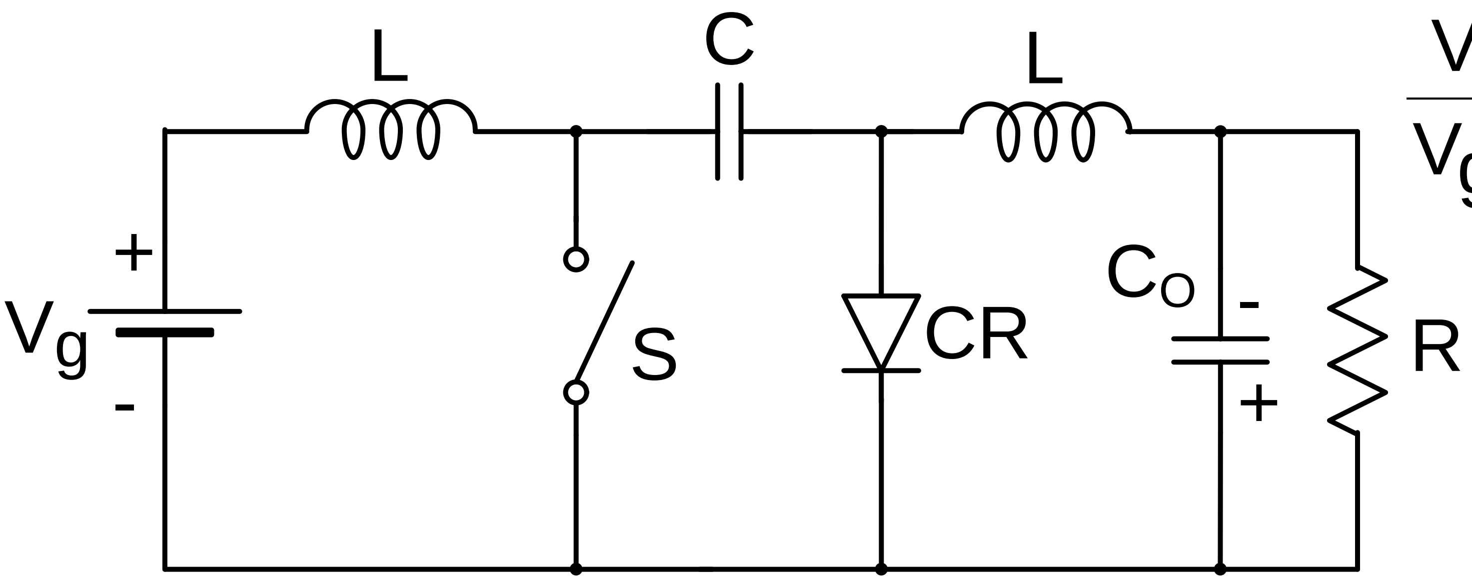
Optimum Topology Ćuk Converter

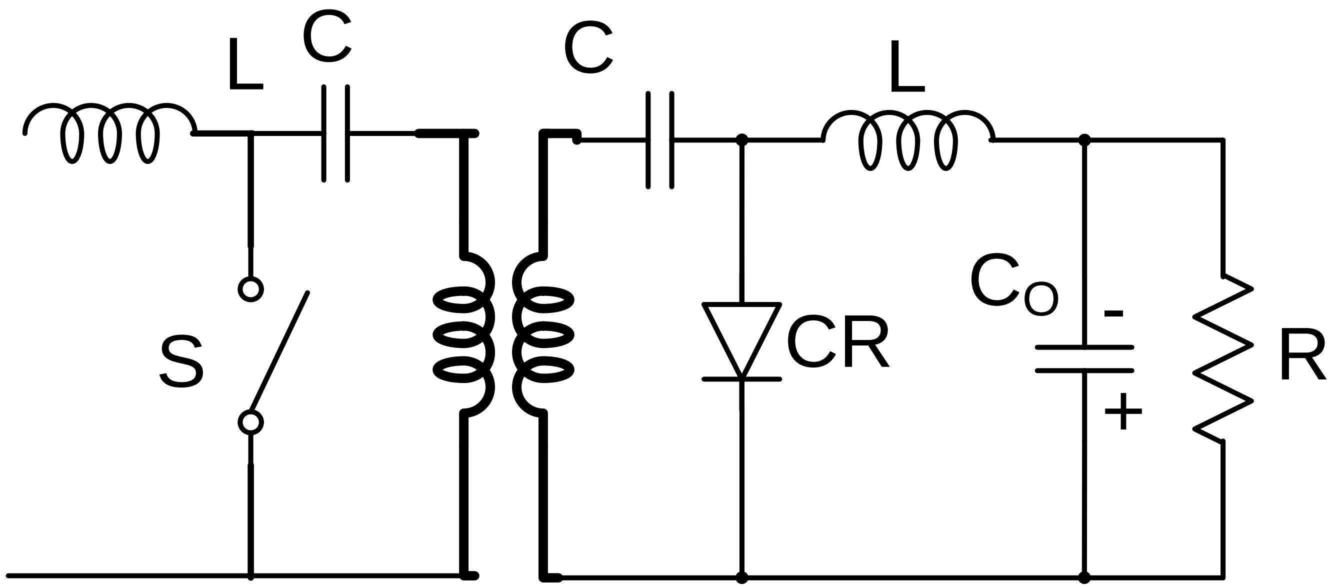


$$\frac{V}{V_g} = \frac{D}{1-D}$$

Step-down/Step-up
"Cuk" converter

CONFIDENTIAL

Optimum Topology Isolated Ćuk Converter



Split floating capacitor into two capacitors in series break their connection & insert an isolation transformer

40 Year Anniversary of:

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

*Slobodan Ćuk and R.D. Middlebrook "Advances in Switched-Mode Power Conversion" Vol. I, II, III, TESLAco, 1983

Problems of classic converter topologies:

1. Large Number of Switching Devices (6 to 14).
2. Excessive switch voltages stresses (3 to 4 times).
3. Large turn-on and turn-off device losses.
4. Hard switching and large switching losses.
5. Transformer leakage inductance losses.
6. Transformer ten times larger than possible.

Conclusion: No fancy new switching devices can fix these inherent deficiencies of the converter topologies now more than 50-years old! Marginal improvements!

New approaches needed offering simultaneously much higher efficiencies, much reduced sizes and costs.

A New Beginning for Power Electronics Systems:

1. Converters with extra capacitive energy transfer
2. New switching methods:
   a) Hybrid switching
   b) Storage-less switching
3. Resonant switching with duty cycle control
4. Transformers and inductors reduced 10 times.
5. Single-stage AC-DC conversion with PFC&isolation.

Together they lead to simultaneous large reduction sizes, losses and costs of the switching converters.

GaN device offers unique improvement over MOSFET!

Equally applicable to DC-DC, AC-DC, DC-AC conversion

Broad Power Electronics Objective

Connect Tesla's Three Phase AC Power to DC Power with an AC-DC converter operating with a high (50 kHz to 100 kHz) switching frequency and providing galvanic isolation and Unity Power Factor in a smallest possible size and highest efficiency converter.

Immediate objective:

A Fast, On-board Charger of 60kW and higher for Electrical Vehicles Providing 20 minutes Charging Time for a 300 miles Driving Range at a Fraction of Cost of External Chargers

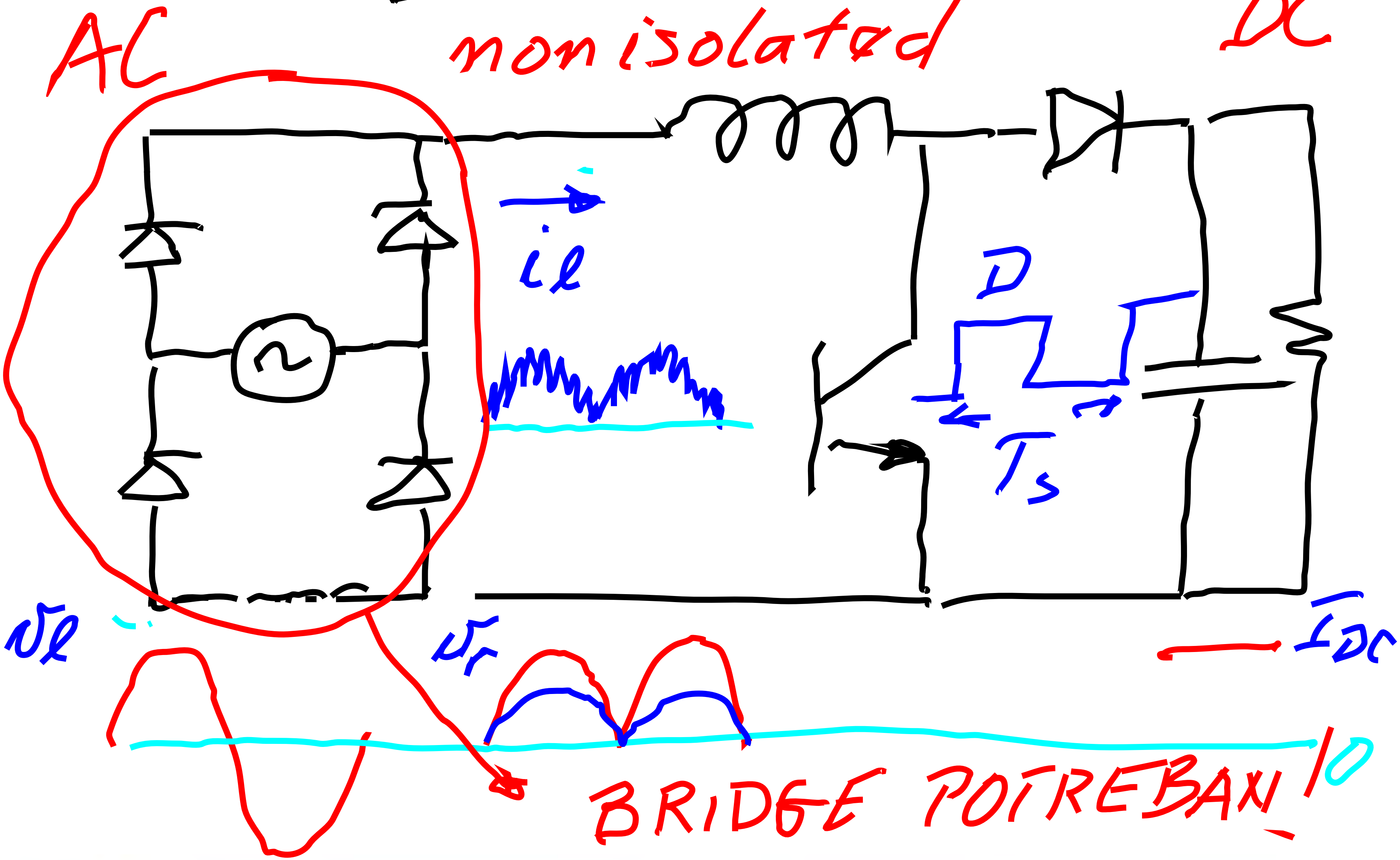
Side accomplishment: connect to smart utility grid

NISAN LEAF: 50 MILES RANGE

25 KWh BATTERY CAPACITY

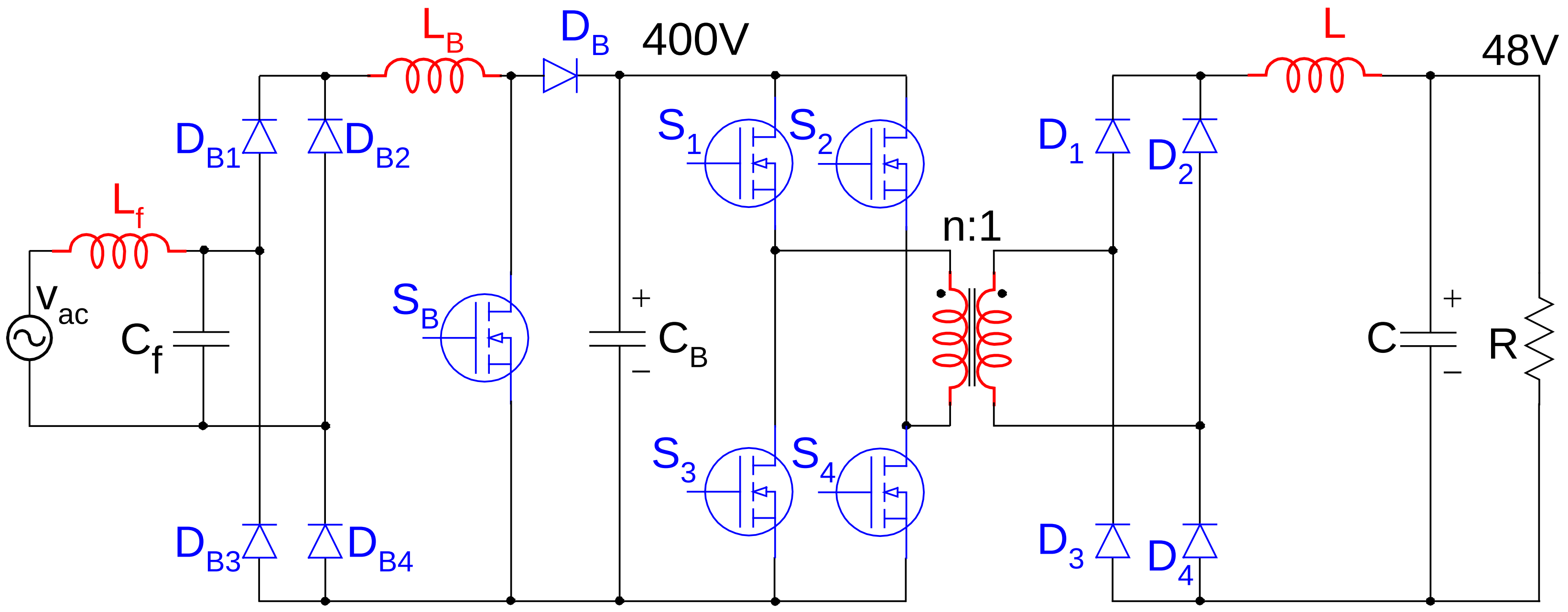
BOOST PFC

non isolated



TESLAco

Conventional Three Power Processing Stages Approach



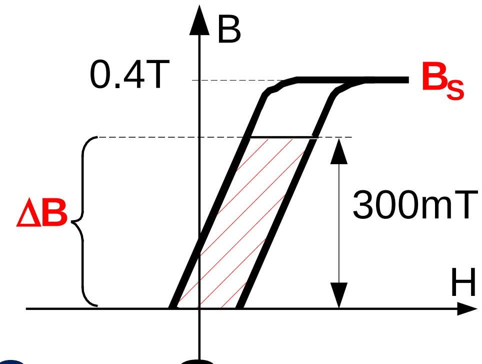
Low efficiency of 90%

14 switching devices

Large magnetics size

Full-Bridge Flux Comparison at 100kHz and 1 MHz

Operating at 100kHz, 300mT

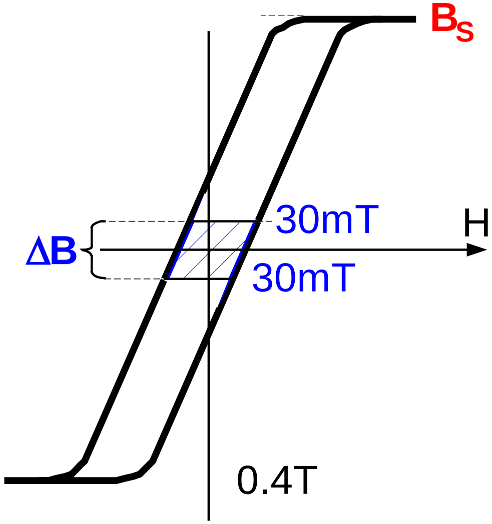


"Low" frequency Ferrite material

Same 100mW/cm3 Core losses

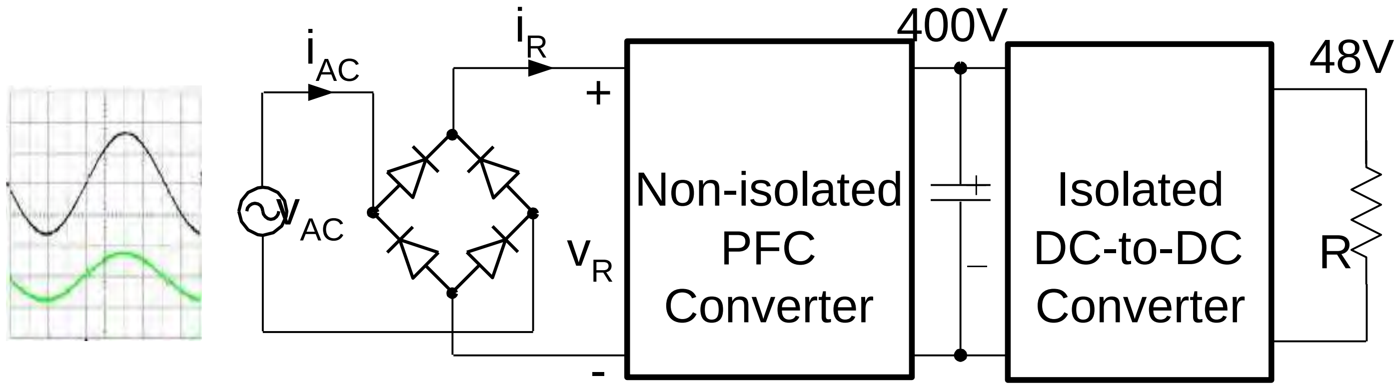
Same cross section and Number of turns

Operating at 1MHz, 30mT



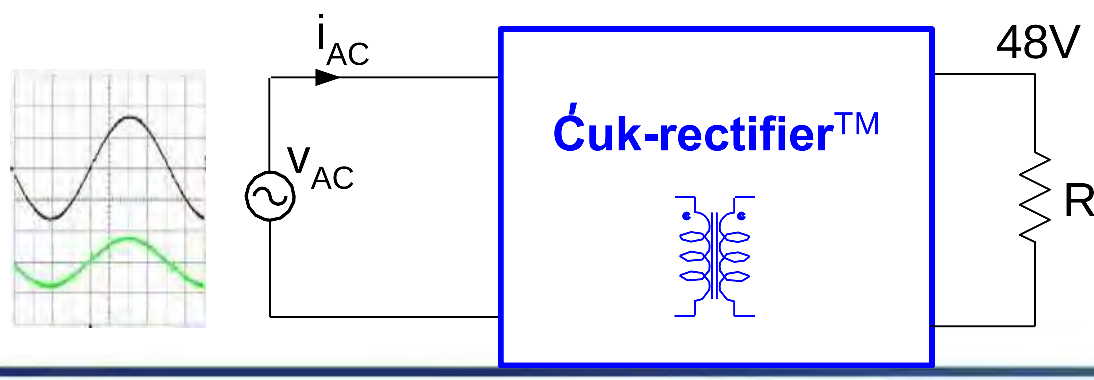
High frequency Ferrite material

Three-stage vs. One-stage Conversion



98% x 97% x 95% = 89%

AC-to-DC efficiency of conventional solution is 89%



Paradox

Battery Charger: 150 kHz

30 kW

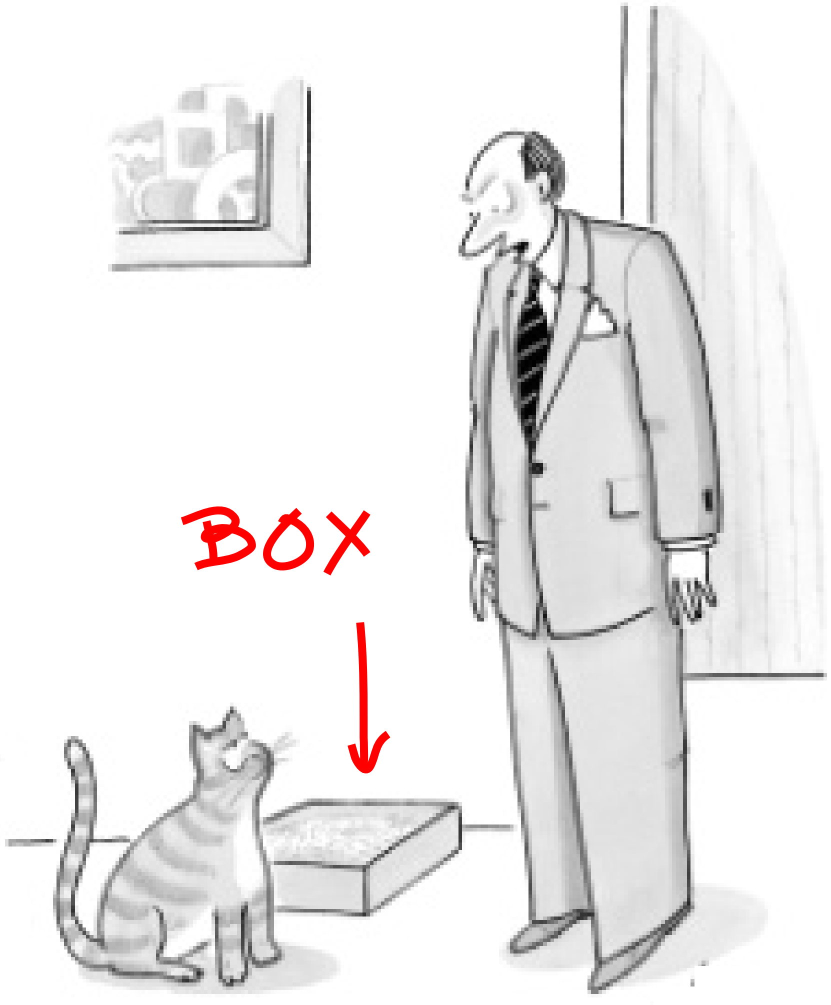
TESLA motor 1.5 kHz

150 kW

Frequency ratio: 100 times

Size ratio: 10 times

Nikad nemoj
da razmisljas
van kutije



Never, ever think outside the box

CUT THE CORD!

Improvement factor

Weight ratio x Loss ratio x Cost ratio

10 10 10 = 1000

Required improvement factor is 1000

IS THIS POSSIBLE? YES ! WHY?

Converter topologies have not changed for last 50 years: A New Beginning is Needed!

True Bridgeless

PFC Converter

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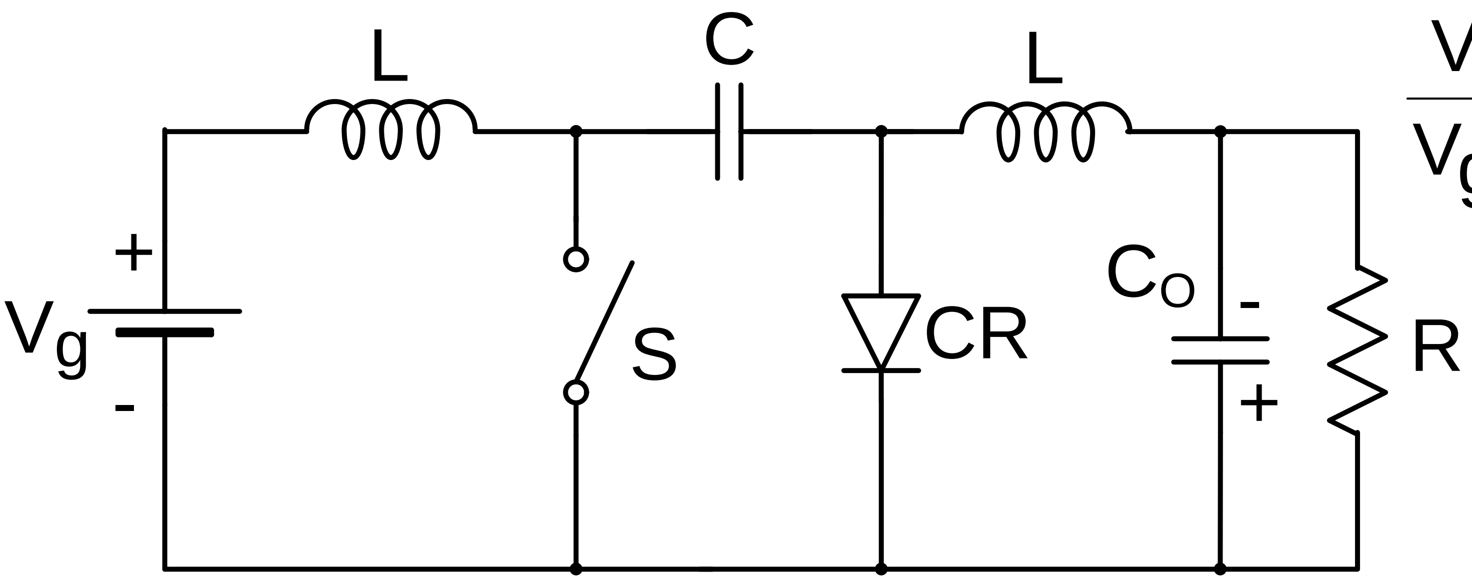
Optimum Topology Ćuk Converter

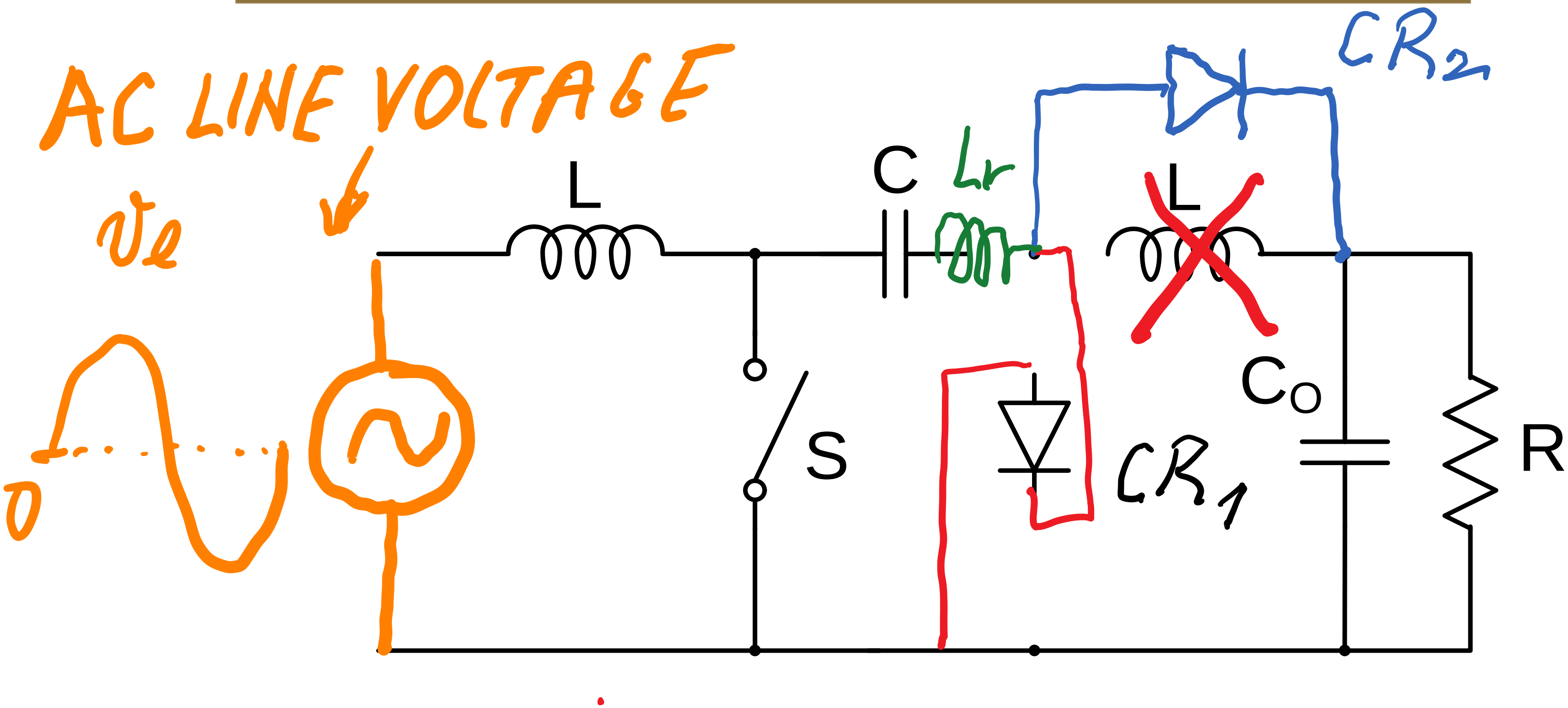


$$\frac{V}{V_g} = \frac{D}{1-D}$$

Step-down/Step-up
"Cuk" converter

CONFIDENTIAL

Optimum Topology Ćuk Converter



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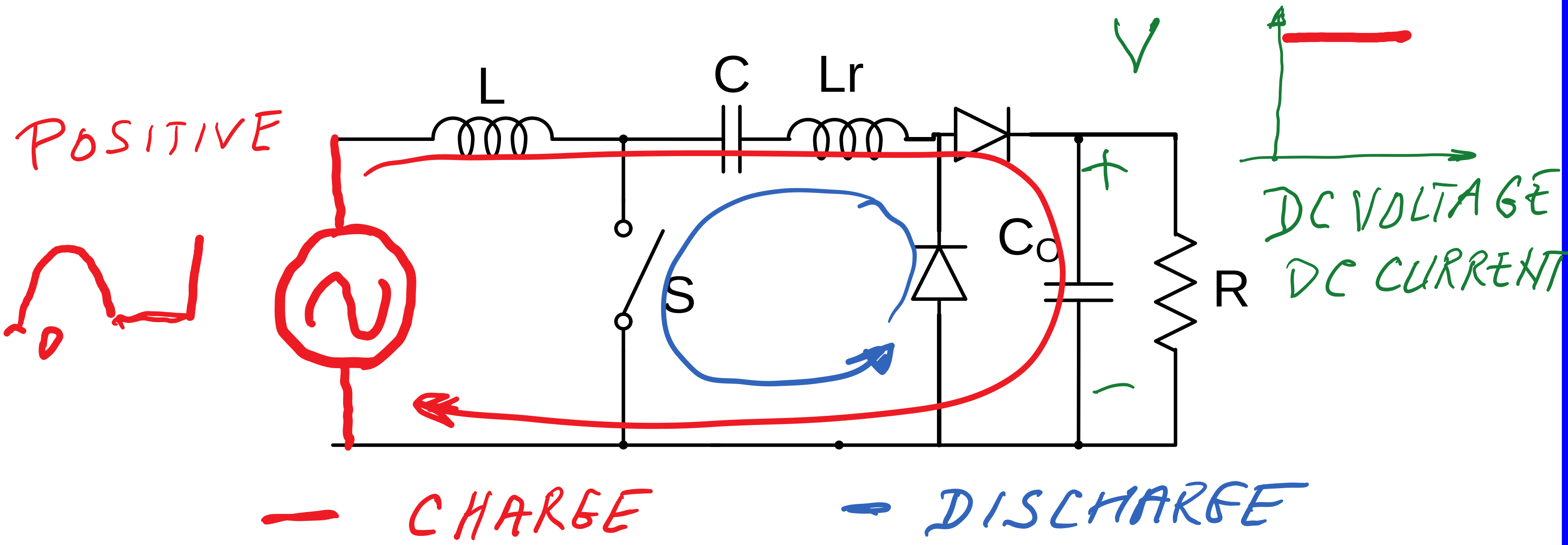
Optimum Topology Ćuk Converter Mofidied into an AC-DC Cuk2 converter



Modifying DC-DC Ćuk converter into an AC-DC Ćuk2 converter with Power factor Correction (PFC)

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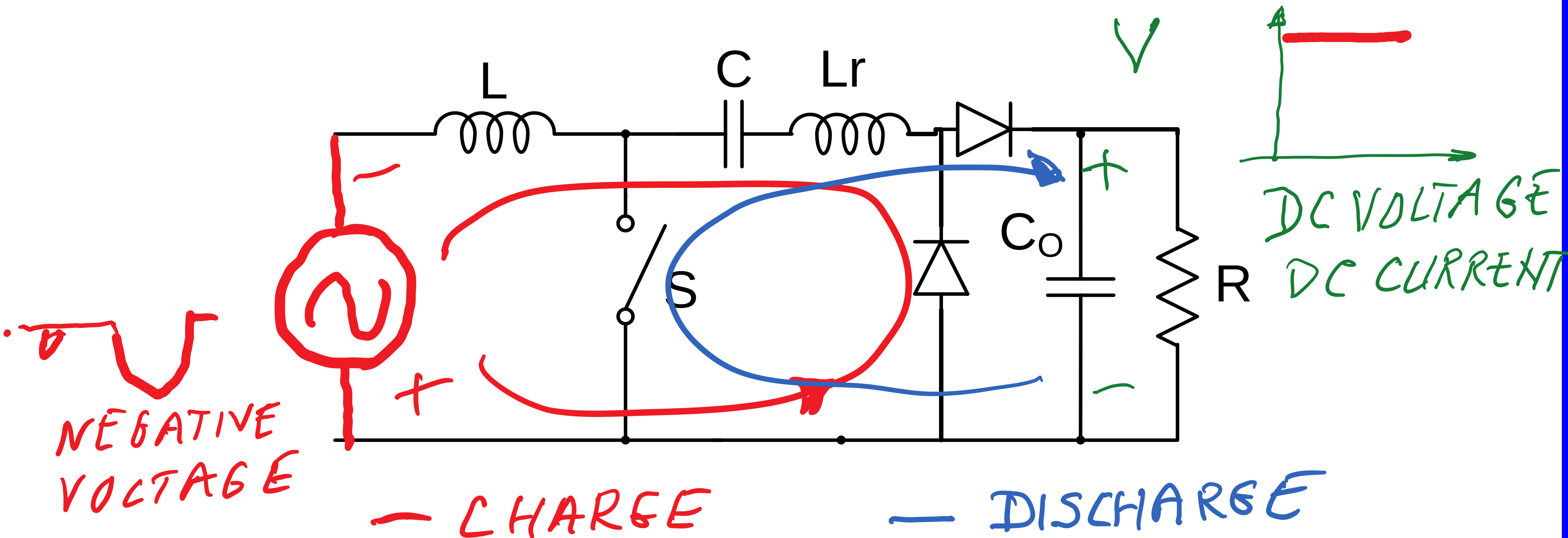
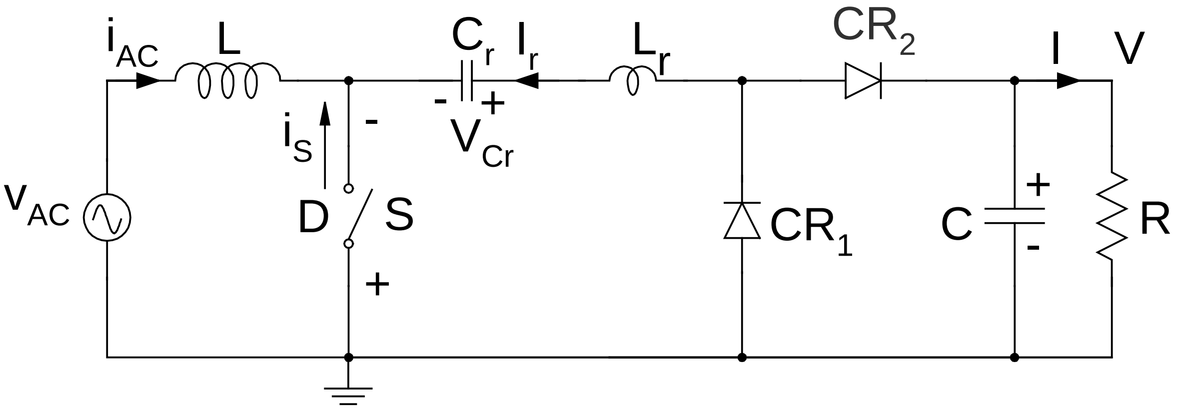
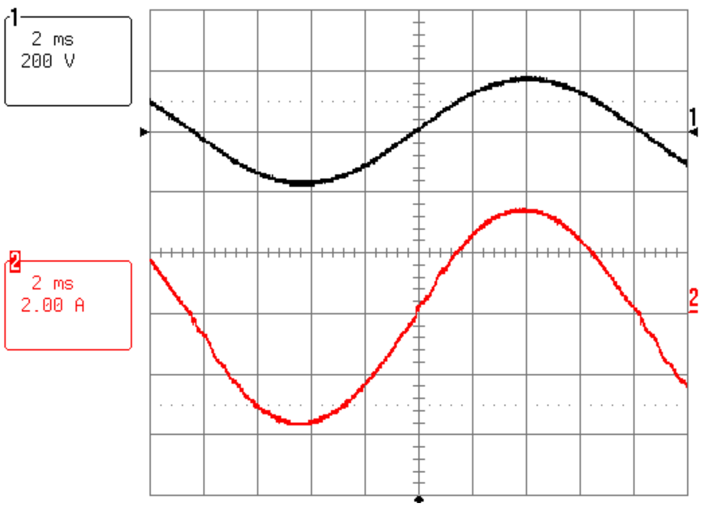
Optimum Topology Ćuk Converter Mofidied into an AC-DC Cuk2 converter



Modifying DC-DC Ćuk converter into an AC-DC Ćuk2 converter with Power factor Correction (PFC)

True Bridgeless PFC Converter*





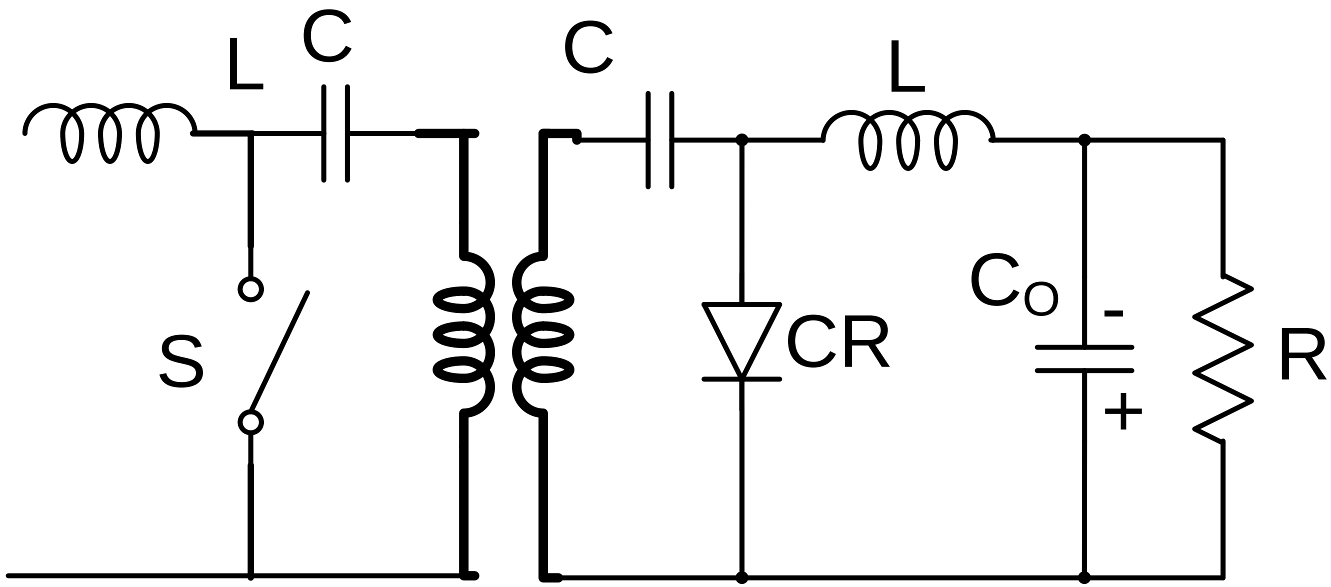
Input Voltage 110V

THD=1.7%
PF=0.999

***US and foreign patents pending**

CONFIDENTIAL

Optimum Topology Isolated Ćuk Converter



Split floating capacitor into two capacitors in series break their connection & insert an isolation transformer

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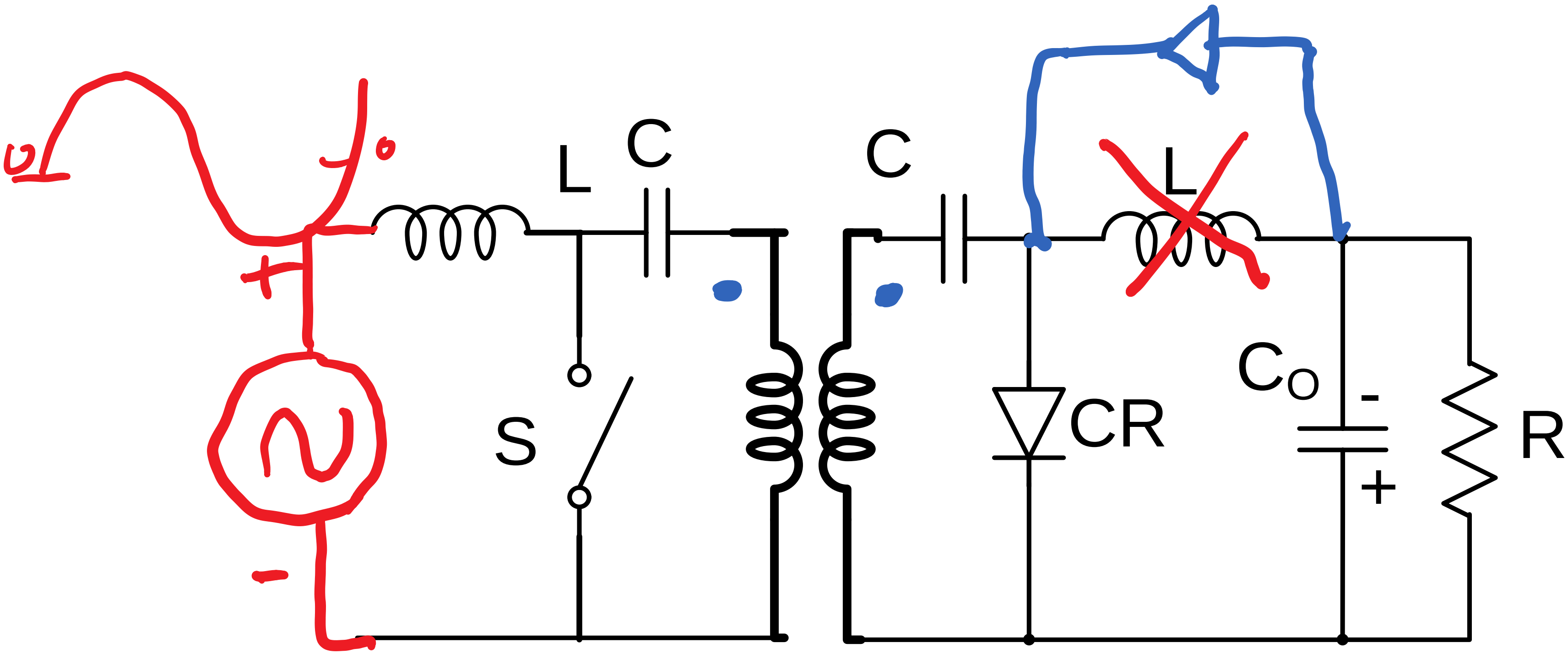
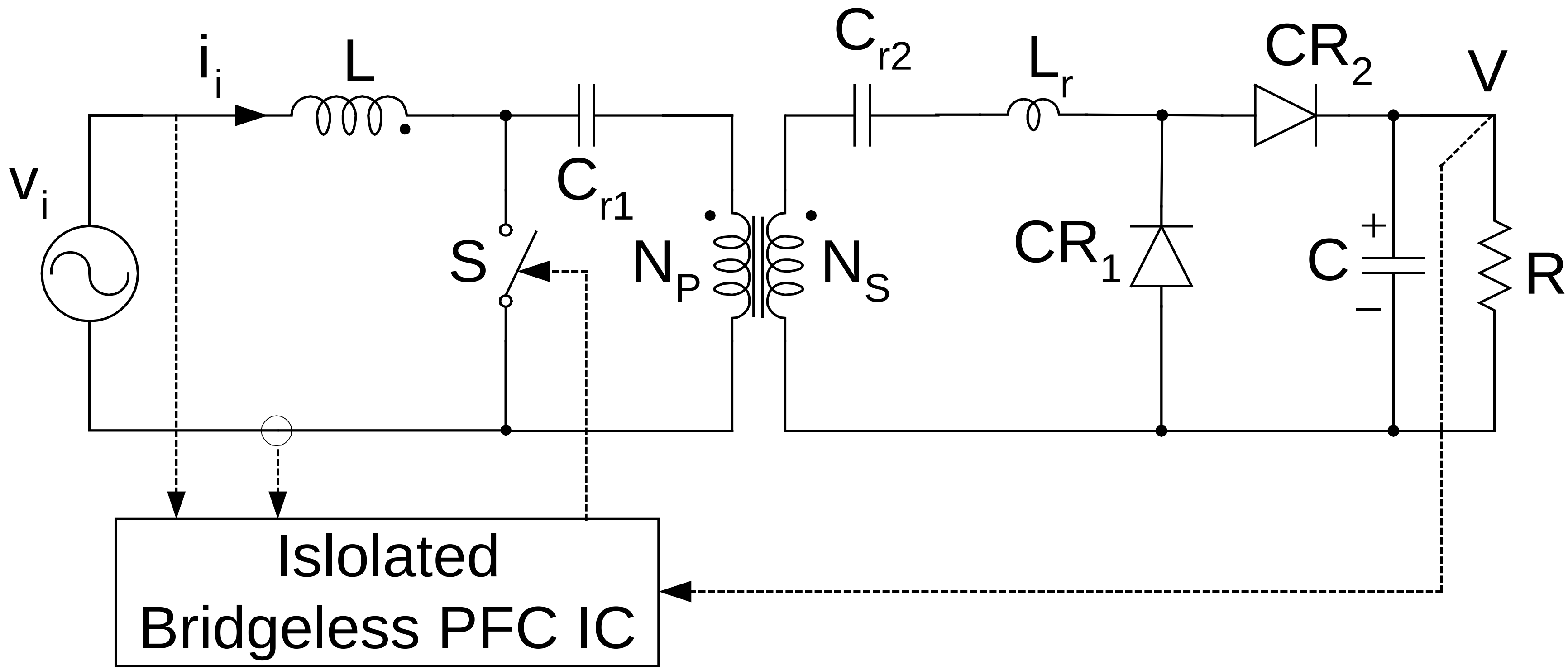
Optimum Topology Isolated Ćuk Converter



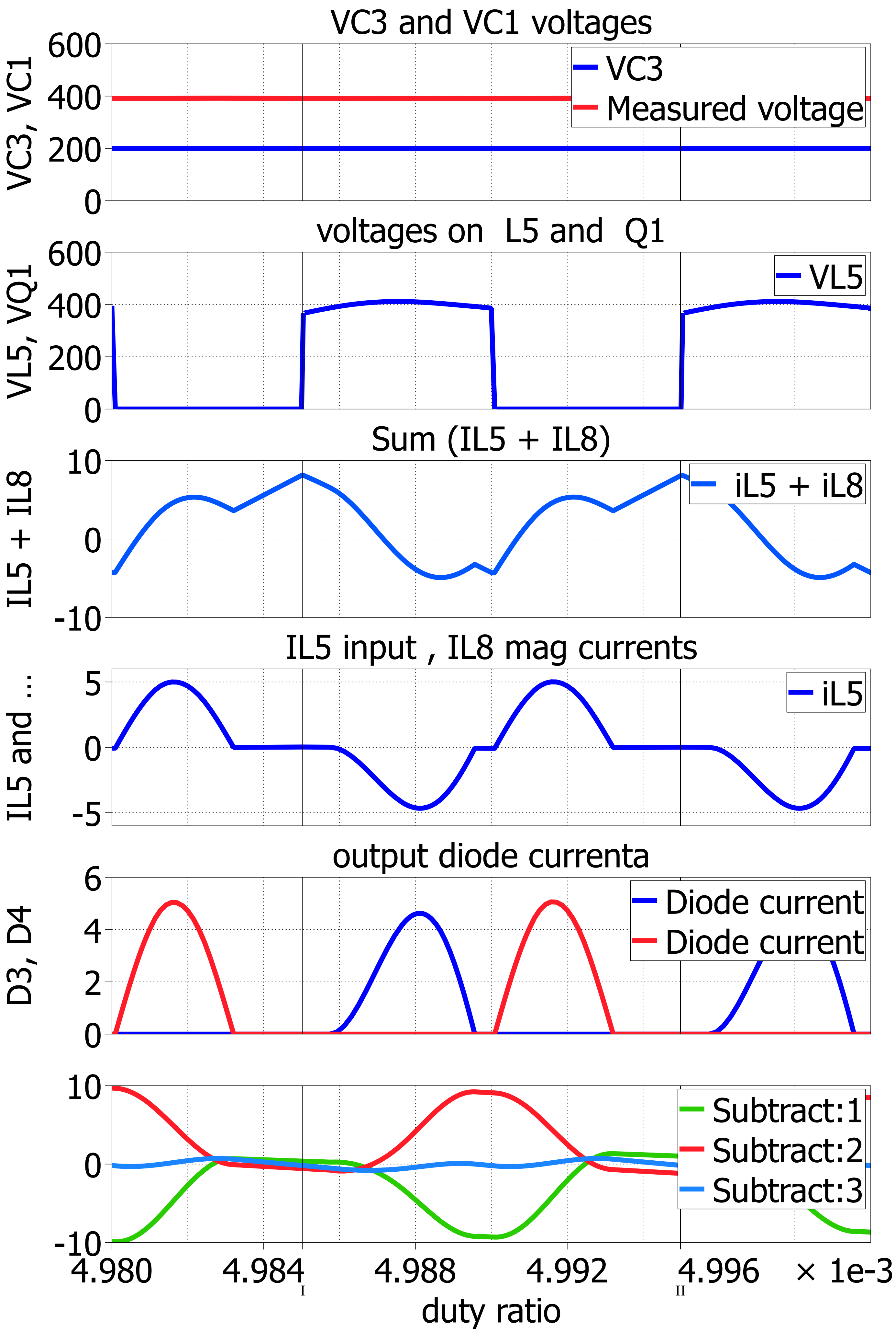
Split floating capacitor into two capacitors in series break their connection & insert an isolation transformer

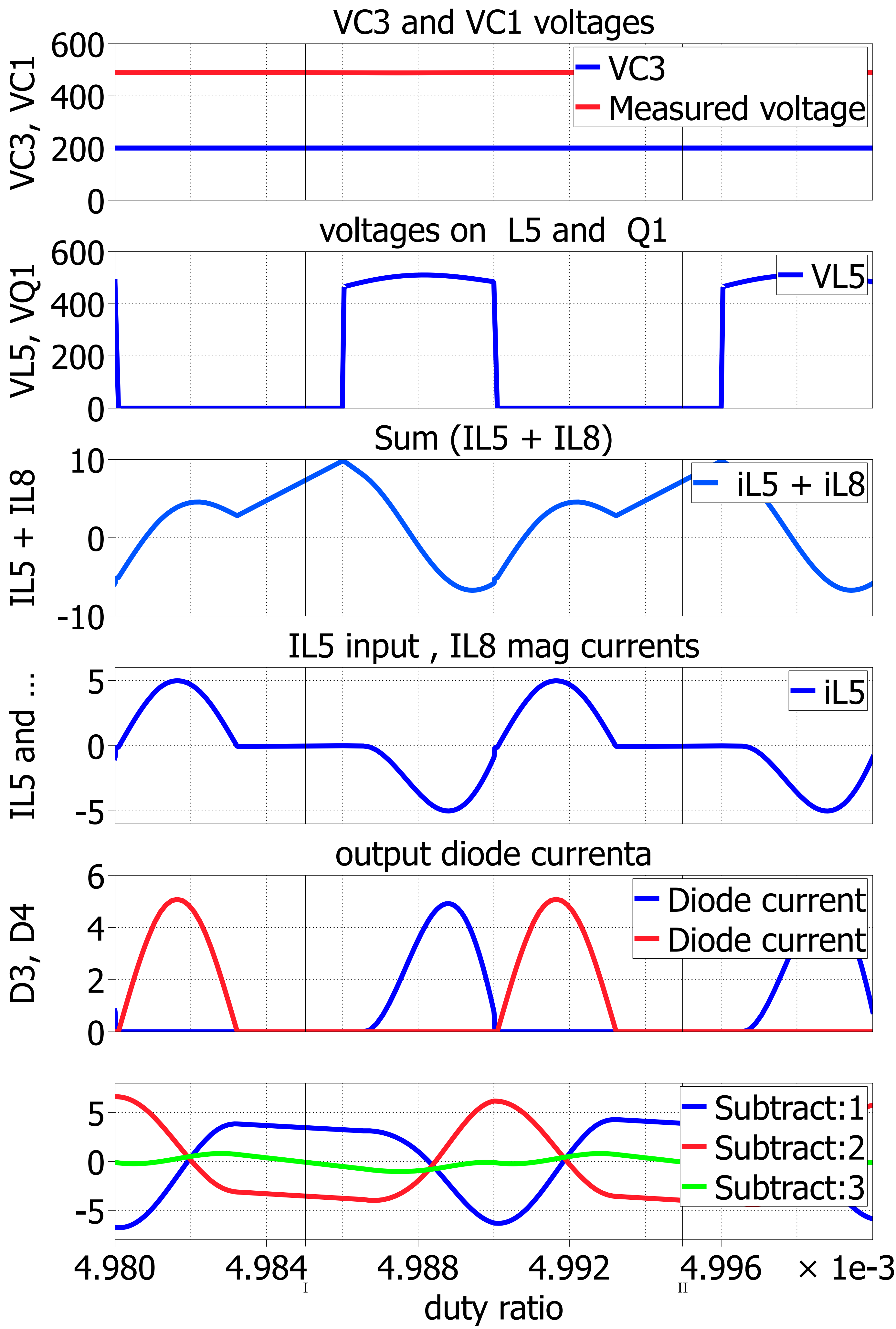
AC-DC Converter for Each Phase with PFC and Isolation*



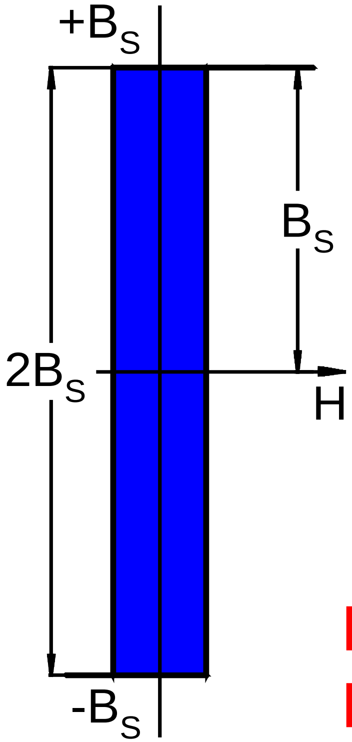
Three Switches Only

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


VC3 and VC1 voltages
VC3, VC1
600
400
200
0
VC3
Measured voltage
voltages on L5 and Q1
VL5, VQ1
600
400
200
0
VL5
Sum (IL5 + IL8)
IL5 + IL8
10
0
-10
iL5 + iL8
IL5 input , IL8 mag currents
IL5 and ...
5
0
-5
iL5
output diode currenta
D3, D4
6
4
2
0
Diode current
Diode current
10
0
-10
Subtract:1
Subtract:2
Subtract:3
4.980
4.984
4.988
4.992
4.996
× 1e-3
I
II
duty ratio


VC3 and VC1 voltages
VC3, VC1
600
400
200
0
VC3
Measured voltage
voltages on L5 and Q1
VL5, VQ1
600
400
200
0
VL5
Sum (IL5 + IL8)
IL5 + IL8
10
0
-10
iL5 + iL8
IL5 input , IL8 mag currents
IL5 and ...
5
0
-5
iL5
output diode currenta
D3, D4
6
4
2
0
Diode current
Diode current
5
0
-5
Subtract:1
Subtract:2
Subtract:3
4.980
4.984
4.988
4.992
4.996
× 1e-3
I
II
duty ratio

True AC Transformer

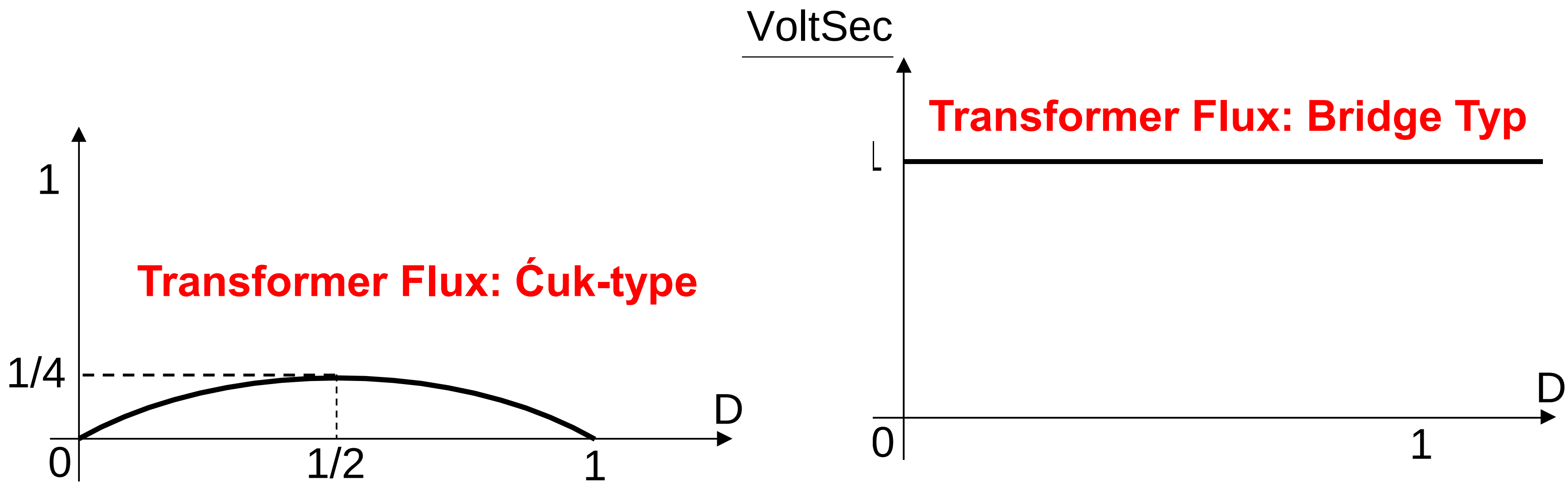


No Air-gap
No Energy Storage
Automatic Reset
Scalable to High Power

Comparison of Transformer Fluxes

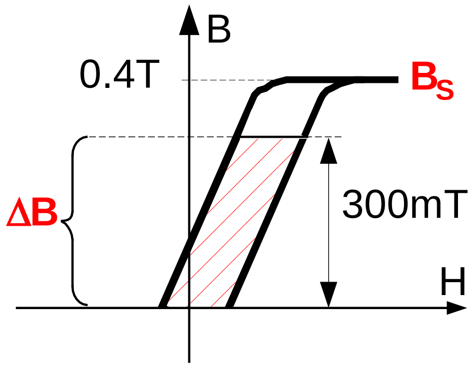
Transformer flux in Ćuk AC-DC Converter

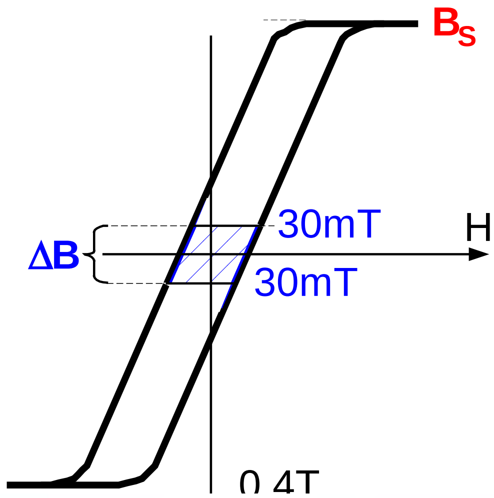
Transformer Flux in Bridge Type Converters

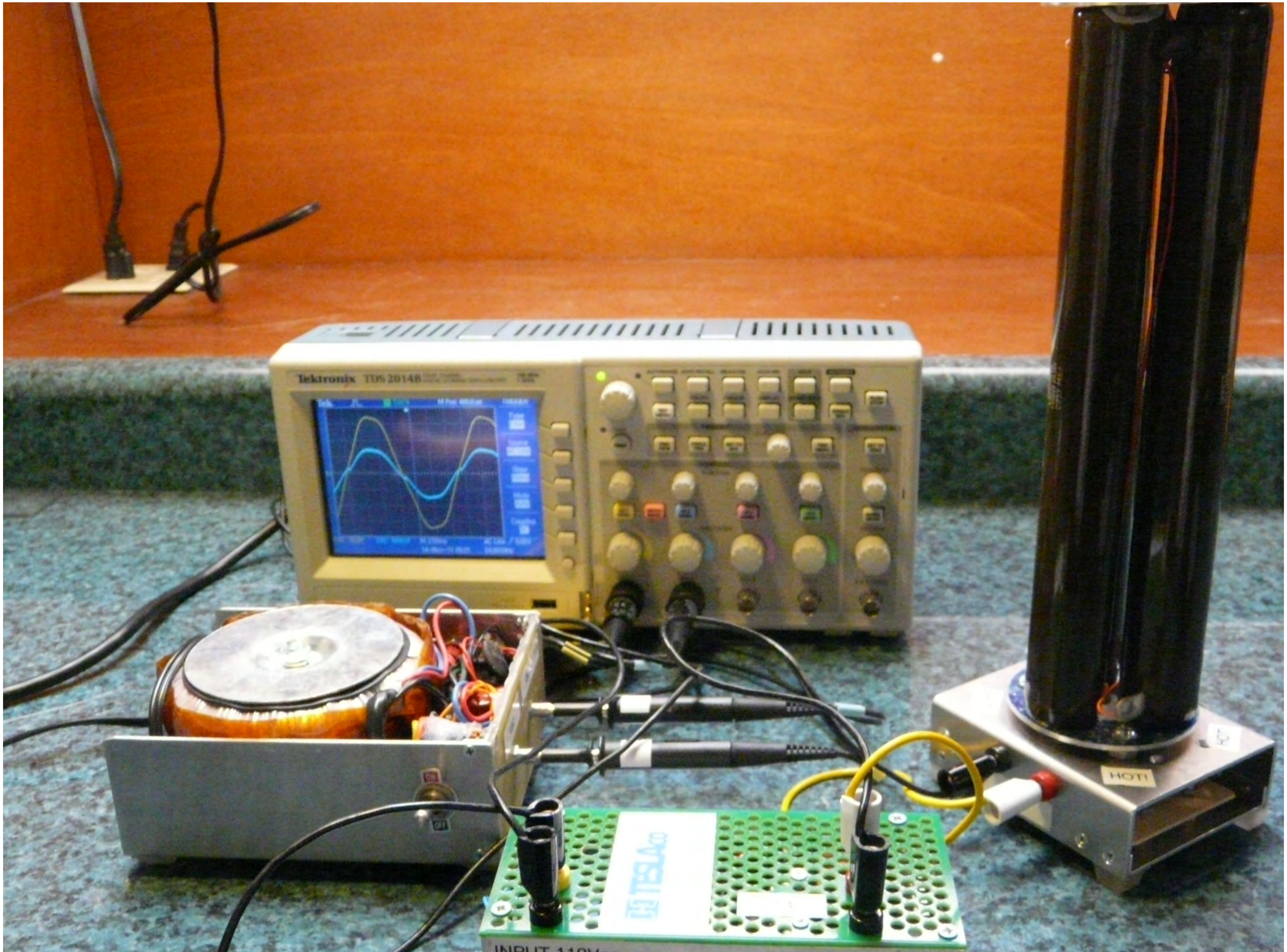


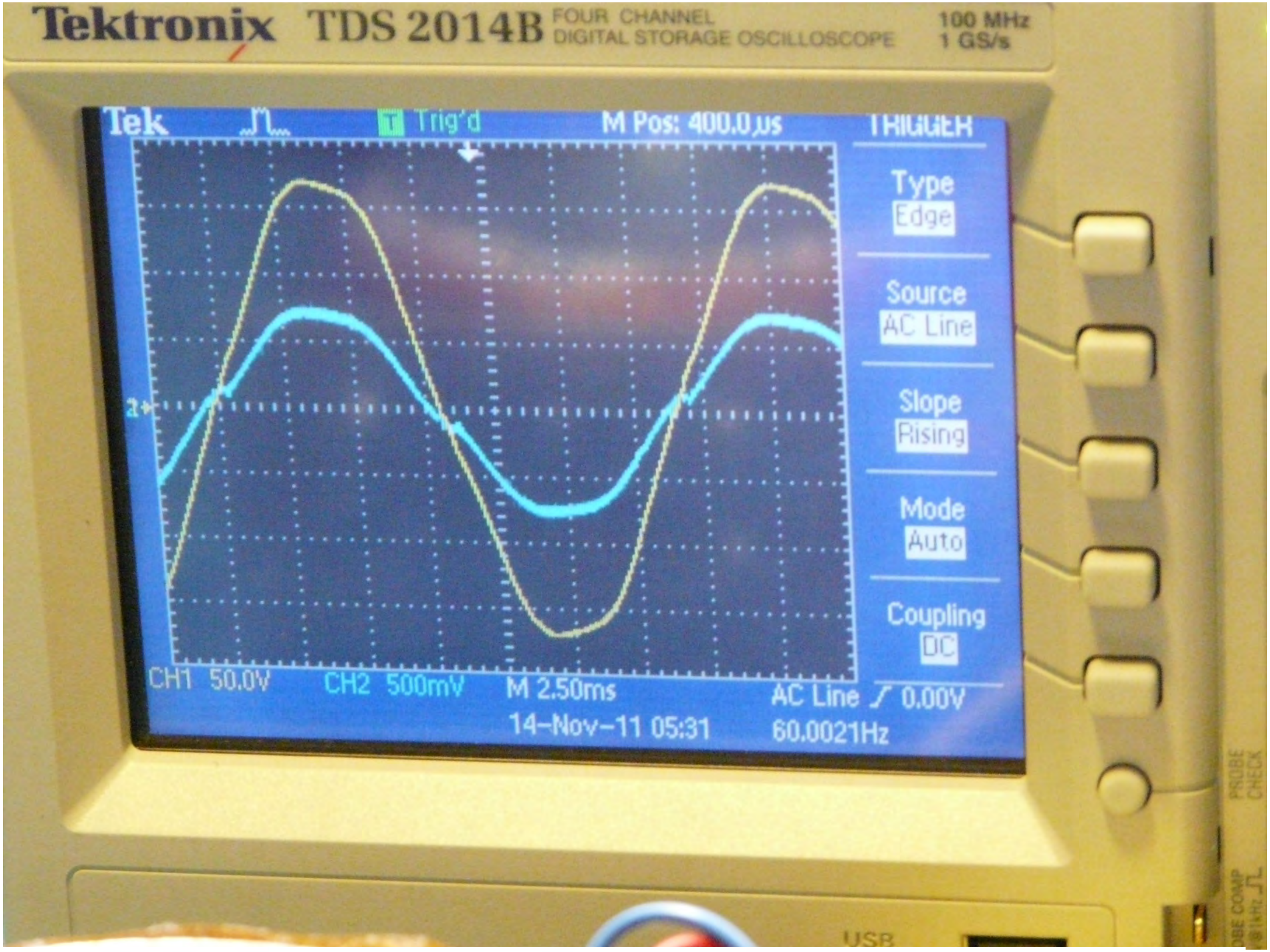
Four to ten times smaller Ćuk transformer flux

Flux Comparison with Forward Converter

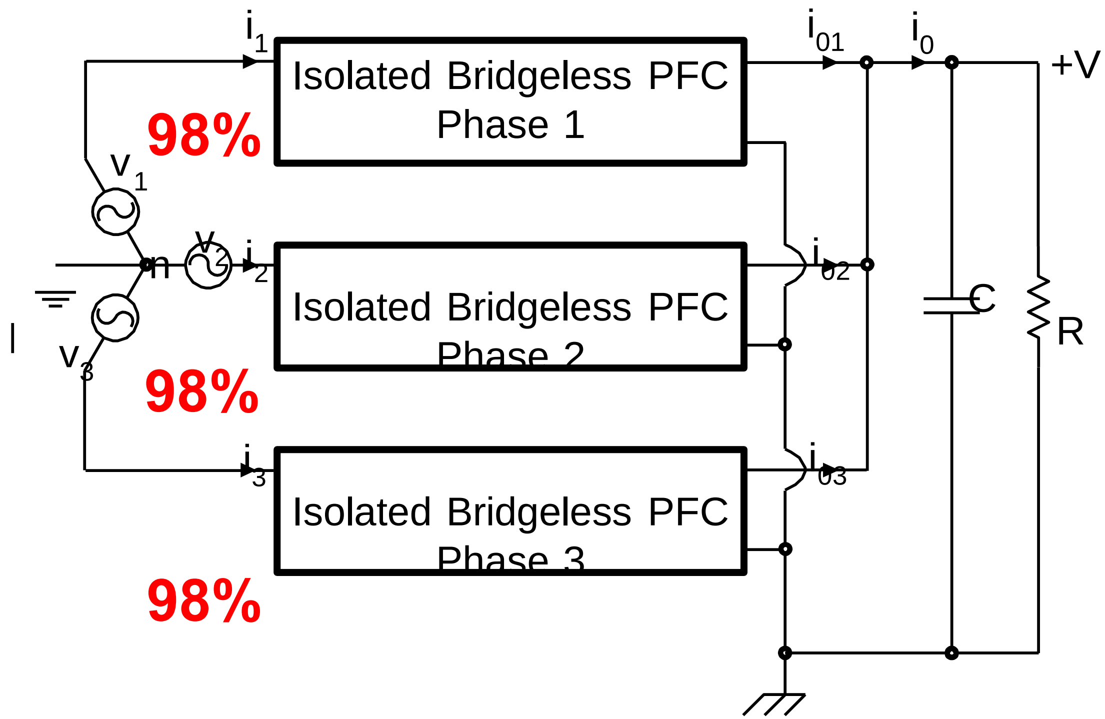





Tektronix
TDS 2014B
TESLAco
INPUT 110Vac
HOT!


Tektronix TDS 2014B FOUR CHANNEL DIGITAL STORAGE OSCILLOSCOPE
100 MHz 1 GS/s
Tek
Trig'd
M Pos: 400.0 µs
TRIGGER
Type
Edge
Source
AC Line
Slope
Rising
Mode
Auto
Coupling
DC
CH1 50.0V
CH2 500mV
M 2.50ms
AC Line 0.00V
14-Nov-11 05:31
60.0021Hz
USB

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

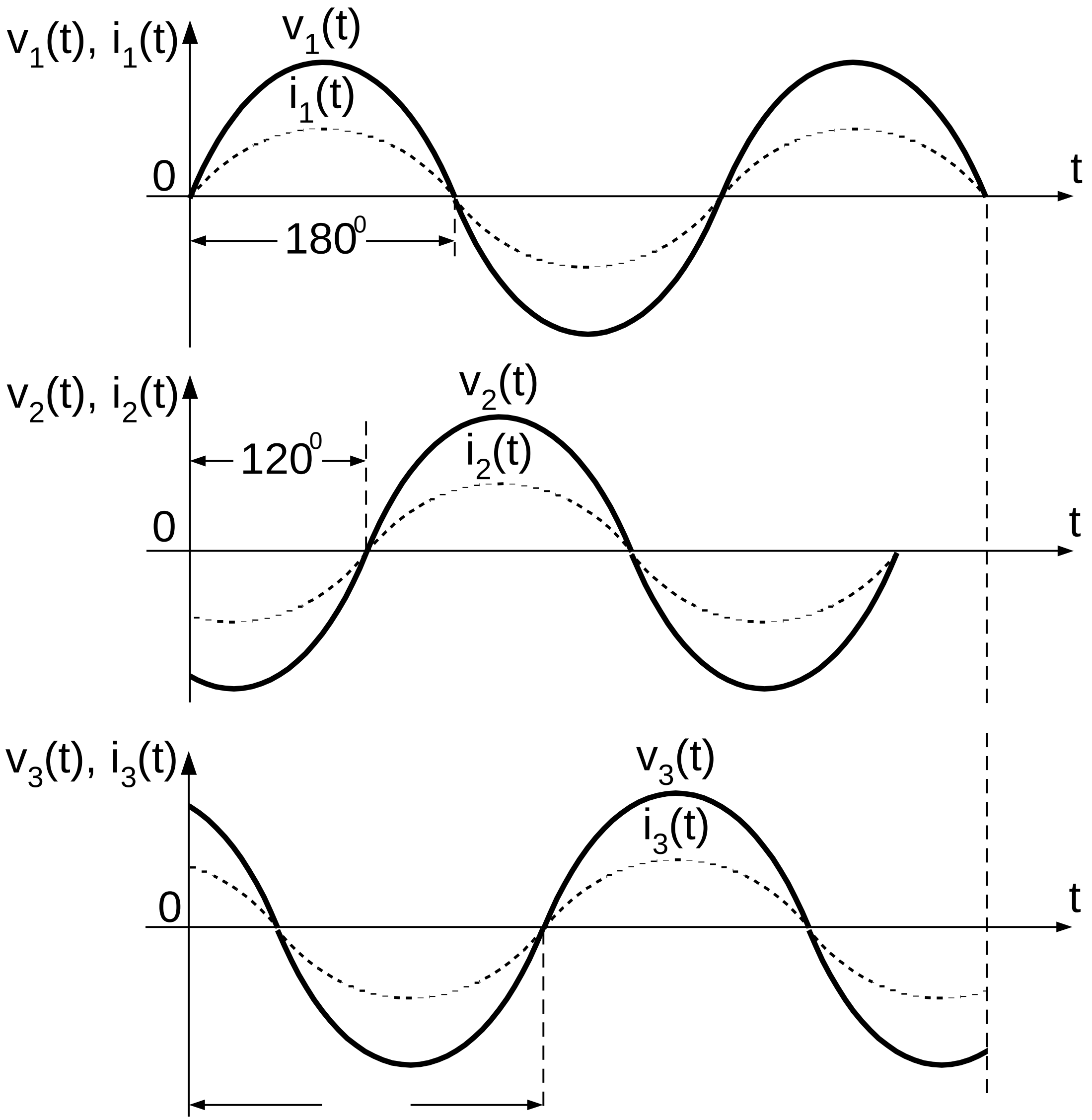


Power processed in parallel and not in series

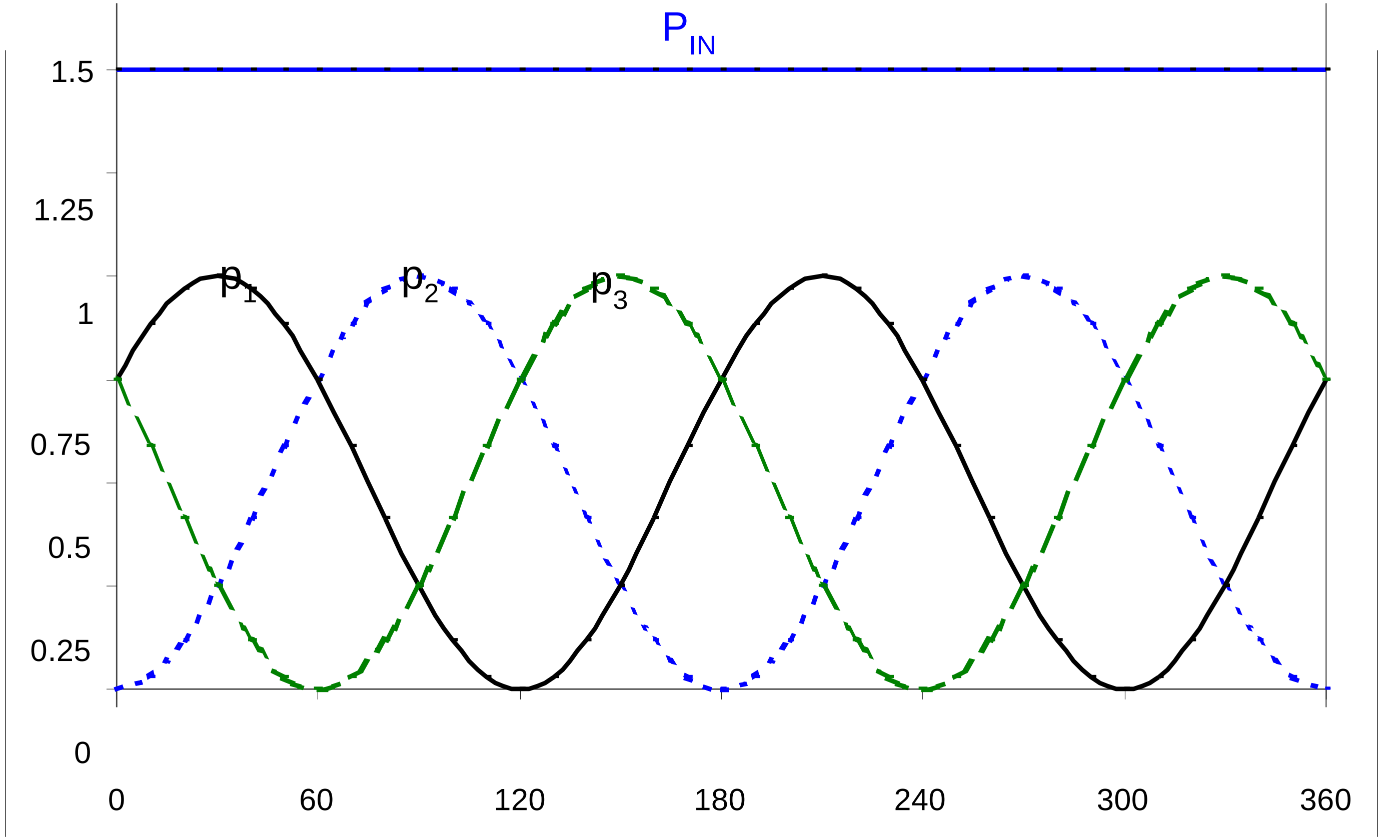
Each Phase Efficiency 98%; TOTAL Efficiency 98%

***US and foreign patents pending**

Input Voltages and Input Currents for Unity Power Factor



Sum of Instantaneous Input Powers of Three Phases is Constant



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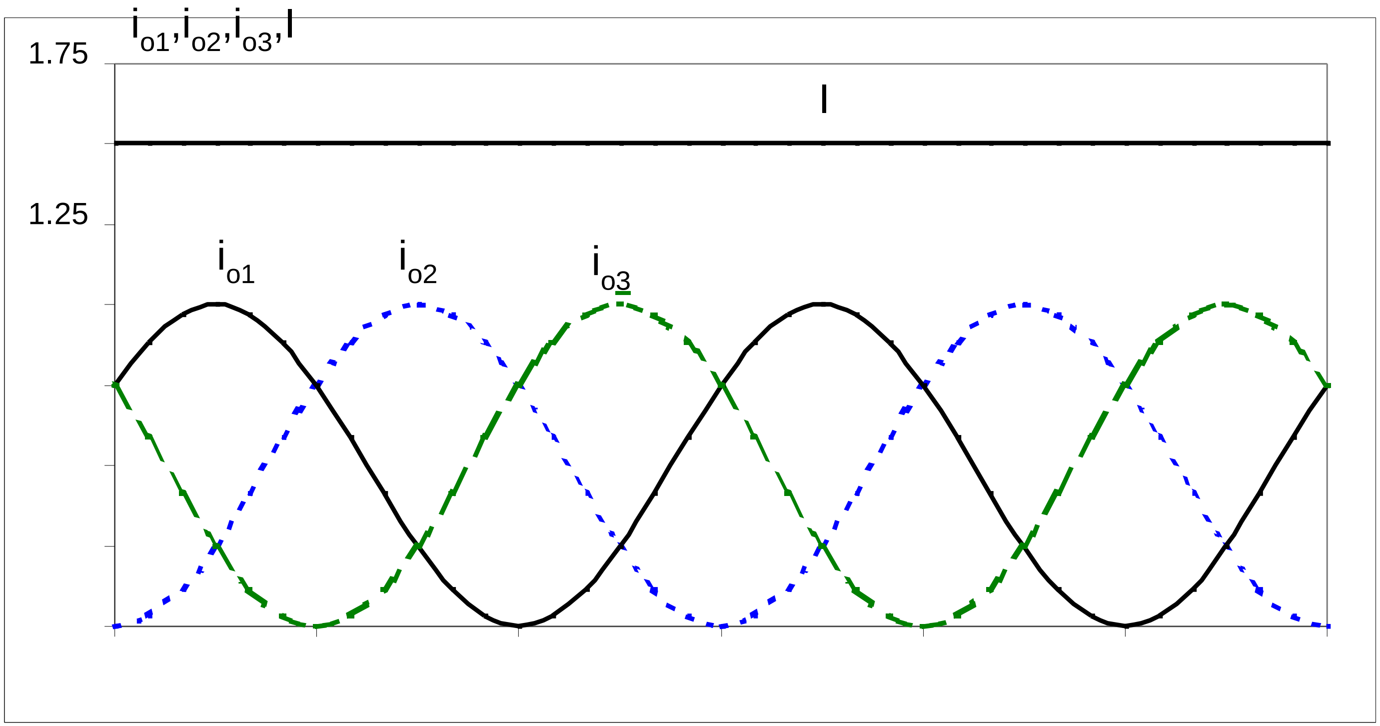
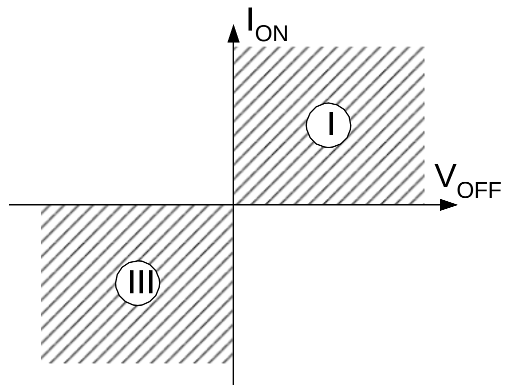
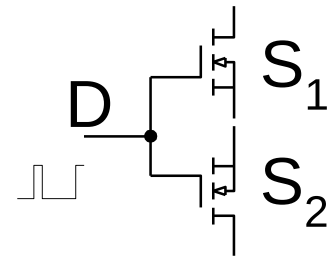
Sum of Instantaneous Output Currents of Each Phase is Constant

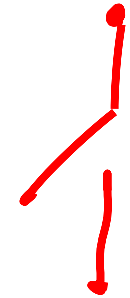


One Implementation of the Controlling Switch



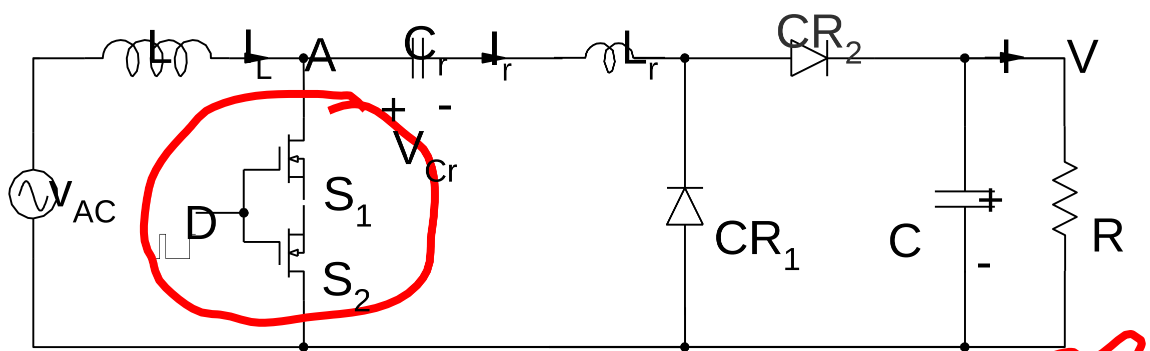
SWITCH





2 MOSFET IMPLEM

IDEAL



PROBLEM: NESTANDARDNI PREKIDAČ

IDEJA!

NOVEMBER 26, 2014

TESLAco

How did you come up with these inventions, Dad?!?

Elementary, my dear ones, I've started working on them some 40 years ago!

CUT THE CORD!

ČUKCHARGER
PHASE 2
NISSAN
Zero Emission
LEAF
DODATNO SMANJENJE
TEZINE, GUBITAKA I CENE

Phase 1 research

Dad, how did you do that!?

Elementary My Dear!

I Started Working on It 40 Years Ago!

Conclusion

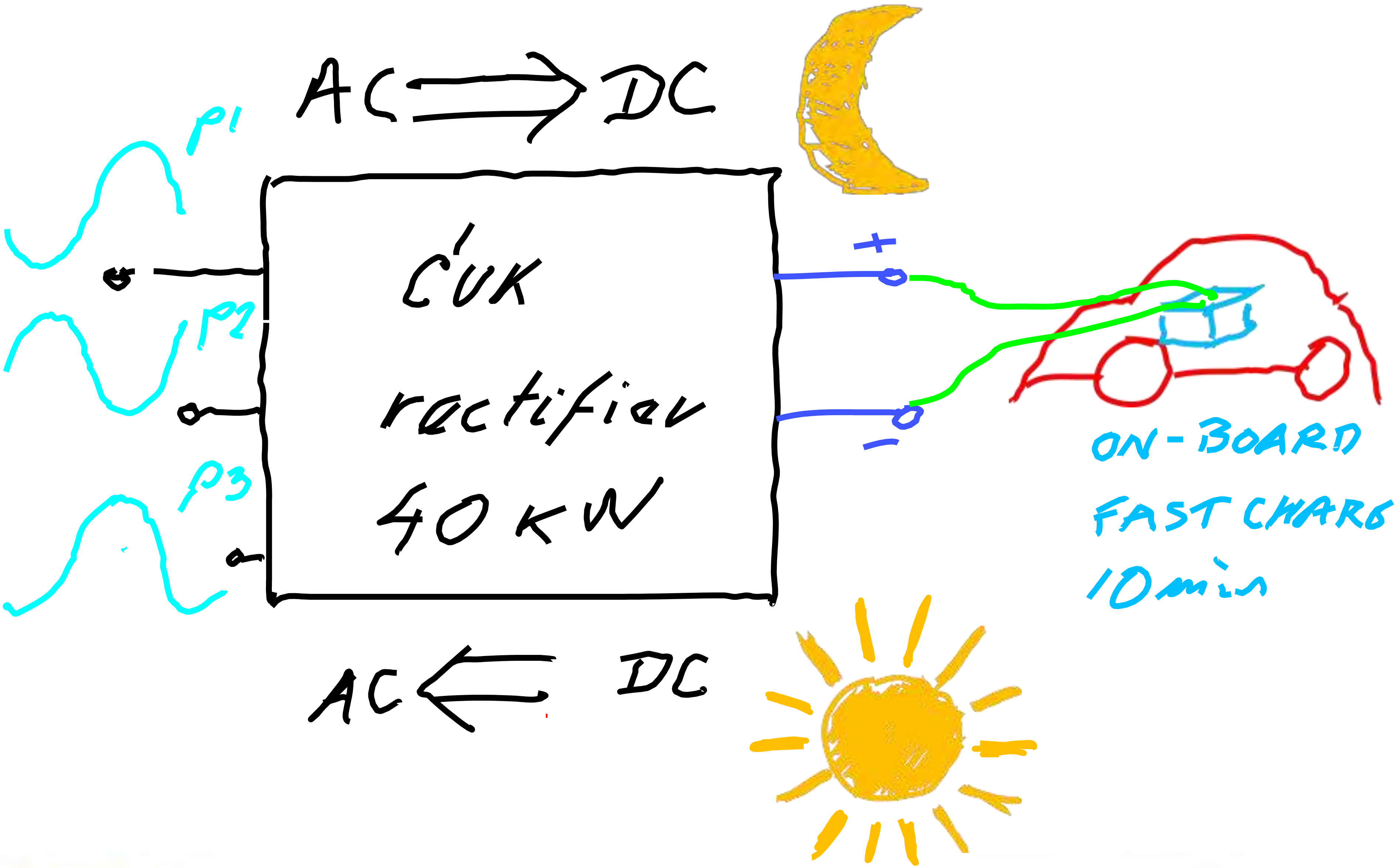
Tesla's Three-Phase

Alternating AC Currents

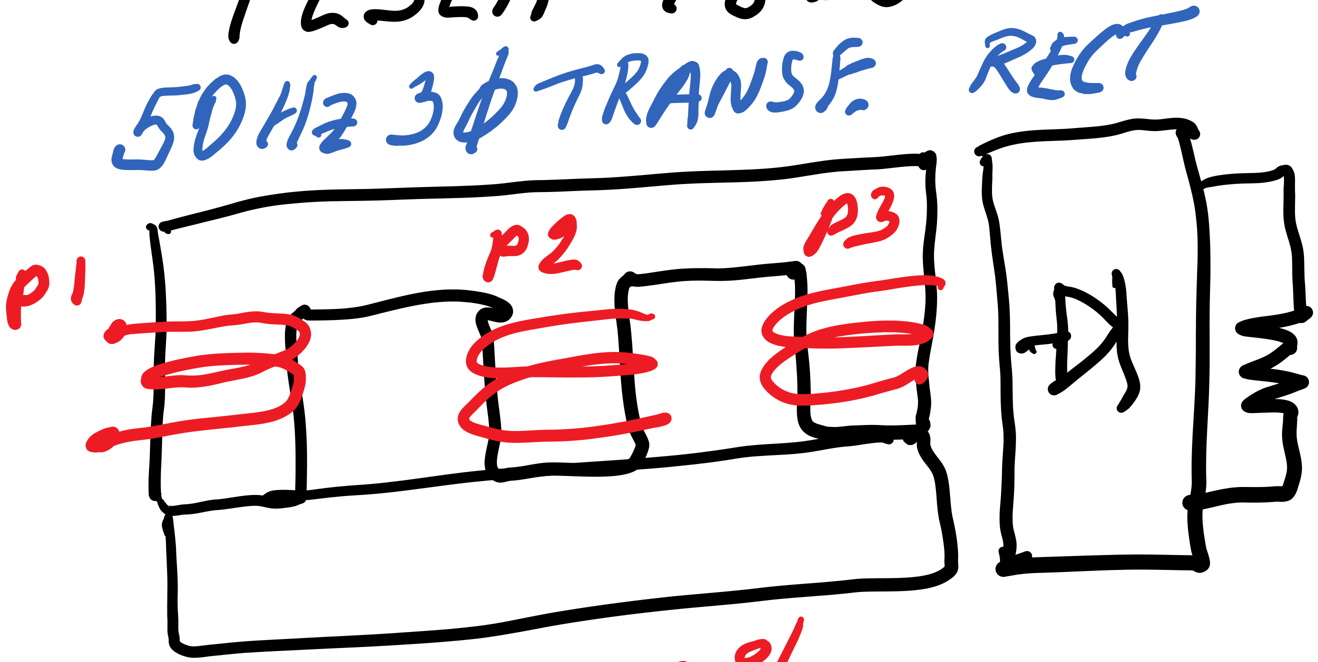
Efficiently Converted

To Direct DC Currents

Ćuk EV Charger for Smart Grid



TESLA 1895



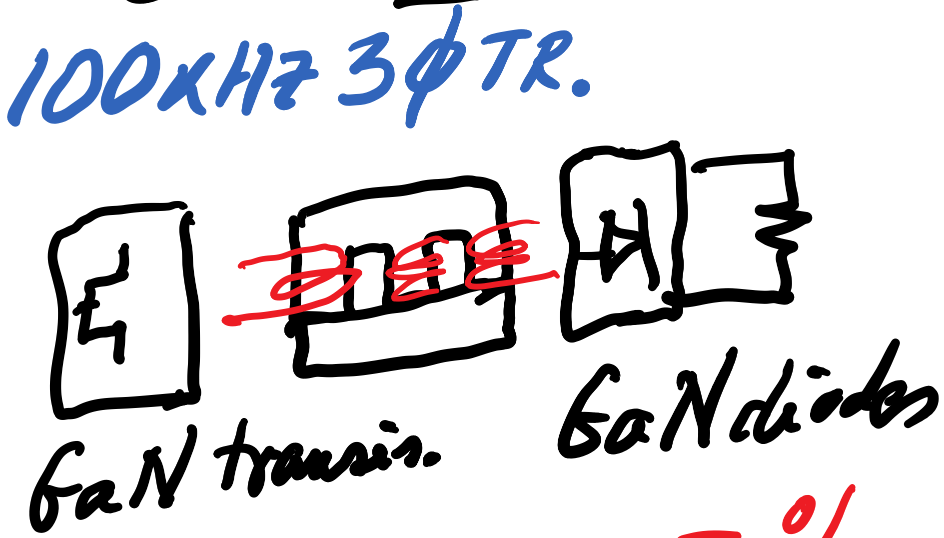
$\eta = 92\%$

PF = 98%

THD > 10%

HUGE SIZE & WEIGHT

ĆUK 2015



$\eta \geq 99.5\%$

PF = 99.9%

THD < 1%

ULTRA SMALL

I would do the same way!

... and one more thing ...

... It got even better!

"Have you been waiting here long?"