Rectifiers

(Line Commutated Rectifiers)

Introduction

Line-Commutated or Naturally Commutating Rectifers

⇨ Un-Controlled (diodes)

⇨ Semi- or Full-Controlled (thyristors)

This Lecture

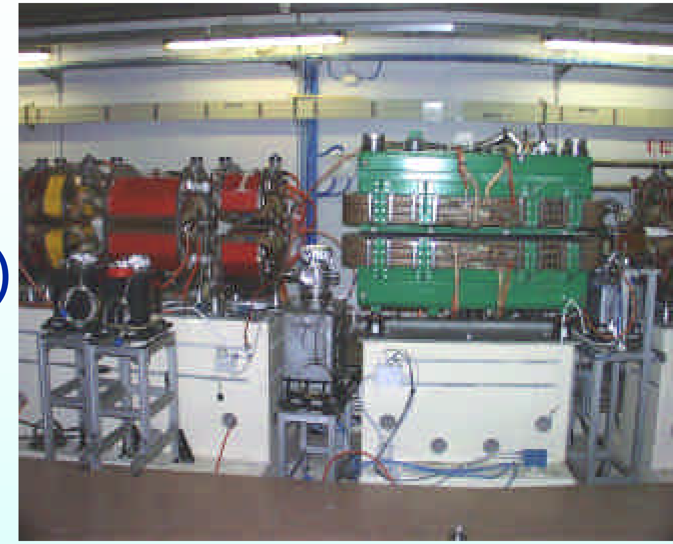
Force-Commutated Rectifiers

⇨ Switch mode (PWM)

What are used for

High Current loads (or multiple low current ones)

- ⇨ Conventional Magnets (low time constant)
- ⇨ SC Magnets (very high time constant)



Elettra – Storage Ring Magnets

High Voltage Loads

- ⇨ Klystrons for RF plants

Elettra – Storage Ring RF Amplifier klystron in its trolley with the modulating cavities

The principles of Rectification

20 kV/380 V AC 50 Hz

Distribution

Rectification

Rectified voltage

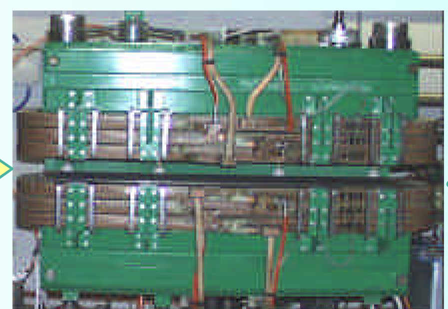
Conversion of the AC mains in DC

- Fully Controlled Bridge (mostly used)
- Current Regulator & Un-controlled Rectifier
- Rectifier and Linear Output Stage

Harmonics Filtering

Direct Current

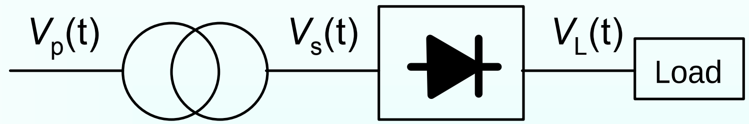
Load



Performance Parameters (some)

Assumptions:

- Ideal Devices (instantaneous switching, no losses)
- Resistive Load



DC voltage on load $$V_{DC} = \frac{1}{T}\int_0^T v_L(t)dt$$

Rectification Ratio (a.k.a efficiency) $$h = \frac{P_{DC}}{P_L + P_D} \Rightarrow \frac{V_{DC}^2}{V_L^2}\frac{1}{1+\frac{R_D}{R}} \xrightarrow{R_D=0} h = \frac{V_{DC}^2}{V_L^2} = \frac{1}{FF^2}$$

rms voltage on load $$V_L = \sqrt{\frac{1}{T}\int_0^T v_L^2(t)dt}$$

Ripple Factor $$RF = \frac{\sqrt{V_L^2 - V_{DC}^2}}{V_{DC}} = \sqrt{FF^2 - 1}$$

Form Factor $$FF = \frac{V_L}{V_{DC}}$$

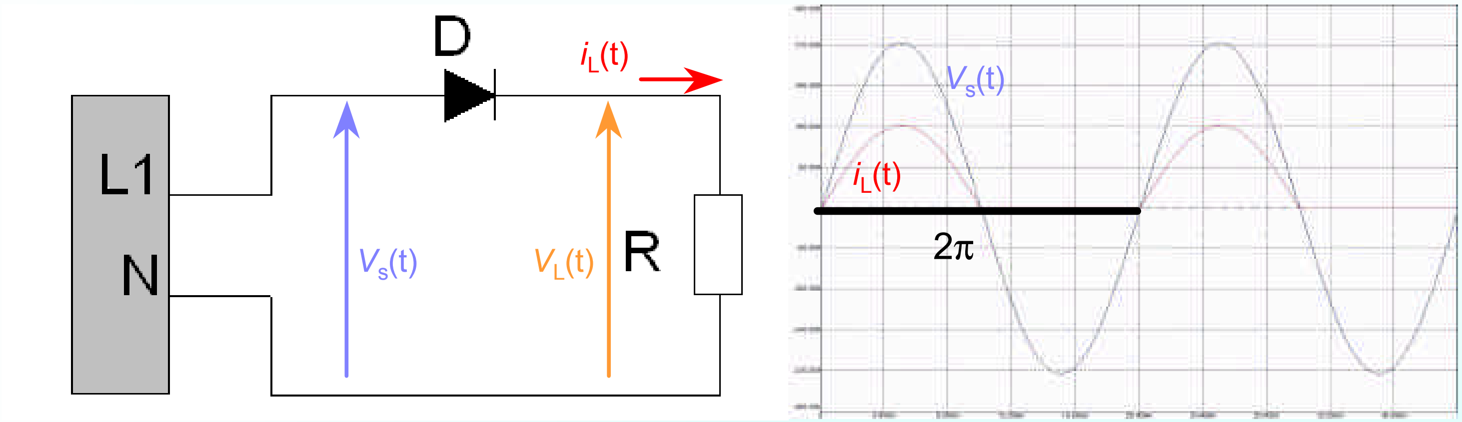
Transformer Utilization Factor $$TUF = \frac{P_{DC}}{Transformer\ VA\ rating} = \frac{P_{DC}}{\frac{VA_p + VA_s}{2}}$$

Some Diode/Thyristor Parameters:

Peak Inverse Voltage, Peak Direct Voltage (Thy. Only), Peak Forward Current, Average Current, Rms Current,…

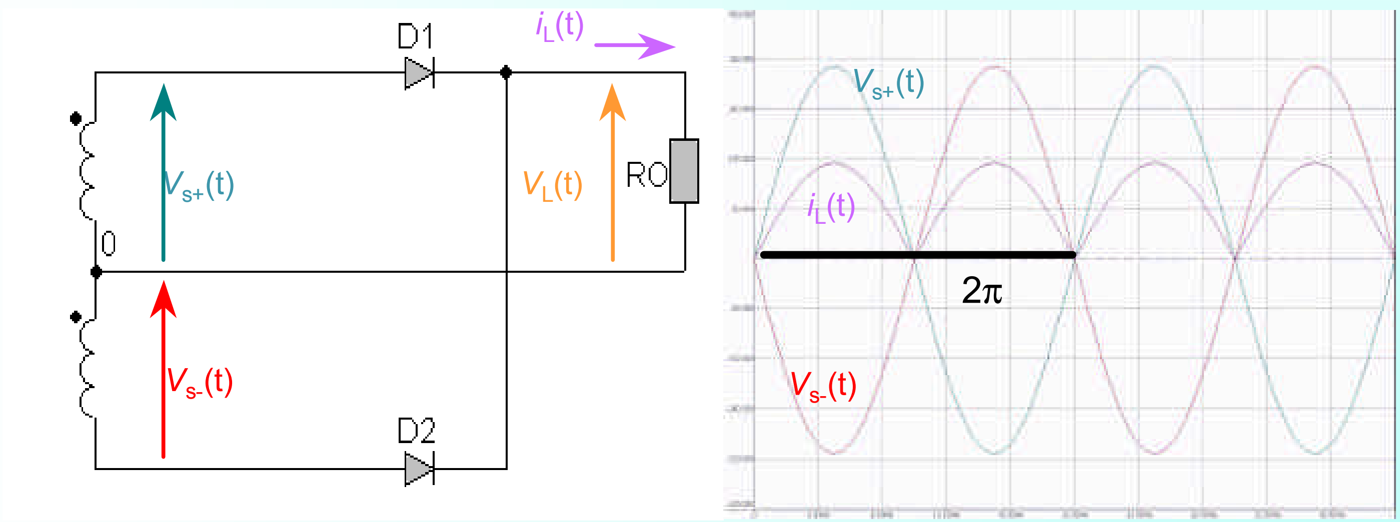
Single-Phase topologies - 1

Single–Way (half-wave, just for comparison)



R = 2 Ω

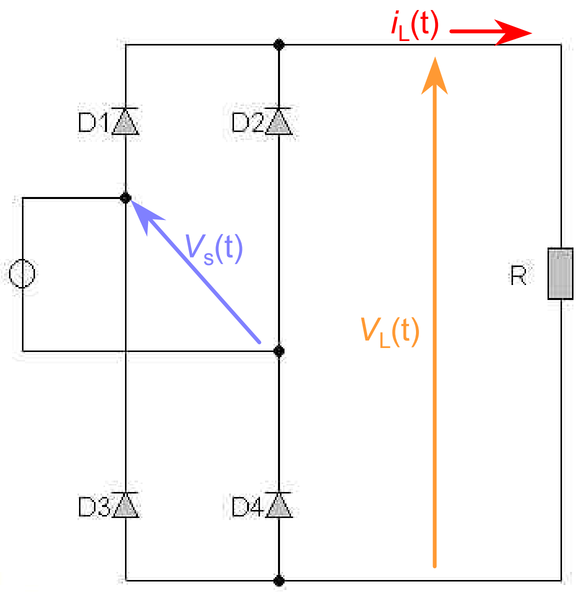
Single–Way (full-wave, Centre-Tapped)



R = 2 Ω

Single-Phase topologies - 2

Double–Way (full-wave, Bridge)



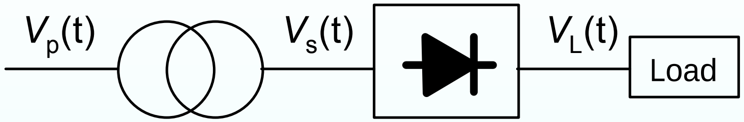
R = 2 Ω

Applications

- Low power loads as stand-alone rectifiers
- Output stage of PWM rectifiers

Comparison among topologies 1–Ph.

- Secondary voltage is sinusoidal: $v_s(t) = V_s \sin(2\pi f_{mains} t)$
- Resistive Load
- Ideal devices (no device losses)



Parameter	Half-Wave	Full – Wave (Center-tapped)	Full – Wave (Bridge)
Rectified Voltage – $\mathbf{V_{DC}}$	$V_s/\pi = 0.318 \cdot V_s$	$2 \cdot V_s/\pi = 0.636 \cdot V_s$	$2 \cdot V_s/\pi = 0.636 \cdot V_s$
rms Output Voltage – $\mathbf{V_L}$	$V_s/2 = 0.318 \cdot V_s$	$V_s/\sqrt{2} = 0.707 \cdot V_s$	$V_s/\sqrt{2} = 0.707 \cdot V_s$
Form Factor – **FF**	1.57	1.11	1.11
Rectification Ratio – h	0.405	0.81	0.81
Ripple Factor – **RF**	1.21	0.482	0.482
Transformer Utilization Factor – **TUF**	0.286	0.572	0.81
Diode Peak Inverse Voltage (PIV) – $\mathbf{V_{RRM}}$	$V_s = \pi \cdot V_{DC}$	$2 \cdot V_s = \pi \cdot V_{DC}$	$V_s = \pi/2 \cdot V_{DC}$
Peak Direct Voltage (PDV – thyristors only) – $\mathbf{V_{DRM}}$	$V_s = \pi \cdot V_{DC}$	$2 \cdot V_s = \pi \cdot V_{DC}$	$V_s = \pi/2 \cdot V_{DC}$
Diode Peak Forward Current – $\mathbf{I_{FRM}}$	$\pi \cdot I_{DC}$	$\pi/2 \cdot I_{DC}$	$\pi/2 \cdot I_{DC}$
Diode Average Current – $\mathbf{I_{F(AV)}}$	I_{DC}	$0.5 \cdot I_{DC}$	$0.5 \cdot I_{DC}$
Diode Rms Current – $\mathbf{I_{F(RMS)}}$	$\pi/2 \cdot I_{DC}$	$\pi/4 \cdot I_{DC}$	$\pi/4 \cdot I_{DC}$
Fundamental Ripple Frequency – $\mathbf{f_R}$	f_{mains}	$2 \cdot f_{mains}$	$2 \cdot f_{mains}$

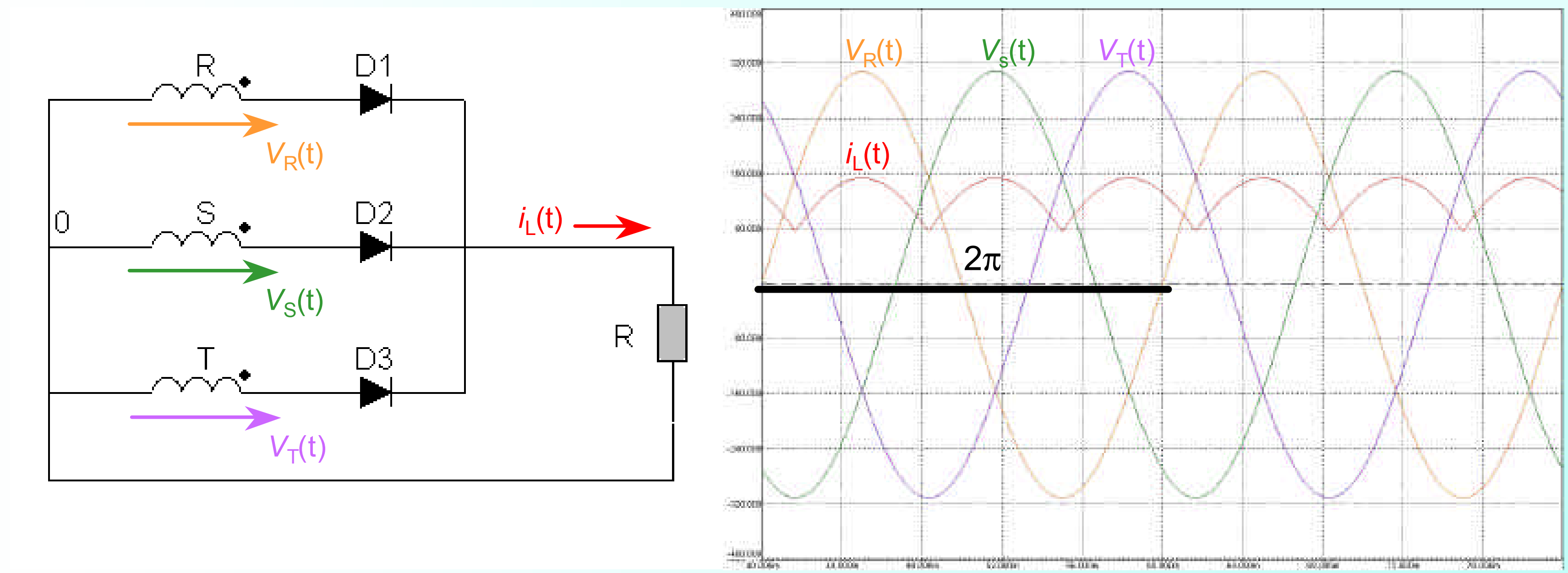
*Extracted from: M.H. Rashid, “Power Electronics Handbook”, Academic Press

Mostly Used Configurations Multi-Ph.

Some Considerations:

- number of phases ® ¥ Þ FF ® 1 & RF ® 0
- Max Practical Numbers: 12 or 24
- The higher the number of phases the more complicated the transformer is for Star-Connected (single-way) diode rectifiers
- Bridge configurations allow to have 6 or 12 pulses without complex transformer connections
  - Single Bridge (6 pulses)
  - Double Bridge – Series/Parallel (12 pulses)

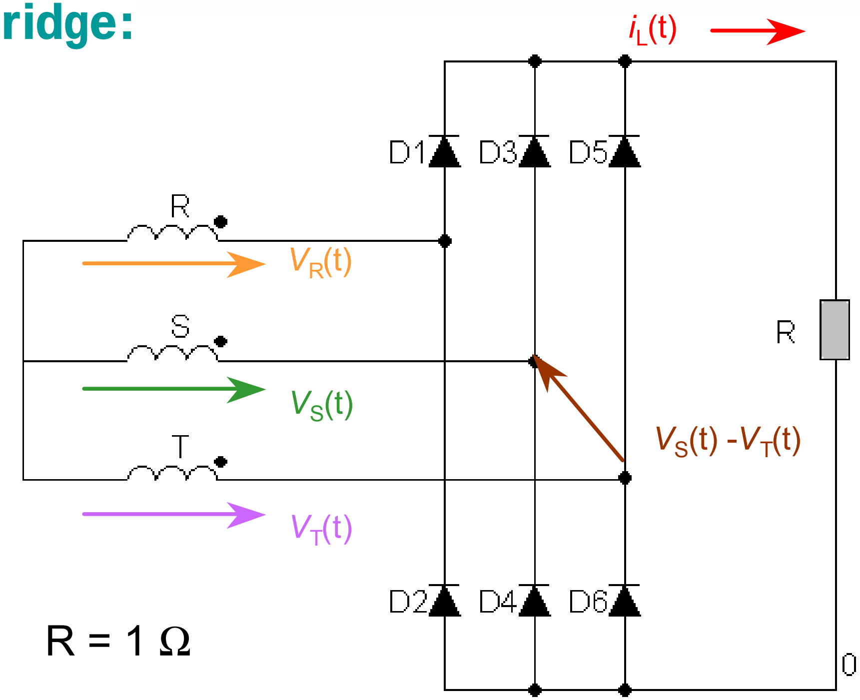
3-Phase Star (single-way, just for comparison)

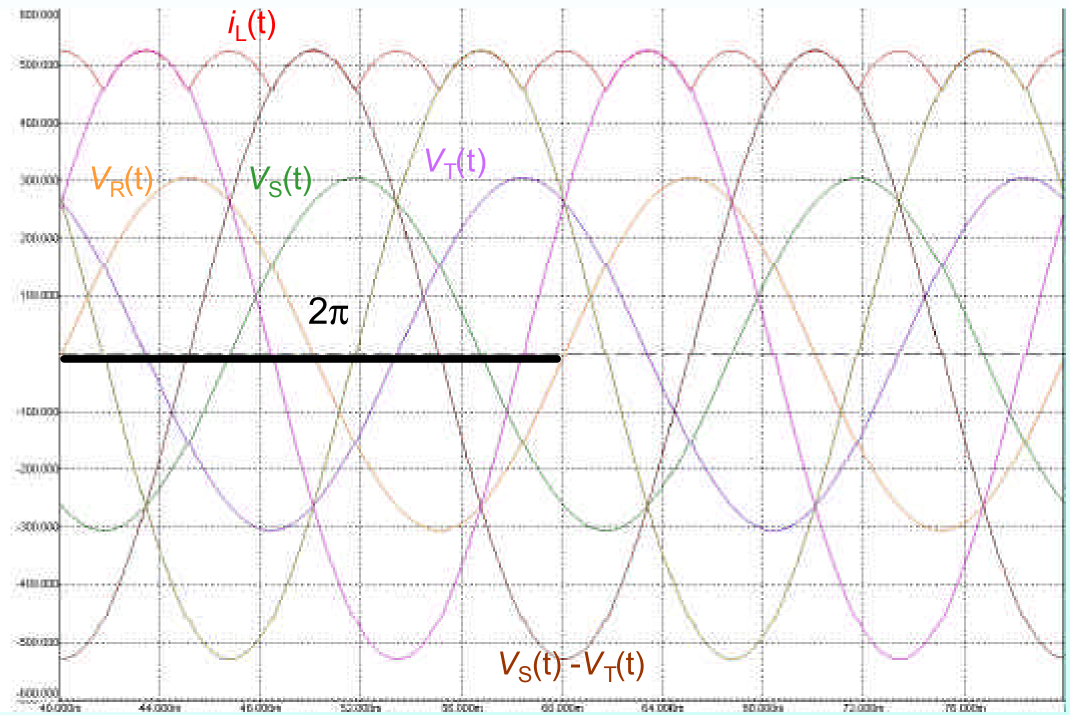


R = 2 Ω

6-p Configuration: Bridge

Bridge:





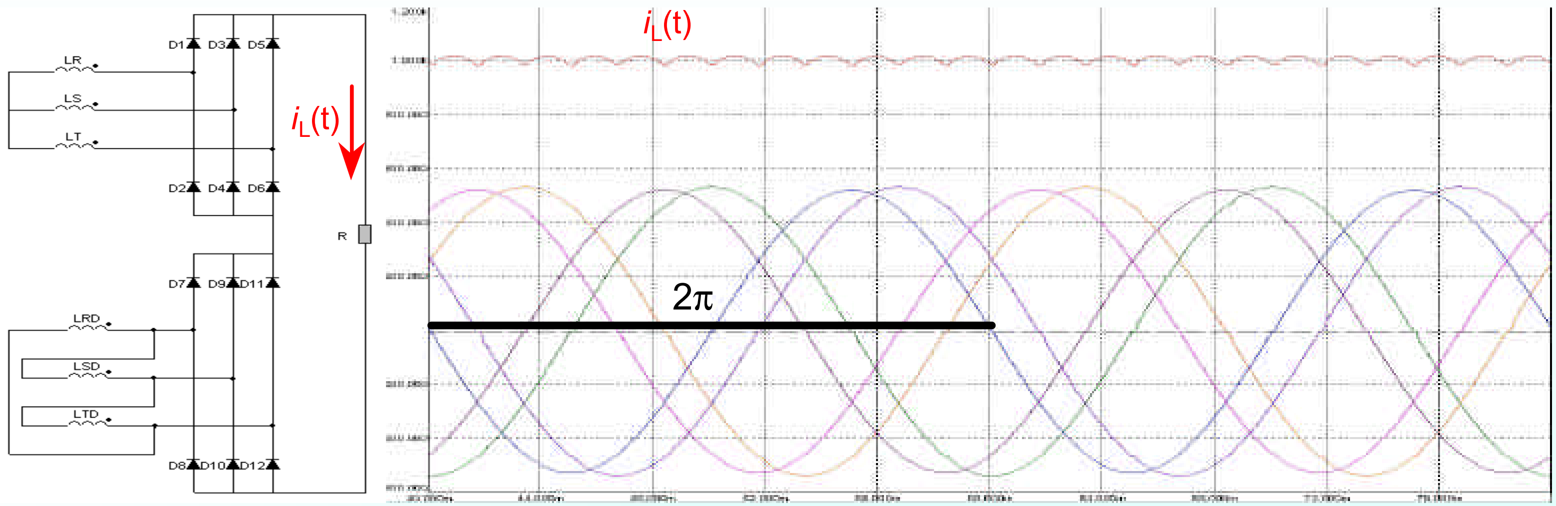
Comments:

- Mostly used configuration
- It is the base for structures with a higher number of pulses
  - Series (same output current, double output voltage)
  - Parallel (double output current, same output voltage)
- This configuration (and those derived) are the best for FF, RF and TUF

12-p Configurations (S & //)

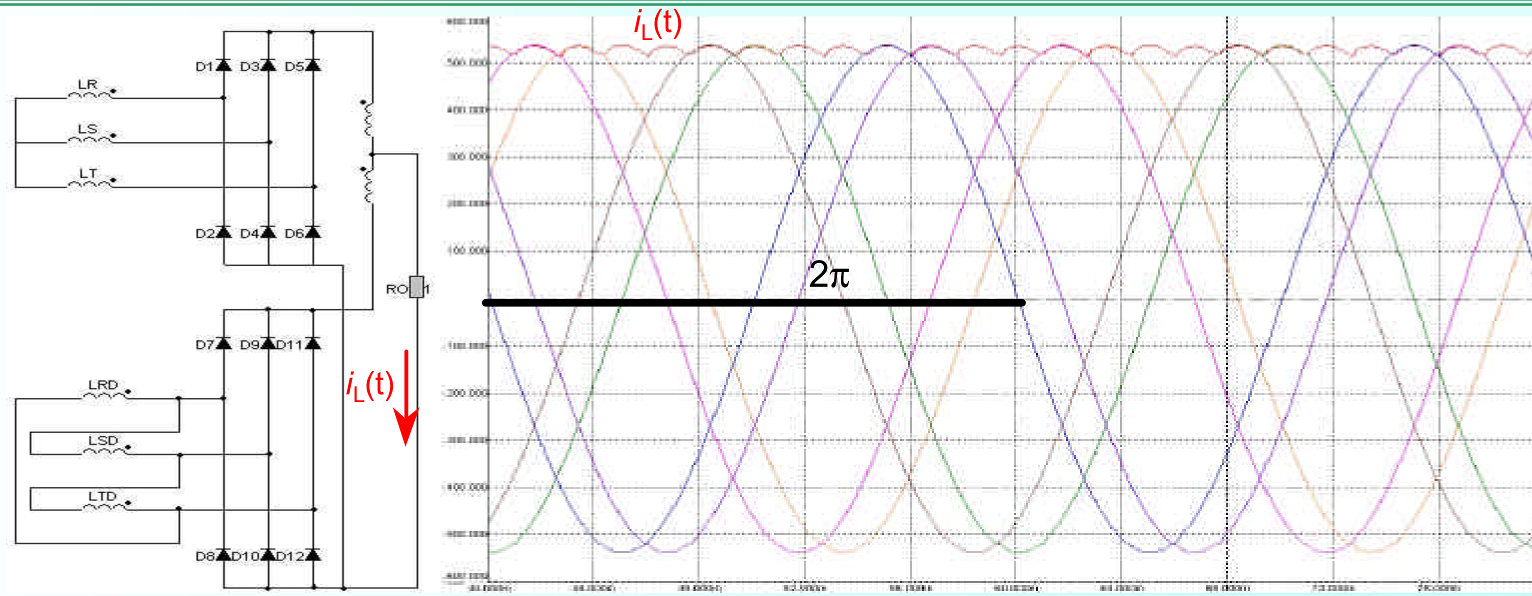
Series:

R = 1 Ω



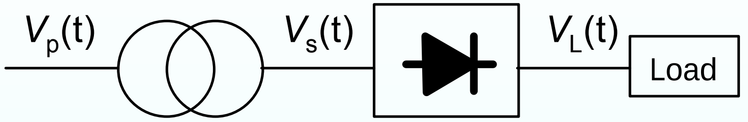
Parallel (with inter-phase reactance):

R = 1 Ω



Comparison among topologies 3–Ph.

- Secondary voltage is sinusoidal: $v_s(t) = V_s \sin(2\pi f t)$
- Resistive Load
- Ideal devices (no device losses)



Parameter	3-Phase Star (Single-Way)	6p Bridge (Double-Way)	12p Bridge (Series)	12p Bridge (Parallel⁺)
Rectified Voltage – $\mathbf{V_{DC}}$	$0.827 \cdot V_s$	$1.654 \cdot V_s$	$3.308 \cdot V_s$	$1.654 \cdot V_s$
rms Output Voltage – $\mathbf{V_L}$	$0.84 \cdot V_s$	$1.655 \cdot V_s$	$3.310 \cdot V_s$	$1.655 \cdot V_s$
Form Factor – **FF**	1.0165	1.0009	1.00005	1.00005
Rectification Ratio – h	0.986	0.998	1.00	1.00
Ripple Factor – **RF**	0.182	0.042	0.01	0.01
Transformer Utilization Factor – **TUF**	0.73	0.95	0.97	0.97
Diode Peak Inverse Voltage (PIV) – $\mathbf{V_{RRM}}$	$2.092 \cdot V_{DC}$	$1.05 \cdot V_{DC}$	$0.524 \cdot V_{DC}$	$1.05 \cdot V_{DC}$
Peak Direct Voltage (PDV – thyristors only) – $\mathbf{V_{DRM}}$	$2.092 \cdot V_{DC}$	$1.05 \cdot V_{DC}$	$0.524 \cdot V_{DC}$	$1.05 \cdot V_{DC}$
DiodePeak Forward Current – $\mathbf{I_{FRM}}$	$1.21 \cdot I_{DC}$	$1.05 \cdot I_{DC}$	$1.01 \cdot I_{DC}$	$0.524 \cdot I_{DC}$
Diode Average Current – $\mathbf{I_{F(AV)}}$	$0.333 \cdot I_{DC}$	$0.333 \cdot I_{DC}$	$0.333 \cdot I_{DC}$	$0.167 \cdot I_{DC}$
Diode Rms Current – $\mathbf{I_{F(RMS)}}$	$0.587 \cdot I_{DC}$	$0.579 \cdot I_{DC}$	$0.576 \cdot I_{DC}$	$0.409 \cdot I_{DC}$
Fundamental Ripple Frequency – $\mathbf{f_R}$	$3 \cdot f_{mains}$	$6 \cdot f_{mains}$	$12 \cdot f_{mains}$	$12 \cdot f_{mains}$

*Extracted from: M.H. Rashid, "Power Electronics Handbook", Academic Press

⁺ With inter-phase transformer

Three-Phase Controlled Rectifiers

Goal

- To be able to vary the output voltage on the load according to the needs
- To be able to recover, if needed, energy from the load to the mains or other energy storage device
- To minimize the losses on some devices when the load requirements are low

Possible Solutions

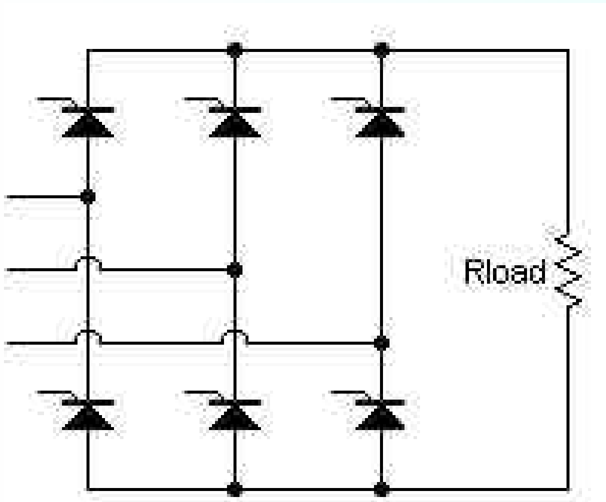
- Use of thyristors in place of diodes
- Use thyristors AND diodes
- Use diodes or thyristors AND transistors

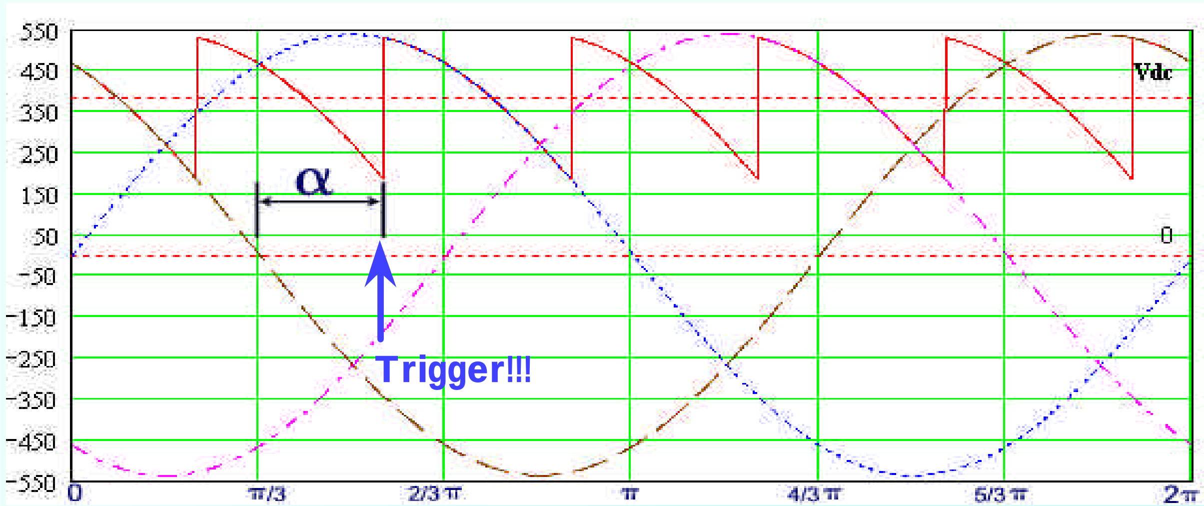
Applications

- High Current loads (magnets)
- High Voltage loads (klystrons)
- Several low current loads supplied from a multi-channel converter (small magnets)
- Supply of current to loads of different characteristics

Three-Phase Fully Controlled Bridge

- Delay Angle a: the span of period between the instant when the thyristor could start to conduct and the instant when the trigger pulse is applied
- Since in stable conditions also the subsequent couple of thyristors are delayed the conduction continues until the next trigger pulse
- The average value, V_{DC}, is anyway lower and depends on a





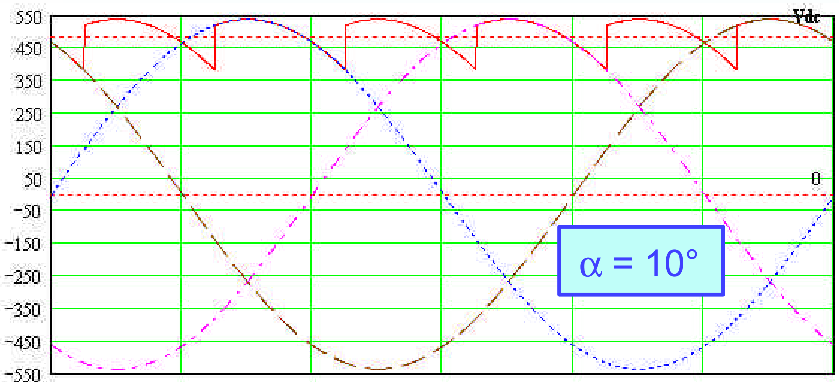
$$V_{DC}(a) = \frac{3\cdot\sqrt{3}}{p}\cdot V_m \cdot cos(a) = V_{DC0}\cdot cos(a) \quad 0 \le a \le \frac{p}{3}$$

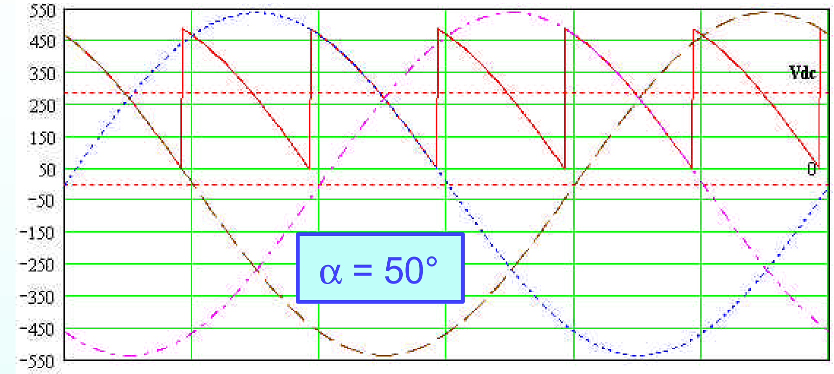
$$V_{DC}(a) = \frac{3\cdot\sqrt{3}}{p}\cdot V_m \cdot \left[1 + cos(a + \frac{p}{3})\right] \quad \frac{p}{3} < a \le \frac{2\cdot p}{3}$$

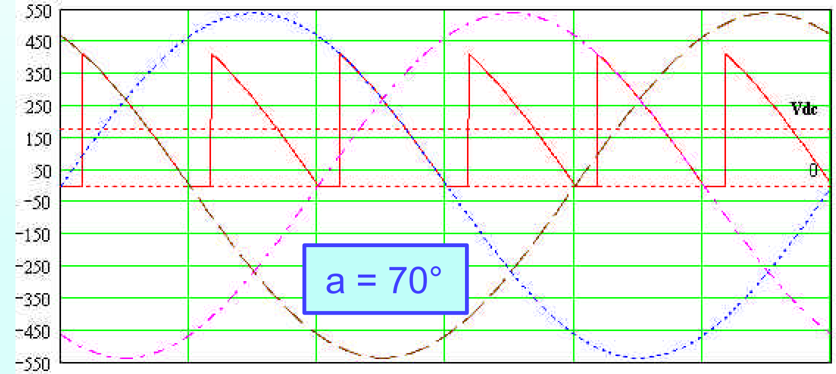
Assumptions:

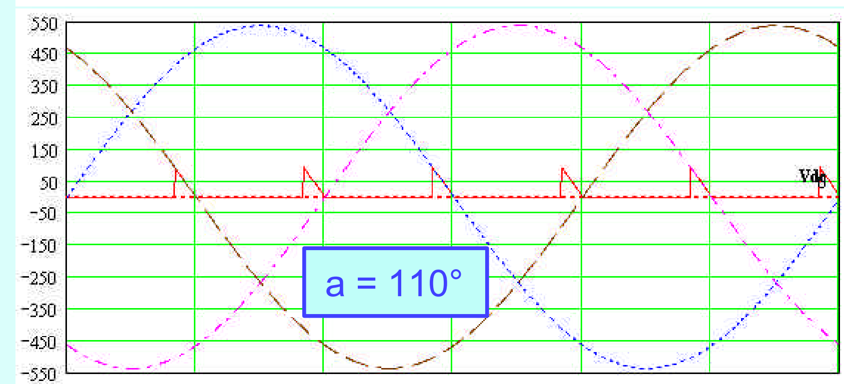
- Ideal Devices (instantaneous switching, no losses)
- Resistive Load

Conduction vs. a (Resistive Load)









0°= a =60°

- Continuous conduction: the output voltage is always positive
- The current flows continuously in the resistive load

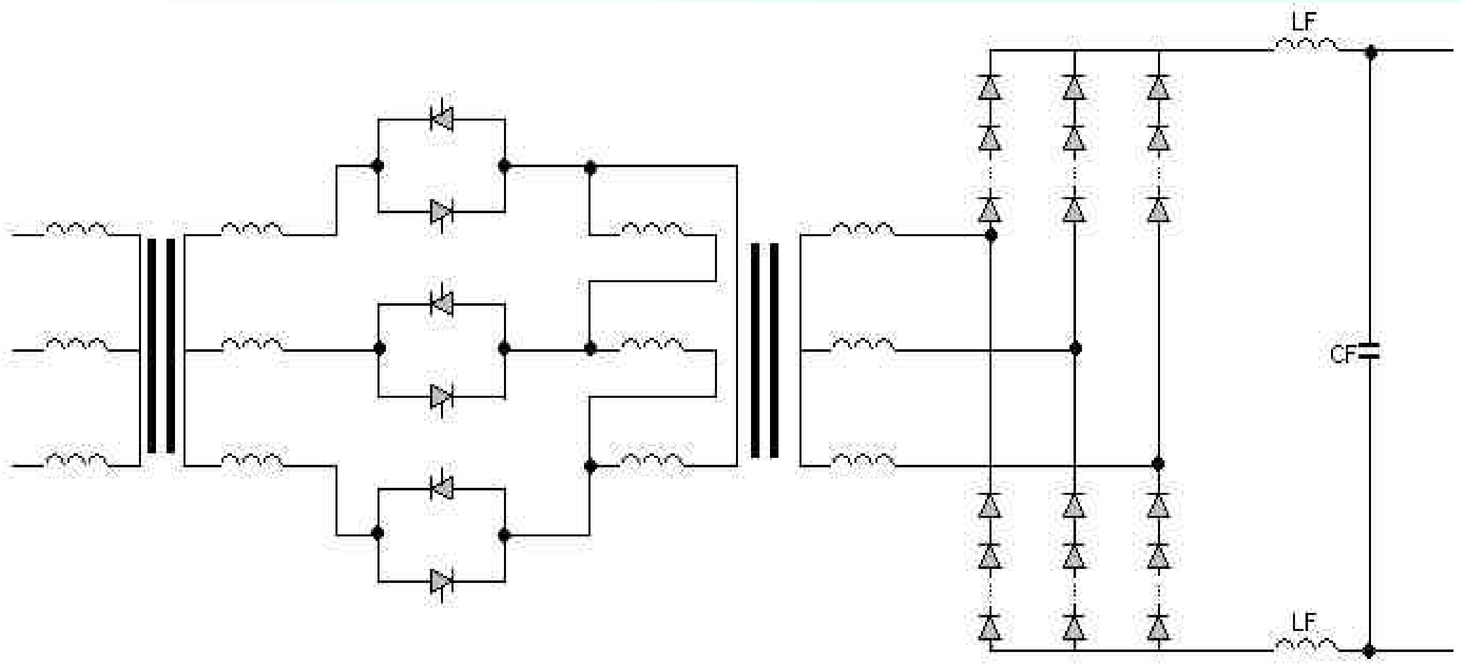
60°< a =120°

- Discontinuous conduction: the output voltage goes to zero for part of each pulse
- The current flows as "pulses" in the resistive load

3-Ph.Current Regulator & Diode Br.

Comments:

- High Voltage Loads (like klystrons) require series connections of switches
- Thyristors in series means a <u>**VERY**</u> good equalization of their firing pulses, diodes are naturally commutating devices
- Pre-regulation of the AC input of the Bridge

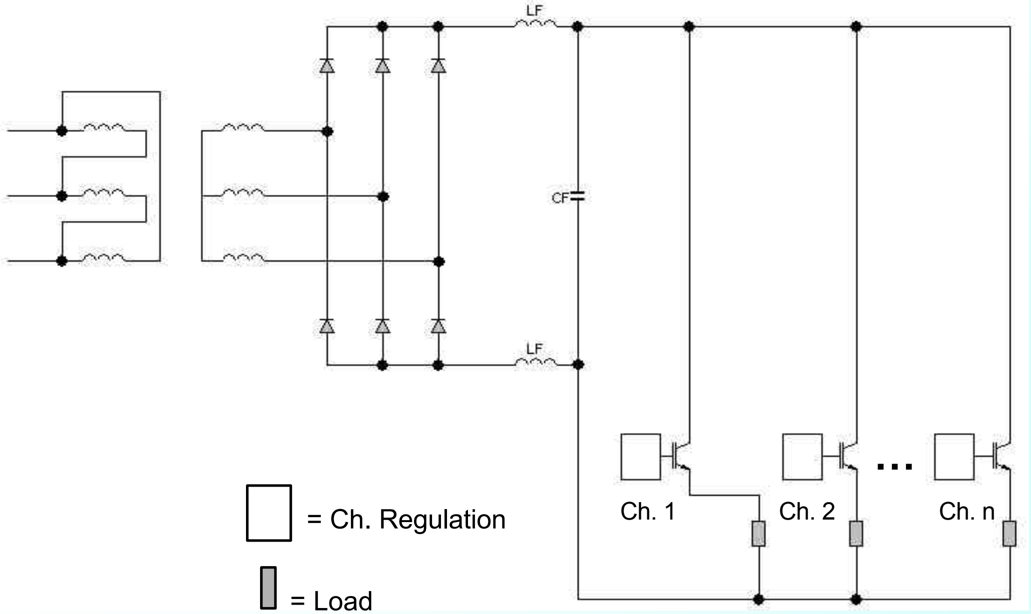


Elettra – Linac Modulator Klystron

3-Ph. Multi-Channel (unregulated)

Comments:

- Good solution when there are several low-power loads.
- The common part (transformer, bridge, filter) and the *n* channels can be housed in a single cabinet.
- Using two bridges in series it is possible to supply bipolar channels (e.g. for corrector magnets)

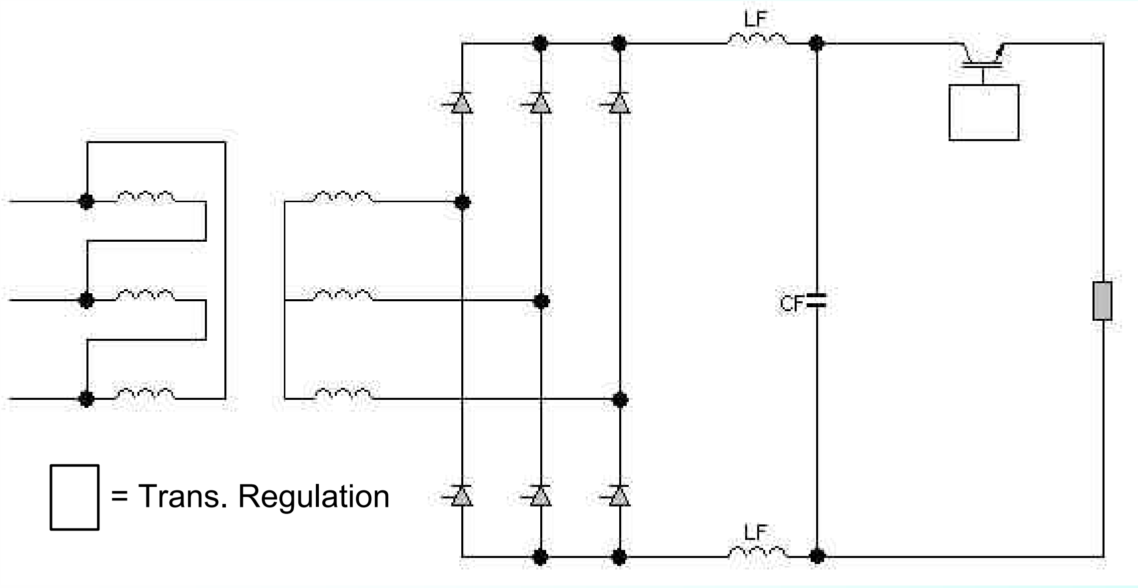


Elettra – Transfer Line Quadrupole followed by 2 correctors

3-Ph.Contr. Br. & Linear Output

Comments:

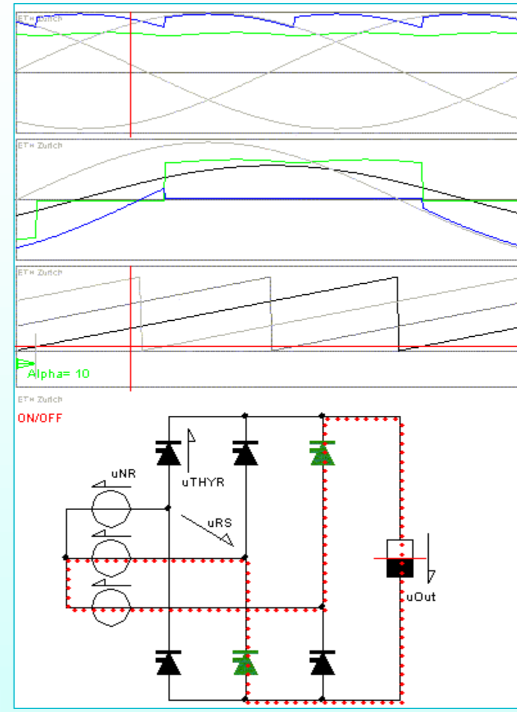
- Good for load which change their characteristics or for loads which need "fast" output current changes
- Acting on the controlled bridge it is possible to reduce the voltage on the **linear** transistor output stage and minimize the power dissipation at low current conditions



Elettra – Storage Ring Electromagnetic Elliptical Wiggler (EEW): for a short time in 2001, due to a major fault to its PWM PS, it was powered by a couple of PS of this type.

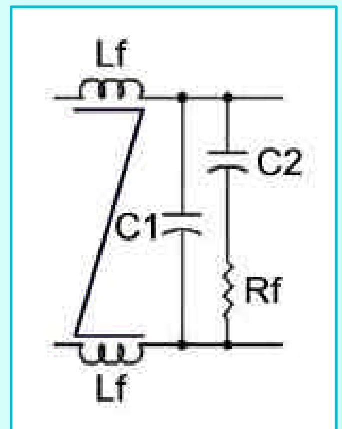
The "real" world – DC Side

- ⇒ The load has a strong inductive component (usually it is a magnet)
- ⇒ The current doesn't follow the output voltage and it is smoothed by the inductance
- ⇒ If the inductance is big enough, the current waveform is continuous even if the voltage one is not
- ⇒ The output voltage can go negative(when $\alpha > 60°$) but the current is still flowing in the same direction (keeping the thyristor in conduction)
- ⇒ The load inductance has a strong influence also on the waveform of the AC line current: the higher the inductance the less distorted the input current



i-PES applet: courtesy of Prof. J. W. Kolar and Dr. U. Drofenik - ETH Zurich

- ⇒ The ripple on the output direct current is normally too high for the applications in accelerators' field
- ⇒ There is the need for a Low-Pass Filter
- ⇒ Cut-off frequency f_0 should be much lower than ripple's 1st harmonic ($f_{ripple1} = p \times f_{mains}$, p = # pulses)
- ⇒ Dumped passive L-C filters are used
- ⇒ If additional attenuation is needed, additional Active Filters on the DC output are also used



$$f_0 = \frac{1}{2 \cdot p \cdot \sqrt{L_f \cdot (C1 + C2)}}$$

$$L_f > \frac{V_{ripple}}{2 \cdot p \cdot f_{ripple1} \cdot I_{DC\,min}}$$

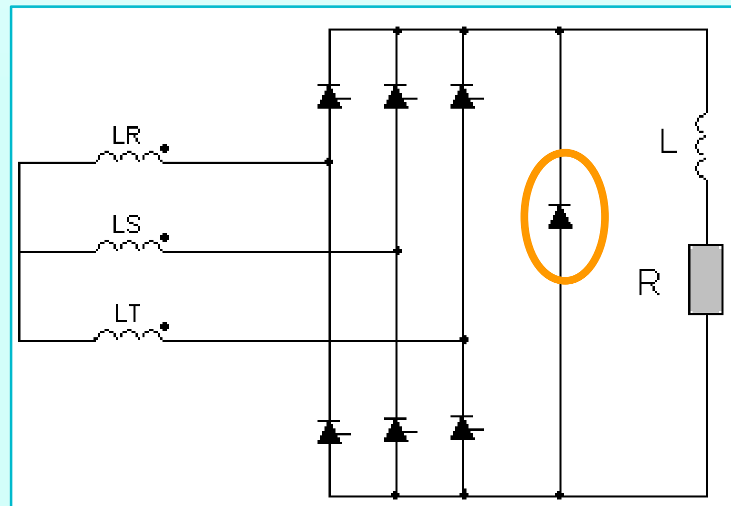
$$C2 = 5 \cdot C1$$

$$R_f = 0.4 \cdot \sqrt{\frac{L}{(C1 + C2)}}$$

Parenthesis: Inversion

- ⇒ With an inductive load, when a > 60°, the output voltage goes temporarily negative while the current is still flowing in the "positive" direction
- ⇒ For a > 90°, the average output voltage becomes negative but the current is still positive: the power is flowing back from the DC side to the AC, the converter is operating in "inverting mode"
- ⇒ The inverting mode can be used to recover energy from an inductive load (or a more stable source of DC like a battery or a solar cell panel) and send it to the AC mains or store in a capacitor.
- ⇒ The maximum delay angle is a » 150° (taking into account the commutation angle m and the thyristor turn-off time t_q)

- ⇒ In "pure" rectifiers to avoid inversion and keep a working range up to a = 120°, a free-wheeling diode is put in parallel to the rectifier output.
- ⇒ The free-wheeling diode creates a path for the load current when the output voltage would become negative.
- ⇒ The free-wheeling diode has a positive effect in the ripple reduction and reactive power.

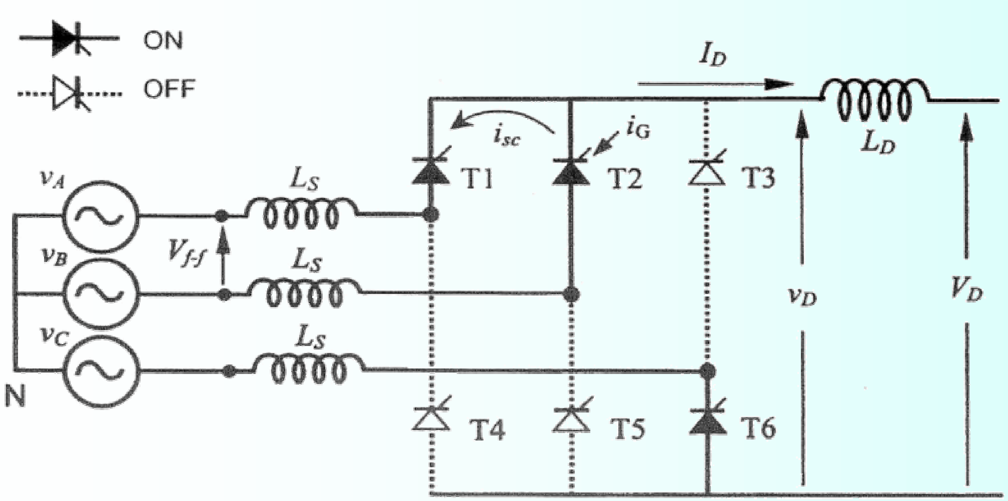


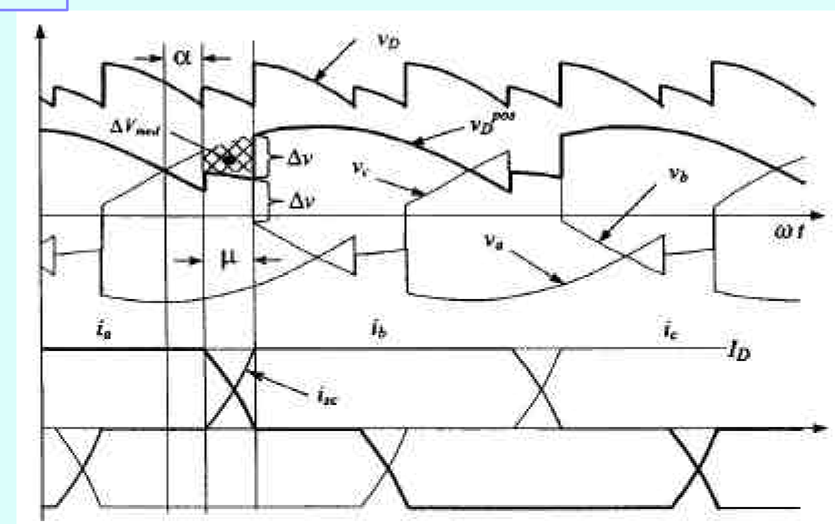
The "real" world – AC Side

- ⇒ There is a **FINITE** inductance on the mains side (the inductance of the secondary of the transformer and the leakage inductance of the line): L_s
- ⇒ The thyristors change their status (on or off) in a **FINITE** time
- ⇒ During commutation from one phase to another there is an "overlapping time" when two thyristors on the same side of the bridge are conducting at the same time shorting the phases through the L_s of each phase – it is indicated as the "overlap angle" m.
- ⇒ For a given $\boldsymbol{I_D}$ and a, the duration of the overlapping depends on $\boldsymbol{V_{f\text{-}f}}$ and L_s (L_D>>0)

$$I_D = \frac{V_{f-f}}{\sqrt{2} \cdot w \cdot L_s} \cdot \left[cos(a) - cos(a + m) \right]$$

($V_{f\text{-}f}$ = peak value of inter-phase voltage)



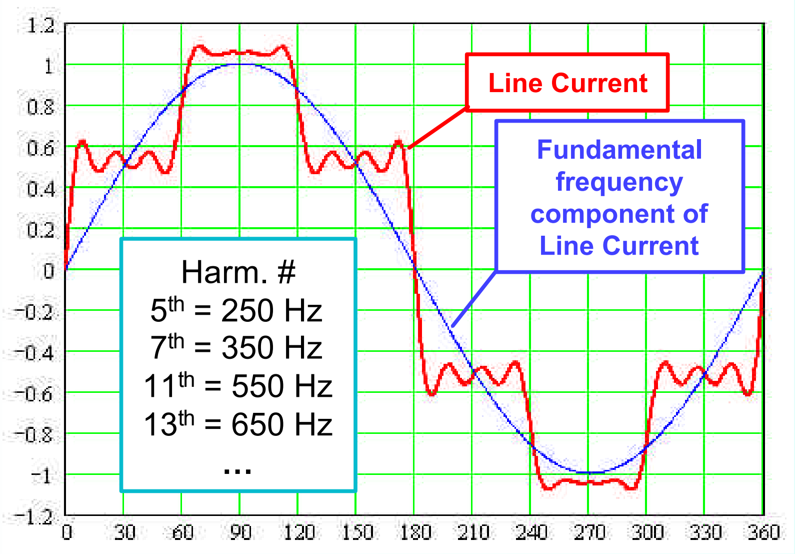


*Extracted from: M.H. Rashid, "Power Electronics Handbook", Academic Press

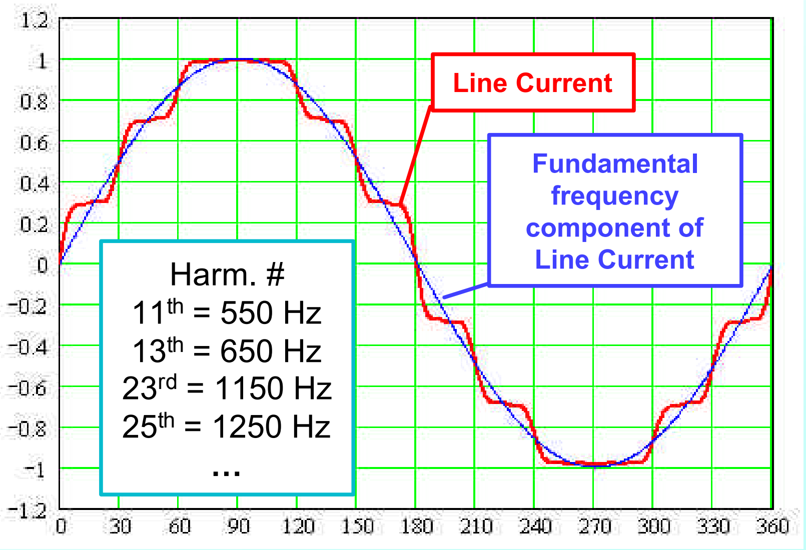
The effects on the mains (current)

Current:

- ⇒ The current drawn from AC supply system is not a pure sinusoid
- ⇒ Fundamental component with superimposed harmonic component
- ⇒ Harmonic frequency: $(n \times p \pm 1) \times f_{mains}$ with n = 1, 2,… p = # pulses)
- ⇒ A 12 pulse converter has a lower harmonic impact on the mains than two 6 pulse units of a comparable size



6 pulse – mains line current (THD=28.45%)



12 pulse – mains line current (THD=9.14%)

*Data extracted from: G.J. Wakileh, “Power Systems Harmonics”, Springer

The effects on the mains (voltage)

Voltage:

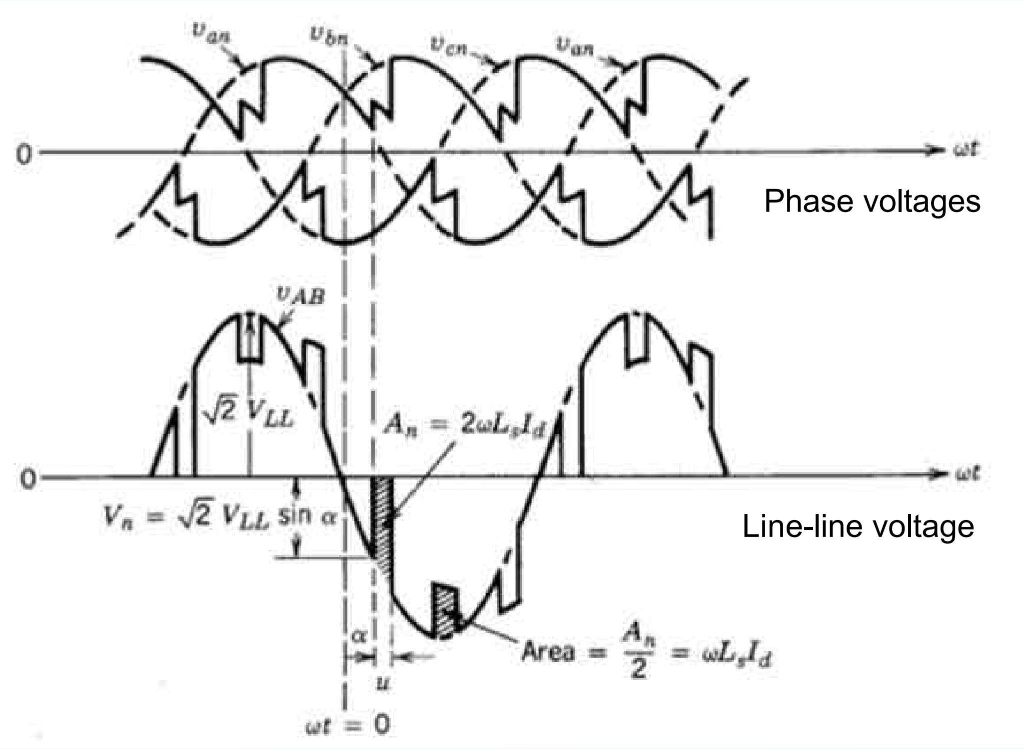
- Notches (due to the commutation between phases)
- Spikes
- Distortion

$$Notch\ Width = \frac{2 \cdot w \cdot L_s \cdot I_{DC}}{V_{f-f} \cdot sin(a\ )}$$

$V_{f\text{-}f}$ = peak value of interphase voltage

$$THD_V = \frac{\sqrt{\sum_{n \geq 2} (I_n \cdot n \cdot w \cdot L_s)^2}}{V_{phase}}$$

V_{phase} = peak value of interphase voltage
I_n = n-th harmonic of the AC input current
L_s = AC source impedance



*Extracted from: N. Mohan-T.M. Undeland-W.P. Robbins, “Power Electronics”, Wiley

The effects on the AC mains (def's)

⇒ Assuming L_D large enough in order that phase R line current $i_R(t) \sim I_{DC}$

⇒ First assumption: $L_s = 0$ (instantaneous commutation, $\mu = 0$)

⇒ Than considering $L_s > 0$ (overlapping, $\mu > 0$)

Displacement Power Factor

$$DPF = cos(f_1) = cos(a)$$

Power Factor

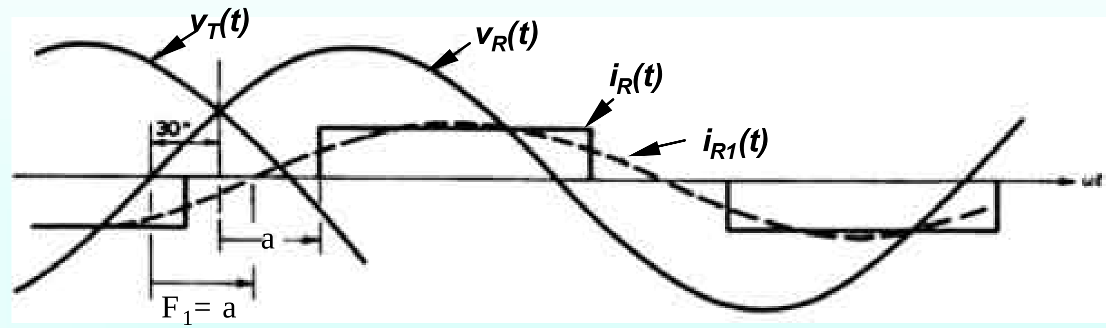
$$PF = \frac{P}{S} = \frac{V_R^{rms} \cdot I_{R1}^{rms} \cdot cos(f_1)}{V_R^{rms} \cdot I_R^{rms}}$$

$$PF = \frac{I_{R1}^{rms}}{I_R^{rms}} \cdot cos(a) = \frac{3}{p} \cdot cos(a)$$

I_{R1} = peak value of fundamental component of R-Phase line current

Displacement Power Factor (L_s >0)

$$DPF \cong \frac{cos(a) + cos(a + m)}{2}$$



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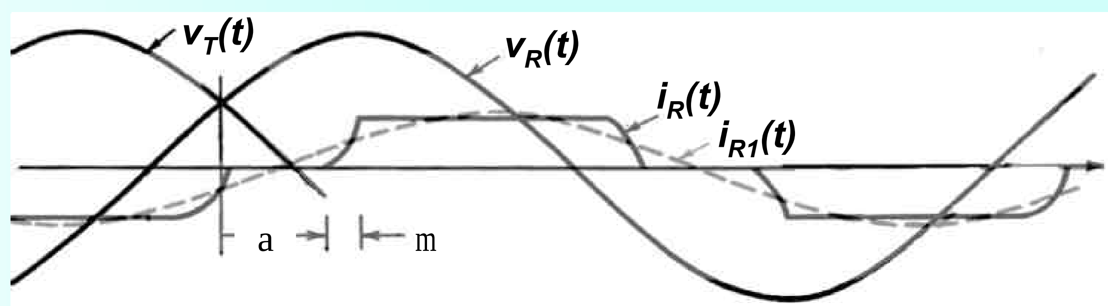


*Extracted from: N. Mohan-T.M. Undeland-W.P. Robbins, "Power Electronics", Wiley

Example: existing 12p Magnet PS

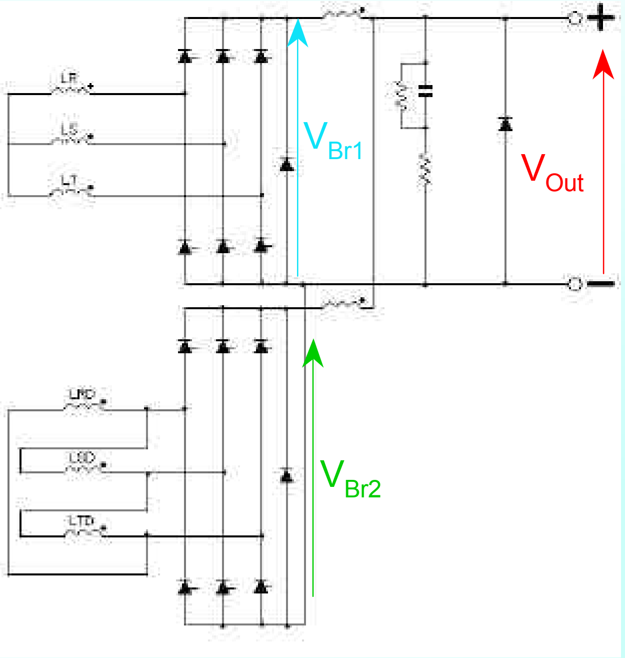
12-pulses Fully controlled Bridge Rectifier:

⇒ Two 6-p bridges in parallel

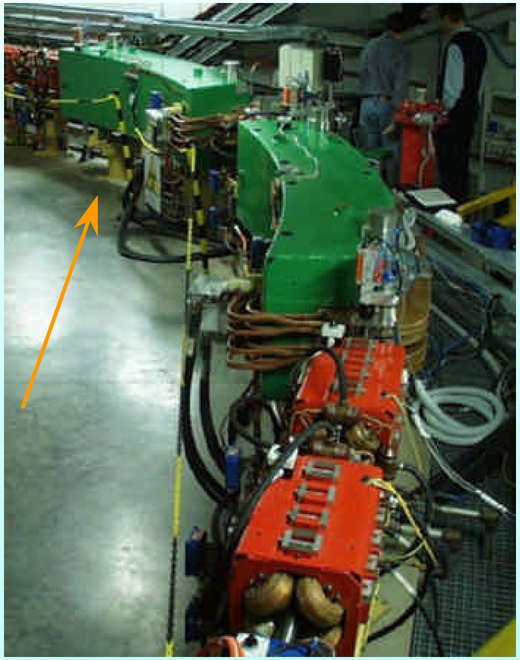
⇒ Free-wheeling diodes

⇒ Passive Filter

Elettra – Transfer Line Dipole Power Supplies: 2 PS (200 V / 1080 A, 12p-bridge & 60 V / 1080 A, 6p-bridge) in one cabinet.



Elettra – Transfer Line Dipole Power Supply PSB_T2.2: 200 V / 1080 A, 12p fully controlled bridge – General Scheme.



Elettra – Transfer Line Dipoles: 2 out of 7 dipole magnets. The first one (arrow) is powered separately from the others.

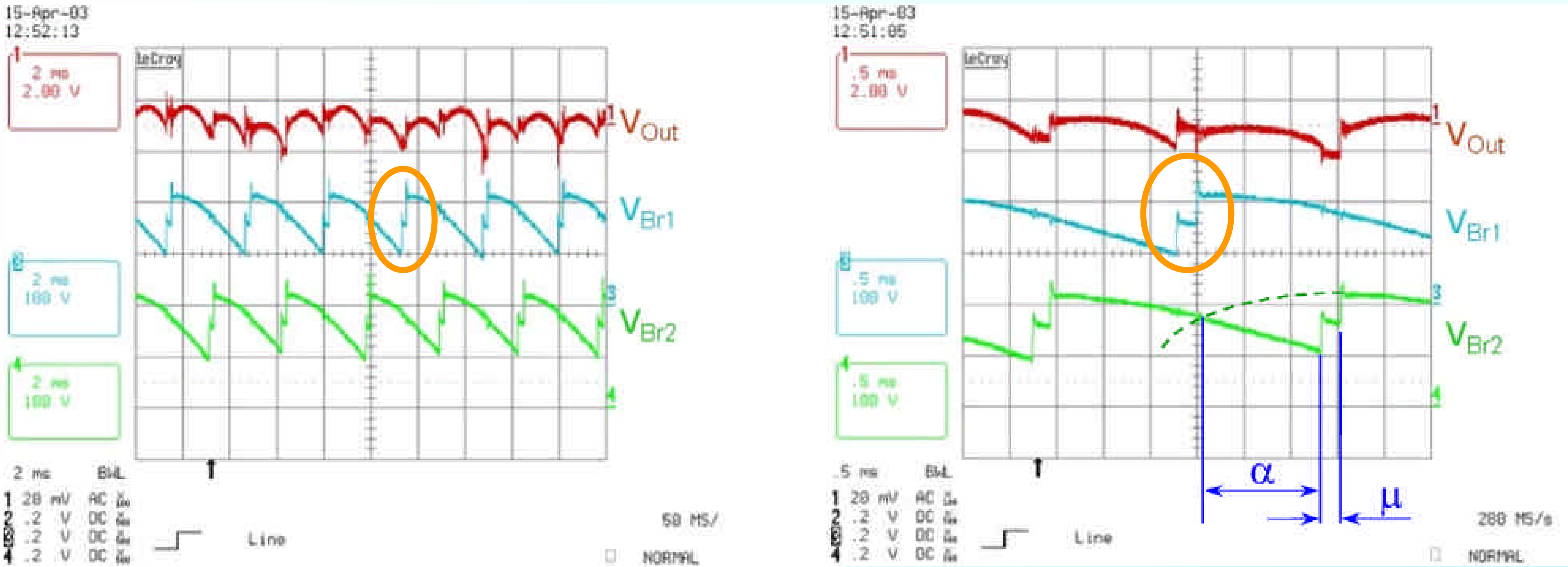
"Real" 3-Ph.12p Contr. Br. Output

⇒ Output voltages of both bridges and PS output voltage ($V_{f\text{-}n}$ = 166 V; I_{out} = 1000 A)

⇒ Delay angle is a ≈ 22.5°

⇒ Overlapping angle is m ≈ 3.4° (overlapping time ~190 µs)

⇒ L_s = 23 µH (as calculated from the formula shown before)



Elettra – Transfer Line Dipole Power Supply PSB_T2.2: 200 V / 1080 A, 12p fully controlled bridge (without inter-phase reactor) – Output Voltage waveforms.

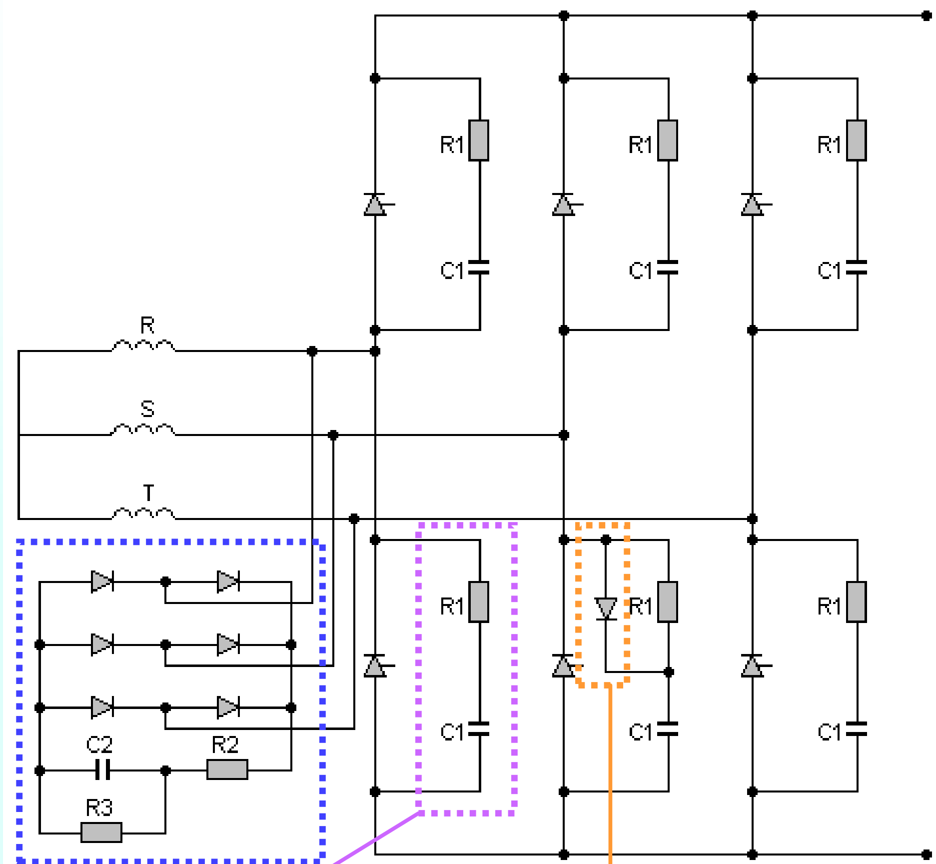
Protection & Interlock - Switches

Protection of Thyristors (Diodes):

- **Overcurrent (preventing the junction temperature to exceed the limit)**
  - Fuses
  - Proper choice of components (ratings 30 to 50% higher than specified)
  - Anode current monitoring acting on the trigger delay angle
- **Overvoltage (avoid the reverse break down and the unwanted turn-on)**
  - Proper choice of components (ratings 30 to 50% higher than specified) both V_{RRM} and V_{DRM}
- **Voltage Transients or Surges**

  Golden Rule: store quickly the surge energy (in C) and dissipate it slowly (in R)

  - AC Input side surges (e.g. due to opening of the main contactor) Þ "Bucket Circuit"
  - Reverse Recovery charge of Thyristor (at turn-off) Þ "Snubber Circuit"

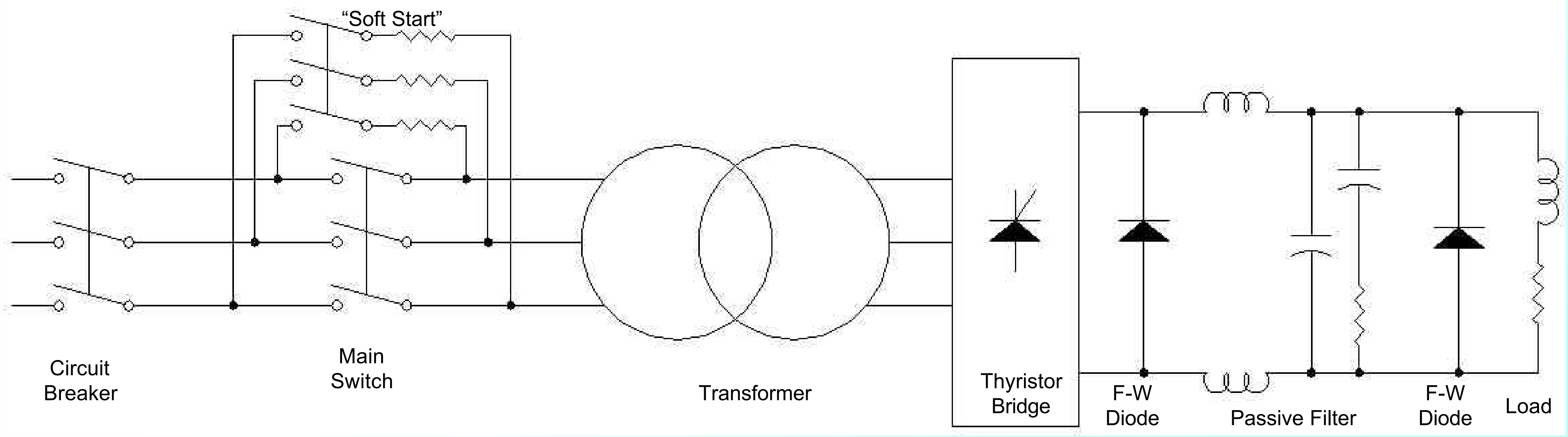


Note
Sometimes a diode is placed in parallel to R1 to charge C1 more efficiently

Protection & Interlock - Converter

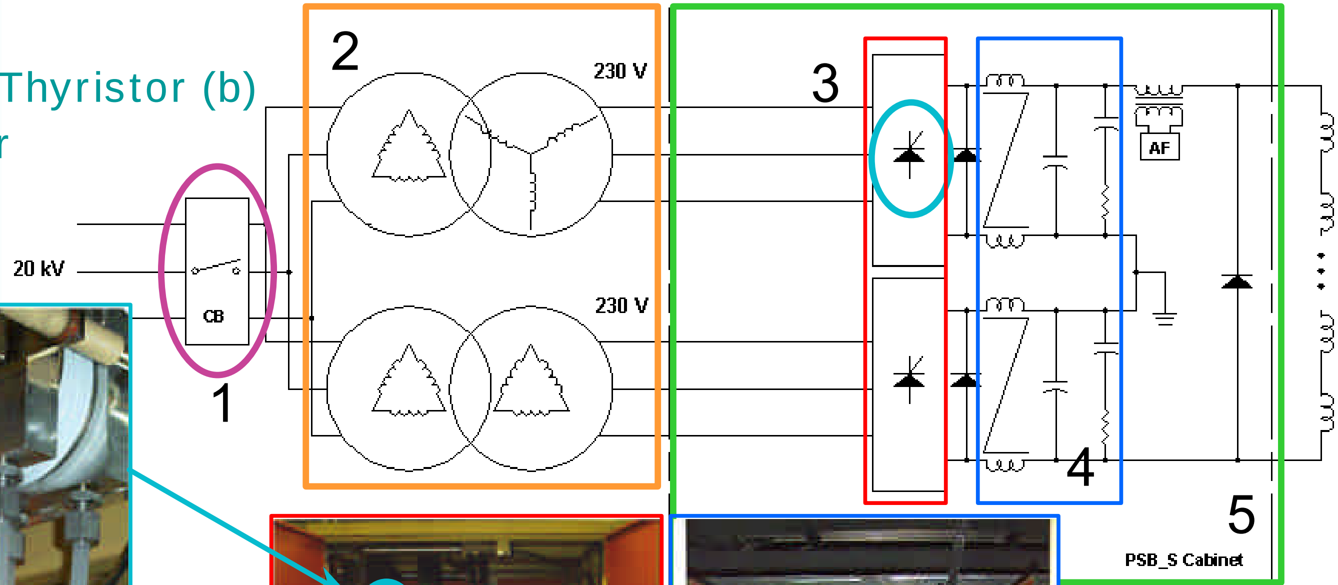
Main Items:

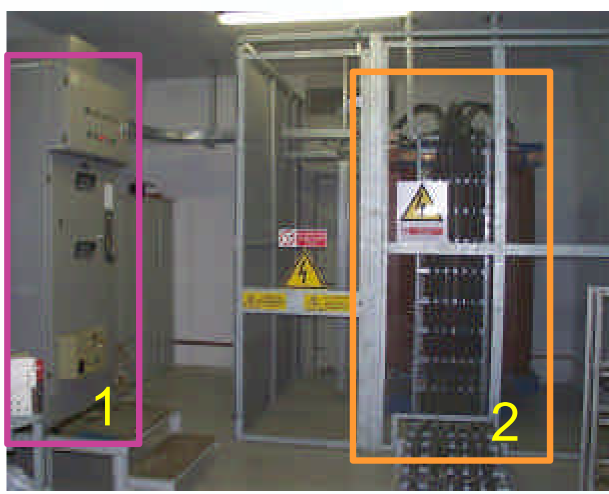
- Circuit Breaker & Contactor (with "Soft Start")
- Transformer (overcurrent, over-temperature)
- Thyristor Bridge (over-temperature)
- Passive Filter (excessive ripple, over-temperature)
- Load (overvoltage, over-temperature)
- Personnel (interlock on doors, emergency off button, ...)

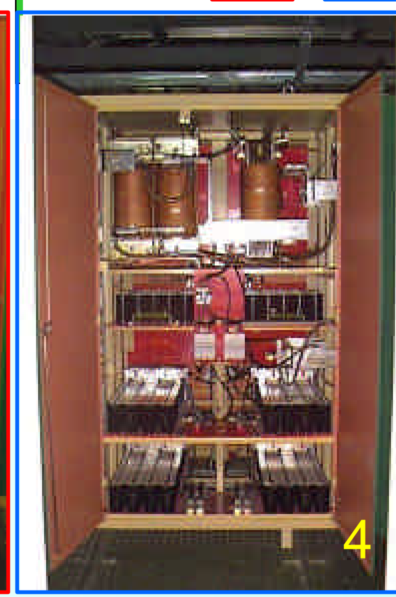


Example: Elettra's SR Dipoles' PS

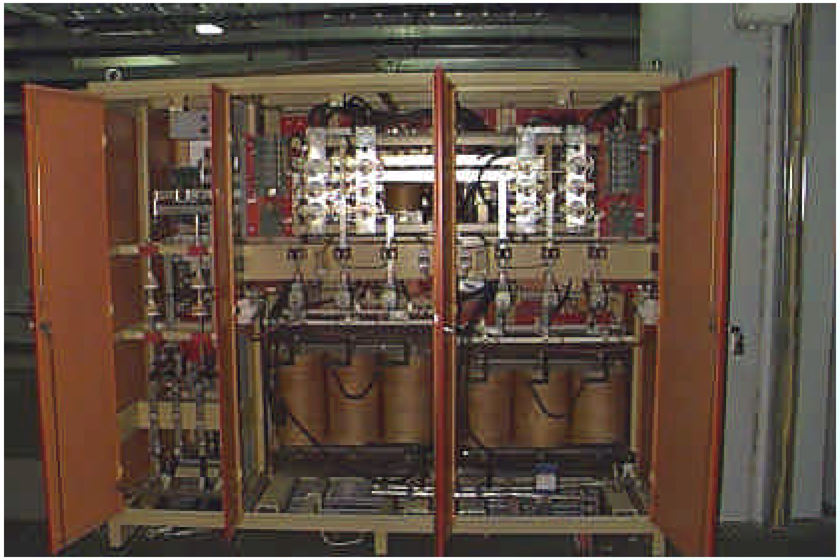
1. Circuit Breaker
2. Transformer
3. Bridge (a) & Thyristor (b)
4. Passive Filter
5. PS cabinet
6. Magnets







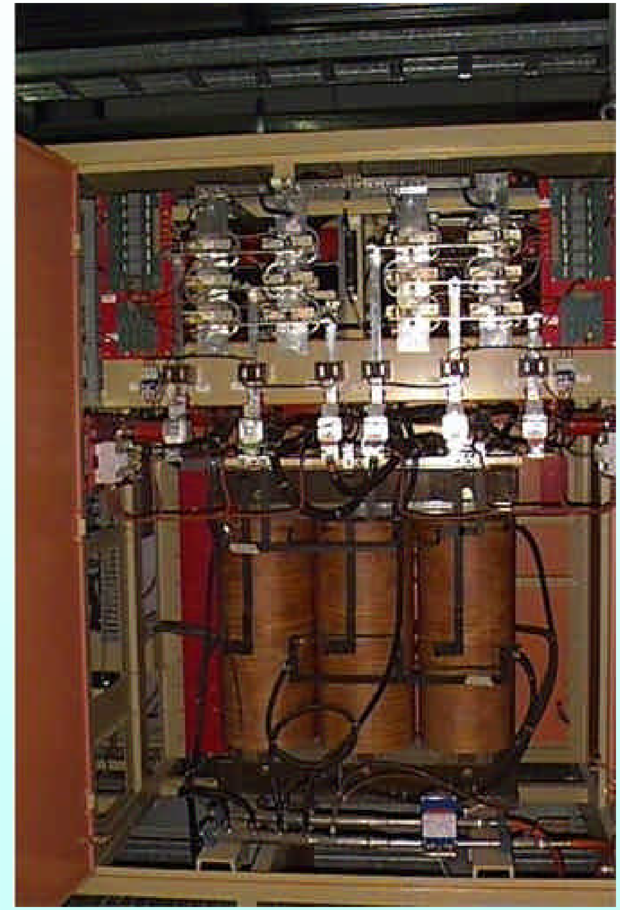
Example: Elettra's SR quads' PS



Elettra – Storage Ring QD and S1Power Supplies Cabinet.

Elettra – Storage Ring Quadrupoles.

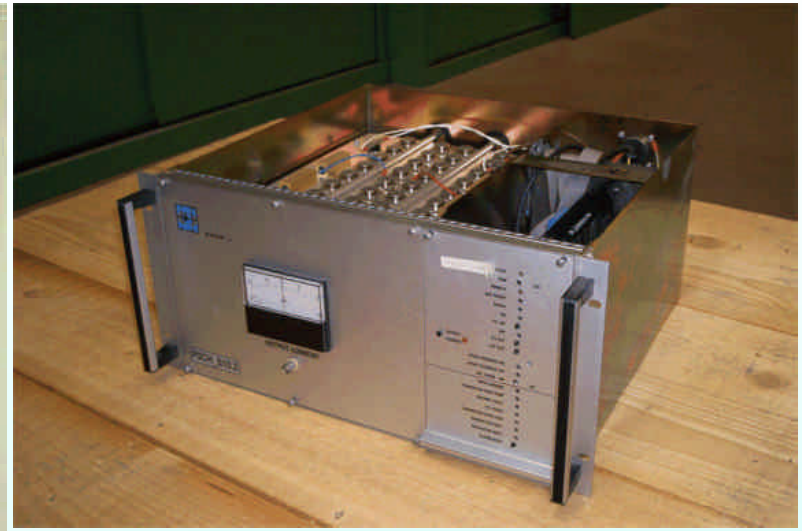
- 6-p and 12-p Converters
- Single and Multiple converters in each cabinet



Elettra – Storage Ring QF Power Supply Cabinet.

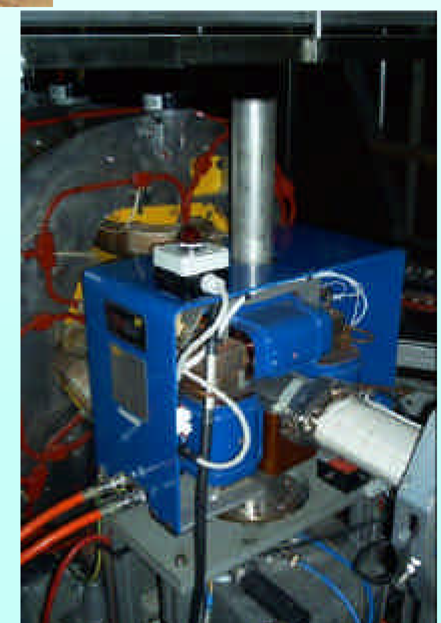
Example: Elettra's SR Steerers' PS

Elettra – Storage Ring Correctors Power Supplies Cabinet.



Elettra – Storage Ring Corrector Power Supply.

Elettra – Storage Ring Combined H+V corrector.



Linear Multichannel:

- Thyristor Pre-Regulator
- 12-p Diode Bridge (in series, "zero" is common point)
- 14 Channels + 2 spares

Line Comm. Rectifiers – Pros & Cons

Pros

- Very well known and established technology with simple structures
- The effect of "parasitic" parameters (inductance and capacitance) is low
- High Efficiency
- High Voltage and High Power Capability
- Used as "building blocks" inside Switched Mode converters with "Unity Power Factor"

Cons

- Bandwidth limited (not really important for DC applications)
- Power factor depending on firing angle, in any case below 0.75
- Strong Harmonic content on input current
- Thyristors notches in mains and noise spikes
- Large and heavy magnetic elements (transformers, chokes)
- Residual ripple at low frequency (300 Hz up) which require large passive filters and, often, active filters to meet specifications

Emerging Topologies...

Goals:

- Reduce alternating current harmonic content
- Improve Power Factor
- Better filtering of output current ripple
- Higher dynamic response
- More flexible control…

⇨ PWM Techniques

On the other hand:

- High Switching Frequency Þ parasitic elements ARE important
- Sometimes quite complicated structures
- EM noise