Unified Analysis of Isolated Bidirectional Converters for Battery Charging

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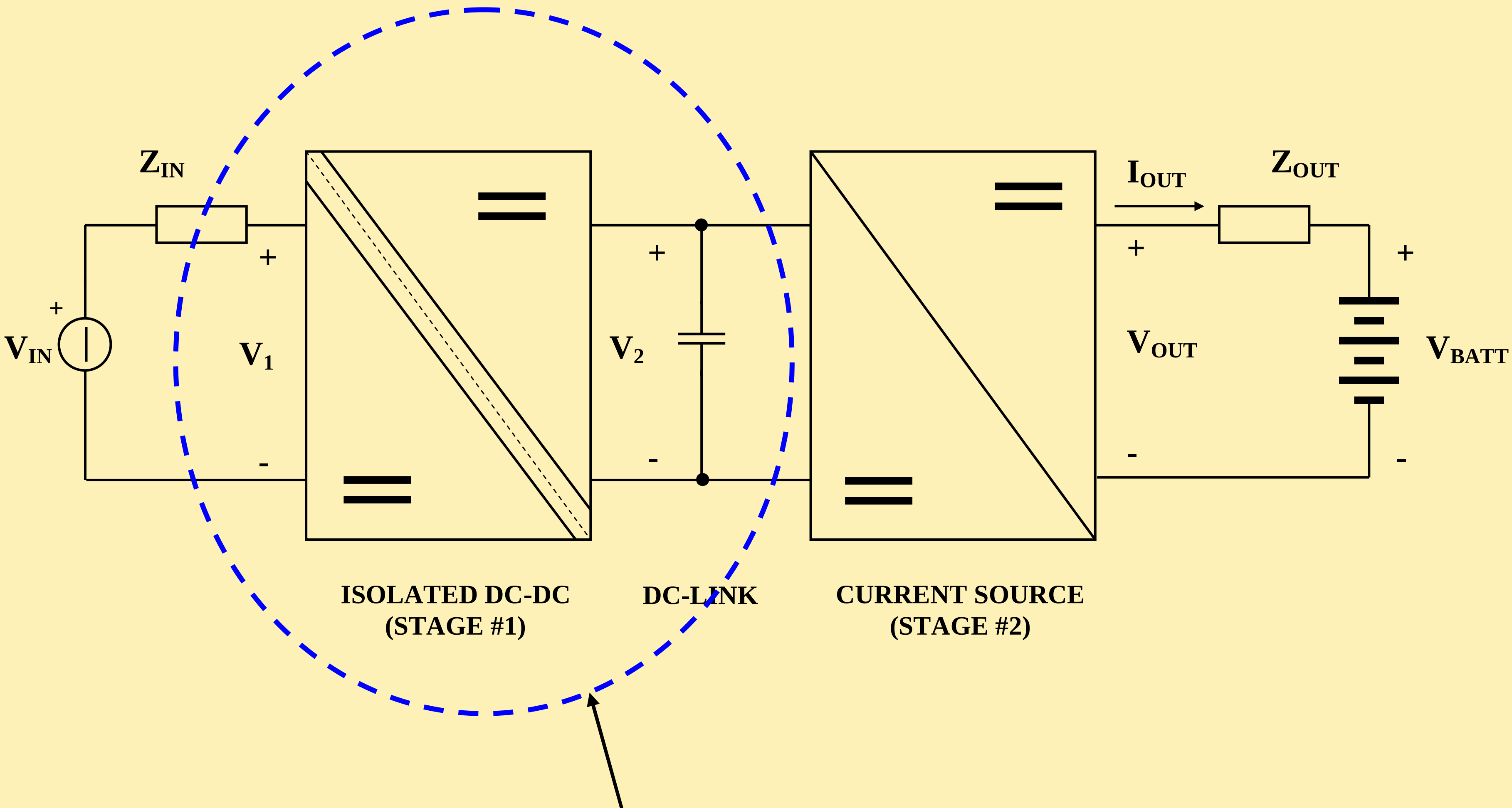
Outline

- Introduction
- Review of Considered Converter Topologies
  - Single-Phase Dual Active Bridge (DAB)
  - Single-Phase Series Resonant DAB (SR-DAB)
  - Three-Phase Dual Active Bridge (DAB)
  - Three-Phase Series Resonant DAB (SR-DAB)
  - Interleaved Boost with Coupled Inductor (IBCI)
- Unified Analysis
- Soft-switching conditions
- Transferred Power Calculation

Introduction



Focus on the isolated stage

(V_1 = high voltage port, V_2 = low voltage port)

Isolated Bidirectional Topologies

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

- **topologies with reduced switch count**
  - **Flyback**
  - **Cuk**
  - **Sepic**
  - **....**
- **topologies with dual bridge (or half-bridge or push-pull) configuration**
  - **Dual Active Bridge (DAB)**
  - **Interleaved Boost with Coupled Inductors (IBCI)**
  - **....**
- **topologies with dual bridge configuration and high frequency resonant networks**
  - **Series Resonant DAB (SR-DAB)**
  - **....**

Reduced Switch Count Topologies

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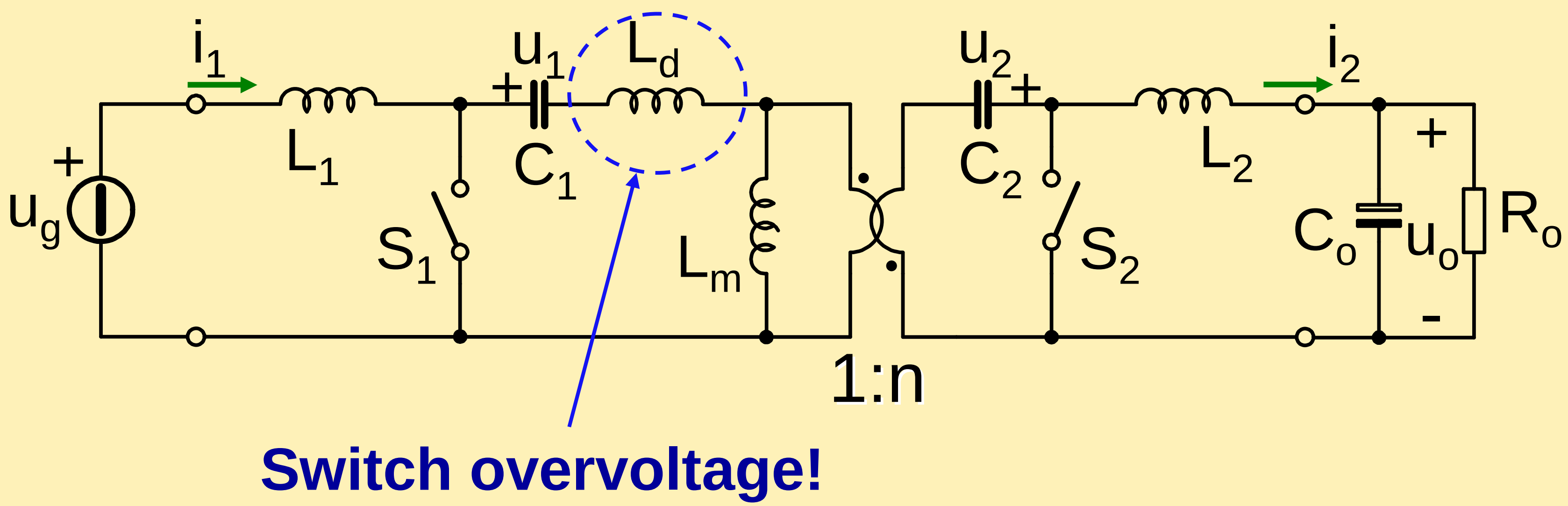
- High voltage and/or current stress on active components
- Limited soft-switching operation
- Transformer leakage inductance requires suitable snubber circuits

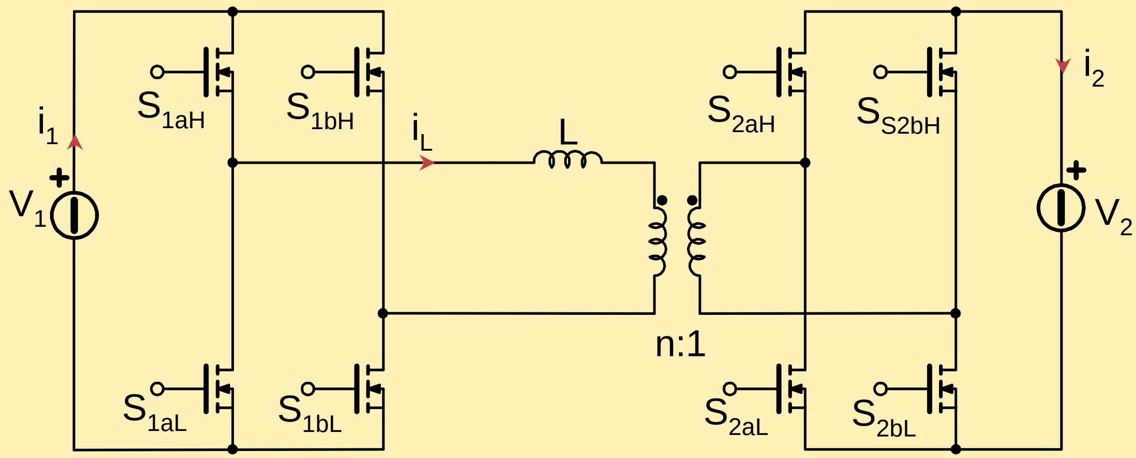
Example: bidirectional Cuk converter



Dual Active Bridge (DAB)

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Single-phase:

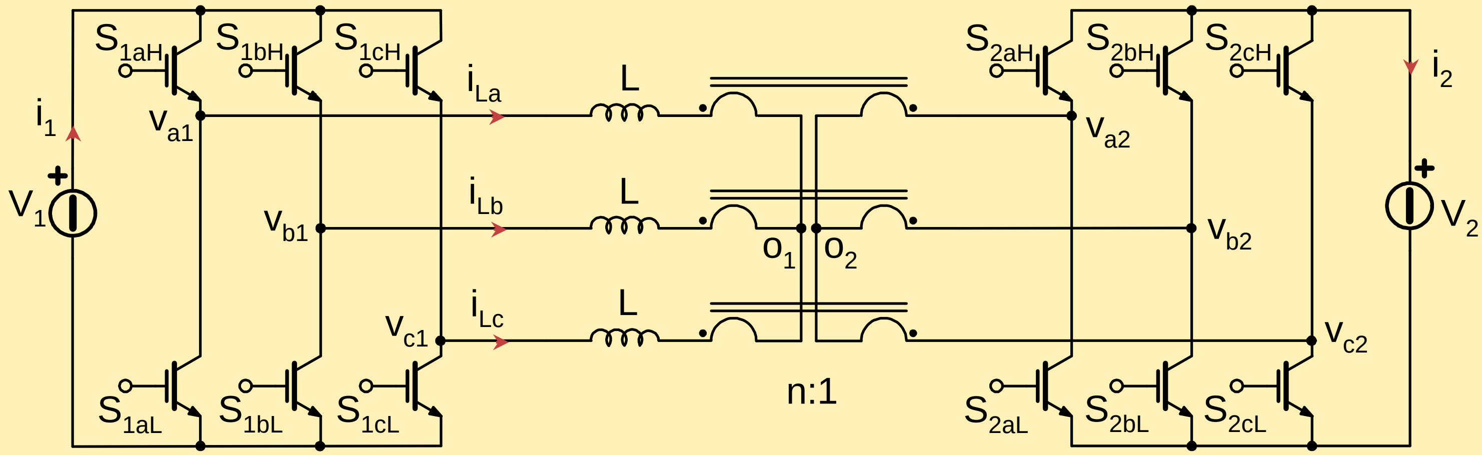


- **Simple phase-shift modulation**
- **Extended soft-switching operation**
- **Exploitation of transformer leakage inductance**
- **Optimum design for constant port voltages V_1 and V_2**

Dual Active Bridge (DAB)

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Three-phase:

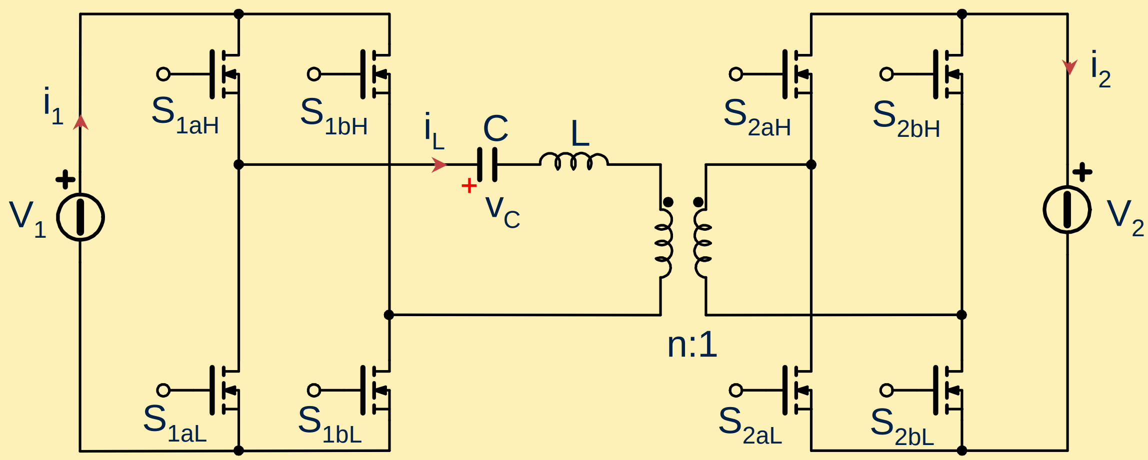


- **Simple phase-shift modulation**
- **Extended soft-switching operation**
- **Exploitation of transformer leakage inductance**
- **Optimum design for constant port voltages V_1 and V_2**
- **Reduced input and output current ripples**

Series Resonant Dual Active Bridge (SR-DAB)

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Single-phase:

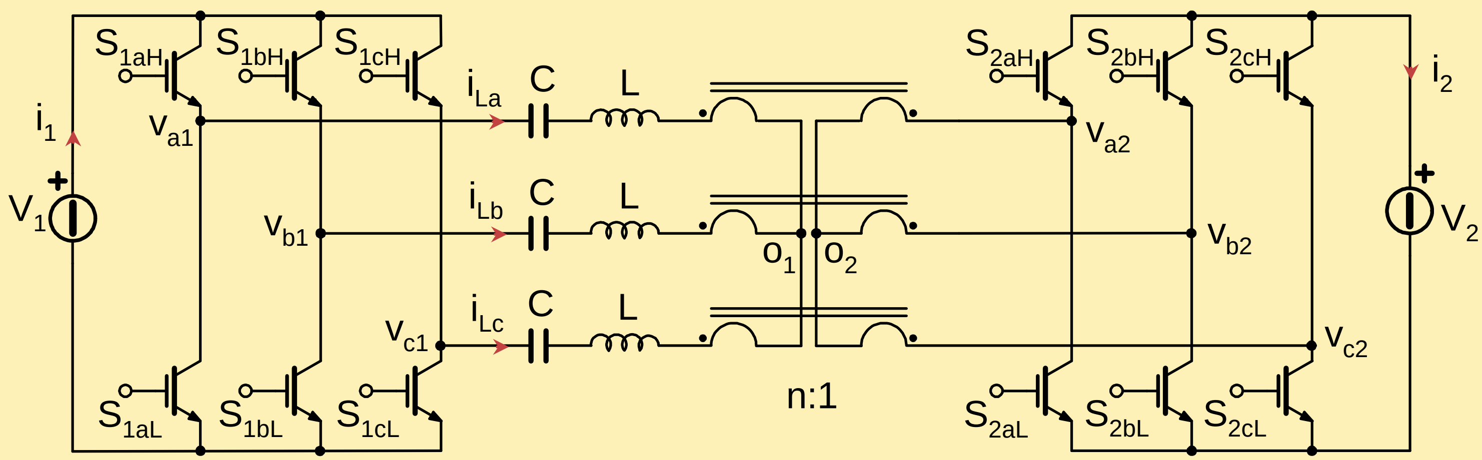


- **Same characteristics as single-phase DAB**
- **Higher degree of freedom (two parameters: L and C)**
- **Inherent protection against transformer saturation (with C split between primary and secondary)**

Series Resonant Dual Active Bridge (SR-DAB)

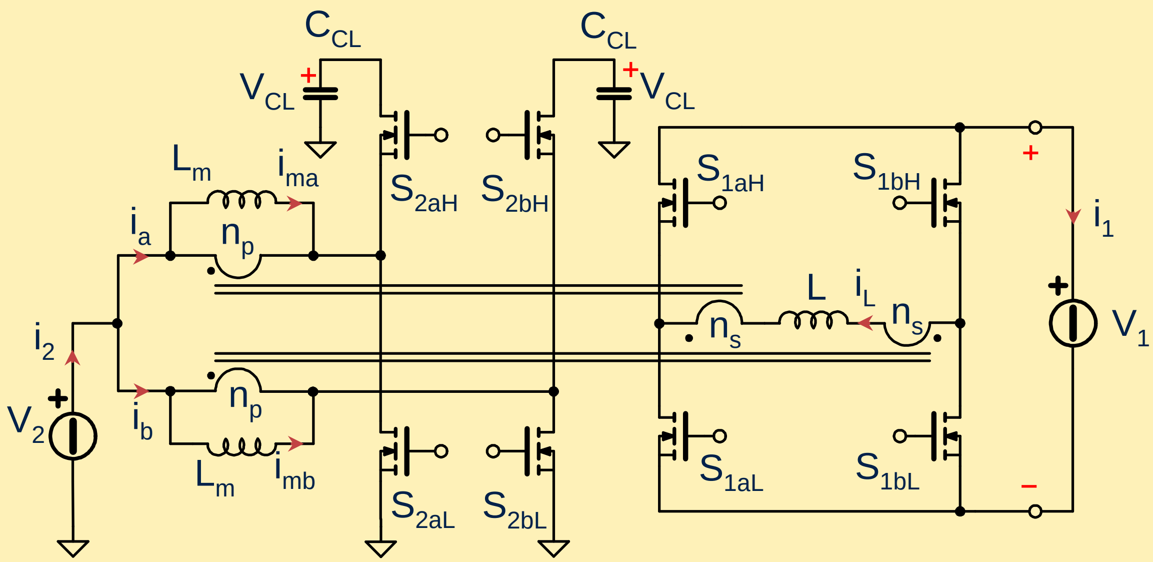
DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Three-phase:



- **Same characteristics as three-phase DAB**
- **Higher degree of freedom (two parameters: L and C)**
- **Inherent protection against transformer saturation (with C split between primary and secondary)**

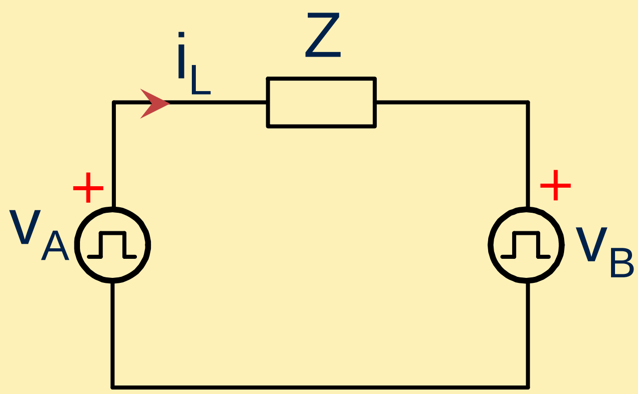
Interleaved Boost with Coupled Inductors (IBCI)



- **Simple phase-shift modulation**
- **Extended soft-switching operation**
- **Exploitation of mutual inductor leakage inductance**
- **Duty-cycle control of port 2 switches for variable port voltages V_1 and V_2**
- **Reduced port 2 current ripple (low-voltage high-current port)**

Unified Analysis

- **All the aforementioned topologies control the power transfer between the two ports by modulating the voltage applied to a current shaping impedance**



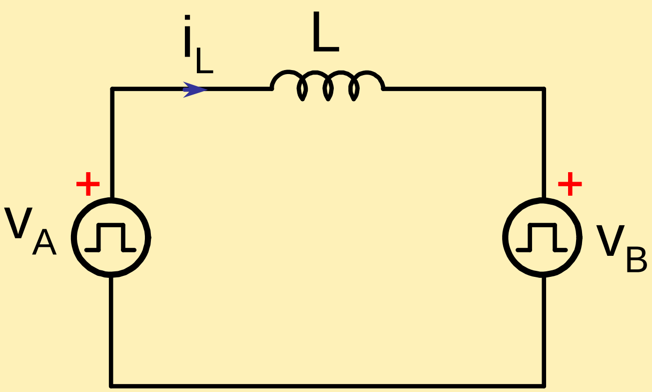
- **For DAB and IBCI topologies, Z is a simple inductor while for SR-DAB topologies Z is a series resonant L-C tank**

Phase-Shift Modulation

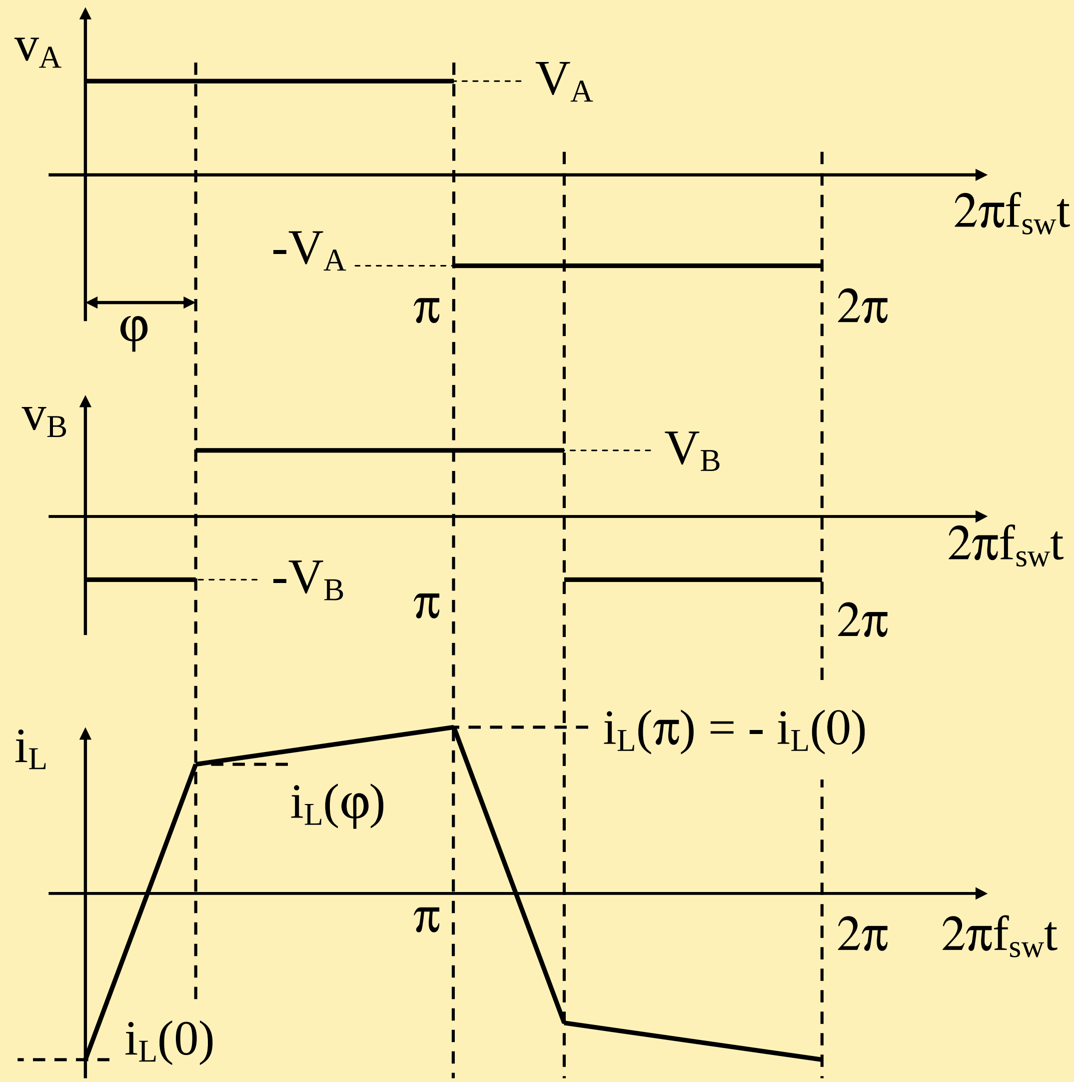
DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Example: power transfer from v_A to v_B

Single-phase DAB



$V_A > V_B$



Phase-Shift Modulation

- **v_A and v_B are square wave voltages of amplitudes V_A and V_B, respectively**

$$V_A = V_1 \qquad\qquad V_B = nV_2$$

- **The power transfer between ports 1 and 2 is controlled through the phase-shift angle φ**

$$0 \le \varphi \le \pi/2 \qquad v_A \xrightarrow{P} v_B$$

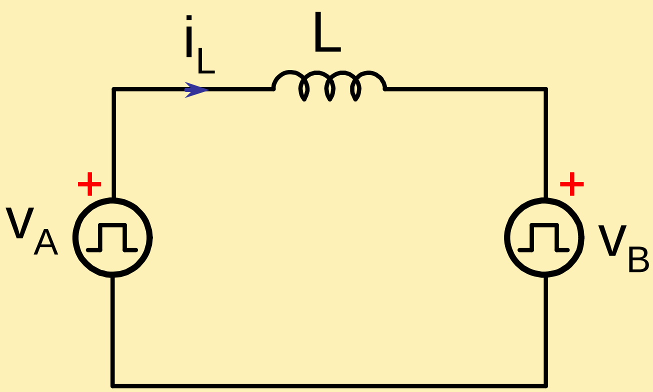
$$-\pi/2 \le \varphi \le 0 \qquad v_A \xleftarrow{P} v_B$$

- **Inductor current has a piecewise linear behavior (DAB)**

Plus Phase-Shift Modulation

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

IBCI converter

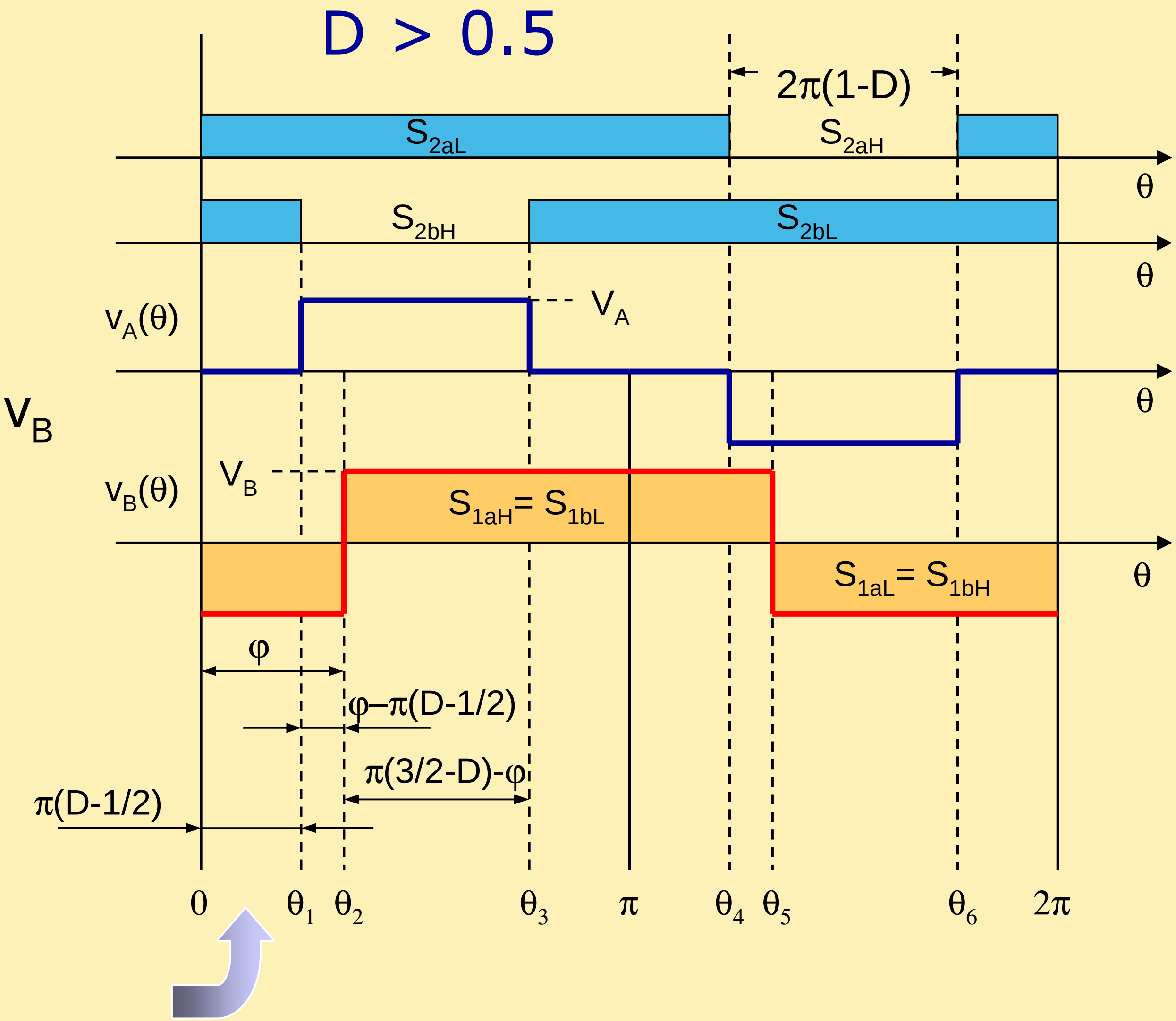


Case A:

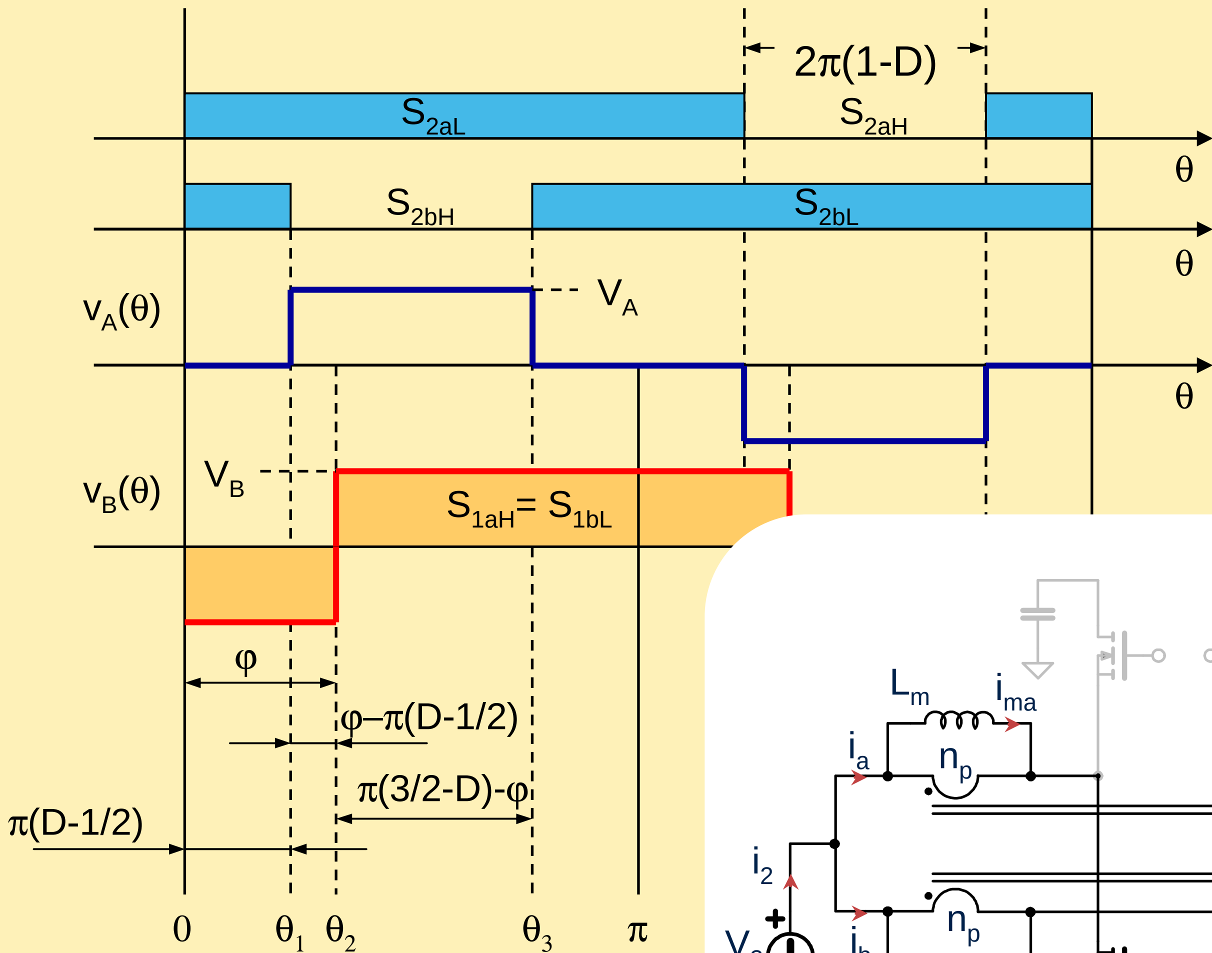
$$0 < \varphi < \pi(D-1/2)$$

Case B:

$$\pi(D-1/2) < \varphi < \pi/2$$



Plus Phase-Shift Modulation

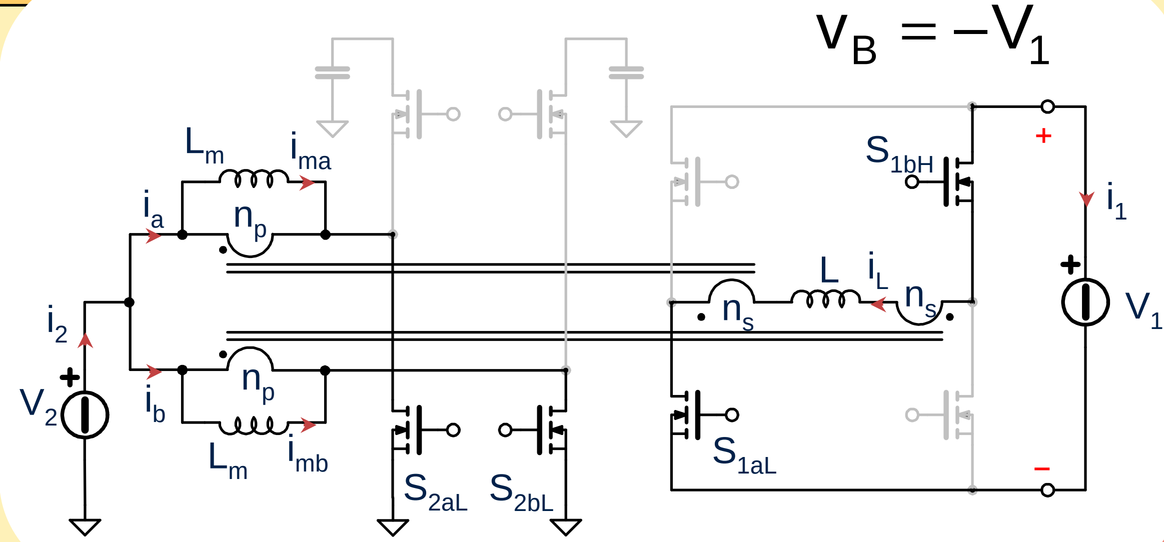


IBCI converter

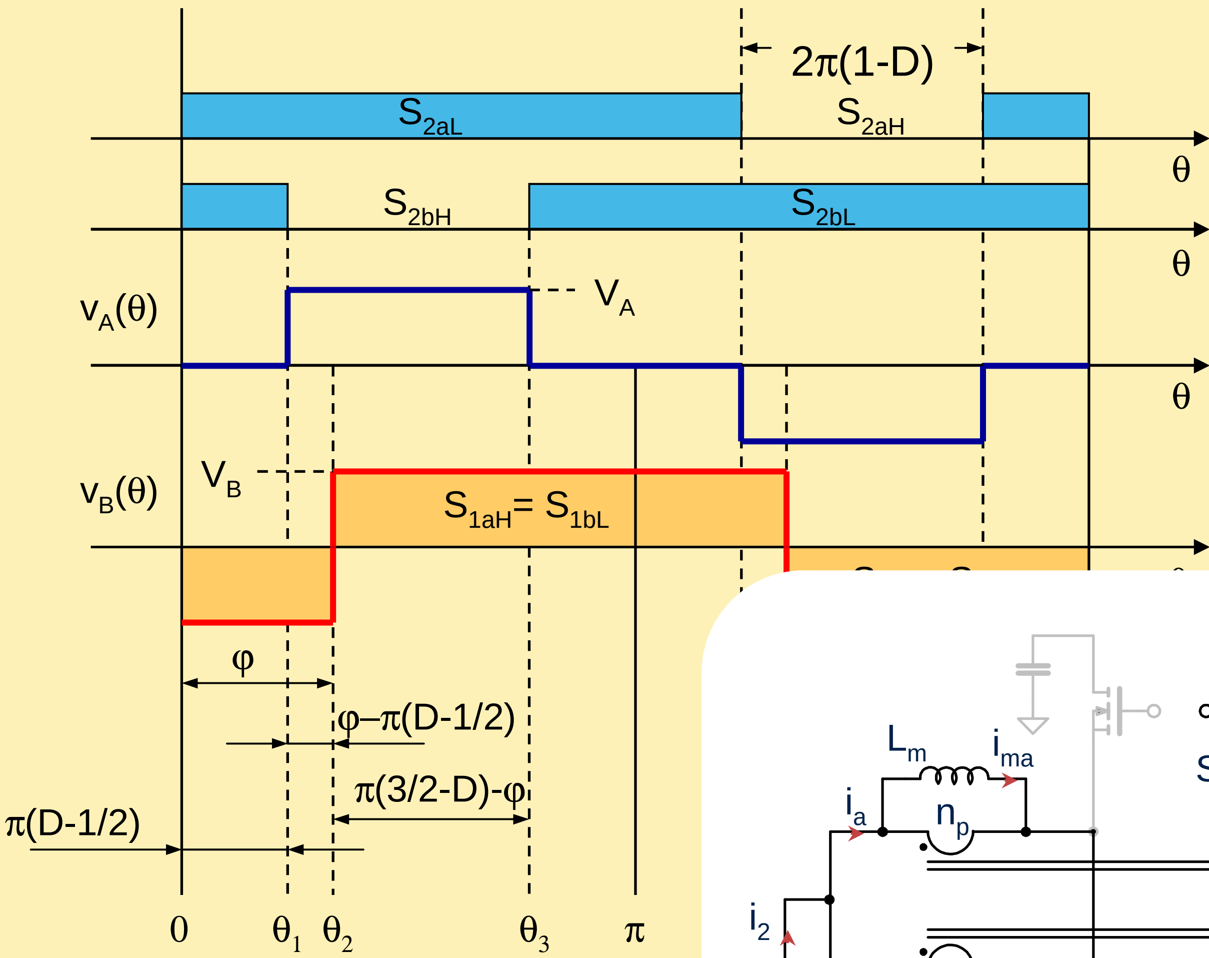
$$0 \le \theta \le \theta_1$$

$$v_A = 0$$

$$v_B = -V_1$$



Plus Phase-Shift Modulation



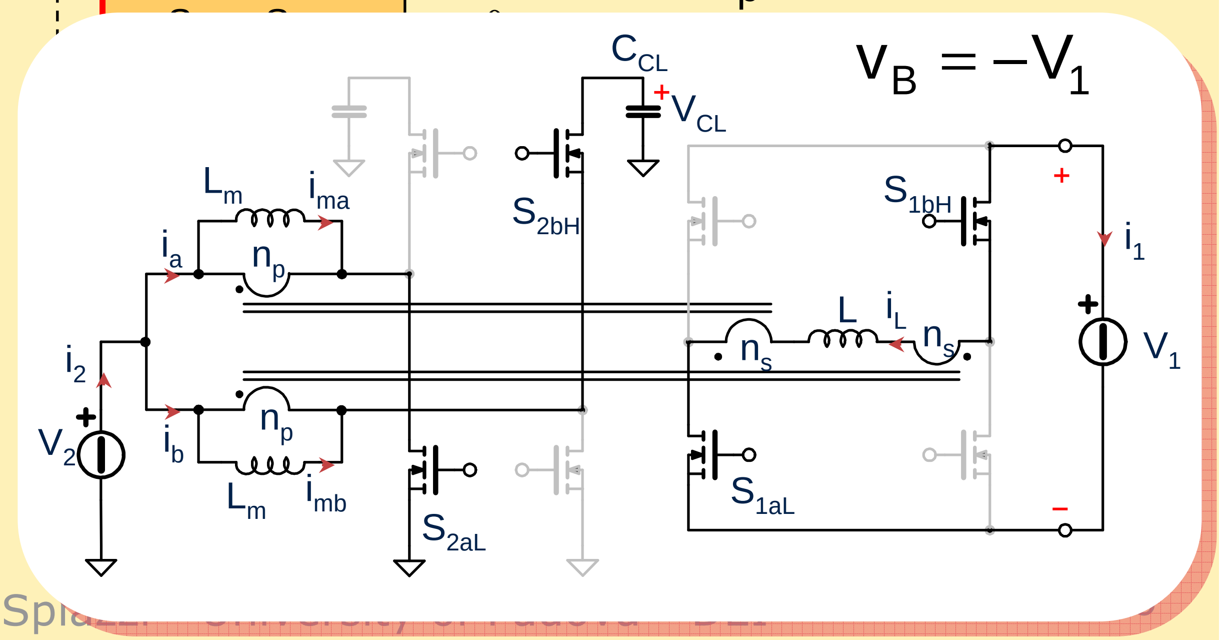
IBCI converter

$$\theta_1 \le \theta \le \theta_2$$

$$v_A = \frac{n_s}{n_p}\left(V_g - V_g + V_{CL}\right)$$

$$= \frac{n_s}{n_p} V_{CL} = V_A$$

$$v_B = -V_1$$



Plus Phase-Shift Modulation

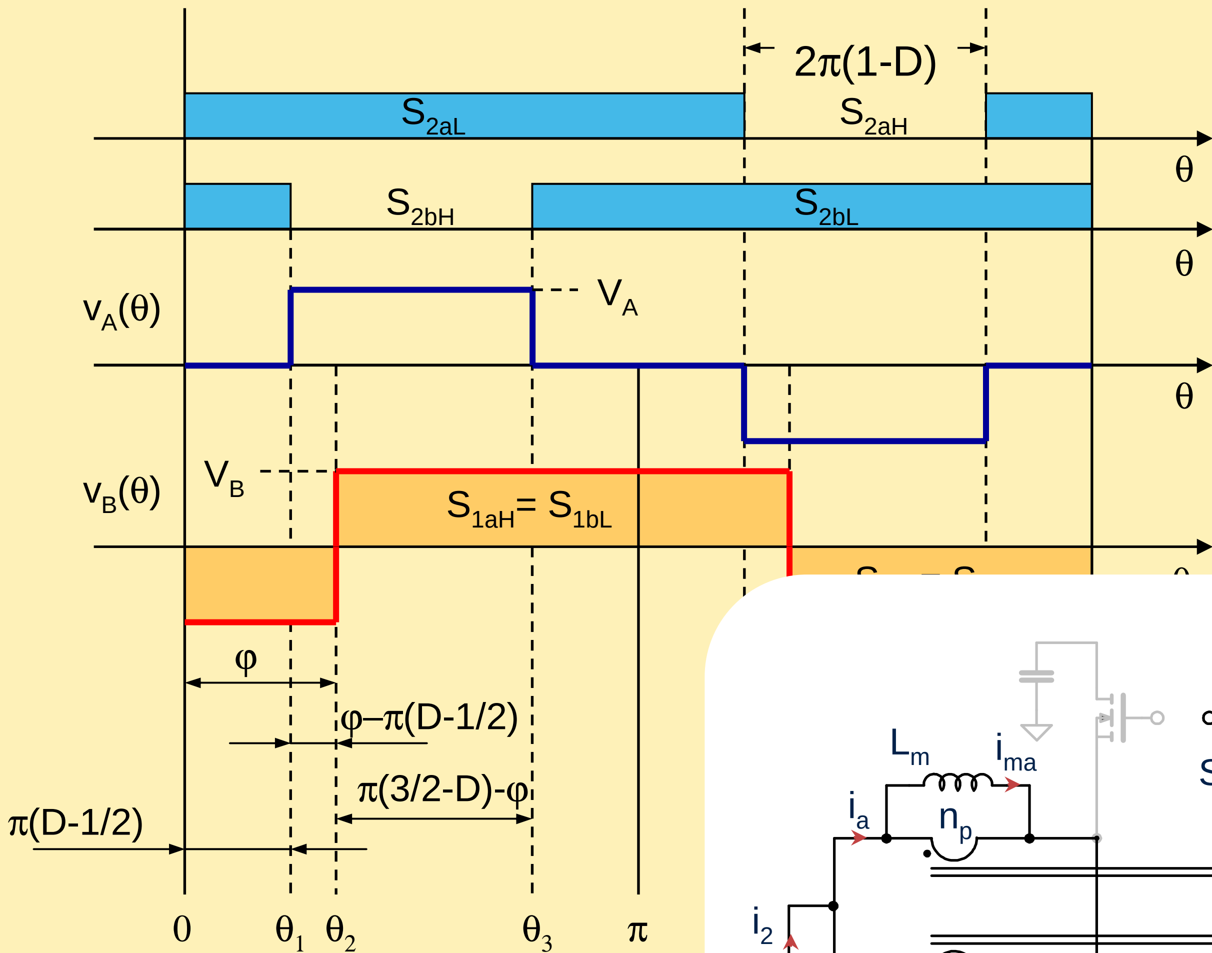
DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

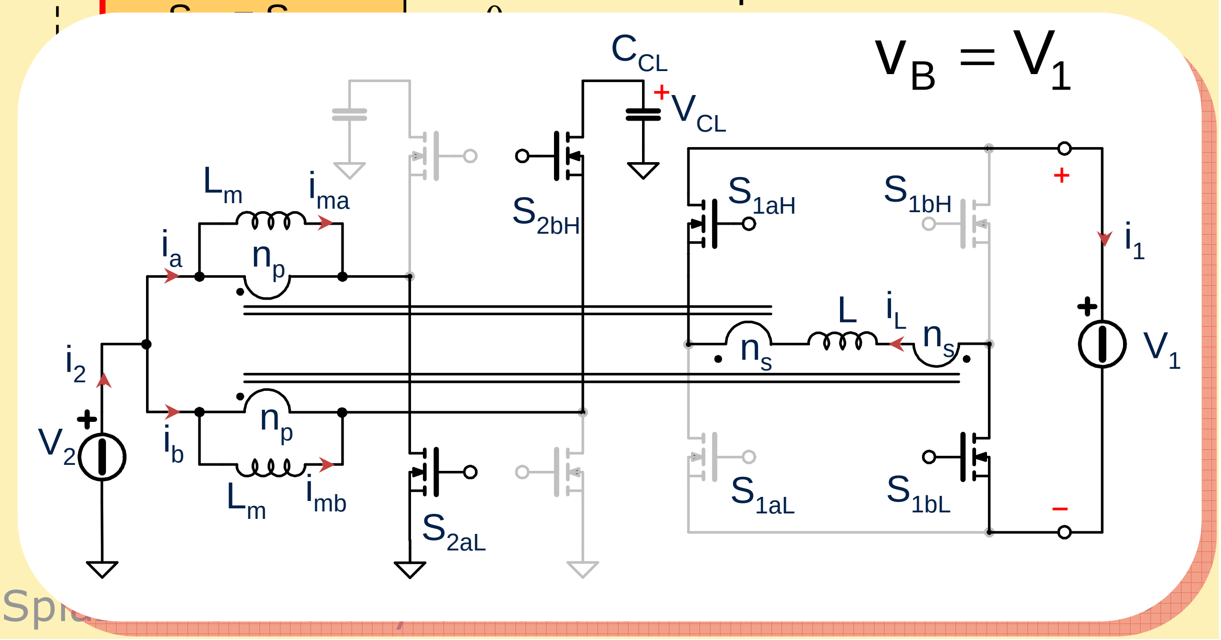
IBCI converter

$$\theta_2 \le \theta \le \theta_3$$

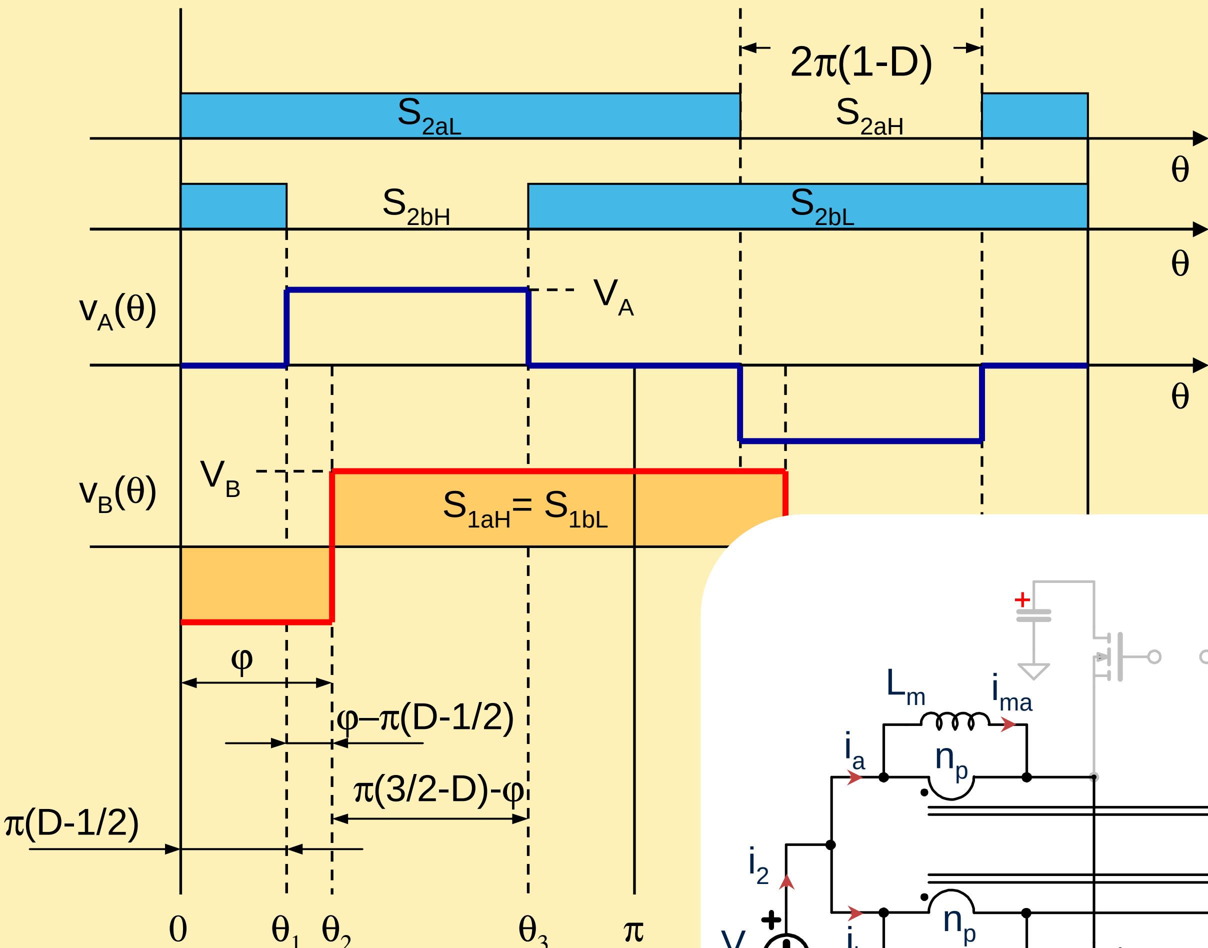
$$v_A = \frac{n_s}{n_p}\left(V_g - V_g + V_{CL}\right) = \frac{n_s}{n_p} V_{CL} = V_A$$

$$v_B = V_1$$





Plus Phase-Shift Modulation

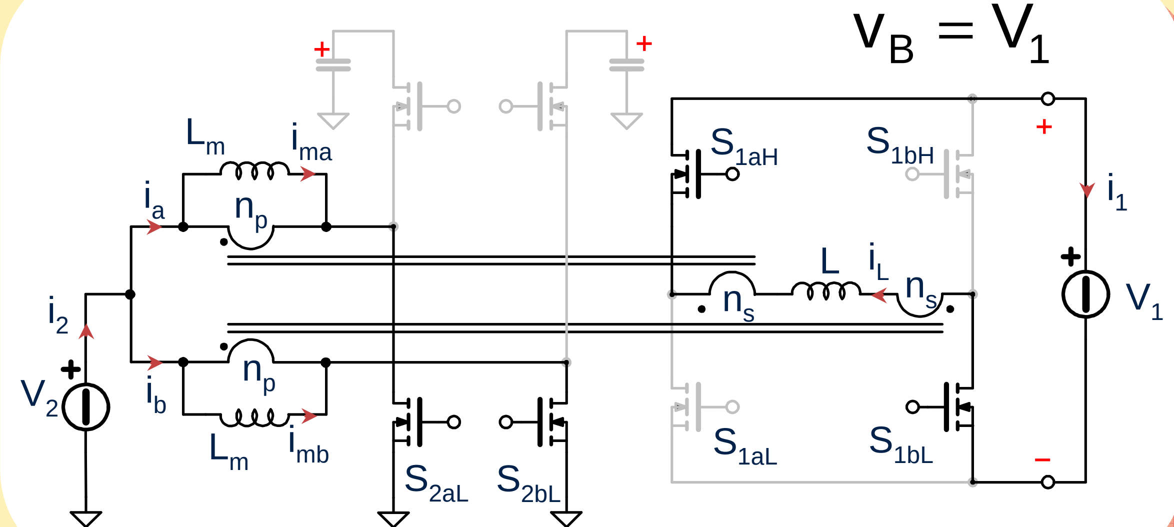


IBCI converter

$$\theta_3 \leq \theta \leq \pi$$

$$v_A = 0$$

$$v_B = V_1$$



Plus Phase-Shift Modulation

- v_A **is a three-level voltage of amplitude** V_A **while** v_B **is a square wave voltage of amplitude** V_B

$$V_g D = (V_{CL} - V_g)(1-D) \quad \Rightarrow \quad V_{CL} = \frac{V_g}{1-D}$$

$$V_A = \frac{n_s}{n_p} V_{CL} = \frac{n_s}{n_p} \frac{V_2}{1-D} \qquad V_B = V_1$$

- **The duty-cycle of port 2 switches is controlled so as to obtain the condition** $V_A = V_B$
- **The power transfer between ports 1 and 2 is controlled through the phase-shift angle** φ

$0 \le \varphi \le \pi/2$ $\quad v_A \xrightarrow{P} v_B$

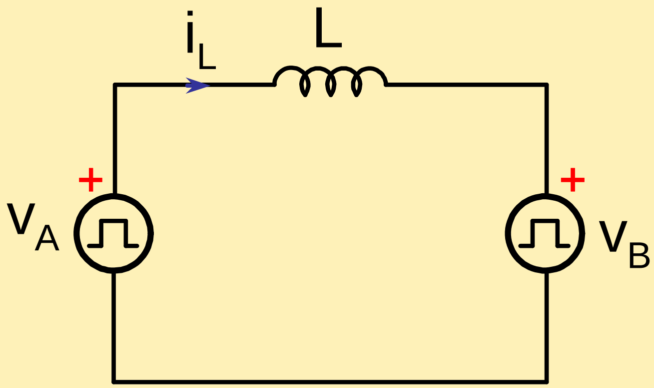
$-\pi/2 \le \varphi \le 0$ $\quad v_A \xleftarrow{P} v_B$

- **Inductor current has a piecewise linear behavior**

Plus Phase-Shift Modulation

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

IBCI converter

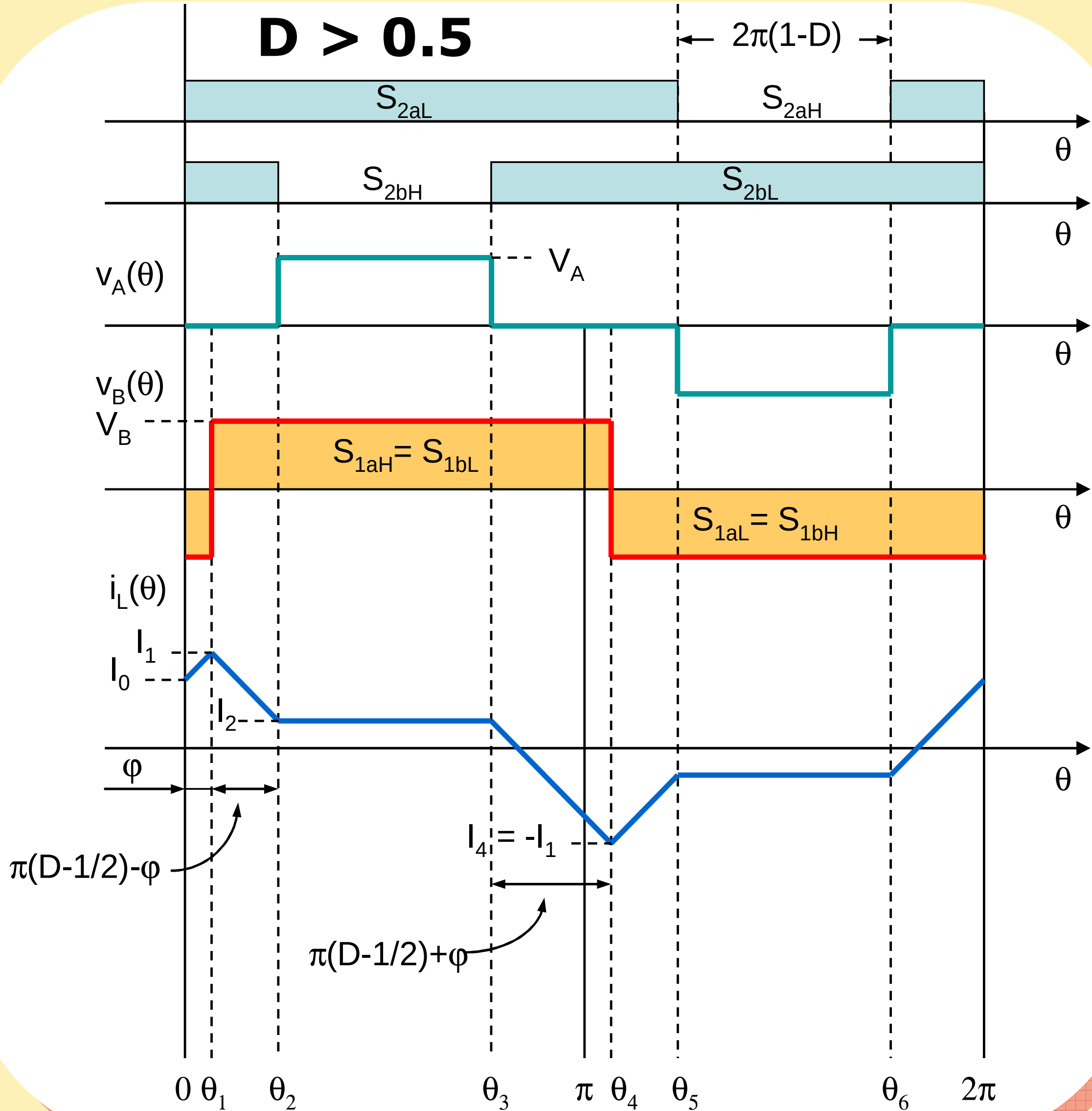


Power flow

Case A:

$$0 < \varphi < \pi(D-1/2)$$

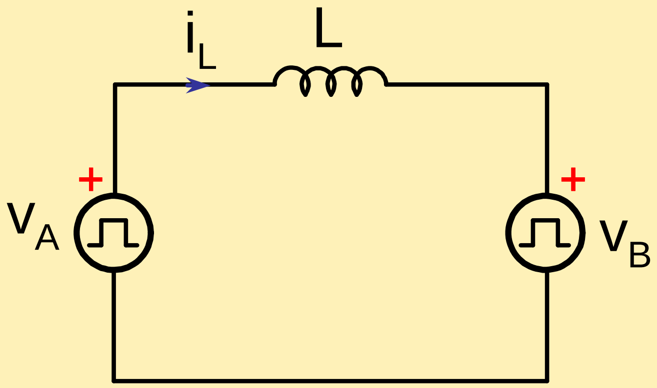
$(V_A = V_B)$



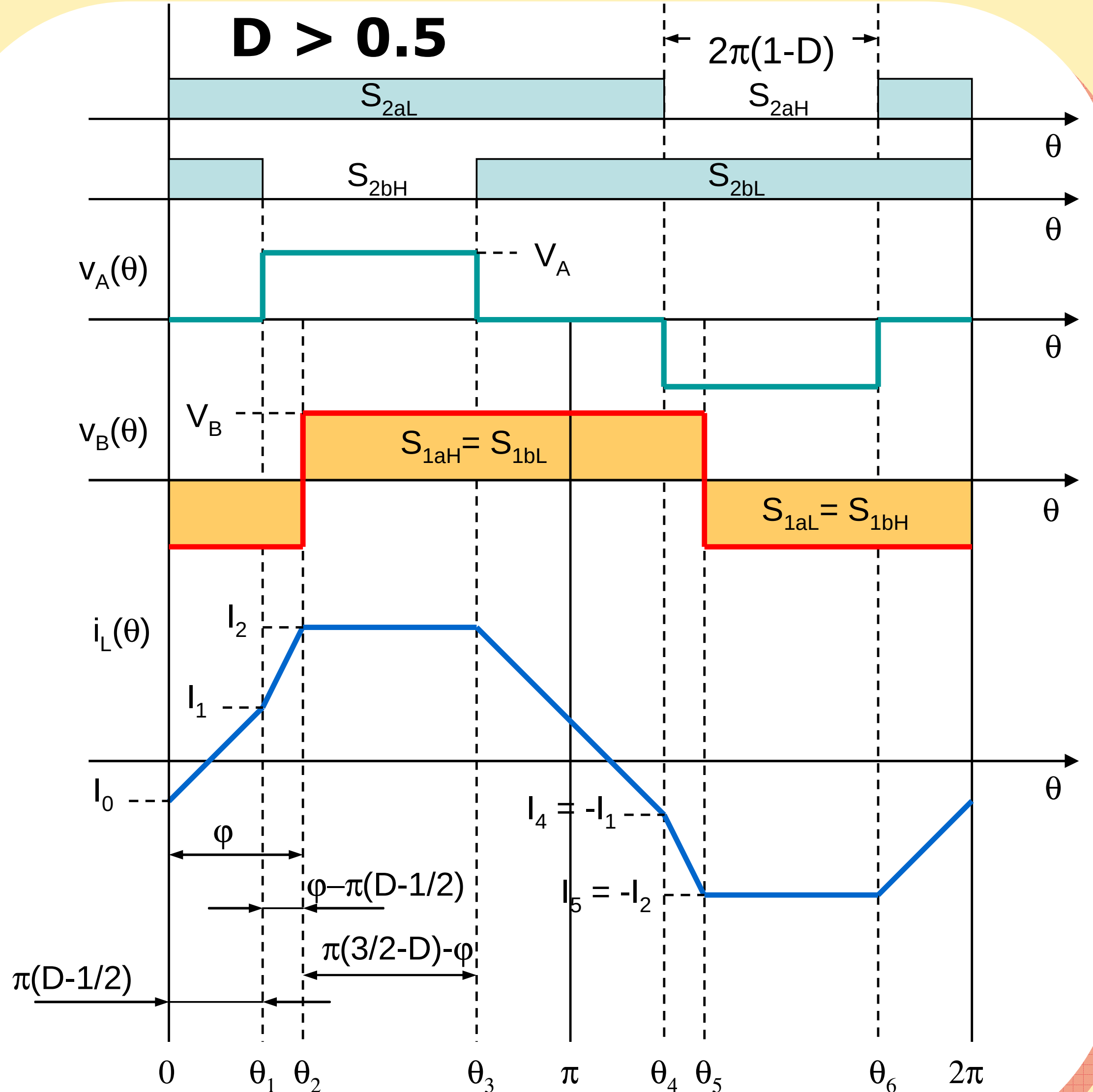
Plus Phase-Shift Modulation

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

IBCI converter



Power flow

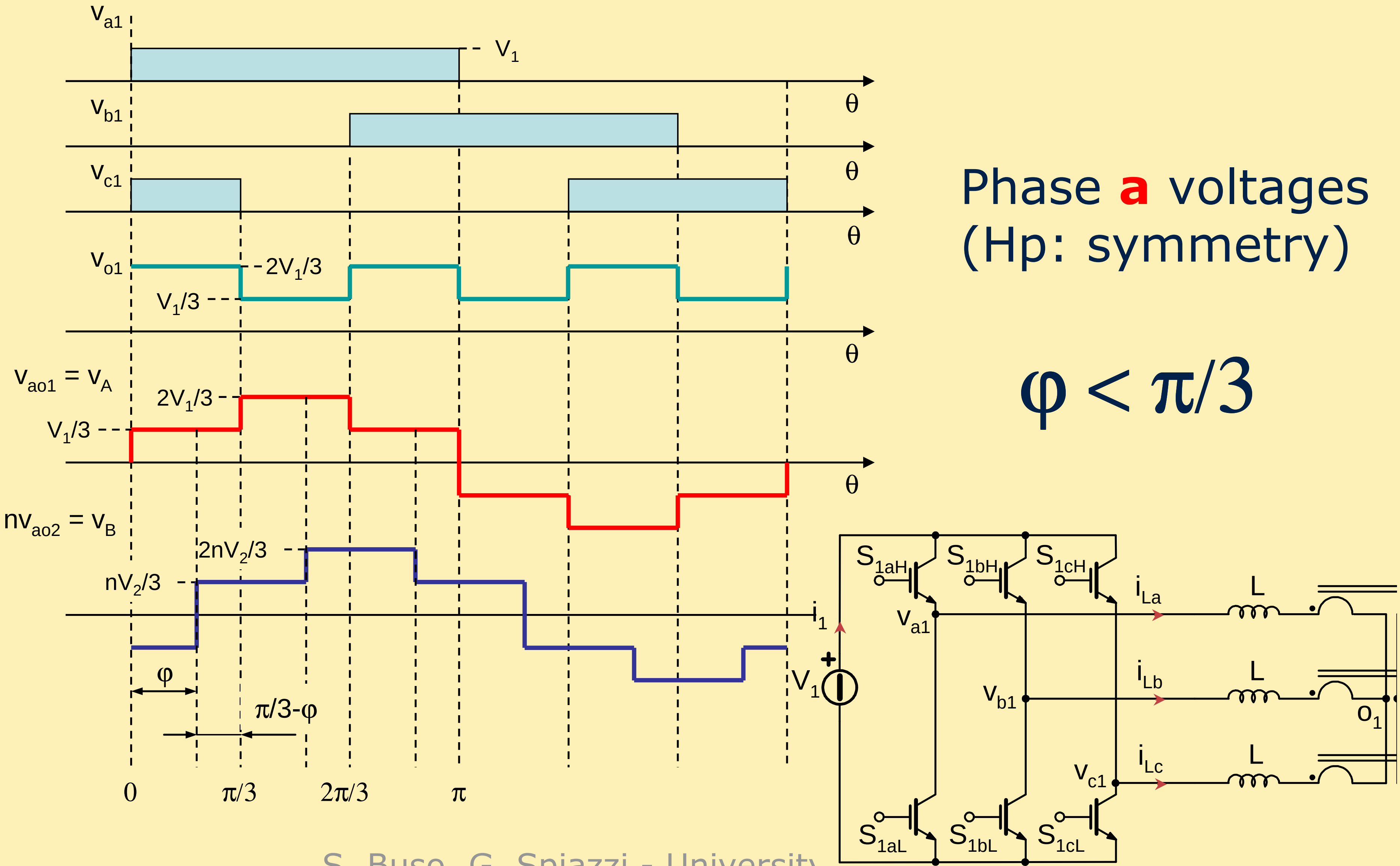


Case B:

$$\pi(D-1/2) < \varphi < \pi/2$$

$(V_A = V_B)$

Phase-Shift Modulation in Three-Phase Converters



Phase **a** voltages
(Hp: symmetry)

$$\varphi < \pi/3$$

Phase-Shift Modulation in Three-Phase Converters

- **Decoupled phase behavior (perfect symmetry)**
- **v_A and v_B are six-step voltage waveforms**
- **The power transfer between ports 1 and 2 is controlled through the phase-shift angle φ**

$0 \le \varphi \le \pi/2 \qquad v_A \xrightarrow{P} v_B$

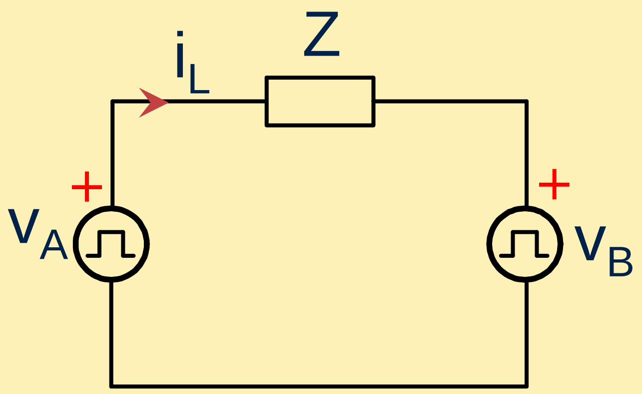
$-\pi/2 \le \varphi \le 0 \qquad v_A \xleftarrow{P} v_B$

- **Two different situations (power from port 1 to port 2):**
  - **$0 \le \varphi \le \pi/3$**
  - **$\pi/3 \le \varphi \le \pi/2$**
- **Inductor current has a piecewise linear behavior (DAB)**

Systematic Steady-State Analysis

- **The analytical determination of the current waveforms requires a systematic method for complex topologies (e.g. three-phase resonant DAB).**
- **The outcome is the mathematical expression of phase currents as a function of phase-shift and other design parameters.**
- **In addition, soft switching conditions can be analyzed in detail by extracting current values at the moment of switch commutations.**

General case:



$$\upsilon = \frac{v_Z}{V_N} = \frac{v_A - v_B}{V_N} \qquad k = \frac{V_B}{V_A}$$

Systematic Steady-State Analysis

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

The half switching period is divided into m subintervals. For each subinterval (*i = 1÷m*), the values of the current shaping impedance state variables x_i at the end of the interval are calculated, in normalized form, as a function of their value x_{i-1} *at the beginning, i.e.:*

$$\mathbf{x_i} = \mathbf{M_i x_{i-1}} + \mathbf{N_i} \upsilon_i$$

We can iterate, obtaining

$$\mathbf{x}_m = \mathbf{M}_{m,1}\mathbf{x}_0 + \left(\sum_{i=1}^{m-1} \mathbf{M}_{m,\mathbf{i}+1} \mathbf{N_i} \upsilon_i \right) + \mathbf{N}_m \upsilon_m = \mathbf{M}_{m,1}\mathbf{x}_0 + \mathbf{F}$$

where $$\mathbf{M}_{j,i} = \prod_{k=i}^{j} \mathbf{M}_k \qquad j \geq i$$

and υ is a column vector containing *m* υ_i elements, i.e.

$$\boldsymbol{\upsilon} = \begin{bmatrix} \upsilon_1 & \upsilon_2 & \cdots & \upsilon_m \end{bmatrix}^T$$

Systematic Steady-State Analysis

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Exploiting the waveform symmetry, we can write:

$$\mathbf{x}_{\mathrm{m}} = \mathbf{M}_{\mathrm{m},1}\mathbf{x}_0 + \mathbf{F} = -\mathbf{x}_0$$

from which the initial state variable values are found:

$$\mathbf{x}_0 = \left(-\mathbf{I} - \mathbf{M}_{\mathrm{m},1}\right)^{-1}\mathbf{F}$$

that can be used to derive the current waveform expressions and to discuss soft-switching conditions

Example: IBCI

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Base variables:

- **Base voltage:** $V_N = V_A$
- **Base impedance:** $Z_N = \omega_{sw} L$
- **Base current:** $I_N = V_N / Z_N$
- **Base power:** $P_N = V_N^2 / Z_N$

The half switching period is subdivided into 4 subintervals (**m = 4**).

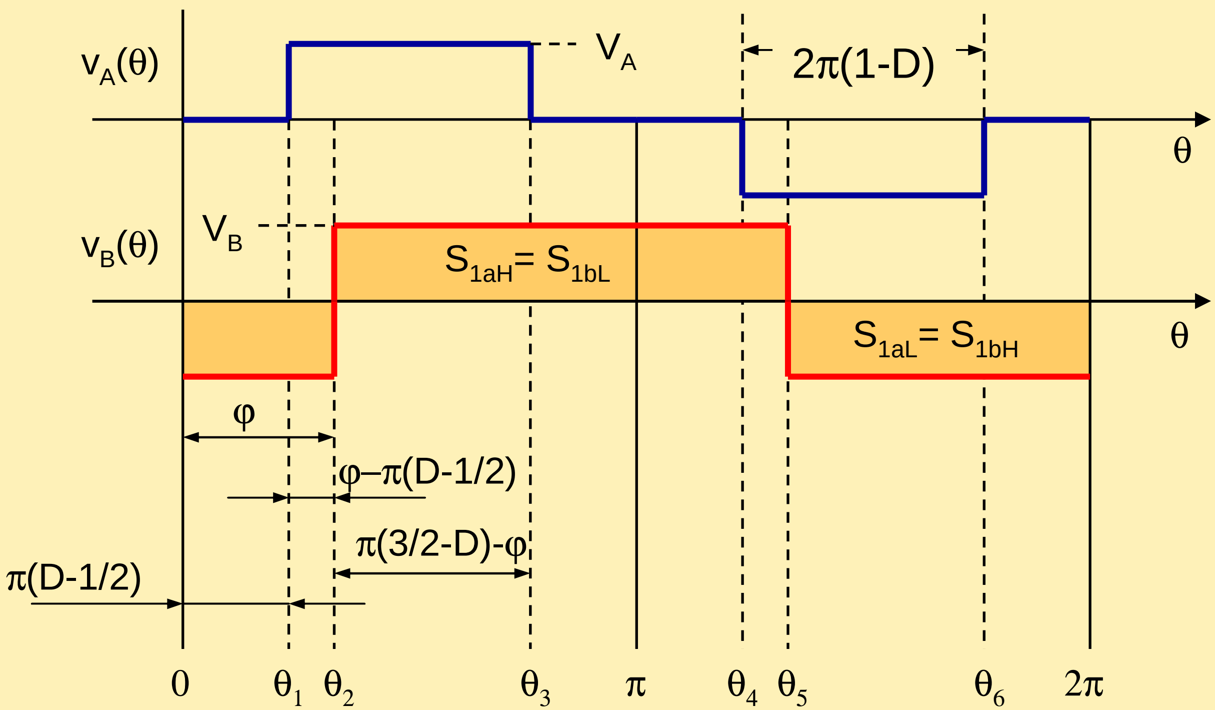
Two situations has to be considered:

Case A: $0 < \varphi < \pi(D-1/2)$

Case B: $\pi(D-1/2) < \varphi < \pi/2$

Example: IBCI

i=	1		2		3		4	
	υ	δ	υ	δ	υ	δ	υ	δ
A	k	φ	-k	$\pi\left(D-\frac{1}{2}\right)-\varphi$	1-k	$2\pi(1-D)$	-k	$\pi\left(D-\frac{1}{2}\right)$
B	k	$\pi\left(D-\frac{1}{2}\right)$	1+k	$\varphi-\pi\left(D-\frac{1}{2}\right)$	1-k	$\pi\left(\frac{3}{2}-D\right)-\varphi$	-k	$\pi\left(D-\frac{1}{2}\right)$



Case B

Example: IBCI

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Defining $j(\theta) = i(\theta)/I_N$ as the normalized inductor current:

$$J_i = J_{i-1} + \upsilon_i \delta_i \quad \text{for} \quad i = 1,\dots,m$$

Comparing with: $\mathbf{x_i} = \mathbf{M_i}\mathbf{x_{i-1}} + \mathbf{N_i}\upsilon_i$

$$\begin{cases} M_i = 1 \\ N_i = \delta_i \end{cases} \quad \text{for} \quad i = 1,\dots,m$$

Example: IBCI

From: $\mathbf{x}_0 = \left(-\mathbf{I} - \mathbf{M}_{m,1}\right)^{-1}\mathbf{F}$

the normalized initial inductor current value is:

$$J_0 = -\frac{1}{2}\sum_{i=1}^{4} \upsilon_i \delta_i$$

For both cases A and B we have:

$$J_0 = -\pi(1-D) + k\left(\frac{\pi}{2} - \varphi\right)$$

For plus phase-shift modulation **k = 1**:

$$J_0 = \pi\left(D - \frac{1}{2}\right) - \varphi$$

Example: SR-DAB

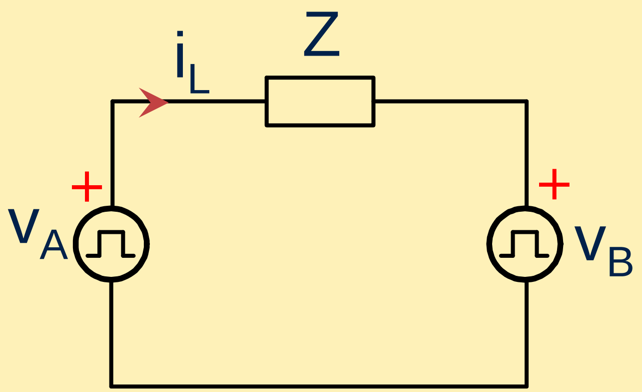
DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Base variables:

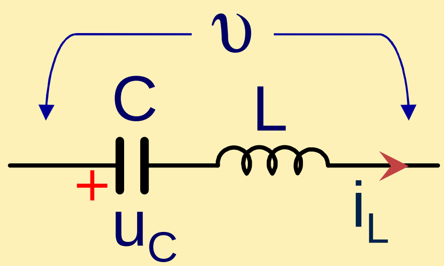
- **Base voltage:** $V_N = V_A$
- **Base impedance:** $Z_N = Z_r$
- **Base current:** $I_N = V_N/Z_N$
- **Base power:** $P_N = V_N^2/Z_N$
- **Base frequency:** $\omega_N = \omega_r$

$$Z_r = \sqrt{\frac{L}{C}}$$

$$\omega_r = \frac{1}{\sqrt{LC}}$$



Example: SR-DAB



Current shaping impedance state variables:

$$\begin{cases} j_L(\theta) = \upsilon \sin\left(\frac{\theta}{f_n}\right) - U_{C0} \sin\left(\frac{\theta}{f_n}\right) + J_{L0} \cos\left(\frac{\theta}{f_n}\right) \\ u_C(\theta) = \upsilon\left(1 - \cos\left(\frac{\theta}{f_n}\right)\right) + U_{C0} \cos\left(\frac{\theta}{f_n}\right) + J_{L0} \sin\left(\frac{\theta}{f_n}\right) \end{cases}$$

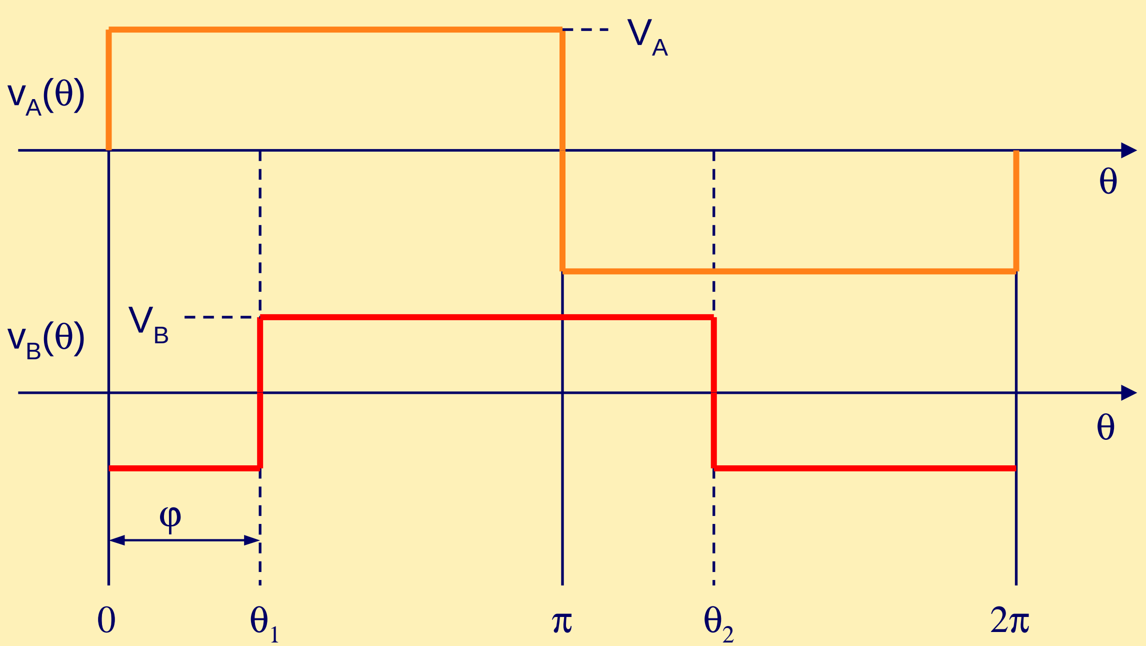
Normalized state variable vector: $\mathbf{x} = \begin{bmatrix} j_L \\ u_C \end{bmatrix}$

Example: SR-DAB

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

The half switching period is subdivided into 2 subintervals (**m = 2**).

i = 1		i = 2	
υ	δ	υ	δ
1+k	φ	1-k	$\pi - \varphi$



Example: SR-DAB

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Current shaping impedance state variables:

$$\begin{bmatrix} J_{Li} \\ U_{Ci} \end{bmatrix} = \underbrace{\begin{pmatrix} \cos\left(\frac{\delta_i}{f_n}\right) & -\sin\left(\frac{\delta_i}{f_n}\right) \\ \sin\left(\frac{\delta_i}{f_n}\right) & \cos\left(\frac{\delta_i}{f_n}\right) \end{pmatrix}}_{\textbf{Matrix M}} \begin{bmatrix} J_{Li-1} \\ U_{Ci-1} \end{bmatrix} + \underbrace{\begin{pmatrix} \sin\left(\frac{\delta_i}{f_n}\right) \\ 1-\cos\left(\frac{\delta_i}{f_n}\right) \end{pmatrix}}_{\textbf{Matrix N}} \upsilon_i \quad \text{for } i = 1,2$$

$$\mathbf{M}_{m,1} = \mathbf{M}_{2,1} = \begin{pmatrix} \cos\left(\frac{\pi}{f_n}\right) & -\sin\left(\frac{\pi}{f_n}\right) \\ \sin\left(\frac{\pi}{f_n}\right) & \cos\left(\frac{\pi}{f_n}\right) \end{pmatrix}$$

Example: SR-DAB

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Matrix F:

$$\mathbf{F} = \begin{pmatrix} \sin\left(\frac{\pi}{f_n}\right) \\ 1-\cos\left(\frac{\pi}{f_n}\right) \end{pmatrix} + \begin{pmatrix} \sin\left(\frac{\pi}{f_n}\right) - 2\sin\left(\frac{\pi-\varphi}{f_n}\right) \\ 2\cos\left(\frac{\pi-\varphi}{f_n}\right) - \cos\left(\frac{\pi}{f_n}\right) - 1 \end{pmatrix} k$$

Initial conditions:

$$\mathbf{x}_0 = \begin{pmatrix} -1-\cos\left(\frac{\pi}{f_n}\right) & \sin\left(\frac{\pi}{f_n}\right) \\ -\sin\left(\frac{\pi}{f_n}\right) & -1-\cos\left(\frac{\pi}{f_n}\right) \end{pmatrix}^{-1} \mathbf{F}$$

Example: SR-DAB

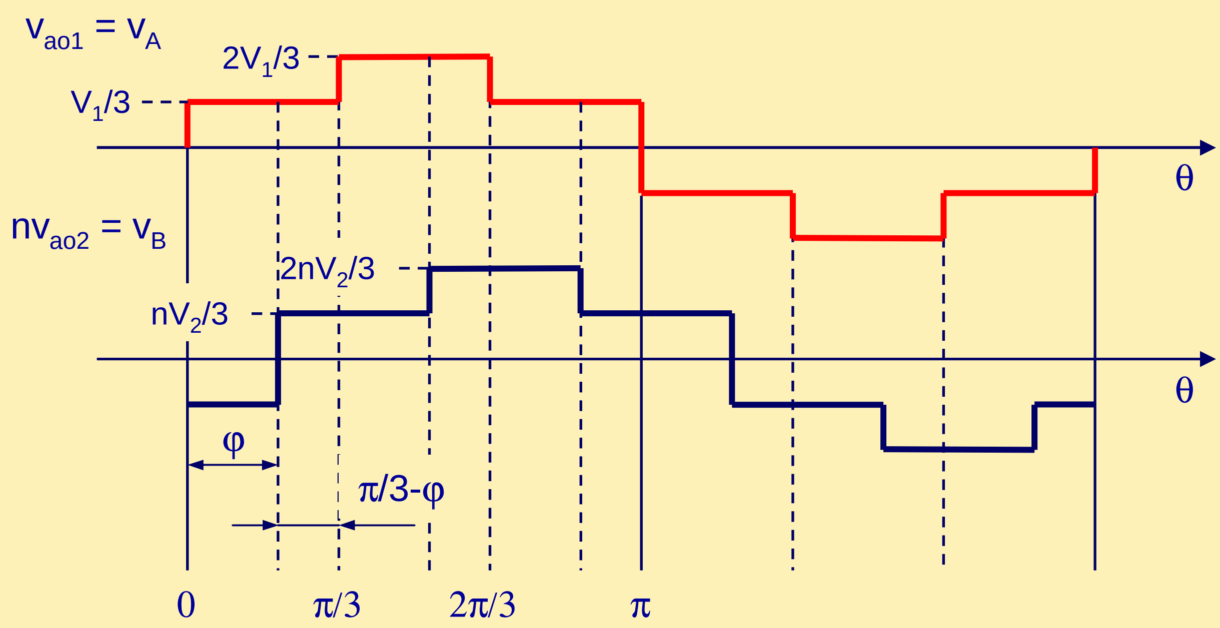
Initial conditions:

$$\mathbf{x}_0 = \frac{1}{1+\cos\left(\frac{\pi}{f_n}\right)}\left[\begin{pmatrix} -\sin\left(\frac{\pi}{f_n}\right) \\ 0 \end{pmatrix} + \begin{pmatrix} \sin\left(\frac{\pi-\varphi}{f_n}\right) - \sin\left(\frac{\varphi}{f_n}\right) \\ 1+\cos\left(\frac{\pi}{f_n}\right) - \cos\left(\frac{\pi-\varphi}{f_n}\right) - \cos\left(\frac{\varphi}{f_n}\right) \end{pmatrix} k\right]$$

$$\Downarrow$$

$$J_{L0}(\varphi) = \frac{-\sin\left(\frac{\pi}{f_n}\right) + k\left[\sin\left(\frac{\pi-\varphi}{f_n}\right) - \sin\left(\frac{\varphi}{f_n}\right)\right]}{1+\cos\left(\frac{\pi}{f_n}\right)}$$

Example: Three-Phase DAB

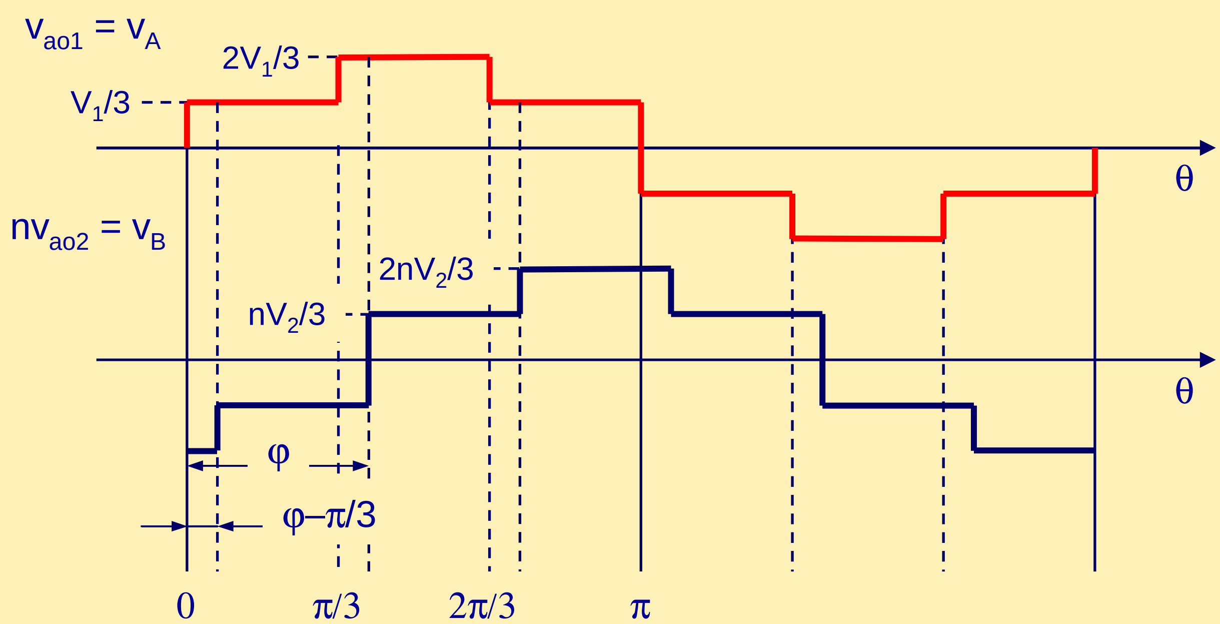


The half switching period is subdivided into 6 subintervals (**m = 6**).

Two situations has to be considered:

Case A: $0 < \varphi < \pi/3$

Example: Three-Phase DAB and SR-DAB



The half switching period is subdivided into 6 subintervals (**m = 6**).

Two situations has to be considered:

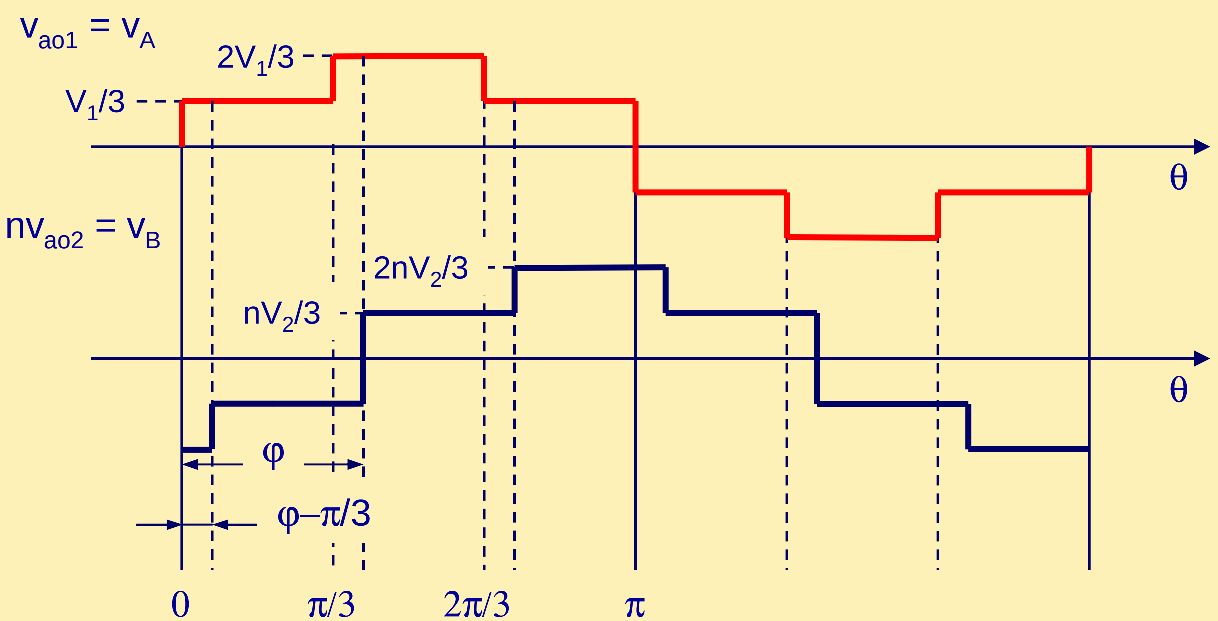
Case B: $\pi/3 < \varphi < \pi/2$

Example: Three-Phase DAB and SR-DAB

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

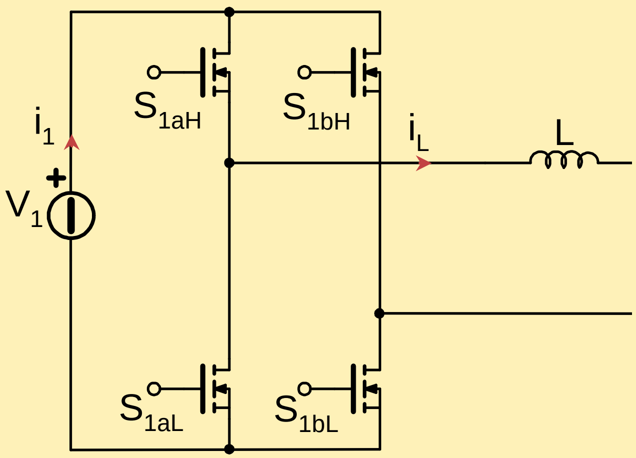
i=	1		2		3		4		5		6	
	υ	δ	υ	δ	υ	δ	υ	δ	υ	δ	υ	δ
A	$\frac{1+k}{3}$	φ	$\frac{1-k}{3}$	$\frac{\pi}{3}-\varphi$	$\frac{2-k}{3}$	φ	$\frac{2(1-k)}{3}$	$\frac{\pi}{3}-\varphi$	$\frac{1-2k}{3}$	φ	$\frac{1-k}{3}$	$\frac{\pi}{3}-\varphi$
B	$\frac{1+2k}{3}$	$\varphi-\frac{\pi}{3}$	$\frac{1+k}{3}$	$\frac{2\pi}{3}-\varphi$	$\frac{2+k}{3}$	$\varphi-\frac{\pi}{3}$	$\frac{2-k}{3}$	$\frac{2\pi}{3}-\varphi$	$\frac{1-k}{3}$	$\varphi-\frac{\pi}{3}$	$\frac{1-2k}{3}$	$\frac{2\pi}{3}-\varphi$

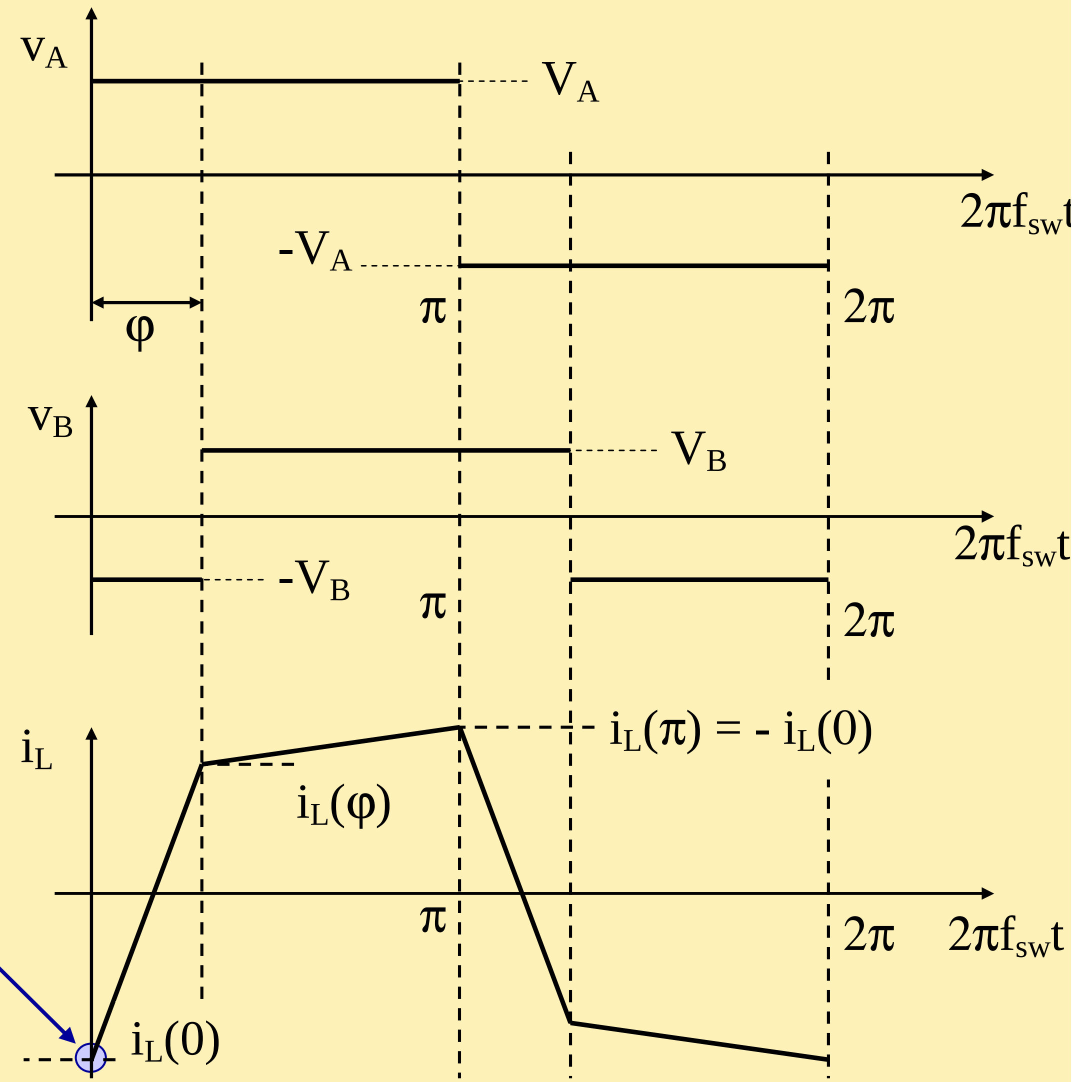
Case B



Soft-switching conditions

Single phase DAB: port 1





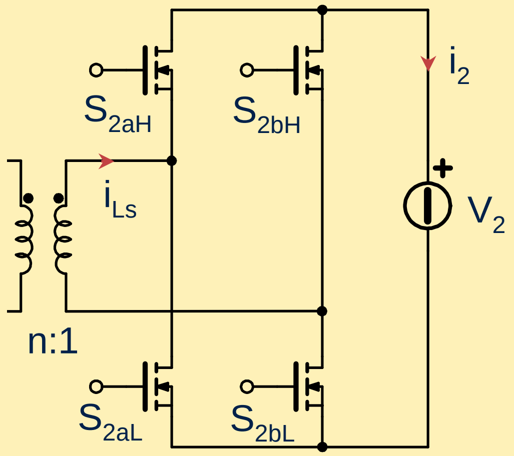
Power flow

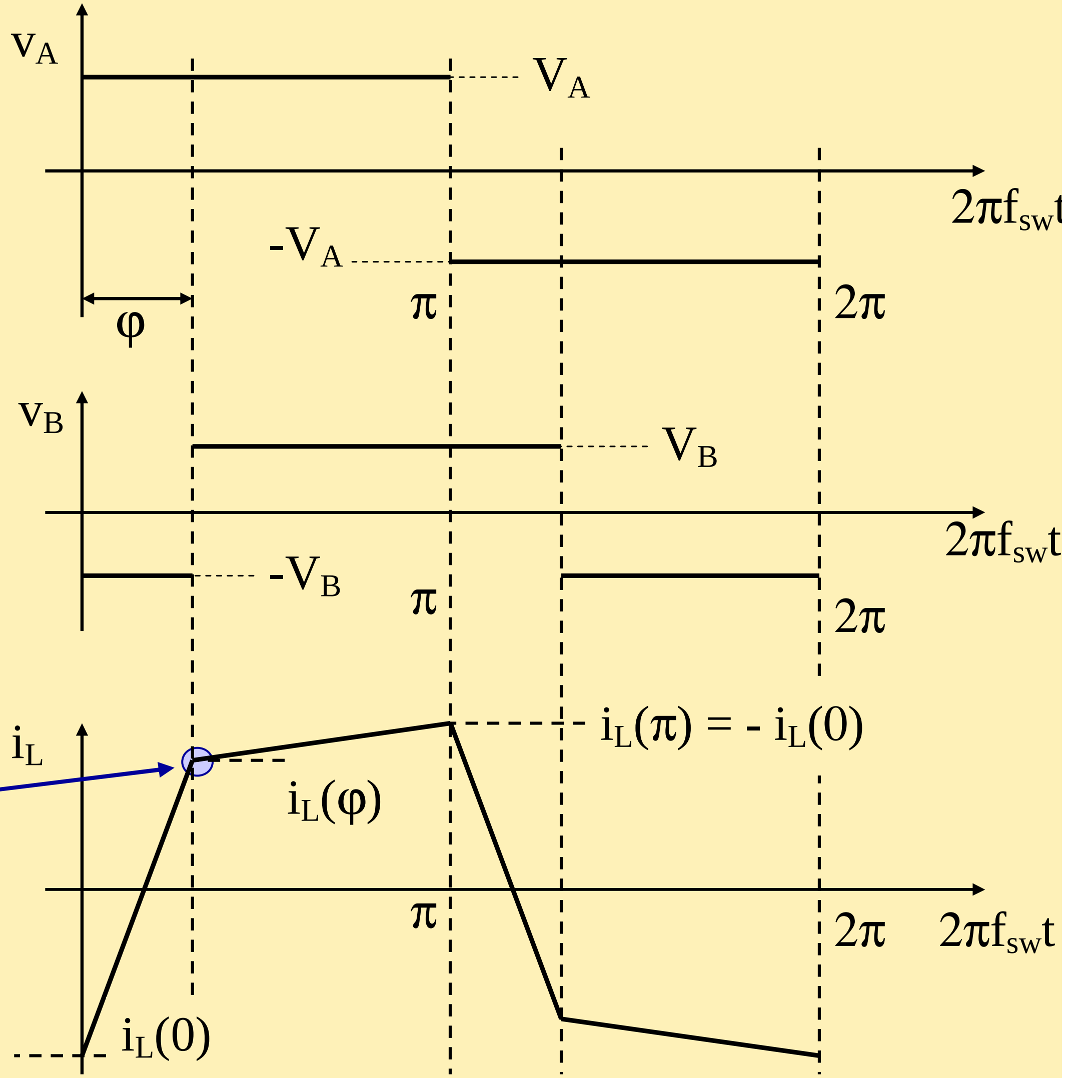
$$j_L(0) = -\varphi \cdot k - \frac{\pi}{2}(1-k) \leq 0$$

$$\varphi \geq \frac{\pi}{2}\left(\frac{1}{k} - 1\right)$$

Soft-switching conditions

Single phase DAB: port 2





Power flow →

$$j_L(\varphi) = \varphi - \frac{\pi}{2}(1-k) \geq 0$$

$$\varphi \geq \frac{\pi}{2}(1-k)$$

Soft-switching conditions

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Single phase DAB

Port 1:

$$\varphi \geq \frac{\pi}{2}\left(\frac{1}{k}-1\right)$$

Port 2:

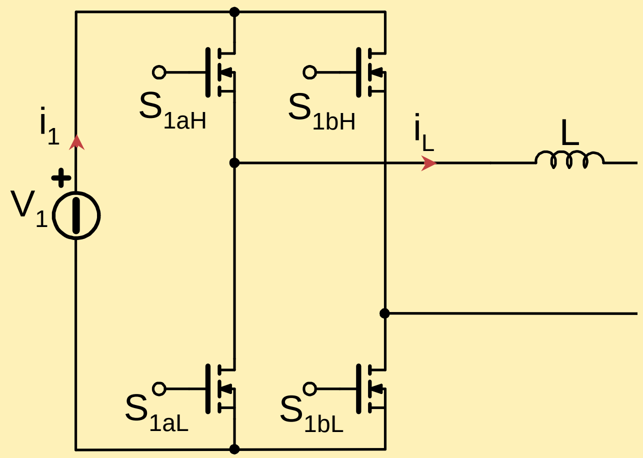
$$\varphi \geq \frac{\pi}{2}(1-k)$$

For a power flow from port 1 to port 2 the phase-shift interval is $0 \leq \varphi \leq \pi/2$. Thus, if **k ≥ 1** the soft switching condition is satisfied for any φ value and for both bridge switches.

The same consideration holds for a power flow from port 2 to port 1 where voltages v_A and v_B are swept and $k' = 1/k$. Now, if **k' ≥ 1** (**k ≤ 1**) the soft switching condition is satisfied for any φ value.

Soft-switching conditions

Single phase DAB



Port 1:

$$\varphi \geq \frac{\pi}{2}\left(\frac{1}{k}-1\right)$$

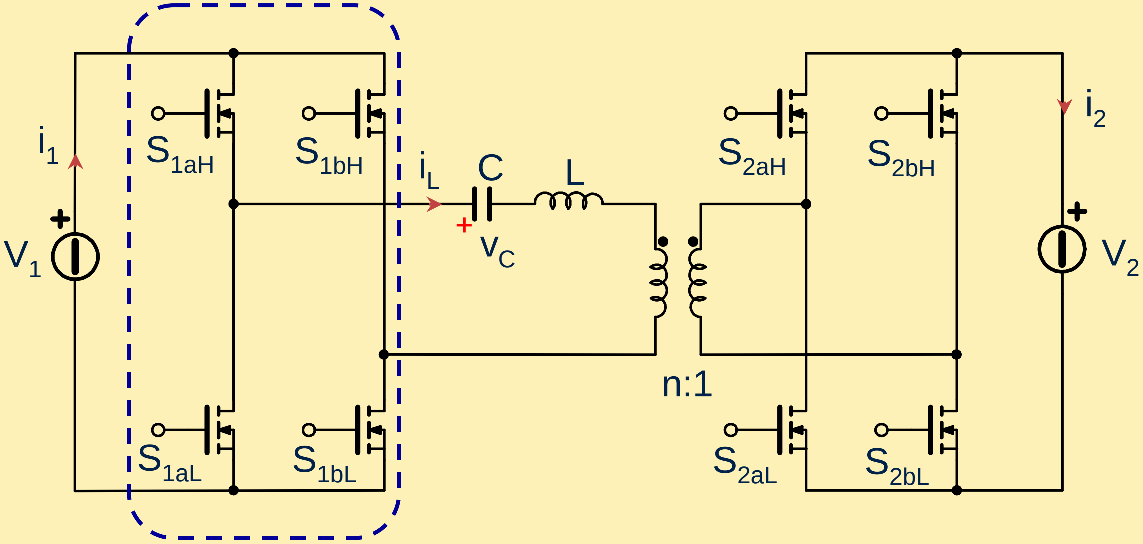
Port 2:

$$\varphi \geq \frac{\pi}{2}(1-k)$$

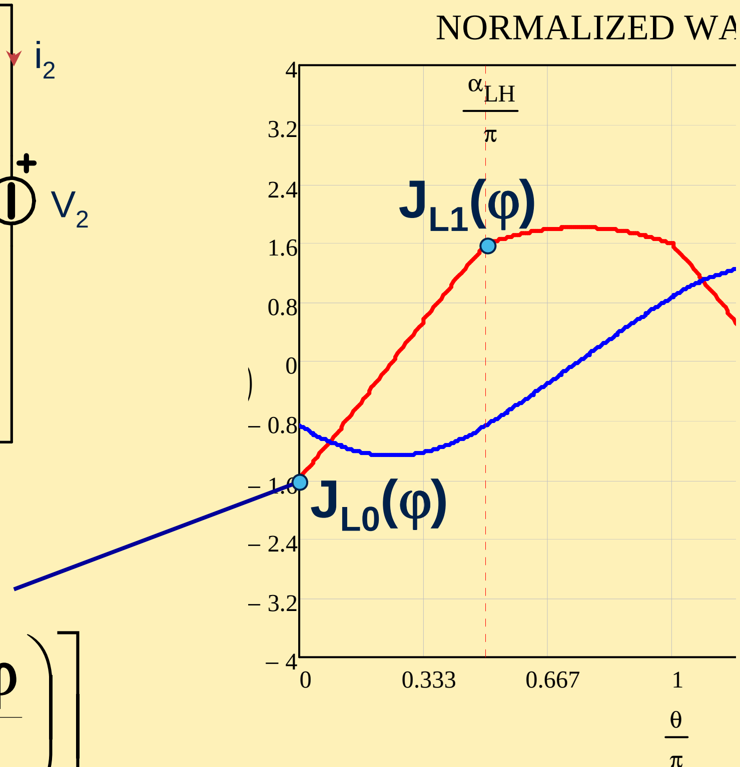
For a bidirectional power flow, if **k = 1** the soft switching condition is satisfied for any φ value between $-\pi/2$ and $\pi/2$.

Soft-switching conditions

Single phase SR-DAB converter: port 1



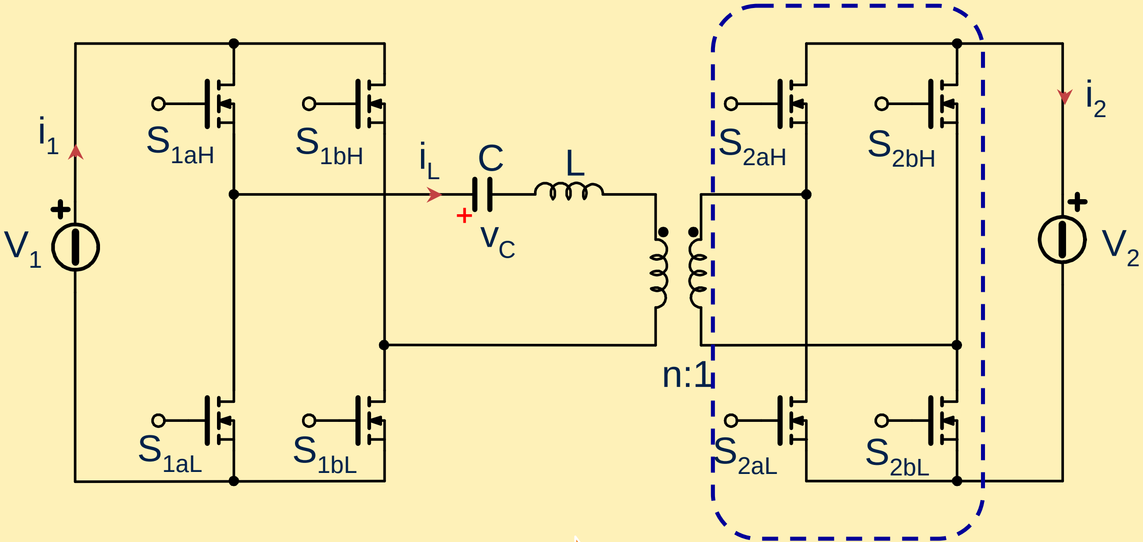
Power flow



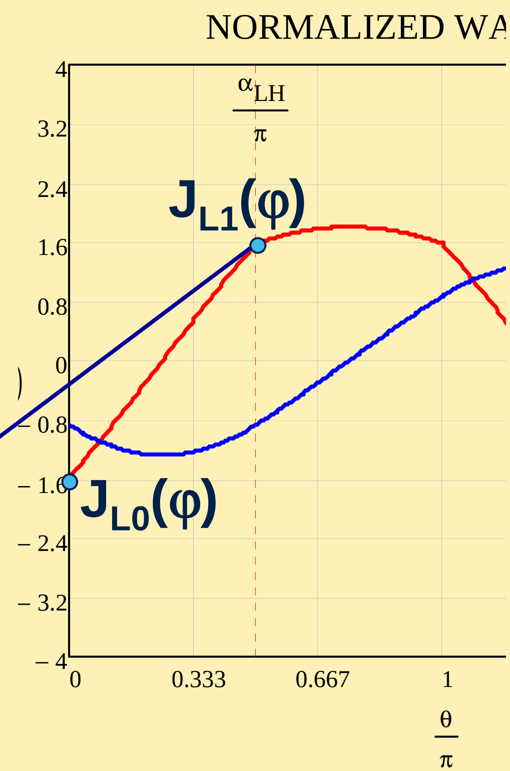
$$J_{L0}(\varphi) = \frac{-\sin\left(\frac{\pi}{f_n}\right) + k\left[\sin\left(\frac{\pi-\varphi}{f_n}\right) - \sin\left(\frac{\varphi}{f_n}\right)\right]}{1+\cos\left(\frac{\pi}{f_n}\right)} < 0$$

Soft-switching conditions

Single phase SR-DAB converter: port 2



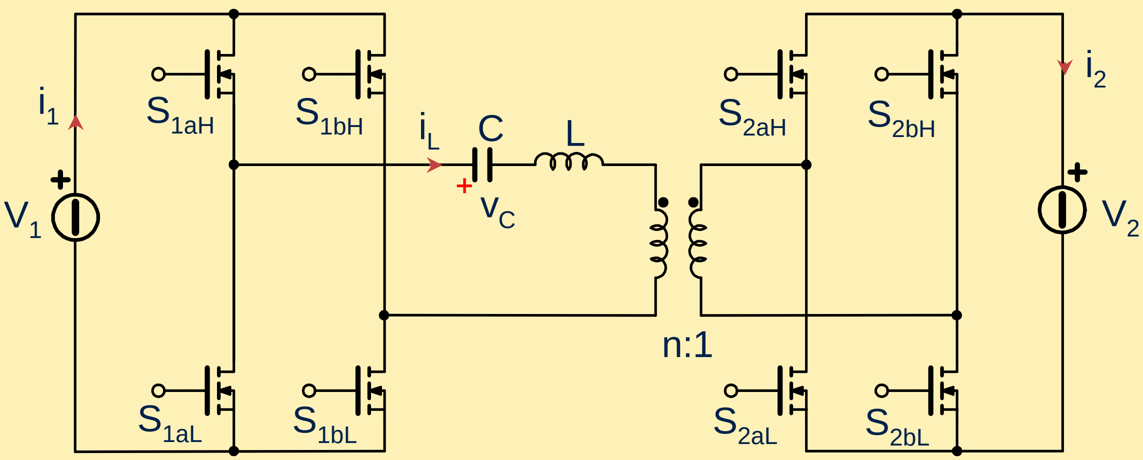
Power flow

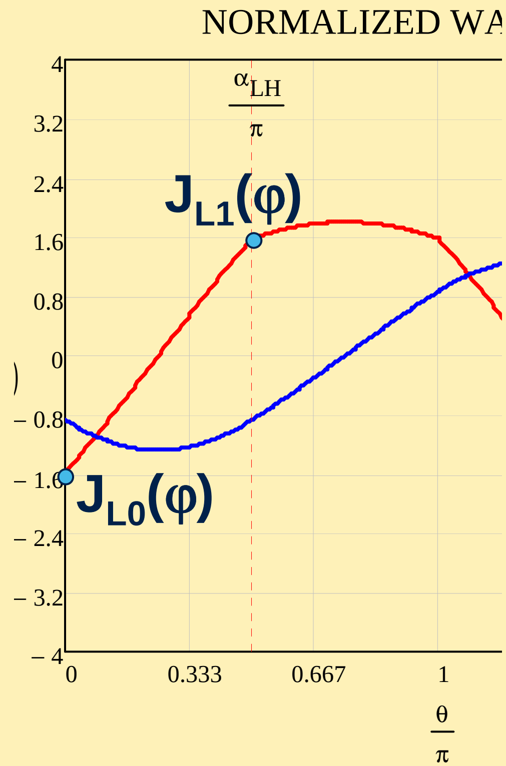


$$J_{L1}(\varphi) = \frac{\sin\left(\frac{\varphi}{f_n}\right) - \sin\left(\frac{\pi-\varphi}{f_n}\right)}{1+\cos\left(\frac{\pi}{f_n}\right)} + \frac{\sin\left(\frac{\pi}{f_n}\right)}{1+\cos\left(\frac{\pi}{f_n}\right)} k > 0$$

Soft-switching conditions

Single phase SR-DAB converter





Power flow ➡

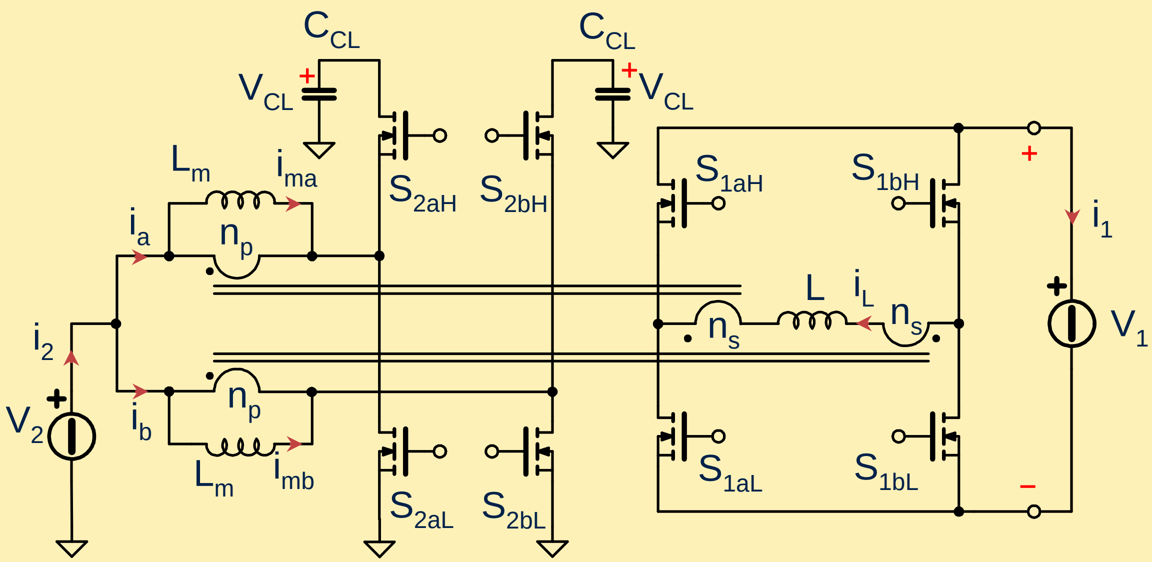
Worst case: φ = 0

$$J_{L0}(0)=J_{L1}(0)=\frac{\sin\left(\frac{\pi}{f_n}\right)}{1+\cos\left(\frac{\pi}{f_n}\right)}(k-1)$$

➡ **K = 1**

Soft-switching conditions

Interleaved Boost with Coupled Inductors

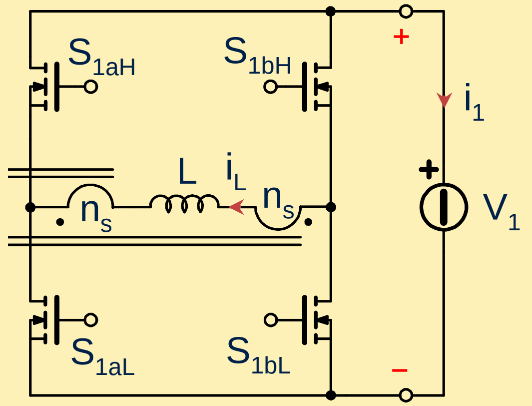


Power flow

Let's analyze the port 1 switch commutations first

Soft-switching conditions

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE



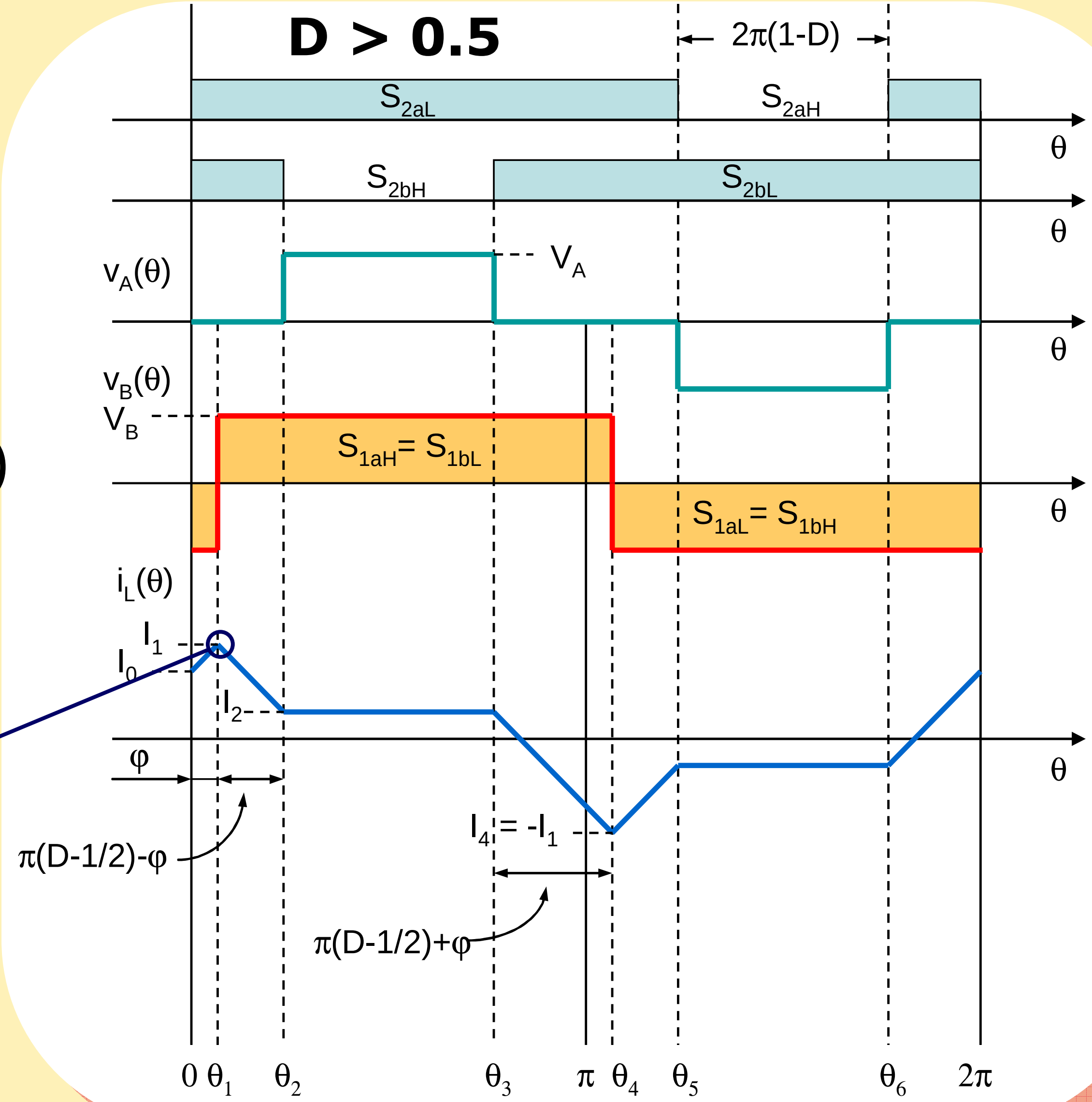
Case A: $0 < \varphi < \pi(D-1/2)$

$$J_1 = J_0 + k\varphi$$

$$= -\pi(1-D) + k\frac{\pi}{2} \geq 0$$

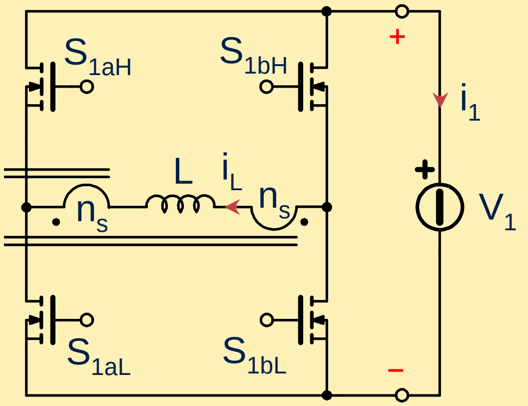
$$\Downarrow$$

$$k \geq 2(1-D)$$



Soft-switching conditions

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

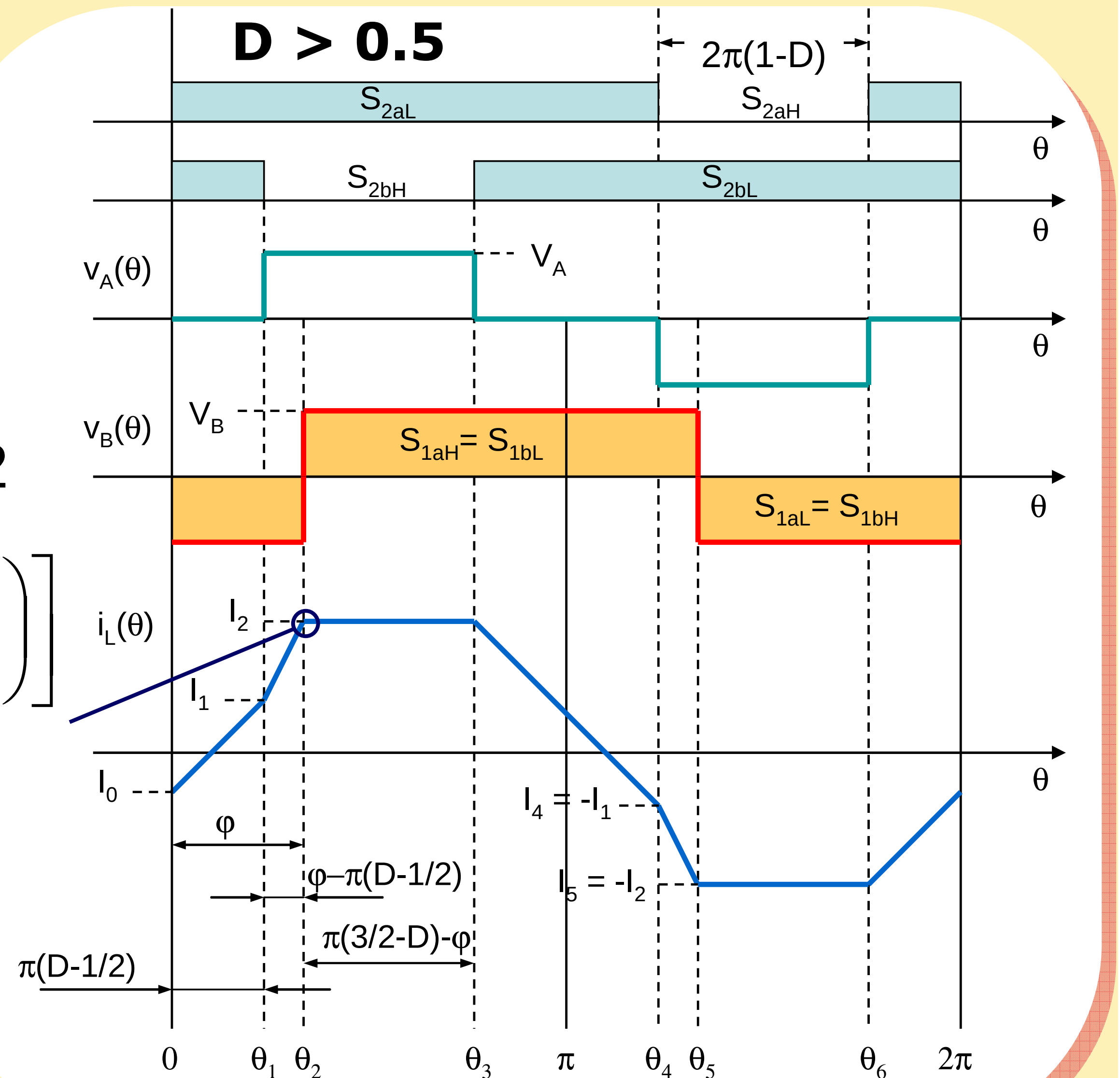


Case B: $\pi(D-1/2) < \varphi < \pi/2$

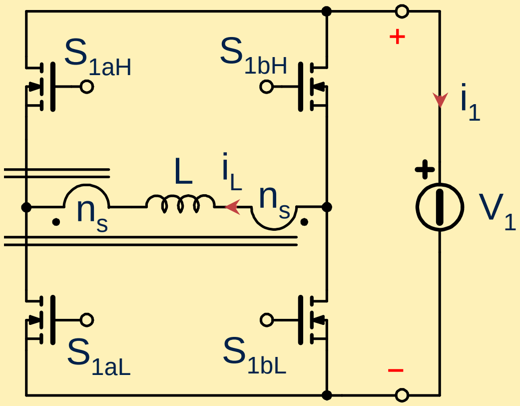
$$J_2 = J_1 + (1+k)\left[\varphi - \pi\left(D - \frac{1}{2}\right)\right]$$

$$= \varphi - \frac{\pi}{2}(1-k) \geq 0$$

$$k \geq 1 - \frac{2}{\pi}\varphi$$



Soft-switching conditions



Case A: $0 < \varphi < \pi(D\text{-}1/2)$ $\qquad k \geq 2(1 - D)$

Case B: $\pi(D\text{-}1/2) < \varphi < \pi/2$ $\qquad k \geq 1 - \frac{2}{\pi}\varphi$

Case B is included in case A!

Same condition holds for reversed power flow

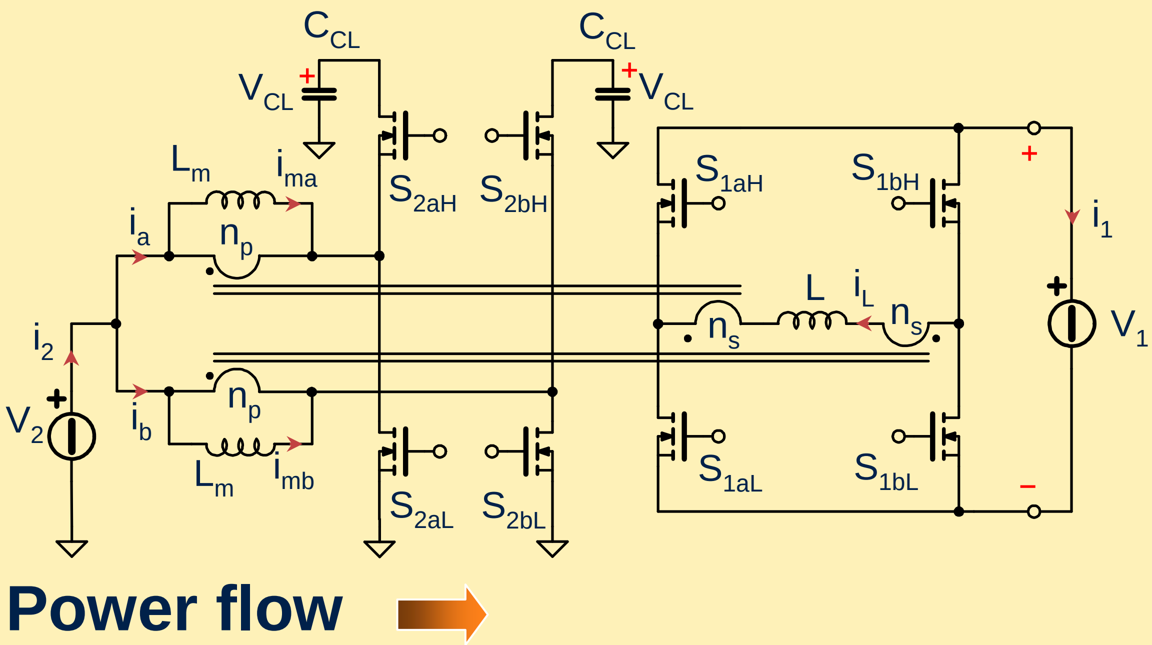
⇓

k = 1 is used to minimize the inductor current crest factor

Soft-switching conditions

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Interleaved Boost with Coupled Inductors



For port 2 switch commutations we have to analyze the currents i_a and i_b which depend also on duty-cycle:

$$i_a = i_{ma} + \frac{n_s}{n_p} i_L \qquad\qquad i_b = i_{mb} - \frac{n_s}{n_p} i_L$$

Soft-switching conditions

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

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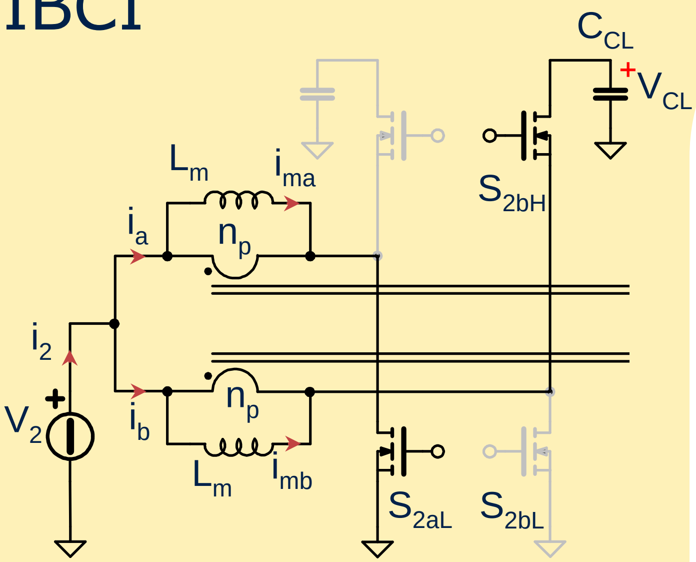

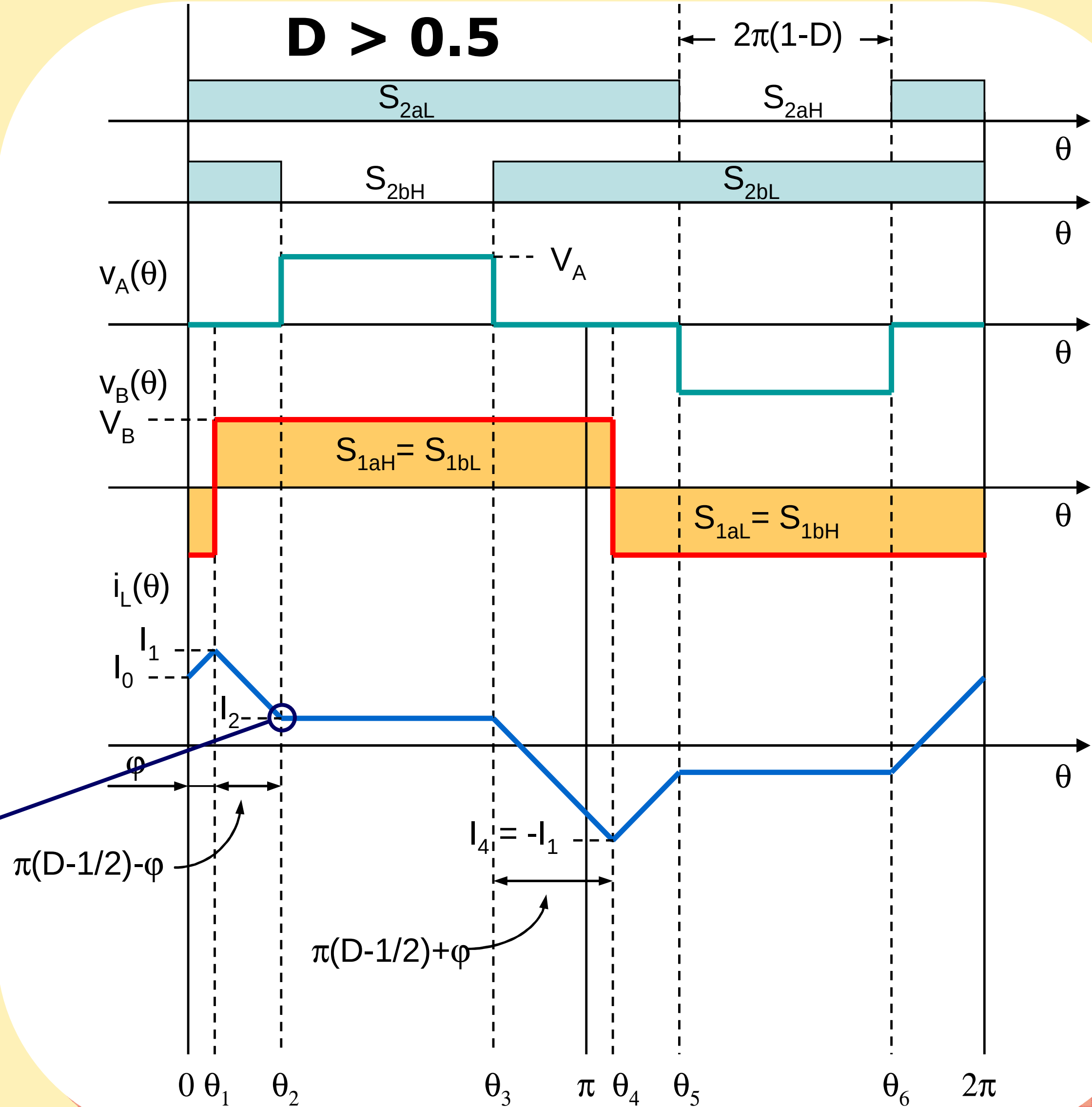

Case A: $0 < \varphi < \pi(D-1/2)$

$$i_b(\theta_2) = I_{mpk} - \frac{n_s}{n_p} I_2 \geq 0$$

Soft-switching conditions

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

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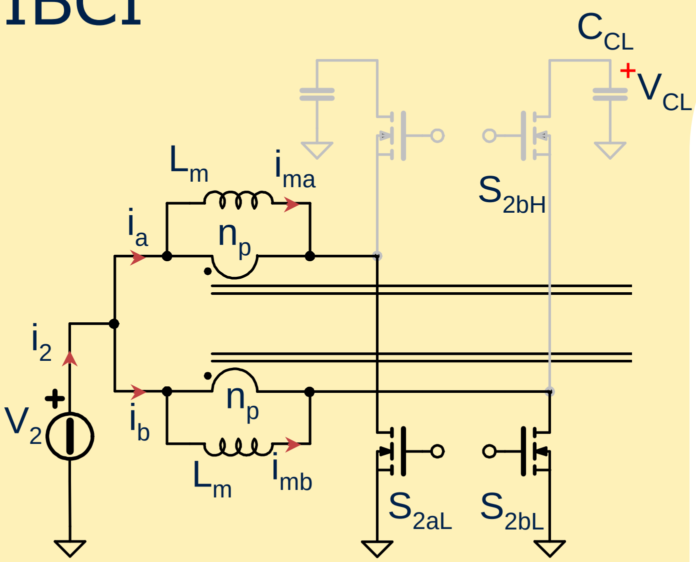
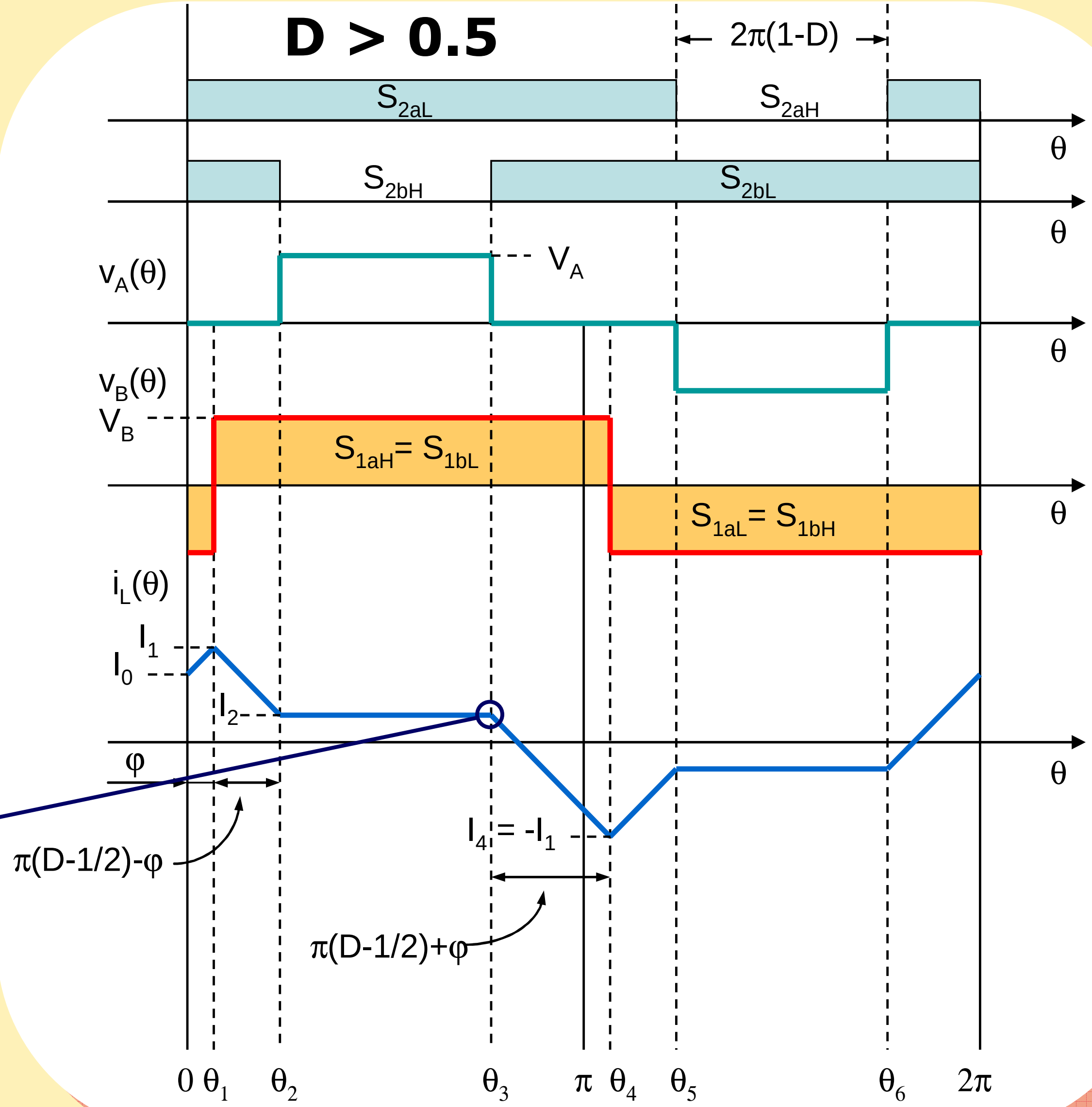


Case A: $0 < \varphi < \pi(D-1/2)$

$$i_b(\theta_3) = I_{mvl} - \frac{n_s}{n_p} I_3 \leq 0$$



Soft-switching conditions

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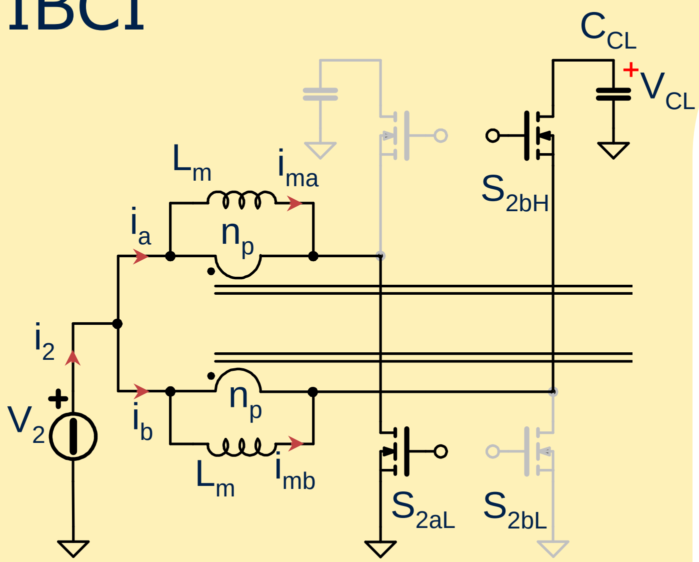
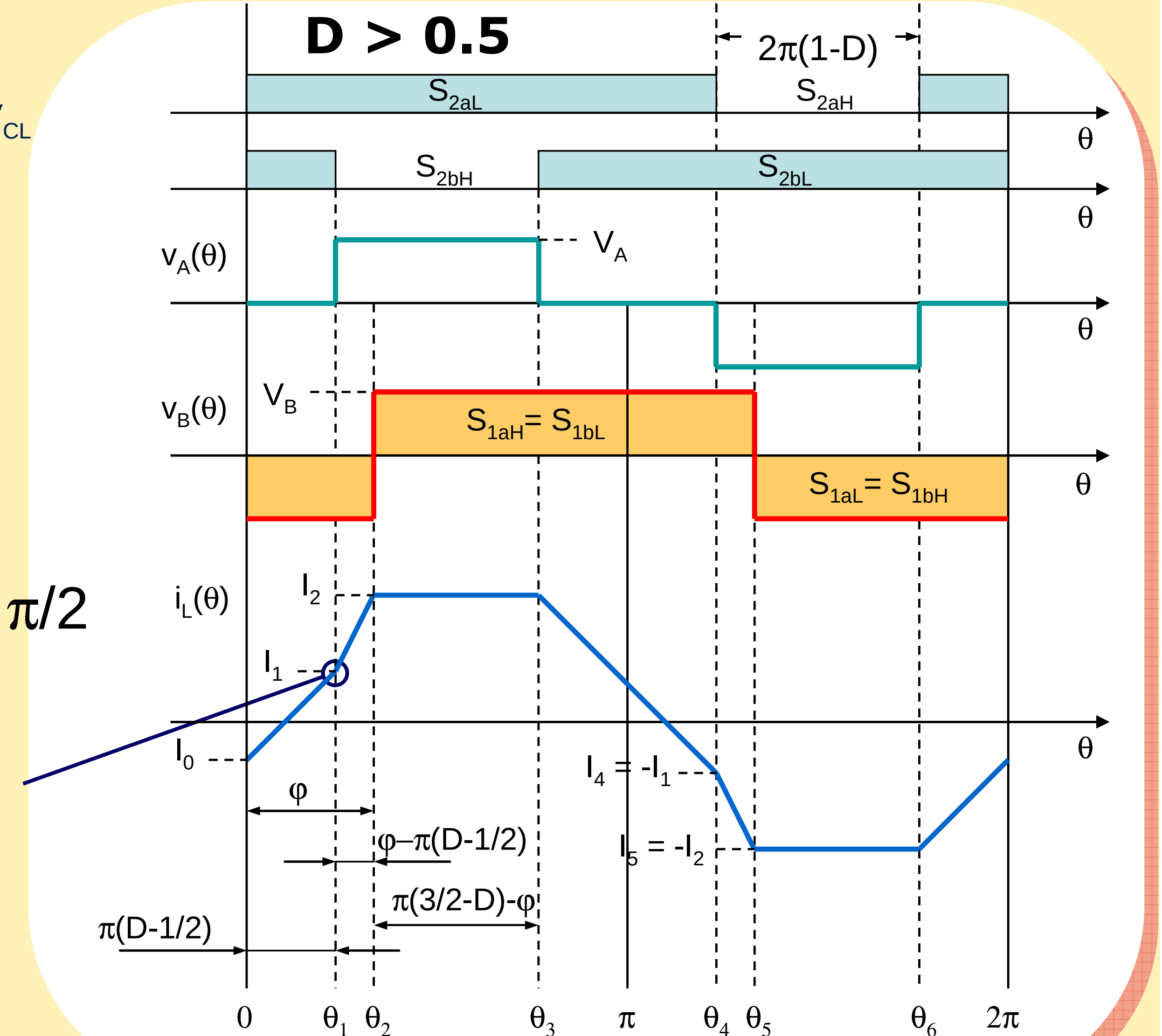


Case B: $\pi(D-1/2) < \varphi < \pi/2$

$$i_b(\theta_1) = I_{mpk} - \frac{n_s}{n_p} I_1 \geq 0$$



Soft-switching conditions

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

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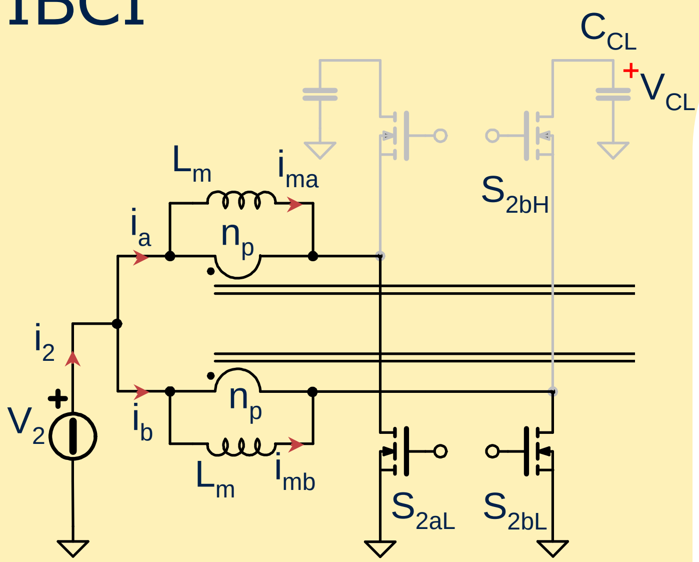
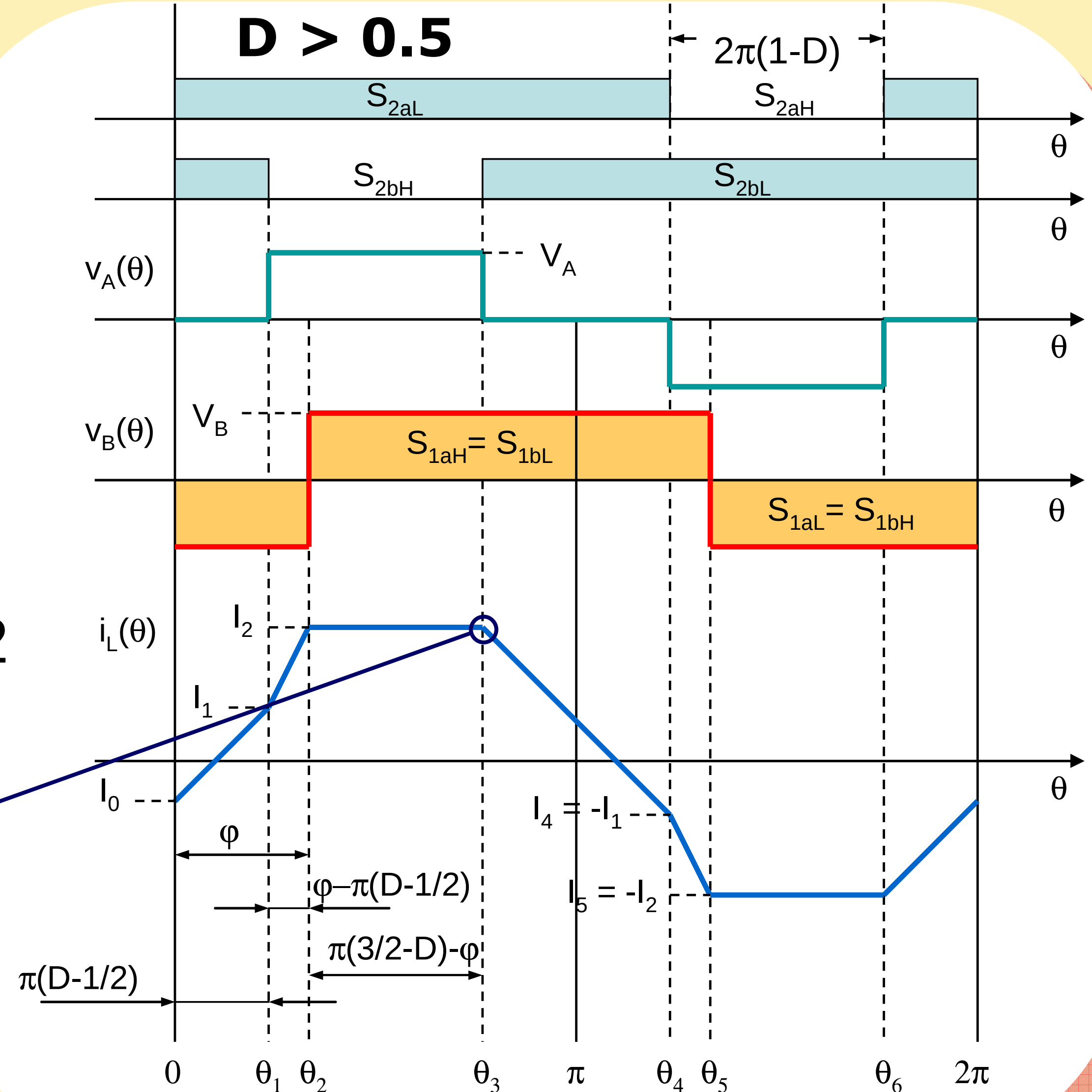


Case B: $\pi(D-1/2) < \varphi < \pi/2$

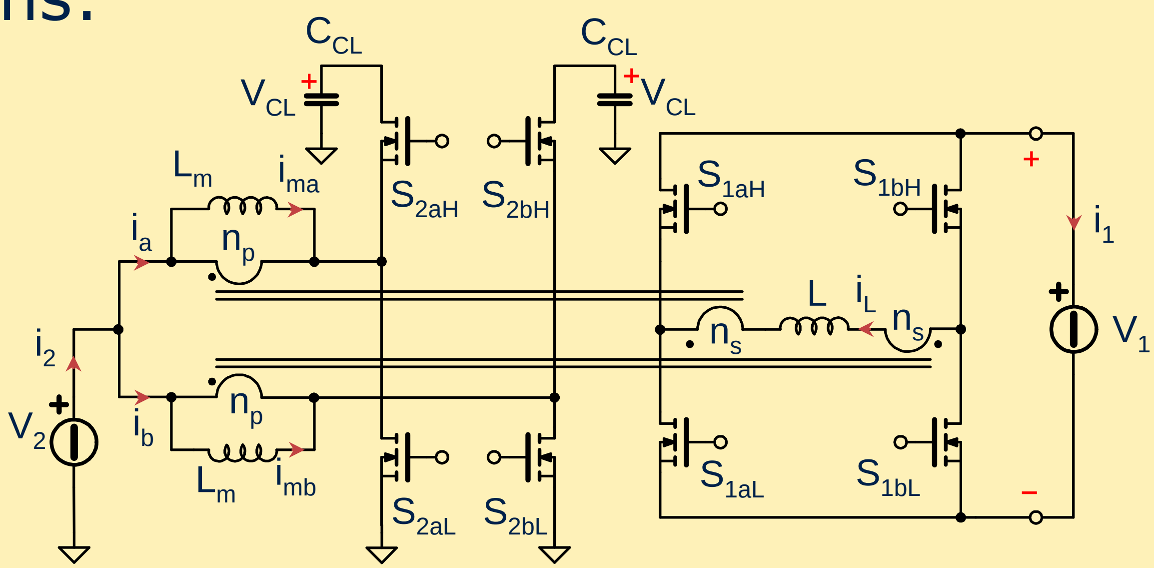
$$i_b(\theta_3) = I_{mvl} - \frac{n_s}{n_p} I_3 \leq 0$$



Soft-switching conditions

DIPARTIMENTO
DI INGEGNERIA
DELL'INFORMAZIONE

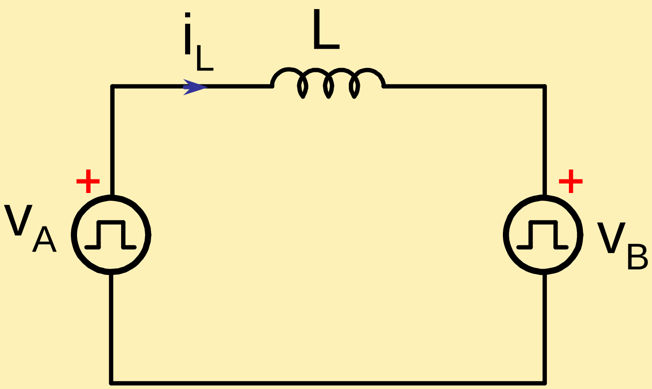
Considerations:



- **The active clamp operation requires the clamp current to have zero average value. This means that the upper switch current must reverse polarity during their conduction interval (help soft-switching)**
- **A non negligible magnetizing inductor ripple helps to satisfy the soft-switching conditions especially at low power levels**

Normalized Transferred Power

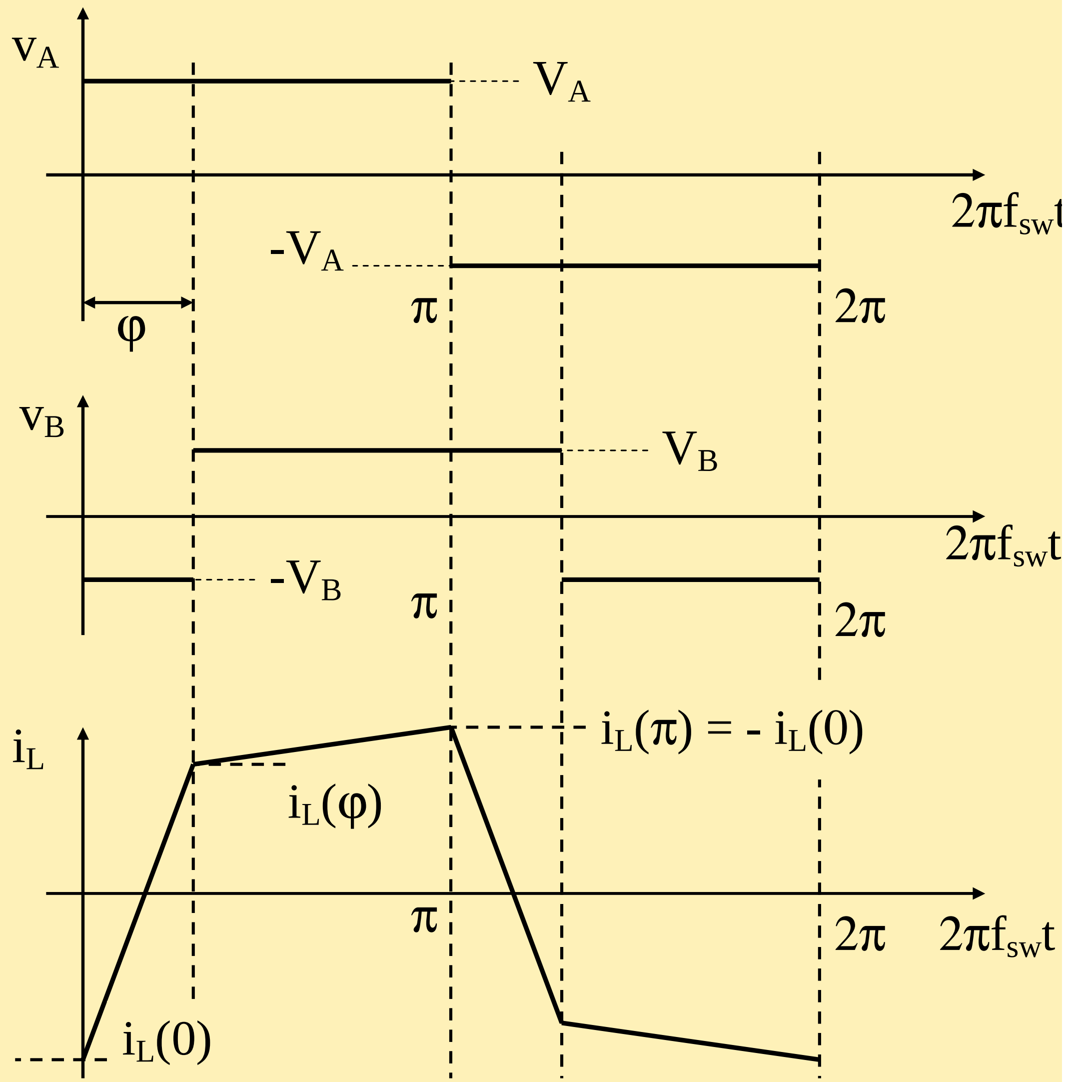
Single-phase DAB



Power flow

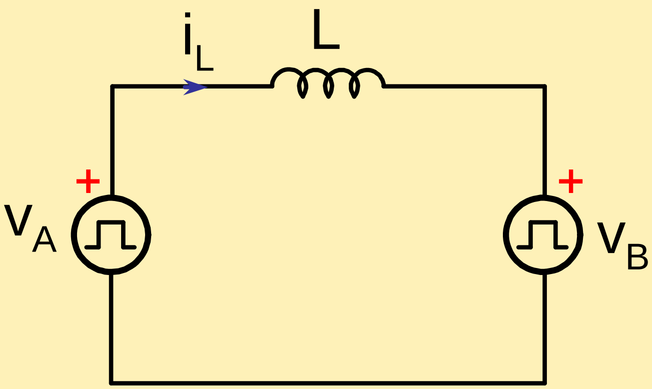
$$\Pi(\varphi) = \frac{P(\varphi)}{P_N}$$

$$= \frac{1}{\pi}\int_0^{\pi} j_L(\theta)d\theta$$



Normalized Transferred Power

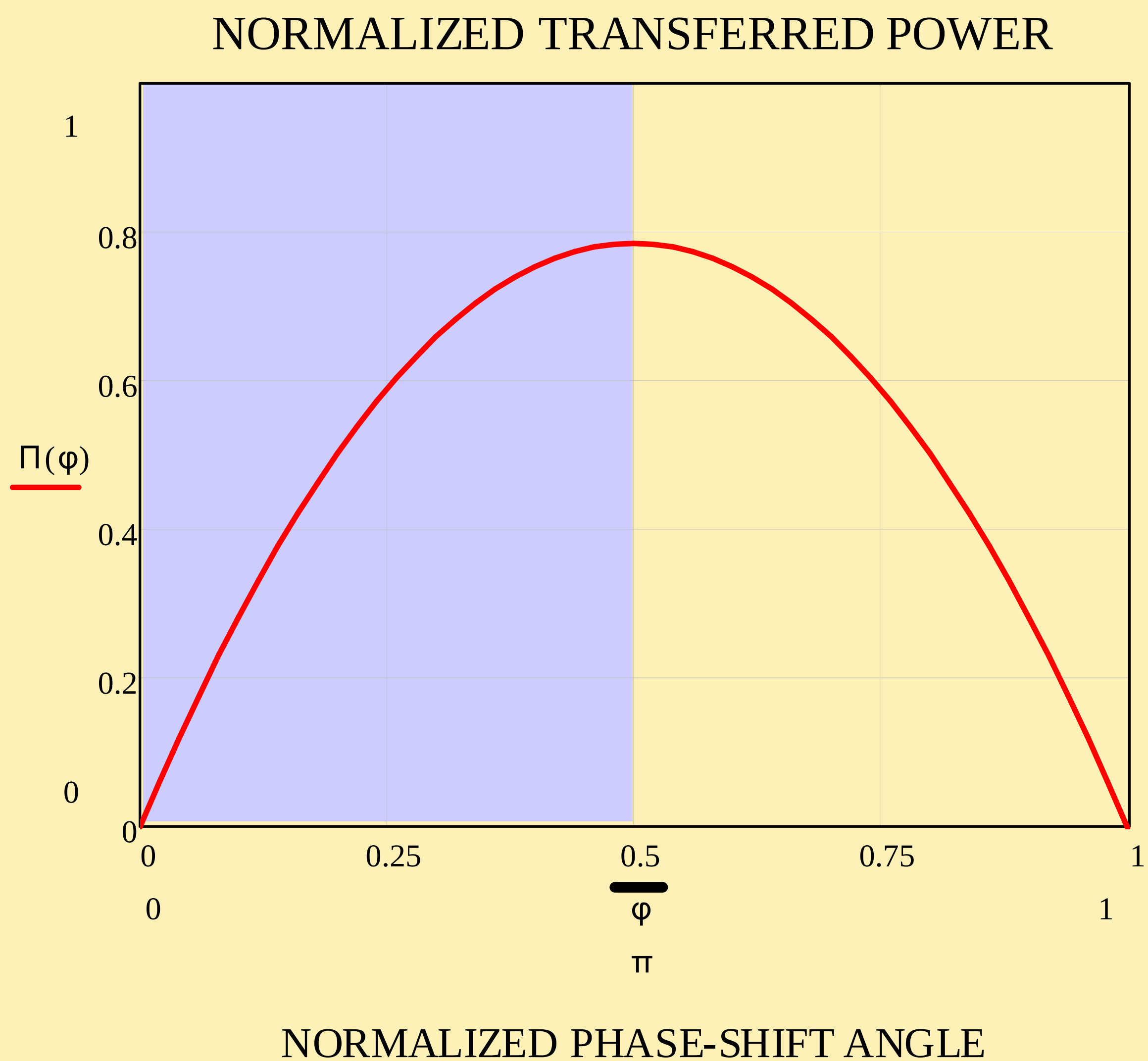
Single-phase DAB



Power flow

$$\Pi(\varphi) = k\varphi\left(1-\frac{\varphi}{\pi}\right)$$

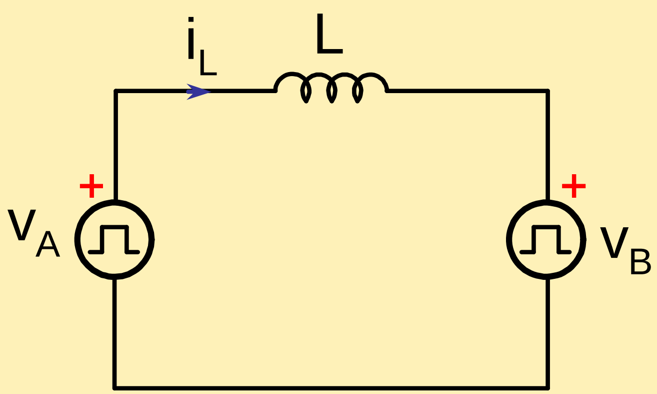
$$k = \frac{V_B}{V_A}$$



Normalized Transferred Power

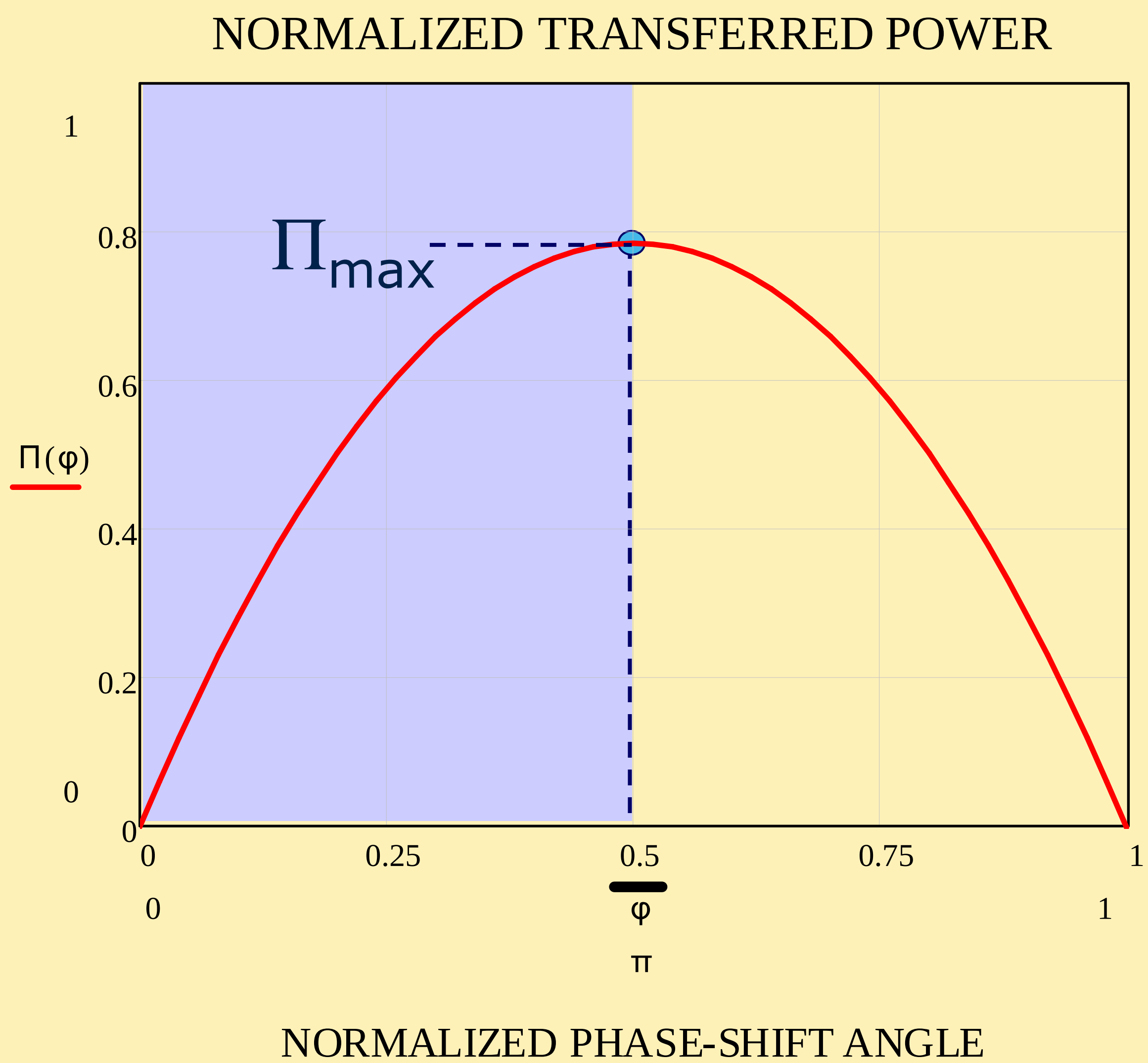
DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Single-phase DAB



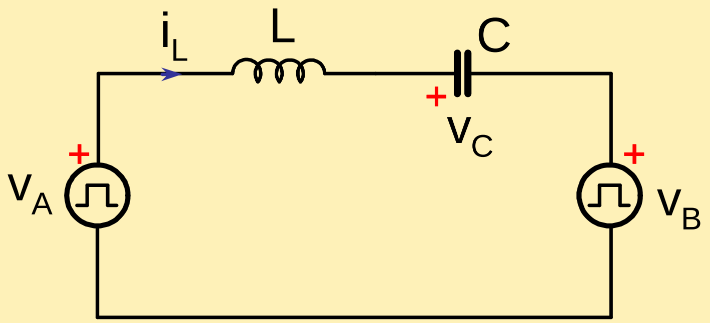
Power flow

$$\Pi_{max} = \Pi\left(\frac{\pi}{2}\right) = k\frac{\pi}{4}$$



Normalized Transferred Power

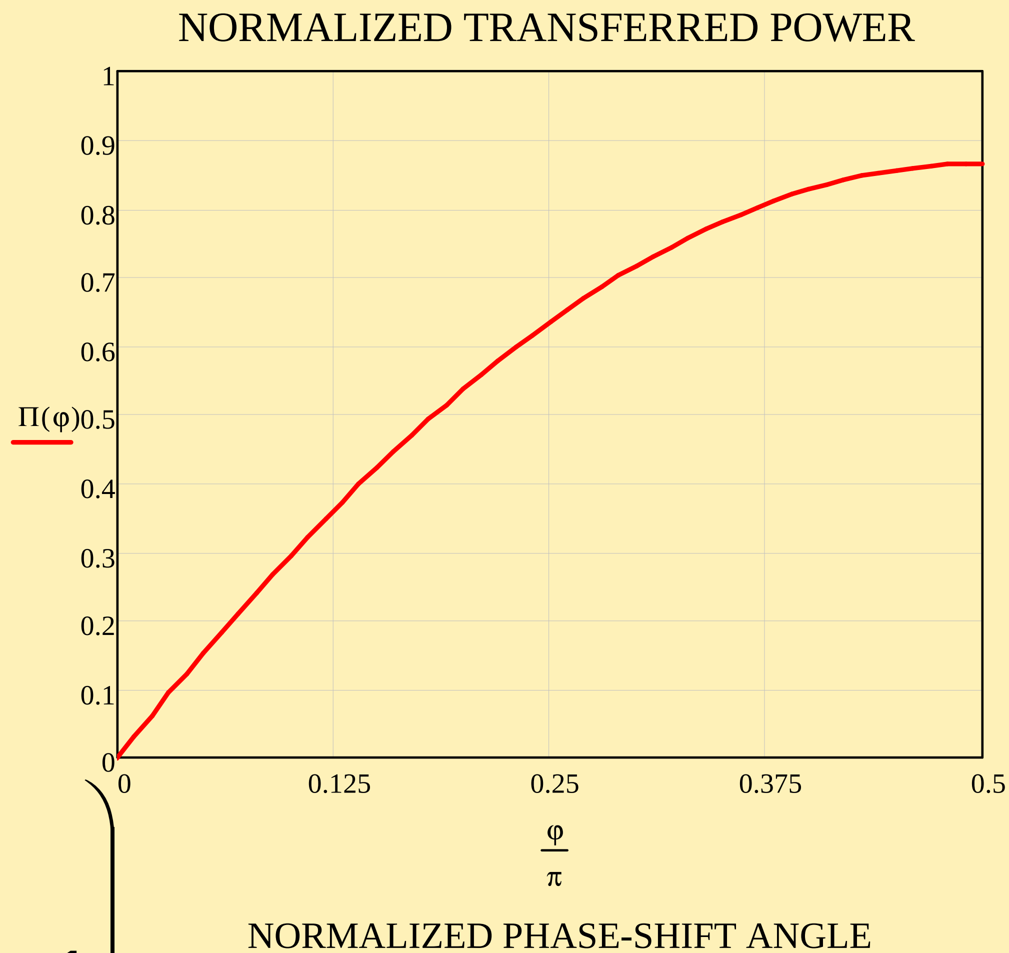
Single-phase SR-DAB



Power flow

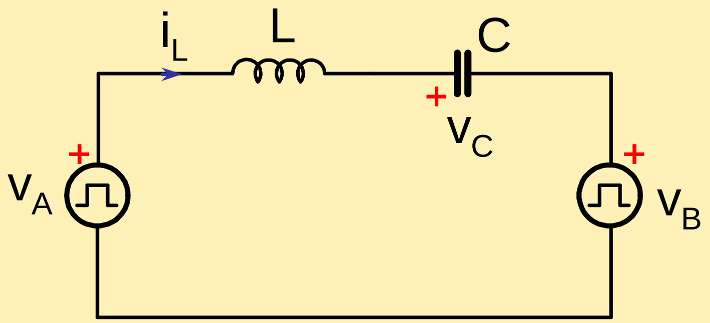
$$\Pi(\varphi) = \frac{P(\varphi)}{P_N}$$

$$= \frac{2kf_n}{\pi}\left(\frac{\cos\left(\frac{\pi - 2\varphi}{2f_n}\right)}{\cos\left(\frac{\pi}{2f_n}\right)} - 1\right)$$



Normalized Transferred Power

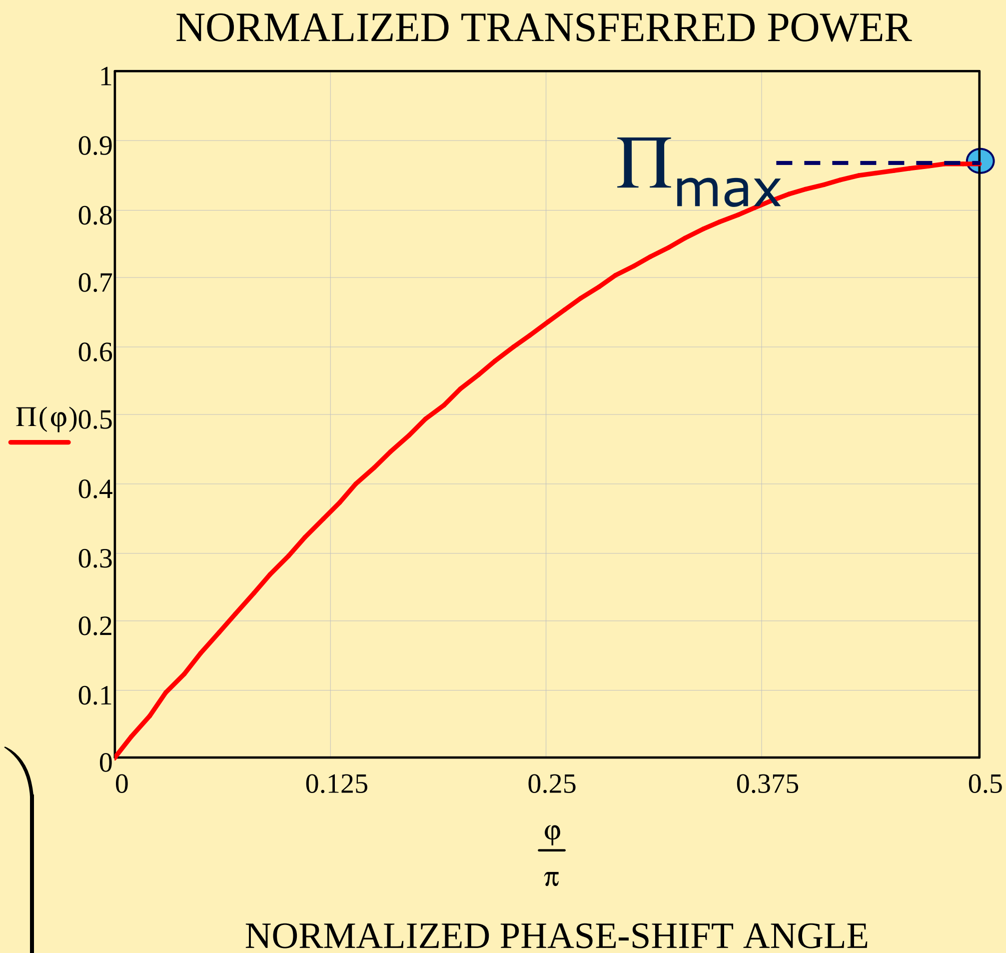
Single-phase SR-DAB



Power flow

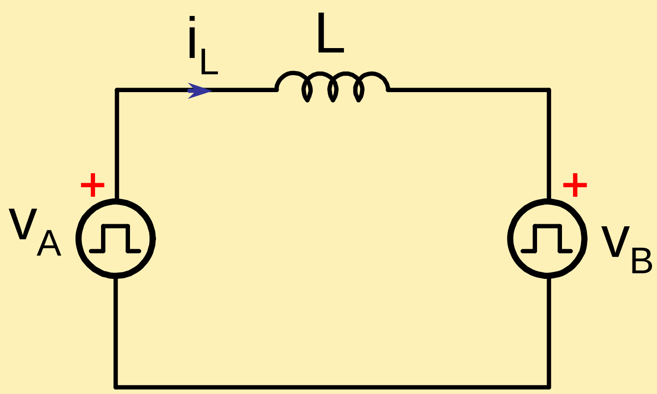
$$\Pi_{max} = \Pi\left(\frac{\pi}{2}\right)$$

$$= \frac{2kf_n}{\pi}\left(\frac{1}{\cos\left(\frac{\pi}{2f_n}\right)} - 1\right)$$



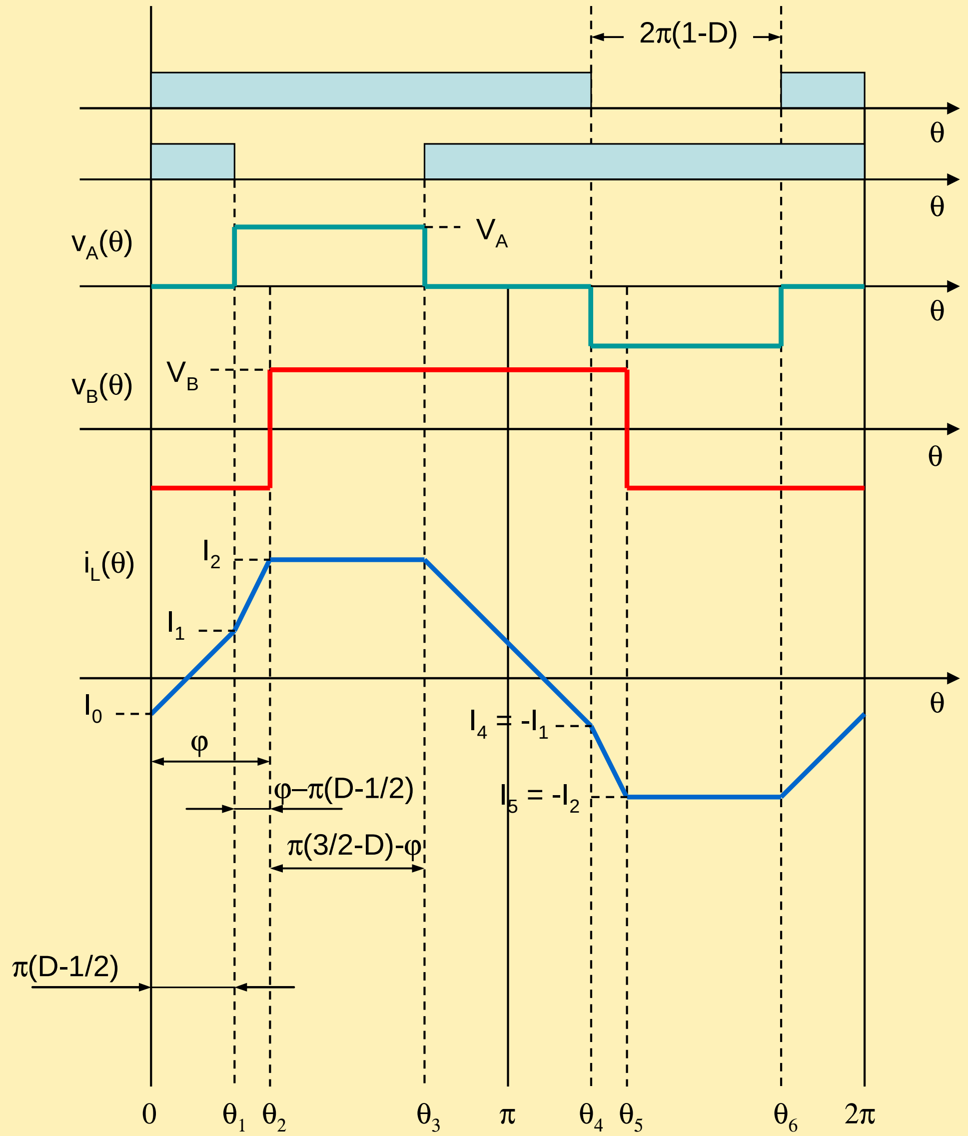
Normalized Transferred Power

IBCI



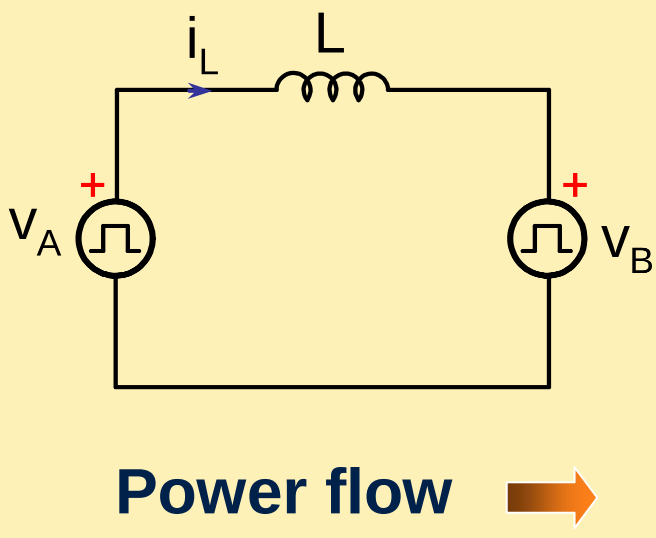
Power flow

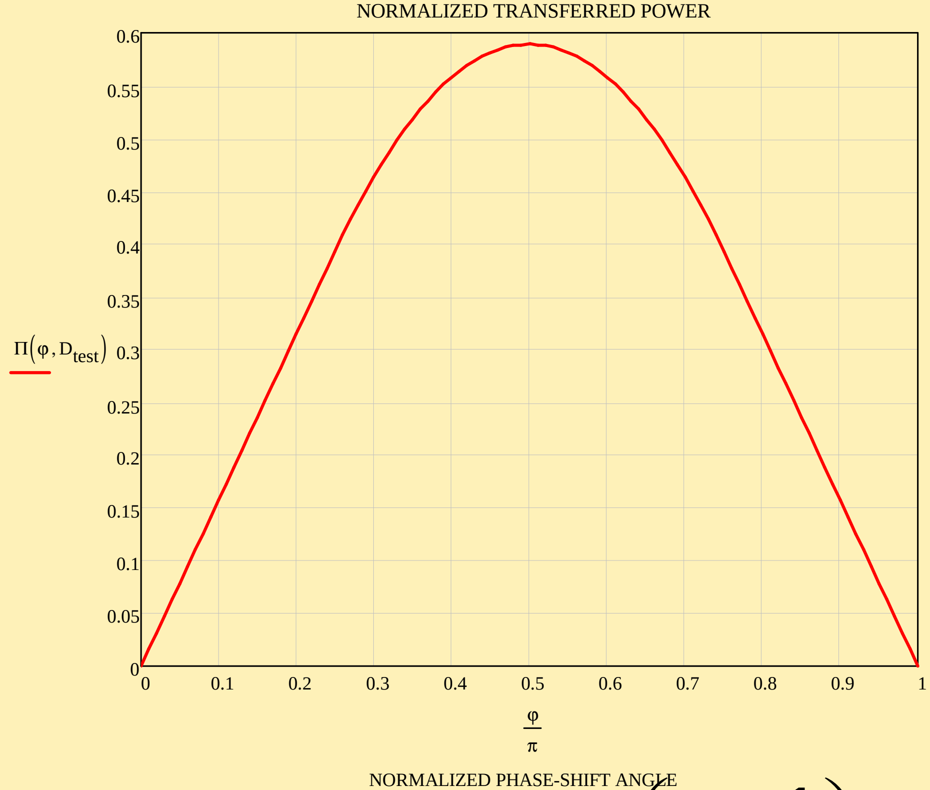
$$\Pi(\varphi) = \frac{1}{\pi}\int_{\theta_1}^{\theta_3} j_L(\theta)d\theta$$



Normalized Transferred Power

IBCI

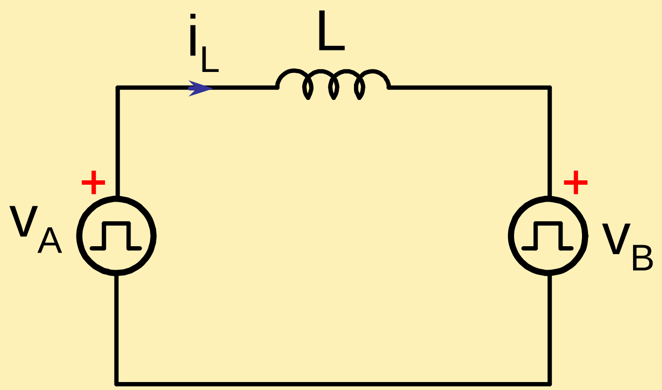




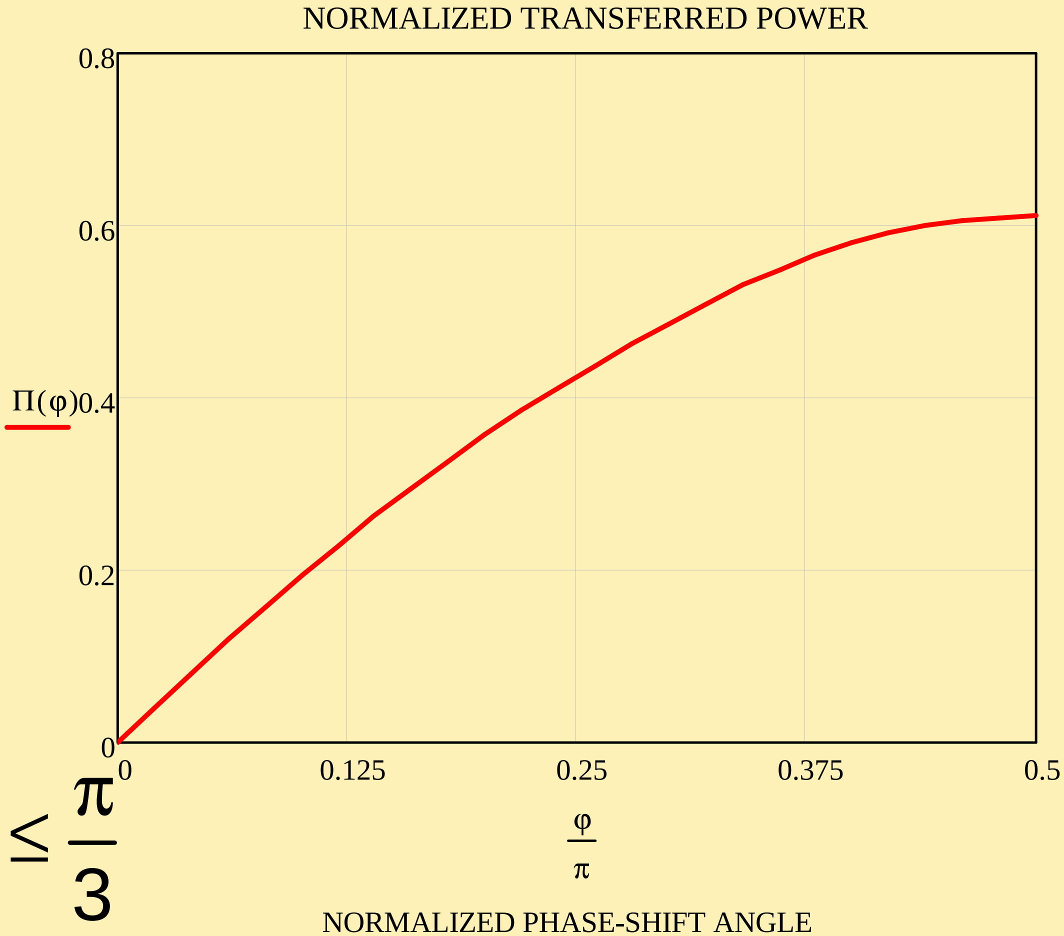
$$\Pi(\varphi)=\begin{cases}2k\varphi(1-D) & \text{for} \quad 0\le\varphi\le\pi\left(D-\frac{1}{2}\right)\\ k\varphi\left(1-\frac{\varphi}{\pi}\right)-k\pi\left(D-\frac{1}{2}\right)^2 & \text{for} \quad \pi\left(D-\frac{1}{2}\right)\le\varphi\le\frac{\pi}{2}\end{cases}$$

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

Three-phase DAB



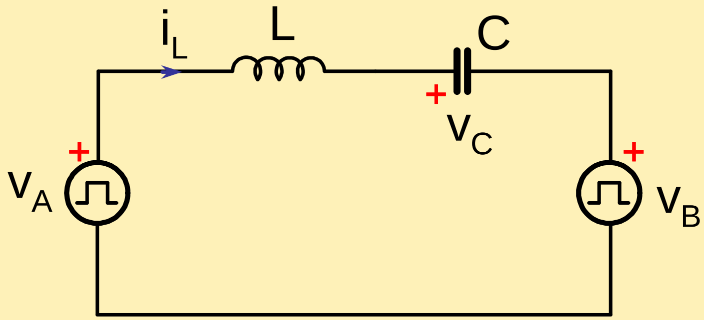
Power flow



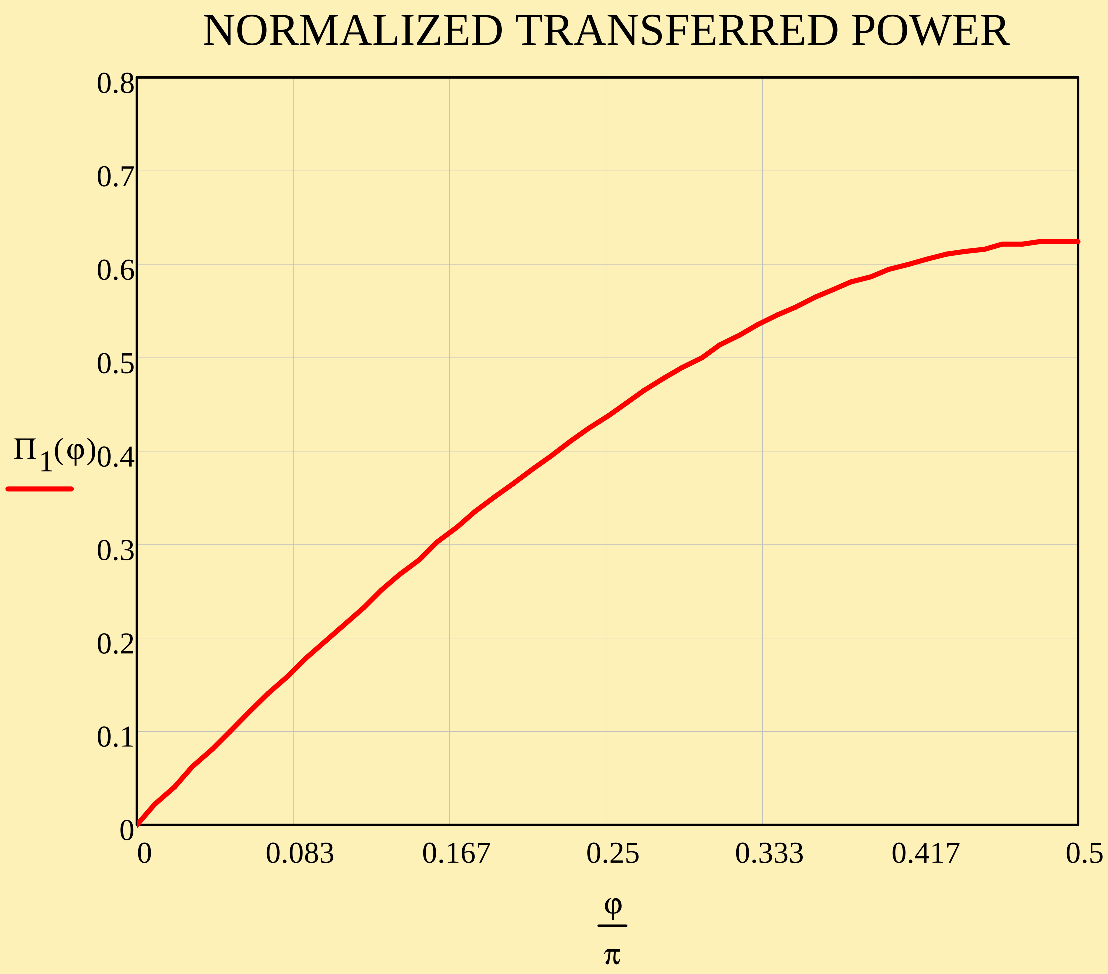
$$\Pi(\varphi) = \begin{cases} \varphi\left(\dfrac{2}{3} - \dfrac{\varphi}{2\pi}\right) & \varphi \le \dfrac{\pi}{3} \\ \varphi - \dfrac{\varphi^2}{\pi} - \dfrac{\pi}{18} & \dfrac{\pi}{3} \le \varphi \le \dfrac{\pi}{2} \end{cases}$$

Normalized Transferred Power

Three-phase SR-DAB



Power flow



No closed form expression for $\Pi(\varphi)$

Conclusions

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

- **Different isolated bidirectional topologies, belonging to the family of dual active bridge structures, have been considered**
- **A unified analysis has been carried out to calculate the steady-state current waveform responsible for the power transfer**
- **Soft-switching conditions have been investigated for each converter topology**
- **The transferred power and its relation with the phase-shift angle has been calculated**