DAB Converter Design Using Scaling Laws

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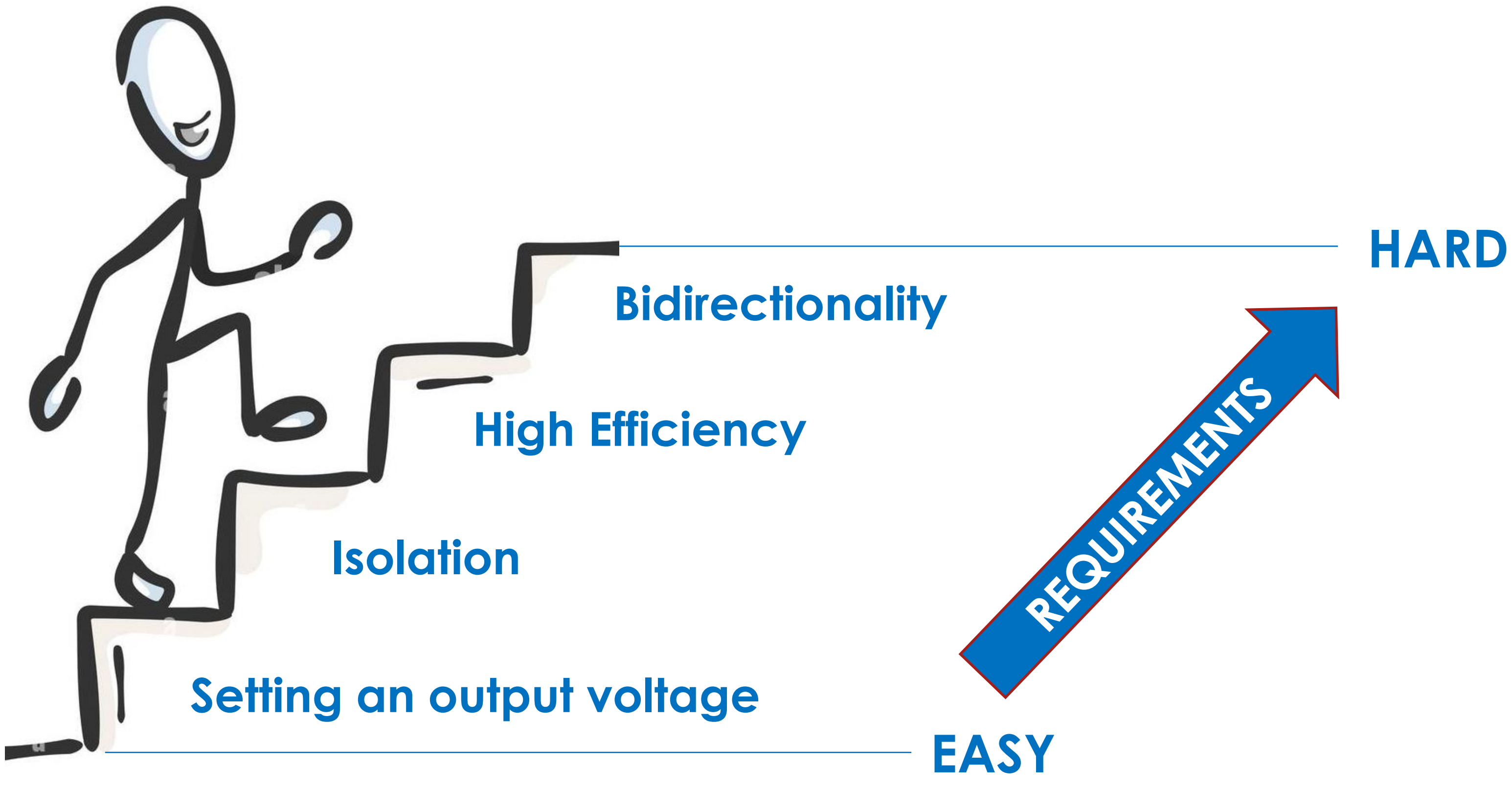
September 22, 2022
10 am California time
7 pm Italian time

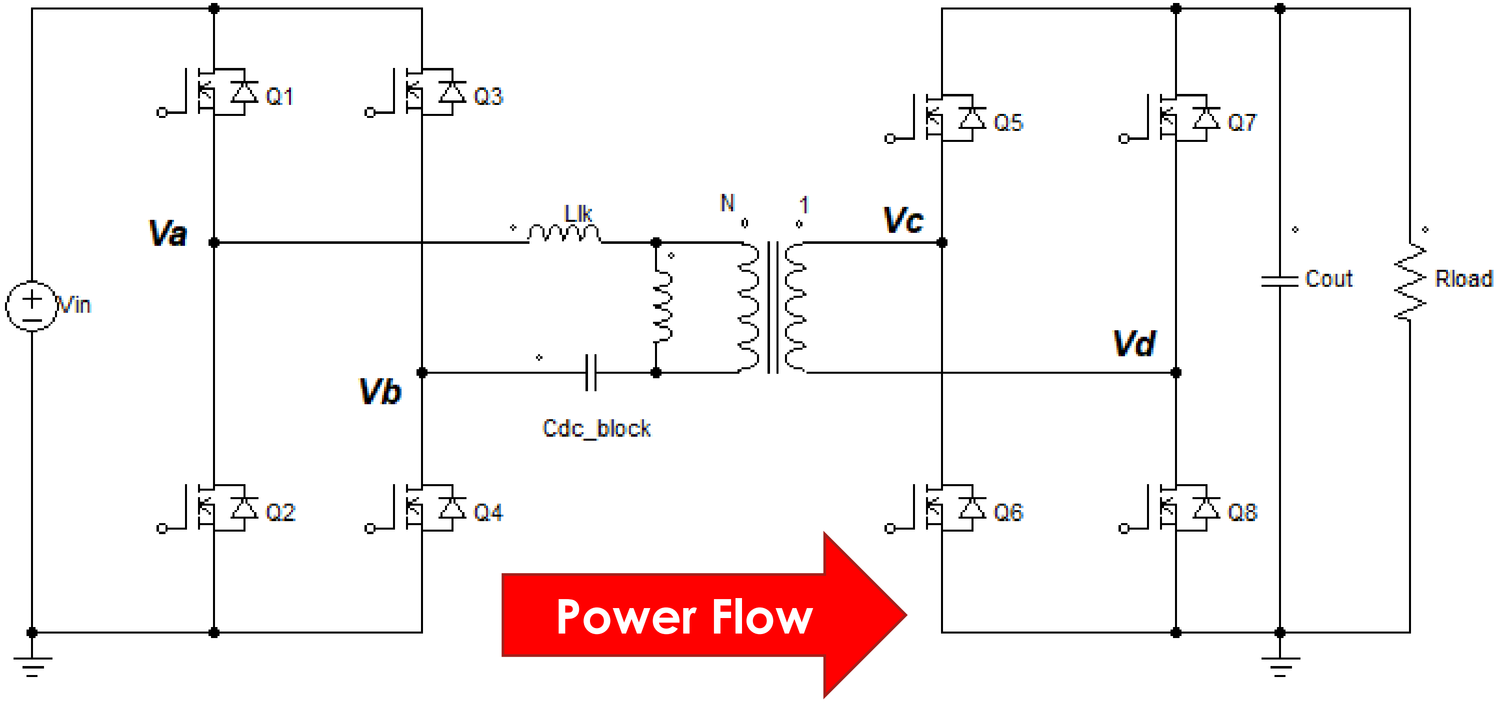
Why Another Topology?



What is the meaning of DAB?

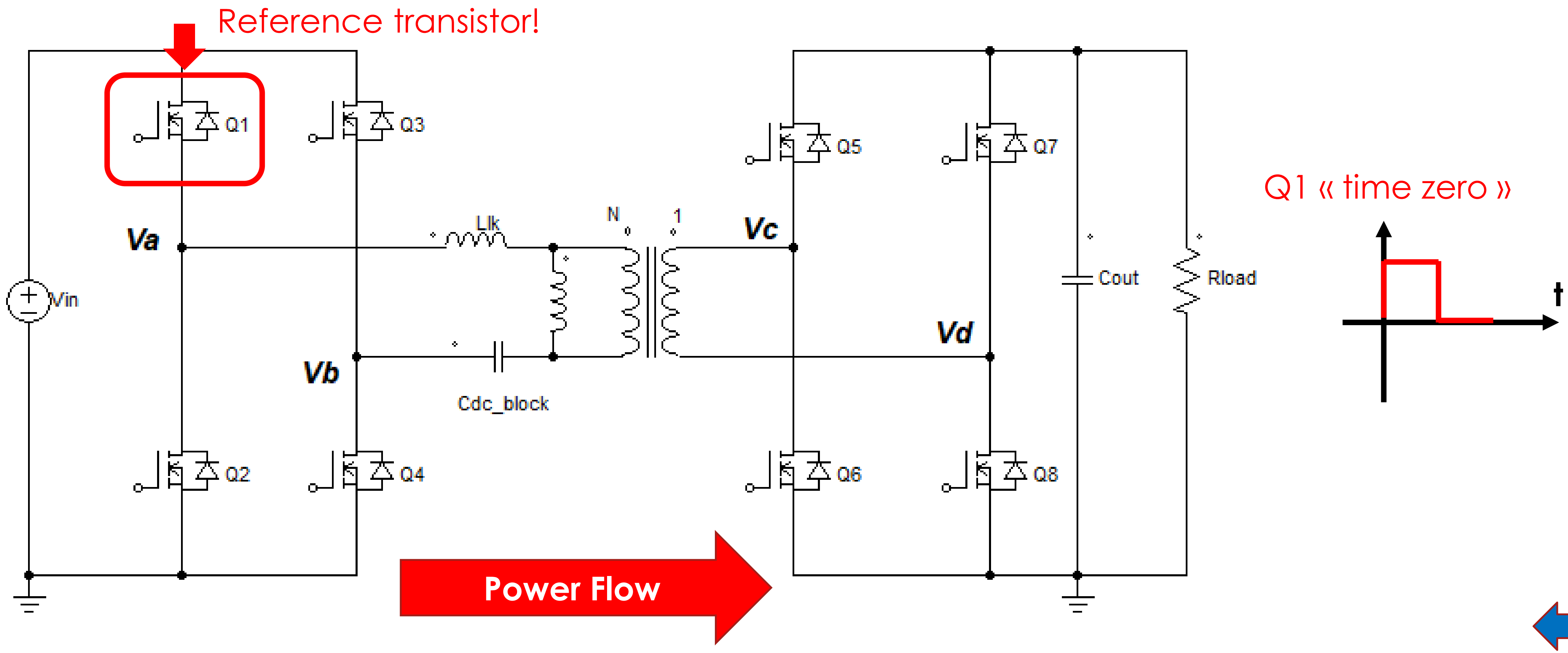
- « DAB » means **D**ual **A**ctive **B**ridge and identifies an isolated power stage topology in which you can identify two Full Bridges.

- Both bridges are intended to be Active and each power switch is turned ON and OFF according the designer's needs. The primary bridge acts as inverter, the secondary one acts as rectifier. Vice versa if we reverse the power flow.



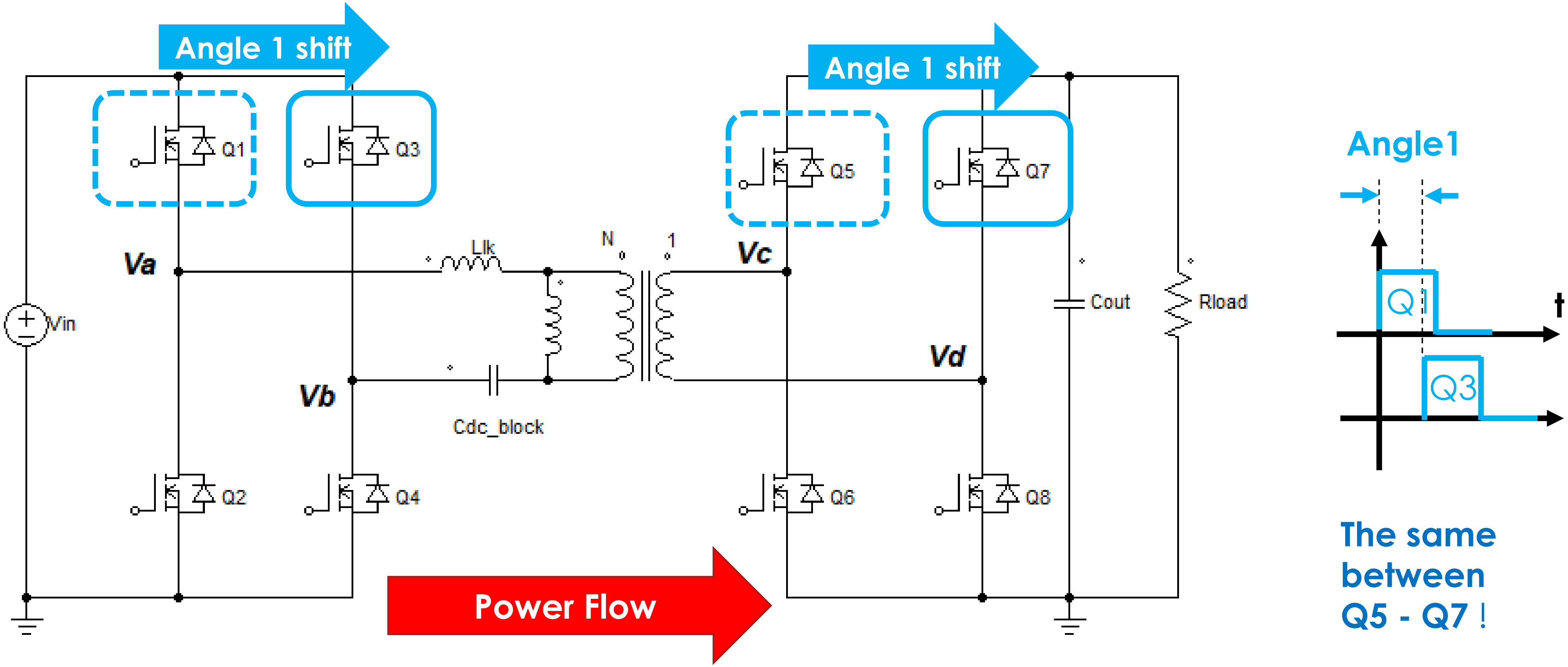
Assumptions

1. All switches have the same switching frequency
2. All switches modulation angles are Q1 referenced



Assumptions

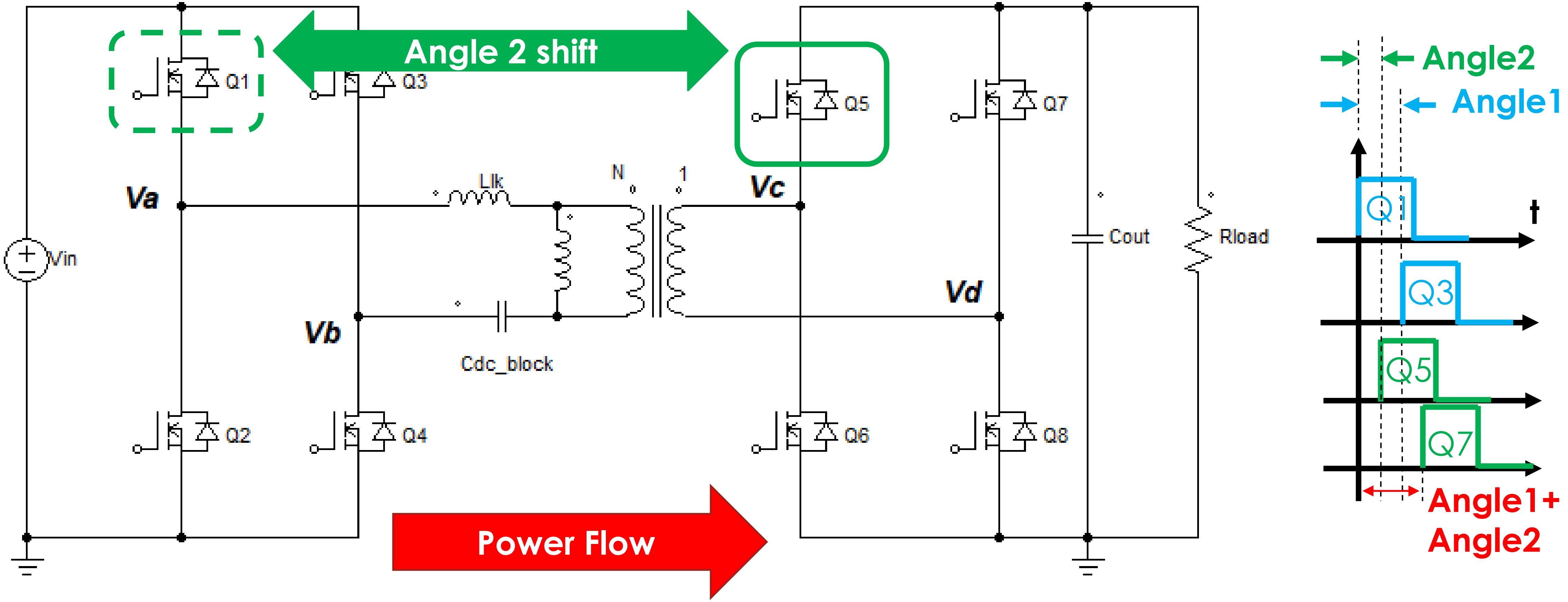
3. The lag between the two high side FETs is D1 × π (radians), and since D1 can be maximum 1, the maximum shift is π radians or 180°. **D1** thus corresponds to what we may refer alternately to as "**Angle 1**", or "**intra-bridge angle**"



The same between Q5 - Q7 !

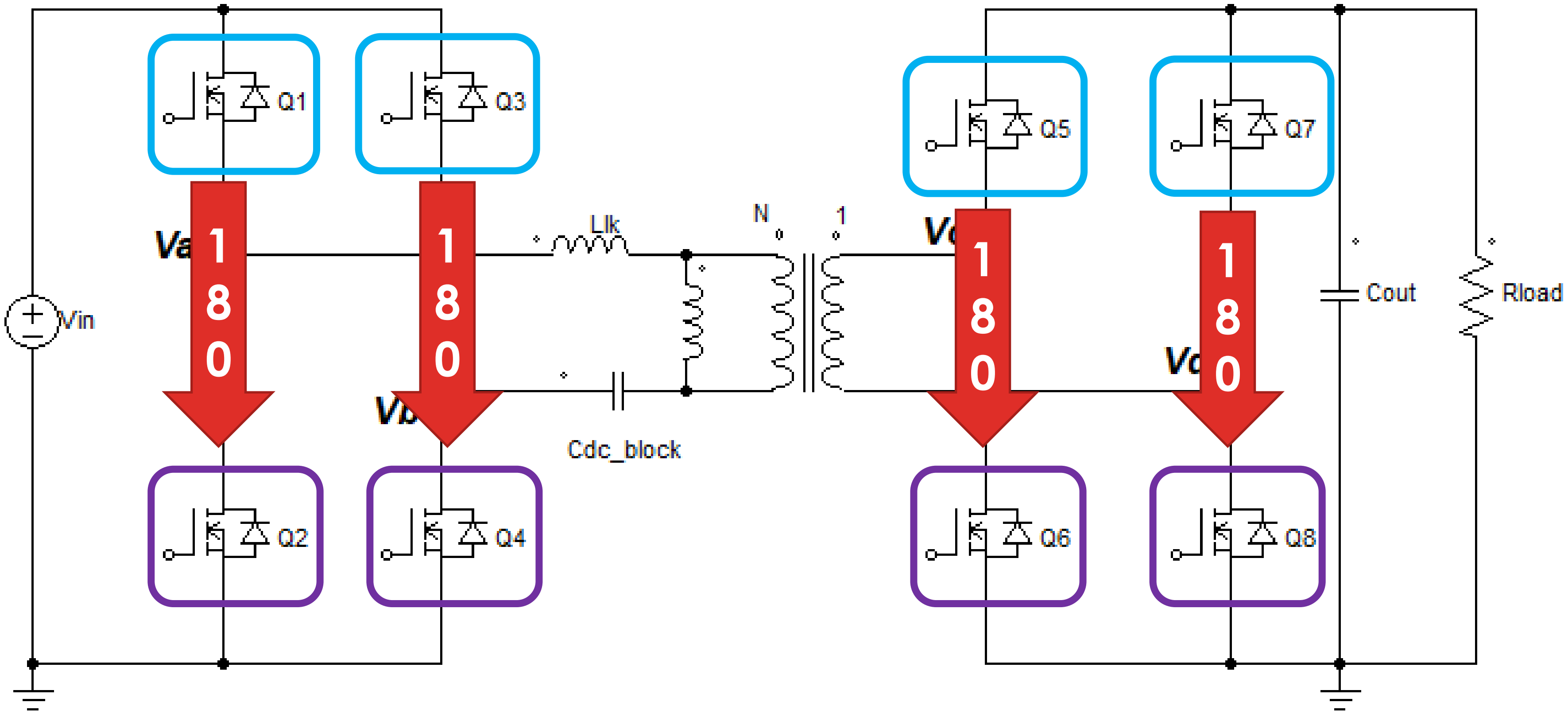
Assumptions

4. Similarly, the lag between Q1 and Q5 is D2 × π (radians). **D2** corresponds to what we may refer alternately to as "**Angle 2**", or "**inter-bridge angle**".



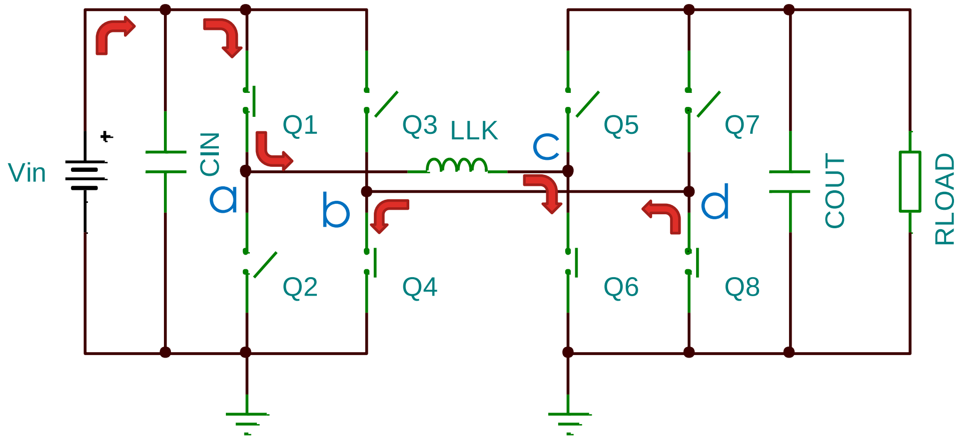
Assumptions

5. Each bottom switch is driven complementarily to its top switch to avoid Shoot-Through Current.

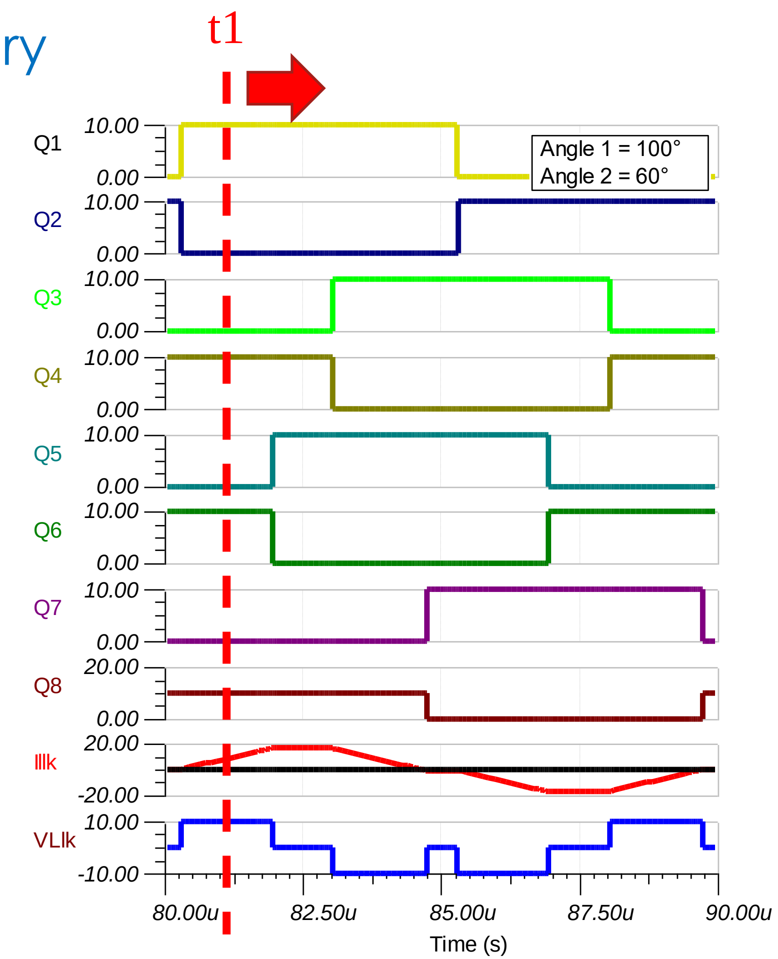


Timing: Step 1/4
Angle1 = 100°, Angle2 = 60°, gain = 1 (8 intervals worst case)

- Removing C_dc_block and Lmag: not relevant for the analysis
- Remove the transformer: it's just a scaling factor
- Q1,Q6,Q8,Q4 ON → Circulating current on the secondary
- No power delivered to the load

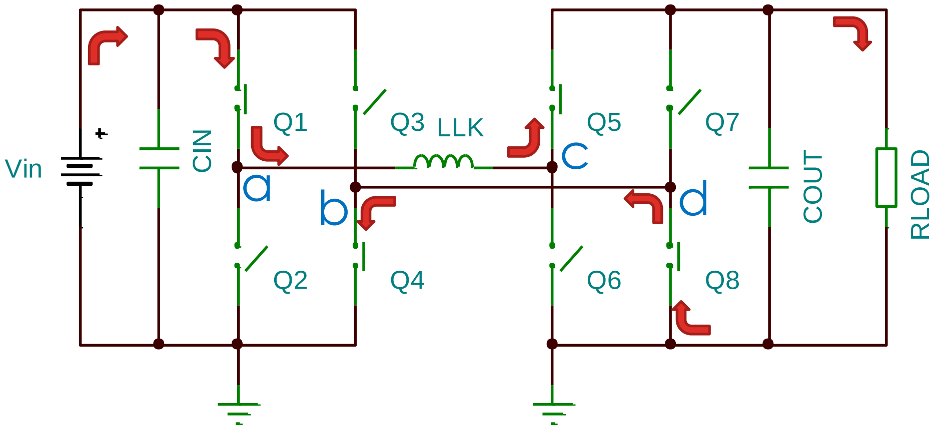


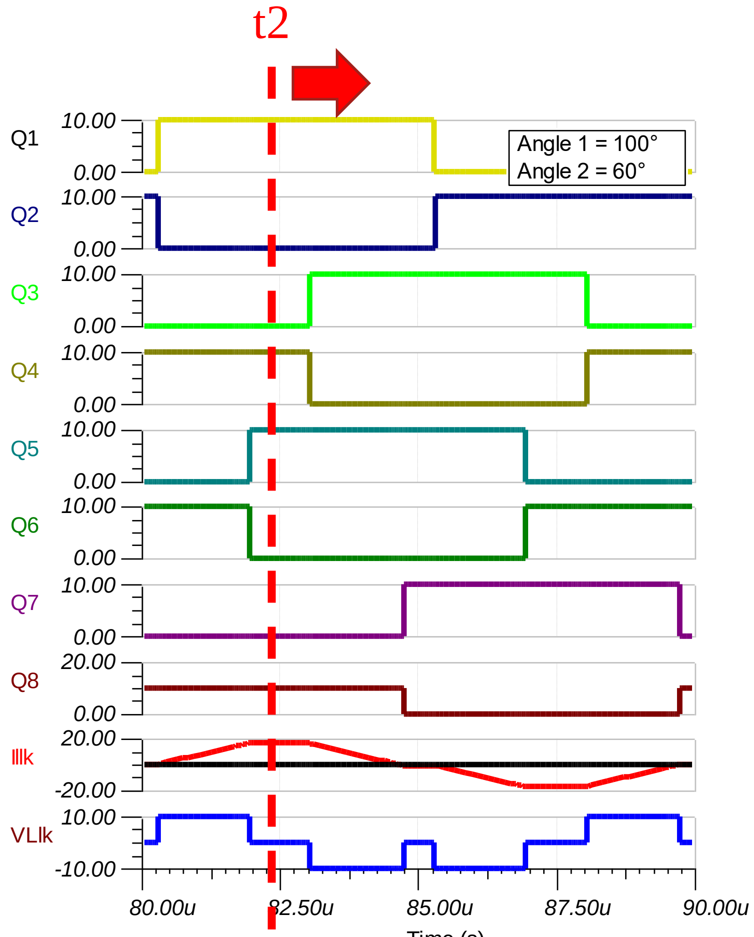
$$V_{Llk} = V_p - V_s = V_a - V_b - (V_c - V_d)$$



Timing: Step 2/4
Angle1 = 100°, Angle2 = 60°, gain = 1 (8 intervals worst case)

- Angle2 < Angle 1 → Q5 (Angle 2) closes first than Q3 (Angle 1)
- Q6 moves complementary to Q5
- Power delivered to the load

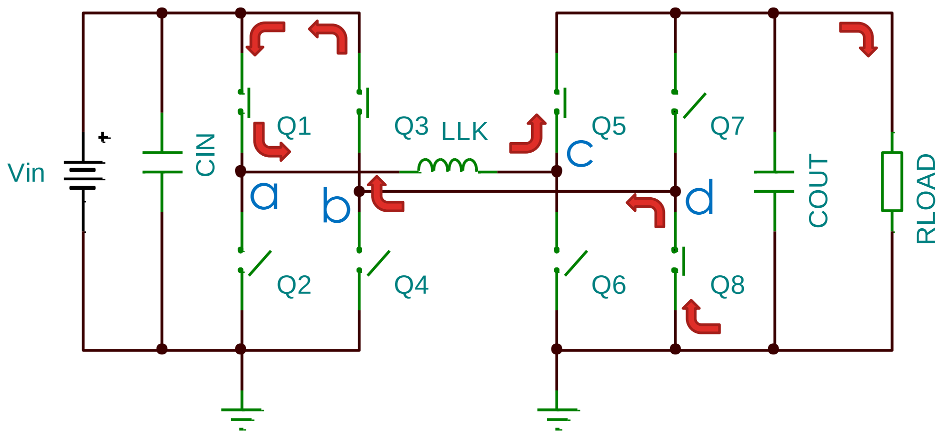




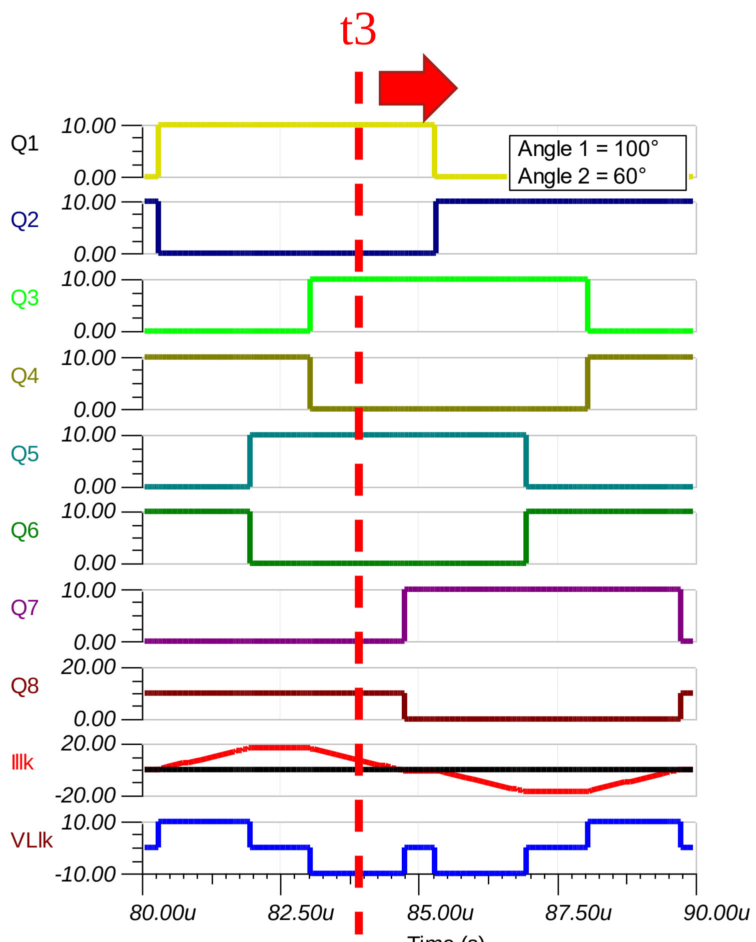
$$V_{Llk} = V_p - V_s = V_a - V_b - (V_c - V_d)$$

Timing: Step 3/4
Angle1 = 100°, Angle2 = 60°, gain = 1 (8 intervals worst case)

- Q3 (Angle 1) closes after than Q5 (Angle 2)
- Q4 moves complementary to Q3
- Circulating current on the primary
- Power delivered to the load

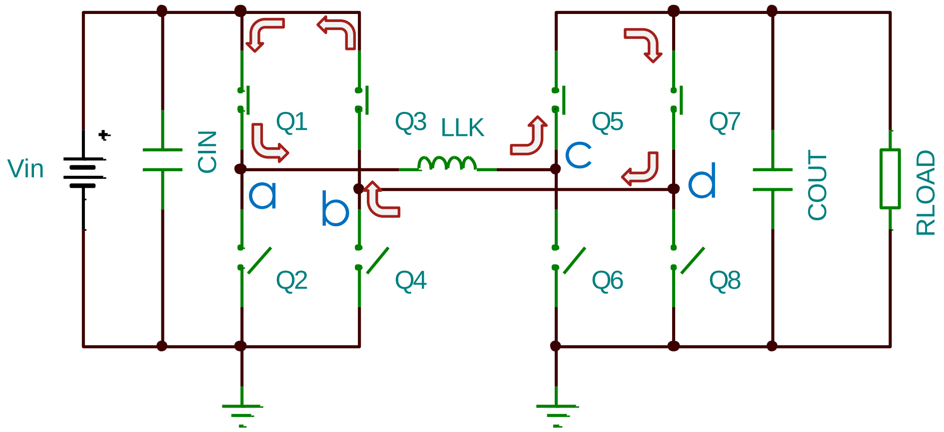


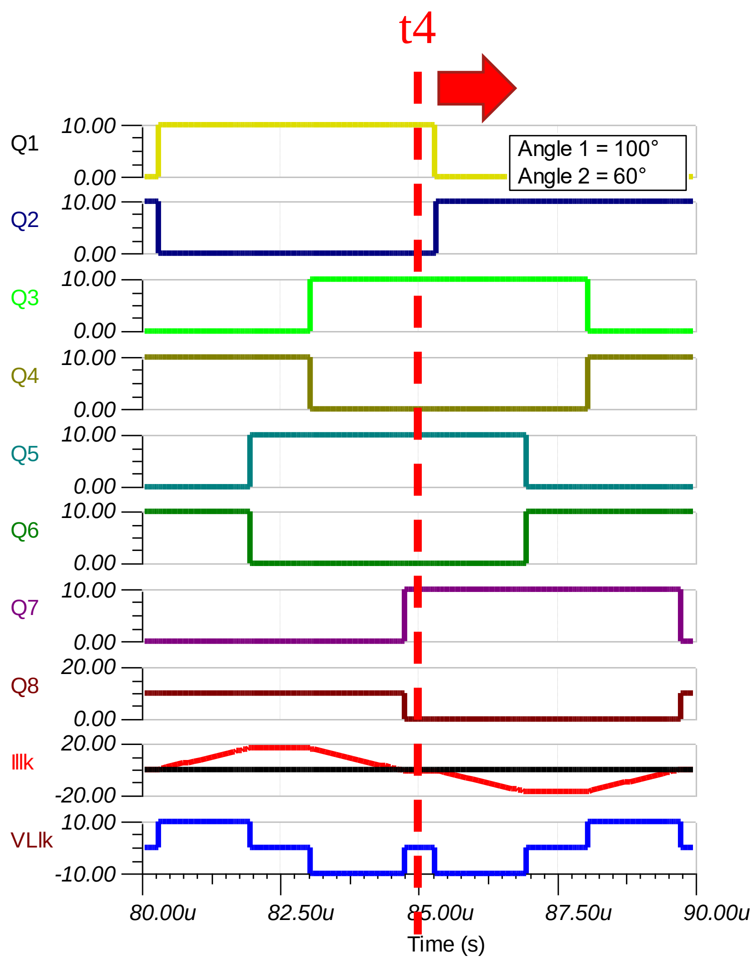
$$V_{Llk} = V_p - V_s = V_a - V_b - (V_c - V_d)$$



Timing: Step 4/4
Angle1 = 100°, Angle2 = 60°, gain = 1 (8 intervals worst case)

- Q7 (Angle 1+Angle 2) closes after than Q3 (Angle 1)
- Q8 moves complementary to Q7
- Fully “circulating” (zero) current
- No power delivered to the load





- **Complementary 4 cycles start later!**
- **The leakage current becomes negative**
- **worst case: 8 segments Leakage Voltage**

A unique DAB design approach

- Study a kernel with random values
- Apply Maniktala's scaling laws and use Rosano's graphical curves

Targets:

- Soft Switching
- Lower RMS currents possible
- Optimal Power shape

Design:

- Leakage inductance
- Turn ratio
- Output capacitance
- DC blocking capacitance (optional)
- Angle 1 and Angle 2 selection

Definitions:

- V_{or} is the ouput voltage reflected on the transformer primary side
- V_{in} is the input bus voltage
- $Gain = \frac{V_{or}}{V_{in}}$, ratio between Llk amplitude voltage extrema
- Do not confuse the «gain» with the transformer turn ratio
  $N = \frac{N_p}{N_s} = \frac{V_{or}}{V_{sec}} = \frac{V_{in} \cdot gain}{V_{out}}$

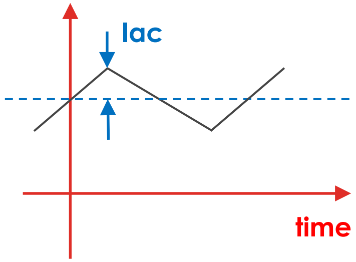
The Scaling laws: « three is a magic number! »

Pointed out by S. Maniktala

- To double the power at a certain frequency (keeping all else unchanged such as the phase angles), we need to halve the inductance and double the capacitance.

- To double the frequency, keeping the same power, once again we just need to halve the inductance and halve the capacitance. Recalling the buck converter equations.

$$L = \frac{V_{out} \cdot (1-D)}{r \cdot f_{sw} \cdot I_{out}} \qquad C = \frac{I_{out} \cdot r}{8 \cdot f_{sw} \cdot \Delta V} \qquad r = \frac{2 \cdot I_{ac}}{I_{dc}}$$



- **Added guest to the party: If we double the input voltage, we will quadruple the power. Proof below:**

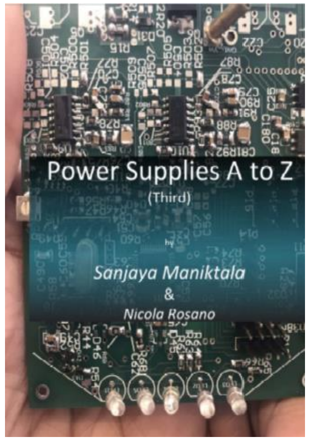
If:

$$\blacktriangleright P_{out} \cong P_{in}$$
$$\blacktriangleright V_{out} = TF_{dc} \cdot V_{in}$$

then:

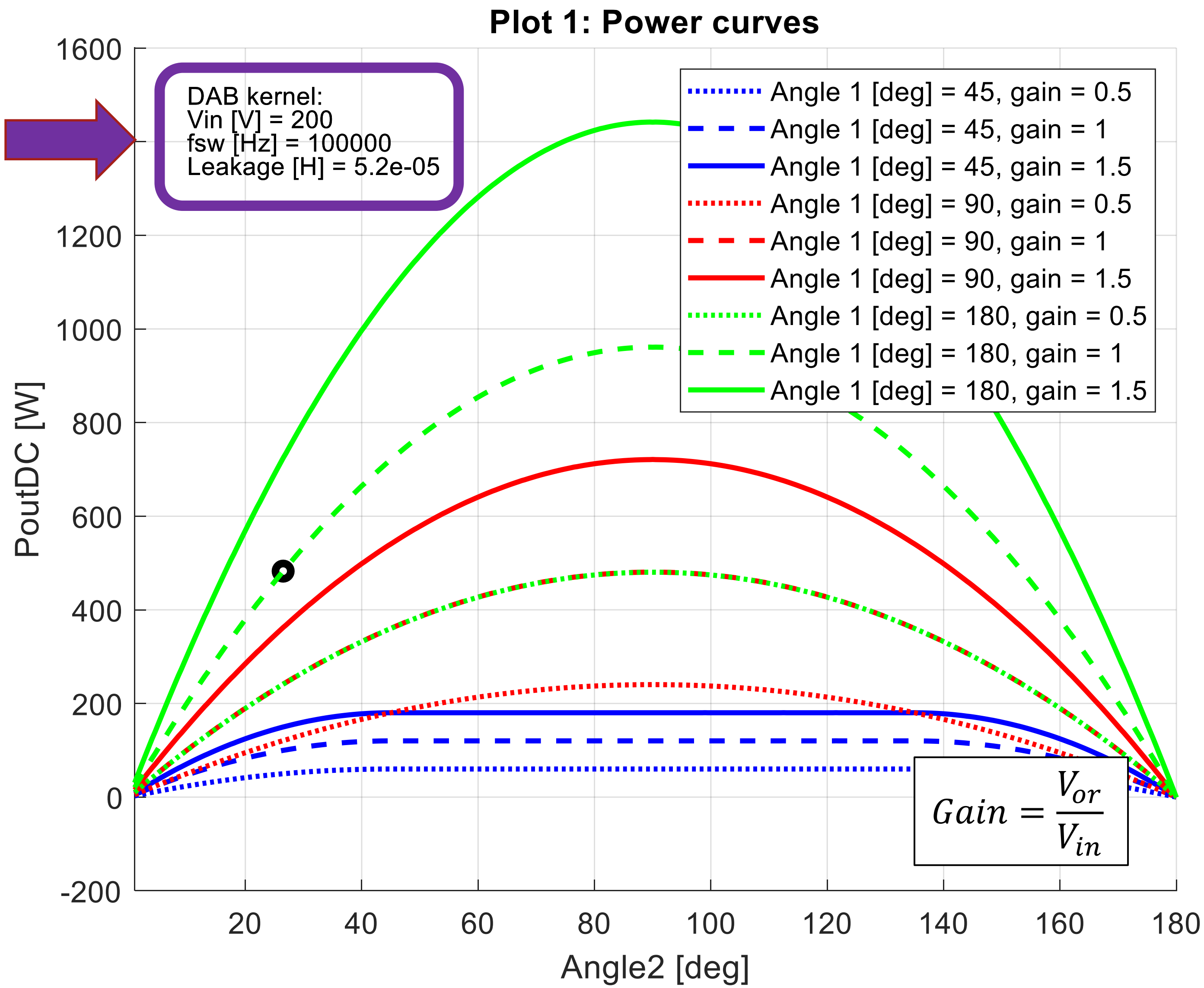
$$\blacktriangleright P_{out} = \frac{V_{out}^2}{R_{load}} = \frac{(TF_{dc} \cdot V_{in})^2}{R_{load}}$$

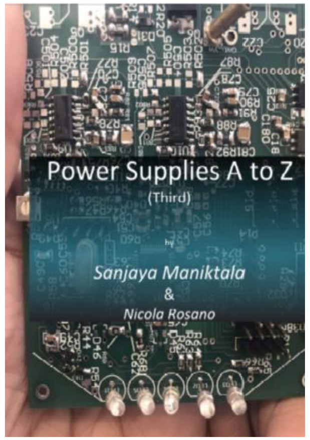
If Vin doubles, to keep the equation valid, the power shall quadruple!



Click me!

The DAB kernel
Plot 1: The power curves





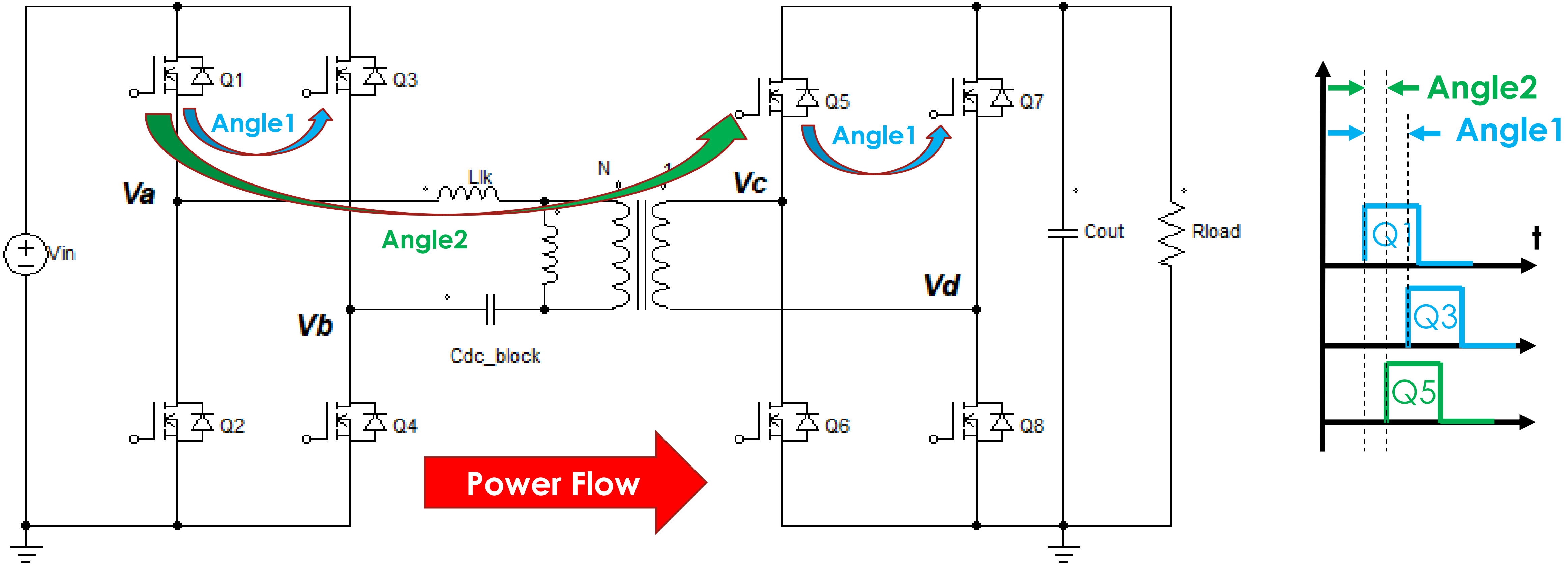
Click me!

The DAB kernel
Plot 1: The power curves. What else does this imply?

- According to the plot 1 we set D1 > D2 **(Always!)**.

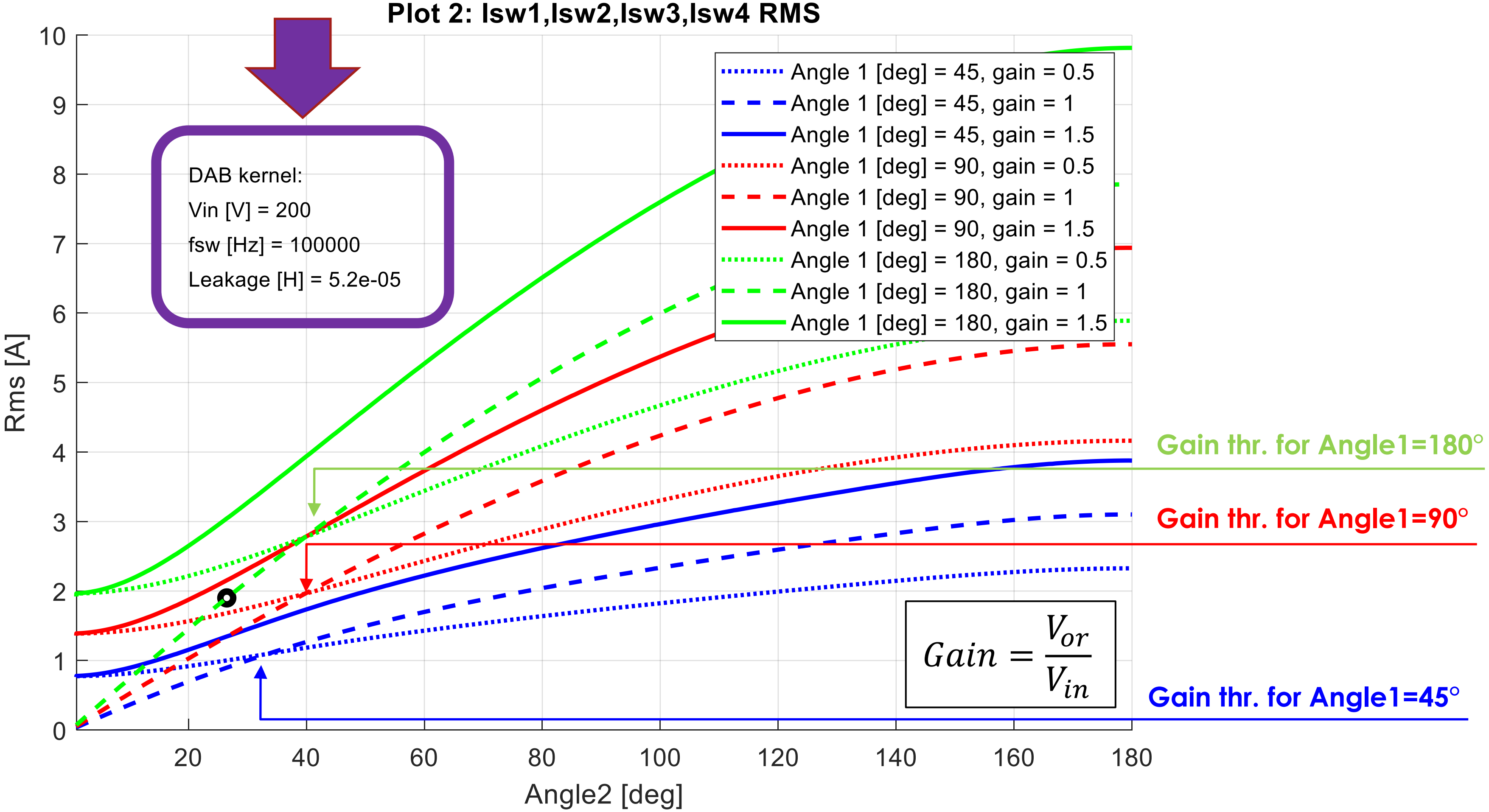
Primary Bridge:
I have more power than you,
check the previous plot 1

Secondary Bridge:
The power is null without contol
so actually I have « more power »
than you!



The DAB kernel
Plot 2: RMS values

- Locking the gain, the more Angle 1 or Angle 2 increases, the more the RMS values increases.
- Locking Angle 1 or Angle 2, the more the gain increases, the more the RMS values **… increase or decrease?**



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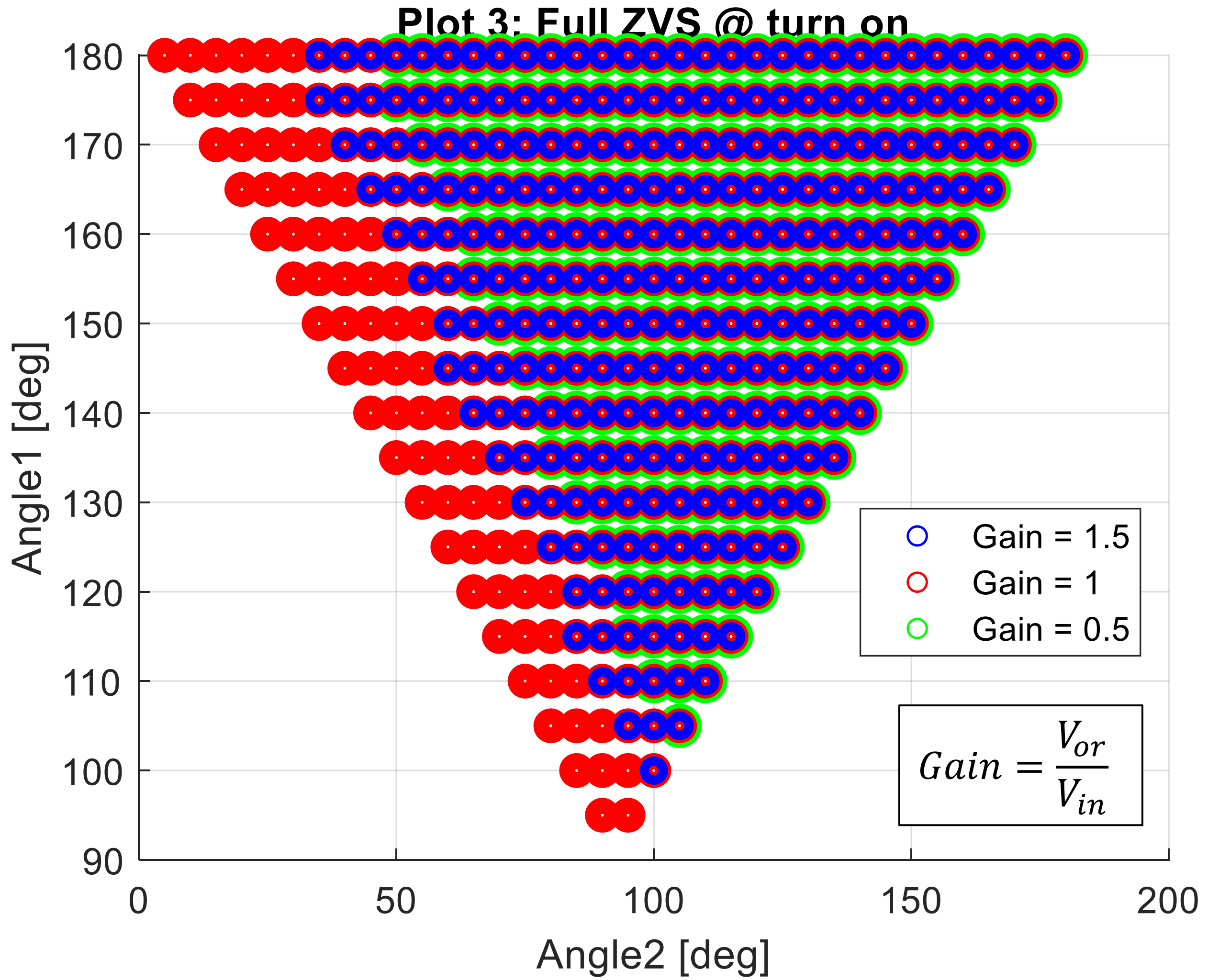
The DAB kernel
Plot 3: ZVS @ turn on

- Gain = 1 enables a greater ZVS area respect the other gain conditions



Never Published

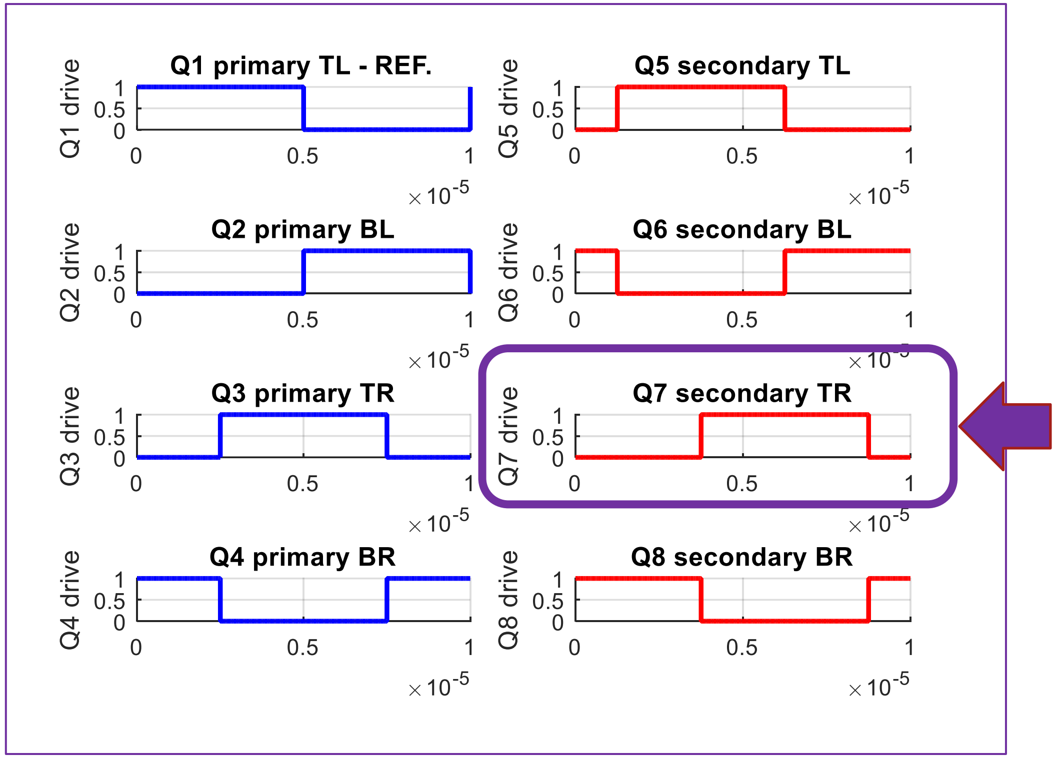
Real time video

The DAB kernel
Subcases

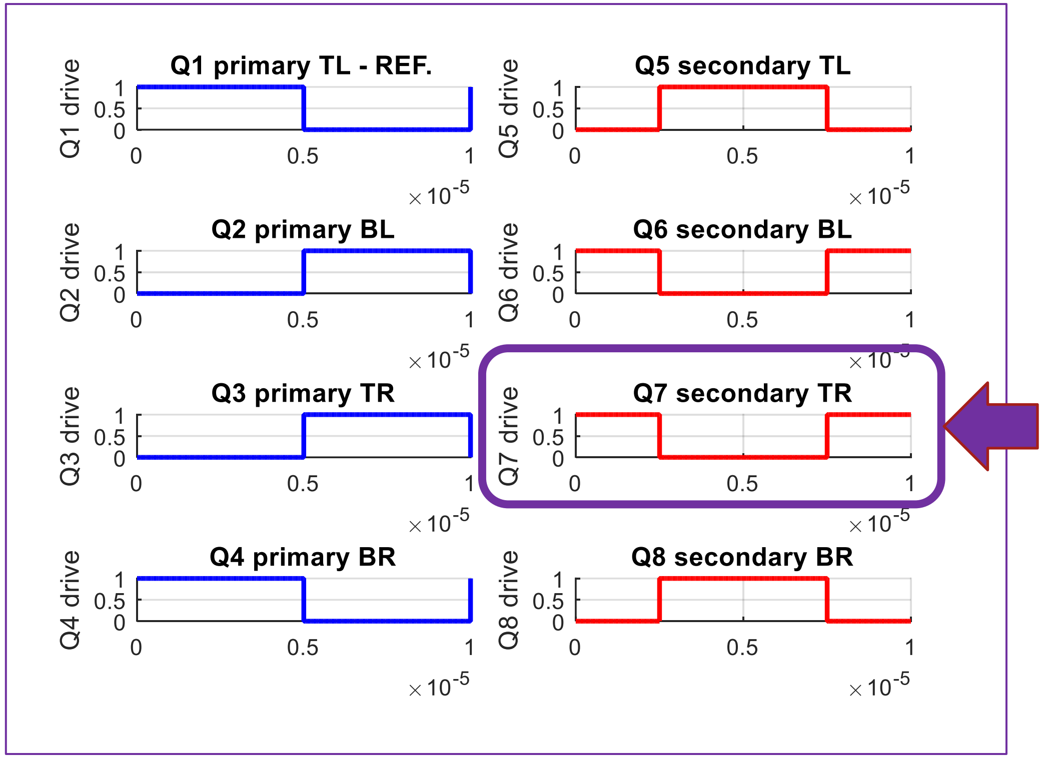
Question for you:
Which one is better?

- D1 > D2 : subcases

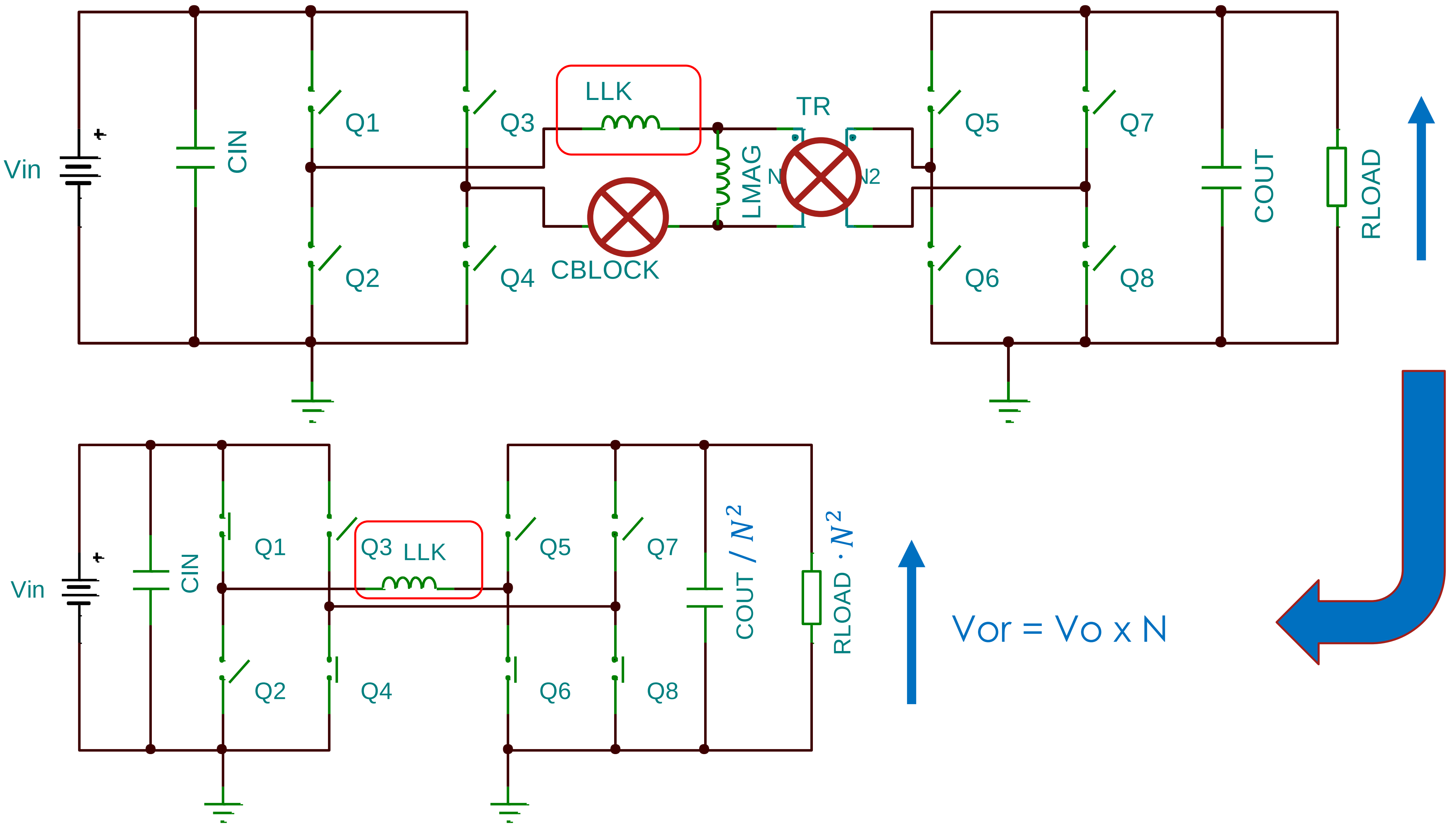
D1+D2 < 1 (or < 180°)
Example: Angle 1 = 90°, Angle 2=45



D1+D2 > 1 (or >180°)
Example: Angle 1 = 180°, Angle 2 = 90°



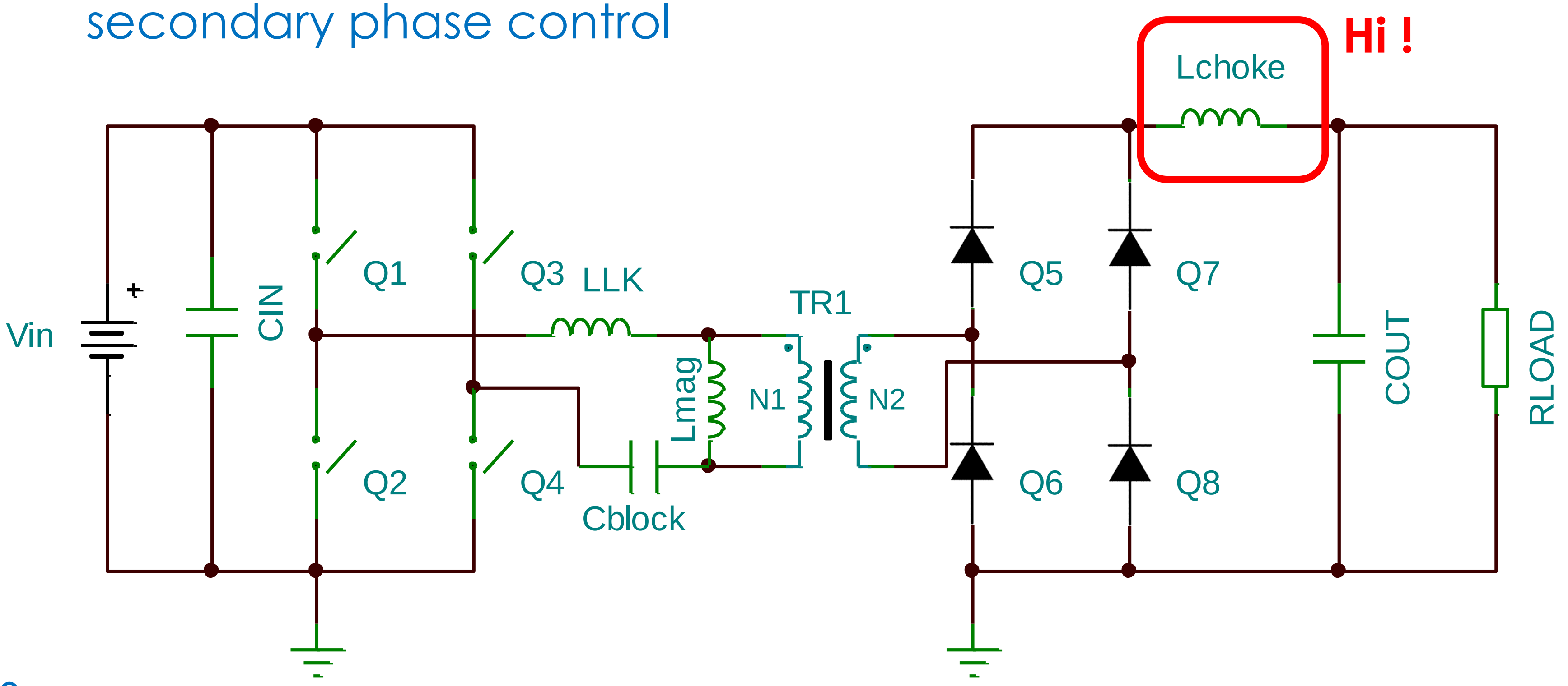
The Role of the Leakage Inductance "LLK"



The DAB is an evolution of the PSFB

PSFB features

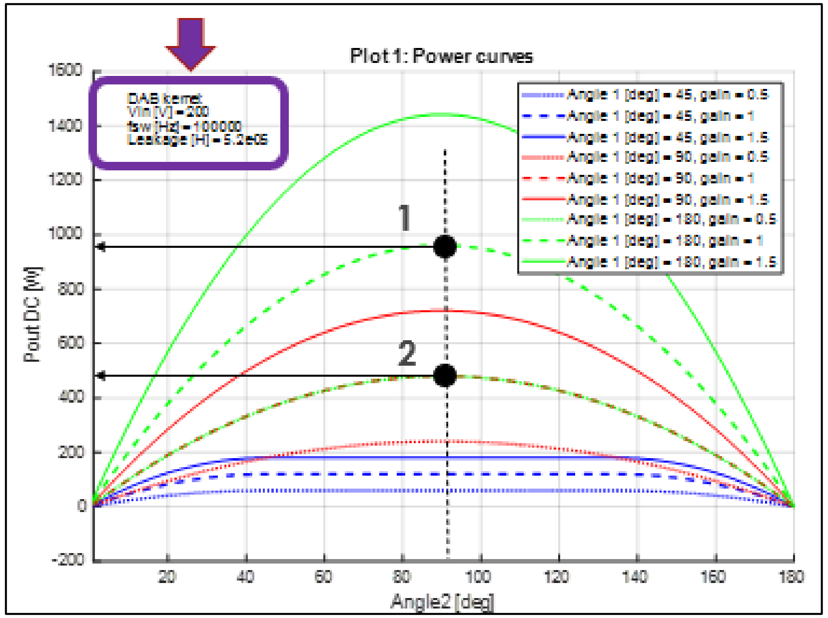
- Lower Leakage inductance to induce ZVS during the dead time
- high current on the secondary → $E = 0.5 \cdot L \cdot I^2$ → Large output inductor to control the power (like the classical Buck/Forward converter)
- All secondary Fets work synchronously only in respect to the primary → no secondary phase control

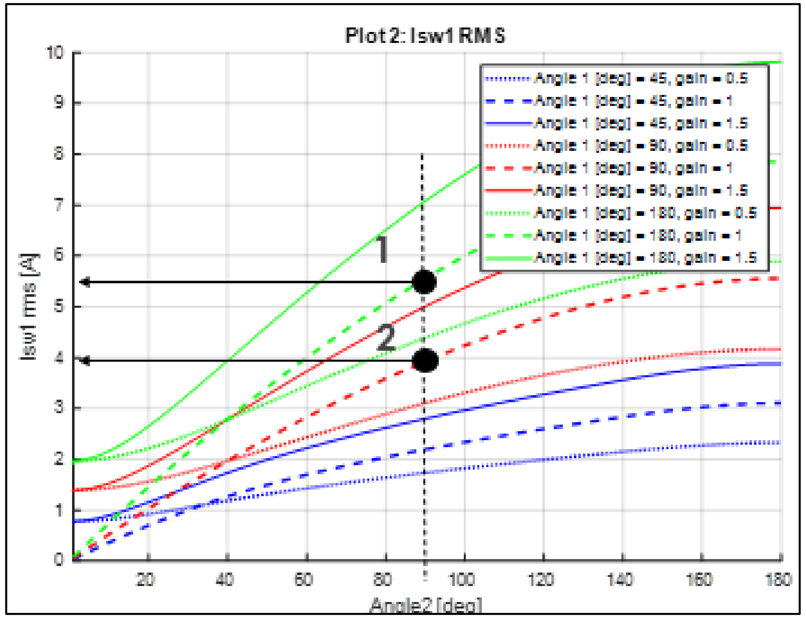


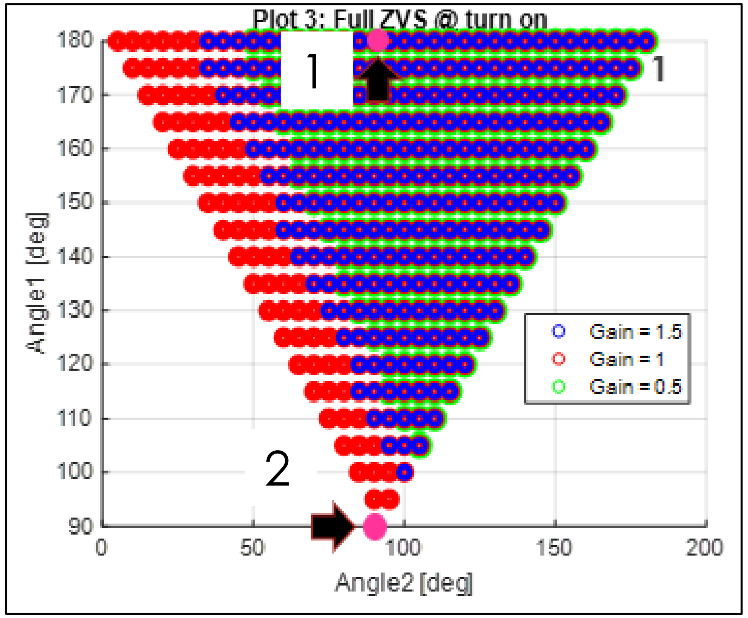
Lout absent in DAB and LLC

Testing the DAB kernel
Vin=200V; Vout=48V; fsw=100k; gain=1; Llk=52μH

	ANGLE 1	ANGLE 2	Pmax	Isw1 rms	ZVS
CASE 1	180	90	960	5,5	ALL
CASE 2	90	90	480	4	Not assured



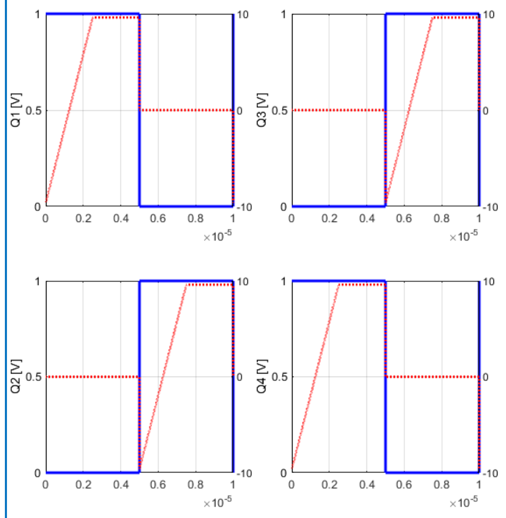




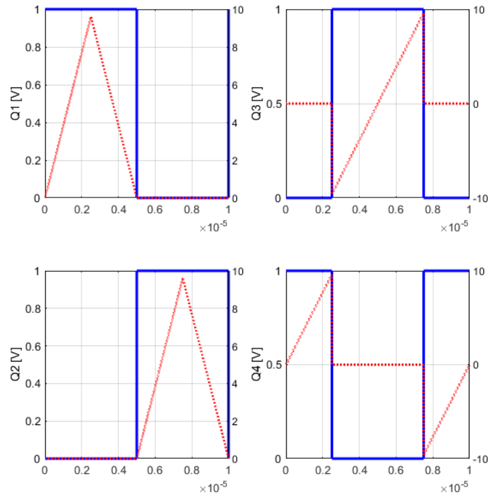
Testing the DAB kernel
Vin=200V; Vout=48V; fsw=100k; gain=1; Llk=52µH

	ANGLE 1	ANGLE 2	Pmax	Isw1 rms	ZVS
CASE 1	180	90	960	5,5	ALL
CASE 2	90	90	480	4	Yes Q3,Q4,Q5,Q6 Quasi Q1,Q2,Q7,Q8

Primary side

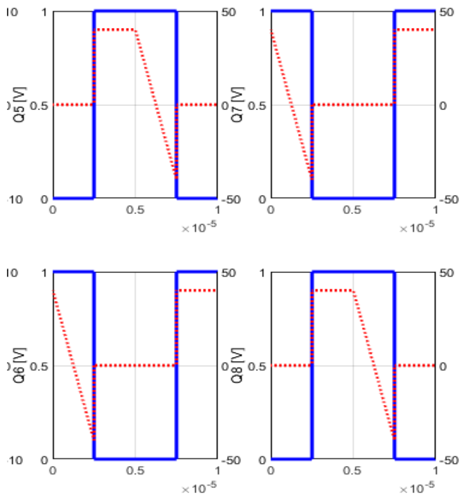


CASE 1

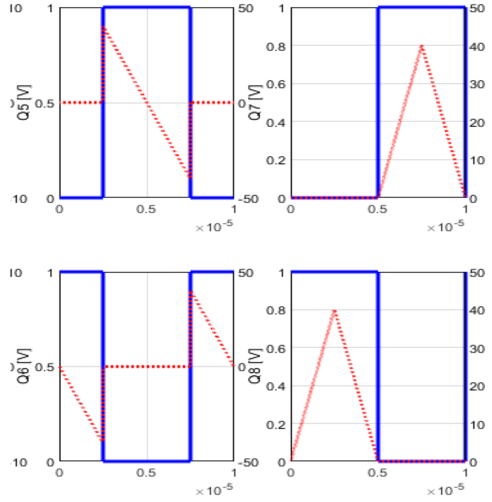


CASE 2

Secondary side



CASE 1

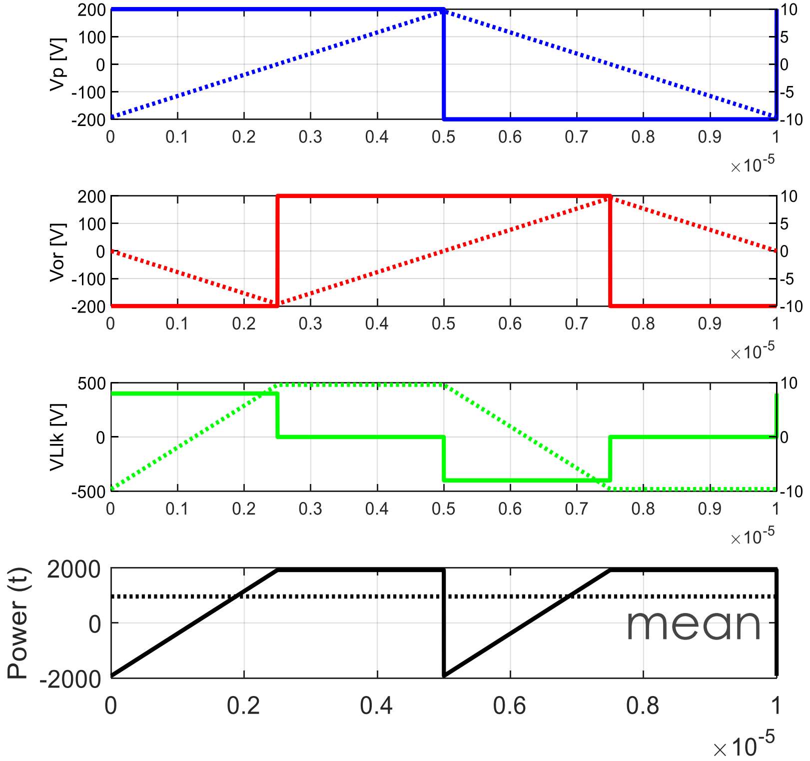


CASE 2

Testing the DAB kernel
Vin=200V; Vout=48V; fsw=100k; gain=1; Llk=52µH

	ANGLE 1	ANGLE 2	Pmax	Isw1 rms	ZVS
CASE 1	180	90	960	5,5	ALL
CASE 2	90	90	480	4	Yes Q3,Q4,Q5,Q6 Quasi Q1,Q2,Q7,Q8

CASE 1



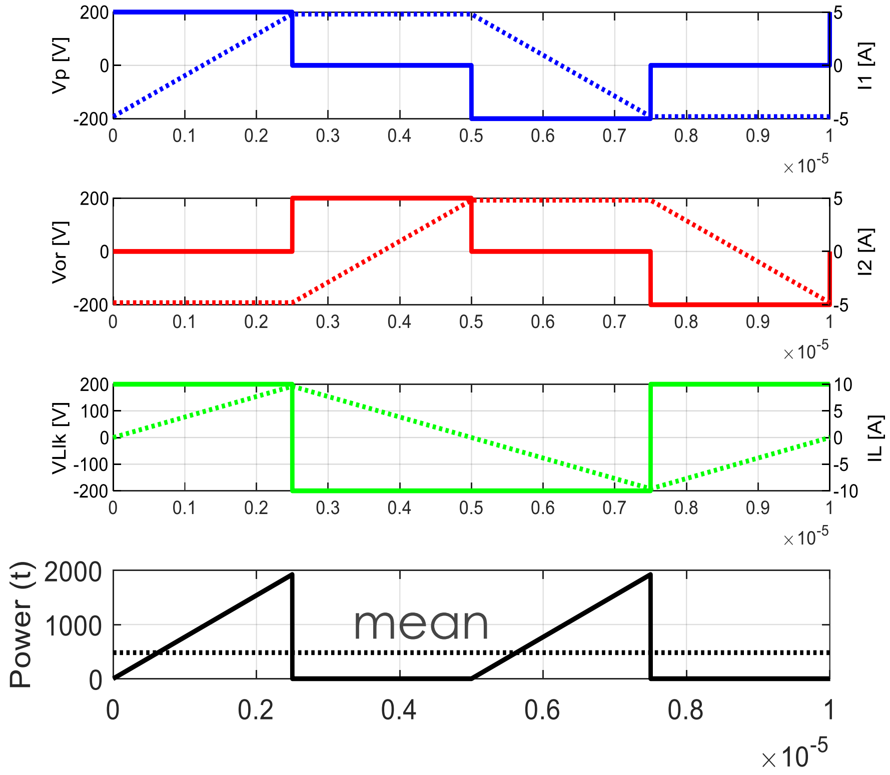
Vp,Ip

Vor,Ior

VLlk,ILlk

Power

CASE 2



Testing the DAB kernel
Vin=200V; Vout=48V; fsw=100k; gain=1; Llk=52μH

	ANGLE 1	ANGLE 2	Pmax	Isw1 rms	ZVS
CASE 1	180	90	960	5,5	ALL
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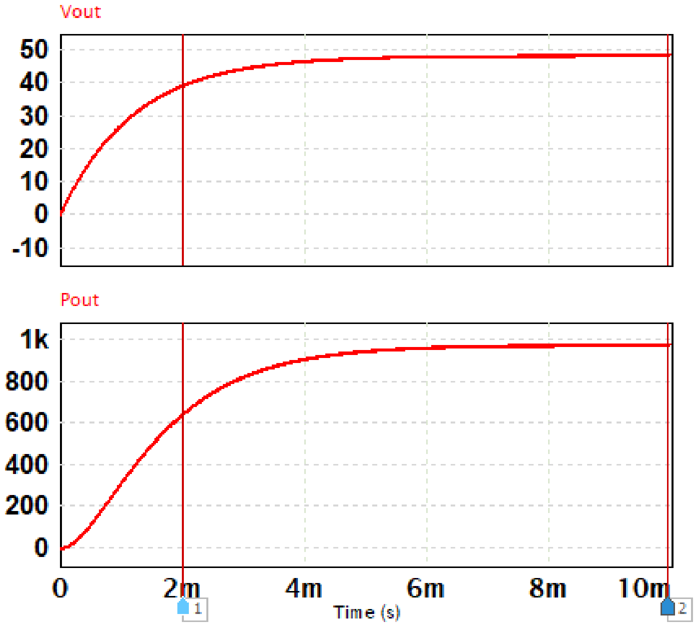
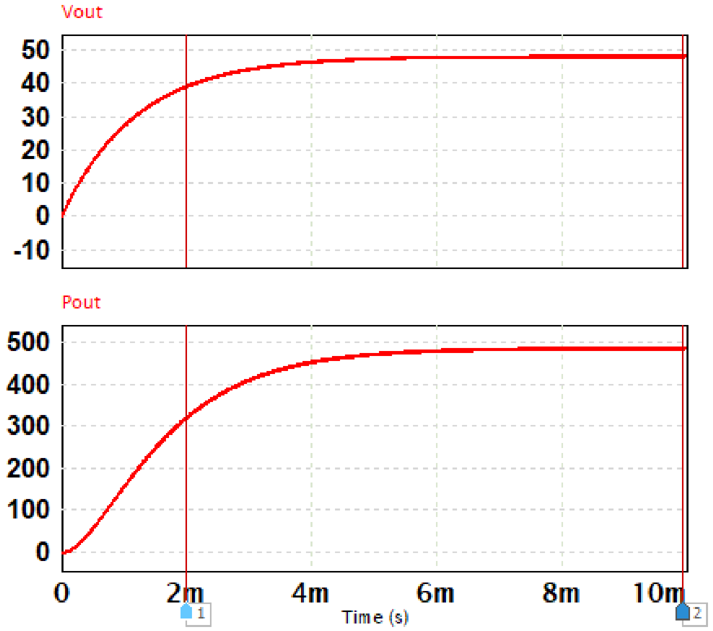
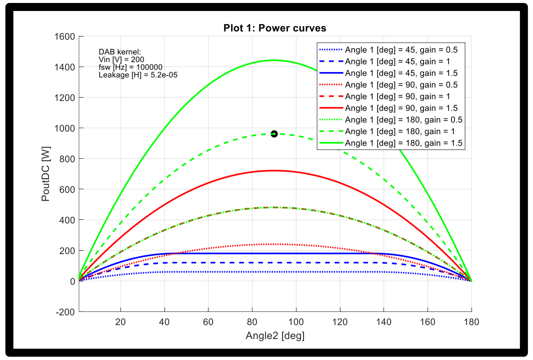
CASE 1



CASE 2



How to chose Angle 1 and Angle 2?



From Plot 1

- Select the Angle 1 to avoid flat zones once Angle 2 is called to increase.

Potential choices are Angle 1 = 90° or Angle 1 =180°

Notes:

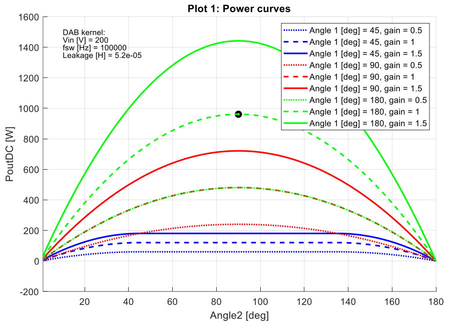
- If Angle 2 = 90° and Angle 1 = 180° we can deliver the maximum possible power from this kernel (see green curves)
- Also the more the power requirement P_{eff} is, the less the leakage inductance value is, the more the size is. In fact: $L_{lk\ eff} \propto \frac{1}{k_p} \rightarrow$ $but\ k_p = \frac{P_{eff}}{P_{kernel}}$
- Both bunch of curves at Angle 1 = 90° and Angle1=180° give a good power shape while offering a different leakage inductance once the baseline kernel power is set. **Angle1=180° could win because it is able to deliver more power while Angle 1= 90° could win because it is able to offer lower RMS current as we will see.**

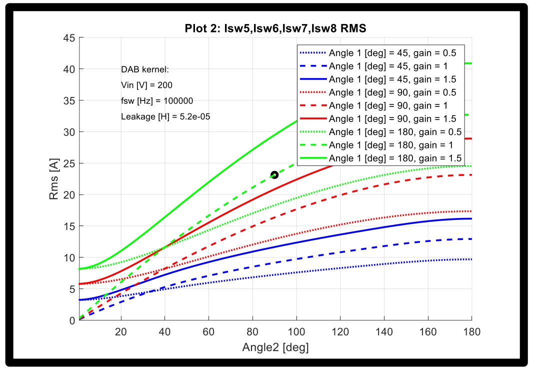
Takeaway

From Plot 1

- **Angle 1 = 90° or Angle 1 =180°**

How to chose Angle 1 and Angle 2?





From Plot 2

- Locking Angle 1, if Angle 2 increases then RMS current increases
- Locking Angle 2, if Angle 1 increases then RMS current increases (working point assumed to be on the right side of the gain threshold)

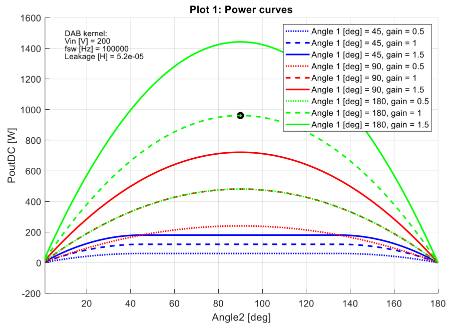
Potential choice is Angle 1 = 90 (low RMS)

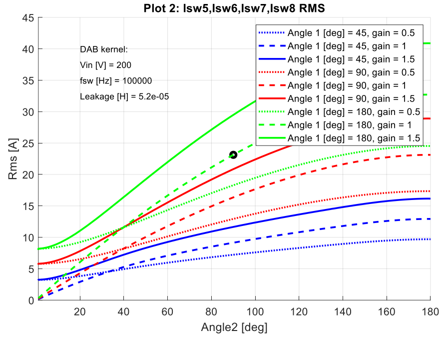
Takeaway

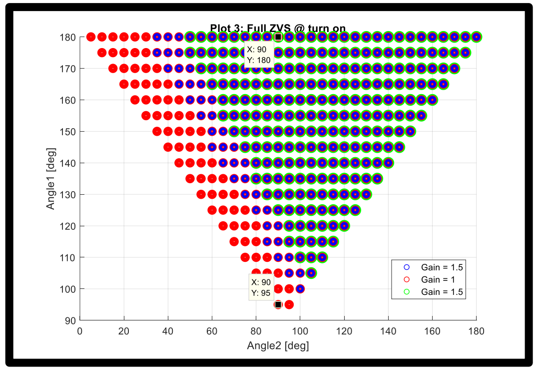
From Plot 1
- **Angle 1 = 90° or Angle 1 =180°**

From Plot 2
- **Angle 1 = 90°**

How to chose Angle 1 and Angle 2?







From Plot 3

- Select the best gain compromise between ZVS and deliverable power.
- If the gain < 1 we decrease ZVS area and we are able to deliver low power.
- If the gain > 1 we decrease ZVS area but we are able to deliver high power.
- *If the gain = 1, by keeping Angle2 lower enough we guarantee the lower RMS current value possible, while keeping a discrete value of power delivery*

Best compromise is Gain = 1 so Vor = Vin!

Notes:

- If Angle 2 = 90° with Angle 1 = 180° we get full ZVS
- If Angle 2 = 90° with Angle 1 = 90° we get quasi ZVS for some FETs

Best compromise is Angle 1 = 180 (full ZVS)

Takeaway

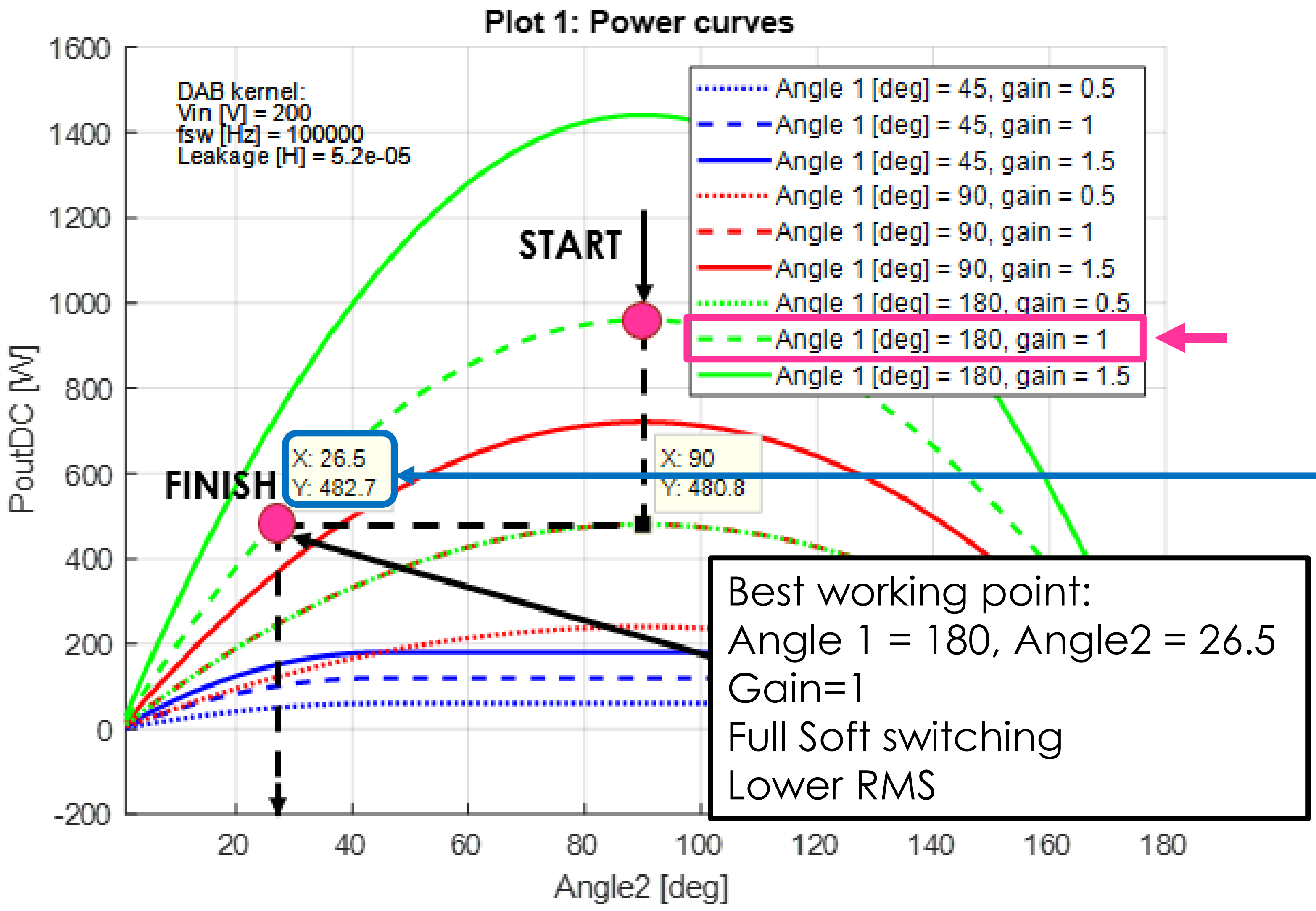
From Plot 1
- **Angle 1 = 90° or Angle 1 =180°**

From Plot 2
- **Angle 1 = 90°**

From Plot 3
- **Angle 1 = 180°**
- **Gain = 1**

Trade off

How to chose Angle 1 and Angle 2?

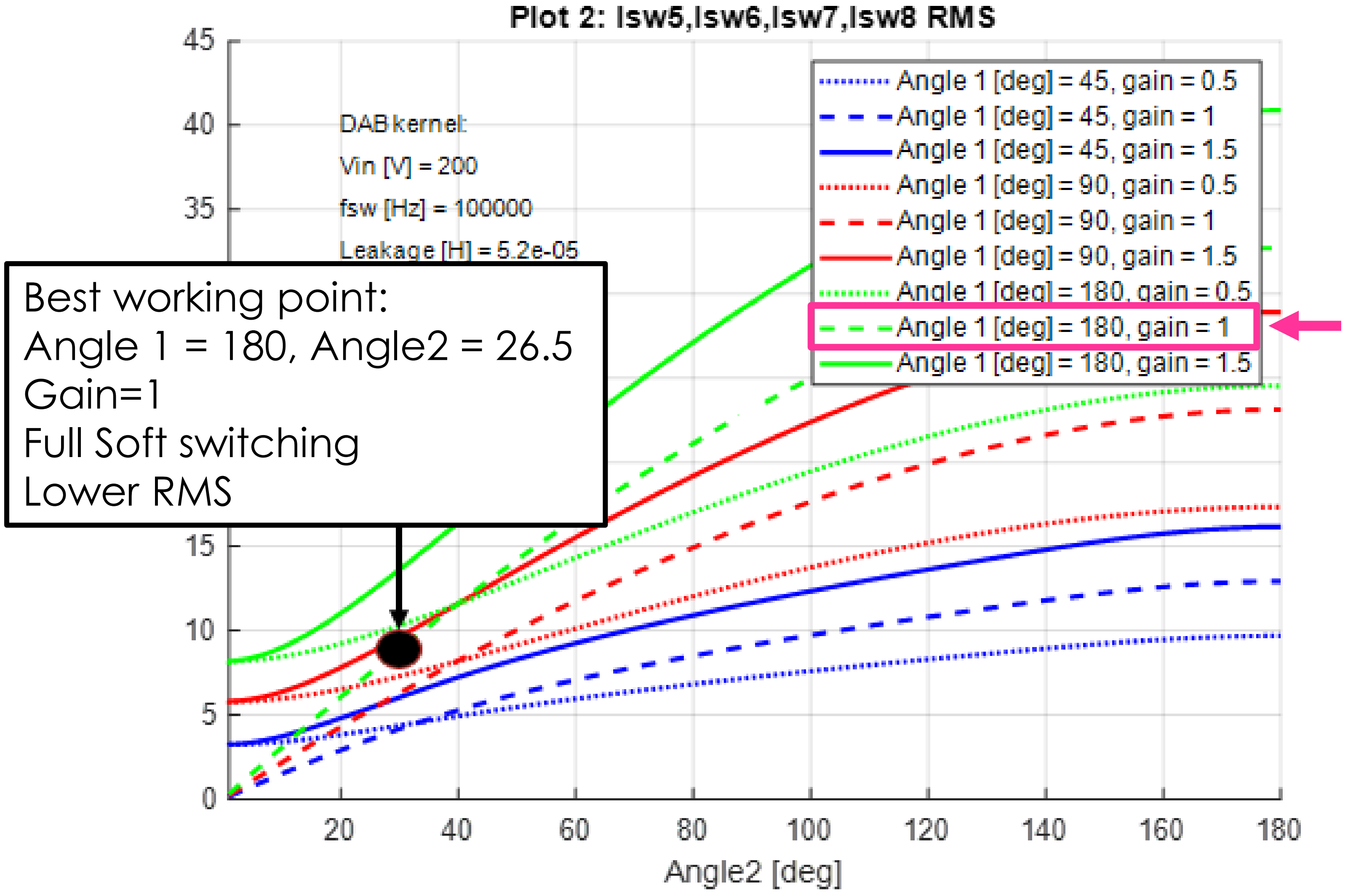


Best working point:
Angle 1 = 180, Angle2 = 26.5
Gain=1
Full Soft switching
Lower RMS

Trade off needed:
Keep the Angle 1 = 180° (best ZVS condition) while keeping Angle 2 equal to the angle for which you get the same power by getting Angle1 = Angle2 = 90° (best RMS condition). Gain=1

All the designs will be scaled according to the kernel power equal to P ≈ 480W

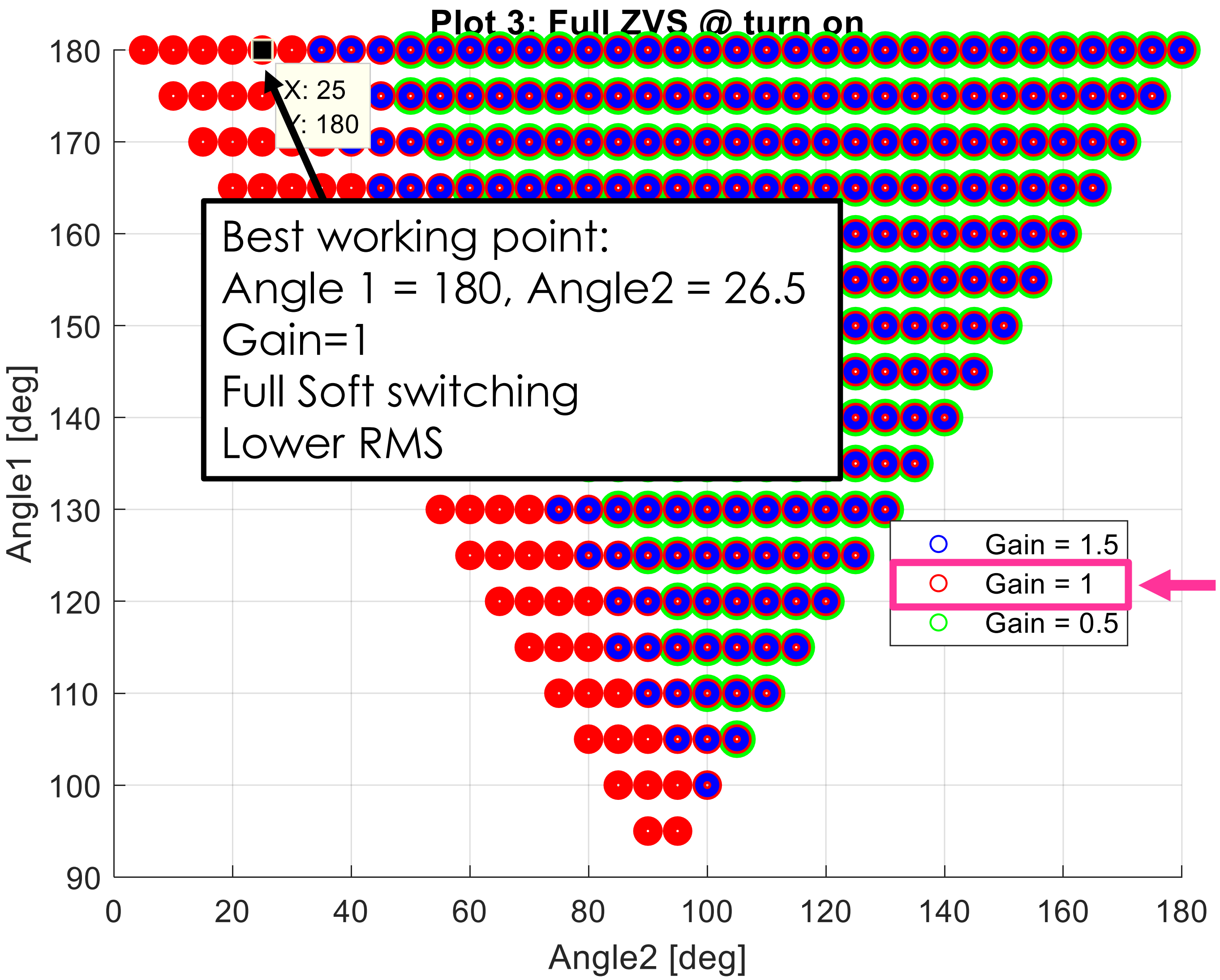
How to chose Angle 1 and Angle 2?



Trade off needed:
Keep the Angle 1 = 180° (best ZVS condition) while keeping Angle 2 equal to the angle for which you get the same power by getting Angle1 = Angle2 = 90° (best RMS condition). Gain=1

All the designs will be scaled according to the kernel power equal to P = 480W

How to chose Angle 1 and Angle 2?

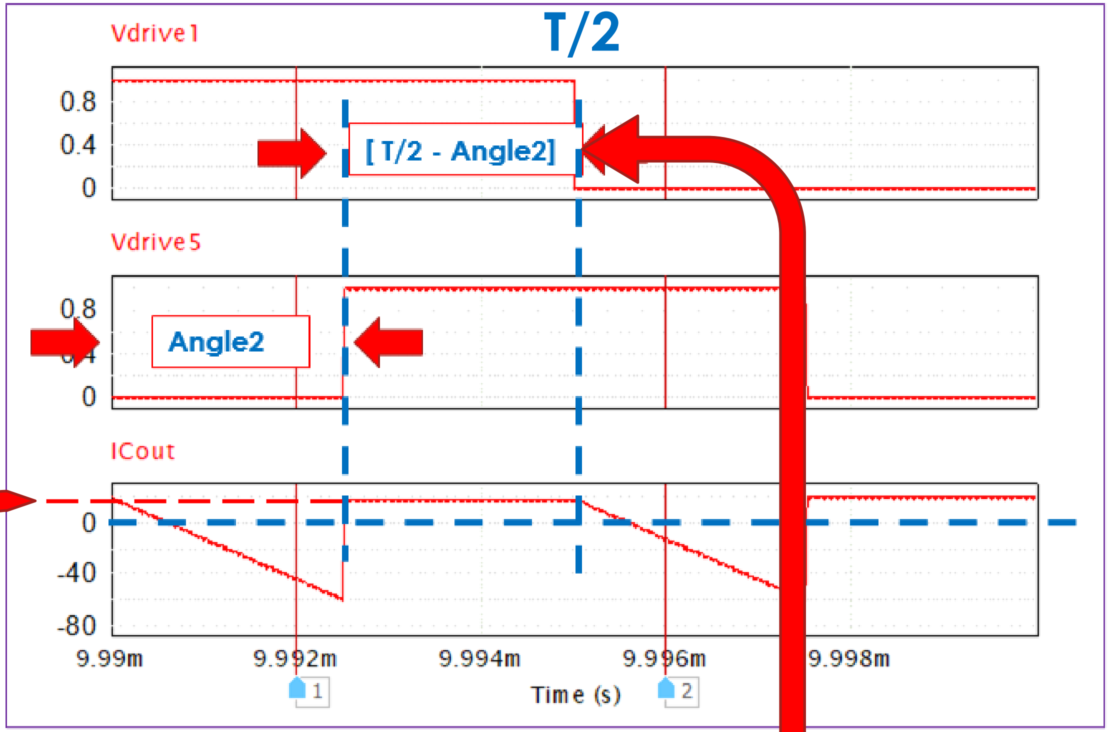


Trade off needed:
Keep the Angle 1 = 180° (best ZVS condition) while keeping Angle 2 equal to the angle for which you get the same power by getting Angle1 = Angle2 = 90° (best RMS condition).
Gain=1

All the designs will be scaled according to the kernel power equal to P = 480W

Sizing the Capacitors

Sizing Cout



$$I_c = C\cdot\frac{\Delta V}{\Delta t} \to C_{out} \approx \boxed{\left(I_{Llk\,peak}\cdot\frac{N_p}{N_s} - \frac{P_{out}}{V_{out}}\right)} \cdot \frac{\boxed{\frac{T}{2} - T_{angle2}}}{\Delta V_{out}}$$

$$I_{Llk\,peak} = \frac{1}{2}\cdot\frac{(V_{in}+V_{or})}{L}\cdot T_{angle2}\Big|$$ valid @ gain = 1

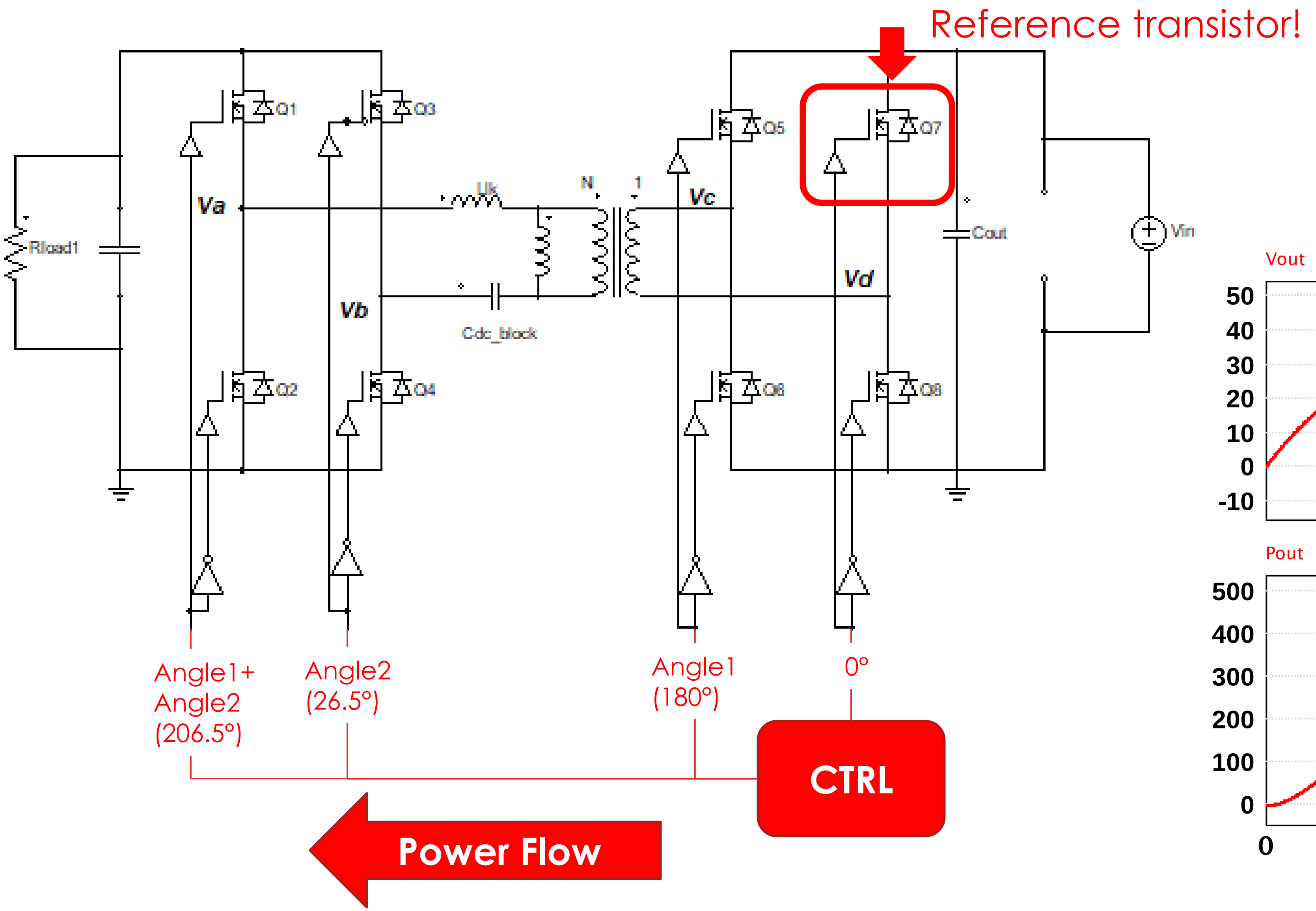
Sizing C_dc_block
(or move for current mode directly)

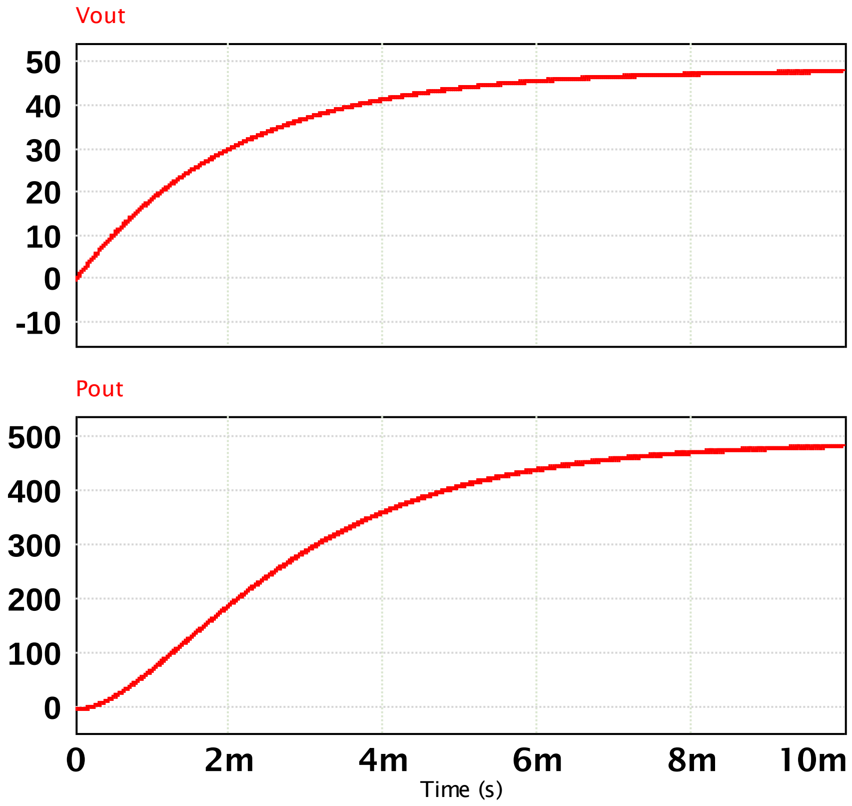
- $Z_{Llk} \gg Z_{C\ dc\ block}$
- $2\cdot\pi\cdot f\cdot L_{lk} \gg \frac{1}{2\cdot\pi\cdot f\cdot C_{dc\ block}}$

$$C_{dc\ block} \approx 100\cdot\frac{1}{4\cdot\pi^2\cdot f^2\cdot L_{lk}}$$

Note:
avoid ripple criteria , we don’t need to filter the noise – like Cout

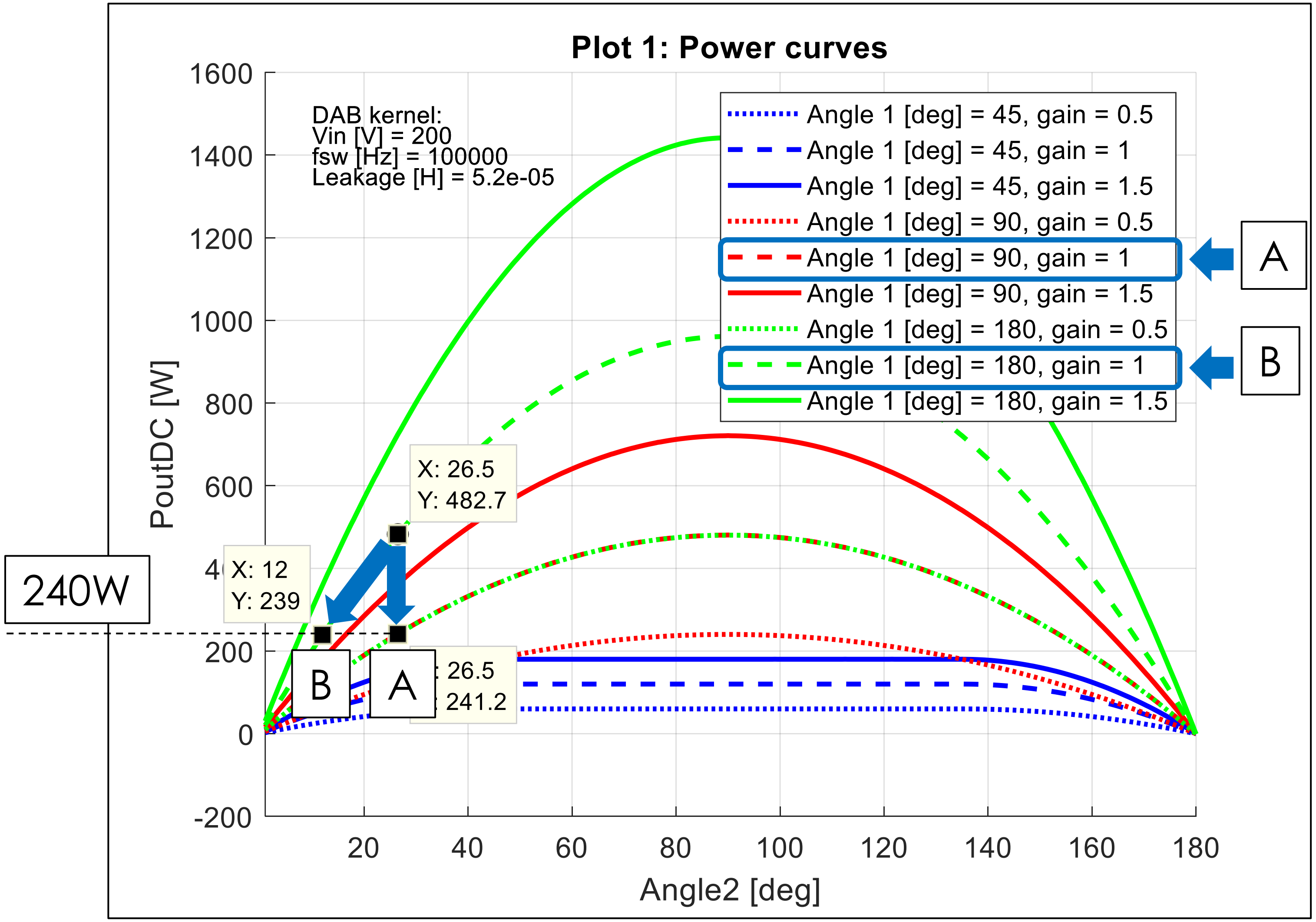
Testing the DAB kernel - Reversing the Power flow
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH





Testing the DAB kernel – Load Regulation
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Load step
480W → 240W



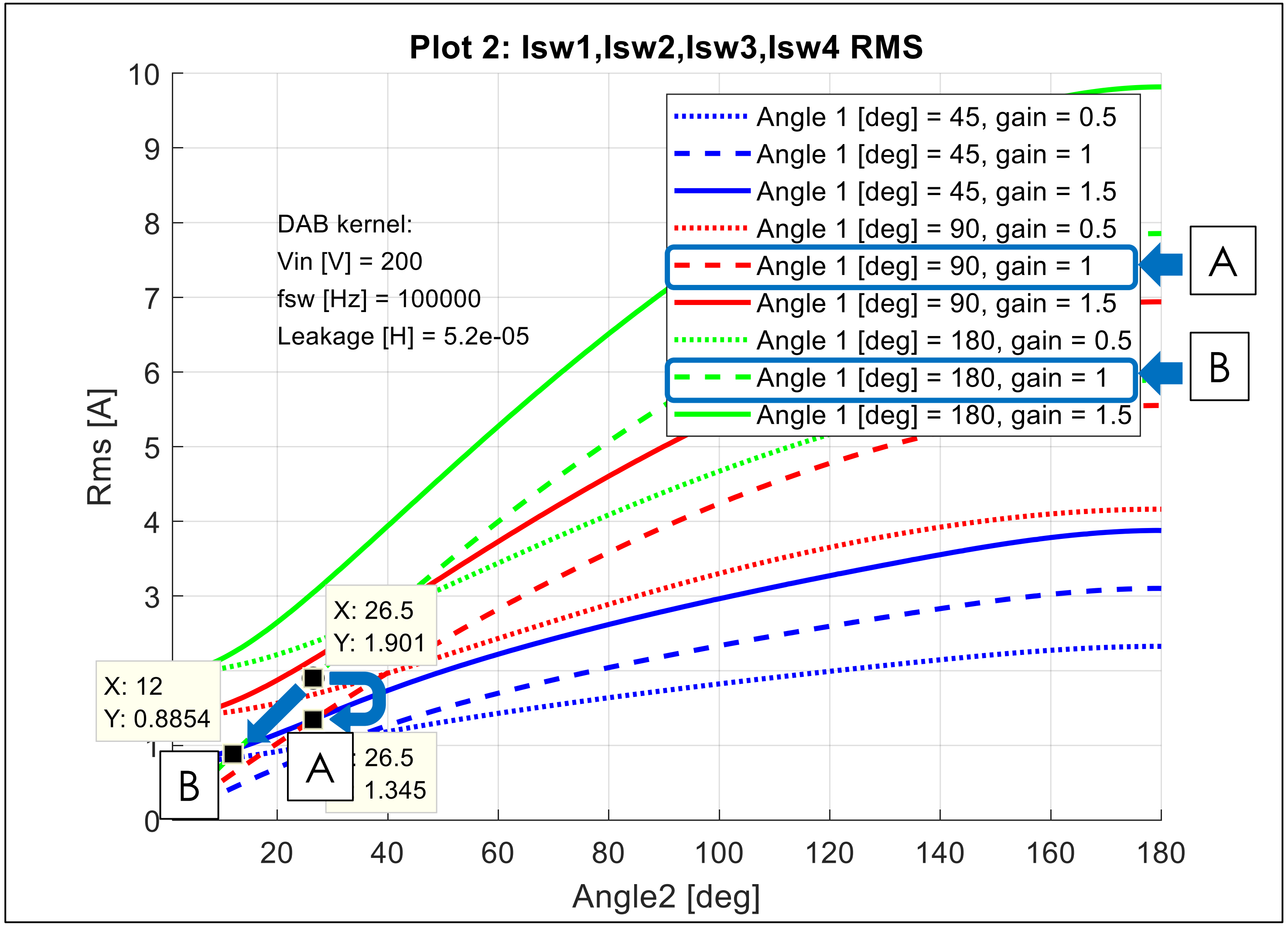
The gain is constant and equal to 1 while the Power varies!

SOLUTIONS

	Angle 1	Angle 2
CASE A	180° → 90°	Locked to 26.5°
CASE B	Locked to 180°	26.5° → 12°
CASE n	Whatever combo gives 240W	

Testing the DAB kernel – Load Regulation
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Load step
480W → 240W



The gain is constant and equal to 1 while the Power varies!

SOLUTIONS

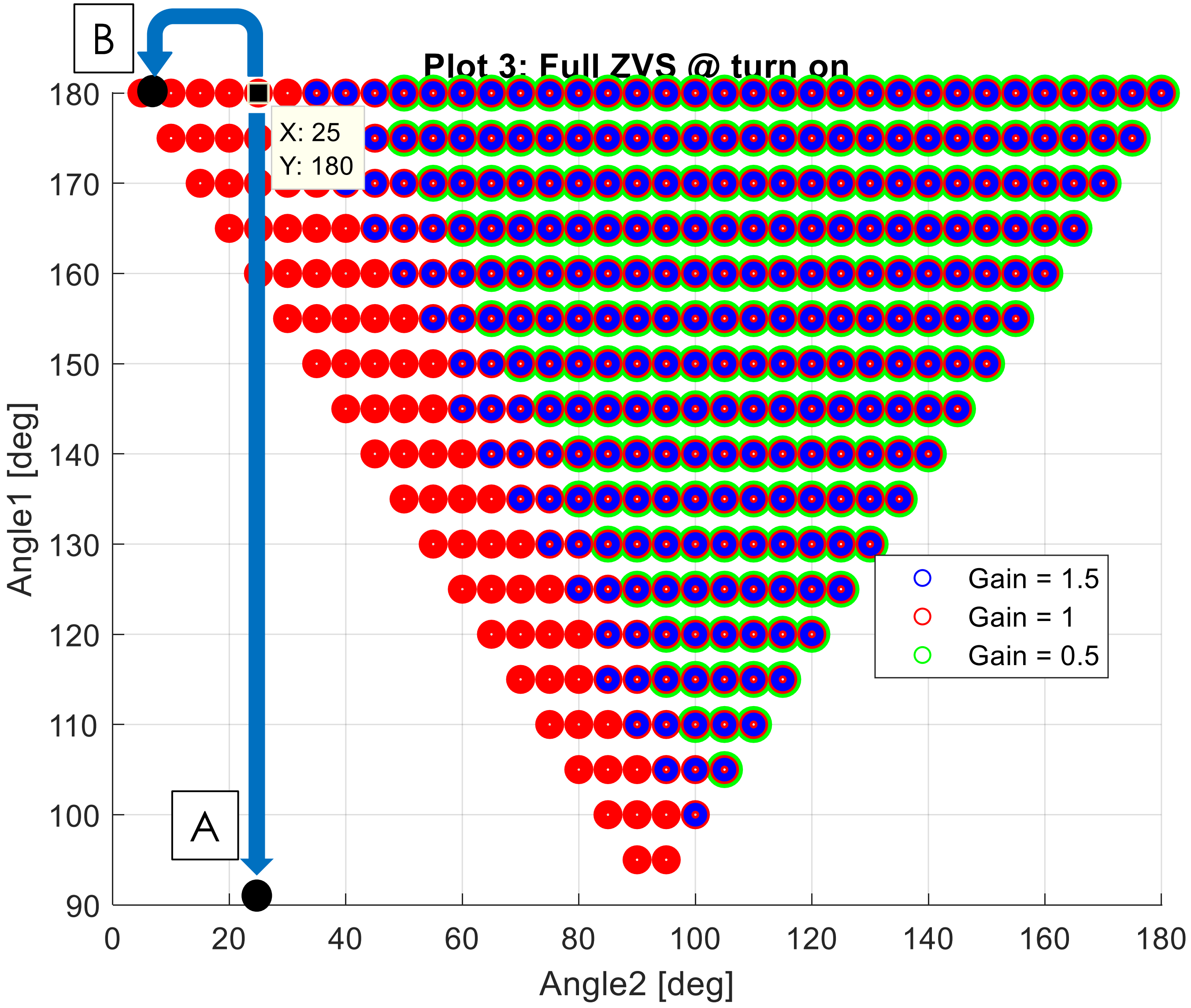
	Angle 1	Angle 2
CASE A	180° → 90°	Locked to 26.5°
CASE B	Locked to 180°	26.5° → 12°
CASE n	Whatever combo gives 240W	

Solution B is better by the RMS side !

Testing the DAB kernel – Load Regulation

Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Load step
480W → 240W



The gain is constant and equal to 1 while the Power varies!

SOLUTIONS

	Angle 1	Angle 2
CASE A	180° → 90°	Locked to 26.5°
CASE B	Locked to 180°	26.5° →12°
CASE n	Whatever combo gives 240W	

Solution B is better by the ZVS side !

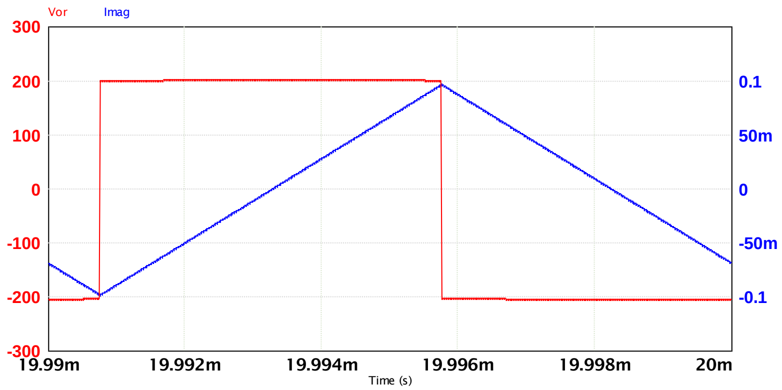
Testing the DAB kernel – Load Regulation

Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

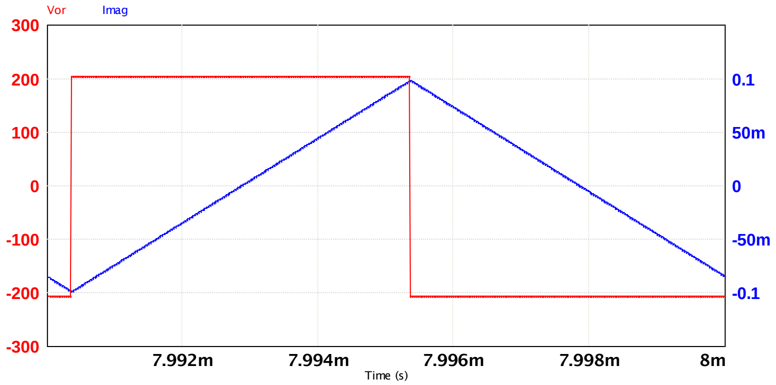
Load step
480W → 240W

	CASE	Vout	Angle 1	Angle 2	Pout	Imag peak	Isw RMS
Baseline Pmax	-	48	180	26	480 W	0.1 A	1.9 A
Step Load Pmax/2	A	48	180→90	26	240 W	50mA	1.34 A
Step Load Pmax/2	B	48	180	26→12	240 W	0.1 A	0.88 A

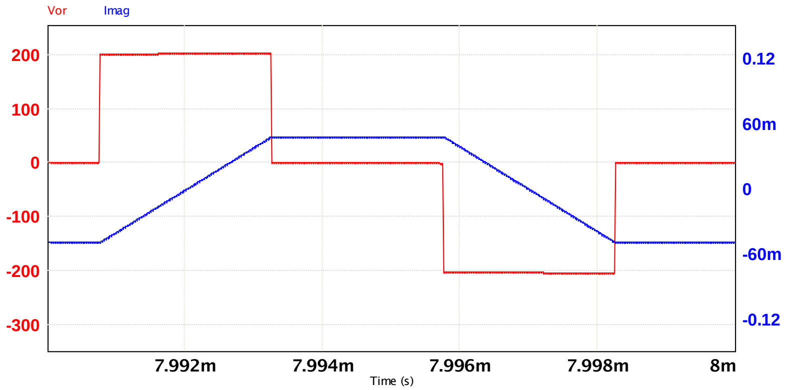
Vout regulated to 48 V in all cases



Baseline



CASE B



CASE A

Question for you: Is Imag load independent? And in LLC?

Testing the DAB kernel – Load Regulation
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Load step 480W → 240W

CASE A

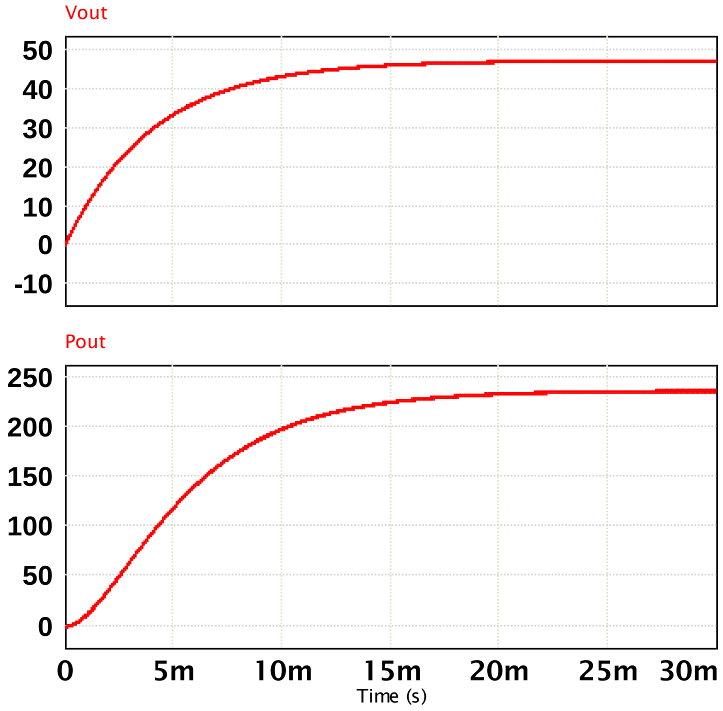
CASE B

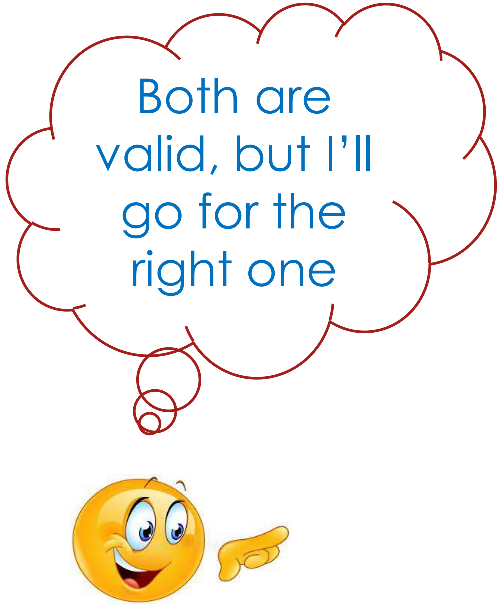
CASE A Circuit Changes:

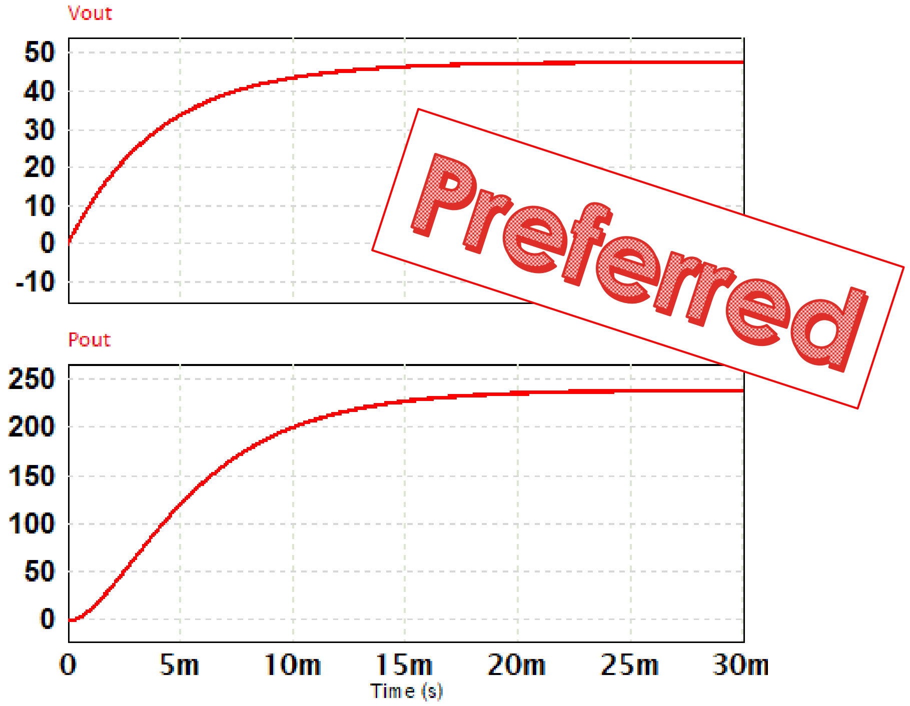
Rload → 2 x Rload
Angle 1: 180° → 90°
Angle 2: locked to 26°

CASE B Circuit Changes:

Rload → 2 x Rload
Angle 2: 26° → 12°
Angle 1: locked to 180°



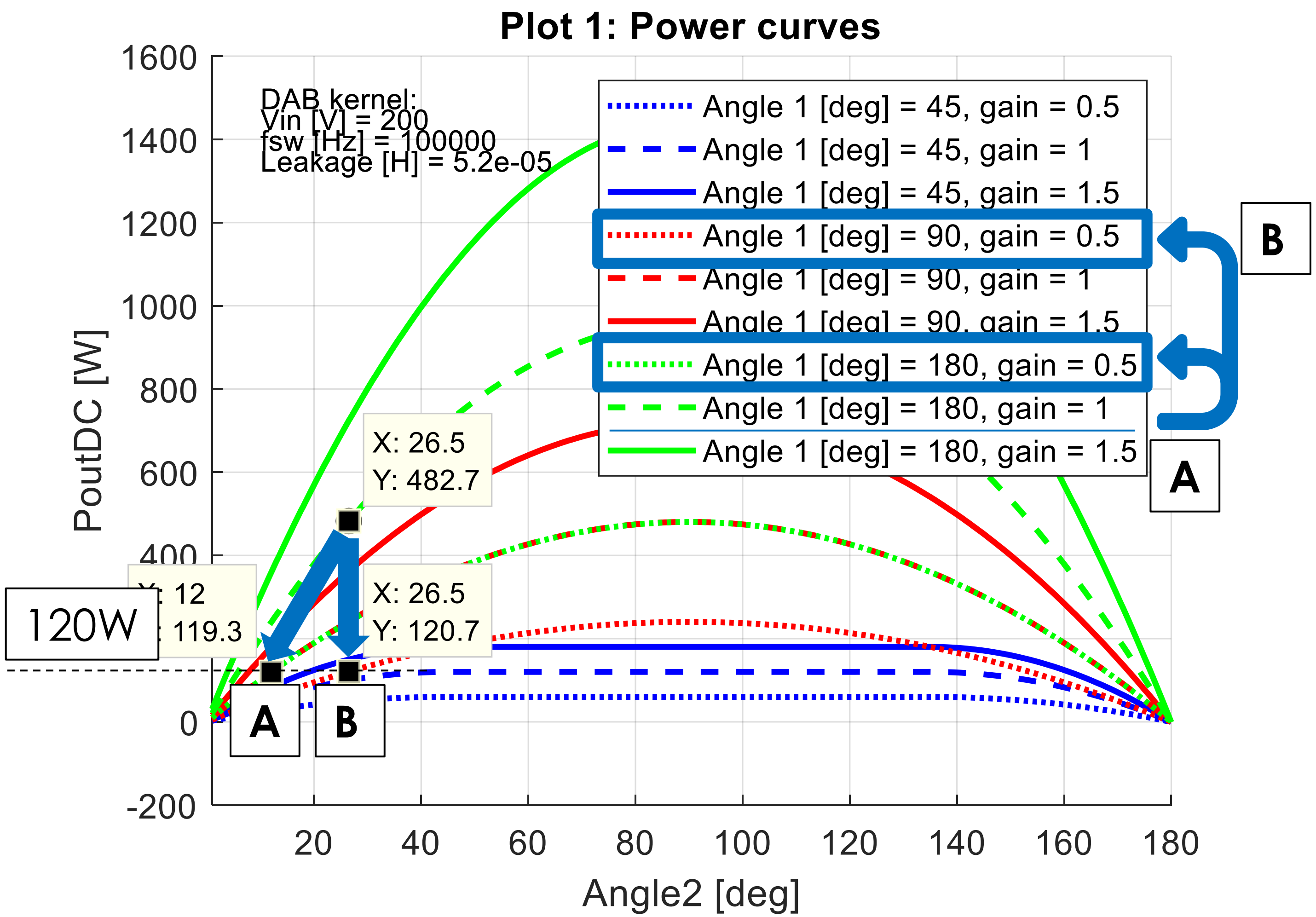




Testing the DAB kernel – <u>Bus Regulation</u>

Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52μH

Bus step
200V → 400V



The Gain is <u>NOT</u> constant (0.5 here) while the Power shall be constant!

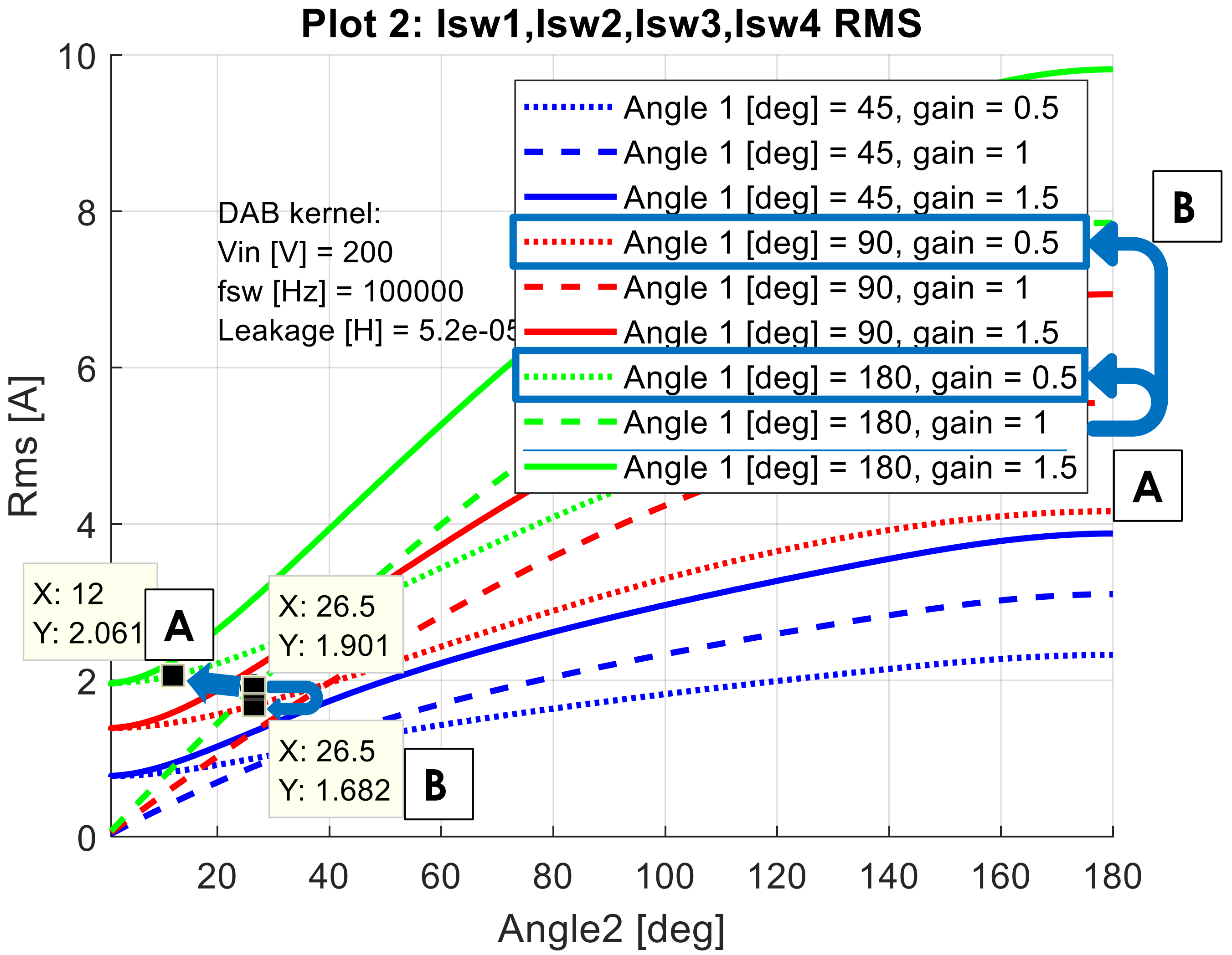
3rd scaling law:
'…Vin x2 gives Pout x 4…'
so Pout ÷ 4 on the power curves gives 480:4=120W @ gain = 0.5

SOLUTIONS

	Angle 1	Angle 2
CASE A	Locked to 180°	26.5° → 12°
CASE B	180° → 90°	Locked to 26.5°
CASE n	Whatever combo gives 120W	

Testing the DAB kernel – Bus Regulation
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Bus step
200V → 400V



The Gain is NOT constant (0.5 here) while the Power shall be constant!

3rd scaling law:
'…Vin x2 gives Pout x 4…'
so Pout ÷ 4 on the power curves gives 480:4=120W @ gain = 0.5

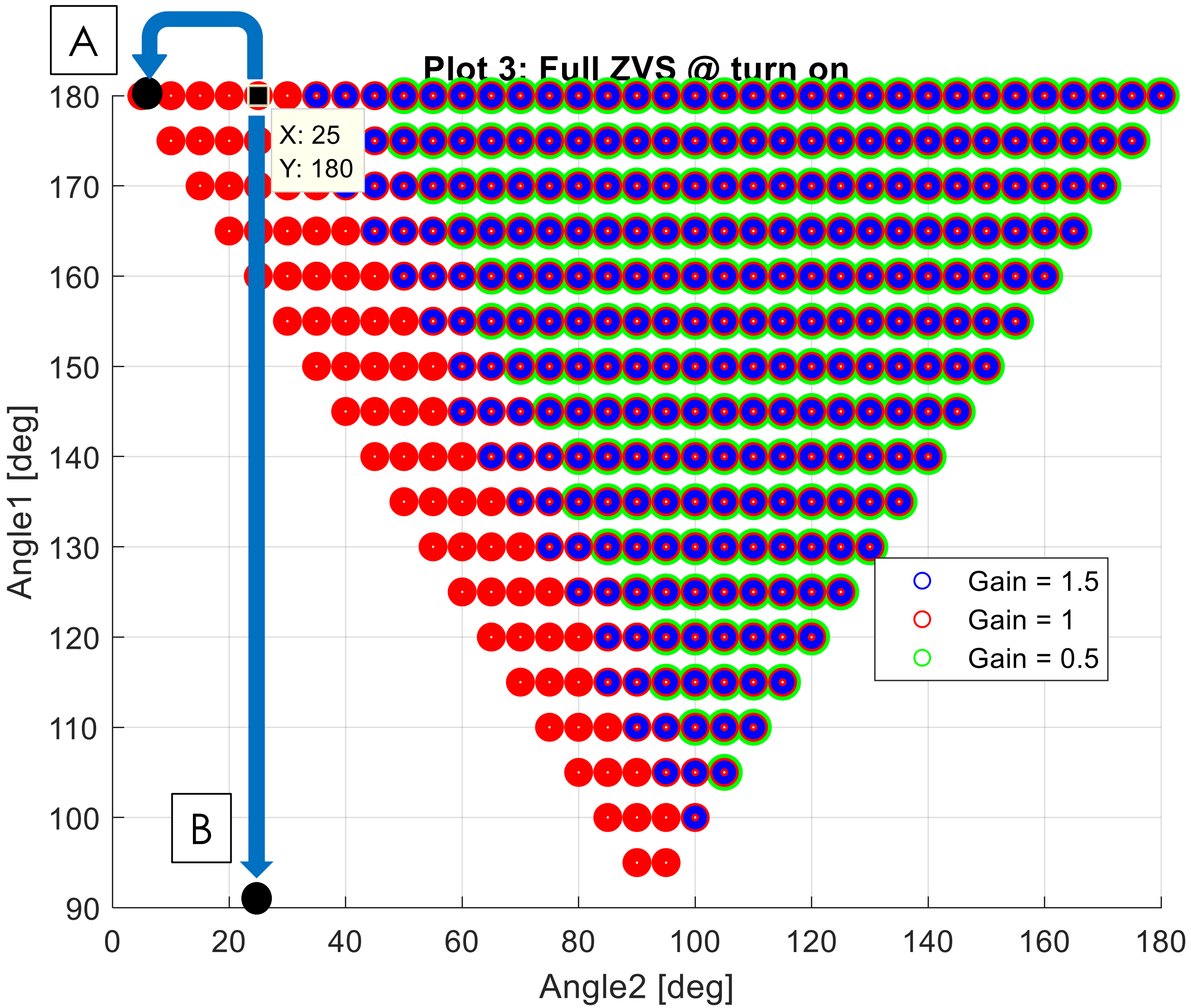
SOLUTIONS

	Angle 1	Angle 2
CASE A	Locked to 180°	26.5° → 12°
CASE B	180° → 90°	Locked to 26.5°
CASE n	Whatever combo gives 120W	

Solution B is better by the RMS side

Testing the DAB kernel – Bus Regulation
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Bus step
200V → 400V



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'…Vin x2 gives Pout x 4…'
so Pout ÷ 4 on the power curves gives 480:4=120W @ gain = 0.5

SOLUTIONS

	Angle 1	Angle 2
CASE A	Locked to 180°	26.5° → 12°
CASE B	180° → 90°	Locked to 26.5°
CASE n	Whatever combo gives 120W	

Both Solutions do not guarantee full ZVS (we are out of the green area @ gain=0.5)

Testing the DAB kernel – Bus Regulation
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Bus step
200V → 400V

CASE A Circuit Changes:

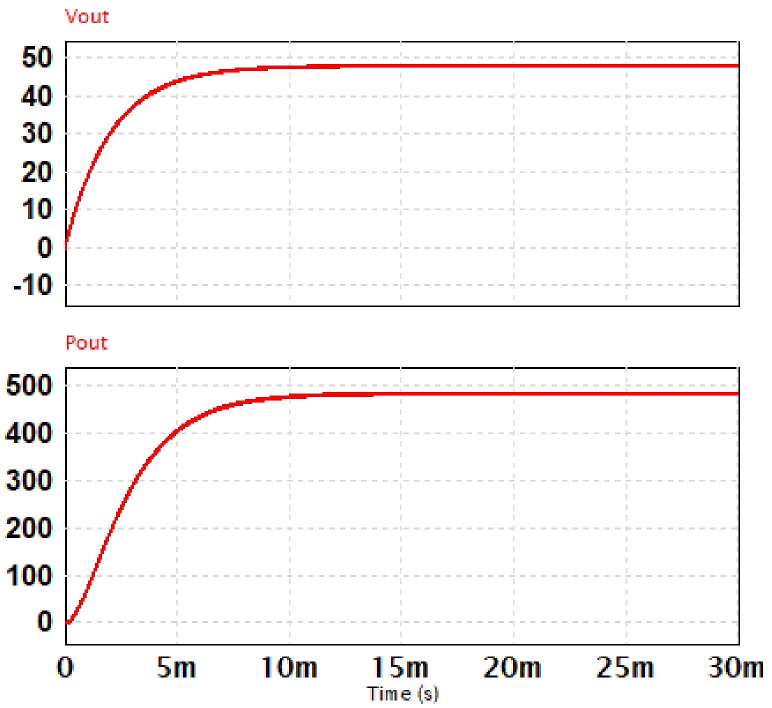
CASE A

Vin → 2 x Vin
Angle 1: locked to 180°
Angle 2: 26° → 12°

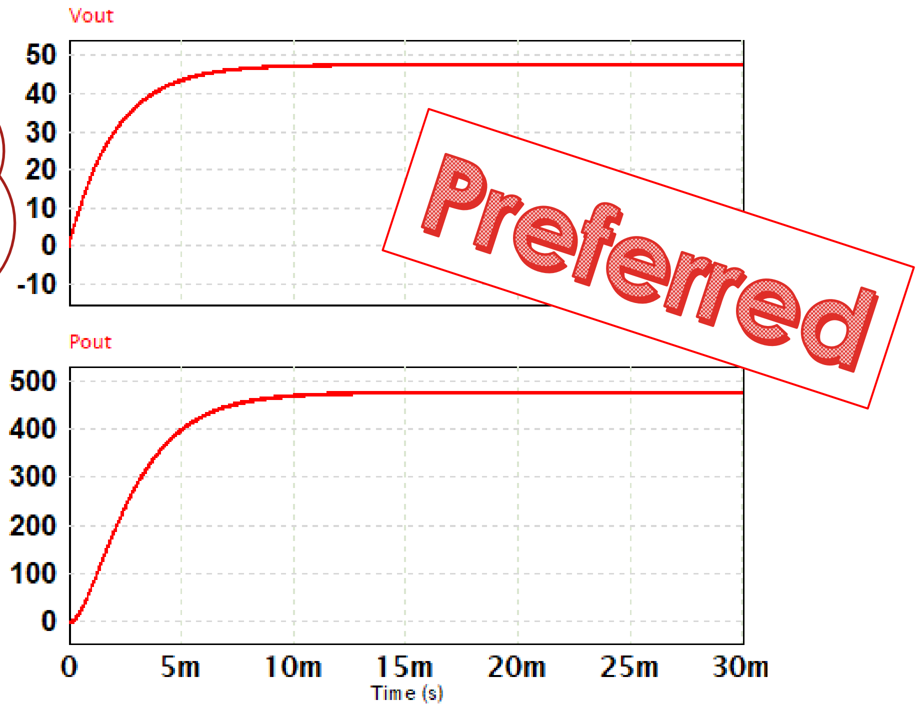
CASE B

CASE B Circuit Changes:

Vin → 2 x Vin
Angle 2: locked to 26°
Angle 1: 180° → 90°



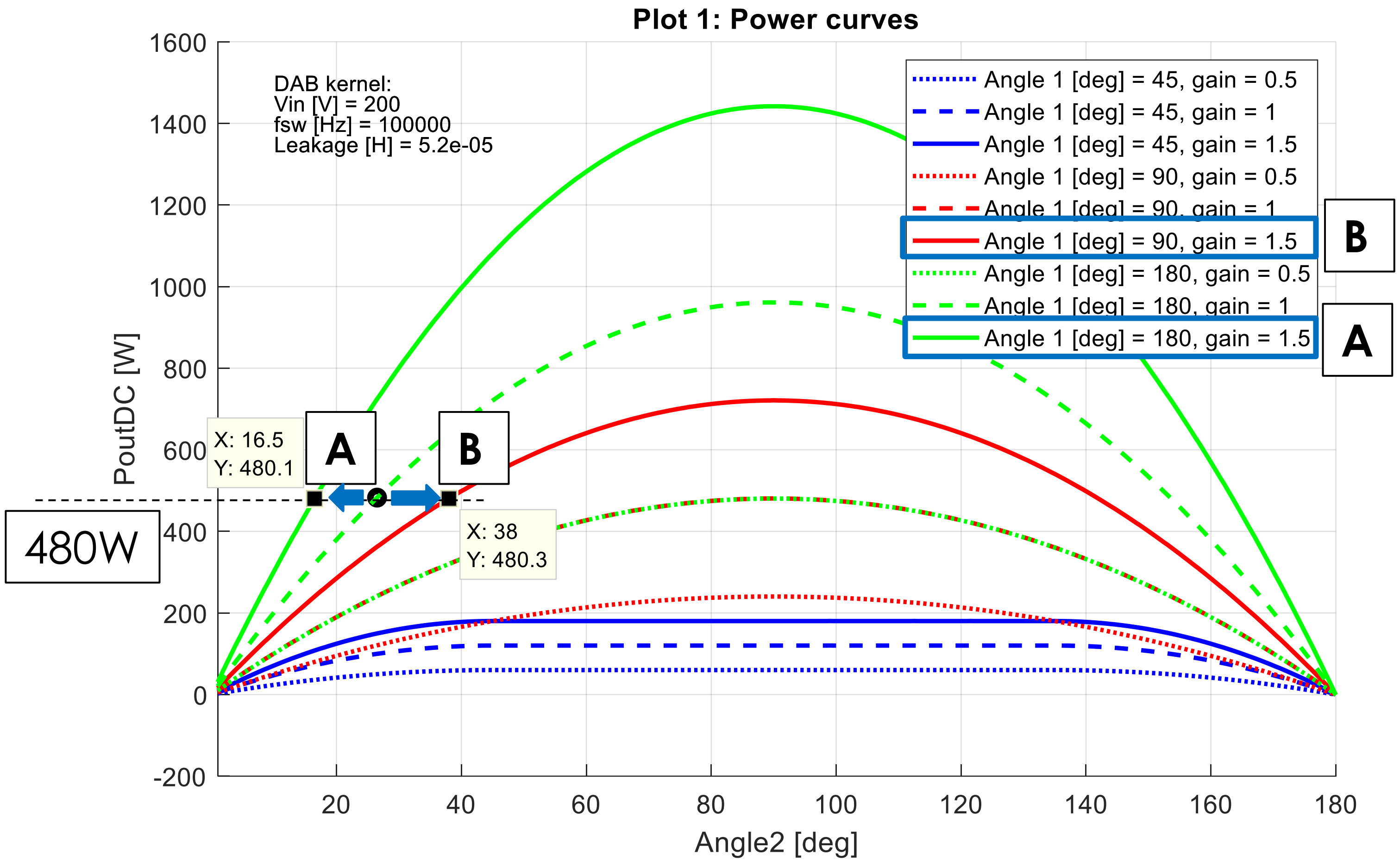
Both are valid, but I'll go for the right one



Testing the DAB kernel – Variable Vout

Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Constant 480W over 48V → 72V



The Gain is NOT constant (1.5 here) while the Power shall be constant!

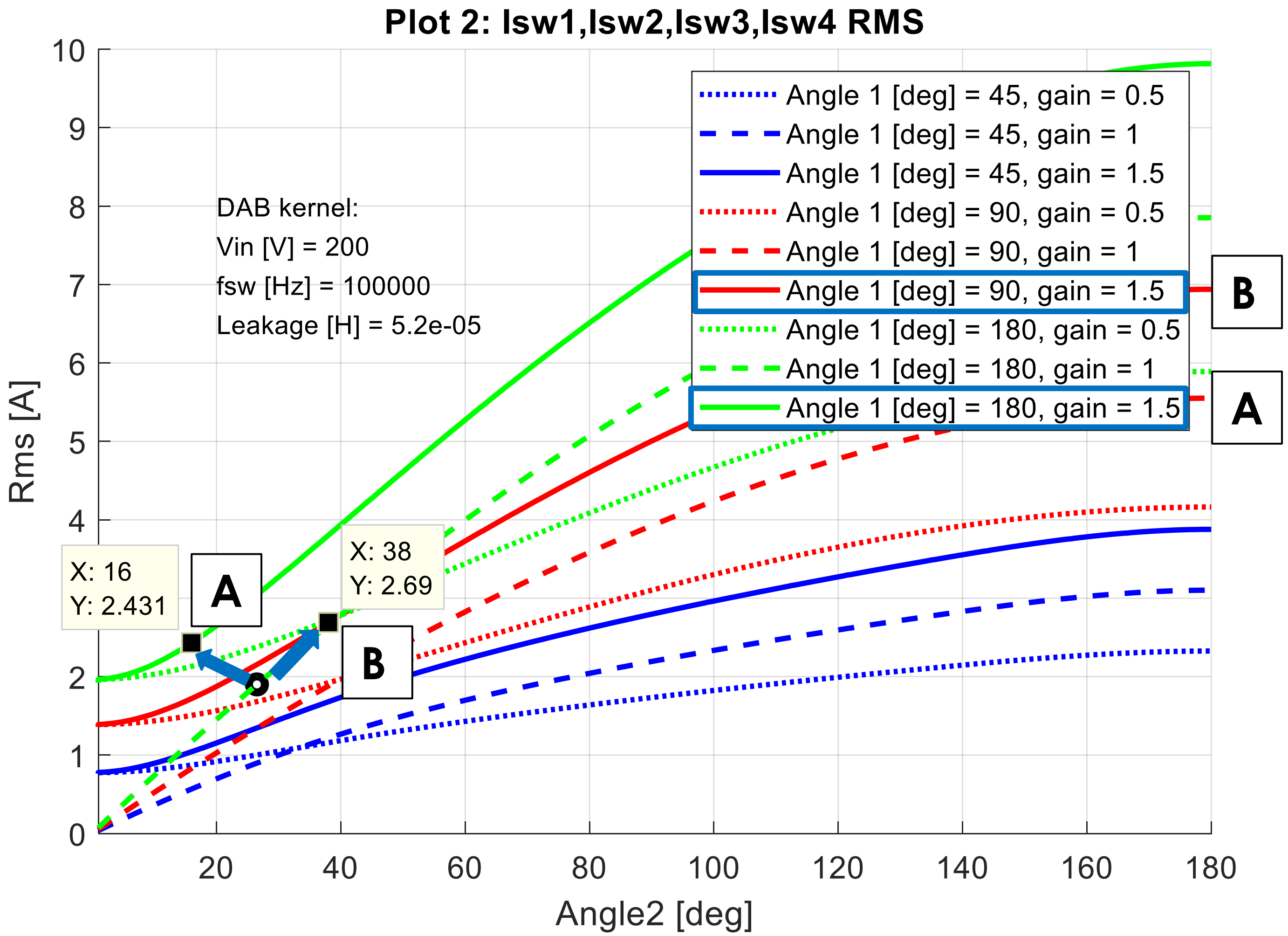
If we need « flat power » at 72V@480W then Rload cannot be the same as 48V@480W !
3rd scaling law: Vout x1.5 gives Pout x 2,25!
Or equivalently Vout x1.5 gives Rload x 2,25

SOLUTIONS

	Angle 1	Angle 2
CASE A	Locked to 180°	26.5° → 16.5°
CASE B	180°→90°	26.5° → 38°
CASE n	Whatever combo gives 480W	

Testing the DAB kernel – Variable Vout
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Constant 480W over 48V → 72V



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3rd scaling law: Vout x1.5 gives Pout x 2,25!
Or equivalently Vout x1.5 gives Rload x 2,25

SOLUTIONS

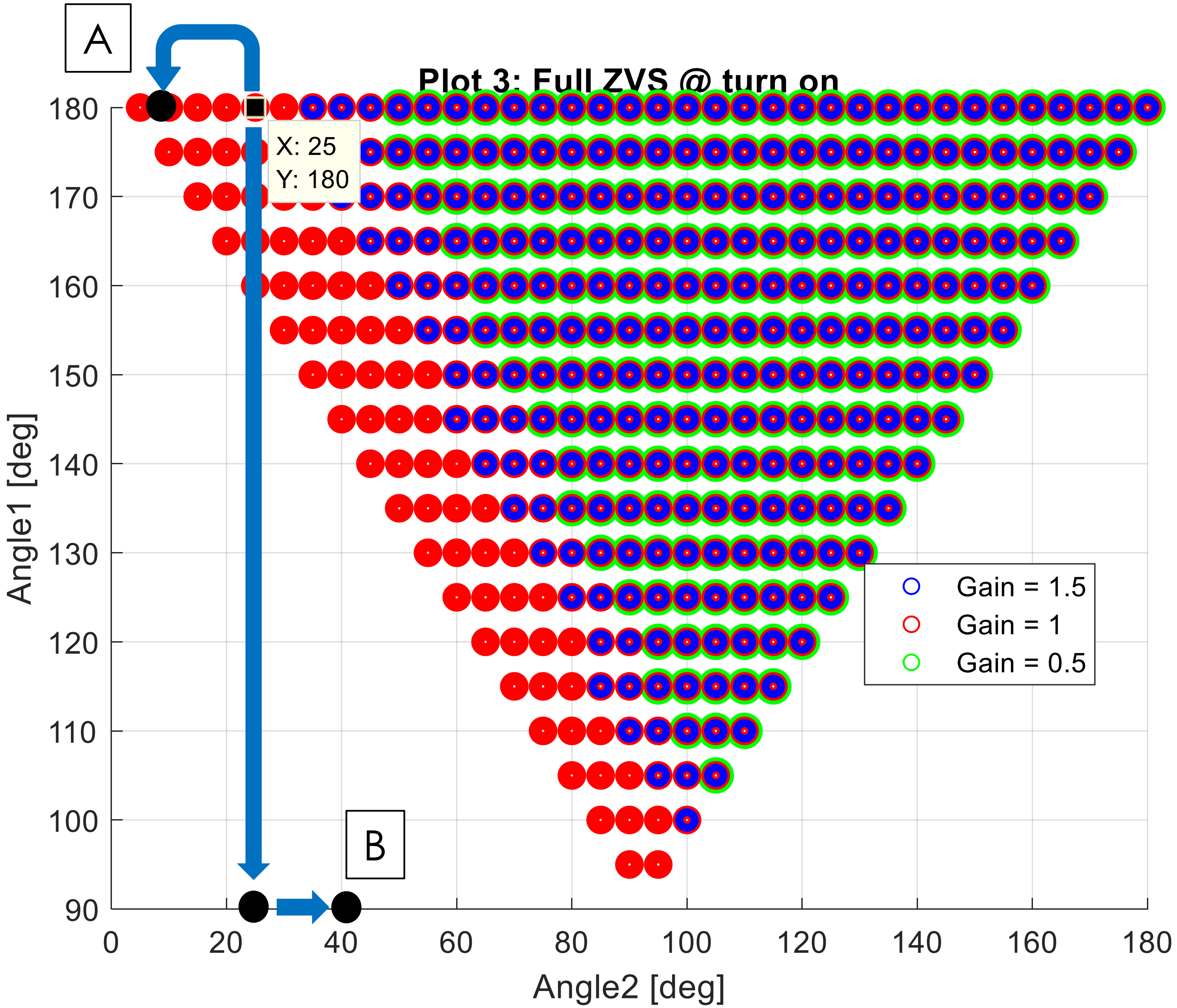
	Angle 1	Angle 2
CASE A	Locked to 180°	26.5° → 16.5°
CASE B	180°→90°	26.5° → 38°
CASE n	Whatever combo gives 480W	

Solution A is better by the RMS side

Testing the DAB kernel – Variable Vout

Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Constant 480W over 48V → 72V



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3rd scaling law: Vout x1.5 gives Pout x 2,25!
Or equivalently Vout x1.5 gives Rload x 2,25

SOLUTIONS

	Angle 1	Angle 2
CASE A	Locked to 180°	26.5° → 16.5°
CASE B	180°→90°	26.5° → 38°
CASE n	Whatever combo gives 480W	

Both Solutions do not guarantee full ZVS (we are out of the blue area @ gain=1.5)

Testing the DAB kernel – Variable Vout

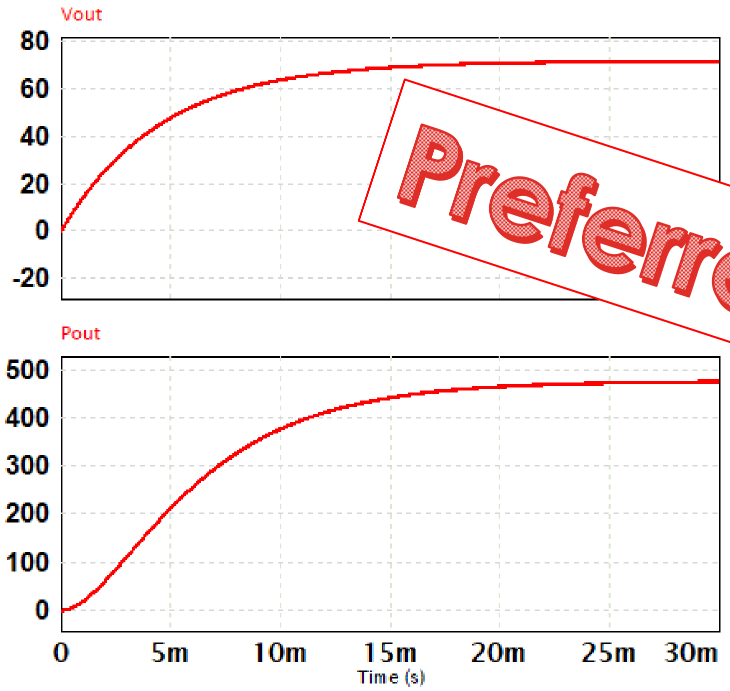
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

Constant 480W over 48V → 72V

CASE A Circuit Changes:

CASE A

Rload → 2,25 x Rload
Angle 1: locked to 180°
Angle 2: 26° → 16.5°

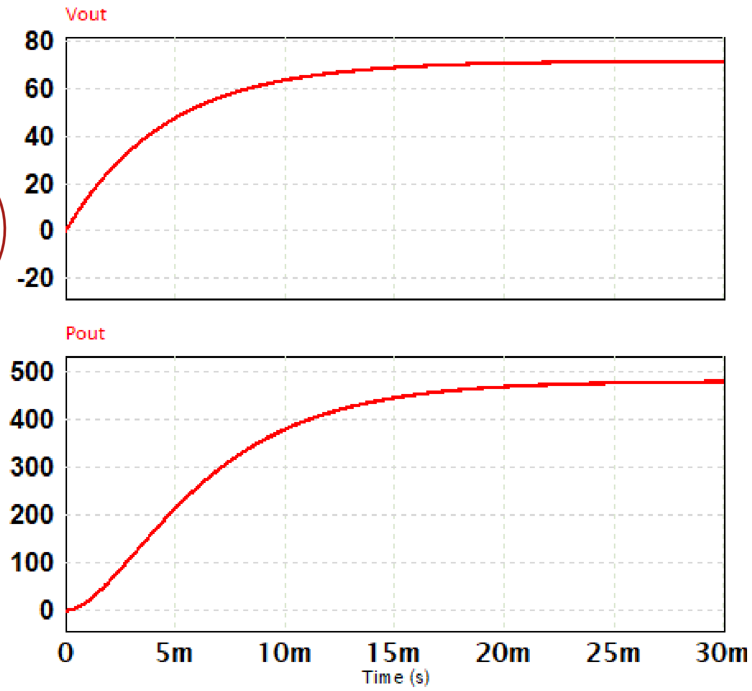


Preferred

CASE B Circuit Changes:

CASE B

Rload → 2,25 x Rload
Angle 1: 180°→90°
Angle 2: 26.5° → 38°



Both are valid, but I'll go for the left one

Testing the DAB kernel
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

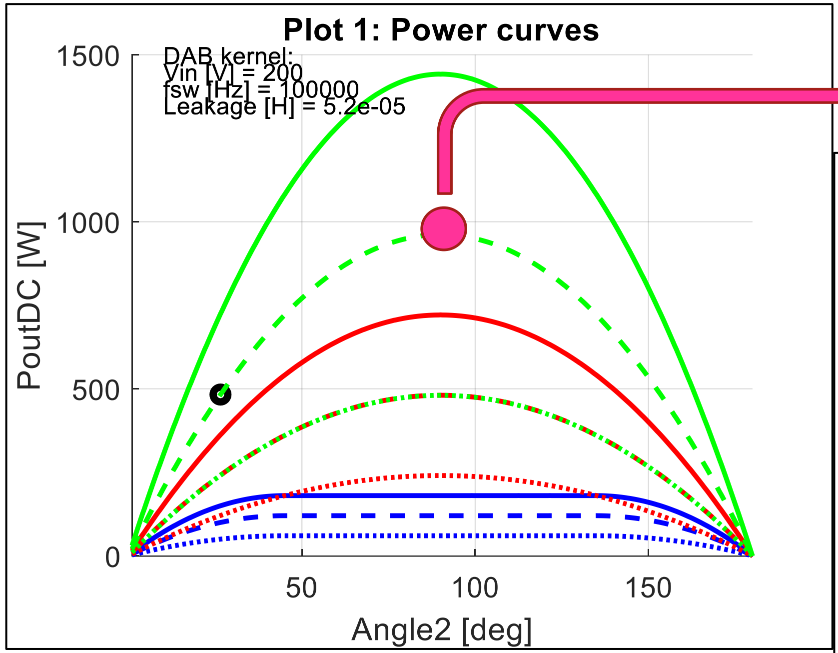
SUMMARY		
System Perturbation	**Preferred Solution**	**Reasons**
Load Step	Control Angle 2	One control variable and lower RMS ZVS preserved
Bus step	Control Angle 1	Same as above ZVS not assured
Flat Power over Vout variations	Control Angle 2	Same as above ZVS not assured

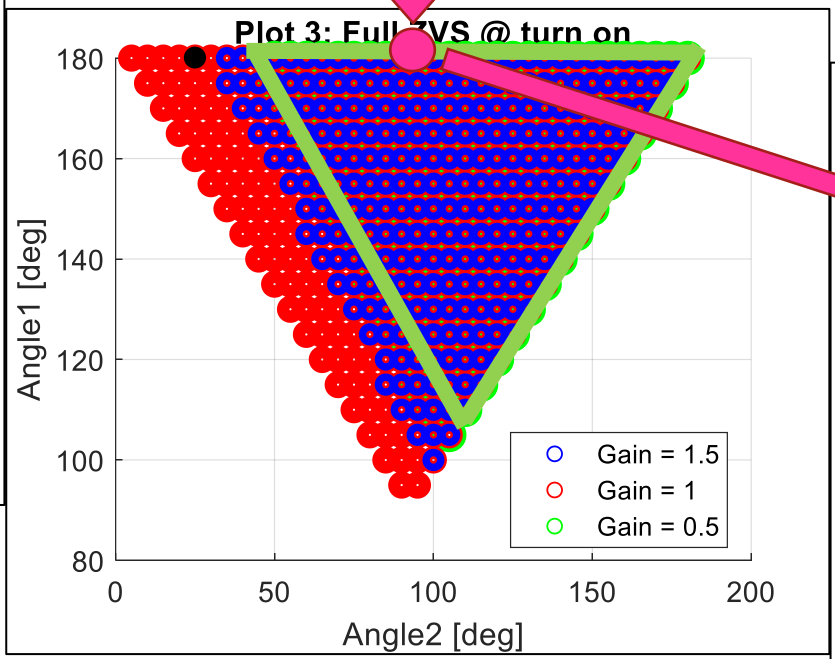
Testing the DAB kernel
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

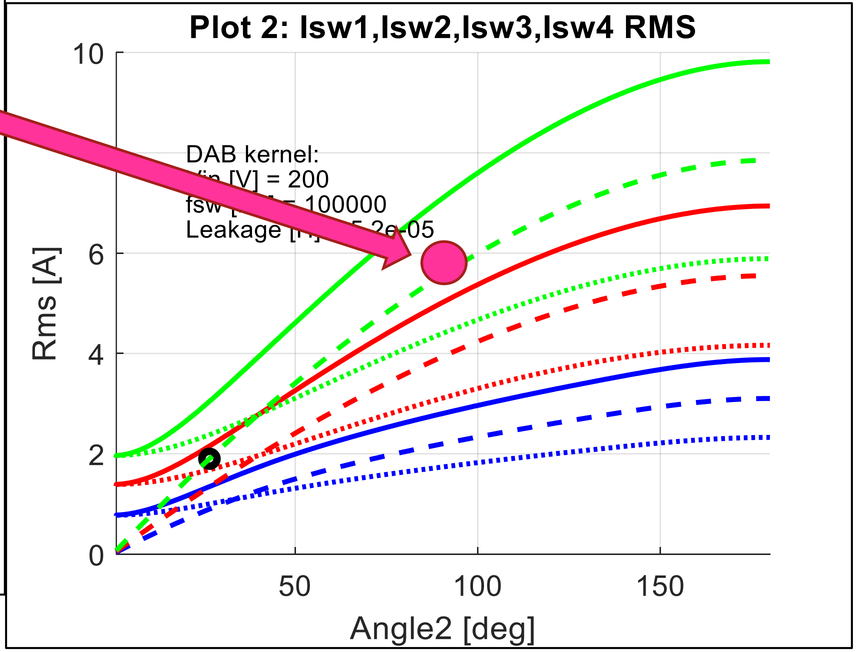
"Could we target Angle2 >26°, trying to preserve ZVS vs huge bus Step?"

Absolutely yes. It's strongly dependent from the requirements!

Question for you:
Is it better to get lower RMS (conduction losses) or preserve soft switching? It depends from the application : nothing comes for free!







$$k_p = \frac{P_{requirements}}{\uparrow P_{kernel}} \downarrow \; but \;\; L_{lk} \propto \frac{1}{k_p} \uparrow$$

DAB Design 1
Pout = 7 kW, Vout = 48V, Vin = 380V, fsw = 100kHz

One Page DAB design

Assumptions

- Best entry Angles are Angle 1 = 180° and Angle 2 ≈26°
- Best gain entry point is: gain = 1

Before: calculate the scaling factors!

$$k_{voltage} = \frac{V_{in\,eff}}{V_{kernel}} = \frac{380}{200} = 1{,}9 \rightarrow Power\ boost = 1{,}9^2$$

$$k_{power} = \frac{P_{eff}}{P_{kernel}} = \frac{7k}{480 \cdot 1{,}9^2} = 4$$

$$k_{frequency} = \frac{f_{eff}}{f_{kernel}} = \frac{100\ k}{100\ k} = 1$$

Scaling from the kernel to the new requirements

After: calculate the Leakage inductance, the turn ratio and both capacitors):

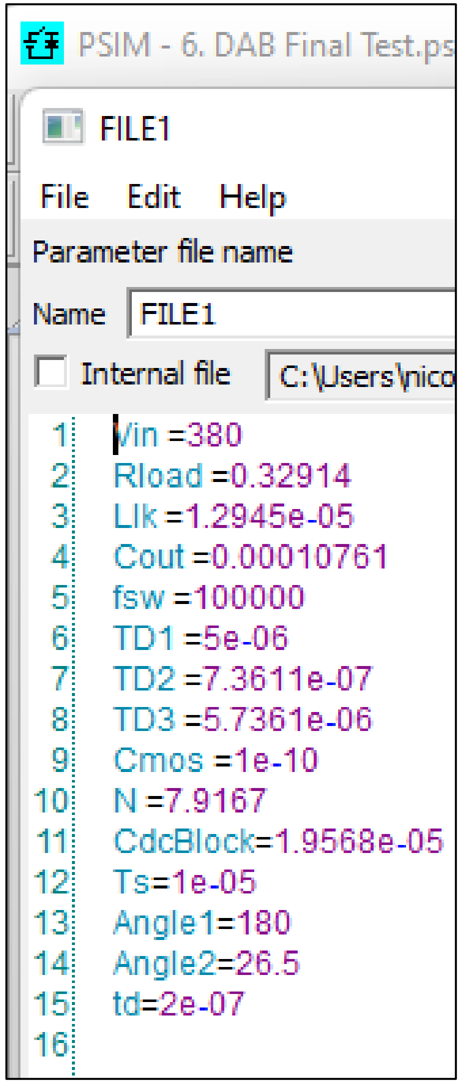
$$L_{Lk} = \frac{L_{kernel}}{k_f \cdot k_p} = \frac{52\ uH}{4} = 12{,}8\ uH$$

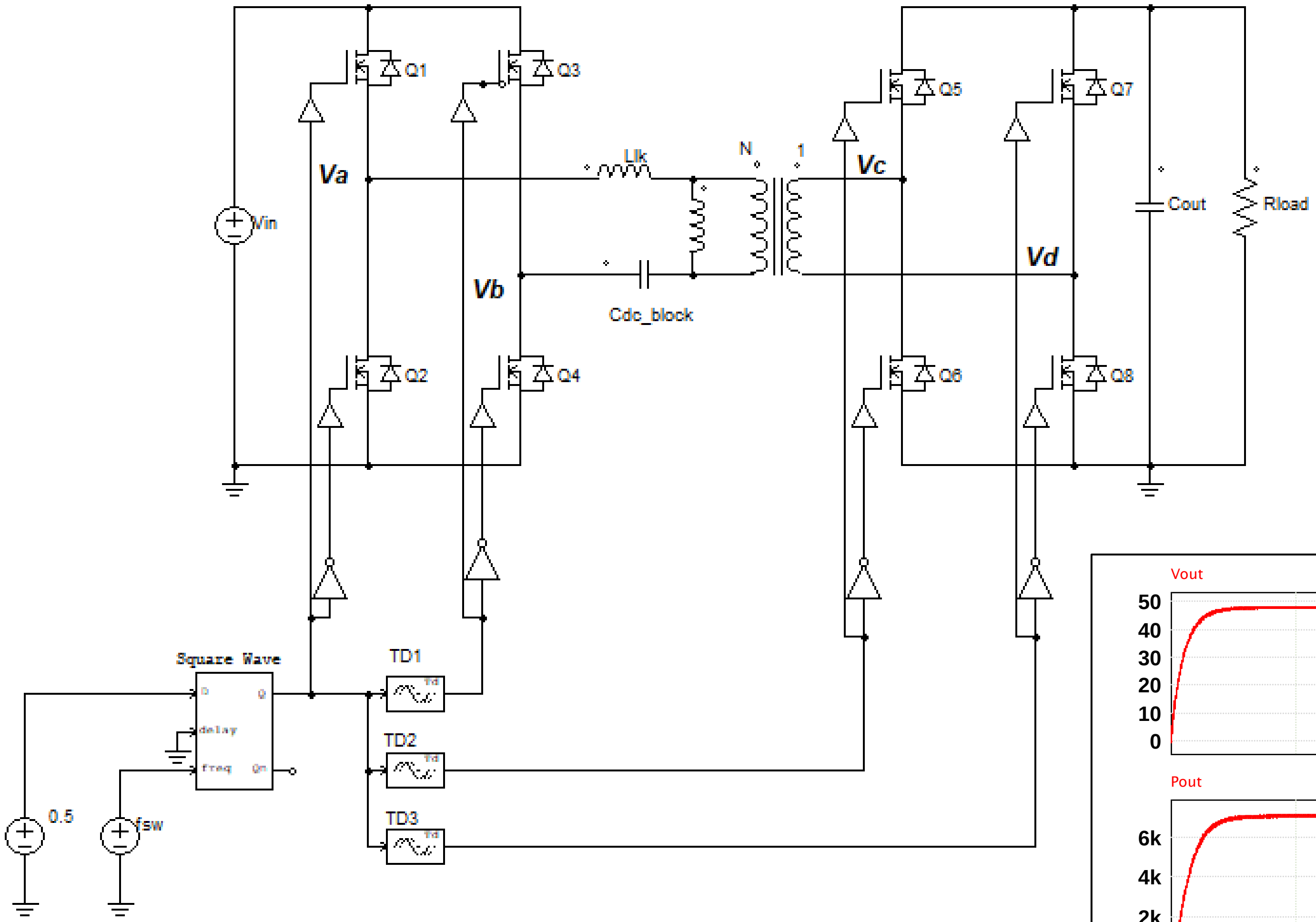
$$N = \frac{N_p}{N_s} = \frac{380}{48} = 7.91$$

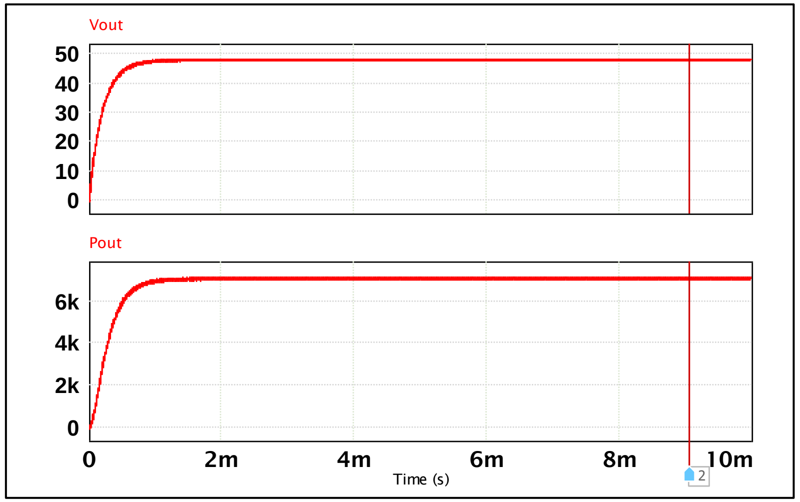
$$C_{dc\ block} \approx 100 \cdot \frac{1}{4 \cdot \pi^2 \cdot f^2 \cdot L_{lk}} \approx 20\mu$$

$$C_{out} \approx \left(I_{Llk\ peak} \cdot \frac{N_p}{N_s} - \frac{P_{out}}{V_{out}}\right) \cdot \frac{\frac{T}{2} - T_{angle2}}{\Delta V_{out\ (1V)}} \approx 110\mu$$

DAB Design 1
Pout = 7 kW, Vout = 48V, Vin = 380V, fsw = 100kHz





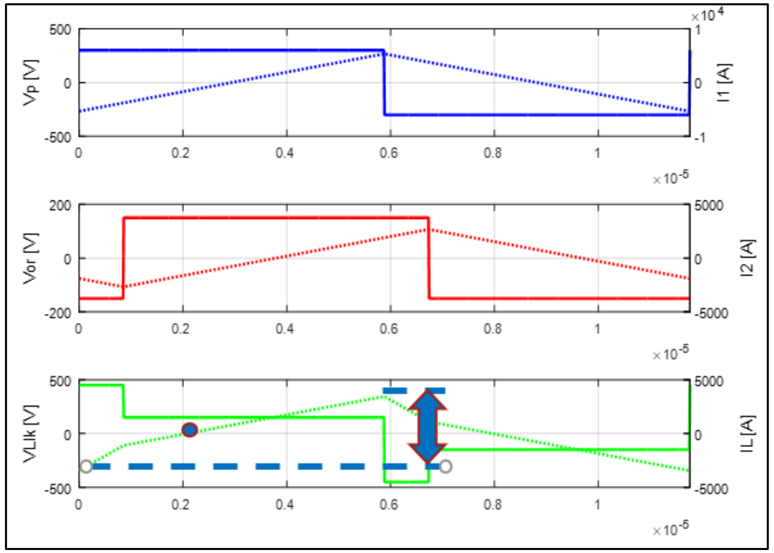


Questions

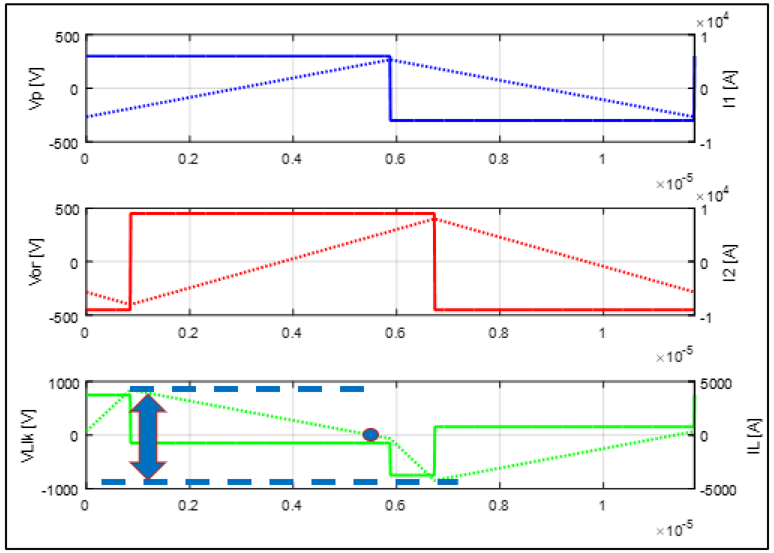
- What if we have D2 > D1?
- What if we run the DAB in synchronous mode?
- What if the gain varies?

Angle 1 = 180°Angle 2 = 26°;

gain = 0,5 (↓ Power, ↓ ZVS, ↓ RMS)



gain = 1,5 (↑ Power , ↓ ZVS, ↑RMS)



Inductor equation (valid for all cases):

$$V_L = L \cdot \frac{\Delta I}{\Delta t} \rightarrow \Delta I = \frac{V_L}{L} \cdot \Delta t \rightarrow \Delta I = \left[\frac{(V_p + V_{or})}{L} \cdot T_{D2} + \frac{(V_p - V_{or})}{L} \cdot \left(\frac{T_s}{2} - T_{D2} \right) \right]$$

Question for you:
Are you able to catch instantly which FET over 8 enables ZVS?

DAB Design 2
Pout = 200 kW, Vout = 800V, Vin = 300V, fsw = 85kHz

Assumptions
- Best entry Angles are Angle 1 = 180° and Angle 2 ≈26°
- Best gain entry point is: gain = 1

One Page DAB design

Before: calculate the scaling factors!

$$k_{voltage} = \frac{V_{in\,eff}}{V_{kernel}} = \frac{300}{200} = 1{,}5 \rightarrow Power\ boost = 1{,}5^2$$

$$k_{power} = \frac{P_{eff}}{P_{kernel}} = \frac{200\,k}{480 \cdot 1{,}5^2} = 185{,}18$$

$$k_{frequency} = \frac{f_{eff}}{f_{kernel}} = \frac{85\,k}{100\,k} = 0{,}85$$

Scaling from the kernel to the new requirements

After: calculate the Leakage inductance, the turn ratio and both capacitors):

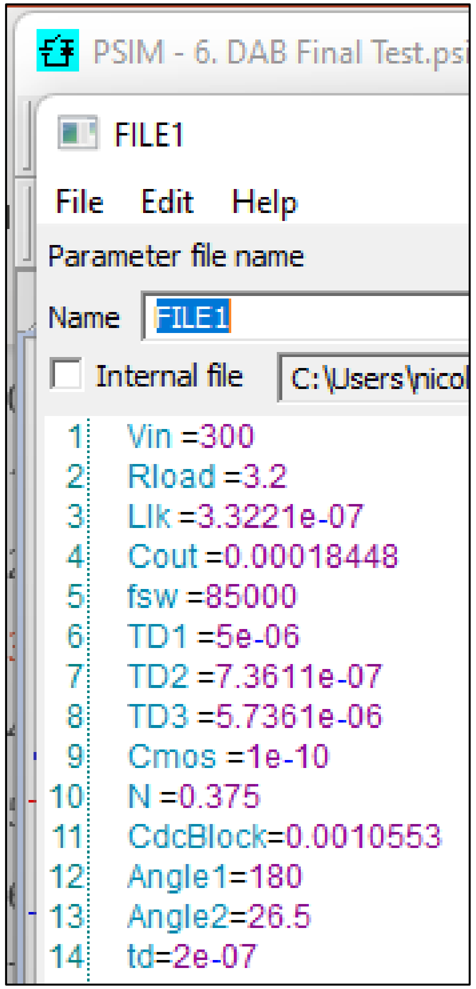
$$L_{Lk} = \frac{L_{kernel}}{k_f \cdot k_p} = 331n$$

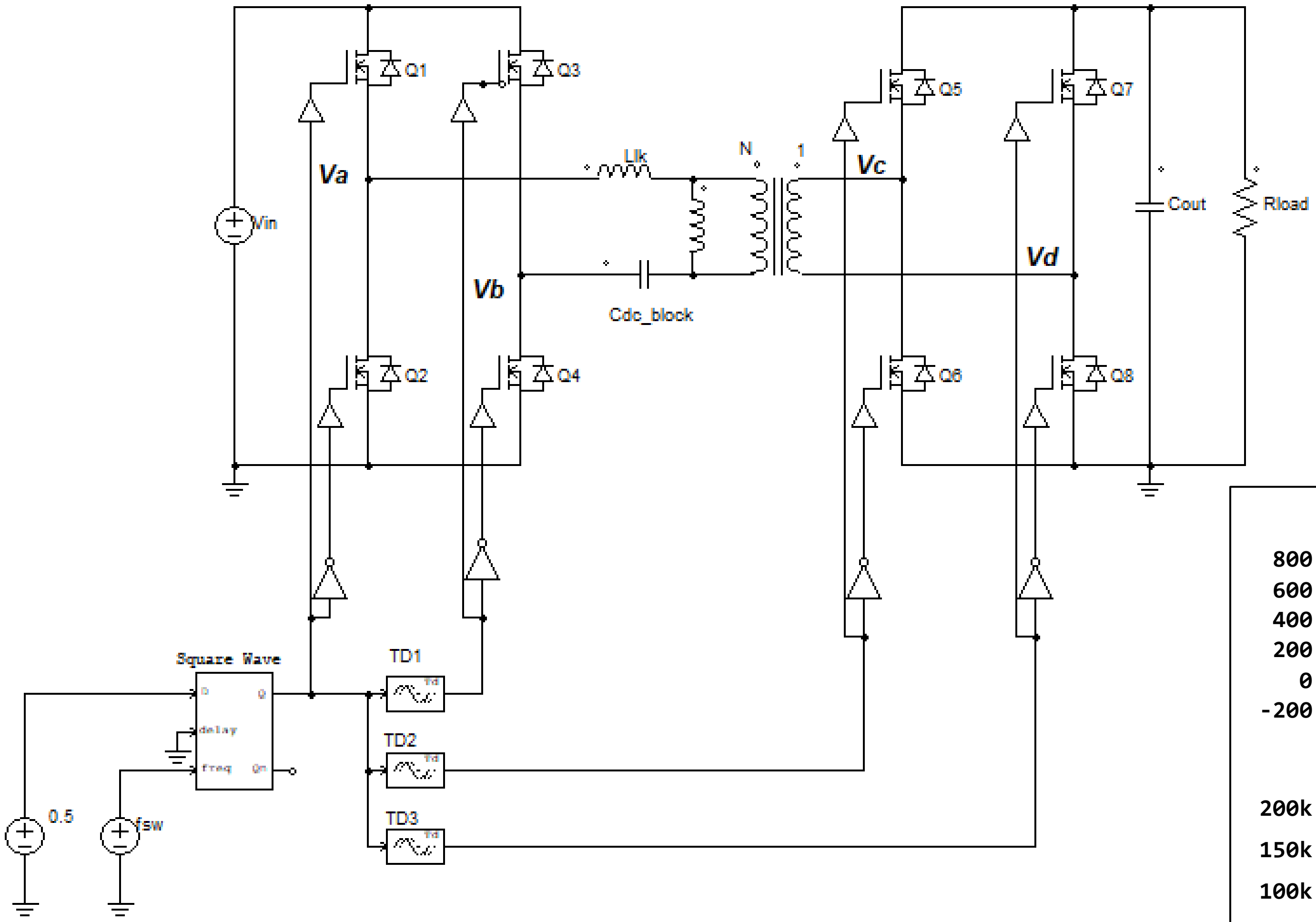
$$N = \frac{N_p}{N_s} = 0{,}375$$

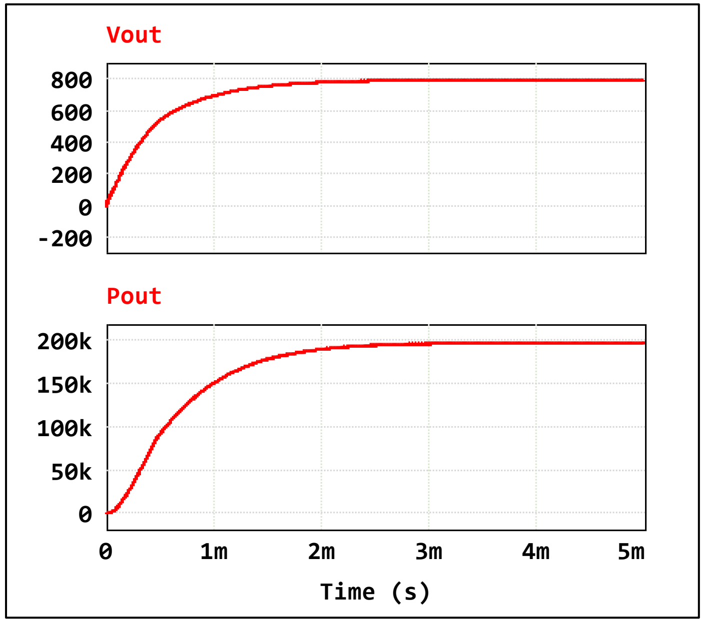
$$C_{dc\ block} \approx 100 \cdot \frac{1}{4 \cdot \pi^2 \cdot f^2 \cdot L_{lk}} \approx 1m$$

$$C_{out} \approx \left(I_{Llk\ peak} \cdot \frac{N_p}{N_s} - \frac{P_{out}}{V_{out}}\right) \cdot \frac{\frac{T}{2} - T_{angle2}}{\Delta V_{out\ (1V)}} \approx 185\mu F$$

DAB Design 2
Pout = 200 kW, Vout = 800V, Vin = 300V, fsw = 85kHz

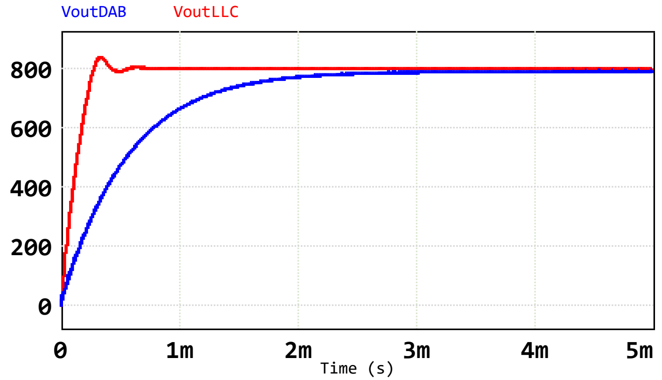




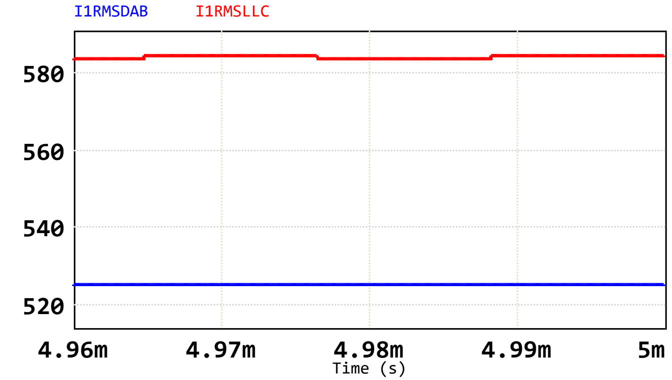


LLC Design comparison
Pout = 200 kW, Vout = 800V, Vin = 300V, fres HI = 110kHz

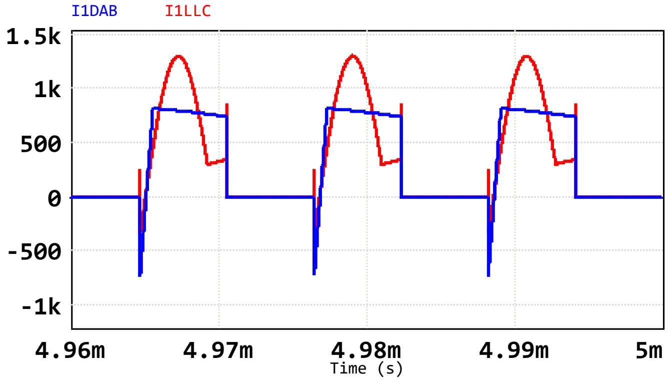
	LLC	DAB
Vbus [V]	300	300
fsw [kHz]	85	85
Llk [H]	**250n**	**331n**
Lmag [H]	**2,25µ**	**100µ**
C dc Block [F]	-	1m (optional)
C res [F]	8.34 µ	-
Isw1 RMS [A]	**585**	**530**
Lm/L_Lk	9	-
Angle 1 Angle 2	-	180 26
Turns Ratio	0.393	0.375



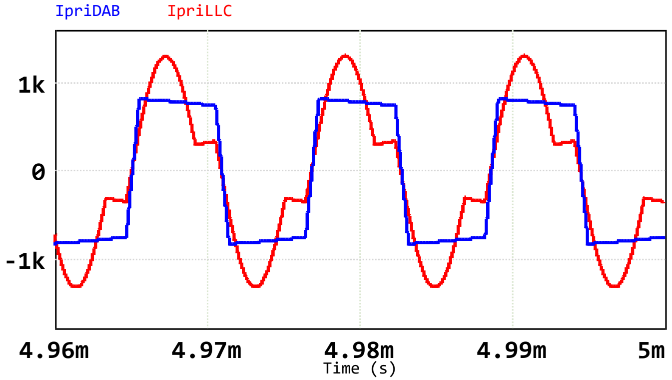
- Vout is perfectly superimposed in steady state
- DAB is slower due to higher electrical values (higher time constants)



- With Angle 1 = 180, Angle 2 = 26 , RMS current is lower for the DAB.
- LLC Lratio = Lm/Llk = 9 (high inductance ratio used for the LLC to keep low RMS).
- LLC assures ZCS on both : On and Off on the secondary, the DAB doesn't with PS modulation.



Deep ZVS @ turn on for DAB and LLC



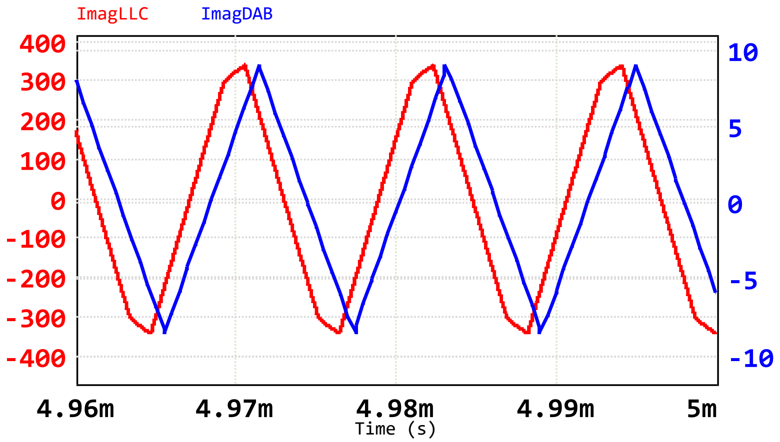
With Angle 1 = 180, Angle 2 = 26 , Iprimary peak is lower for the DAB, as well as the RMS

LLC Design comparison
Pout = 200 kW, Vout = 800V, Vin = 300V, fres HI = 110kHz

DAB						
Conduction Losses			Switching Losses **OFF**			
Irms1 [A]	530		Imax1 [A]	750		
Irms5 [A]	130		Imax5 [A]	300		
Rds on [Ohm]	0.01		tcross [s]	1.50E-08		
Q1 [W]	2809		Q1 [W]	143.44		2952.438
Q5 [W]	169		Q5 [W]	153		322
x4 Mos Pri						11809.75
x4 Mos Sec						1288
Efficiency	**0.938536**					**13097.75**

LLC						
Conduction Losses			Switching Losses			Ploss tot
Irms1 [A]	580		Imax1 [A]	350		
Iavg5 [A]	125		Imax5 [A]	**NA**		
Rds on [Ohm]	0.01		tcross [s]	1.50E-08		
Q1 [W]	3364		Q1 [W]	6.69E+01		3430.938
Q5 [W]	62.5		Q5 [W]	**NA**		62.5
x4 Mos Pri						13723.75
x4 Mos Sec						250
Efficiency	**0.934694**					**13973.75**

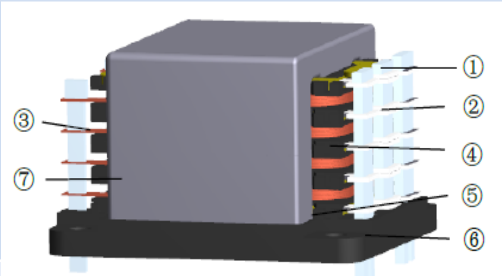
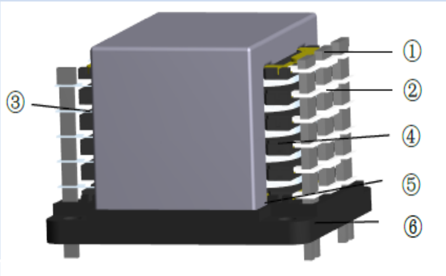
Coincidence!
What we gain in RMS with DAB is gained with free ZCS in LLC.
Electrical Performance is quite similar here, but a crosscheck comparison is always recommended for the specific application.
What about magnetics volume and their losses?



$$B_{peak} = \frac{L}{N \cdot A_e} \cdot I_{peak} \rightarrow \left| \begin{array}{l} L \cdot I_{peak\ DAB} \approx 1000\mu \\ L \cdot I_{peak\ LLC} \approx 800\ \mu \end{array} \right.$$

LLC Design comparison
Pout = 200 kW, Vout = 800V, Vin = 300V, fres HI = 110kHz

Fast prototyping from Sunlord Magnetics

	DAB	LLC
Core (custom)		
Dimensions [cm]	13.4 x 10.4 x 9	same
L_pri [μH]	100	2.25
L_sec [μH]	600	14
L_Lk [μH]	0.33	0.25
Turns ratio [pri/sec]	2:5 ± 0.5	same
DCR pri [mΩ]	0.5	same
DCR sec [mΩ]	2	same
Layers	6 pri / 5 sec	same
GAP [mm]	No gap	14
Losses [W]		≈ 250

Sunlord

Focal point: Max Soriano
max_soriano@sunlordinc.com

Detailed datasheet available

LLC vs DAB Takeaway

	LLC	DAB	Notes
Soft Switching	Yes with limitations	Yes with limitations	LLC: If the working point falls in the «middle frequency range» between resonances then Soft switching is assured on both sides primary ZVS and secondary ZCS. DAB: To assure ZVS soft switching there are two degrees of freedom: Modulation Angles and gain. Or move for advanced modulation techniques (es: triangular, trapezoidal modulations etc.)
Isolation	YES	YES	
RMS current	585 (Pout=200k)	530 (Pout=200k)	LLC RMS currents are Lratio=Lm/Llk dependent, so keep it high being careful to the frequency variation range over the Vbus swing. If Lratio ↑ , then RMS ↓ , while fspan ↑ vs Vbus step. DAB RMS currents are modulation angles and gain dependent. If their selection will be Angle1 = 180 and Angle 2=26 then Soft switching is assured on both sides, plus lower RMS current will be guaranteed.
Frequency	Variable	Fixed	
Components	Higher	Lower	DAB: does not require C_dc_Block if used with Current Mode Contol LLC: does require a secondary side cap. if used in reverse power flow otherwise Vout clamps Lmag. Also, resonant Cap on the primary is required to get resonant action
Bidirectionality	Possible	Possible	
Scalability	Hard	Medium	Easy to replace magnetics; Hard to replace Caps for the LLC due to Layout limitations. Investigate current sharing capability: Hard with variable frequency, but feasible.
Control	Medium	Hard	DAB: requires 8 switches to be controlled. Passive (or synch.) secondary not recommendend because the power falls dramatically. In this case it's convenient to reivent the PSFB adding, Lout. LLC: requires just 4 switches to be controlled with primary Full Bridge; or 2 switches only in Half Bridge mode. Passive secondary assumed for the LLC.
Efficiency	High	High	
Primary Bridge	Half / Full	Full	Volume and cost impact
Secondary Bridge	Half / Full	Full	Volume and cost impact

Ending notes

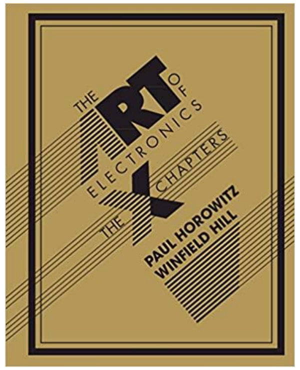
- Check always Soft Switching → look at the waveforms

- No particular math needed: Ohm’s law only.

"It’s easy to be dazzled by the apparent power of mathematics but please resist the temptation to take refuge in complex equations to understand how the circuit really works".
[Horowitz – Hill. The Art of Electronics - Chap 4]

- Sweeping Angles gives much more info than mathematical formulas !

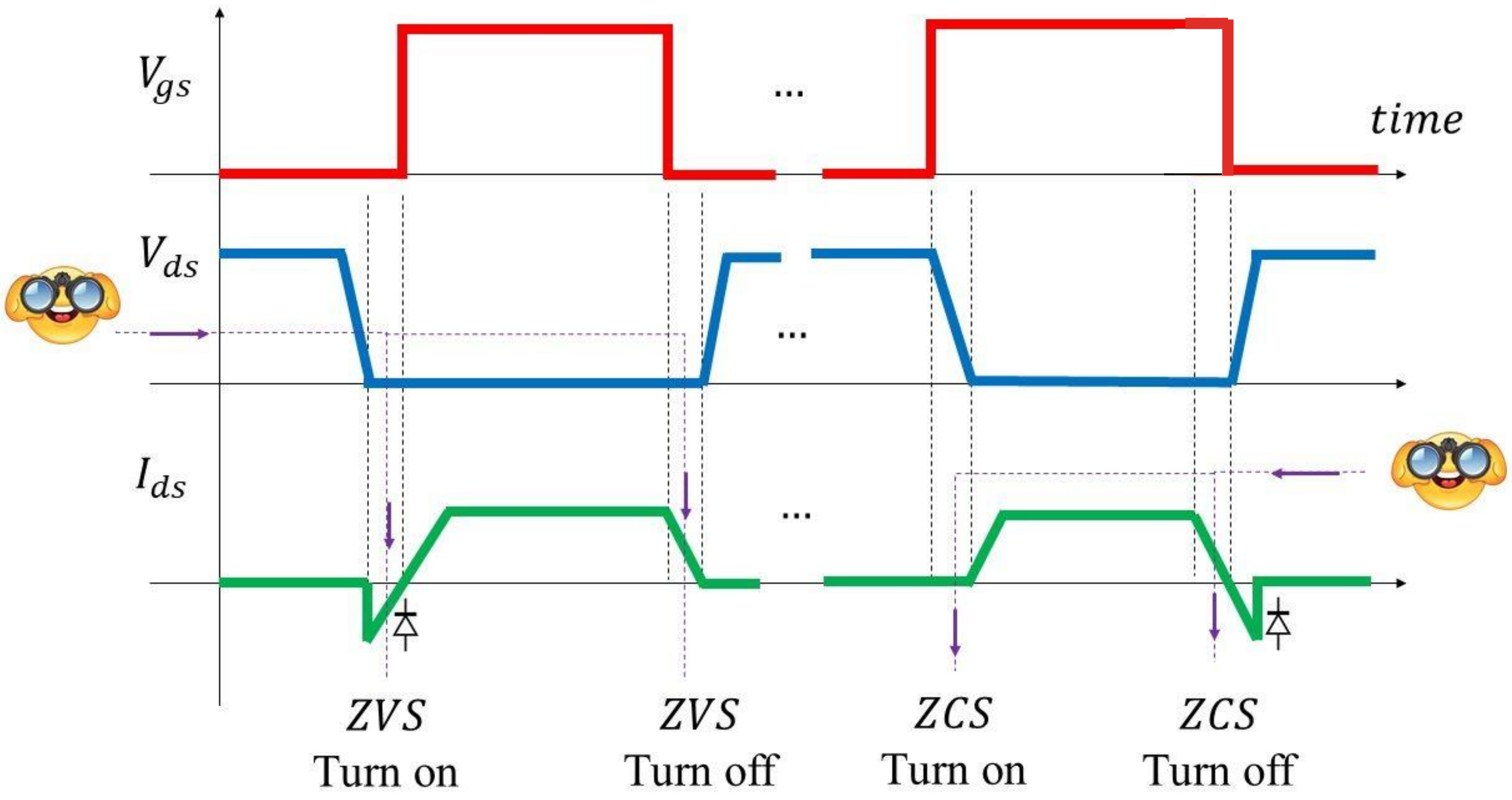
- Combine N. Rosano’s plots with S. Maniktala Scaling Laws



Question for you:
Did you notice, for the DAB, we didn’t talk about Lmag?
Why didn’t we call out a specific value for Lmag in all examples?

Advanced DAB Topics

Advanced modulation techniques
Full Soft Switching : ZCS and ZVS



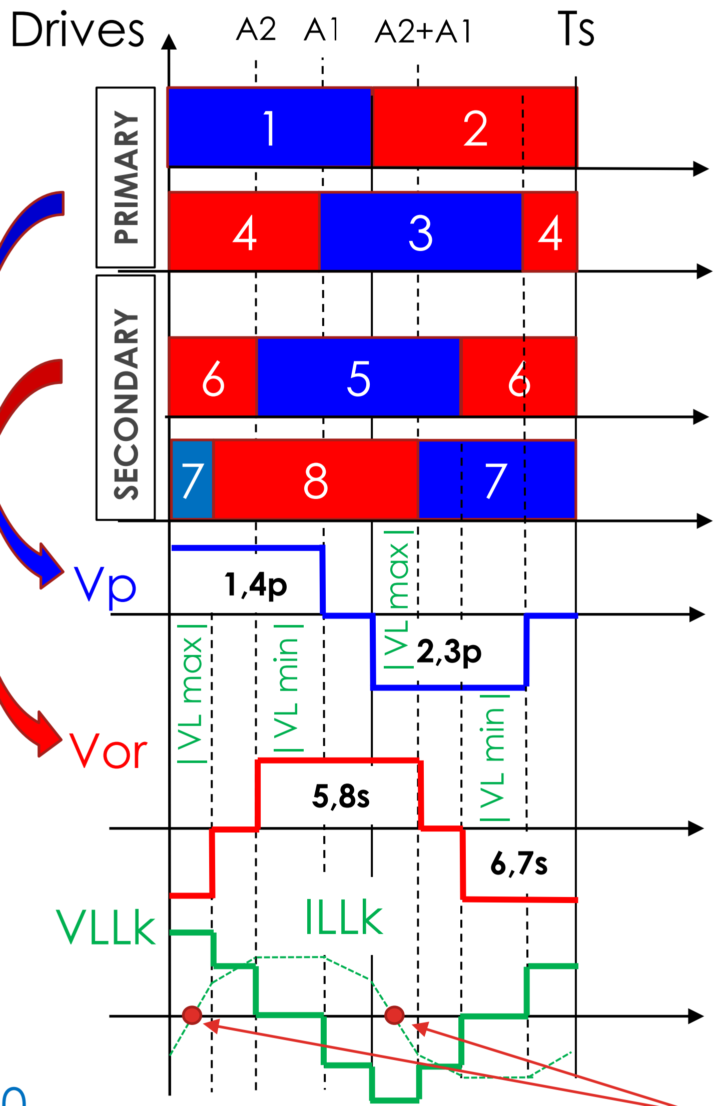
How can we get these?

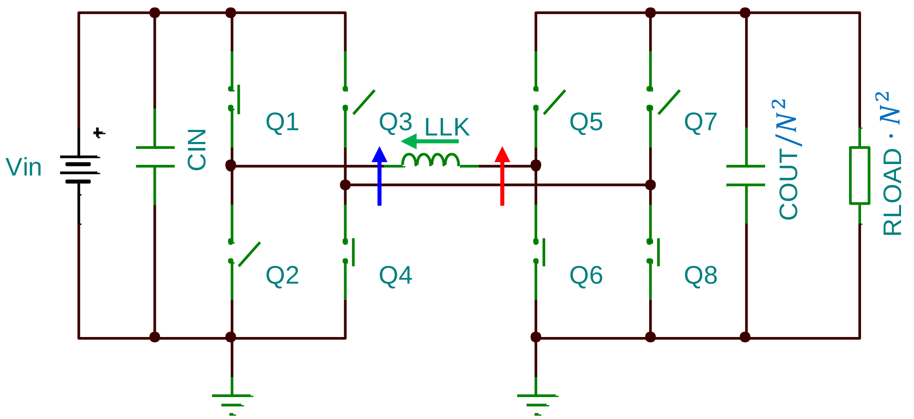
- Select a suitable topology which automatically enables soft switching
- Acting on the control «forcing» soft switching
- Advanced modulation techniques: triangular, trapezoidal, combined etc.

What do we need to look at in the DAB?

- Voltages (Vp and Vor)
- Currents (leakage current)

Advanced modulation techniques
Full Soft Switching : ZCS and ZVS





	ZVS @ turn on	ZCS @ turn off
Q1	i (0) < 0	i (Ts/2)=0
Q2	i (Ts/2)>0	i (0) = 0
Q3	i (A1)> 0	i (A1+Ts/2)= 0
Q4	i (A1+Ts/2)< 0	i (A1)= 0
Q5	i (A2)> 0	i (A2+Ts/2)= 0
Q6	i (A2+Ts/2)< 0	i (A2)= 0
Q7	i (A1+A2)< 0	i (A1+A2+Ts/2)=0
Q8	i (A1+A2+Ts/2)> 0	i (A1+A2)= 0

Switch here to get ZCS but we cannot assure fixed phase shift

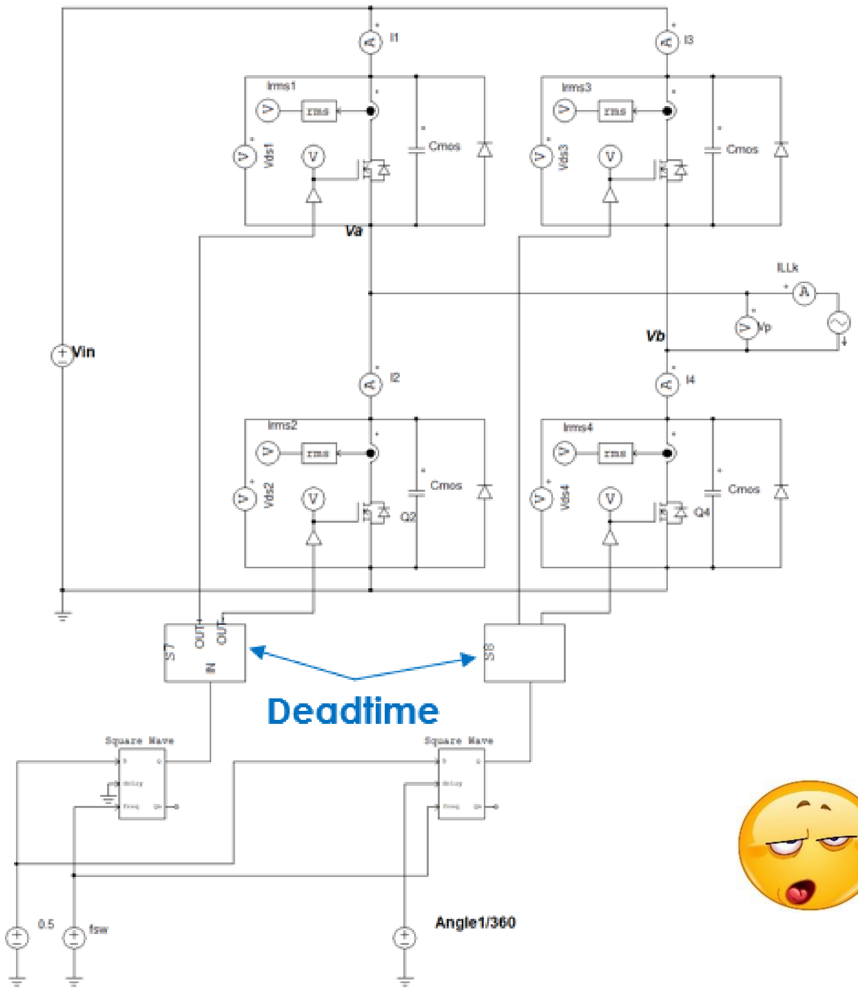
How can we get these?

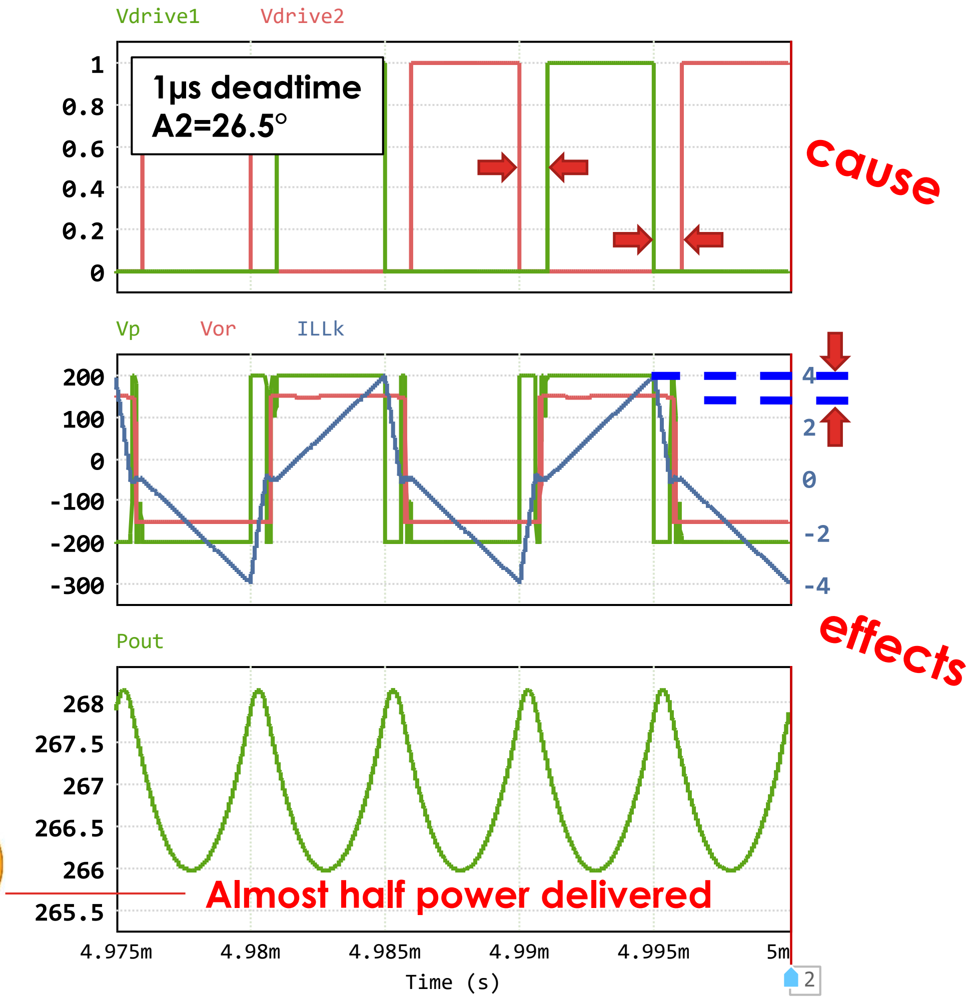
- Select a suitable topology which automatically enables soft switching
- Acting on the control «forcing» soft switching
- Advanced modulation techniques: triangular, trapezoidal, combined etc.

What do we need to look at in the DAB?

- Voltages (Vp and Vor)
- Currents (leakage current)

Testing the DAB kernel – Deadtime effects
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH





Focus on Va node during tdead

- $if\ I_{LLk} < 0\ then$
  $\rightarrow D1_{on} \rightarrow V_a = V_{in}$
- $if\ I_{LLk} > 0\ then$
  $\rightarrow D2_{on} \rightarrow V_a = 0$

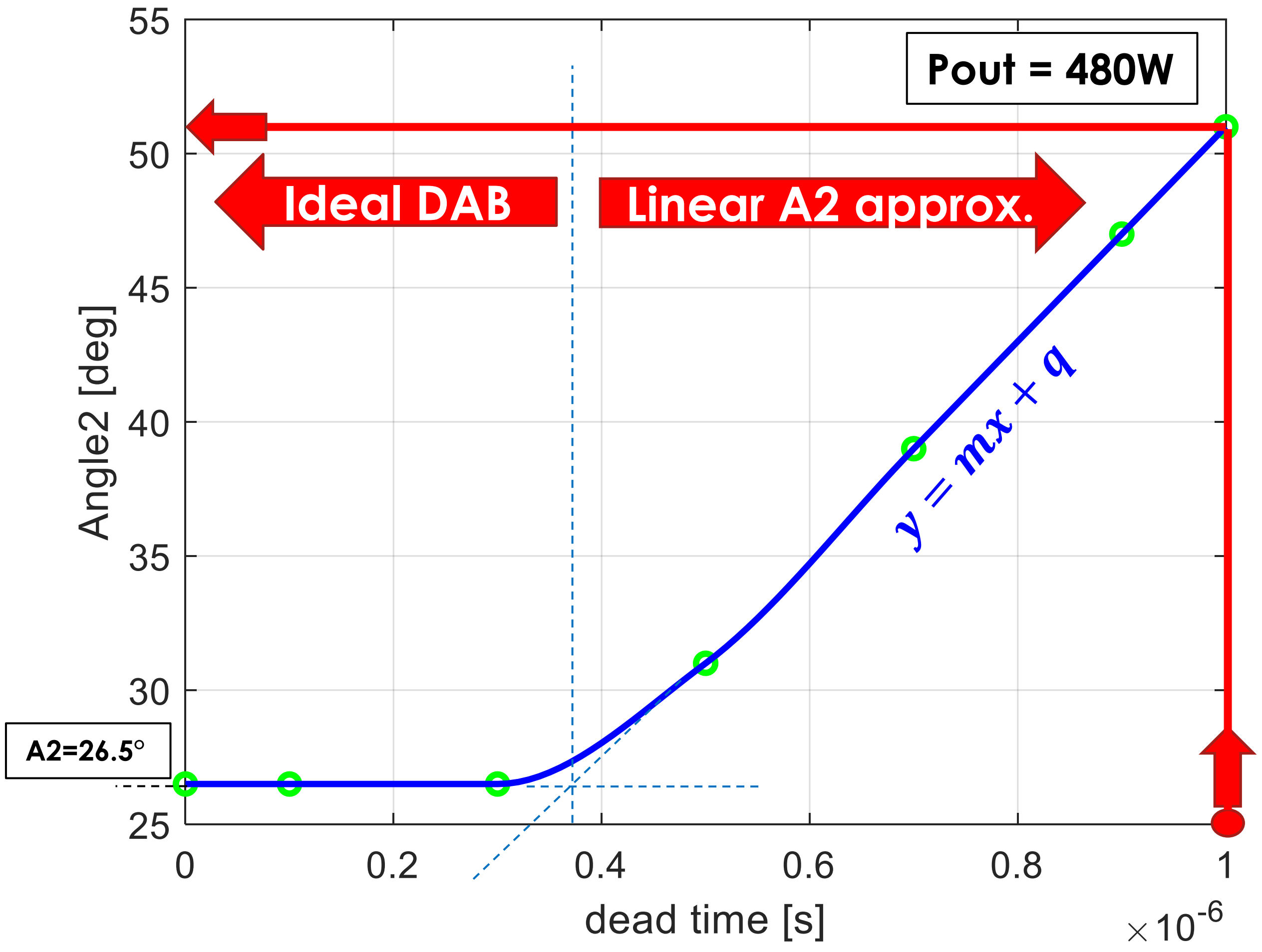
Same as for Vb node.

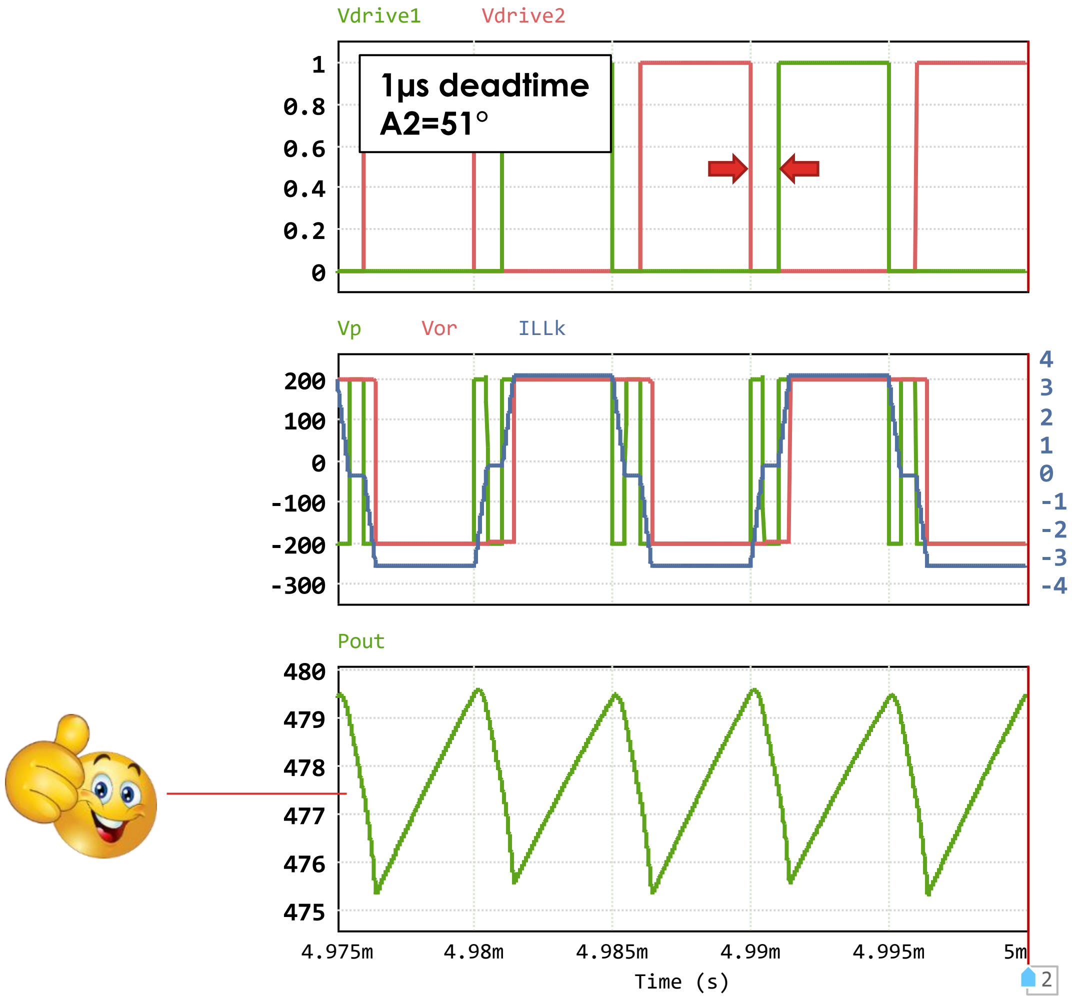
Deadtime cons:

- *Voltage polarity inversion on Vp*
- *Average voltage nodes shift*
- *Output power drop*
- $Gain = \frac{V_{or}}{V_{in}} \neq 1$

Testing the DAB kernel – Deadtime effects

Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

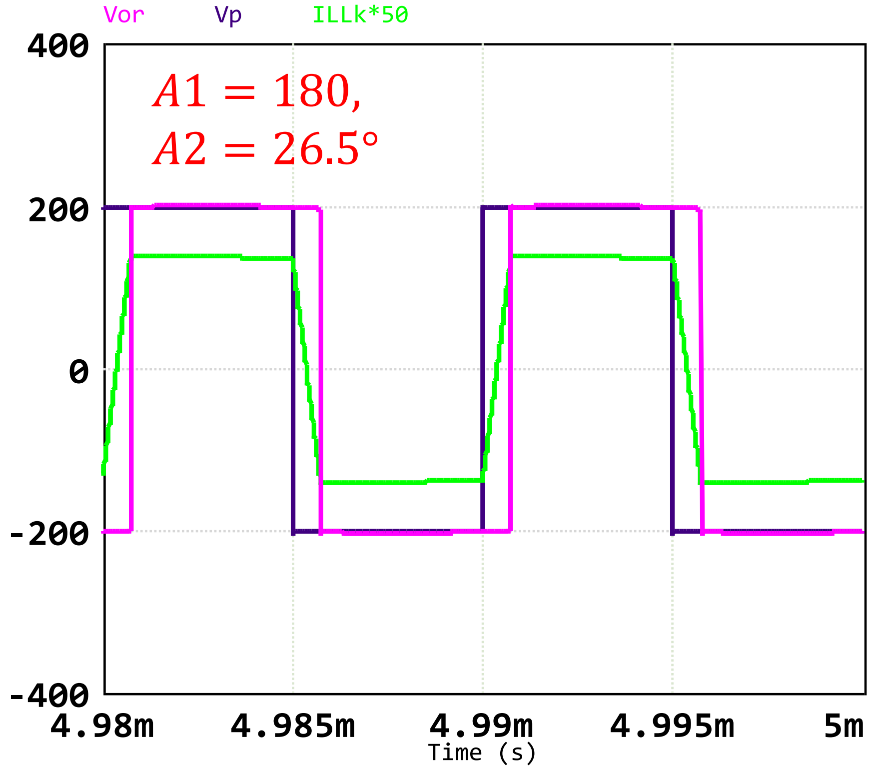




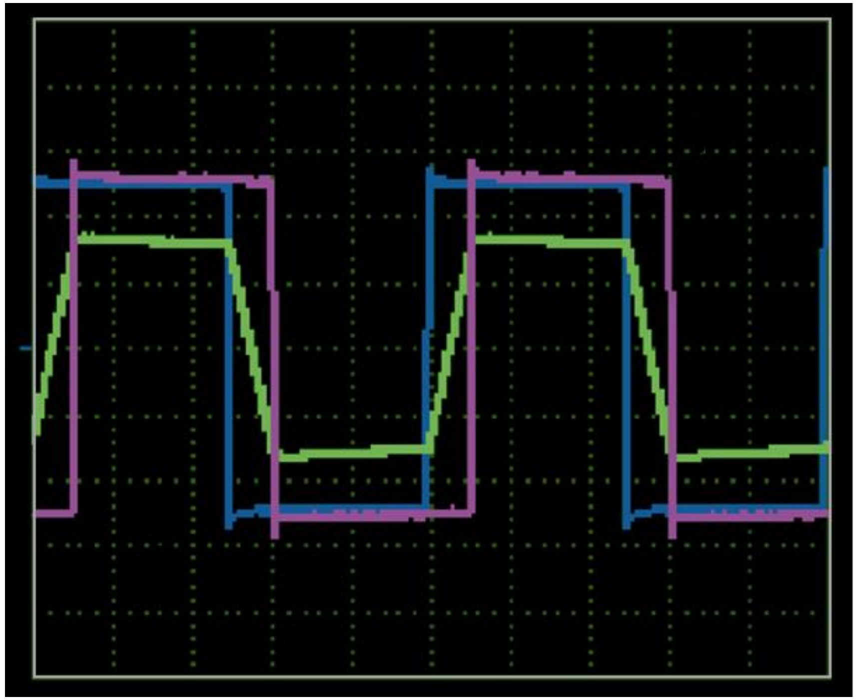
Solution:
Keep the dead time not so short to enable Cds discharge, as well as not so long increasing antiparallel diode losses plus the output power drop effect. Td is strongly dependent on the application (leakage inductance – Fet selection VS working conditions).

Testing the DAB kernel – Deadtime effects
Vin=200V; Vout=48V; P=480W; fsw=100k; gain=1; LLk=52µH

PSIM

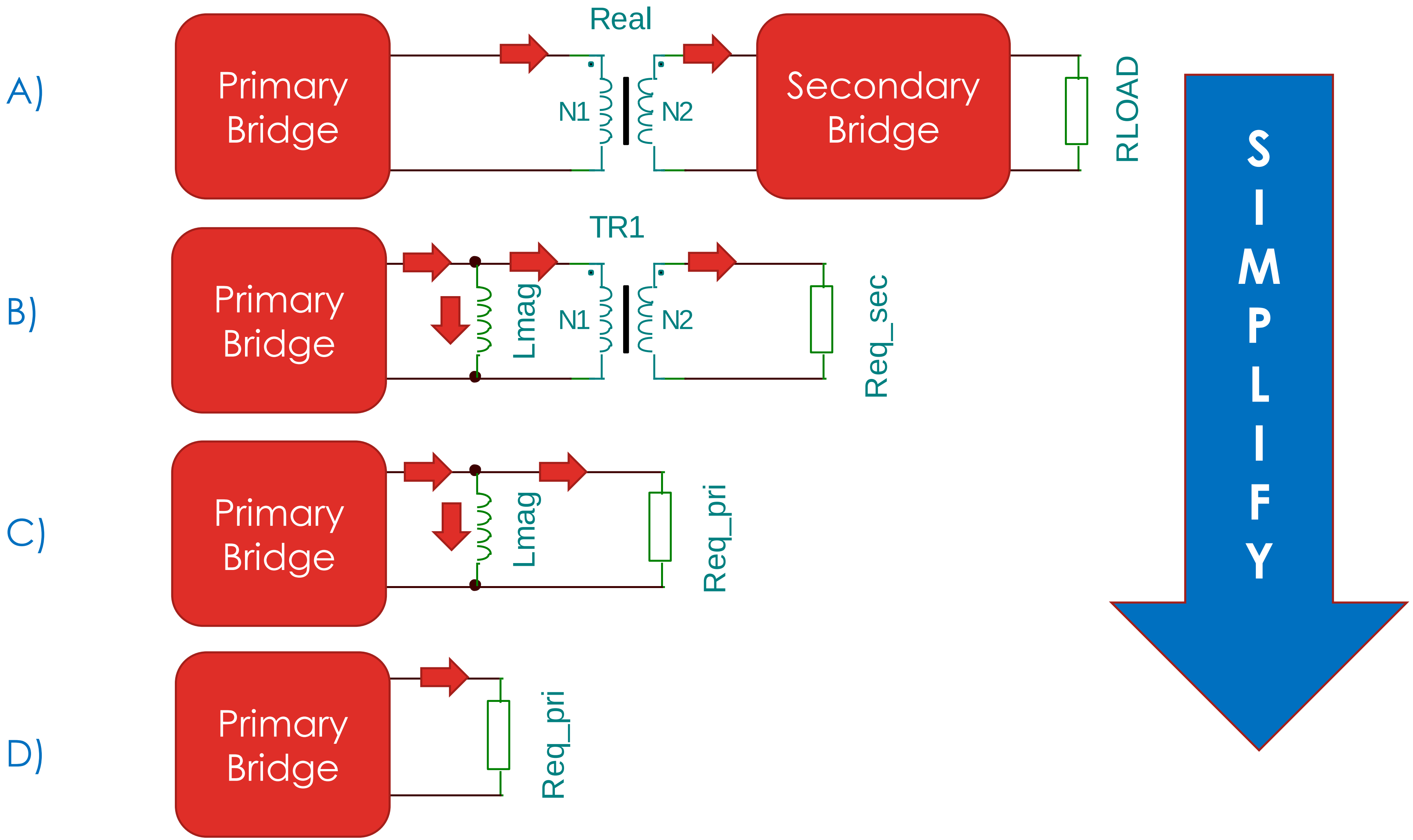


Hardware



Solution:
Keep the dead time not so short to enable Cds discharge, as well as not so long increasing antiparallel diode losses plus the output power drop effect. Td is strongly dependent on the application (leakage inductance – Fet selection VS working conditions).

Understanding the transformer action

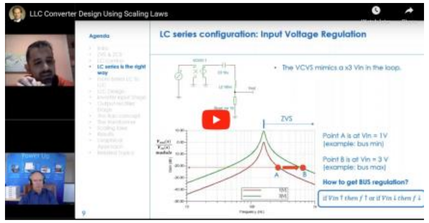


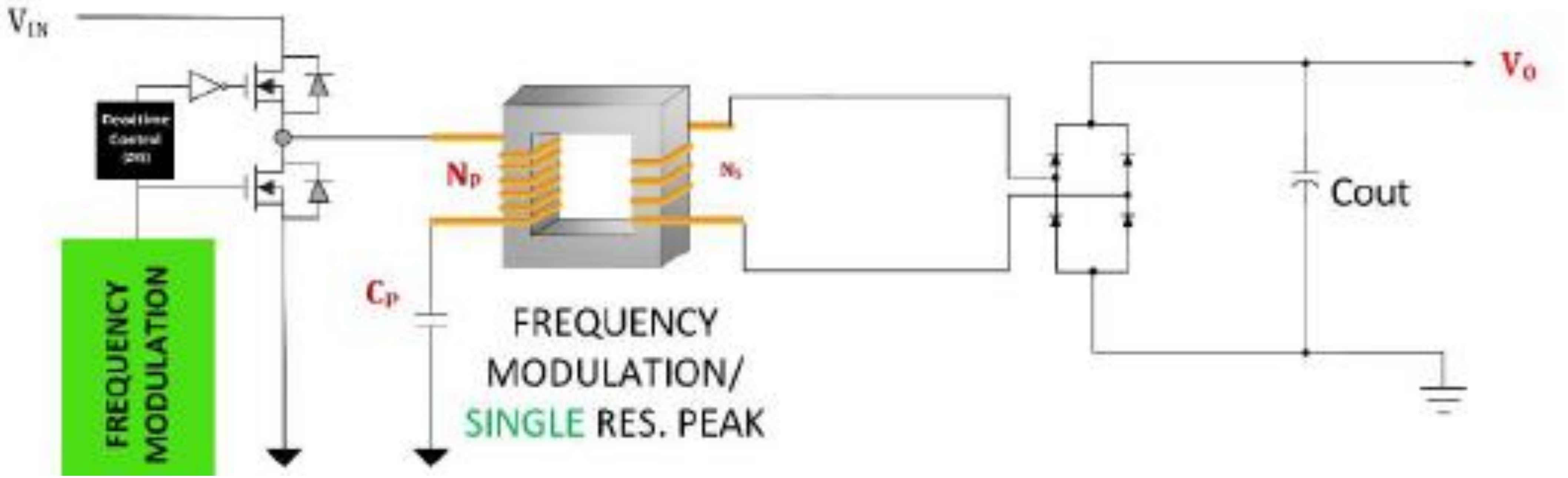
Nicola Rosano Projects

Rosano Projects: Highly Efficient Wireless Power Transfer Systems

100% grip on LLC converter

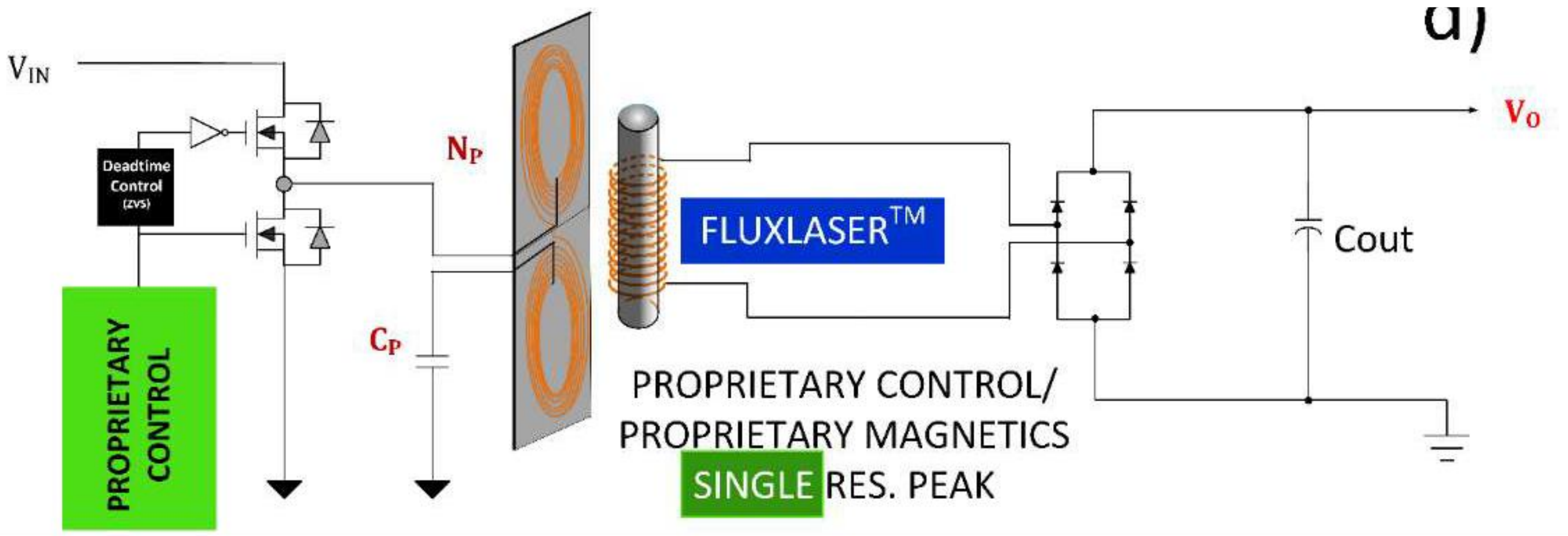
Get a grip here:





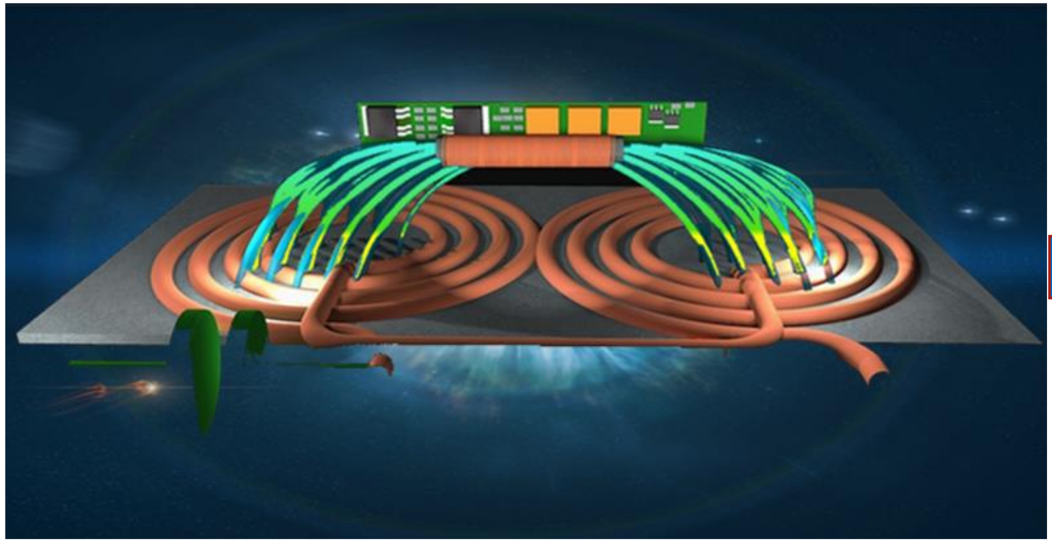
Rosano Projects: Highly Efficient Wireless Power Transfer Systems

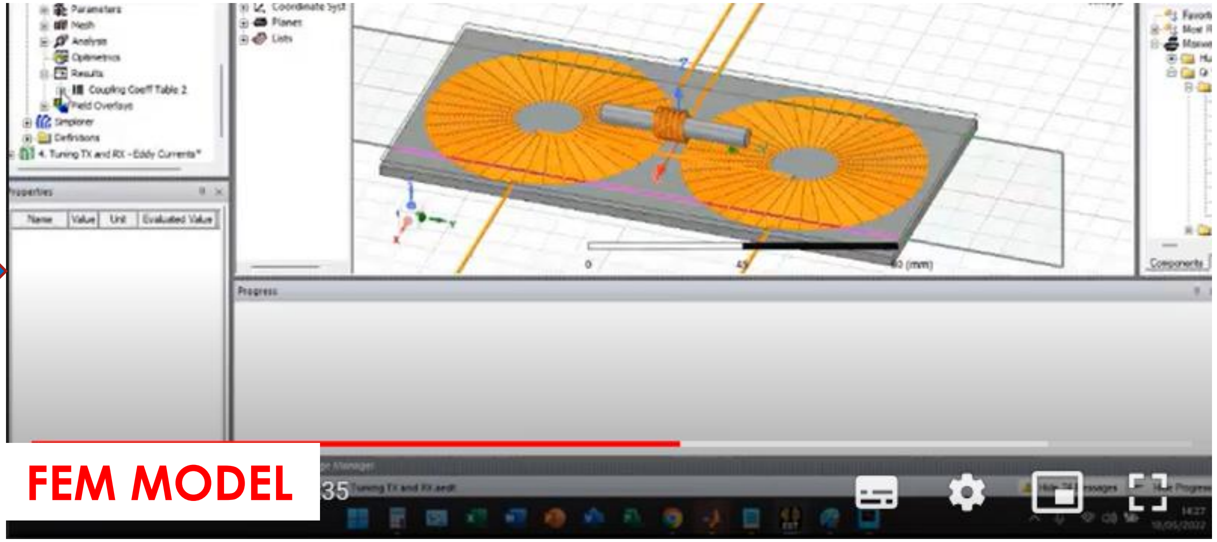
100% grip on LLC converter → Mapping the LLC to the WPT brother



Rosano Projects: Highly Efficient Wireless Power Transfer Systems

100% grip on LLC converter → Mapping the LLC to the WPT brother → Confirm intuitions with simulation



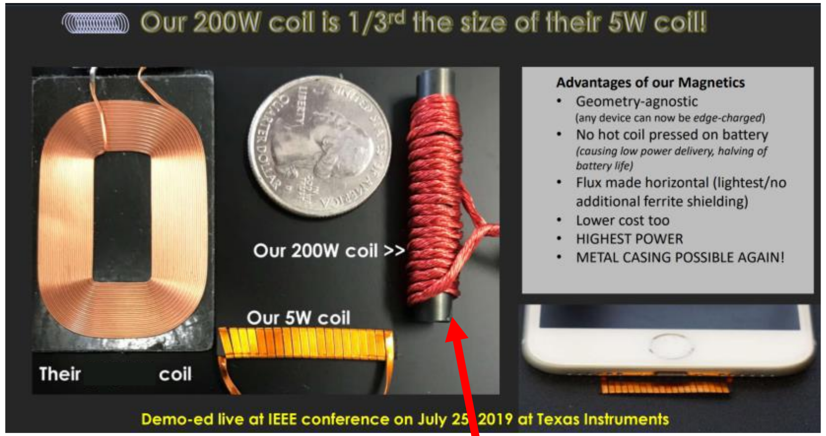


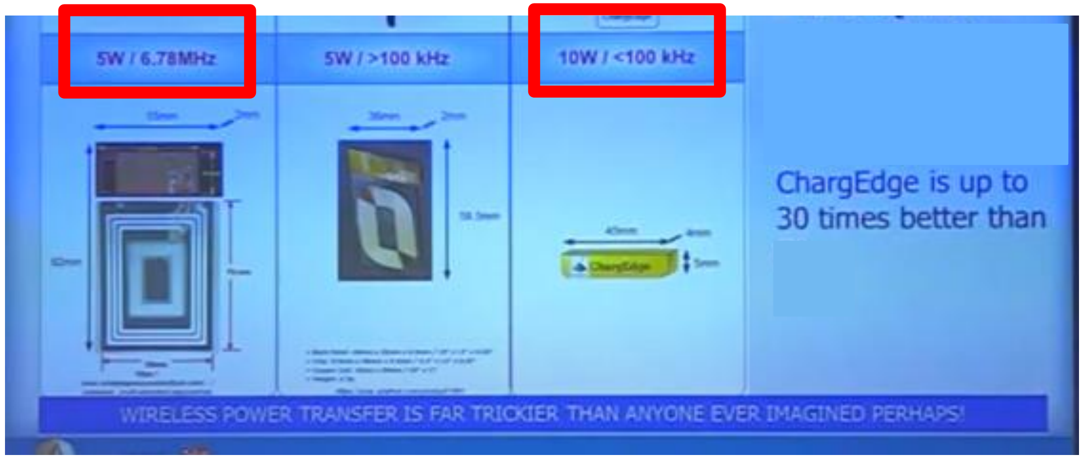
(12) **United States Patent**
Maniktala et al.

(10) **Patent No.: US 10,804,726 B2**
(45) **Date of Patent: Oct. 13, 2020**

Rosano Projects: Highly Efficient Wireless Power Transfer Systems

100% grip on LLC converter → Mapping the LLC to the WPT brother → Confirm intuitions with simulation → Studying Competitors

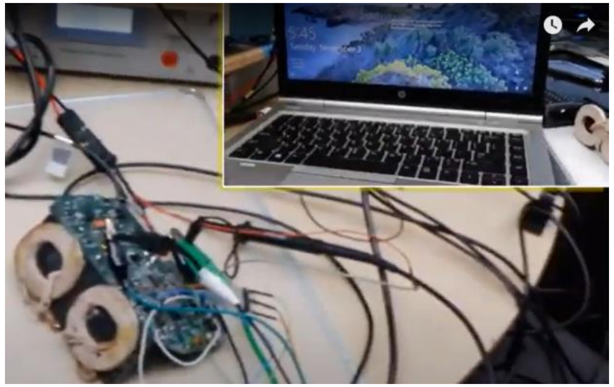




Look at power vs dimensions
(Chargedge RX)

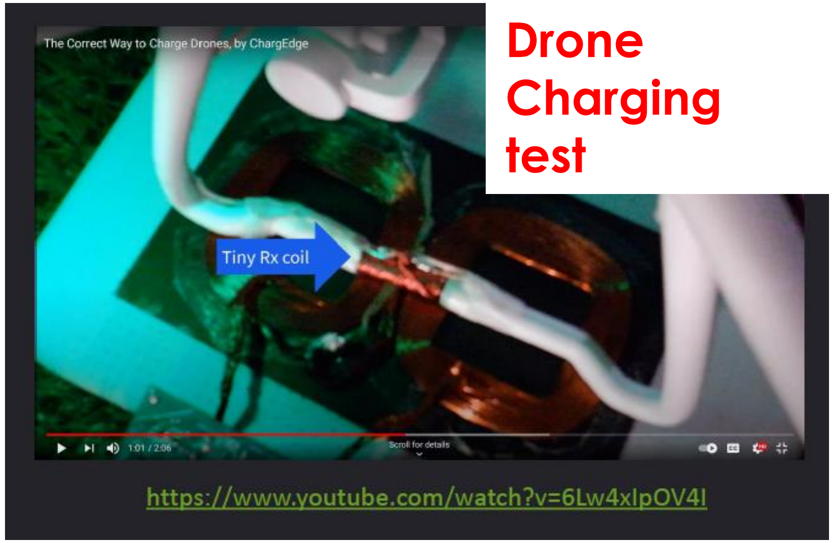
Rosano Projects: Highly Efficient Wireless Power Transfer Systems

100% grip on LLC converter → Mapping the LLC to the WPT brother → Confirm intuitions with simulation → Studying Competitors → FACTs (Sanjaya style)



Laptop 60W test

100 and 200W Led lamp test



Drone Charging test

Rosano Projects: Highly Efficient Wireless Power Transfer Systems

100% grip on LLC converter → Mapping the LLC to the WPT brother → Confirm intuitions with simulation → Studying Competitors → FACTs (Sanjaya style) → Scaling Laws to Electric Vehicles >6kW

Almost 5 years

ChargeEdge is open to collaborations!

Nicola Rosano: nicolarosano85@gmail.com

Contacts:
Gregory Clark: gregg@chargedge.com
Robert Tetrault: bob.tetrode@gmail.com

Acknowledgements

- Ray Ridley, for hosting me and his massive contribution to our world as well as his patience to give technical support to all power electronics engineers.

- Power Supply Design FaceBook Goup

- Ridley Engineering Power Supply Design Center

RIDLEY ENGINEERING

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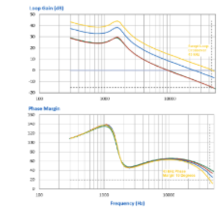
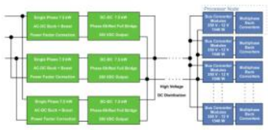
Our Most Popular Design Center Articles

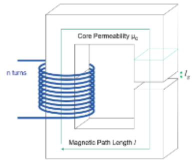
[114] TRANSIENT LOOP SWEEPS OUTPERFORM SMALL-SIGNAL MODELS



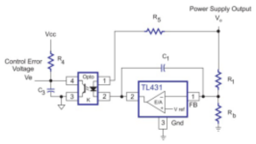
FEATURED ARTICLE: [111] ZVS FULL-BRIDGE CONVERTER EMPLOYING AN ACTIVE SNUBBER



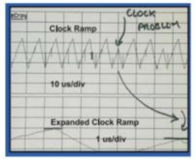
[102] CUSTOM INDUCTORS – ONE DESIGN EQUATION



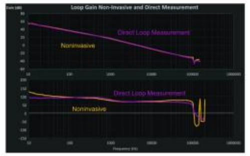
[A21] DESIGNING WITH THE TL431



[A08] SIX COMMON REASONS FOR POWER SUPPLY INSTABILITY



[083] NONINVASIVE LOOP GAINS FROM OUTPUT IMPEDANCE MEASUREMENTS



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