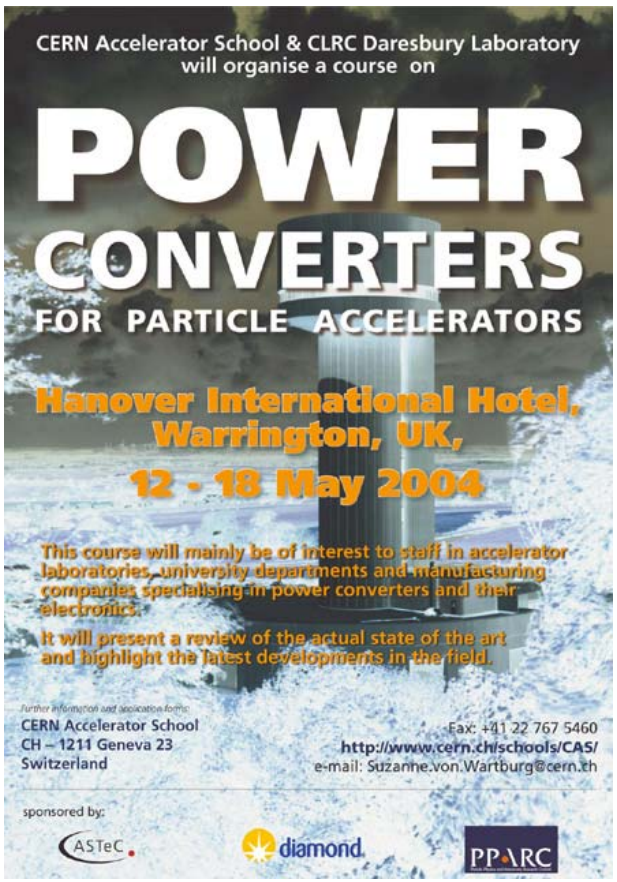
Power converters

Definitions and classifications
Converter topologies



Frédérick BORDRY
CERN

12-18th May 2004
Power Converters
for particle accelerators
Warrington, UK

Power converters : Definitions

The source of the beam blow-up when we could not prove it was the RF (Control room operator)

A powerful small black box able to convert MAD files into currents (Accelerator Physics group member)

An equipment with three states, ON, OFF and FAULT (Another operator)

Is it the same thing as a power supply? (Person from another physics lab)

A big box with wires and pipes everywhere and blinking lamps. Occasionally it goes BANGG! (Group secretary view)

Power converters : Definitions (cont'd)

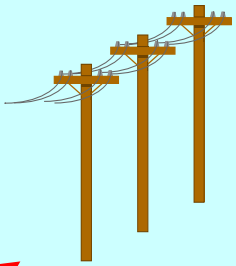
That which feeds the magnets (a visitor)

A stupid installation taking a non-sinusoidal current at poor power factor (power distribution engineer)

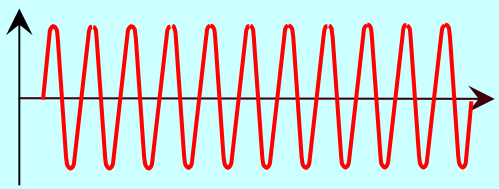
A standard piece of equipment available from industry off-the-shelf
(a higher management person, not in in this room !)

Something which converts your time in money.
Efficiency ??? Especially last week-ends !!!... (my wife)

Energy source



50 or 60 Hz ; AC



Power converter

The task of a power converter is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads.

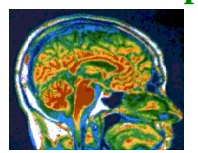
Control

Applications

Traction and auxiliary

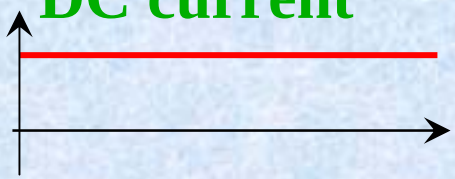
Domestic Appliance

Medical applications



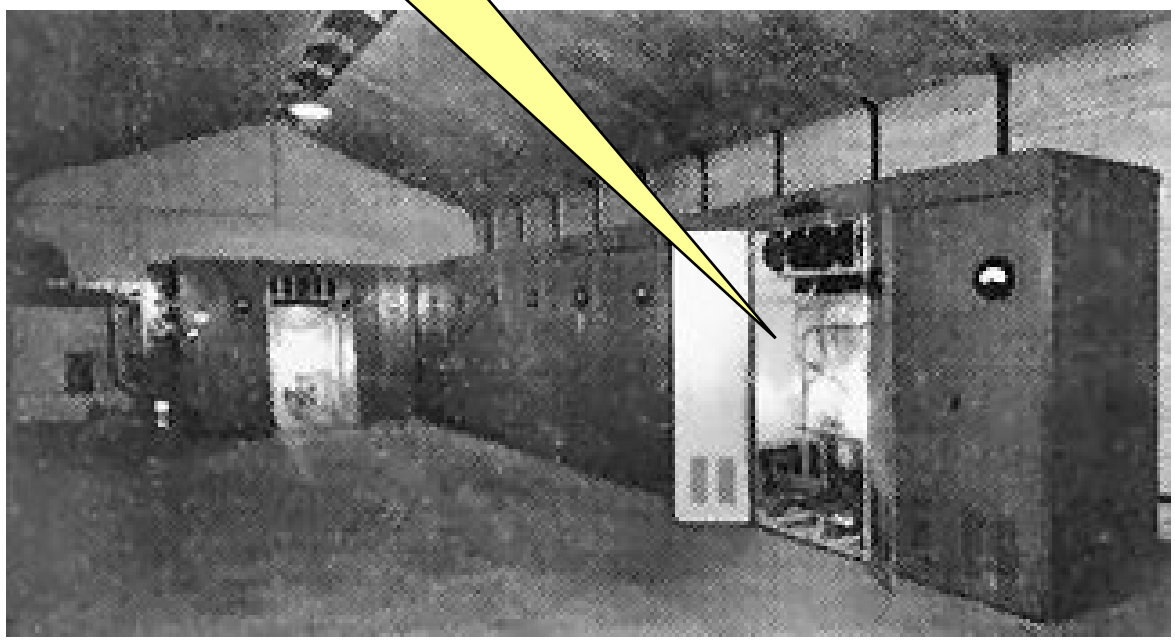
Indutrial applications, Welding, Induction Heating, ….

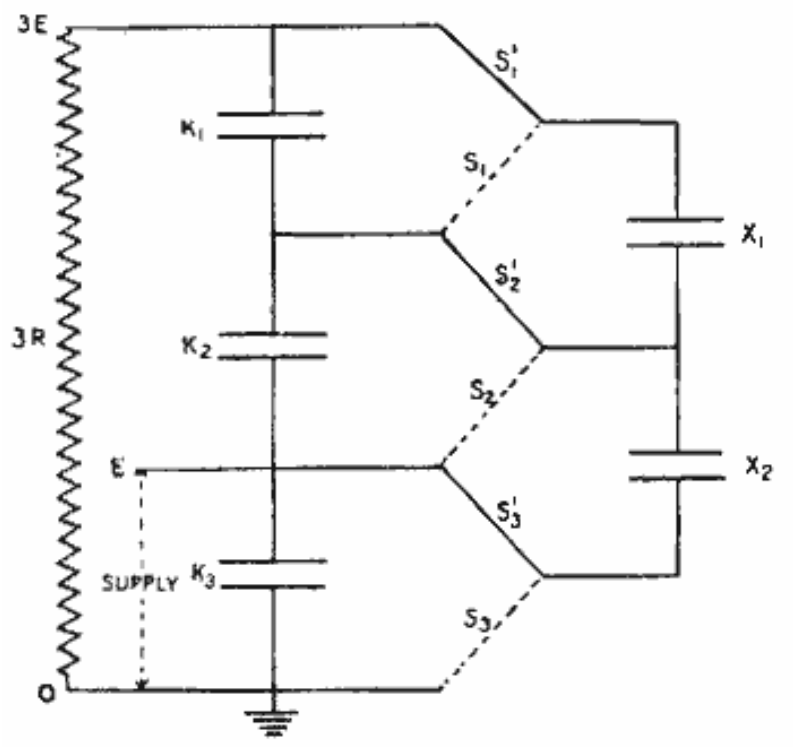
DC current

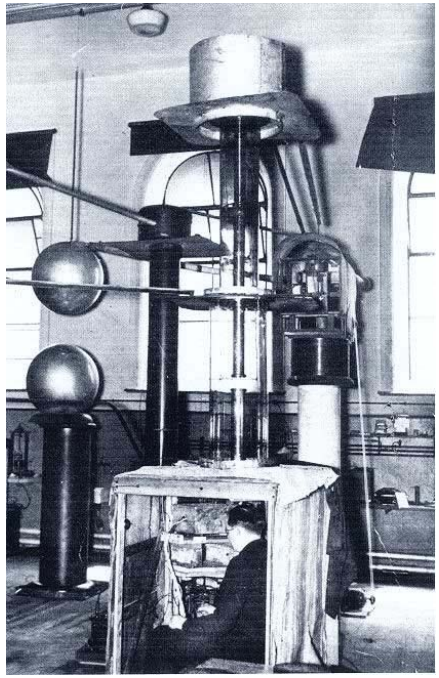


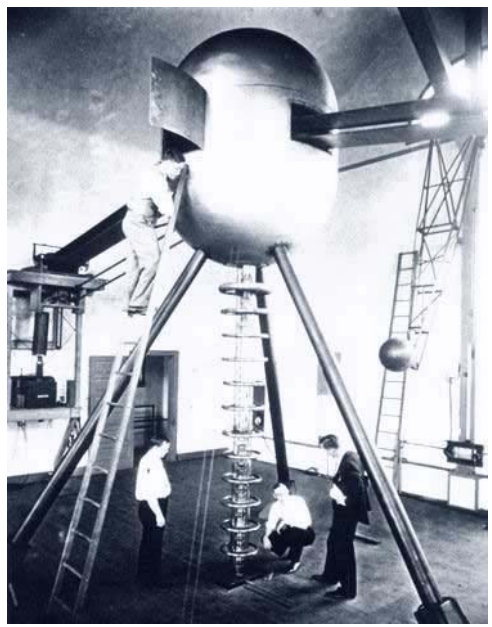
Once upon a time…. not so far

This is a 6-phase device, 150A rating with grid control.
It measures 600mm high by 530mm diameter.









Schematic of Cockcroft and Walton's voltage multiplier. Opening and closing the switches S transfers charge from capacitor K3 through the capacitors X up to K1.

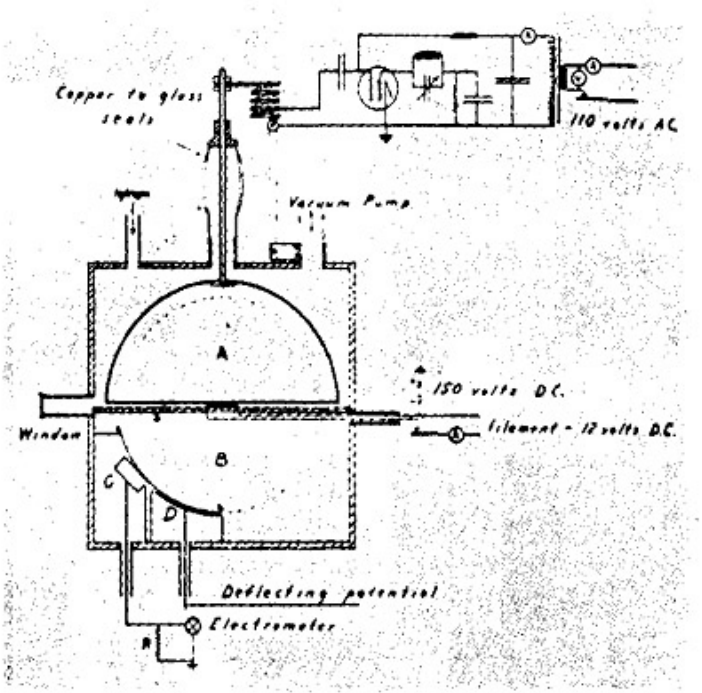
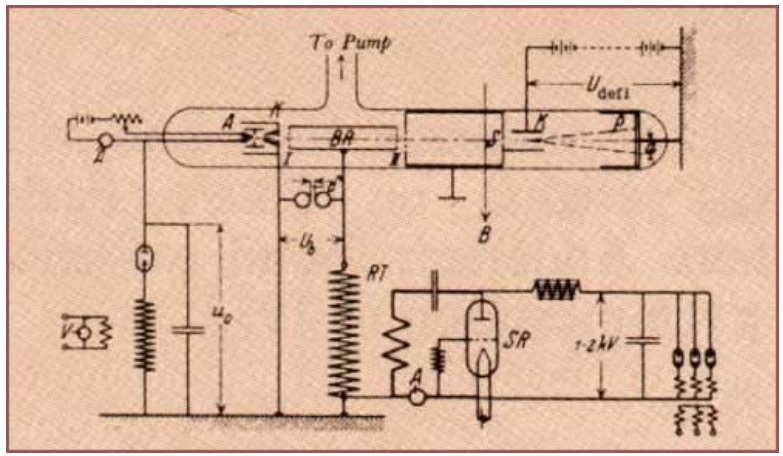
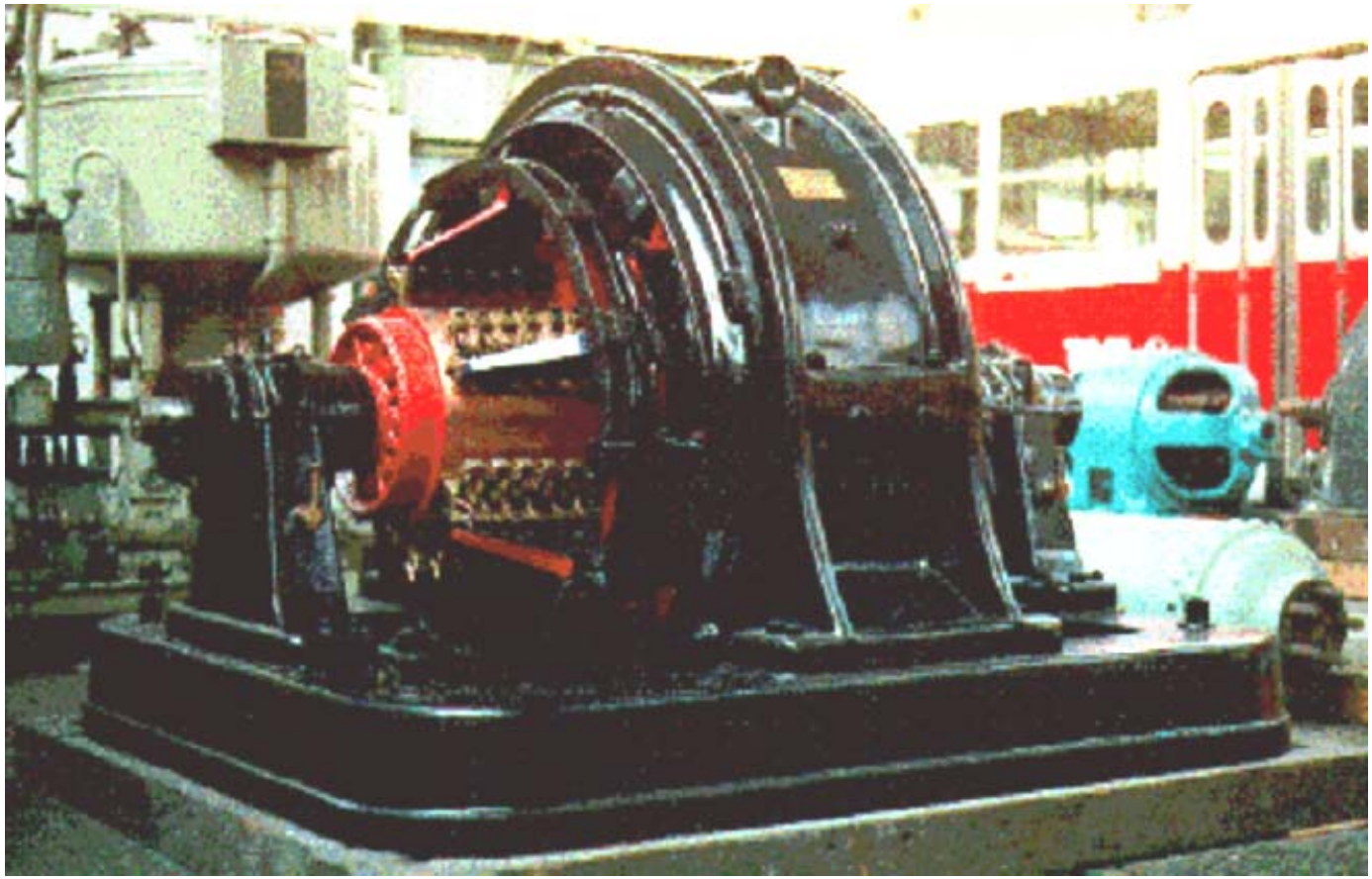


Diagram of the first successful cyclotron constructed by Lawrence and M. S. Livingston. The single dee is five inches in diameter.



The difficulties of maintaining high voltages led several physicists to propose accelerating particles by using a lower voltage more than once. Lawrence learned of one such scheme in the spring of 1929, while browsing through an issue of *Archiv für Elektrotechnik*, a German journal for electrical engineers. Lawrence read German only with great difficulty, but he was rewarded for his diligence: he found an article by a Norwegian engineer, Rolf Wideröe, the title of which he could translate as “On a new principle for the production of higher voltages.” The diagrams explained the principle and Lawrence skipped the text.

In the beginning…

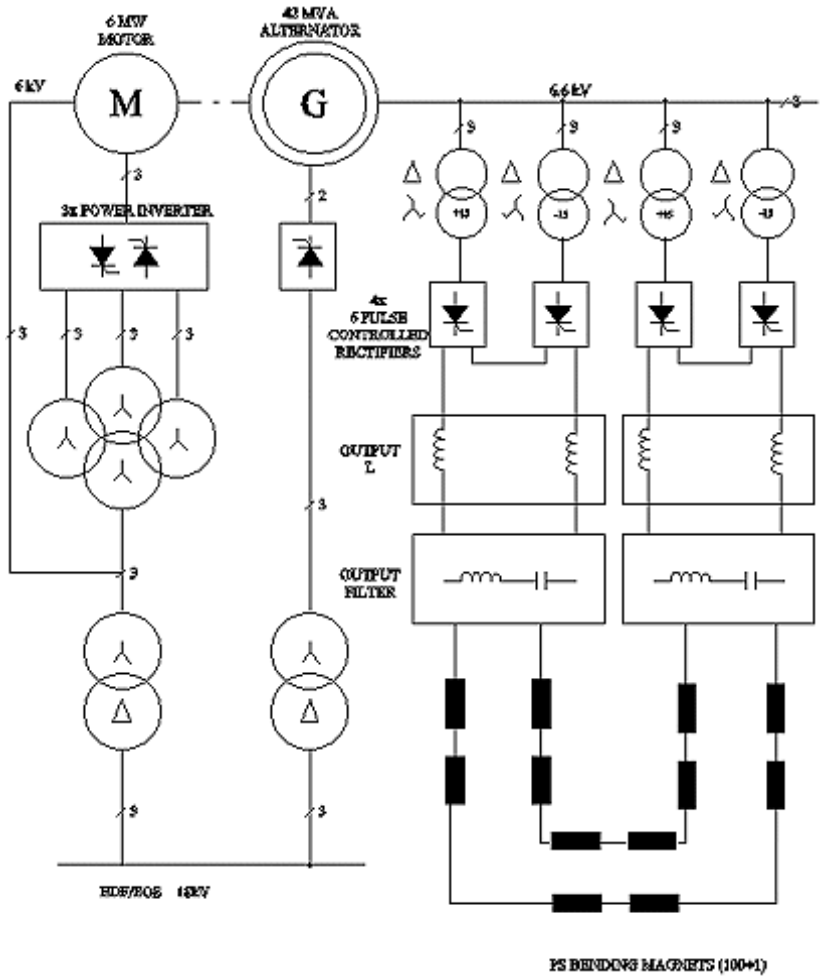


une commutatrice des tramways de Saint-Etienne, datant de 1907 et ayant fonctionné jusqu'en avril 1991

and still now…

Brookhaven National Laboratory - AGS

CERN - PS



Evolution of Power semiconductors

From mercury arc rectifier, grid-controlled vacuum-tube rectifier, inignitron ,….

Power Electronics

From 1960

Power Diode and Thyristor

or SCR (Silicon-Controlled Rectifier)

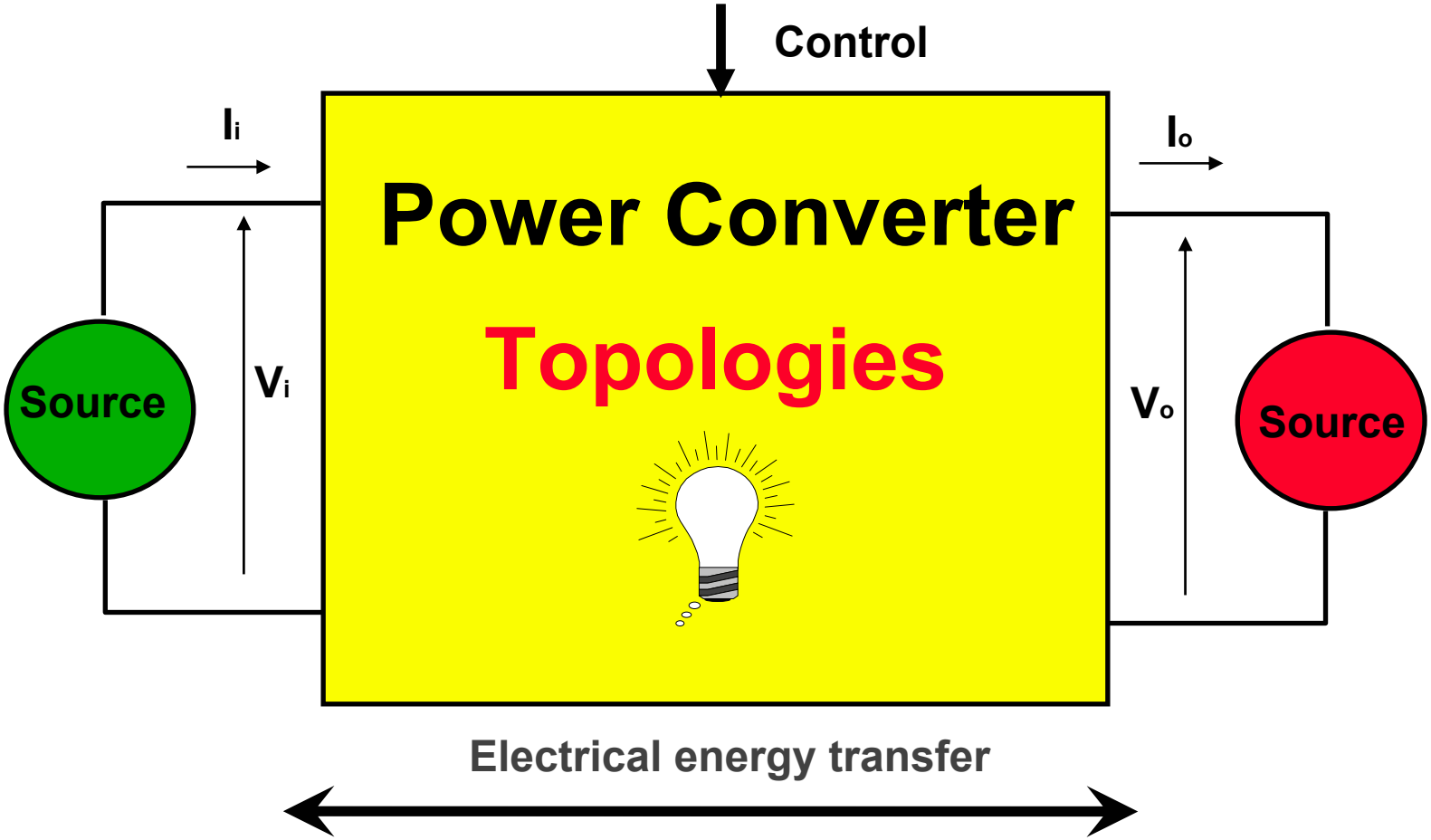
Link to frequency of the electrical network
50 Hz (60 Hz)

From 1985

High frequency power semiconductors :

MosFet, IGBTs , GTOs, MCTs,….

High frequency => high performances (ripple, bandwidth, perturbation rejection,...)
small magnetic (volume, weight)

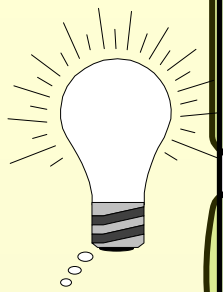


Power Converter

- performance
- efficiency
- reliability, repairability, availability
- low cost
- effect on environment (RFI, noise,...)

Inductances and capacitors

Switches



Connection rules

Sources

Power Converter

Topologies

Source definition

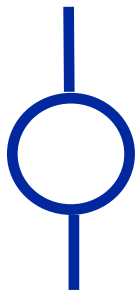
Source definition: any element able to impose a voltage or a current, independently of, respectively, the current flowing through, or the voltage imposed at its terminals.

A source could be a generator or a receptor.

Two types of sources:

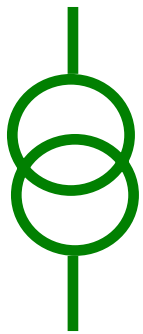
Voltage source

which imposes a voltage independently of the current flowing through it. This implies that the series impedance of the source is zero (or negligible in comparison with the load impedance)



Current source

which imposes a current independently of the voltage at its terminals.
This implies that the series impedance of the source is infinite (or very large in comparison with the load impedance)



Source definition

The principle of operation of a converter is based on the switch mode action of its switches. Commutations of these switches generate very fast current and/or voltage transients so that the transient behaviour of the sources is fundamental.

A source is a voltage source if the voltage across its terminals can't undergo a ***discontinuity*** due to the ***external*** circuit variation.

A source is a current source if the current flowing through it can't undergo a ***discontinuity*** due to the ***external*** circuit variation.

A square wave voltage (current) generator is indeed a voltage (current) source, since the discontinuity are not caused by the external circuit.

Source definition

Instantaneous impedance :
the limit of the impedance Z(s) when the Laplace operator s tends towards infinity.

New definitions:
Voltage Source has a zero instantaneous impedance

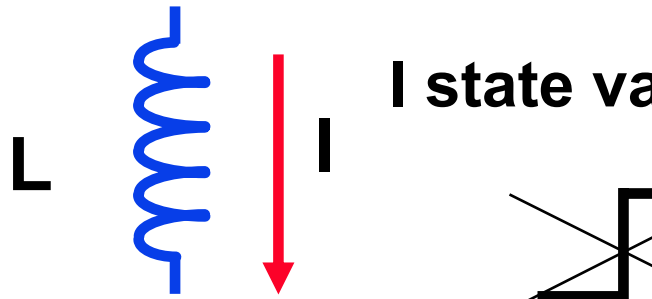
Current Source has an infinite instantaneous impedance

Example:

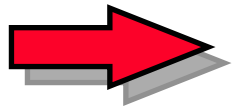
- Capacitor: Z(s) = 1 / (C.s) , limit $s \to \infty$ Z(s) = 0 => voltage source

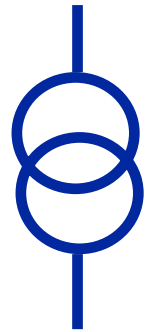
- Inductance : Z(s) = L.s , limit $s \to \infty$ Z(s) = ∞ => current source

Source examples



I state variable

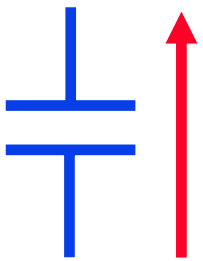




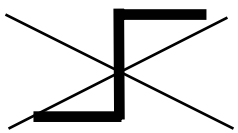
$E_L = \frac{1}{2} LI^2$

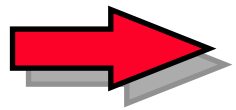
dI/dt ≠ ∞

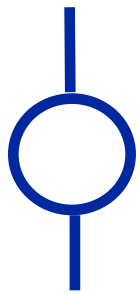
“ Current source “



V state variable





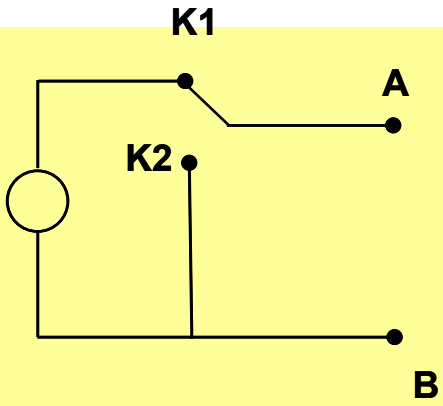


$E_C = \frac{1}{2} CV^2$

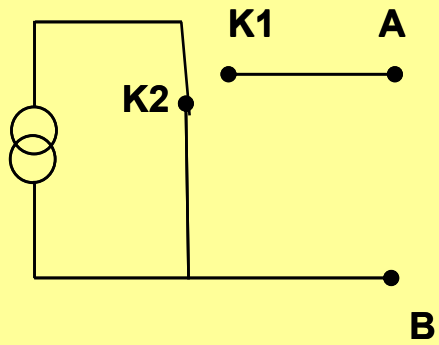
dV/dt ≠ ∞

“ Voltage source “

Source examples



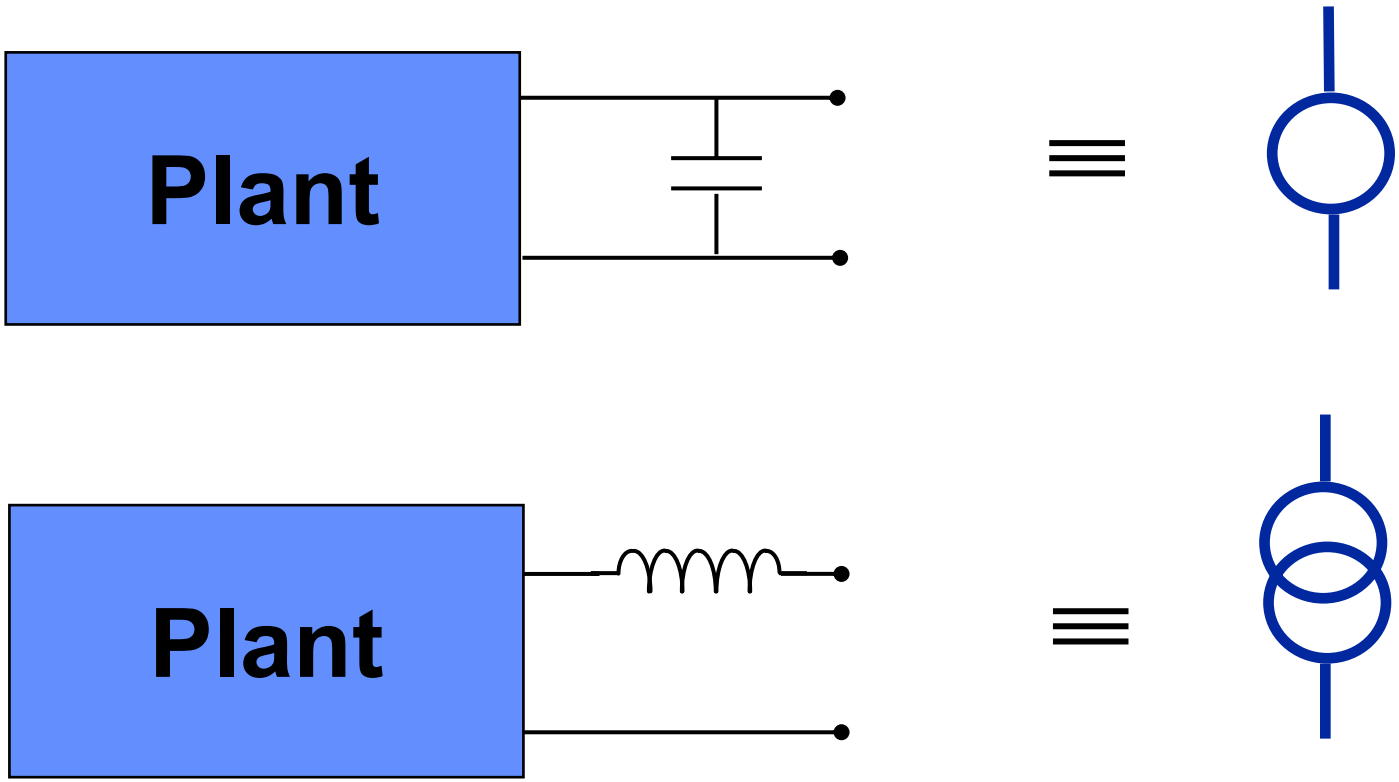
Voltage source between A and B :
$Z_{AB} = 0$



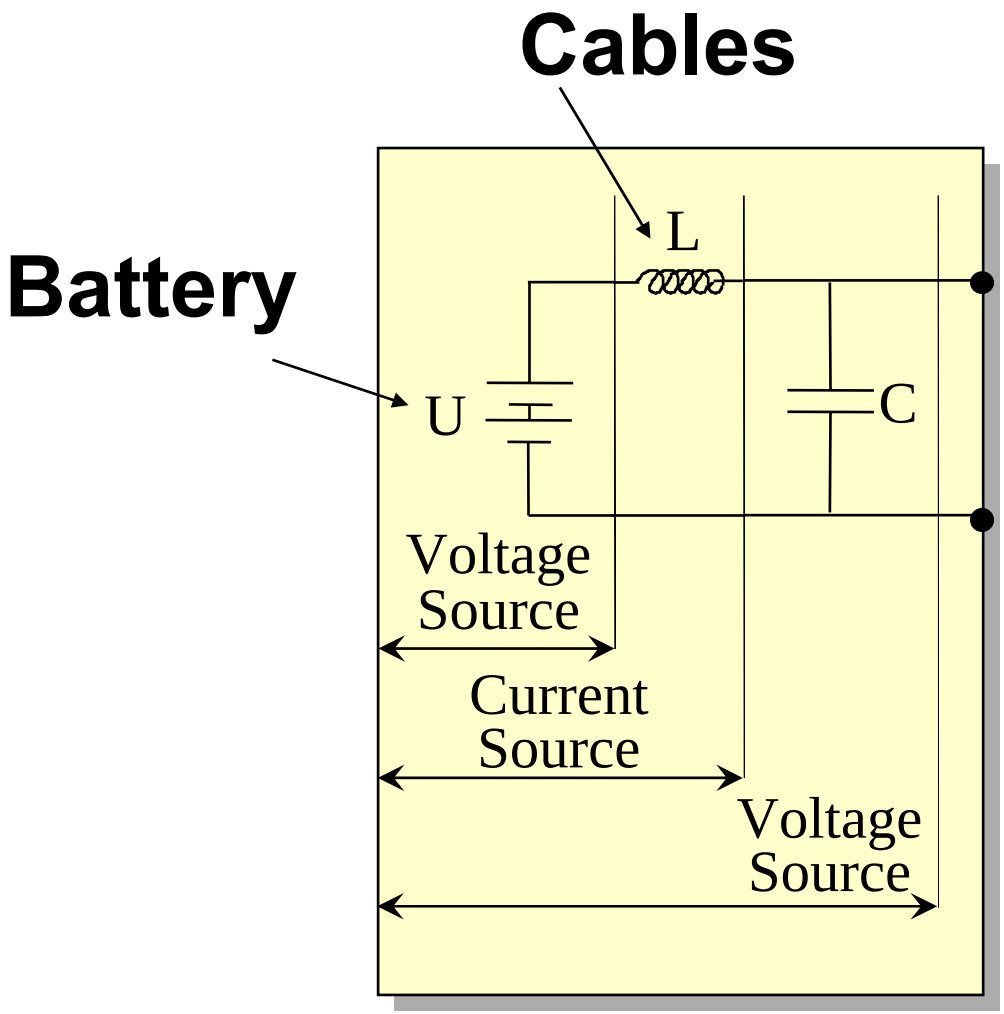
Current source between A and B :
$Z_{AB} = \infty$

"intermediate position : neither voltage, neither current source"

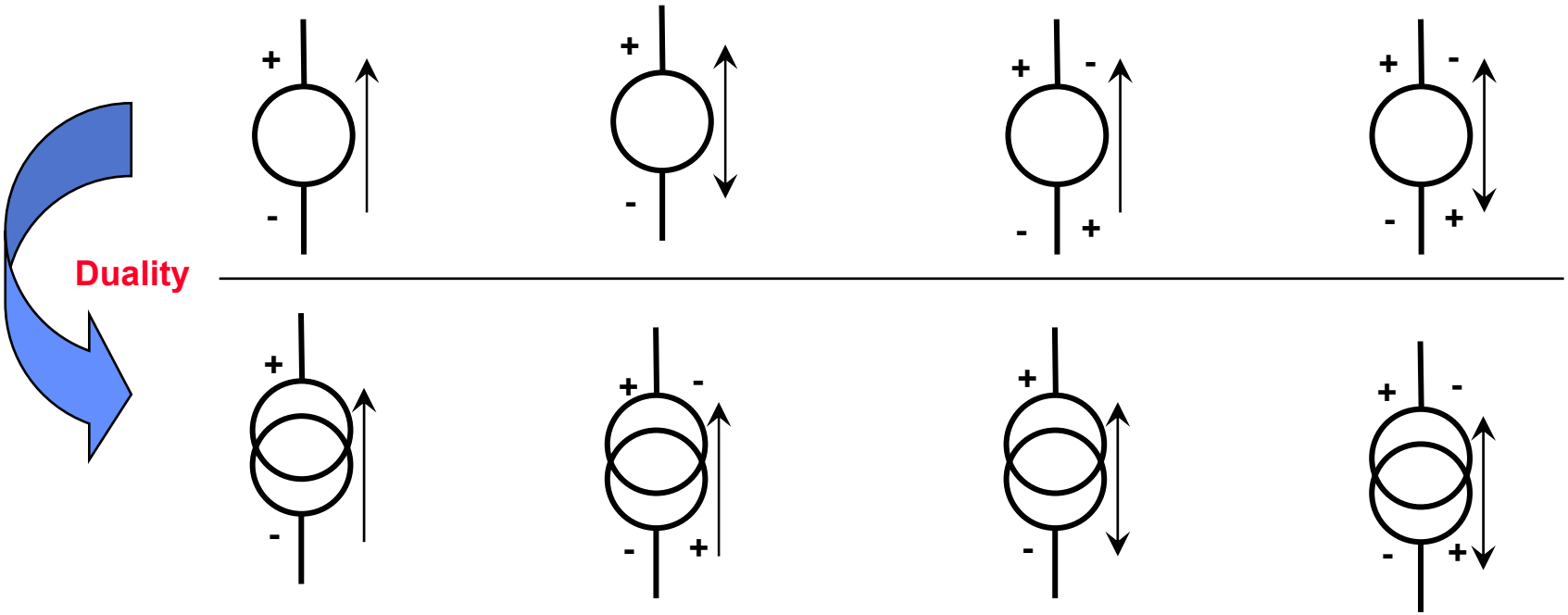
Source nature imposition



Modification of source nature



Eight types of sources



Unidirectional source

voltage : if the voltage, across its terminal, can't change sign

current : if the current, flowing through it, can't reverse

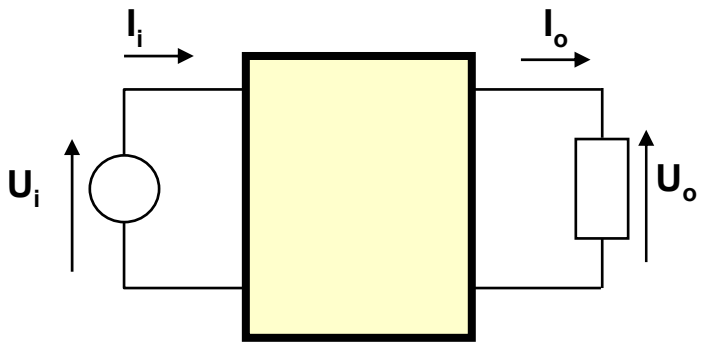
Bidirectional (reversible) source :

voltage : if the voltage, across its terminal, can change sign

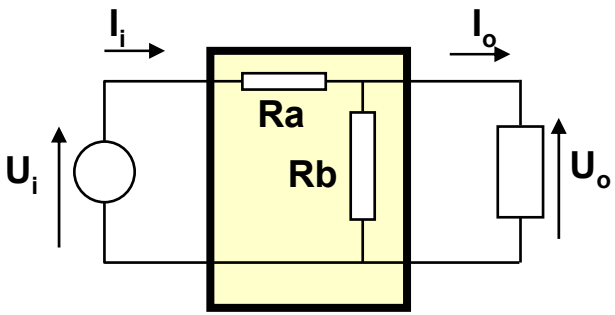
current : if the current, flowing through it, can reverse

Energy conversion : transfer of energy between two sources.

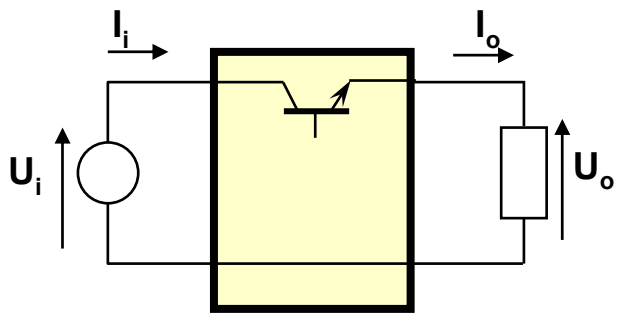
Introductive example



Converter



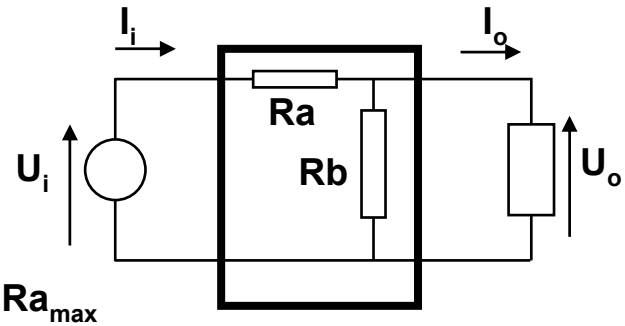
Resistive solution



Linear solution

Introductive example:
Transfer of energy between
- DC voltage source Ui
- DC source (nature is not defined) : Uo, Io

Resistive bridge solution



Model of the output source : Ro = Uo/ Io

Uo/ Ui = (Ro//Rb) / (Ra + Ro//Rb)

=> Rb = Ro . Ra / [(Ui-Uo)/Io - Ra] with Ra < (Ui-Uo)/Io = Ra_{max}

$P_{Ra} = (Ui - Uo)^2 / Ra$

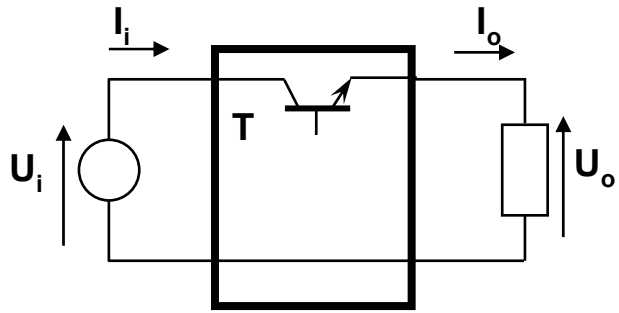
$P_{Rb} = Uo^2 . [(Ra_{max} - Ra] / (Ro + Ra)$

Efficiency of the converter is equal to $E = Po / (Po + P_{Ra} + P_{Rb})$; **optimum Rb = ∞**

Example : Ui = 24V ; Uo = 10 V and Io = 600A => efficiency < 42 %
Ui = 24V ; Uo = 5 V and Io = 600A => efficiency < 21 %
Ui = 48V ; Uo = 10V and Io = 600A => efficiency < 21 %

Furthermore, fixed values of the resistances.
No mean to vary the output voltage or current

Second solution : Linear component



Po = Uo . Io = 10 . 600 = 6'000 W

P_T (power dissipated by the switch) = U_T. I_T = (Ui – Uo) . Io = (24 – 10) . 600 = 8'400 W

Converter efficiency = Po / (P_T + Po) = 42 % !!!!!

Furthermore, it'll be difficult to find a component (semiconductor) able to dissipate 8'400 W .

Then impossible for medium and high power conversion

Commutation

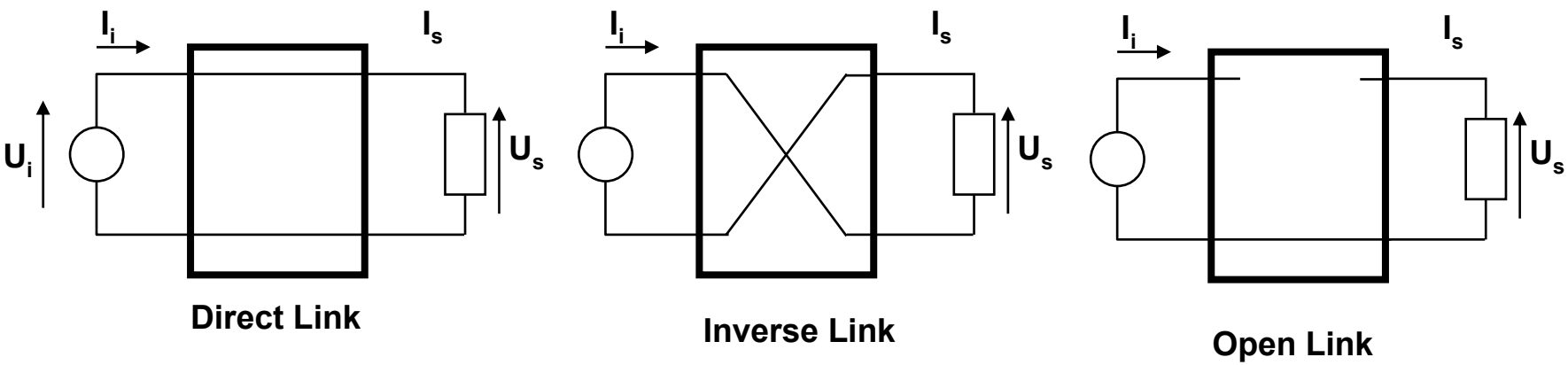
- $U_T = 0$ if $I_T \neq 0$
- $I_T = 0$ if $U_T \neq 0$

} $P_T = 0$

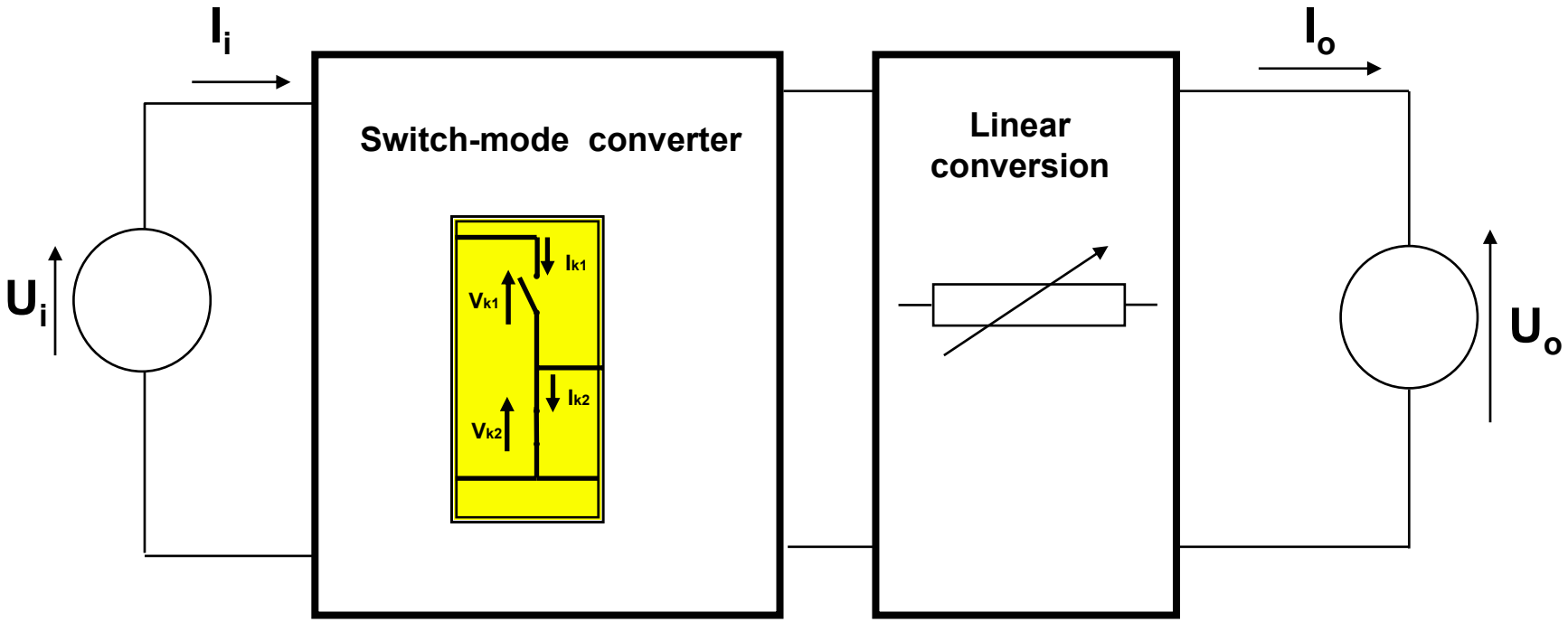
~~Linear mode~~ → **switch mode (saturated-blocked)**

Commutation

Active components used as switches to create a succession of link and no link between sources to assure an energy transfer between these sources with high efficiency.



Special case for linear application



- Active filter
- 4-quadrant converters (see Mr. Thurel's presentation)

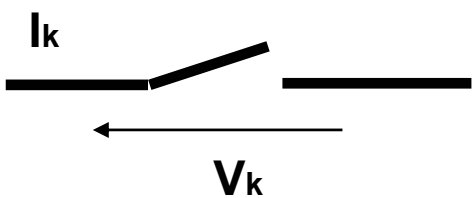
The problem :

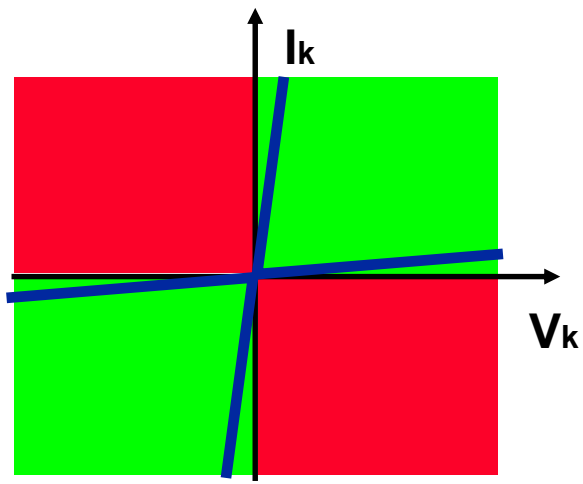
the interconnection of sources by switches

Fundamental rules and source natures

Power converter topologies

switch characteristics





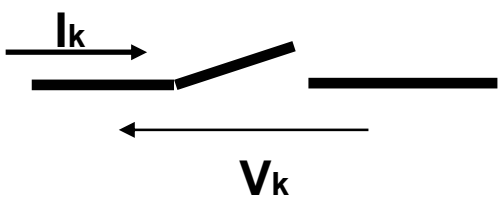
Switch characteristics

Switch : *semiconductor device functioning in commutation*

The losses in the switch has to be minimized

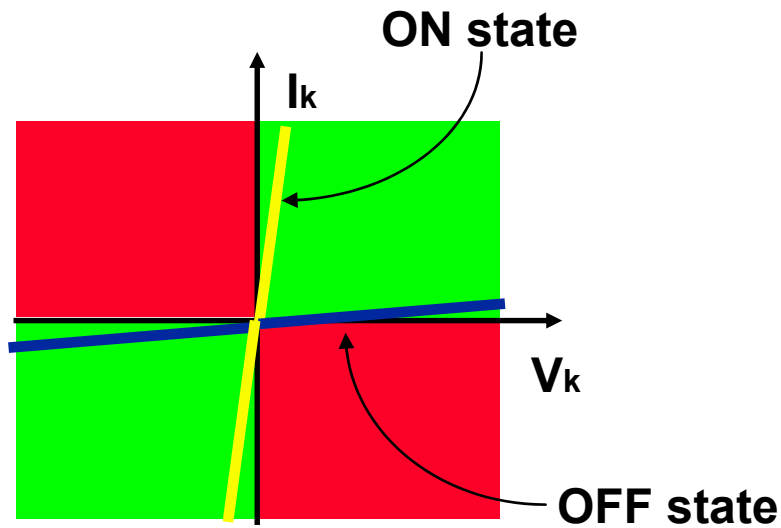
Zon very low

Zoff very high



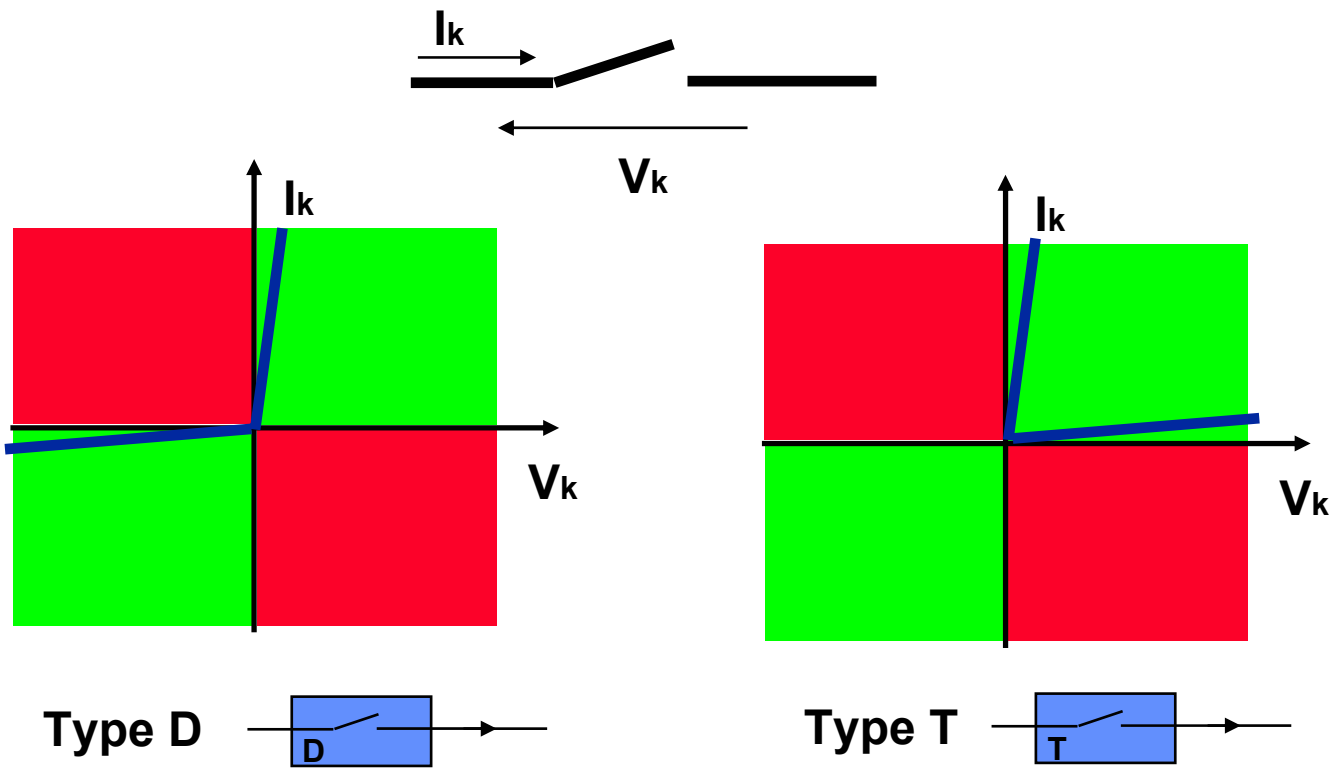
Switch : at least two orthogonal segments

(short and open circuit are not switches)

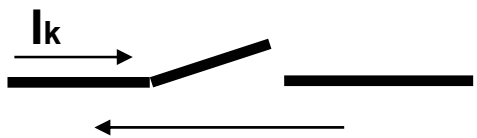


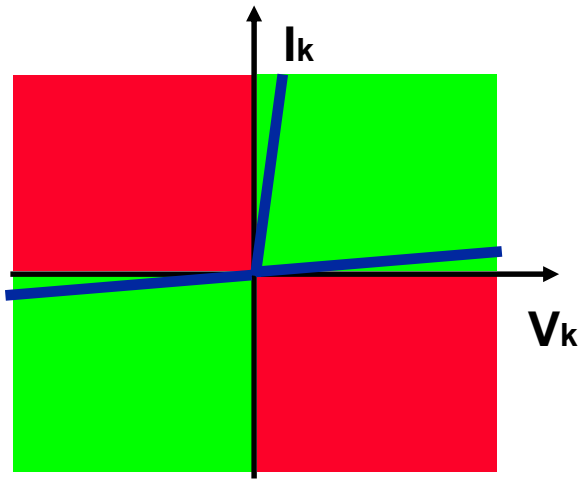
Switches : two segments

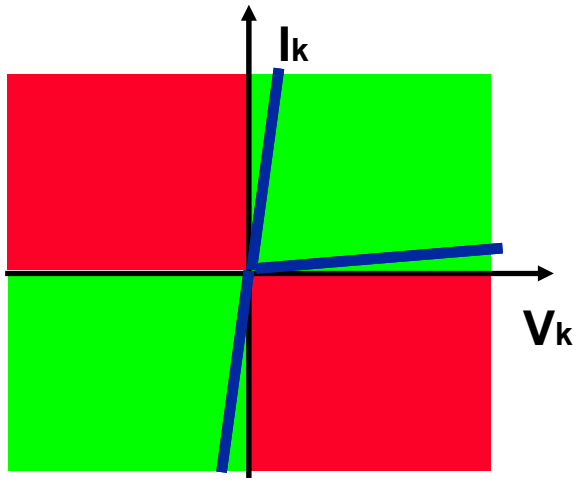
Static characteristics

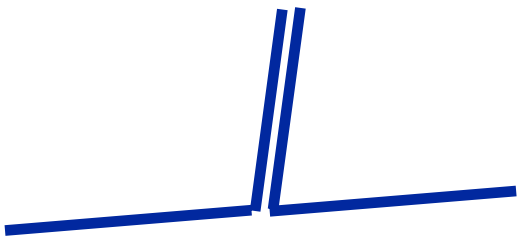


Switches : three segments
Static characteristics

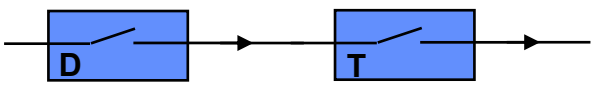


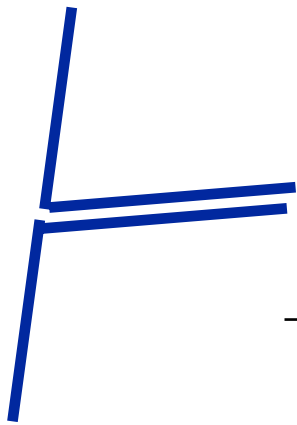




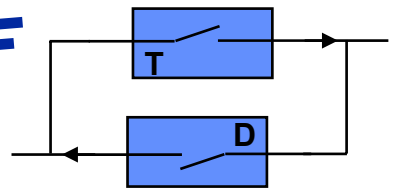


D and T in series

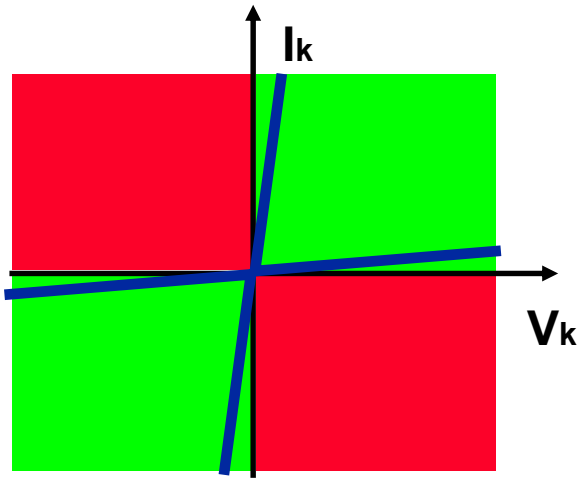


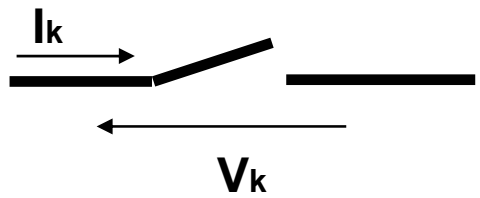


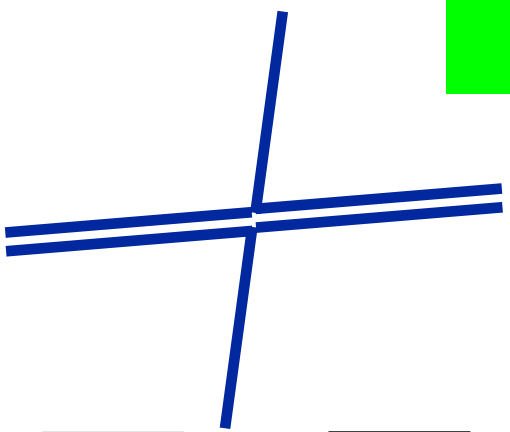
D and T in parallel



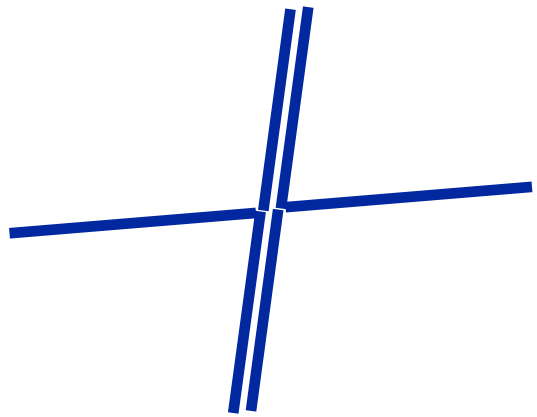
Switches : four segments
Static characteristics

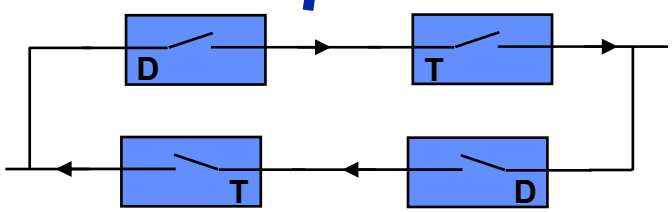


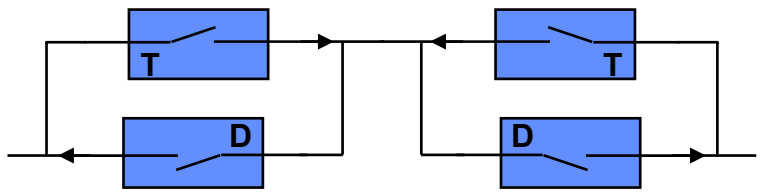




or







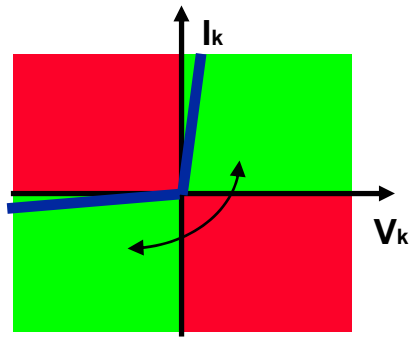
Switches
Dynamic characteristics

ON state ← **?** → **OFF state**

- **spontaneous commutation**

  change of quadrant

  (auto turn-on ; auto turn-off)

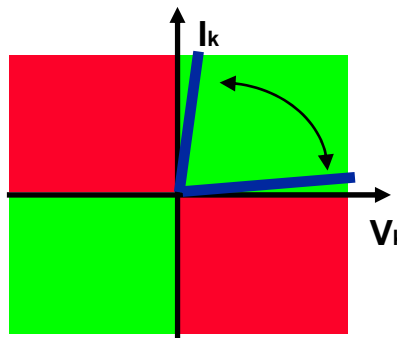


no losses

- **controlled commutation**

  no change of quadrant

  (controlled turn-on ; controlled turn-off)

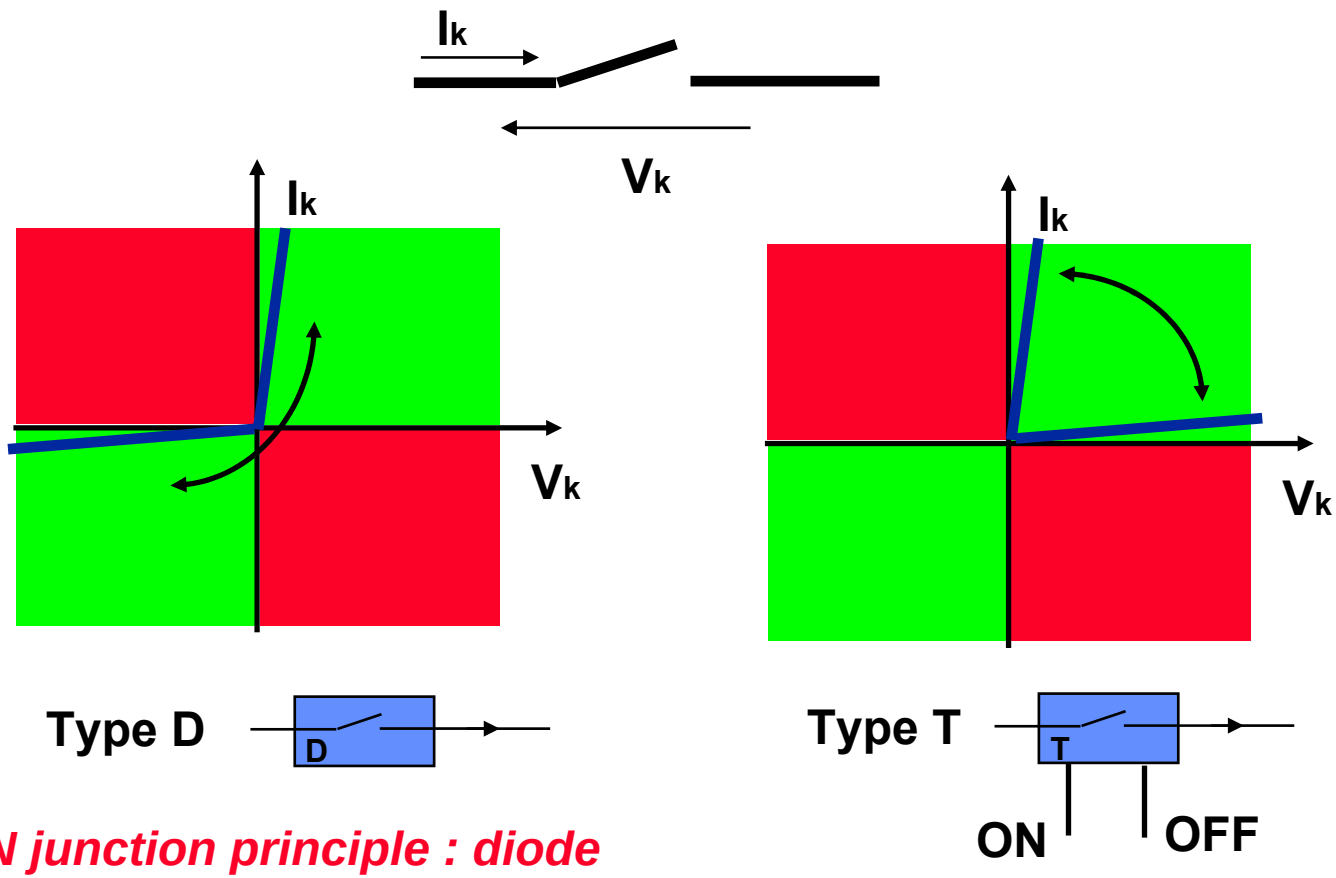


losses

gate

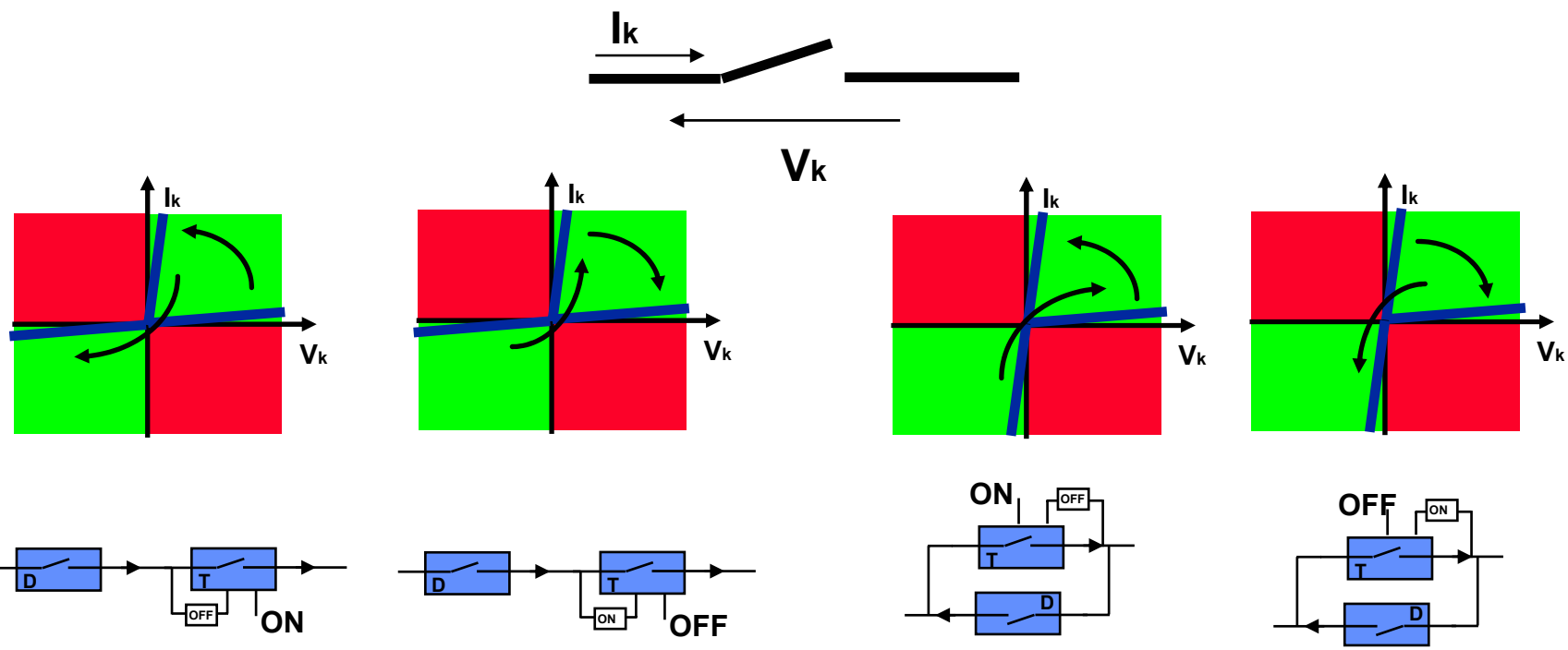
Switches : two segments

Dynamic characteristics



PN junction principle : diode

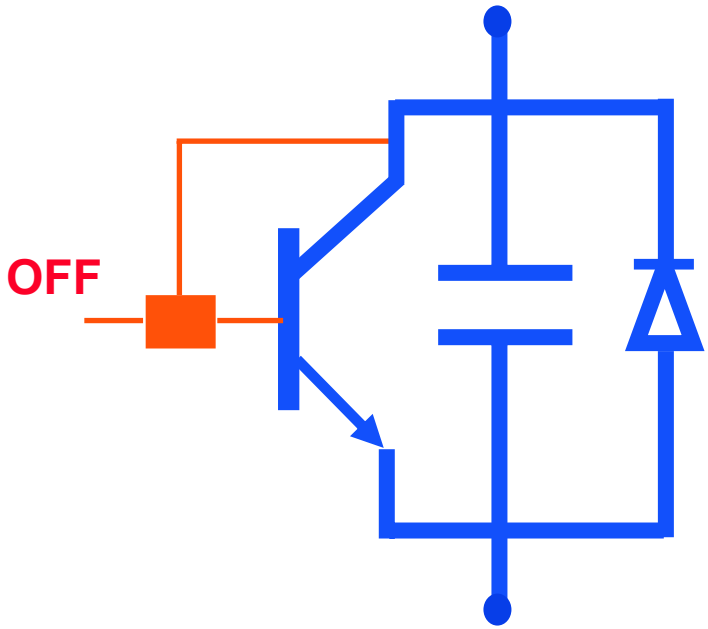
Switches : three segments
Dynamic characteristics

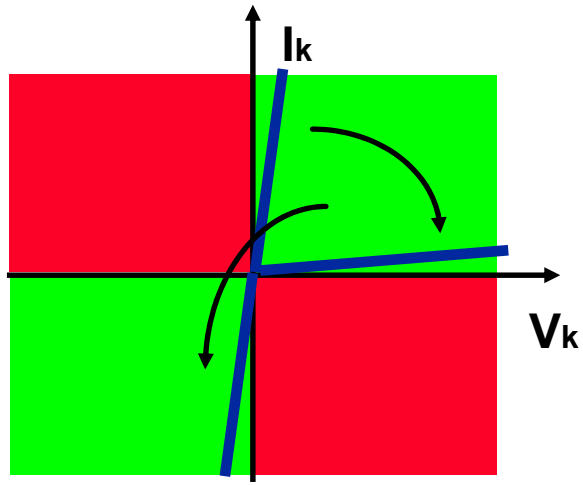


One controlled commutation and one spontaneous commutation

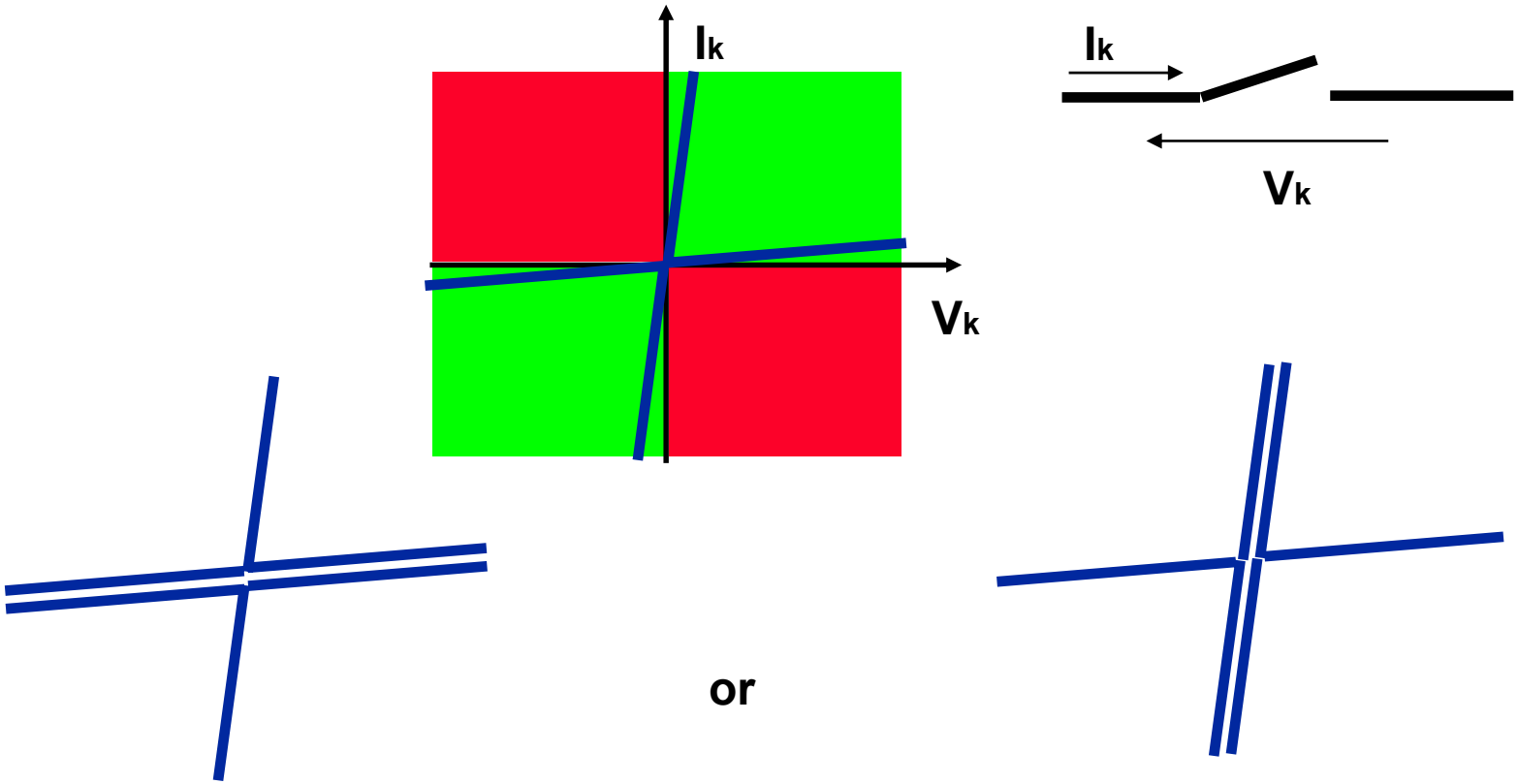
Synthesized switches (except thyristor)

DUAL THYRISTOR

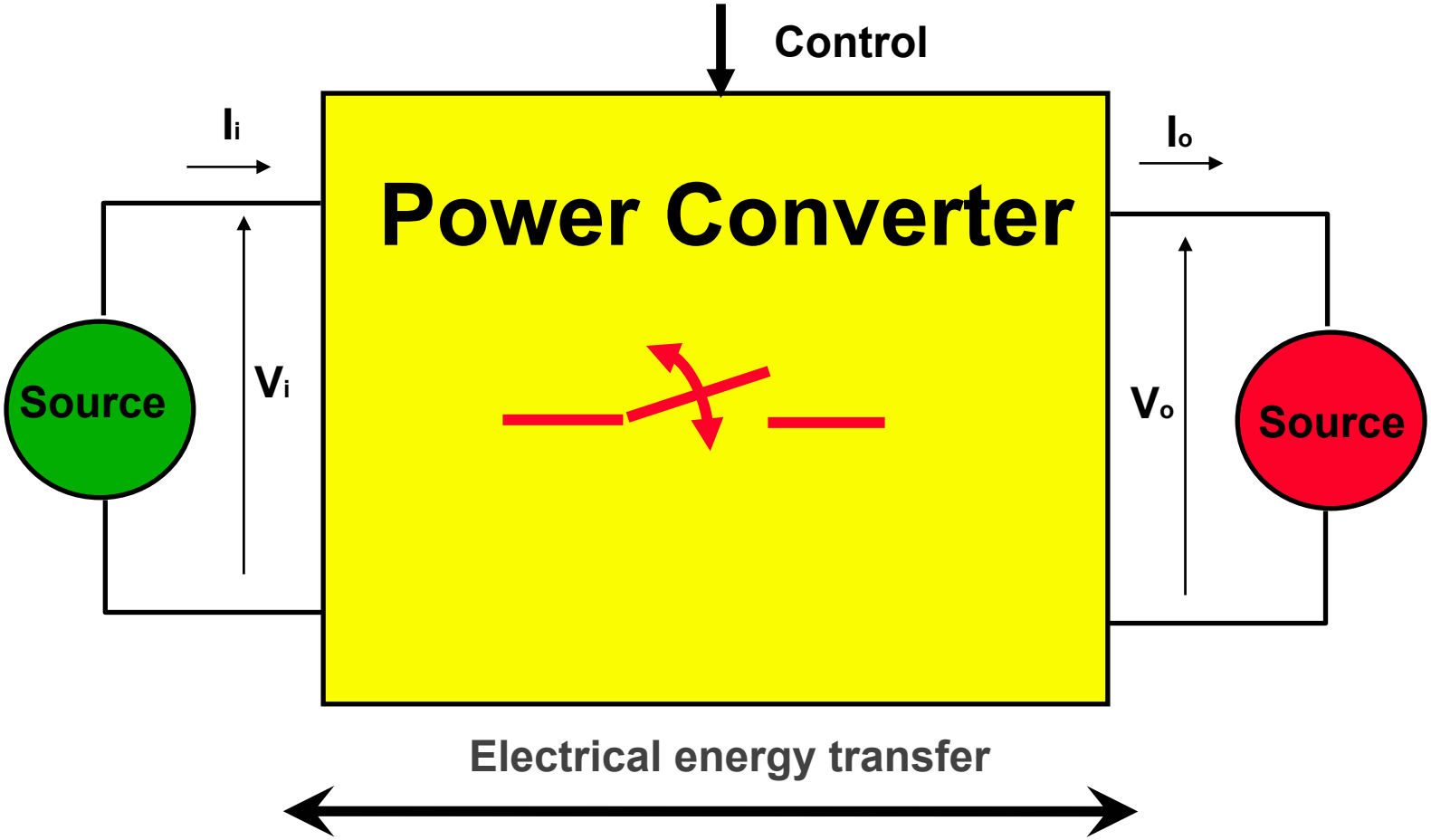




Switches : four segments
Dynamic characteristics



Three segments synthesis => 6 types of switches

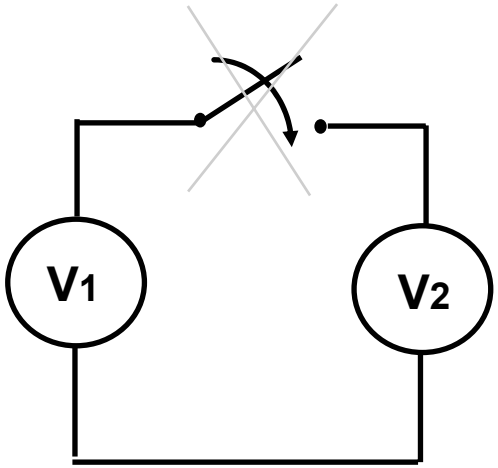


Power Converter

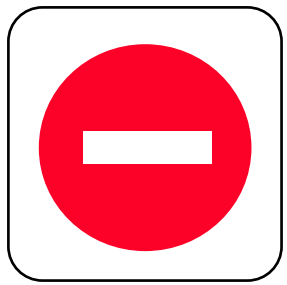
- performance
- efficiency
- reliability, repairability, availability
- low cost
- effect on environment (RFI, noise,...)

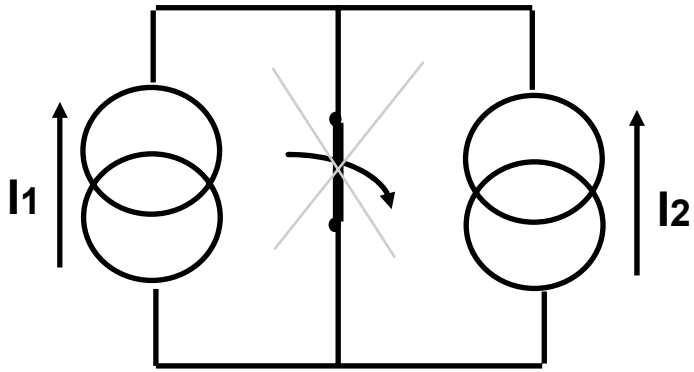
Commutation rules

- *electronic switches modify the interconnection of impeding circuits*
- *any commutation leading instantaneous variations of a state variable is prohibited*



Turn On impossible



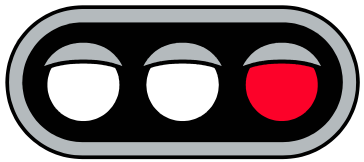


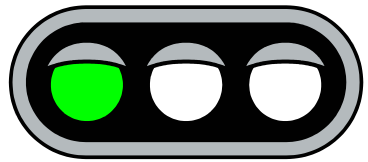
Turn Off impossible

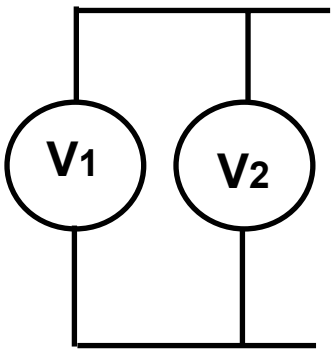
Interconnection between two impeding networks can be modified only if :

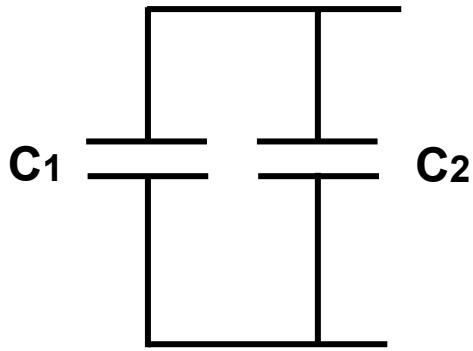
- **the two networks are sources of different natures (voltage and current)**
- **the commutation is achieved by TWO switches. The states of the two switches must be different.**

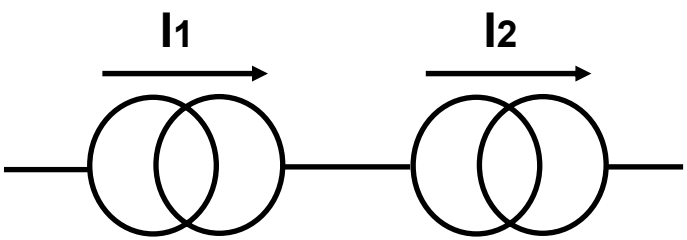
Association of sources and components











Connection of the components at zero voltages or zero currents

Converter topology

Sources have different natures:

→ Direct link configuration

Sources have same natures:

→ Indirect link configuration :

need to had intermediate element

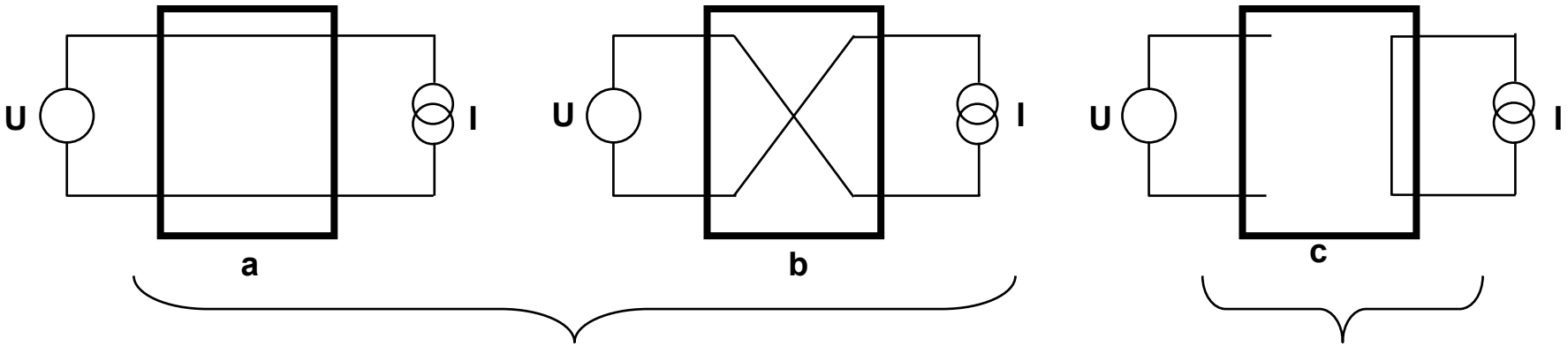
- modification of source nature

- use of two direct link structures

- indirect structure

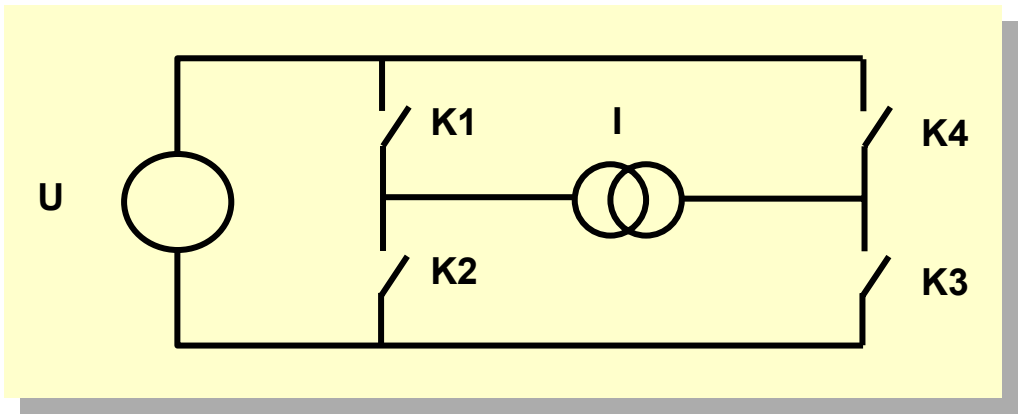
Direct link configuration

- Direct voltage-current converters



Connexion
(energy flow between sources)

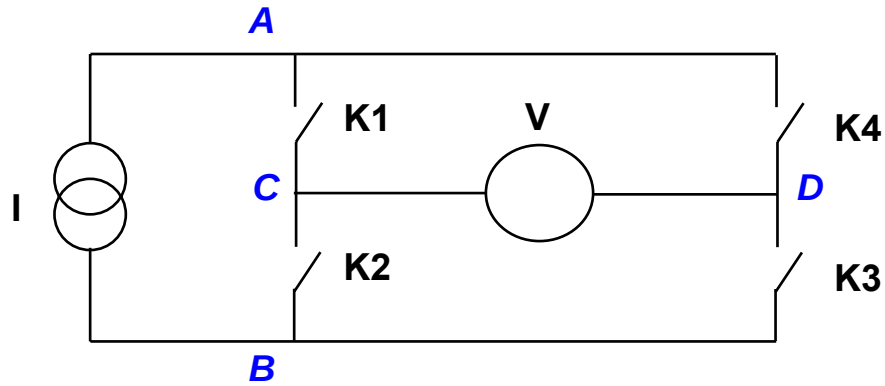
Disconnexion
(current source short-circuited, voltage source open circuited)



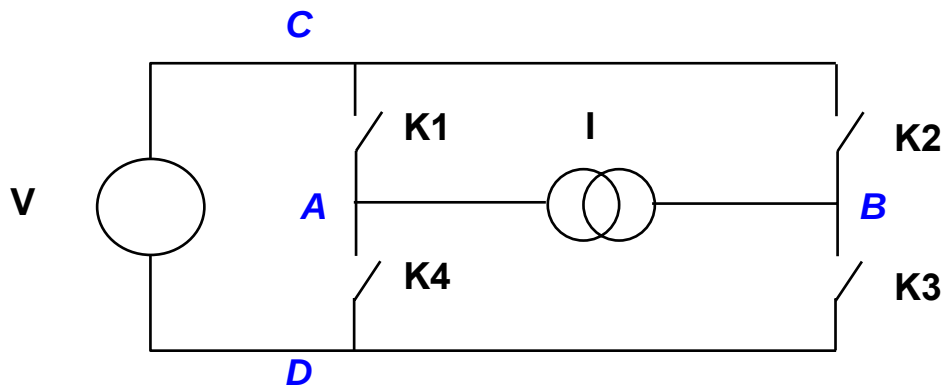
- K1 and K3 closed => a
- K2 and K4 closed => b
- K1 and K4 (or K2 and K3) closed => c

Direct link configuration

- Direct Current-Voltage converters



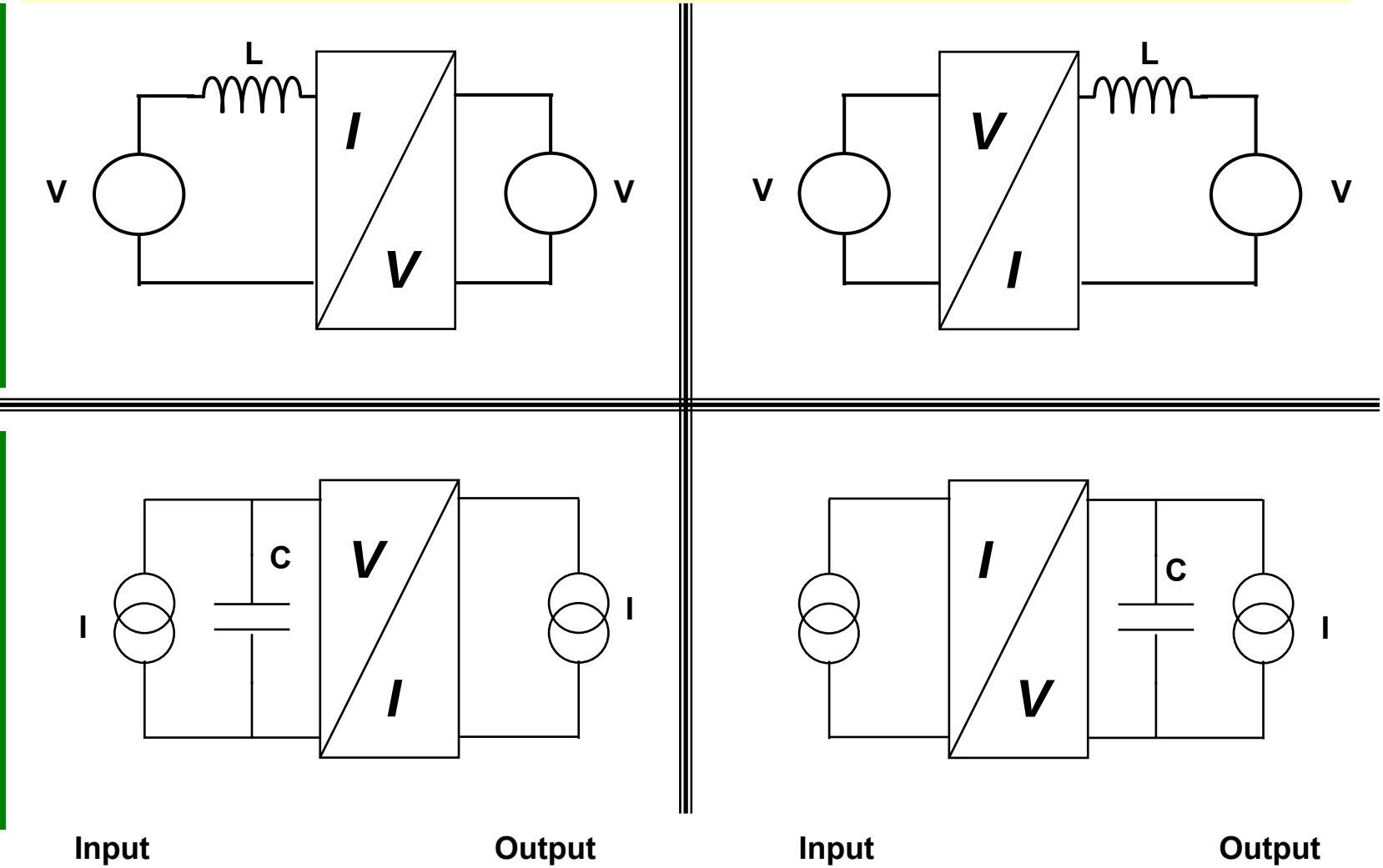
Identical problem : same basic converter configuration



Indirect Conversion

- Two sources have the same natures => need to had intermediate element

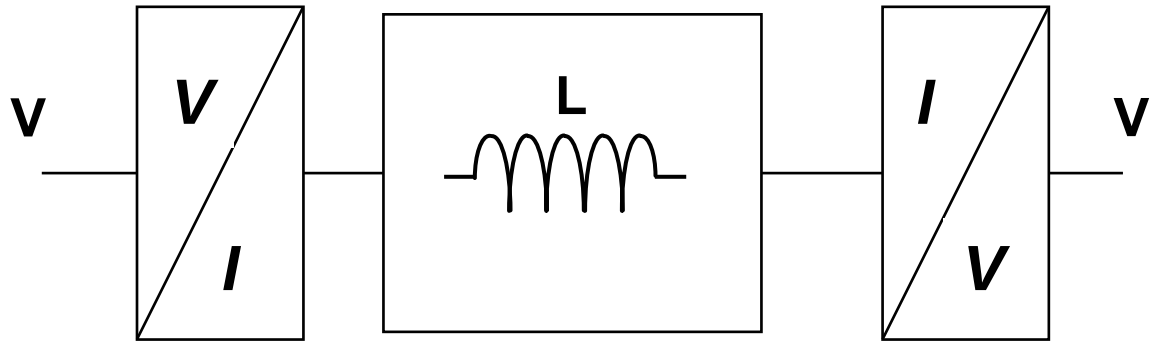
1) Modification of the input or output source nature



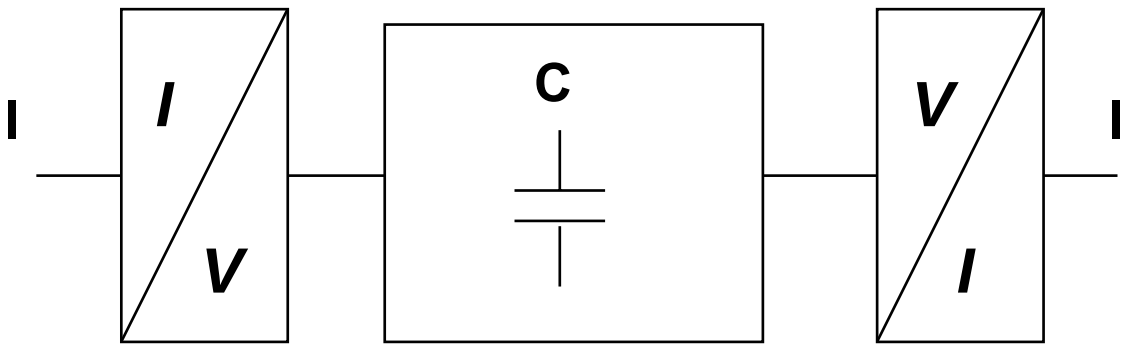
Indirect Conversion

- Two sources have the same natures => need to had intermediate element

2) Indirect conversion using two direct converters



Inductance buffer

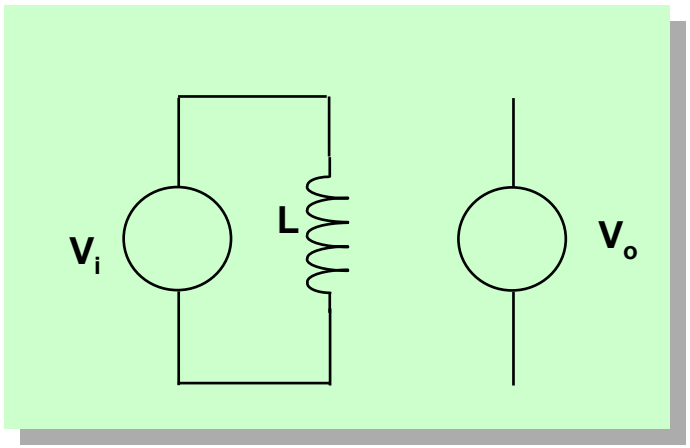


Capacitor buffer

Indirect Conversion

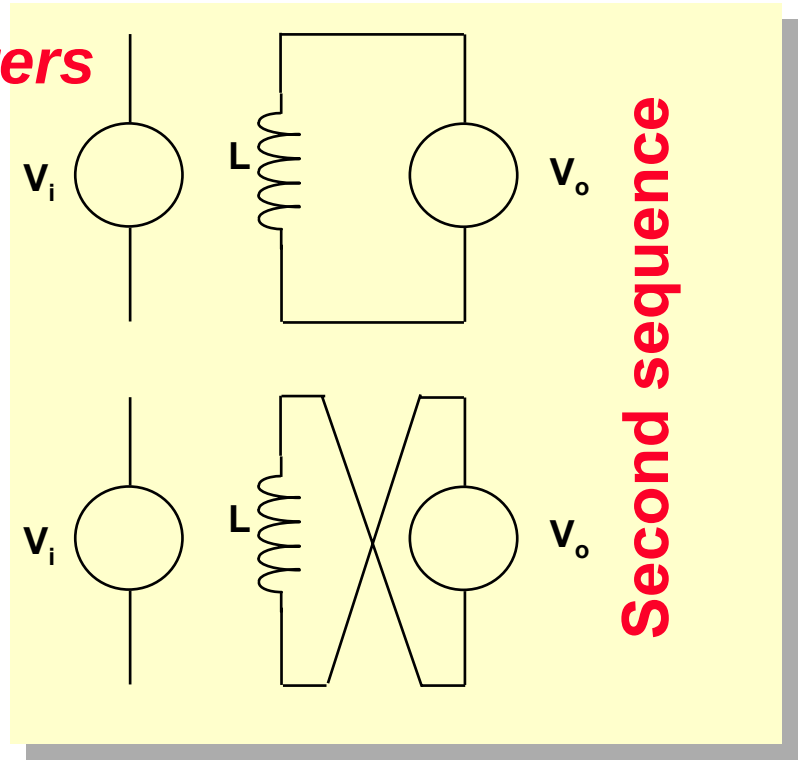
- Two sources have the same natures => indirect converters

Voltage-Voltage Indirect Converters

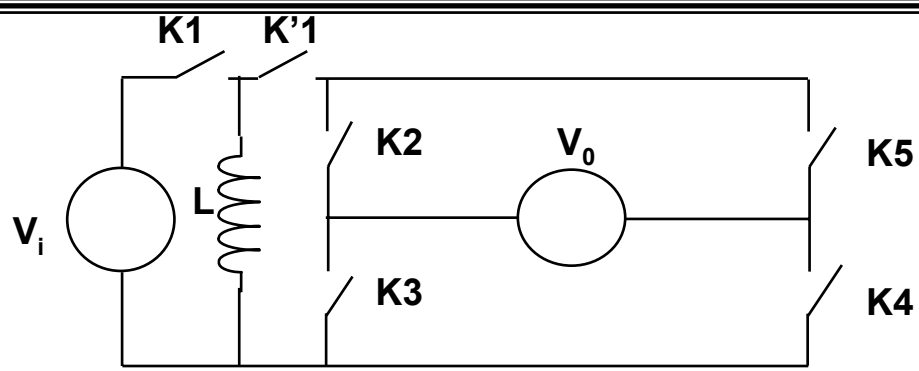


First sequence

OR



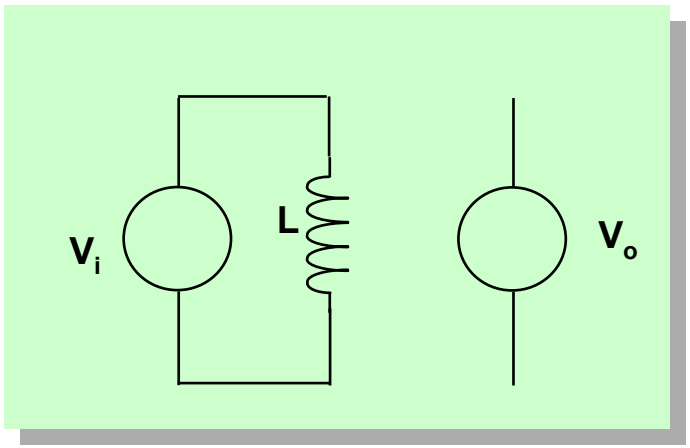
Voltage-Voltage Indirect Converters
basic configuration



Indirect Conversion

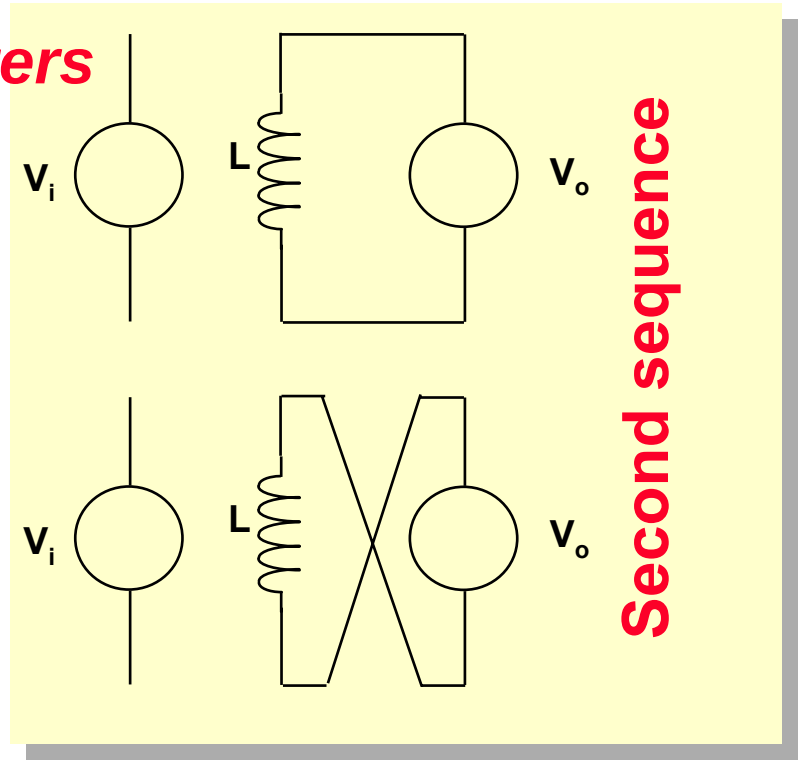
- Two sources have the same natures => indirect converters

Voltage-Voltage Indirect Converters

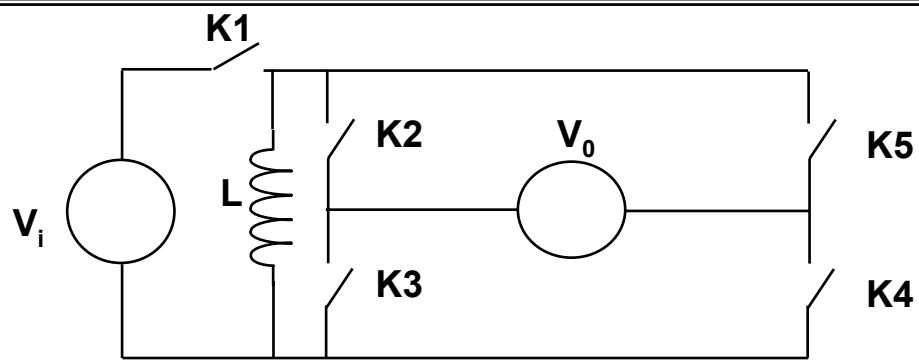


First sequence

OR



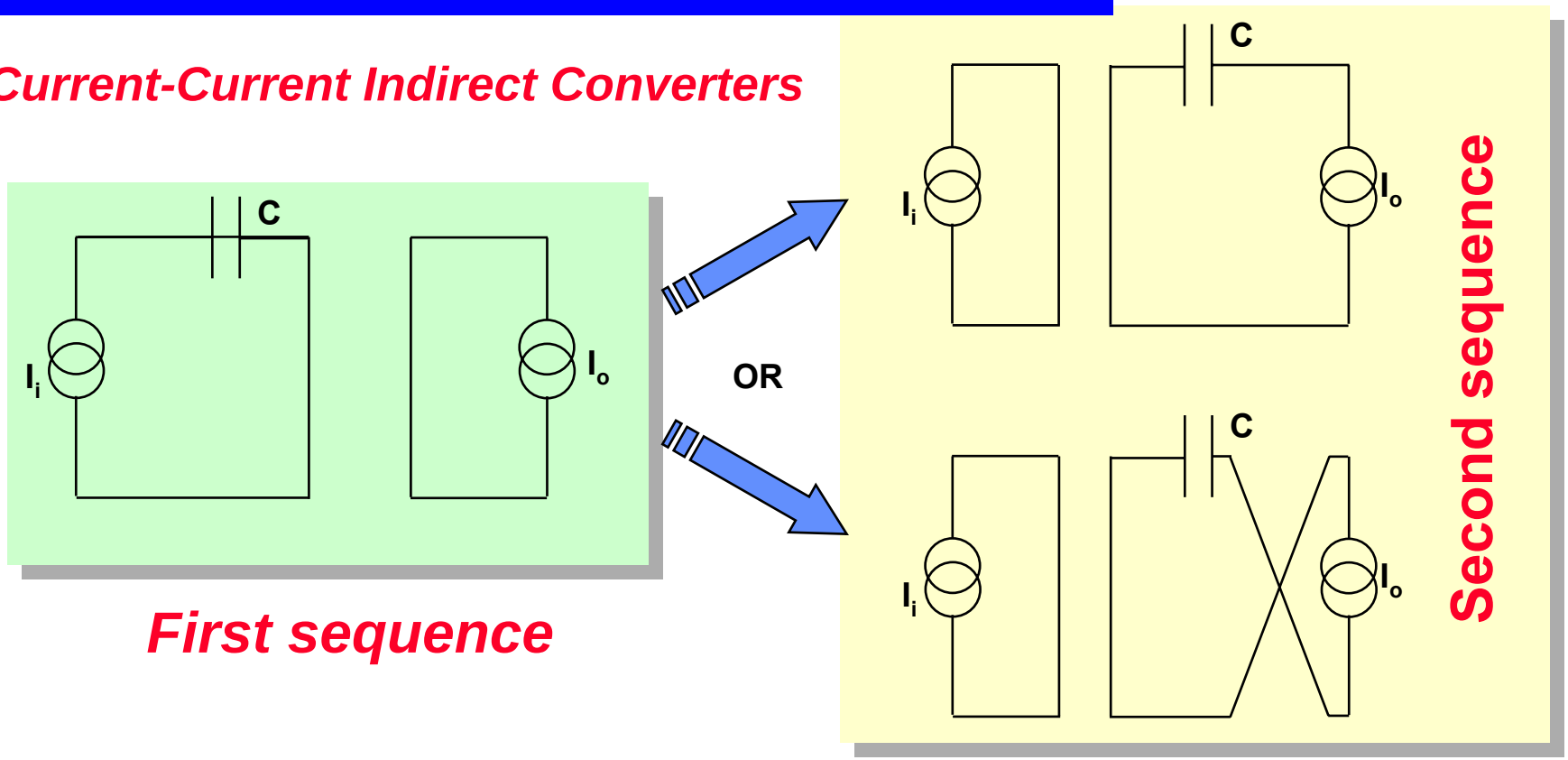
Voltage-Voltage Indirect Converters
basic configuration



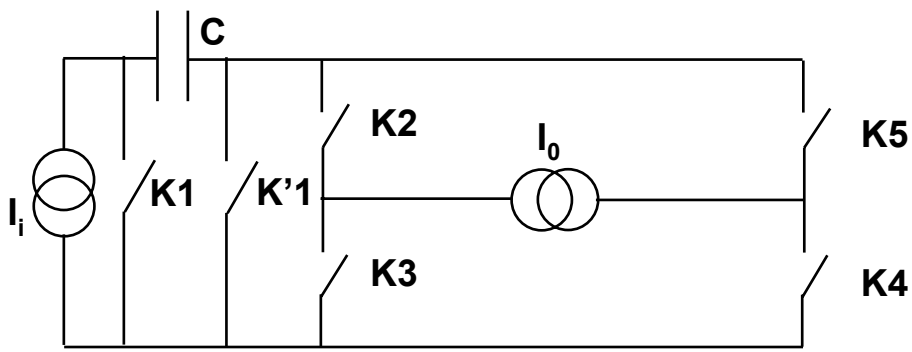
Indirect Conversion

- Two sources have the same natures => indirect converters

Current-Current Indirect Converters



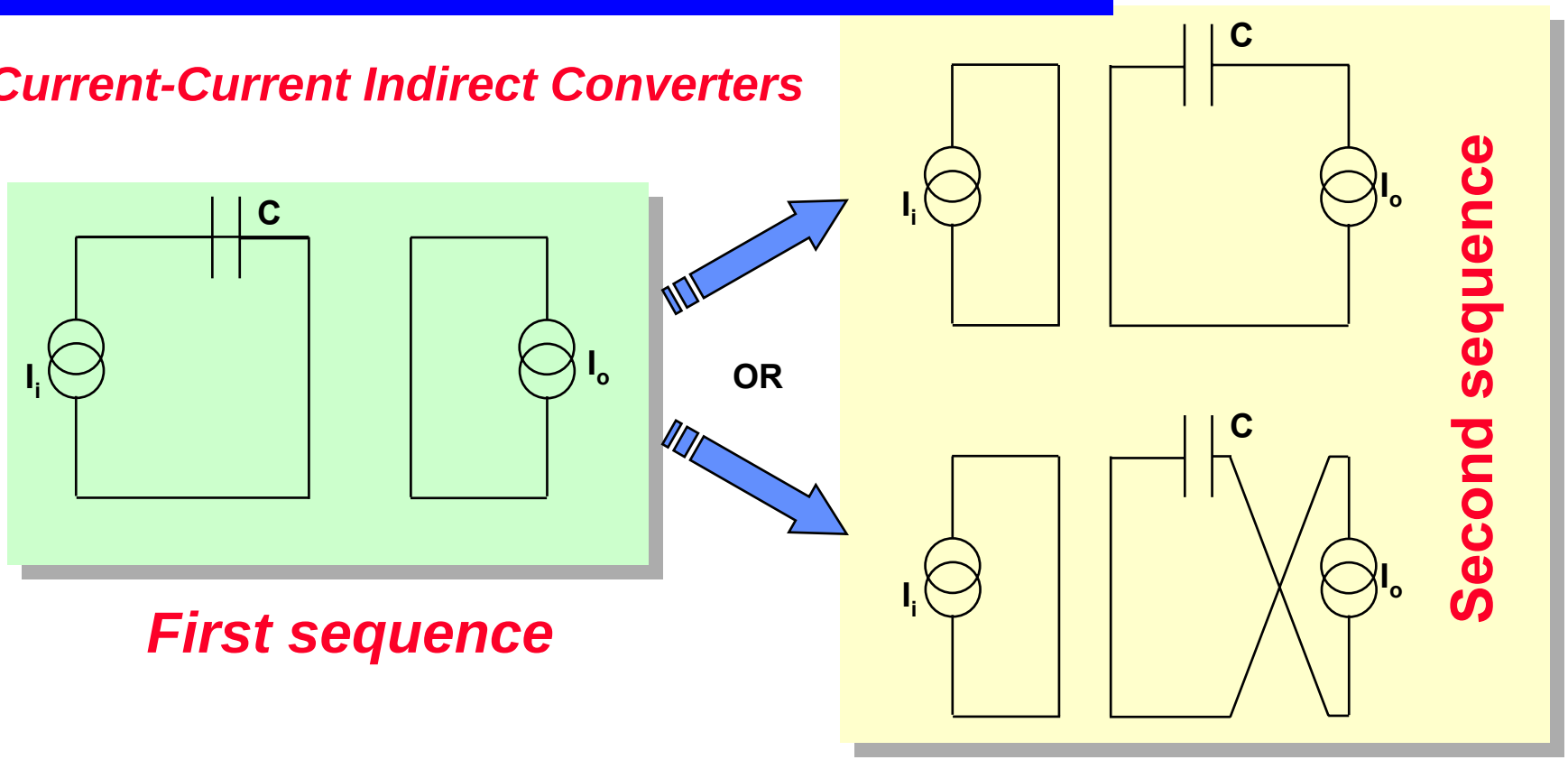
Current-Current Indirect Converters basic configuration



Indirect Conversion

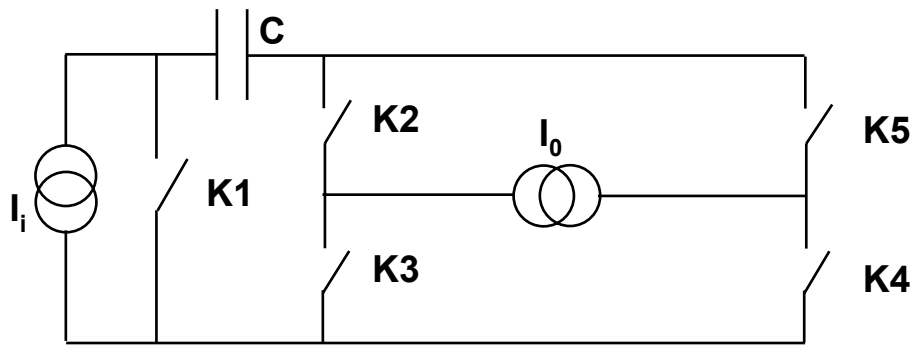
- Two sources have the same natures => indirect converters

Current-Current Indirect Converters

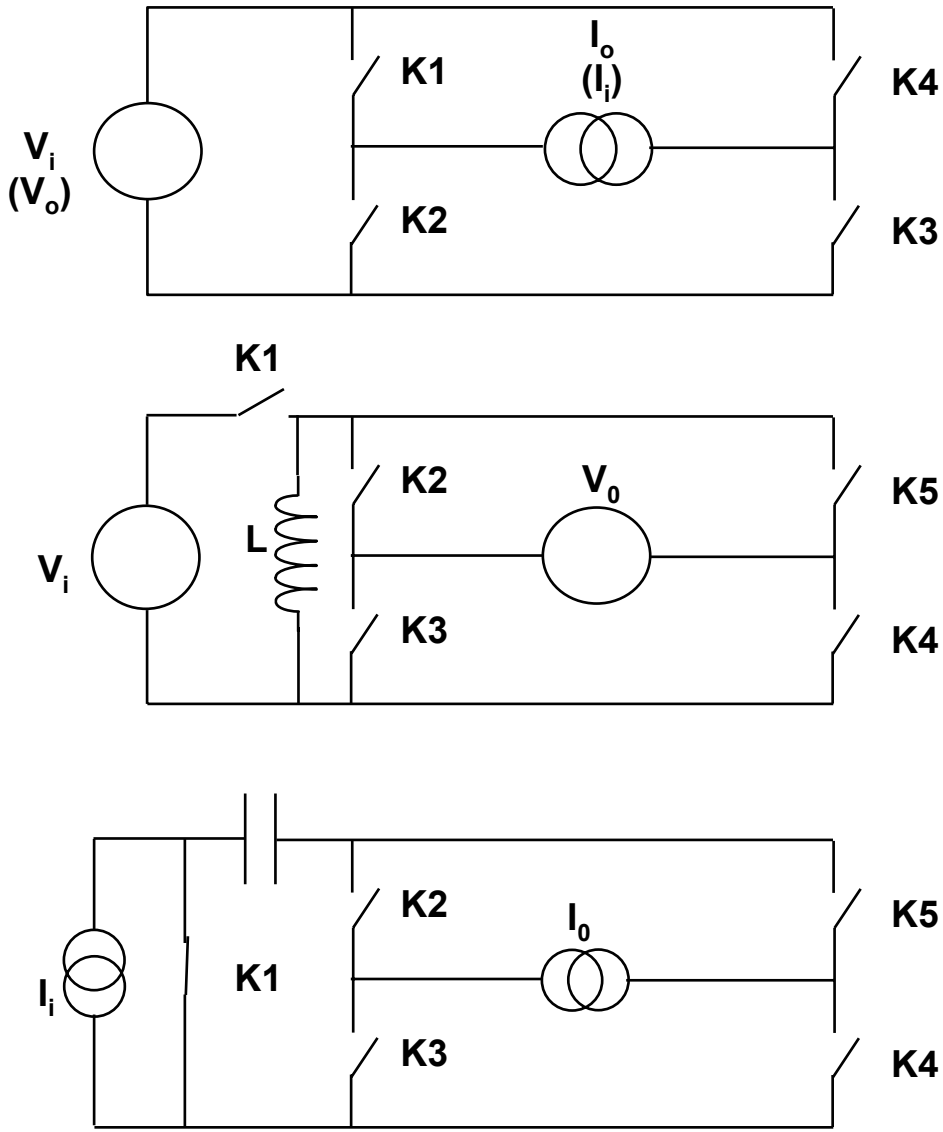


First sequence

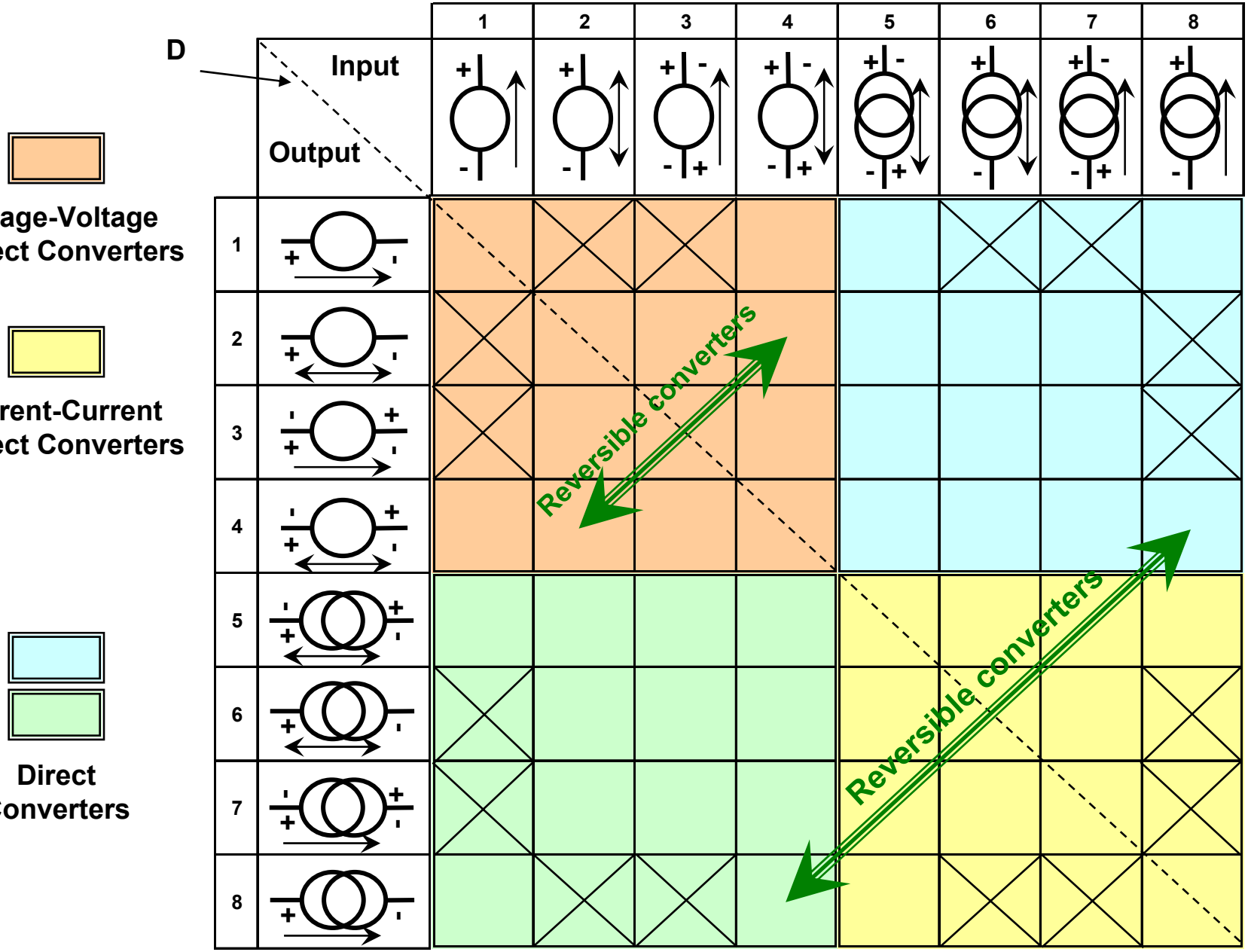
Current-Current Indirect Converters
basic configuration

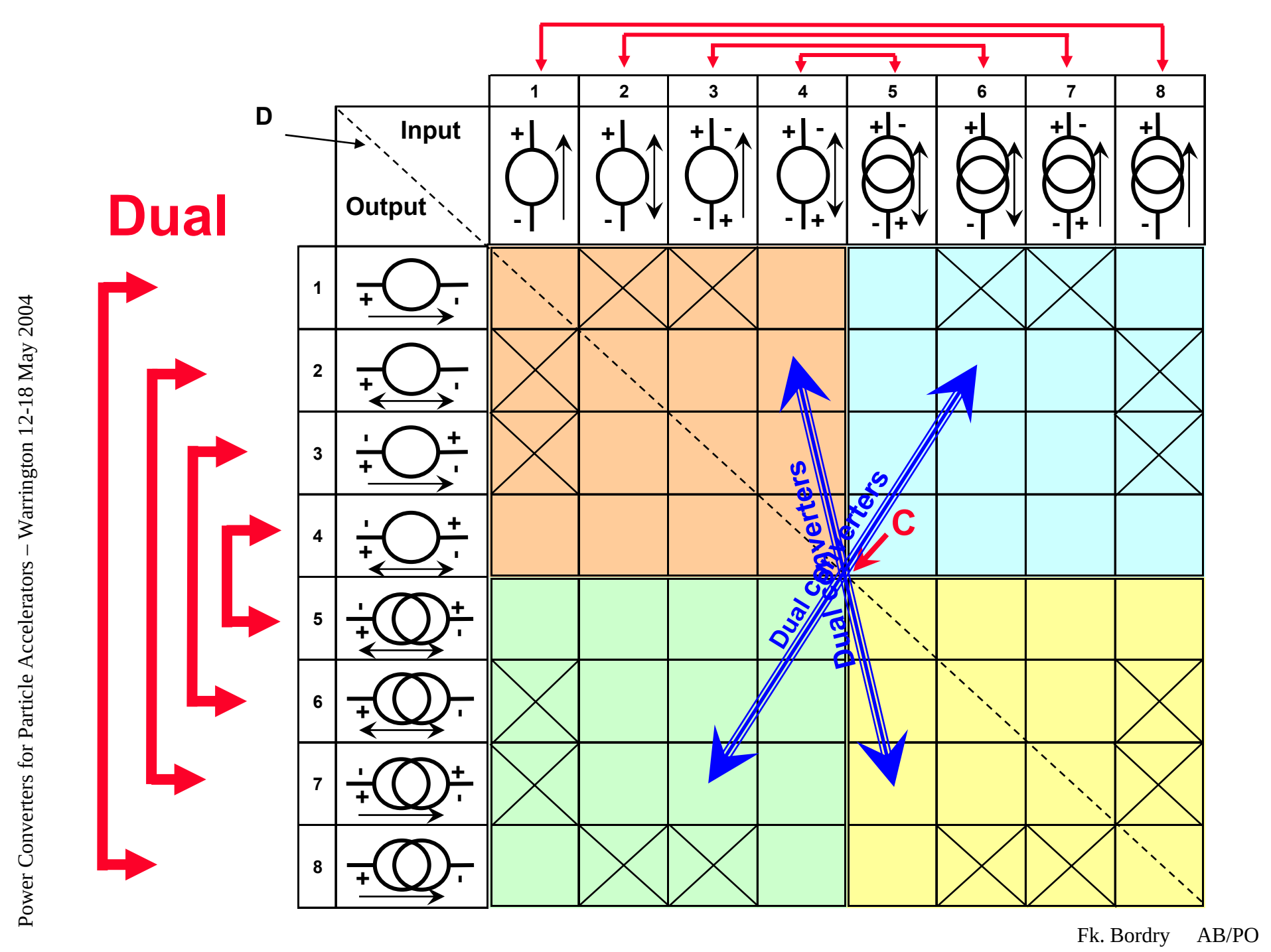


Three basic converters structures



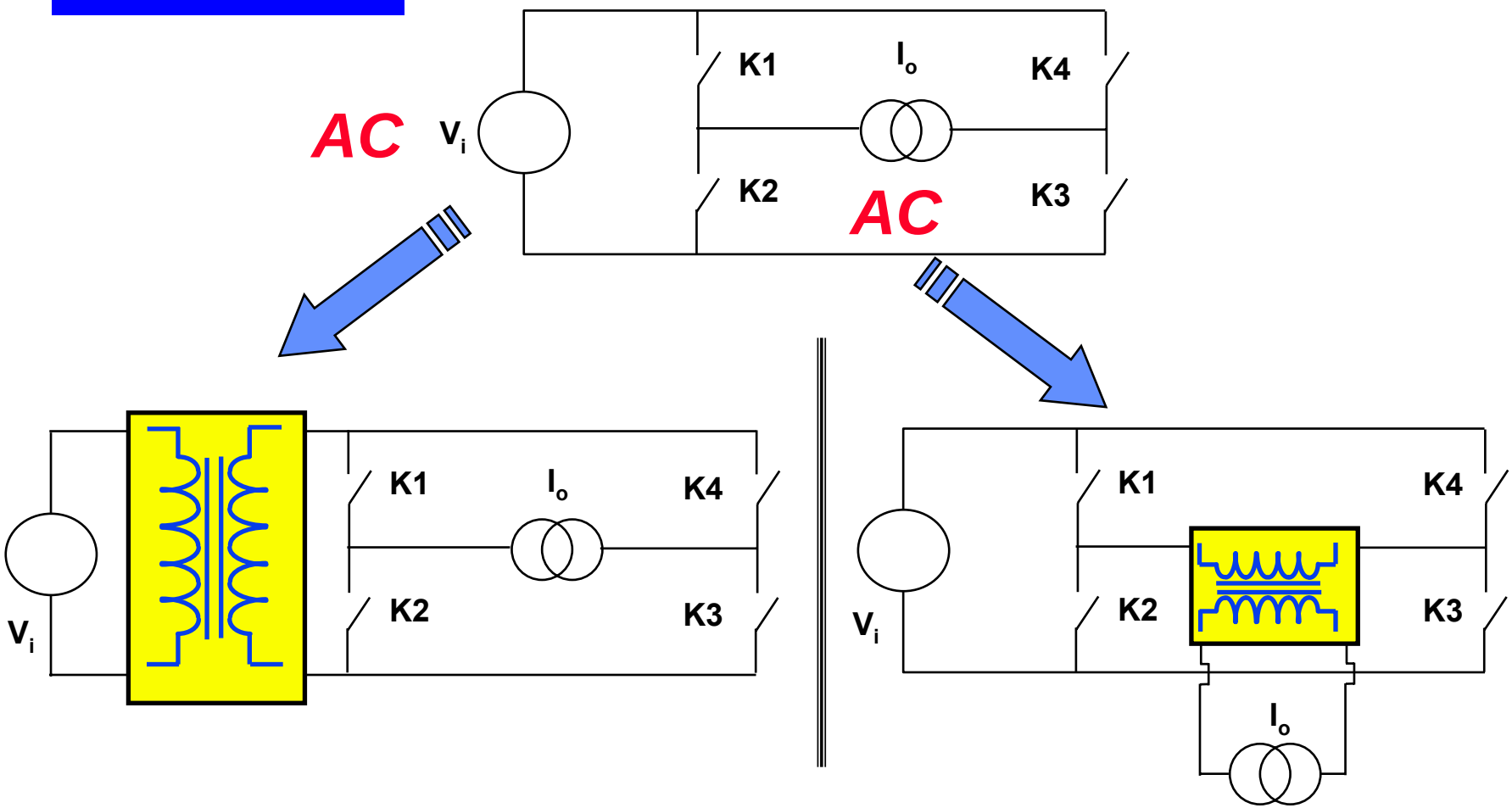
Power converter general table




Dual
D
Input
Output
1
2
3
4
5
6
7
8
Dual converters
Dual converters
C

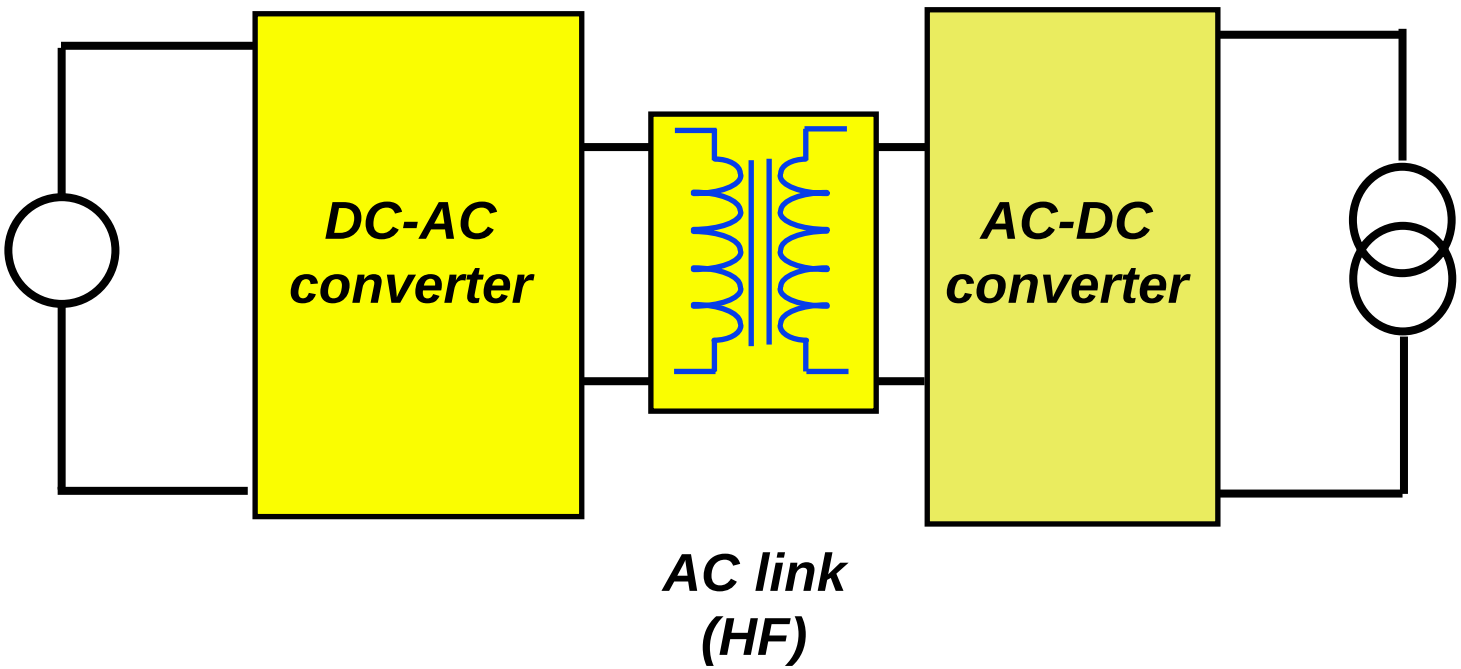
Galvanic isolation : introduction of transformer

- AC source



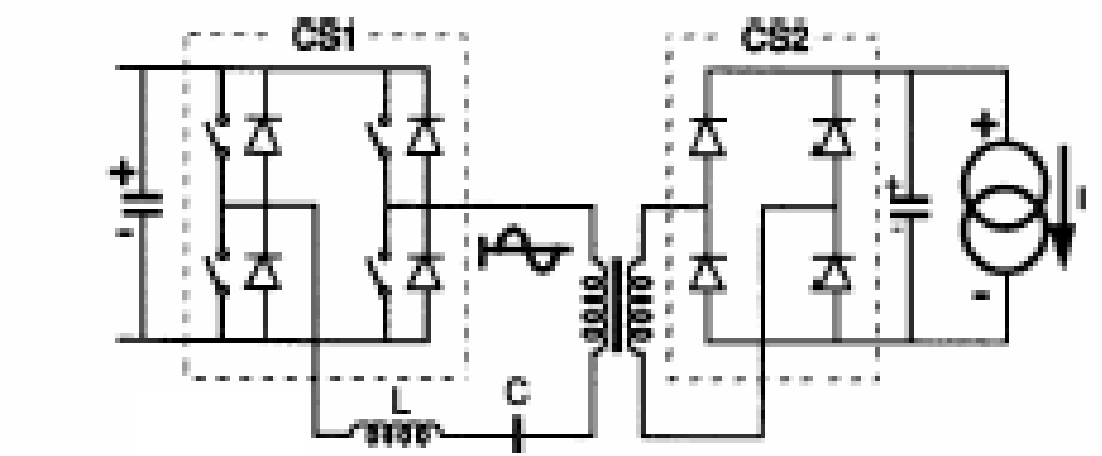
Transformer : source frequency

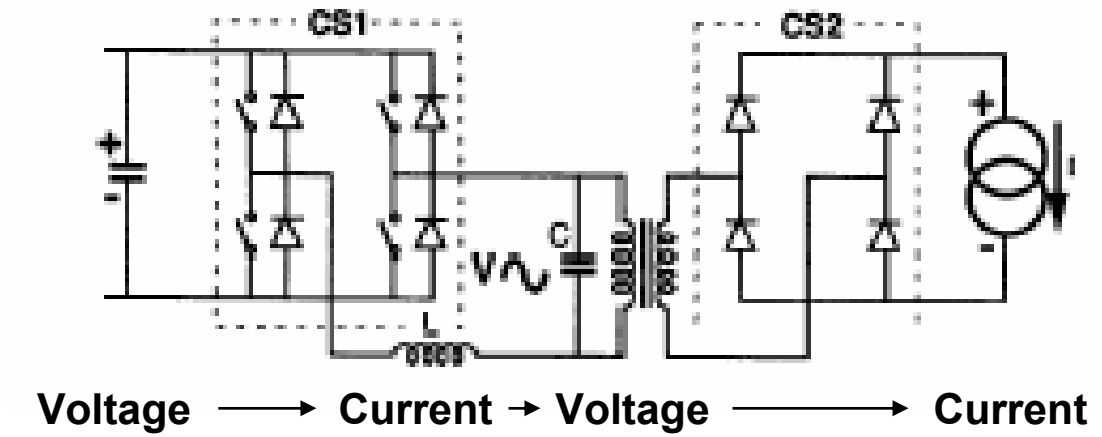
- AC link (voltage or current link)

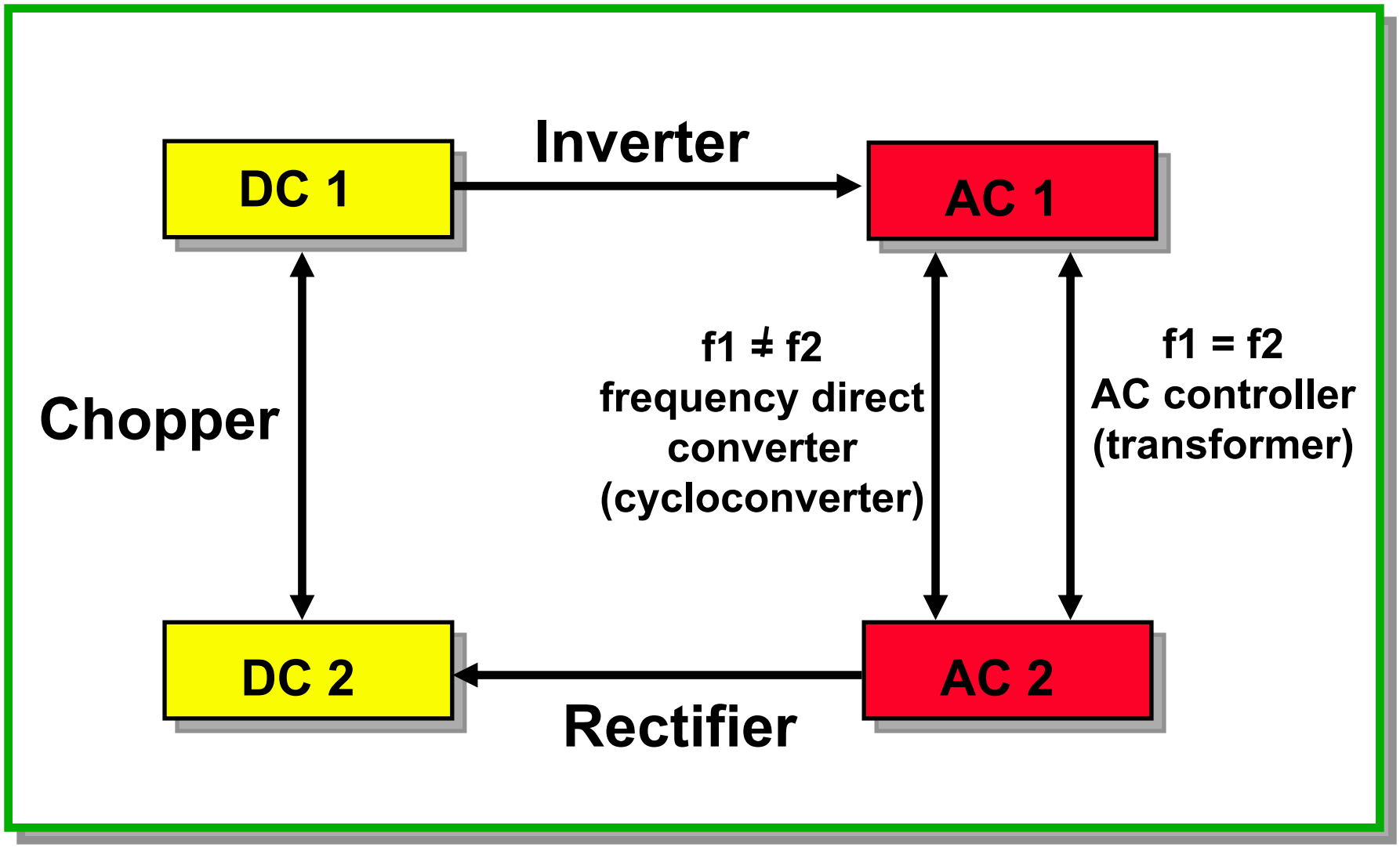


-AC link (voltage or current link)

example : resonant converters







Converter classification

Commutation

Operation of a static converter can be split into a sequence of elementary modes. Each elementary mode is characterized by an electrical network different to the previous one and derived by interconnection modifications of the active branches.

The network branches connected to this static devices must fulfil the connection rules of the sources:

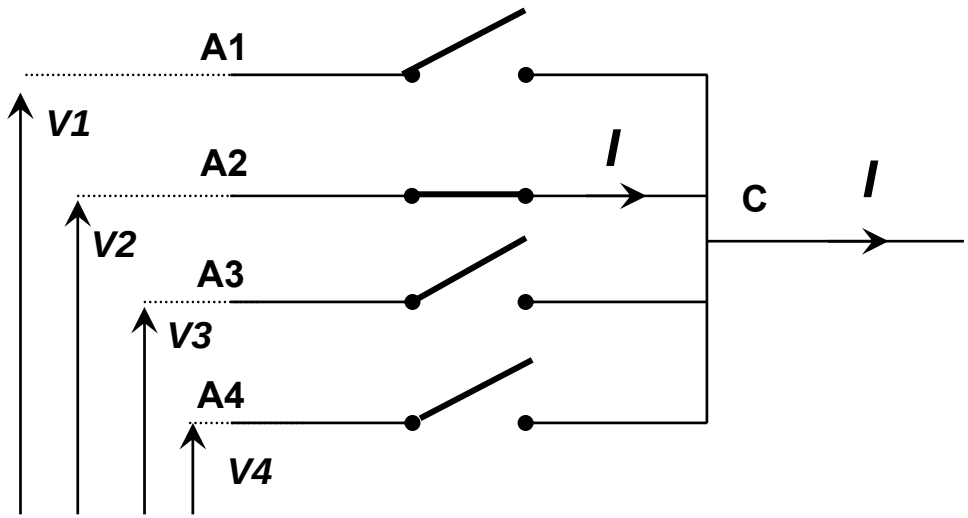
- each switch is connected to a voltage source (otherwise opening a switch would result in open-circuiting a current source)

- the node at the centre of the star is connected to a current source since a voltage source can be connected only to a current source through a controlled switch.

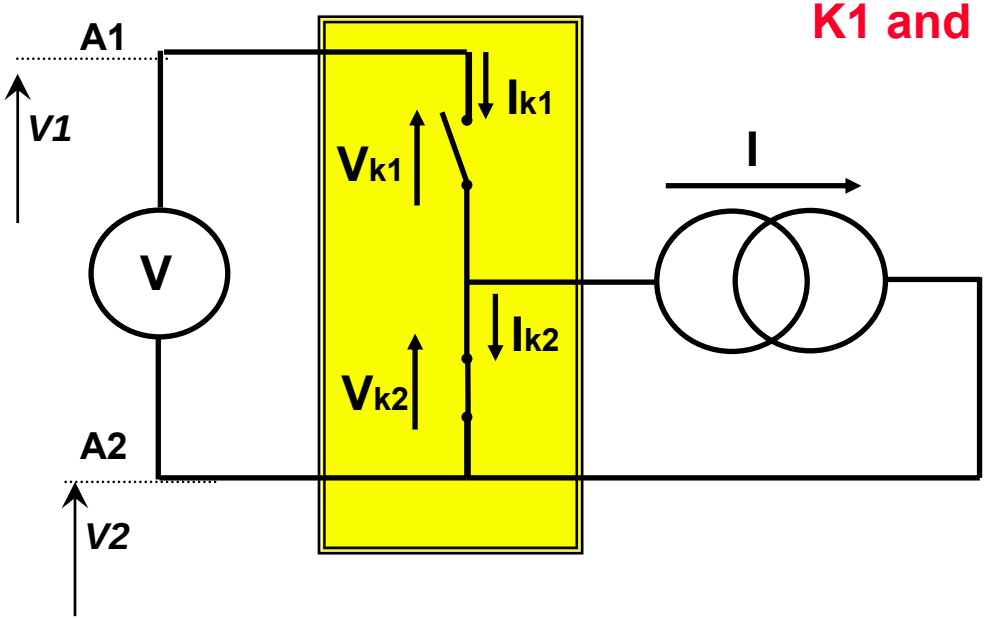
- at a given time one an only one switch must be ON to avoid connecting two voltages sources and open-circuiting the current source.

Each commutation only involves two switches.

Star-connected electronic switches.



Elementary Commutation cell



K1 and K2 are complementary switches

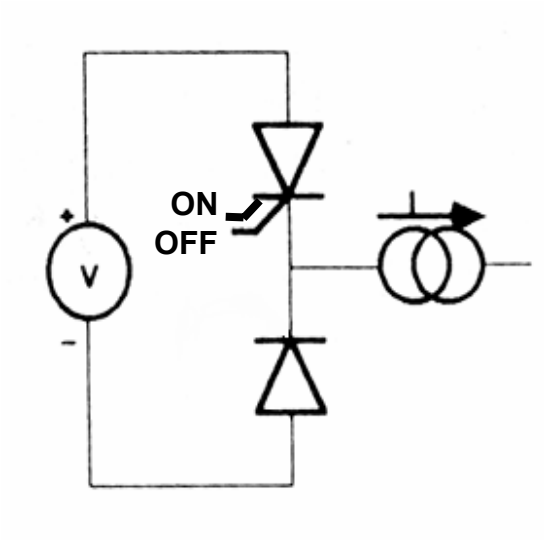
$$V_{k1} + V_{k2} = V$$
$$I_{K1} - I_{K2} = I$$

No discontinuity of the variables V and I

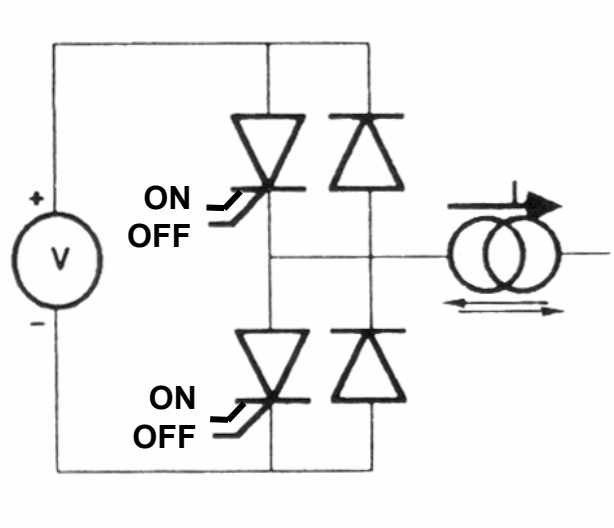
$$V = V1 - V2$$

The reversibilities of the voltage and current sources determine the static characteristics of the switches. The switches need to have static characteristics with the same number of current and voltage segments.

Six type of elementary commutation cells

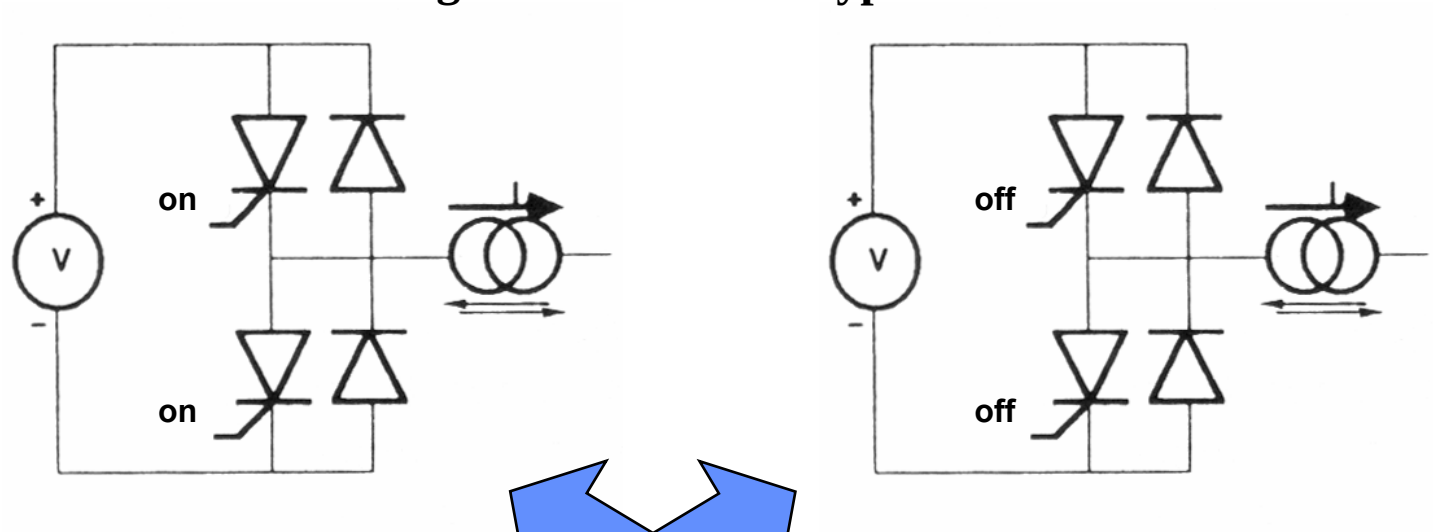


Chopper-type cell

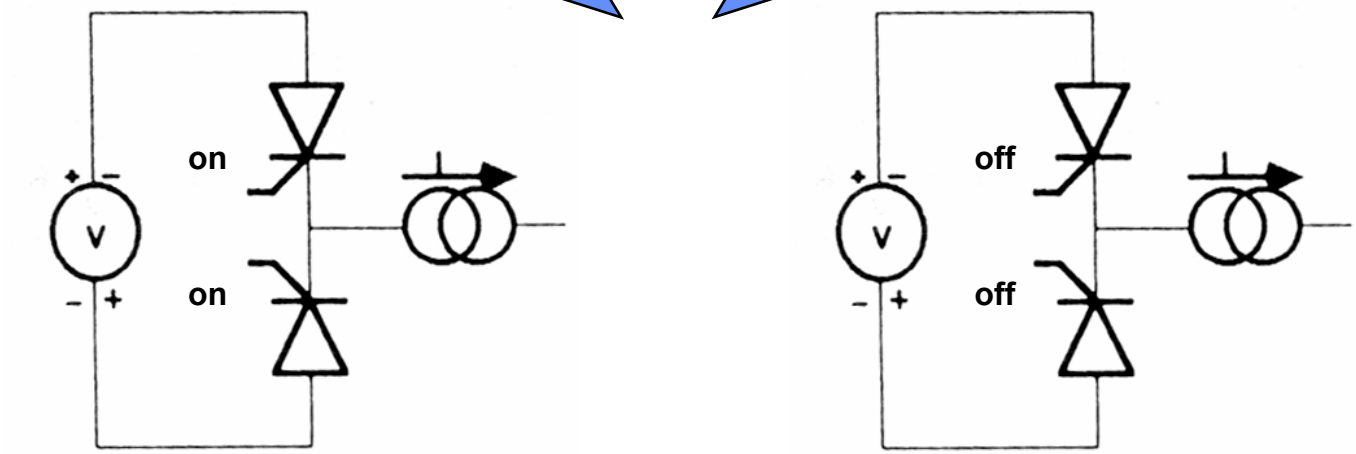


PWM inverter cell

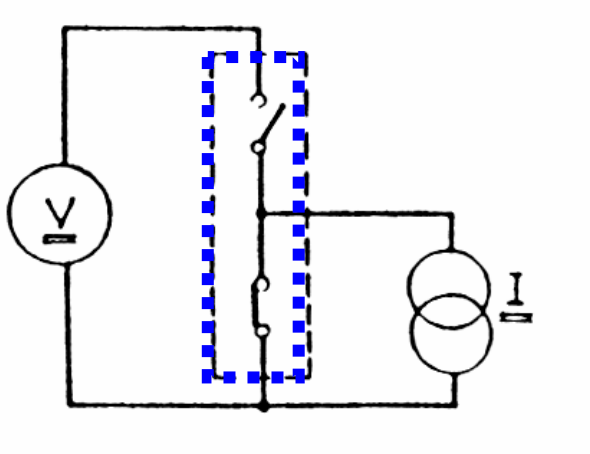
Voltage-source inverter type cells



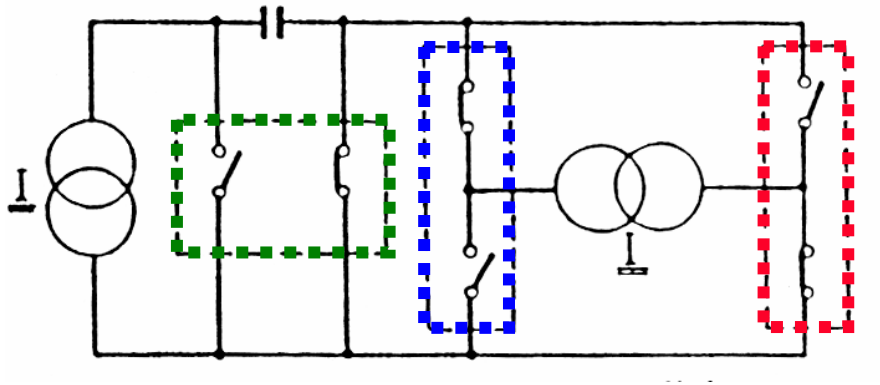
Duality



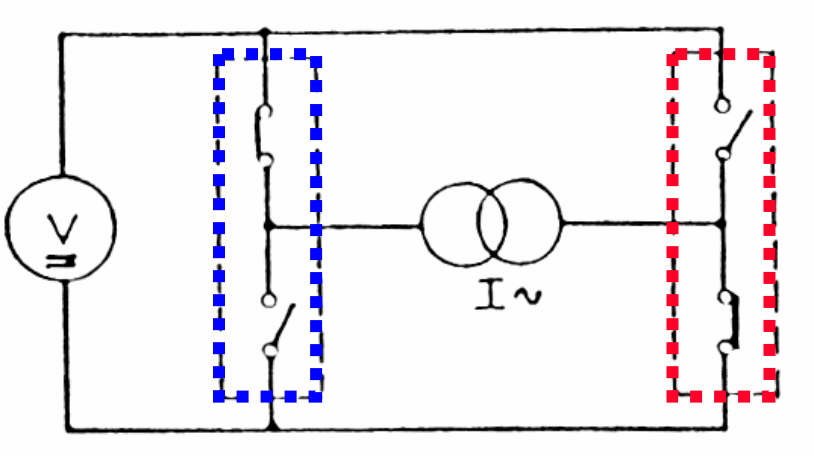
Current-source inverter type cells



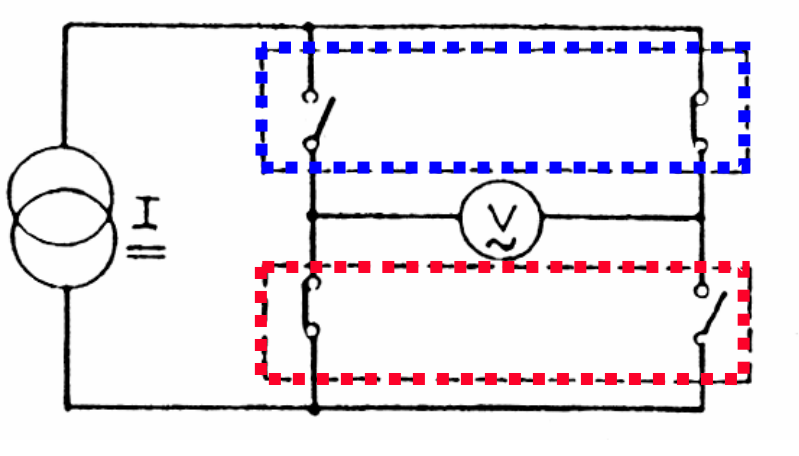
Chopper



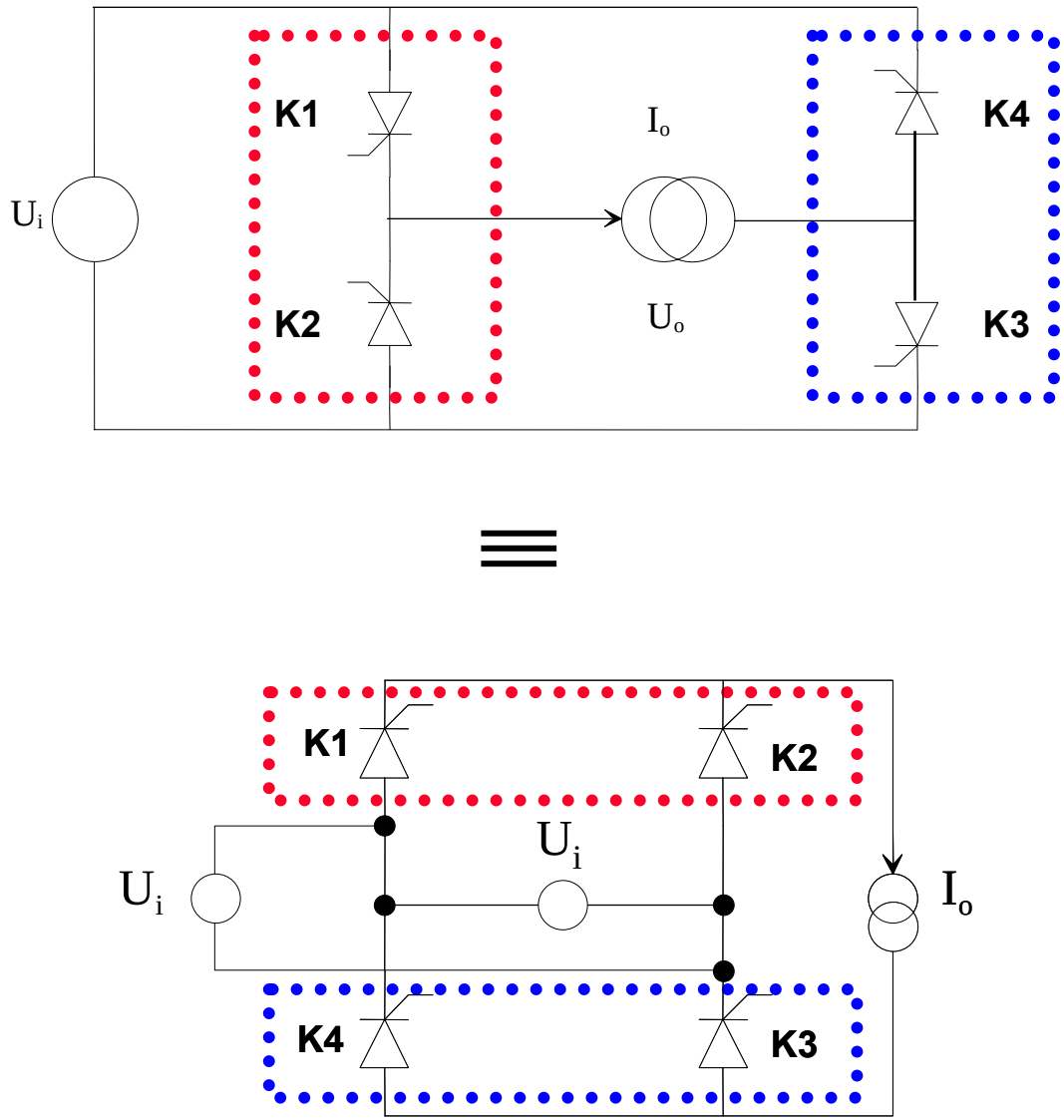
Converter with DC voltage link

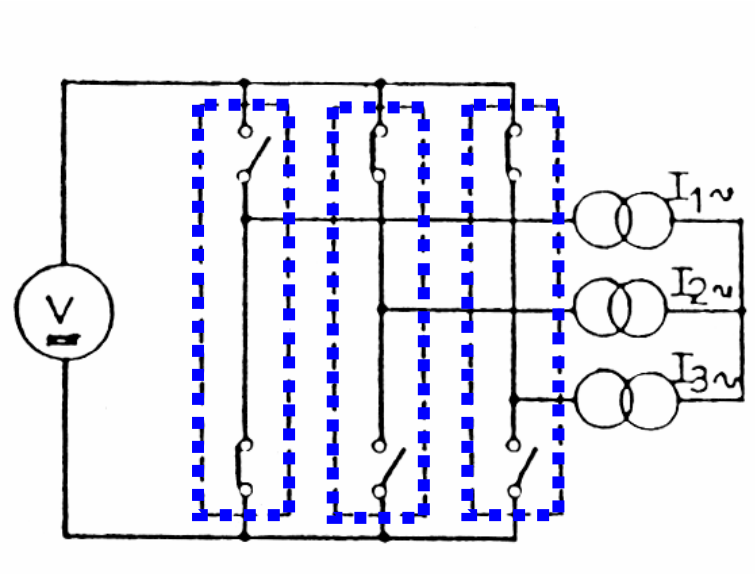


Single phase voltage-source inverter

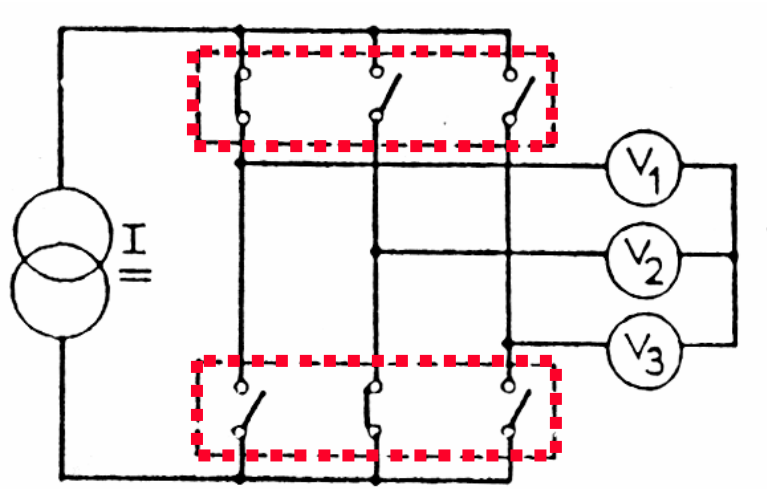


Single phase current-source inverter

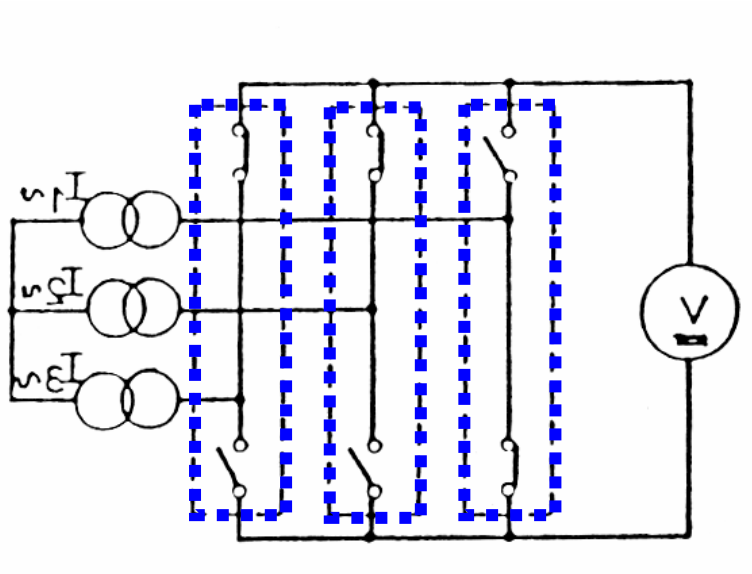

K1
K2
K3
K4
U_i
I_o
U_o
U_i
U_i
I_o



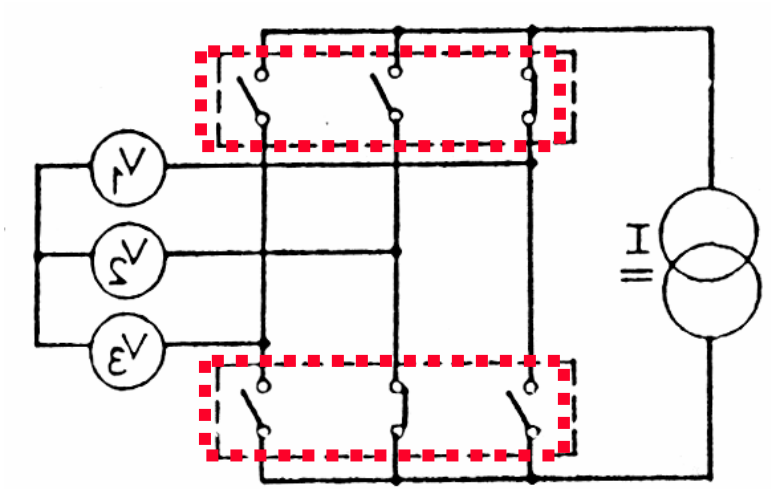
Three-phase voltage-source inverter



Three-phase current-source inverter

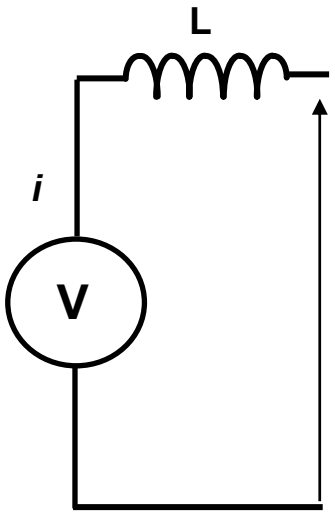


Three-phase voltage-source inverter

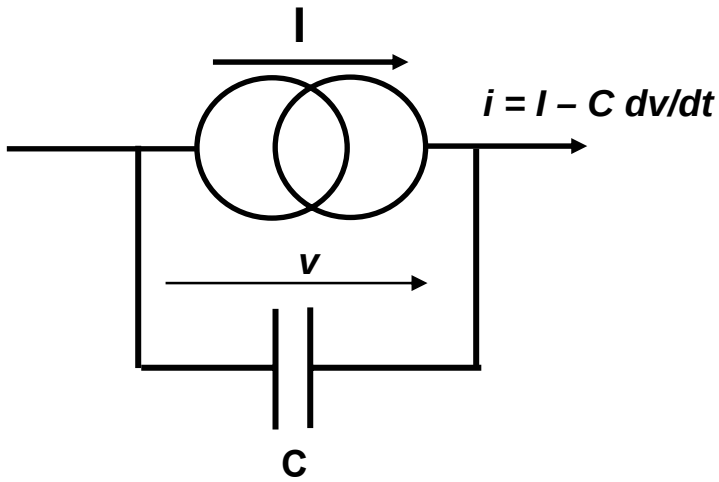


Three-phase current-source inverter

Commutation cell with parasitic components: real nature of the sources

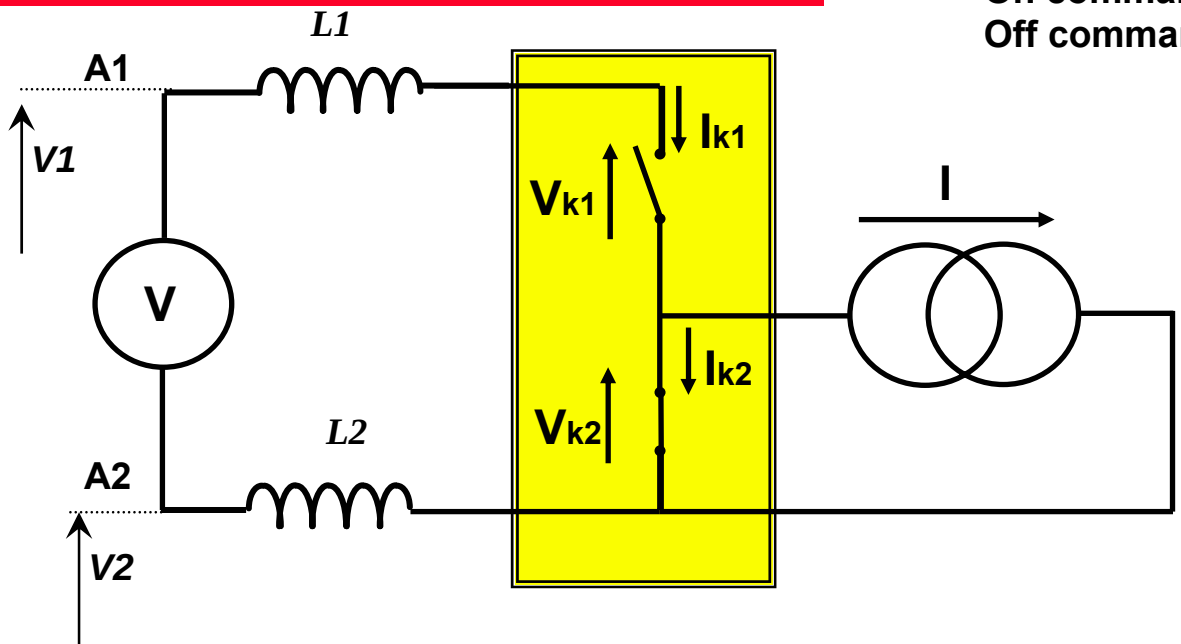


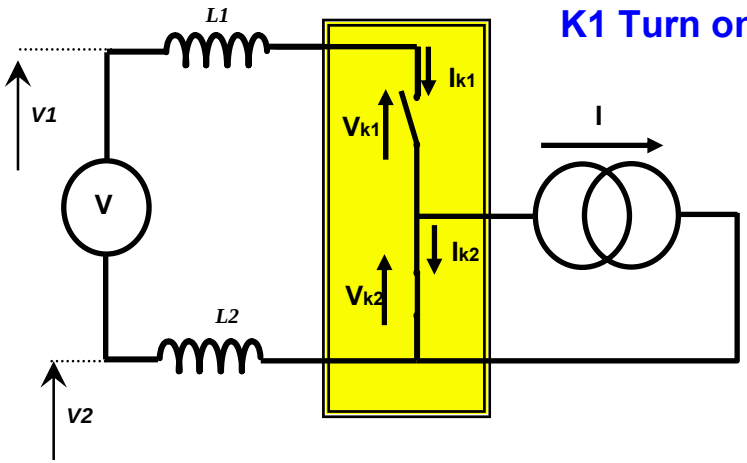
$v = V - L\ di/dt$



Example of commutation cell with inductive voltage source

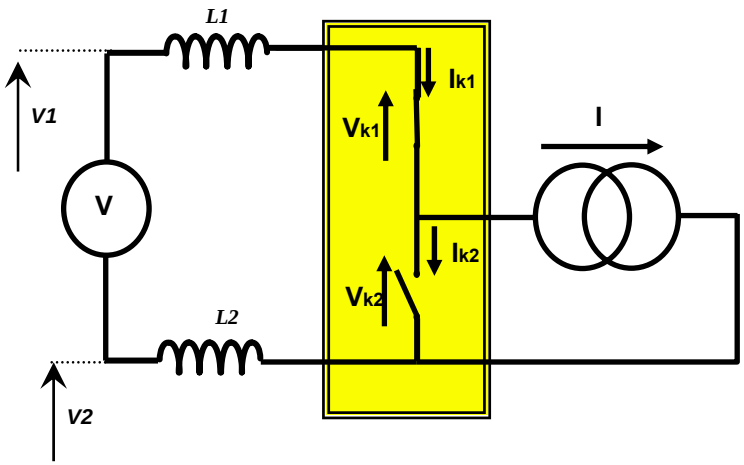
On command : OK
Off command : overvoltage



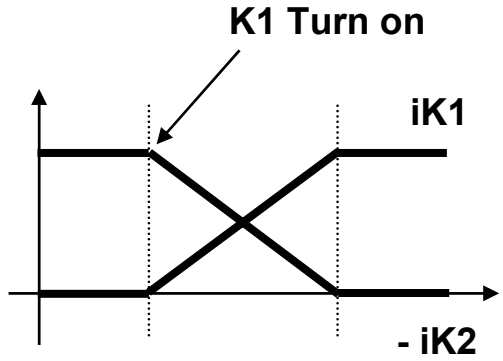


K1 Turn on

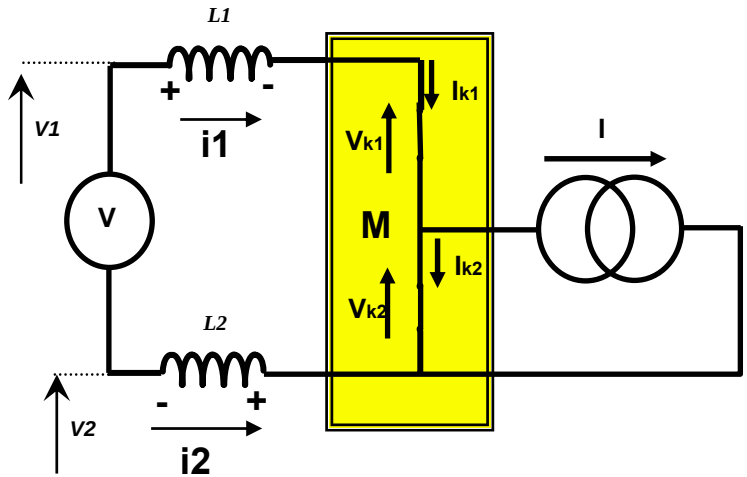
Vk1 = V ; Ik1 = 0
Vk2 = 0 ; Ik2 = - I



Vk1 = 0 ; Ik1 = I
Vk2 = V ; Ik2 = 0



Commutation duration defined by L1 and L2 (new phase)



V1 – L1 di1/dt –V2 – L2 di2/dt = 0
Ik1 – Ik2 = I

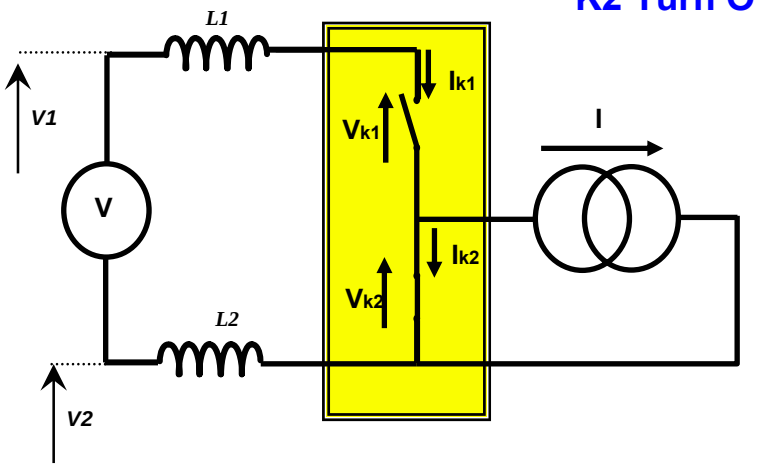
dIk1/dt = di1/dt and dIk2/dt = di1/dt

dik1/dt = diK2/dt = (V1-V2) / (L1 + L2)

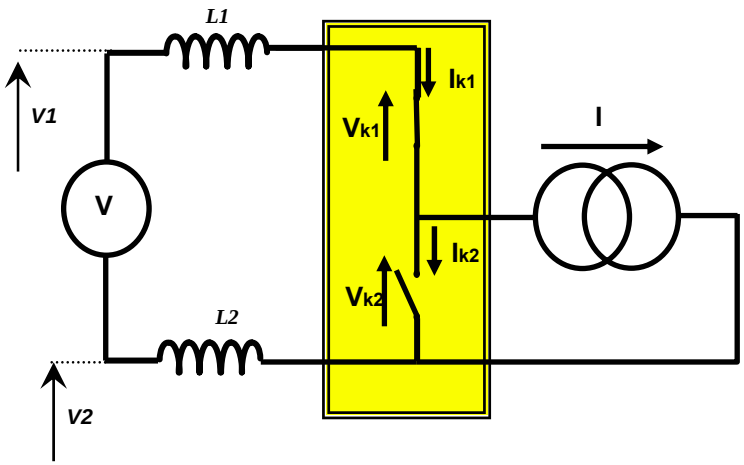
$V_M = (V1 + V2) / 2$

Soft commutation (natural commutation) with overlapping

K2 Turn OFF



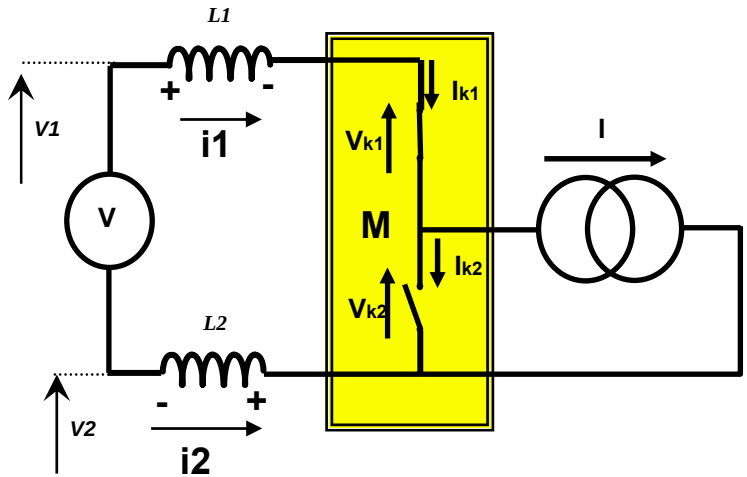
Vk1 = V ; Ik1 = 0
Vk2 = 0 ; Ik2 = - I



Vk1 = 0 ; Ik1 = I
Vk2 = V ; Ik2 = 0

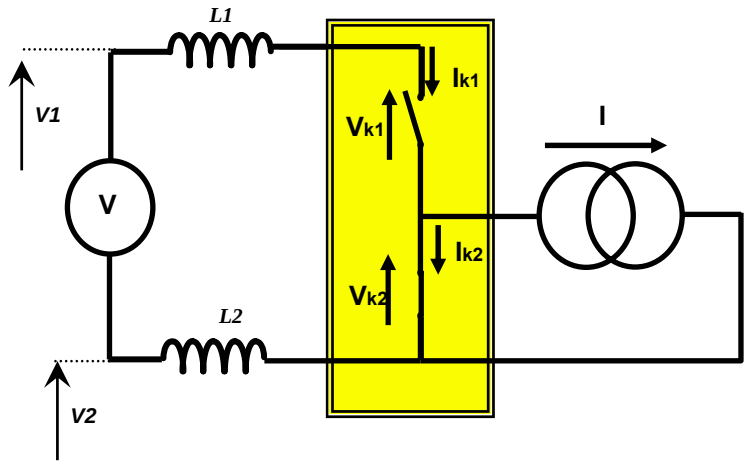
Vk1 = 0 (spontaneous On of K1)
Vk2 = V + (L1+ L2) di2/dt
(closing of inductive circuit)

→ over voltage on K2

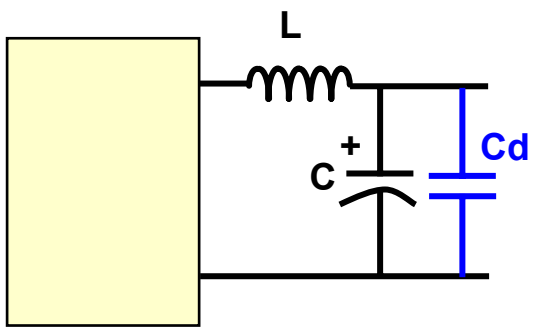


Solution:
-Decoupling of the commutation cell
-Forced commutation.

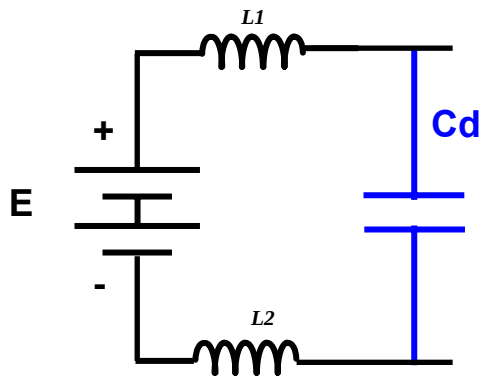
-Decoupling of the commutation cell



For example….

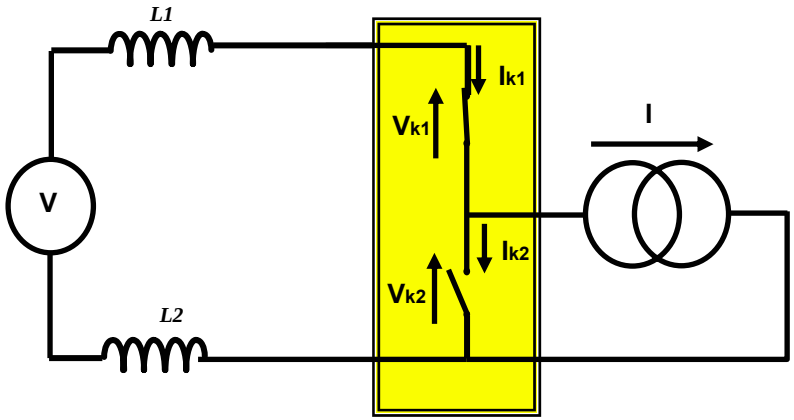


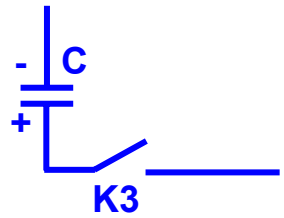
Output of LC filter
(with electrochemical capacitor)



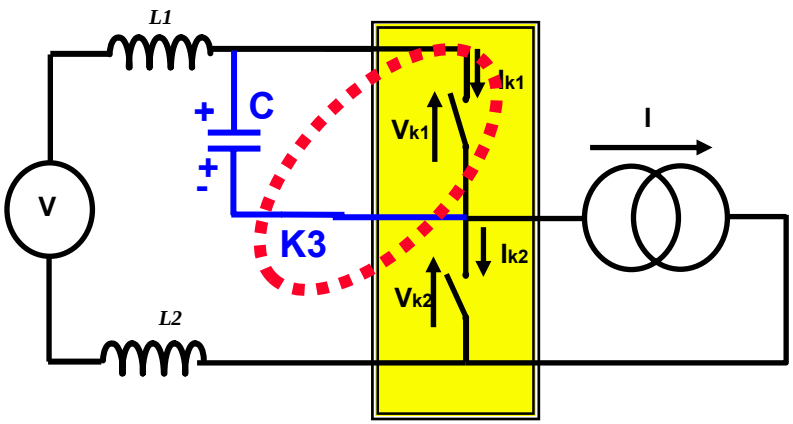
Battery with cables

- Forced commutation: how to avoid the K1 control turn off ?

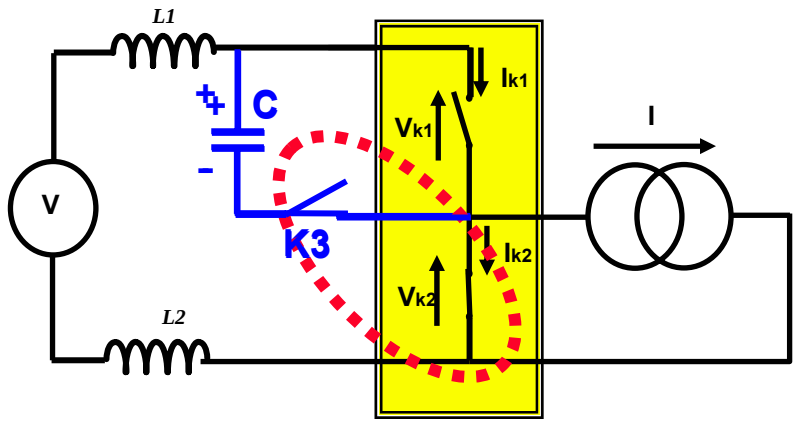




K1 and K3 : turn ON control
- Must revert C polarity
- (See C. De Almeida's talk)



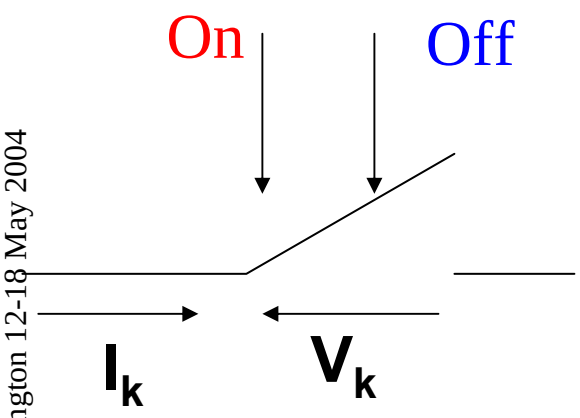
Commutation cell : K1-K3
K3 : Control Turn On
K1 : Spontaneous Turn Off

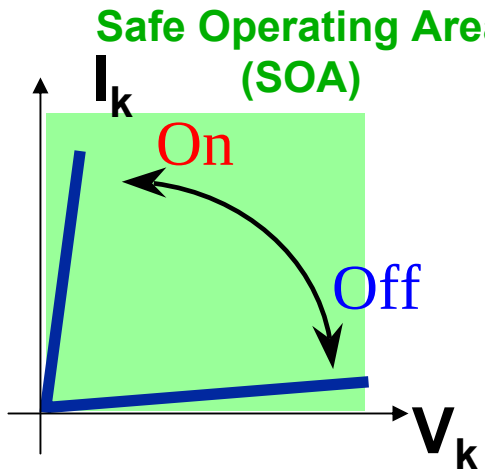


Commutation cell : K2-K3
K2 : Spontaneous Turn On
But no immediate K3 Turn OFF
(V L1L2 C loop : K3 off when Ic =0)

Hard Commutation

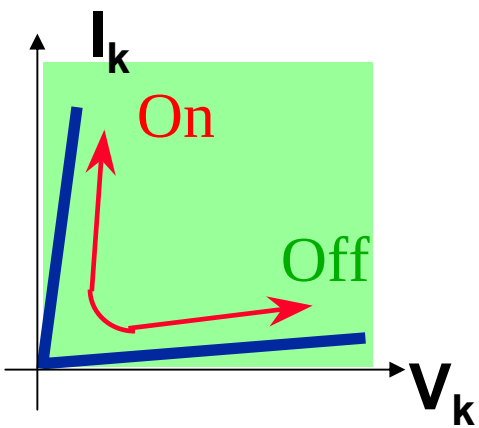
(switches two segments)





High commutation losses
=> frequency limitation

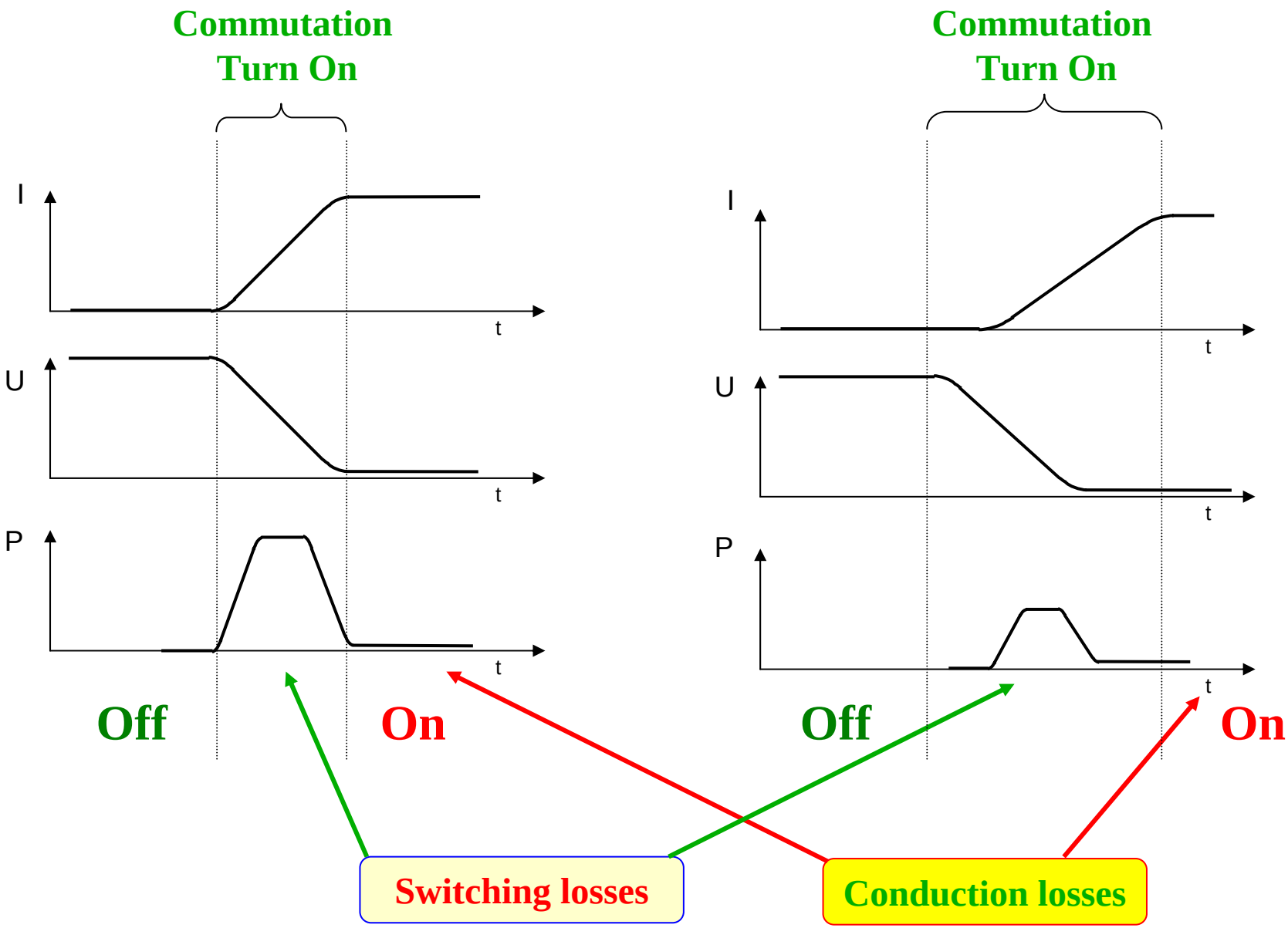
To limit the losses :
high dI/dt and /or dV/dt
=> **EMI problem**



Aided commutation : addition of aided commutation network (snubber)
Series Inductance : turn On
Parallel capacitor : turn Off
Should discharge the snubber before the next commutation ! (losses, extra components,….)

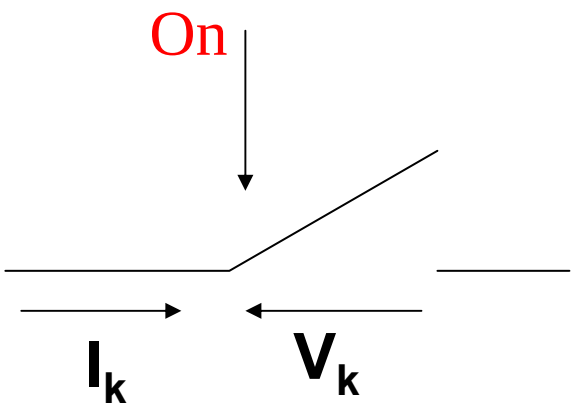
Hard Commutation

Aided commutation

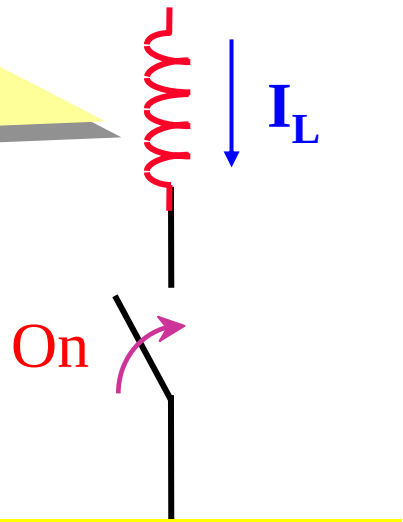


Soft Commutation ZCS

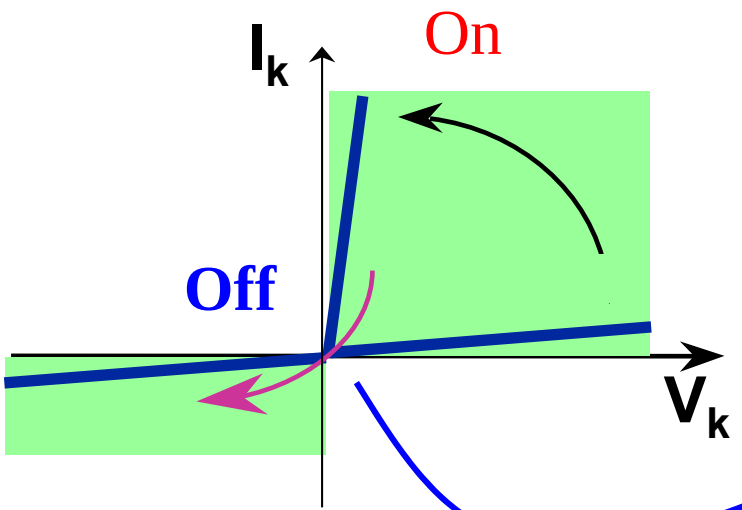
(switches three segments)



High inductance can be added to reduce the turn ON losses



Thyristor Turn On control

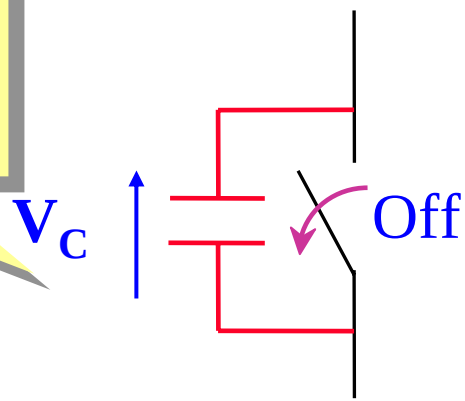


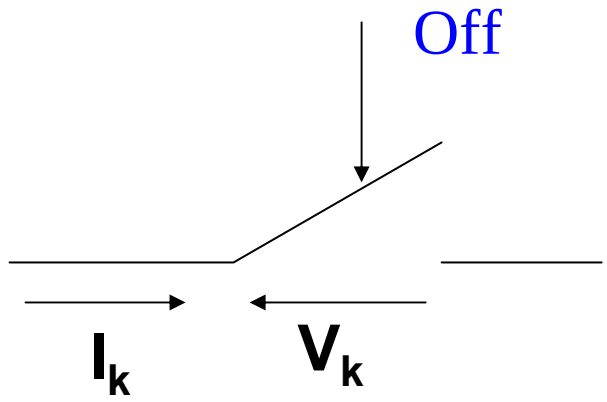
Off : no control;
by the circuit topology
$I_L = 0$

Soft Commutation : ZVS

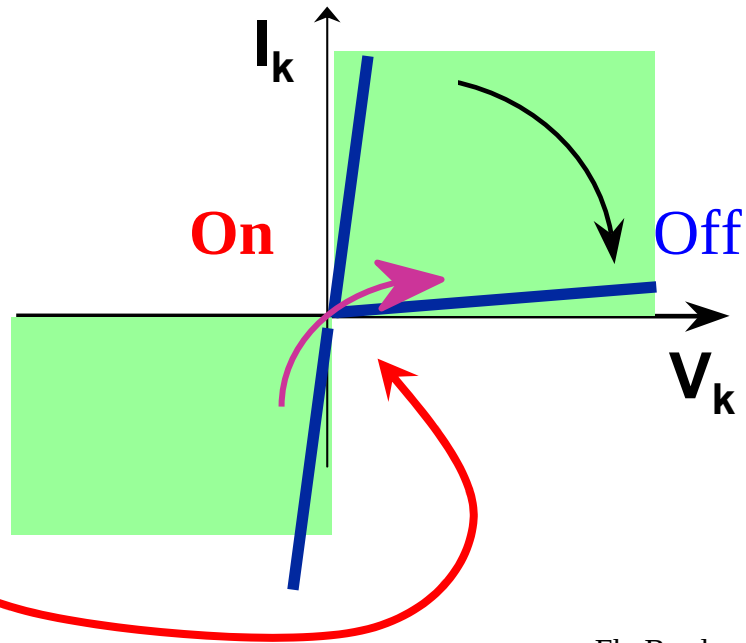
(switches three segments)

High capacitance can be added to reduce the turn OFF losses





Dual Thyristor Turn Off control



On : no control;
by the circuit topology
$V_C = 0$

Conditions of soft-commutation:

- Switches with three-segments characteristic.
- This characteristic is entirely described at each period
- The converter must include reversible source(s) able to provoke the conditions of the spontaneous commutation of the switches at the right instant

- Lossless circuit can be added to the switch to limit the losses due to the controlled commutation

(*aided-commutation circuit*)

Soft-commutation is not a slow commutation !!!!

General method for converter synthesis:

a) Determine the natures of input and output sources => basic configuration

b) From the specification, deduce the voltage and current reversibilities of the input and output sources (one configuration of general table)

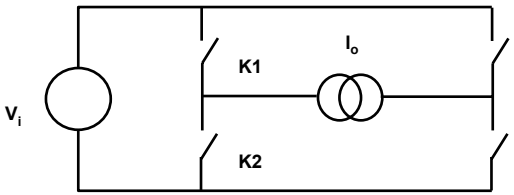
c) From the basic configuration, identify the different phases of operation according to the reversibilities and the energy transfer control. If necessary, simplify the configuration (short-circuit or open switches)

d) For the various phases, check the sign of the current through the ON switches and the sign of the voltage across the OFF switches
=> $I_k(V_k)$ static characteristics of each switches

e) From the specification (desired output current and/or voltage functions), deduce the sequence of the different phases. For every commutation, represent the working point of each switches before and after the commutation.

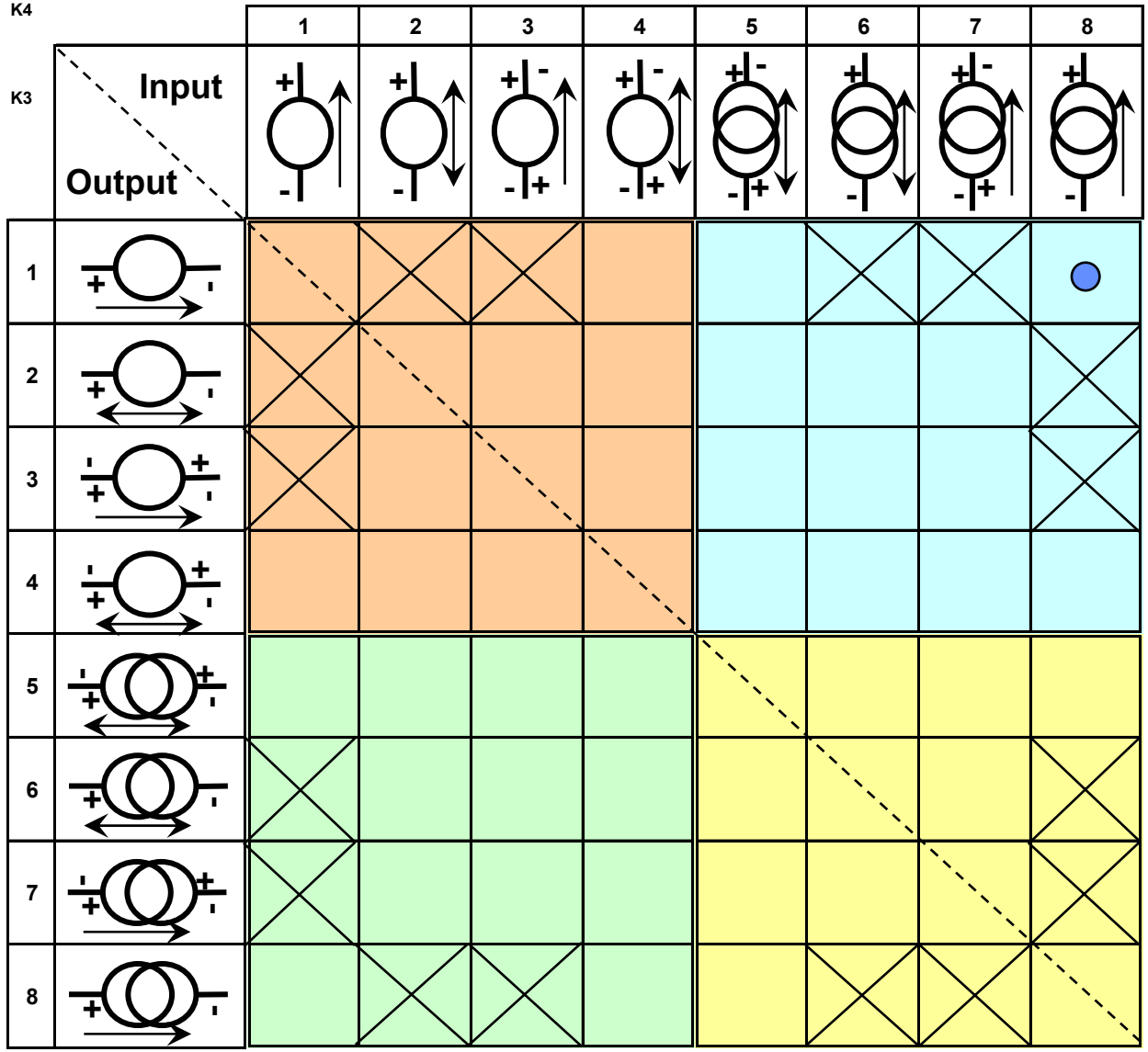
f) From static and dynamic characteristics, choose the type of switches (=> semiconductor type)

First Example

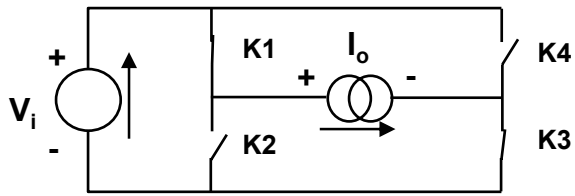


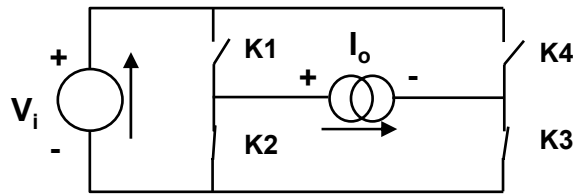
Chopper:

Non reversible in current



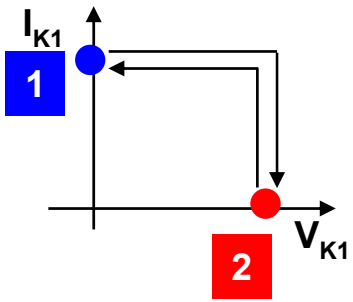
First example : Non reversible current chopper

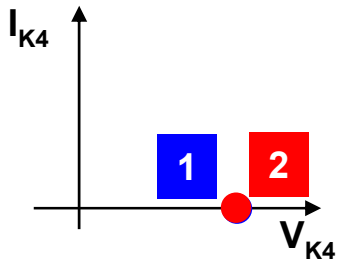


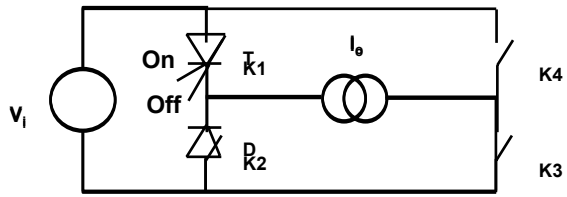


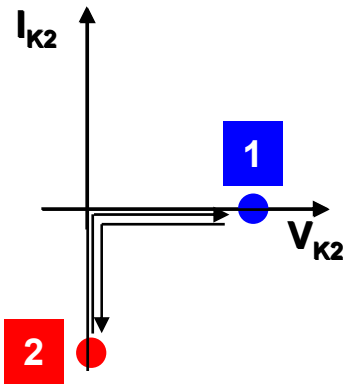
1

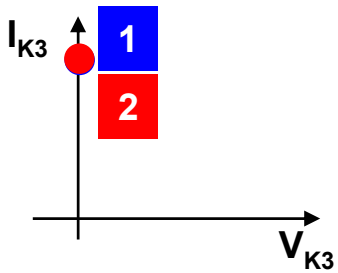
2



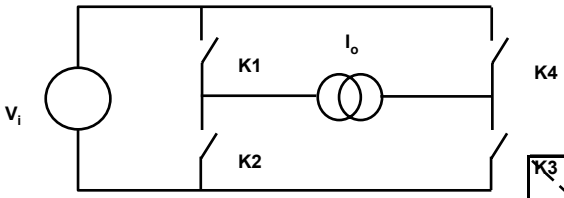






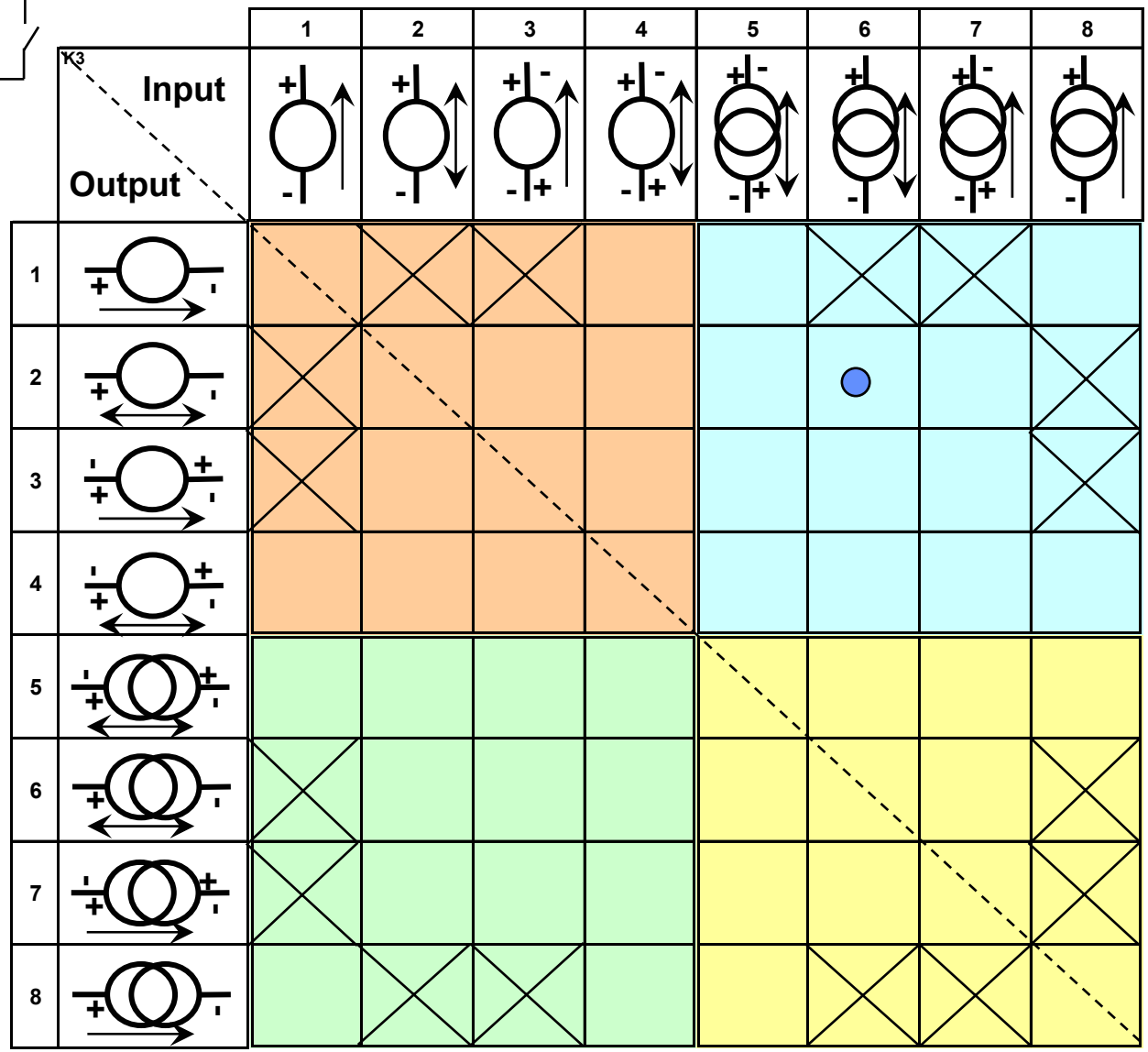


Second Example



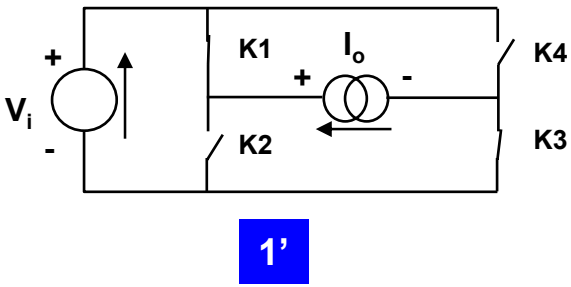
Chopper:

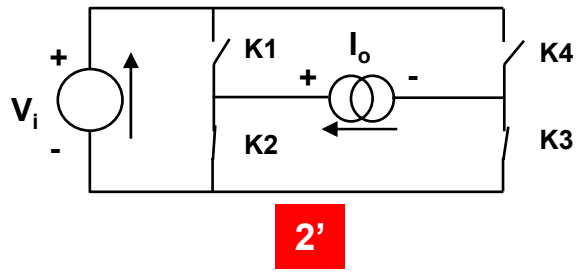
Reversible in current

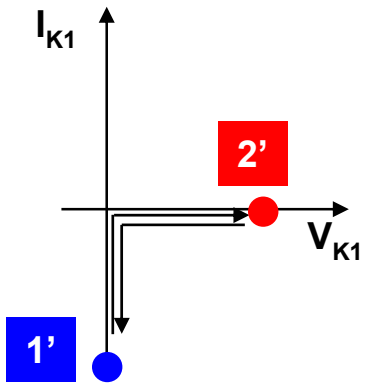


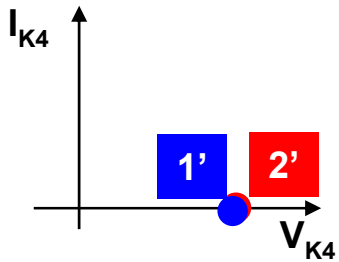
Second example : Reversible current chopper

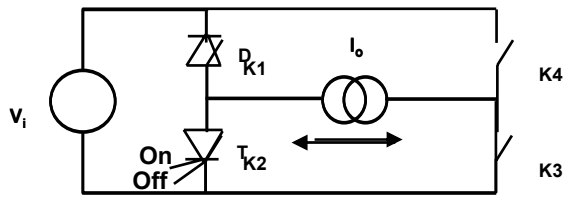
Energy: Output => Output
Bidirectional example

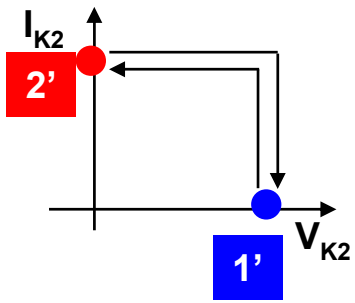


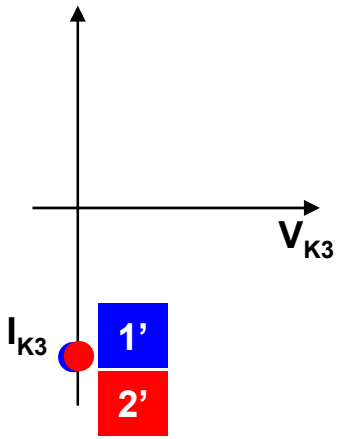




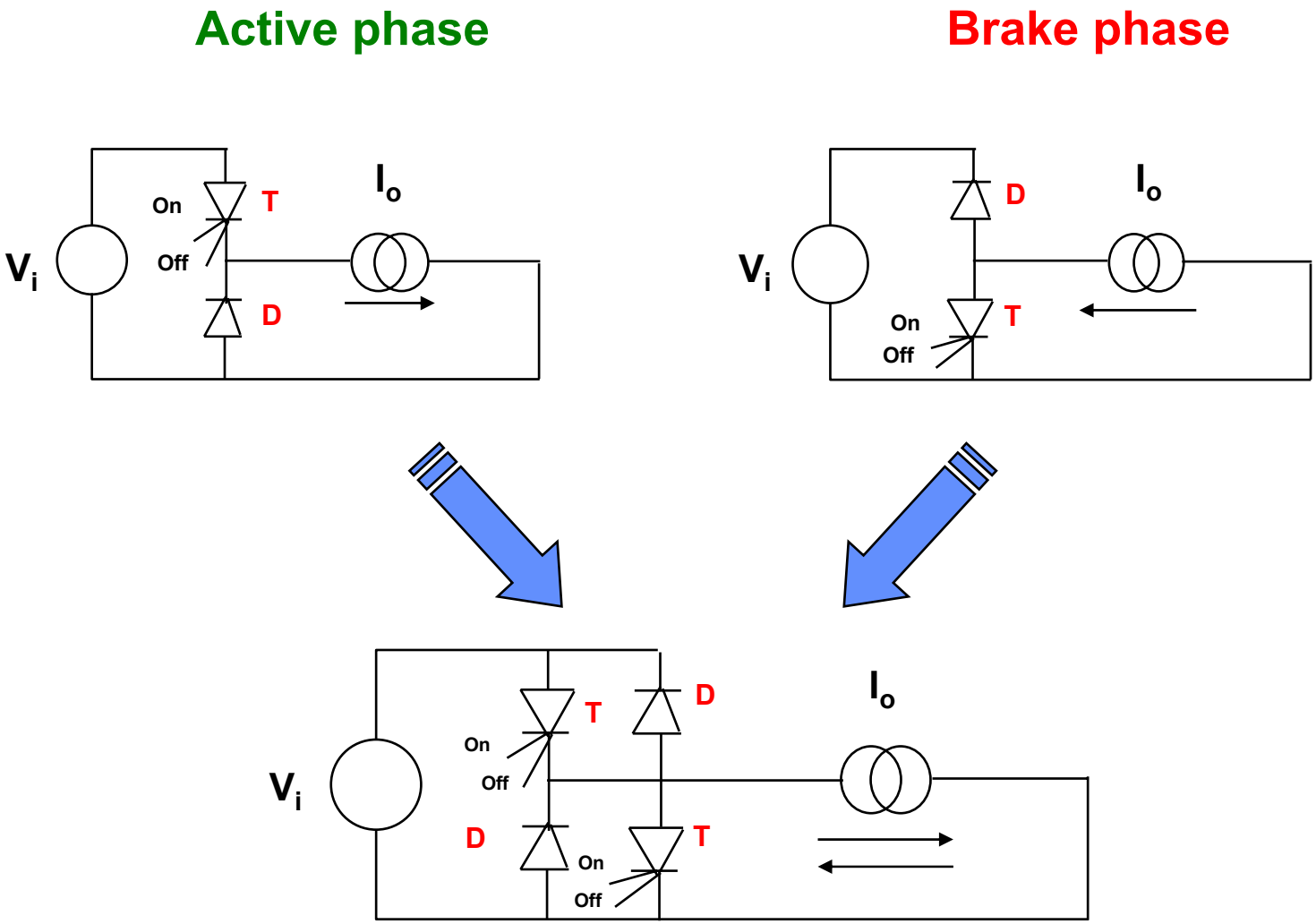




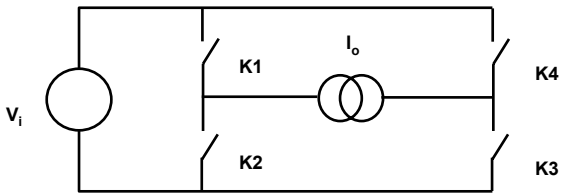




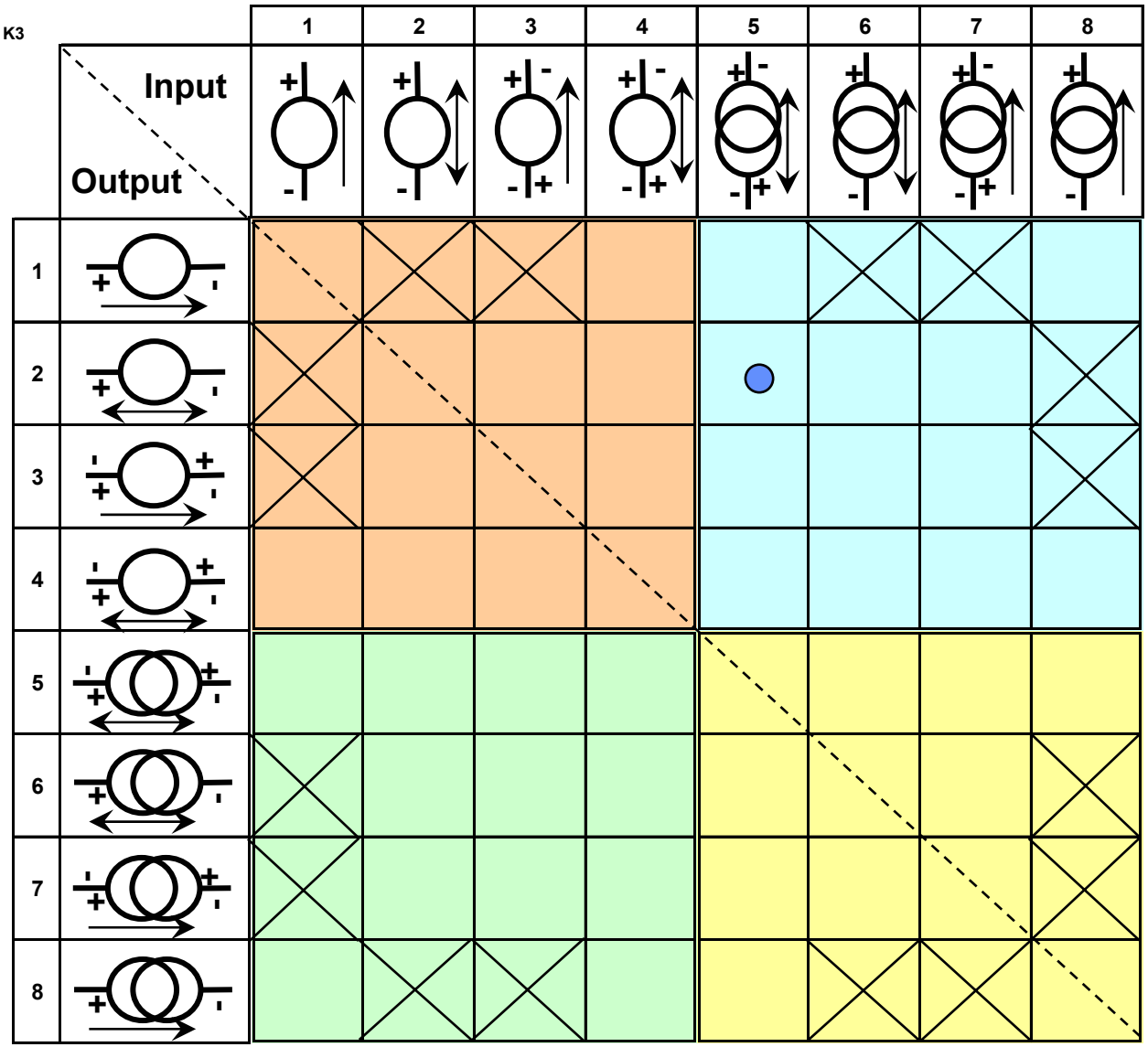
Reversible current chopper



Third Example

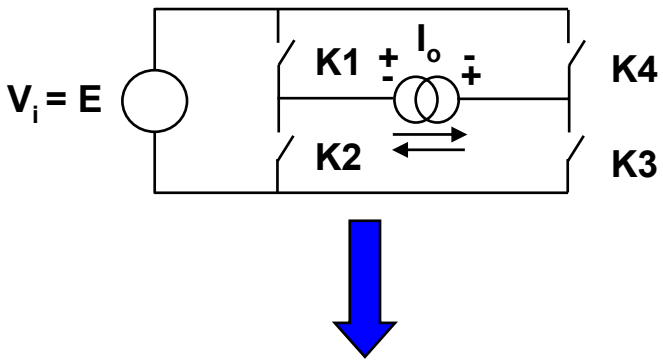


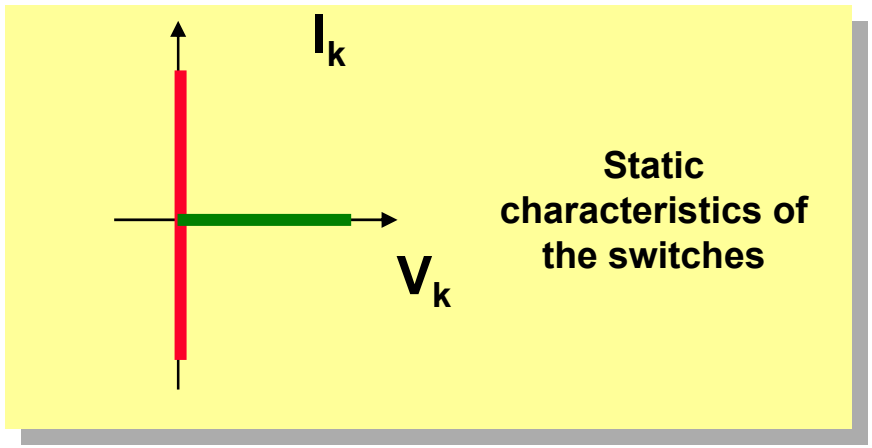
Voltage Inverter



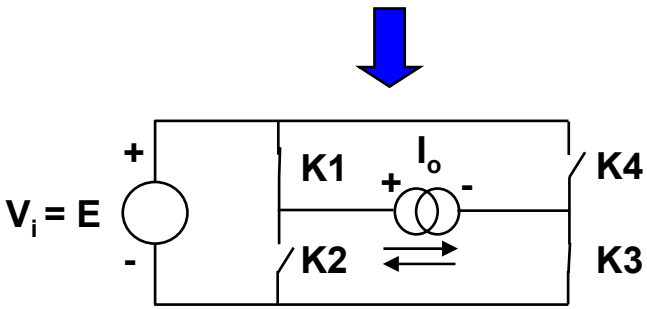
Third example : Voltage inverter

Input source: voltage source (DC source: E) ; reversible current
Output source : current source (AC source) ; reversible voltage and current

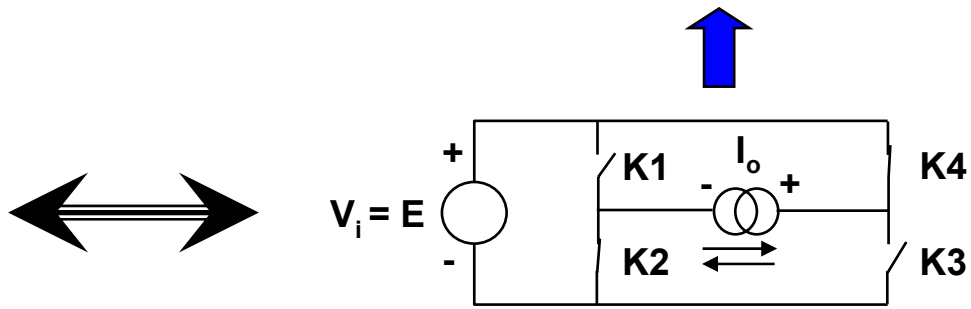




Specifications : +E and –E on the load

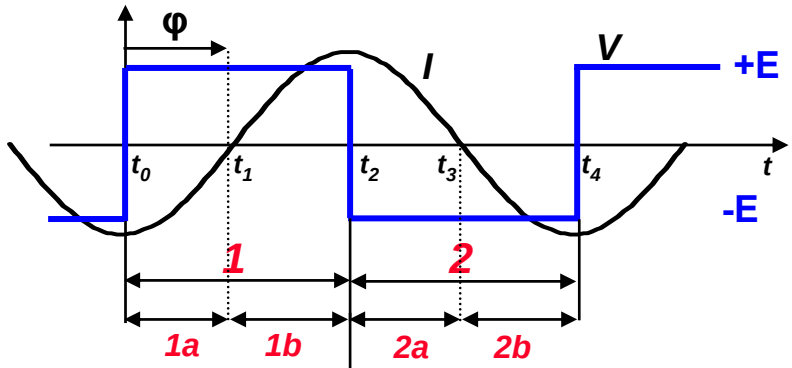


1



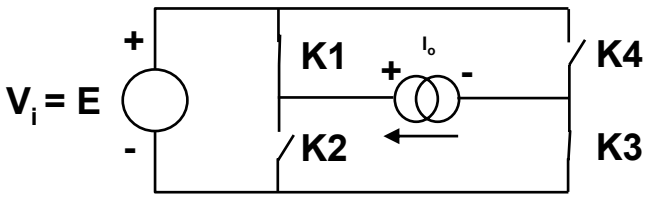
2

Third example : Voltage inverter

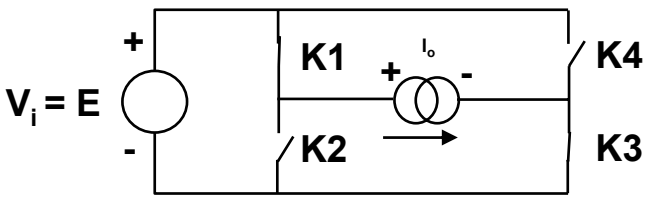


Lag between voltage and current
φ>0

1



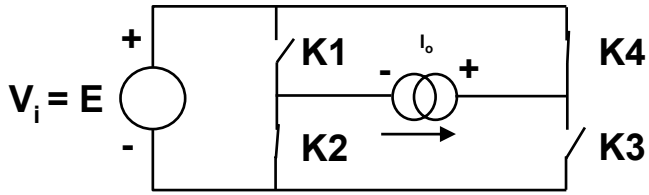
1a



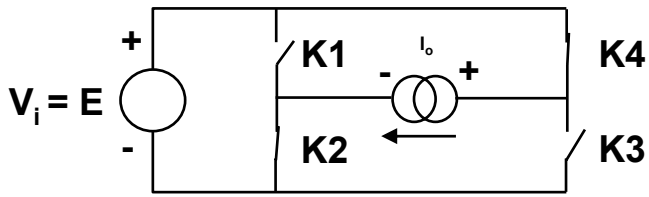
1b

2

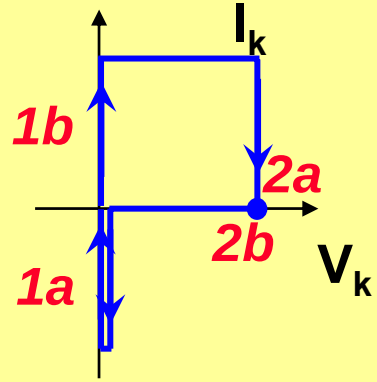
2a



2b

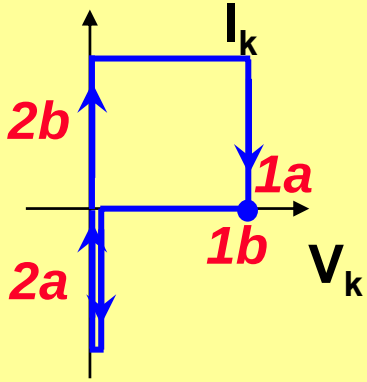


K1 and K3

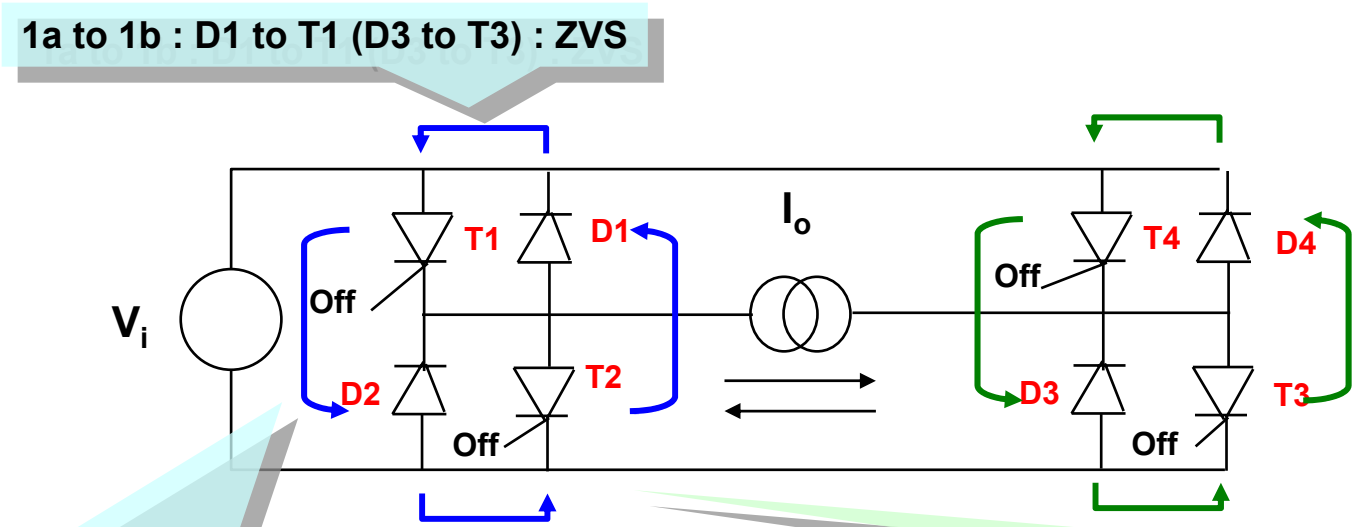


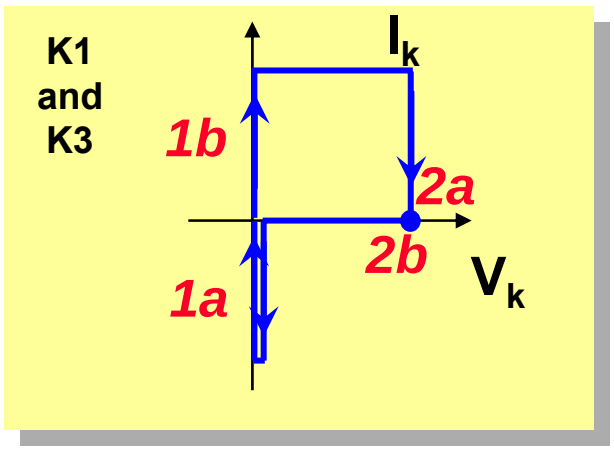
Dynamic characteristics of the switches

K2 and K4

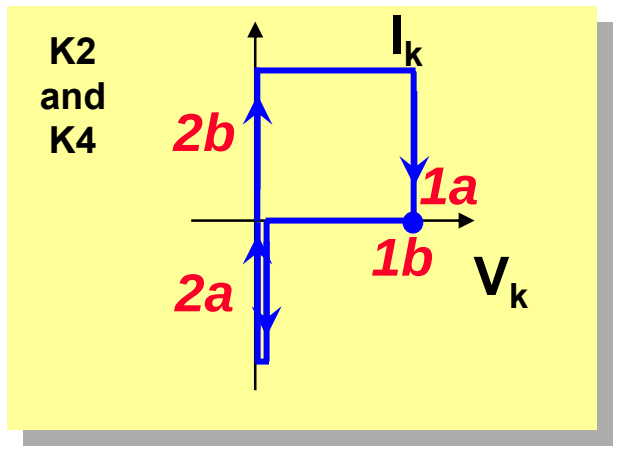


Inverter structure : turn-off control

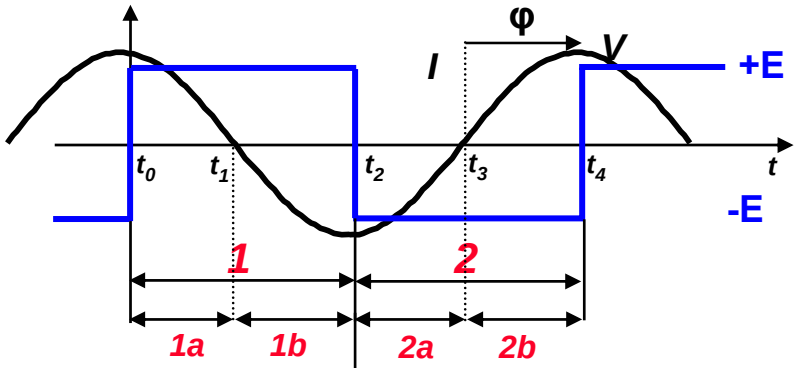




Dynamic characteristics of the switches

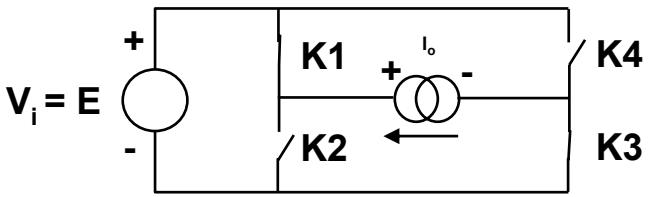


Third example : Voltage inverter

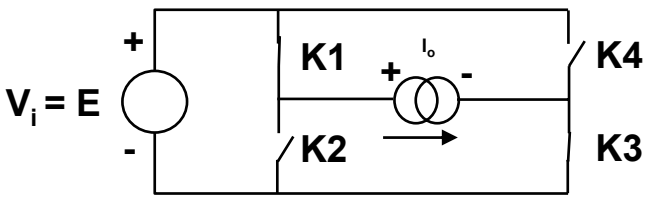


Lag between current and voltage
φ>0

1



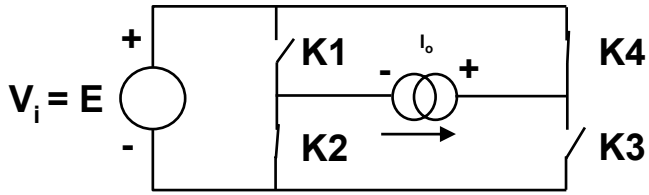
1a



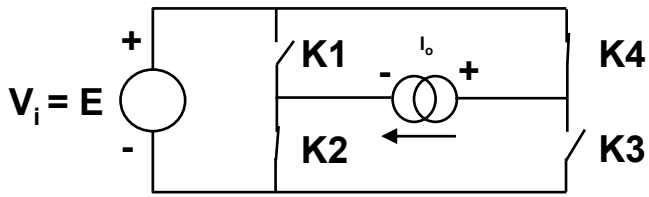
1b

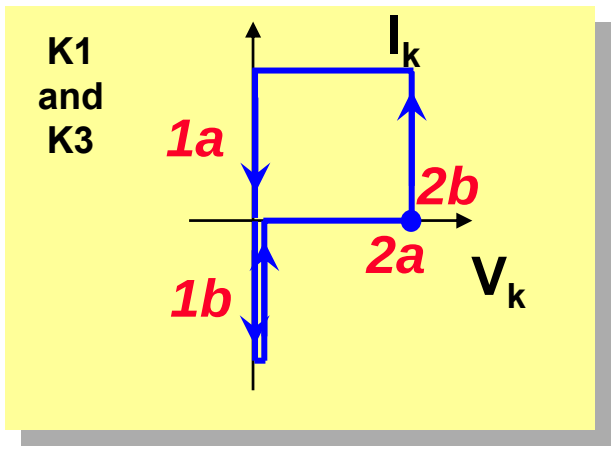
2

2a

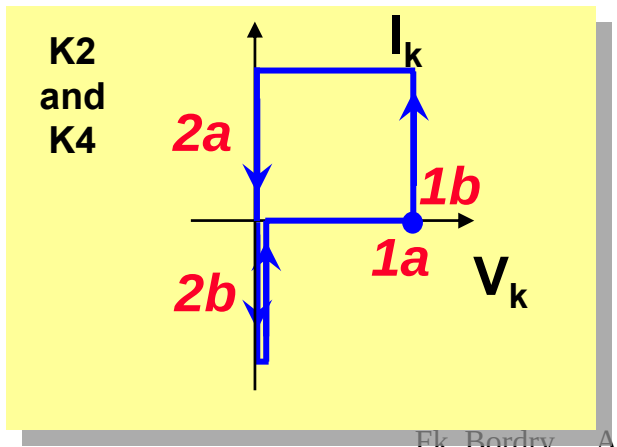


2b

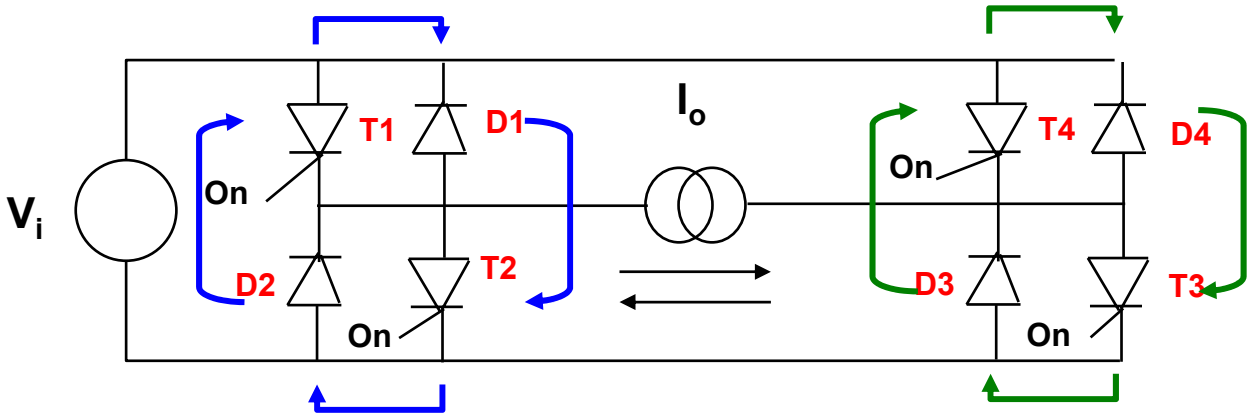




Dynamic characteristics of the switches

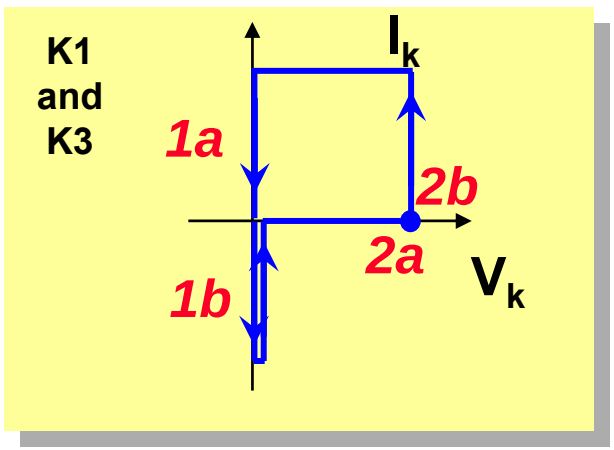


Inverter structure : turn-on control

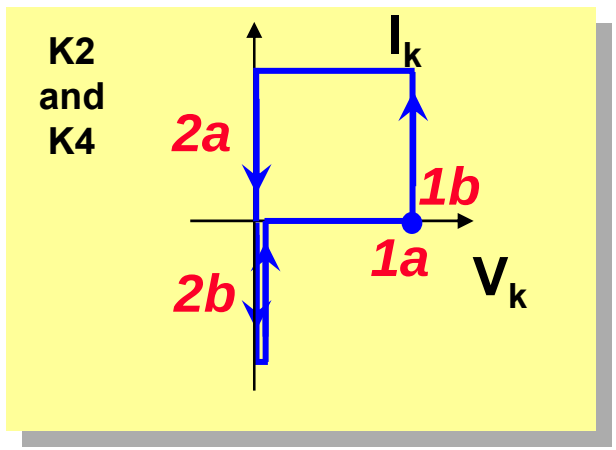


1a to 1b : T1 to D1 (T3 to D3) : ZCS
1b to 2a : D1 to T2 (D3 to T4) : ON command

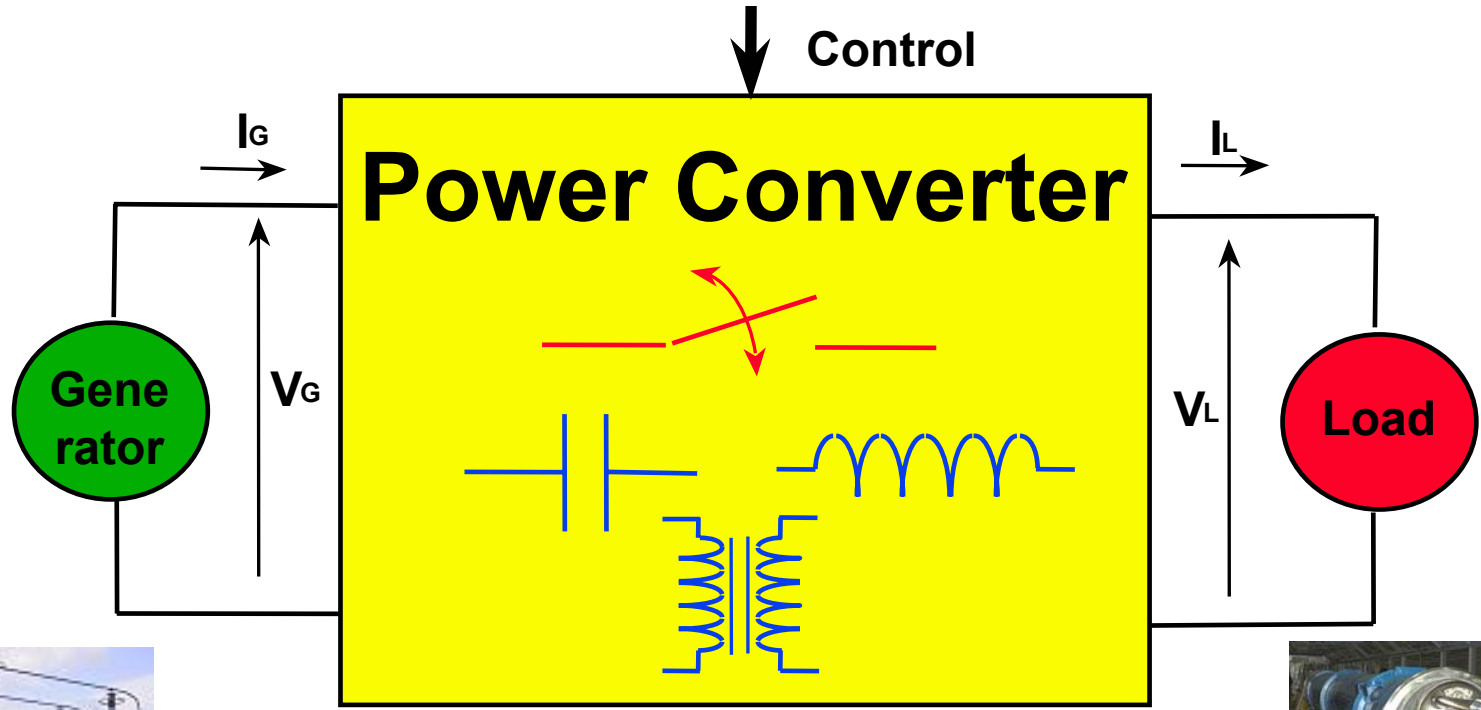
2a to 2b : T2 to D2 (T4 to D4) : ZCS
2b to 1a : D2 to T1 (D4 to T3) : ON command



Dynamic characteristics of the switches



Power Converter for magnets



Power Converter

- performance
- efficiency
- reliability, repairability, availability
- low cost
- effect on environment (RFI, noise,...)

Power Converter Topologies

AC

3 phase mains
(50 or 60 Hz)

I_G

V_G

I_L

V_L

Load

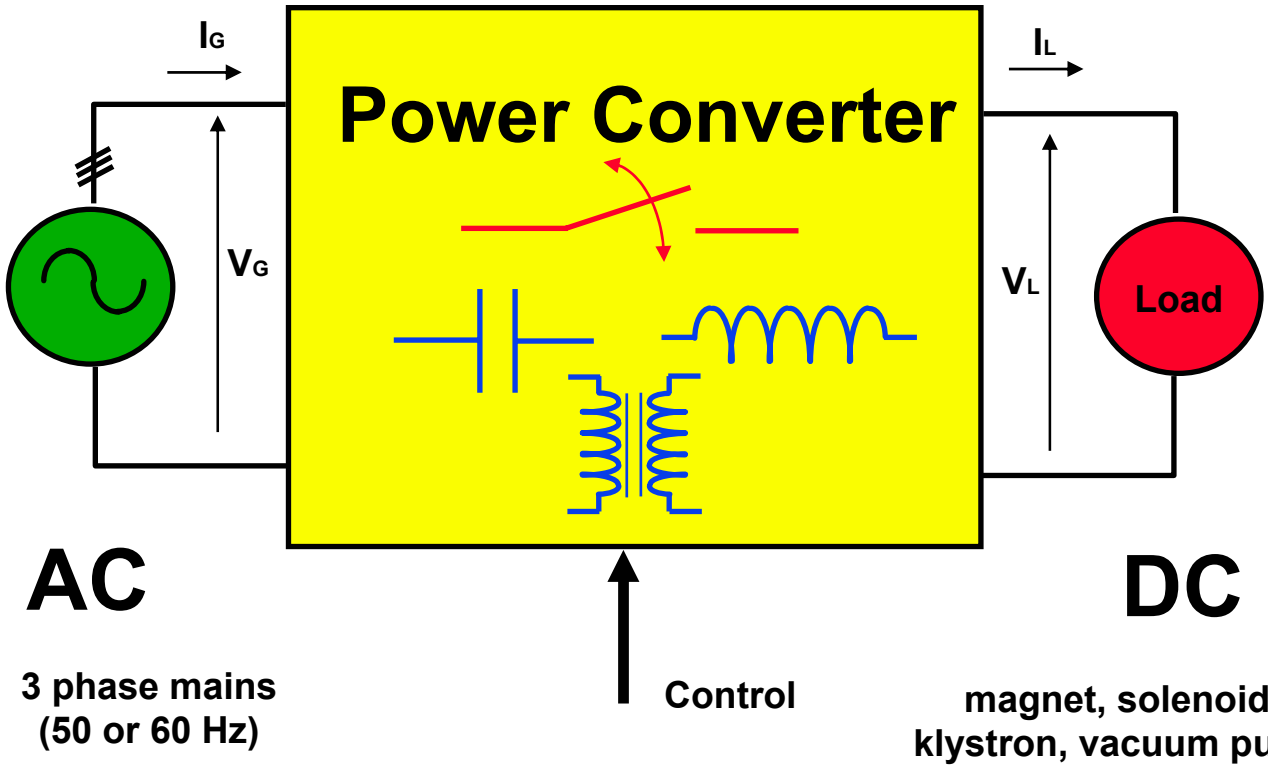
DC

magnet, solenoid,

Control

Voltage source

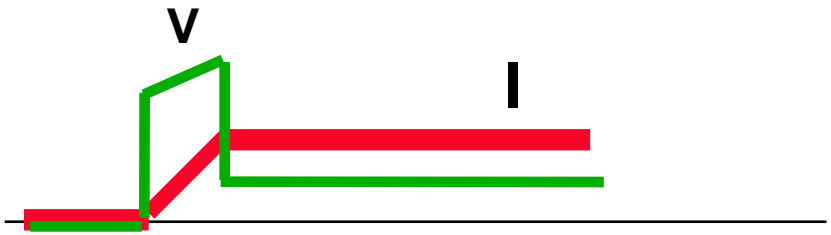
Current source

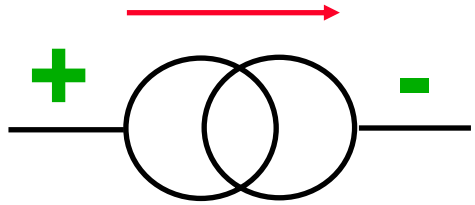


- low mains harmonic distortion
- power factor (closest to 1)

- low ripple (current)
- reproducibility (short and long term)
- rejection of mains disturbance
- dynamic response

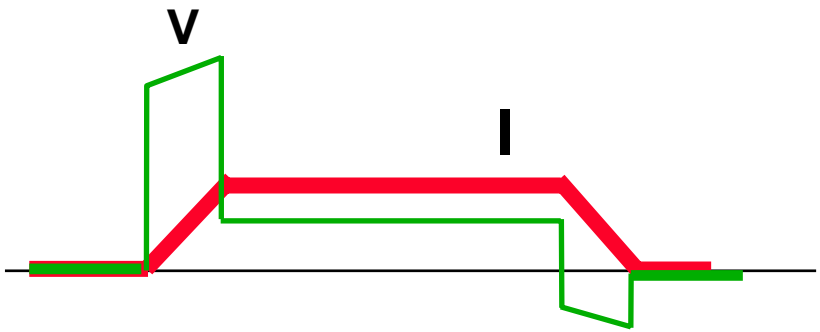
Achieving high performance : COMPROMISE

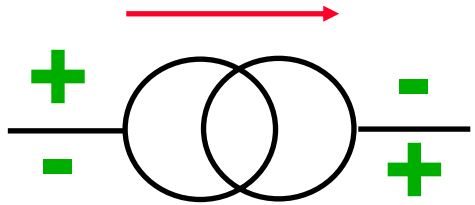




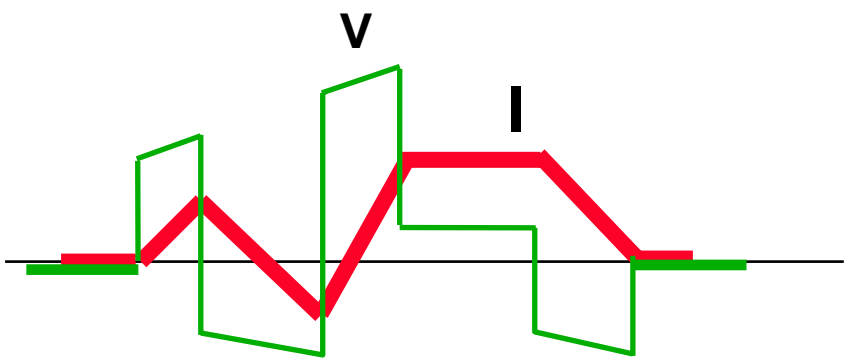
1 Quadrant mode

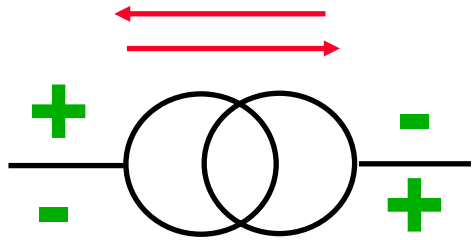
Output Source



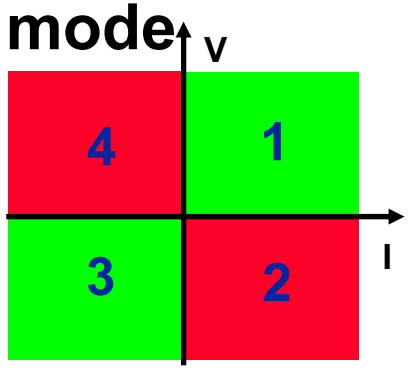


2 Quadrants mode



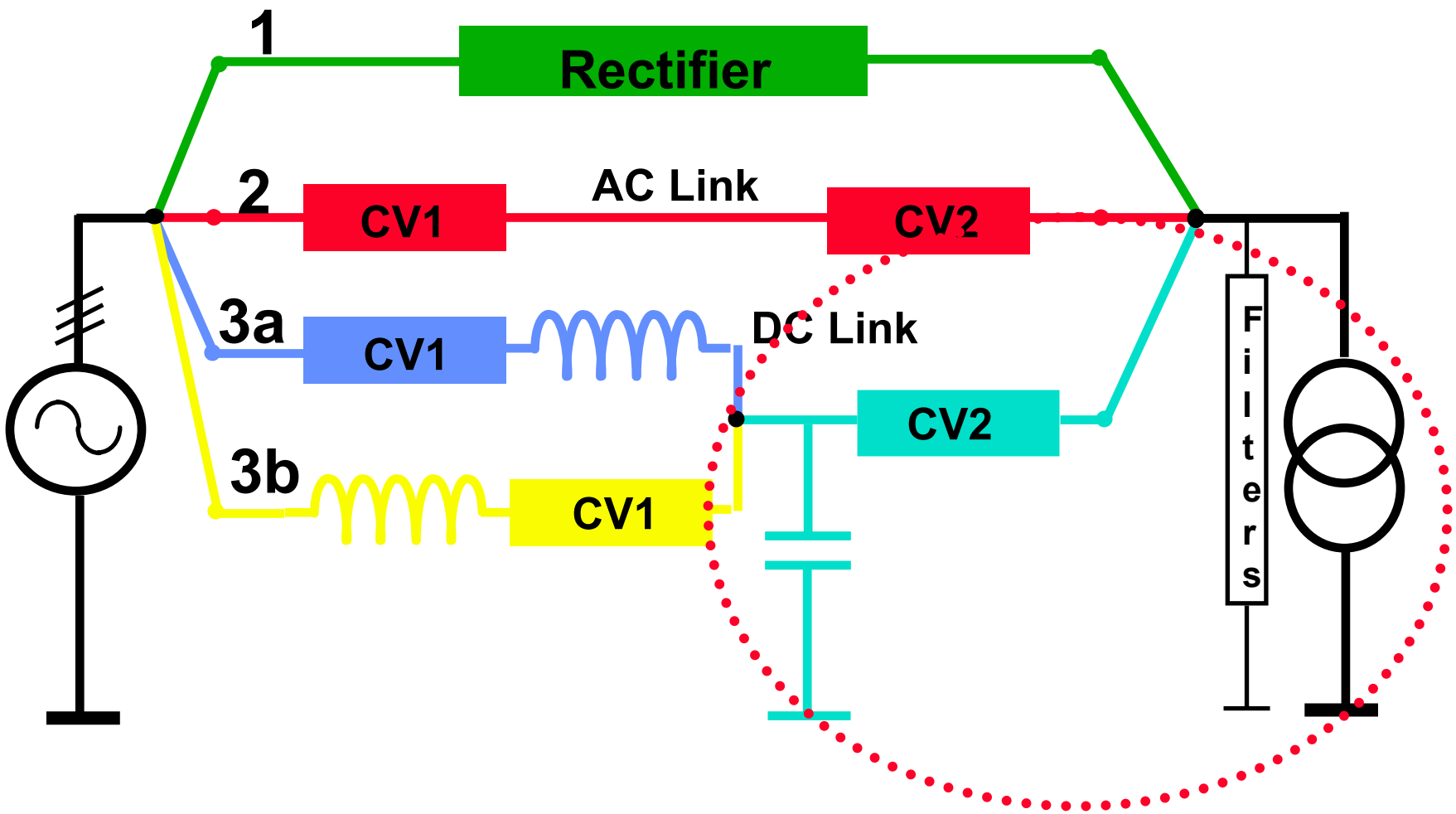


4 Quadrants mode

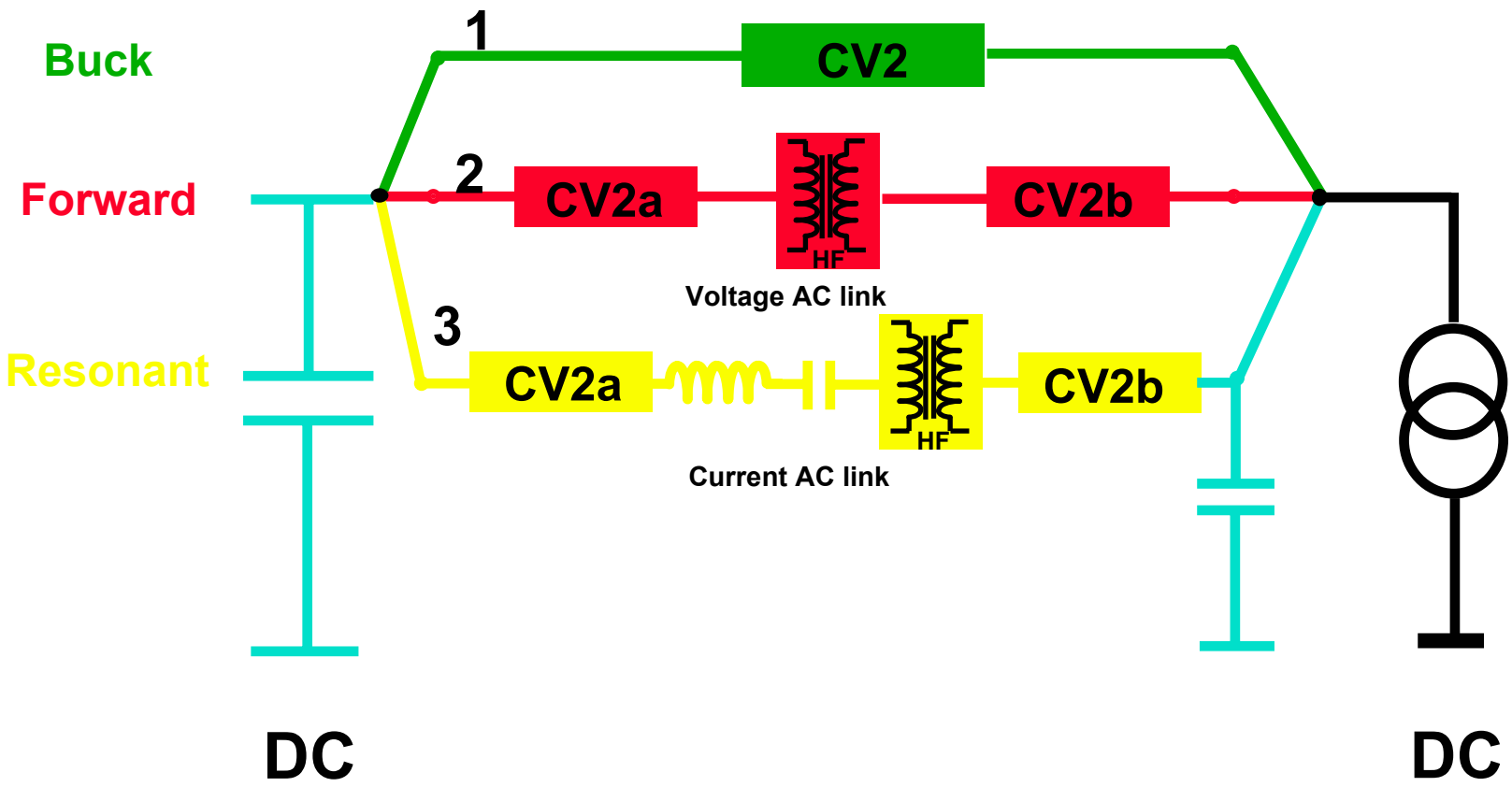


Operating Modes

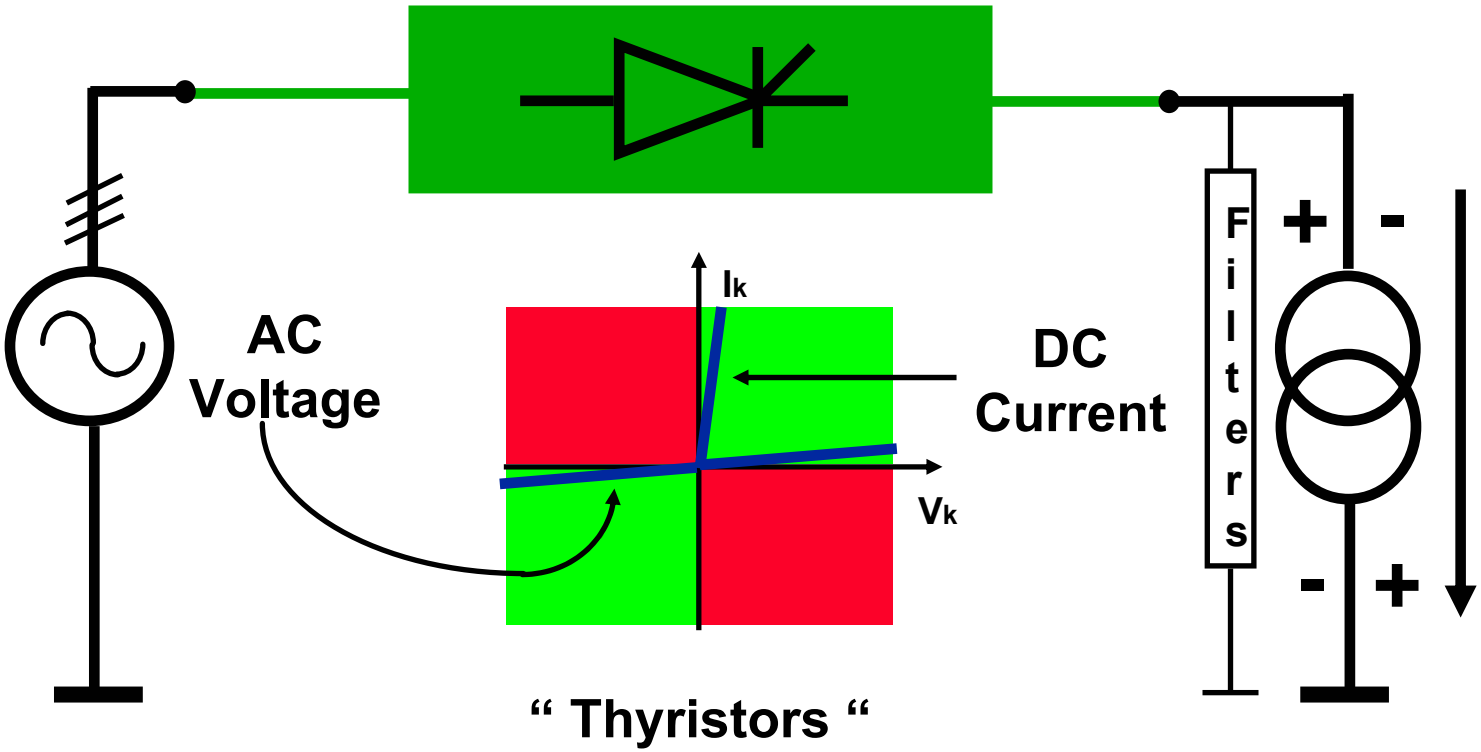
General power converter topologies



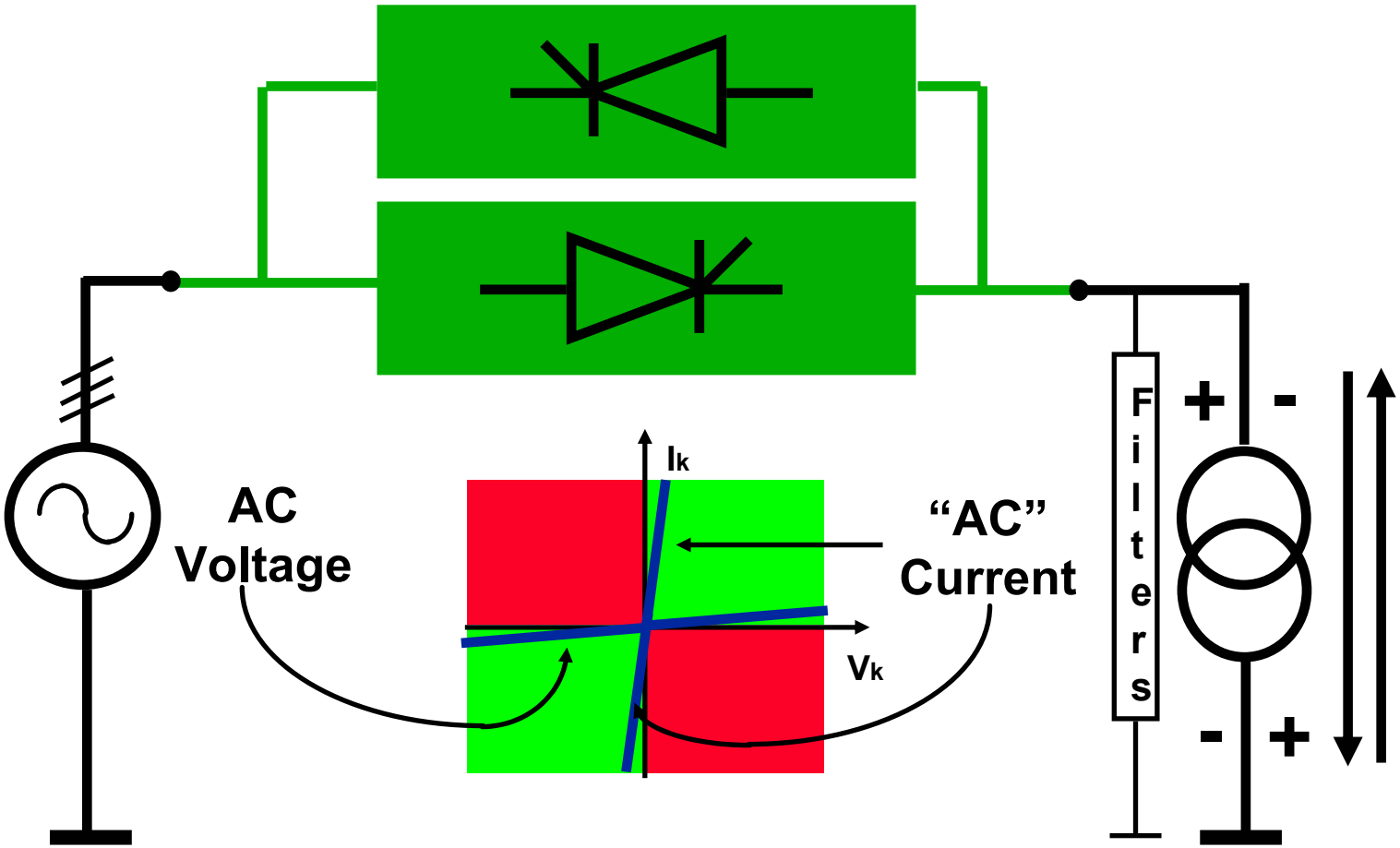
Power converter topologies : DC - DC



Direct Converters : Rectifiers

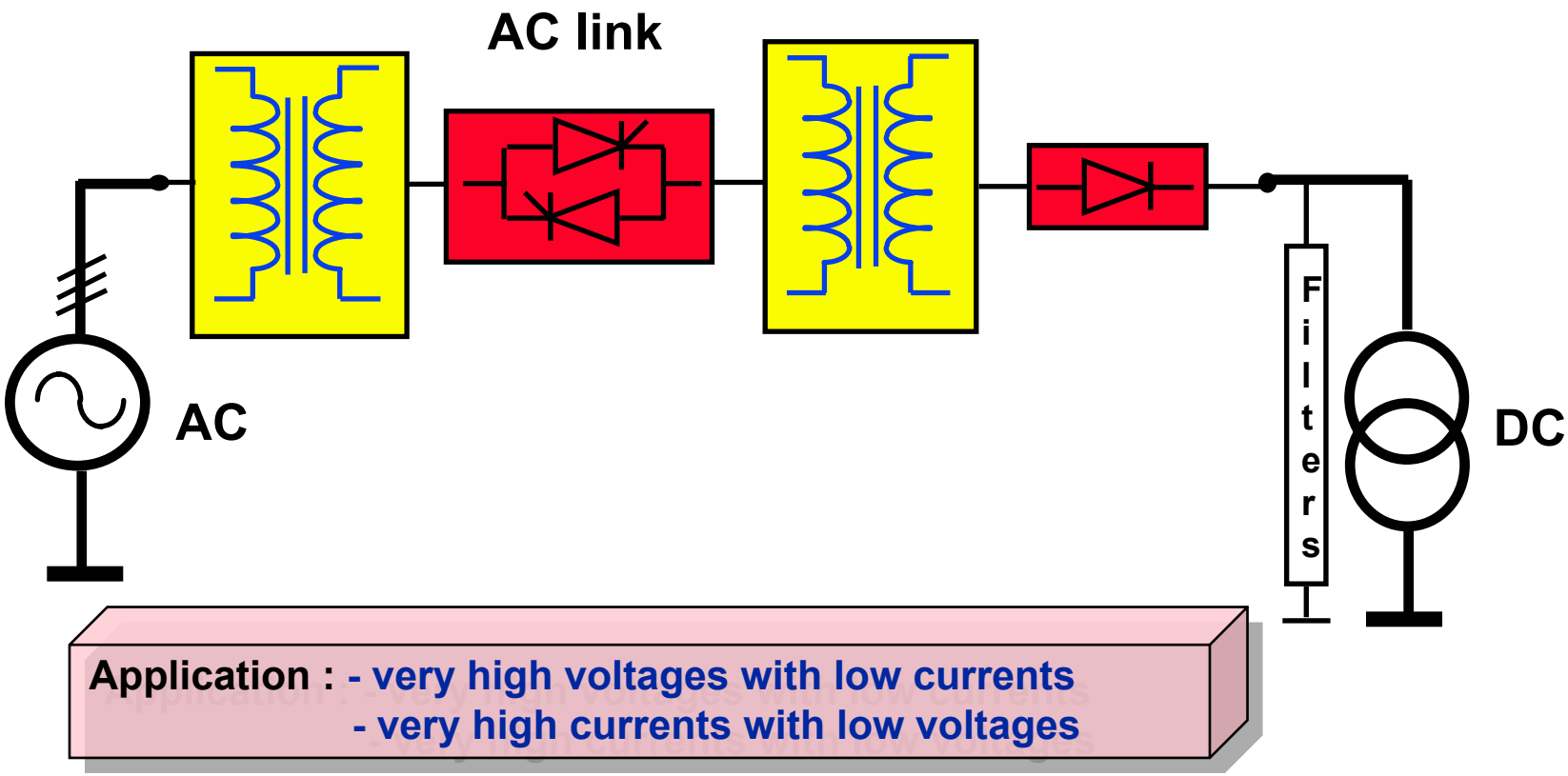


Direct Converters : Rectifiers



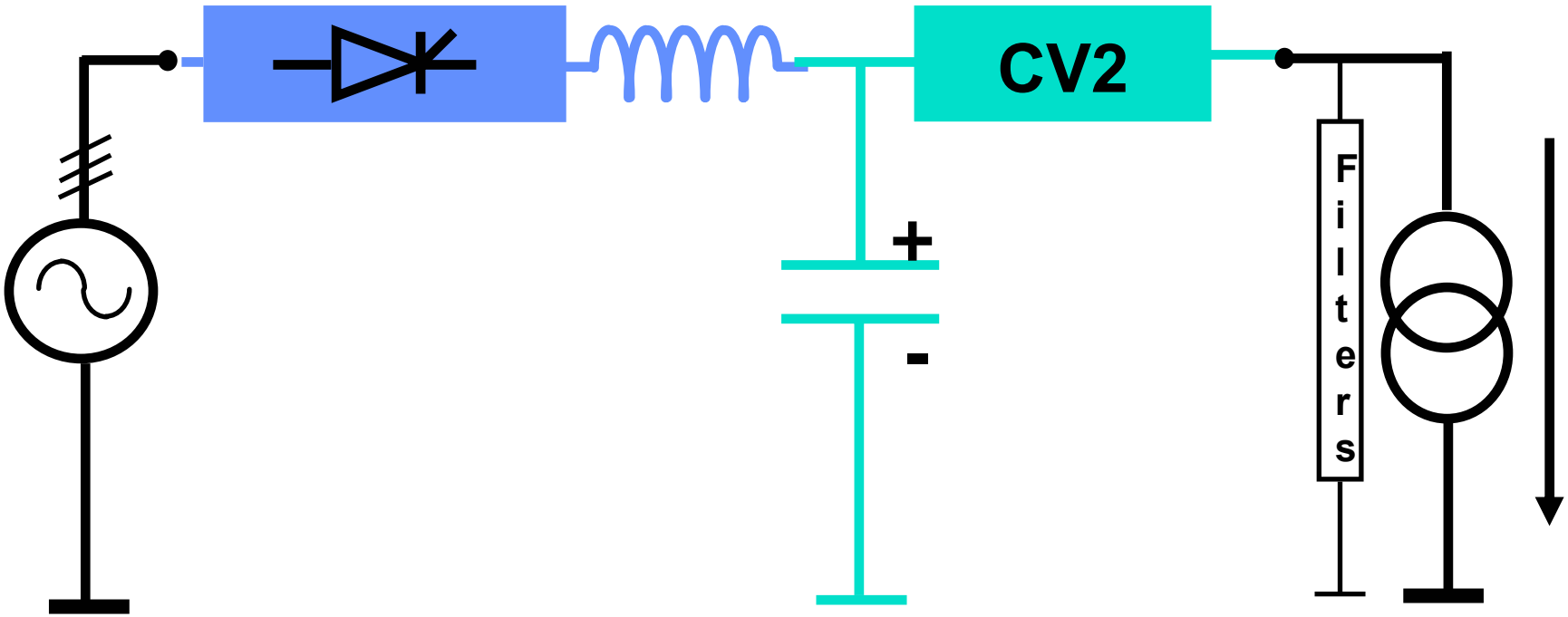
Indirect Converters : AC link

An AC link (with high frequency stage) leads to complex structures; no industrial solutions



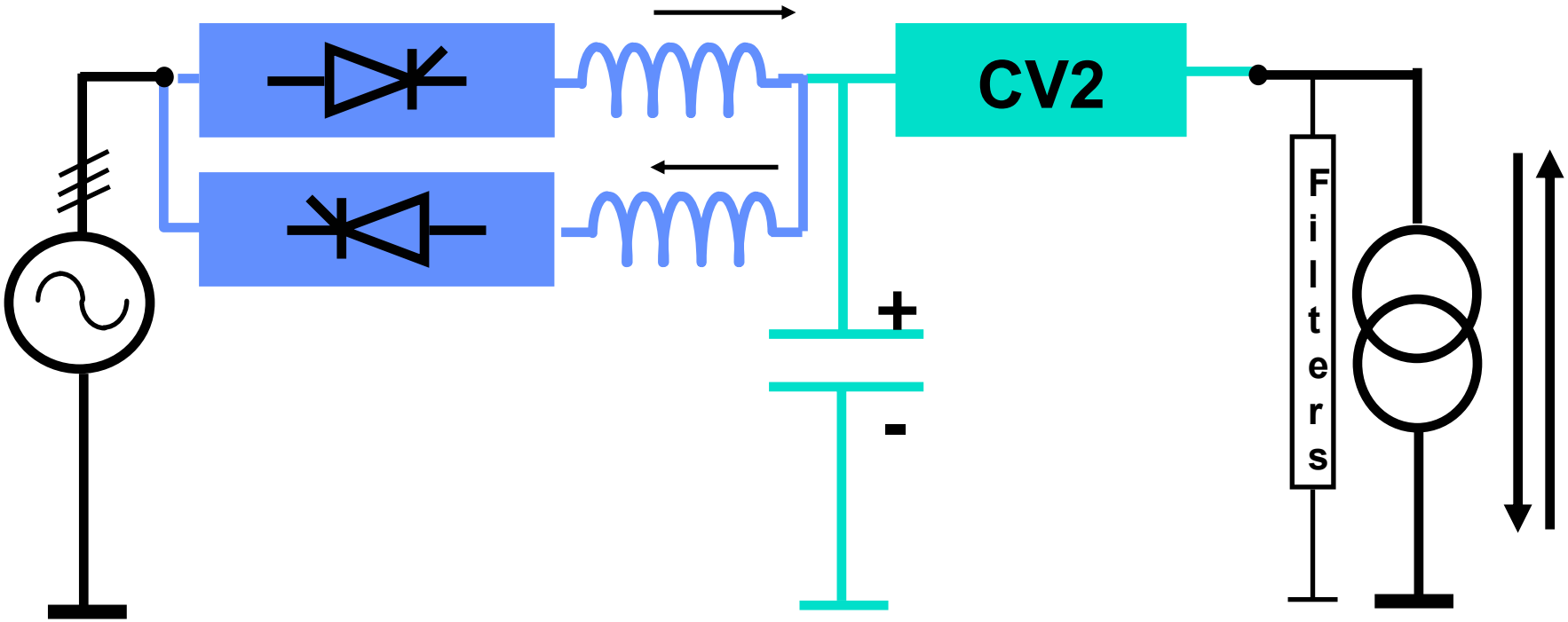
Indirect Converters : DC link

Input Converter : AC / DC



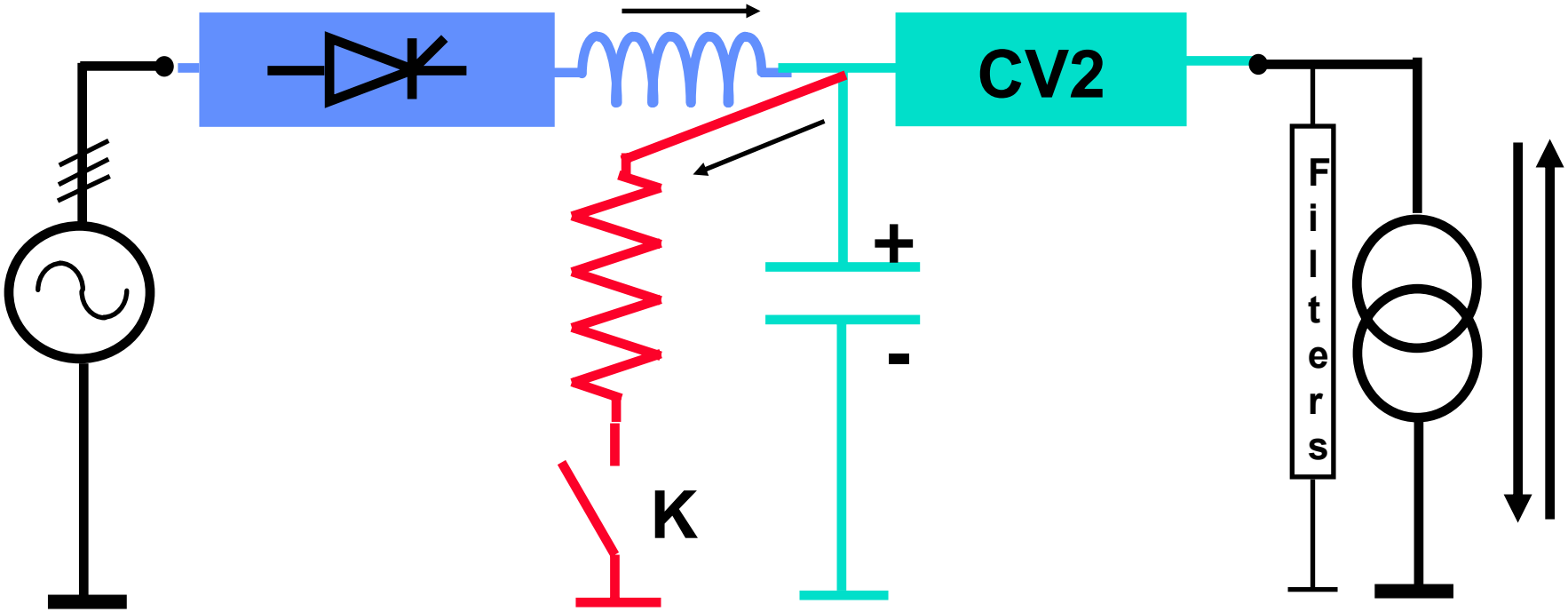
Indirect Converters : DC link

Input Converter : AC / DC



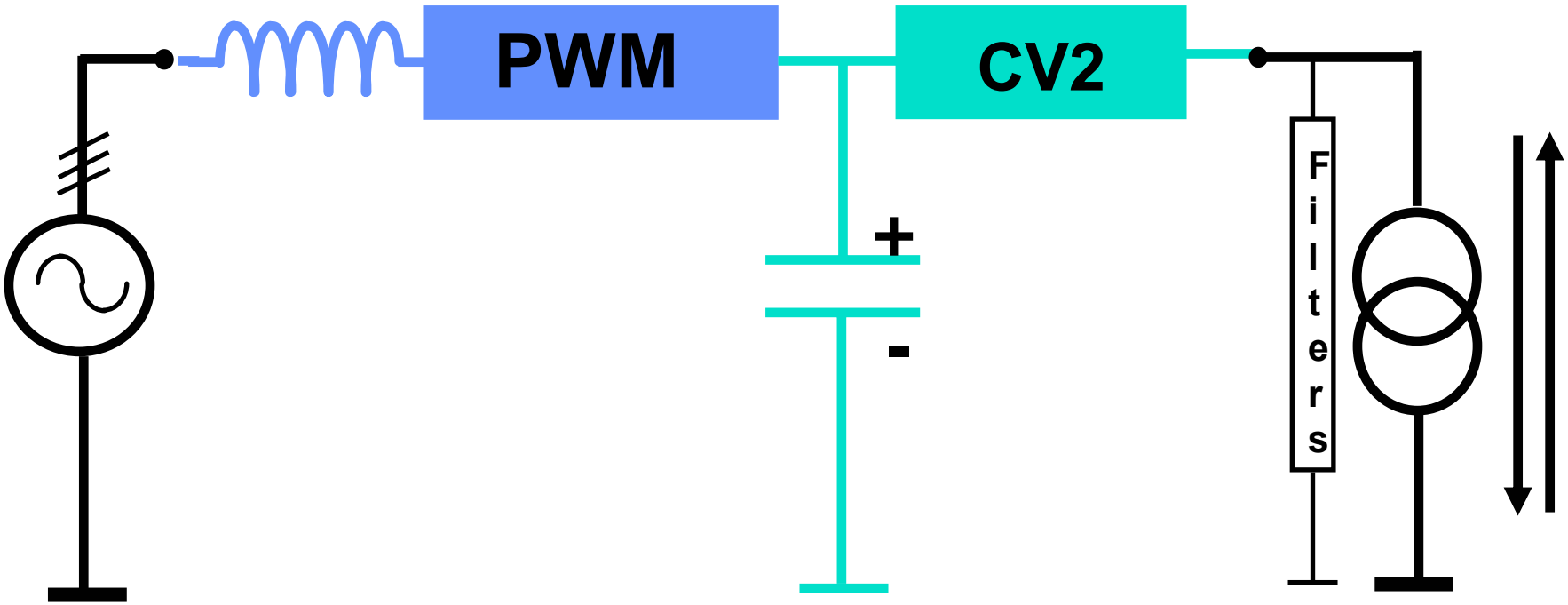
Indirect Converters : DC link

Input Converter : AC / DC

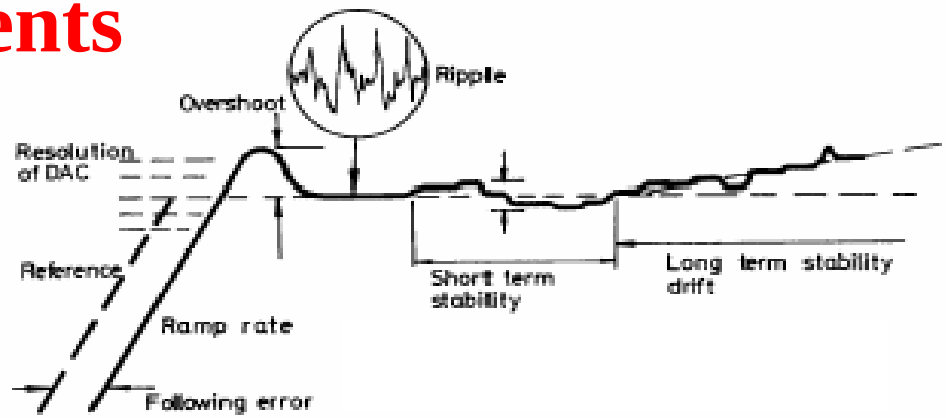


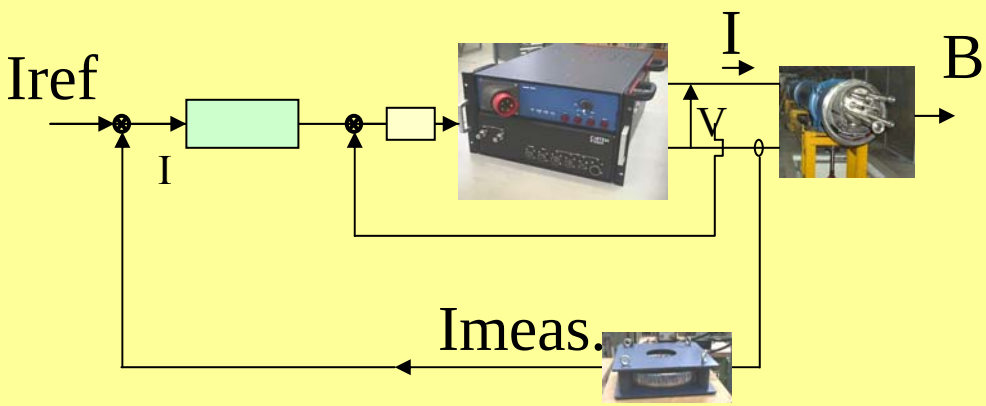
Indirect Converters : DC link

Input Converter : AC / DC



Power converter
Performance requirements





Accuracy **Reproducibility** **Stability**

Resolution

Overshoot

Bandwidth

?

In general, accelerator designers are not power converter experts and vice versa.

Interface is the list of ***power converter specifications.***

The apparent belief on one side that anything is possible and the impression on the other side that the specification have been chosen at random, sometimes leads to rather cynical feelings such as

- **if in doubt, ask an extra order of magnitude, there is never a problem**

or

- **whatever it is, or however it is calculated, 1 in 10^3 will be good enough in the end**

Some definitions

✔ **PPM** : Part Per Million = $10^{-6} = 2^{-20}$ (20 bits)

✔ **Nominal value (e.g. $I_{Nominal}$)** : Normal maximum value (it 's a choice)

✔ **ppm of nominal** : e.g 10^{-6} x $I_{Nominal}$ (Amp)

Example :

For $I_{Nominal}$ = 13 kA, 1 ppm of nominal = 13 mA

For $I_{Nominal}$ = 600 A, 10 ppm of nominal = 0.6 mA

For $I_{Nominal}$ = 60 A, 10 ppm of nominal = 60 µA

100 years = 36’625 days = 876’600 hours = 52’596’000 minutes

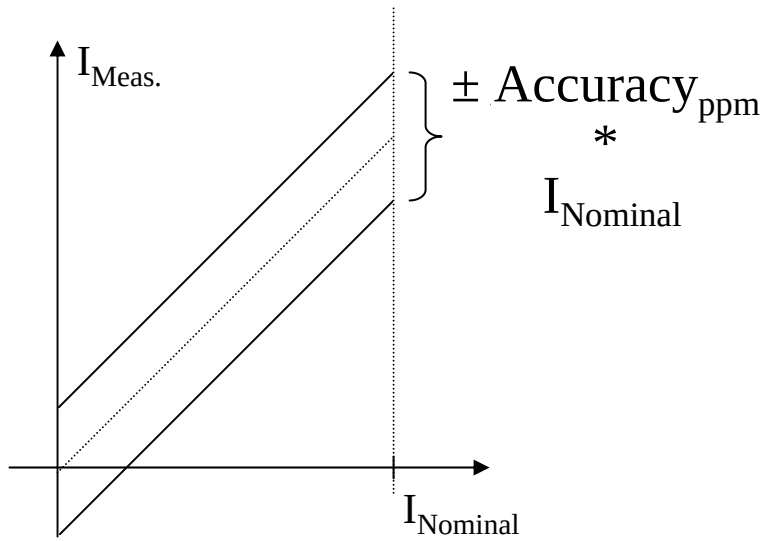
1 ppm of your life = 52 minutes

You support me (today) only 2.3 ppm of our life

Accuracy

Long term setting or measuring uncertainty taking into consideration the full range of permissible changes* of operating and environmental conditions.

***requires definition :**
(e.g. Electrical distribution system perturbation, temperature variation,…)

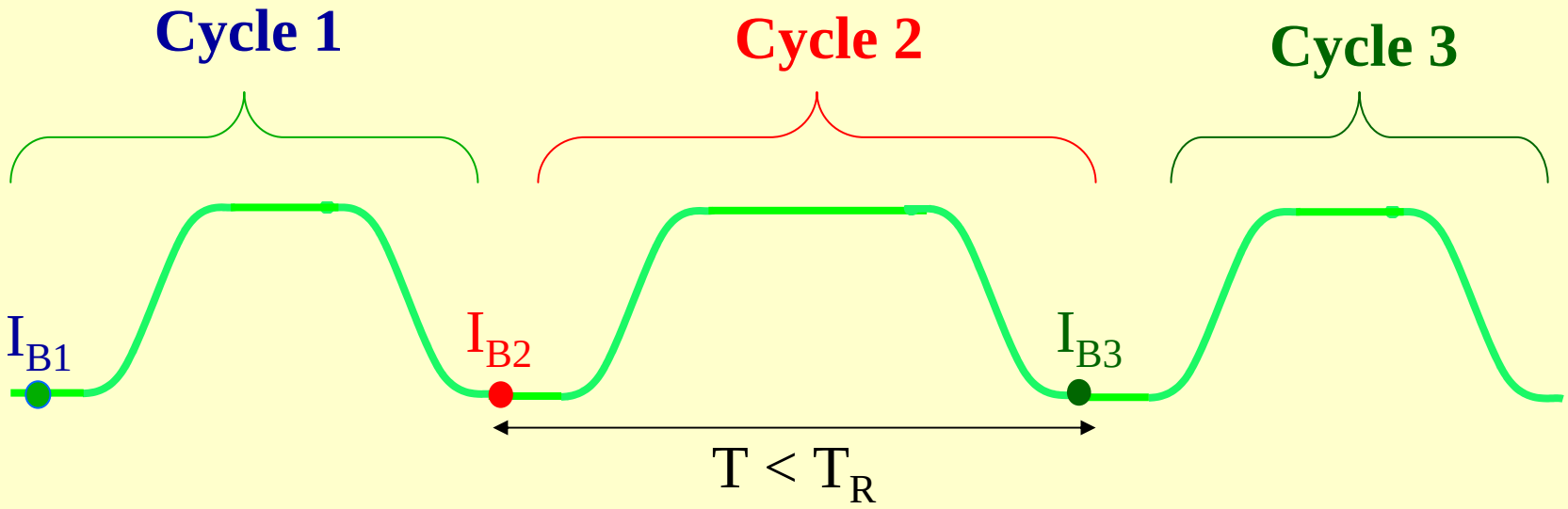


The accuracy is defined by default for a defined period (Ta)
(e.g. one year)
The accuracy is expressed in ppm of $I_{Nominal}$.
If the defined period (Ta) is too large, a calibration process should be executed more often (e.g every month)

Reproducibility

Uncertainty in returning to a set of previous working values from cycle to cycle of the machine.

The reproducibility is defined by default for a period of time T_R without any intervention affecting the calibrated parts (e.g. DCCT, ADC)
The reproducibility is expressed in ppm of $I_{Nominal}$.

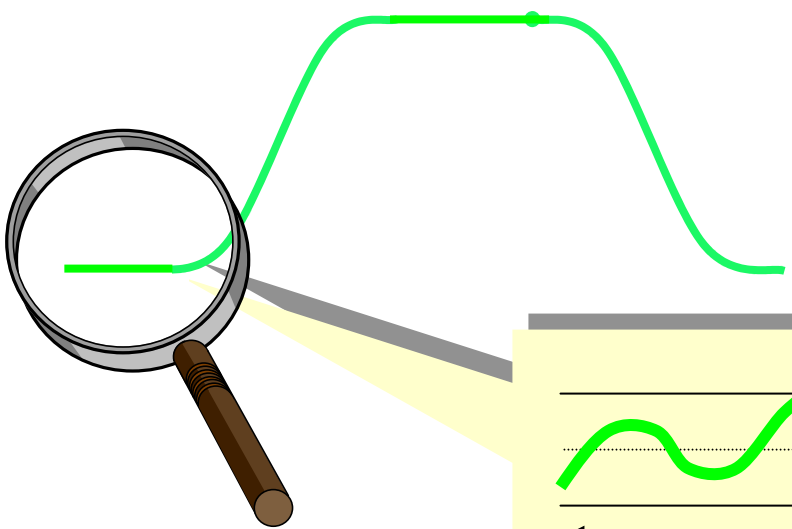


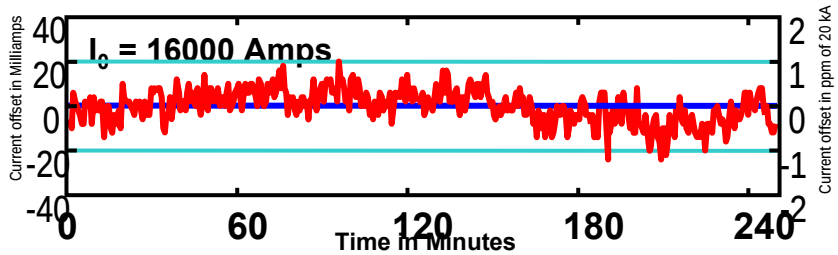
$$I_{B2} = I_{B1} \pm (\text{Reproducibility}_{pmm} \cdot I_{nominal})$$
$$I_{B3} = I_{B2} \pm (\text{Reproducibility}_{pmm} \cdot I_{nominal})$$

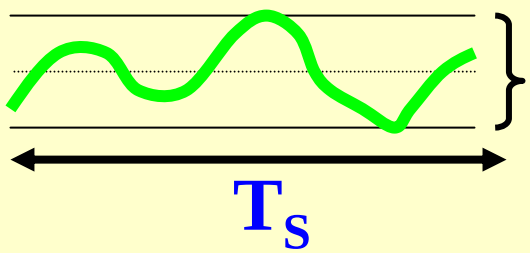
Stability

Maximum deviation over a period with no changes in operating conditions.

The stability is defined by default for a period of time T_S (typically ½ hour)
The stability is expressed in ppm of $I_{Nominal}$.







$$\pm \text{Stability}_{ppm} \cdot I_{Nominal}$$

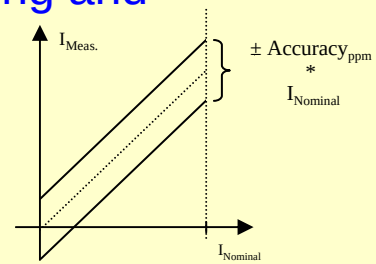
Glossary

Precision

– Accuracy

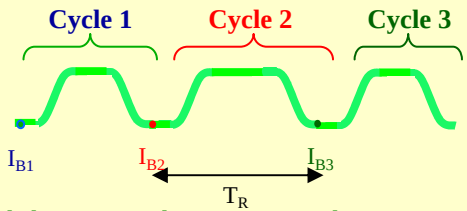
Long term setting or measuring uncertainty taking into consideration the full range of permissible changes* of operating and environmental conditions.

* requires definition



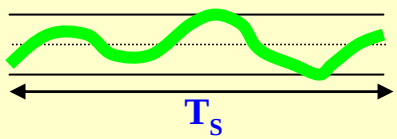
– Reproducibility

Uncertainty in returning to a set of previous working values from cycle to cycle of the machine.



– Stability

Maximum deviation over a period with no changes in operating conditions.



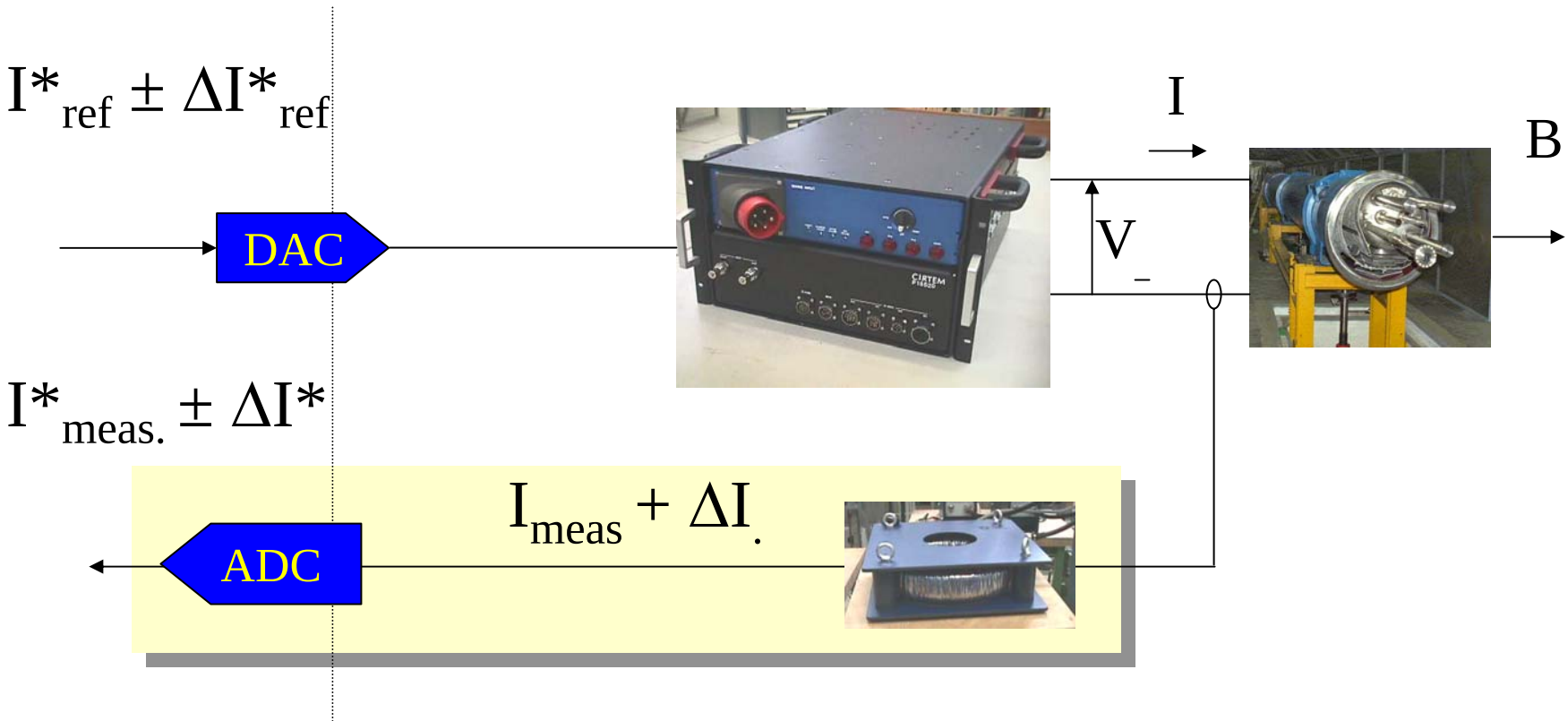
Accuracy, reproducibility and stability are defined for a given period

Precision is qualitative . Accuracy is quantitative.

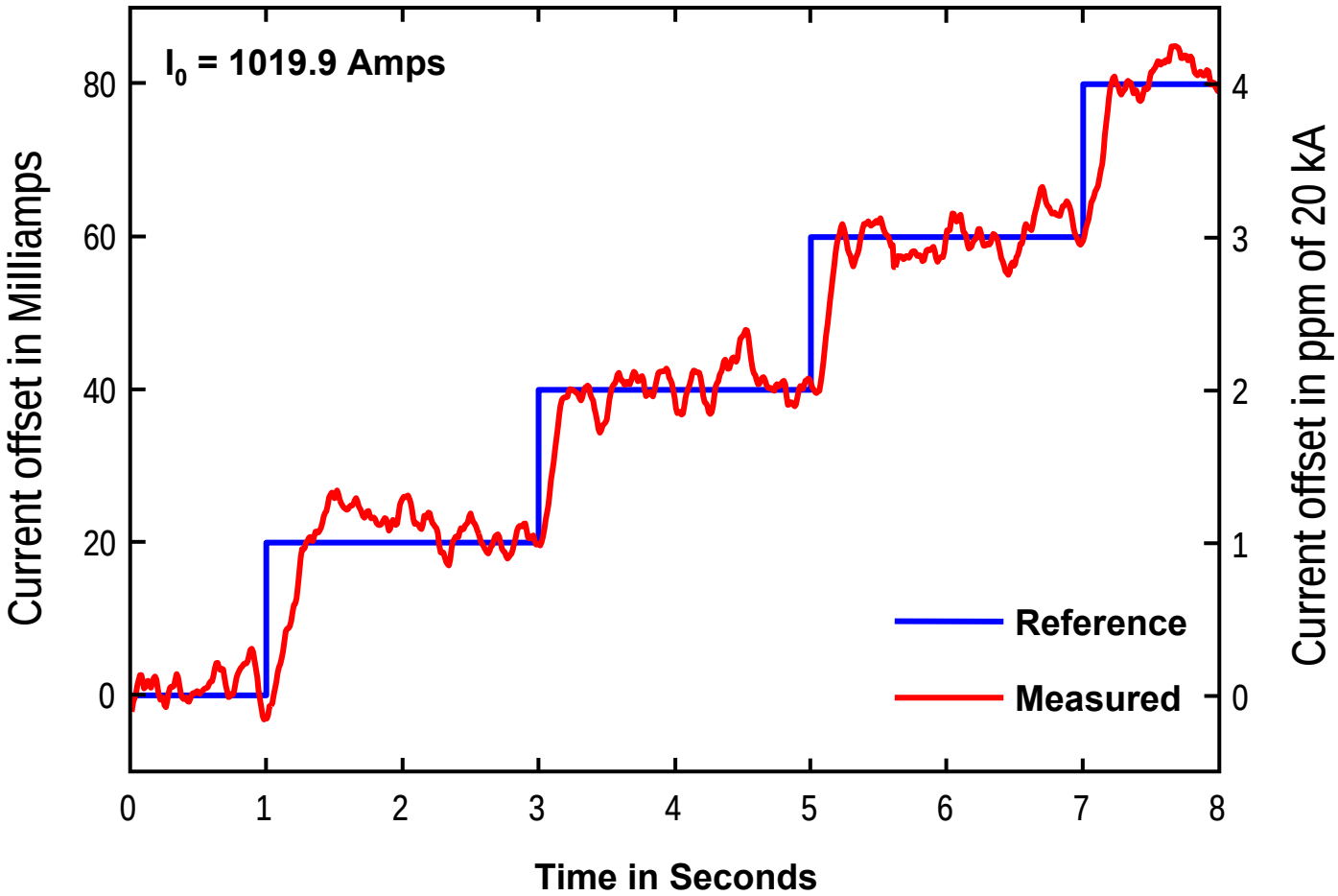
Resolution

Smallest increment that can be induced or discerned.

The resolution is expressed in ppm of $I_{Nominal}$.
Resolution is directly linked to A/D system



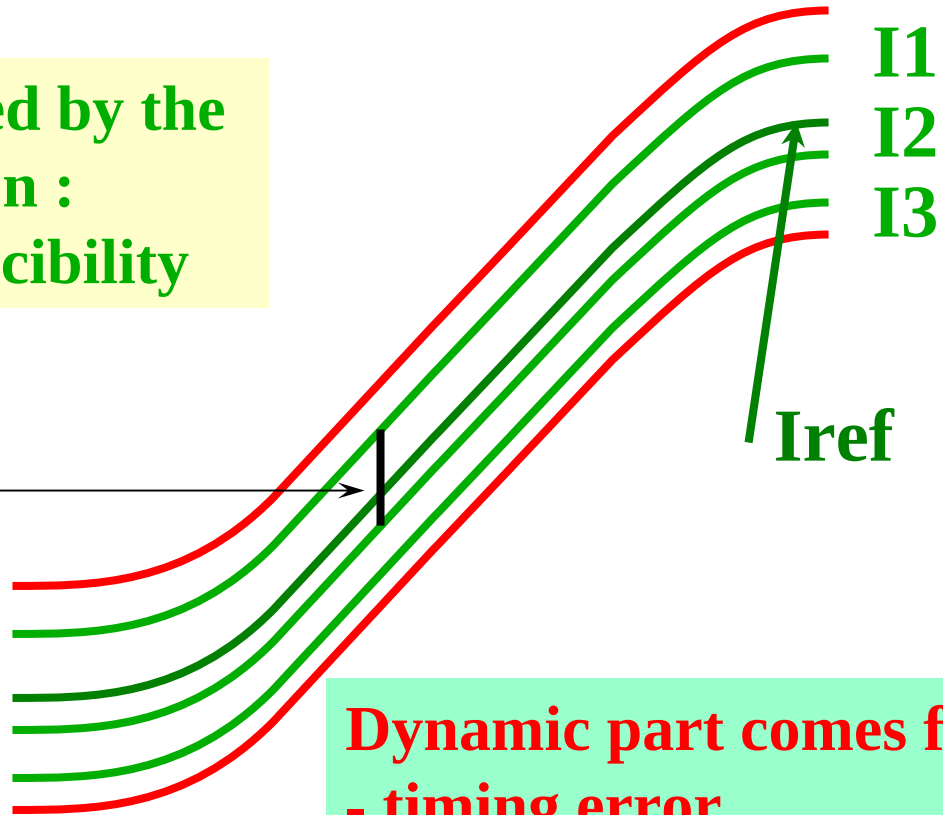
Results of Resolution Test with the LHC Prototype Digital Controller



Tracking

Ability of the converterS to follow the reference function (static, dynamics)

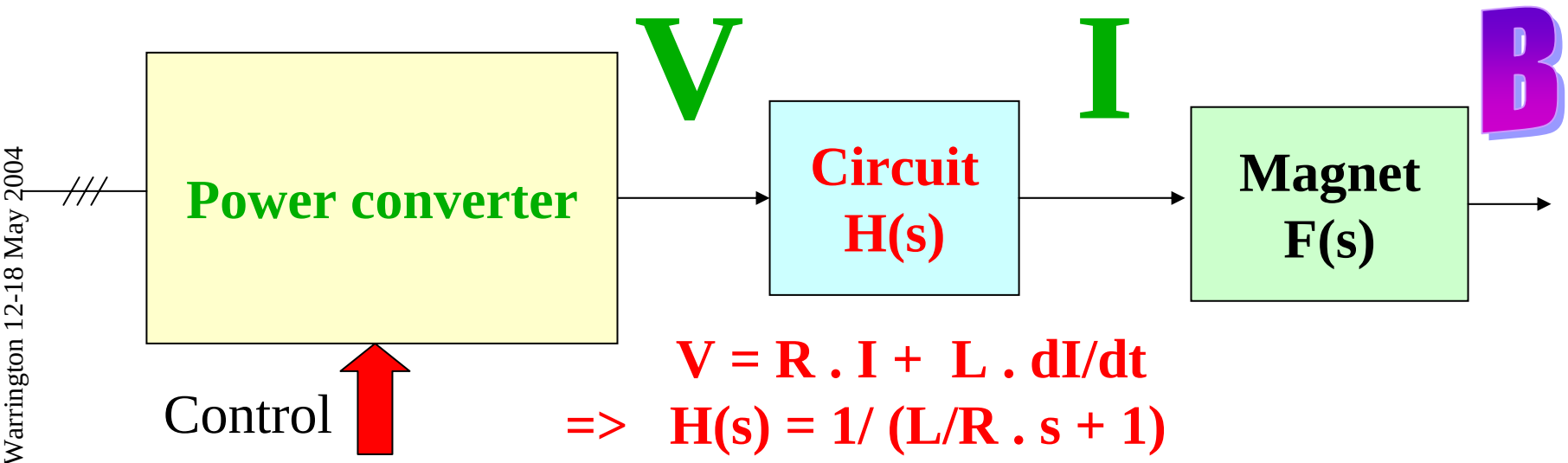
Static part is covered by the static definition : accuracy, reproducibility



Tracking error between I1 and I2

Dynamic part comes from :
- timing error
- lagging error in the regulation

RIPPLE



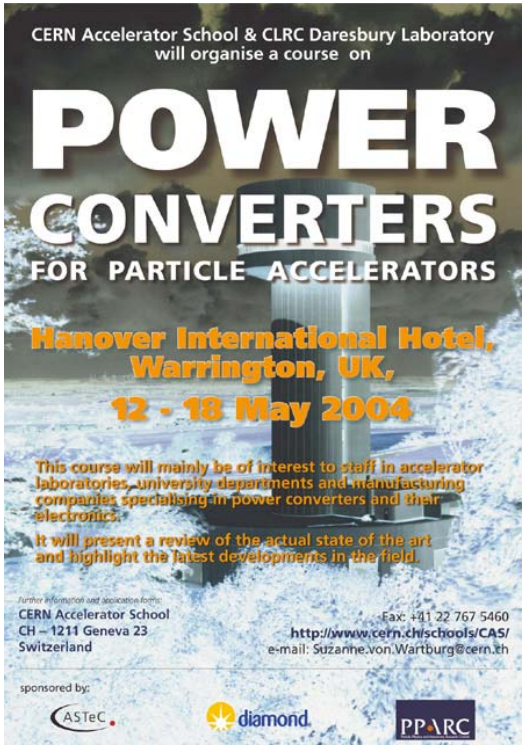
Voltage ripple is defined by the power converter

Current ripple : load transfer function

(cables, magnet inductance,…)

(good identification is required if the load is a long string of magnets)

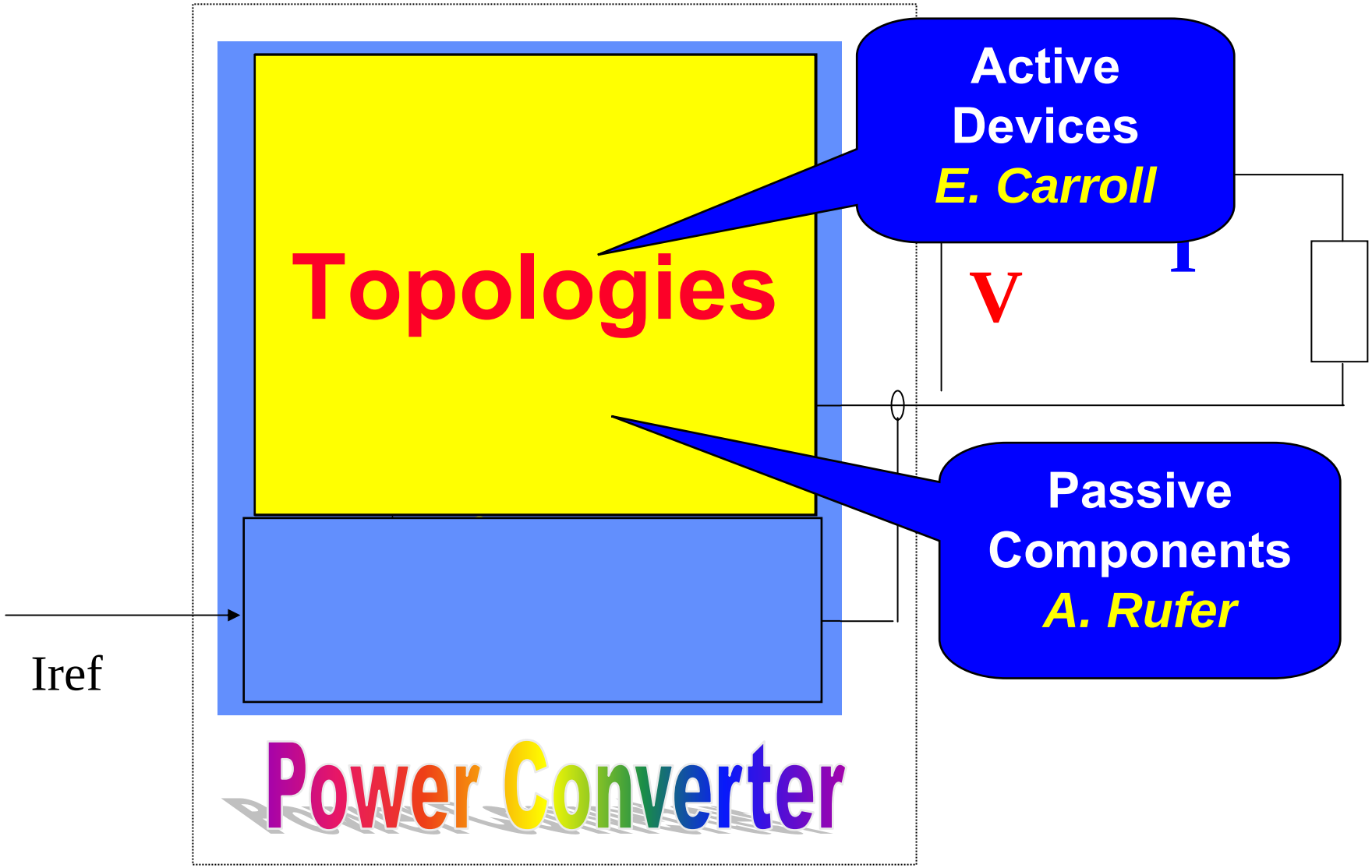
Field ripple : magnet transfer function (vacuum chamber,…)

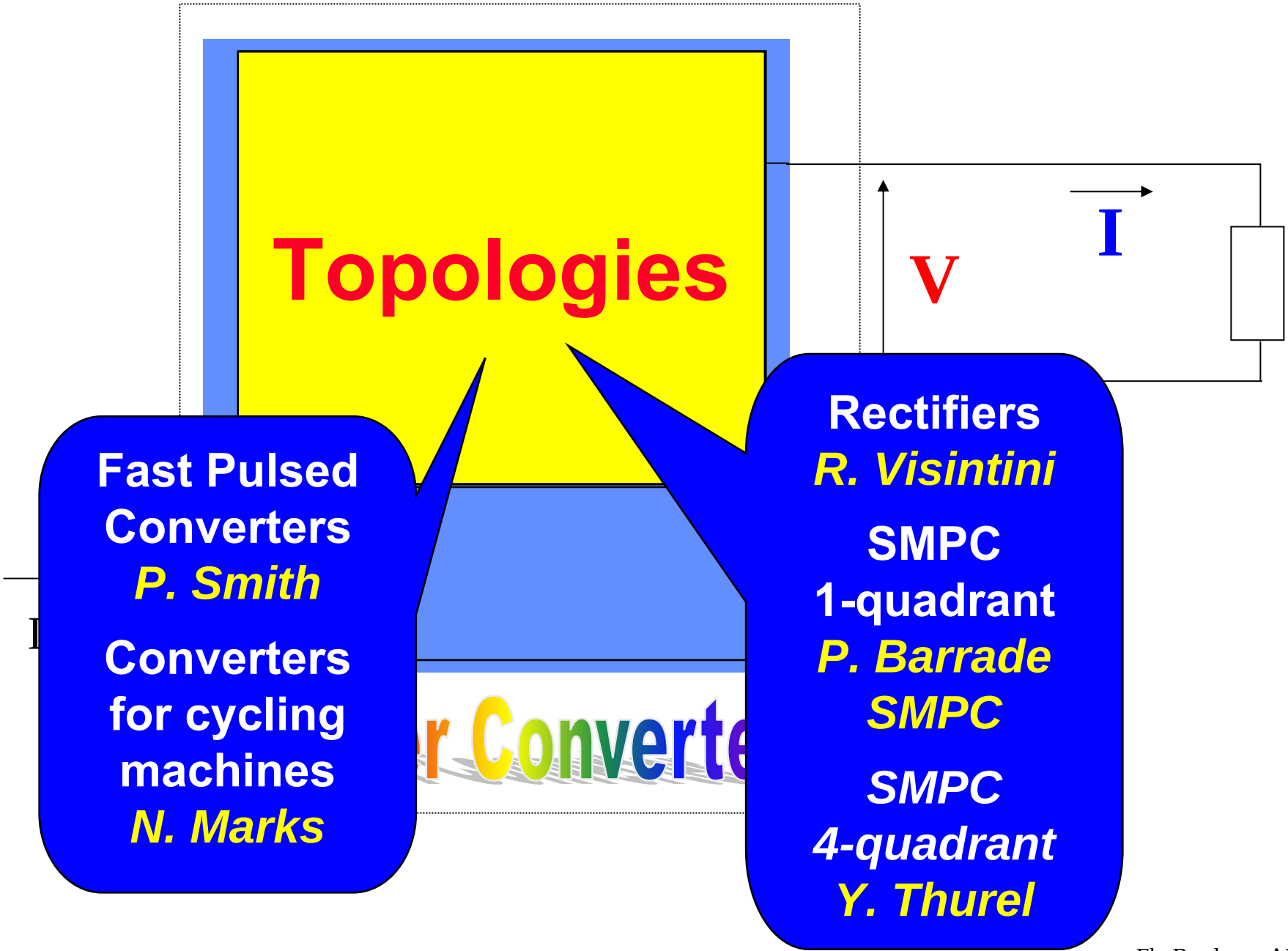


Program construction

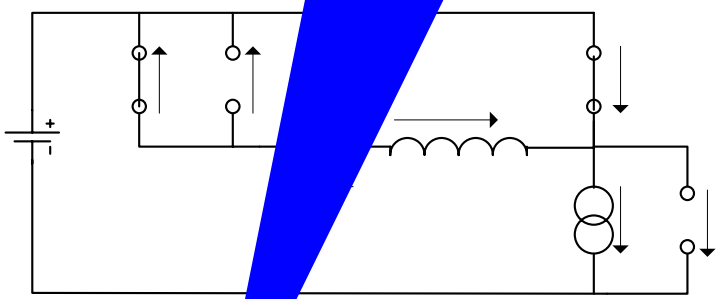
POWER CONVERTERS FOR PARTICLE ACCELERATORS,
Hanover International Hotel, Warrington, 12-18 May 2004

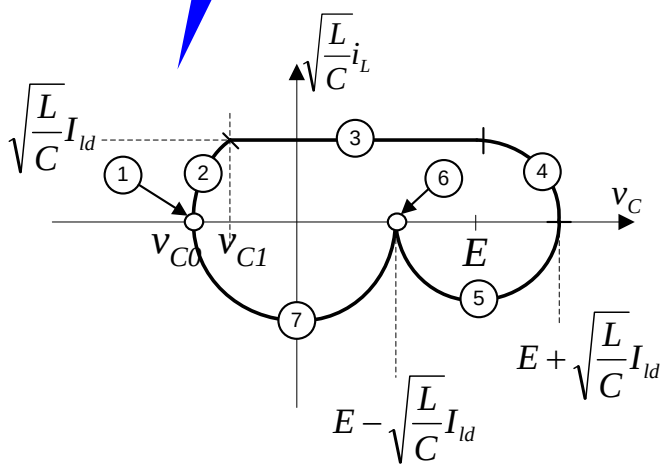
Time	Wednesday 12 May	Thursday 13 May	Friday 14 May	Saturday 15 May	Sunday 16 May	Monday 17 May	Tuesday 18 May
08 :30	Opening Remarks	Passive Components	**DAY AT DARESBURY** Fast Pulsed Converters I		Converters for Cycling Machines II	Protection, Interlocks and Diagnostics	Challenges for The Future
09 :30		A. Rufer	P. Smith		N. Marks	S. Griffiths	N. Marks
09:30	Accelerator Basics	Systematical Analysis	Fast Pulsed Converters II		Regulation Theory	EMC	Discussion on Challenges
10:30	D. Brandt	C. De Almeida Martins	P. Smith		F. Bordry	A. Charroy	F. Bordry
	COFFEE			E	**COFFEE**		
11:00	Power Converters and Accelerators	Rectifiers	Converters for Cycling Machines I	X	High Precision Measurements	Electrical Network and Power Converters	Closing Remarks
12:00	N. Marks	R. Visintini	N. Marks	C	G. Fernqvist	H.-U. Boksberger	
	LUNCH		**LUNCH**	U		**LUNCH**	
14:00	Power Converters Definitions & Classifications I	Switched Mode Converters (1 Quadrant)	L	R	DAC-ADC	Simulation Tools	BUSES TO AIRPORT
15:00	F. Bordry	P. Barrade	A	S	J. Pickering	P. Jenni	
15:00	Power Converters Definitions & Classifications II	Switched Mode Converters (4 Quadrants)	B	I	Controls and Interfaces	Demo	
16:00	F. Bordry	Y. Thurel	V	O	Q. King	P. Jenni	
	TEA		I	N	TEA		
16:30	Active Devices	**Seminar**	S		**Seminar**	**Seminar**	
17:30	E. Carroll		I T				
17:30 18:30	TIME FOR DISCUSSIONS				TIME FOR DISCUSSIONS		
18:30 20:00	**RECEPTION DINNER**	**DINNER**	**DINNER**	**DINNER**	**DINNER**	**BANQUET**	

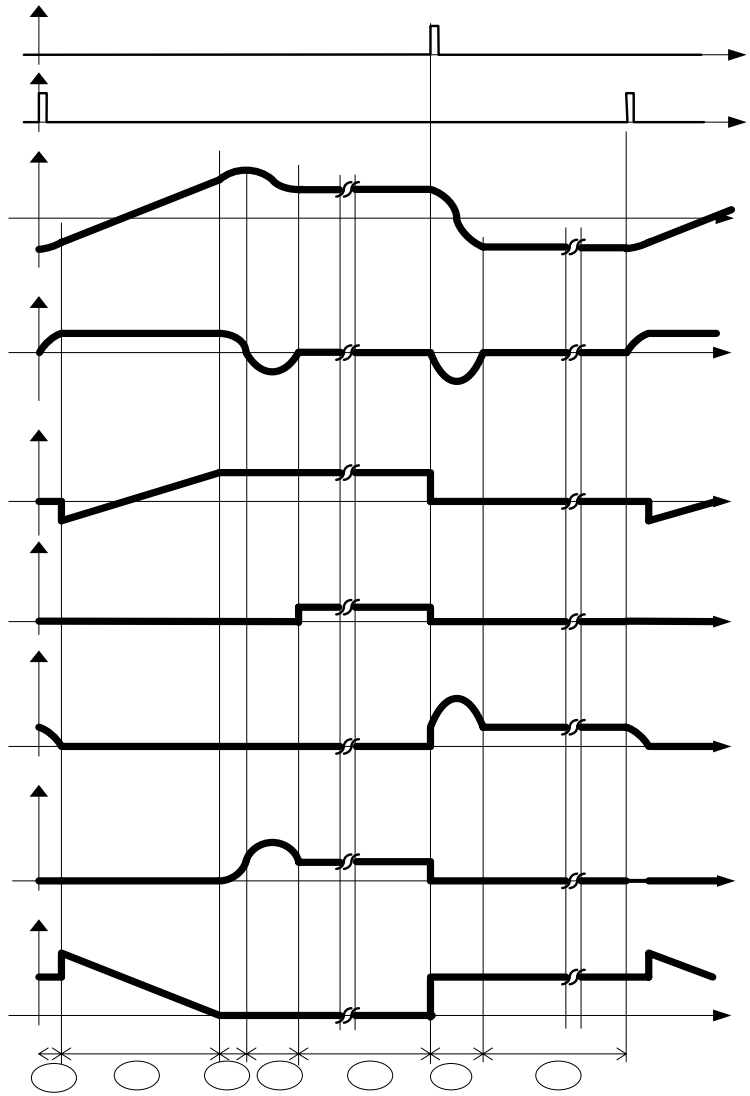

Topologies
Active Devices
E. Carroll
I
V
Passive Components
A. Rufer
Iref
Power Converter

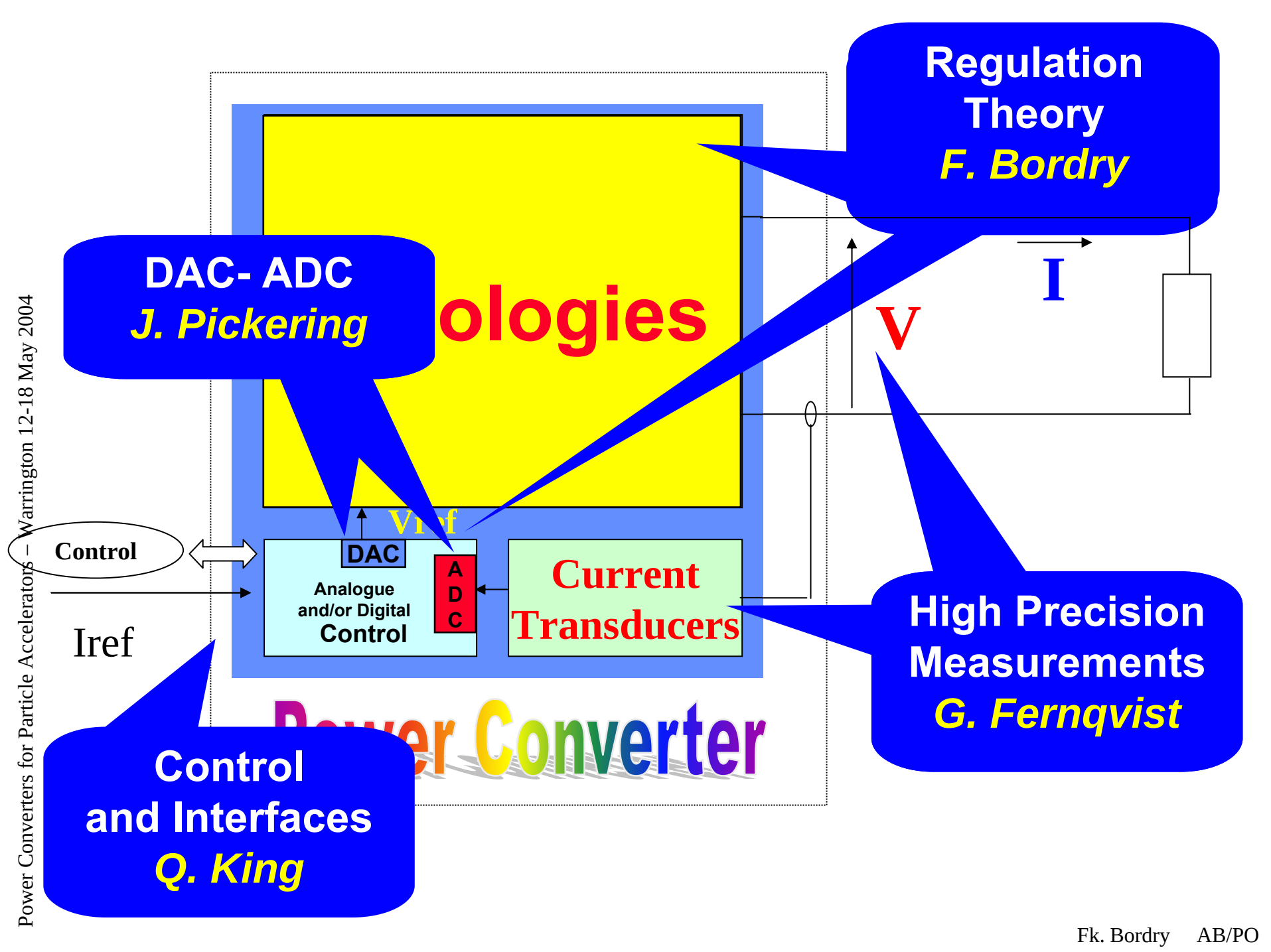

Topologies
V
I
Fast Pulsed Converters
P. Smith
Converters for cycling machines
N. Marks
Rectifiers
R. Visintini
SMPC 1-quadrant
P. Barrade
SMPC
SMPC 4-quadrant
Y. Thurel

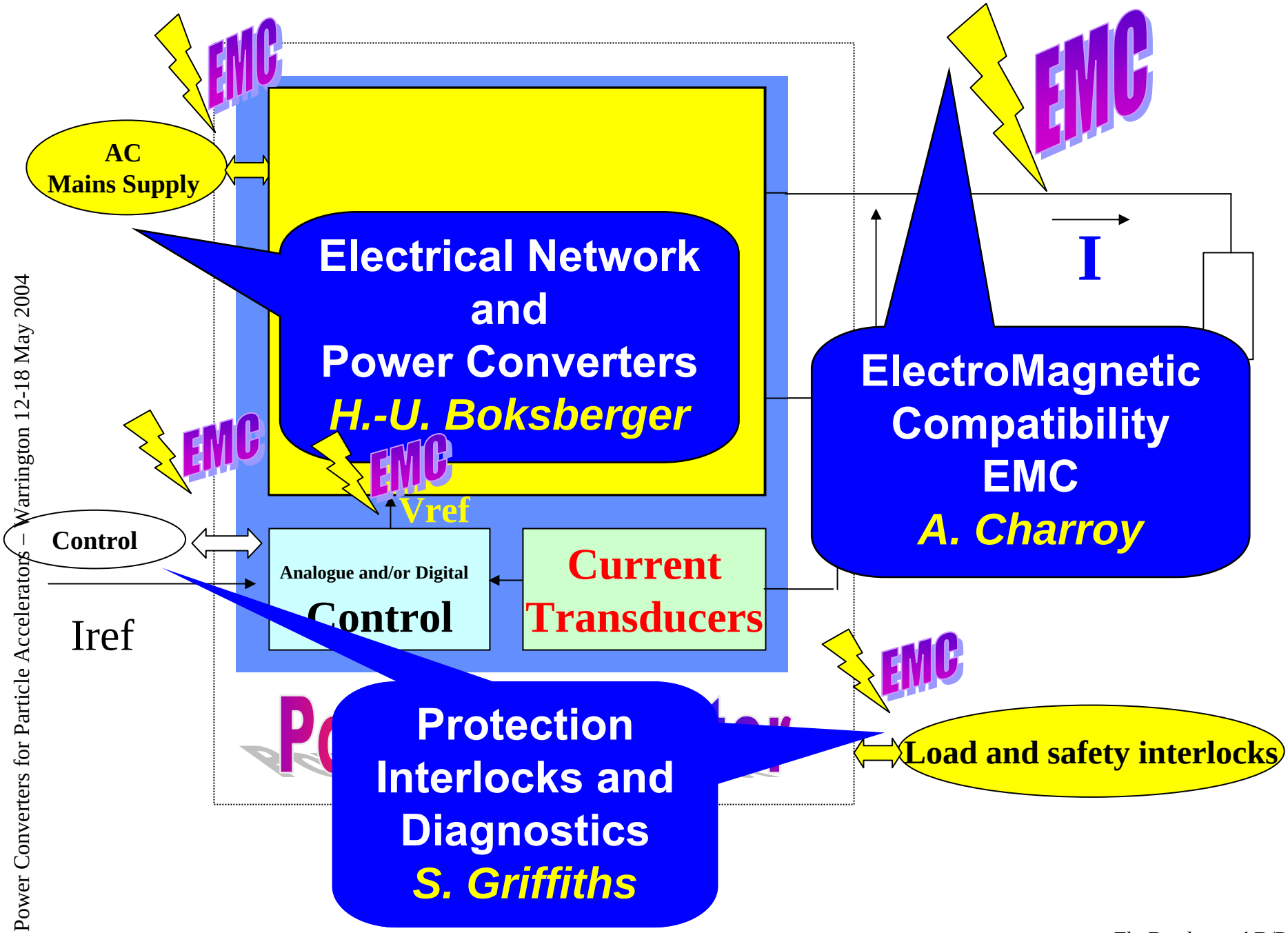
Systematical Analysis
C. De Almeida








Regulation Theory
F. Bordry
DAC- ADC
J. Pickering
ologies
I
V
Vref
Control
DAC
Analogue and/or Digital Control
ADC
Current Transducers
Iref
High Precision Measurements
G. Fernqvist
Power Converter
Control and Interfaces
Q. King


EMC
AC
Mains Supply
Electrical Network
and
Power Converters
H.-U. Boksberger
EMC
EMC
I
ElectroMagnetic
Compatibility
EMC
A. Charroy
Vref
Control
Analogue and/or Digital
Control
Current
Transducers
Iref
EMC
Protection
Interlocks and
Diagnostics
S. Griffiths
Load and safety interlocks

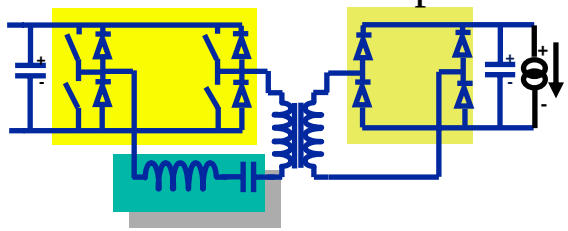
Pre-Processor : more and more user-friendly

Netlist

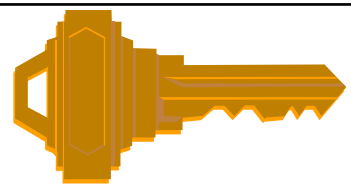
```
Vin 1 0 pwl(0.0 .1m,1 5m,1 5.1m,0)
R1 1 2 1350
C1 5 0 3.528uF
.....
```

and/or

Schematic input



Simulation Program :



Reliability, robustness, numerical errors

accu

Loca

Po

Scop

Way

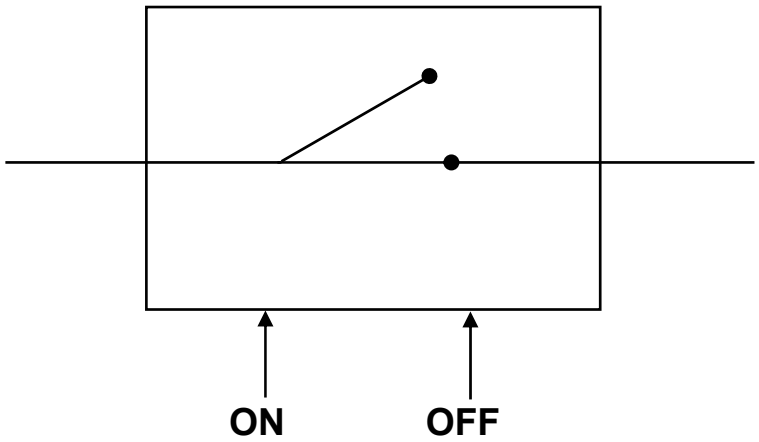
Nice

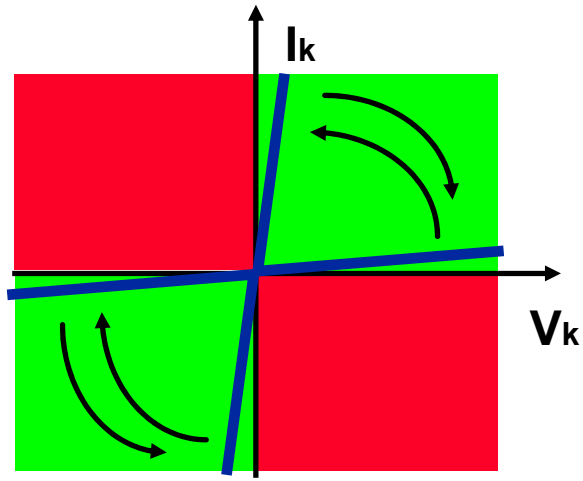
Simulations Tools

Demo

P. Jenni

I had a dream…





V_k up to 10 kV
I_k up to 1kA
In a few ns

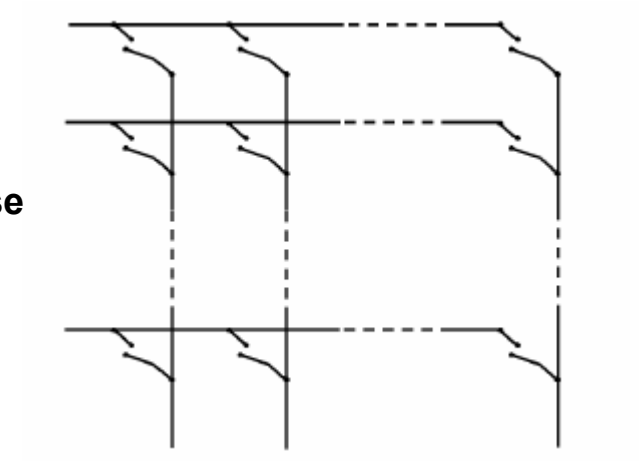
-Stress on other components (sources, capacitors, inductances…)
- high dI/dt and dVdt: stresses and EMI problem (Which driver to use ?)
- switching losses

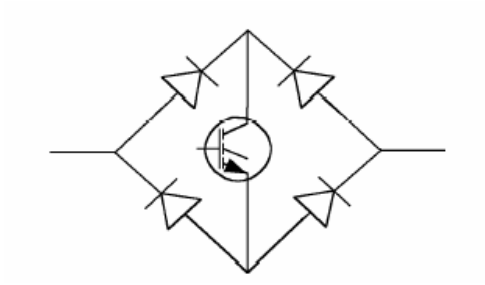
It became a nightmare…

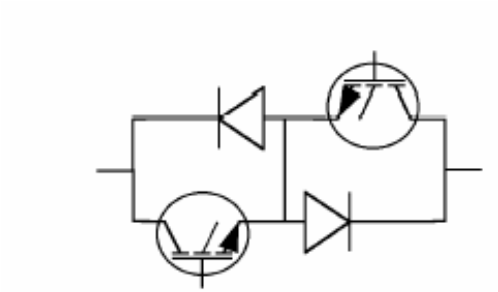
Matrix converters…

Ideally an all silicon solution for power conversion ("no need for reactive energy storage components" !!!!...)

Dream

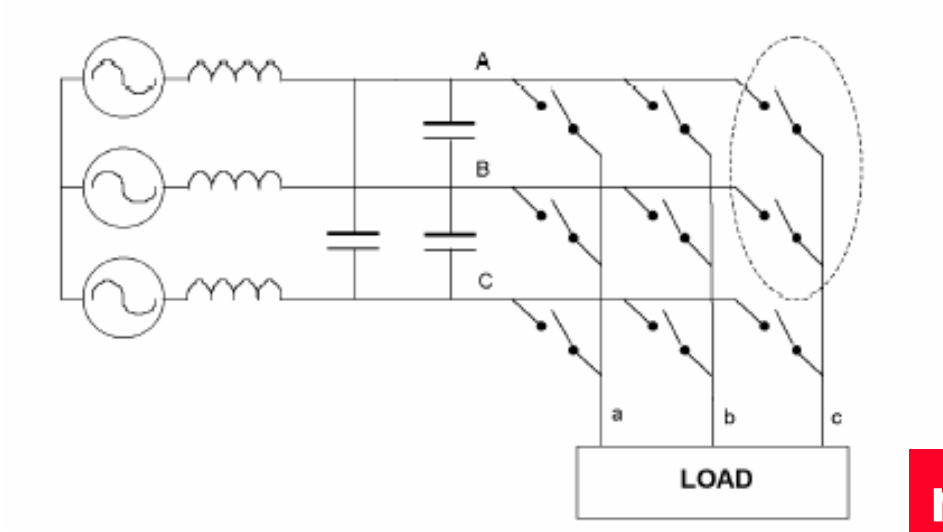






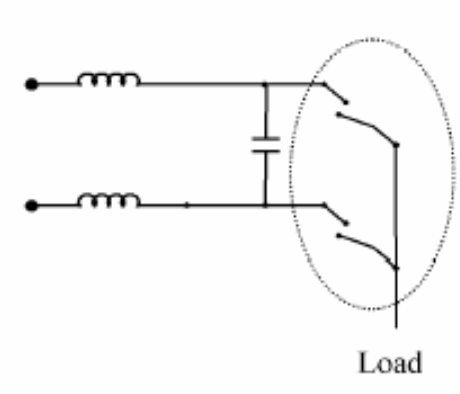
n x m bi-directional switches arranged so that any of the output lines can be connected to any of the input lines.
A line filter are necessary to circulate high frequency switching harmonics.
Switches are modulated in such a way as to generate the desired output waveform

Most current Matrix Converter researches are focussed on 3-phase to 3-phase converters: 9 bi-directional switches.

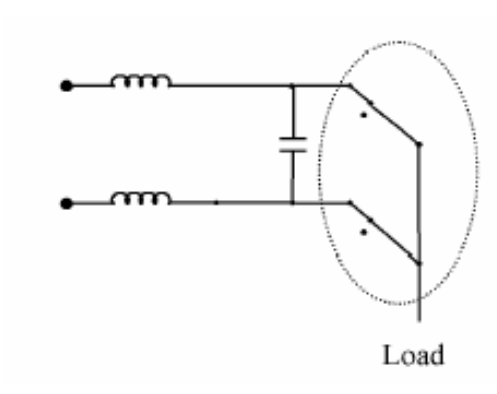


A lot of theory but ...

nightmare



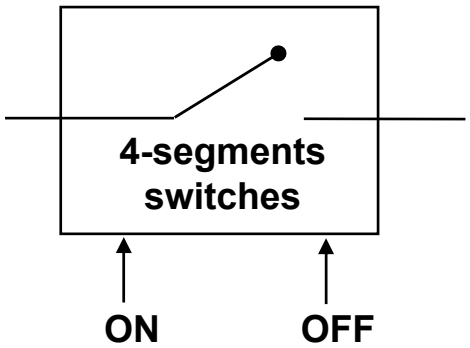
Opening of the current source



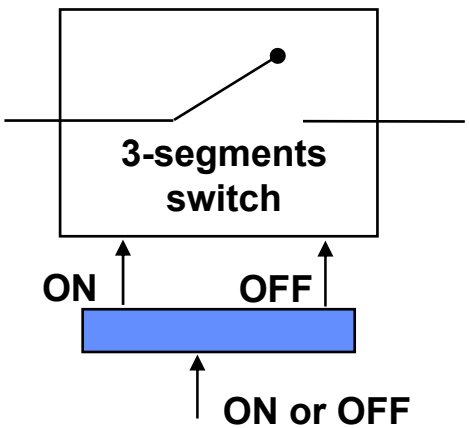
Short-circuit of the voltage source

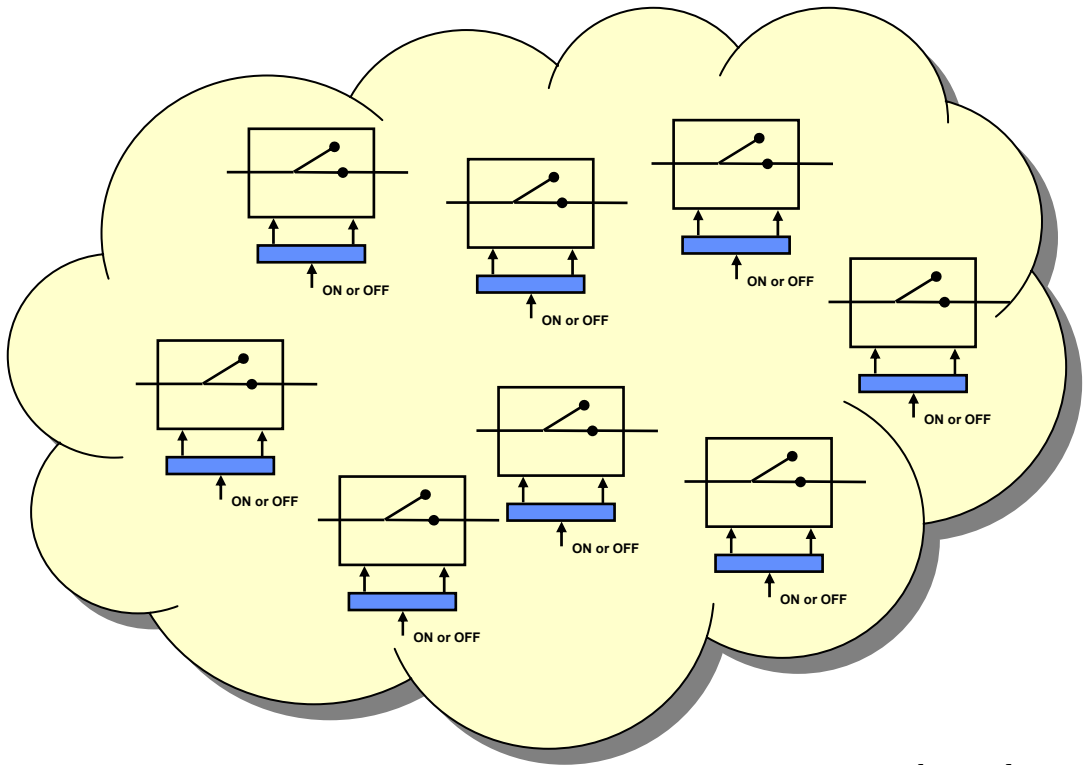
Is it not better to work at structure level ?

Instead of

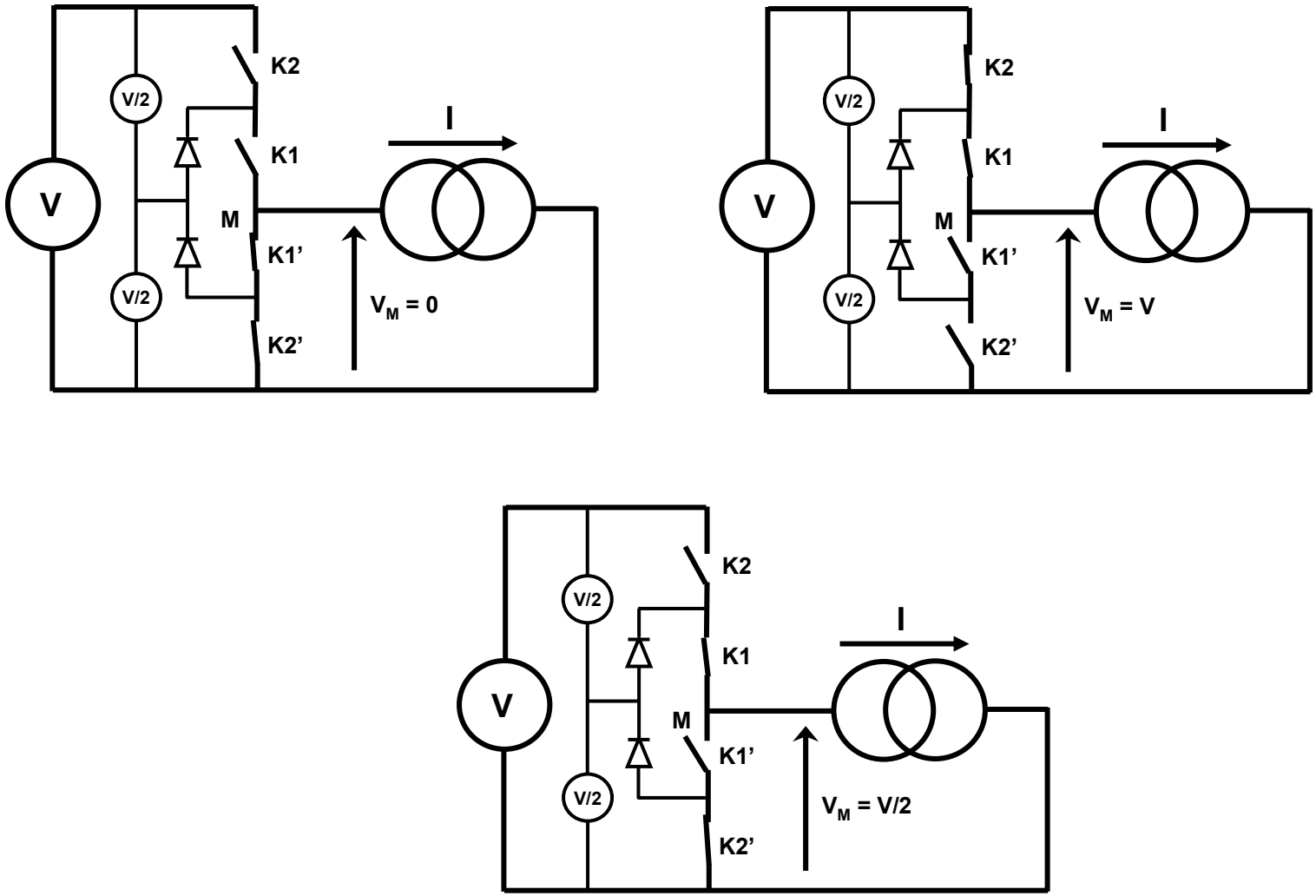


ZVS / ZCS association
Series or parallel converters
Multilevel converters
….



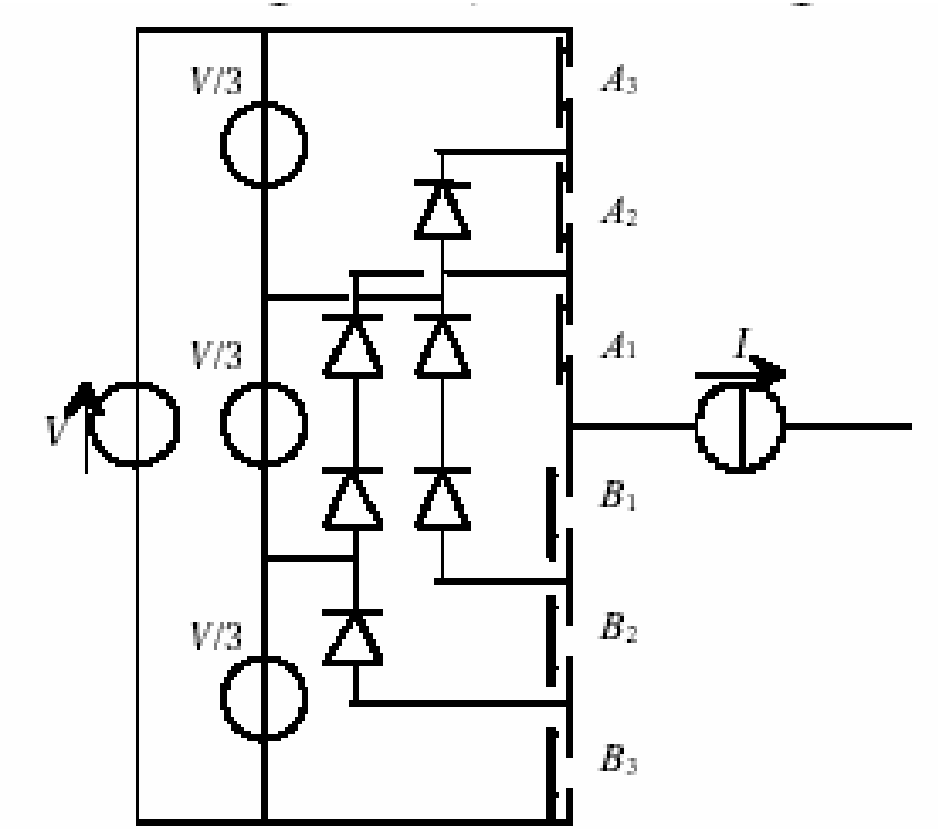


Multilevel converters: Neutral Point Clamped



Three states of "Neutral Point Clamped" commutation cell

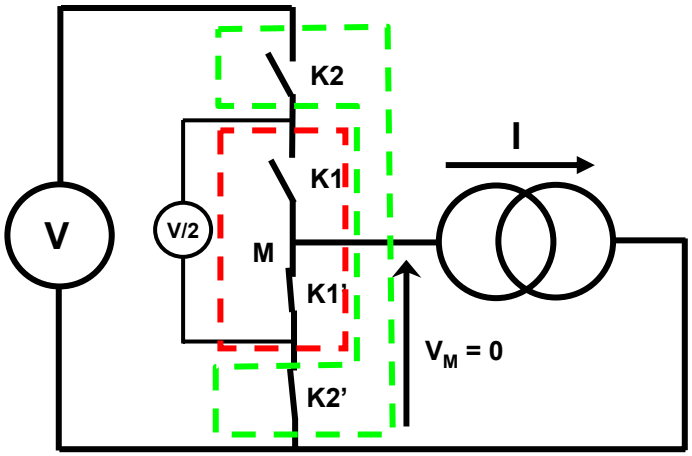
"Neutral Point Clamped“ multilevel : difficult to generalize

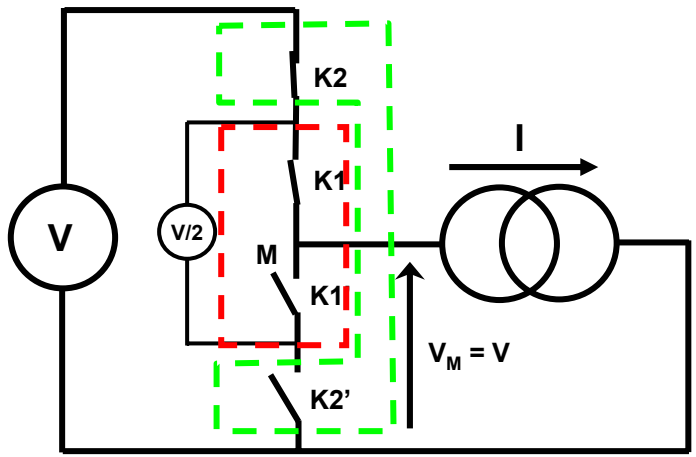


"Neutral Point Clamped" :
4-level commutation cell

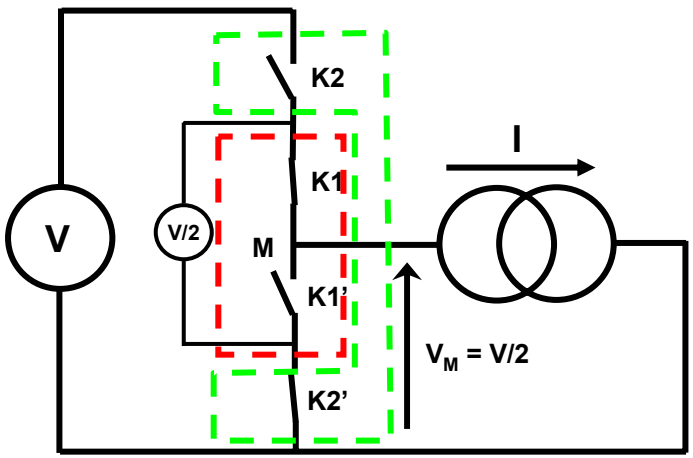
Multicell concept

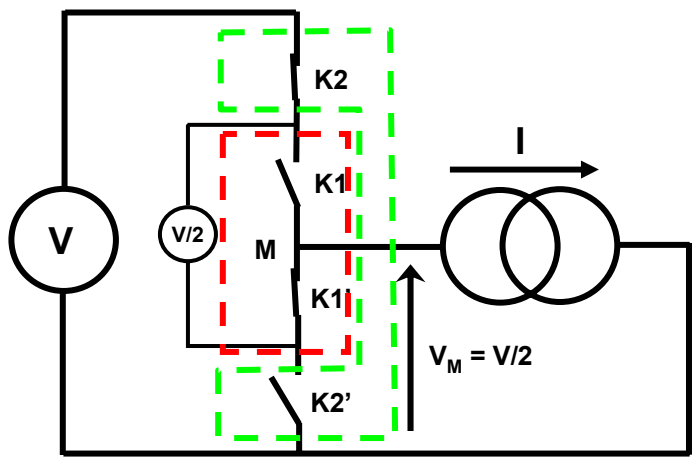
Main states of "2-cell" commutation cell





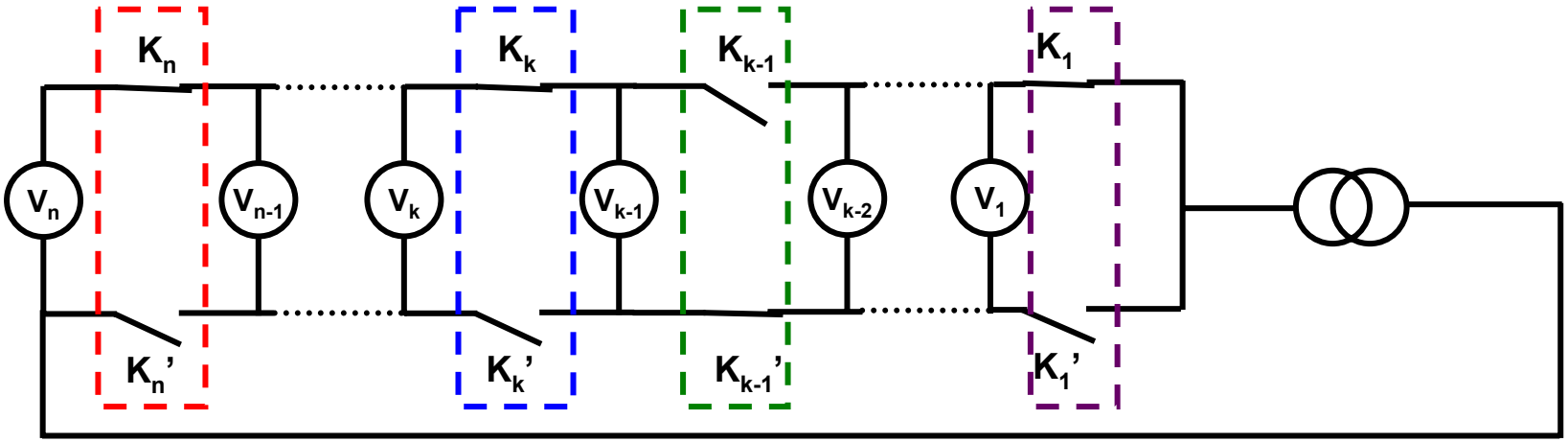
Extra states of "2-cell" commutation cell





Multicell concept : easy to generalize

n independent cells: phase shift between cells is possible

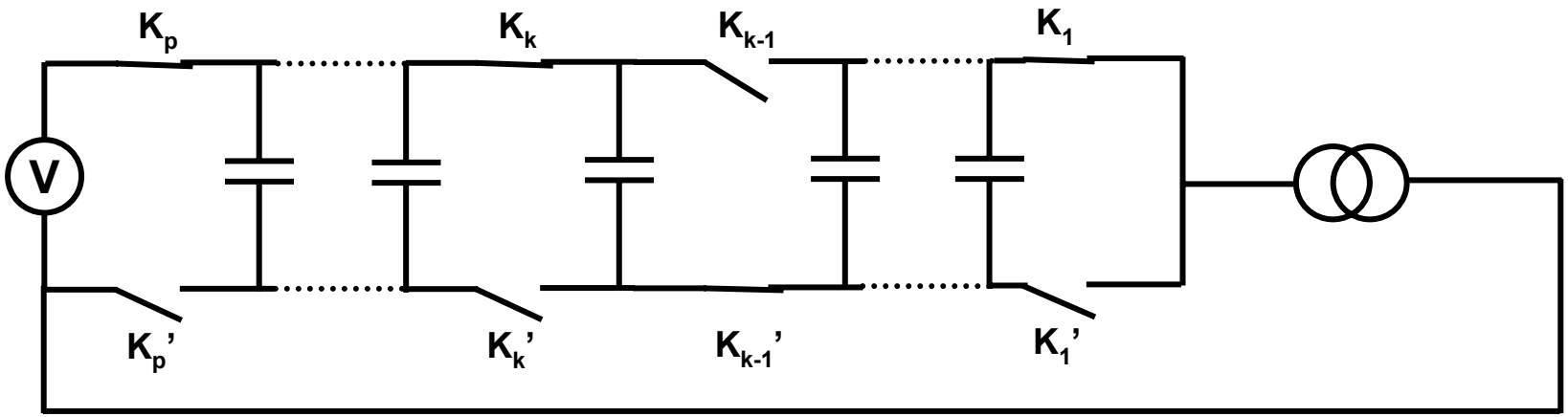


$V_n = V$;…. $V_k = k \cdot V / n$; …. ; $V_1 = V / n$

K_k off => K_k' on : $V_{Kk} = V_k - V_{k-1} = V / n$

Half of switches is ON and half is OFF

Multicell concept : Flying capacitor concept



$V_n = V$;…. $V_k = k \cdot V / n$; …. ; $V_1 = V / n$

K_k off => K_k' on : $V_{Kk} = V_k - V_{k-1} = V / n$

Half of switches is ON and half is OFF

Standard Model

Particles

Leptons

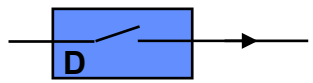
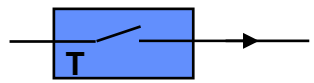
	Electric Charge		Electric Charge
Tau	-1	Tau Neutrino	0
Muon	-1	Muon Neutrino	0
Electron	-1	Electron Neutrino	0

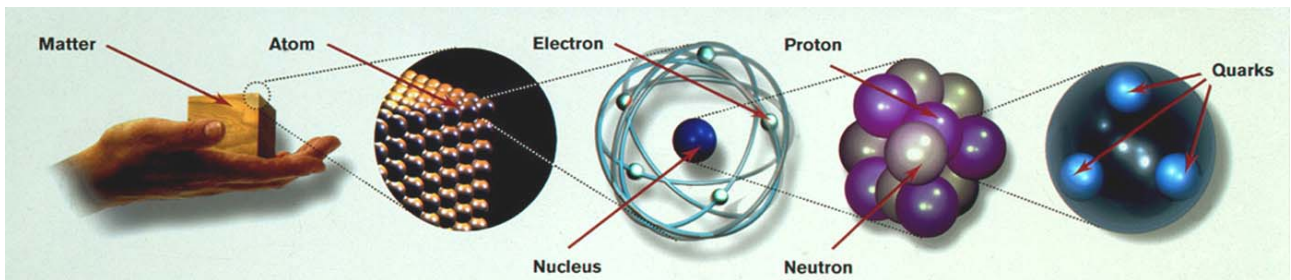
Quarks

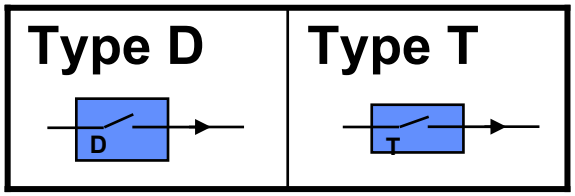
	Electric Charge		Electric Charge
Bottom	-1/3	Top	2/3
Strange	-1/3	Charm	2/3
Down	-1/3	Up	2/3

each quark: ●R, ●B, ●G 3 colors

Voltage source	**Capacitor**
Current Source	**Inductance**

Type D	Type T
	

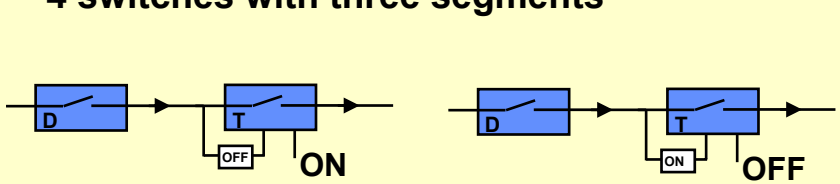




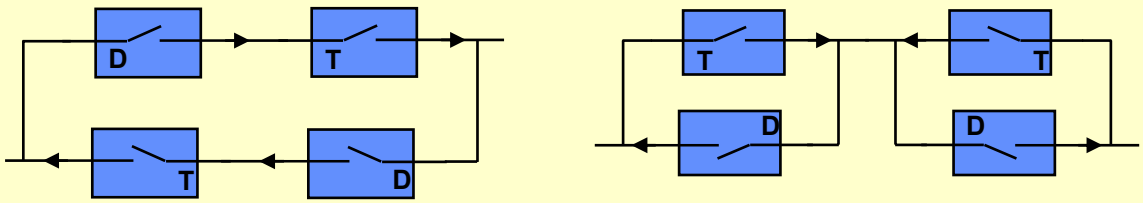
"Quark Level : D and T quarks"

" Proton Level "

4 switches with three segments



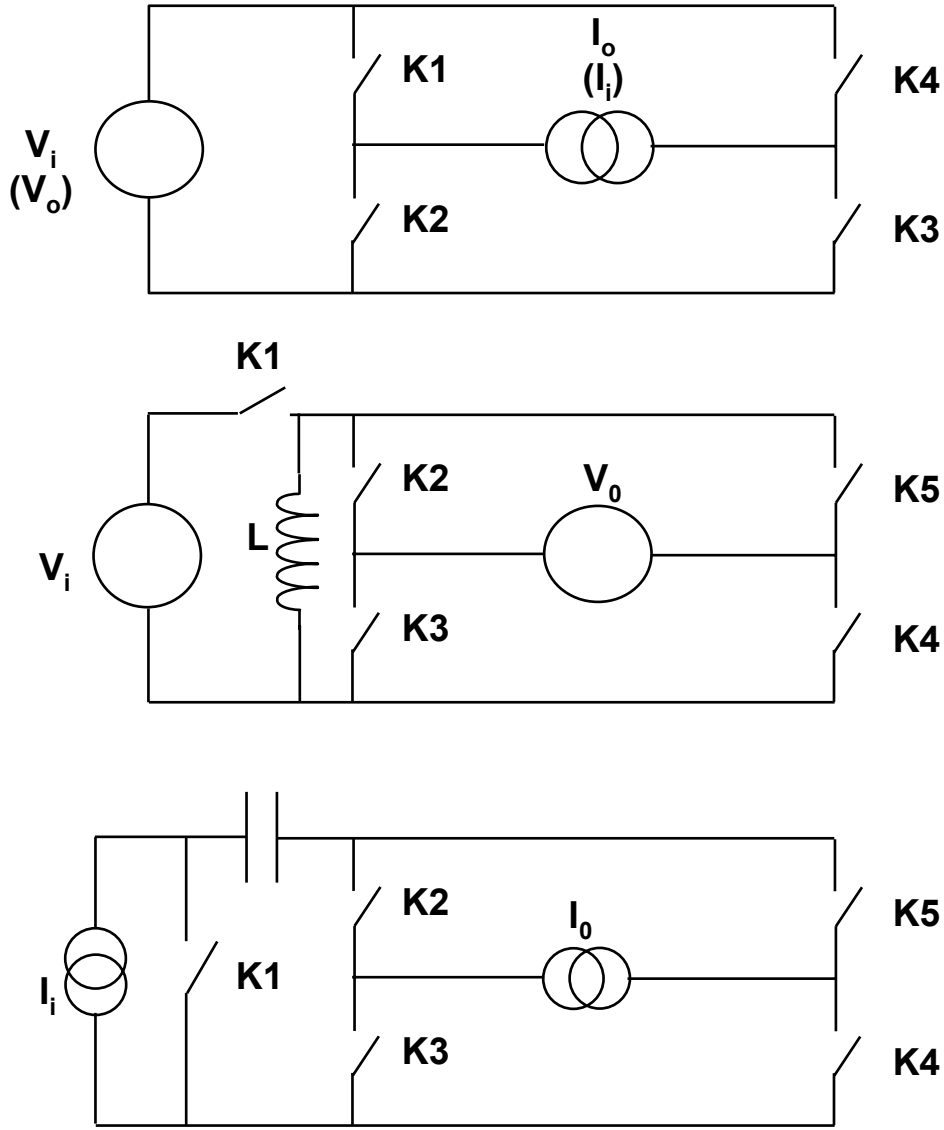
6 switches with four segments



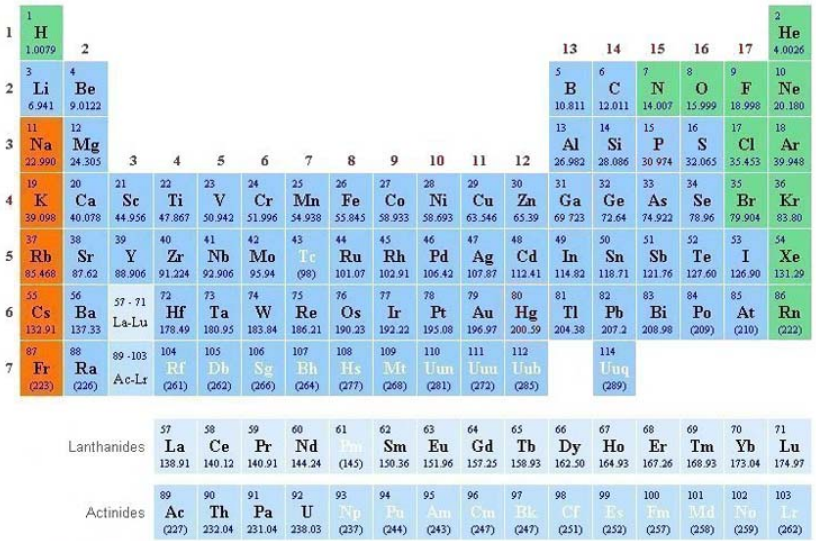
Etc…

Protons + Leptons
=
Atoms

Cohesion laws:
Never short-circuit a voltage source
Never open a current source



Mendeleiev Table

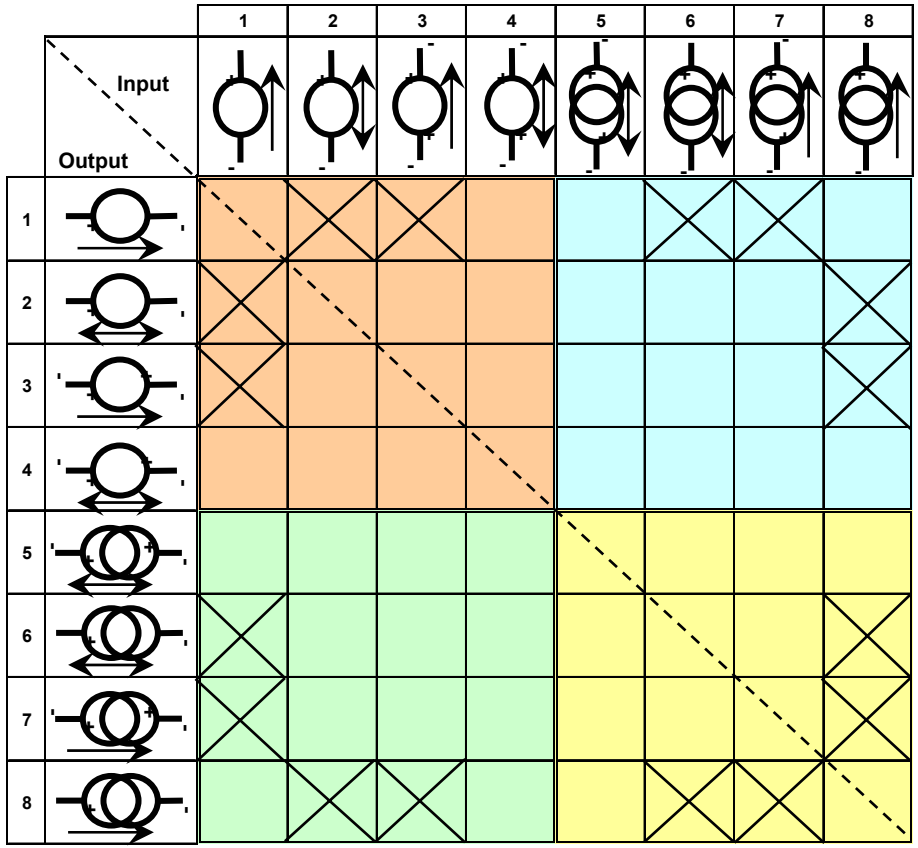


64 cells in the table
But only 8+(56/2) = 36 (due to symmetry)

36 – 8 = 28

Duality => 18 structures

Of course a lot of isotopes….



Thank for your attention

Regards for your participation