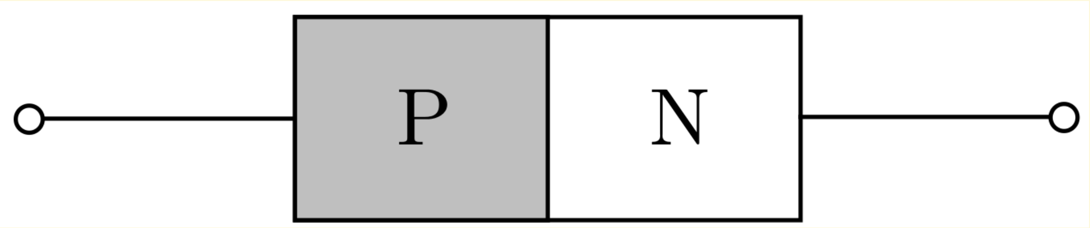
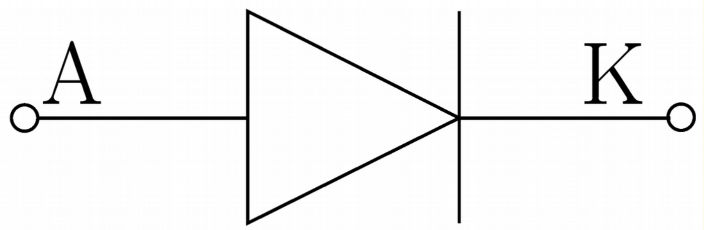
Power conditioning circuits

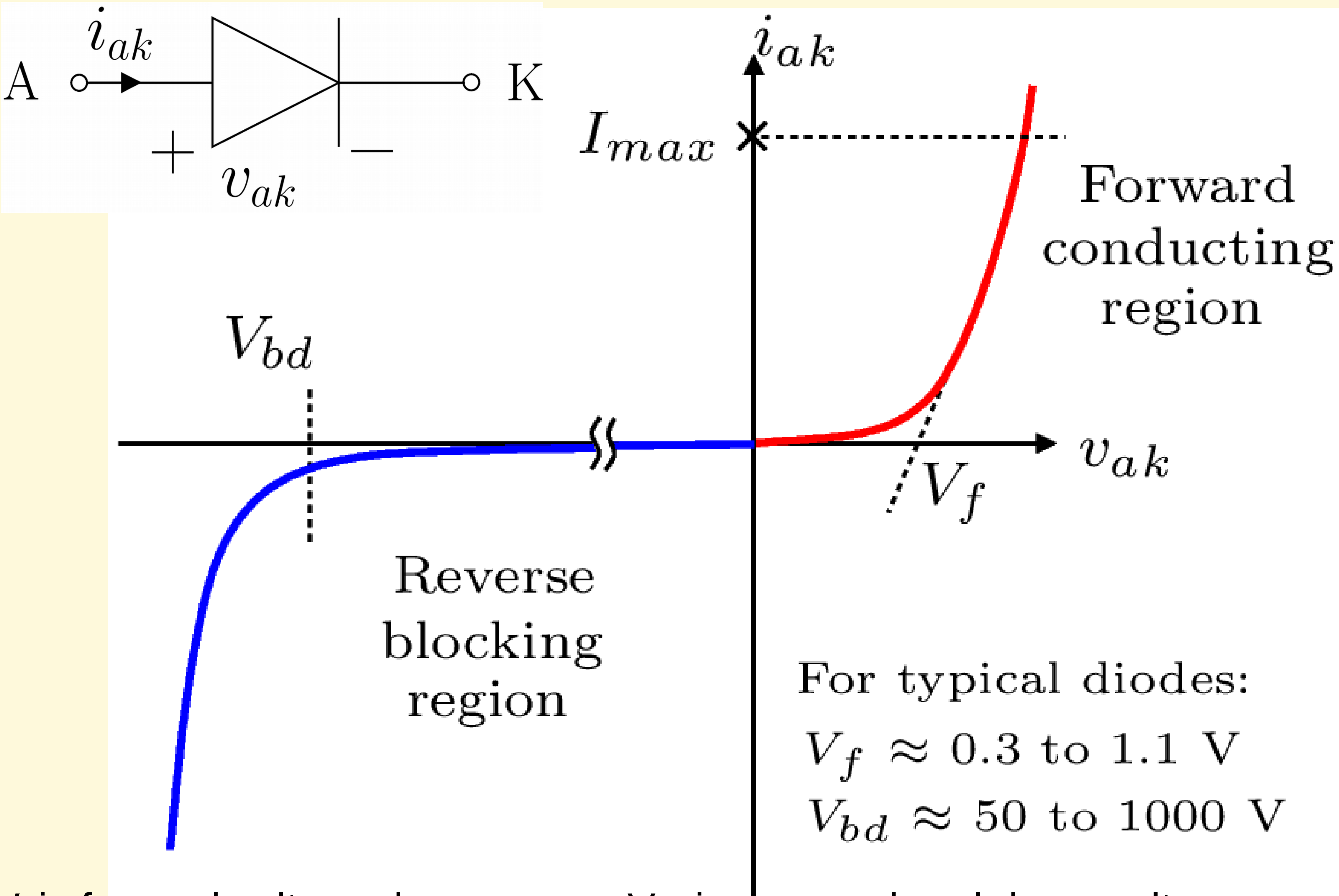
Diodes:





Anode Cathode

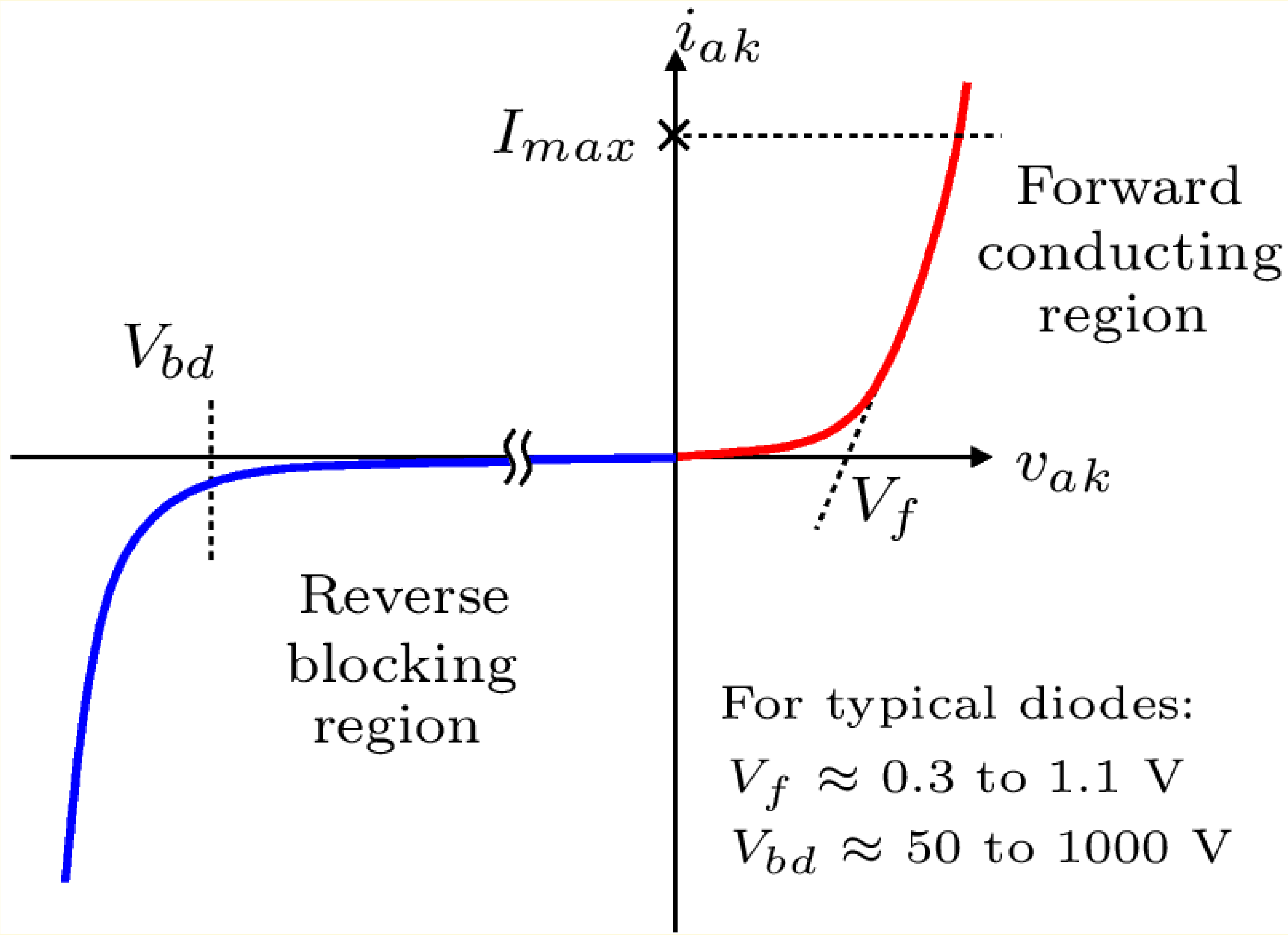
Diode characteristics:

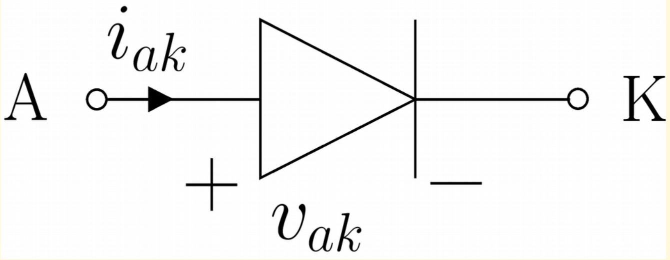


V_f is forward voltage drop, V_{bd} is reverse breakdown voltage.

Diode characteristics:

Model-1

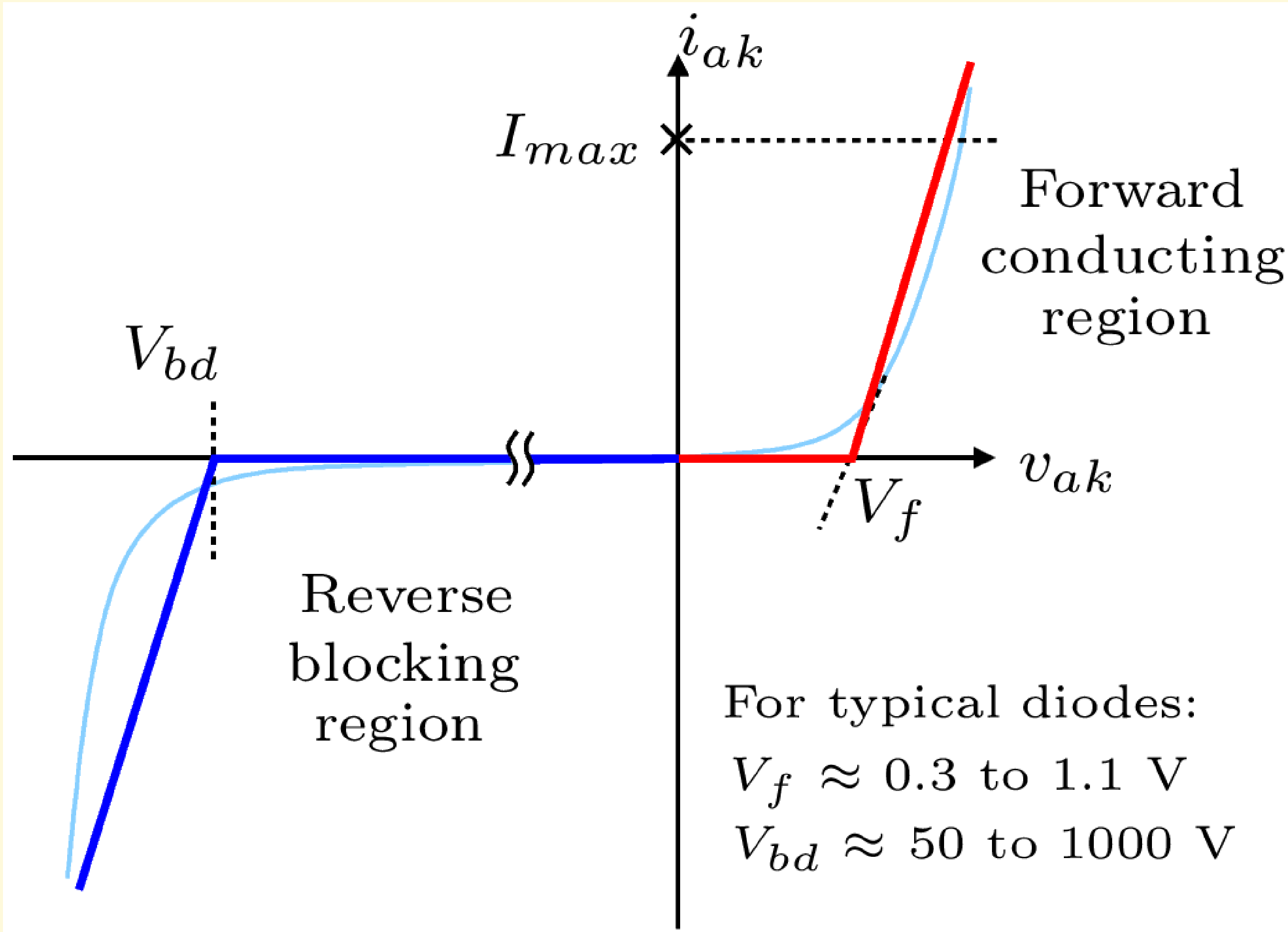


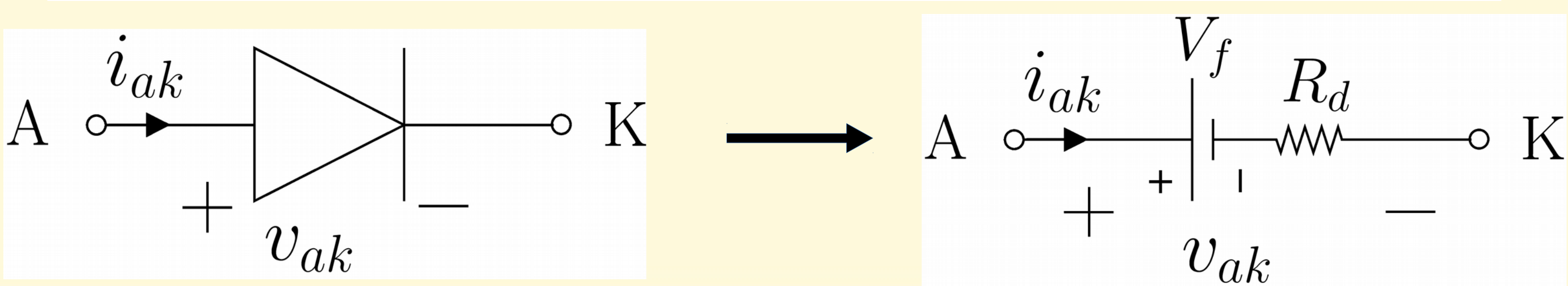


Non-linear
diode model.

Diode characteristics:

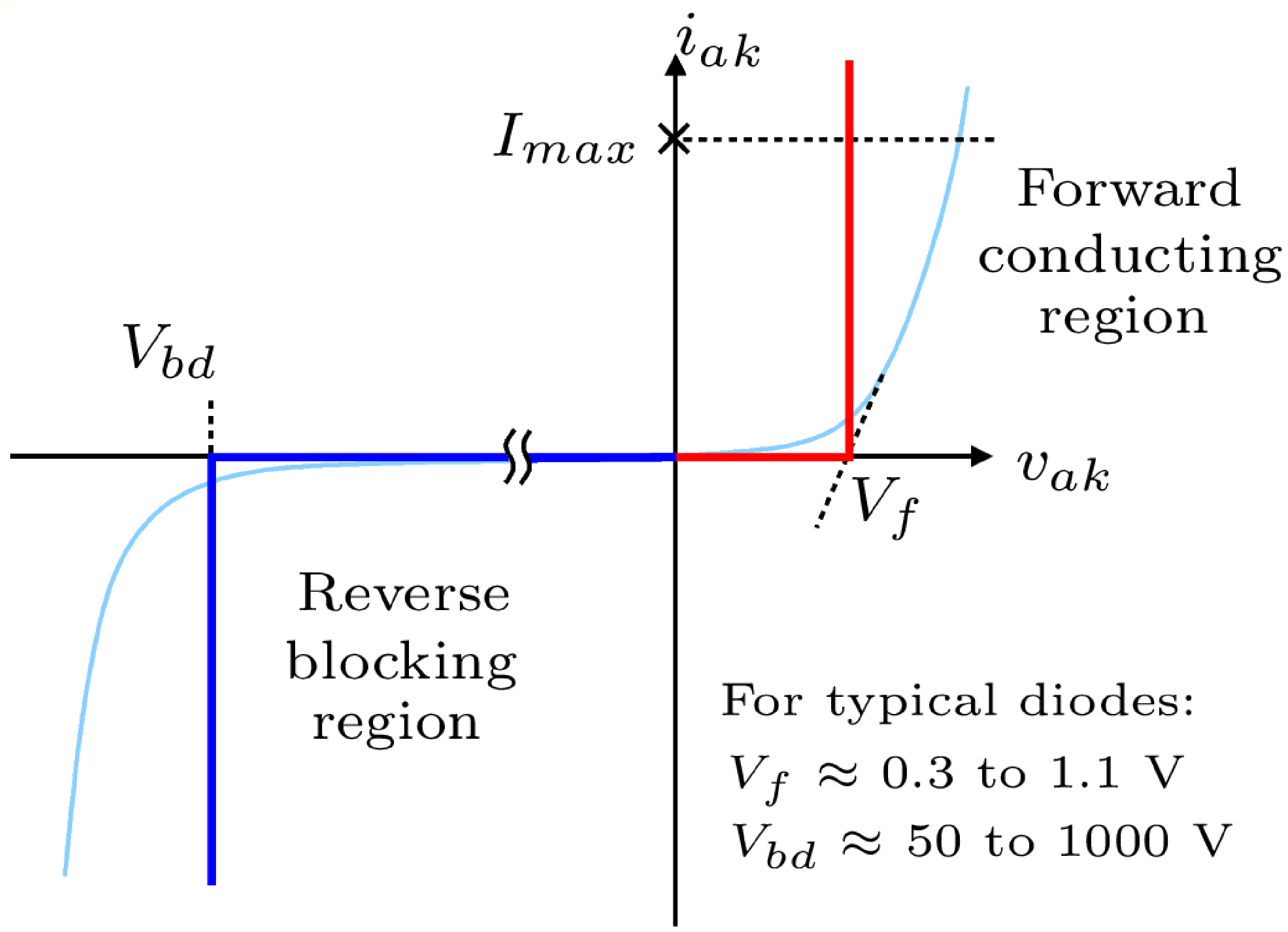
Model-2

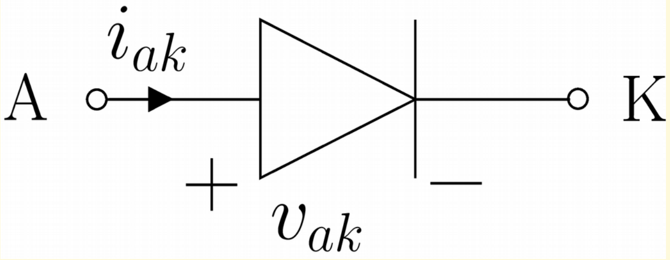


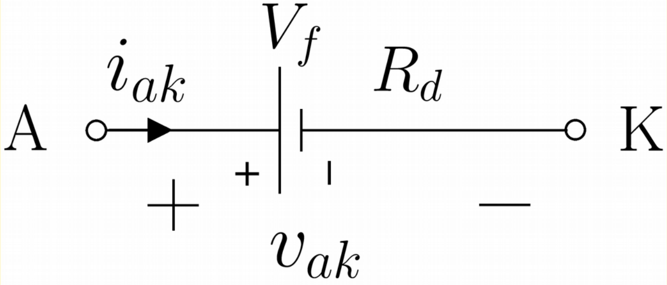


Diode characteristics:

Model-3

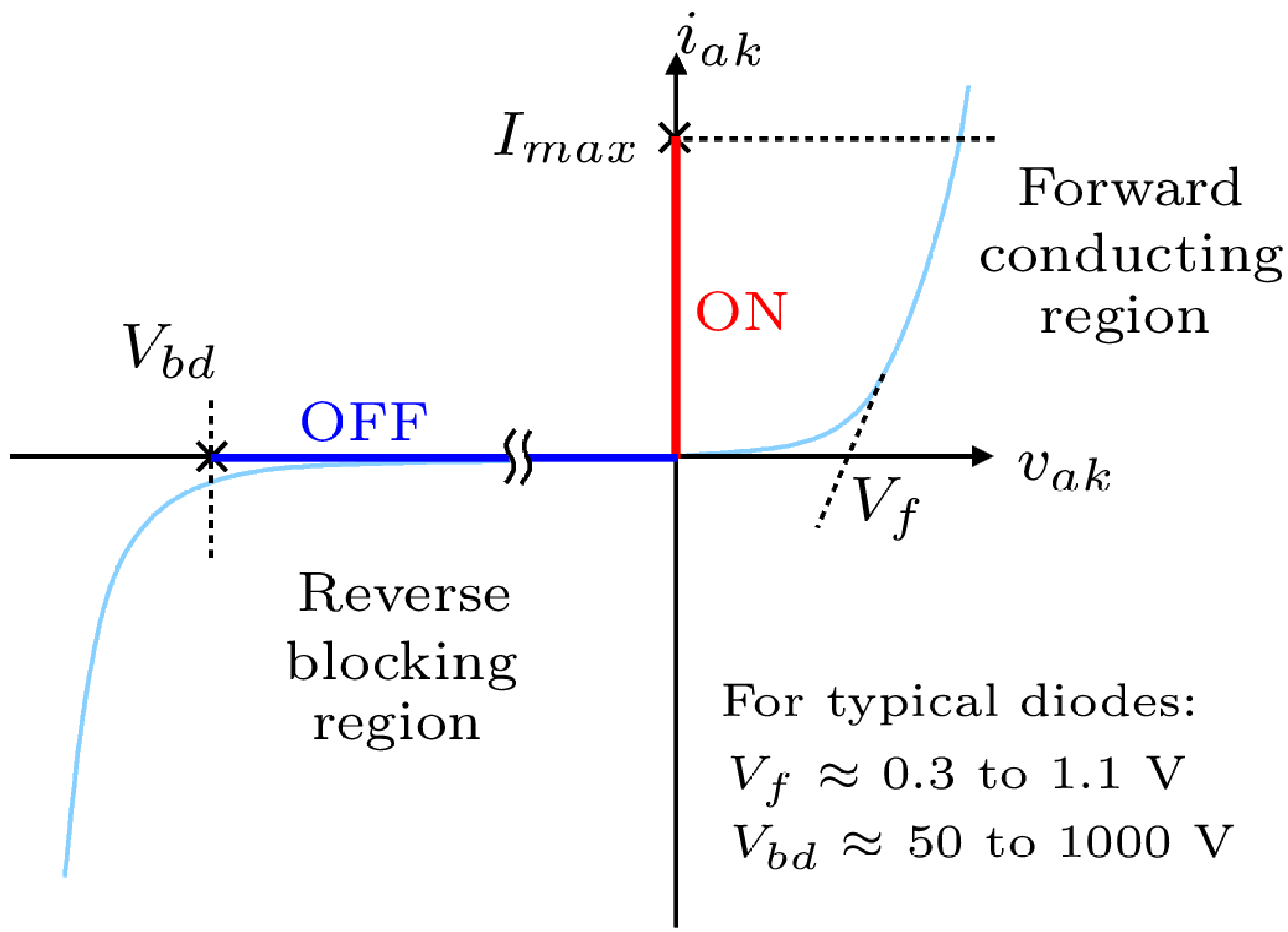


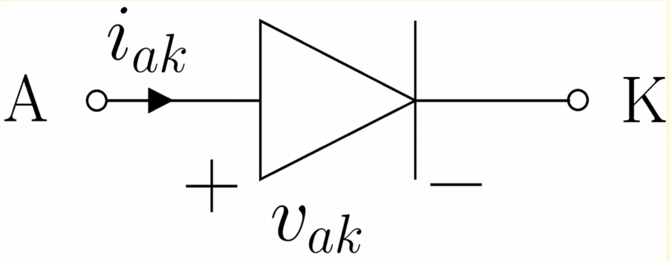




Diode characteristics:

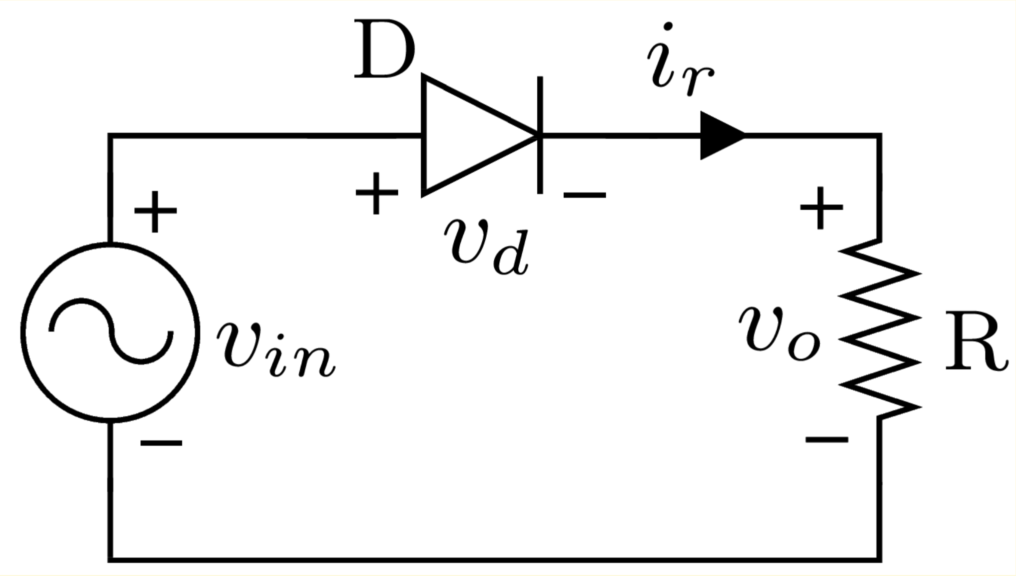
Model-4



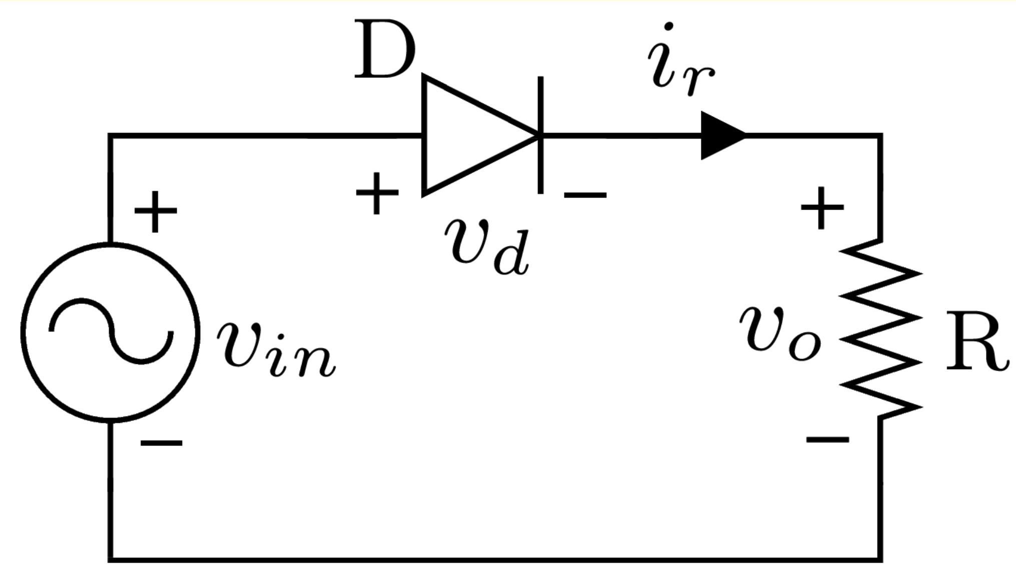


ON-OFF
(2 states) model.

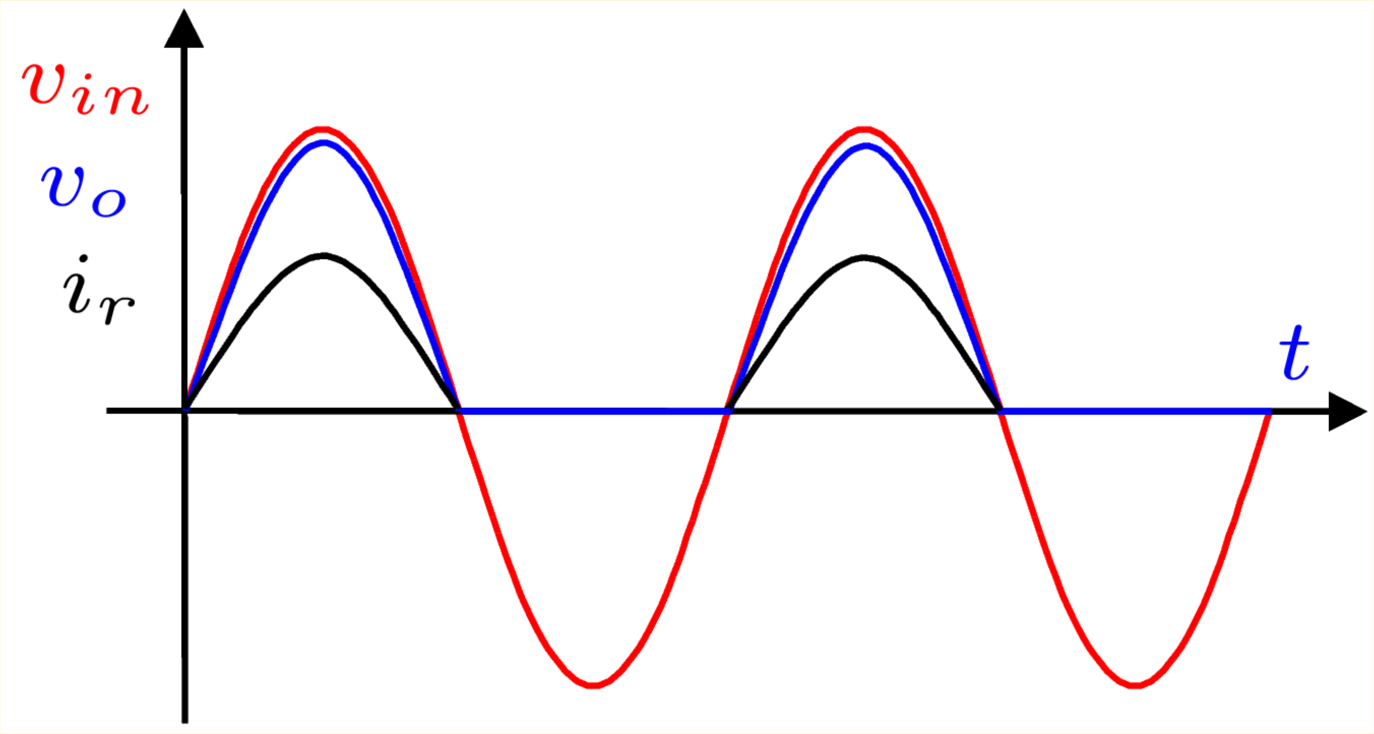
Simple circuits with diode:



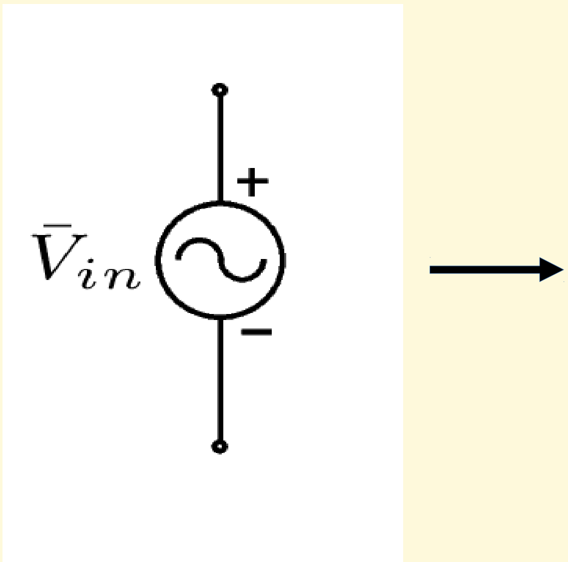
Simple circuits with diode:



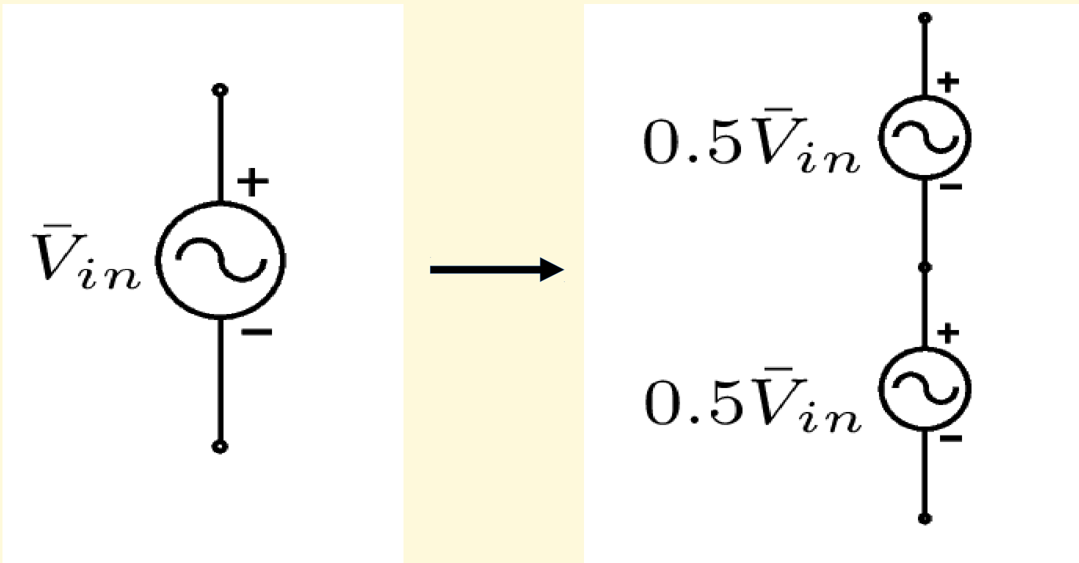
Single-phase **half wave** rectifier

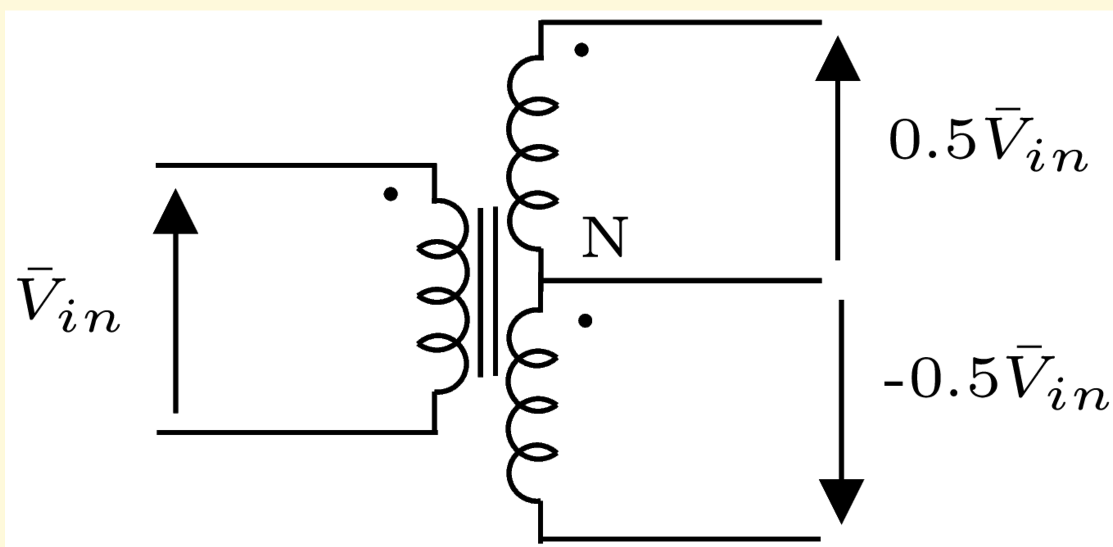


Simple circuits with diode:

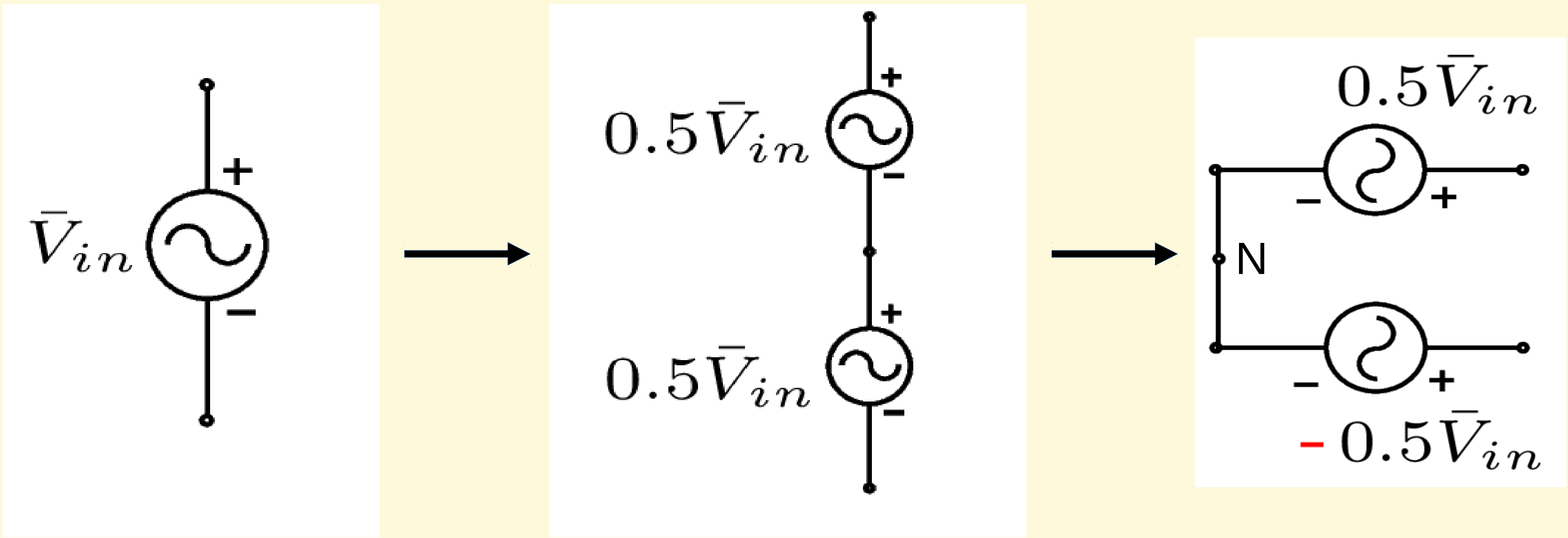


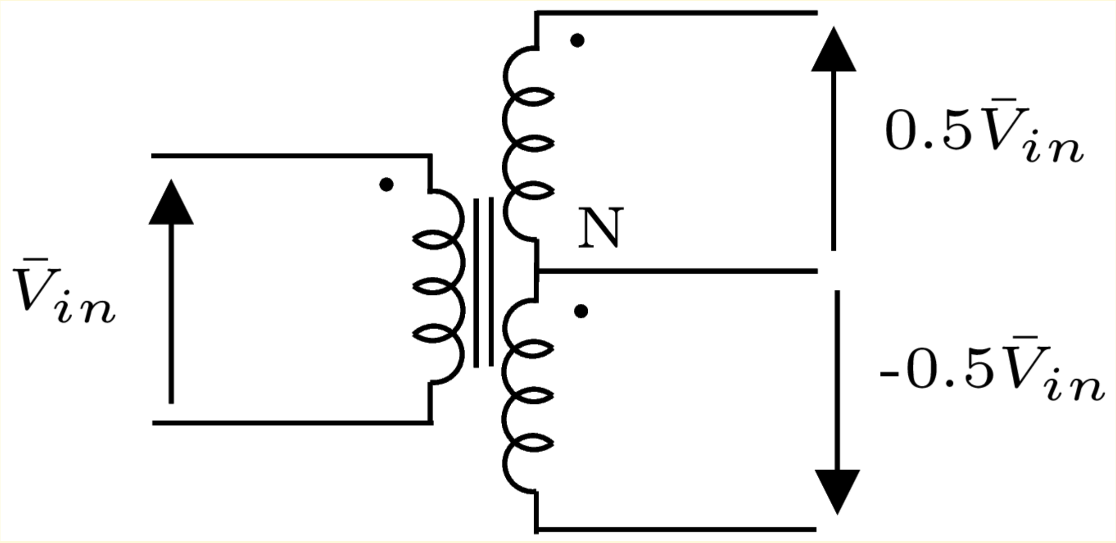
Simple circuits with diode:



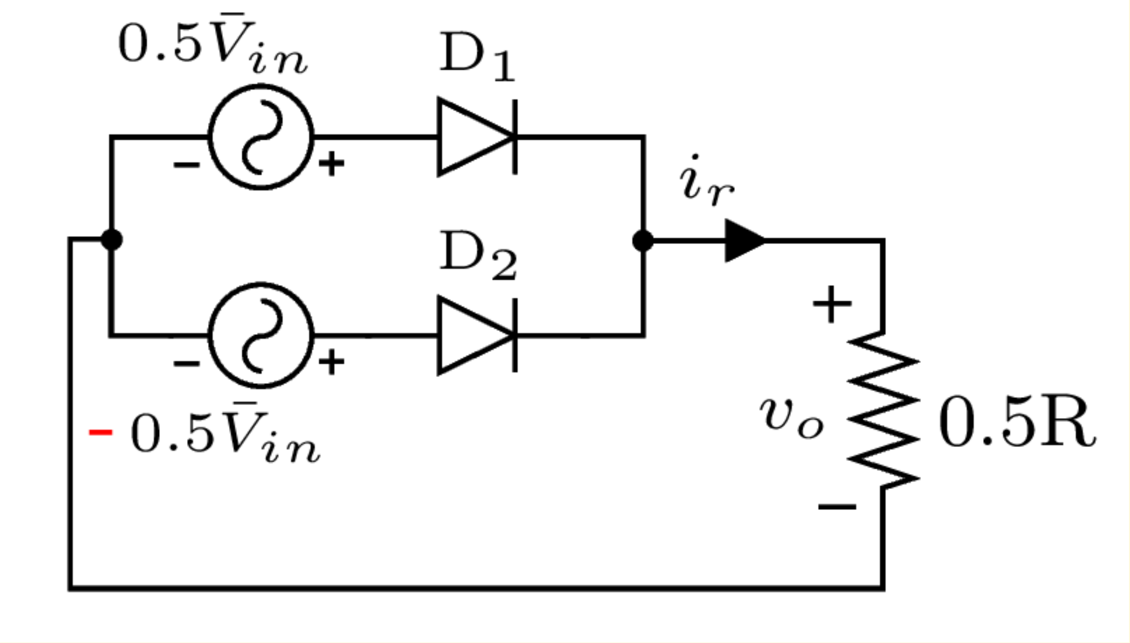


Simple circuits with diode:



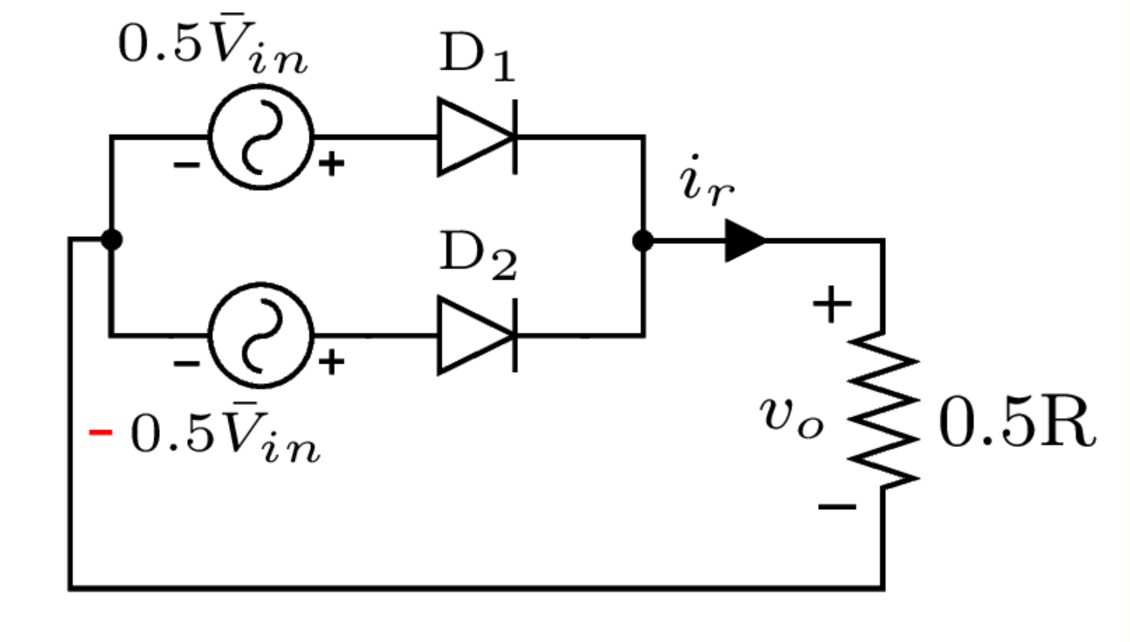


Simple circuits with diode:

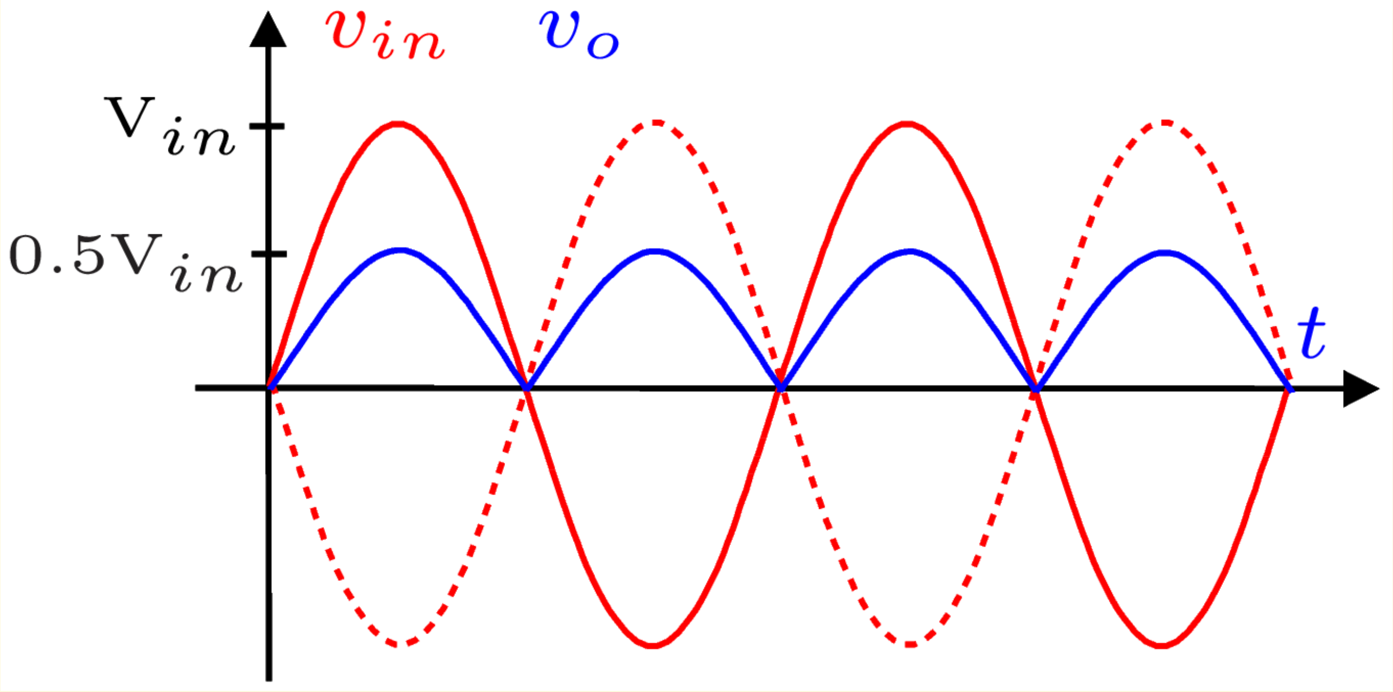


Single-phase center tapped **full wave** rectifier

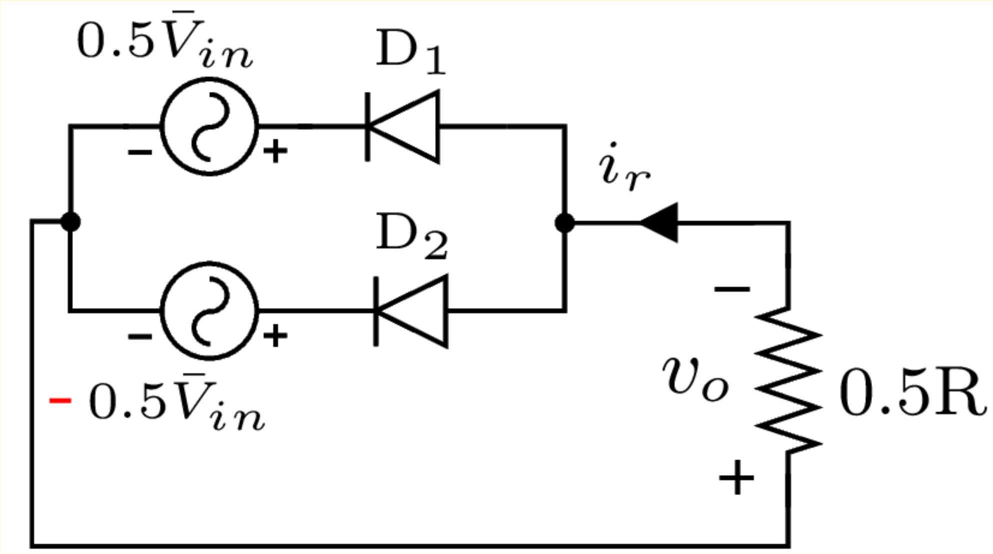
Simple circuits with diode:



Single-phase center tapped **full wave** rectifier

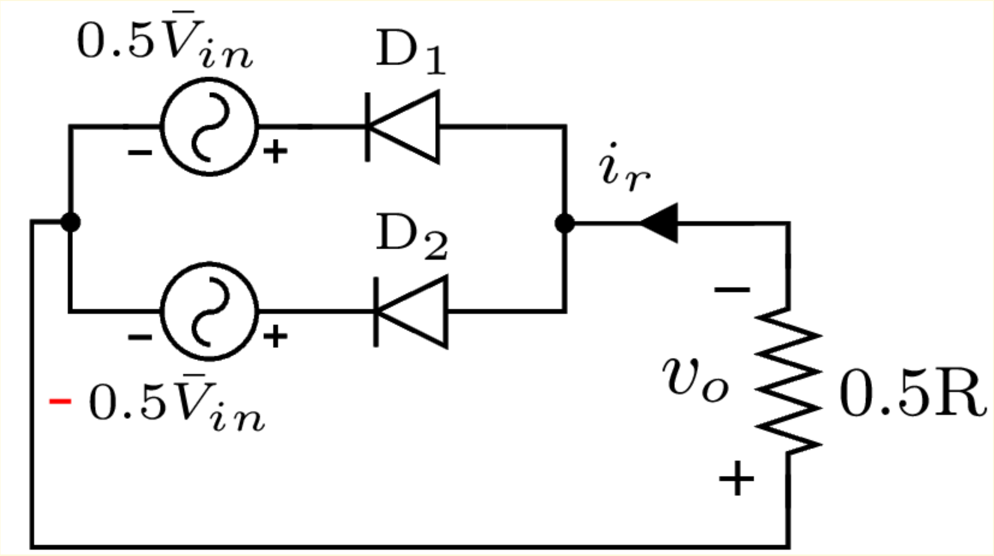


Simple circuits with diode:

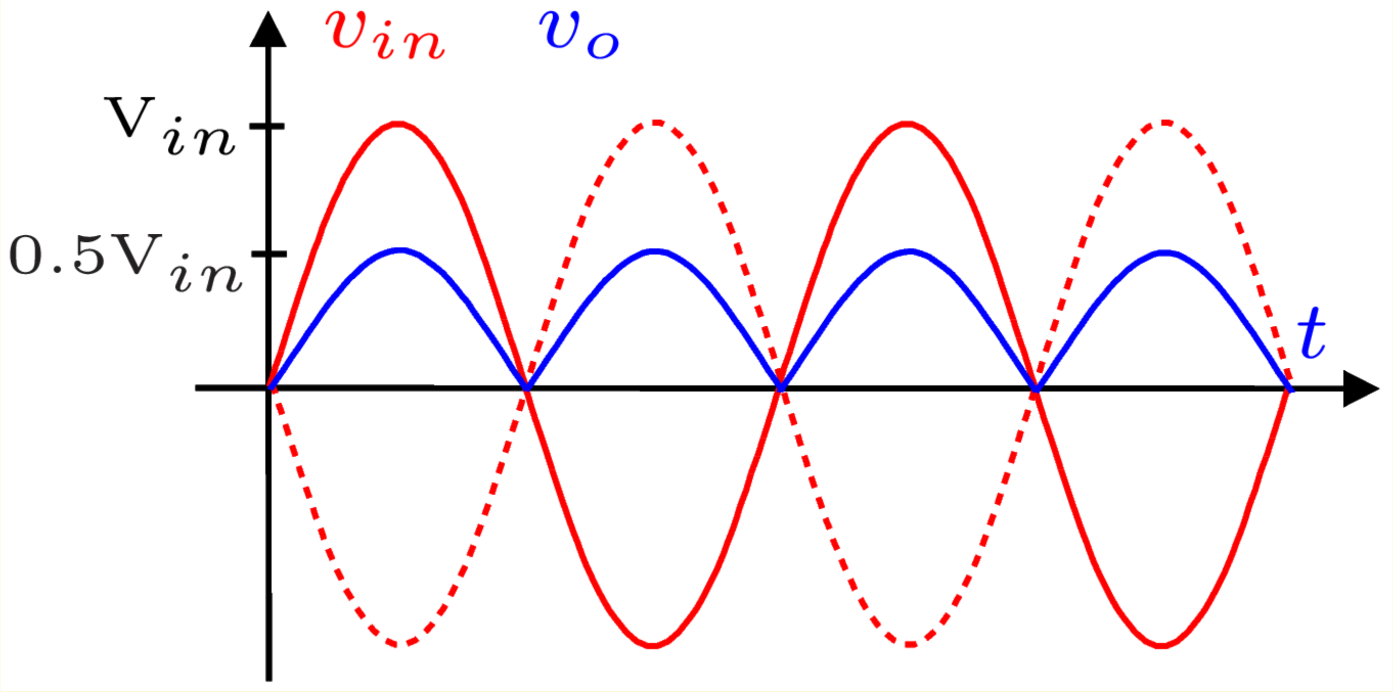


Single-phase center tapped **full wave** rectifier

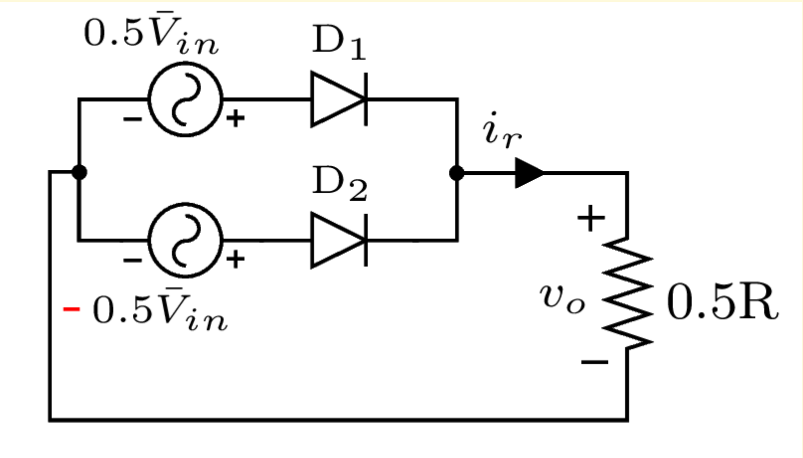
Simple circuits with diode:

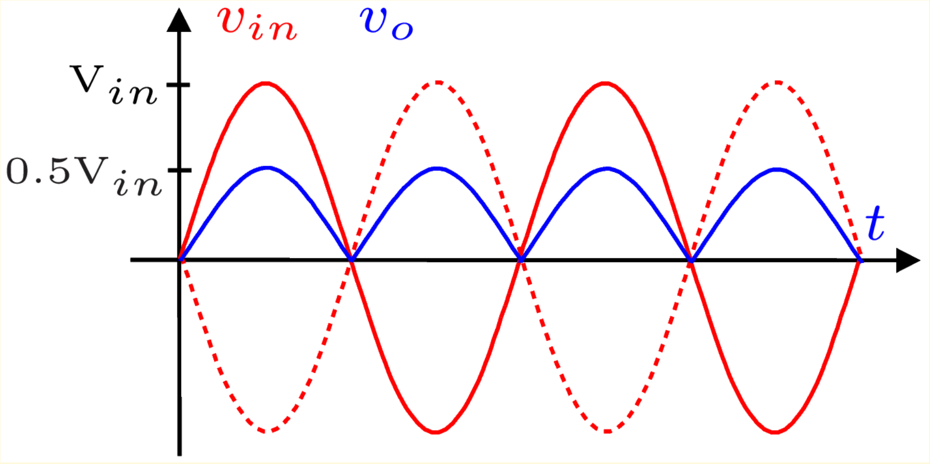


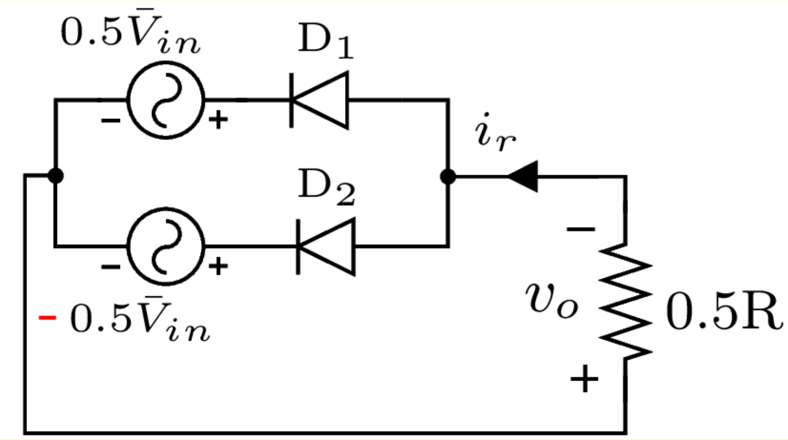
Single-phase center tapped **full wave** rectifier

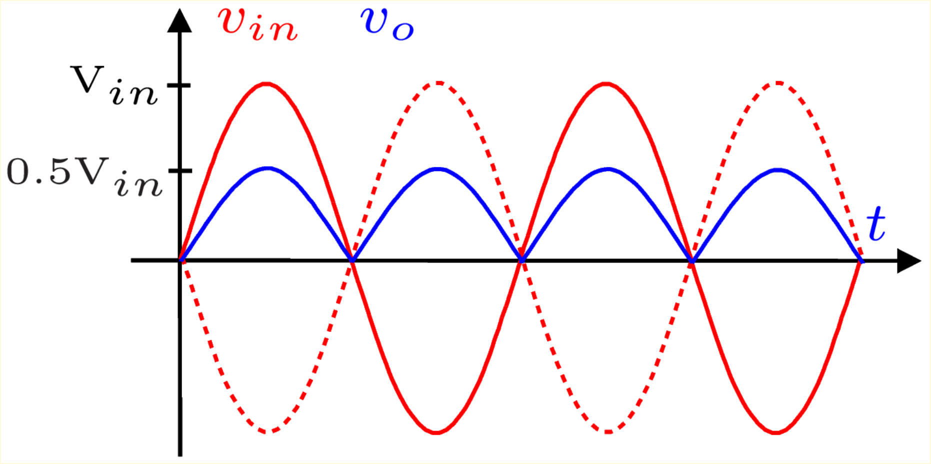


Simple circuits with diode:

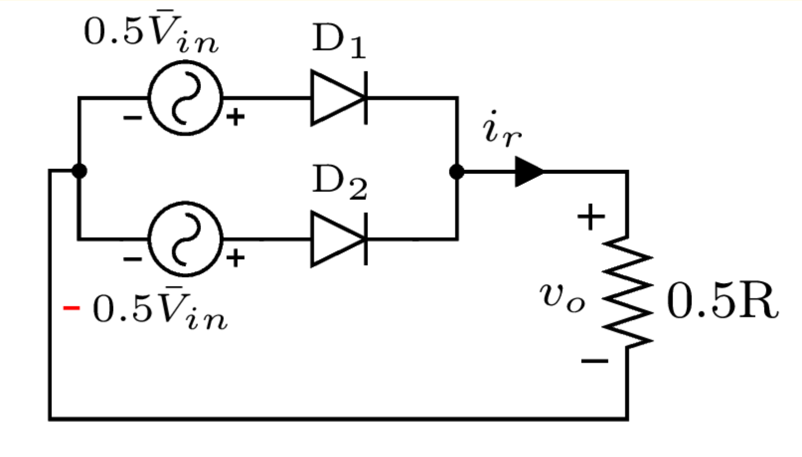


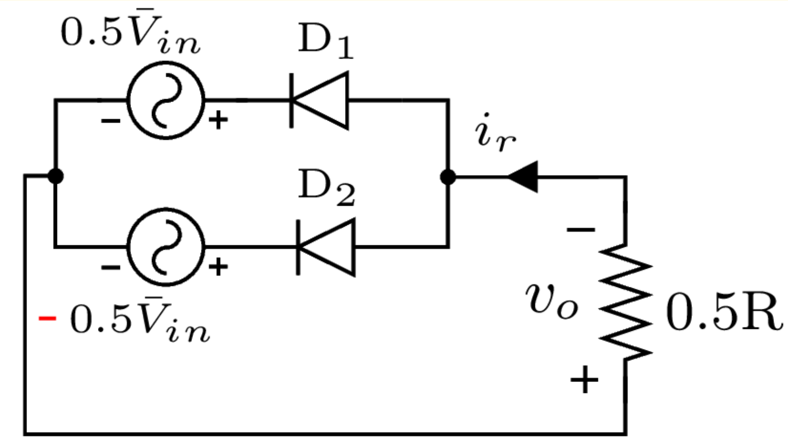


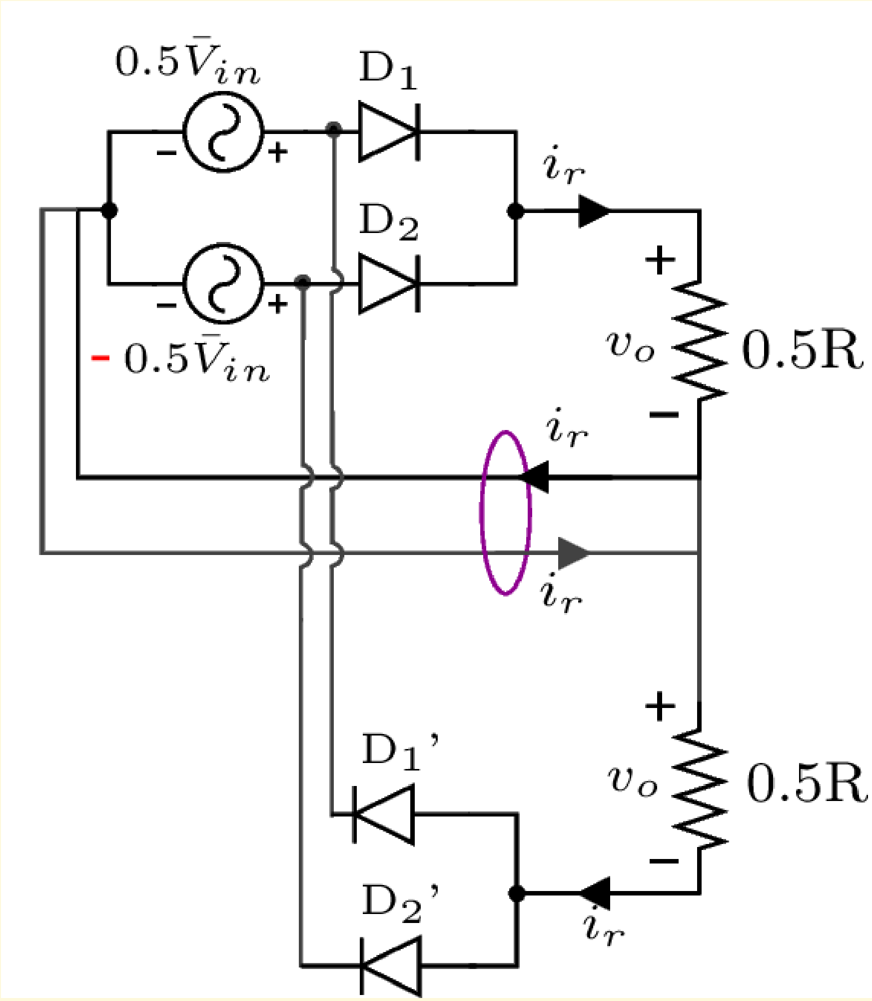




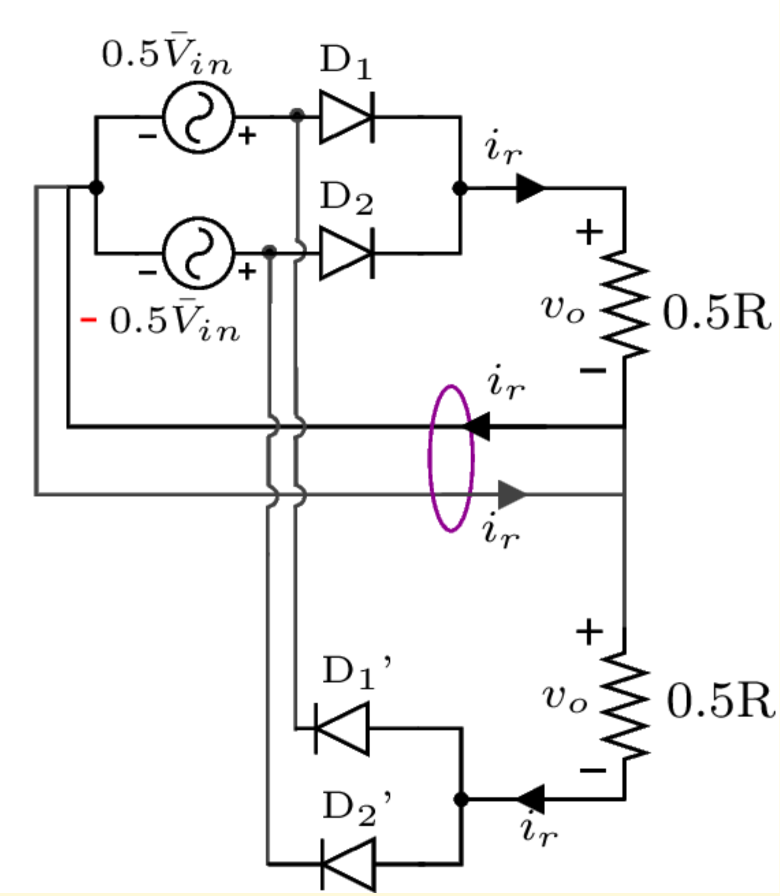
Simple circuits with diode:



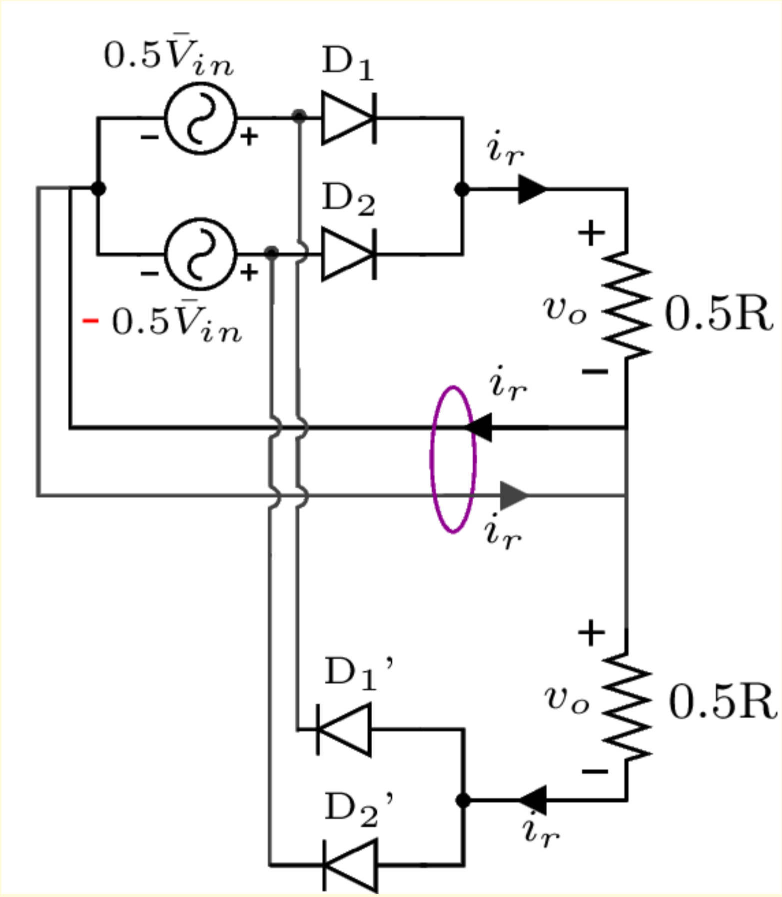


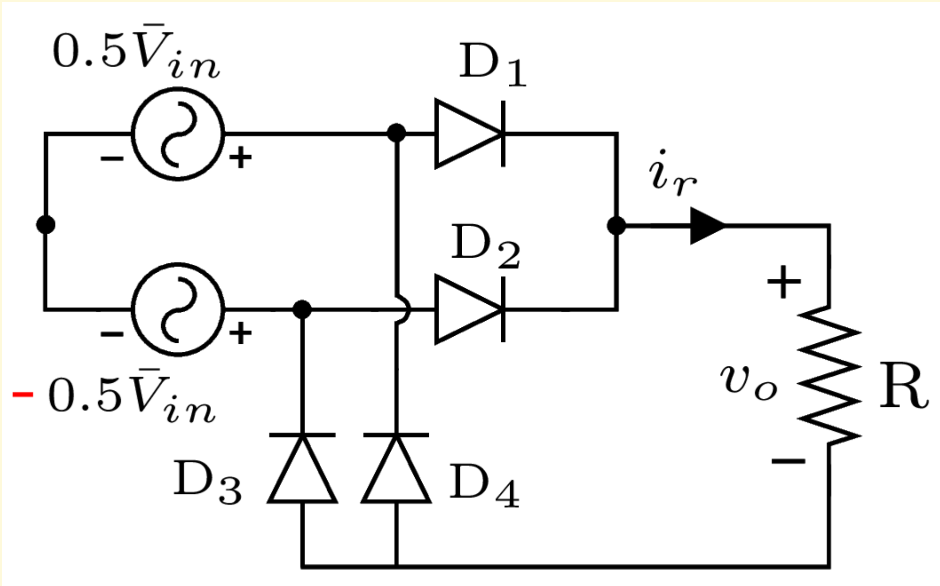


Simple circuits with diode:

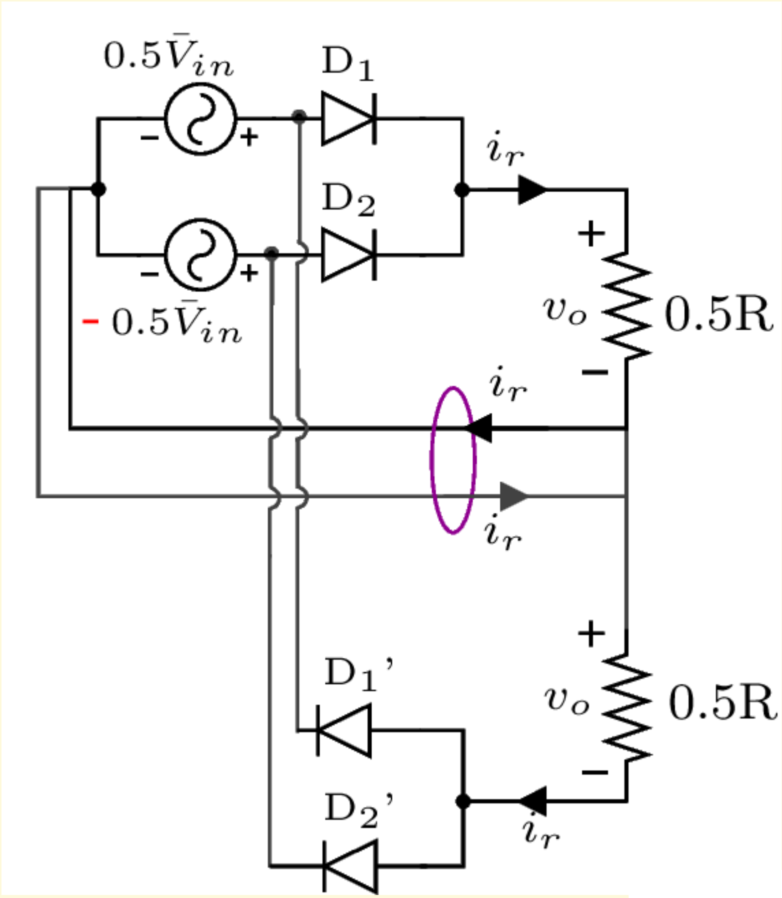


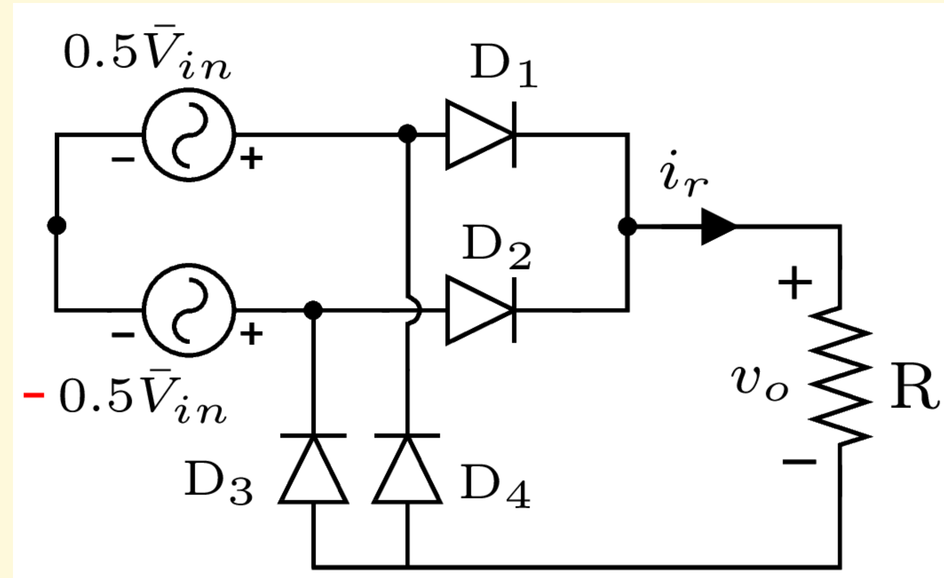
Simple circuits with diode:

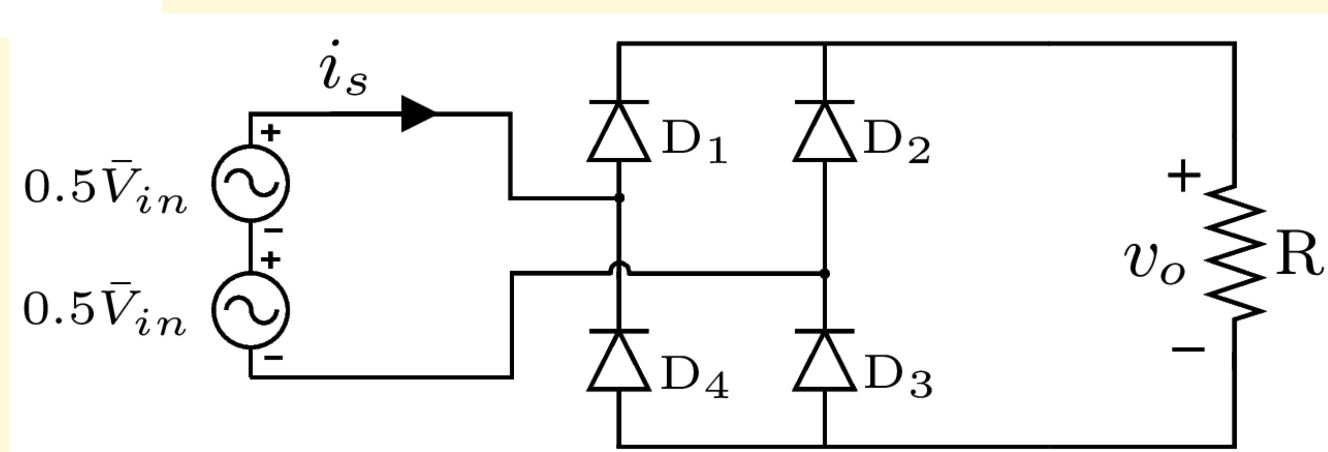




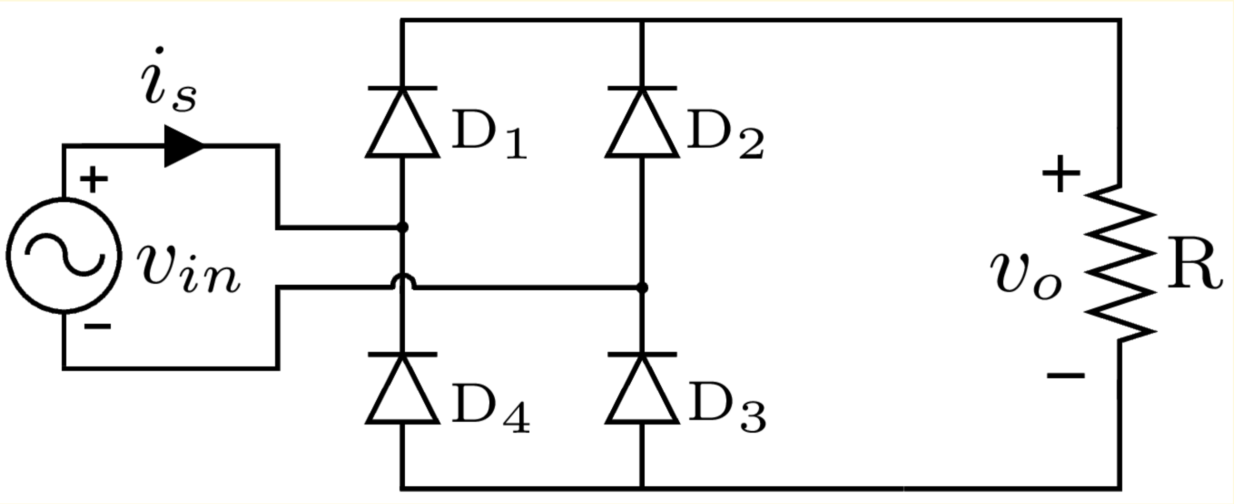
Simple circuits with diode:



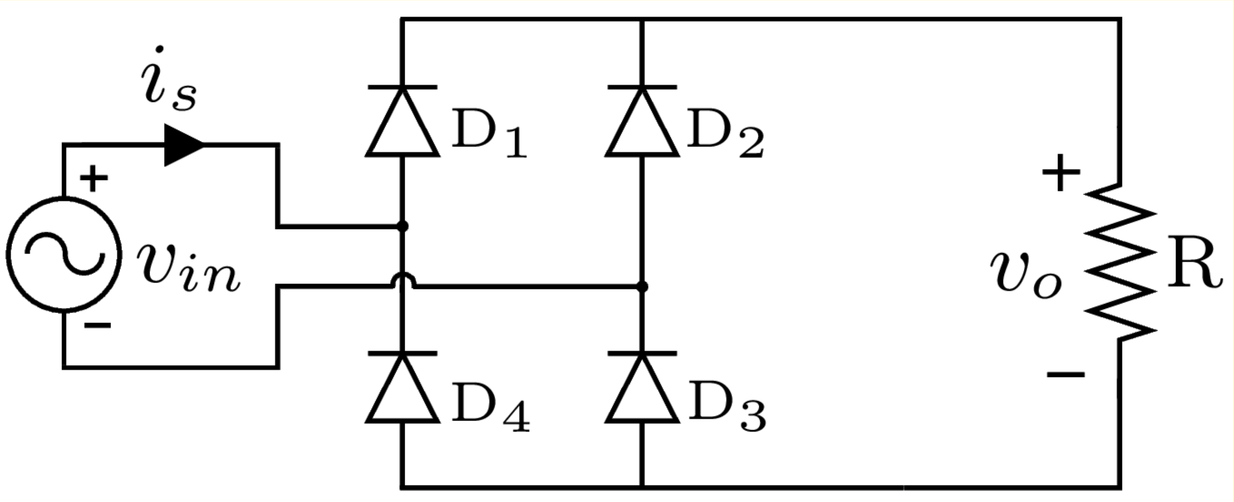




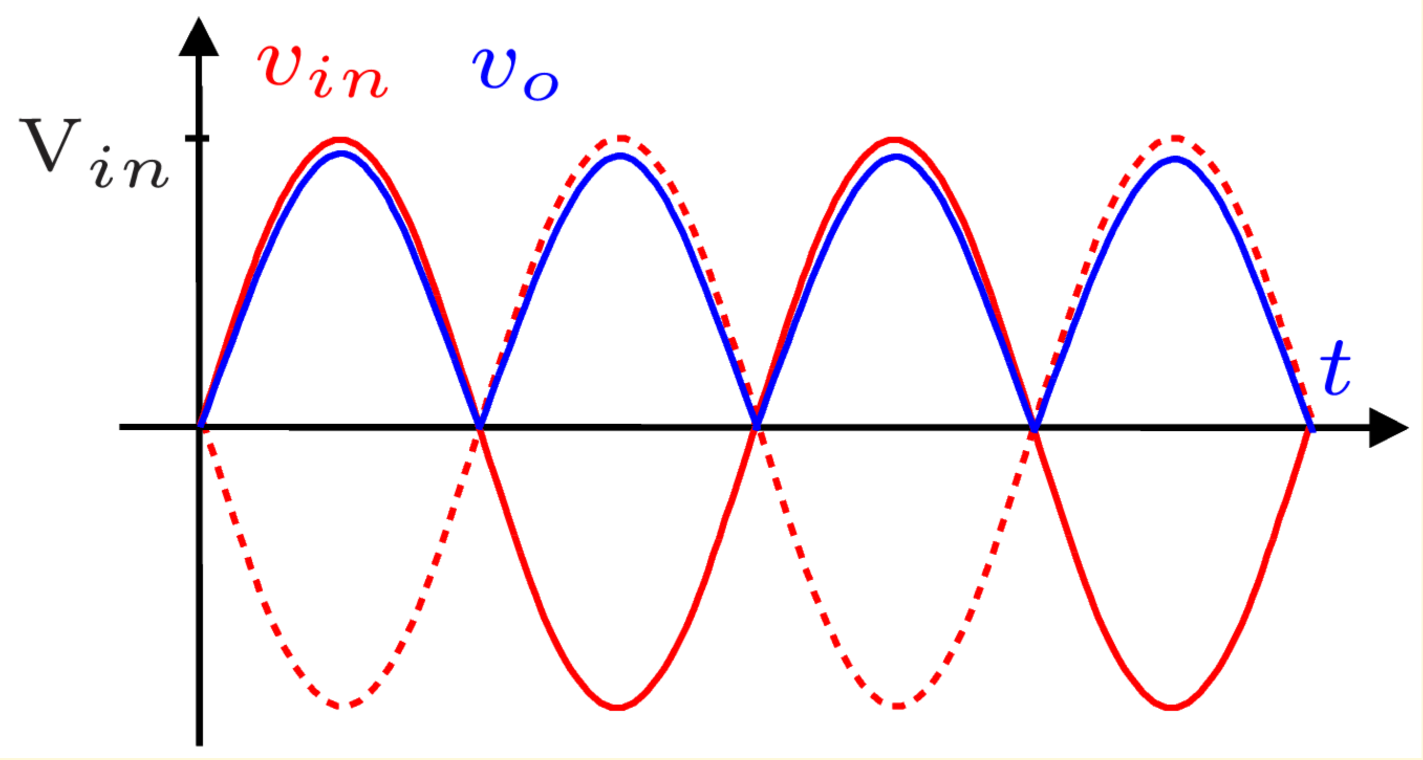
Simple circuits with diode:



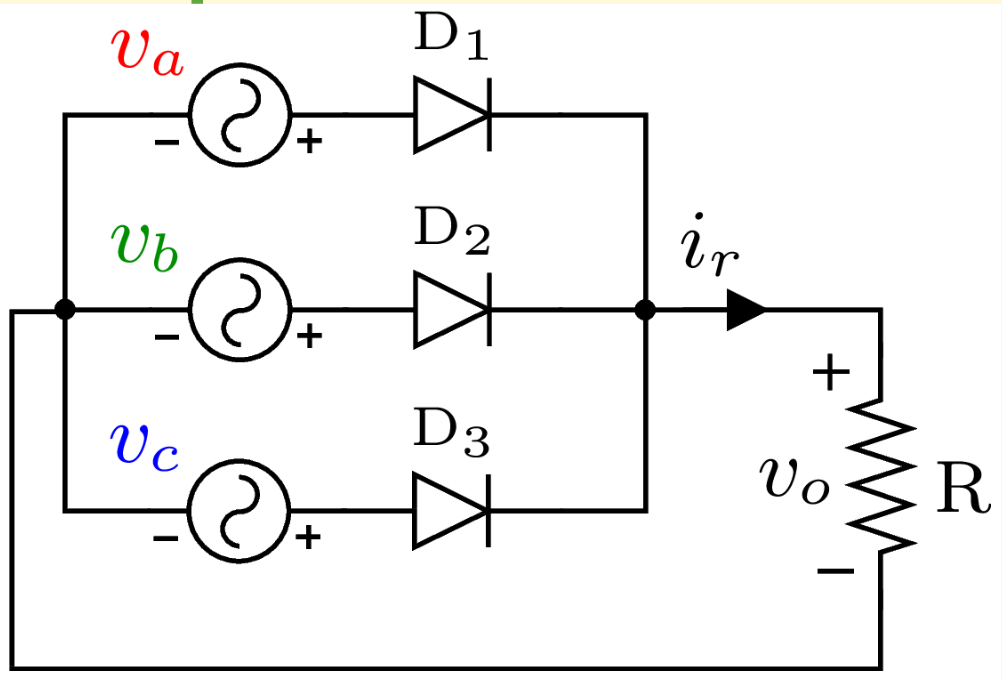
Simple circuits with diode:



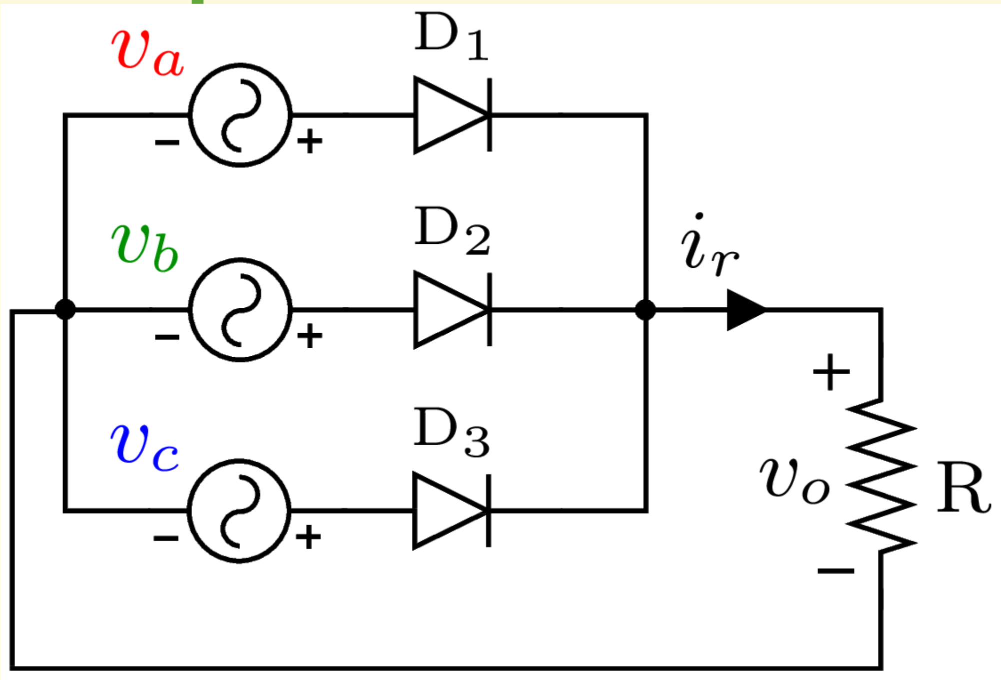
Single-phase **full wave bridge** rectifier



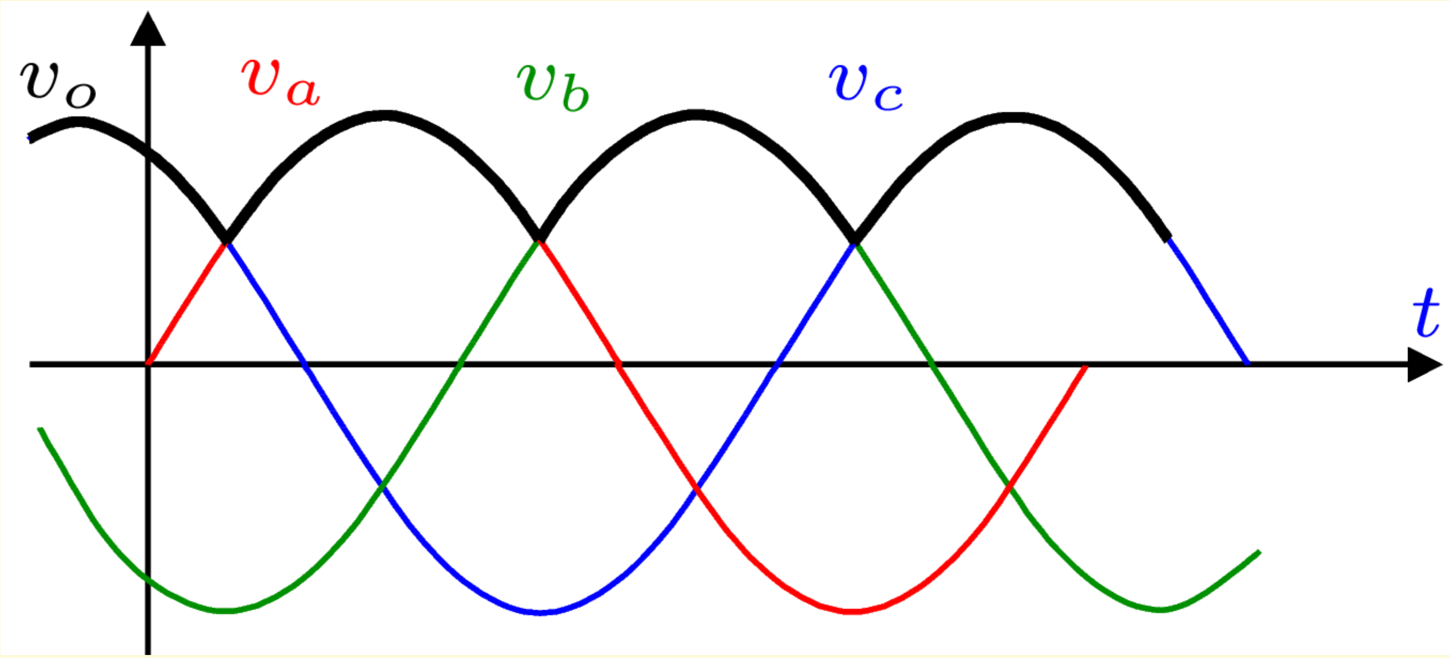
Simple circuits with diode:



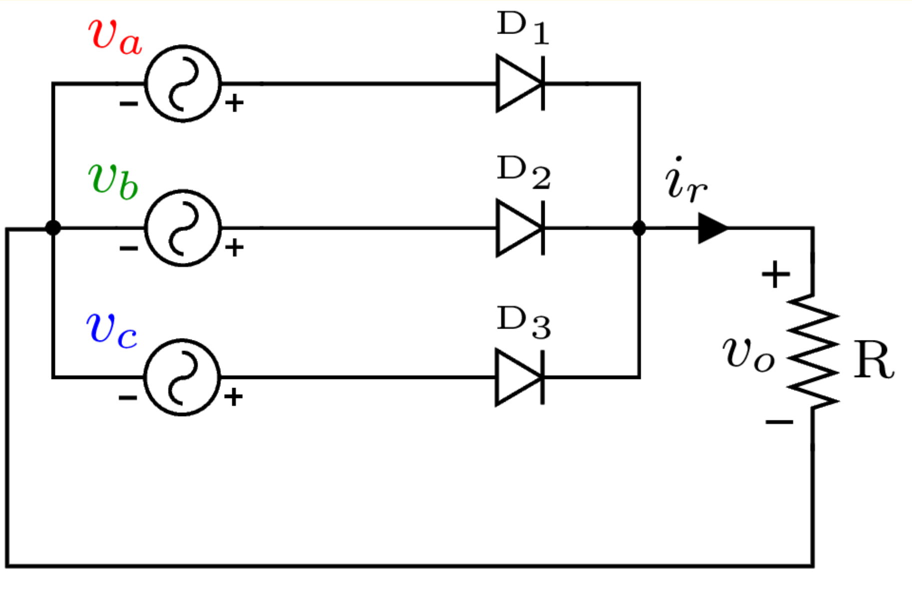
Simple circuits with diode:



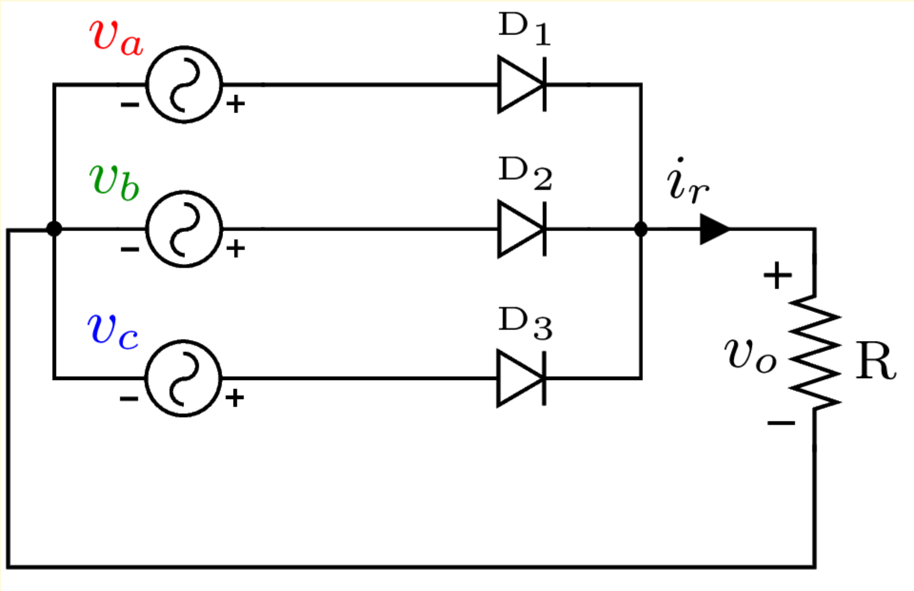
Three-phase **half wave** rectifier

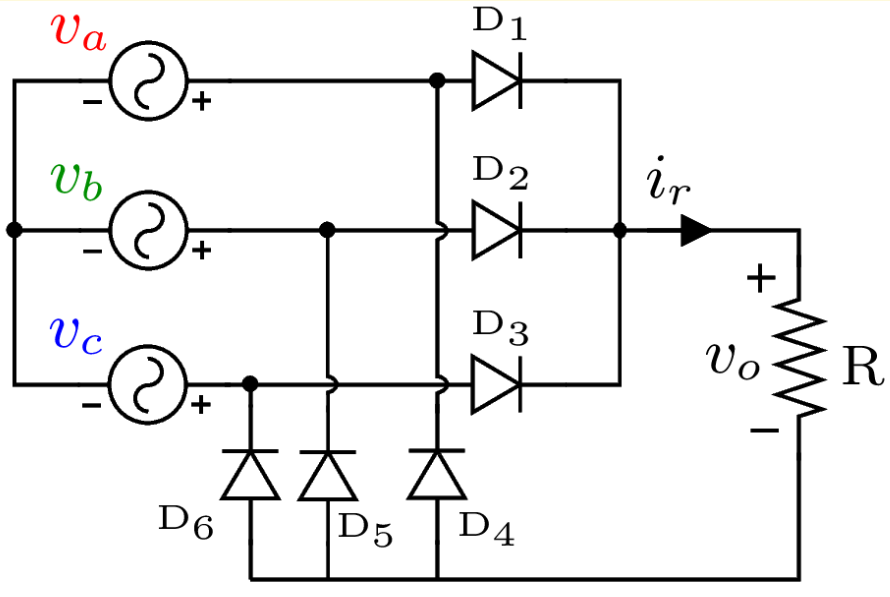


Simple circuits with diode:

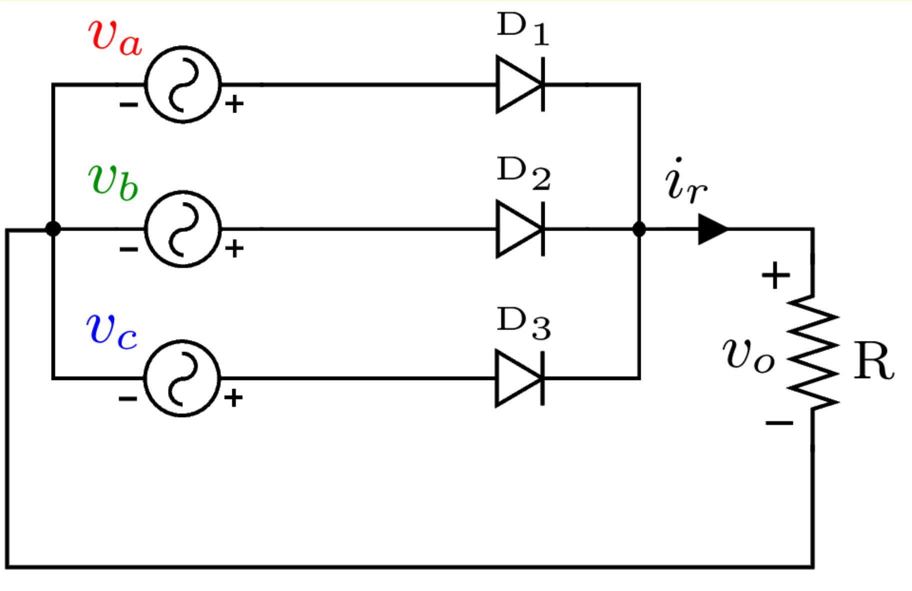


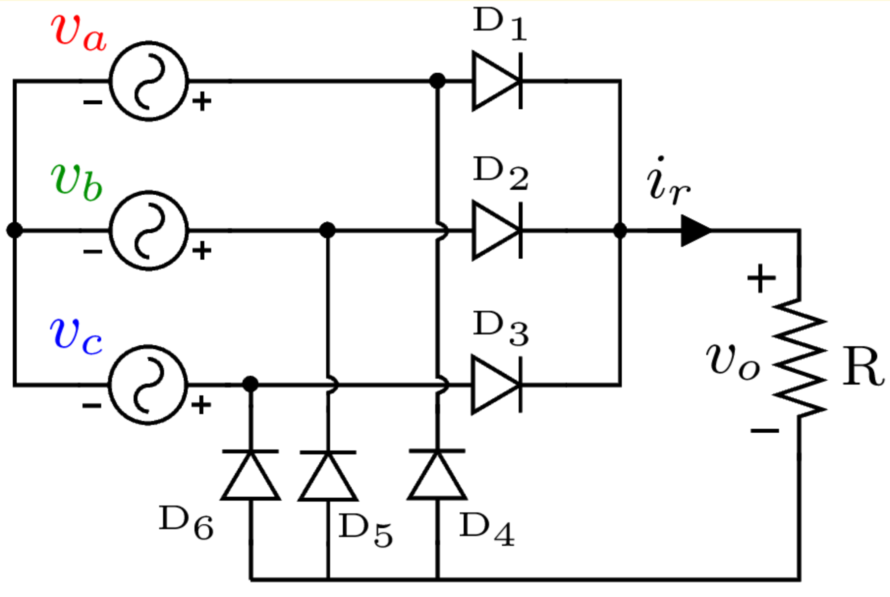
Simple circuits with diode:

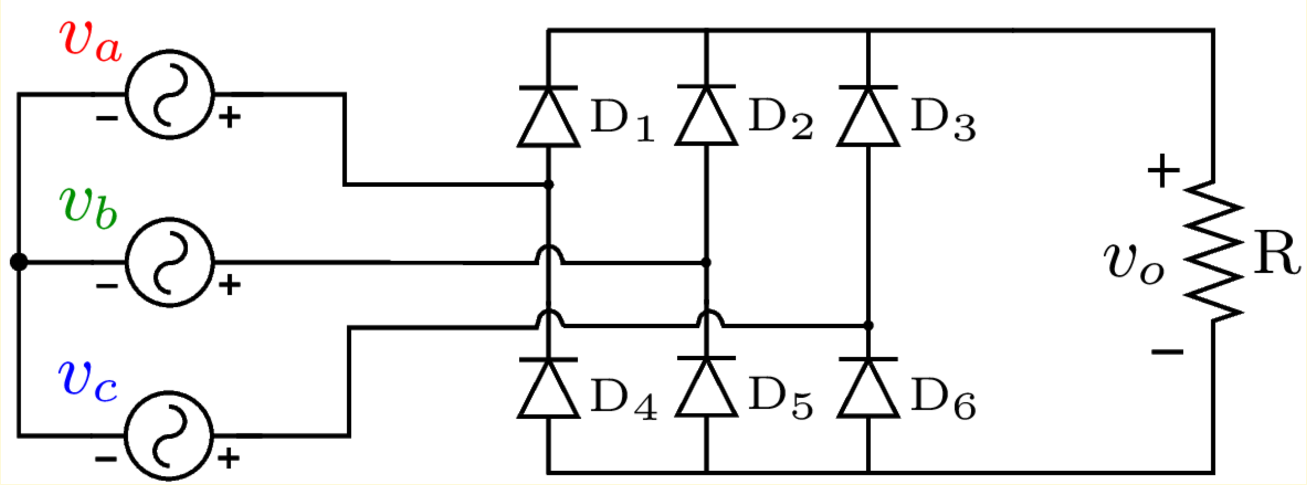




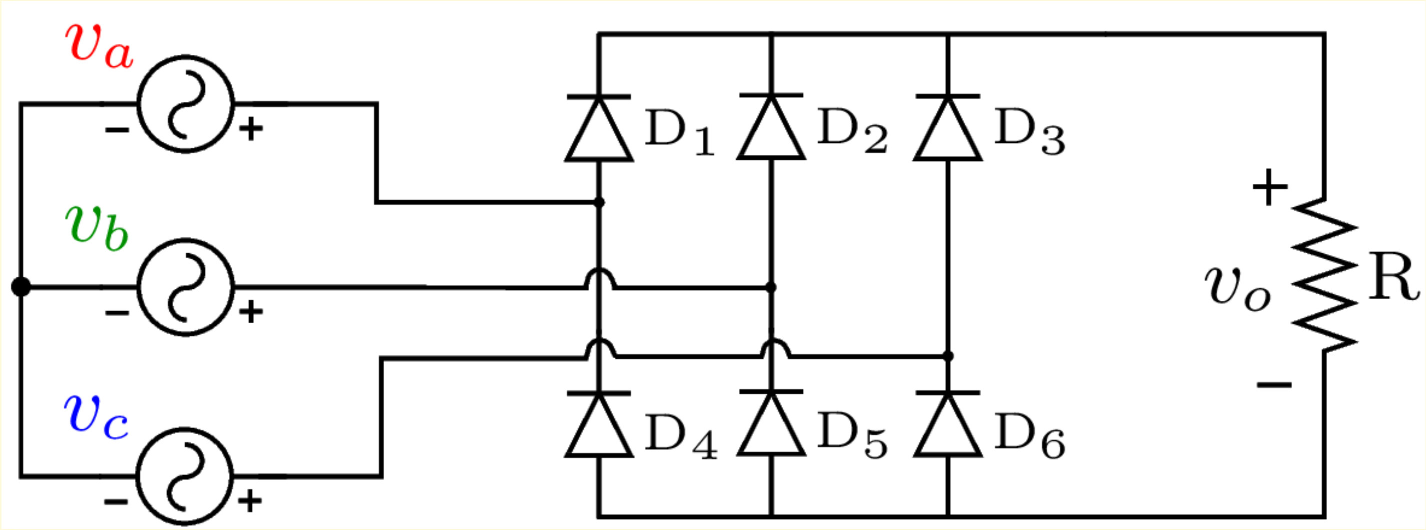
Simple circuits with diode:



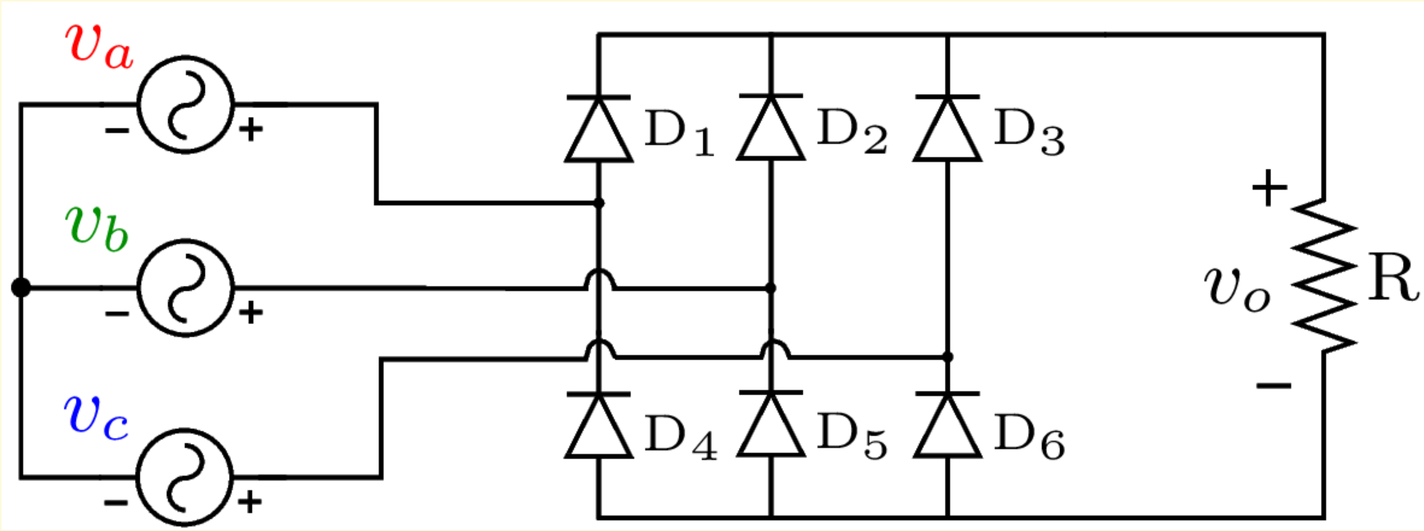




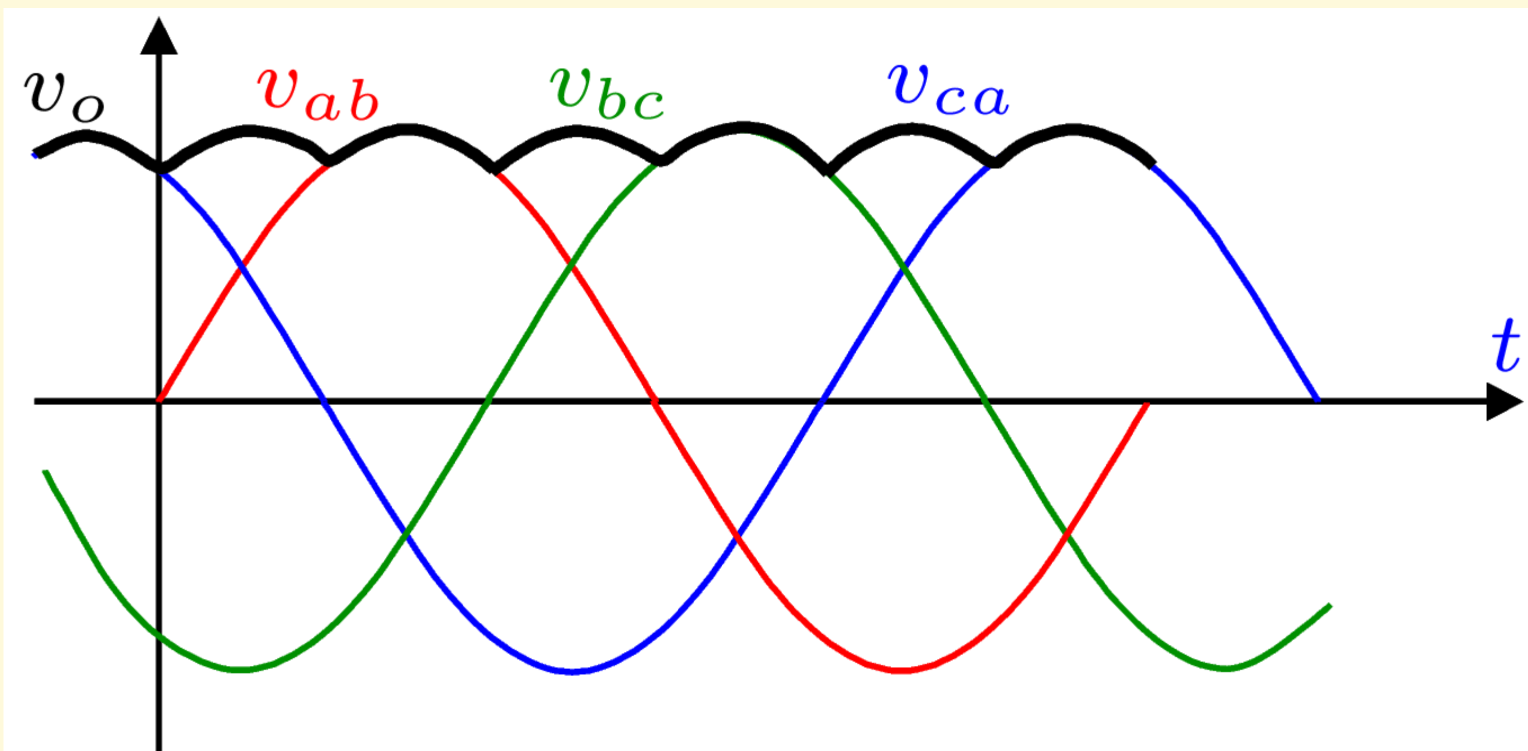
Simple circuits with diode:



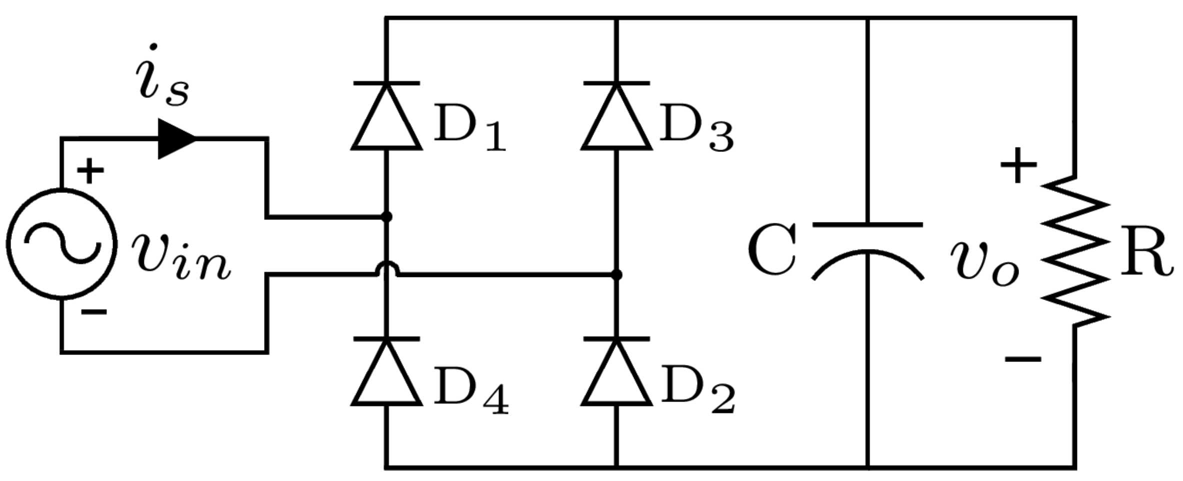
Simple circuits with diode:



Three-phase **full wave bridge** rectifier

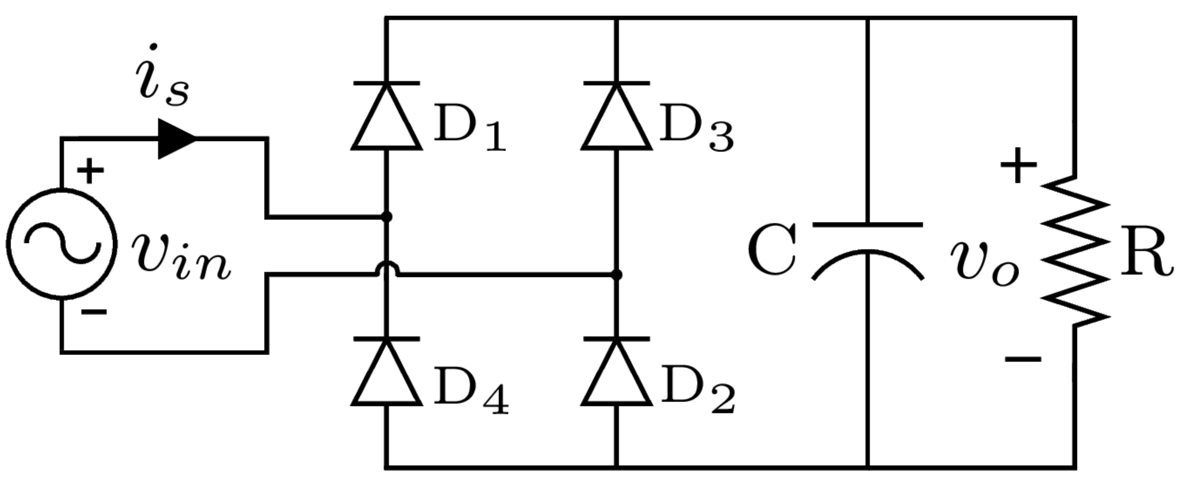


Simple circuits with diode:

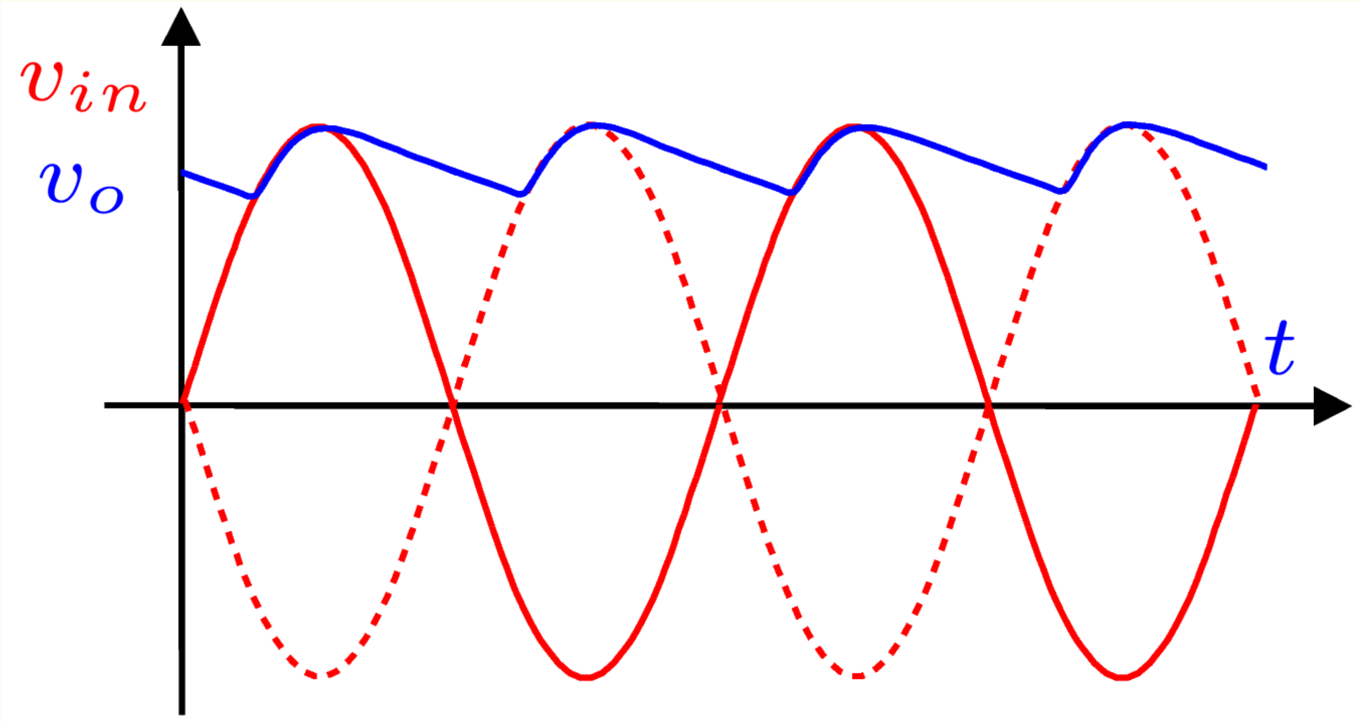


Single-phase **full wave bridge** rectifier with **capacitive** filter

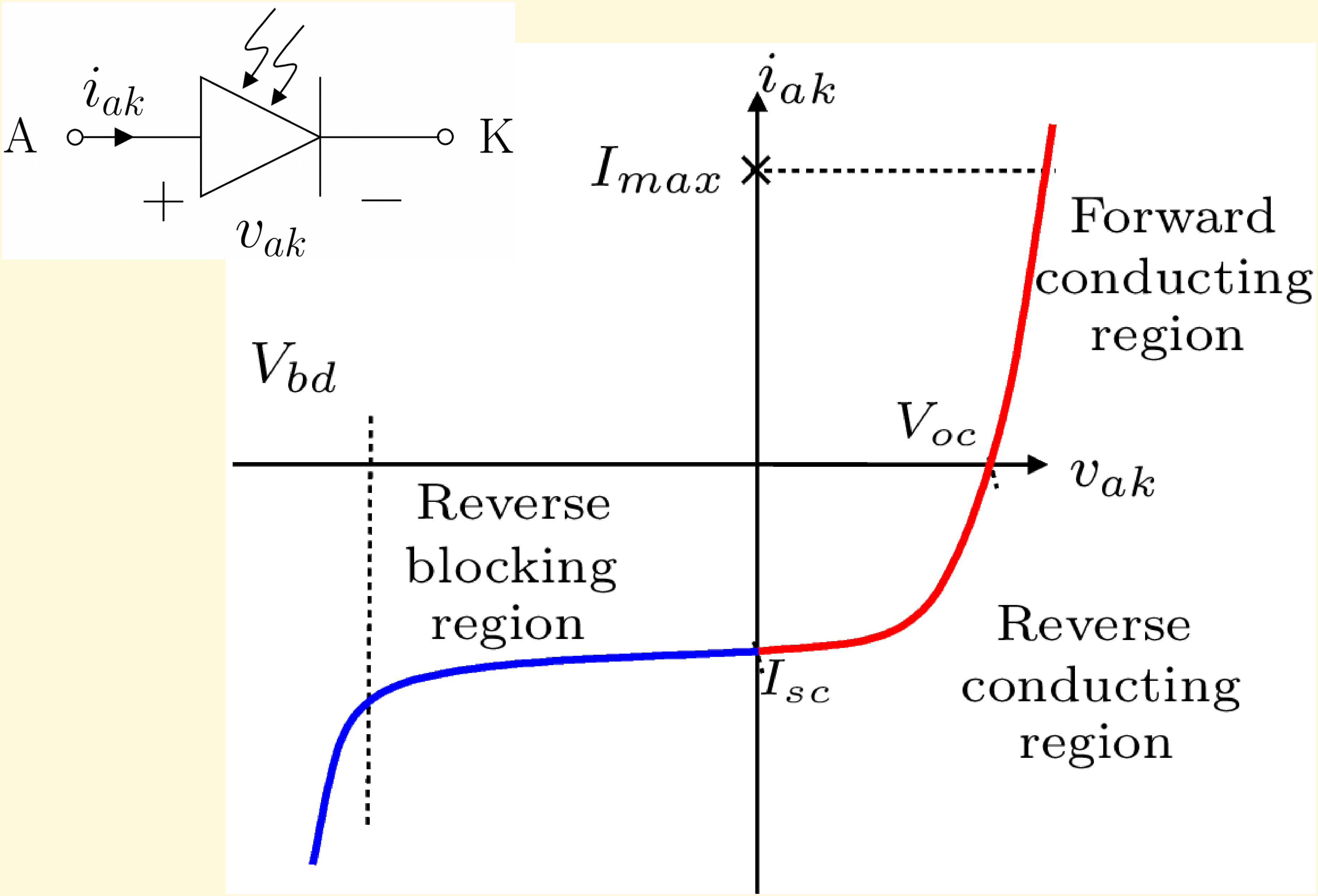
Simple circuits with diode:



Single-phase **full wave bridge** rectifier with **capacitive** filter

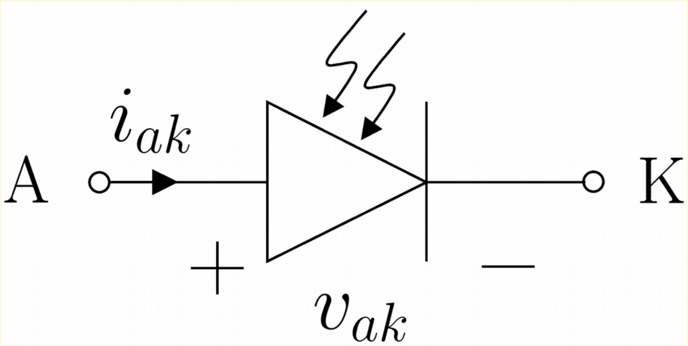


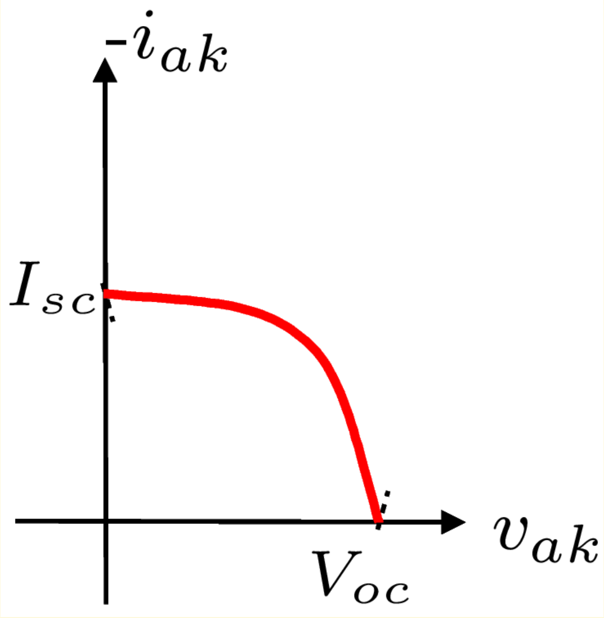
Solar cells:



i_{ak}
A
K
+
−
v_{ak}
i_{ak}
I_{max}
Forward
conducting
region
V_{bd}
V_{oc}
v_{ak}
Reverse
blocking
region
I_{sc}
Reverse
conducting
region

Solar cells:





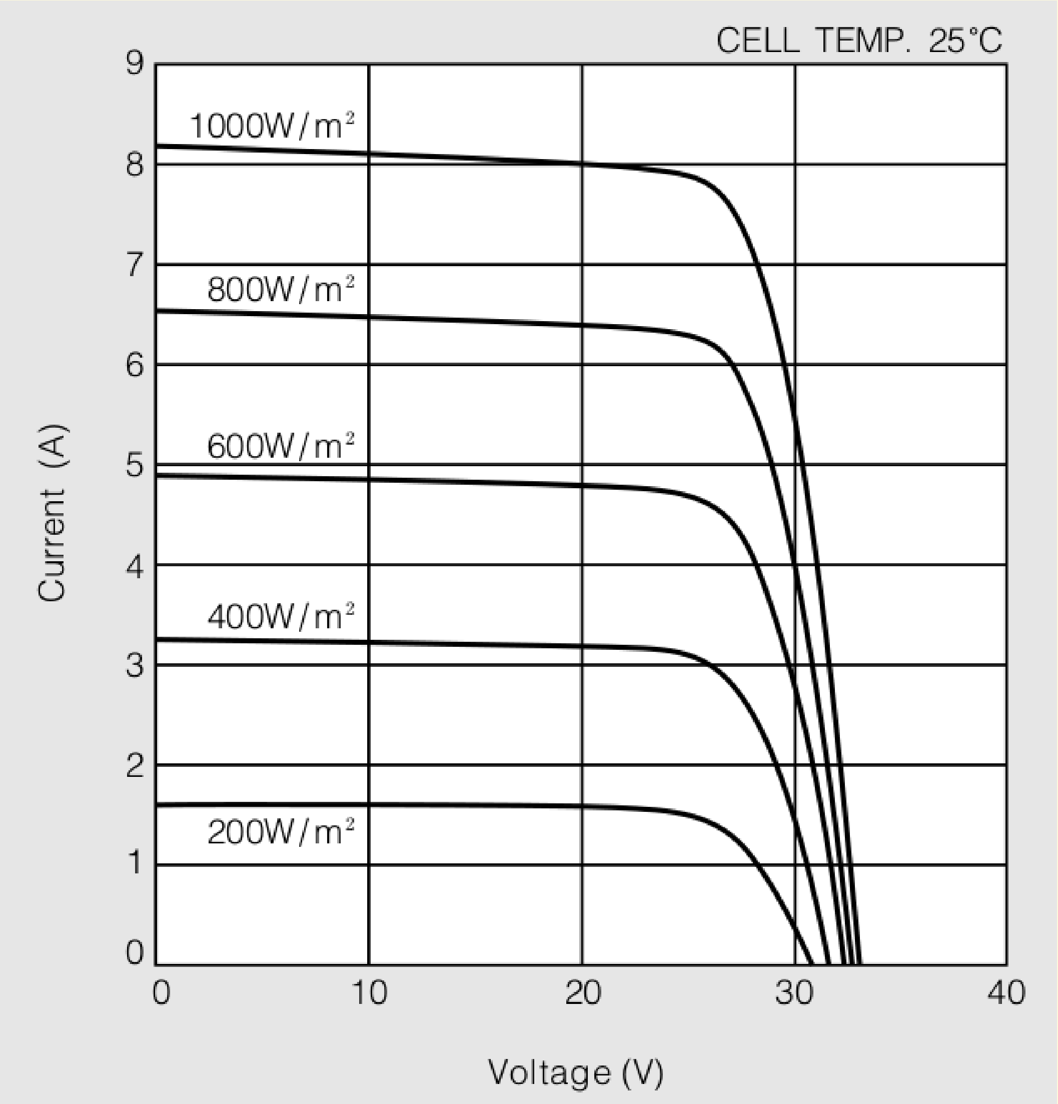
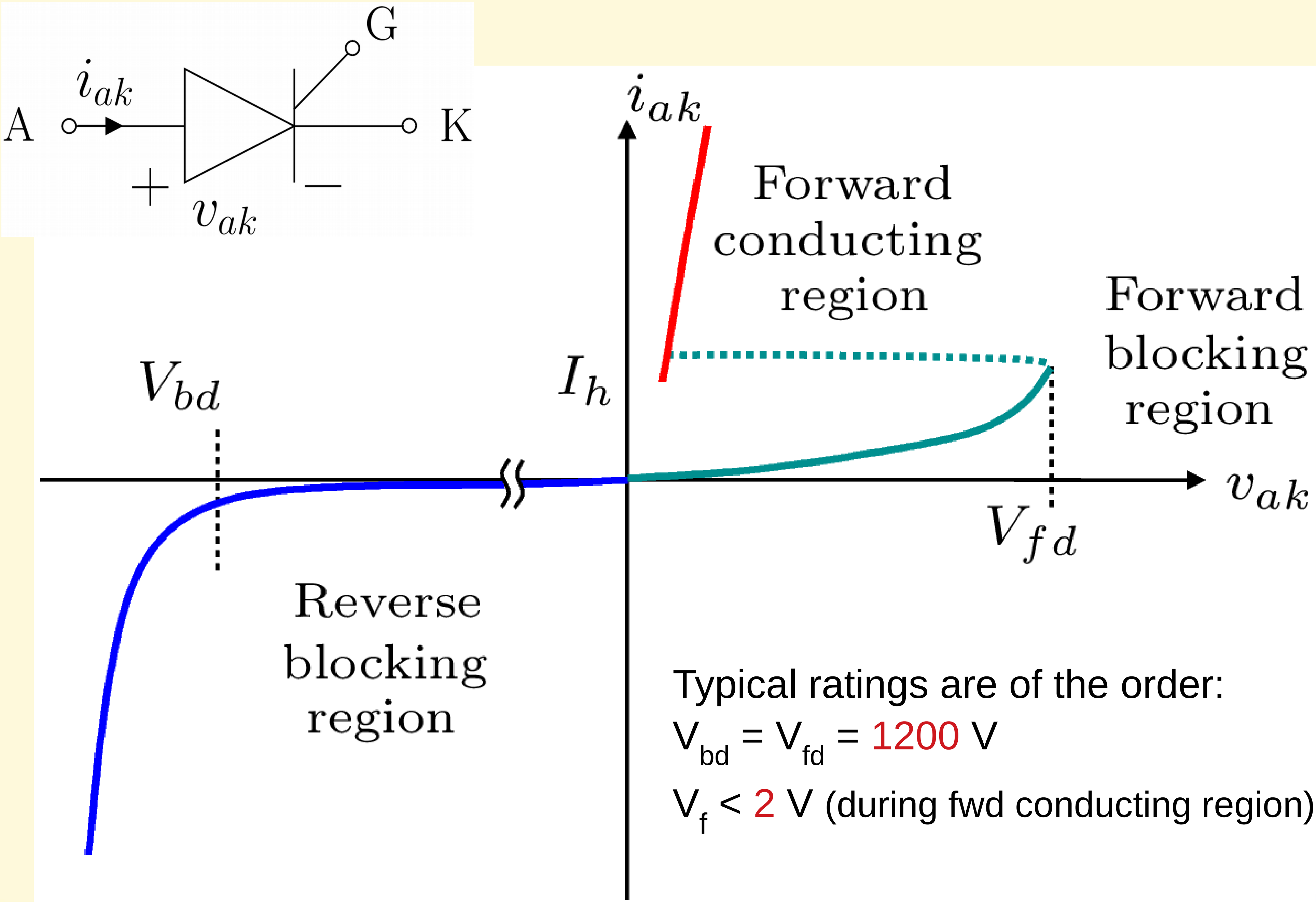


Image source: Specification sheet for KC200GT solar panel.

Thyristors:



Typical ratings are of the order:

$V_{bd} = V_{fd} =$ 1200 V

$V_f <$ 2 V (during fwd conducting region).

Simple circuits with thyristors:

IXYS **MCMA140PD1200TB**

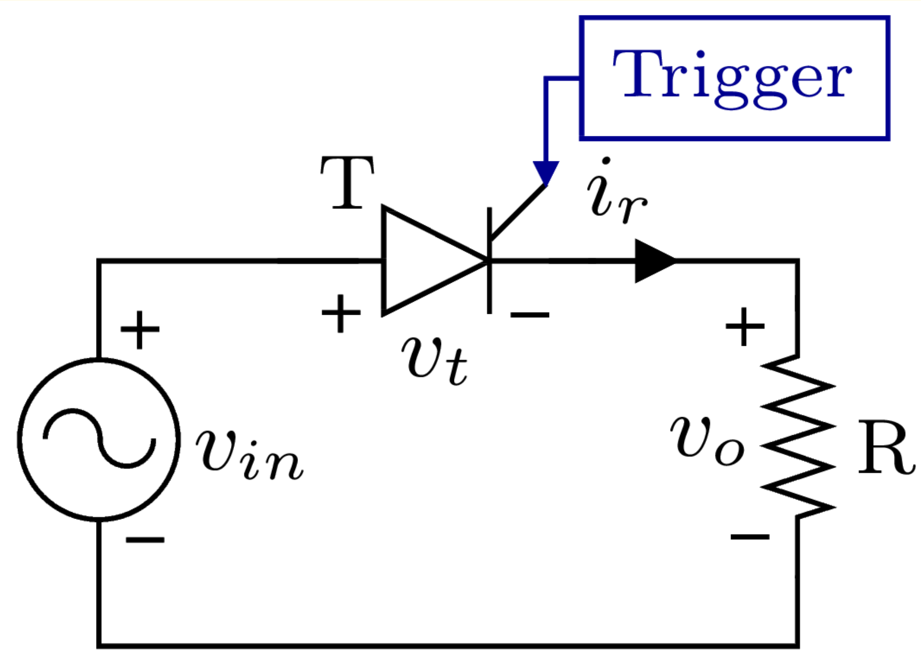
Rectifier				Ratings			
Symbol	**Definition**	**Conditions**		**min.**	**typ.**	**max.**	**Unit**
$V_{RSM/DSM}$	*max. non-repetitive reverse/forward blocking voltage*		T_{VJ} = 25°C			1300	V
$V_{RRM/DRM}$	*max. repetitive reverse/forward blocking voltage*		T_{VJ} = 25°C			1200	V
$I_{R/D}$	*reverse current, drain current*	$V_{R/D}$ = 1200 V	T_{VJ} = 25°C			100	µA
		$V_{R/D}$ = 1200 V	T_{VJ} = 140°C			10	mA
V_T	*forward voltage drop*	I_T = 150 A	T_{VJ} = 25°C			1.29	V
		I_T = 300 A				1.63	V
		I_T = 150 A	T_{VJ} = 125°C			1.28	V
		I_T = 300 A				1.70	V
I_{TAV}	*average forward current*	T_C = 85°C	T_{VJ} = 140°C			140	A
$I_{T(RMS)}$	*RMS forward current*	180° sine				220	A

Typical ratings of the thyristor:

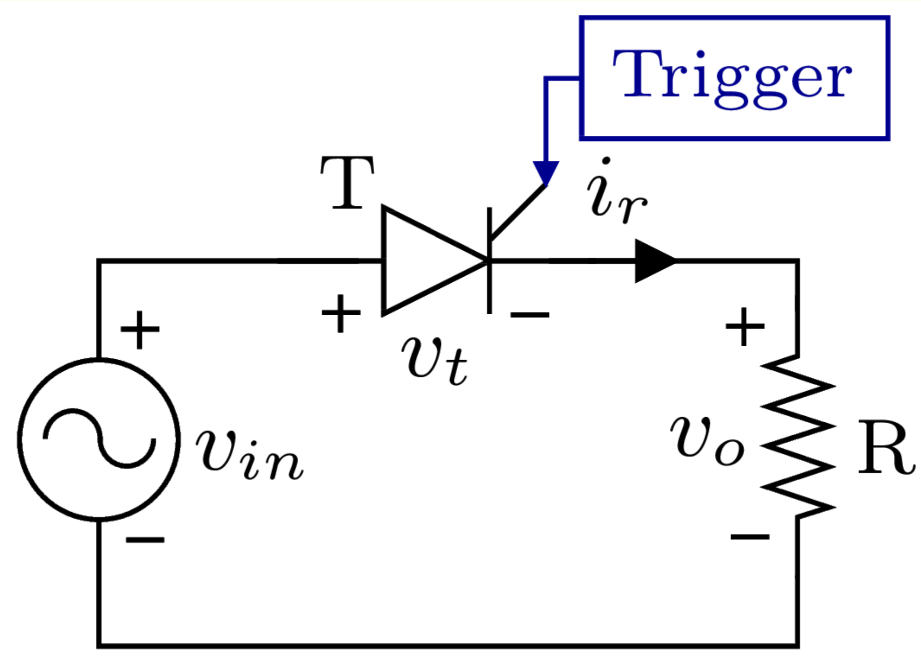
$$V_{bd} = V_{fd} = 1200 \text{ V} \quad \text{and} \quad V_f < 2 \text{ V}$$

Datasheet reference: http://ixapps.ixys.com/datasheet/mcma140pd1200tb.pdf

Simple circuits with thyristors:



Simple circuits with thyristors:



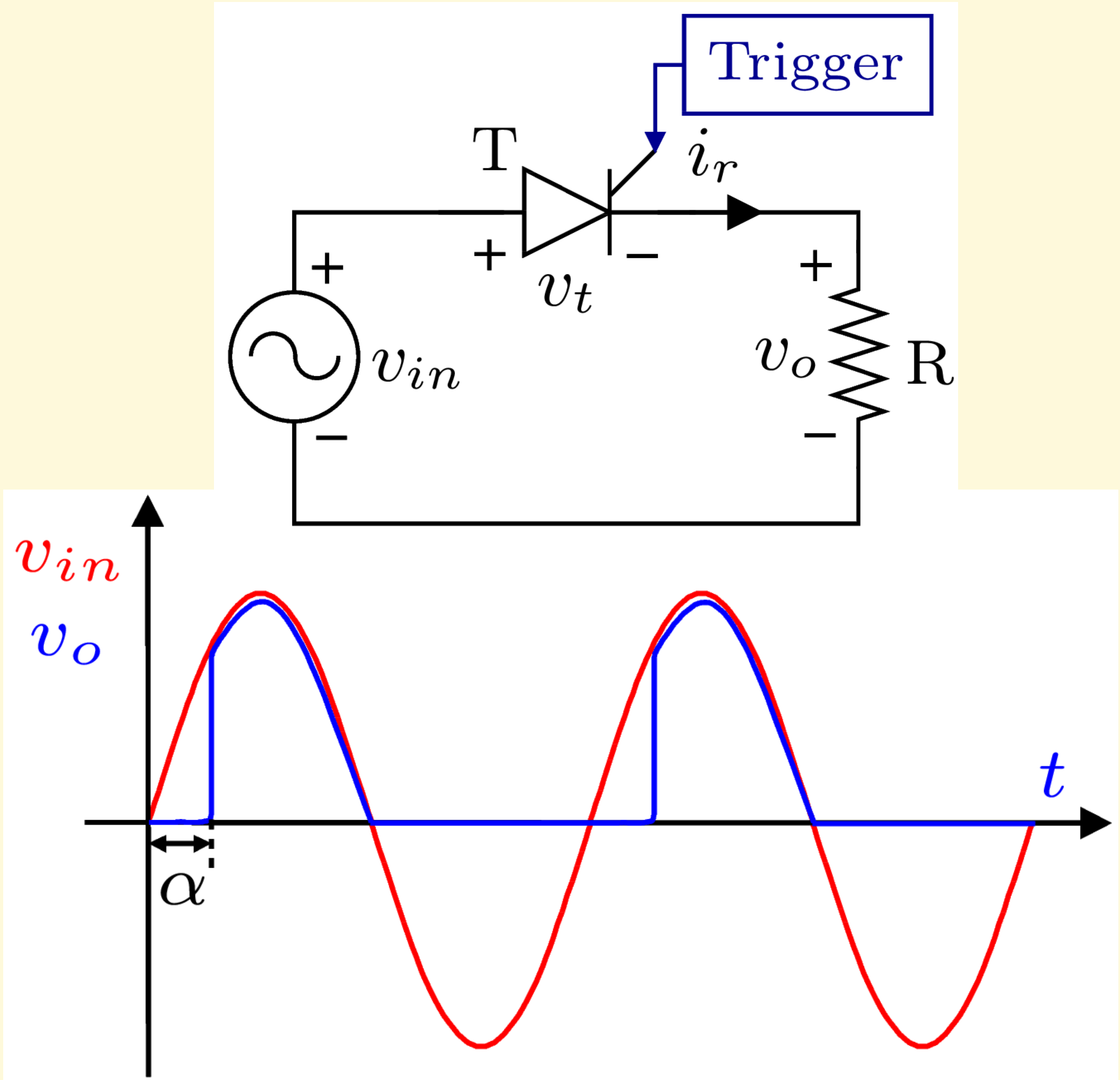
Note the thyristor is switched on:

--> Thyristor is forward biased (i.e. $v_t > 0$) and

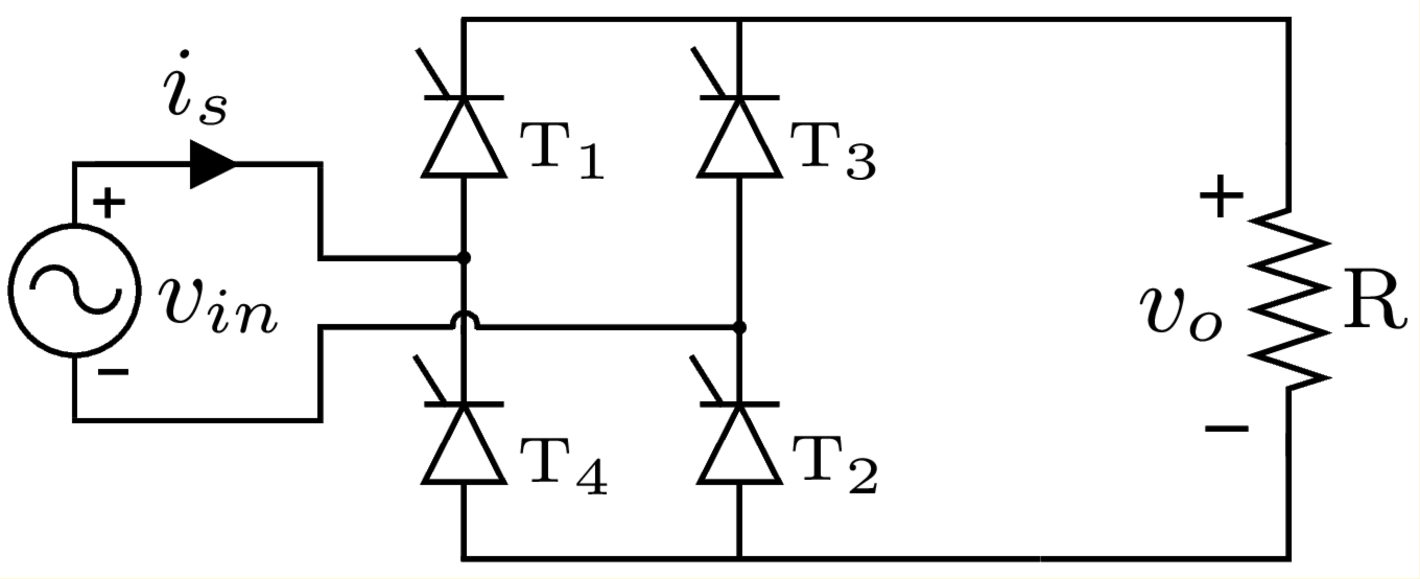
--> Trigger current is applied at some instant (decided by a logic circuit), through the gate cathode terminals.

Also in reverse biased condition thyristor behaves similar to that of the diode.

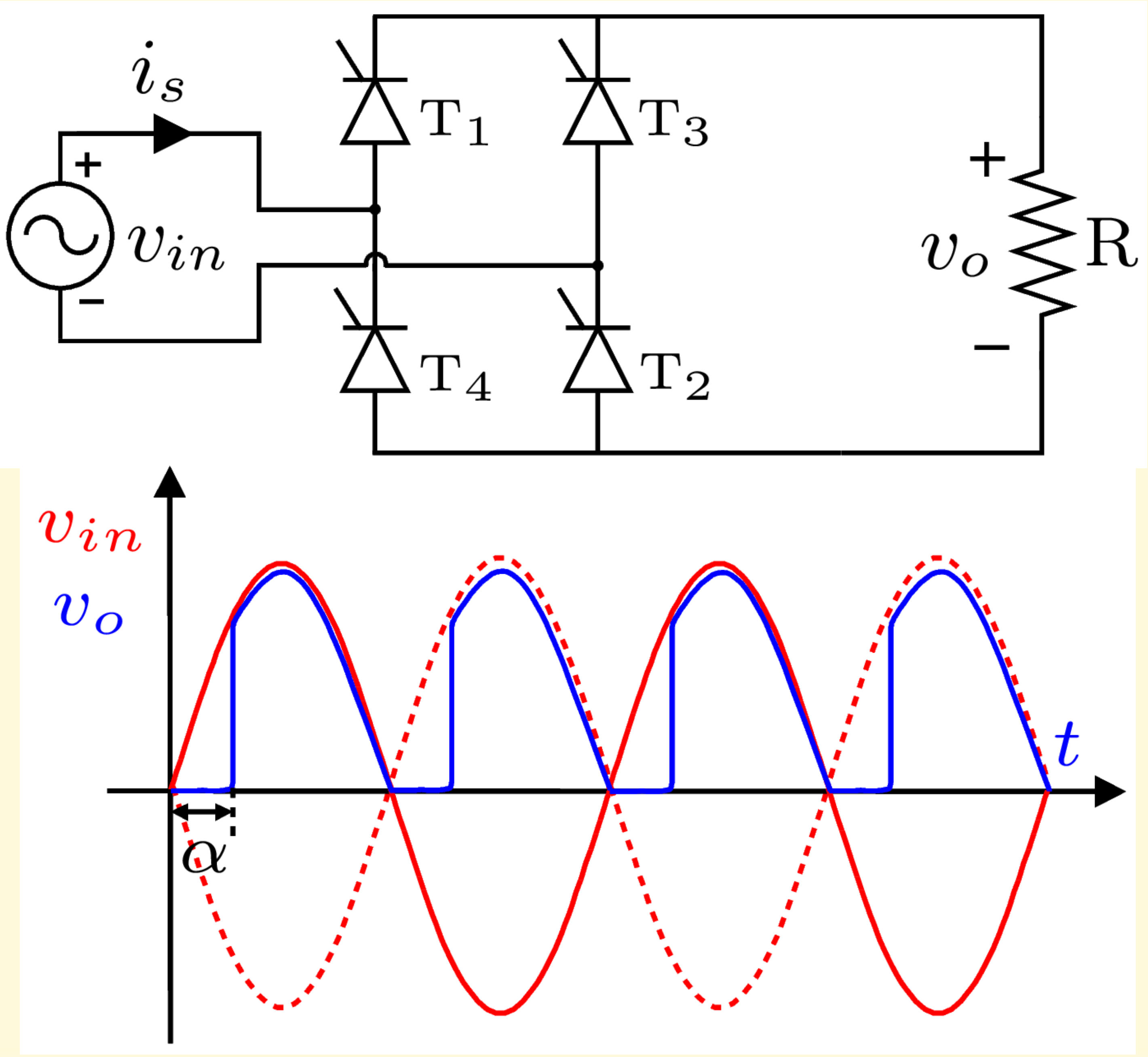
Simple circuits with thyristors:



Simple circuits with thyristors:

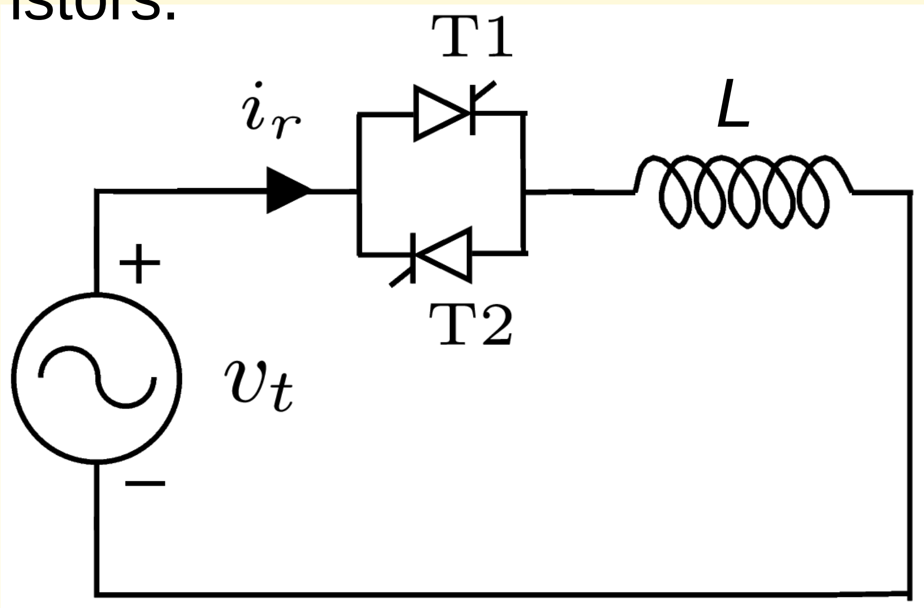


Simple circuits with thyristors:



Thyristor Controlled Reactor (TCR):

Back to back thyristors.



Thyristor Controlled Reactor (TCR):

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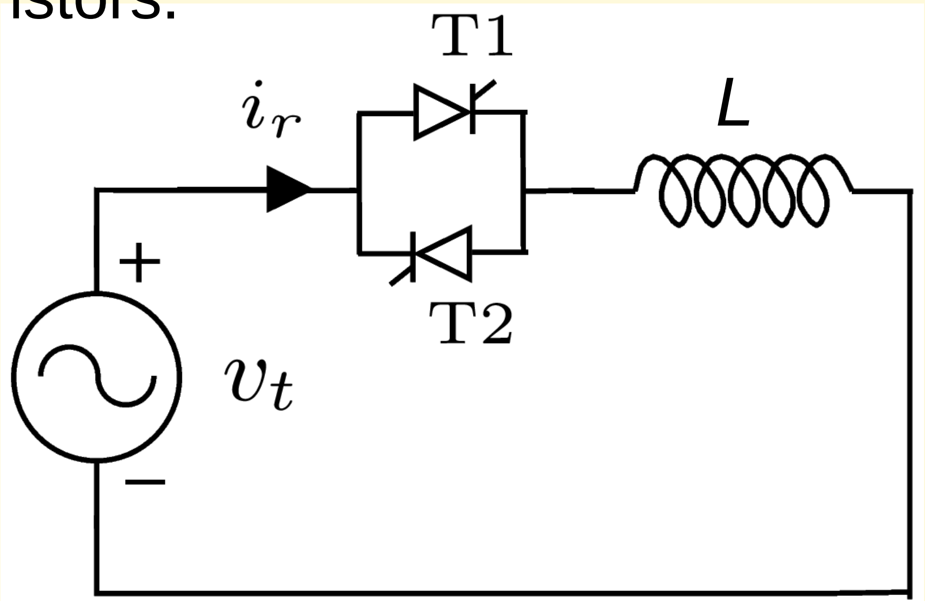
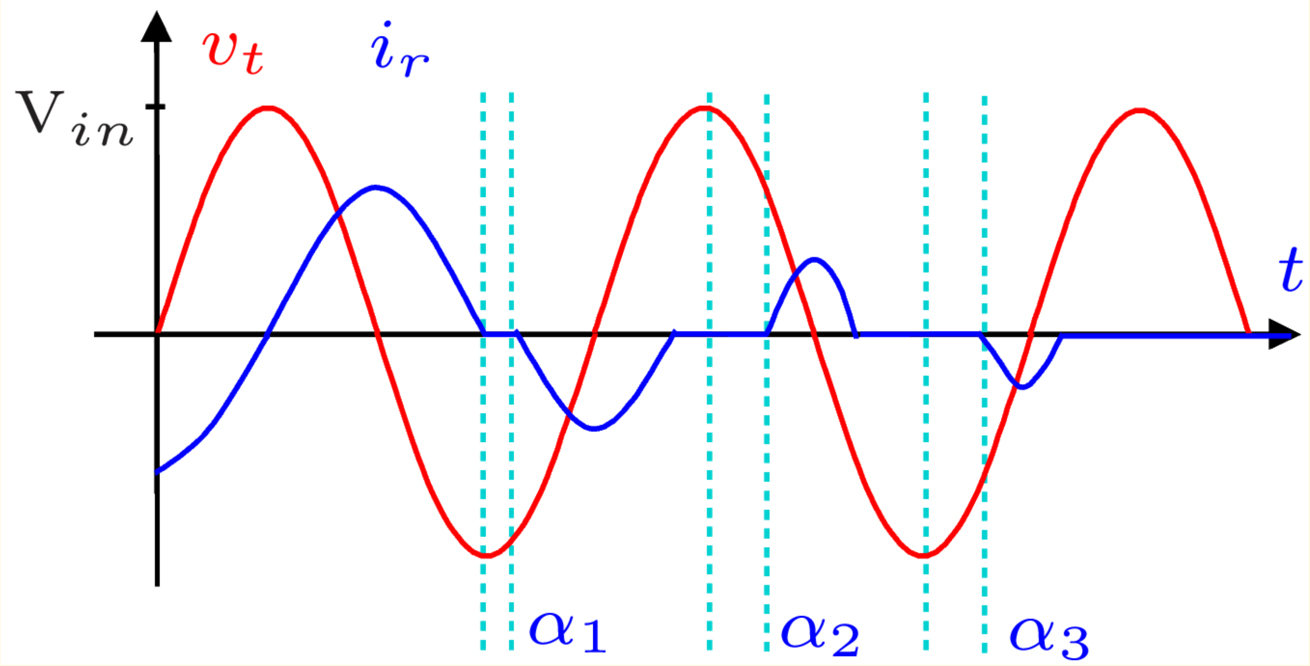
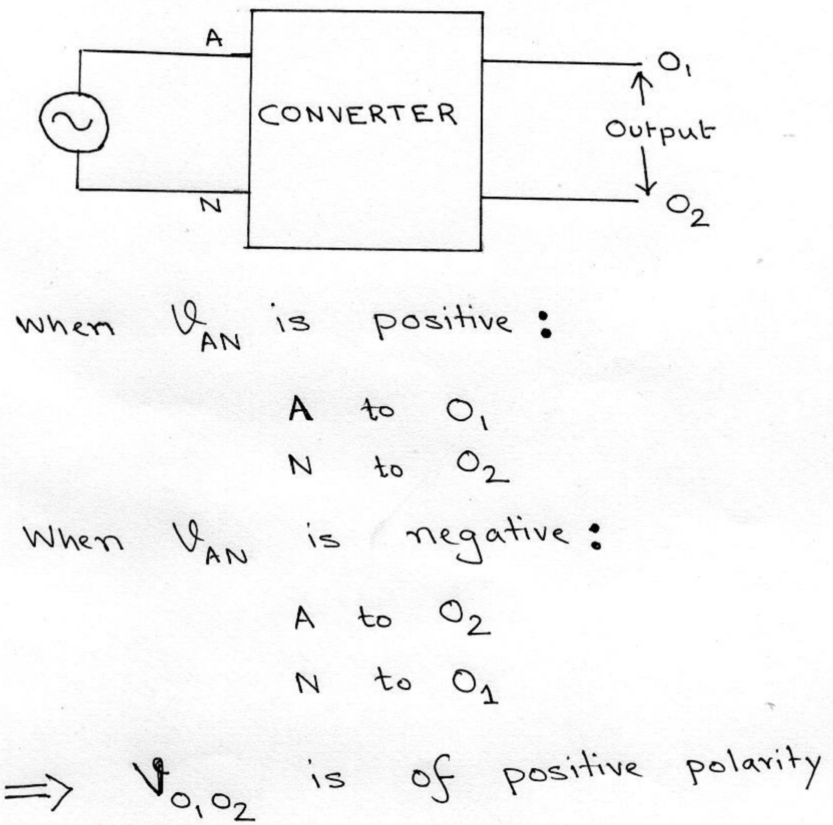




Philosophy of AC to DC Conversion

- Connection of input terminals to output terminals is changed based on the polarity of the input voltage waveform
- Output dc voltage is constructed from parts of input ac voltage
- Output is not a perfect dc

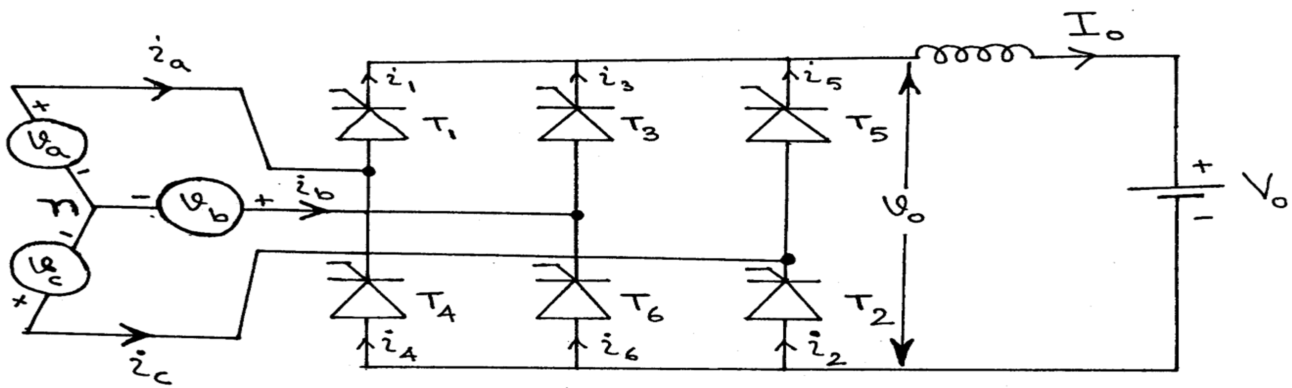


Source: lecture slides of Prof. Kishore Chatterjee, EE-IITB.

HVDC converter operation

- Three phase Full Wave Converter
- Six pulse converter
- Assumptions :
  1) Switches are ideal
  2) AC source is infinite
  3) L_f is large so that output current is a perfect dc current.

6-pulse Converter



$$v_{ab} = \sqrt{3}\, V_m \sin(\omega t + 60^\circ)$$

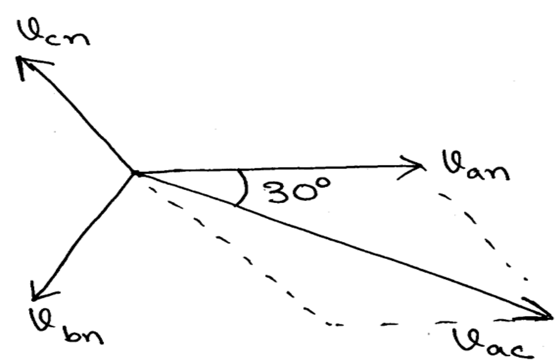
$$v_{ac} = \sqrt{3}\, V_m \sin(\omega t)$$

$$v_{bc} = \sqrt{3}\, V_m \sin(\omega t - 60^\circ)$$

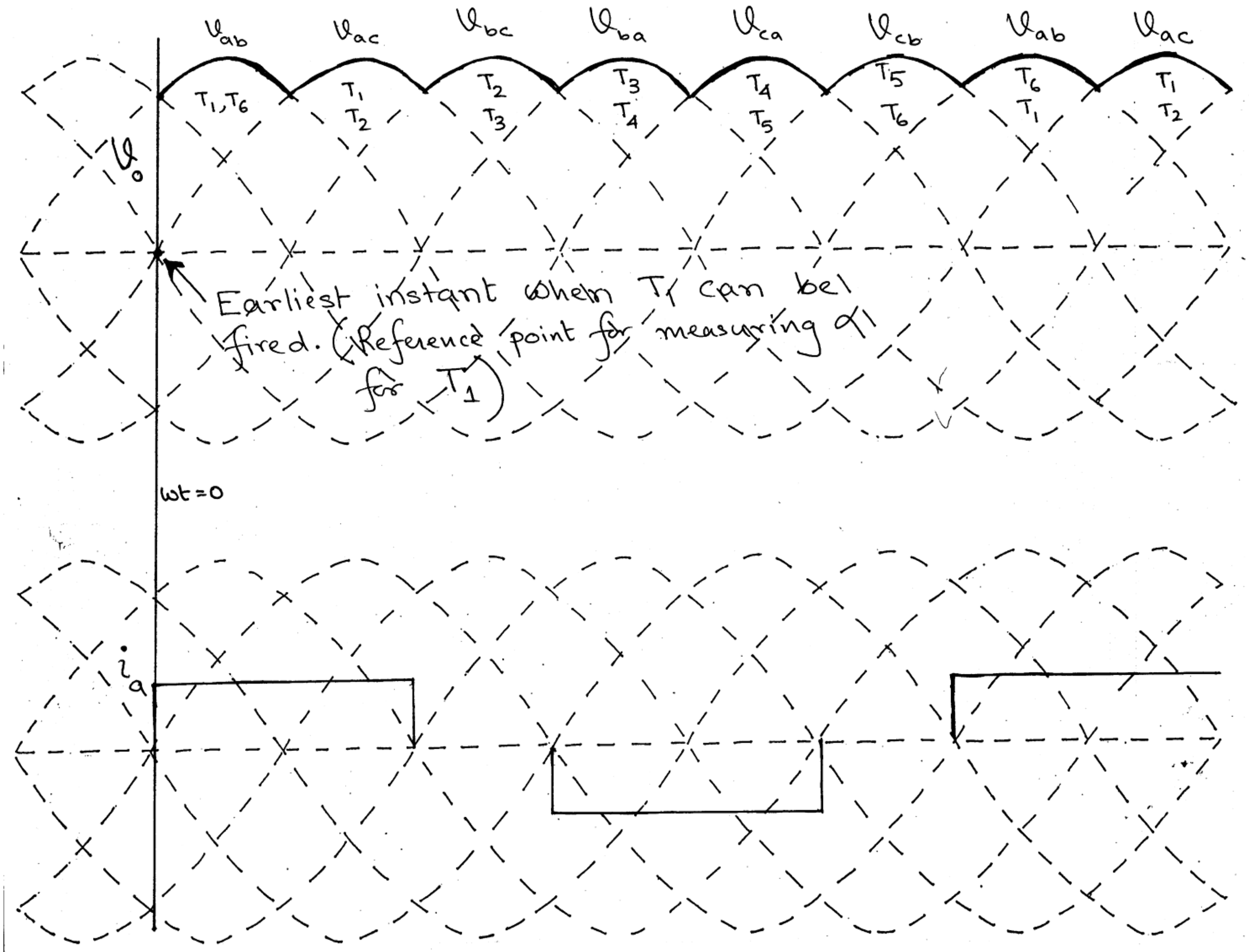
$$v_{an} = V_m \sin(\omega t + 30^\circ)$$

$$v_{bn} = V_m \sin(\omega t - 90^\circ)$$

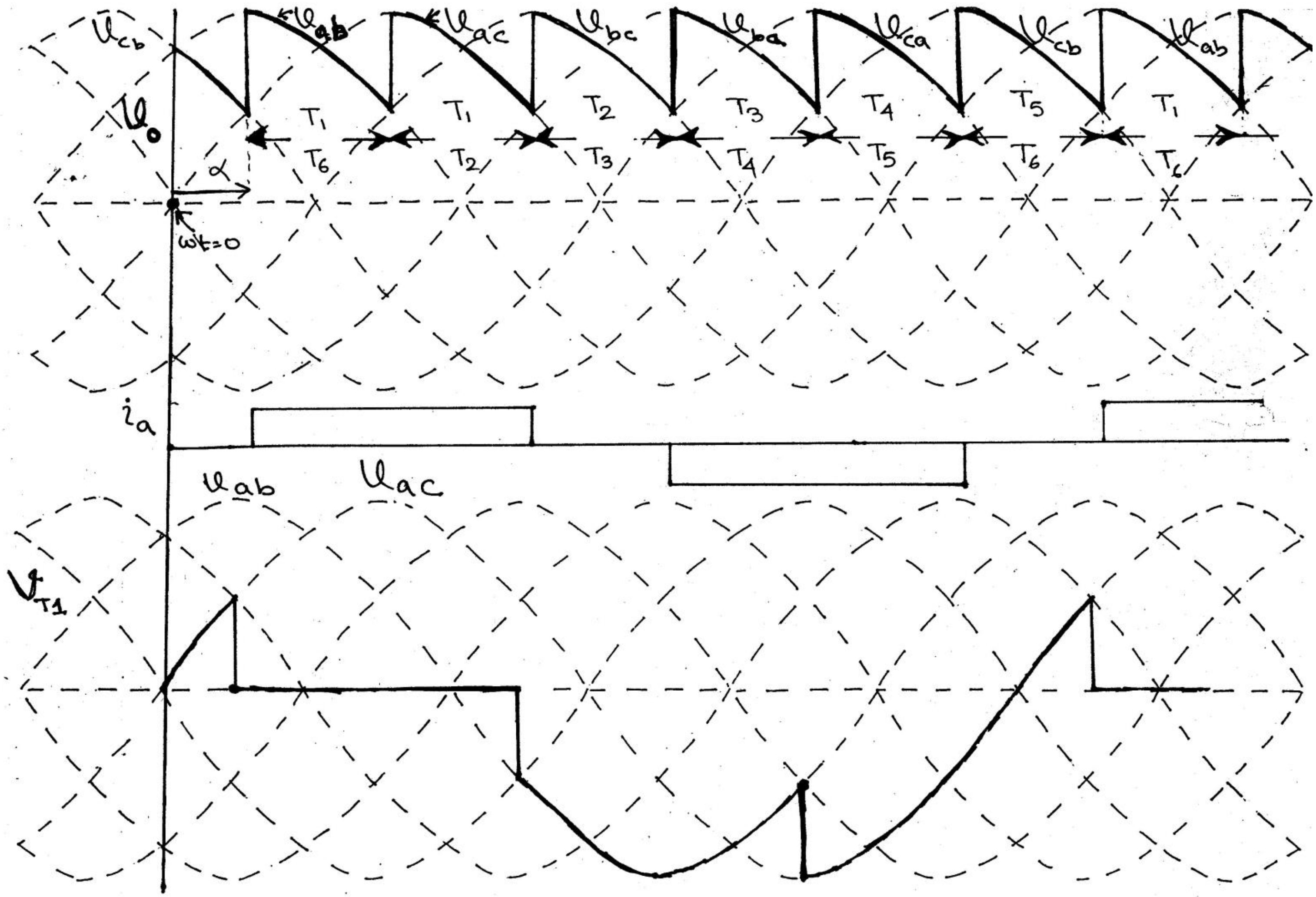
$$v_{cn} = V_m \sin(\omega t - 210^\circ)$$



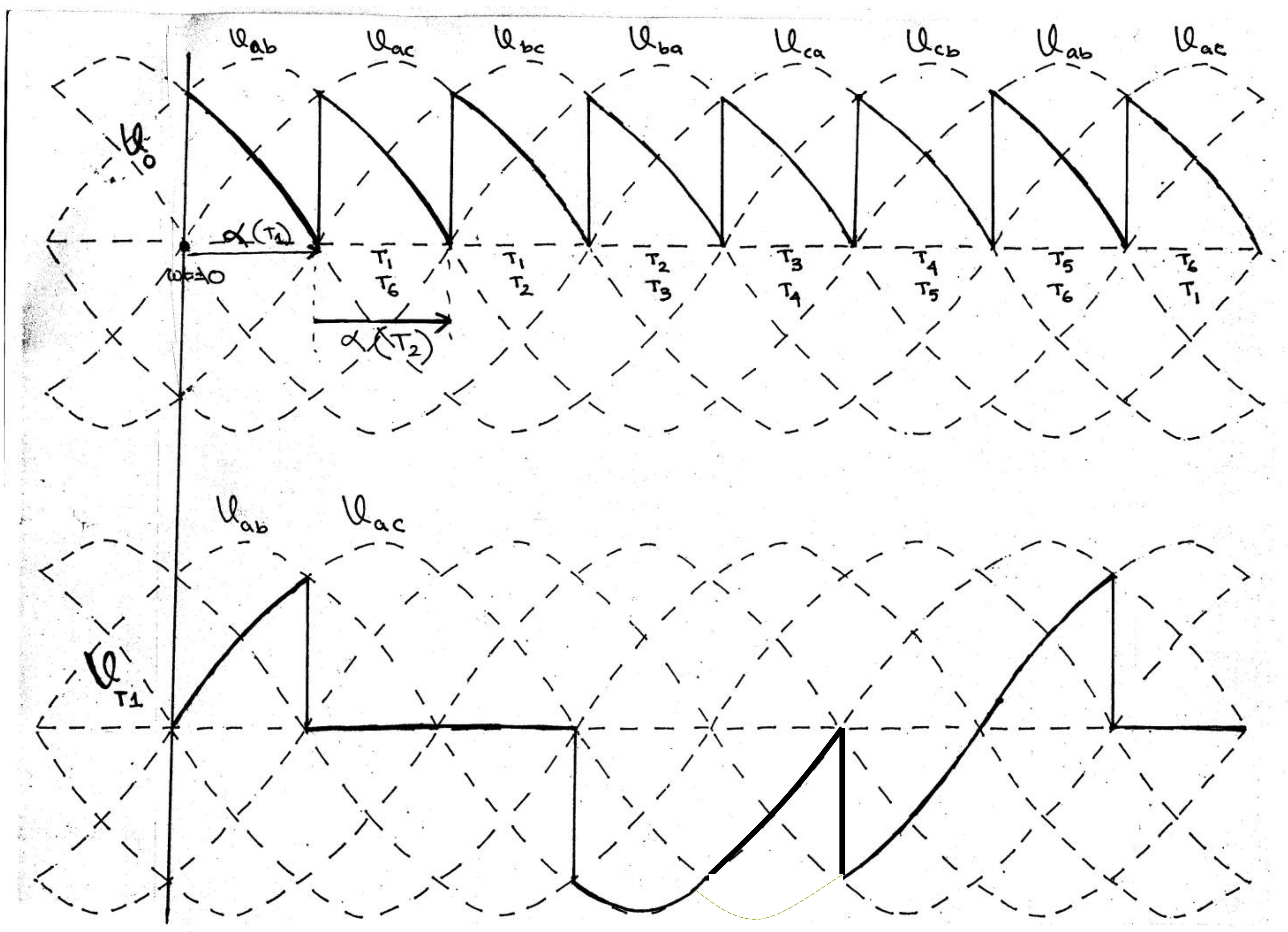
When all the thyristors are permanently provided with gating signals



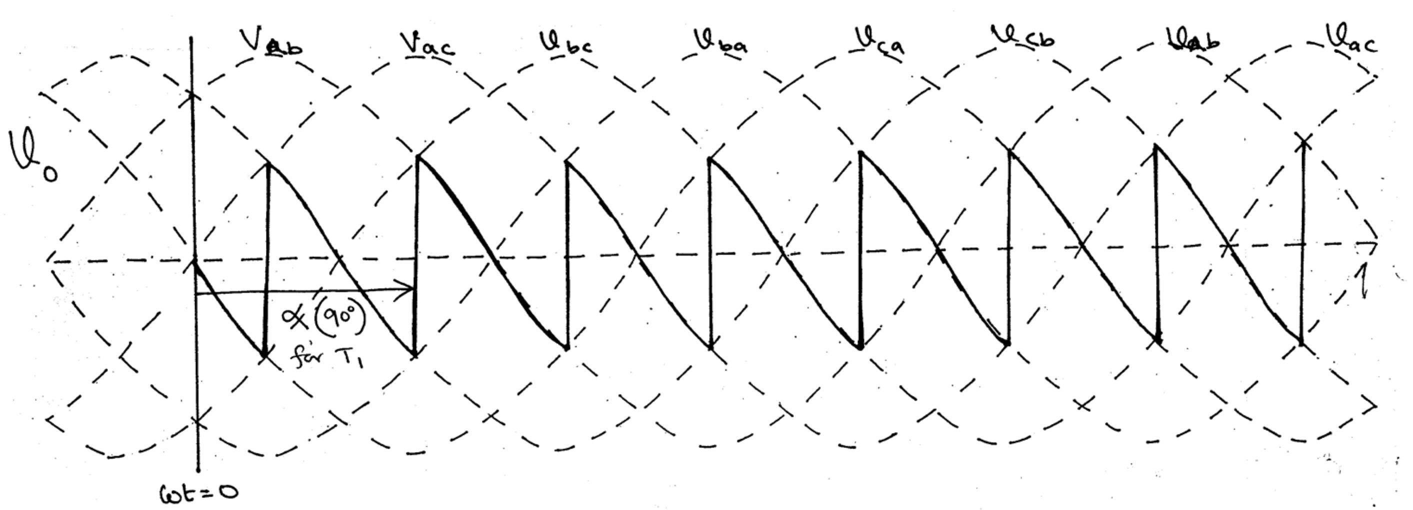
Firing delay angle α = 30°

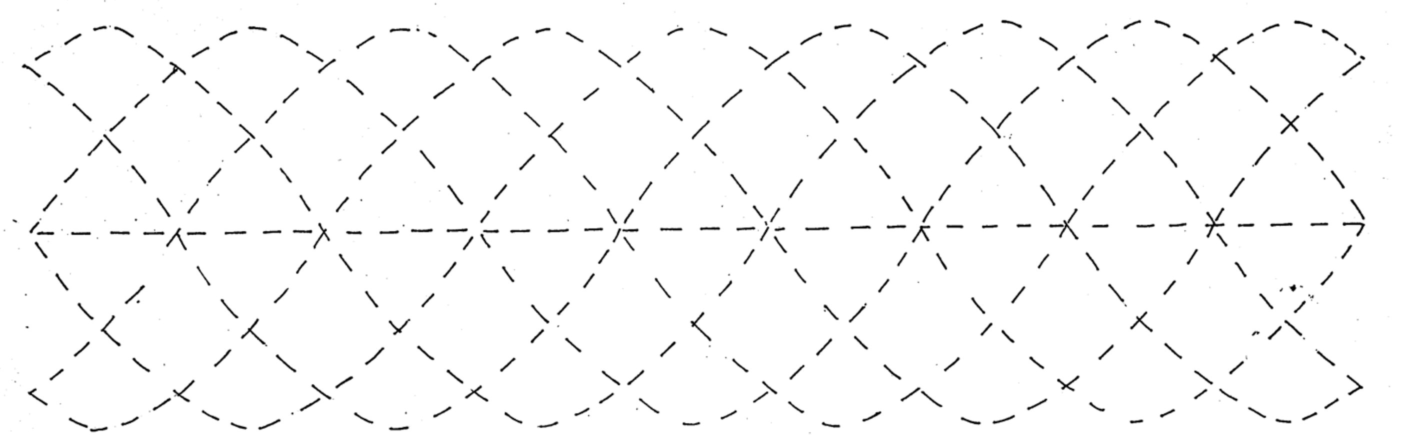


Firing delay angle $\alpha = 60^o$



Firing delay angle α = 90°





Average output voltage

$$V_o = \frac{6}{2\pi}\int_{\alpha}^{\alpha+60^\circ} v_{ab}\, d(\omega t)$$

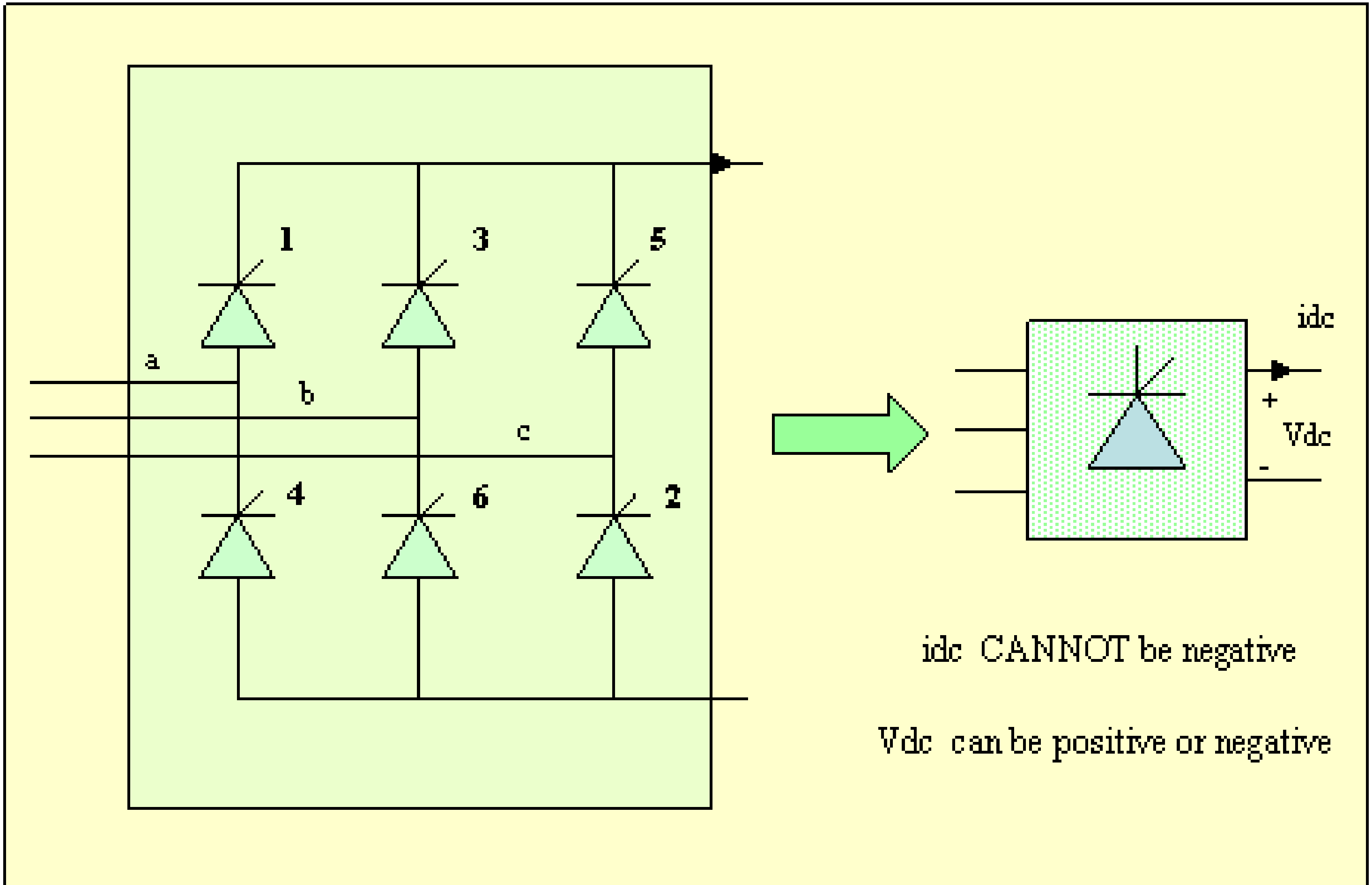
$$= \frac{6}{2\pi}\int_{\alpha}^{\alpha+60^\circ} \sqrt{3}\, V_m \sin(\omega t + 60^\circ)\, d(\omega t)$$

$$= \frac{3\sqrt{3}\, V_m}{\pi}\cos\alpha$$

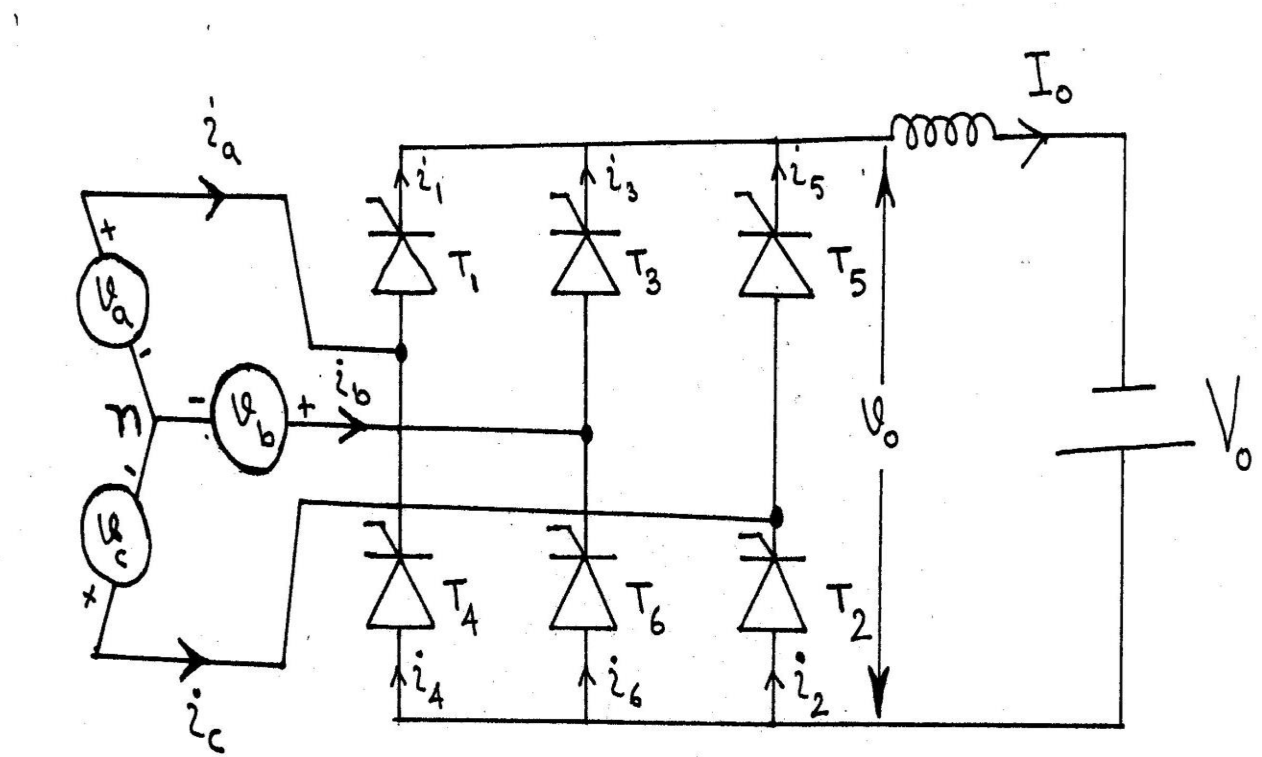
$$= V_{do}\cos\alpha \qquad \left[V_{do} = \frac{3\sqrt{3}\, V_m}{\pi} \right]$$

Equivalently, Vdo = 1.383 times line-line rms voltage on AC side

Converter Characteristics

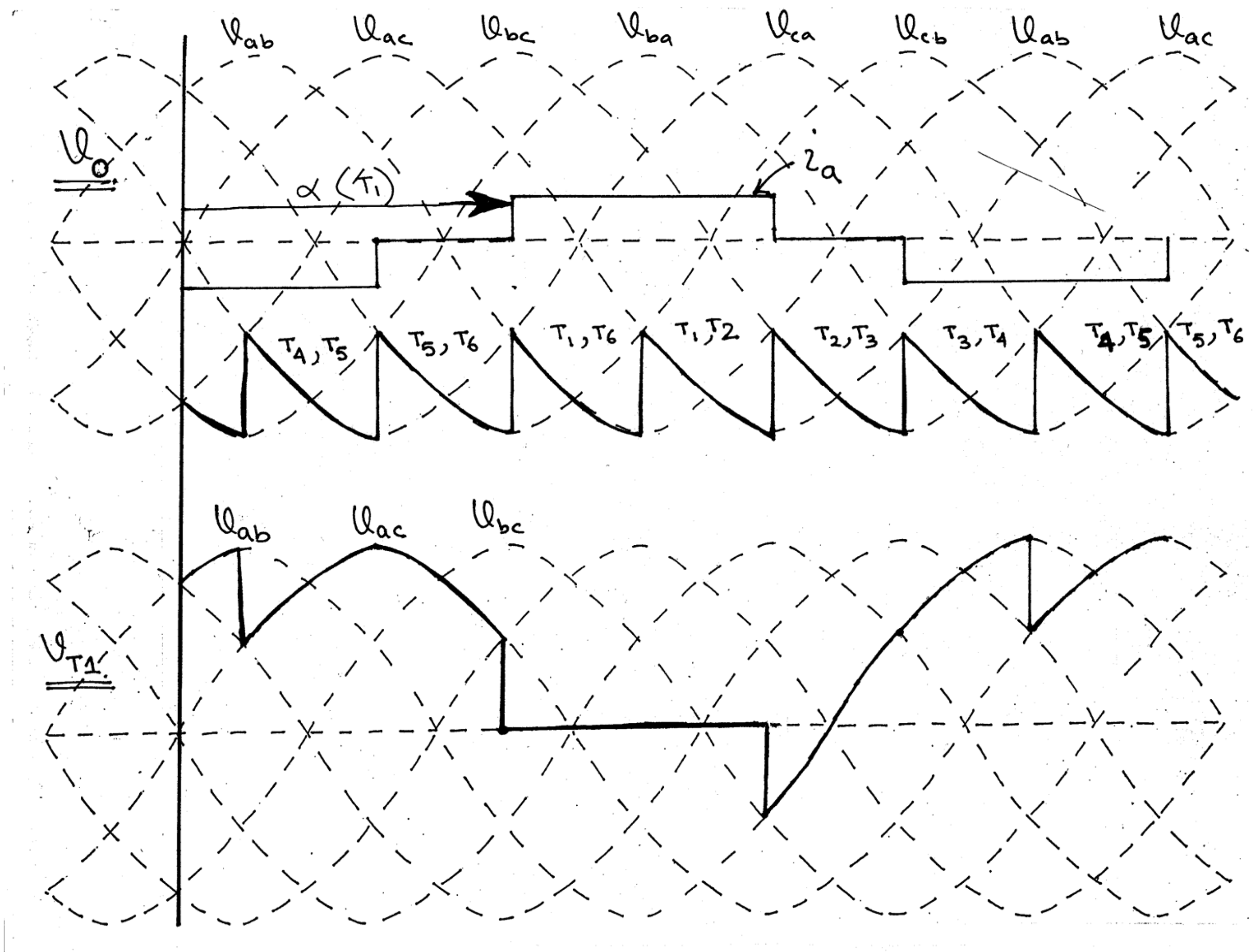


Operation in inverting mode



Current is maintained because of Vo – this role is played by the rectifier in an HVDC system.

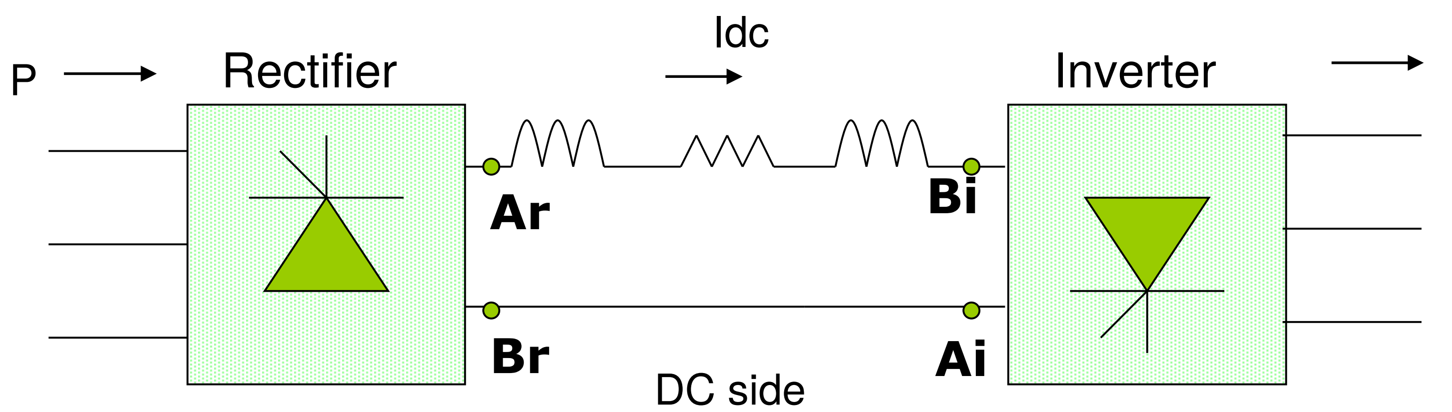
Firing delay angle α = 150°



HVDC System – Two Terminal

$V_{Ar}-V_{Br} > 0$ $V_{Bi}-V_{Ai} > 0$

$(V_{Ar}-V_{Br}) > (V_{Bi}-V_{Ai})$



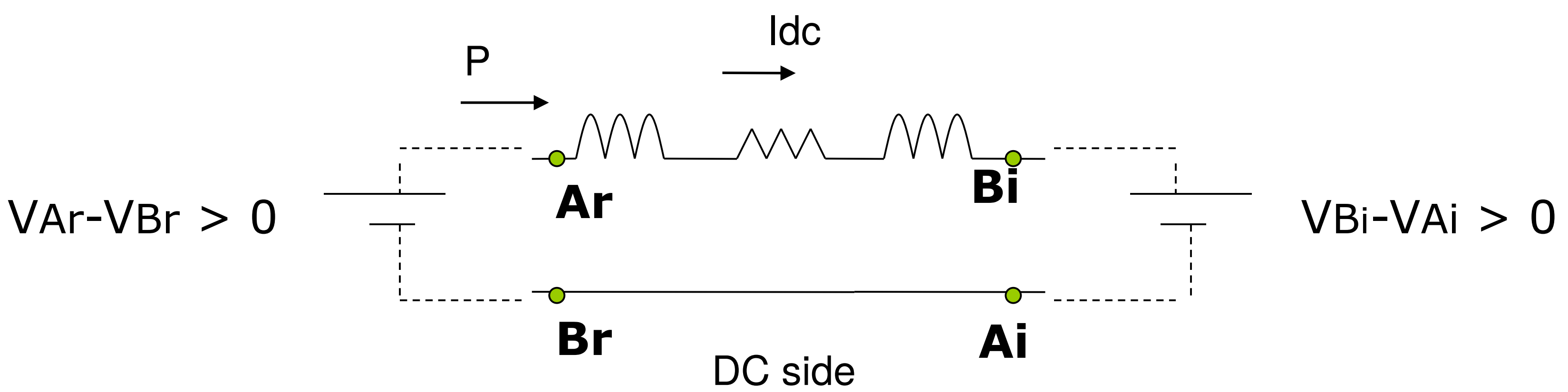
$0 < \alpha < 90$

$90 < \alpha < 180$

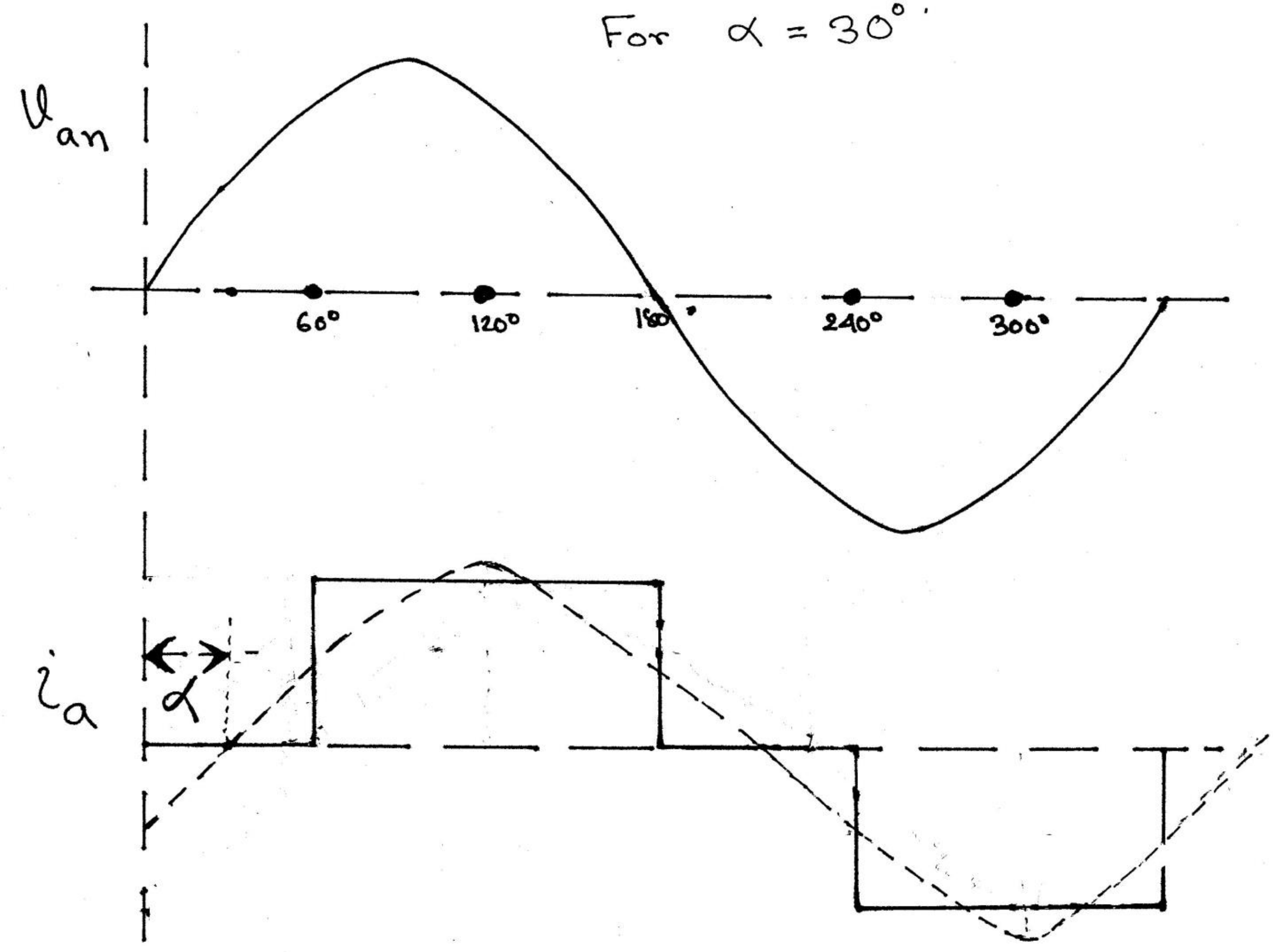
α: Delay Angle of Converter

HVDC System – Two Terminal

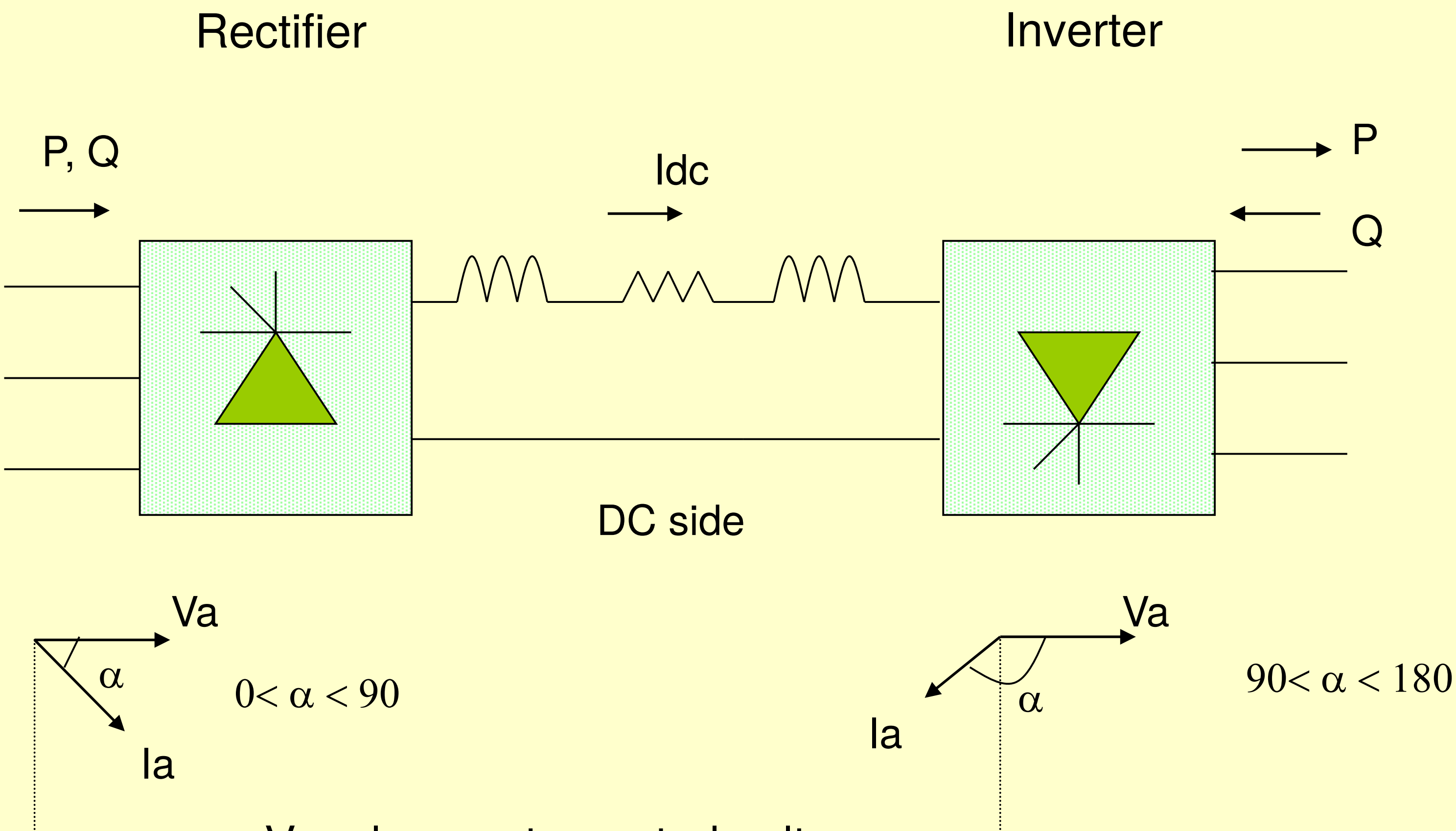
$(V_{Ar}-V_{Br}) > (V_{Bi}-V_{Ai})$



Phase relation between Ph-A voltage and converter Ph-A fundamental input current



Both Sides Draw Reactive Power !



Va: phase a to neutral voltage

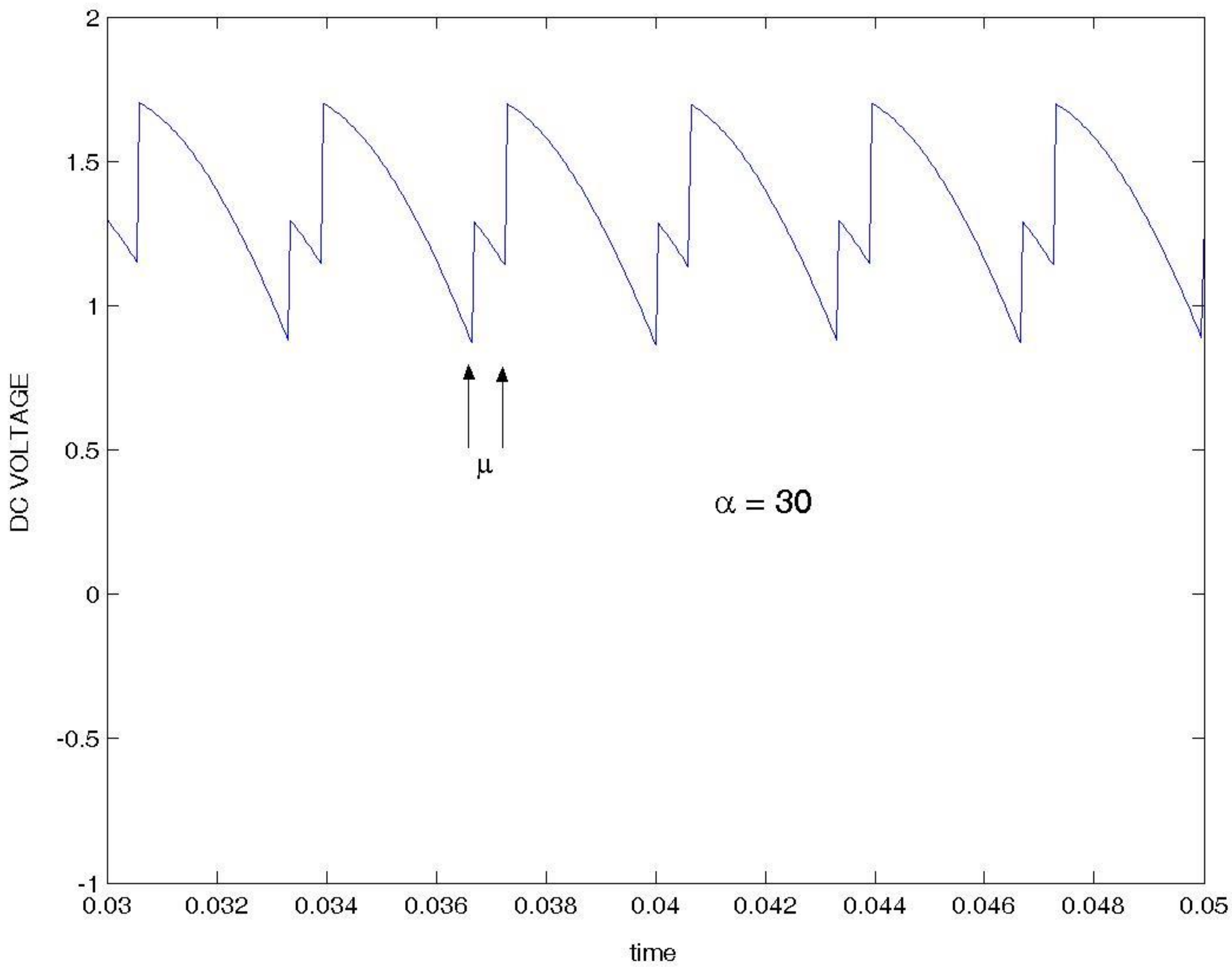
Ia : phase a current flowing **into** the converter

α: Delay Angle of Converter

Effect of Firing angle delay

- Reduction in V_d by a factor of $\cos\alpha$
- Increment in output voltage ripple
- Negative voltage period for $\alpha > 60^o$
- Increases phase difference between phase current and voltage

α=30º and u<60º



Commutation Margin: modified relationships

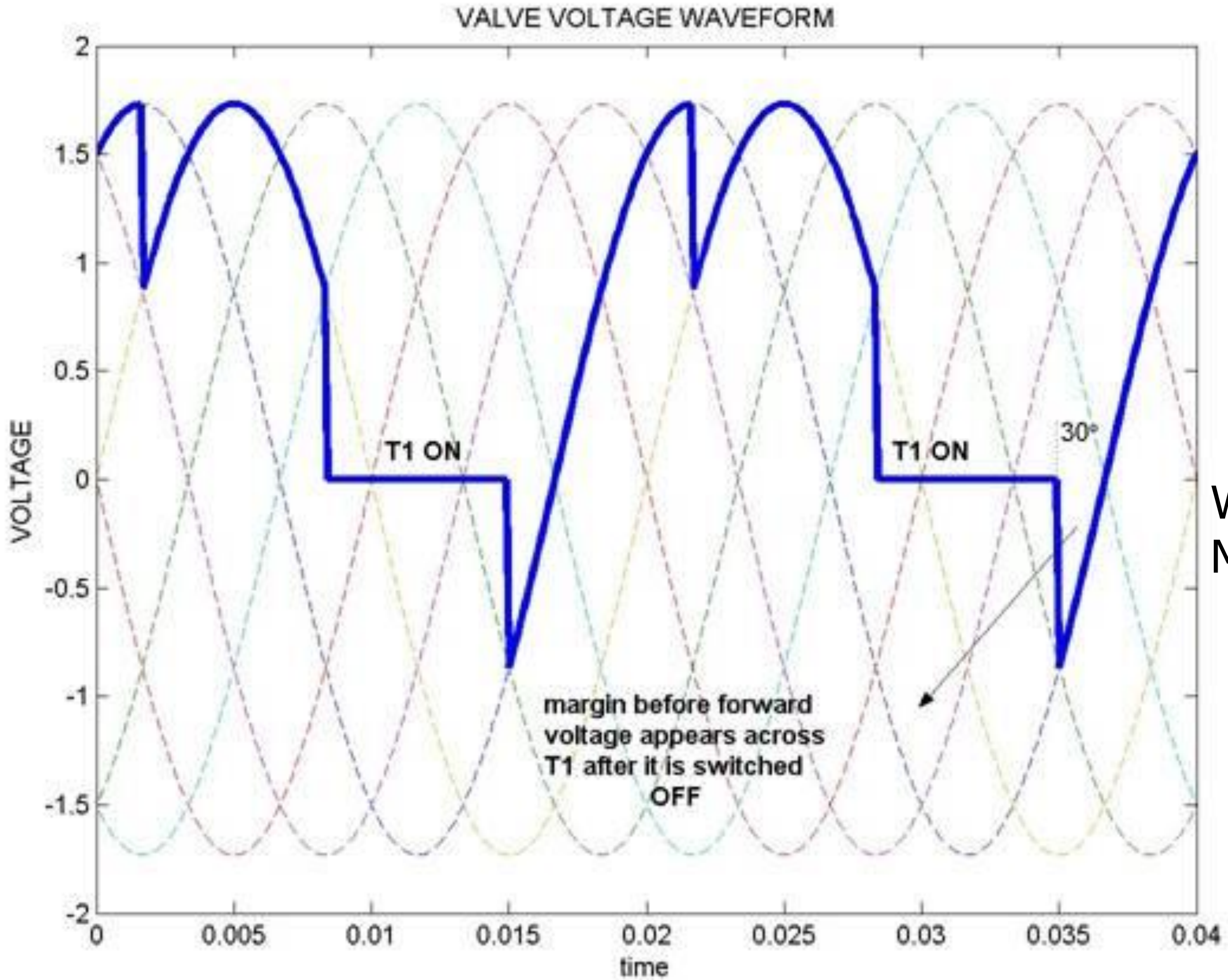
$$\therefore I_o = \frac{\sqrt{3}V_m}{2\omega L_c}\left\{\cos\alpha - \cos(\alpha+u)\right\}$$

DC current high, or AC Voltage Low: μ is larger

Magnitude of dc voltage reduces; minor effect on AC current harmonics

$$V_o = V_{do}\cos\alpha - \frac{3\omega L_c}{\pi} I_o$$

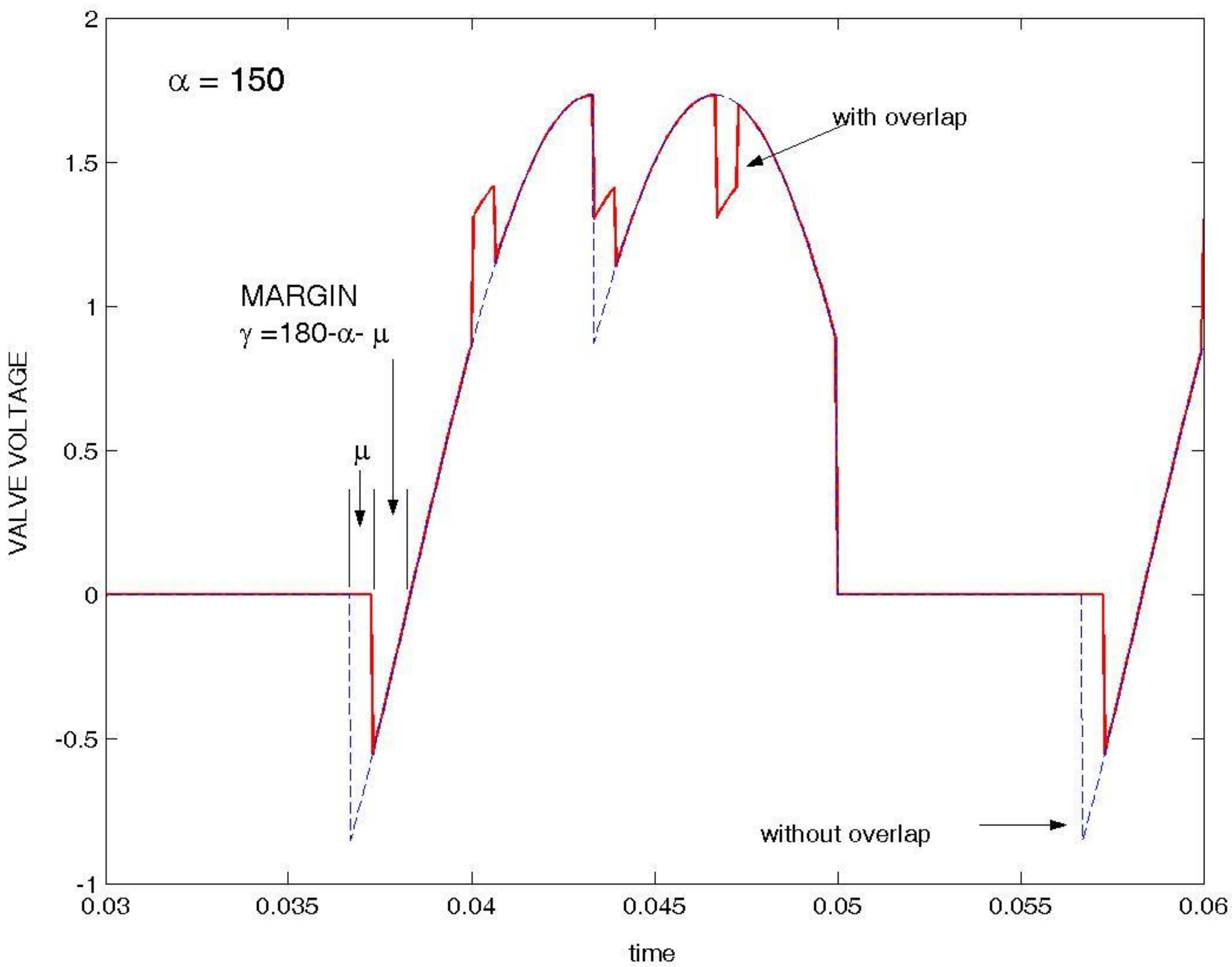
What is Commutation Margin ? (Inverter Valve voltage waveform)



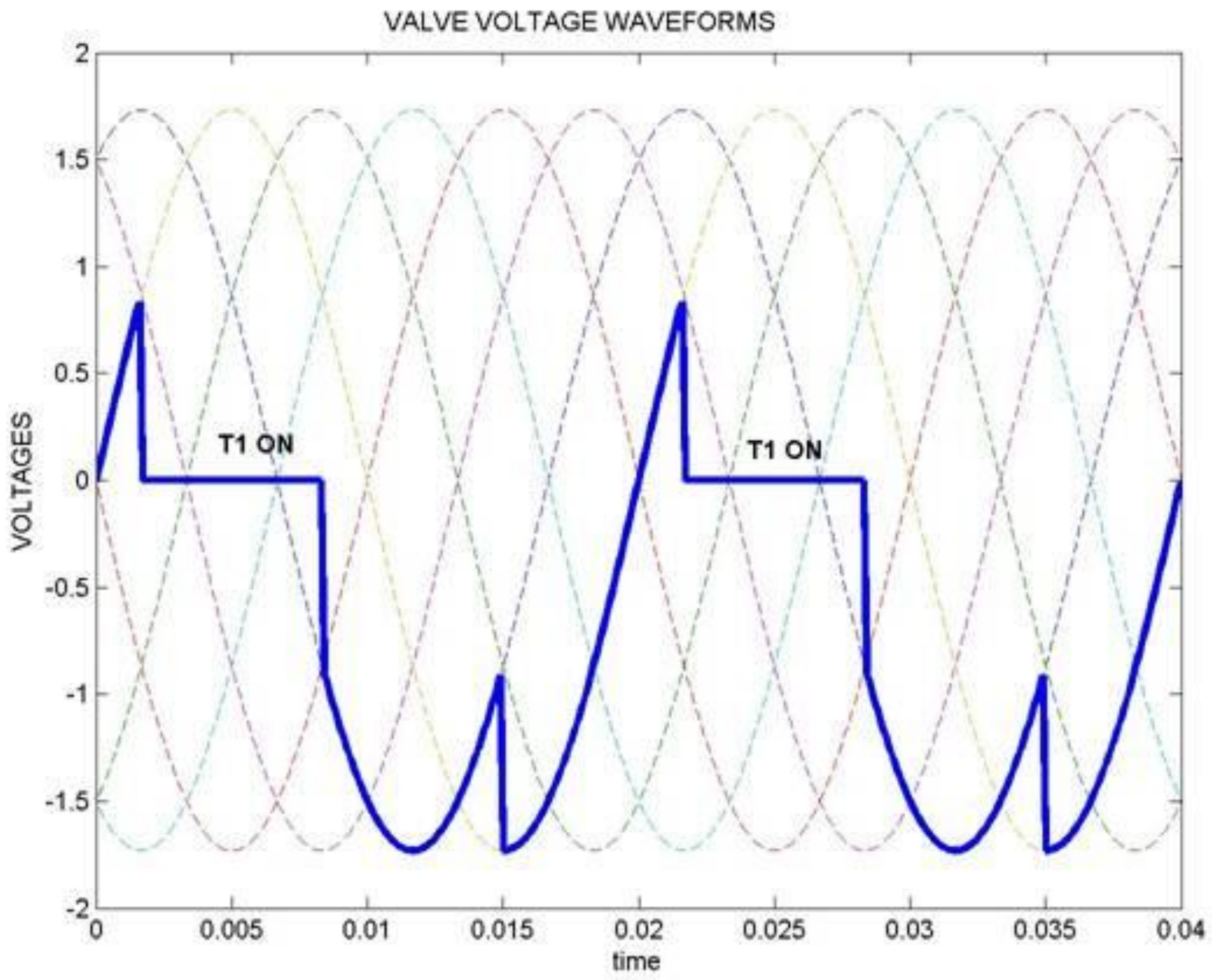
$\alpha = 150$

Without overlap,
Margin = (180 – α)

What is Commutation Margin ? (Inverter Valve voltage waveform)

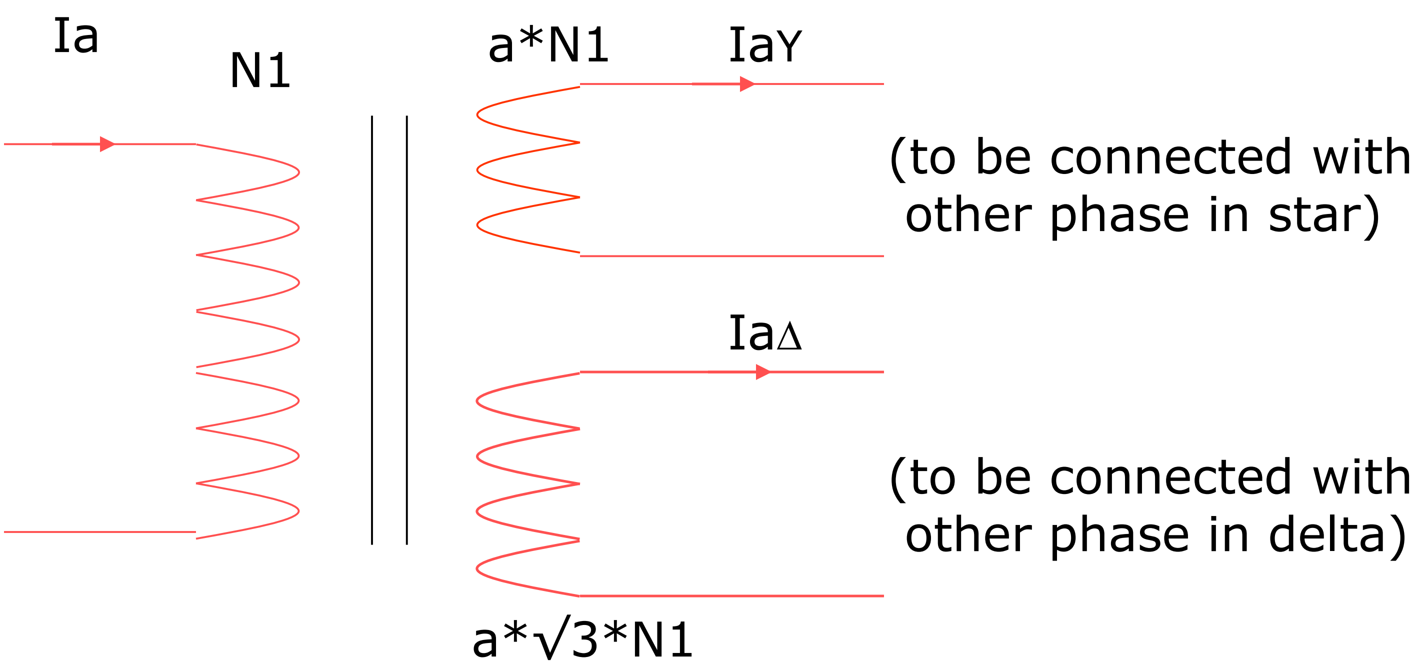


Commutation Margin (Rectifier Valve voltage waveform)



$\alpha = 30$

12 pulse configuration - Transformer

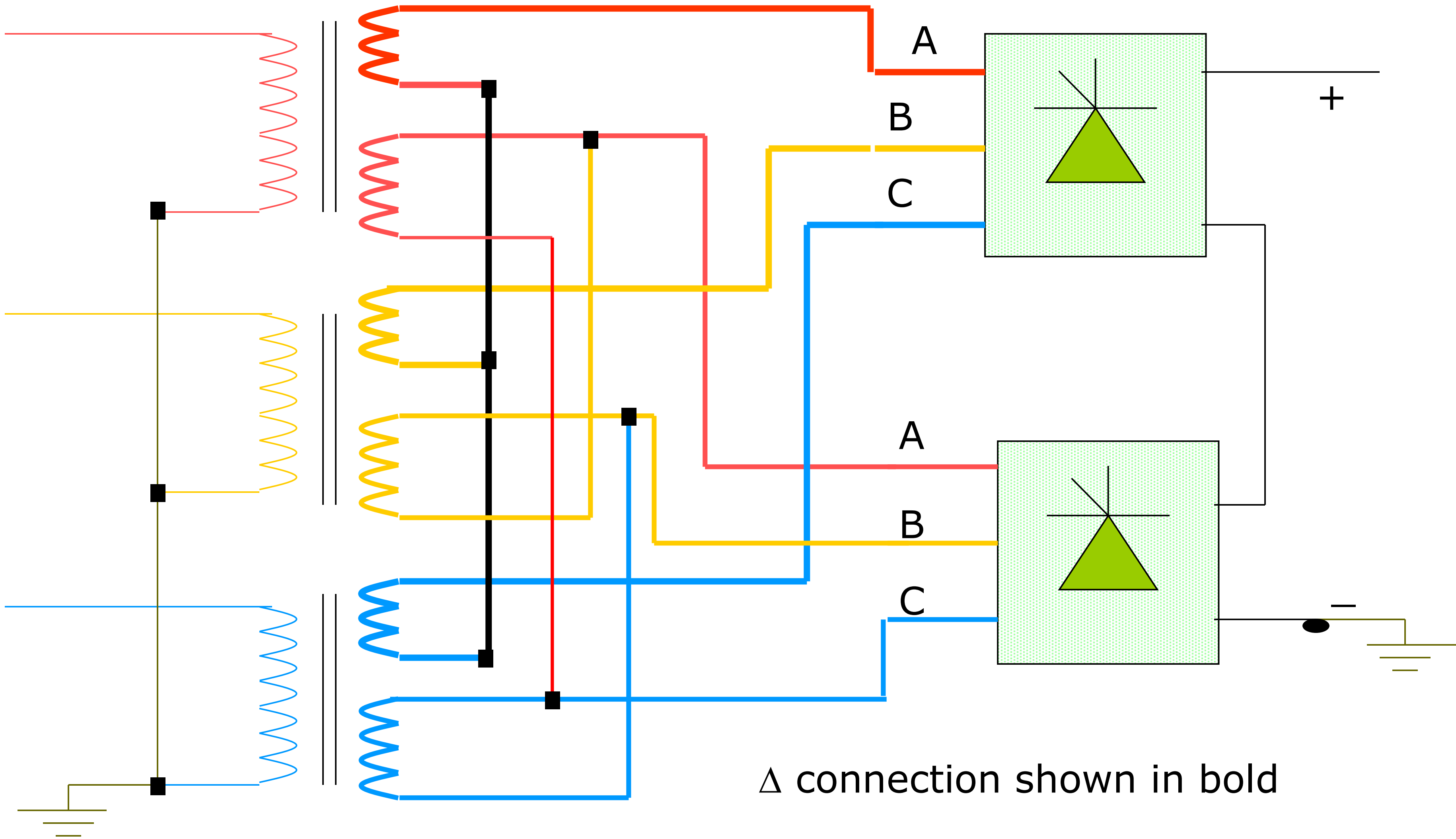


Single phase 3 winding transformer

From mmf balance:

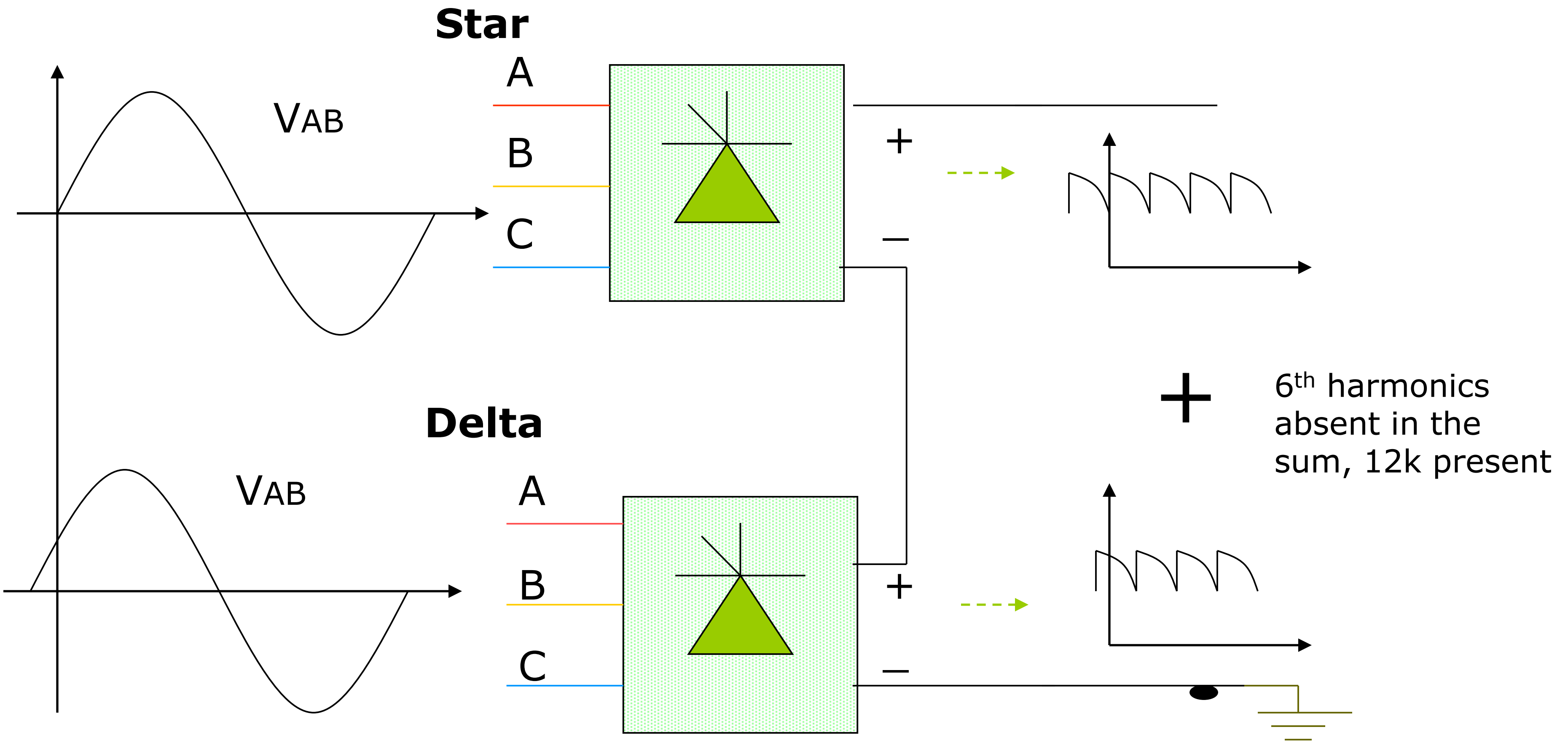
$a*I_{aY} + a*\sqrt{3}*I_{a\Delta} \cong I_a$

12 pulse configuration - Typical



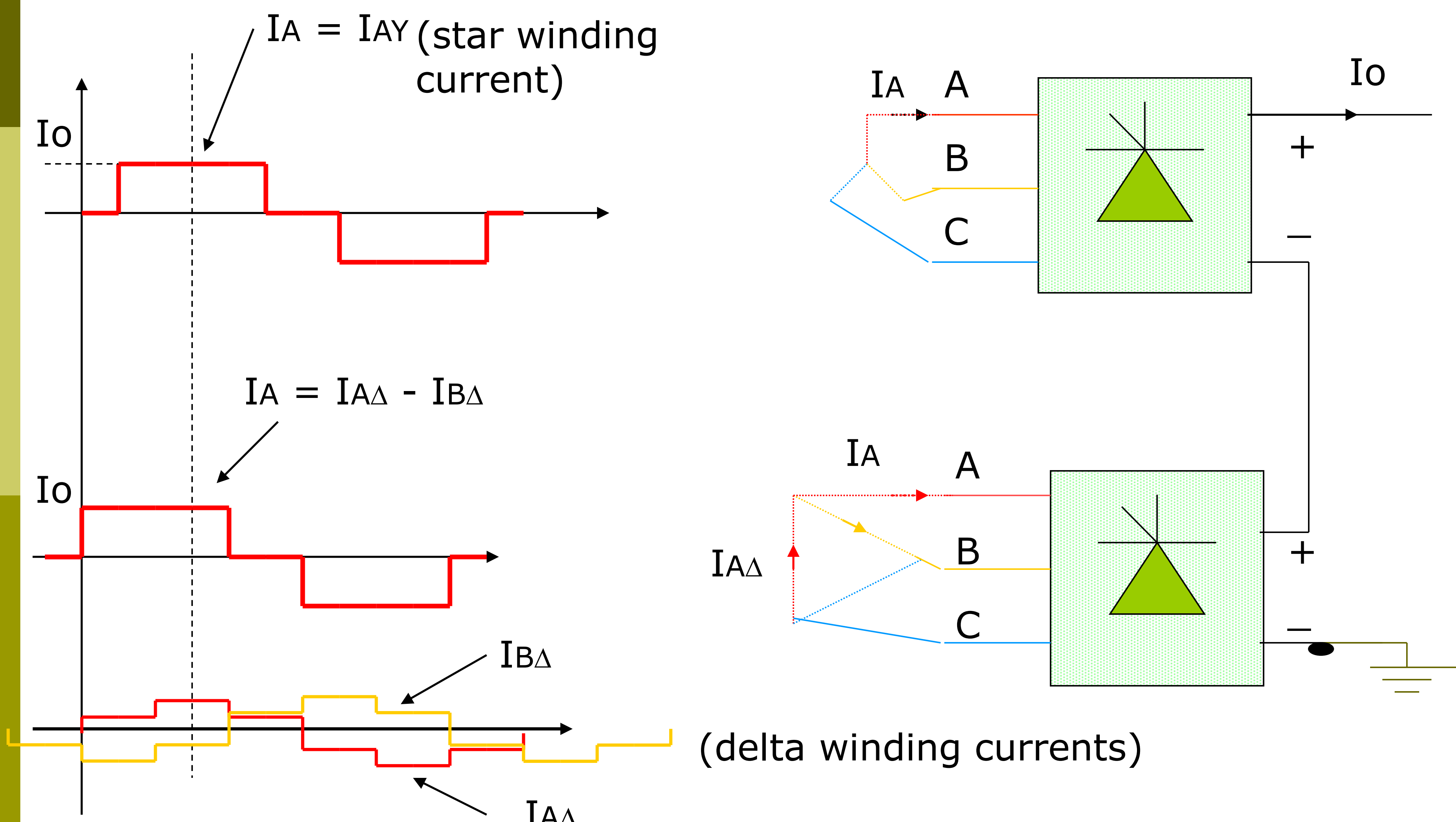
Δ connection shown in bold

AC and DC voltages



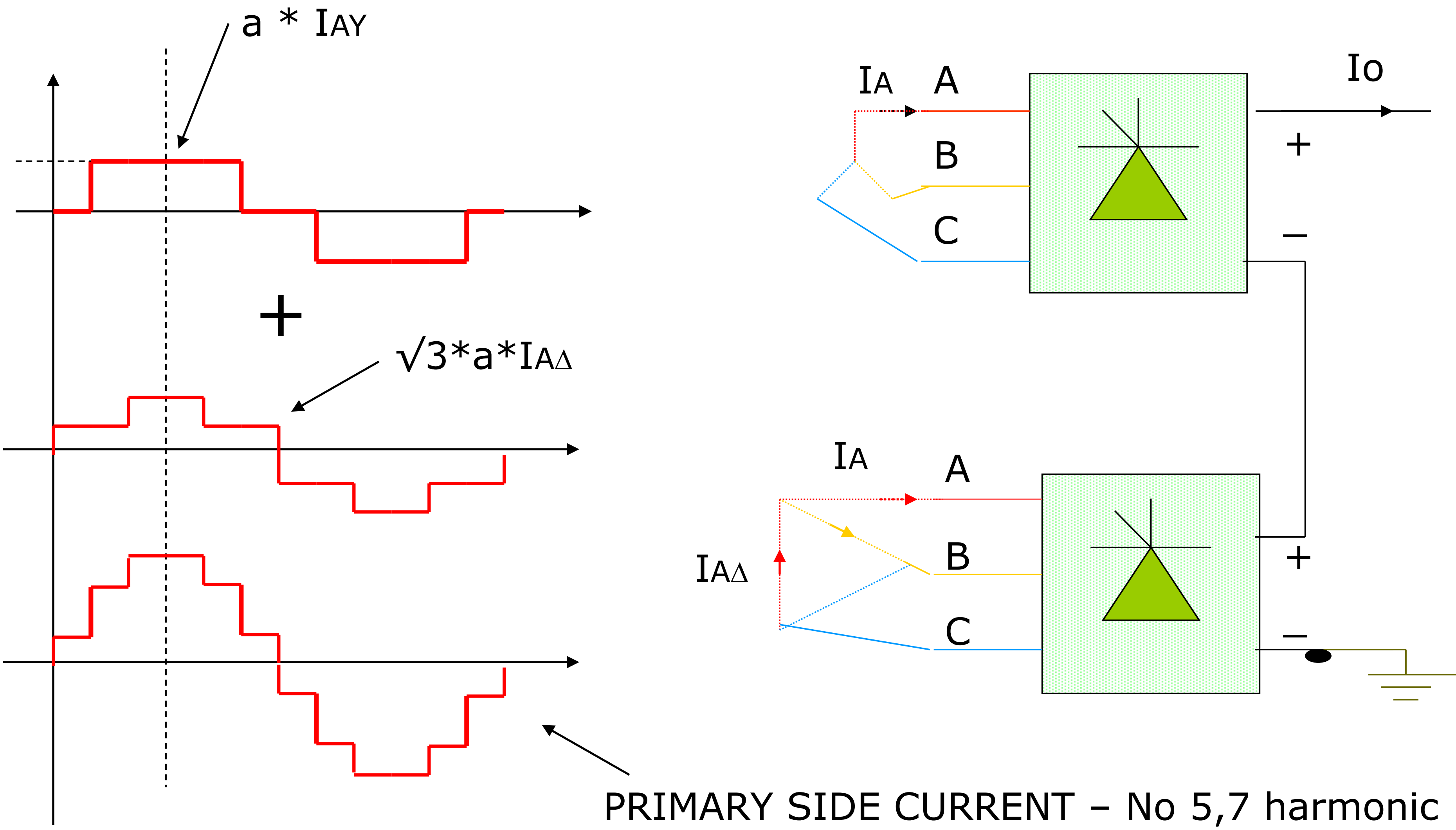
Magnitude of AC voltage same (due to turns ratio), but phase shift of 30

AC side currents



(delta winding currents)

AC side currents



Types of HVDC systems

Two terminal (with DC transmission line, one rectifier terminal + one inverter terminal)

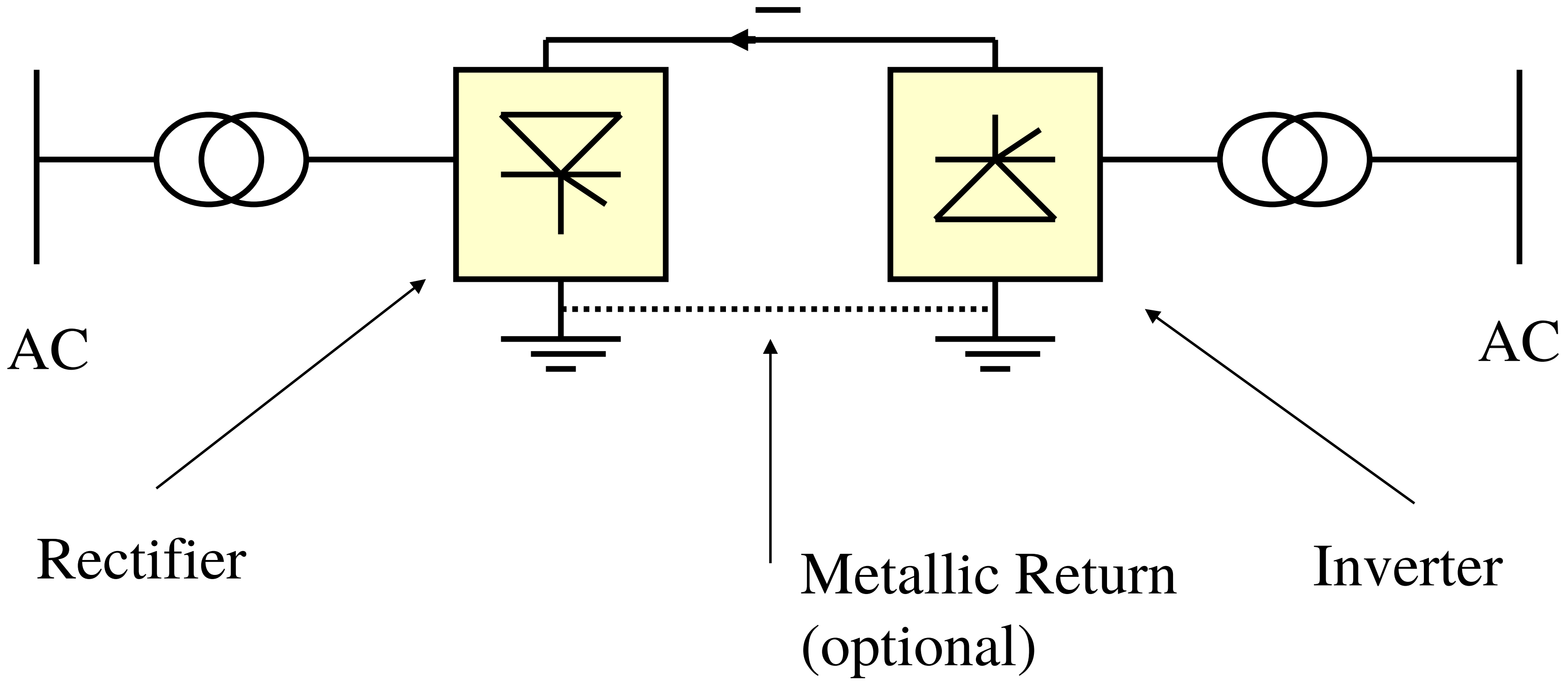
Back – to –Back (two terminal with no DC line – used for asynchronous tie)

Multi-terminal (with DC lines and several rectifier and/or inverter terminals connected to more than 2 nodes of the AC network)

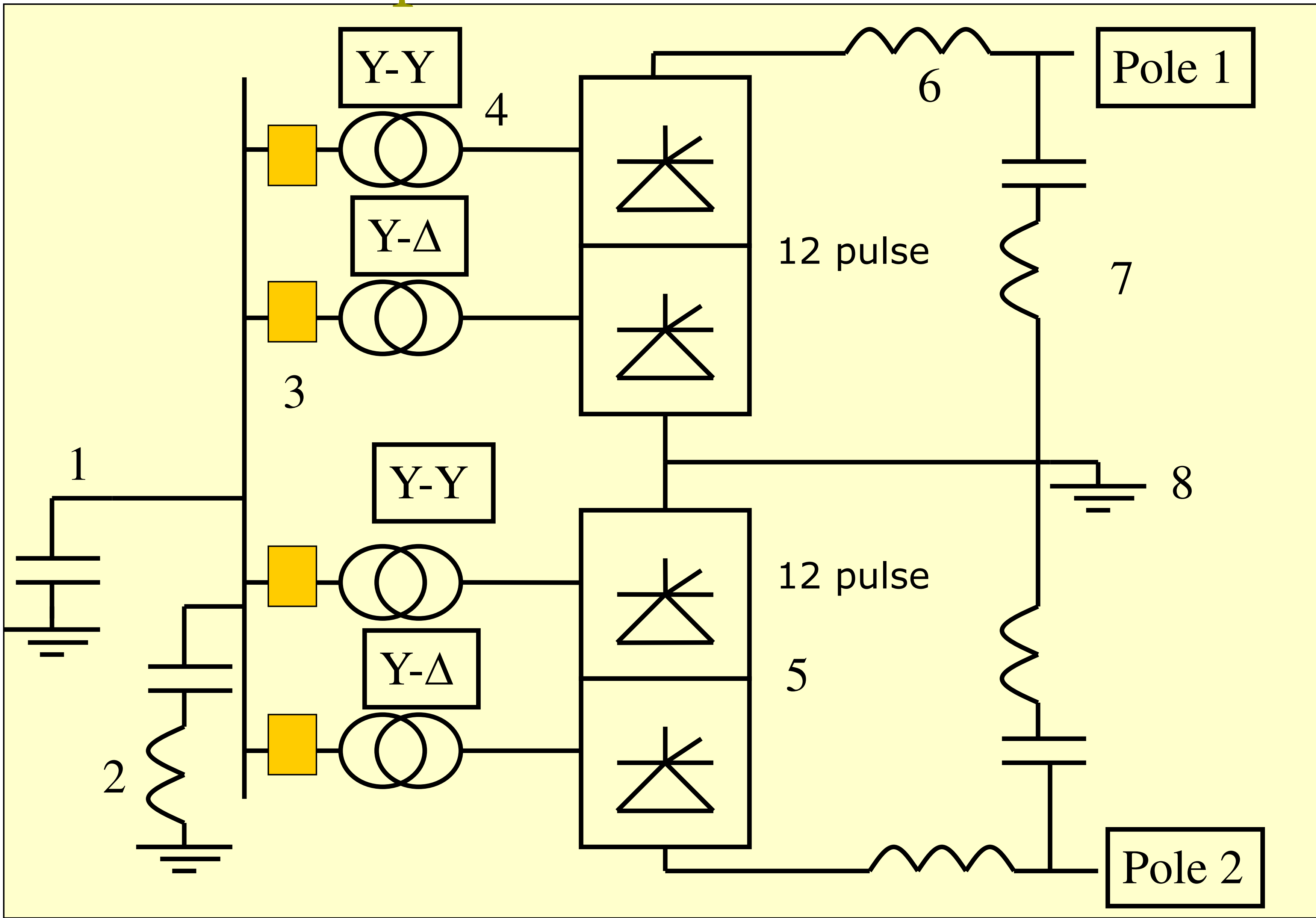
- **Types of links**

  a) Monopolar b) Bipolar

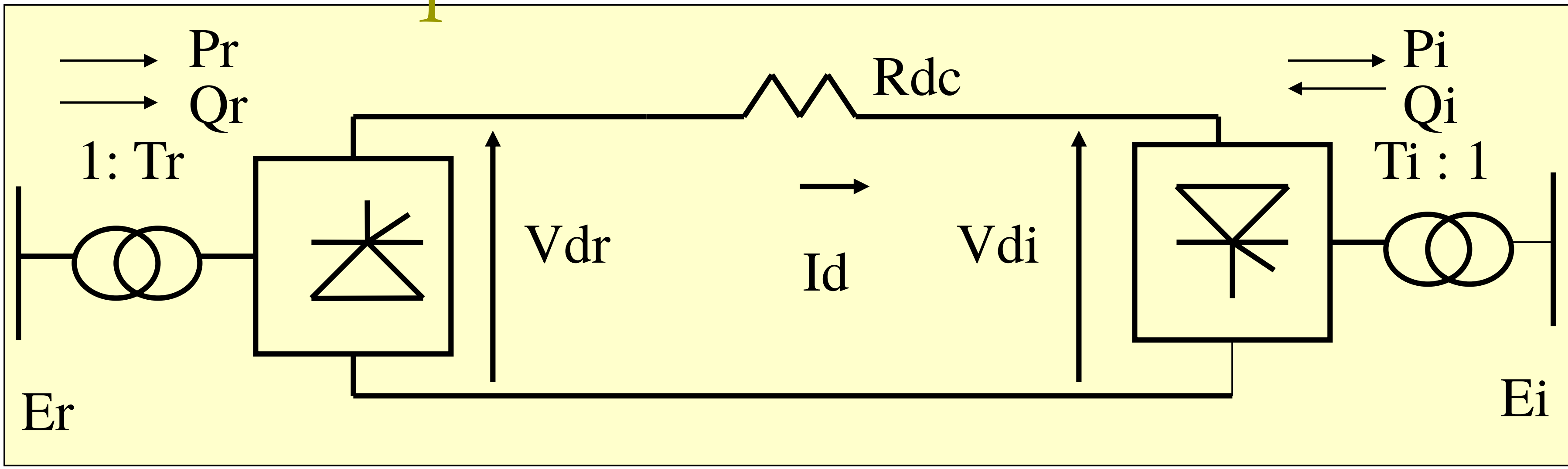
Types of Links : Monopolar



HVDC bipolar converter station



Basic Equations



Vd , Id = direct voltage / current **per pole,** E = line to line rms AC voltage, T : Turns ratio (note that taps are usually provided),

B = number of bridges **per pole ,** Rdc = resistance of dc line **per pole**

P = active power, Q=reactive power, Xc= ω Lc = commutating reactance per bridge / per phase,

Subscripts 'r' and 'I' denote rectifier and inverter respectively.

α = delay angle , γ = extinction angle

Note : Figure above has one bridge and one pole.

12 pulse converters have 2 bridges per pole.

Control Hierarchy

System Control

1. **Power Scheduling**
   (Load Dispatch Centre)
2. **Auxiliary Control**
   --- Damping control
   --- SSR Damping Control
   --- Reactive Power Control
   ---Power/ Frequency Control

(Higher Level Control)

Converter Control

Firing Angle Control

(Lower Level Control)

AC – DC system interaction

- Weak /Strong AC systems.

  Short Circuit ratio = short circuit MVA of AC system / dc converter MW rating
- Effective SCR also includes effect of filters, shunt capacitors, synchronous condensers etc.

  “High ESCR” = (around 5), “Moderate ESCR” = 3 – 5, “Low SCR” = less than 2.
- Effective Inertia constant = Total H of AC system / MW rating of link.

  EIC should be atleast 2-3.
- Problems with weak systems : High dynamic overvoltages, voltage instability, harmonics and flicker