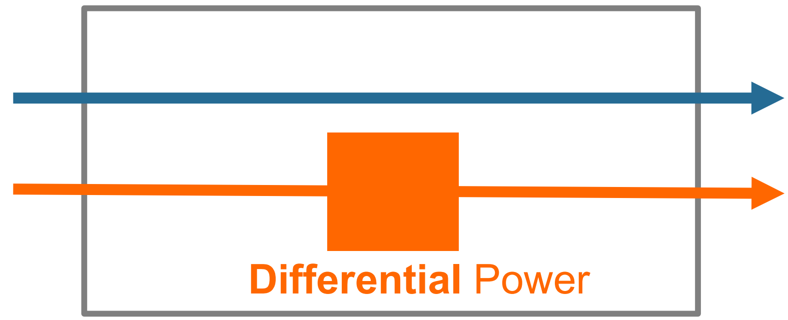
CEI UPM
Centro de Electrónica Industrial

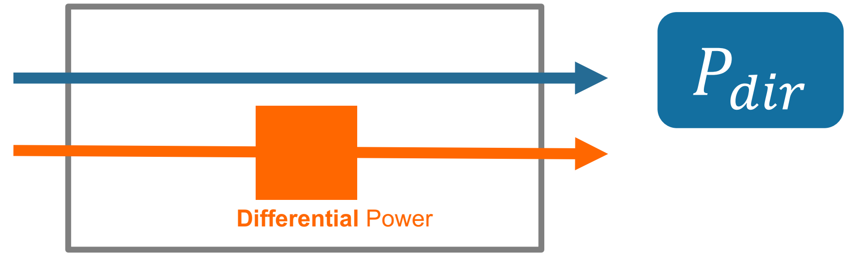


Fundamental Limits
of Power Conversion

Energy Buffered converters

José A. Cobos
June 2017

POLITÉCNICA



"**Differential Power**" is the ***minimum possible value*** of the "AC power", OR "Indirect Power", OR "**Internal Power**"

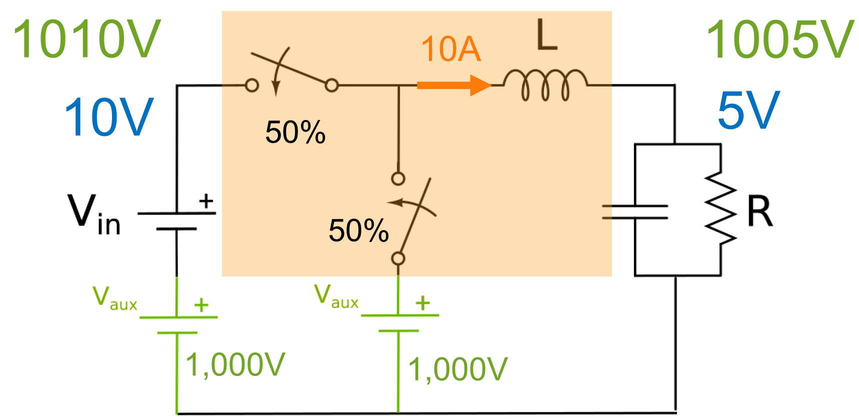
…that is, the **power processed by the components**
(energy stored and delivered by reactive components, times frequency)

…which is **different than the nominal power** because there is some "direct power"

…it is **NOT about reducing the nominal power** at system level
("differential power converters", "partial power",…)

Same "Differential" Power, P_{diff}…

…but arbitrary "Nominal" Power!



P = 50W

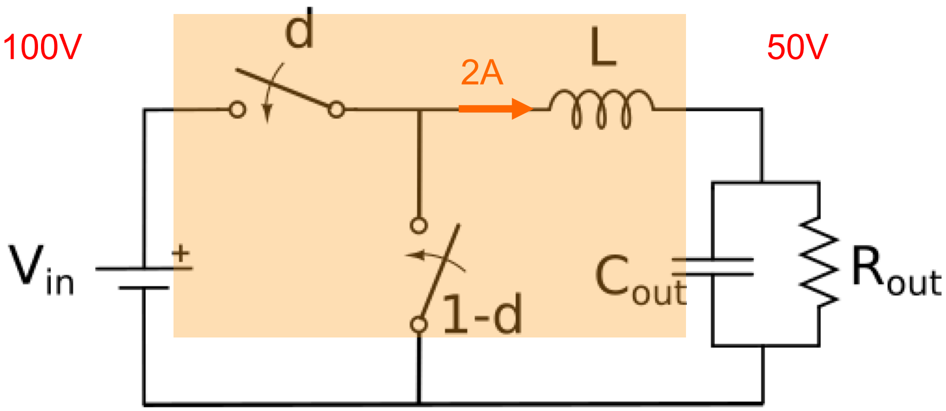
P = 10kW

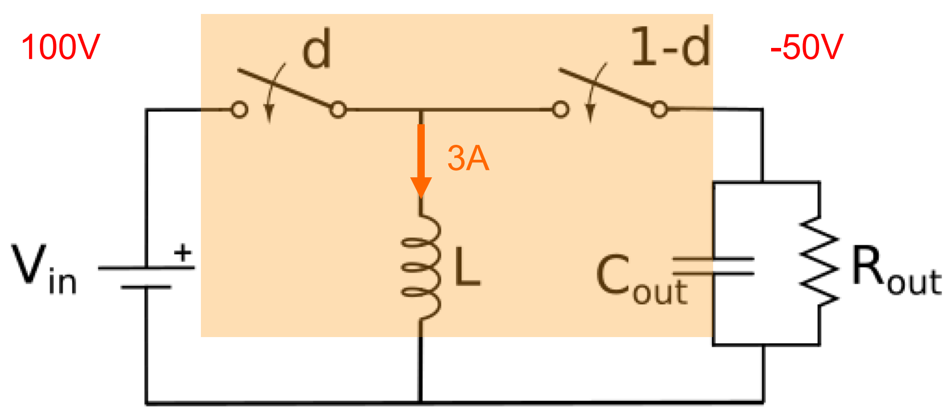
x200

…with same components and losses, very different power levels may be converted

Buck vs Buck-boost

For the same v_{in}, v_o, i_{in}, i_o, different Volume and losses





P = 100W

P = 100W

VA rating (400VA) | x2.25 | VA rating (900VA)

Volume L_1 | x2.25 | Volume L_2

…Size and losses are smaller
in a Buck converter than in a Buck-boost

"Differential Power" is half in Buck (in this example)

Context

Timeline

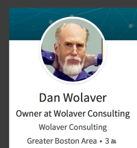
Think P_{diff} !!

Wilson et al.

1966

P_{ac}
P_{dc}
VA_{rating}

D. H. Wolaver



1969

Formal bounds

J. Sebastián et al.

1996 (PESC)

TI-Buck

Sanders et al.

2008

Bounds in SC

LITTLE BOX CHALLENGE

2014-2015

\$1,000,000
(**Volume**, no cost)

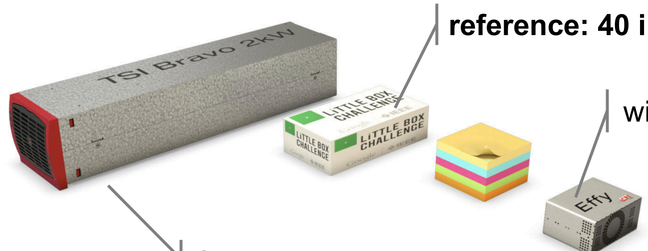
CEI UPM

2014- ….

“Single stage Energy buffered converter”

reference: 40 in3

winner, 14 in3



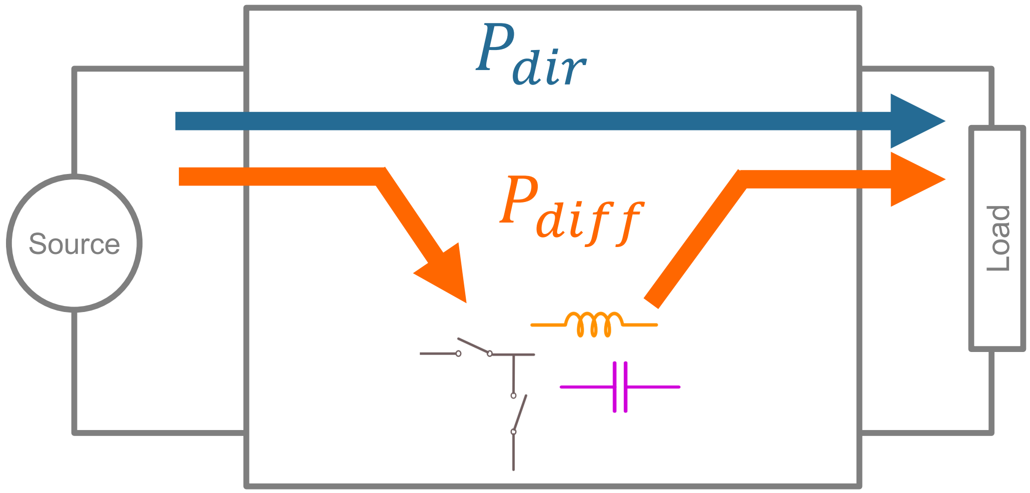
Standard inverter

CET POWER
WWW.CET-POWER.COM

DEFINITION

Differential Power

Direct Power does not contribute to losses, volume, …



Nominal power:

$$P_o \approx P_{in} = P$$

$$\boxed{P_{int} \geq P_{diff} = P - P_{dir}}$$

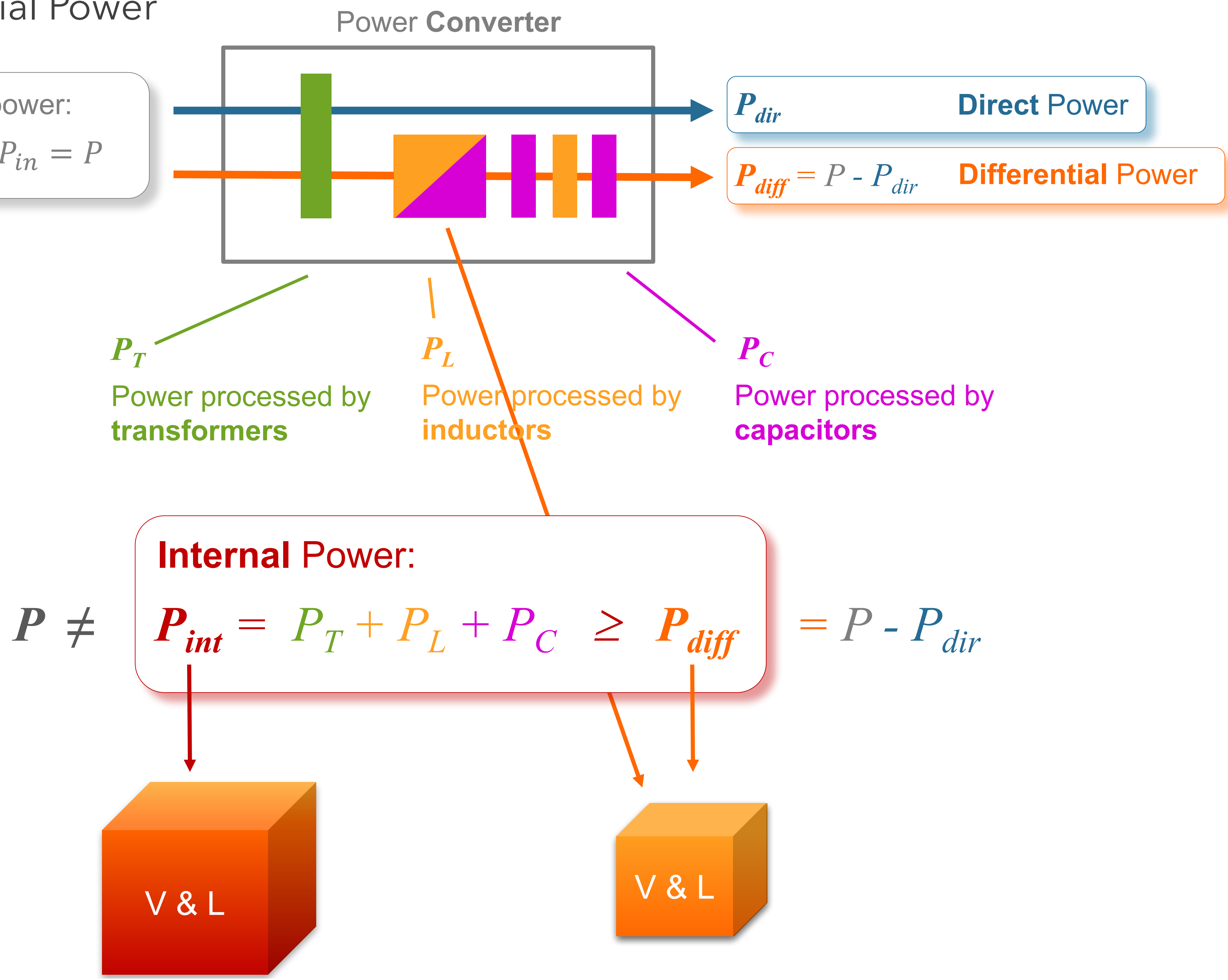
- **Maximize P_{dir}**
- **Minimize P_{int}**
- **LIMIT is P_{diff}**

Power processed by converter **components**

Minimum possible value of P_{int}

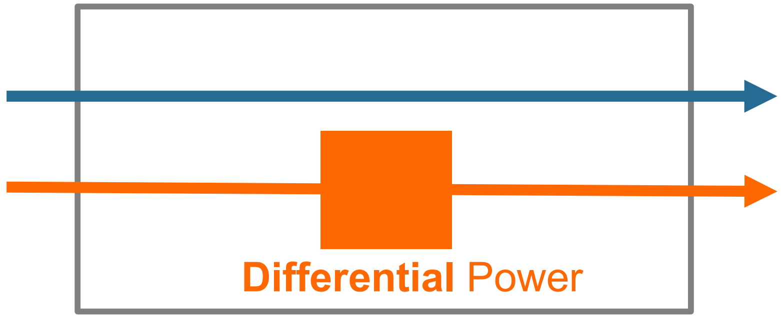
DEFINITION

Differential Power



What for

High-level metric
to compare power architectures



Wilson → Wolaver → "ac active resistors" / "dc active resistors"

$P \neq$ **Reactive**: $P_{int} = P_T + P_L + P_C \geq P_{diff} = P - P_{dir}$

Switches: $VA_{rating} \geq (4+4)\, P_{diff}$

Key question:

What is the impact of $P_T + P_L + P_C$ and VA_{rating} on Volume & Losses?

Answer for P_L:

$P_L = \bar{\imath} \cdot \Delta i \cdot L \cdot f_s$

For ReSC:

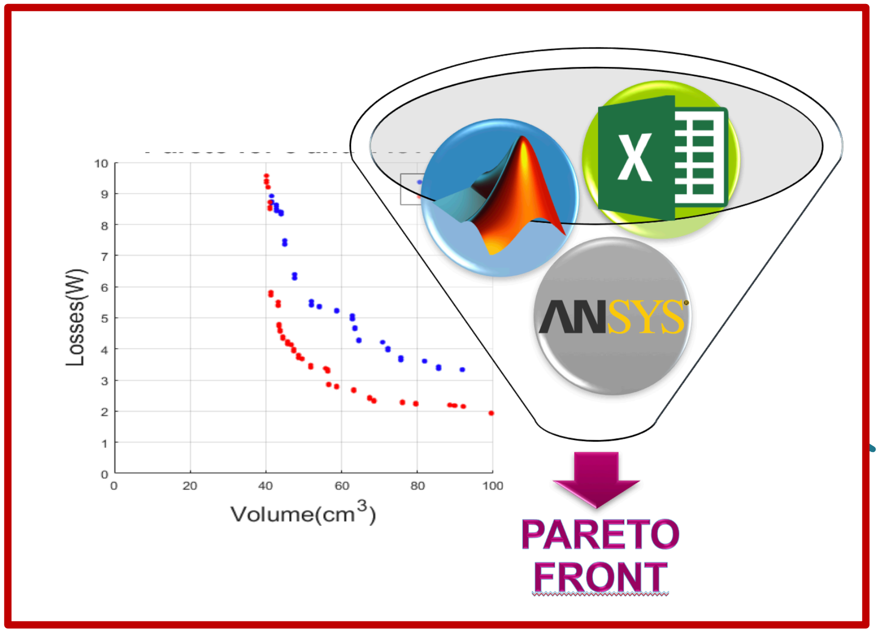
P_L and P_C vs VA ...??

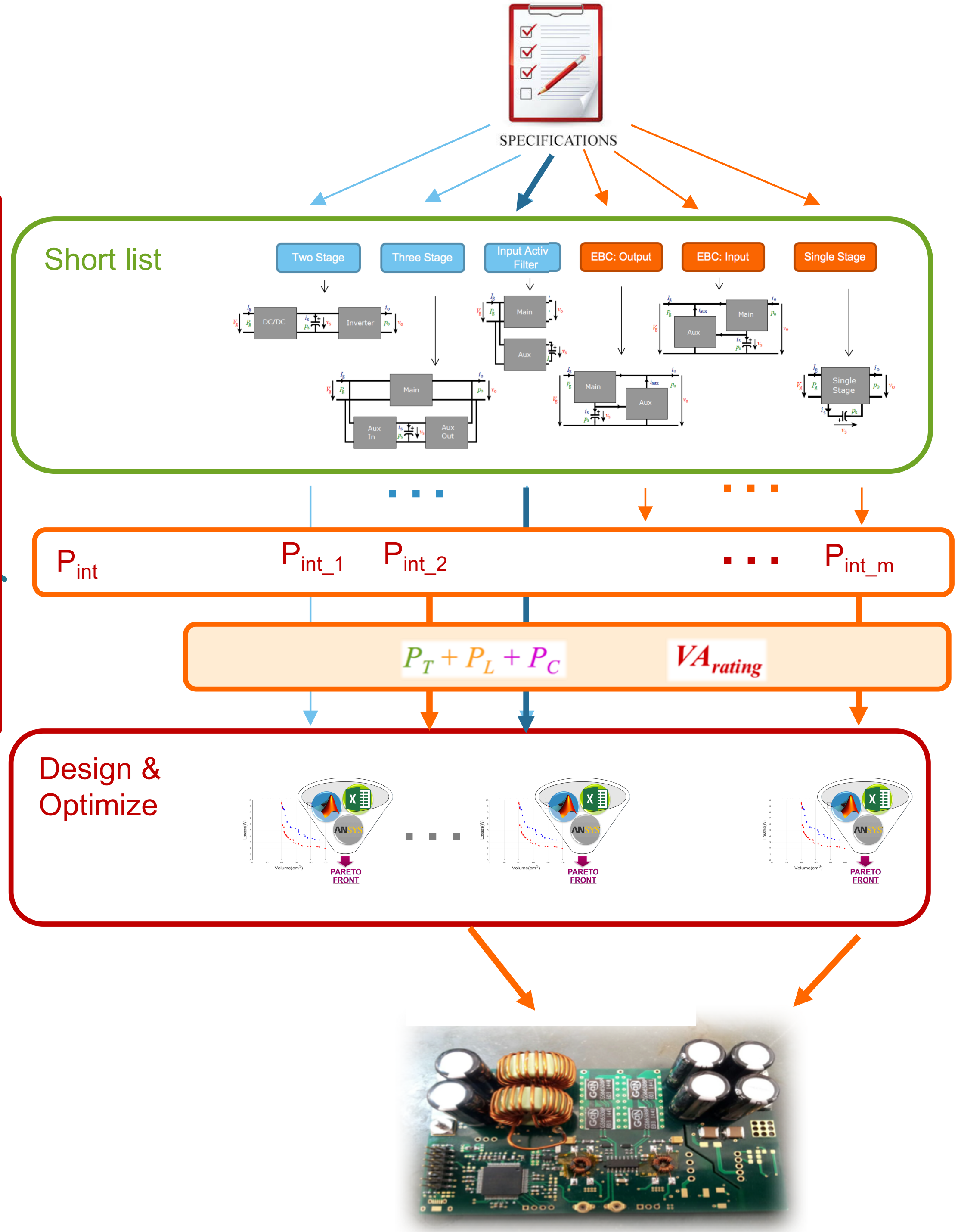
For DCX:

P_T vs P_L ...??

What for

High-level metric
to compare power architectures





DEFINITION

- P_{dir}, P_{diff}, P_{int}
- P_T, P_L, P_C
- VA_{rating}

Related concepts:
- Differential converters
- Partial Power
- Gain vs Regulation

History:
- Wilson: Pac, Pdir
- Wolaver: Paths, Bounds
- Sanders: SC bounds

"**Differential Power**" is the ***minimum possible value*** of the:
- "AC power"
- OR "Indirect Power",
- OR "**Internal Power**"

How to

- **System** level - Average model
- **Device** level – P_L, P_C

Design Case:
- **Energy buffered inverter**
- TI-Buck

Generalization:
- Step-up, step-down
- "Indirect" (buck-boost, Flyback) converter
- Z-source inverter
- 3-level Buck (n-level Flying capacitor)
- Resonant SC
- Cascaded and stacked converters

Trends today:
- WBG
- Hybrid converters
- Metric necessary

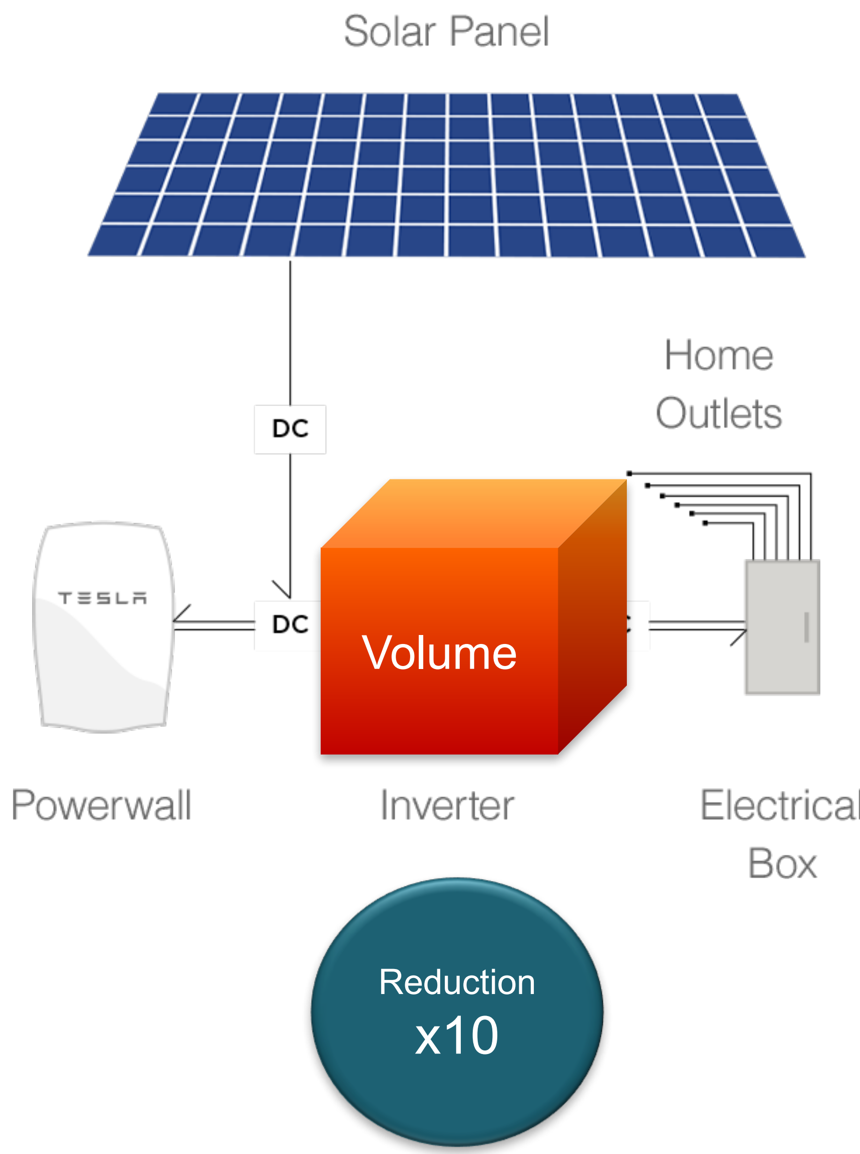
What for

- **High level metric** for comparison
- **Invent** new architectures

Energy Buffered converters

- **Fundamental Limit**
- EBC
- Comparison (2-stage, Active Filter, EBC)
- **Single stage**

CEI UP



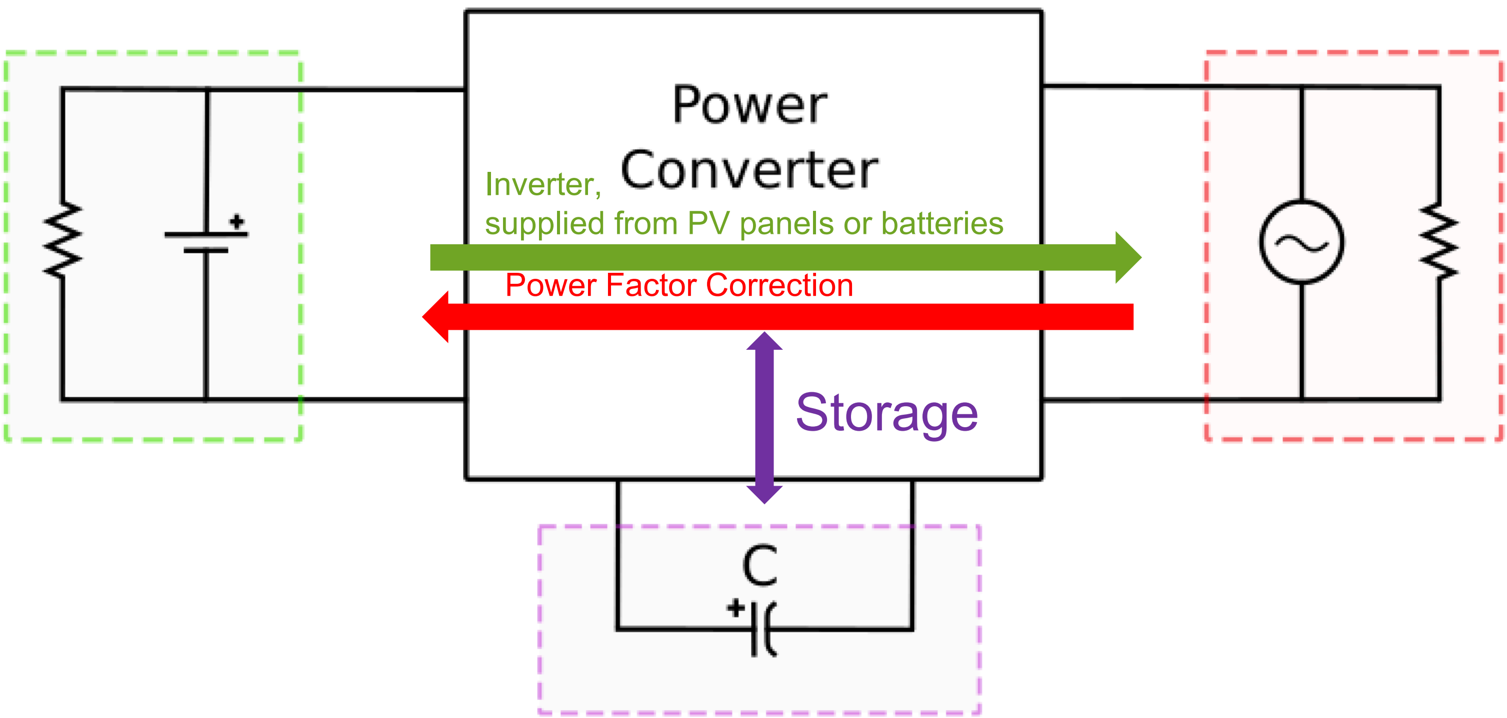
1
120Hz ripple
(constant input current)

2
Miniaturization of Components
(HF Power Conversion)

3
Thermal
(T=60ºC)

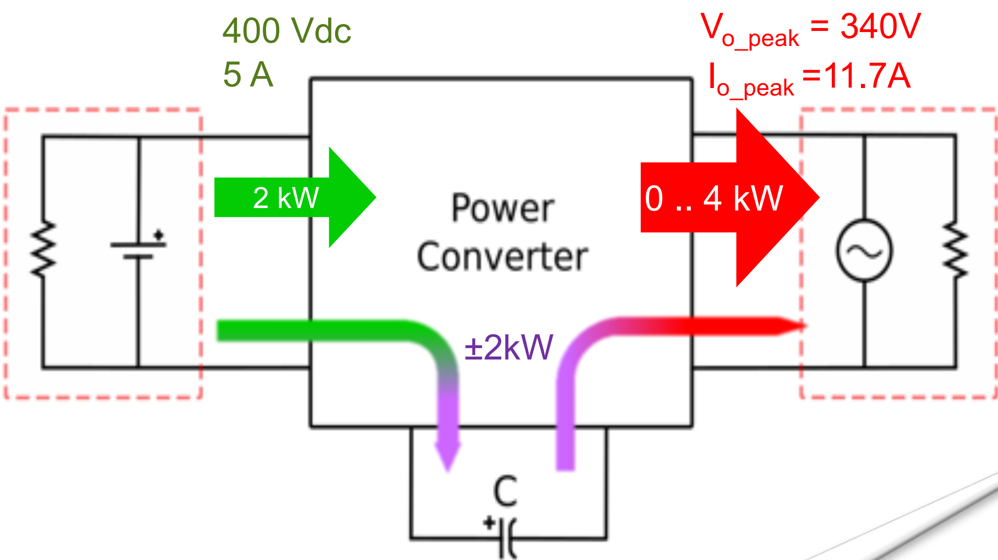
4
EMC

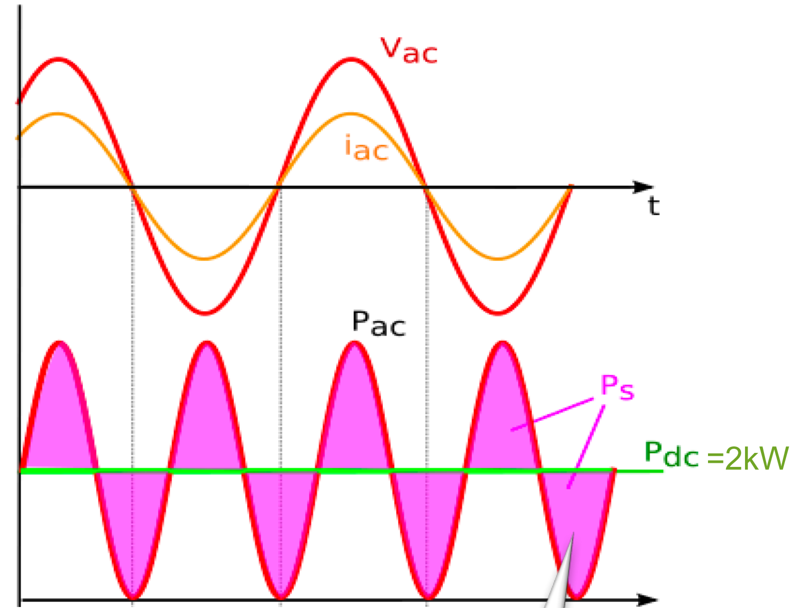
Energy Buffered Converters:



Energy Buffered converters

Power unbalance





"**Discharge ratio**" $D = \Delta v / V_{max}$ has strong impact on volume:

- C_s
- Power stage

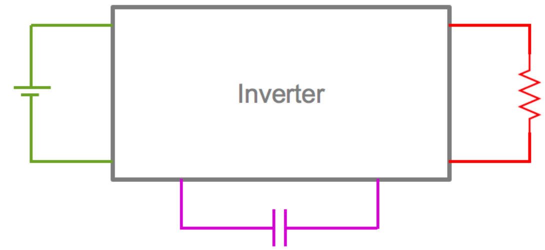
$$\text{Volume } C \sim E_{Cmax} = E_{Cmin} + E_{req} = \frac{E_{req}}{D(2-D)}$$

$$E_{req} = \frac{1}{2} C \left({v_{max}}^2 - {v_{min}}^2 \right)$$

$$E_{req} = C \cdot \bar{v} \cdot \Delta v = 5.3J$$

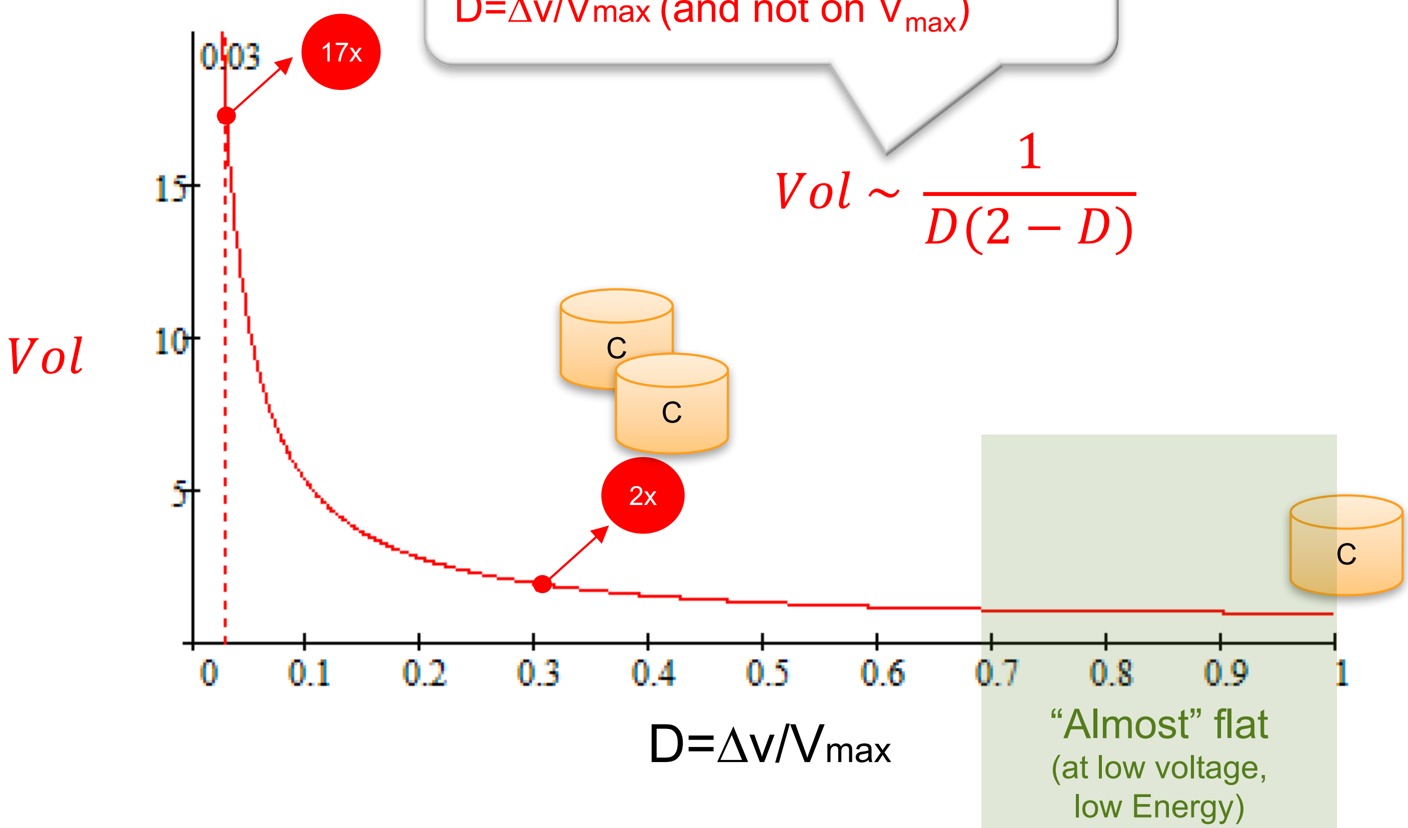
Energy Buffered converters

Challenge #1: Energy buffer at 120Hz



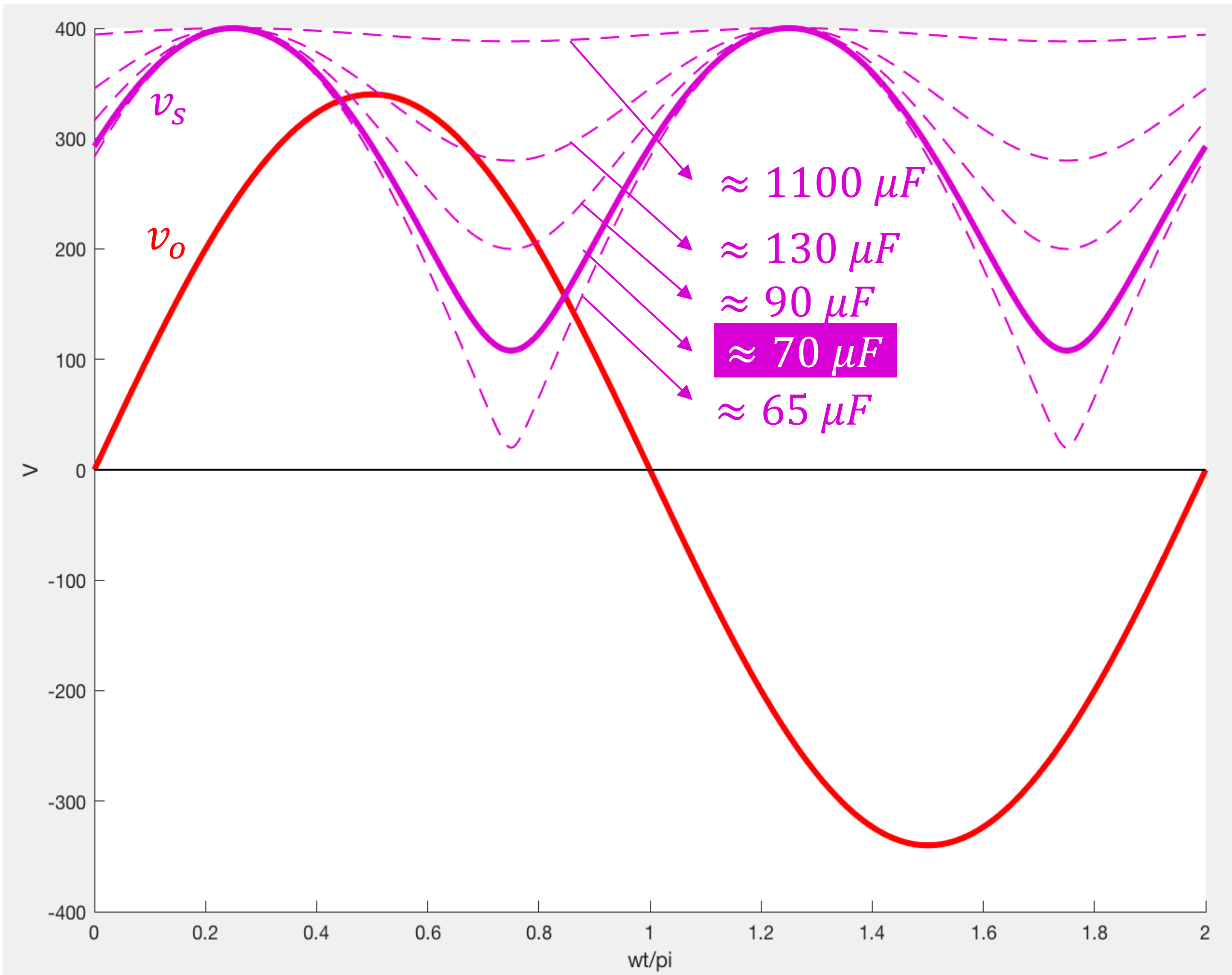
For a given Capacitor technology, VOLUME depends only on $D=\Delta v/V_{max}$ (and not on V_{max})

$$Vol \sim \frac{1}{D(2-D)}$$



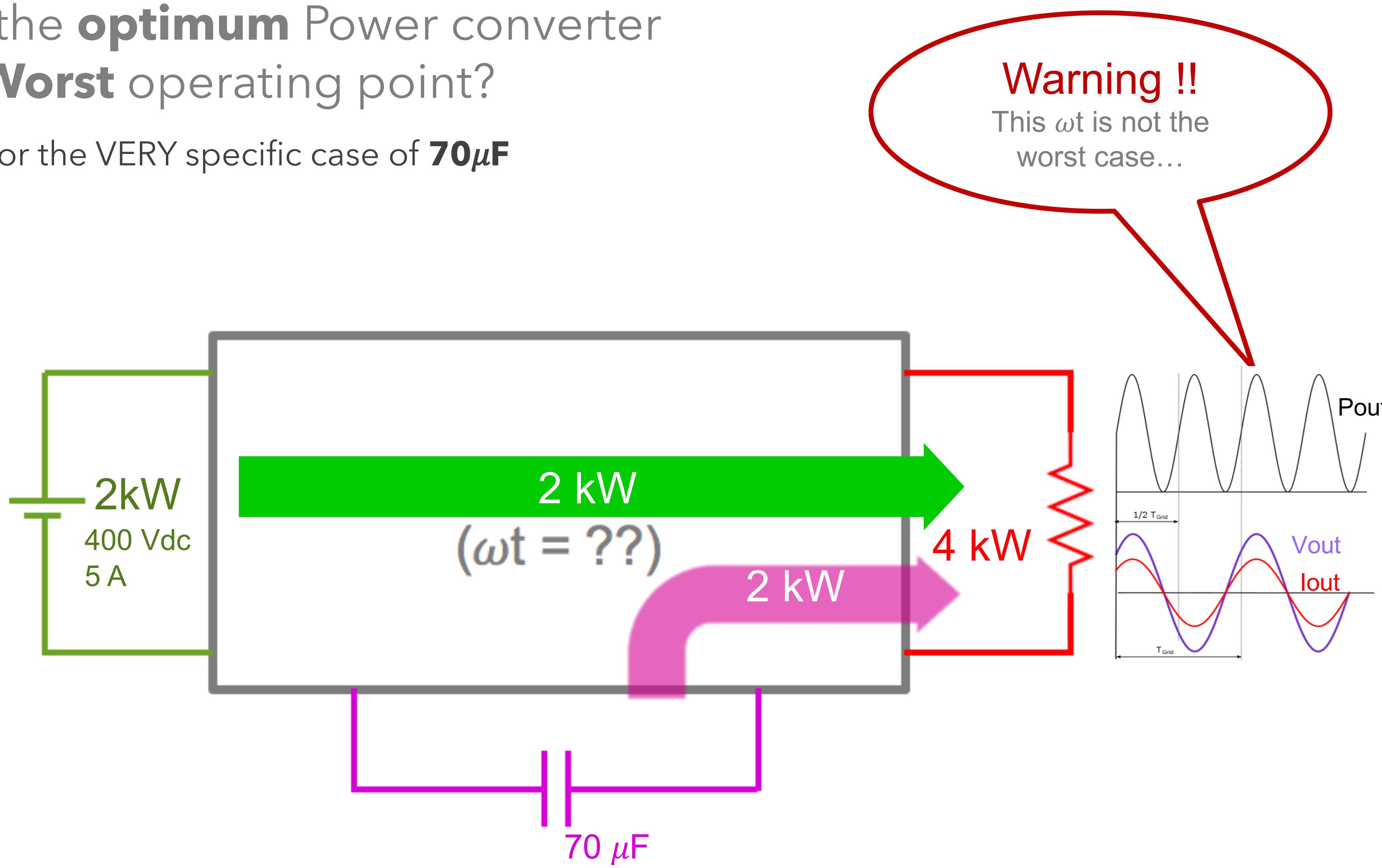
Energy Buffered converters

Non-linear Impact of C_s on Δv_s



What is the **optimum** Power converter for the **Worst** operating point?

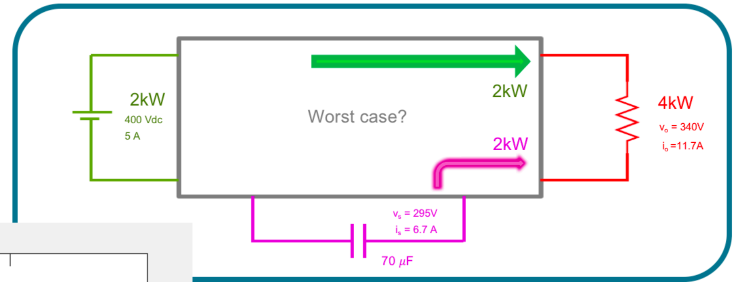
Let us see, for the VERY specific case of **70μF**

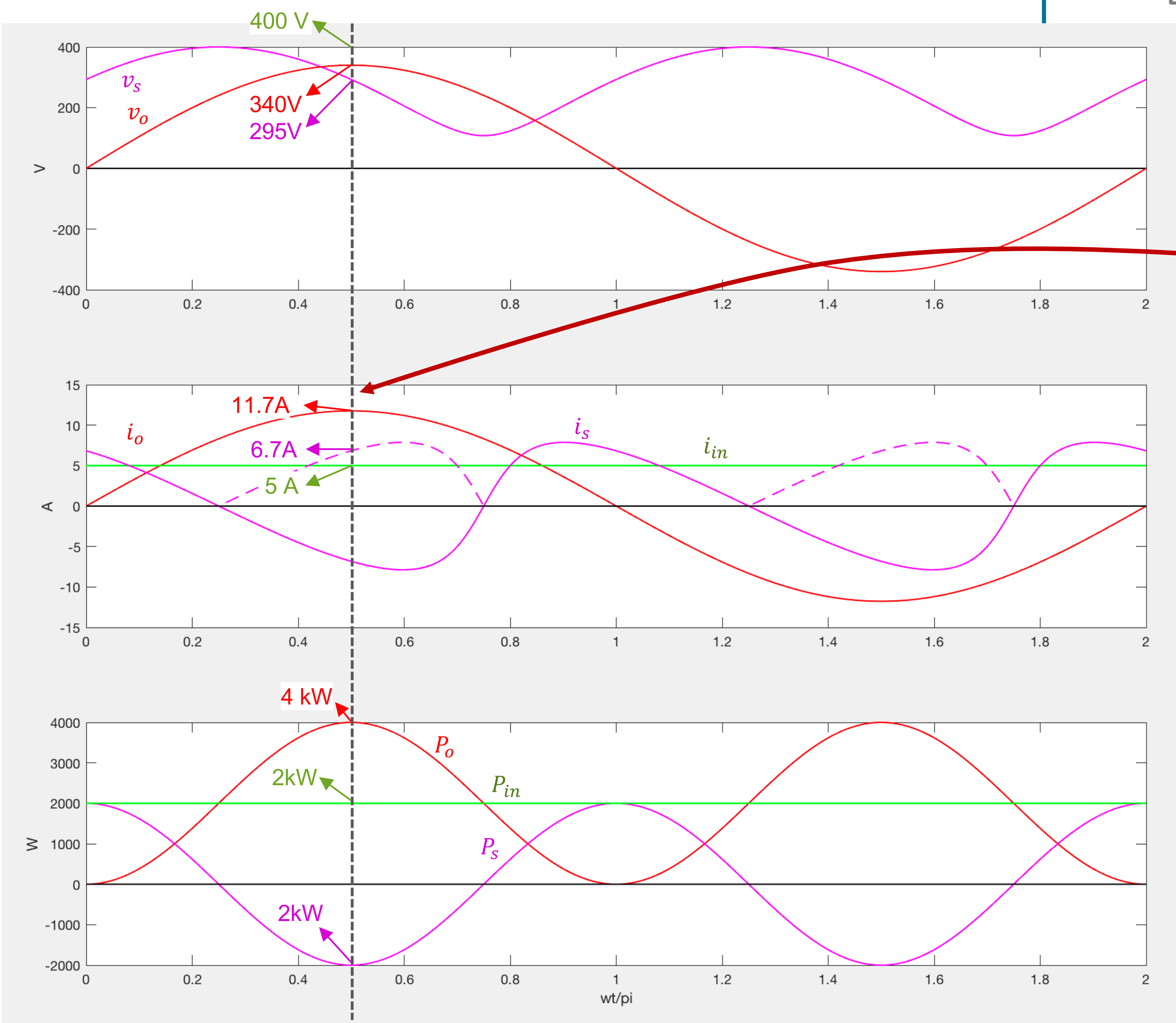


…and what is the optimum power topology for these voltage and current levels?

What is the **optimum** Power converter for the **Worst** operating point?

Let us see, for the VERY specific case of **70μF**





Only for C = 70 μF !

What is the **optimum** Power converter for the **Worst** operating point?

Let us see, for the VERY specific case of **70μF**

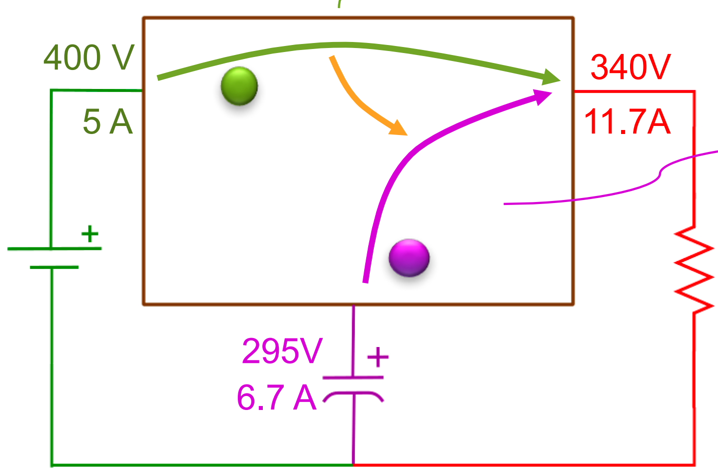
Only for this specific value !

$$P_+ = 5A \cdot (400 - 340) = 300W$$

Same value !!

$$E_+ = q \cdot (400 - 340)$$

$$P_- = 6.7A \cdot (295 - 340) = -300W$$

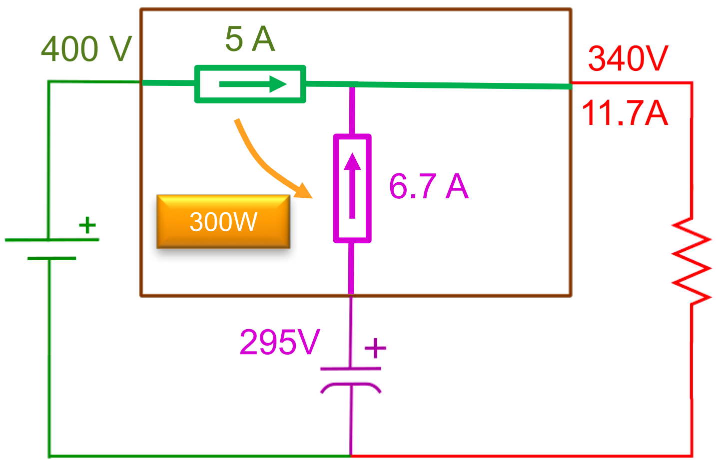


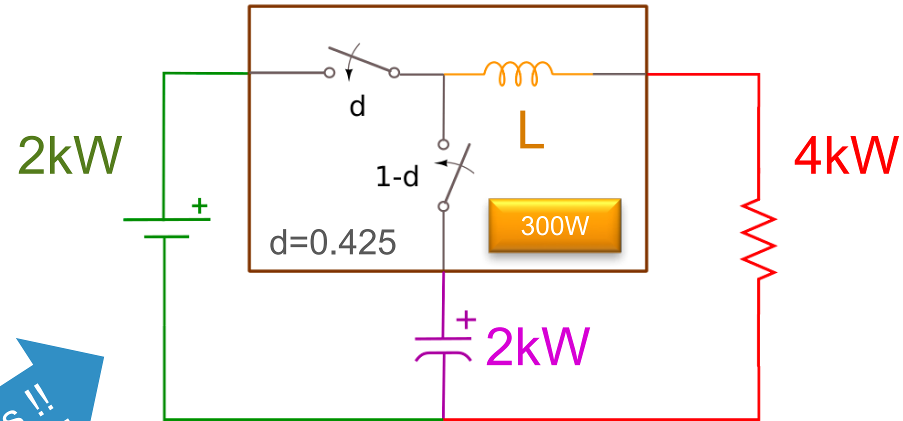
$$E_- = q \cdot (295 - 340)$$

Is it possible to combine both processes ?

What is the **optimum** Power converter for the **Worst** operating point?

Let us see, for the VERY specific case of **70μF**

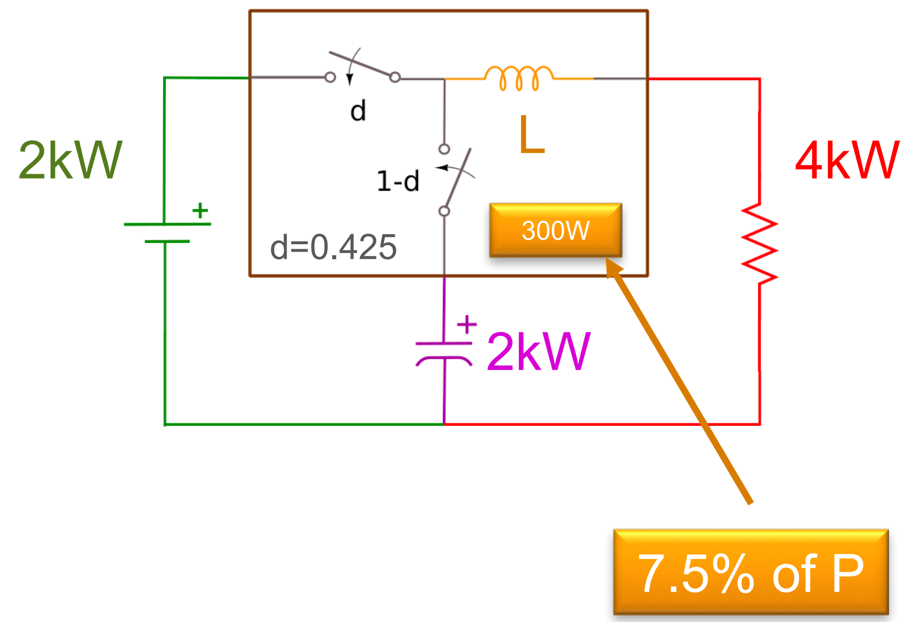




Is it possible to implement a 300W converter to perform both functions?

What is the **optimum** Power converter for the **Worst** operating point?

Let us see, for the VERY specific case of **70μF**



At that specific instant ($\omega t = \pi/2$):

- 4kW output power (P)
- 3.7kW flow "**DIRECTLY**" to the load (P_{dir})
- 0.3kW are **internally processed** by the power stage !! (P_{diff})

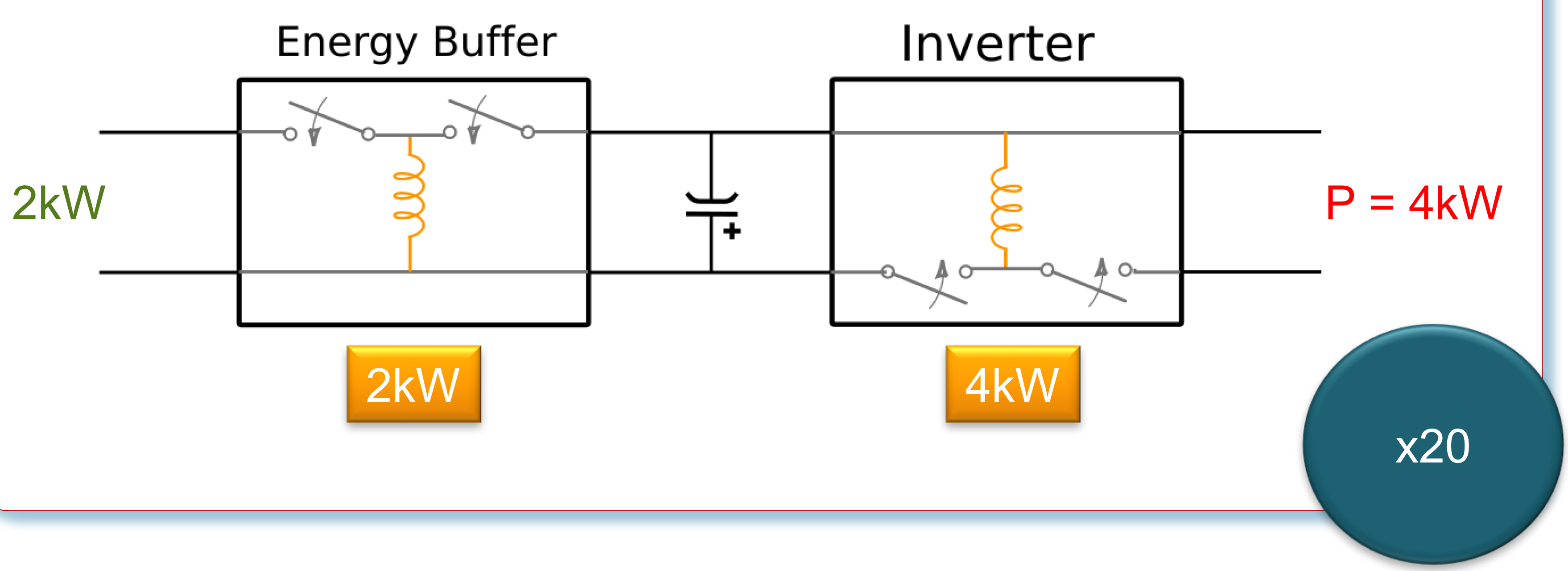
1. What about typical architectures?
2. How to calculate P_{dir} and P_L
3. Can this be extended to the whole line cycle?

What is the **optimum** Power converter
for the **Worst** operating point?

Let us see, for the VERY specific case of **70μF**

At that specific instant ($\omega t = \pi/2$):

In a 2-stage approach, using Buck-boost (!)



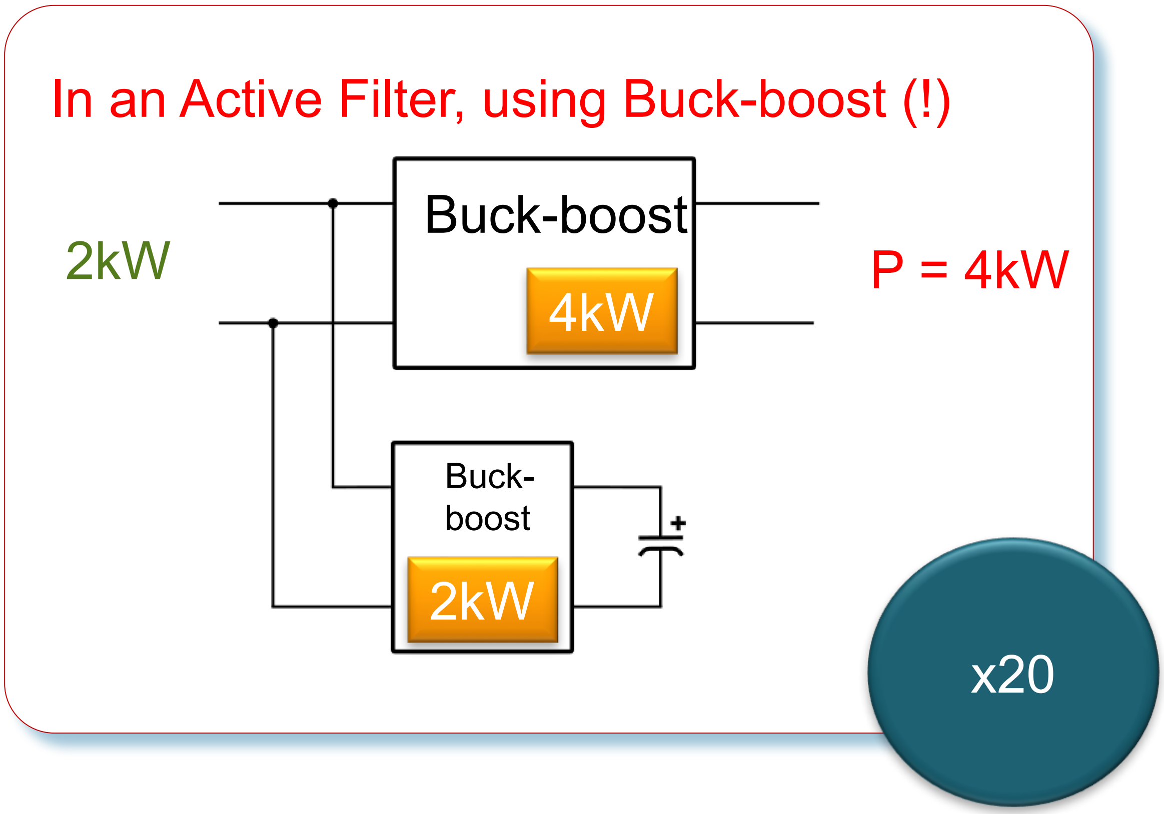
6kW of internal power processing (P_L), compared to 300W !!

It is because P_{dir} = 0 in buck-boost stages

What is the **optimum** Power converter for the **Worst** operating point?

Let us see, for the VERY specific case of **70μF**

At that specific instant ($\omega t = \pi/2$):



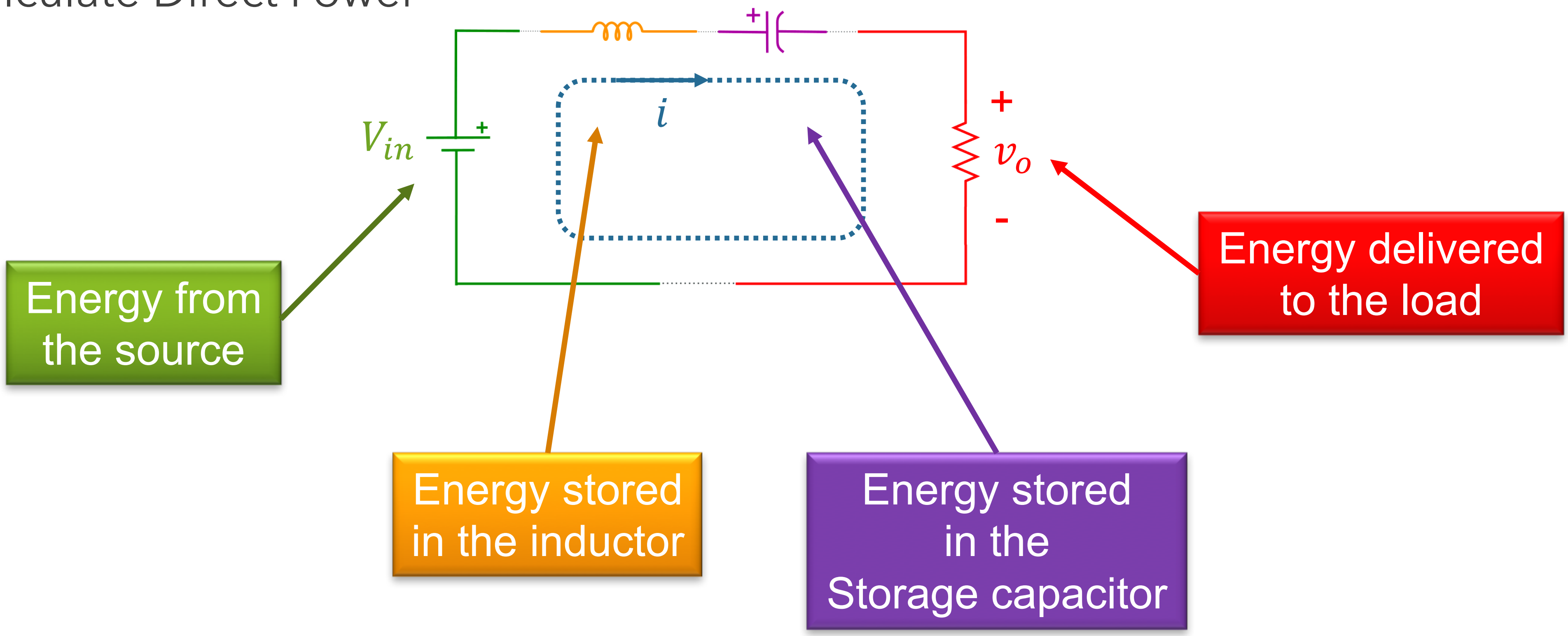
6kW of internal power processing (P_L) compared to 300W !!

It is because P_{dir} = 0 in buck-boost stages

How to

Calculate Direct Power

At time t

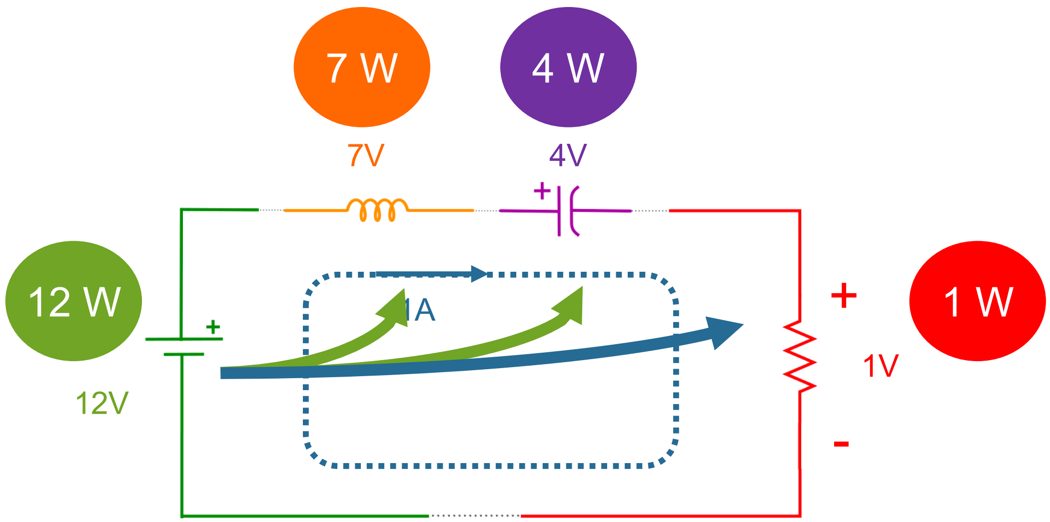


Same current for "n" functions

How to

Direct Power

At time t



1 W

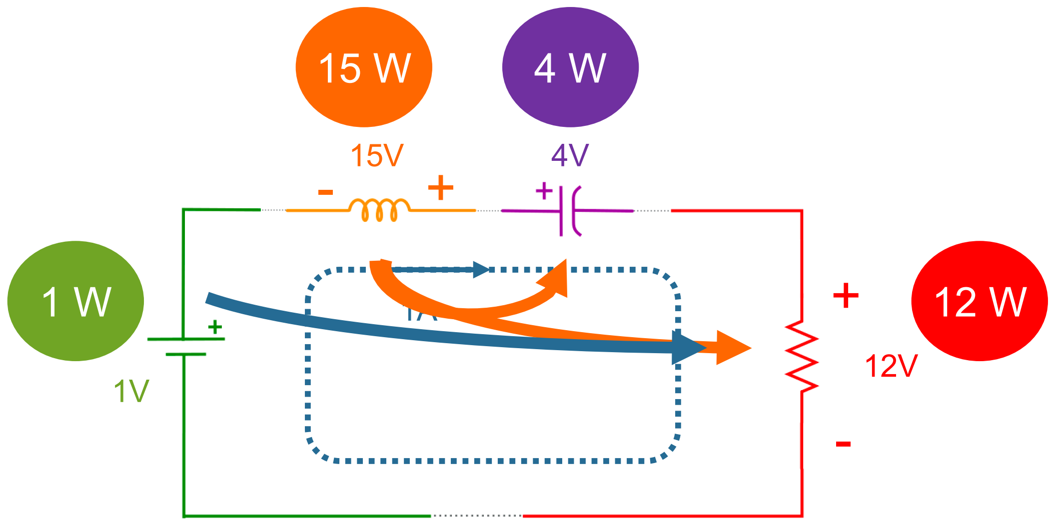
$$P_{dir}(t) = i(t) \cdot \min(V_{in}, v_o)$$

1A 1V

How to

Direct Power,…

At time t



1 W

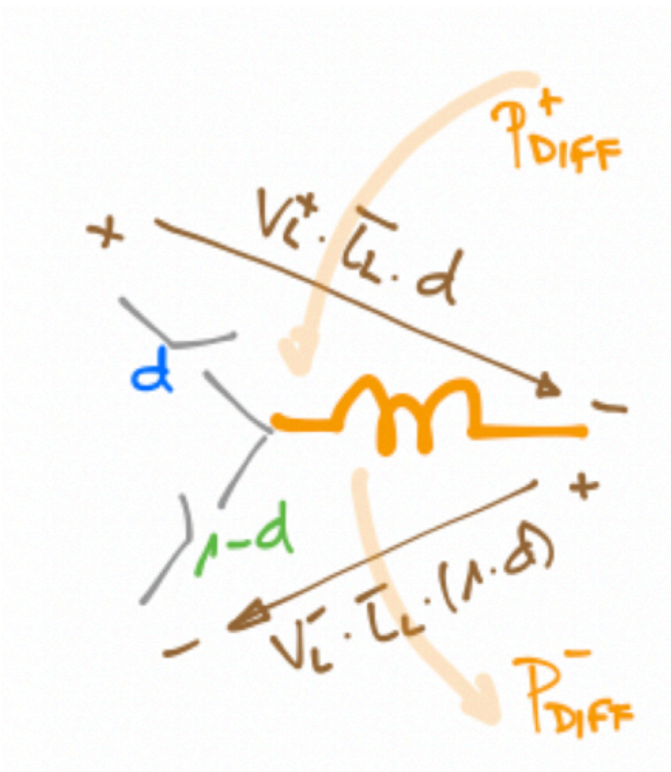
$$P_{dir}(t) = i(t) \cdot \min(V_{in}, v_o)$$

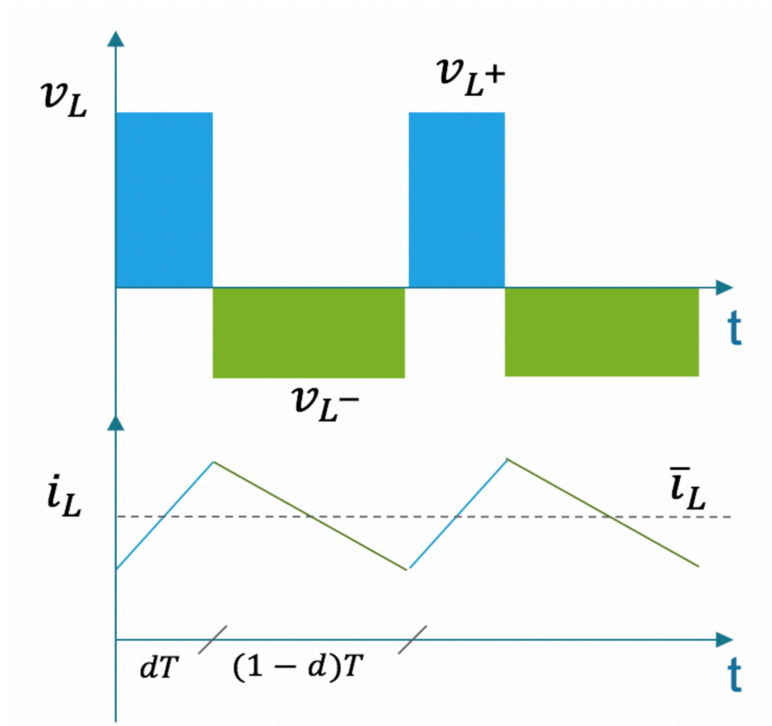
1A 1V

Differential Power

How to

Device level





$$P_{diff^+} = \bar{\imath}_L \cdot {v_L}^+ \cdot d$$

$$P_{diff^-} = \bar{\imath}_L \cdot {v_L}^- \cdot (1-d)$$

How to

Average model

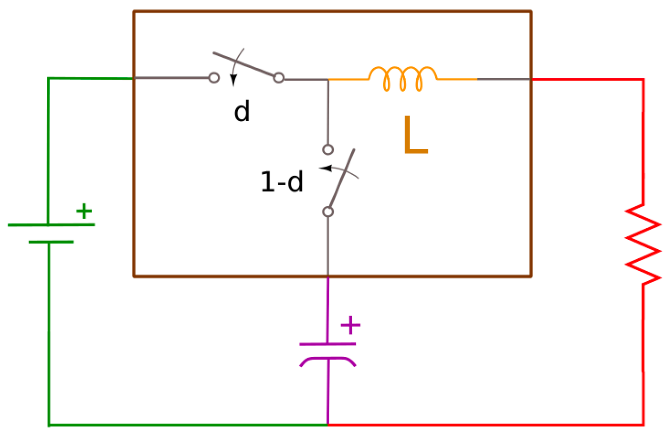
Device level

Calculate $P_{dir}(t)$, $P_{dir}(t)$,… and average intervals

Practice!!

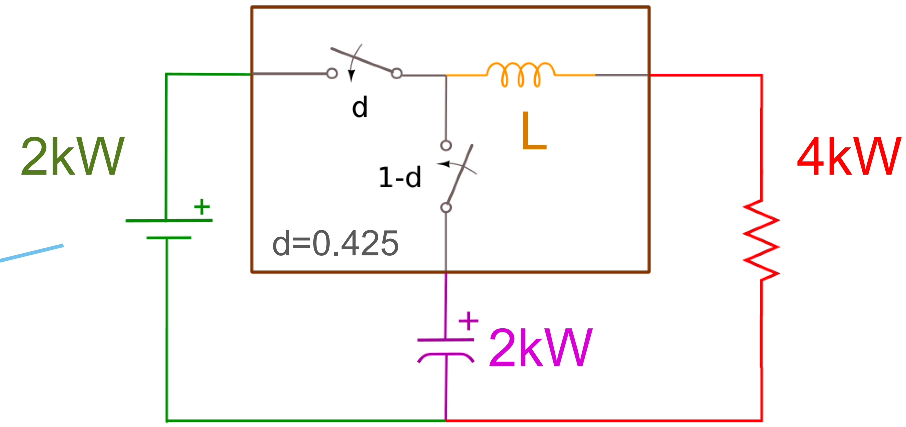
- Buck, Boost, Buck-boost
- TI-Buck
- Z-source inverter (Pdir<0)
- …

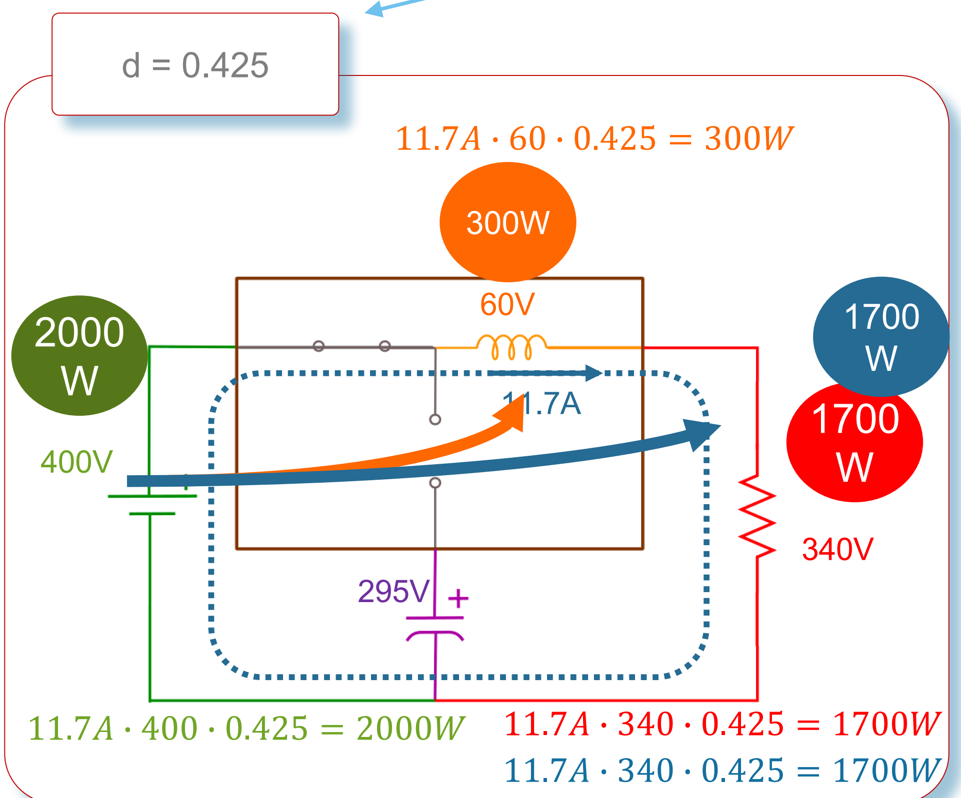
We practice with our "optimum" converter

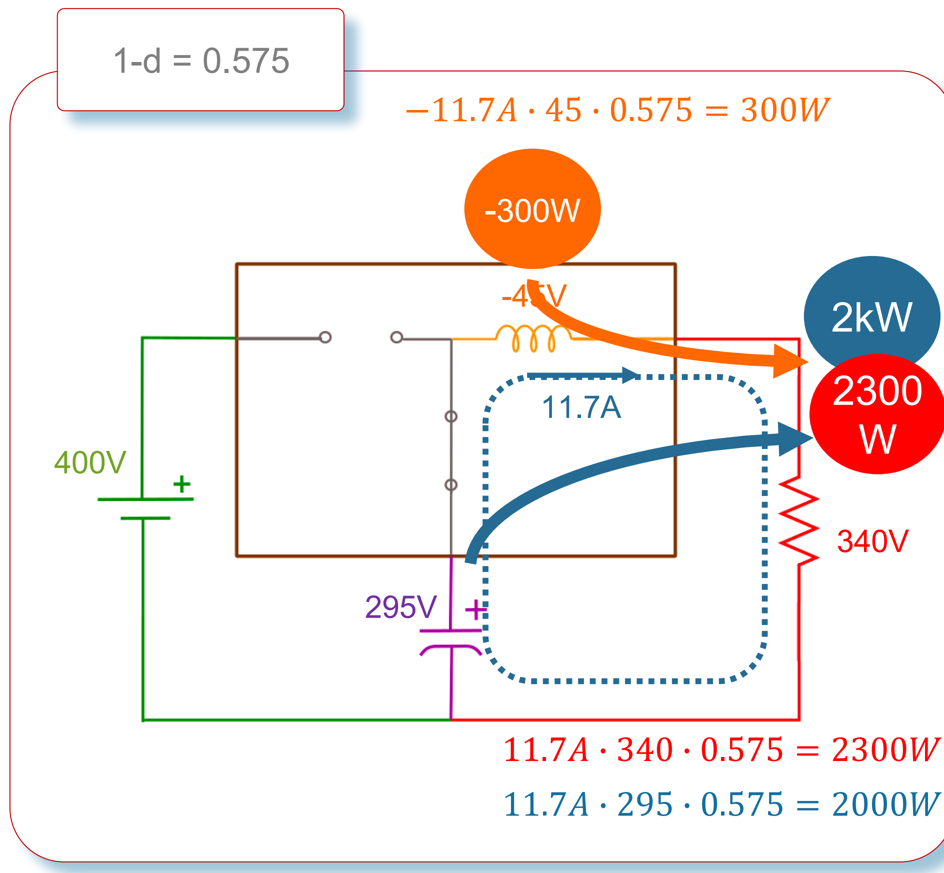


How to

Calculate P_{dir} and P_L







- 4kW output power (P)
- 3.7kW flow “**DIRECTLY**” to the load (P_{dir})
- 0.3kW are **internally processed** by the power stage (P_{diff})

Differential Power

How to

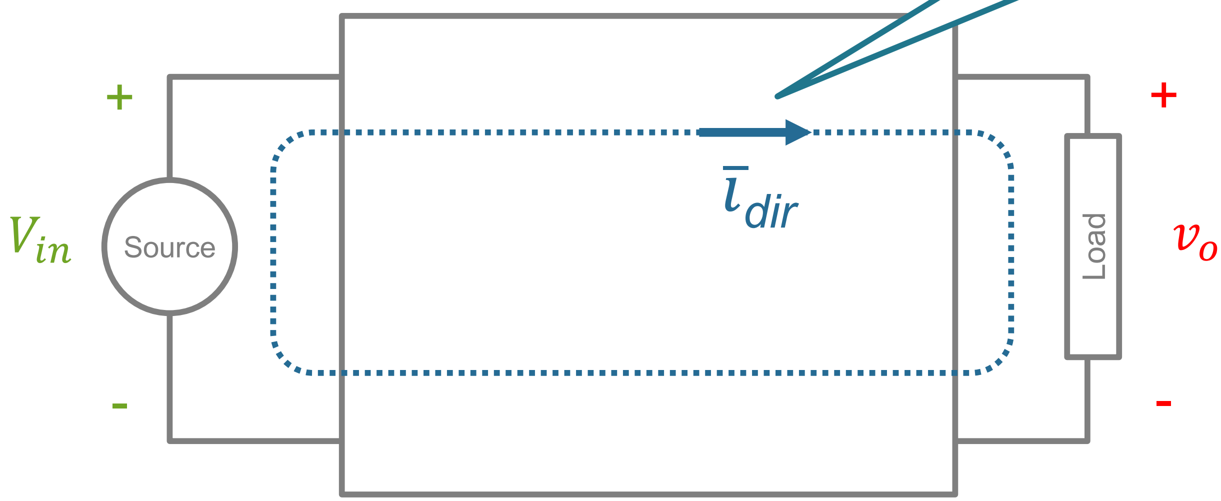
Average model, no need to know the specific topology !!

Device level — Calculate $P_{dir}(t)$, and average intervals

Converter level — Draw $\bar{\imath}_{dir}$ directly

$\bar{\imath}_{dir}$ = 0 in Buck-boost

$\bar{\imath}_{dir} < 0$ in some converters



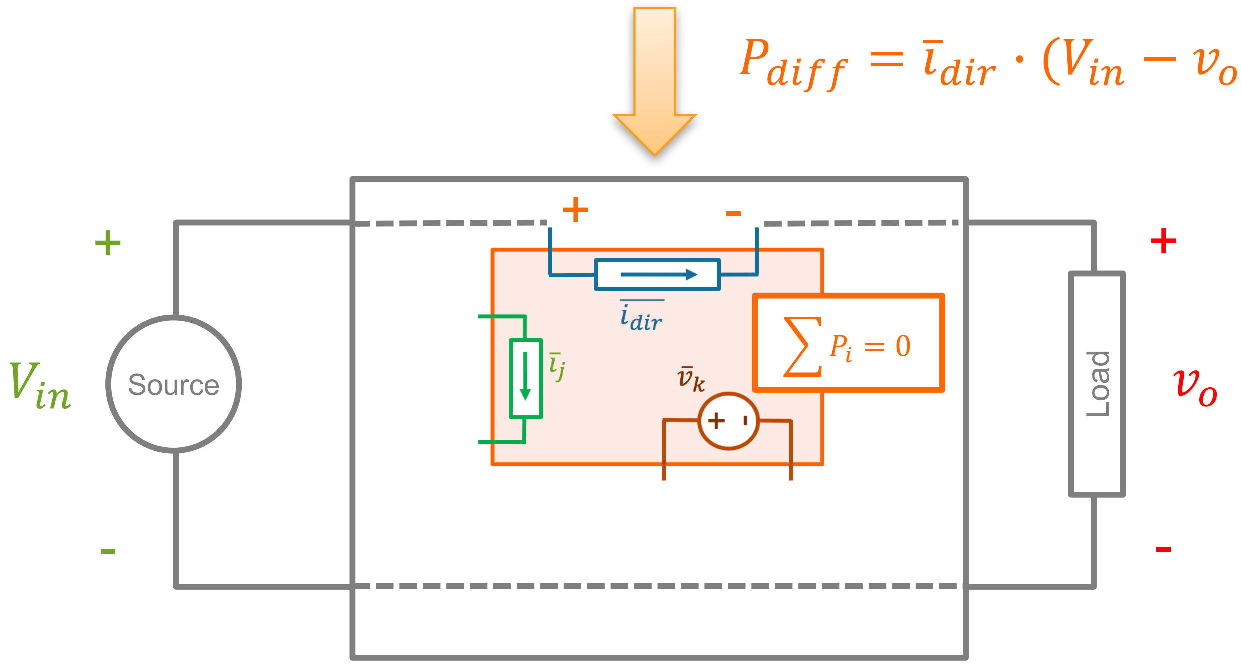
$$P_{dir} = \bar{\imath}_{dir} \cdot \min(V_{in}, v_o)$$

Differential Power

How to

Average model

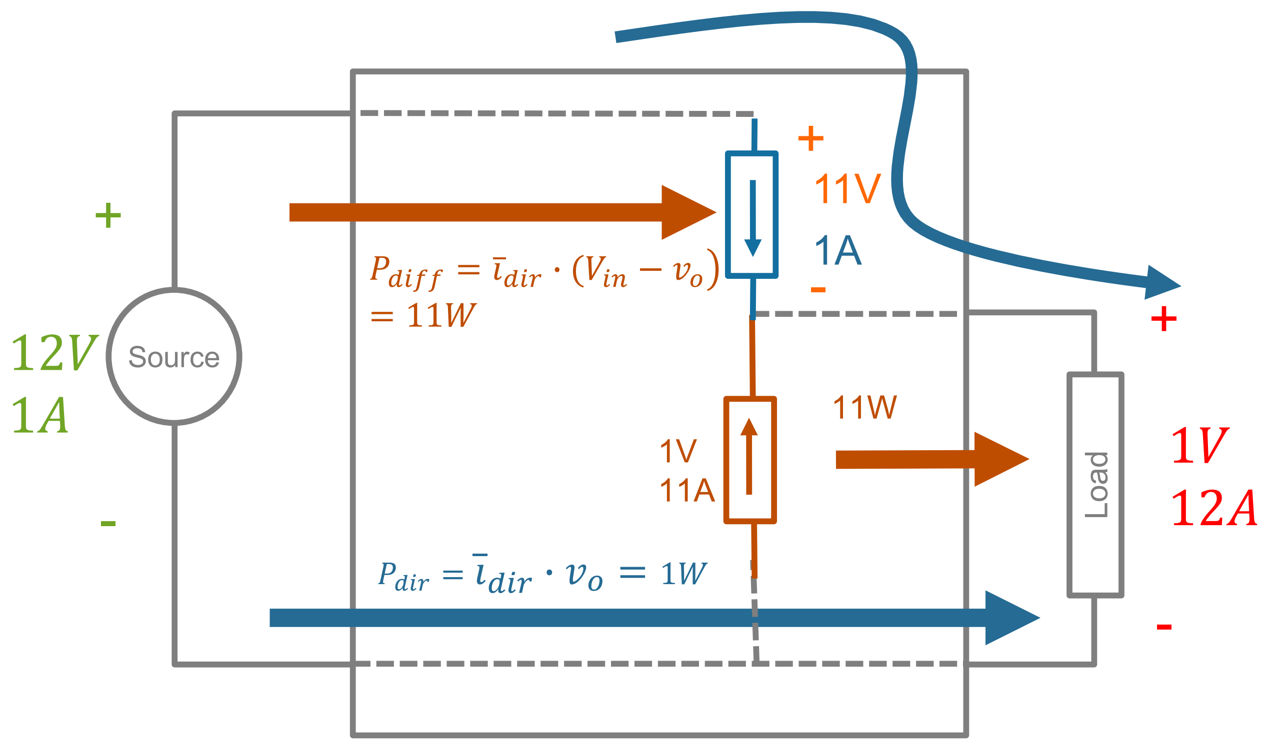
$$P_{diff} = \bar{\imath}_{dir} \cdot (V_{in} - v_o)$$



$$\left.\begin{array}{l} P^{+}_{diff} = \sum P_j > 0 \\[2em] P^{-}_{diff} = \sum P_k < 0 \end{array}\right\} =$$

Step down

Example



$$P_{diff^+} = \bar{\imath}_{dir} \cdot (V_{in} - v_o)$$

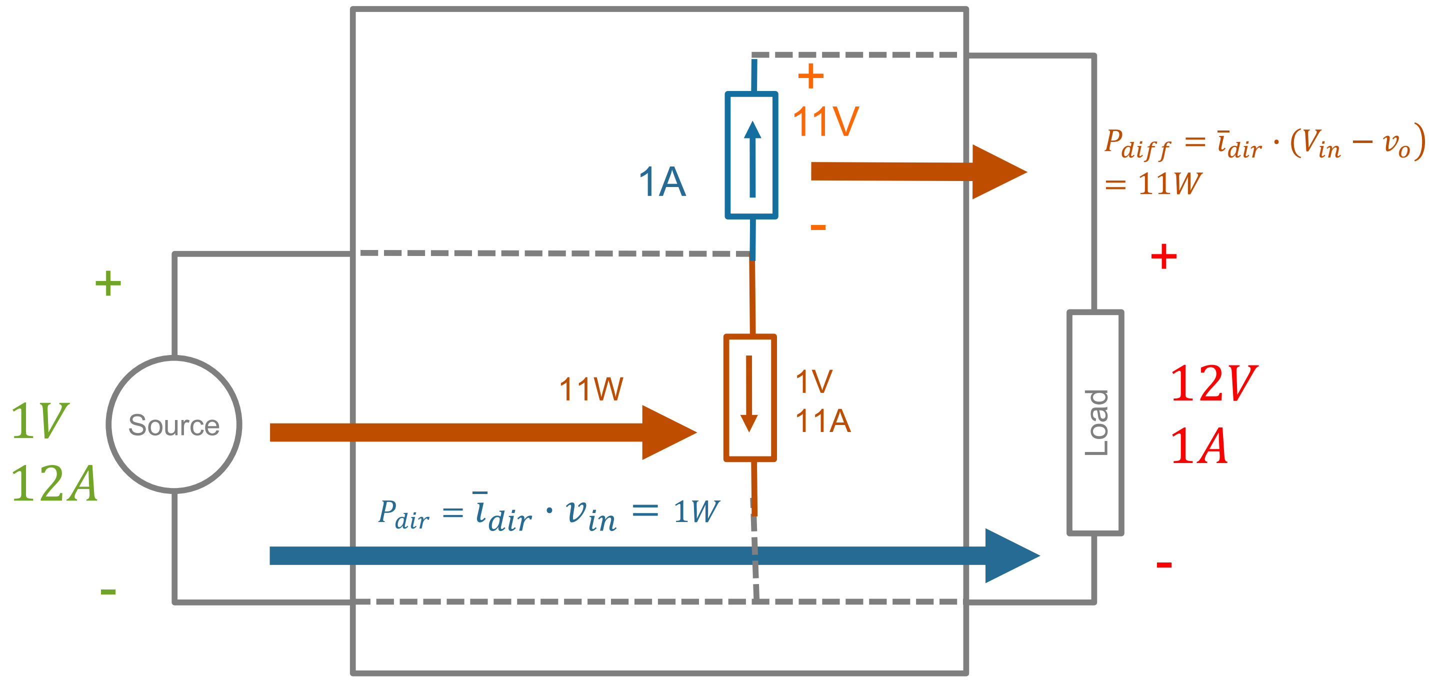
$$= P_{diff^-} = (i_o - \bar{\imath}_{in}) \cdot v_o$$

$$\boxed{= \boldsymbol{P \cdot \left(1 - \frac{v_o}{V_{in}}\right)}}$$

How to

Step up

Example



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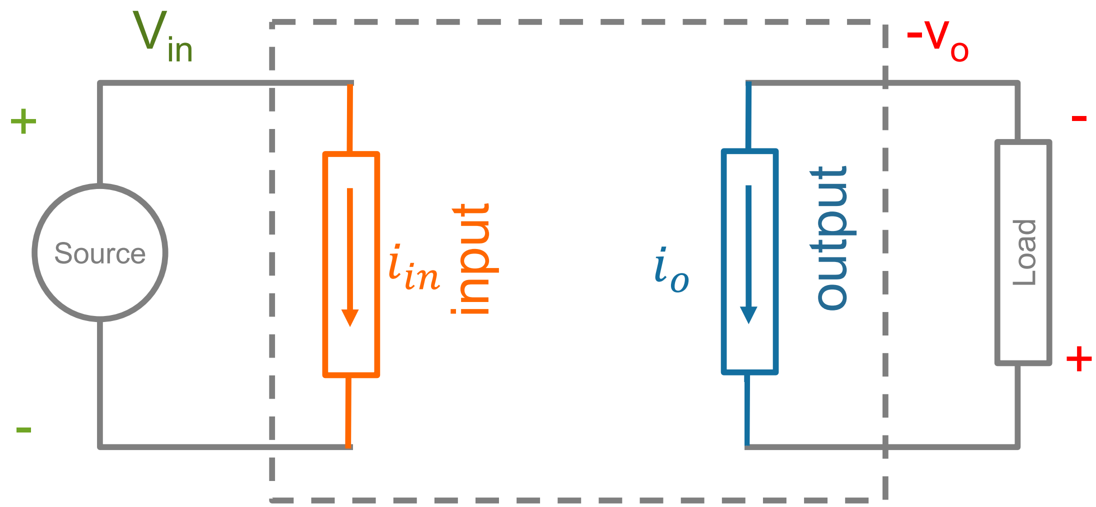
$$= P_{diff^-} = (i_o - \bar{\imath}_{in}) \cdot v_o$$

$$\boxed{= \boldsymbol{P} \cdot \left(\mathbf{1} - \frac{\boldsymbol{v_o}}{\boldsymbol{V_{in}}}\right)}$$

How to

Buck-boost

Differential Power



P = Pdiff + Pdir

$v_o \cdot i_o = V_g \cdot i_g$ + 0

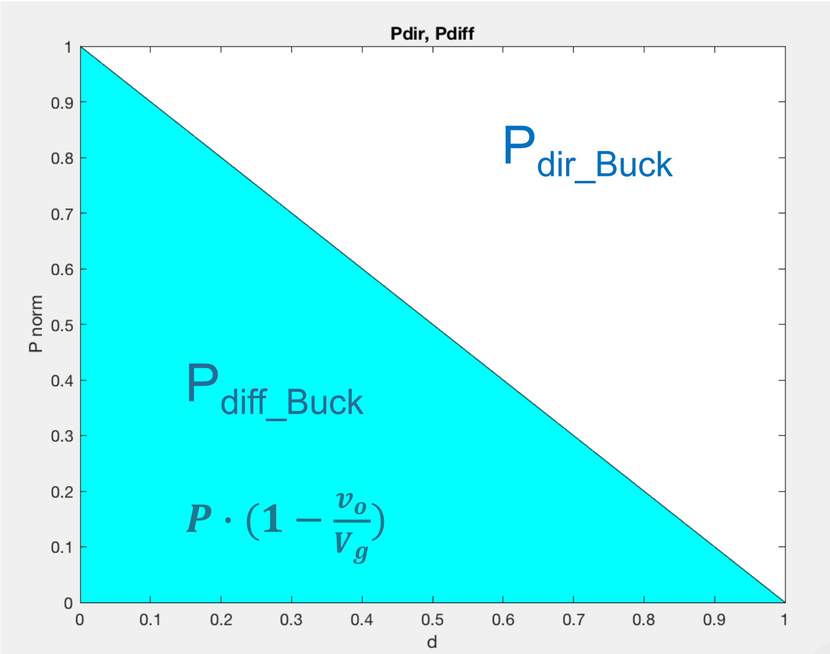
$$P_{diff^+} = i_g \cdot V_g$$

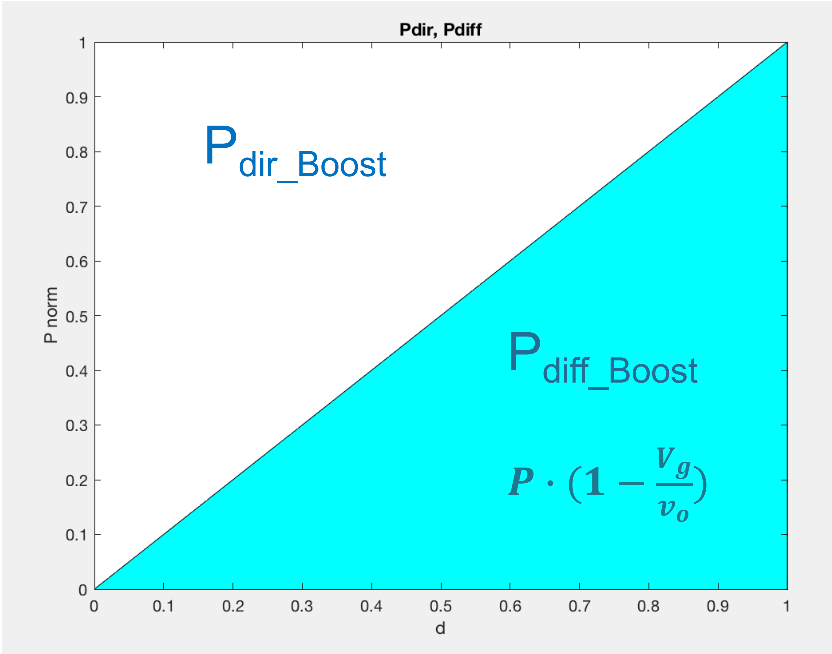
$$P_{diff^-} = i_o \cdot v_o$$

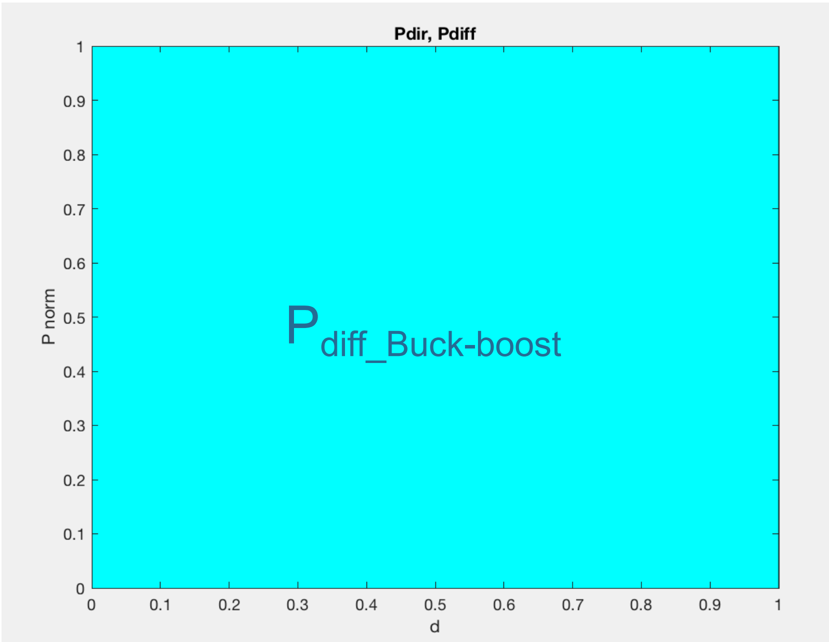
$$\boxed{= \boldsymbol{P}}$$

How to

Differential Power







DEFINITION

- P_{dir}, P_{diff}, P_{int},
- P_T, P_L, P_C
- VA_{rating}

Related concepts:
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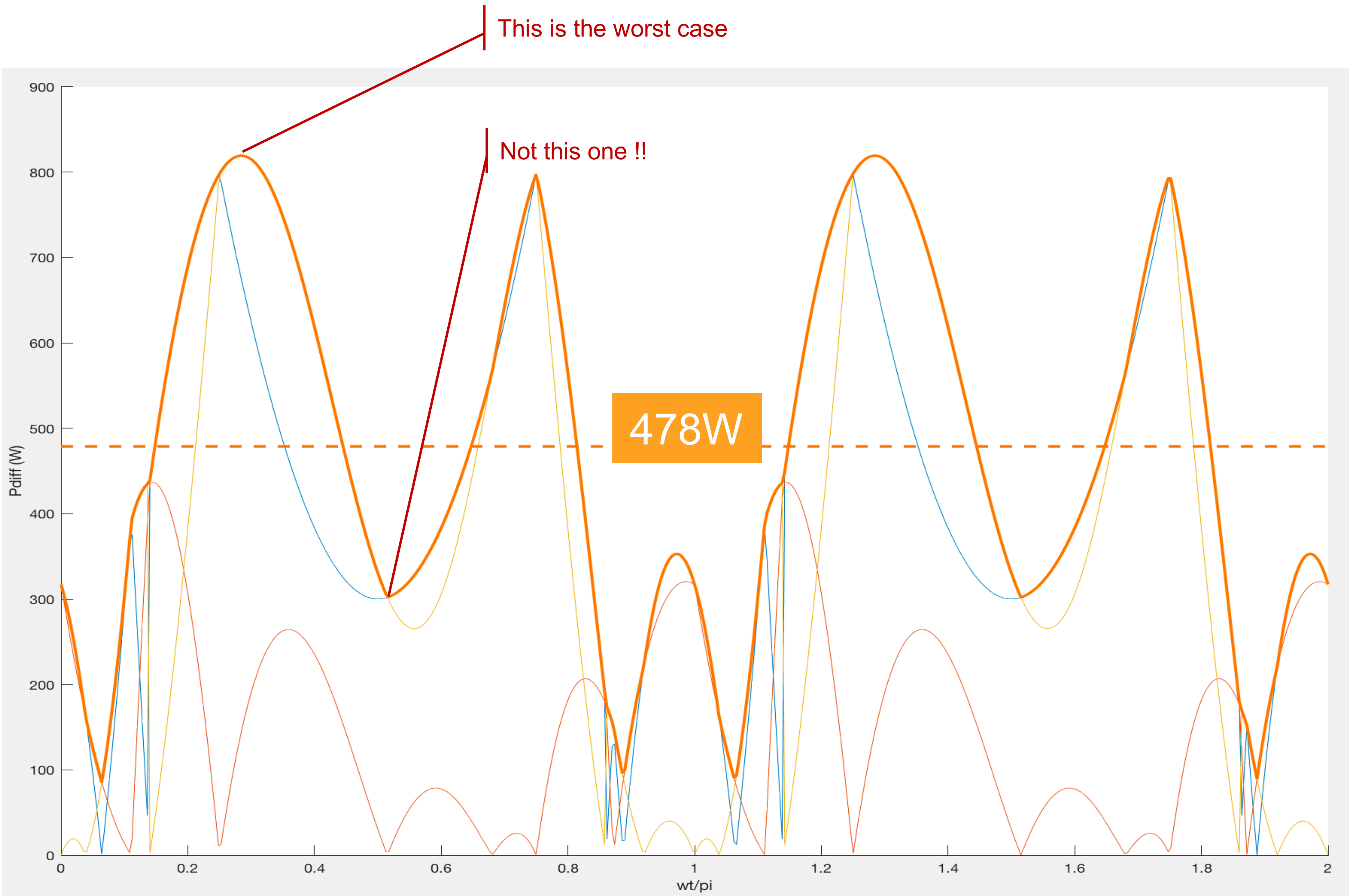
- **Invent** new architectures

Energy Buffered converters

- **Fundamental Limit**
- EBC
- Comparison (2-stage, Active Filter, EBC)
- **Single stage**

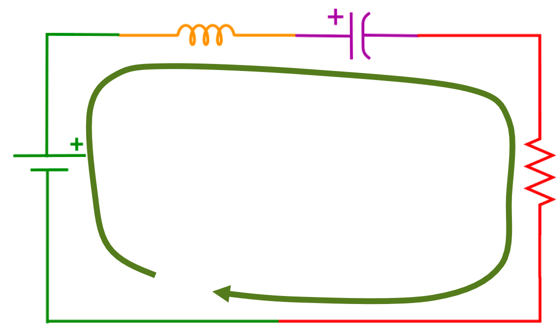
Energy Buffered converters

Differential Power, for **30% discharge ratio**

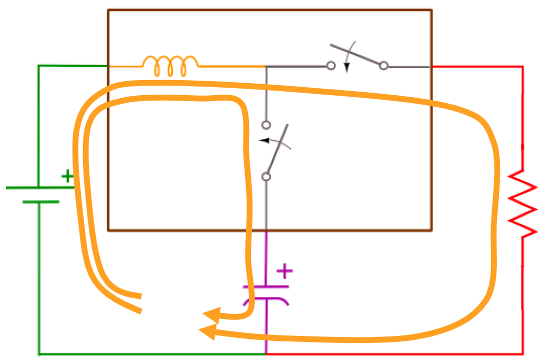


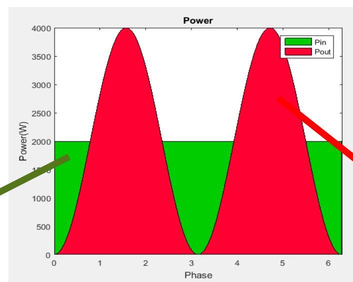
P_{diff} = 478/2,000 = 0.24

How to implement such inverter ??

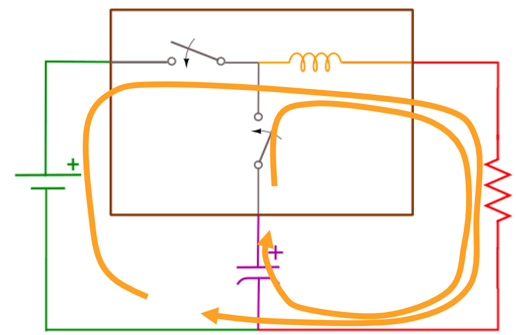


2kW





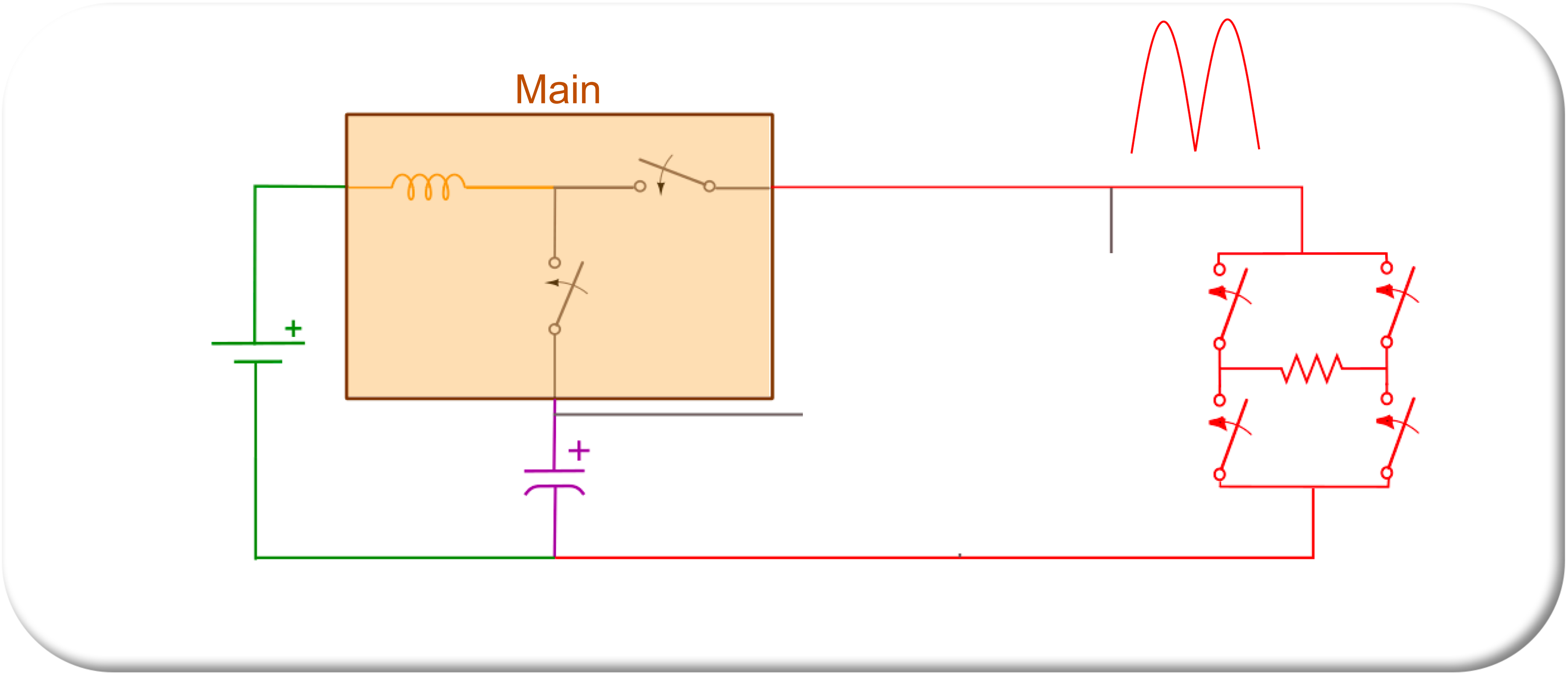
4kW



Charging phase

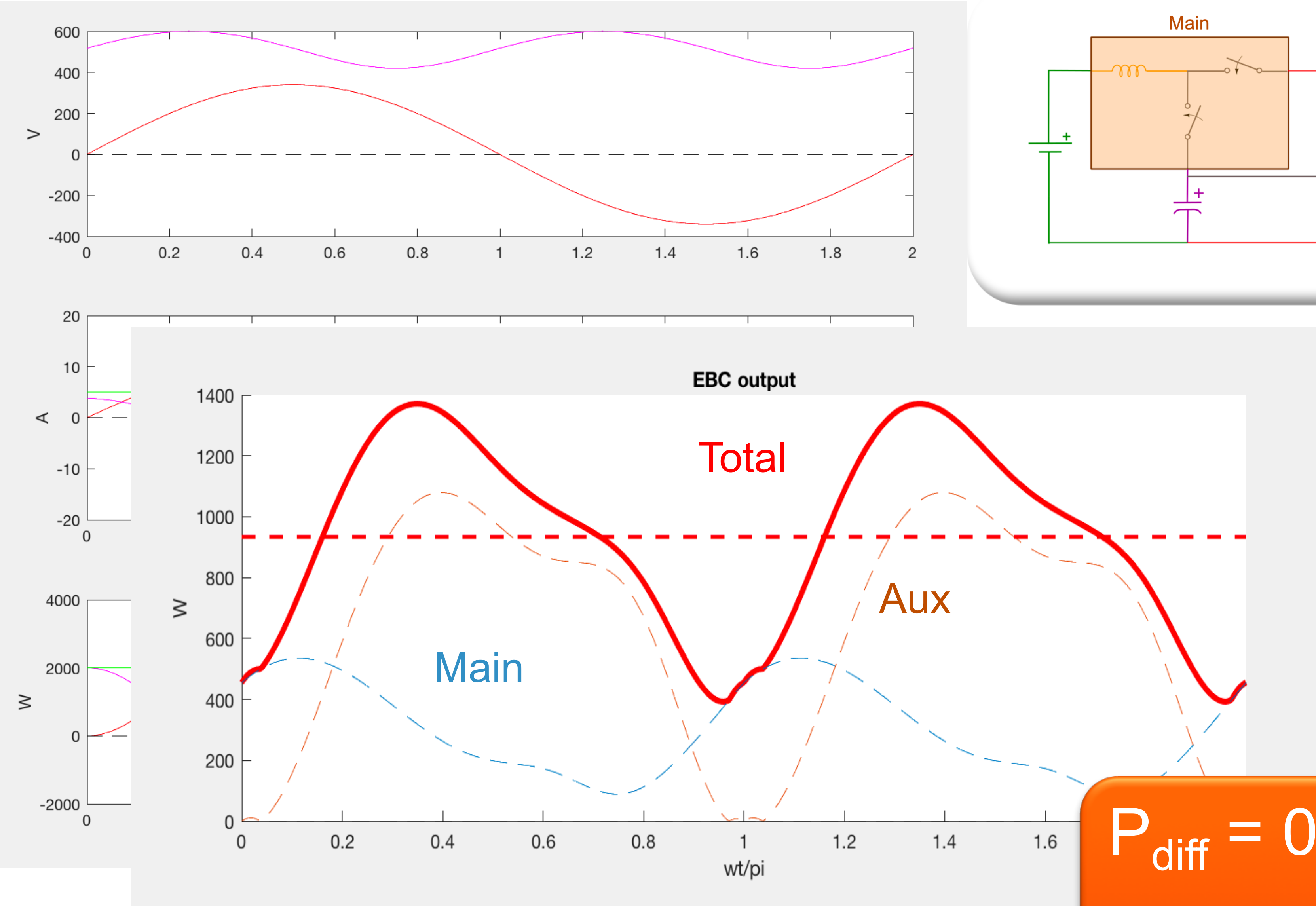
DIS-Charging phase

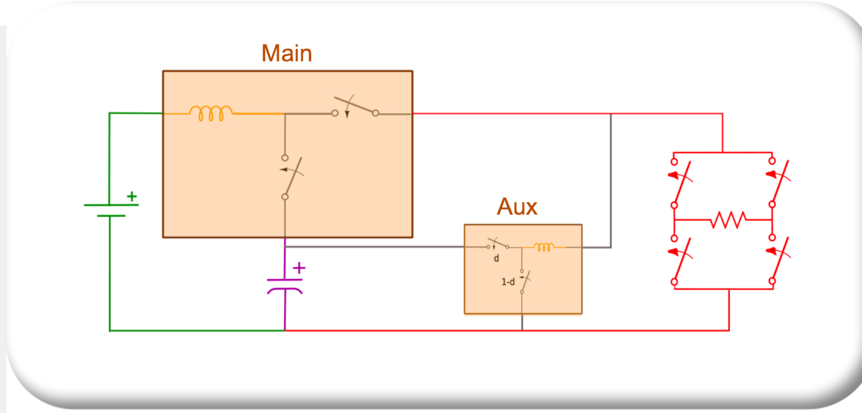
Based on the charging phase:



We calculate P_{diff} to check if it is a good idea

Can this concept be extended to the whole line cycle?



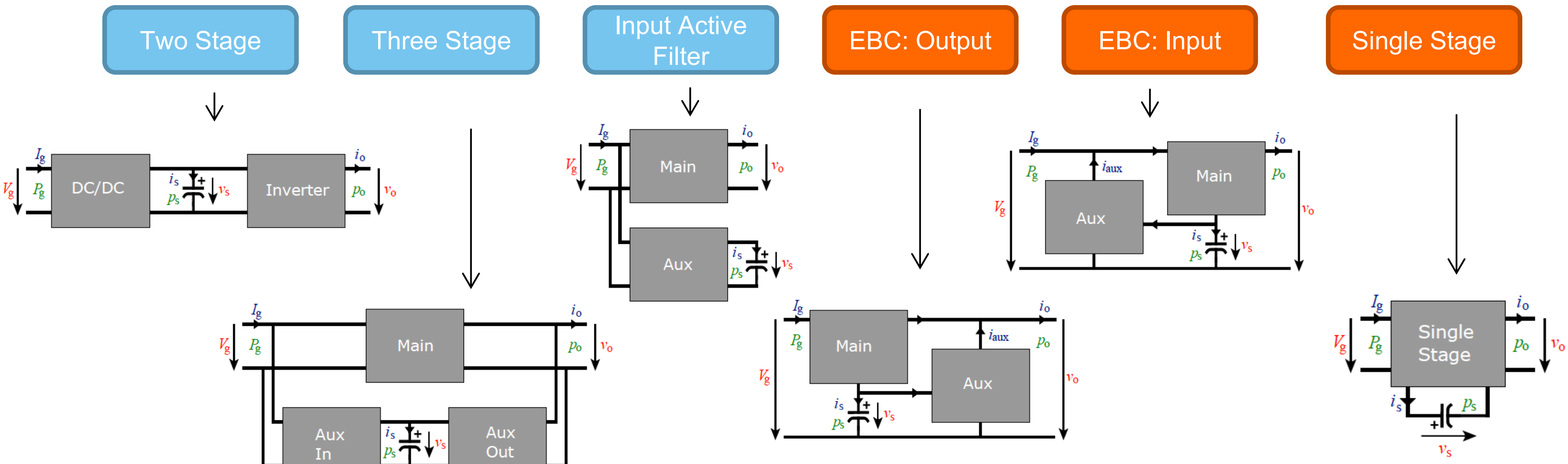


$P_{diff} = 0.47\ P_o$

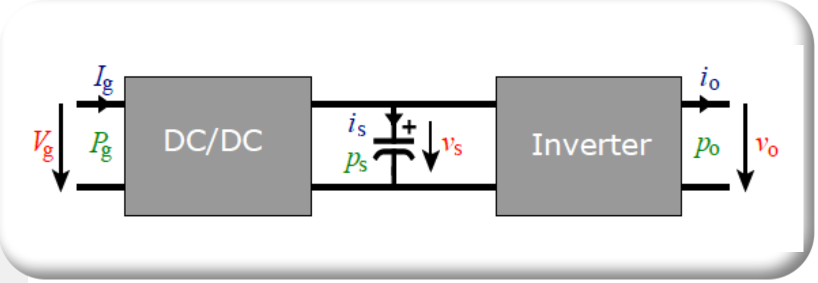
- 933W
- 30% discharge ratio
- V_{bus} = 600V

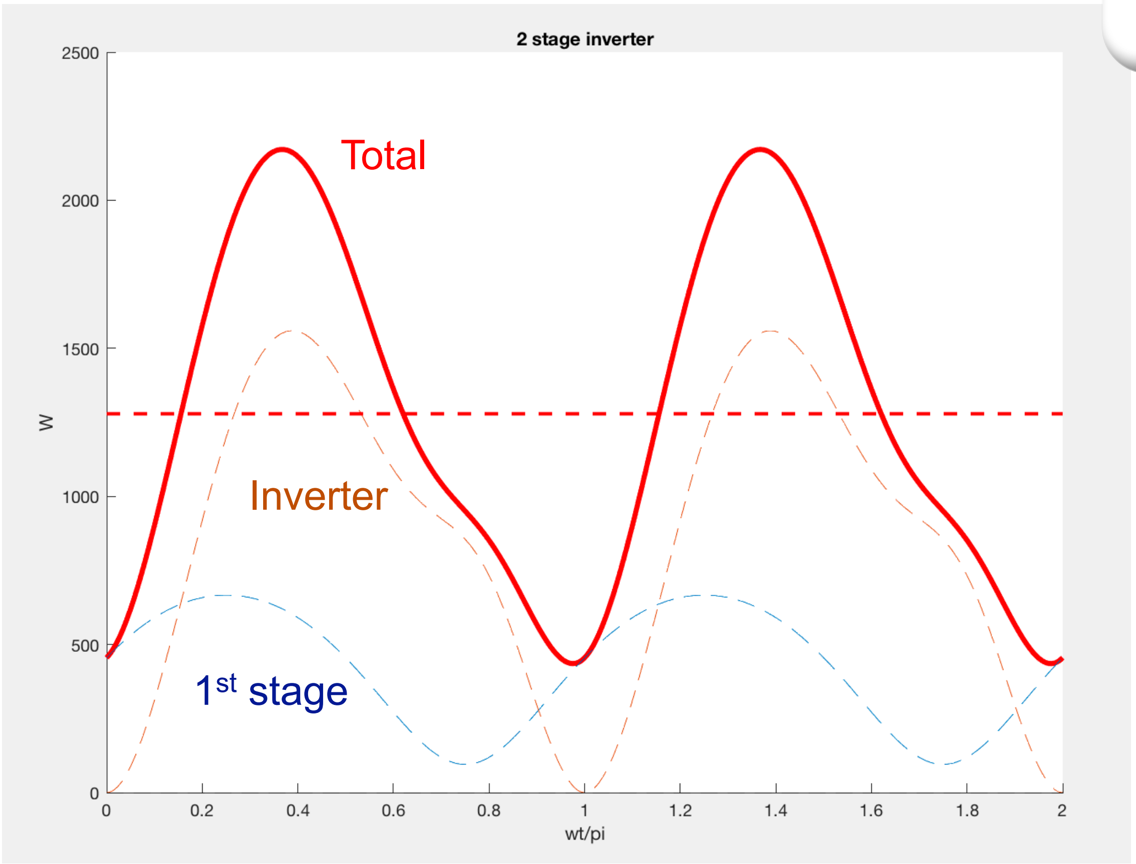
Far from optimum P_{diff} = 0.24

We have the methodology to compare…



Comparison at 600V and 30% discharge ratio





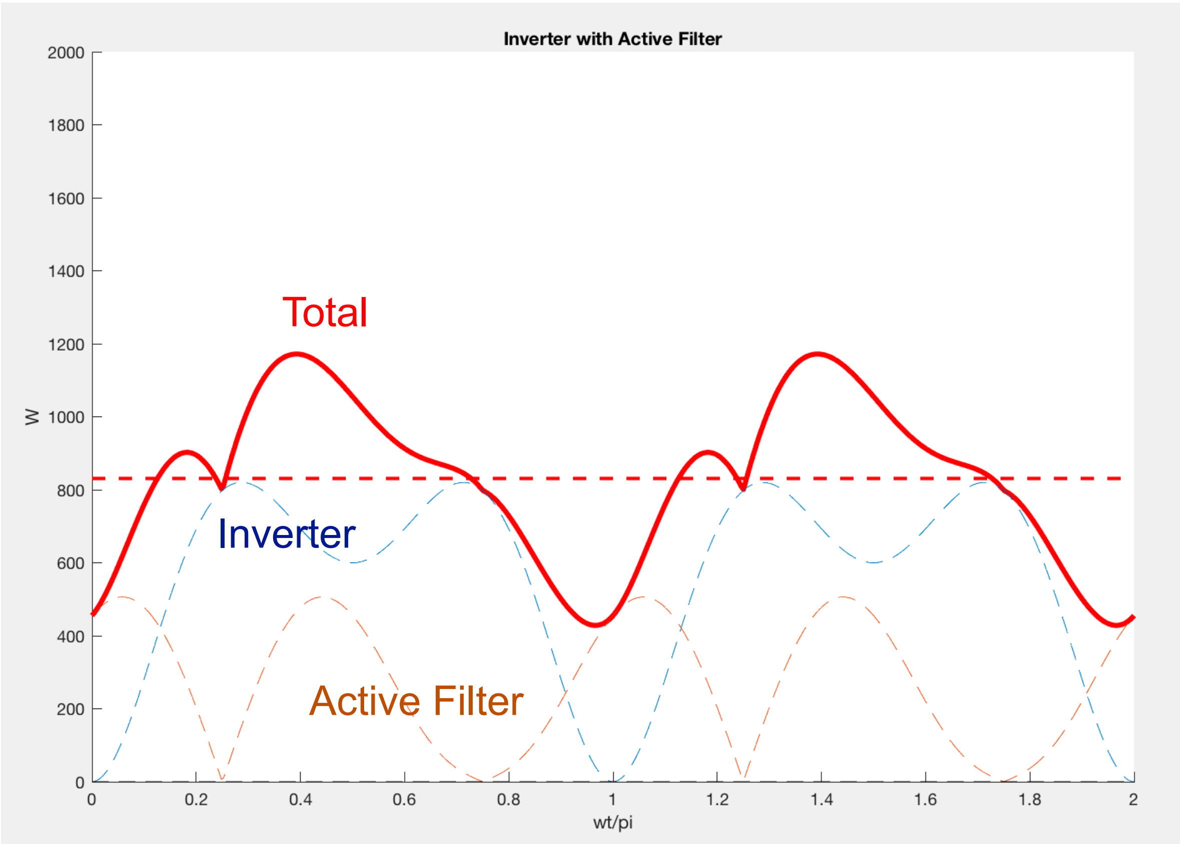
$P_{diff} = 0.64\ P_o$

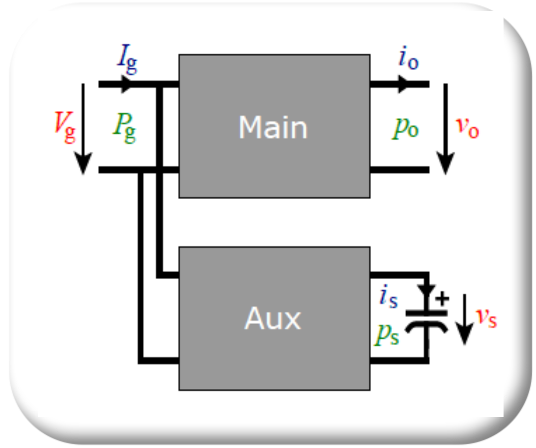
- 1300W
- 30% discharge ratio
- V_{bus} = 600V

Our "EBC_output invention" was better than "2 stage" at 600V

Remind, optimum P_{diff} = 0.24

Comparison at 600V and 30% discharge ratio





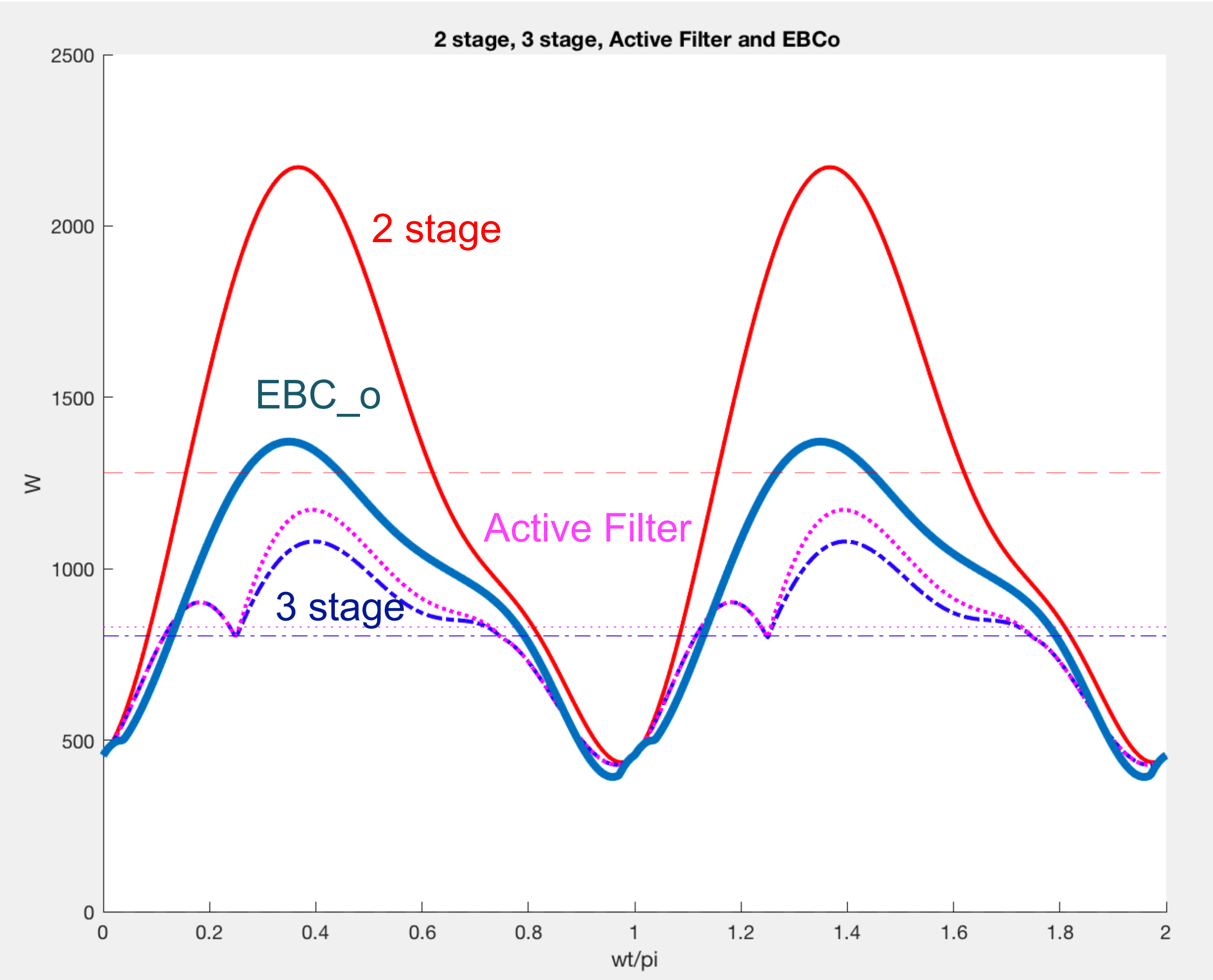
$P_{diff} = 0.42\ P_o$

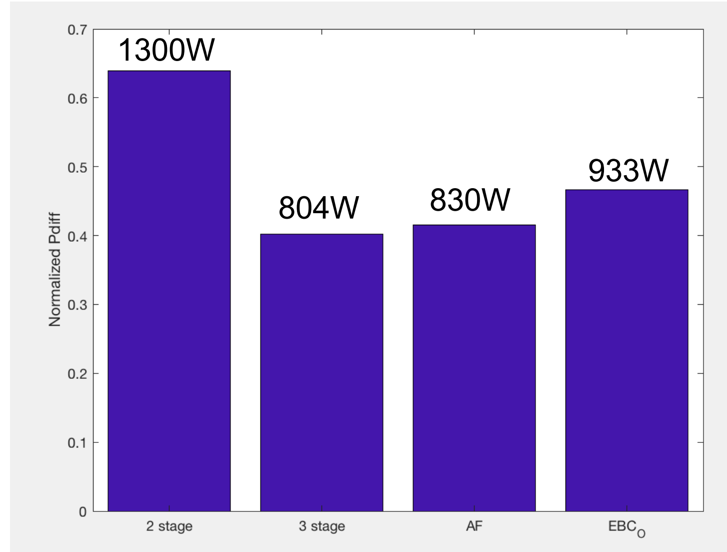
- 830W
- 30% discharge ratio
- V_{bus} = 600V

Our “EBC_output invention” was worse than “Active Filter” at 600V

Remind, optimum P_{diff} = 0.24

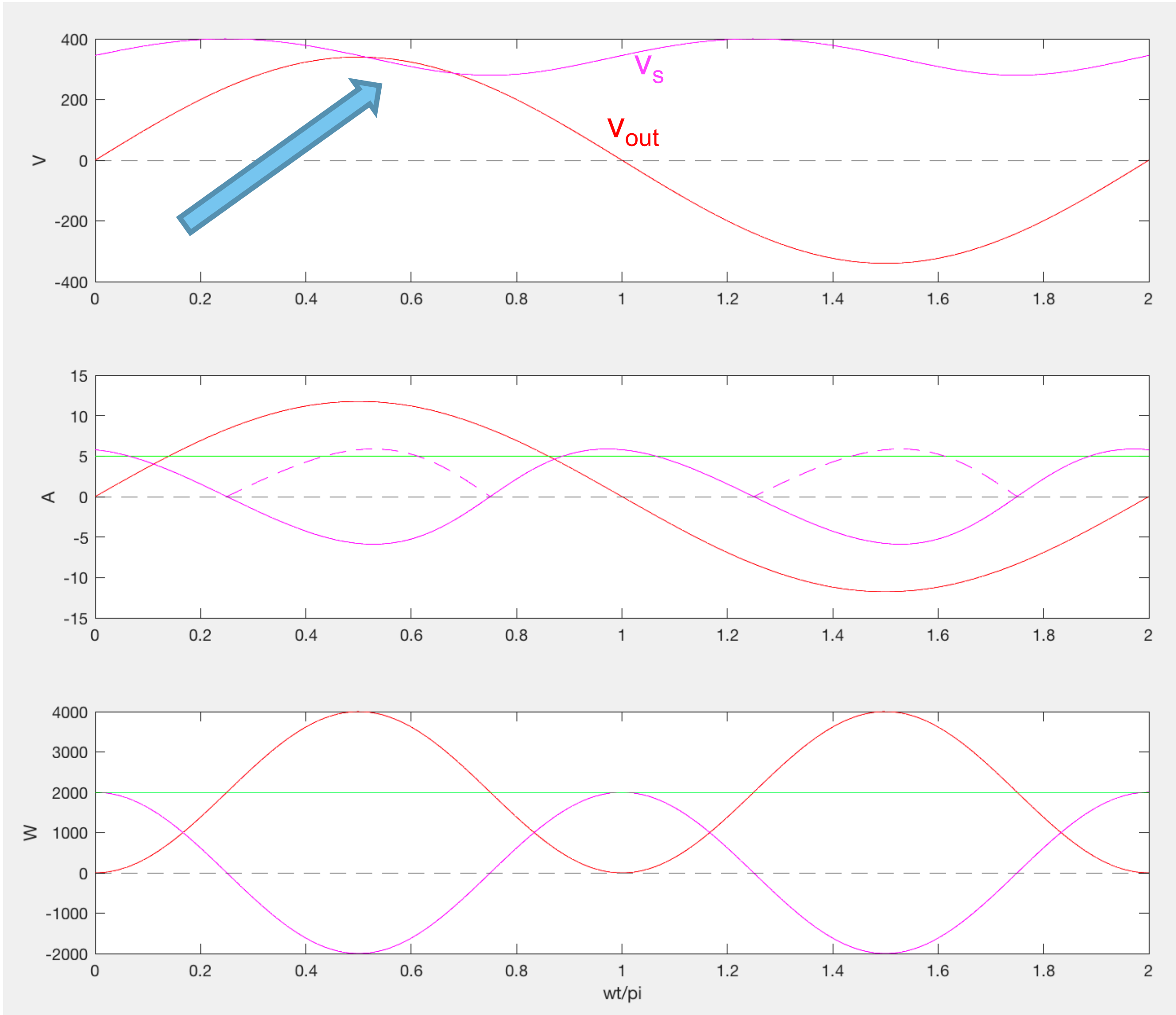
Comparison at 600V and 30% discharge ratio





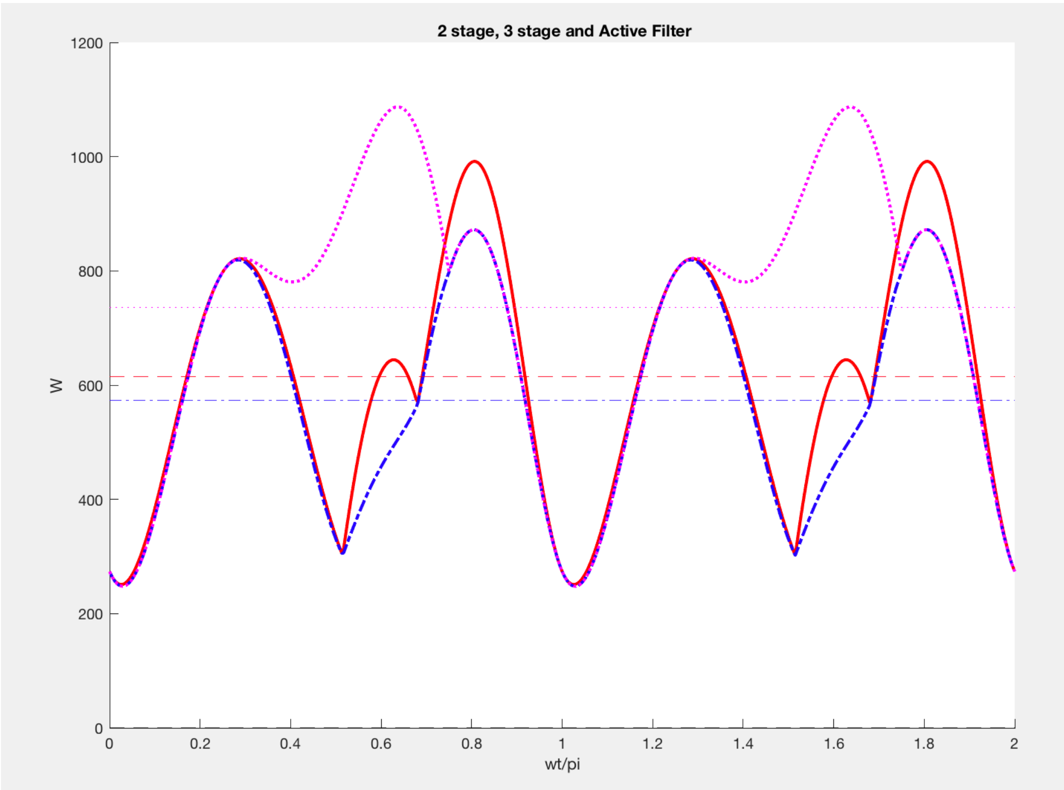
Active Filter is the best choice at V_{bus} = 600V and 30% discharge ratio

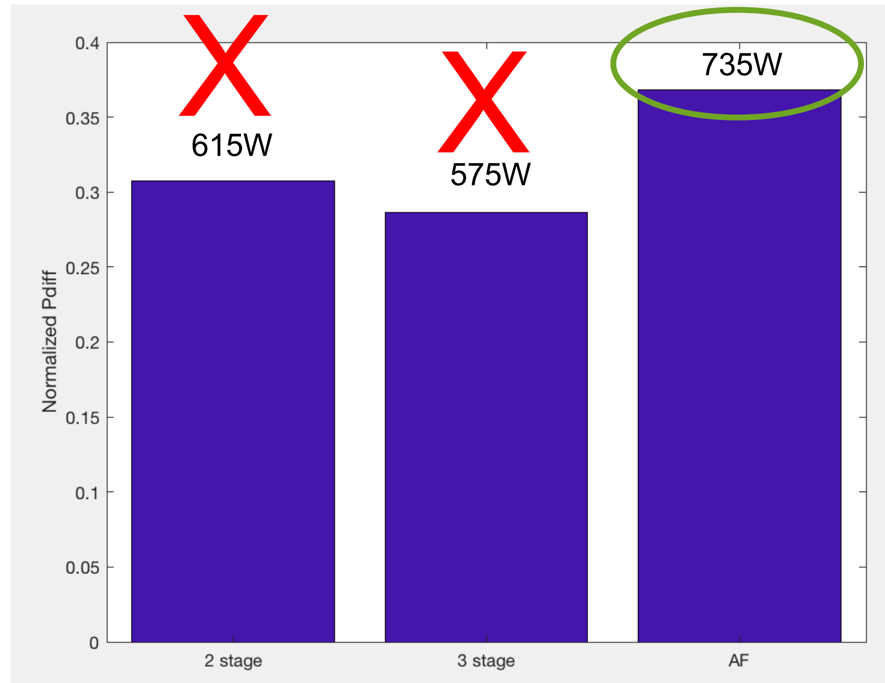
Comparison at 400V and 30% discharge ratio



Discharge ratio limited to 20% in “2 stage” and “3 stage” converters

Comparison at 400V and 30% discharge ratio

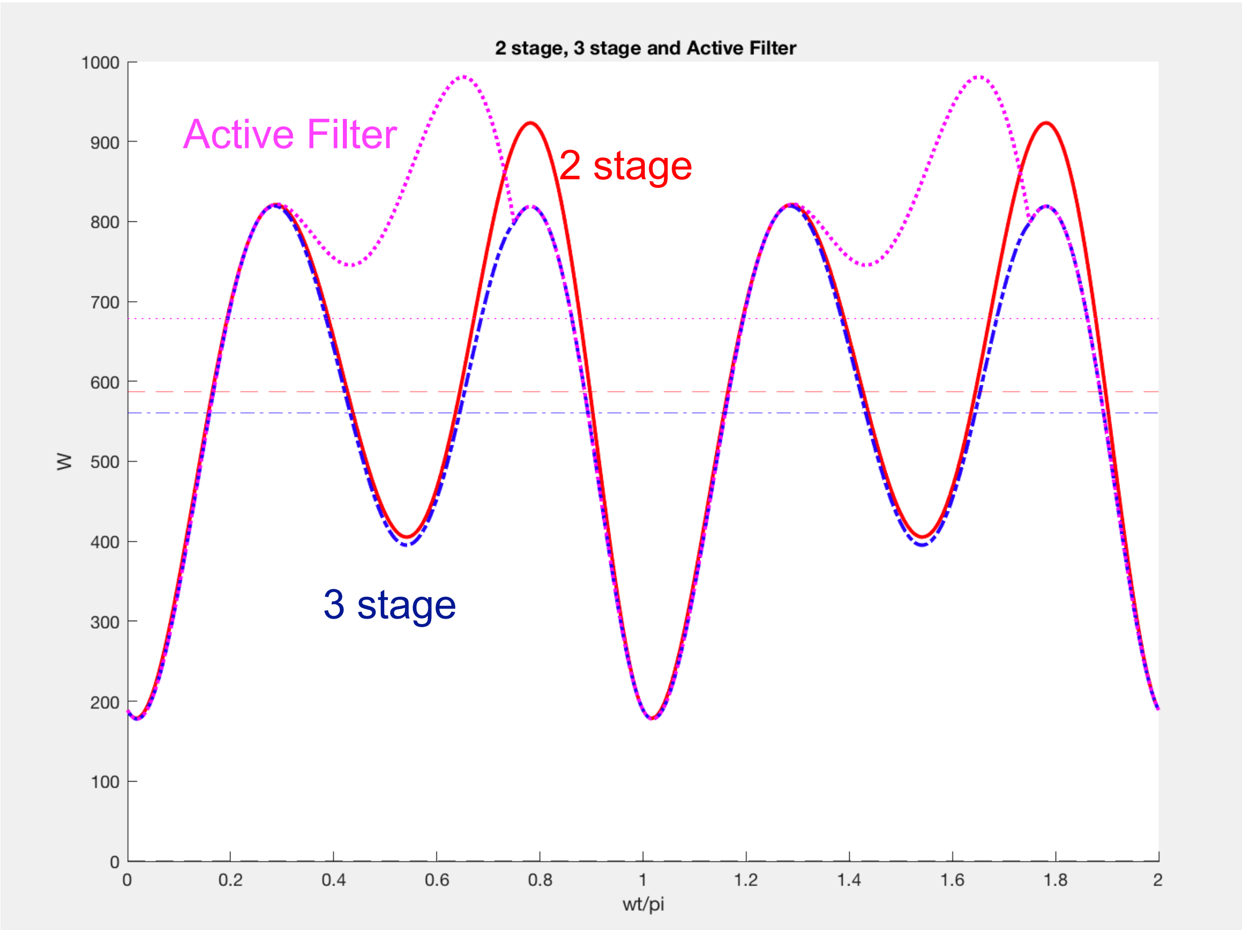




- “2 stage” would be preferred BUT…
  …both step-down and step-up functions are needed.

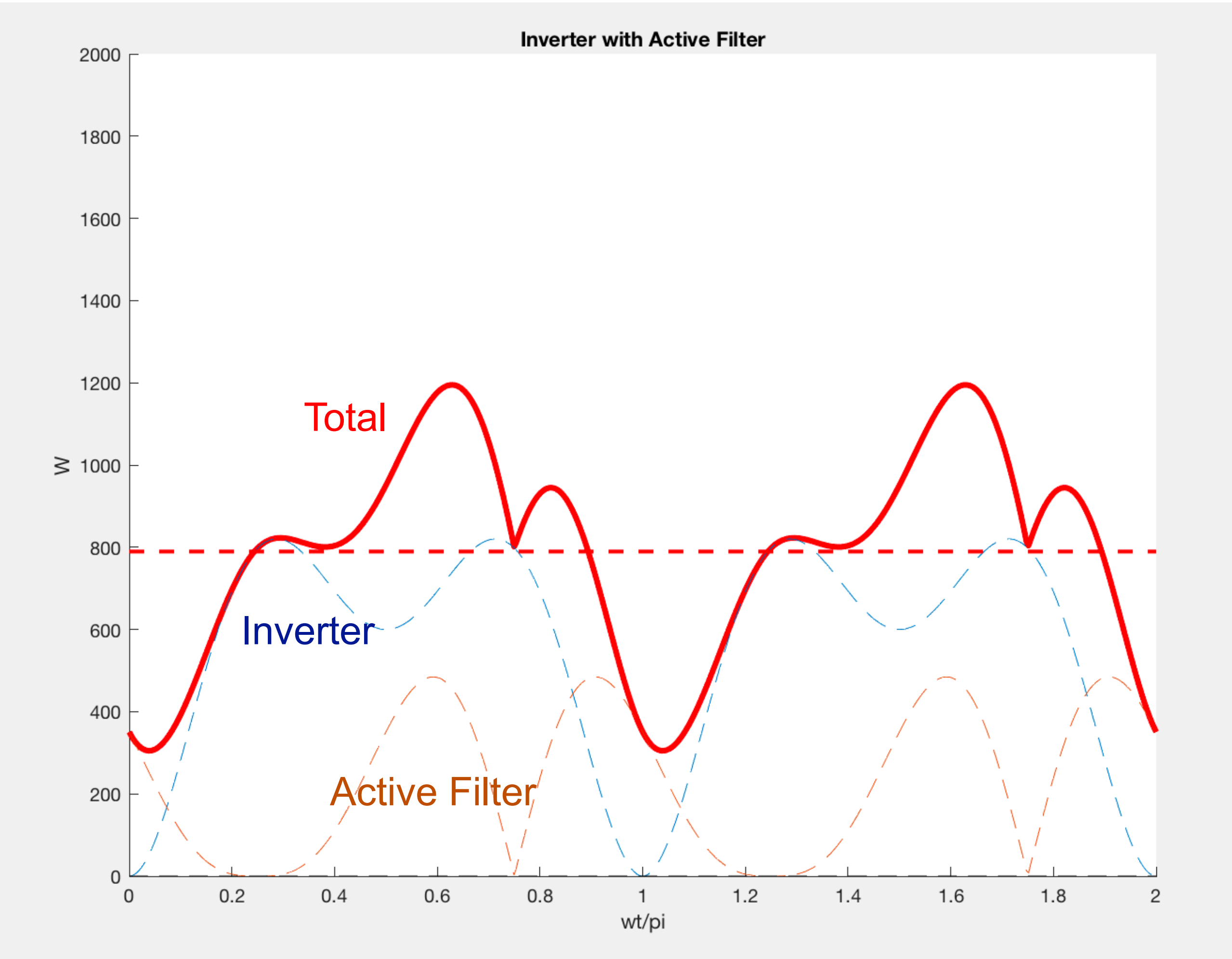
- “Active Filter” is therefore preferred

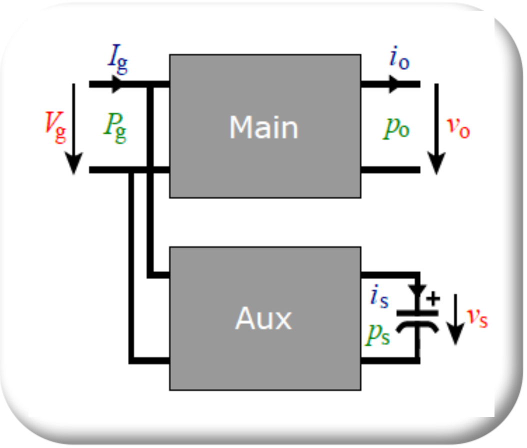
Comparison at 400V and 20% discharge ratio



- But 20% discharge ratio implies **“large” capacitor**.
- Discarded for the competition, but **good for “low cost” products**

Comparison at 400V and 40% discharge ratio





$P_{diff} = 0.39\ P_o$

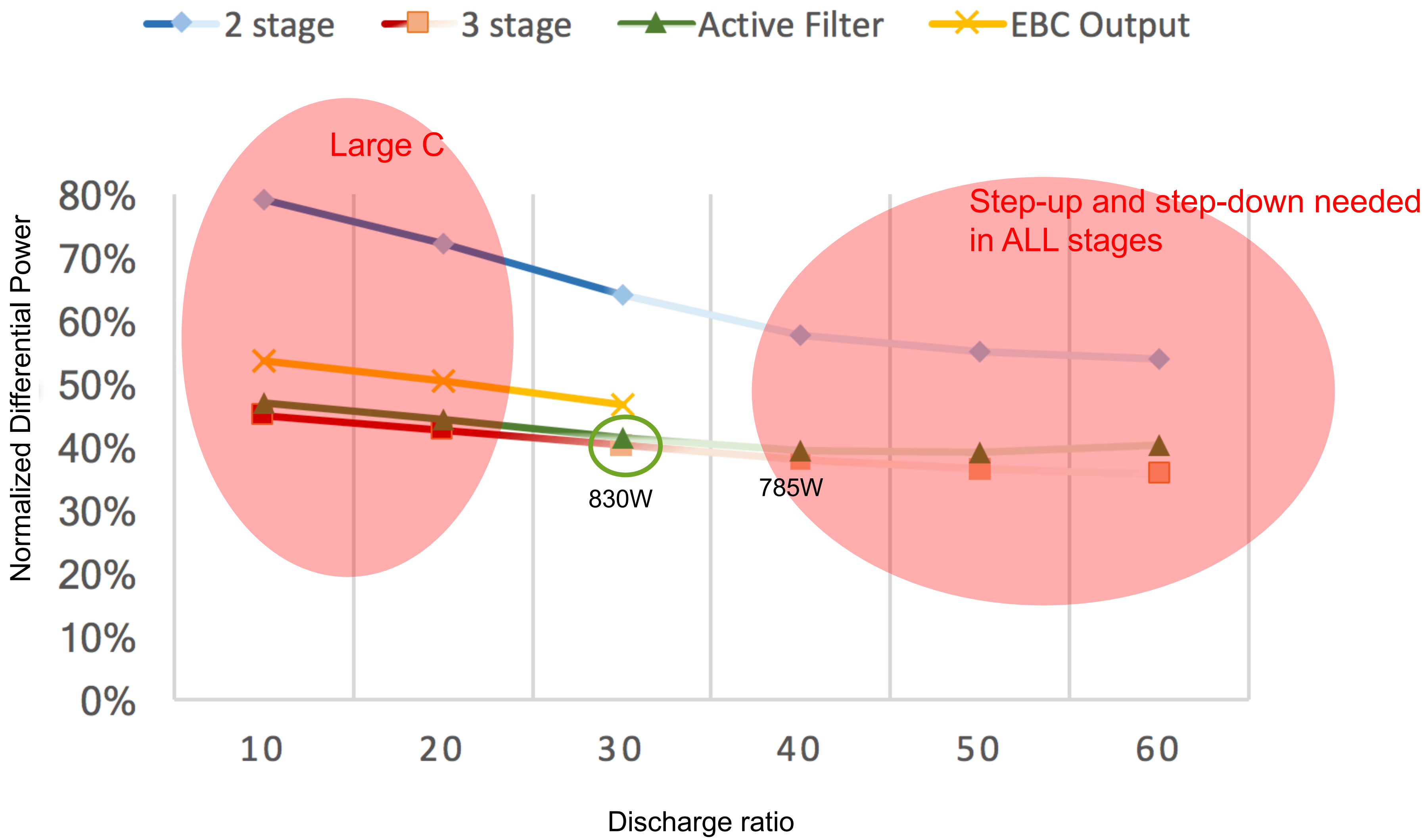
- 800W
- 40% discharge ratio
- V_{bus} = 400V

This has been the preferred option of most teams !!

Remind, optimum P_{diff} = 0.24

Comparison

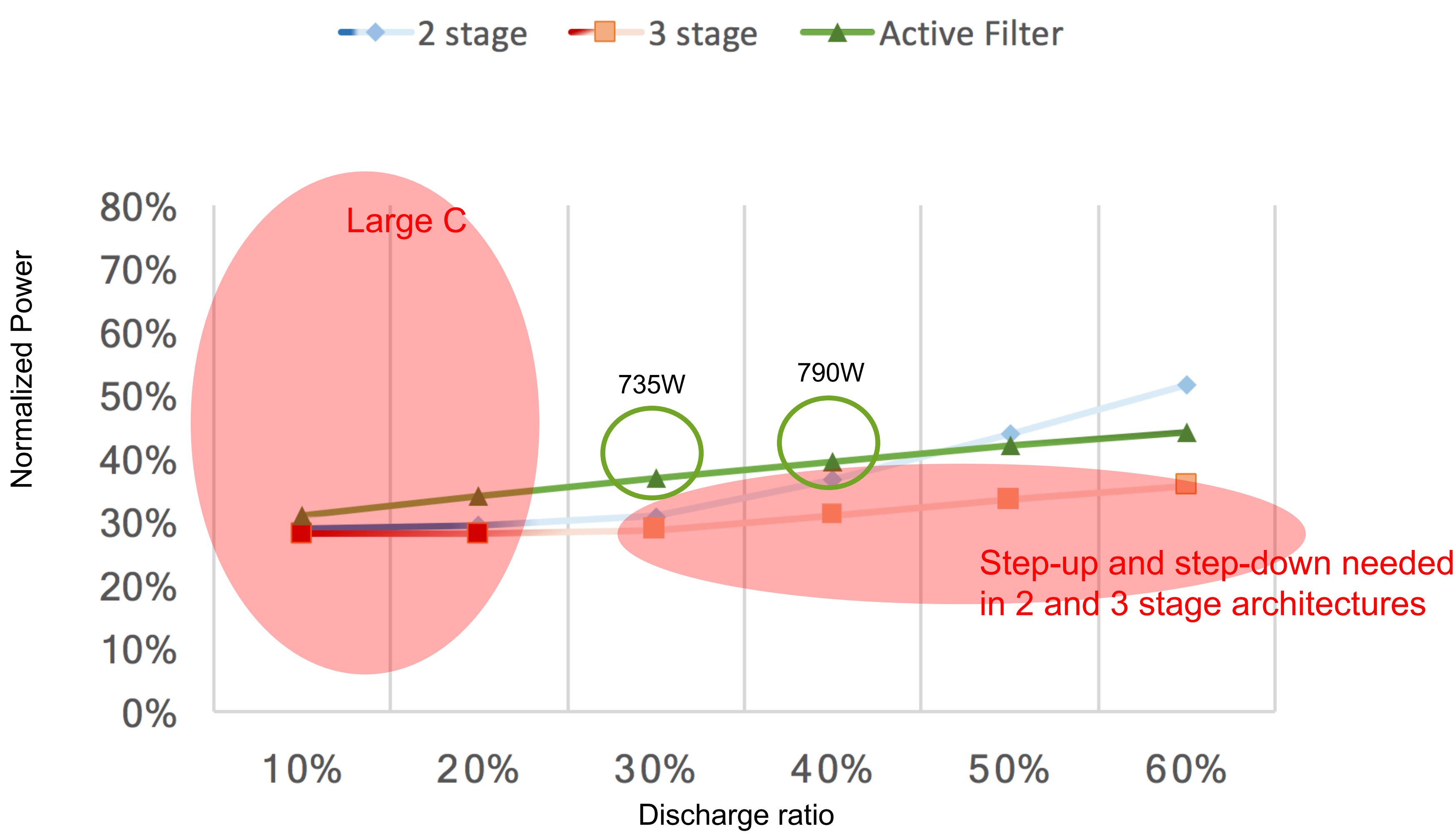
$V_{bus} = 600V$



Active Filter preferred option at 600V

Comparison

$V_{bus} = 400V$



Active Filter preferred option at 400V by most teams !!

DEFINITION

- P_{dir}, P_{diff}, P_{int},
- P_T, P_L, P_C
- VA_{rating}

Related concepts:

- Differential converters
- Partial Power
- Gain vs Regulation

History:

- Wilson: Pac, Pdir
- Wolaver: Paths, Bounds
- Sanders: SC bounds

"**Differential Power**" is the ***minimum possible value*** of the:

- "AC power"
- OR "Indirect Power",
- OR "**Internal Power**"

Differential Power

How to

- **System** level - Average model
- **Device** level – P_L, P_C

Design Case:

- **Energy buffered inverter**
- TI-Buck

Generalization:

- Step-up, step-down
- "Indirect" (buck-boost, Flyback) converter
- Z-source inverter
- 3-level Buck (n-level Flying capacitor)
- Resonant SC
- Cascaded and stacked converters

Trends today:

- WBG
- Hybrid converters
- Metric necessary

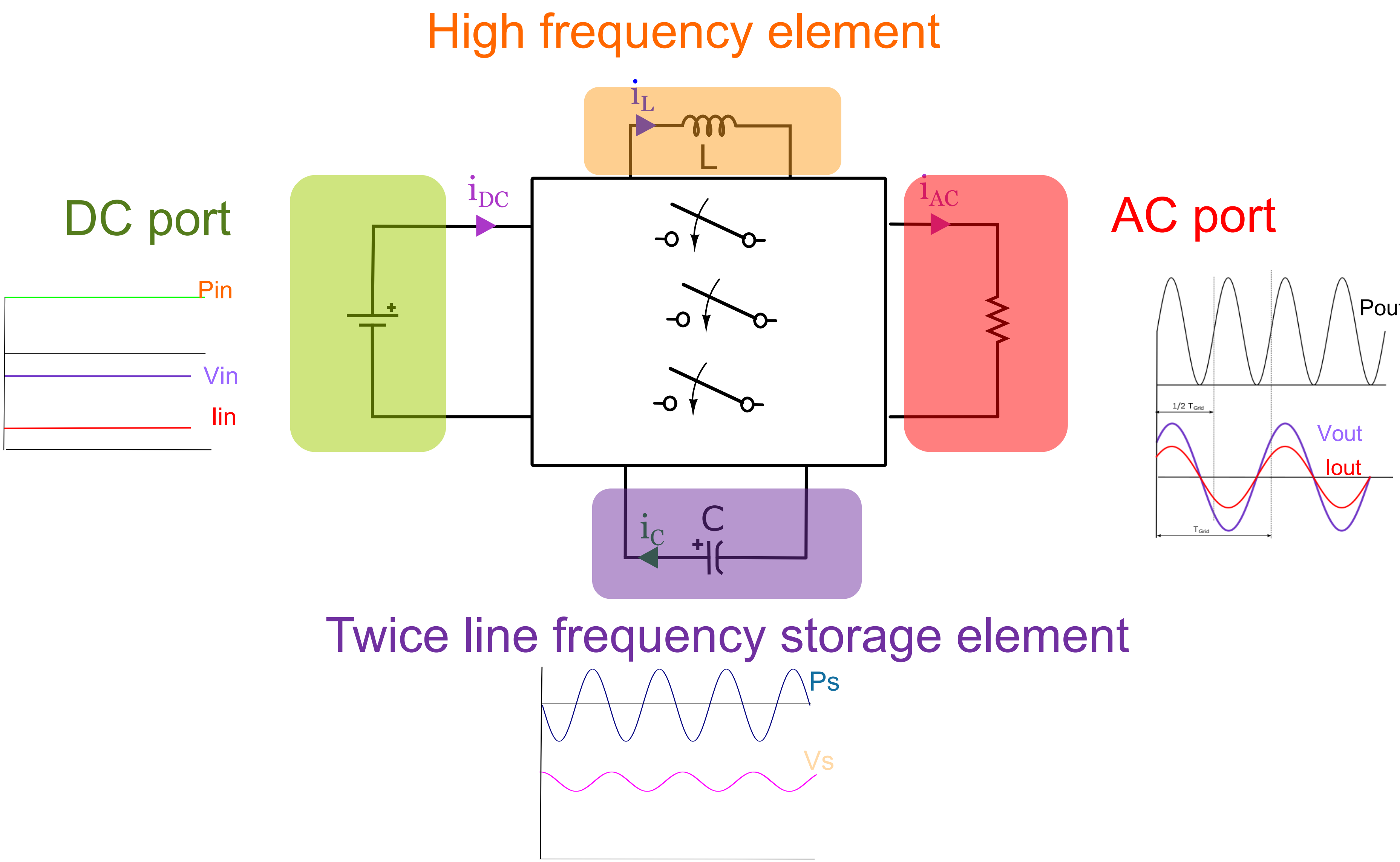
What for

- **High level metric** for comparison
- **Invent** new architectures

Energy Buffered converters

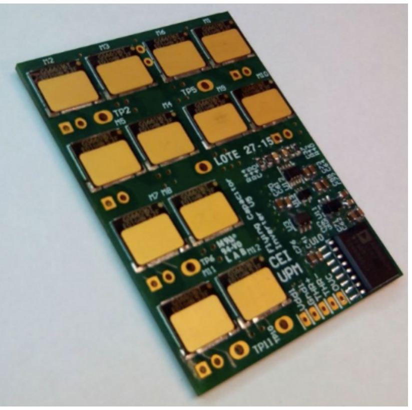
- **Fundamental Limit**
- EBC
- Comparison (2-stage, Active Filter, EBC)
- **Single stage**

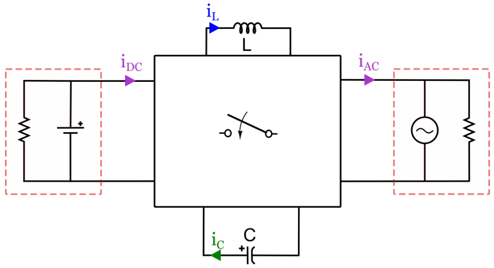
Single stage, single inductor converter



A given power architecture…

…may process different Pdiff, depending on how you operate it

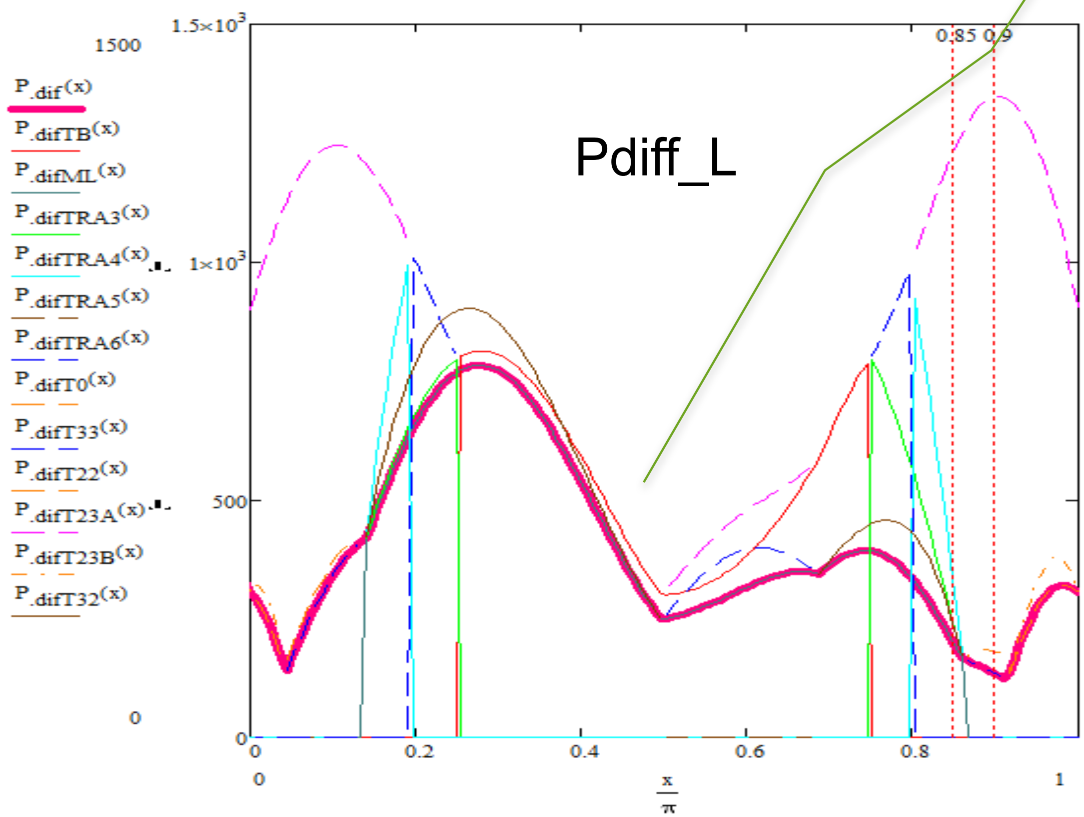


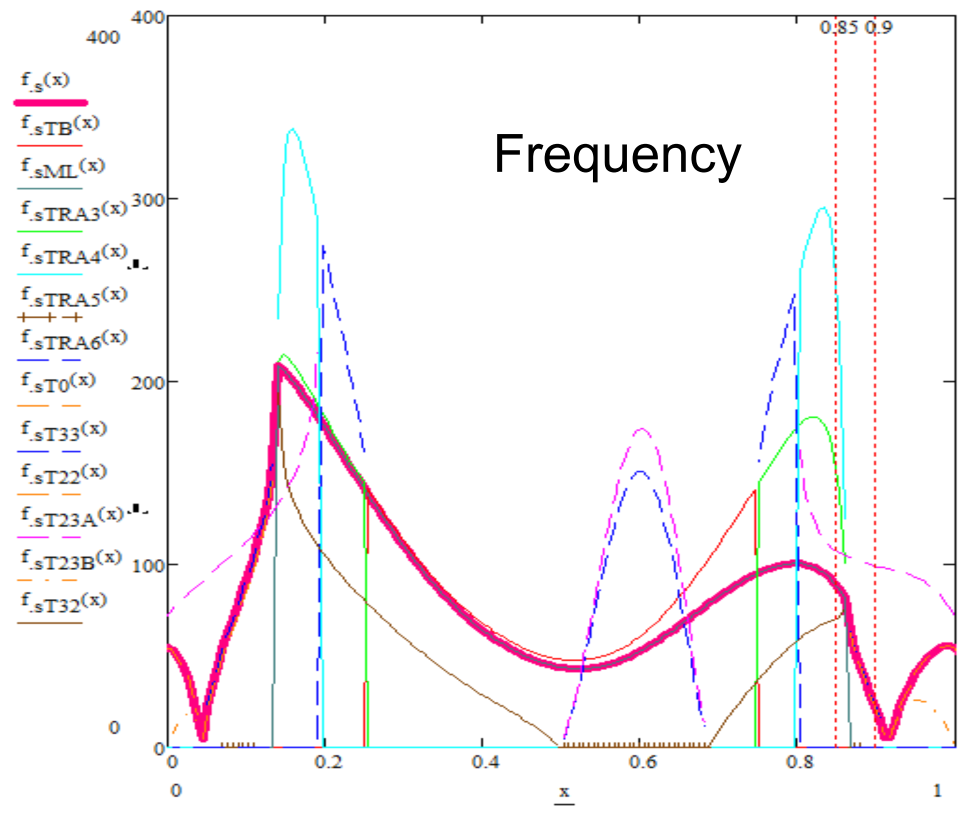


P_{diff_L} = 385W

P_{diff} facilitates the OPTIMIZATION of the power converter & architecture

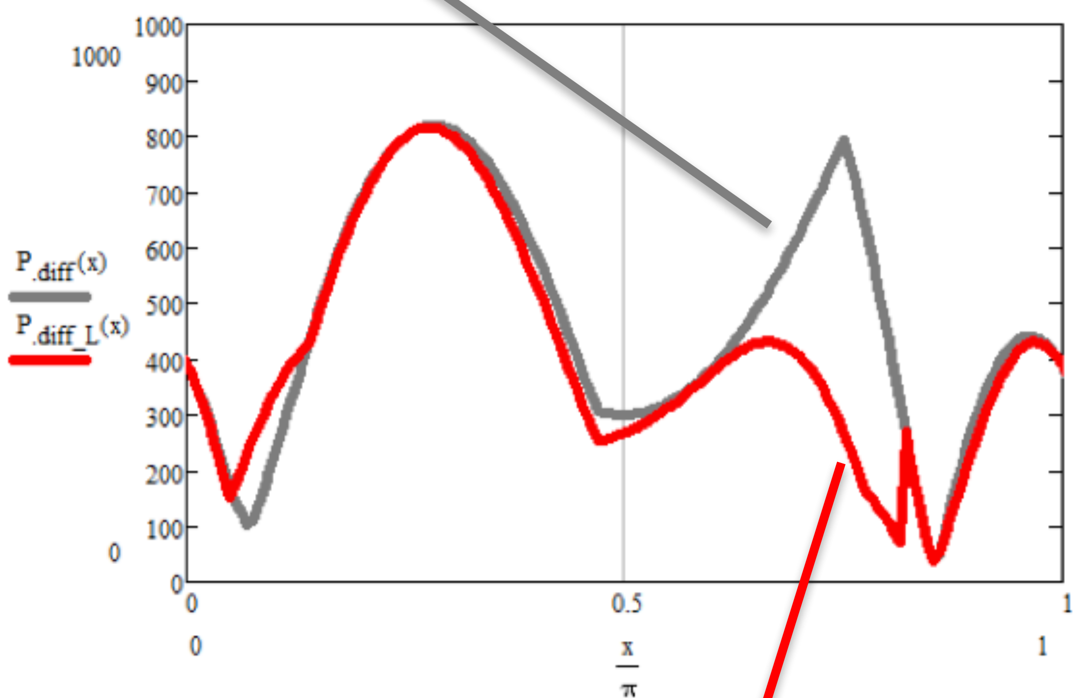
0.19 P_o

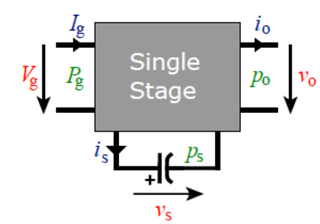




Theoretical P_{diff}

Single Stage

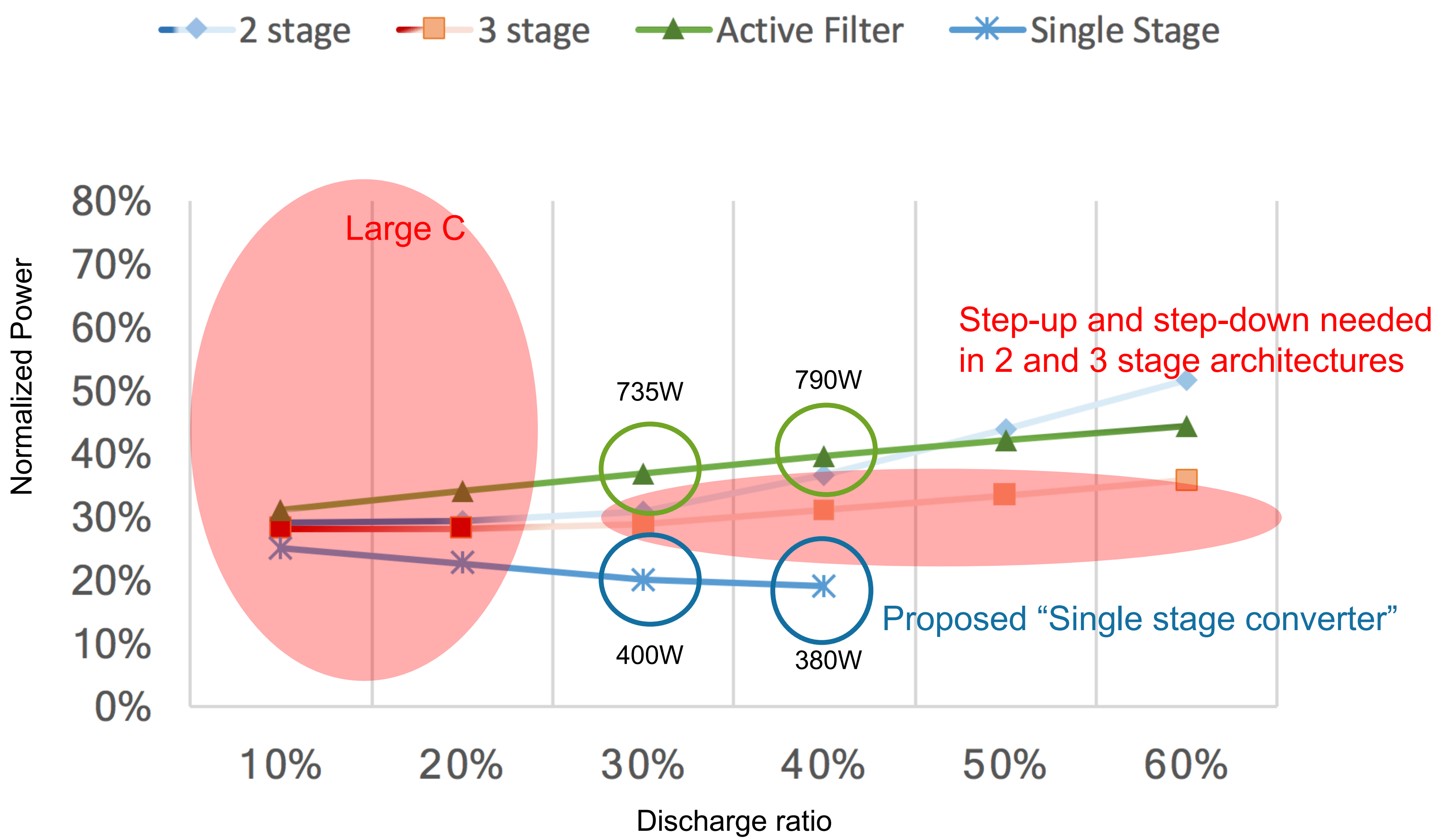




CEI-UPM converter

P_{diff_L} in the proposed converter

CEI@UPM team inverter



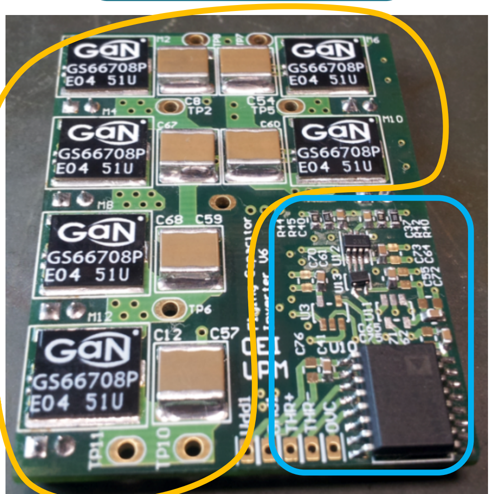
Internal power is HALF !!

"Google 1" prototype

2 x Phases

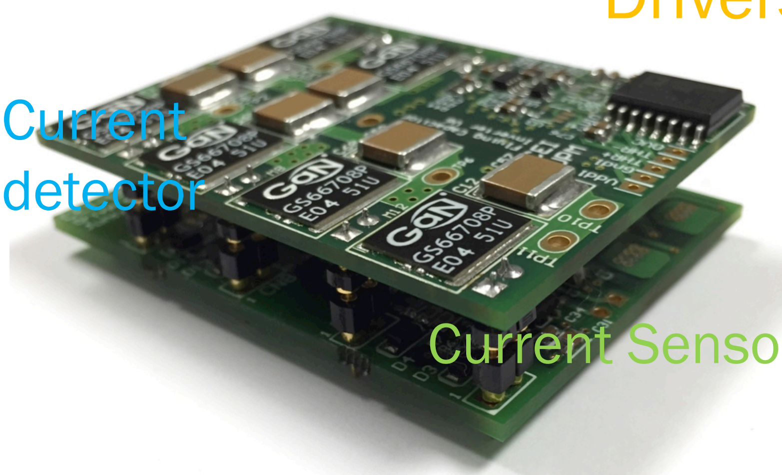
Power stage

Drivers



MOSFET

Current detector

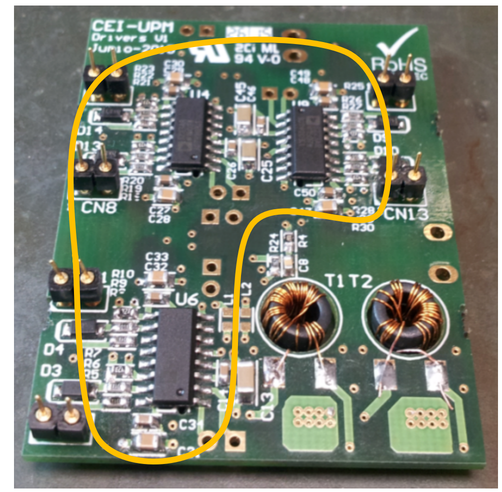


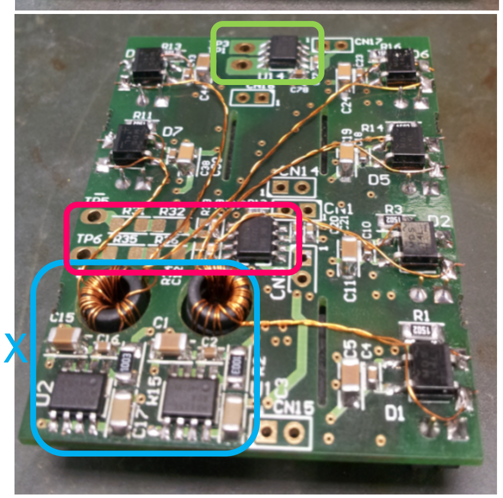
Drivers

Current Sensor

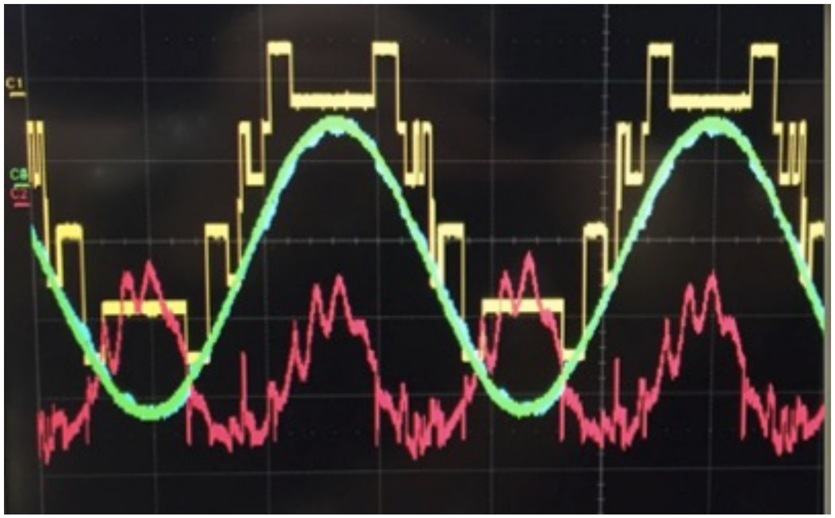
Voltage sensor

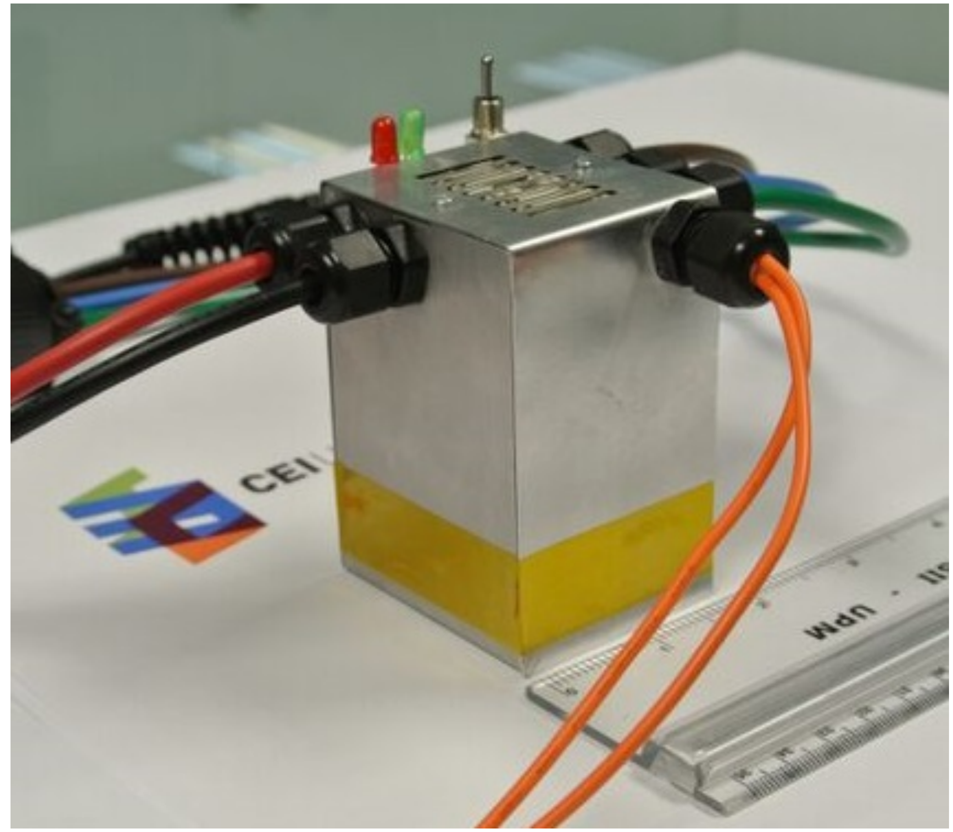
Vaux





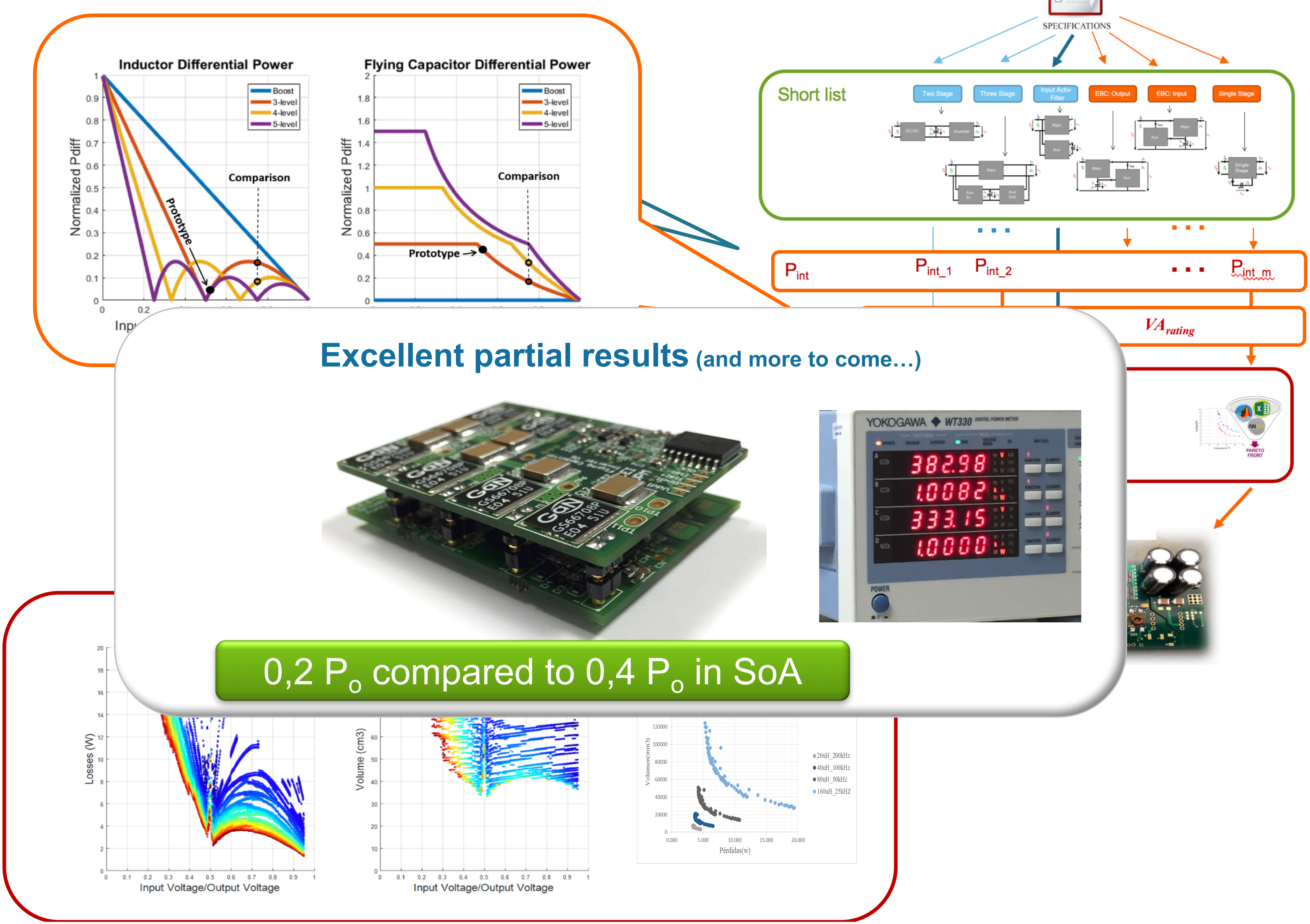
Partial Results





2kW
16W loss
(only one mode)
Efficiency: 99,2%
12,9 in3
Tmáx = 55,5ºC

- **High-level metric**
  to compare power architectures



… enables Energy Efficiency