Partial Power Processing Converters

-A Way to go Beyond the Limits-

Univ.-Prof. Dr. Petar J. Grbović & MSc Igor Lopušina

Innsbruck Power Electronics Lab. (**i-PEL**)

petar.grbovic@uibk.ac.at

igor.lopusina@uibk.ac.at

Univ.-Prof. Dr. Petar J. Grbović

- **Dipl. Ing. (B. Sc.)** and the **Magister (M.Sc.);** the School of Electrical Engineering, University of Belgrade, Serbia
- **Doctor (Ph.D);** the Laboratoire 'Électrotechnique et d'Électronique de Puissance de Lille, l'Ecole Centrale de Lille, France.

- 20 years of R&D experience: PDL Electronics, New Zealand; Schneider Electric, France; General Electric, Germany; and Huawei Technologies, Germany/China
- Scientific Committee member of ***C-PED***, Roma TRE University, Roma, Italy
- Full Professor at Innsbruck Power Electronics Lab (***i-PEL***), the University of Innsbruck
- Research: Cutting-edge technology of Power Devices & Applications, Power Converters Topologies, Energy Storage Devices
- >60 ***IEEE*** papers, 18 ***IEEE*** tutorials and ***IEEE Press*** monograph
- 17 US & EP patents granted and 9 patent applications pending

Igor Lopušina, MSc

- **Dipl. Ing. (B. Sc.);** the School of Electrical Engineering, University of Belgrade, Serbia
- **Master of Science (MSc);** the School of Engineering, École Polytechnique Fédérale de Lausanne, Switzerland

- PhD student and teaching assistant at the Innsbruck Power Electronics Laboratory

OUTLINE

A. Static Power Conversion

1) Background of Power Converters
2) Where we are Today and
3) What we have to do Tomorrow?

B. Partial Power Rated (Processing) Converters

1) Foundation of Partial Power Rated Converters
2) Voltage Balancing Issue,
3) Series Resonant Converter as a Voltage Balancing Circuit,
4) ISOP Converters with „Intrinsic“ Voltage Balancing Capability
5) Application Cases
6) Is it good concept as it looks like?
7) A bit of History

C. Conclusion

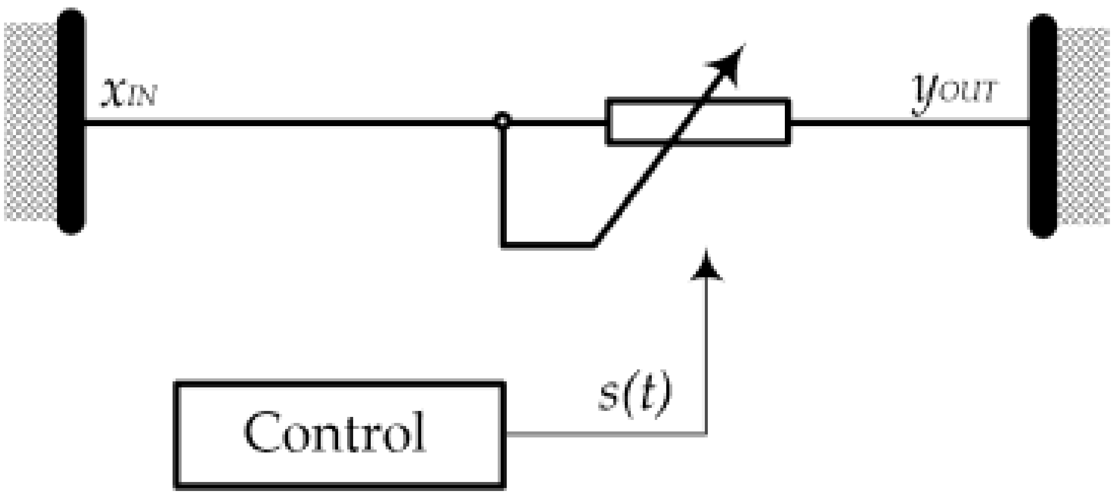
OUTLINE

Background of Power Converters

- Power Electronics is an engineering & applied science discipline that deals with conversion & control of electric power without (significant) losses
- It combines several scientific disciplines: Mathematics, Physics, Electromagnetics, Circuit & Signals Theory, Materials , etc. ,etc.

Background of Power Converters

- Power Converter is a device that converts one electric quantity into another
  - Voltage, Current, Frequency, Phase
- Could it be a resistor or a network of resistors ?



- Old Generation of DC and AC Variable Speed Drives (VSD)

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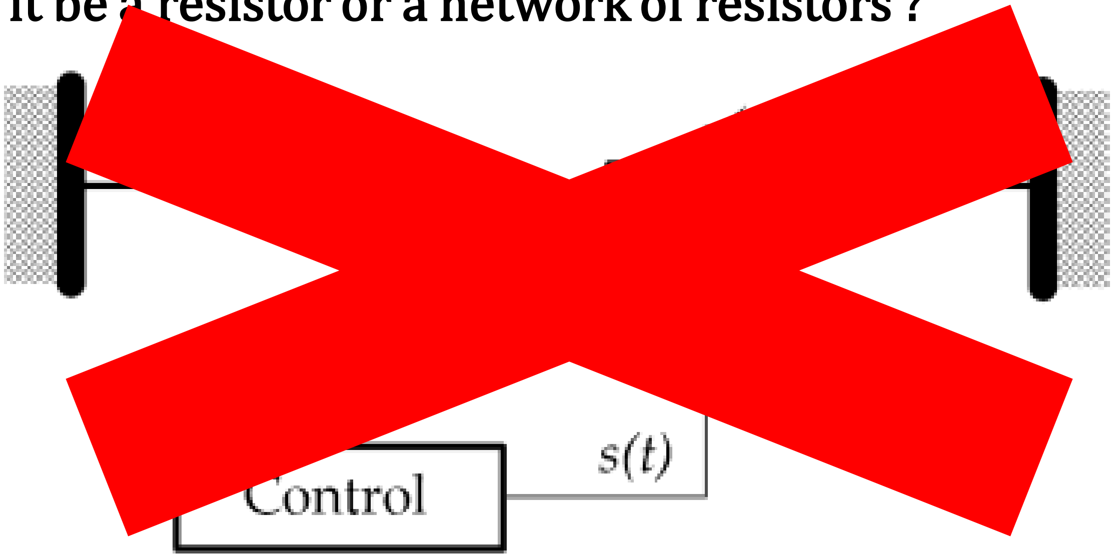
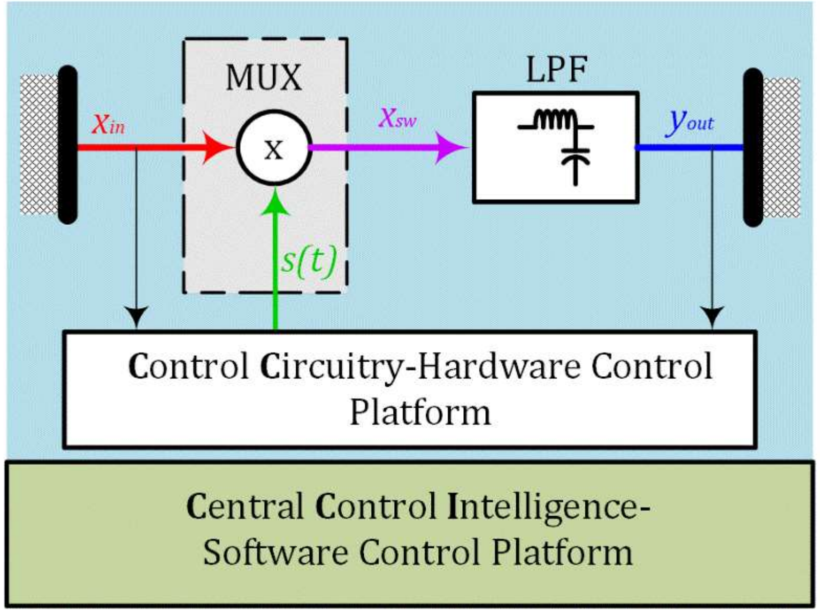


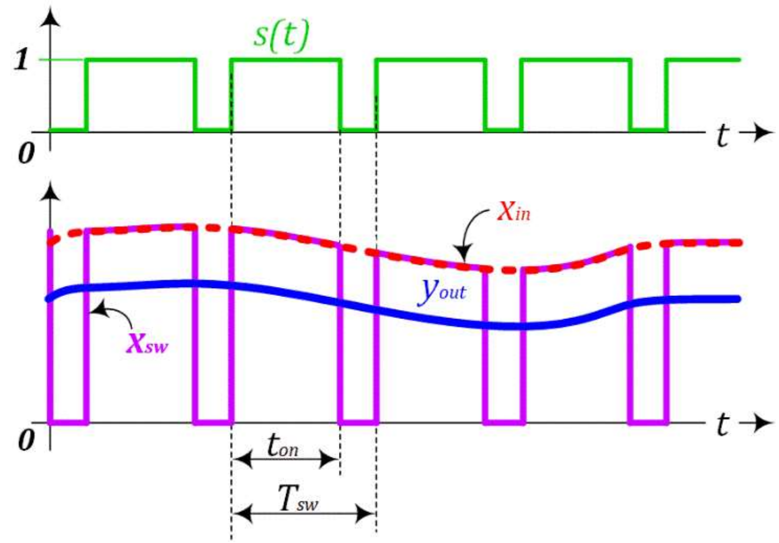
- Old Generation of DC and AC Variable Speed Drives (VSD)

We do not use it any more…efficiency

Background of Power Converters

- **Power Converter is a device that converts one electric quantity into another**
  - BUT without (significant) losses





$$x_{sw}(t) = \frac{1}{T_{sw}} \int_{0}^{T_{sw}} x_{in} dt + \sum_{k=1}^{+\infty} X_{0(k)} \sin(k\omega_{sw} t + \psi_k) = \frac{t_{on}}{T_{sw}} x_{in} + \Delta x_{sw}(t)$$

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Background of Power Converters

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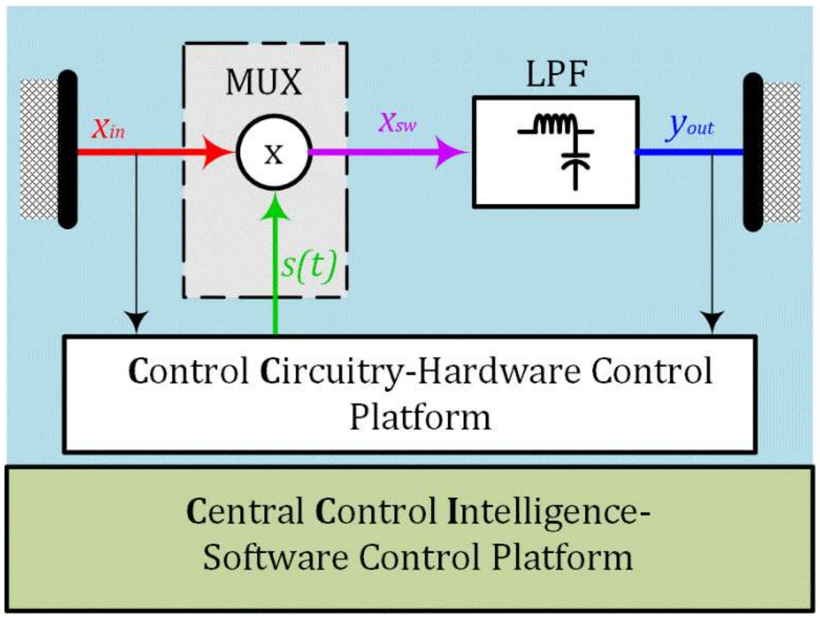

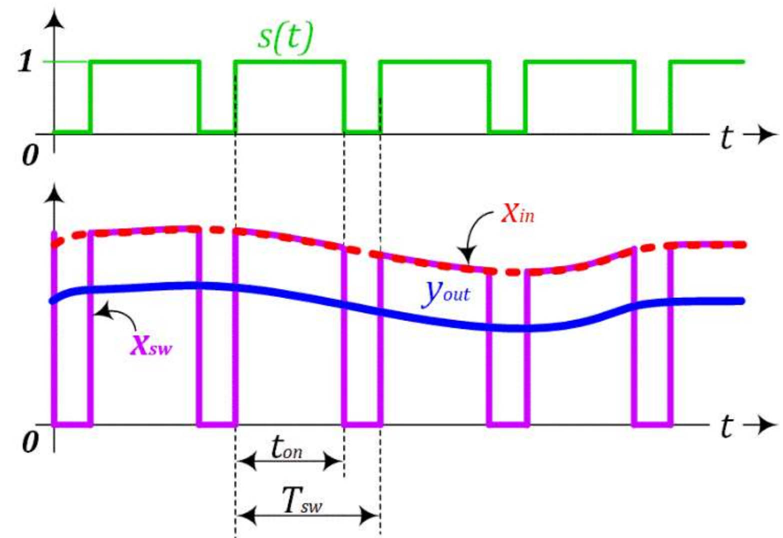

$$y_{out}(t) = \frac{1}{T_{sw}} \int_0^{T_{sw}} x_{in}(t)dt + \sum_{k=1}^{+\infty} X_{0(k)} \sin(k\omega_{sw} t + \psi_k) = \frac{t_{on}}{T_{sw}} x_{in}(t)$$

Background of Power Converters

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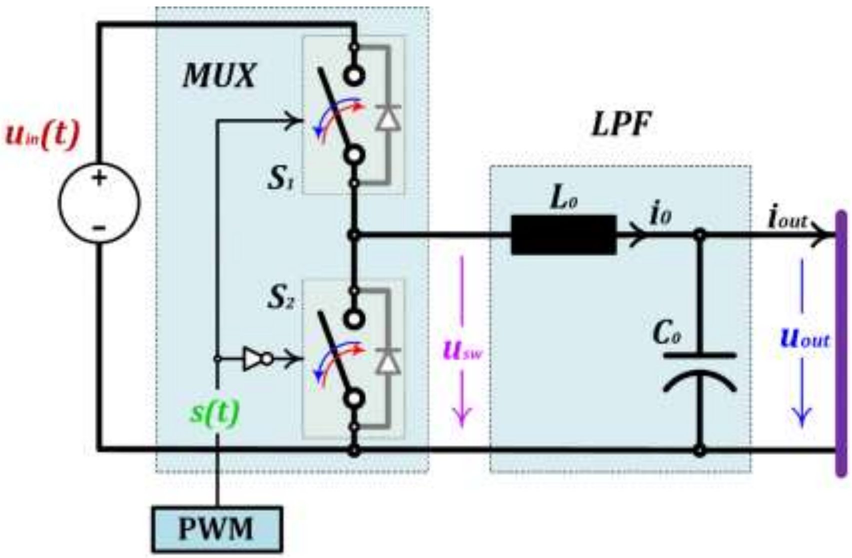
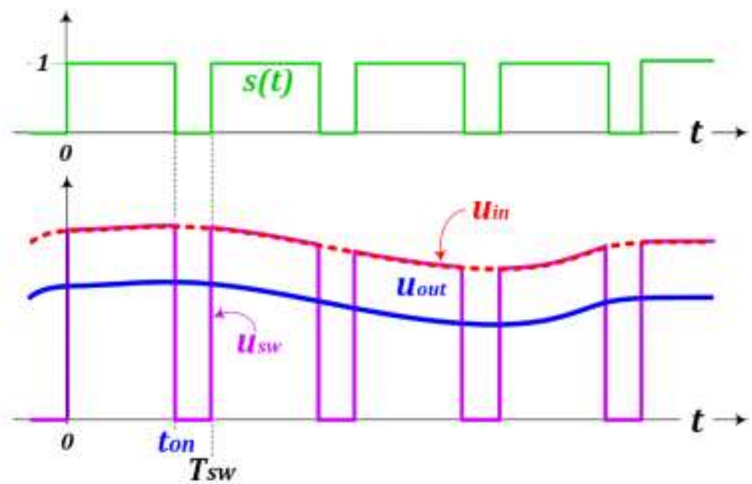
  - BUT without (significant) losses

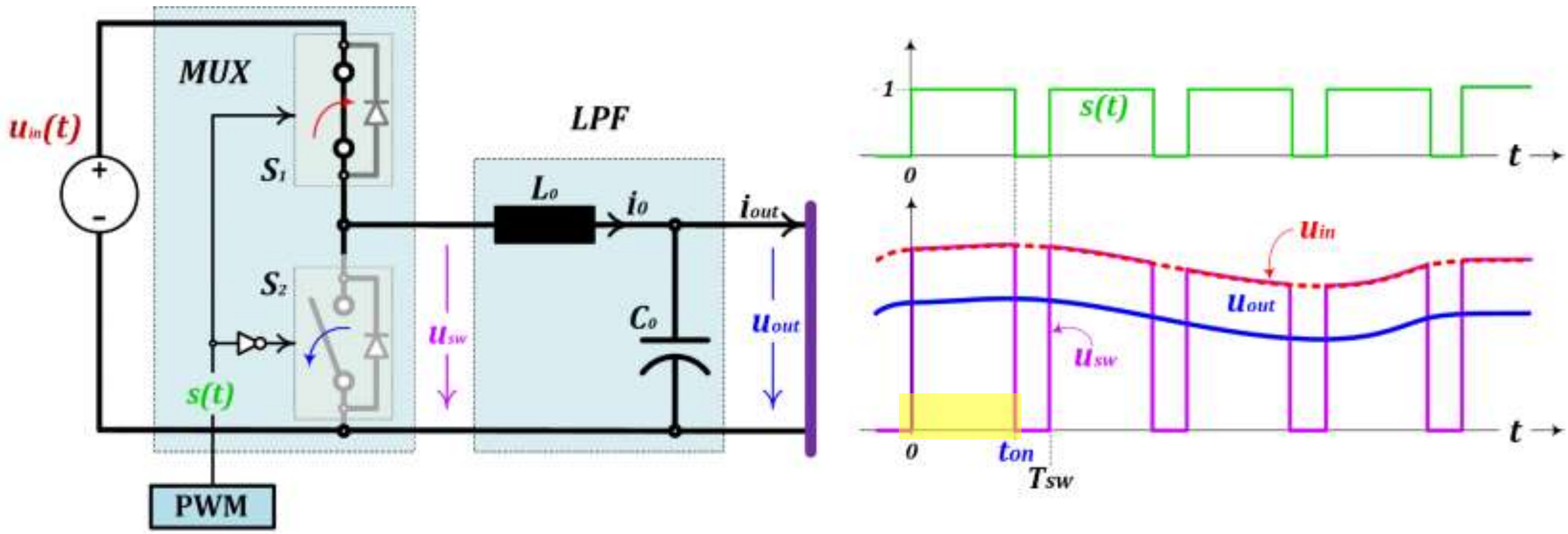




$$u_{out}(t) = \frac{1}{T_{sw}} \int_{0}^{T_{sw}} u_{in}(t)dt \cancel{+ \sum_{k=1}^{+\infty} U_{0(k)} \sin(k\omega_{sw} t + \psi_k)} = \frac{t_{on}}{T_{sw}} u_{in}(t)$$

Background of Power Converters

- Power Converter is a device that converts one electric quantity into another
    - BUT without (significant) losses



$$s(t) = \begin{cases} 1 & kT_{sw} < t < (kT_{sw} + t_{on}) \\ 0 & (kT_{sw} + t_{on}) < t < (k+1)T_{sw} \end{cases} \rightarrow u_{sw}(t) = u_{in}(t)$$

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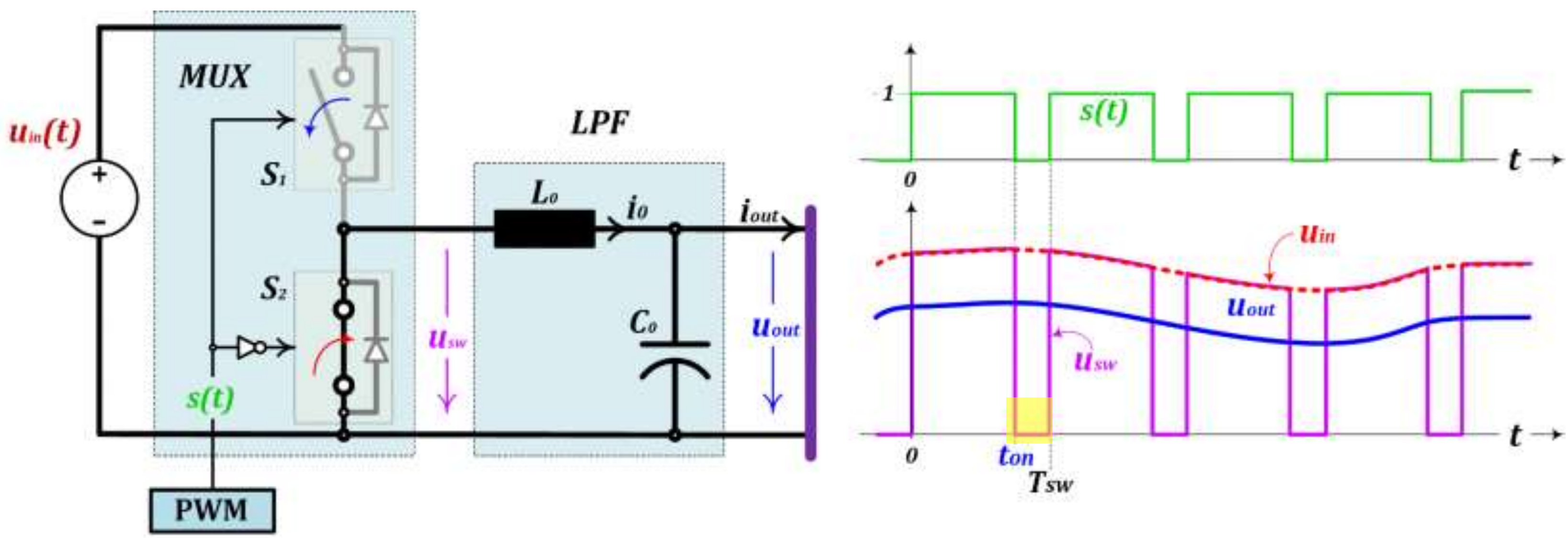

$$s(t) = \begin{cases} 1 & kT_{sw} < t < (kT_{sw} + t_{on}) \\ 0 & (kT_{sw} + t_{on}) < t < (k+1)T_{sw} \end{cases} \rightarrow u_{sw}(t) = 0$$

Background of Power Converters

- Power Converter is a device that converts one electric quantity into another
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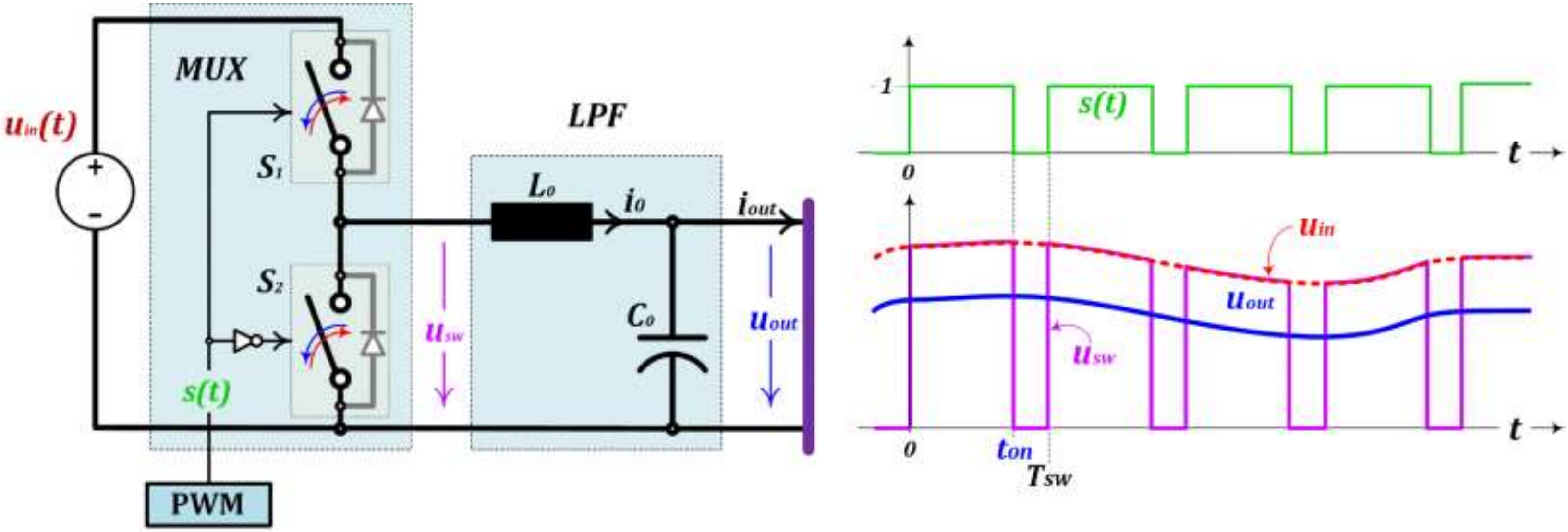
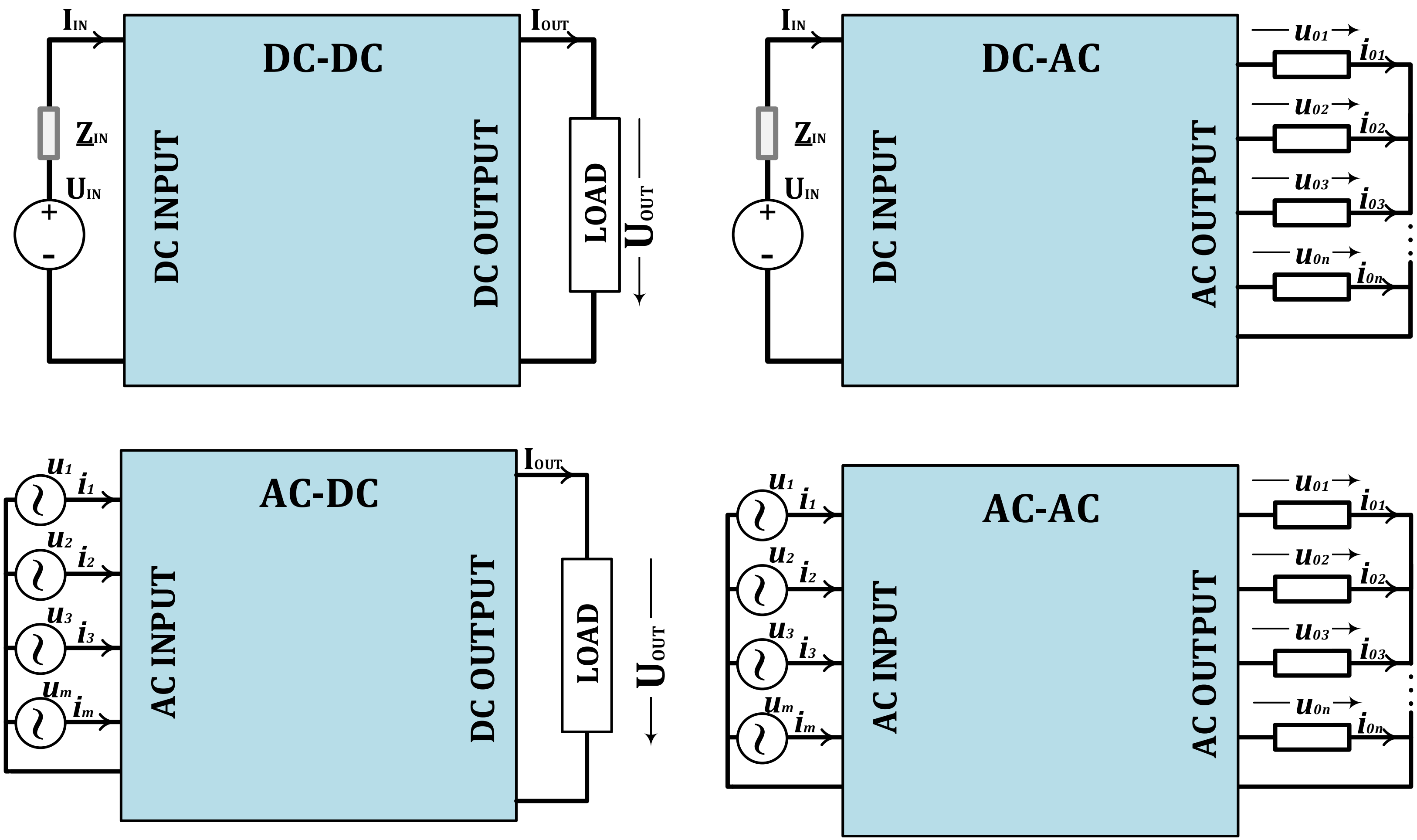


$$u_{out}(t) = \frac{1}{T_{sw}}\int_0^{T_{sw}} u_{in}(t)dt + \sum_{k=1}^{+\infty} U_{0(k)}\sin(k\omega_{sw}t + \psi_k) = \frac{t_{on}}{T_{sw}}u_{in}(t)$$

Basic Power Converetrs



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C. Conclusion

Power Converters Toady?

Where we are Today

- Power Electronics is Today part of our life !!!
  - Home Appliance, Process Industry, Heavy Industry, Information & Communication Technology, Transportation, Energy "Production", Transmission and Distribution, Health Care, Military......
- All this has a "signature" of Power Electronics !!!

"Power Electronics, was and still is the Essential Pillar of Technology Revolutions"

Power Converters Toady?

Home Appliance

Industry

Robotics

Power Converters Toady?

Renewable Energy

Construction and Mining

Information & Communication Technology (ICT)

Transportation

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Power Converters Toady?

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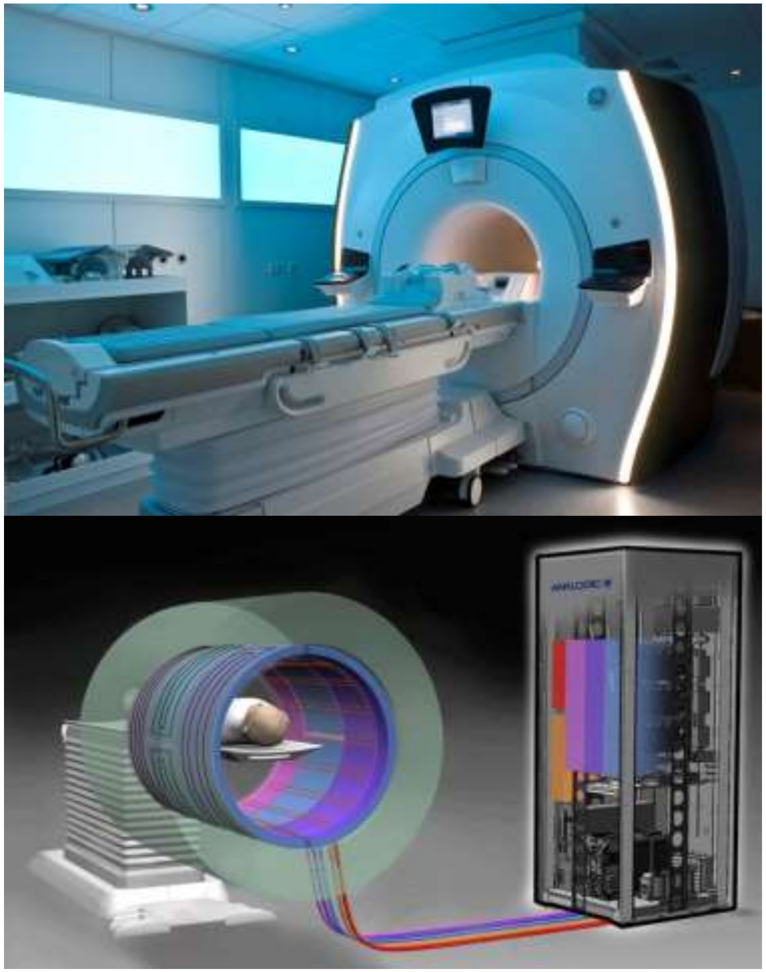
Magnetic Resonance Imaging (MRI) system



Automated External Defibrillator (**AED**)

Power Converters Toady?

Military & Defense





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Power Converters Tomorrow?

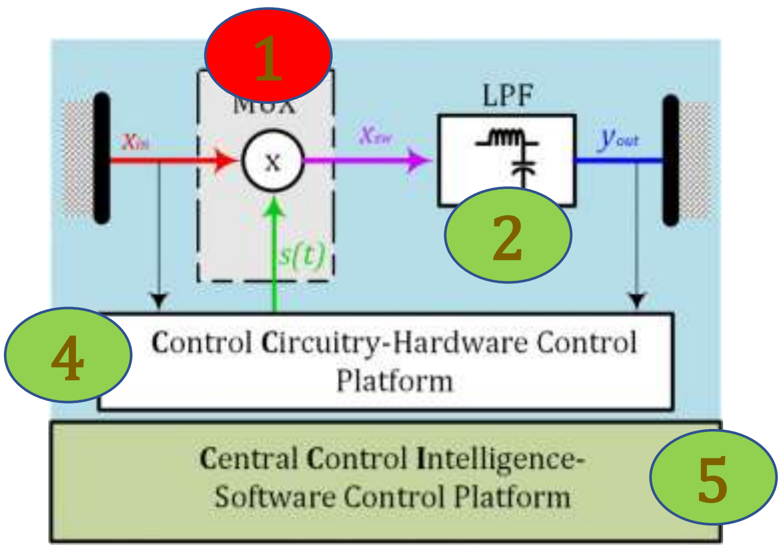
I. Consumption of electric energy is increasing….

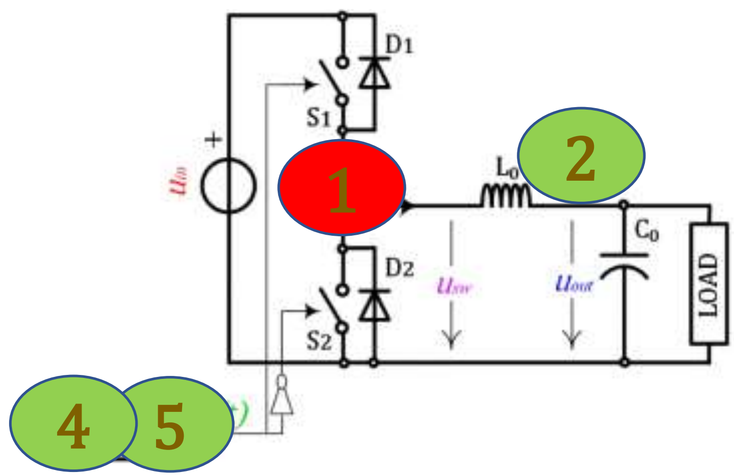
II. We need better power converters

a) Higher efficiency
b) Smaller and lighter (Higher power density and specific power)
c) Improved reliability

The Main Ingrediens of a Power Converter

1) Set of Switches	3) Topology	2) Passive LC Filter
4) H/W Controller & Drivers	5) S/W & Control Algorithm	

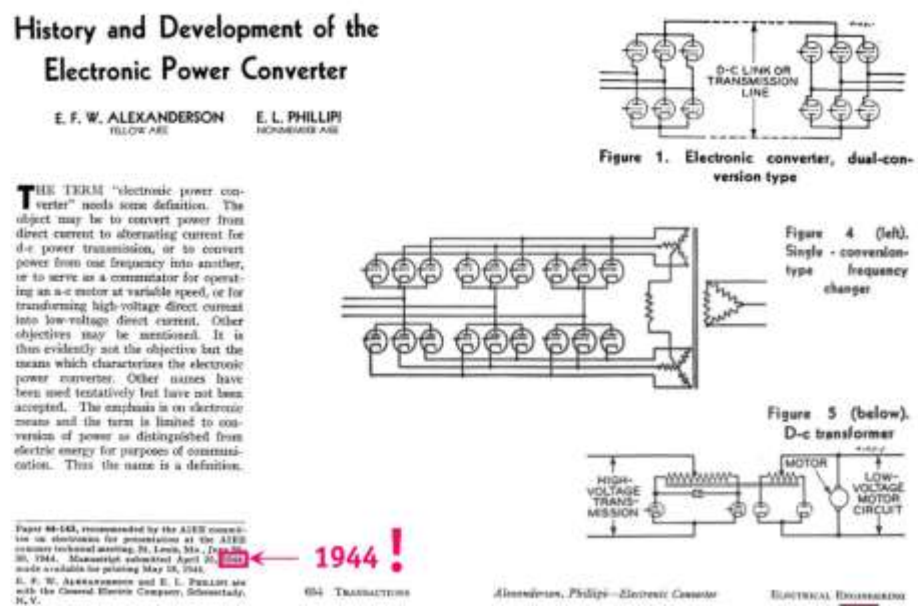




Power Converters Tomorrow?

A. What topology should be selected for given specification?

B. Is there something new? Is there a magic topology taht will solve all our problems?


History and Development of the Electronic Power Converter

E. F. W. ALEXANDERSON   E. L. PHILLIPI

THE TERM "electronic power converter" needs some definition. The object may be to convert power from direct current to alternating current for d-c power transmission, or to convert power from one frequency into another, or to serve as a commutator for operating an a-c motor at variable speed, or for transforming high-voltage direct current into low-voltage direct current. Other objectives may be mentioned. It is thus evidently not the objective but the means which characterizes the electronic power converter. Other names have been used tentatively but have not been accepted. The emphasis is on electronic means and the term is limited to conversion of power as distinguished from electric energy for purposes of communication. Thus the name is a definition.

Figure 1. Electronic converter, dual-conversion type

Figure 4 (left). Single - conversion-type frequency changer

Figure 5 (below). D-c transformer

Prof. Dr. Johann W. Kolar 2015

Power Converters Tomorrow?

A. What topology should be selected for given specification?

B. Is there something new? Is there a magic topology taht will solve all our problems?

No, Thers is no magic topology!!

We need to explore existing topologies and use them in a bit different way....

a) Partial Power Processing Converters
b) Multi-Level & Multi-Cell Topologies
c) Current Source Converters
d) Quantum Mode Resonant Converters

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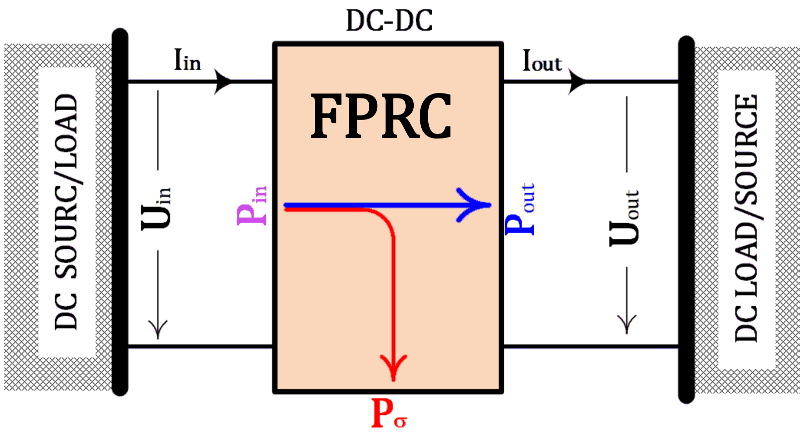
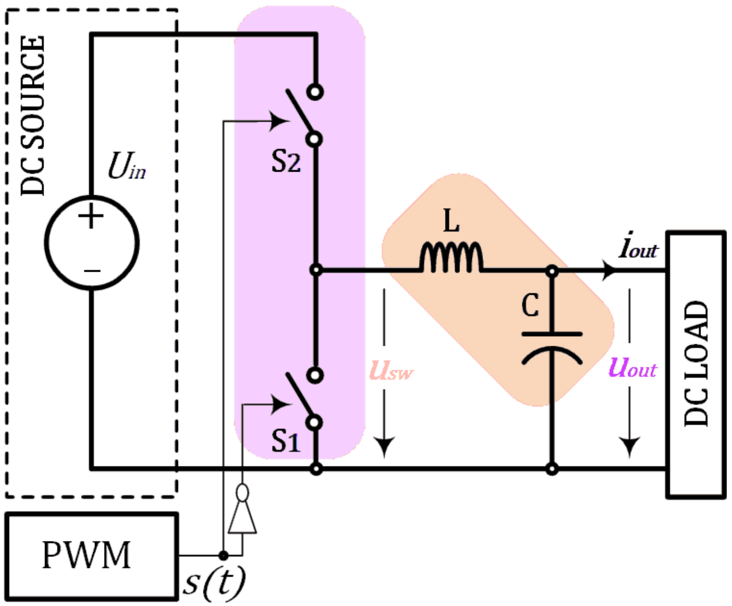
Fundamentals of PPRC

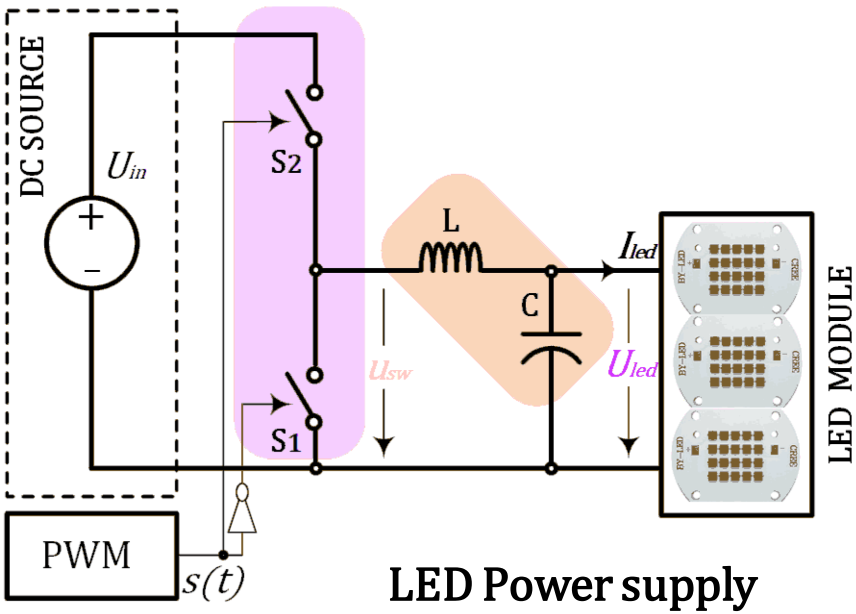




Full Power Rated Converter

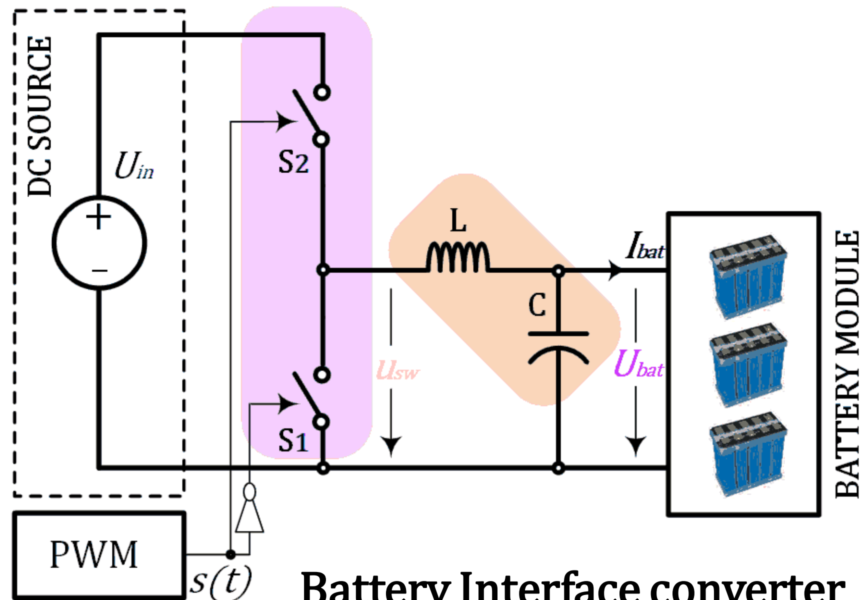
- The converter is handling full voltage and full current
- The output is (can be) controlled in the range 0-to-100%
- Active devices apparent power rating
- LC Filter apparent power rating

Fundamentals of PPRC



LED Power supply

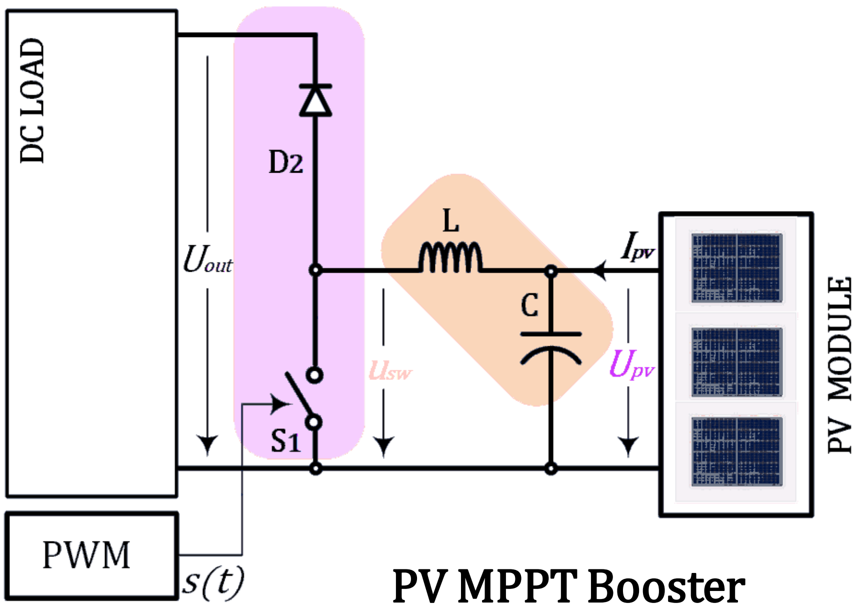
$U_{in} = 54$ [V]
$U_{led} = U_n \pm 10[\%] = 44\sim52[V]$
$\boldsymbol{U_{sw} = k_u\, U_{in} = 75\ [V]}$
$\boldsymbol{I_{sw} = k_i I_{led}}$
$\boldsymbol{L \sim U_{in}}$



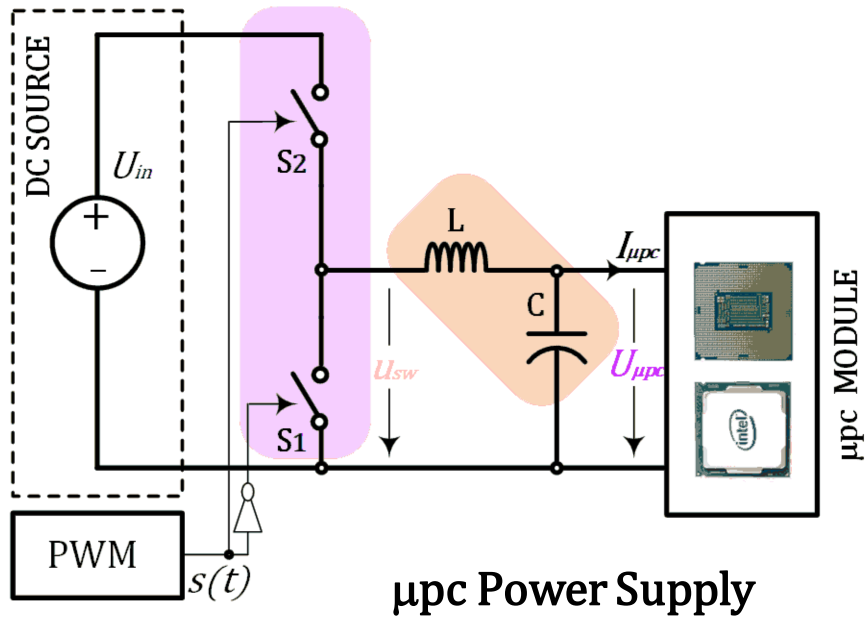
Battery Interface converter

$U_{in} = 750$ [V]
$U_{bat} = U_{bat(n)} \pm 15\%$[V]
$\boldsymbol{U_{sw} = k_u\, U_{in} = 1200\ [V]}$
$\boldsymbol{I_{sw} = k_i I_{bat}}$
$\boldsymbol{L \sim U_{in}}$

Fundamentals of PPRC



PV MPPT Booster

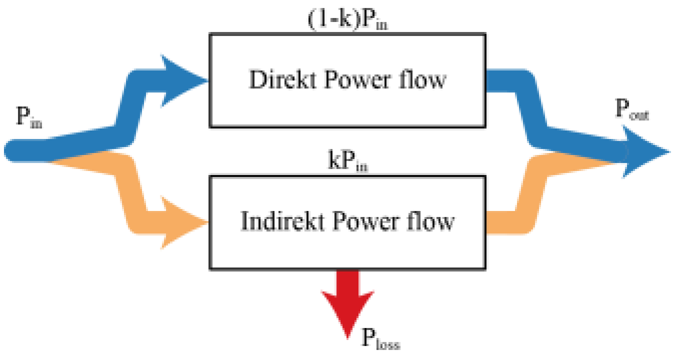


μpc Power Supply

$U_{out} = 850$ [V]
$U_{pv} = 500 \sim 850[V]$
$\boldsymbol{U_{sw} = k_u \, U_{in} = 1200 \, [V]}$
$\boldsymbol{I_{sw} = k_i I_{pv}}$
$\boldsymbol{L \sim U_{in}}$

$U_{in} = 12$ [V]
$U_{\mu pc} = 1[V]$
$\boldsymbol{U_{sw} = k_u \, U_{in} = 30 \, [V]}$
$\boldsymbol{I_{sw} = k_i I_{\mu pc}}$
$\boldsymbol{L \sim U_{in}}$

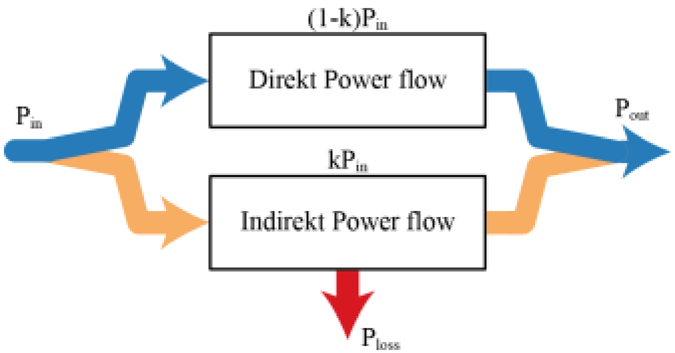
Fundamentals of PPRC



$$P_{\xi} \propto P_{processed}$$

$$P_{processed} \downarrow \quad \Rightarrow \quad P_{\xi} \downarrow$$

Fundamentals of PPRC



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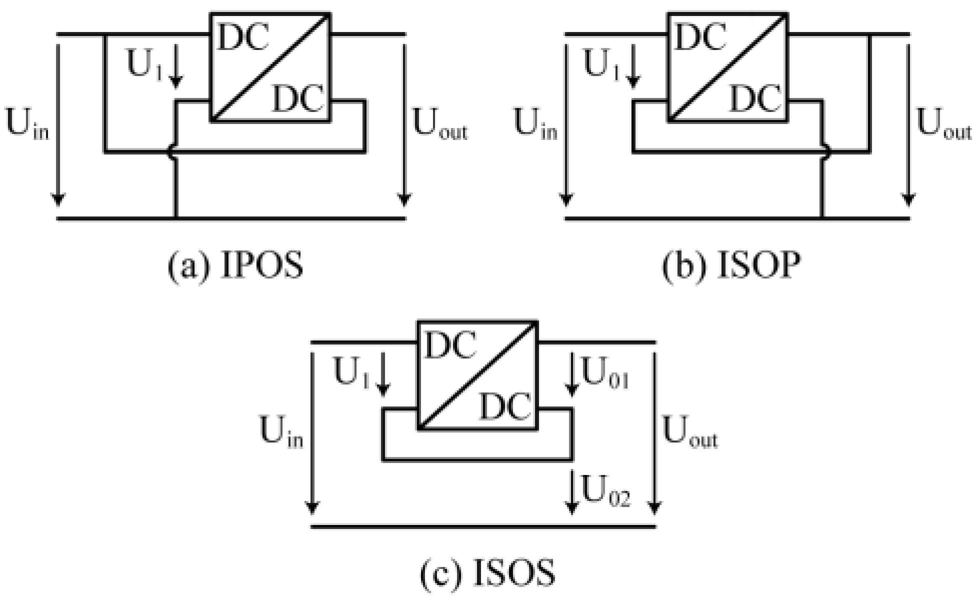

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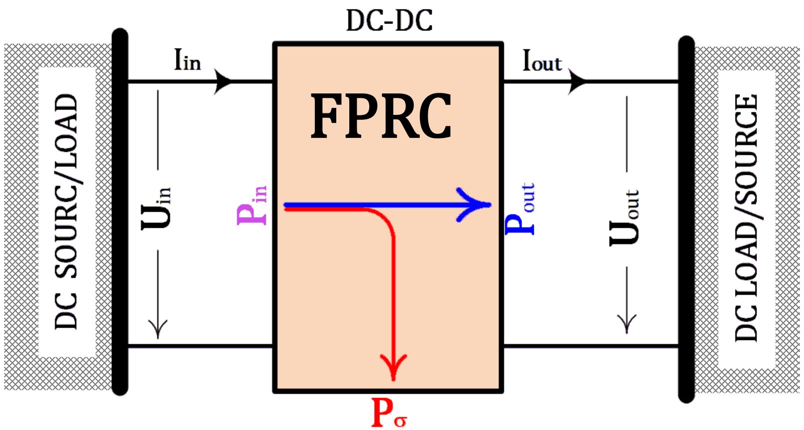
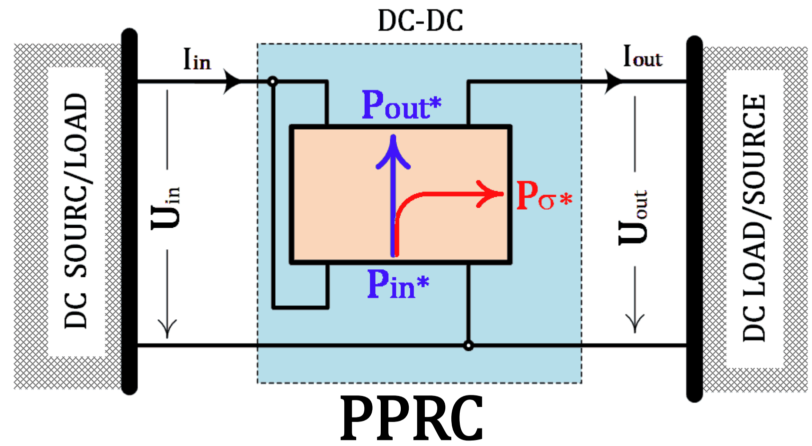




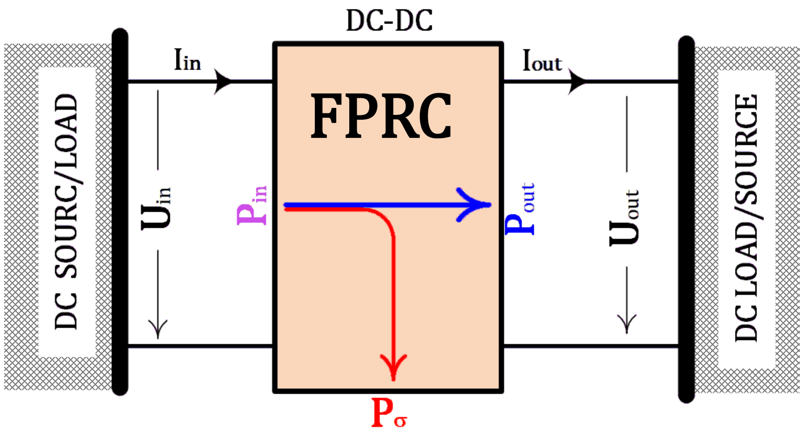
Full Power Rated Converter

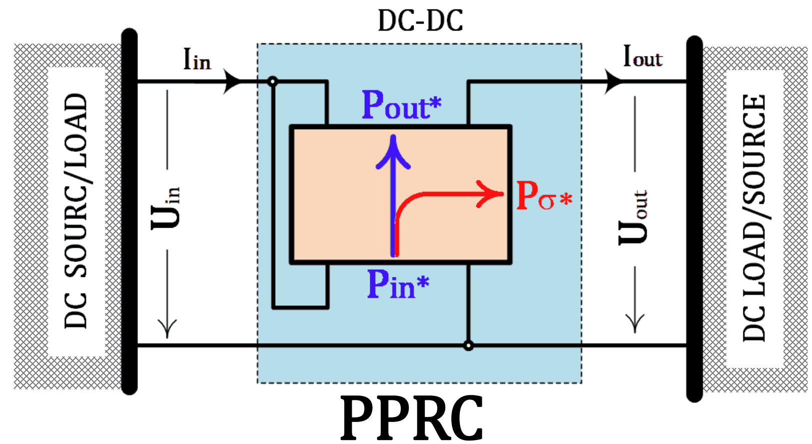
- The converter is handling full voltage and full current
- The output is (can be) controlled in the range 0-to-100%
- Active devices apparent power rating
- LC Filter apparent power rating

Partial Power Rated Converter

- The converter is handling a fraction of voltage or current
- The output is (can be) controlled in narrow range
- Active devices apparent power rating
- LC Filter apparent power rating

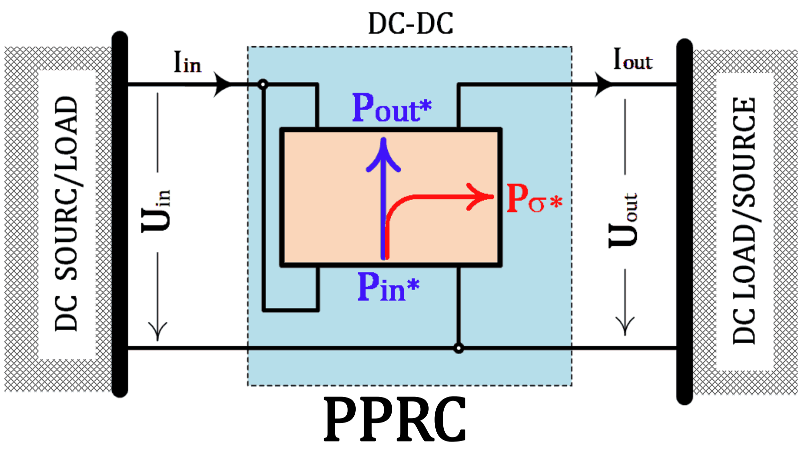
Fundamentals of PPRC

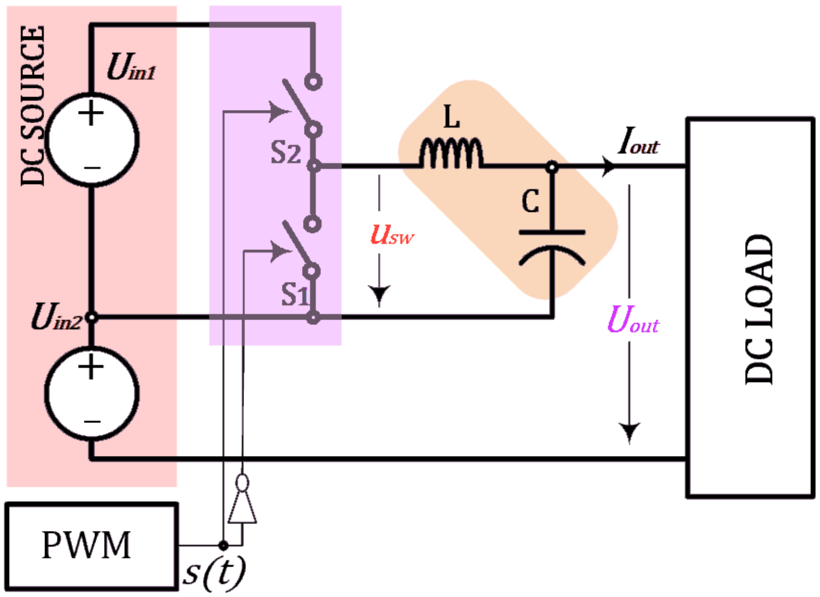




Converter Output Power	P_{out}	$P^{*}_{out} = k_p P_{out}$
Converter Efficiency	η_c	η_c
Converter Losses	$P_{\sigma(c)} = P_{out} \frac{1-\eta_c}{\eta_c}$	$P^{*}_{\sigma(c)} = P_{out} k_p \frac{1-\eta_c}{\eta_c}$
System Losses	$P_{\sigma(s)} = P_{out} \frac{1-\eta_c}{\eta_c}$	$P_{\sigma(s)} = P_{out} k_p \frac{1-\eta_c}{\eta_c}$
System Efficiency	$\eta_s = \eta_c$	$\eta_s = \frac{\eta_c}{\eta_c + k_p(1-\eta_c)}$

Fundamentals of PPRC



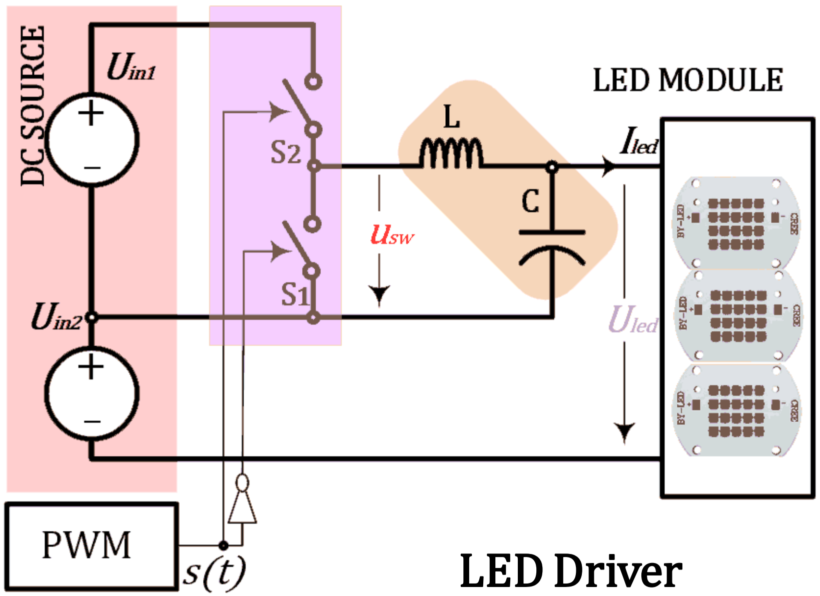


Partial Power Rated Converter

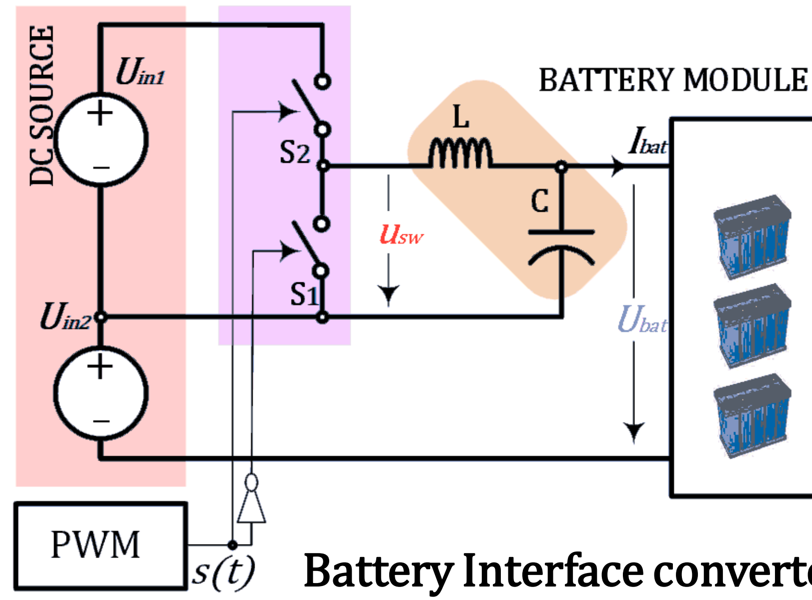
- The converter is handling a fraction of voltage or current
- The output is (can be) controlled in narrow range
- Active devices apparent power rating
- LC Filter apparent power rating

$U_{in} = 750$ [V]
$U_{bat} = U_{bat(n)} \pm 15\%$[V]
$U_{in1} = U_{in2} = 375$ $[V]$
$\boldsymbol{U_{sw} = k_u U_{in1} = 650}$ $[V]$
$\boldsymbol{I_{sw} = k_i I_{bat}}$
$\boldsymbol{L \sim U_{in1}}$

Fundamentals of PPRC



LED Driver

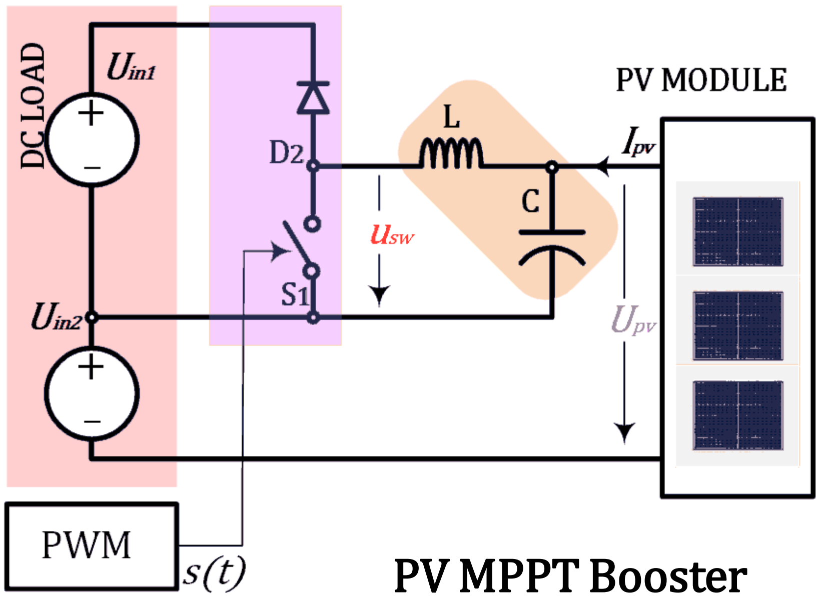


Battery Interface converter

$U_{in} = 54$ [V]
$U_{led} = U_n \pm 10[\%] = 44\sim52[V]$
$U_{in1} = U_{in2} = 26\ [V]$
$U_{sw} = k_u\, U_{in1} = 40\ [V]$
$I_{sw} = k_i I_{led}$
$L \sim U_{in1}$

$U_{in} = 750$ [V]
$U_{bat} = U_{bat(n)} \pm 15\%[V]$
$U_{in1} = U_{in2} = 375\ [V]$
$U_{sw} = k_u\, U_{in1} = 650\ [V]$
$I_{sw} = k_i I_{bat}$
$L \sim U_{in1}$

Fundamentals of PPRC



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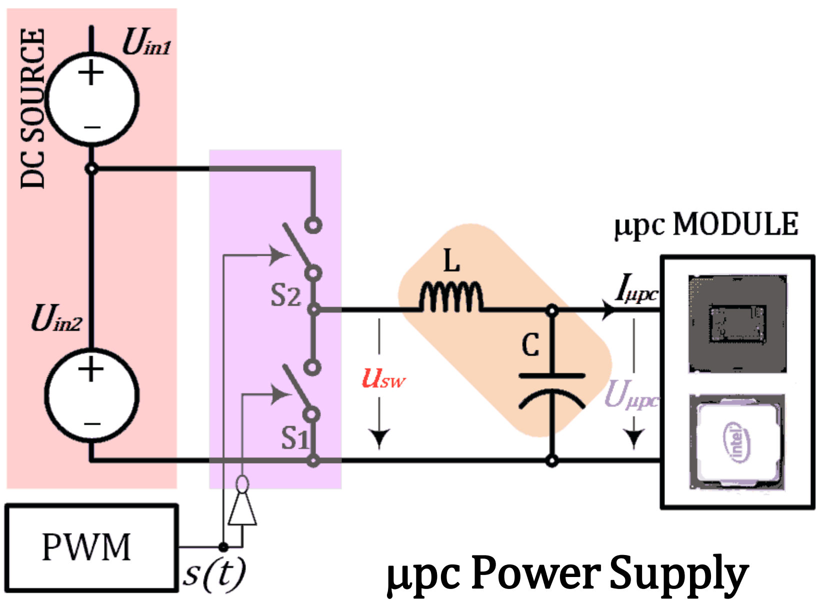
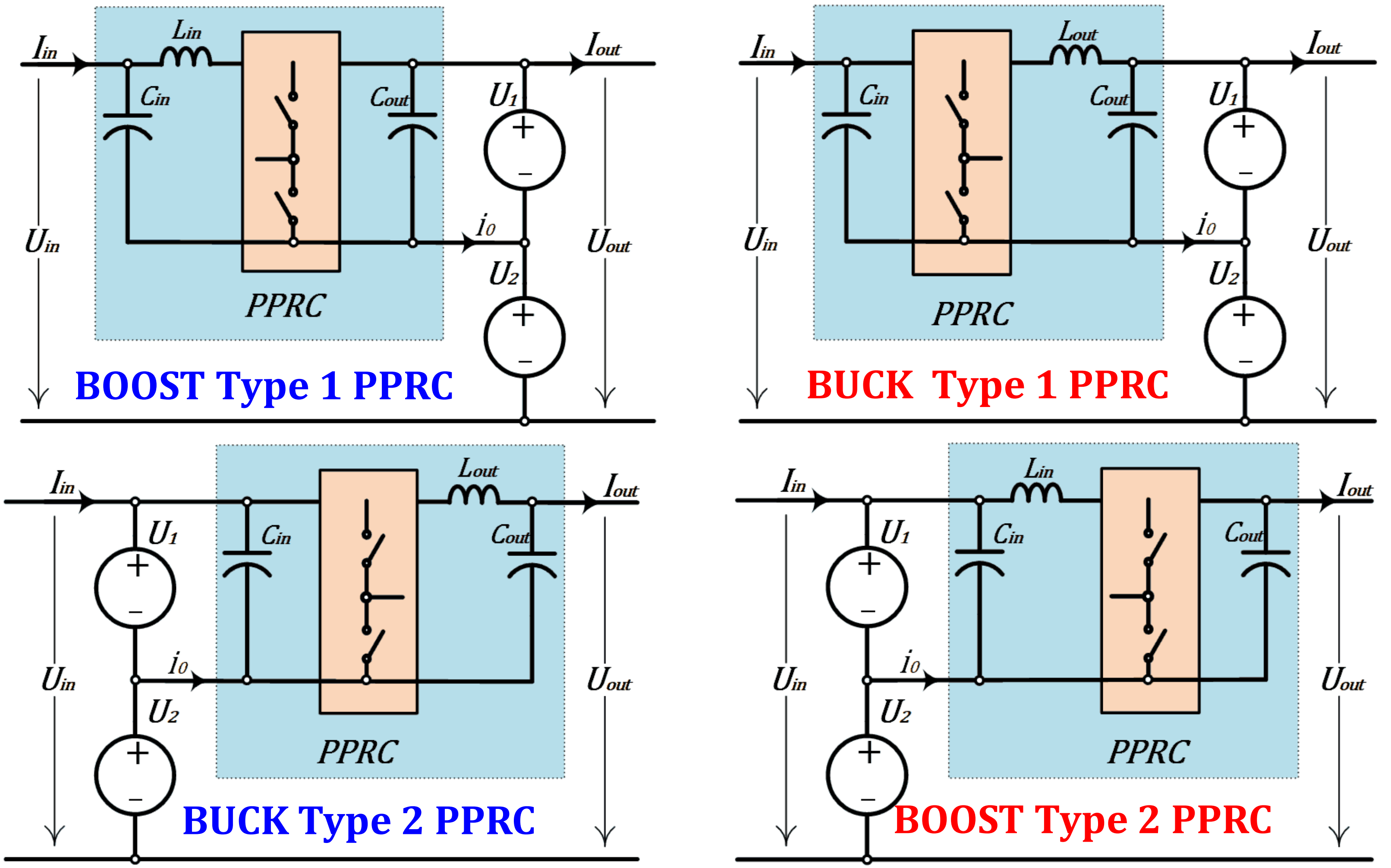


µpc Power Supply

$U_{out} = 850\ [V]$
$U_{pv} = 500{\sim}850[V]$
$U_{in1} = U_{in2} = 425\ [V]$
$\boldsymbol{U_{sw} = k_u\, U_{in1} = 650\ [V]}$
$\boldsymbol{I_{sw} = k_i I_{pv}}$
$\boldsymbol{L{\sim}U_{in1}}$

$U_{in} = 12\ [V]$
$U_{\mu pc} = 1[V]$
$U_{in1} = U_{in2} = 6\ [V]$
$\boldsymbol{U_{sw} = k_u\, U_{in1} = 20\ [V]}$
$\boldsymbol{I_{sw} = k_i I_{\mu pc}}$
$\boldsymbol{L{\sim}U_{in1}}$

Fundamentals of PPRC



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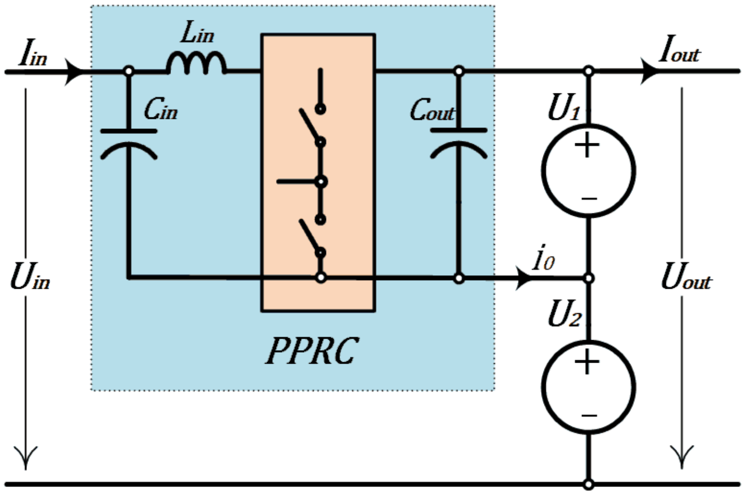
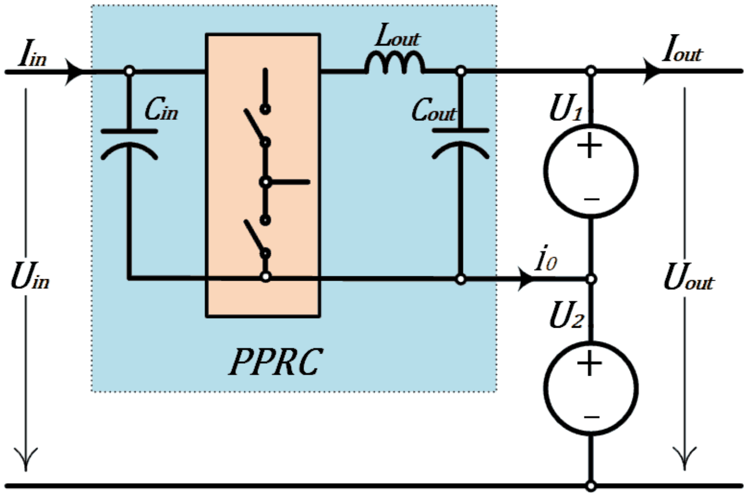


	$U_1 = U_{out}k_1$
Voltage Gain [V/V]	$\frac{U_{out}}{U_{in}} = \frac{1}{1 + d_0 k_1 - k_1}$
Switch Voltage Rating [V]	$U_{sw} = U_{out}k_1$
Switch Current Rating [A]	$I_{sw} = I_{in}$
Switch Power Rating [VA]	$P_{sw} = P_{in}\frac{k_1}{1 + d_0 k_1 - k_1}$
Filter Inductance	$L_{in} = \frac{U_{out}k_1}{\Delta i_0 f_{sw}} d_0(1 - d_0)$
Input Capacitor Voltage Rating	$U_{c(in)} = U_{out}\frac{d_0 k_1}{1 + d_0 k_1 - k_1}$
Output Capacitor Voltage Rating	$U_{c(out)} = U_{out}k_1$

BOOST Type 1 PPRC

- Basic Switching Cell (BSC) DC bus connected in parallel with TOP voltage U_1
- The BSC input is connected between the input and the dc bus mid point
- The BSC operates as a Boost converter

Fundamentals of PPRC

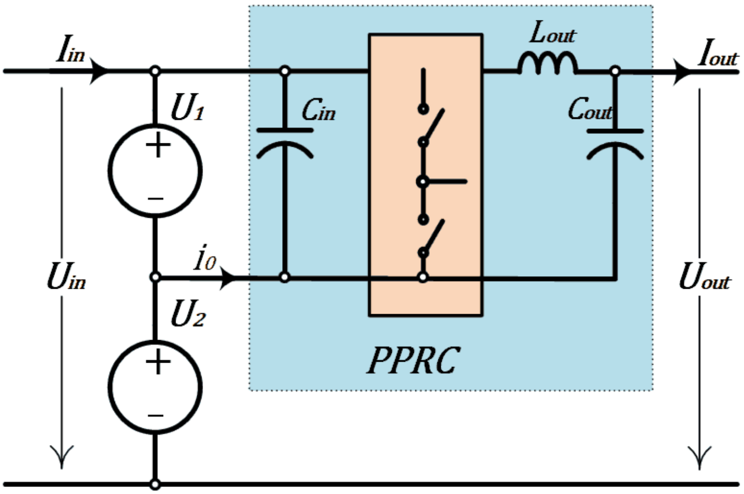


BUCK Type 1 PPRC

- Basic Switching Cell (BSC) DC bus connected between mid point and input,
- The BSC output connected in parallel with TOP voltage U_1
- The BSC operates as a Buck converter

	$U_1 = U_{out}k_1$
Voltage Gain [V/V]	$\frac{U_{out}}{U_{in}} = \frac{d_0}{d_0(1-k_1)+k_1}$
Switch Voltage Rating [V]	$U_{sw} = U_{in}\frac{2d_0(1-k_1)+k_1}{d_0(1-k_1)+k_1}$
Switch Current Rating [A]	$I_{sw} = \frac{I_{in}}{d_0}$
Switch Power Rating [VA]	$P_{sw} = P_{in}\frac{2d_0(1-k_1)+k_1}{\left(d_0^2(1-k_1)+d_0k_1\right)}$
Filter Inductance	$L_{in} = \frac{U_{c(in)}}{\Delta i_0 f_{sw}} d_0(1-d_0)$
Input Capacitor Voltage Rating	$U_{c(in)} = U_{out}\frac{2d_0(1-k_1)+k_1}{d_0}$
Output Capacitor Voltage Rating	$U_{c(out)} = U_{out}k_1$

Fundamentals of PPRC

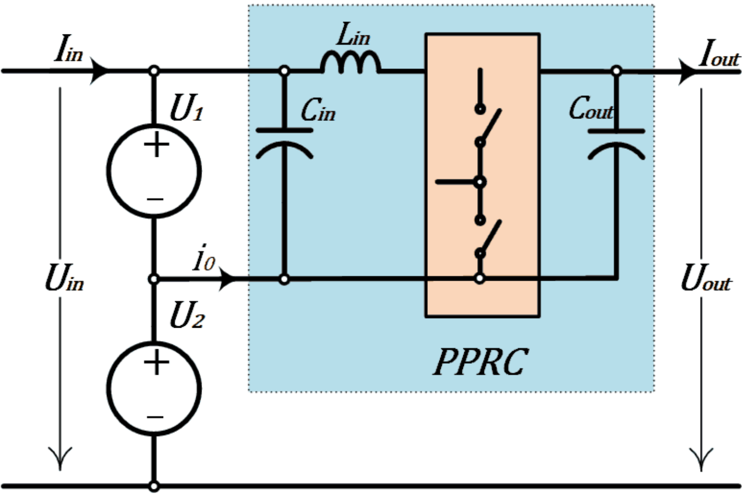


BUCK Type 2 PPRC

- Basic Switching Cell (BSC) DC bus connected in parallel with TOP voltage U_1
- The BSC output connected between mid point and the converter output
- The BSC operates as a Buck converter

	$U_1 = U_{in}k_1$
Voltage Gain [V/V]	$\frac{U_{out}}{U_{in}} = 1 + d_0k_1 - k_1$
Switch Voltage Rating [V]	$U_{sw} = U_{in}k_1$
Switch Current Rating [A]	$I_{sw} = I_{out}$
Switch Power Rating [VA]	$P_{sw} = P_{out}\frac{k_1}{1 + d_0k_1 - k_1}$
Filter Inductance	$L_{in} = \frac{U_{in}k_1}{\Delta i_0 f_{sw}} d_0(1 - d_0)$
Input Capacitor Voltage Rating	$U_{c(in)} = U_{in}k_1$
Output Capacitor Voltage Rating	$U_{c(out)} = U_{out}\frac{d_0k_1}{1 + d_0k_1 - k_1}$

Fundamentals of PPRC

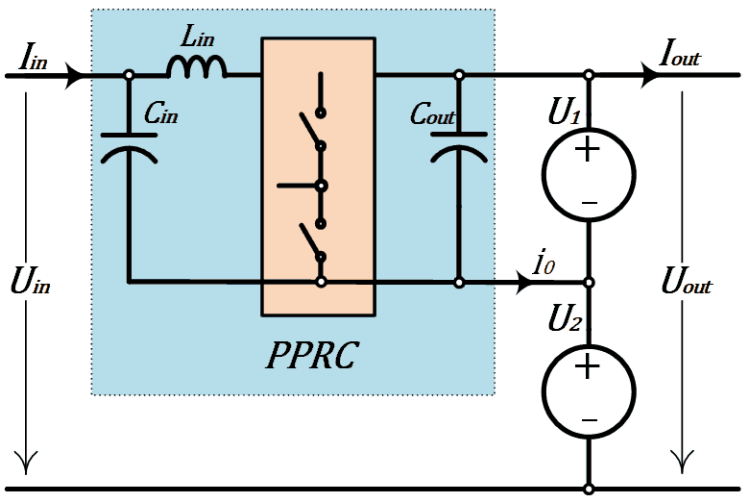


BOOST Type 2 PPRC

- Basic Switching Cell (BSC) DC bus connected between mid point and the output,
- The BSC input connected in parallel with TOP voltage U_1
- The BSC operates as a Boost converter

	$U_1 = U_{in}k_1$
Voltage Gain [V/V]	$\frac{U_{out}}{U_{in}} = \frac{1}{1 + d_0 k_1 - k_1}$
Switch Voltage Rating [V]	$U_{sw} = U_{out}k_1$
Switch Current Rating [A]	$I_{sw} = I_{in}$
Switch Power Rating [VA]	$P_{sw} = P_{in}\frac{k_1}{1 + d_0 k_1 - k_1}$
Filter Inductance	$L_{in} = \frac{U_{c(out)}}{\Delta i_0 f_{sw}} d_0(1 - d_0)$
Input Capacitor Voltage Rating	$U_{c(in)} = U_{out}k_1(1 + d_0 k_1 - k_1)$
Output Capacitor Voltage Rating	$U_{c(out)} = U_{out}\frac{2d_0(1 - k_1) + k_1}{d_0}$

Why the PPRC should be better than the FPRC?



Boost Type 1 PPRC

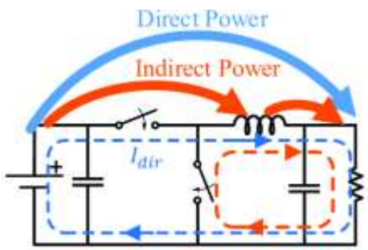
- The BSC DC Bus Voltage is a fraction of the total DC Bus voltage $U_1 = U_{out} k_1 = U_{sw}$

a) Switch and diode voltage rating is reduced
   i. Reduced on-state resistance
      $R_{ds} \sim U_{sw}^{2,5}$
   ii. Better switching
      Different switch technology
      IGBT → MOSFET
      SiC → GaN…

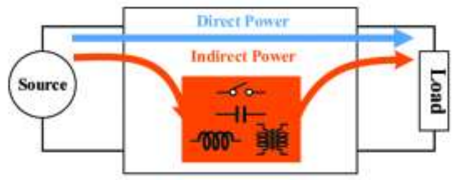
b) The inductor flux is reduced
   i. Smaller and more efficient Inductor(s)

c) Input filter Capacitor voltage reduced
   i. Smaller capacitor

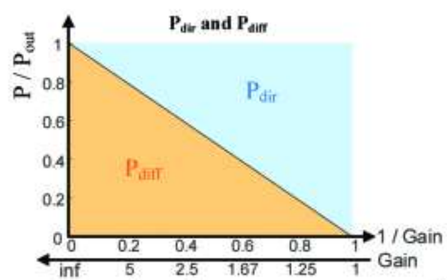
Fundamentals of PPRC



(a) Illustration of P_{ind} and P_{dir} in a buck converter



(b) Illustration of P_{ind} and P_{dir} in a DC-DC converter block



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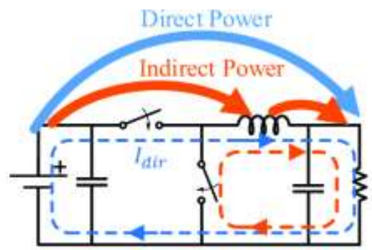
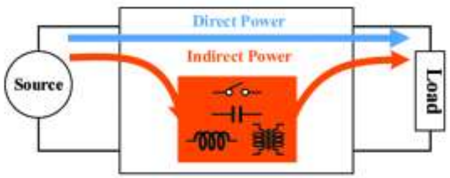
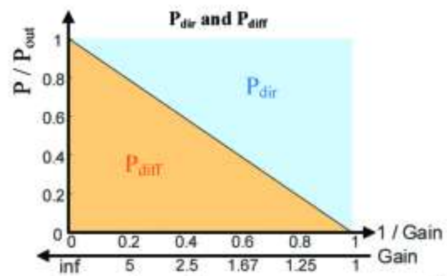
Fundamentals of PPRC



(a) Illustration of P_{ind} and P_{dir} in a buck converter



(b) Illustration of P_{ind} and P_{dir} in a DC-DC converter block



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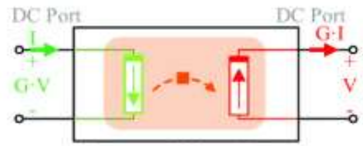
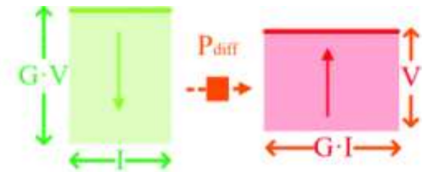


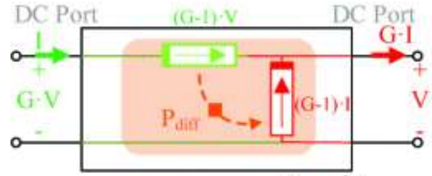
$$P_{diff} = GVI = P_{out}$$

(a) CPM of an isolated cell



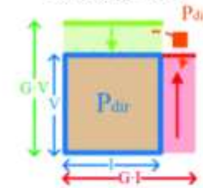
$$P_{dir} = 0$$

(b) VA area interpretation of an isolated cell



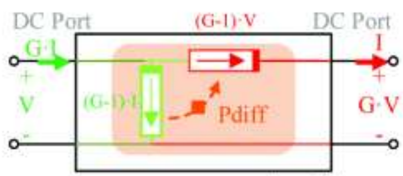
$$P_{diff} = (G-1)V\cdot I = \left(1-\frac{1}{G}\right)P_{out}$$

(c) CPM of a step-down cell



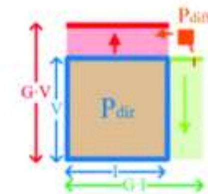
$$P_{dir} = V\cdot I = \frac{1}{G}P_{out}$$

(d) VA area interpretation of a step-down cell



$$P_{diff} = V\cdot(G-1)I = \left(1-\frac{1}{G}\right)P_{out}$$

(e) CPM of a step-up cell



$$P_{dir} = V\cdot I = \frac{1}{G}P_{out}$$

(f) VA area interpretation of a step-up cell

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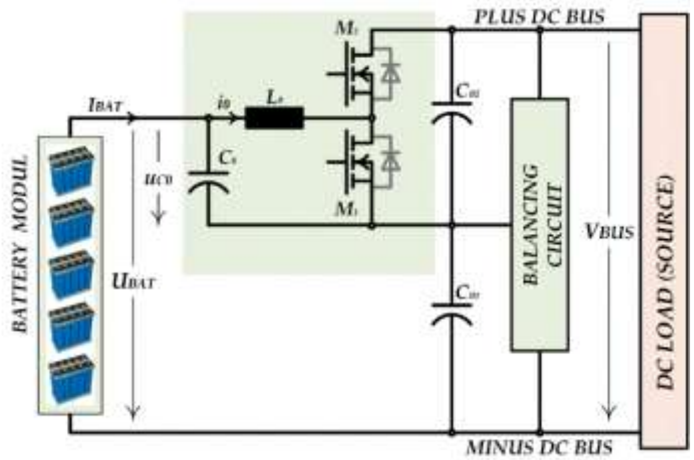
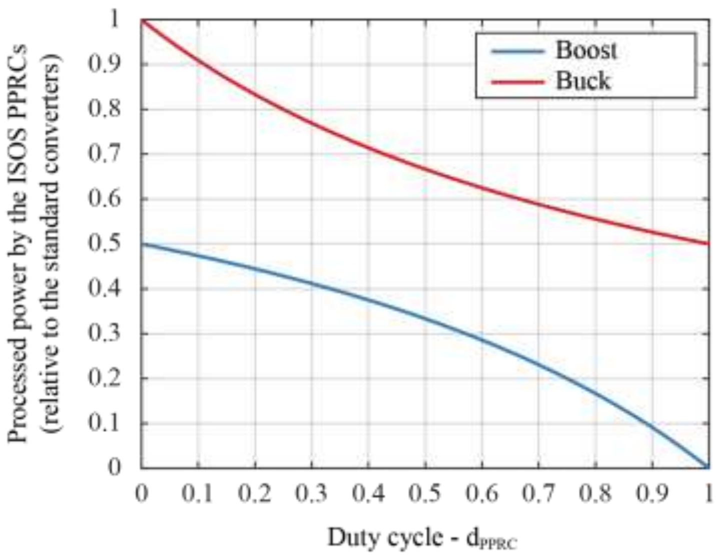
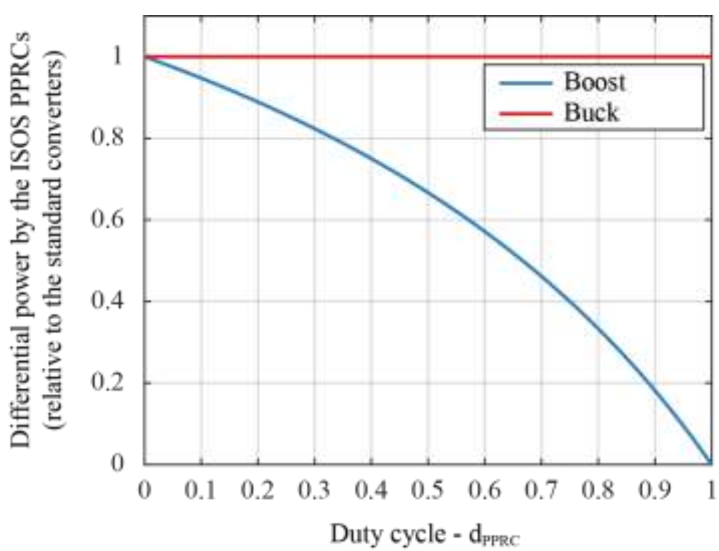
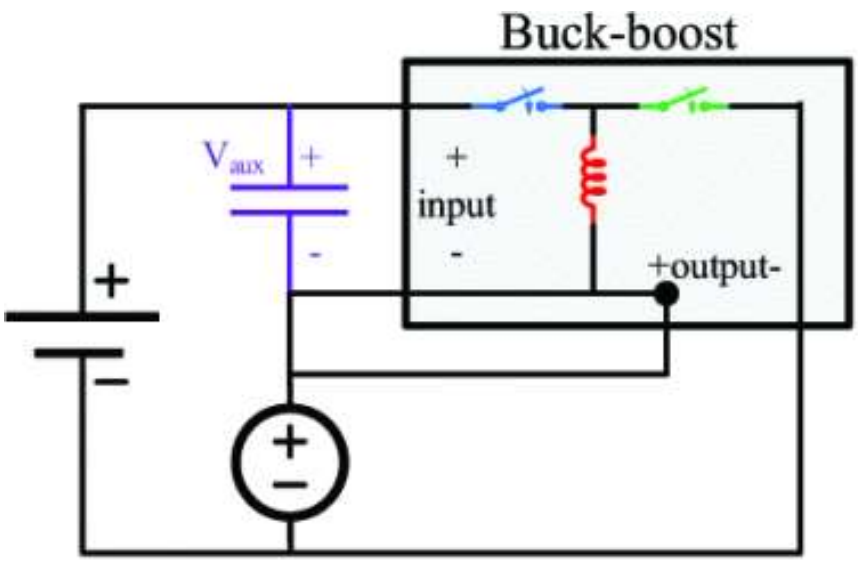
Fundamentals of PPRC





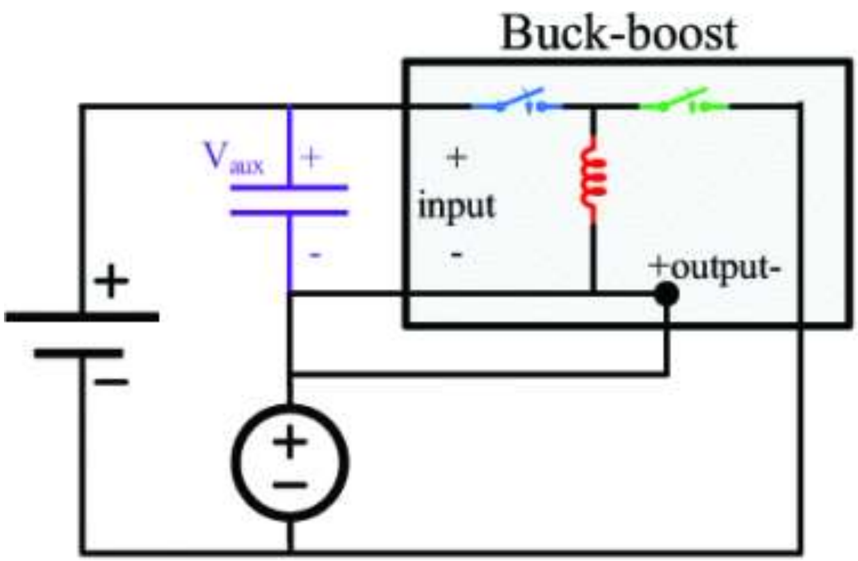


Fundamentals of PPRC



(a) Buck-boost example

Fundamentals of PPRC



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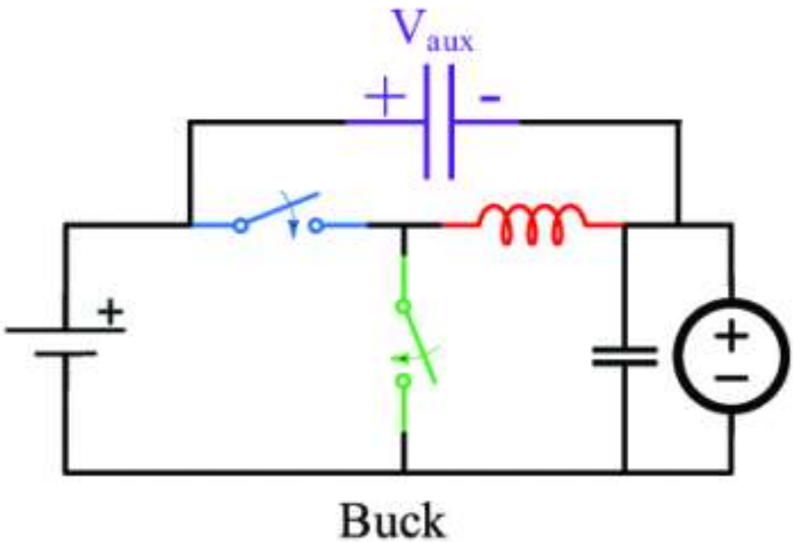
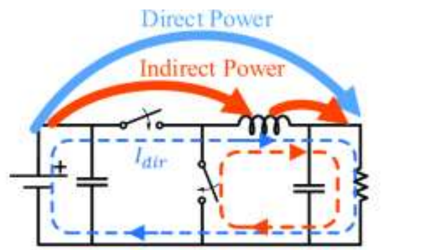
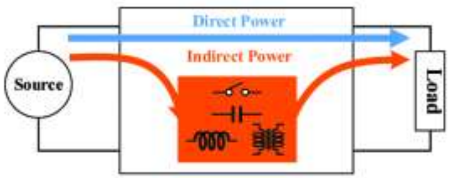


(b) Re-arranged buck-boost PPC

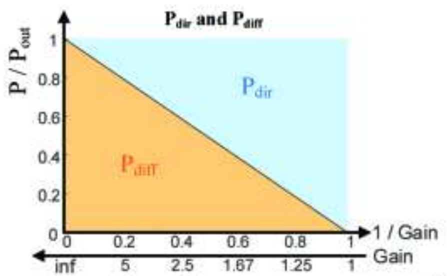
Fundamentals of PPRC



(a) Illustration of P_{ind} and P_{dir} in a buck converter



(b) Illustration of P_{ind} and P_{dir} in a DC-DC converter block



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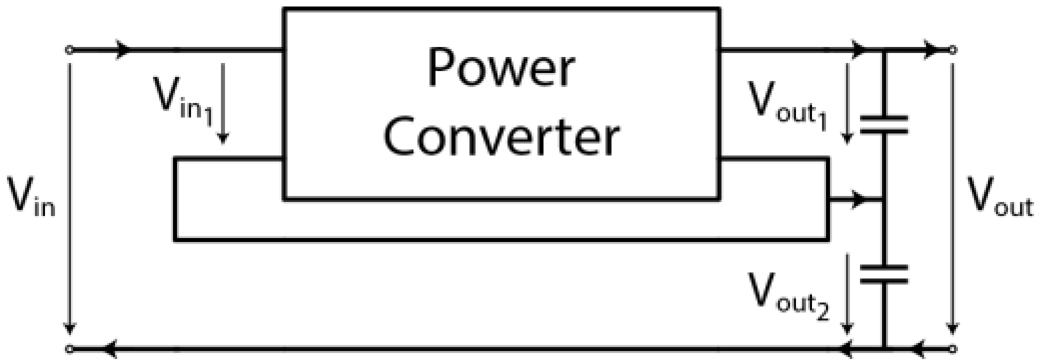
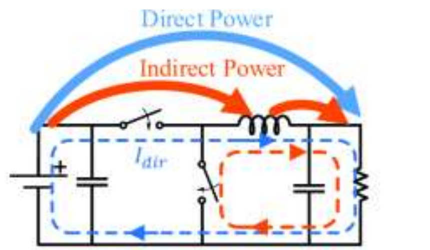


Fundamentals of PPRC



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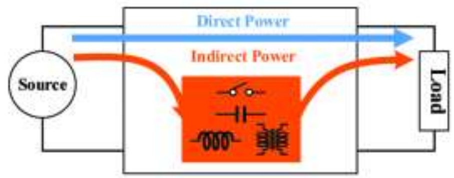

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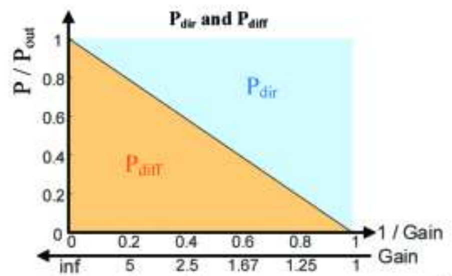

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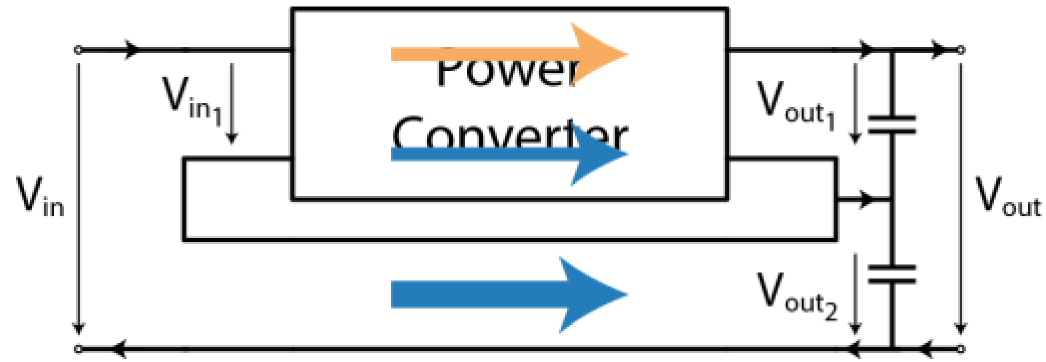


OUTLINE

A. Static Power Conversion

1) Background of Power Converters
2) Where we are Today and
3) What we have to do Tomorrow?

B. Partial Power Rated (Processing) Converters

1) Foundation of Partial Power Rated Converters
2) Voltage Balancing Issue,
3) Series Resonant Converter as a Voltage Balancing Circuit,
4) ISOP Converters with „Intrinsic“ Voltage Balancing Capability
5) Application Cases
6) Is it good concept as it looks like?
7) A bit of History

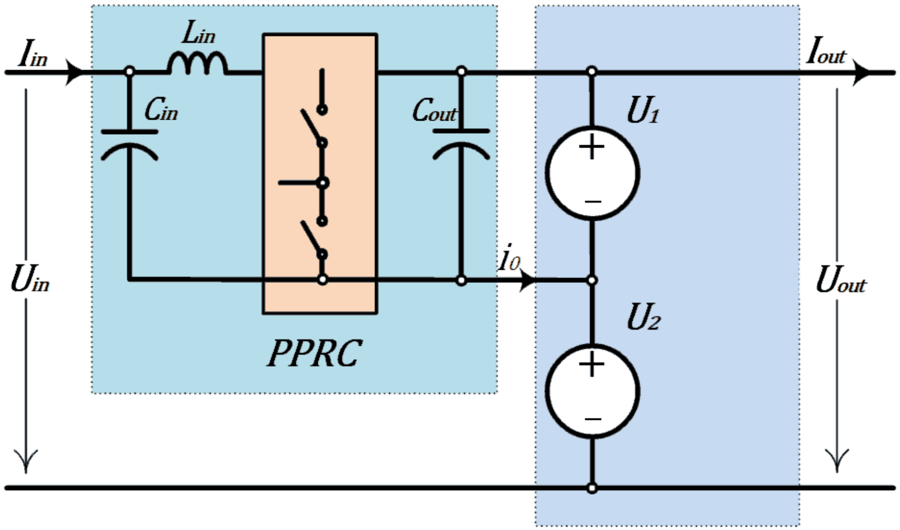
C. Conclusion

Voltage Balancing Issue!

The following has been assumed:

a) The Input or Output is spilt voltage source
   - $U_1 = k_1 U_{out}$
   - $U_2 = (1 - k_1)\, U_{out}$

b) The voltages ratio is constant regardless on the input/output current variation



- In some specific applications the input (output) source (load) is (could be) split voltage source
  - PV string
  - Battery string..

Voltage Balancing Issue!

The following has been assumed:

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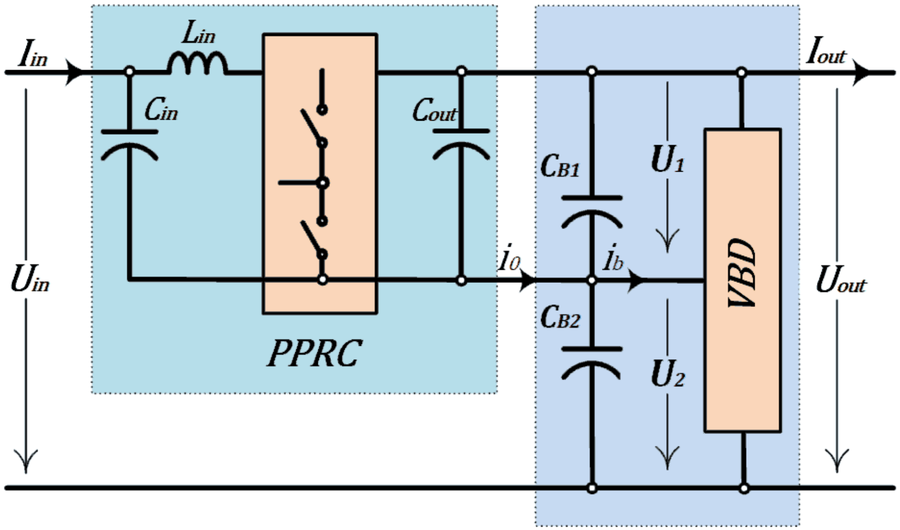
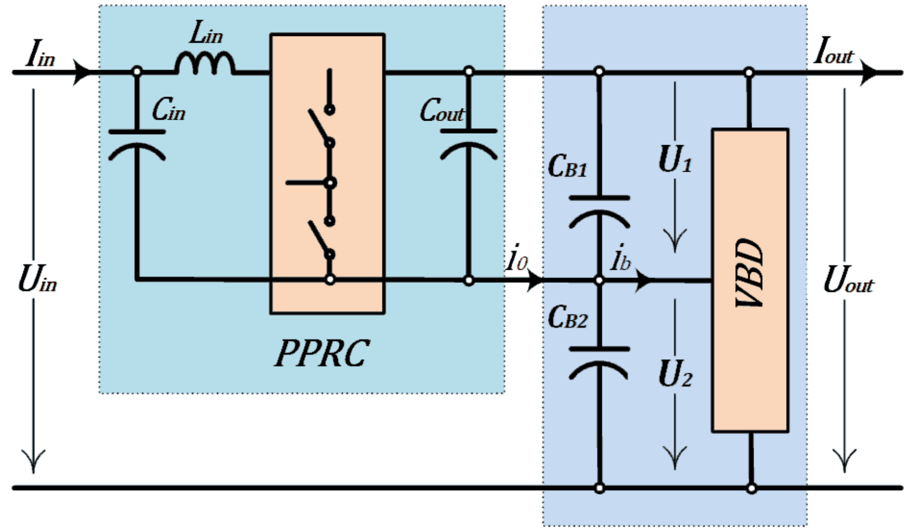


- However, in most of real applications that is not a case
  - There is a ingle voltage source or a passive load that must be spilt into two voltage sources..
  - The DC BUS capacitor is split into two series connected capacitors
    - Similar to Three-Level NPC and T type converters!

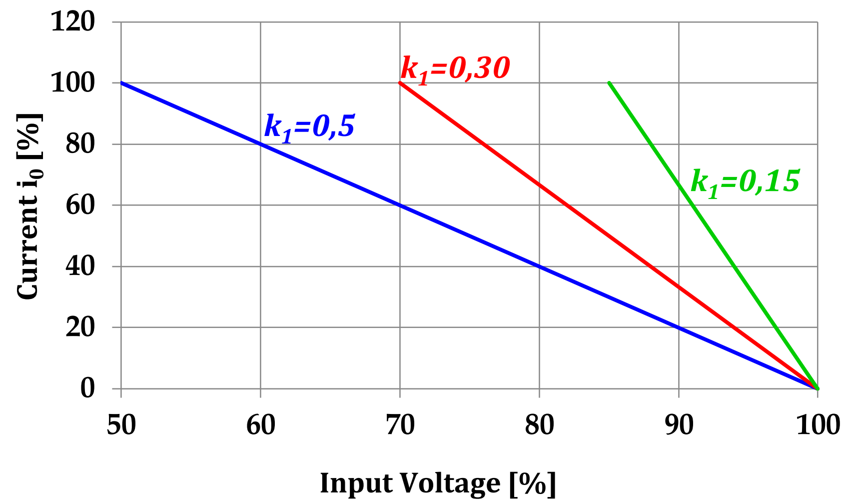
Voltage Balancing Issue!

- The DC BUS spilt into two cells
  - $C_{B1}, C_{B2} \rightarrow U_1, U_2$

  But, no Meal for Free!
- The PPRC injects average current i_0 into the dc bus caps. mid point!
- Steady State Condition: The caps. average current must be zero!
  - The current i_0 must be canceled by i_b current!

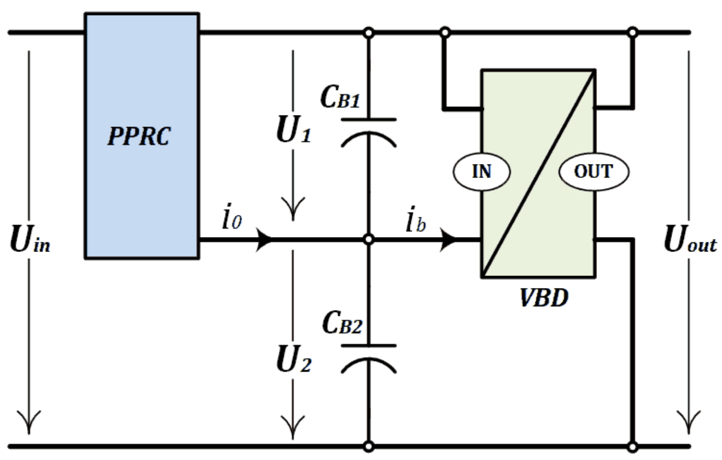


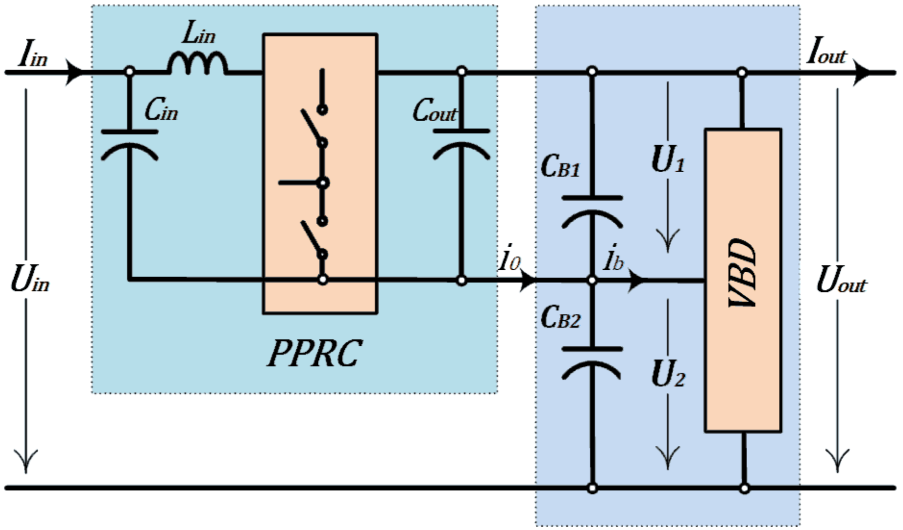
$$i_0 = i_b = I_{in} \frac{U_{out} - U_{in}}{k_1 U_{out}} \quad \& \quad U_1 = k_1 U_{out}$$



Voltage Balancing Issue!

TOP INPUT - OUTPUT



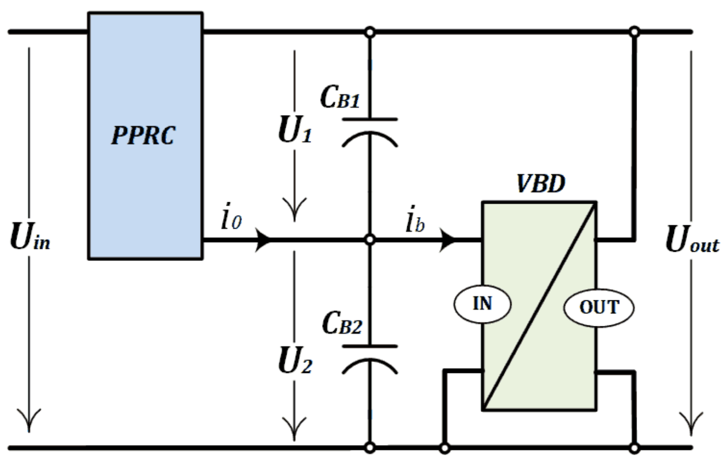


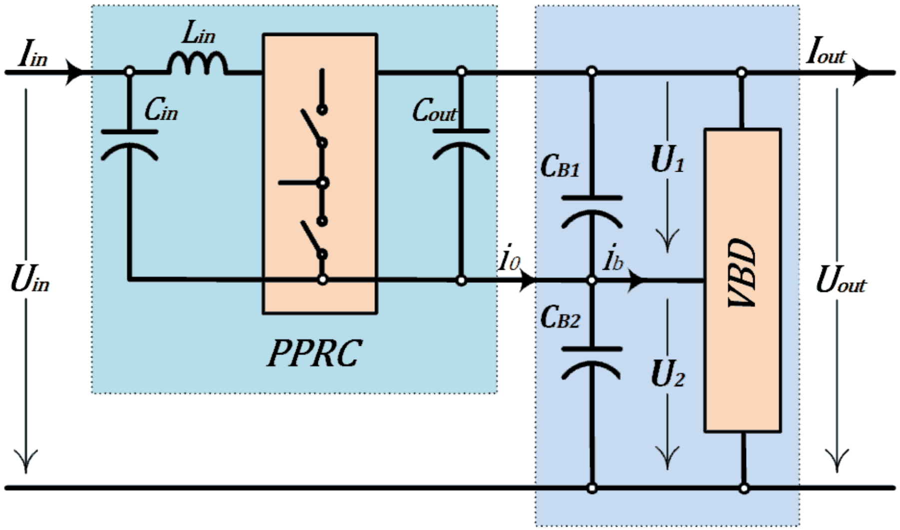
Voltage Balancing Device (VBD)

a) Two Terminal Device (INPUT & OUTPUT)
b) Uni-Directional or Bi-Directional
c) Isolated or Non-Isolated

Voltage Balancing Issue!

BOTTOM INPUT - OUTPUT





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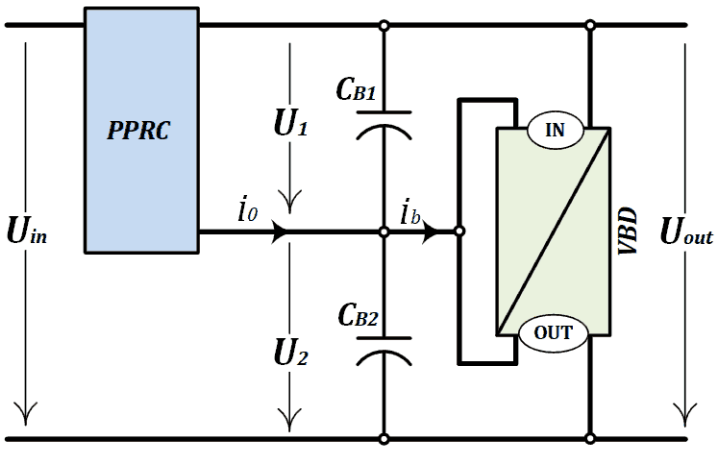

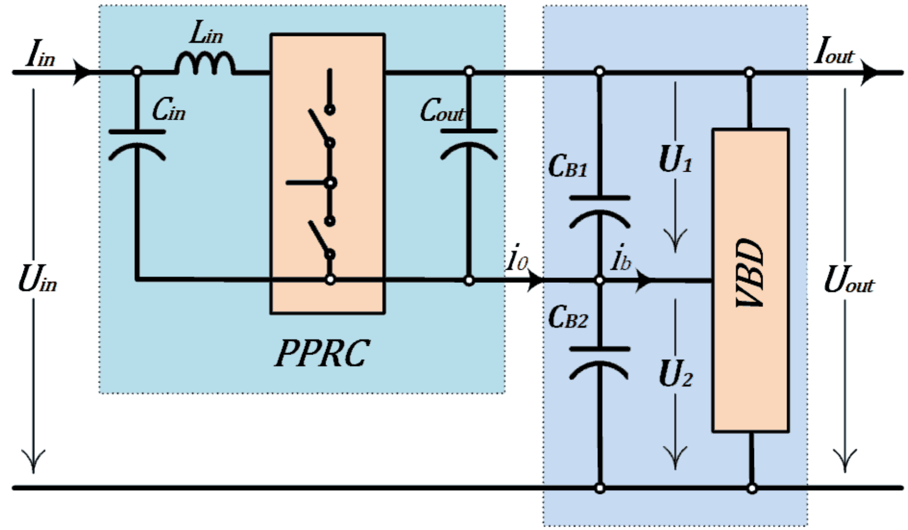

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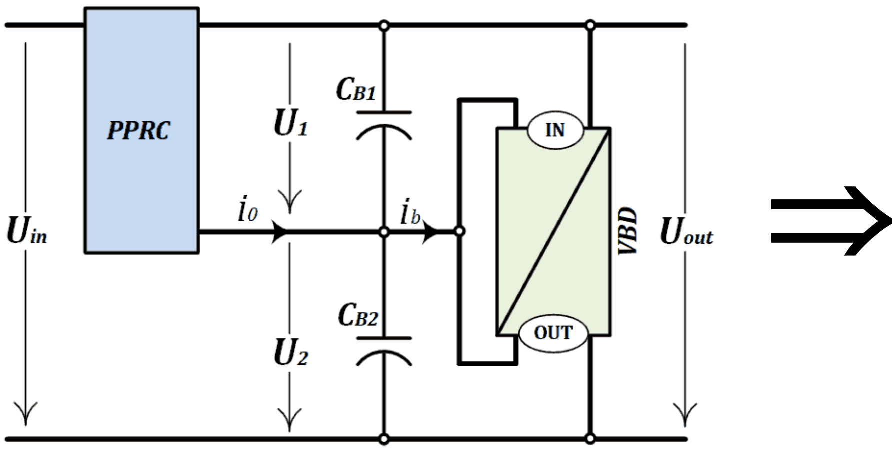
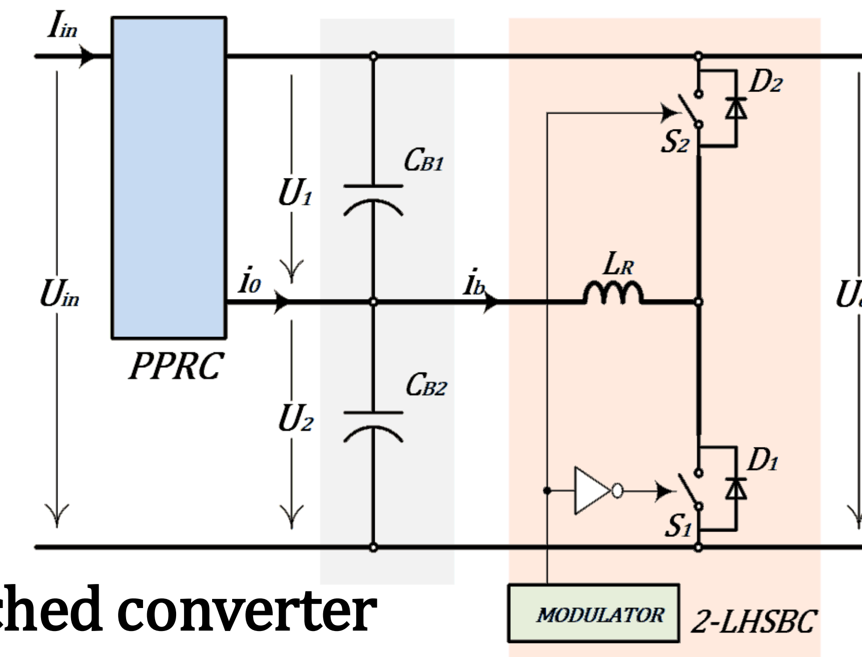




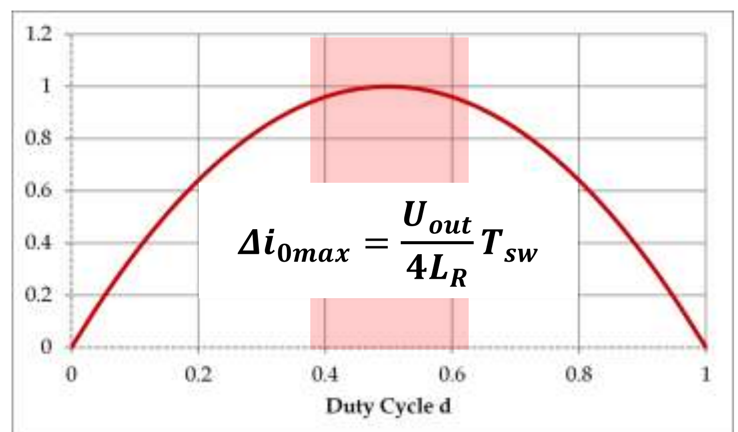
VBD is an ordinary 2L hard switched converter

a) Easy control
- $U_1 = (1-d)U_{out}$ & $d = 1 - k_1$

b) Large Inductor L_R
- The worst case condition d~0,5

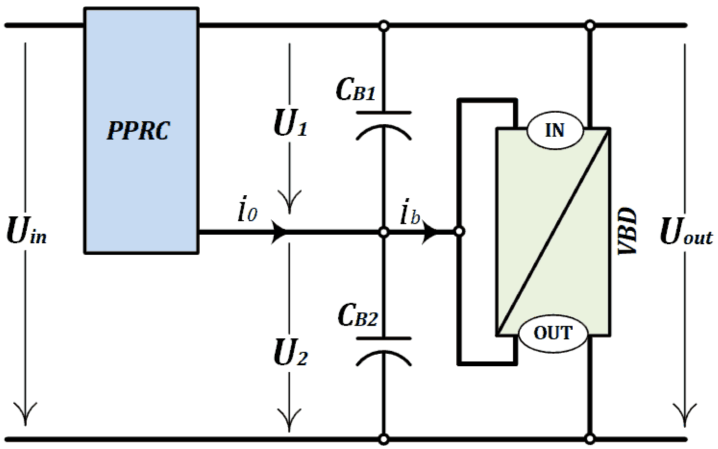
c) Full voltage rated switches & diodes

d) Switching losses



Voltage Balancing Issue!

TOP INPUT – BOTTOM OUTPUT



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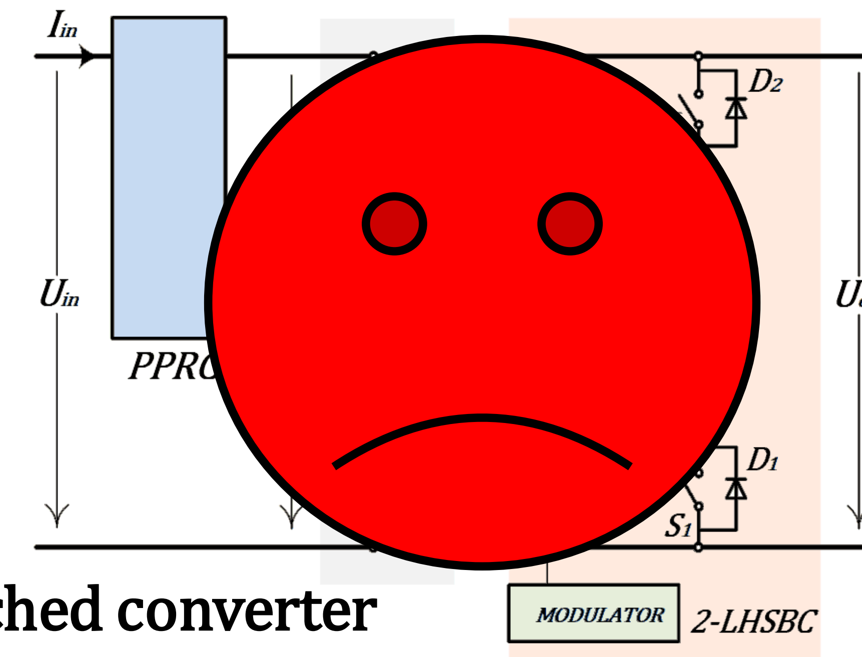


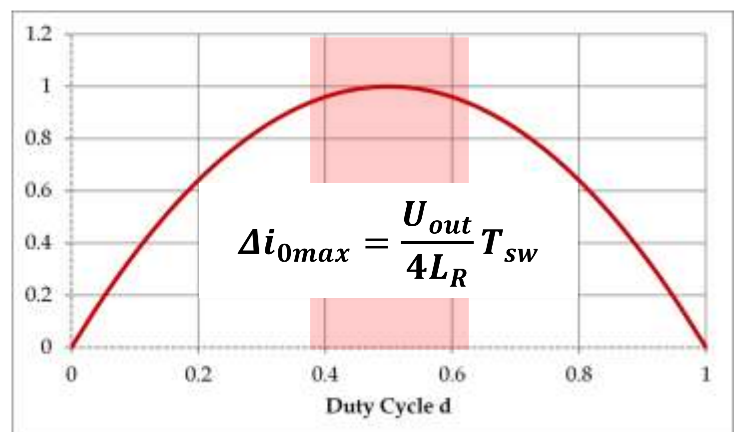
VBD is an ordinary 2L hard switched converter

a) Easy control
- $U_1 = (1-d)U_{out}$ & $d = 1 - k_1$

b) Large Inductor L_R
- The worst case condition d~0,5

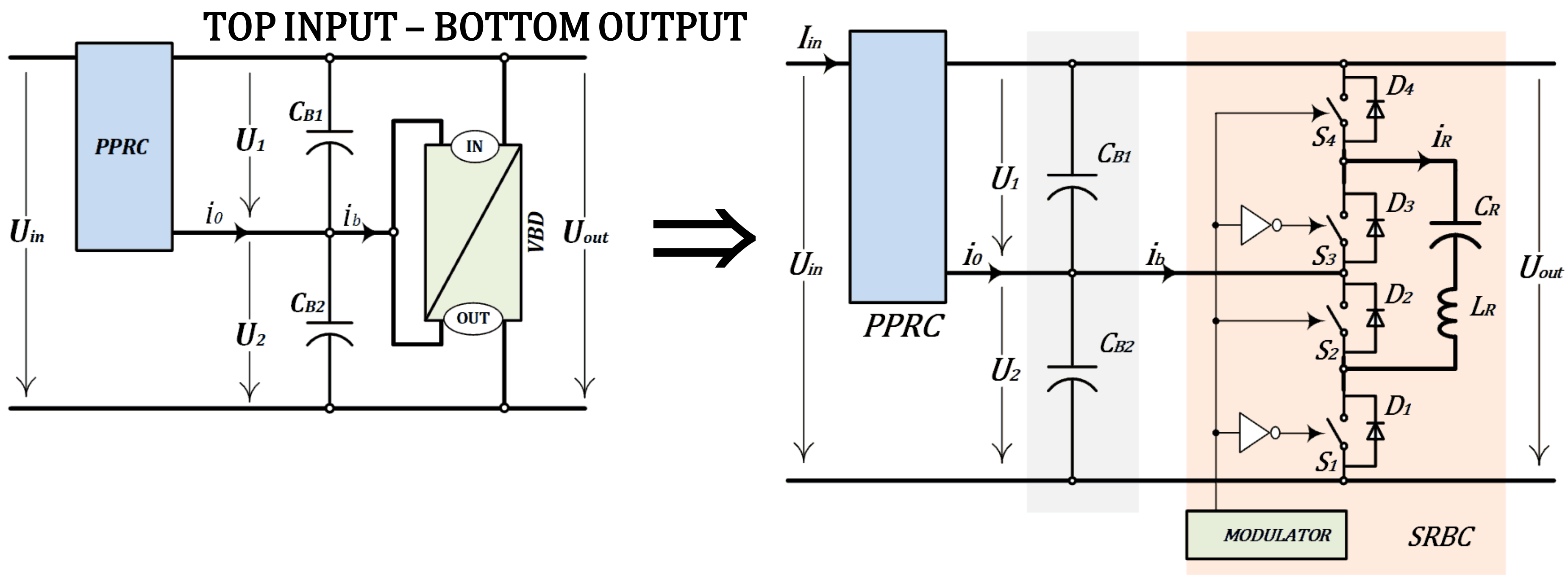
c) Full voltage rated switches & diodes

d) Switching losses



OUTLINE

SRC as Voltage Balancing Device



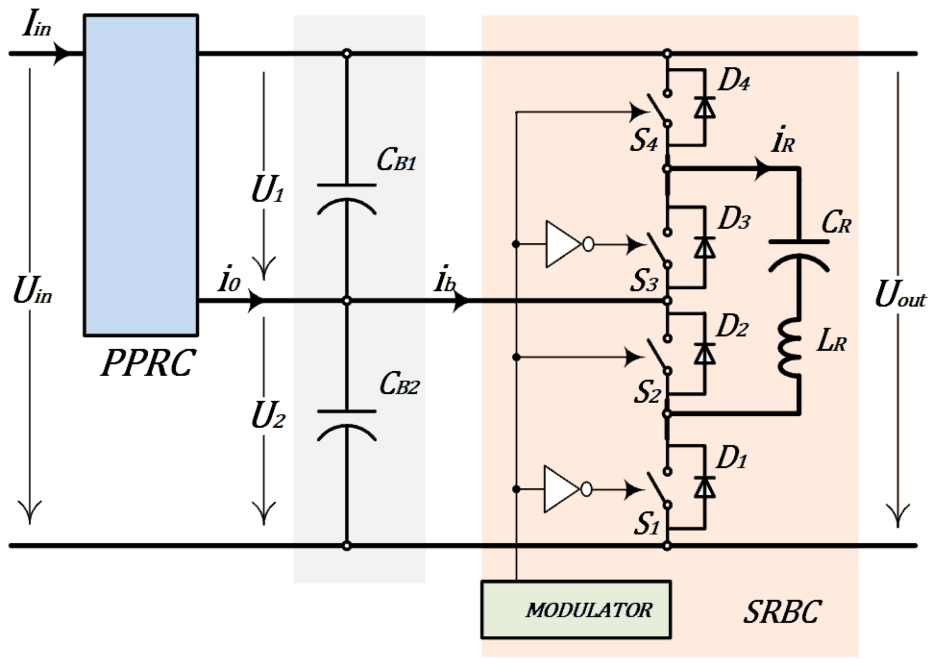
1. **Petar J. Grbović**, Philippe Delarue and Philippe Le Moigne, "A novel three-phase diode boost rectifier using hybrid half-DC-BUS-voltage rated boost converter," *IEEE Trans. Industrial Electronics,* Vol. 58, No. 4 pp. 1316-1329, April 2011.
2. Miroslav Vasić, Diego Serrano, Pedro Alou, Jesus A. Oliver, **Petar J. Grbović** and Jose A. Cobos, "Comparative Analysis of Two Compact and Highly Efficient Resonant Switched Capacitor Converters", Applied Power electronics Conference, APEC 2018, San Antonio, Texas, USA, March 4th to 8th, 2018.

SRC as Voltage Balancing Device

Series Resonant Voltage Balancing Device (SR-VBD)

a) Two switching cells (1-2 & 3-4) connected across the bottom and the top dc bus capacitors
b) A resonant tank (L_R C_R) connected between the cells
c) The cells duty cycle $d \cong 0,5$

d) Switches & diodes voltage rating is half of the output voltage
e) Zero Current Switching
f) No large inductors required
g) More devices and gate drivers
h) Resonant capacitor current stress



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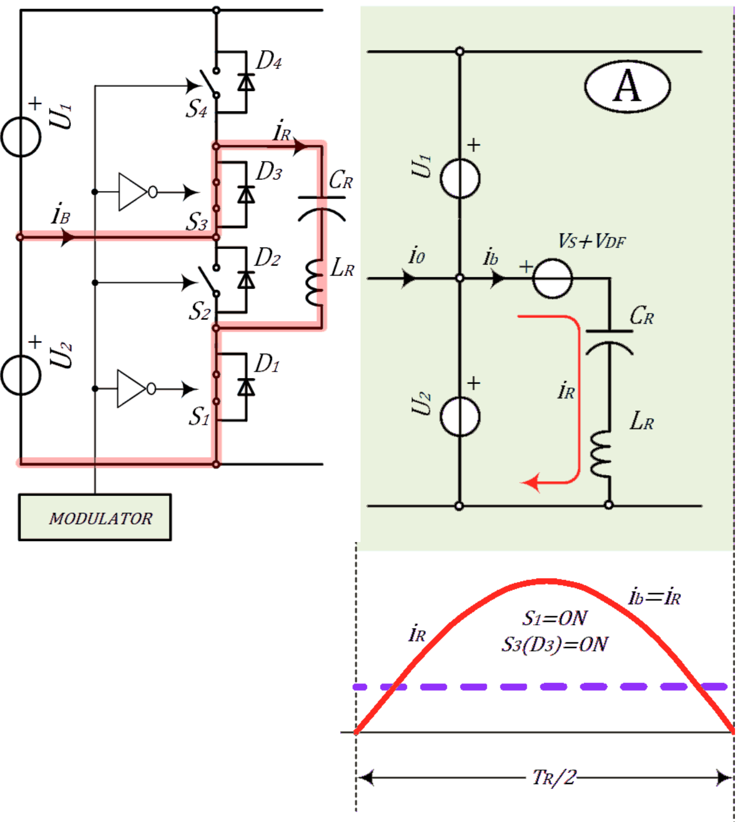
SRC as Voltage Balancing Device

One cycle switching sequence…A..B..C..D



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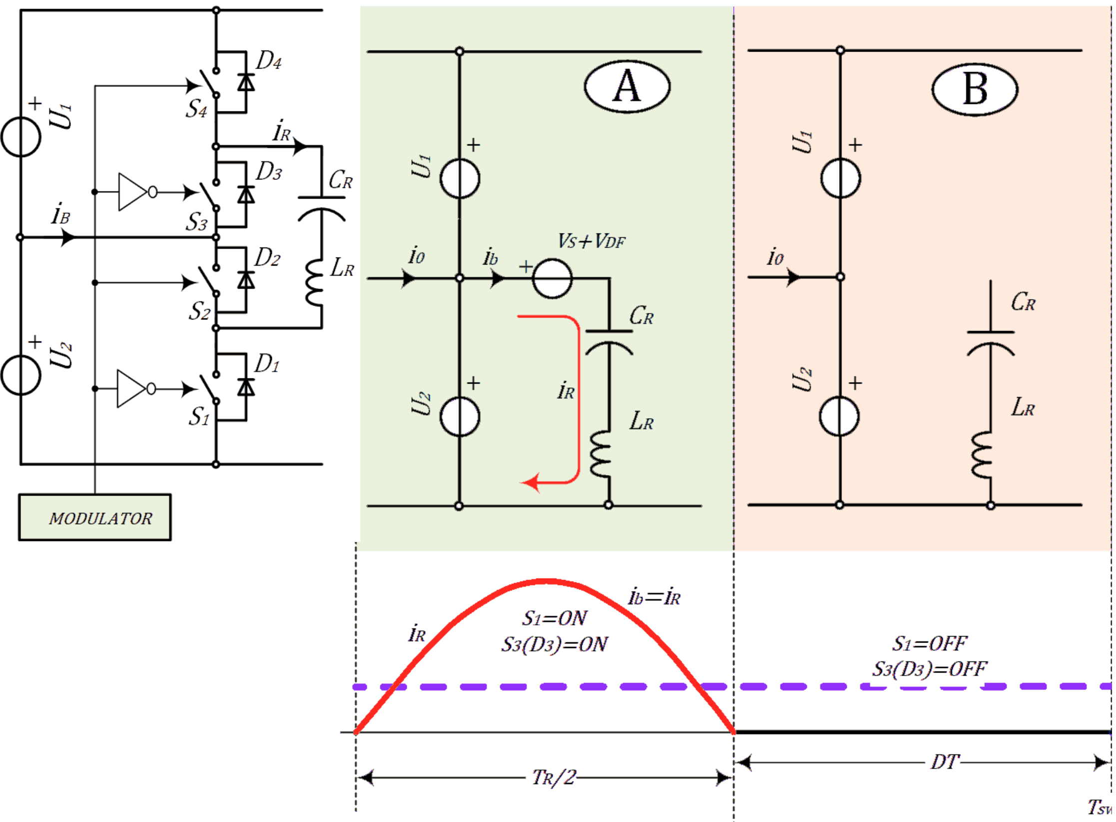

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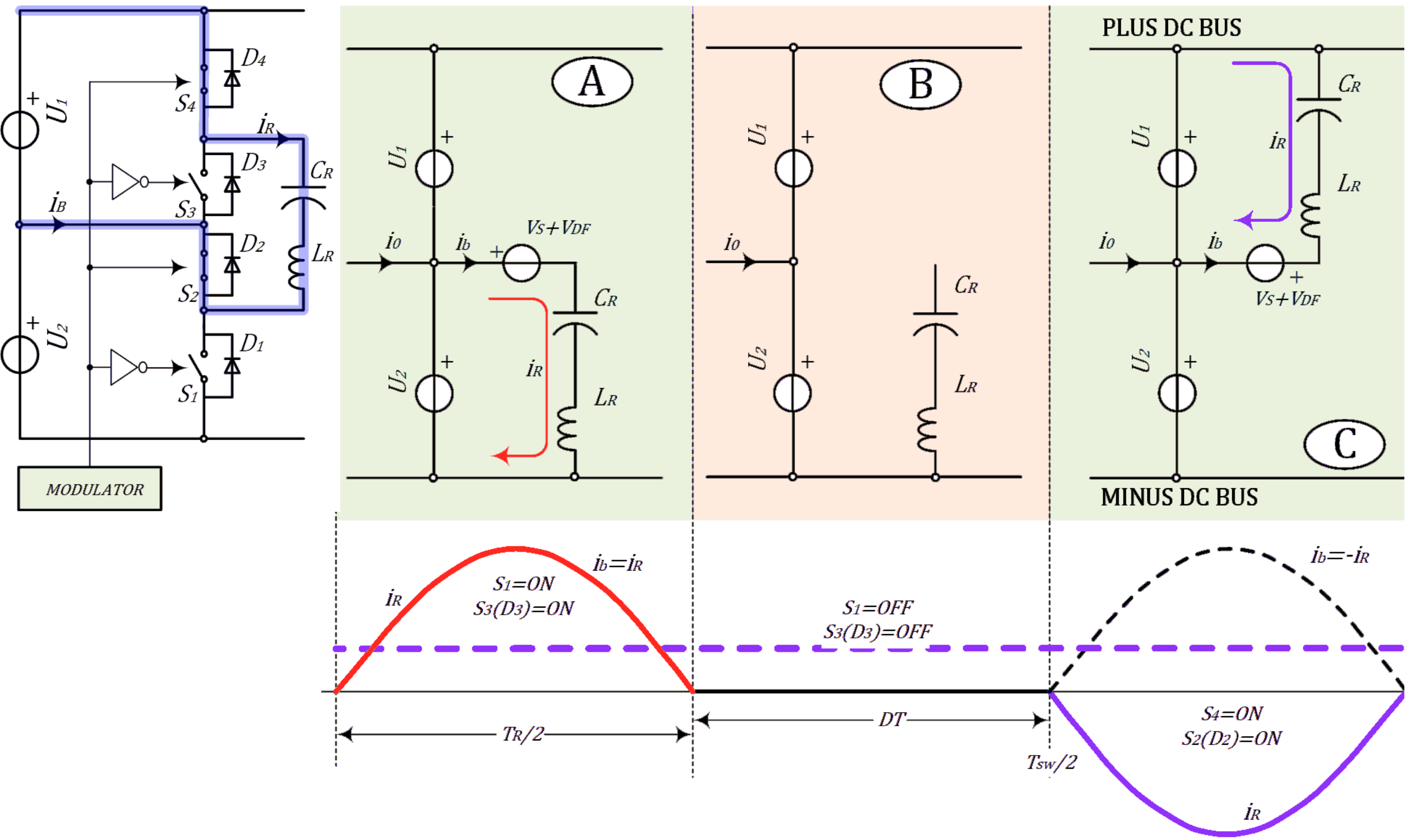

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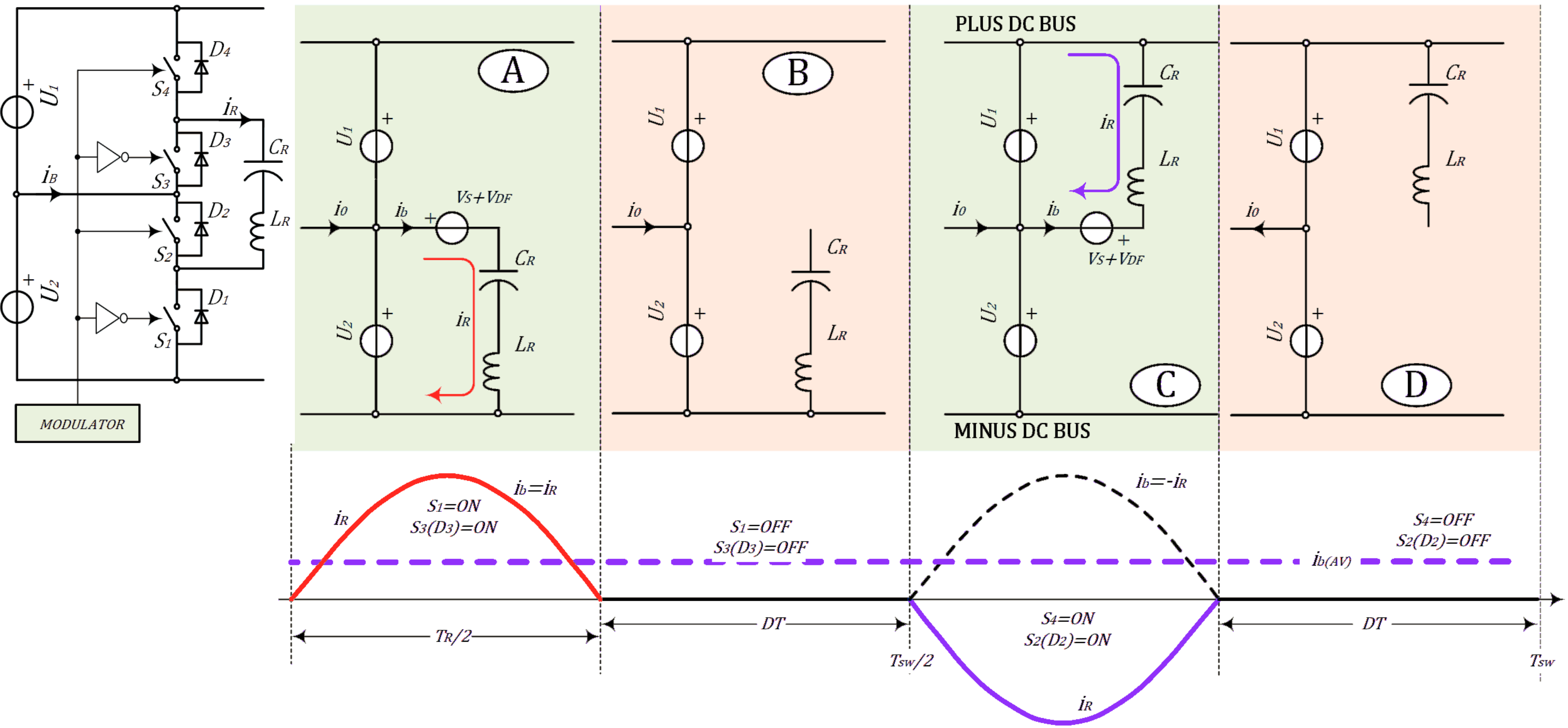
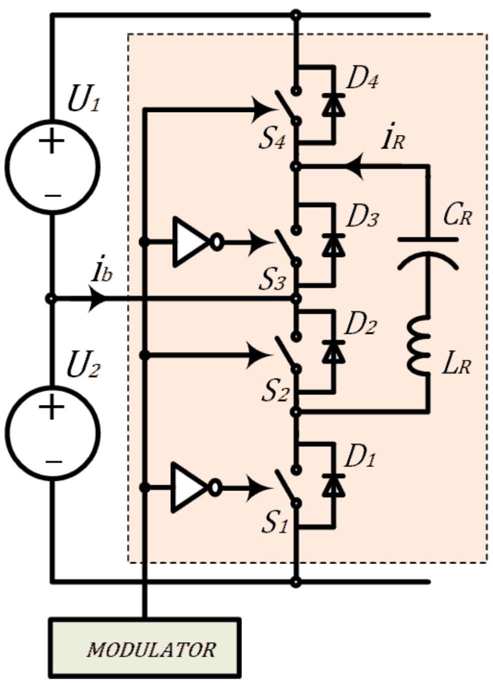


SRC as Voltage Balancing Device

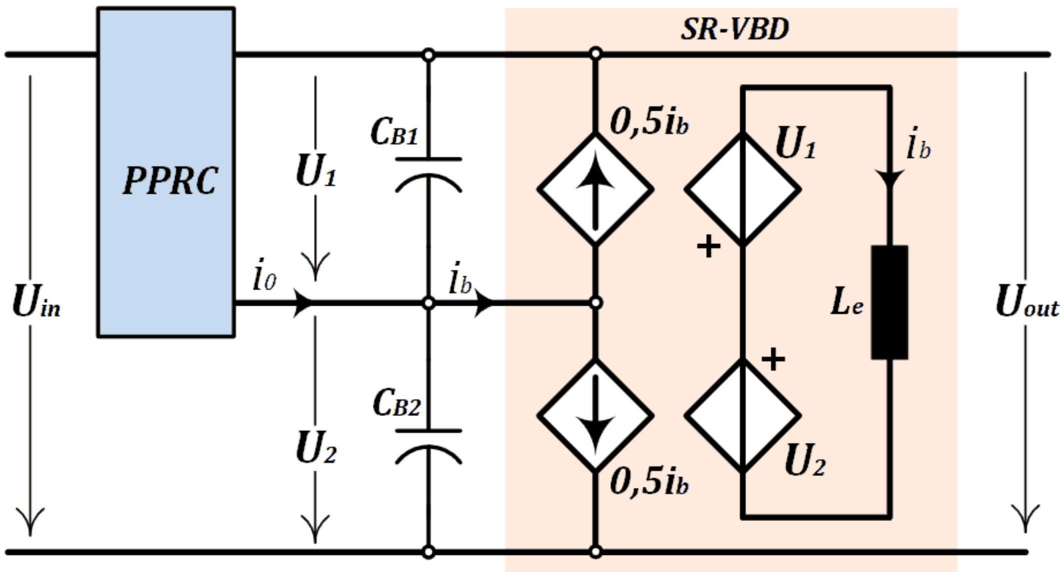


$$i_R(t) = \begin{cases} i_b \frac{\pi}{2}\frac{T_{sw}}{T_R} & 0 < t < \frac{T_R}{2} \\ 0 & \frac{T_R}{2} < t < \frac{T_{sw}}{2} \\ -i_b \frac{\pi}{2}\frac{T_{sw}}{T_R} & \frac{T_{sw}}{2} < t < \frac{T_R + T_{sw}}{2} \\ 0 & \frac{T_R + T_{sw}}{2} < t < T_{sw} \end{cases}$$

In Steady State the resonant tank current $i_R(t)$ is pricewise sinusoidal current with pause DT and constant magnitude $I_r = i_b \frac{\pi}{2}\frac{T_{sw}}{T_R}$

SRC as Voltage Balancing Device

Average model of SR-VBD



$$\frac{\Delta i_{b(av)}}{\Delta T} L_e = U_1 - U_2$$

$$L_e = L_R \frac{\pi^2}{2} \left(\frac{T_{sw}}{T_R} \right)^2$$

In Steady State average current $i_{b(av)}$ must be constant

$$\frac{\Delta i_{b(av)}}{\Delta T} = 0 \quad \rightarrow \quad U_1 = U_2$$

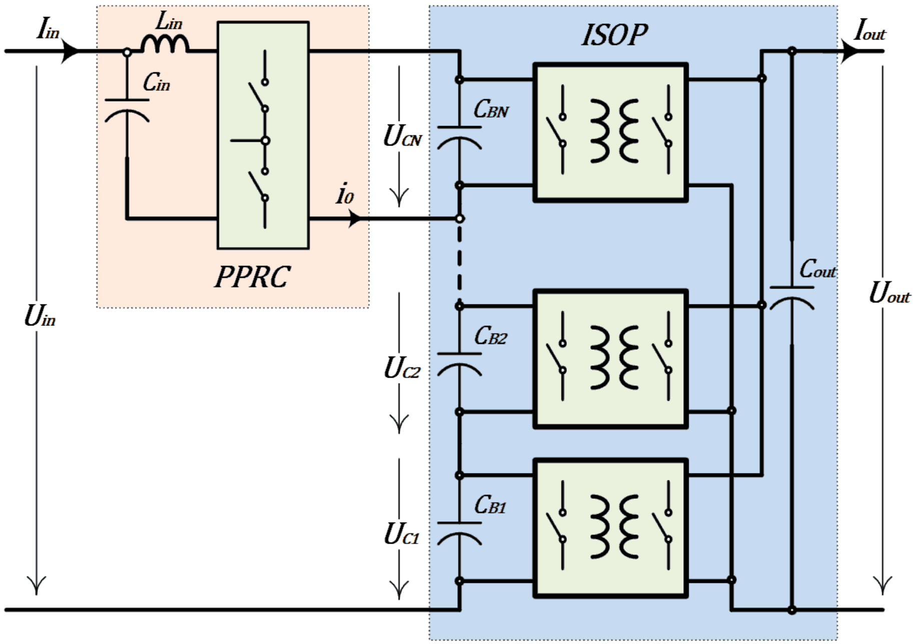
The switches and diodes are not ideal..... Voltage mismatch between U_1 & U_2

$$U_2 = \frac{U_{out} + sgn(i_b)(V_{sw} + V_{DF})}{2} \quad \& \quad U_1 = \frac{U_{out} - sgn(i_b)(V_{sw} + V_{DF})}{2}$$

OUTLINE

ISOP as Voltage Balancing Device

- Voltage Balancing is a MUST and it is additional burden in most of the applications
- In some specific applications, the voltage balancing device can be an intrinsic feature of the converter



- Input Series Output Parallel (ISOP) ISO Converters
- One Cell can be used as a VBD
  - No additional VBD is required
  - Power distribution is not symmetrical between all cells

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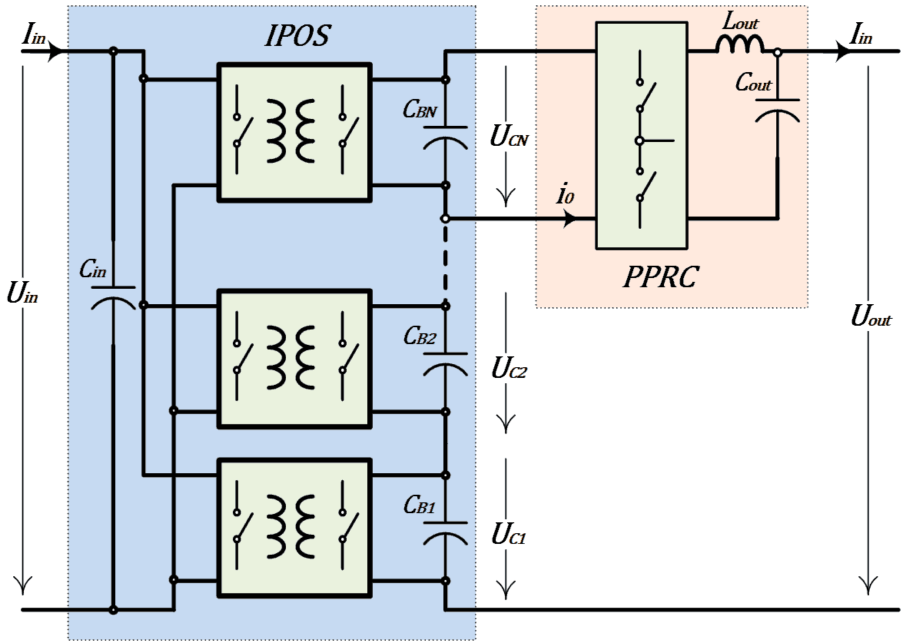

- Input Series Output Parallel (ISOP) ISO Converters
- The same concept can be used with Input Parallel Output Series (IPOS) ISO Converters
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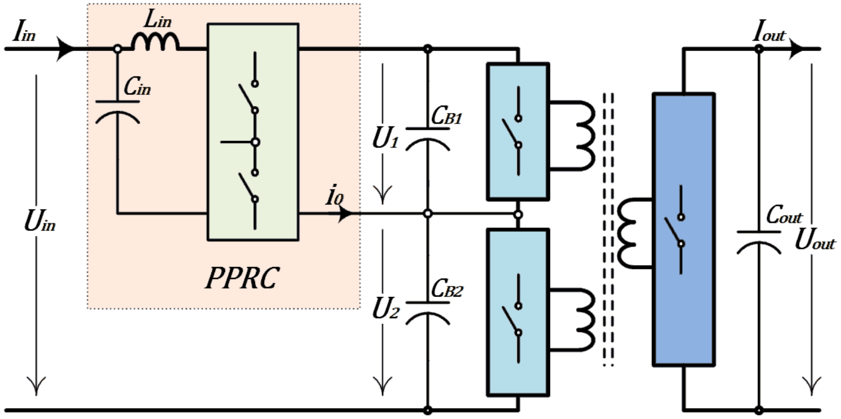

- Similar concept can be used with Single Transformer Multi-Input ISO Converters
  - No additional VBD is required
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-

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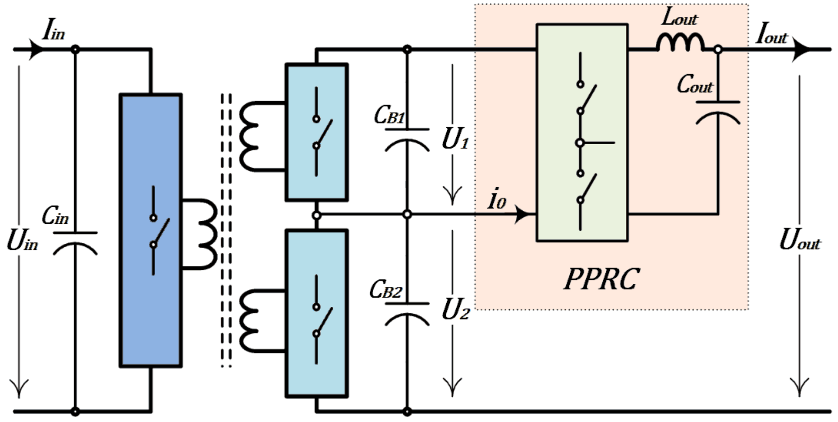

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- Similar concept can be used with Single Transformer Multi-Output ISO Converters
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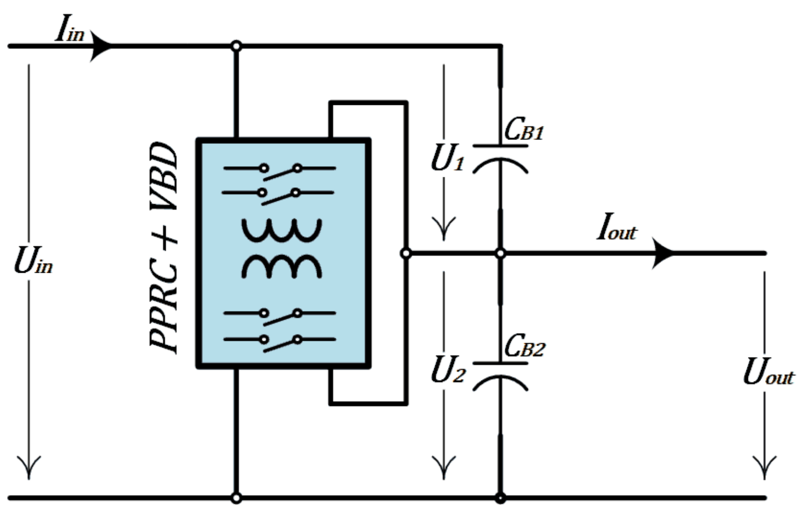


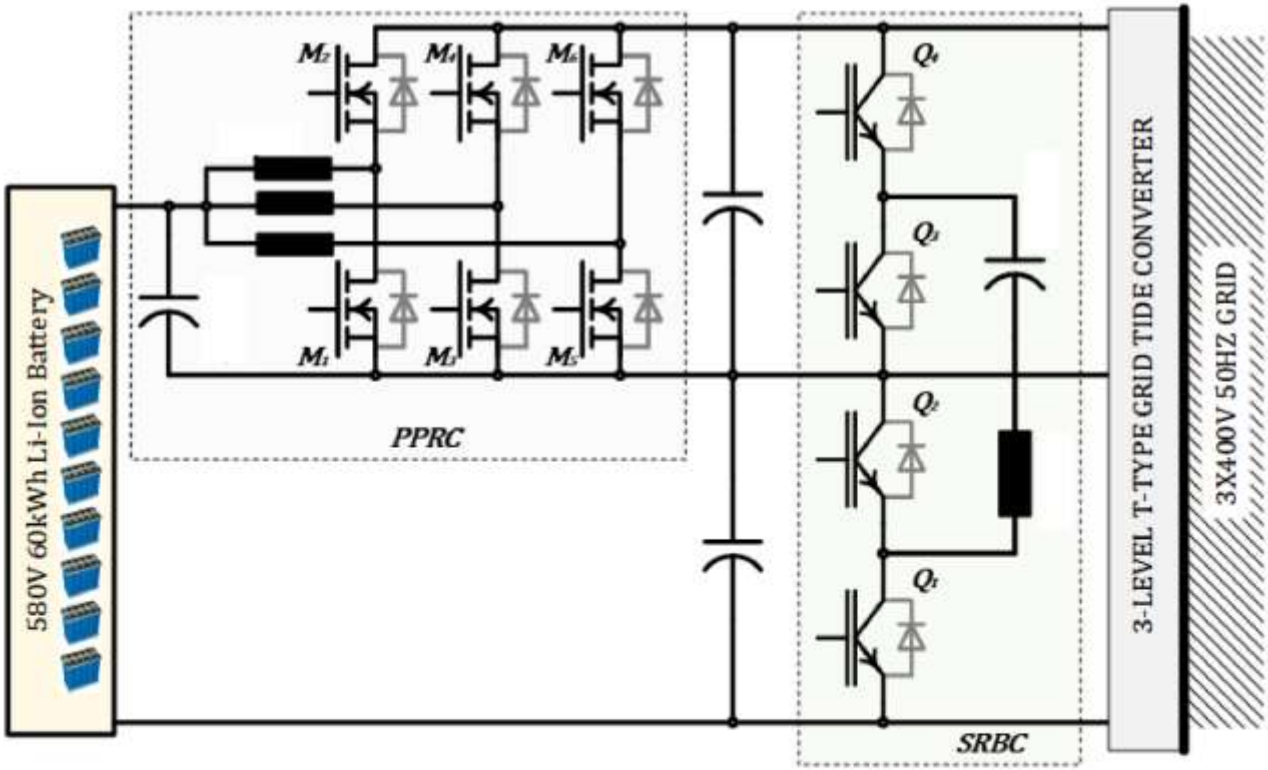
- Similar concept can be used with TOP Input-BOTTOM Output ISO VBD
  - U_1 to U_2 voltage ratio is not constant
  - $U_{out} < U_{in}$ (BUCK)
  - The converter is PPRC + VBD
    - DAB
    - SRC
    - LLC
    - PS FB
    - ……

OUTLINE

Case 1: Battery Interface DC-DC

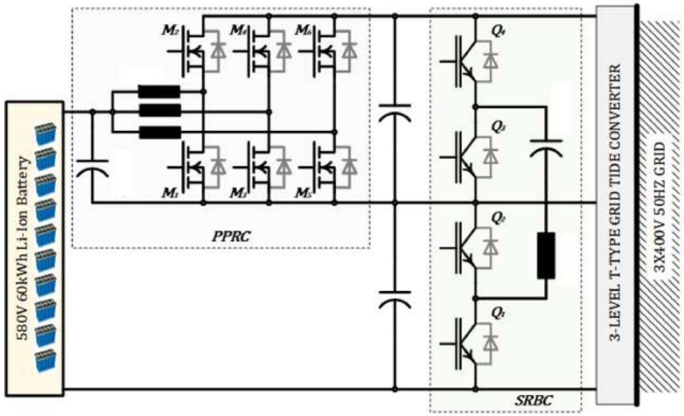
Interface DC-DC converter for grid connected Li-Ion battery energy storage system

- $U_{B(min)} = 400[V]$
- $U_{B(max)} = 580V[V]$
- $U_{BUS} = 700\ [V]$
- $P_{B(n)} = 30[kW]$
- $f_{sw(PPRC)} = 280\ [kHz]$
- $f_{sw(SR-VBD)} \cong 80\ [kHz]$
- SR-VBD
  - IGBT IKW75N65EL5
- PPRC:
  - CoolMOS IPZ60R017C7



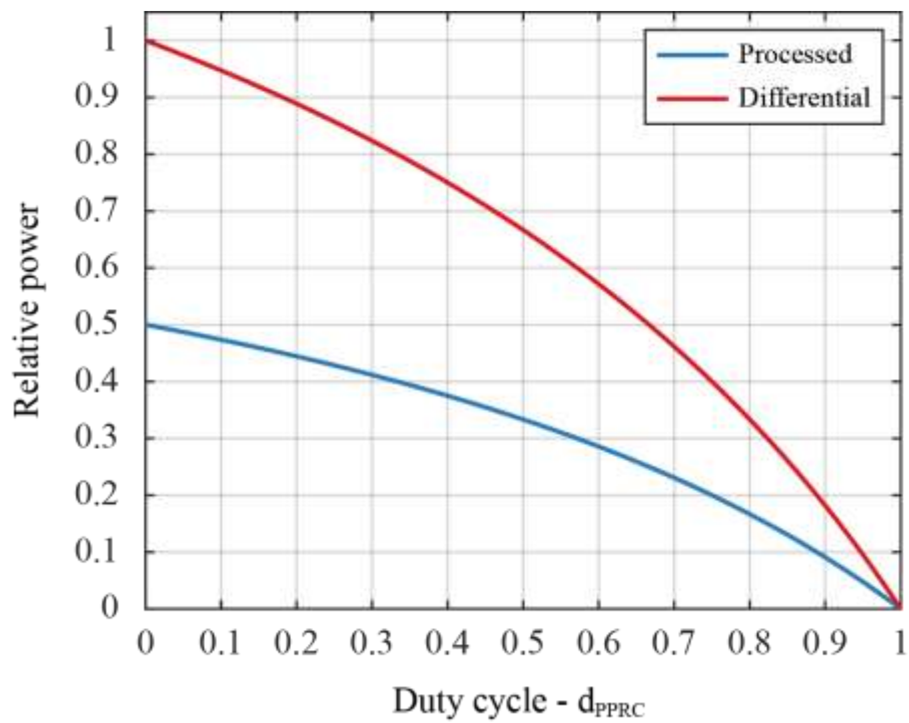
- P. J. Grbović, "Partial Power Rated DC/DC Converters: A Way to Go Beyond the Limits"
  - 30kW
  - >99.5% Efficiency…>50kW/dm³ & 25kW/kg….Si Only (no WBG)!!

Case 1: Battery Interface DC-DC



$$k_{PP} = \frac{1 - d_{PPRC}}{2 - d_{PPRC}}$$

$$k_{diff} = 2\frac{1 - d_{PPRC}}{2 - d_{PPRC}}$$



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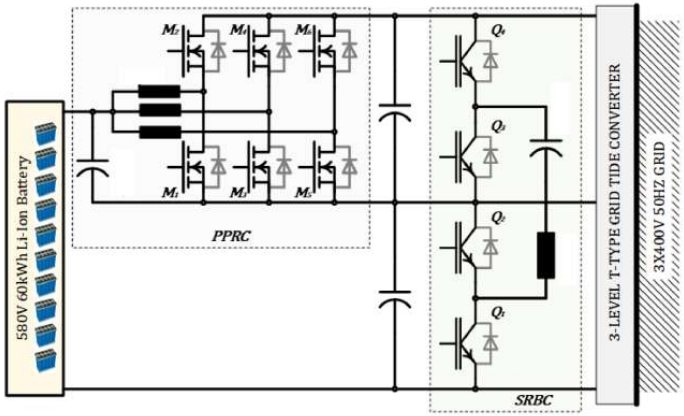

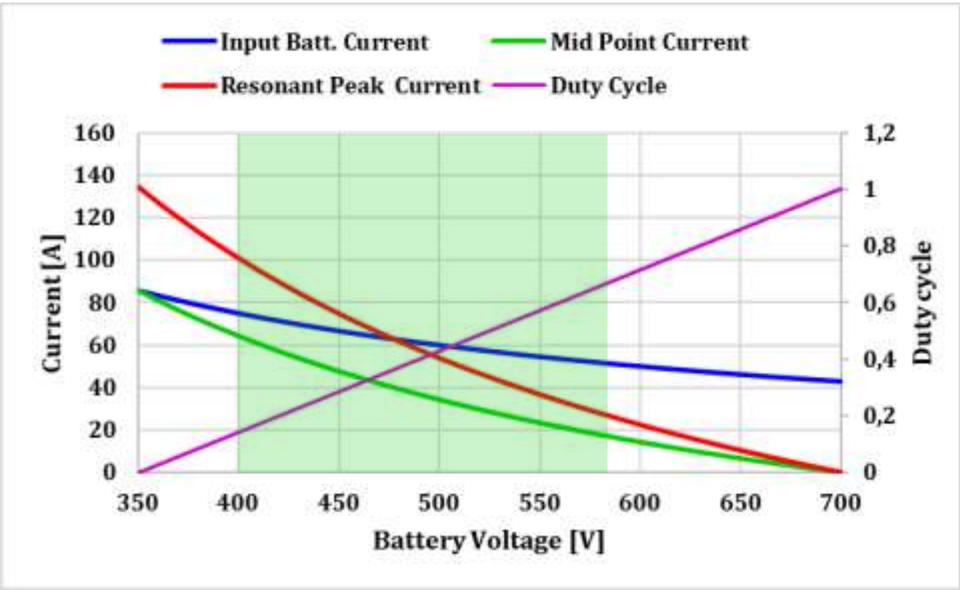

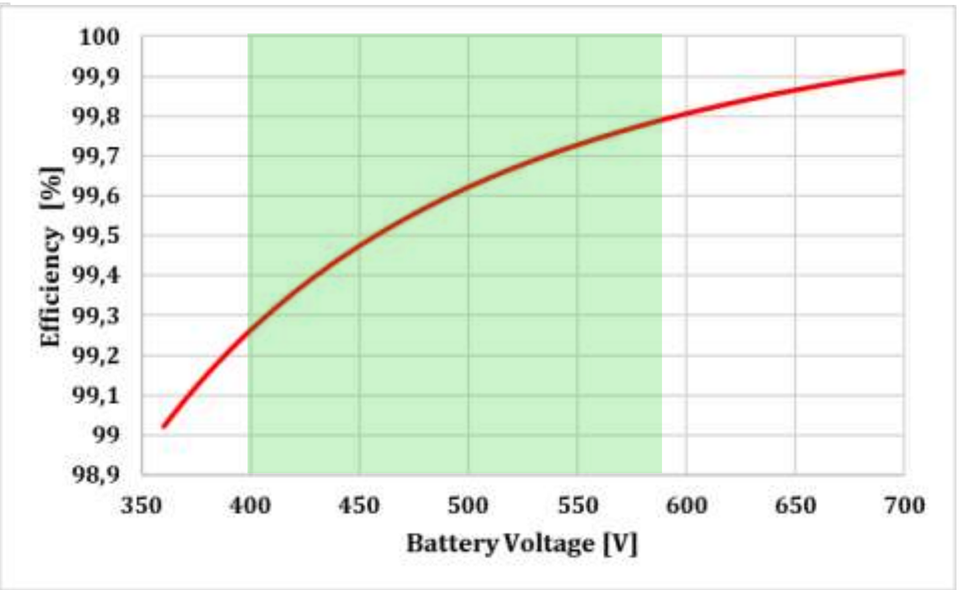

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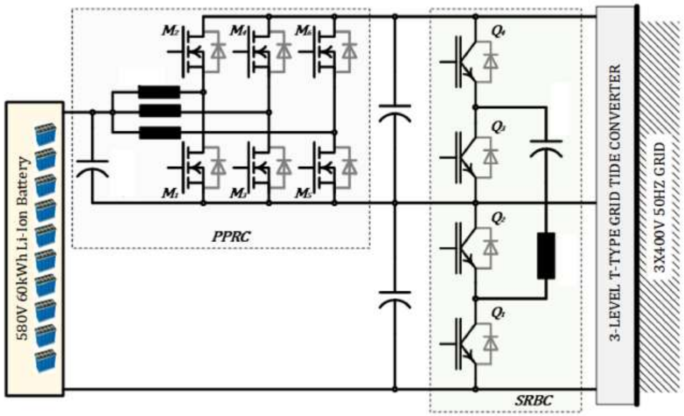

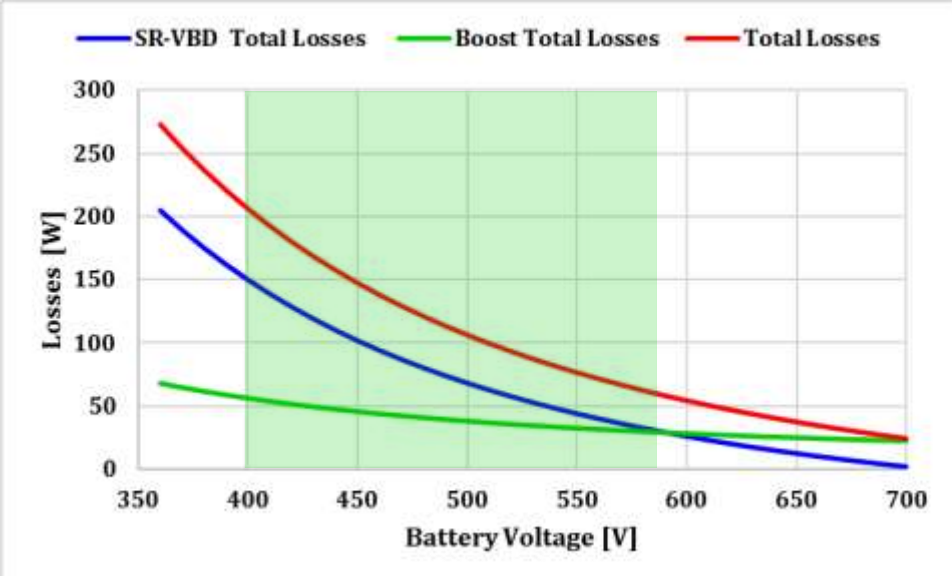

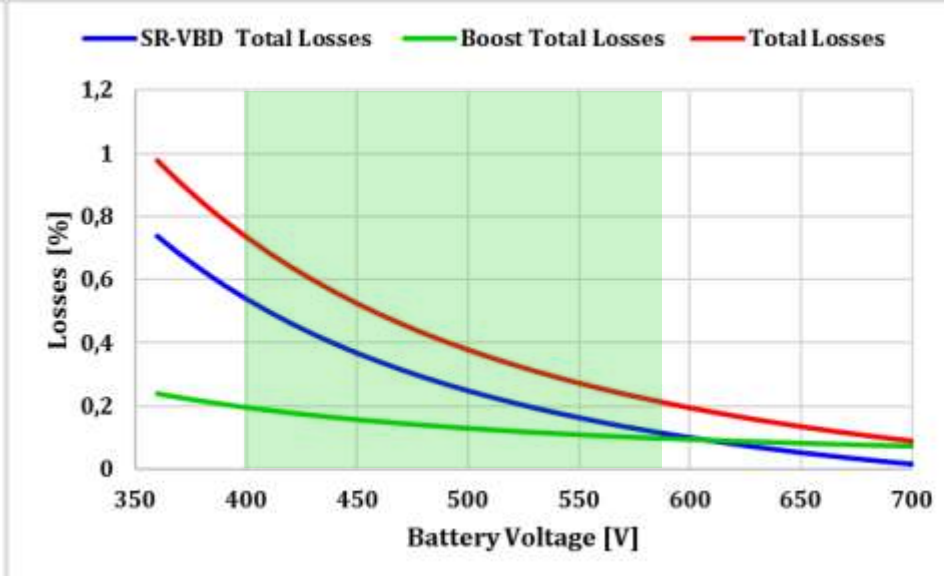

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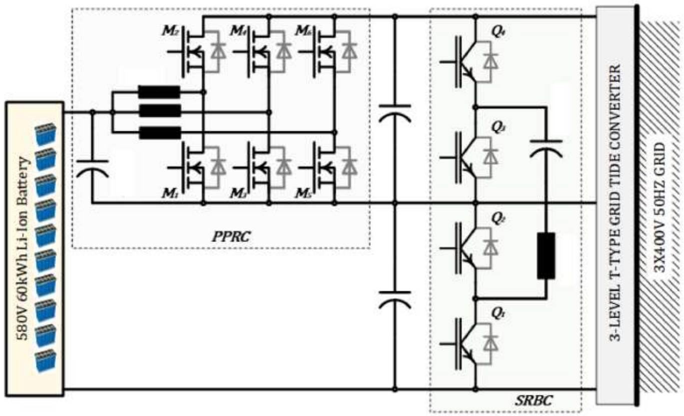

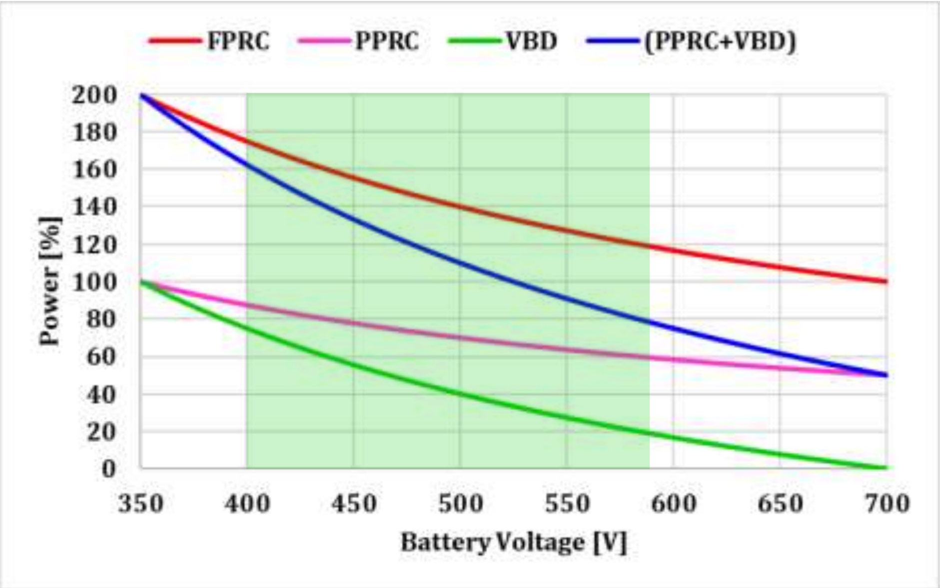

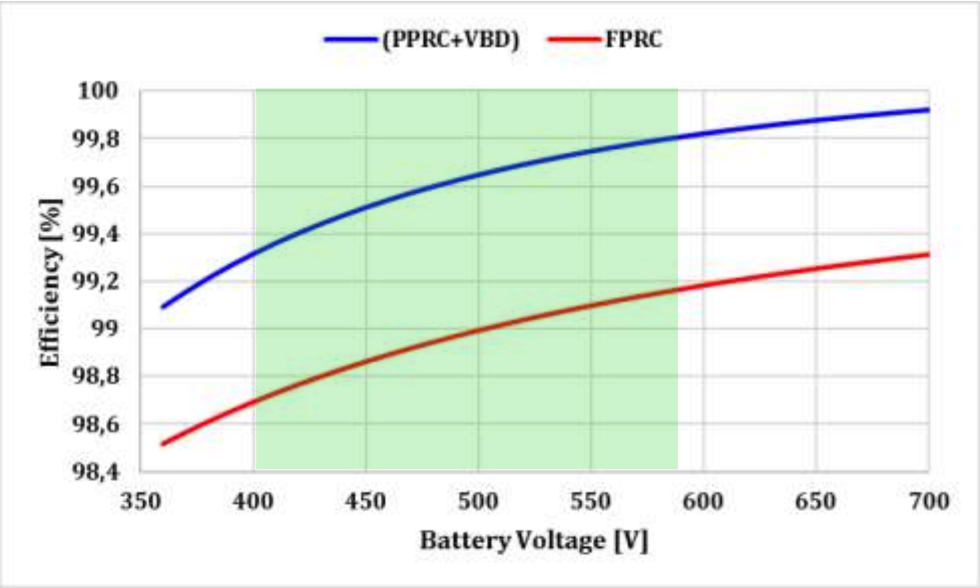

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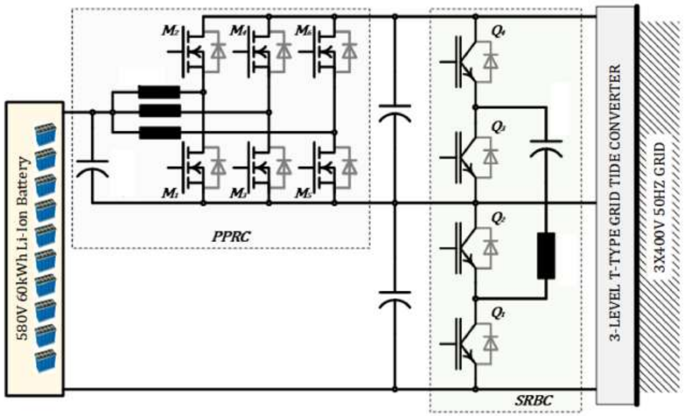
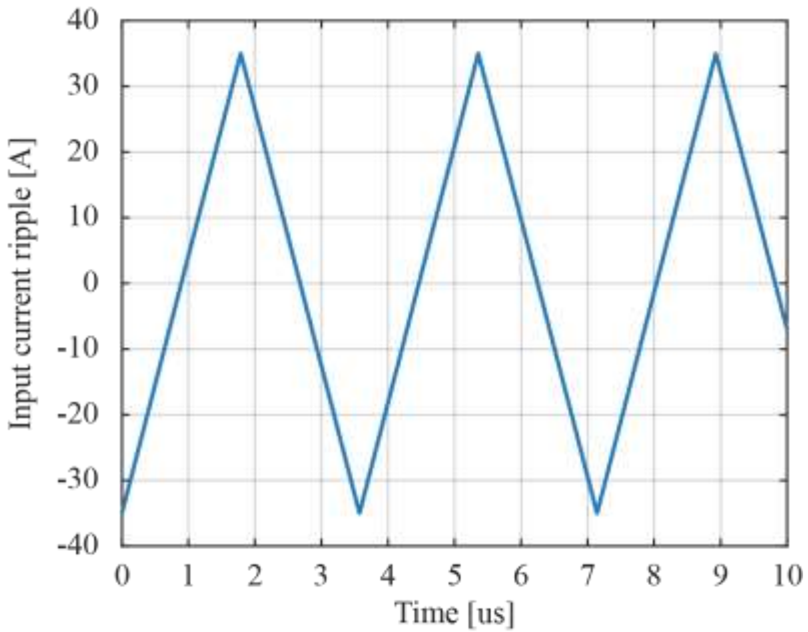


ZVS & Interleaving

$V_{block} \in 350\ [V]$ → ZVS required

Inductor current waveform: $\Delta i_{L_{pp}} > 2I_{L_{DC}}$

→ Interleaving to reduce input current ripple:



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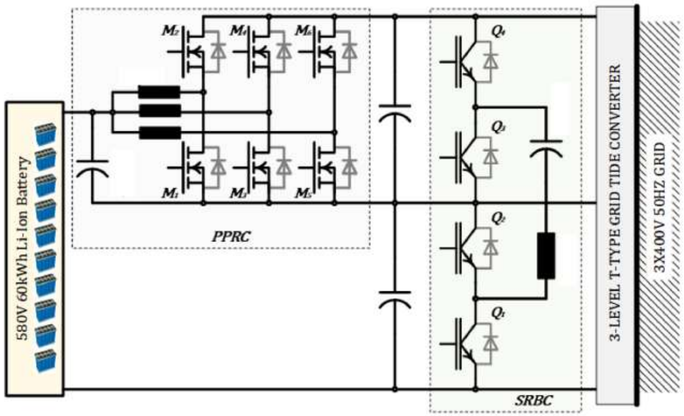

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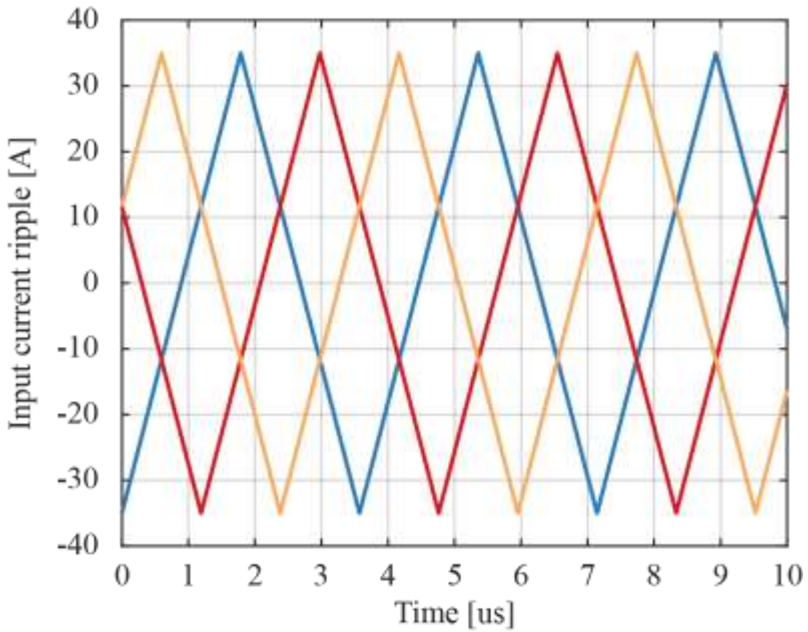

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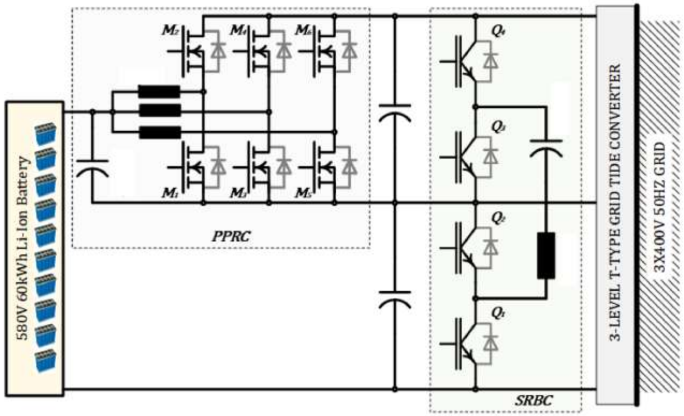

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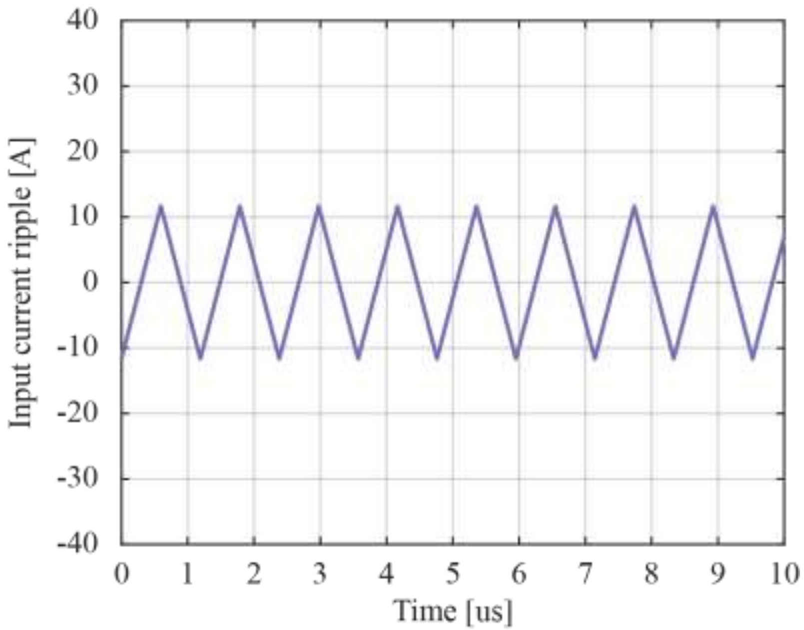

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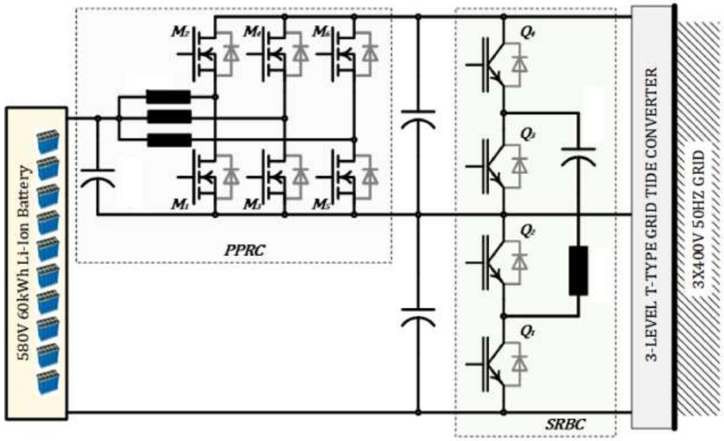

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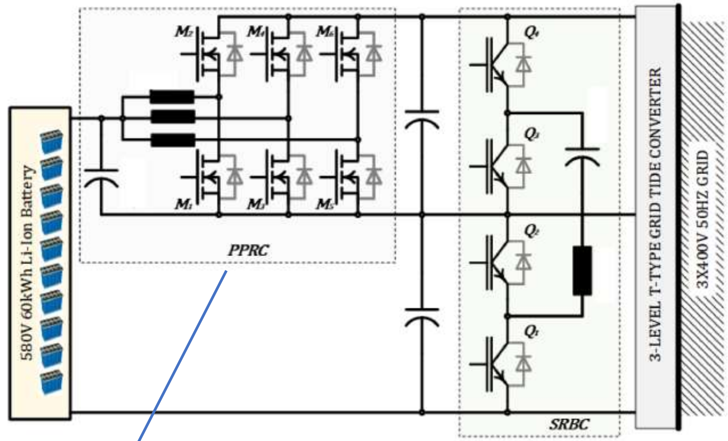
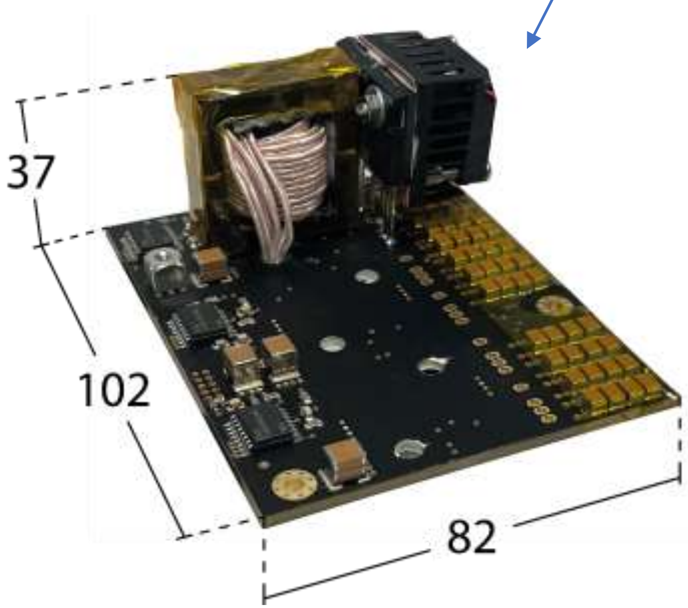
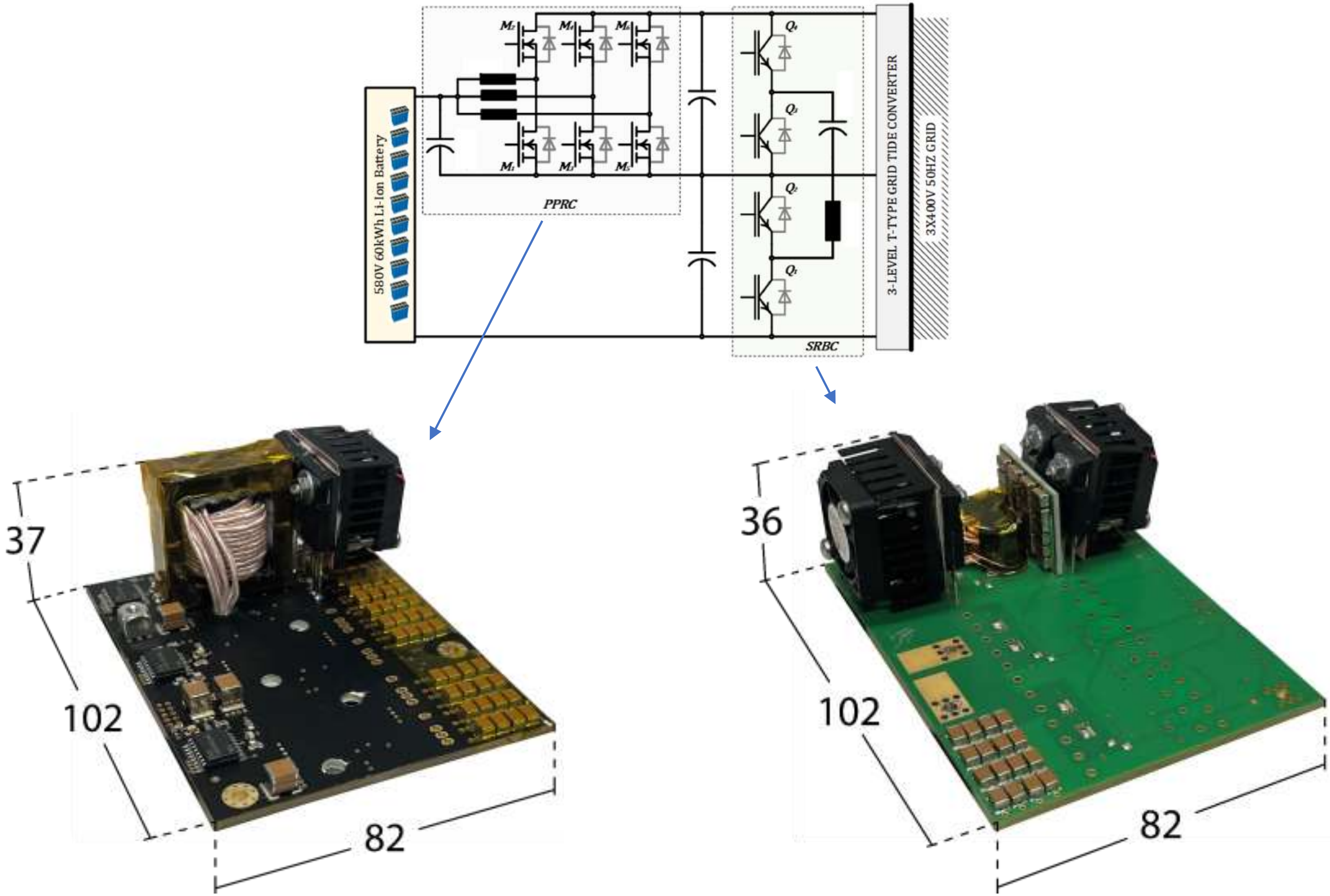




universität innsbruck
Unit of Electrical Engineering

Case 1: Battery Interface DC-DC

i-PEL
Innsbruck Power Electronics Lab.

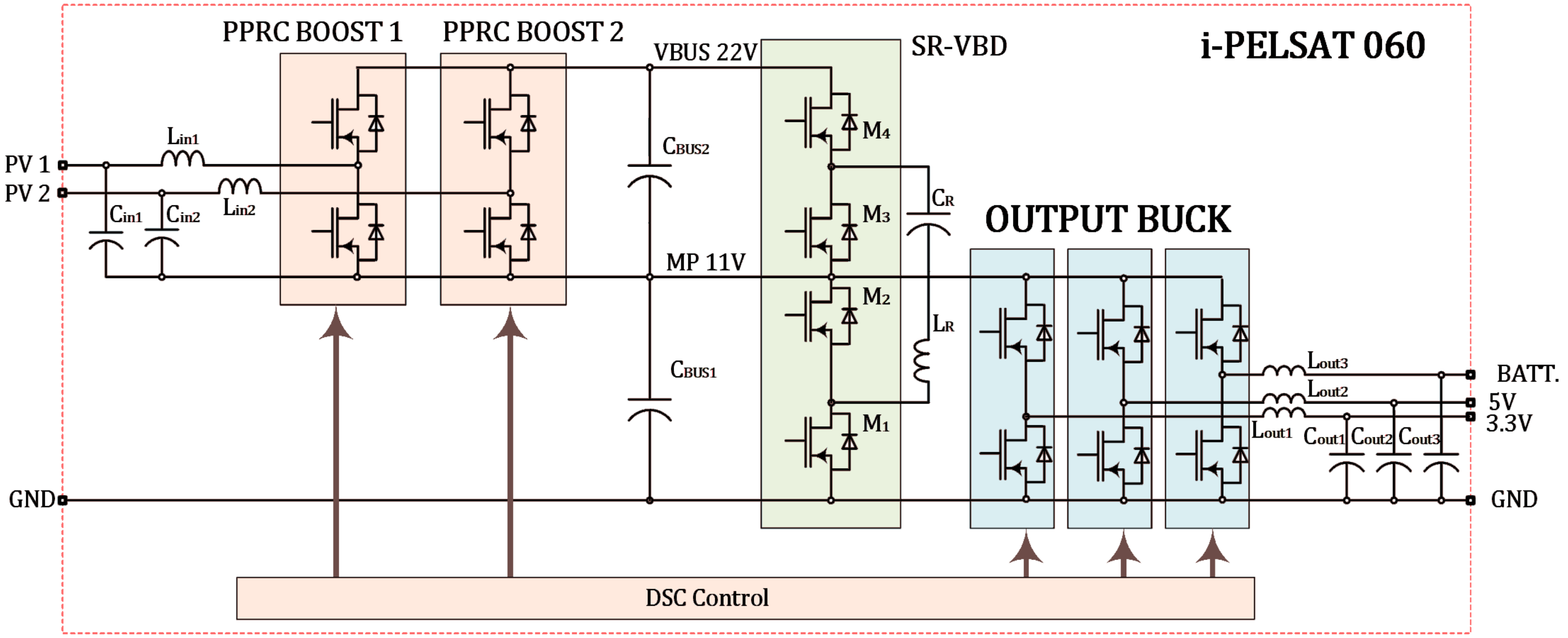


Case 2: Nano-Satelit Power Supply

IEEE PELS International Future Energy Challenge Student Project

- Power Supply for Nano Satellite
- Input 2 x PV Panels (20Vmax & 3Amax)
- Storage Battery (8V 2600 mAh)

- Outputs:
  - 5V @ 4A
  - 3,3 V @ 5A



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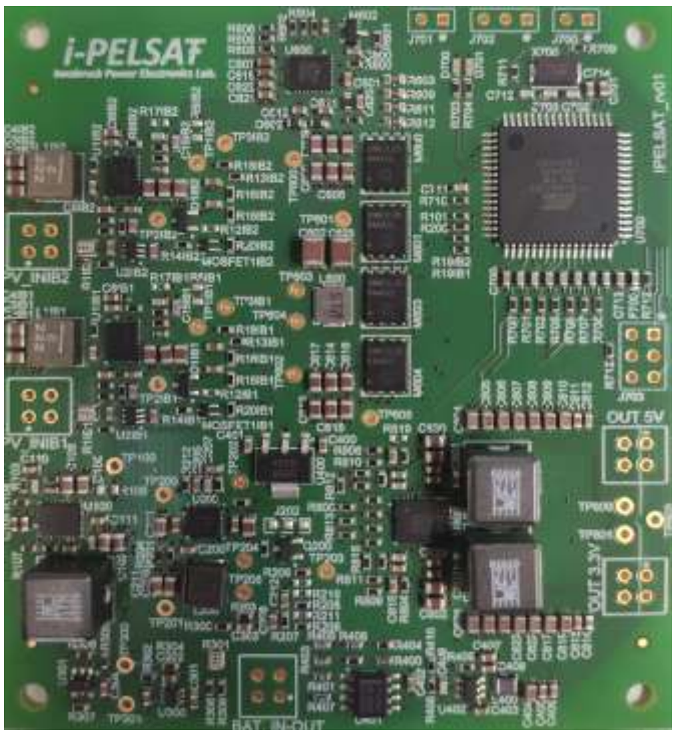

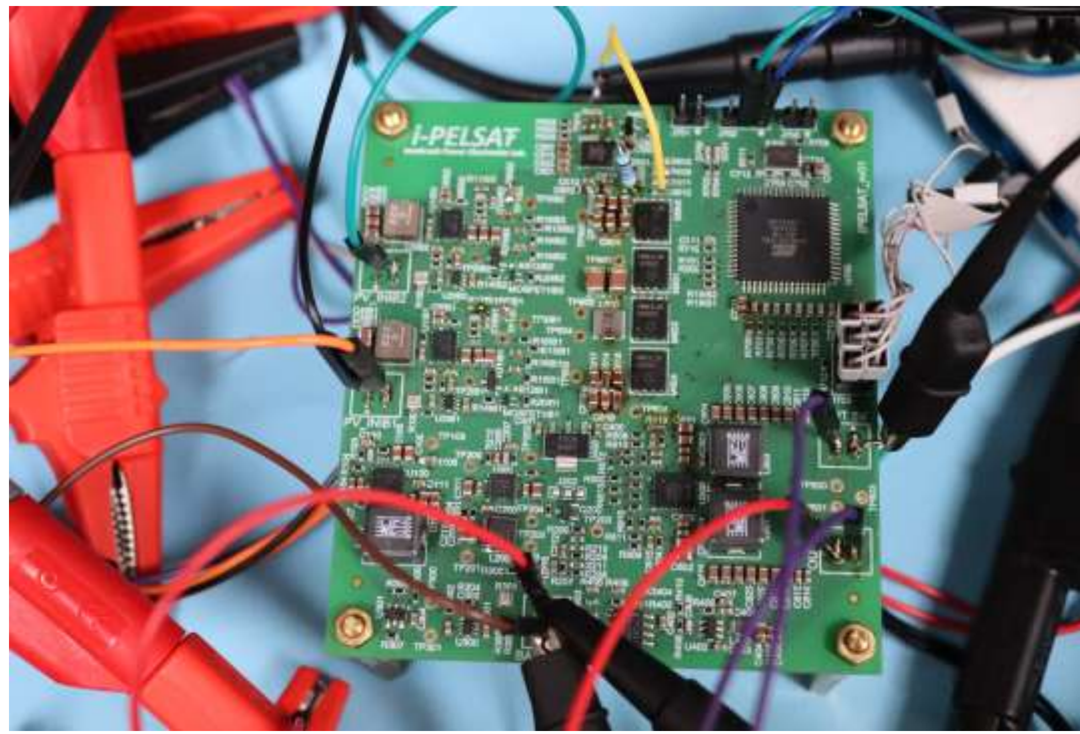

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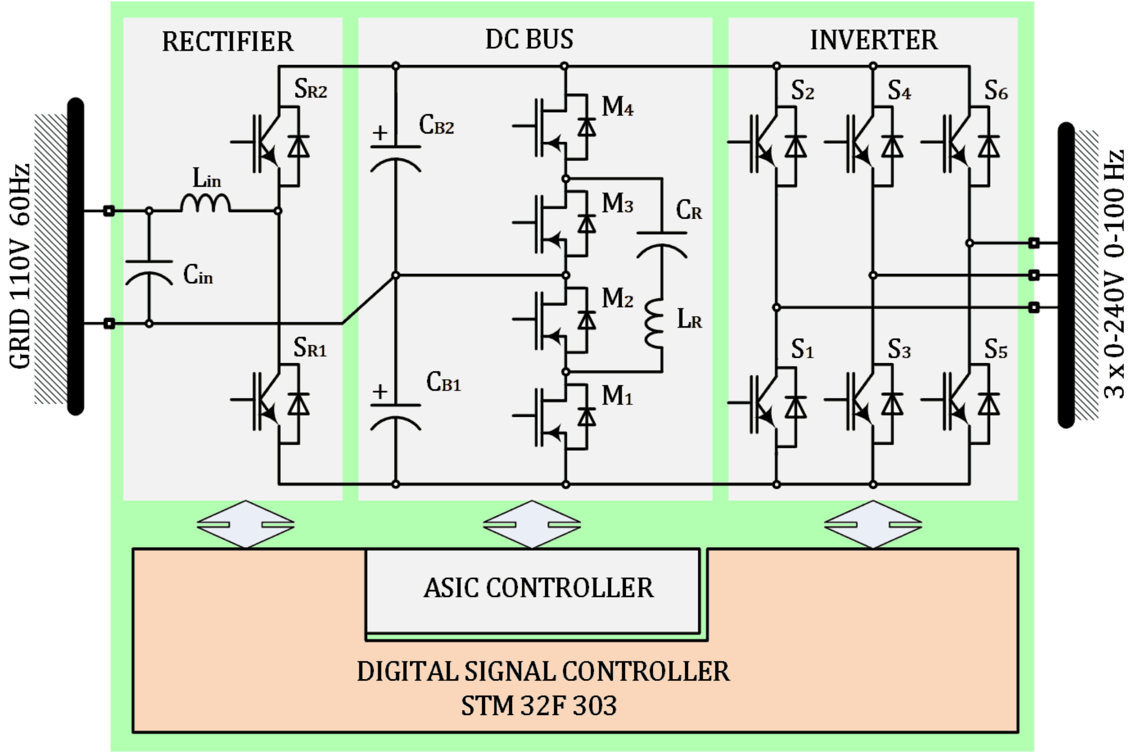
SPECIFICATION	UNIT	TARGET	PROTORYPE	COMPARISON
Maximum power consumption	[W]	5	5,5	111 [%]
Maximum PCB weight	[g]	200	34	17 [%]
Maximum dimension (L x W x H)	[mm]	90x96x25	78x87x8,7	27 [%]
Maximum voltage ripple@ 5V, 4A	[mV]	100	18	18 [%]
Maximum current ripple@ 5V, 4A	[mA]	120	12	10 [%]
Maximum voltage ripple@ 3,3V, 5A	[mV]	66	14	21 [%]
Maximum current ripple@ 3,3V, 5A	[mA]	150	12	8 [%]

Case 3: Hybrid DC BUS Capacitor

Rated Power [kW]	**3**
Input Voltage [V]	110
Input Current [A]	32
Output Voltage [V]	3x220
DC BUS Voltage [V]	350
DC BUS voltage Ripple [V]	50
Life Time [h]	30k



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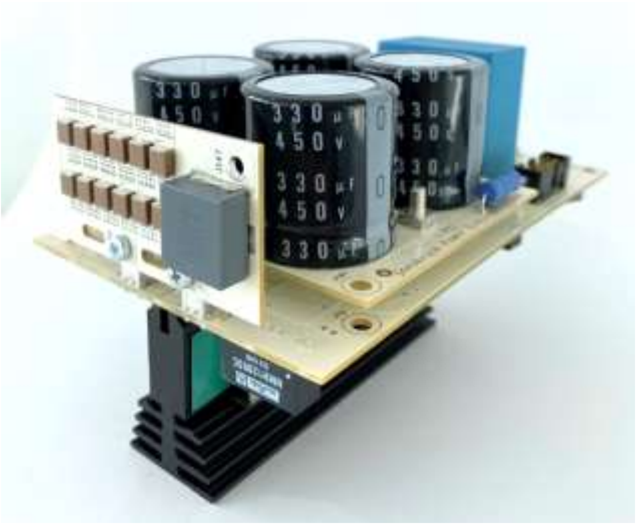
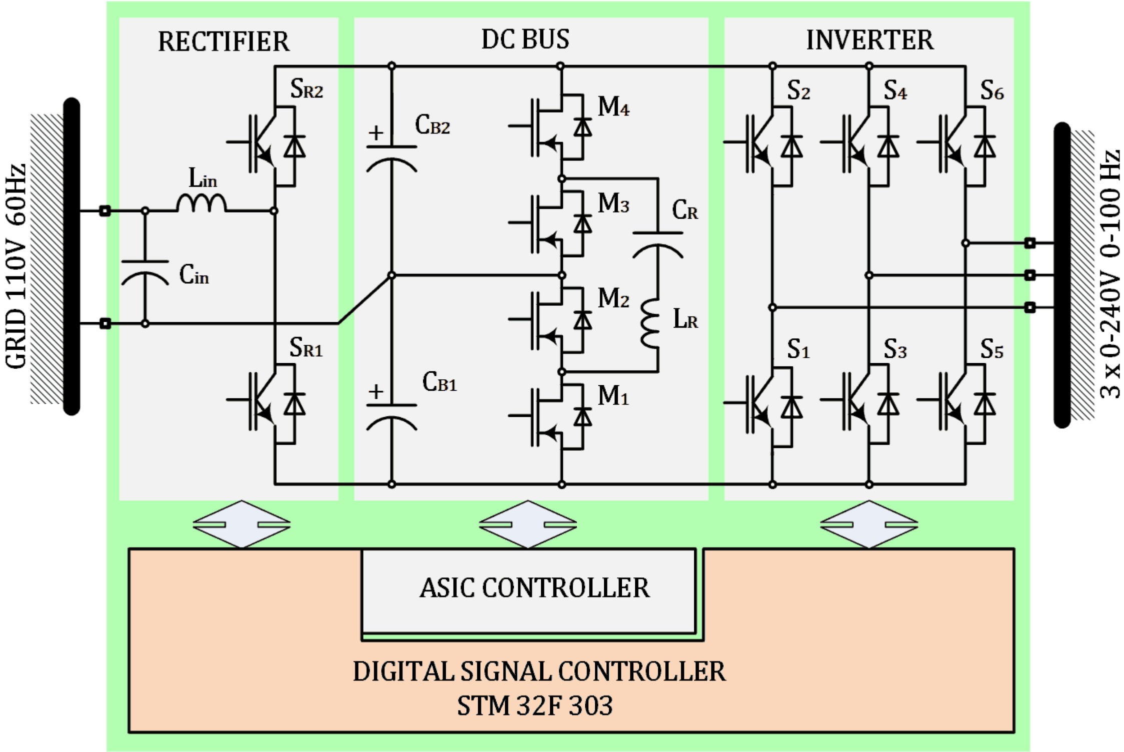
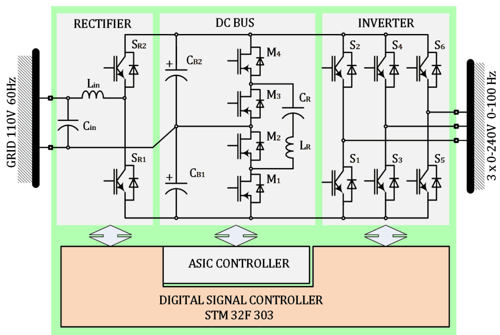


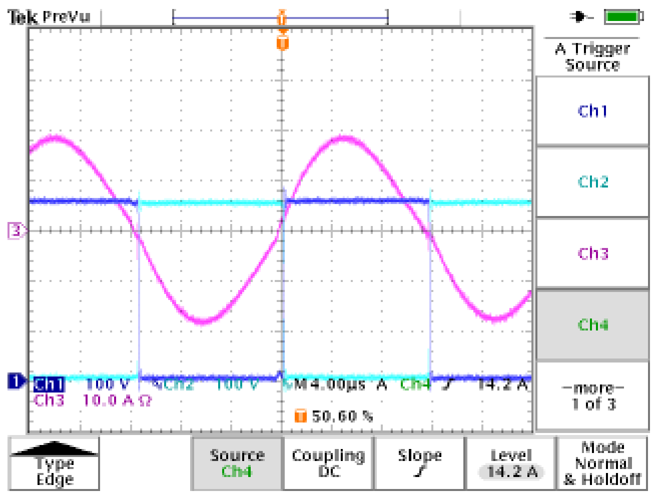


Case 3: Hybrid DC BUS Capacitor

	An Ordinary Rectifier	Rectifier with Active Voltage Balancing
Rectifier current [A]	32	32
DC BUS 60Hz Current [A]	16	0
DC BUS 120Hz Current [A]	9.33	9.33
DC BUS HF RMS Current [A]	8.93	8.93
DC BUS Equivalent RMS Current [A]	21.56	12.04
	DC BUS DESIGN	
Selected Capacitors	**Epcos B43547E2227M0** 220µF/250V 20 cells in parallel/series	**Epcos B43547A2337M0** 330 µF/200V 10 cells in parallel/series
DC Bus Losses [W]	22	8
DC BUS Capacitors Volume [cm^3]	245.4	122.7
	SR-VBD DESIGN	
Resonant Balancing Circuit		C_R: CGA9P3X7T2E225K250KA (12 in parallel) L_R : Custom Made Inductor Switches: **IPB64N25S3-20** (3 in parallel)
Resonant Balancing Circuit Losses [W]		15
Resonant Balancing Circuit Volume [cm^3]		15
	COMPARISON	
Total Losses [W]	**22 (100%)**	**23 (105%)**
Total Volume [cm^3]	**245.4 (100%)**	**137.7 (56.5%)**

Case 3: Hybrid DC BUS Capacitor





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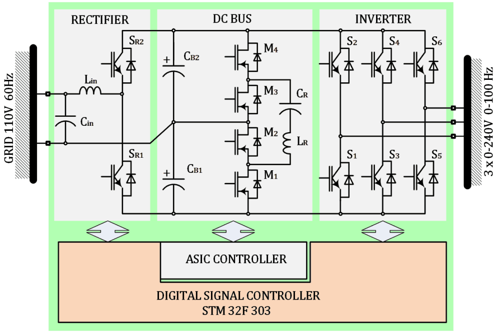

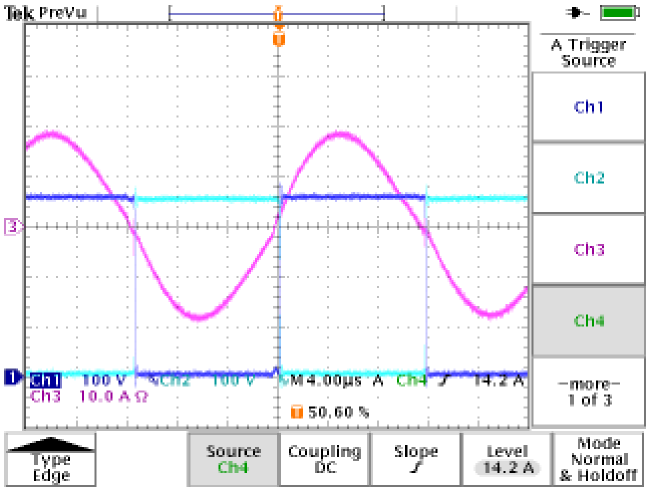

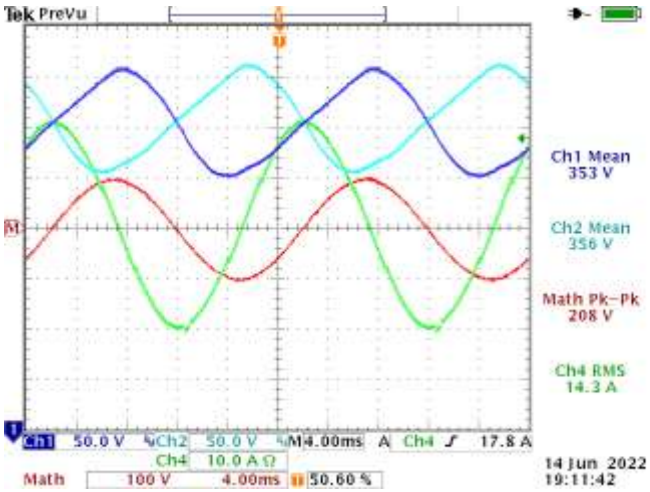

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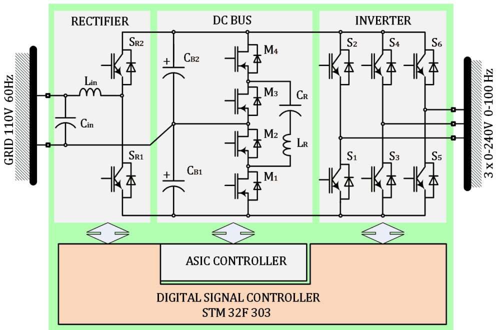

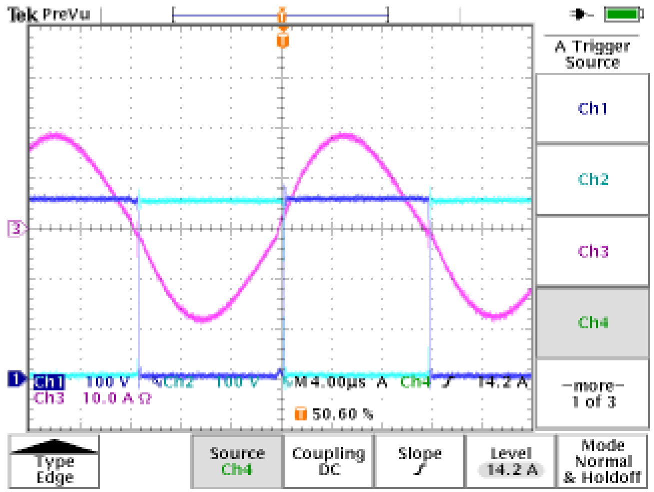

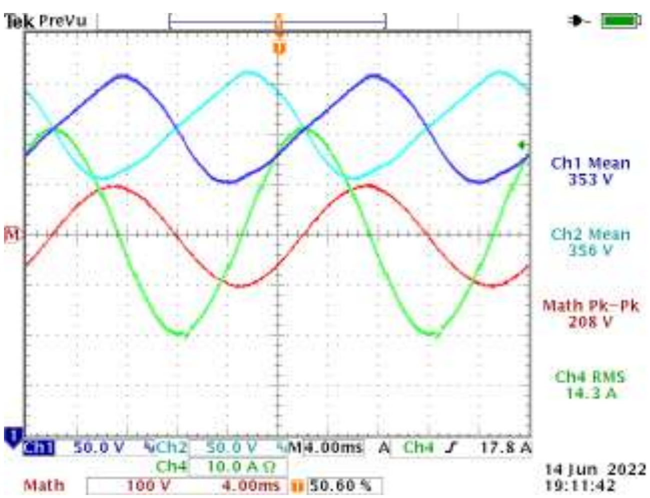

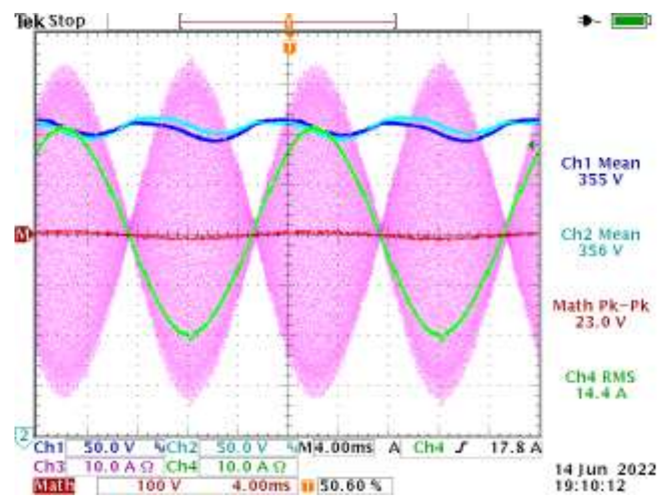

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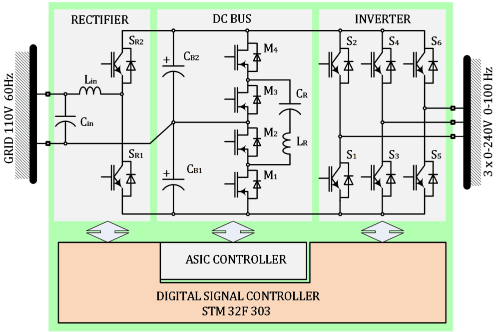
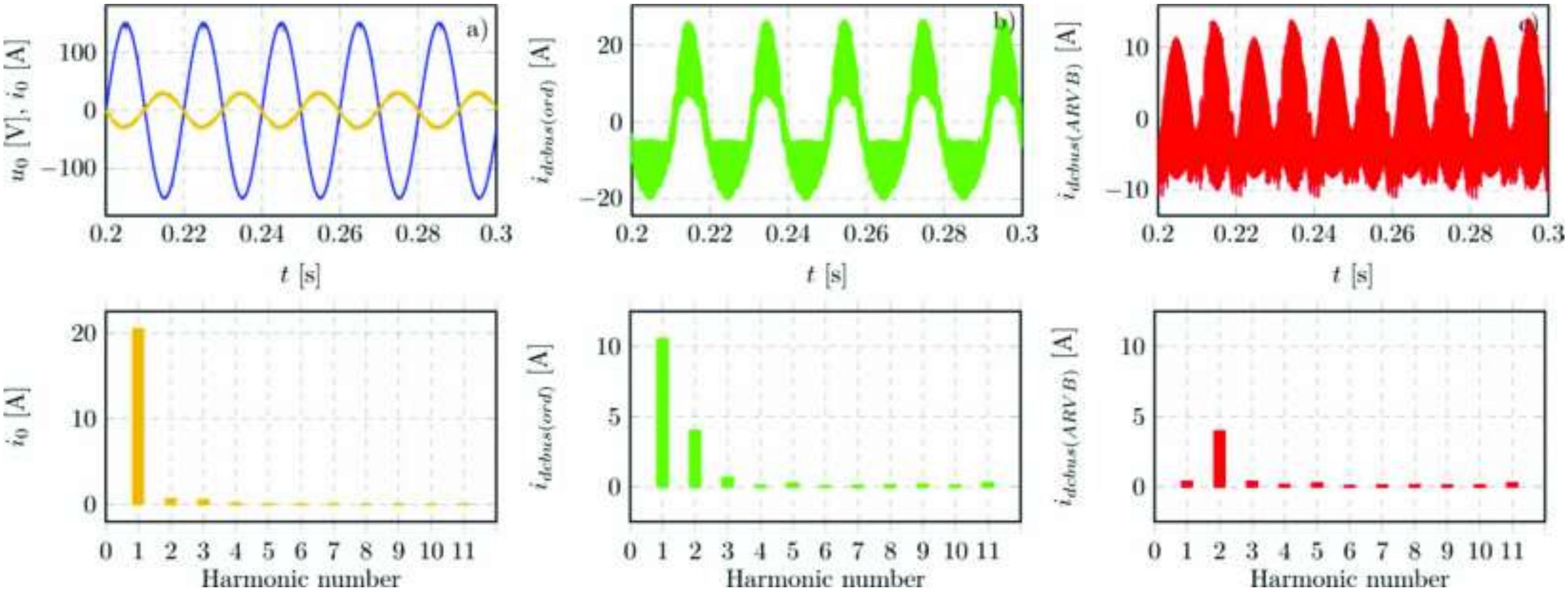




OUTLINE

A. Static Power Conversion

1) Background of Power Converters
2) Where we are Today and
3) What we have to do Tomorrow?

B. Partial Power Rated (Processing) Converters

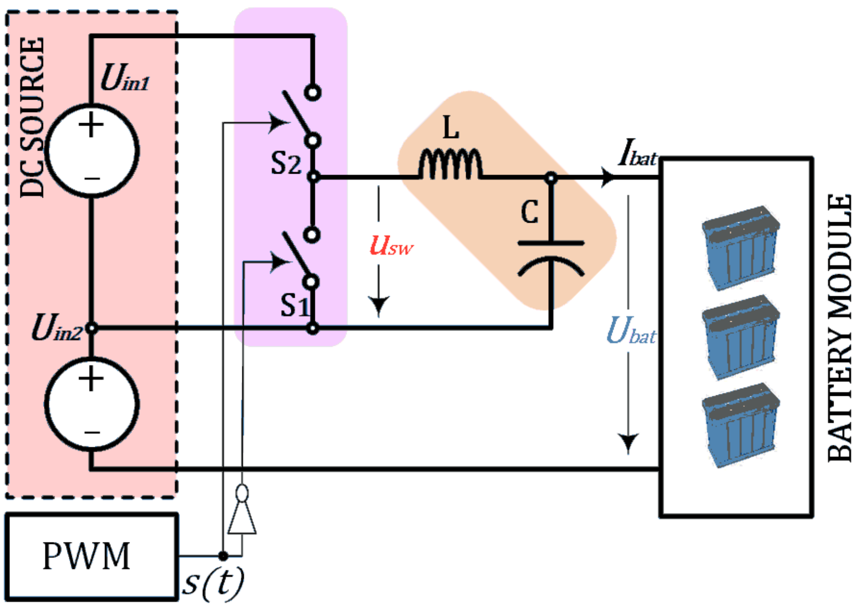
1) Foundation of Partial Power Rated Converters
2) Voltage Balancing Issue,
3) Series Resonant Converter as a Voltage Balancing Circuit,
4) ISOP Converters with „Intrinsic“ Voltage Balancing Capability
5) Application Cases
6) Is it good concept as it looks like?
7) A bit of History

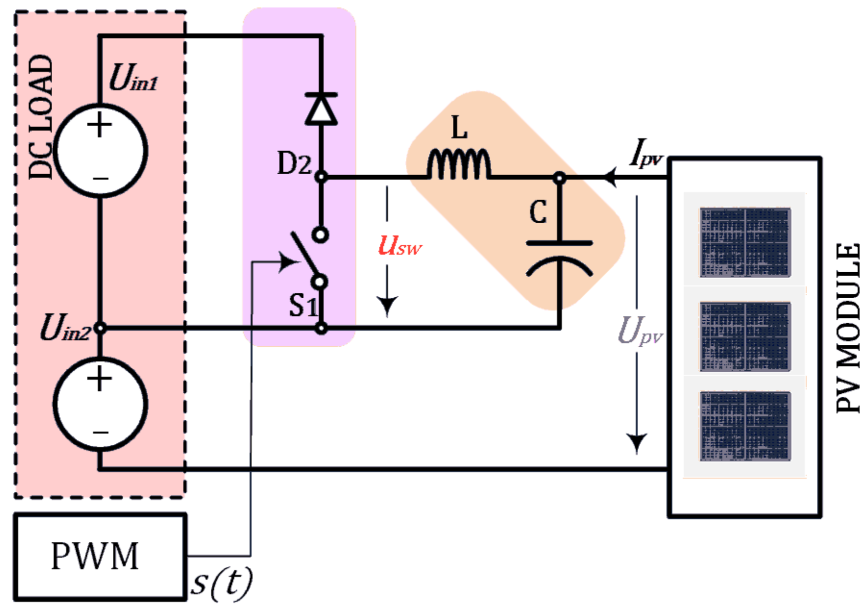
C. Conclusion

Is it good as it looks like?

It looks like the PPRC is an exotic concept that could solve lot of design issues

- Extreme efficiency and power density…
- Various industrial and commercial applications..





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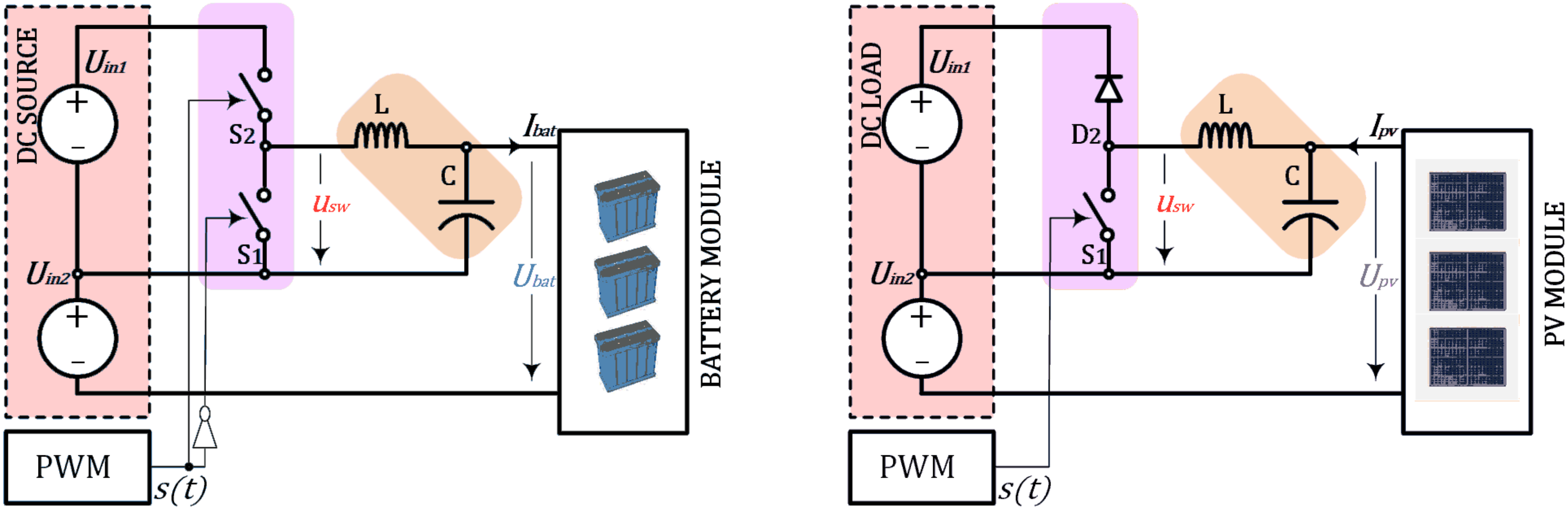

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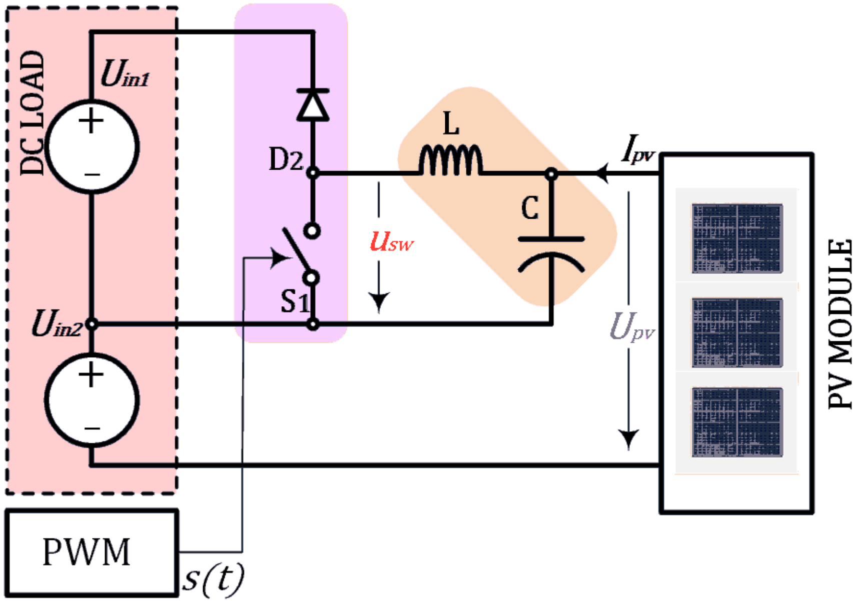

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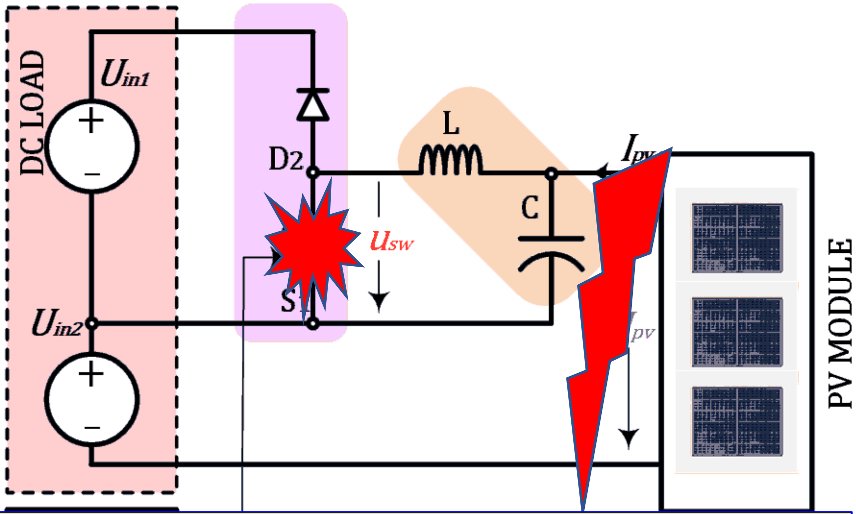
Short circuit fault on the input is a realistic scenario

a) Bottom Switch S1 will be revers polarized
   - The switch and entire converter will blowup



Fault management and protection is MUST…which is not for free!

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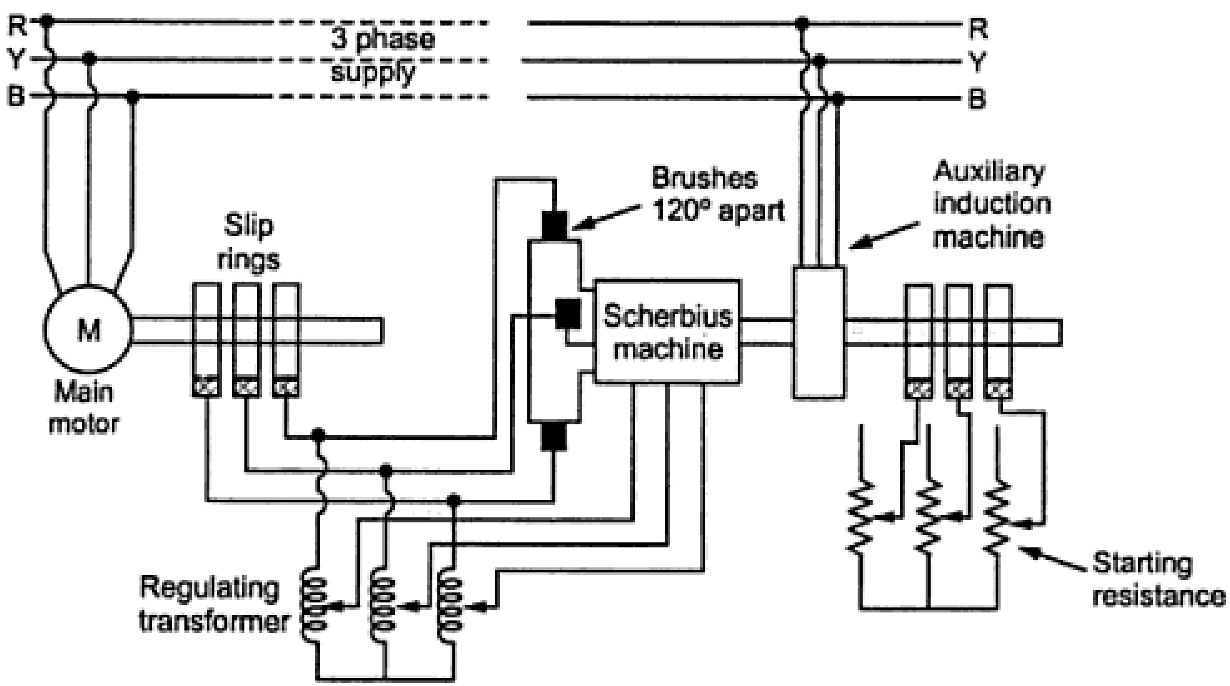
A Bit of History

Is the PPRC concept a new concept?

ADKINS, B. , GIBBS, W. J. Polyphase Commutator Machines. 1951

Is the PPRC concept a new concept?

- **In fact not at all, the PPRC concept is going back to 1930s ...**
  a) Slip Power Recovery or Scherbius Drive



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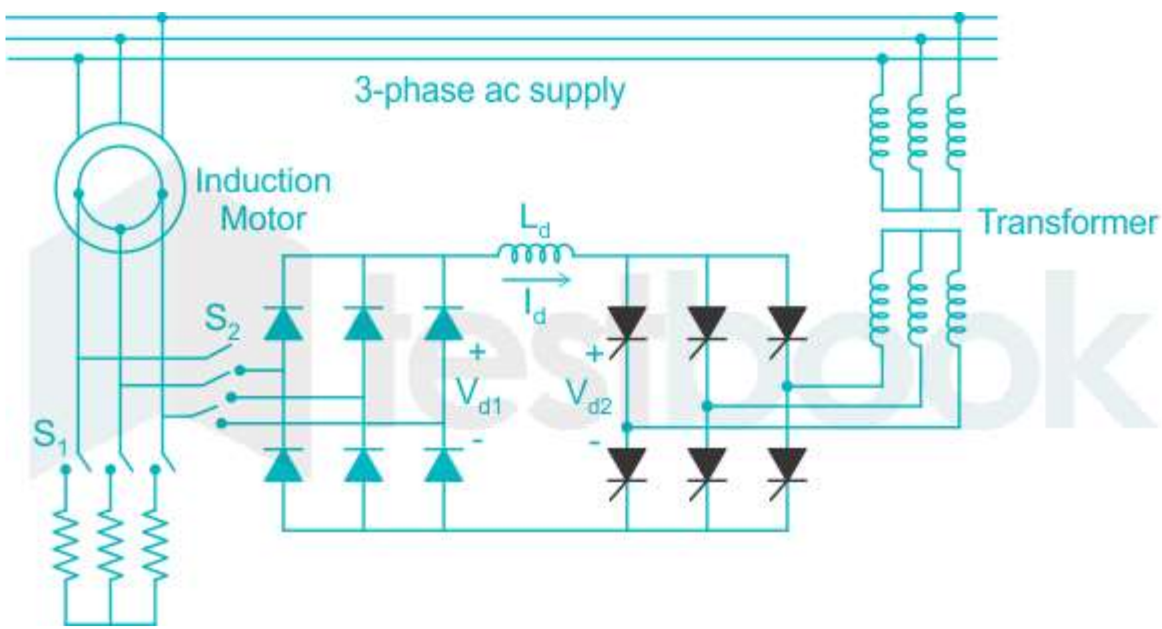

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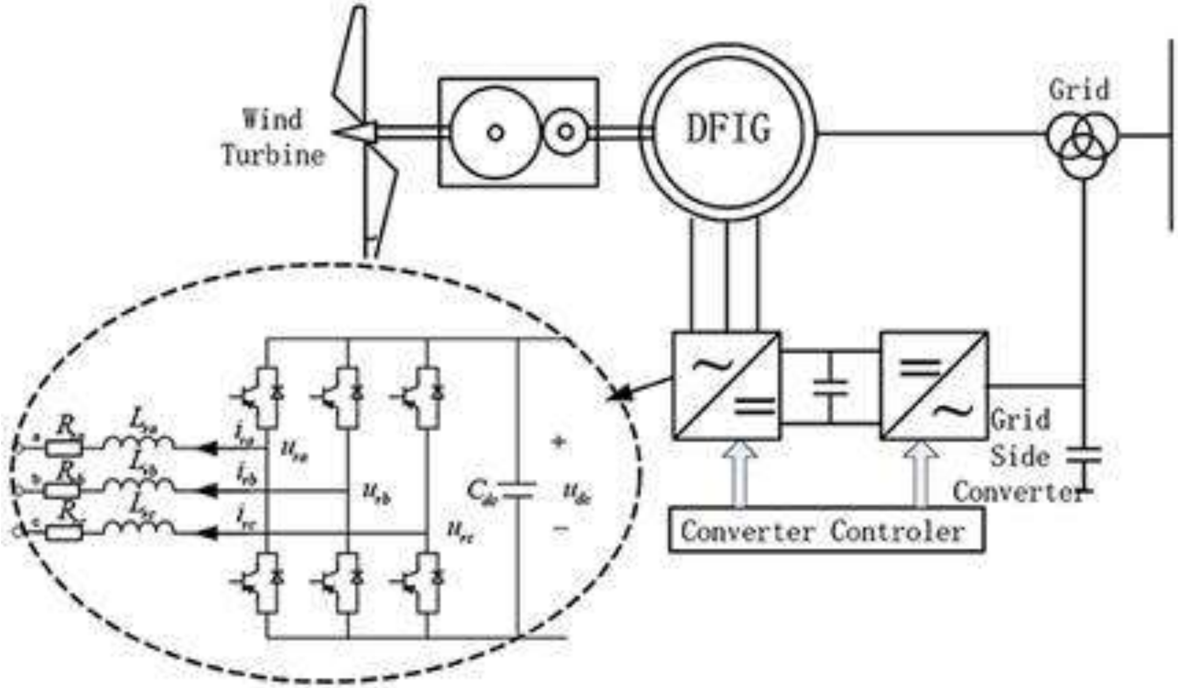
- In fact not at all, the PPRC concept is going back to 1930s ...
  a) Slip Power Recovery or Scherbius Drive
  b) Static Scherbius Drive
  c) IGBT Based Double Fed Induction Machine



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Conclusion

A. **There is no a magic topology that will solve all our problems....**

B. **There are no new topologies, all we use today and we will use tomorrow is well known since long time ago…**

C. **We need to explore existing topologies and use them in different ways**

   a) **Partial Power Processing Converters**

   b) **Current Source Converters**

   c) **Multi-Level & Multi-Cell Topologies**

   d) **Quantum Mode Resonant Converters**

Conclusion

A. Partial Power Processing Converters

a) Promising concept for various applications

b) Extreme efficiency and power density is possible

c) High level integration is possible and necessary

d) However, fault management is a problem that still remains unsolved

e) Without appropriate solution, the PPRC concept cannot be deployed in most of applications!

Thank you for your time

If you may have any qustion, please contact me

petar.grbovic@uibk.ac.at

igor.lopusina@uibk.ac.at

www.uibk.ac.at/mechatronik/i-pel/