3416
Wind Energy Systems

Chapter 3: Power Electronics

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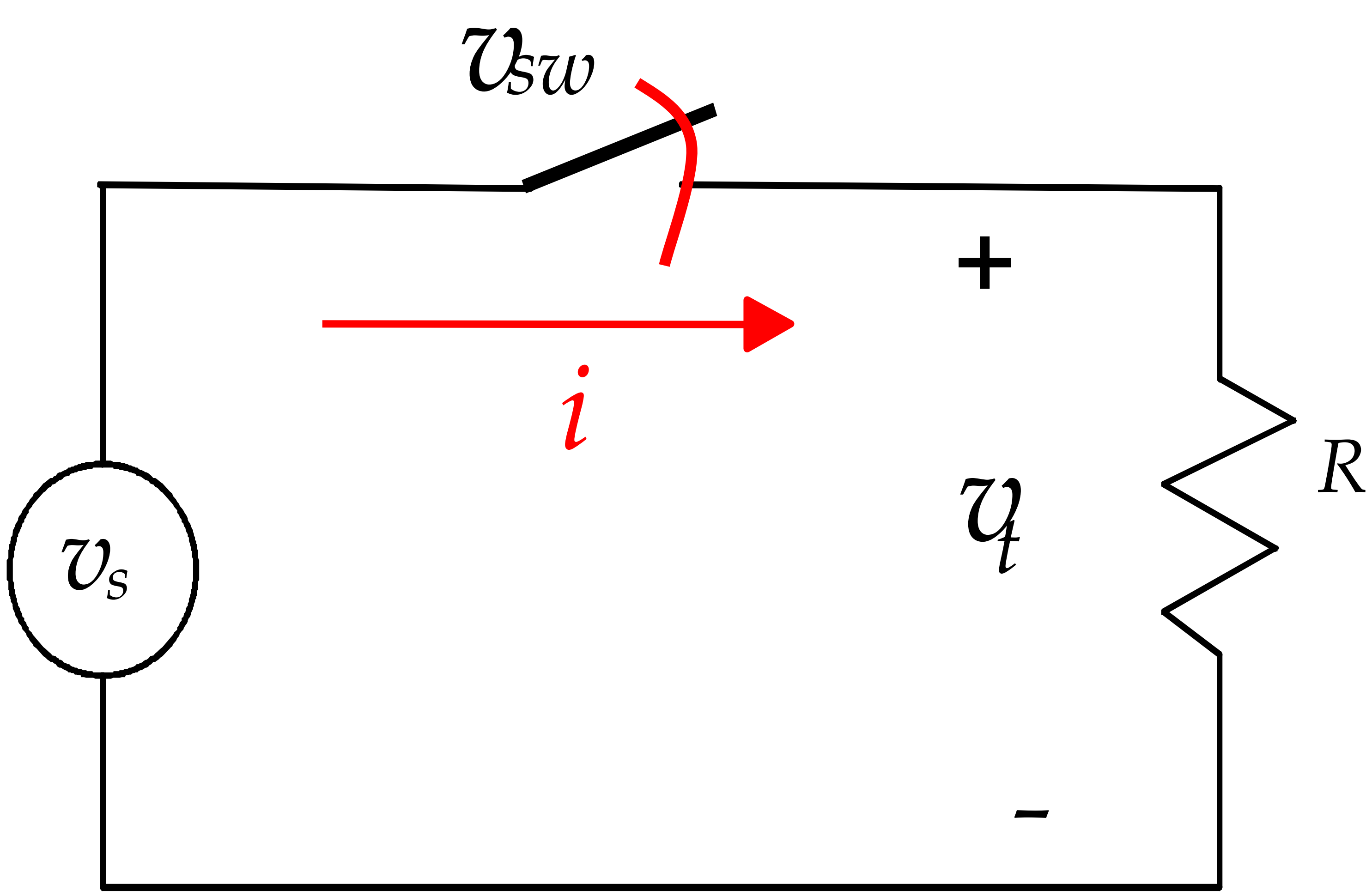
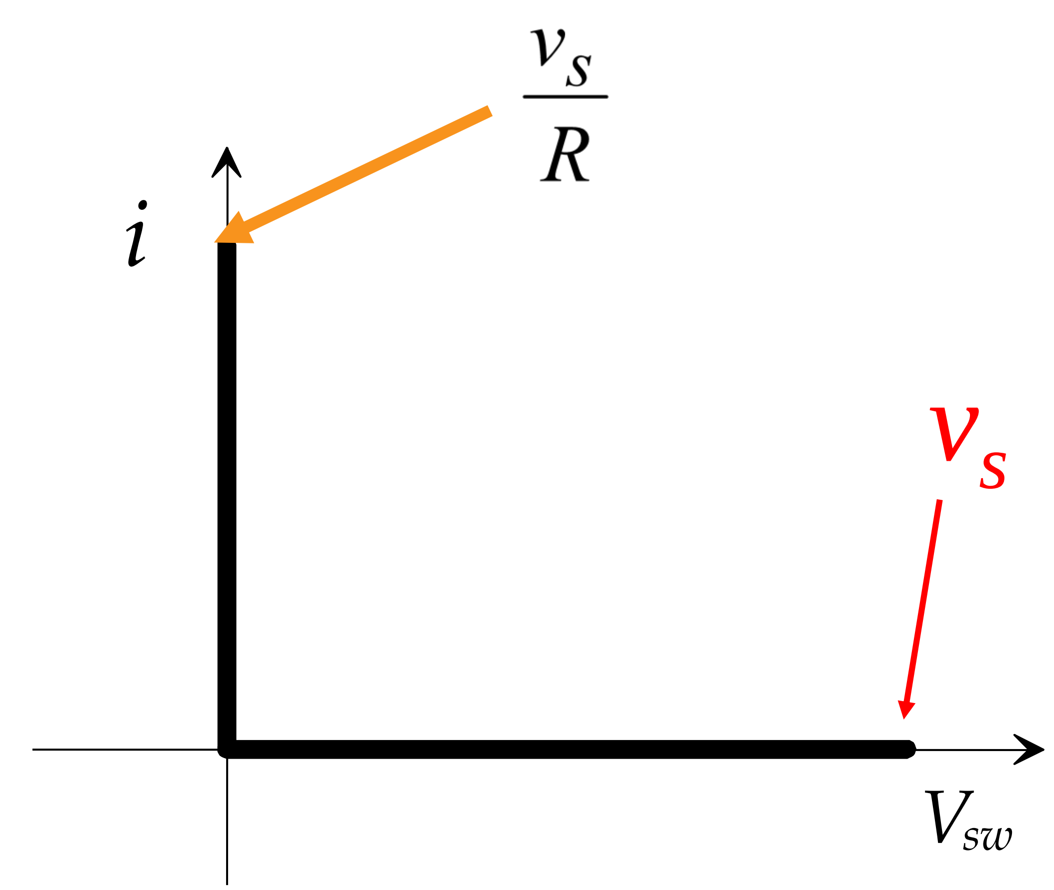
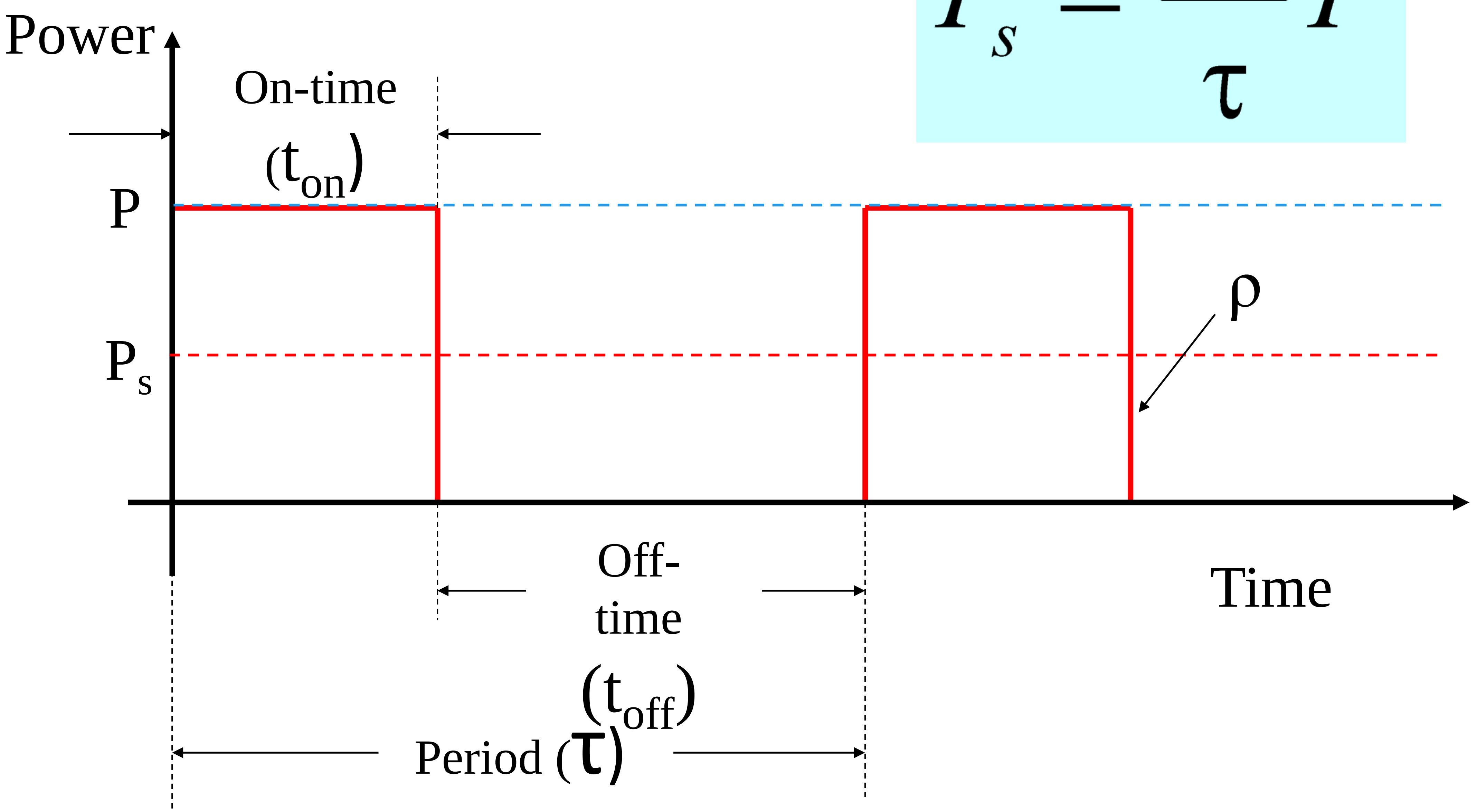
Ideal Switch



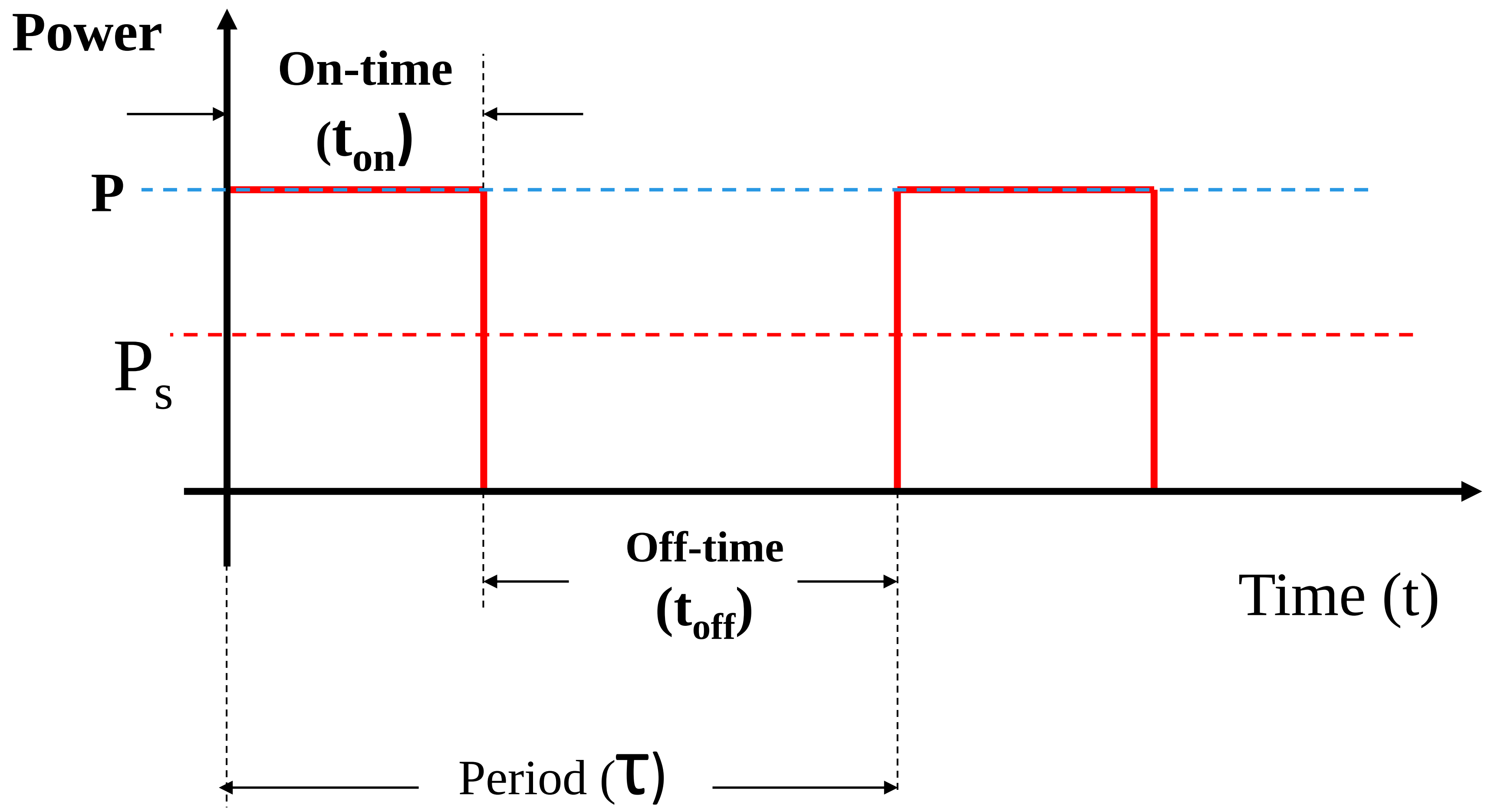


Power Control

$$P_s = \frac{t_{on}}{\tau} P$$



Energy Consumption (E)

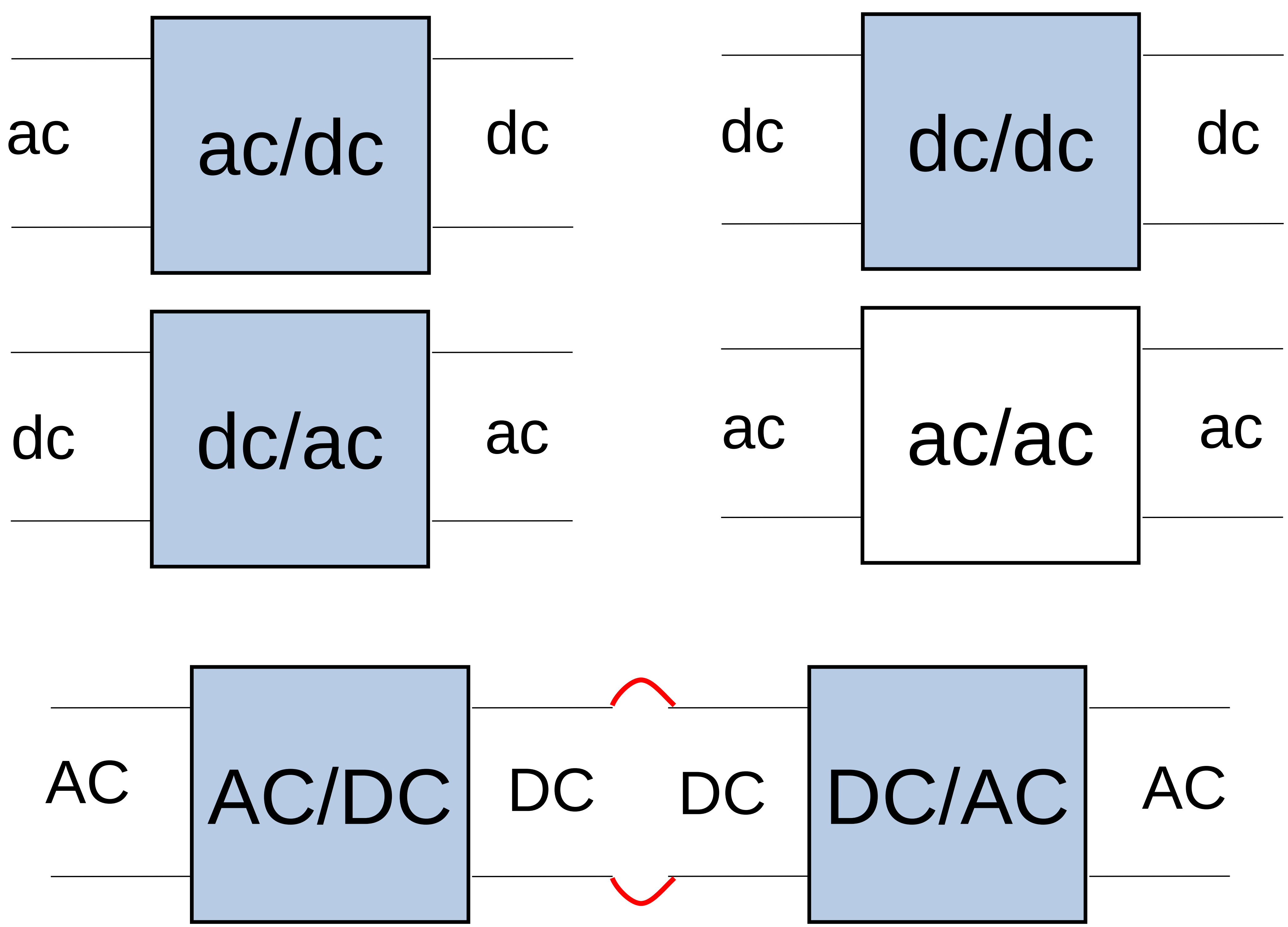


Duty Ratio (K)

$$E \equiv P\,t$$

$$E_s = P_s\,t = \frac{t_{on}}{\tau} P\,t$$

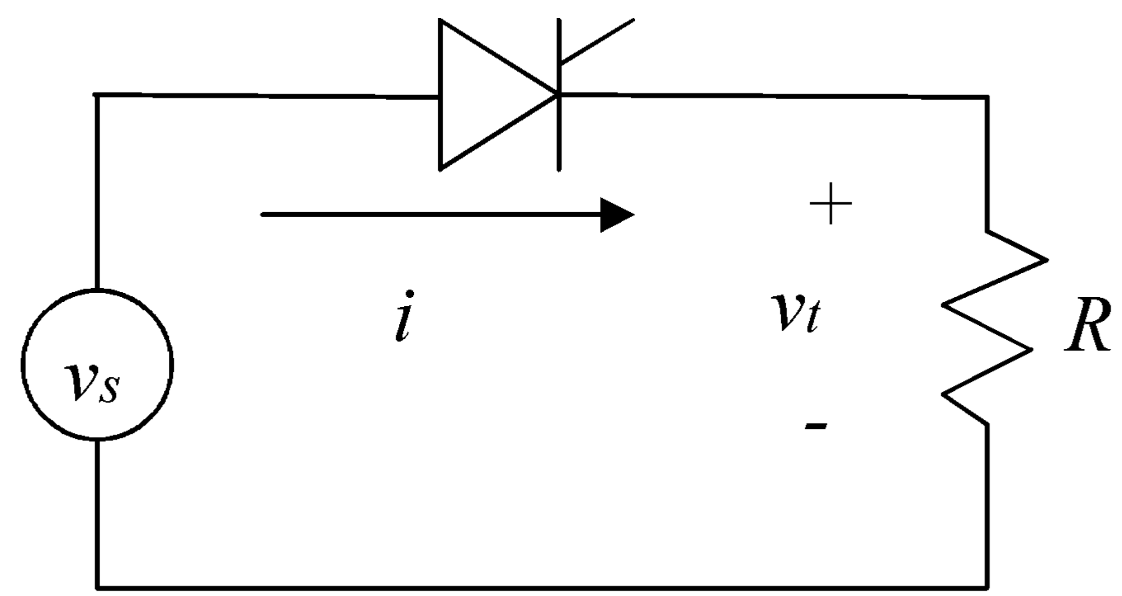
Types of Converters



AC/DC Converters

Single-Phase, Half-Wave

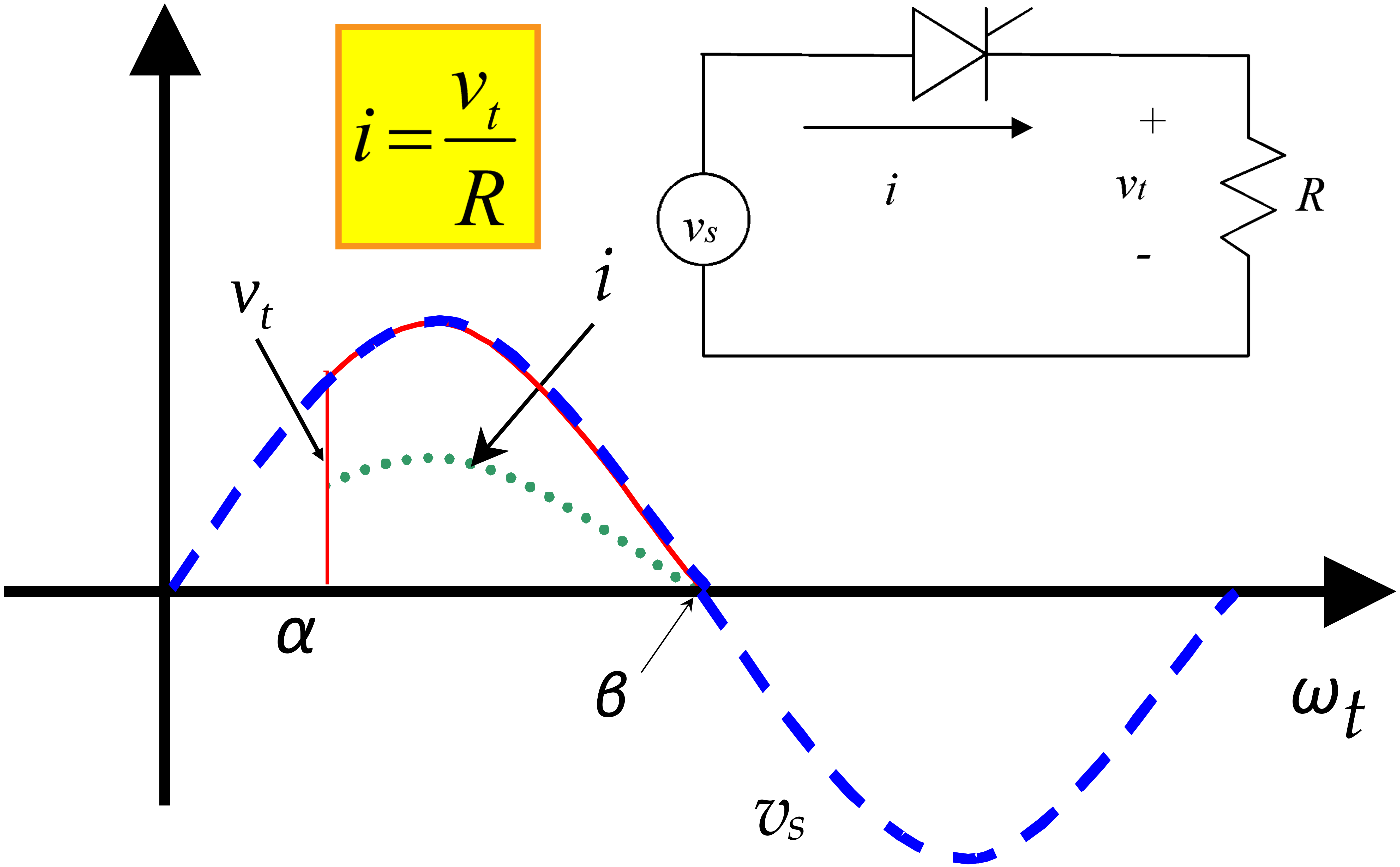
$$v_s = V_{max} \sin(\omega t)$$



$$i = \frac{v_s}{R} \text{(only when SCR is closed)}$$

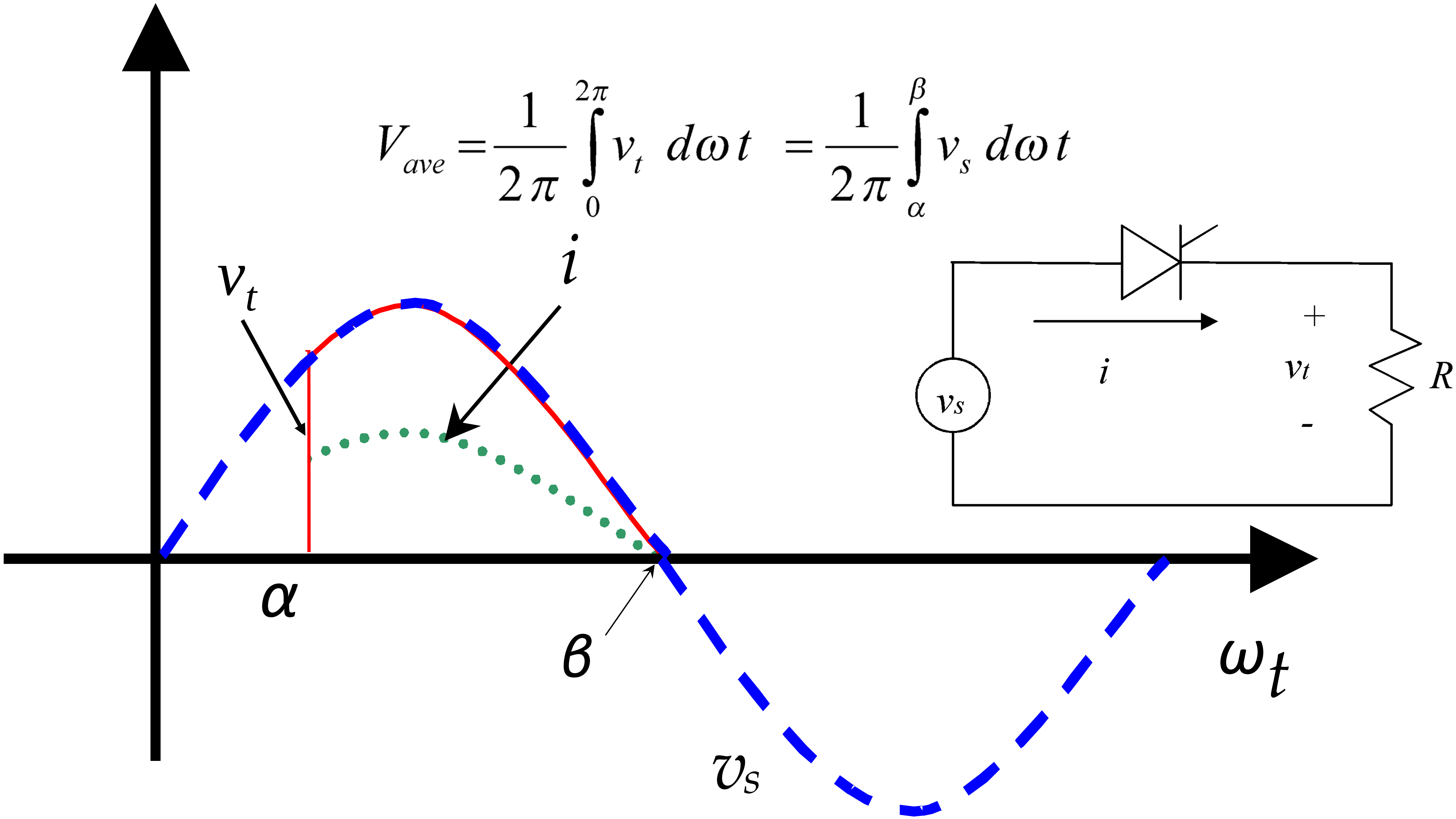
$$v_t = i\ R = v_s \text{ (only when SCR is closed)}$$

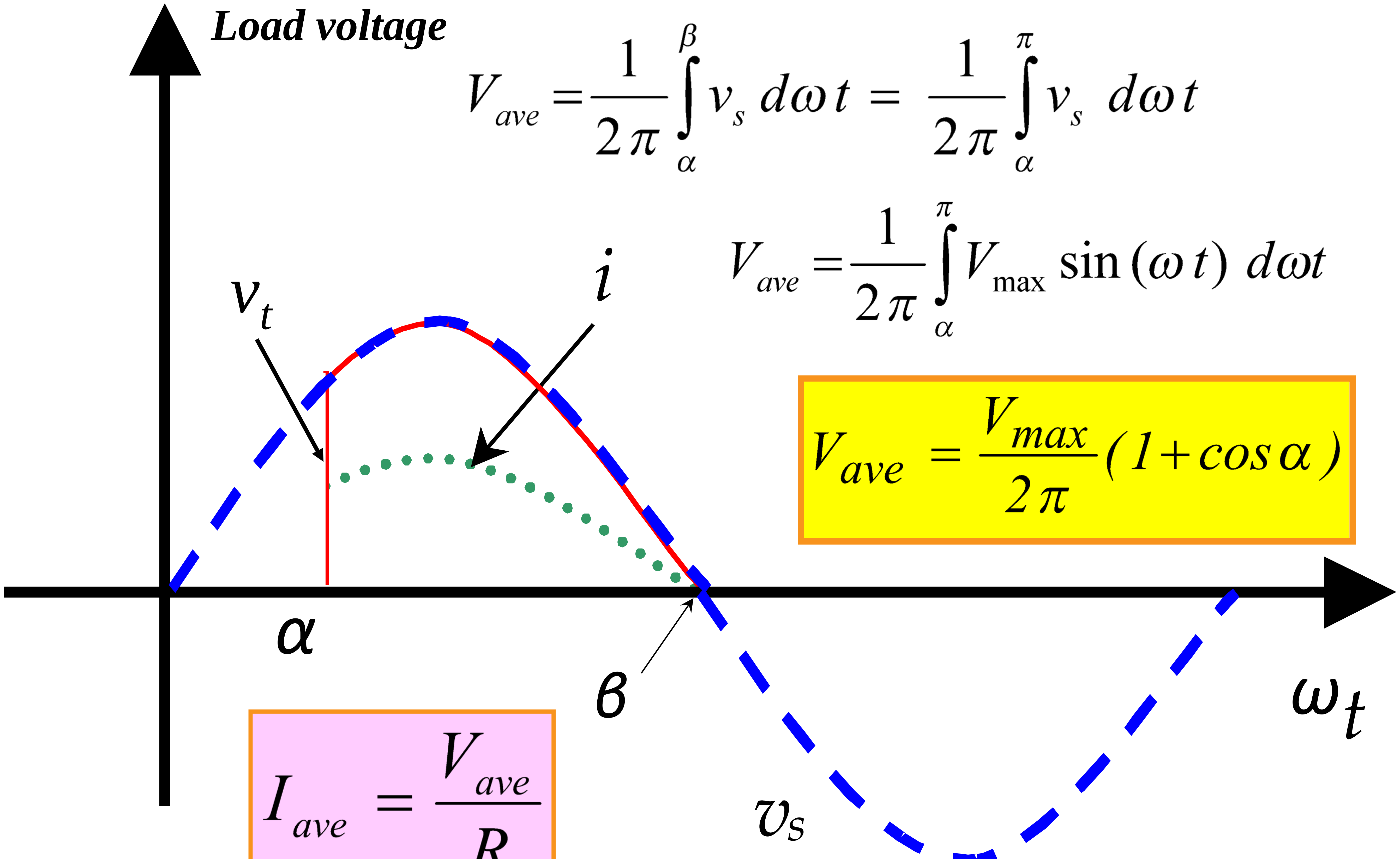
$$i = \frac{v_t}{R}$$



Average Voltage Across the Load

$$V_{ave} = \frac{1}{2\pi}\int_0^{2\pi} v_t \; d\omega t \; = \frac{1}{2\pi}\int_\alpha^{\beta} v_s \, d\omega t$$





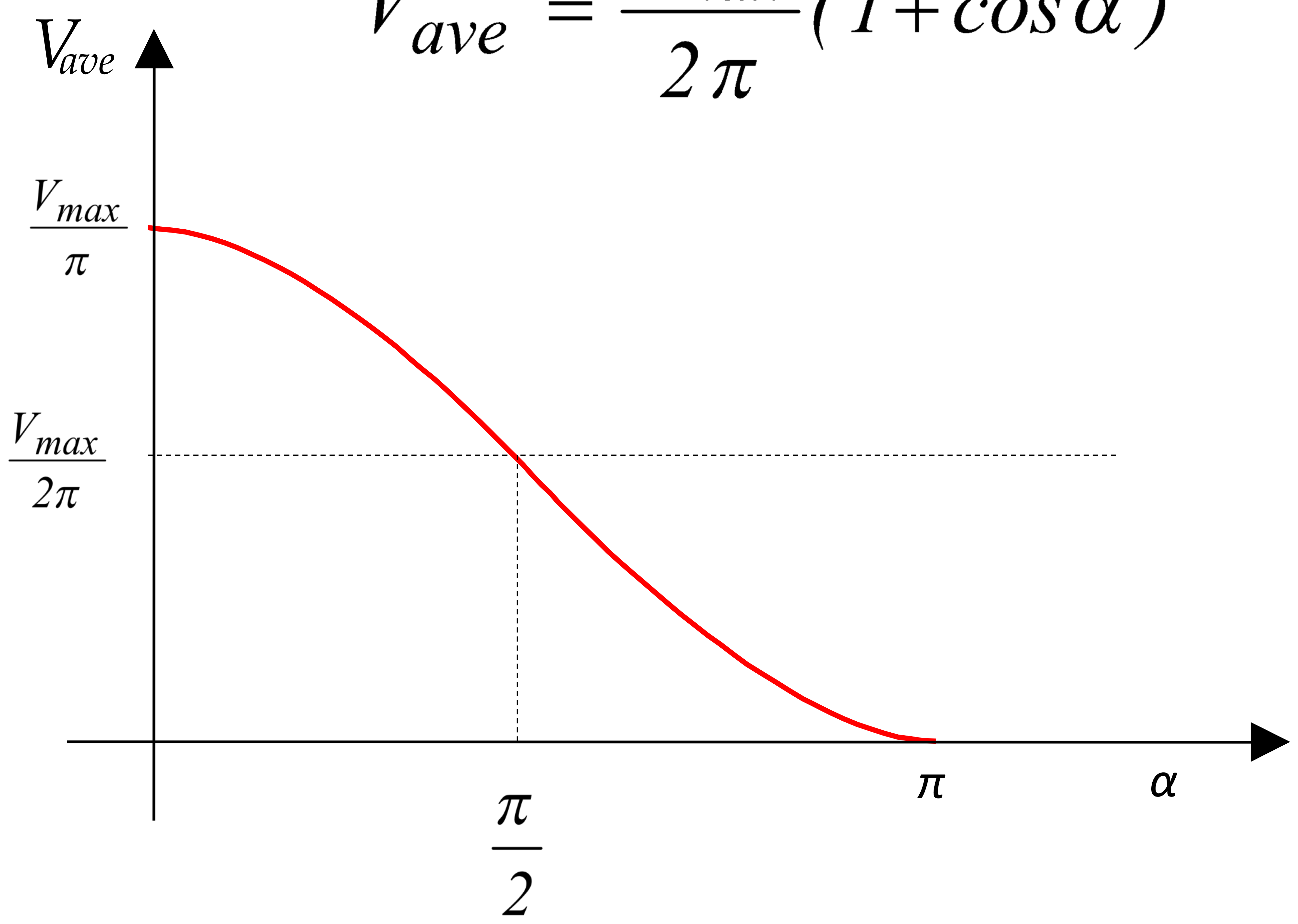
$$V_{ave} = \frac{1}{2\pi}\int_{\alpha}^{\beta} v_s \, d\omega t = \frac{1}{2\pi}\int_{\alpha}^{\pi} v_s \, d\omega t$$

$$V_{ave} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_{\max} \sin(\omega t) \, d\omega t$$

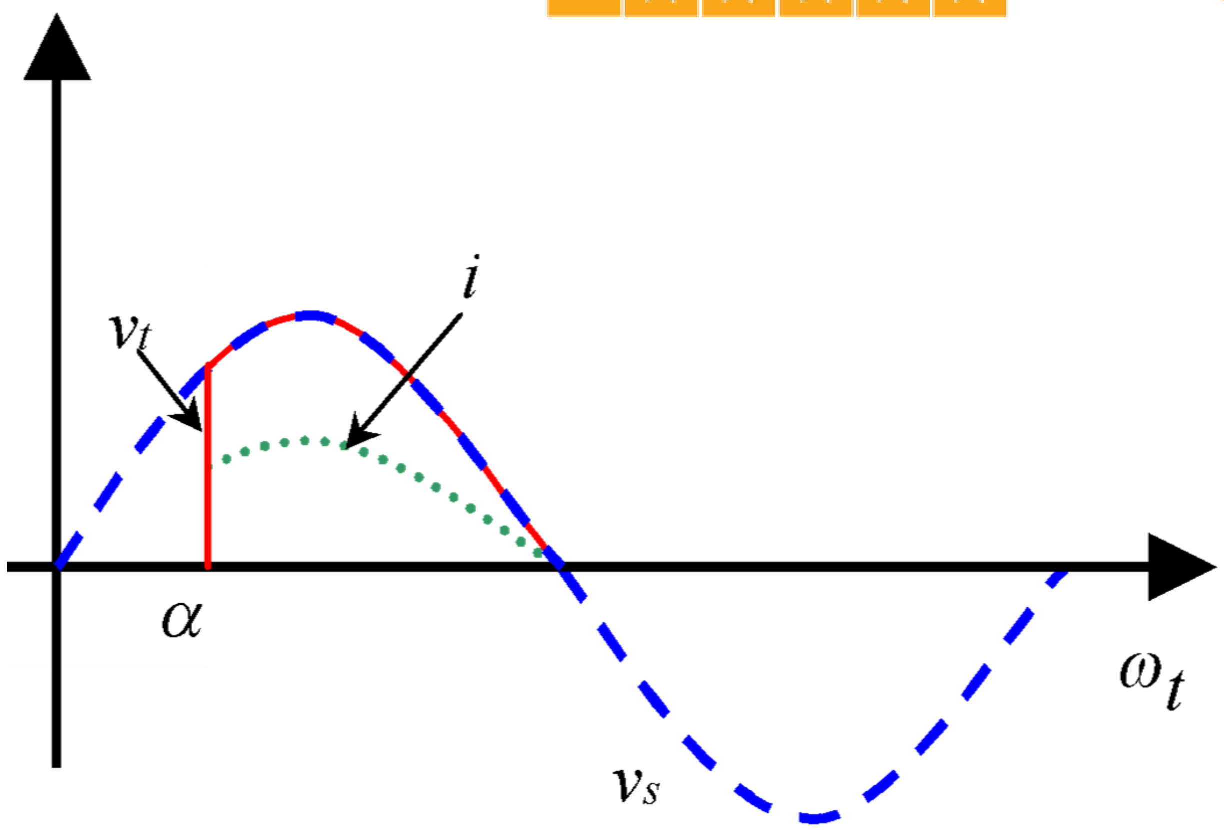
$$V_{ave} = \frac{V_{max}}{2\pi}(1 + \cos\alpha)$$

$$I_{ave} = \frac{V_{ave}}{R}$$

$$V_{ave} = \frac{V_{max}}{2\pi}(1 + \cos\alpha)$$



RMS of load voltage

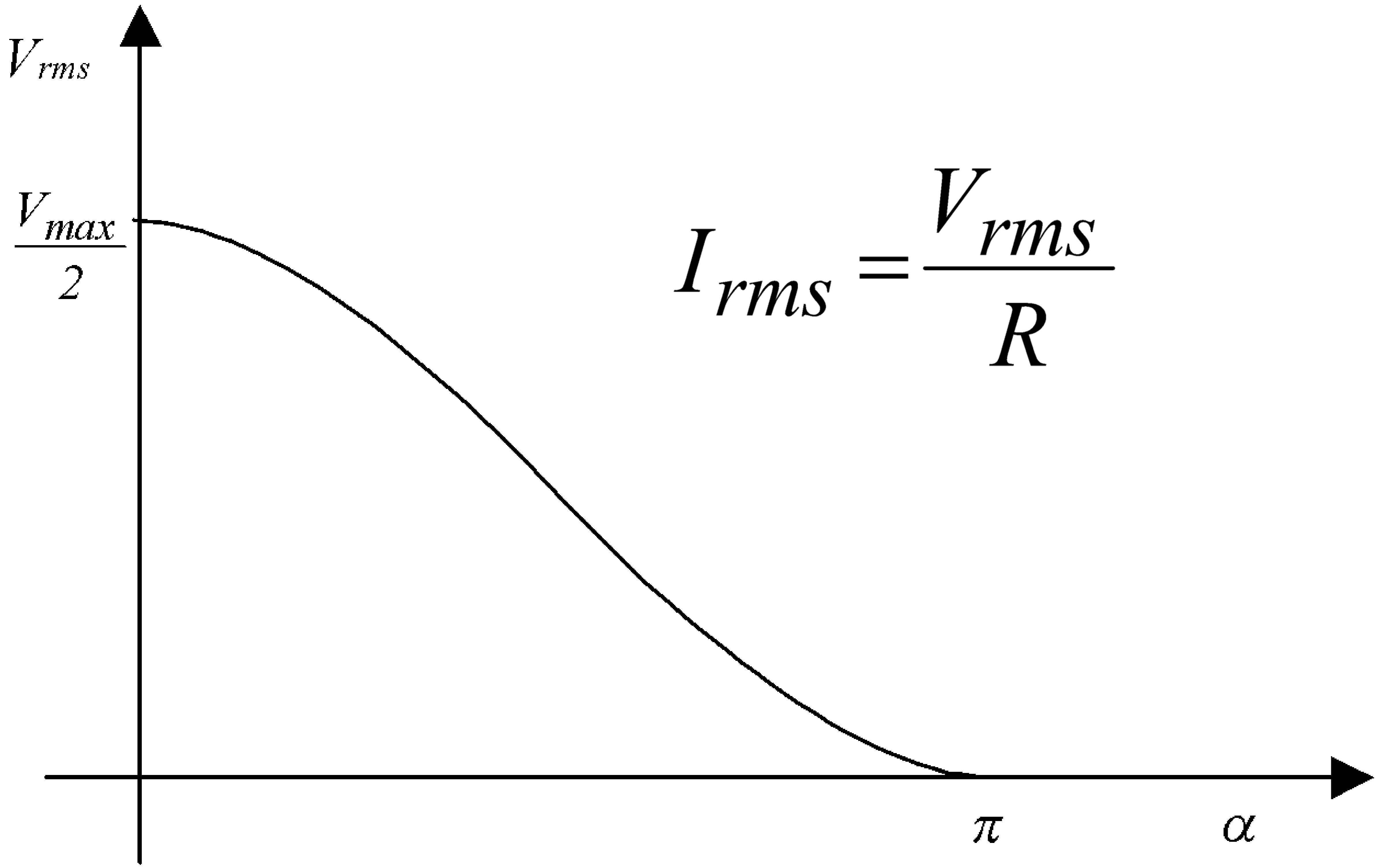


$$V_{rms} = \sqrt{\frac{V_{max}^2}{2\pi}\int_{\alpha}^{\pi}[sin(\omega t)]^2 d\omega t} = \sqrt{\frac{V_{max}^2}{4\pi}\int_{\alpha}^{\pi}[1 - cos(2\omega t] d\omega t}$$

$$V_{rms} = \frac{V_{max}}{2}\sqrt{[1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}]}$$

$$V_{max} = \sqrt{2}\, Vs_{rms}$$

RMS of Supply Voltage



$$I_{rms} = \frac{V_{rms}}{R}$$

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$$P = \frac{V_{rms}^2}{R} = I_{rms}^2 R$$

$$P = \frac{V_{max}^2}{8\pi R}\left[2(\pi - \alpha) + \sin(2\alpha)\right]$$

Single-Phase, Full-Wave, AC-to-DC 2-SCRs and 2 Diodes

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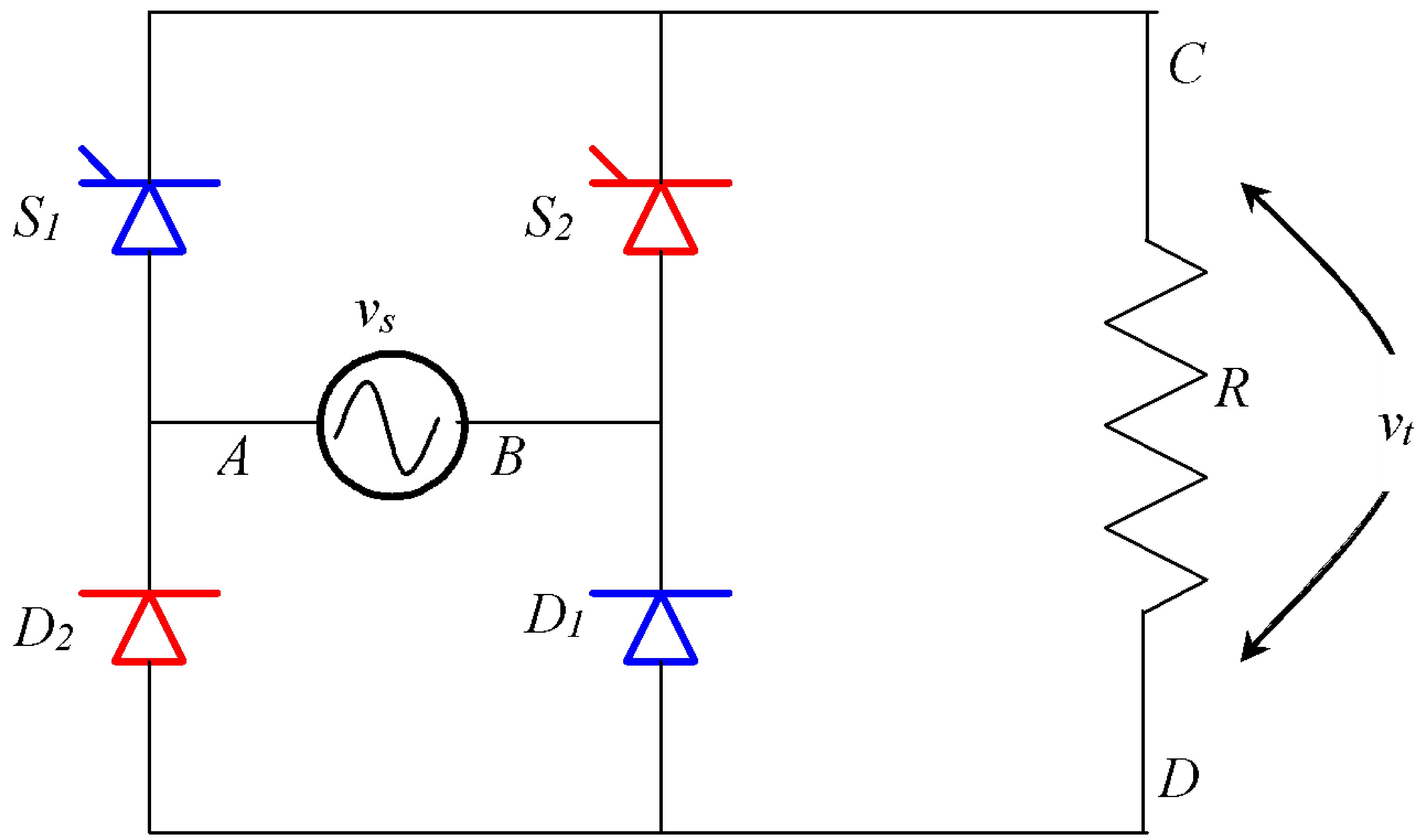
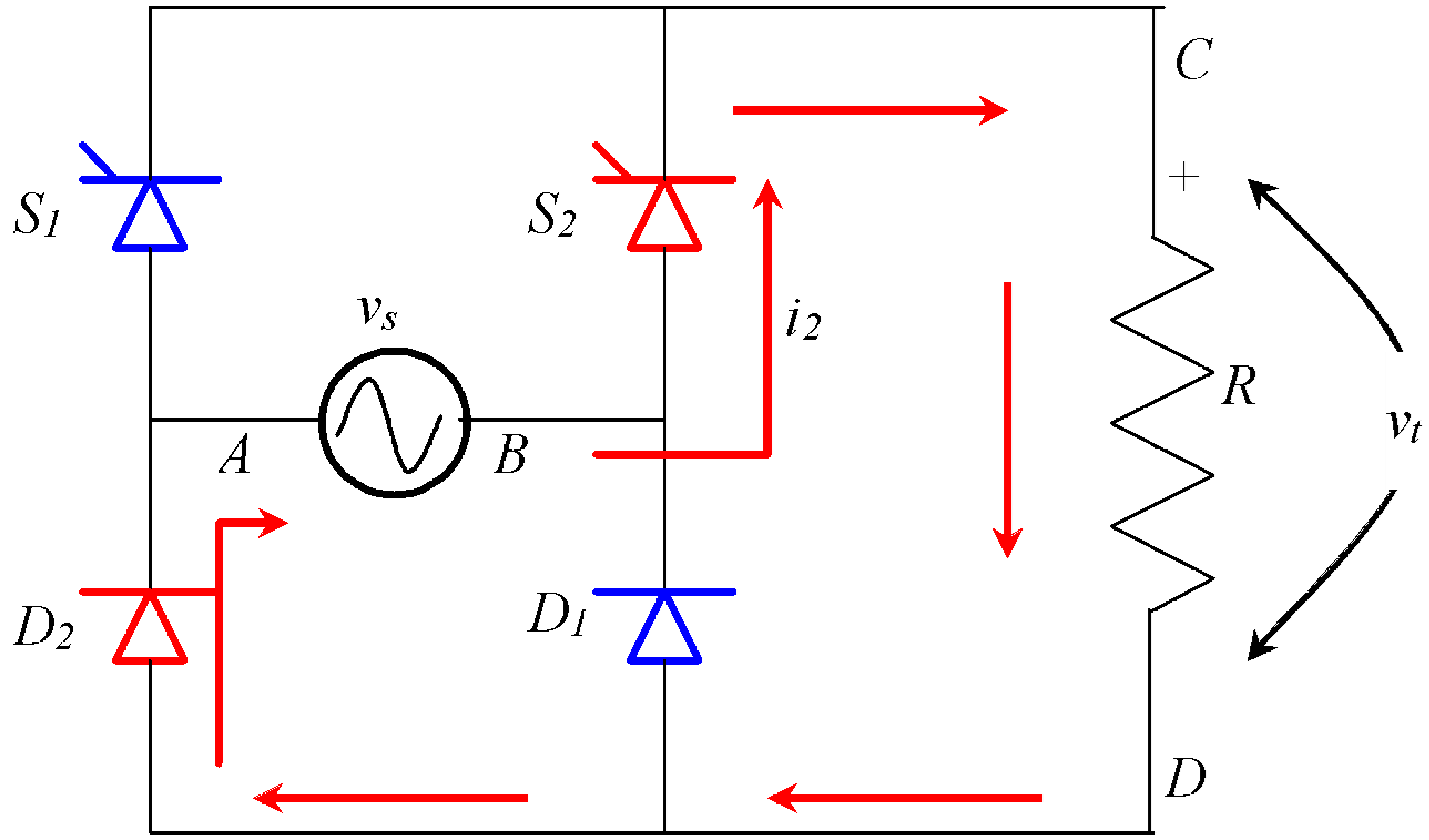
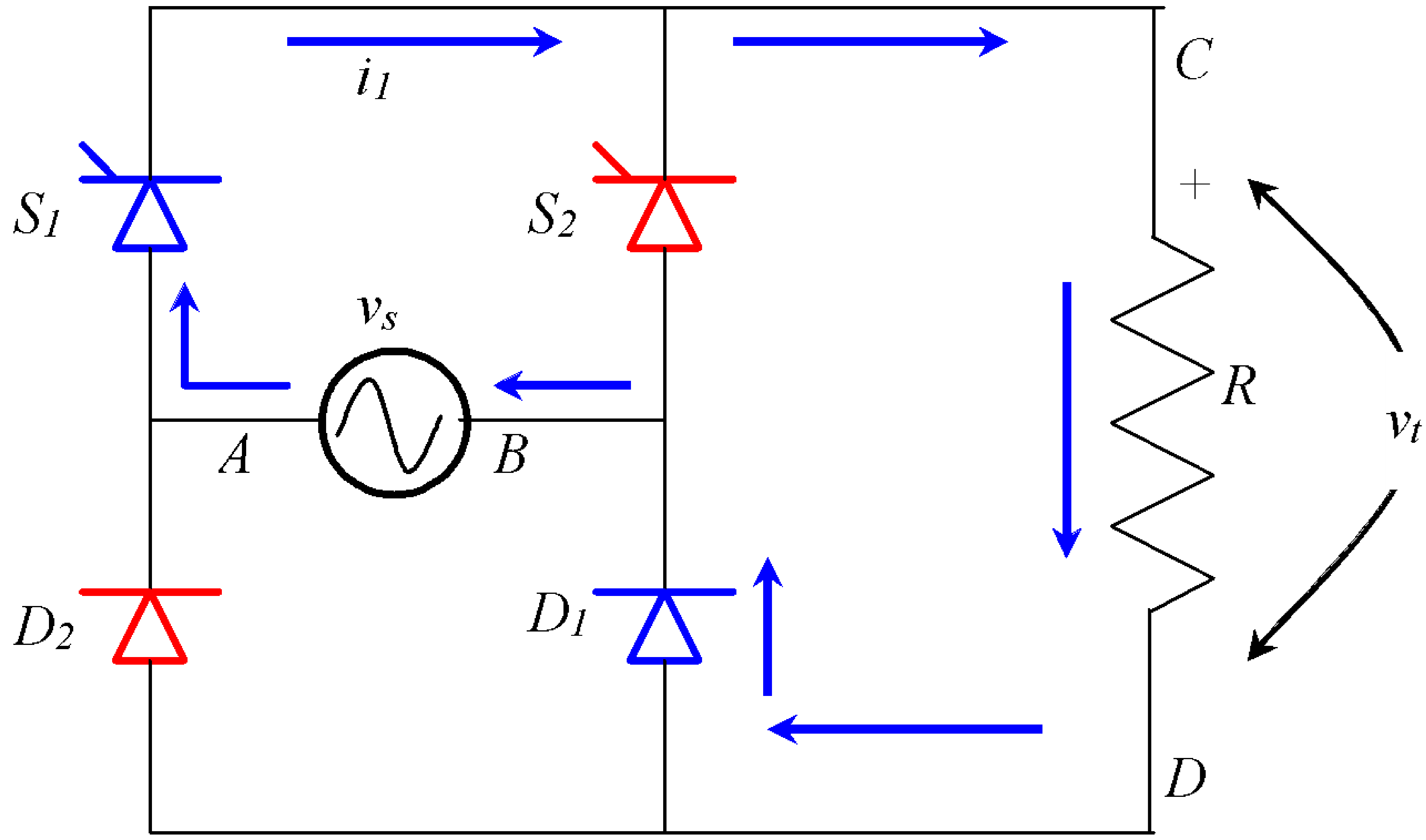
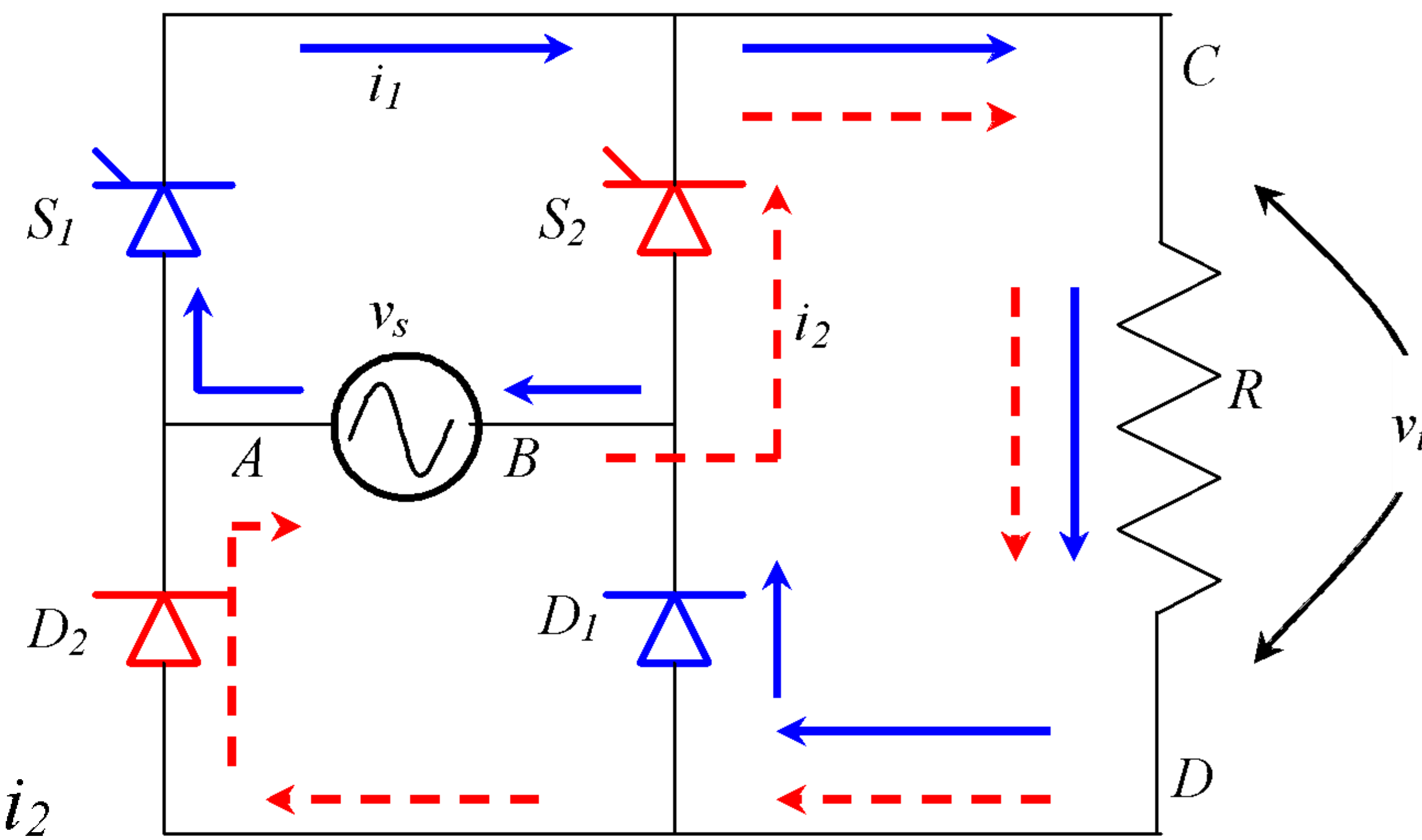


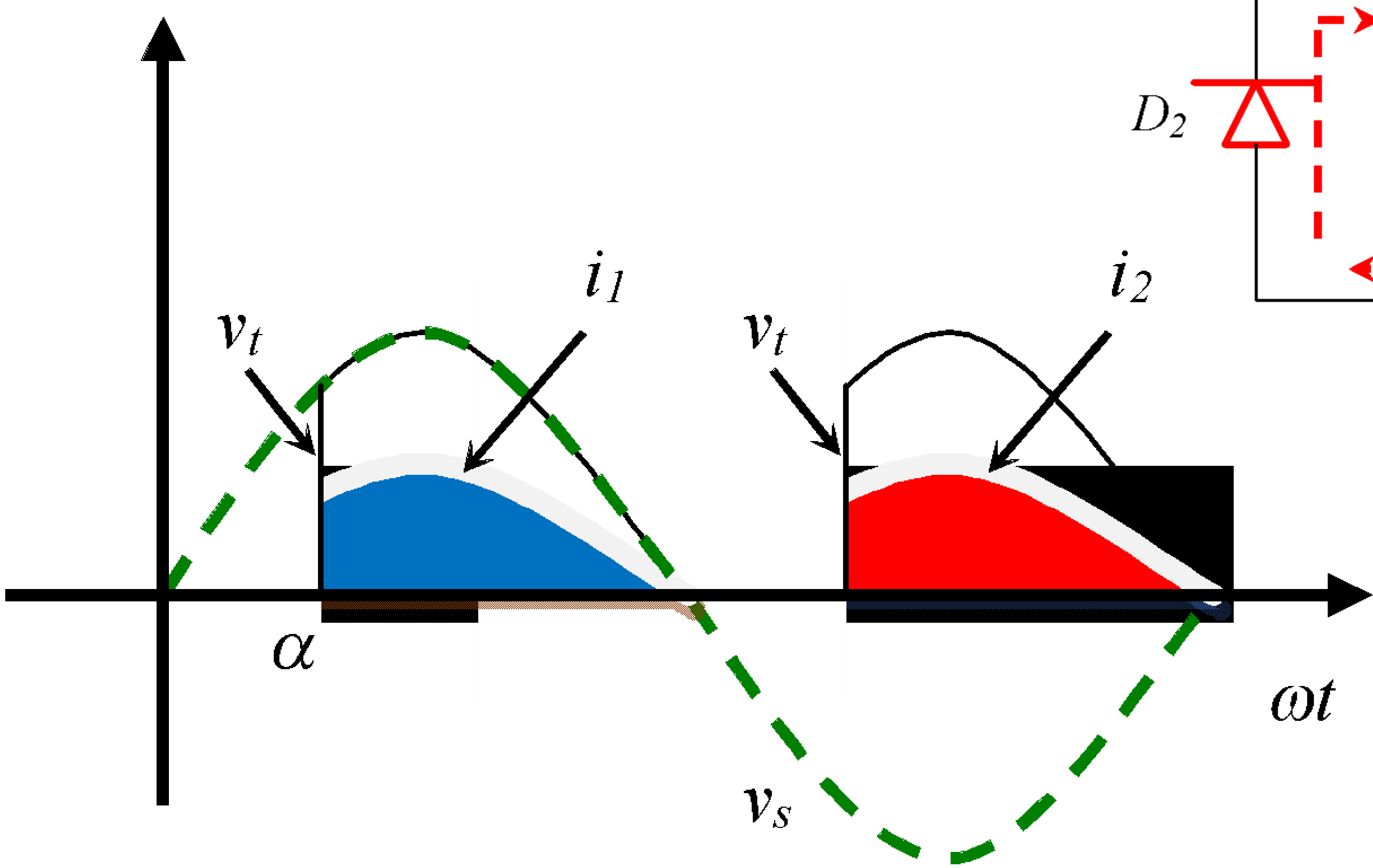
Single-Phase, Full-Wave, AC-to-DC 2-SCRs and 2 Diodes

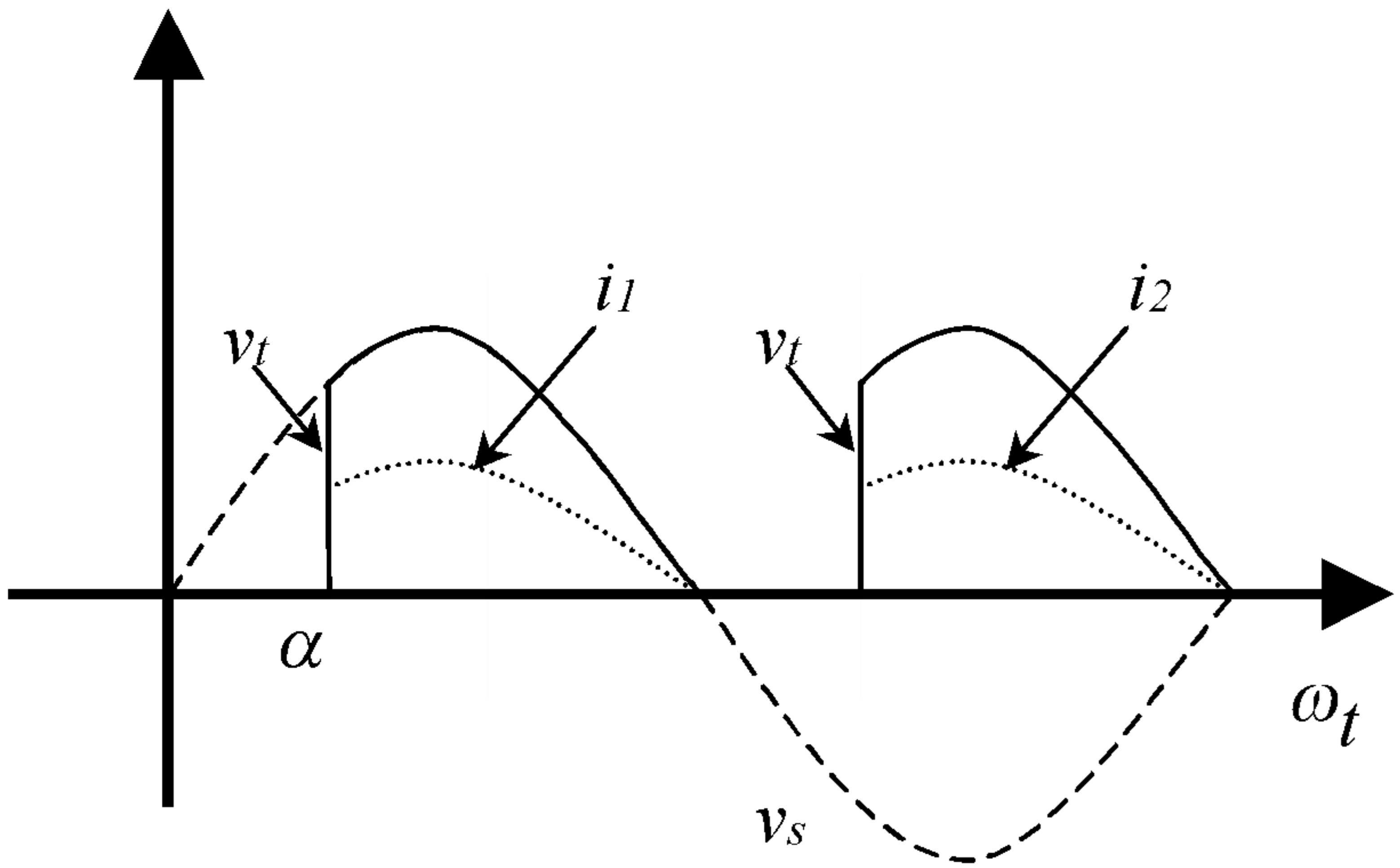


Single-Phase, Full-Wave, AC-to-DC 2-SCRs and 2 Diodes




i_1
C
S_1
S_2
v_s
i_2
R
v_t
A
B
D_2
D_1
D


v_t
i_1
v_t
i_2
α
ωt
v_s



$$V_{ave} = \frac{1}{\pi}\int_{\alpha}^{\pi} v_t \; d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi} V_{max}\, sin(\omega t)\; d\omega t = \frac{V_{max}}{\pi}(1+cos\,\alpha)$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_{0}^{2\pi} v(t)^2 \; d\omega t} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} [V_{\max}\;\sin(\omega t)]^2 \; d\omega t}$$

$$V_{rms} = \sqrt{\frac{V_{max}^2}{\pi}\int_{\alpha}^{\pi} sin(\omega t)^2 \; d\omega t} = \sqrt{\frac{V_{max}^2}{2\pi}\int_{\alpha}^{\pi} [1 - cos(2\omega t)] \; d\omega t}$$

$$V_{rms} = \frac{V_{max}}{\sqrt{2}} \sqrt{\left[1 - \frac{\alpha}{\pi} + \frac{sin(2\alpha)}{2\pi}\right]}$$

$$P = \frac{V_{rms}^2}{R} = \frac{V_{max}^2}{4\pi R}[2(\pi - \alpha) + sin(2\alpha)]$$

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Half Wave Versus Full Wave

	Half Wave	***Full Wave***
Average Voltage	$V_{ave} = \frac{V_{\max}}{2\pi}(1+\cos\alpha)$	$V_{ave} = \frac{V_{\max}}{\pi}(1+\cos\alpha)$
RMS Voltage	$V_{rms} = \frac{V_{\max}}{2}\sqrt{\left[1-\frac{\alpha}{\pi}+\frac{\sin(2\alpha)}{2\pi}\right]}$	$V_{rms} = \frac{V_{\max}}{\sqrt{2}}\sqrt{\left[1-\frac{\alpha}{\pi}+\frac{\sin(2\alpha)}{2\pi}\right]}$
Power	$P = \frac{V_{\max}^2}{8\pi R}[2(\pi-\alpha)+\sin(2\alpha)]$	$P = \frac{V_{\max}^2}{4\pi R}[2(\pi-\alpha)+\sin(2\alpha)]$

3-phase, AC/DC Transistor Converter

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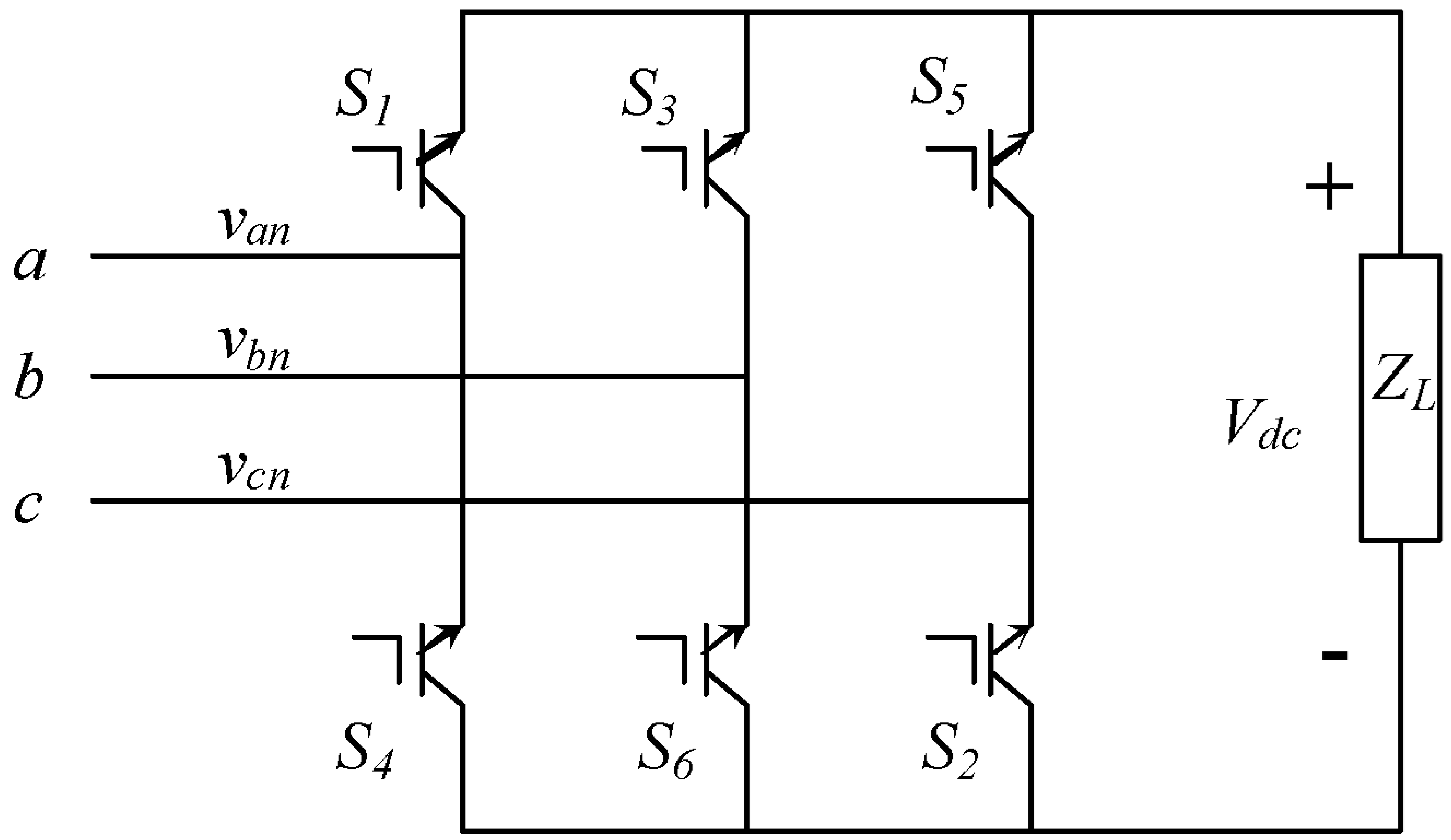
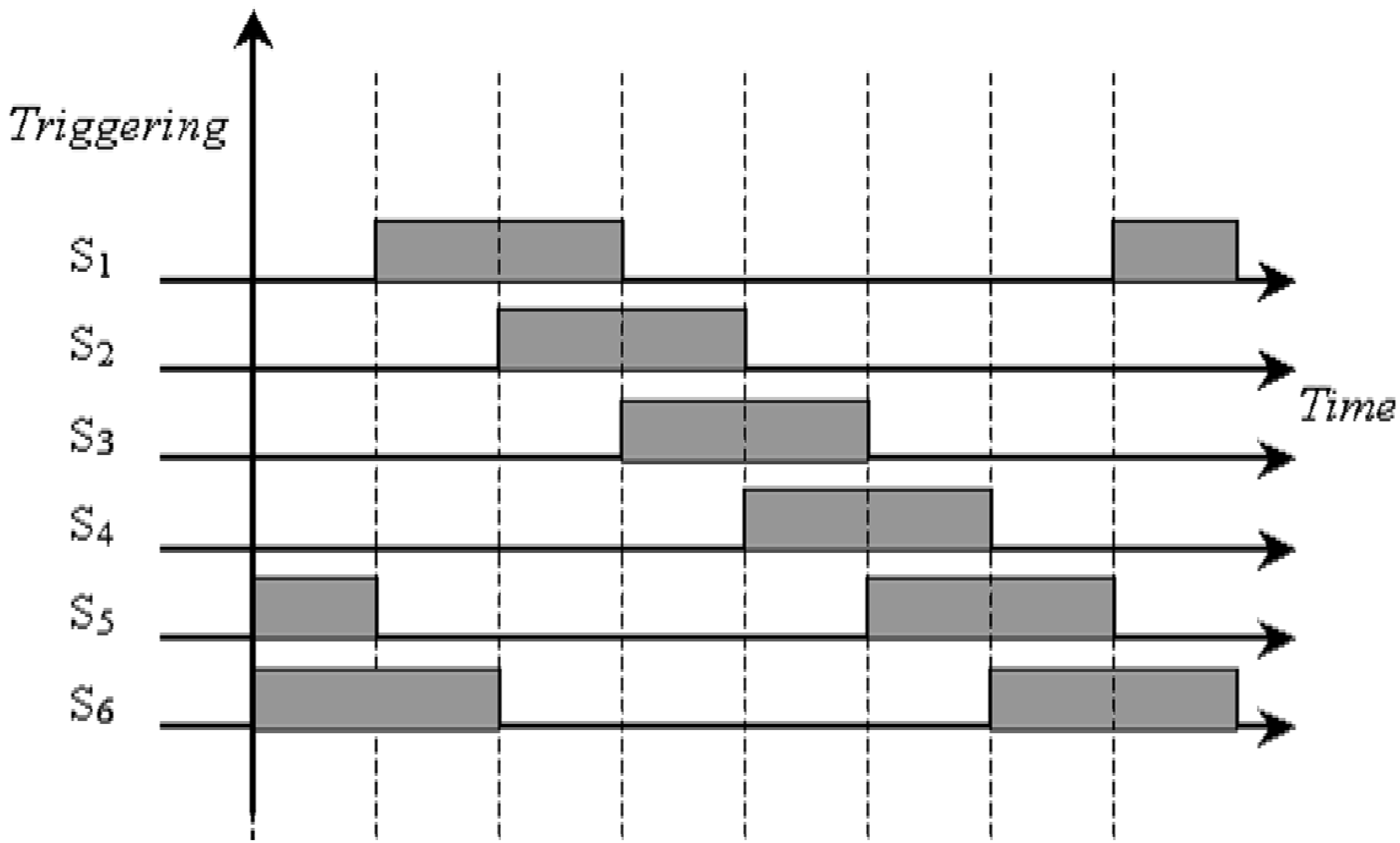
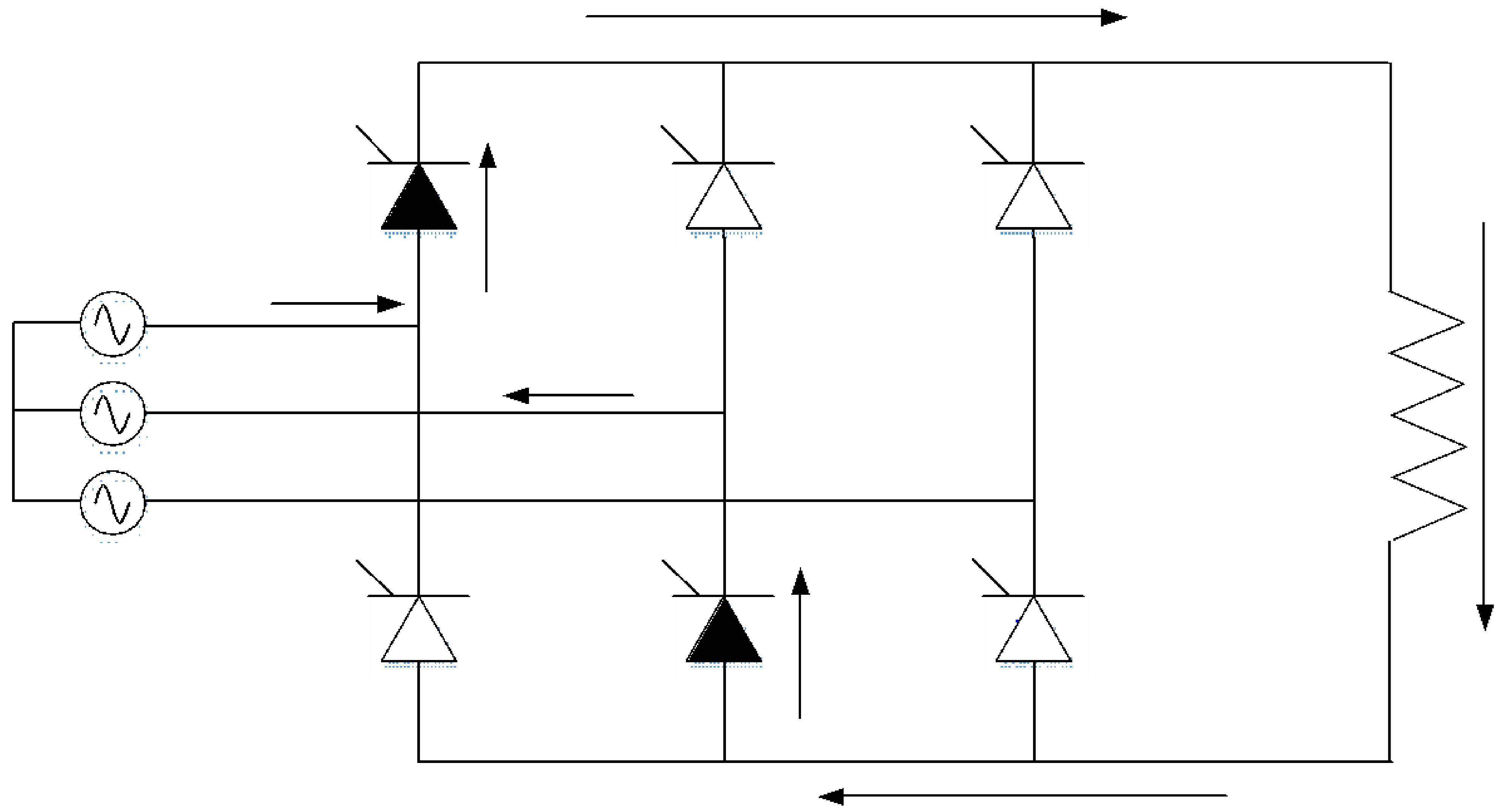


3-phase, AC/DC Conversion: Switching Sequence



3-phase AC/DC SCR Converter

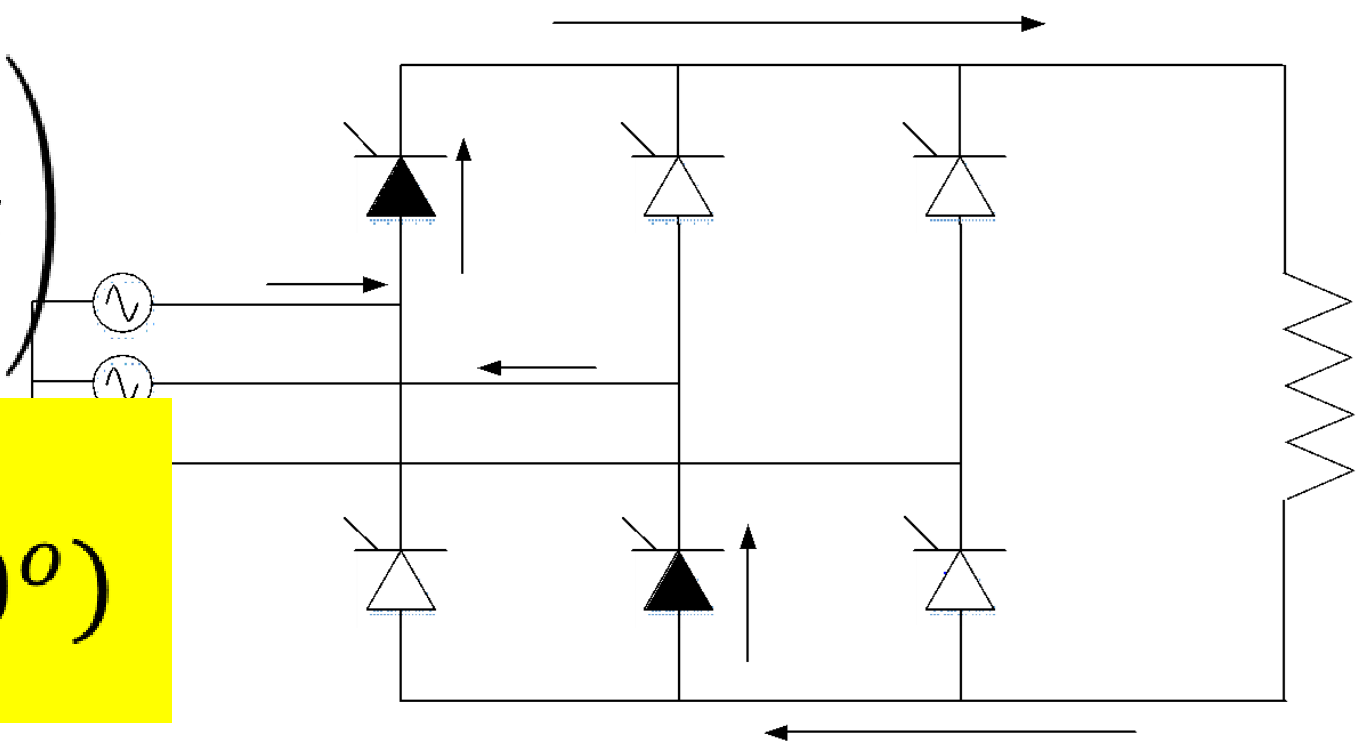
$when\ v_{ab} > all\ other\ voltages$

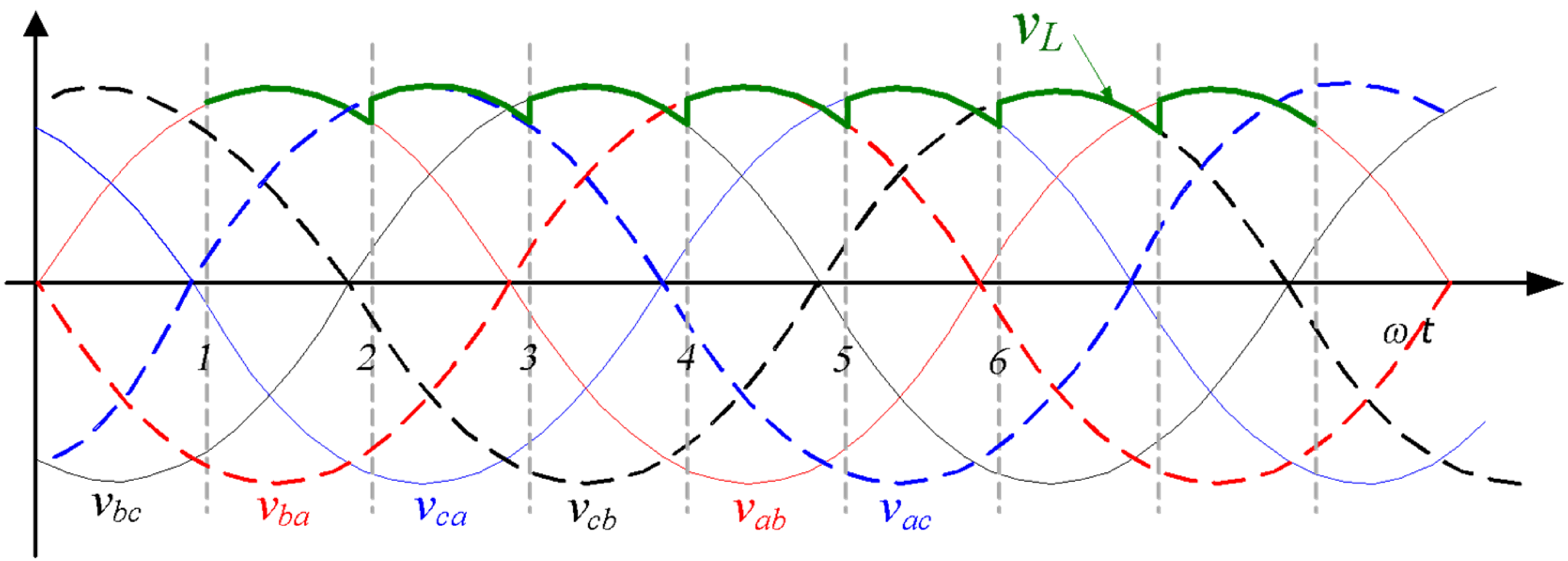


$$V_{ave} = 6\left(\frac{1}{2\pi}\int_{\alpha_{ab}}^{\alpha_{ab}+60^o} v_{ab}\, d\omega t\right)$$

$$= 6\left(\frac{1}{2\pi}\int_{\alpha_{ab}}^{\alpha_{ab}+60^o} \sqrt{3}\, V_{max} \sin\omega t\ \ d\omega t\right)$$

$$V_{ave} = \frac{3\sqrt{3}\, V_{max}}{\pi}\sin(\alpha_{ab} + 30^o)$$



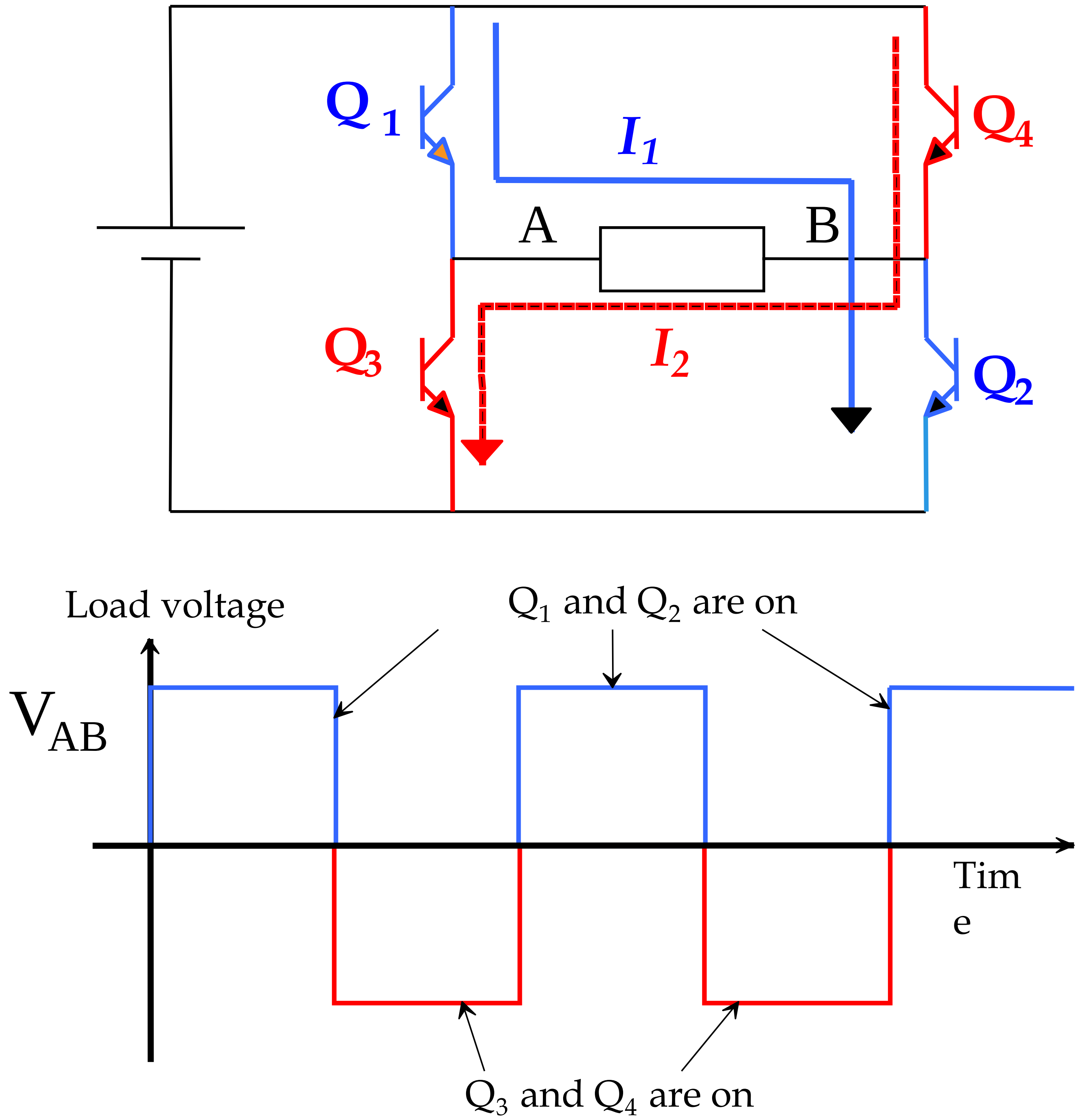


$$V_{rms} = \sqrt{\frac{6}{2\pi}\int_{\alpha_{ab}}^{\alpha_{ab}+60^o}\left(\sqrt{3}\,V_{max}\sin\omega t\right)^2 d\omega t} = \frac{3\,V_{max}}{\sqrt{2}}\sqrt{\frac{1}{3}-\frac{\sqrt{3}}{2\pi}\cos(2\alpha_{ab}+60^o)}$$

$$120^o \geq \alpha_{ab} \geq 60^o$$

DC/AC Converters

DC/AC Conversion



3-Phase DC/AC

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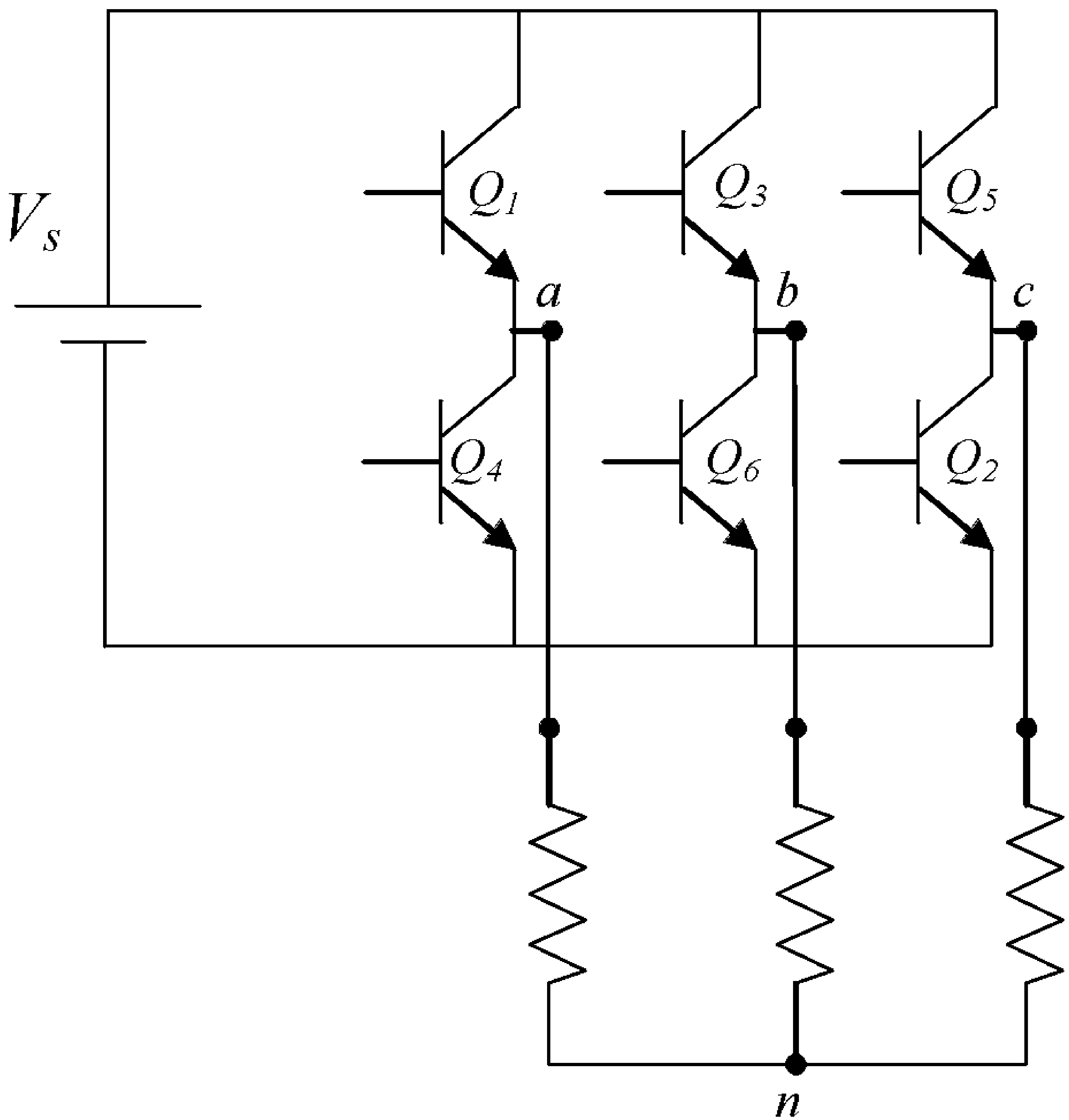
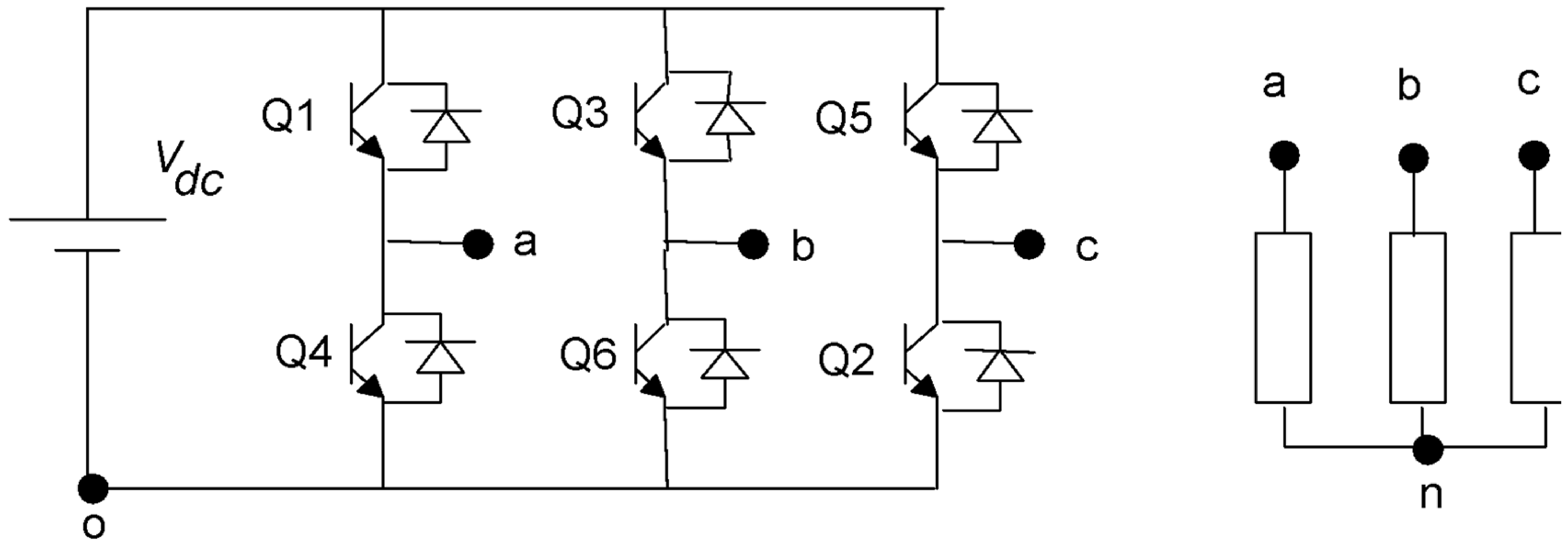
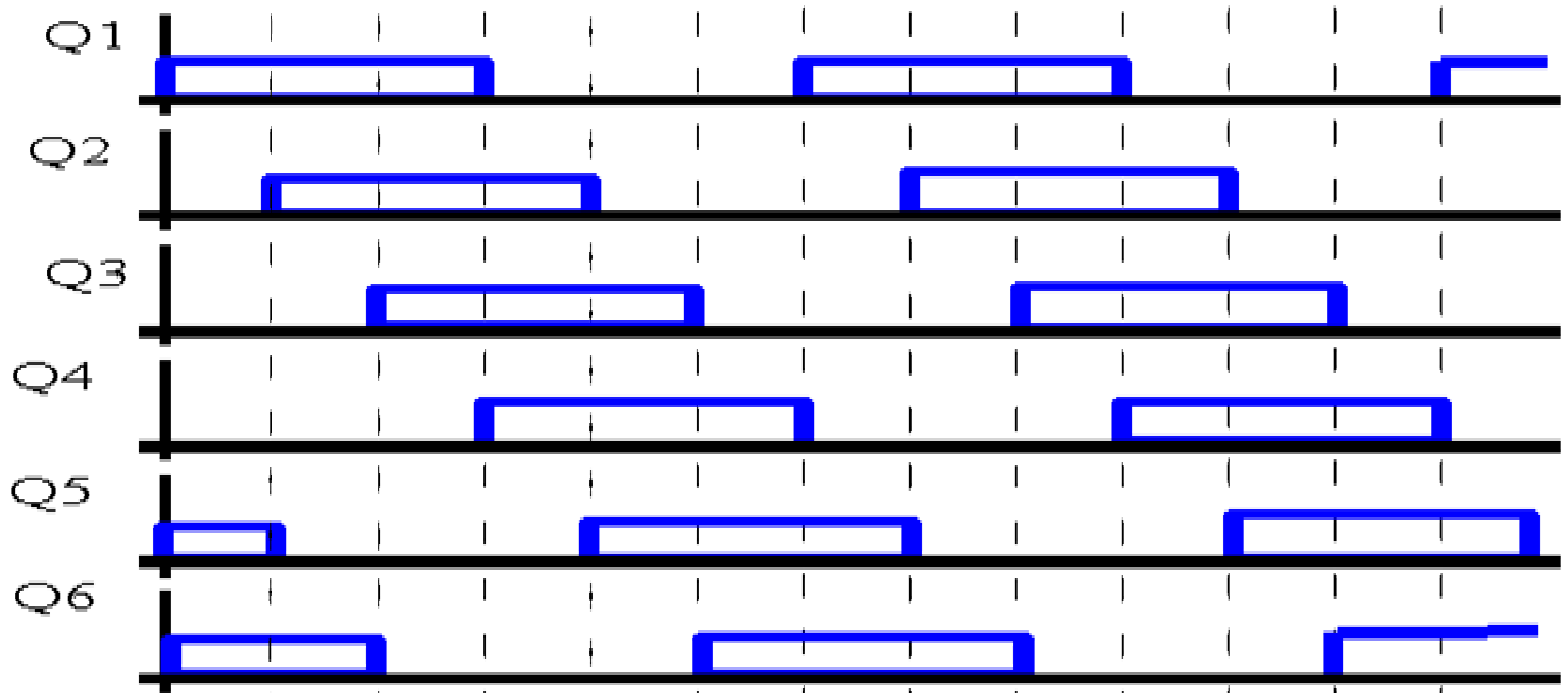
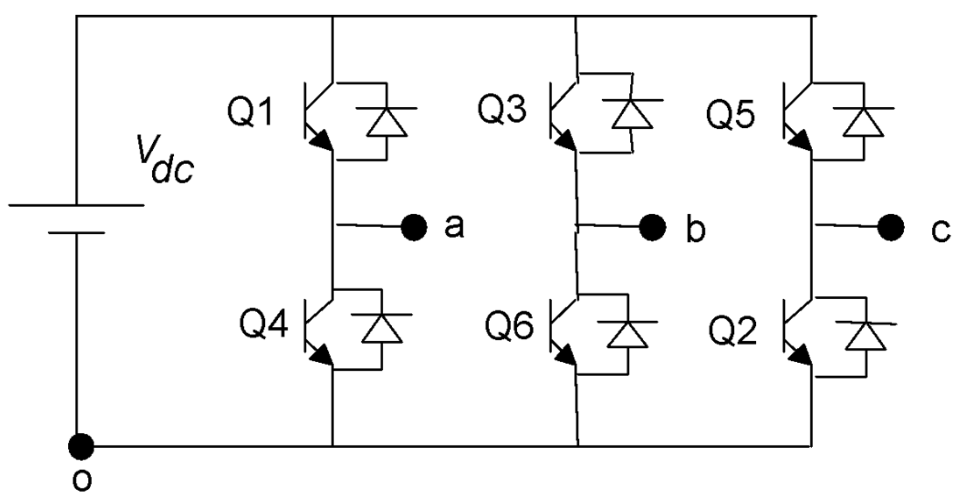
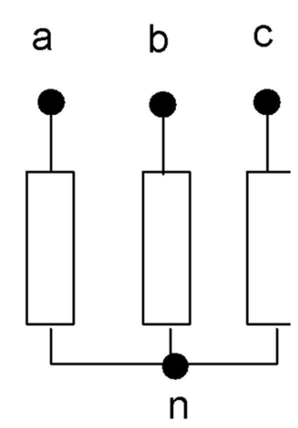


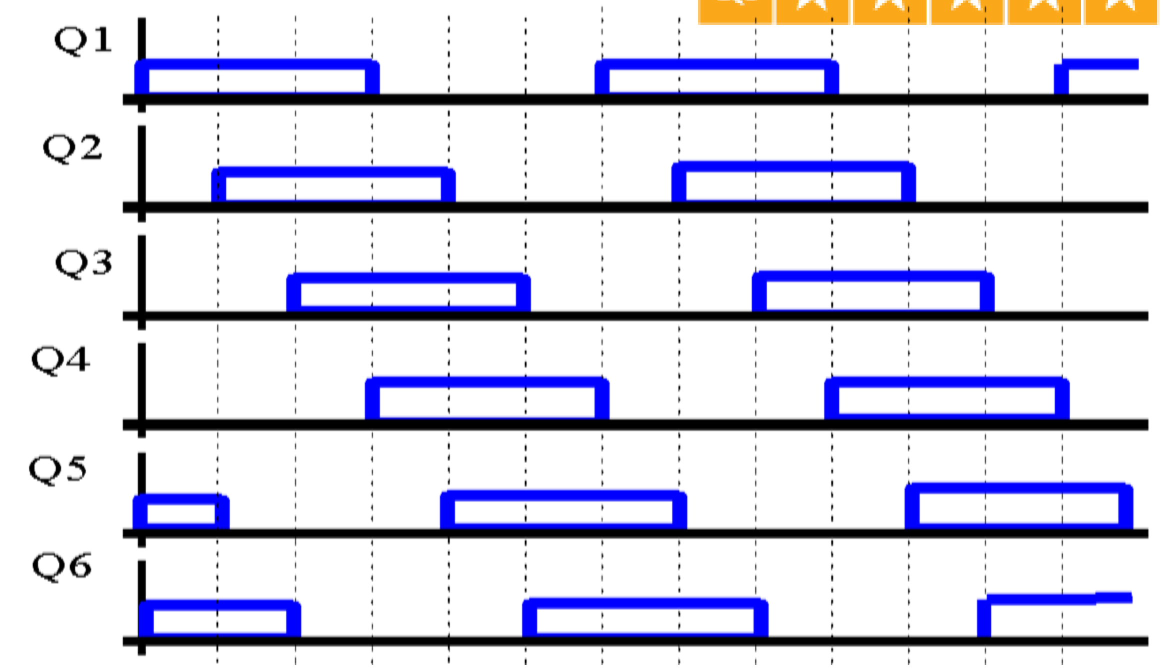

Q1
Q3
Q5
Vdc
a
b
c
Q4
Q6
Q2
o
a
b
c
n


Q1
Q2
Q3
Q4
Q5
Q6

First Time Interval



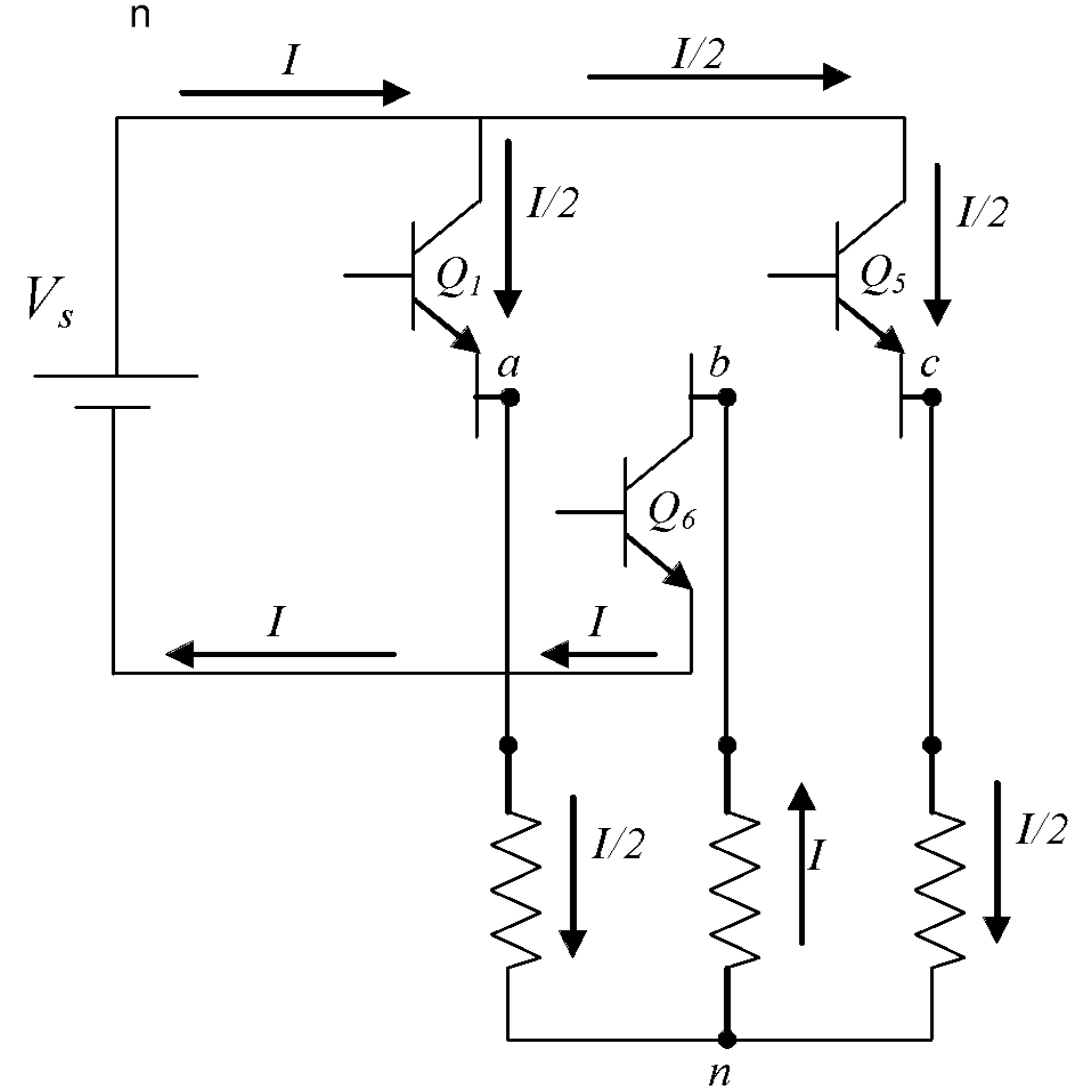




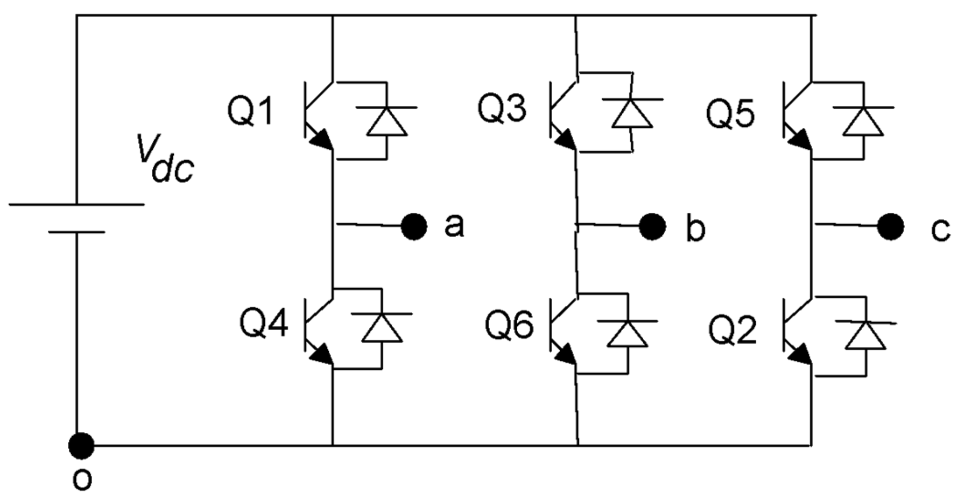
$$v_{ab} = v_a - v_b = V_{dc}$$

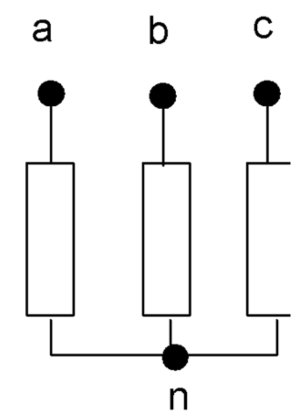
$$v_{bc} = v_b - v_c = -V_{dc}$$

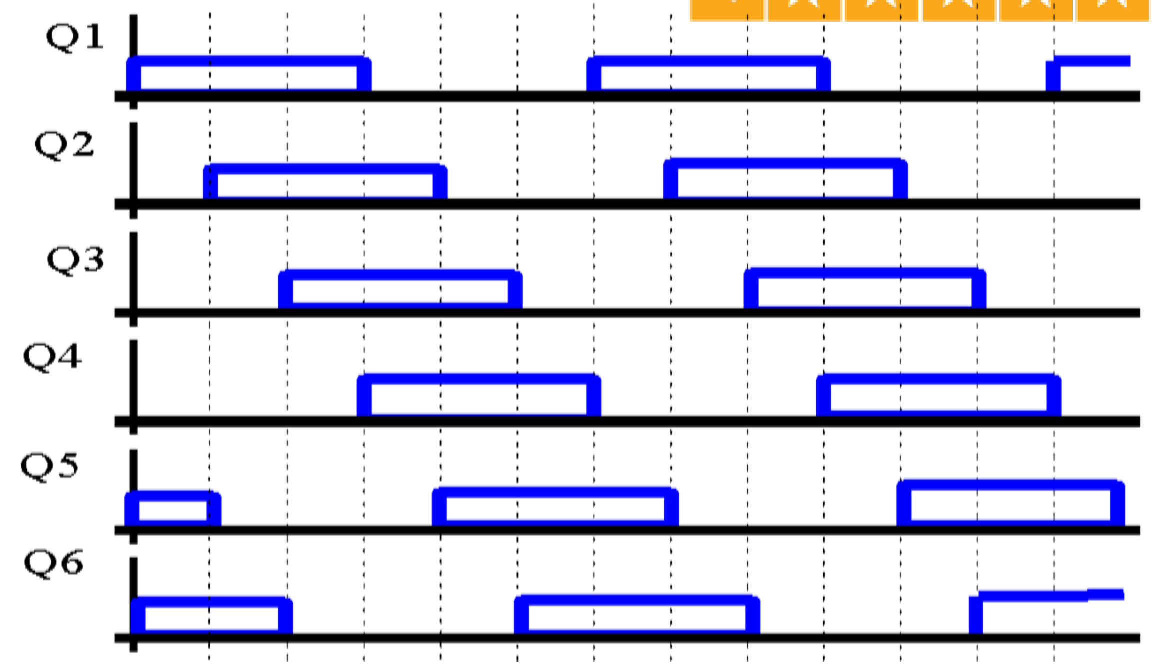
$$v_{ca} = v_c - v_a = 0$$

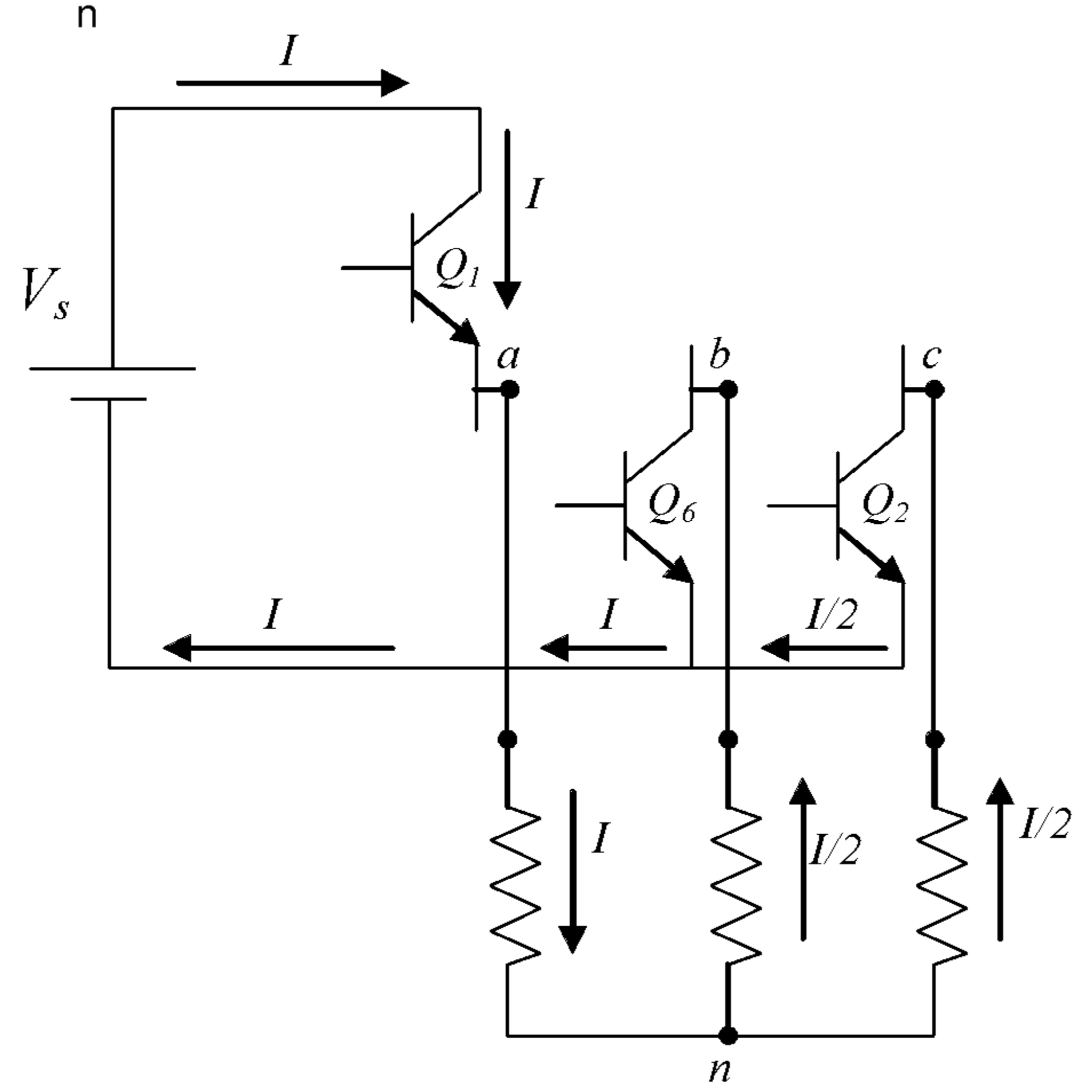


Second Time Interval







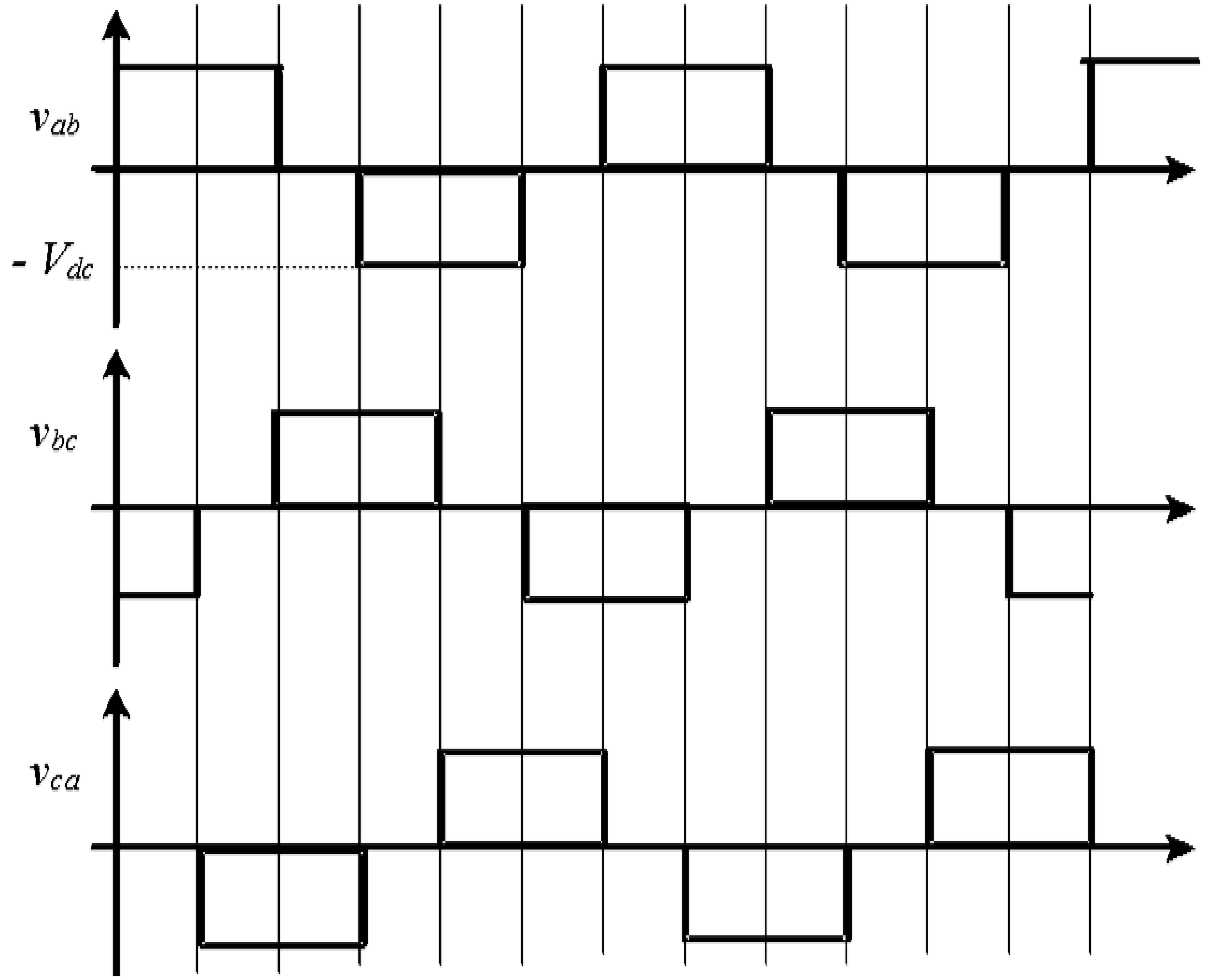


$$v_{ab} = v_a - v_b = V_{dc}$$

$$v_{bc} = v_b - v_c = 0$$

$$v_{ca} = v_c - v_a = -V_{dc}$$

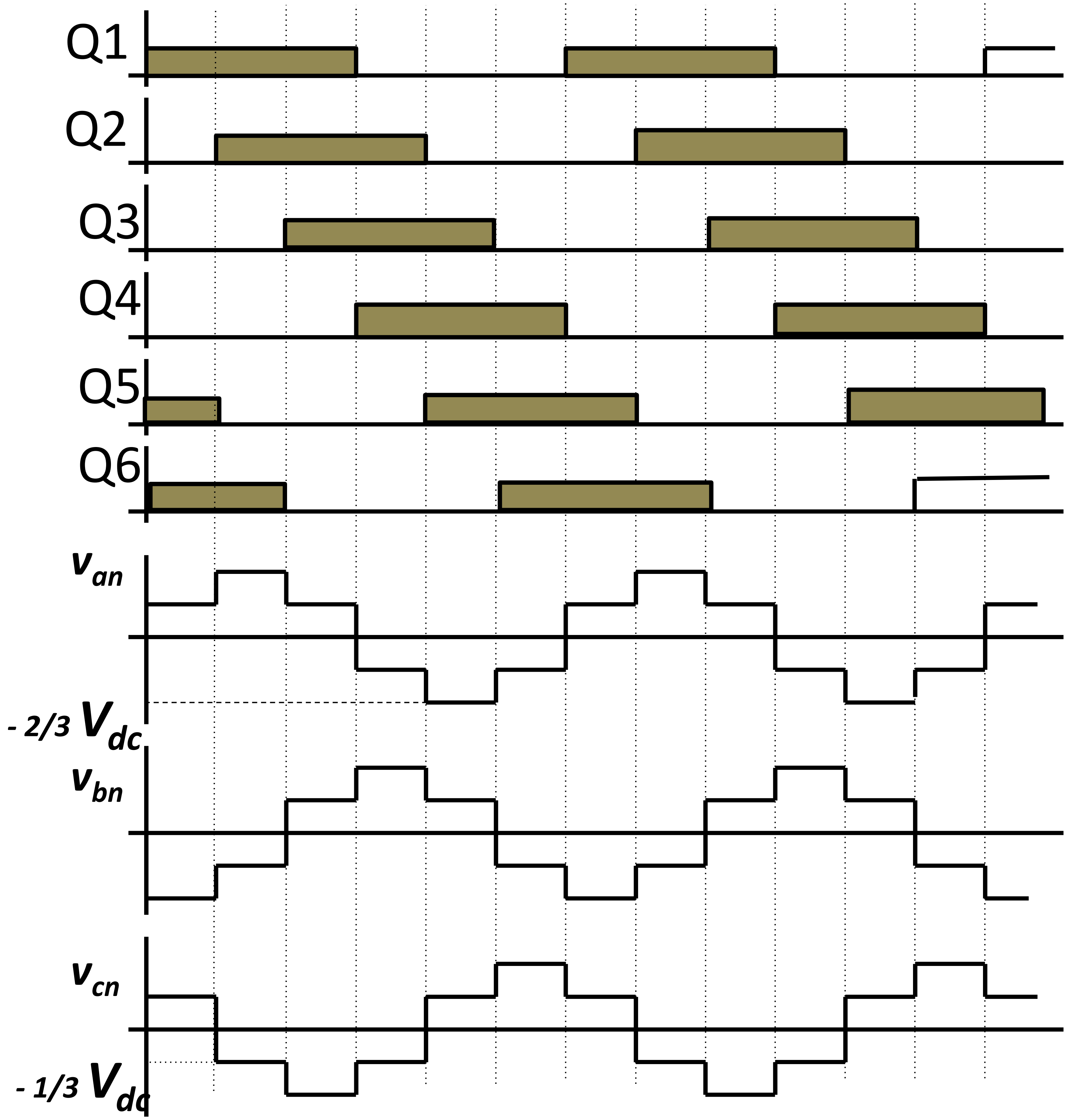
Voltage Waveforms Across Load



- Waveforms are symmetrical and equal in magnitude
- Waveforms are shifted by 120 degrees

$$V_{rms} = \sqrt{\frac{2}{9}}\; V_{dc}$$

$$V_{rms} = 0.47\; V_{dc}$$



DC/DC Converters

DC-to-DC Conversion

* Step-down (Buck) converter: the output voltage of the converter is lower than the input voltage

* Step-up (Boost) converter: the output voltage is higher than the input voltage.

* Step-down/step-up (Buck-Boost) converter.

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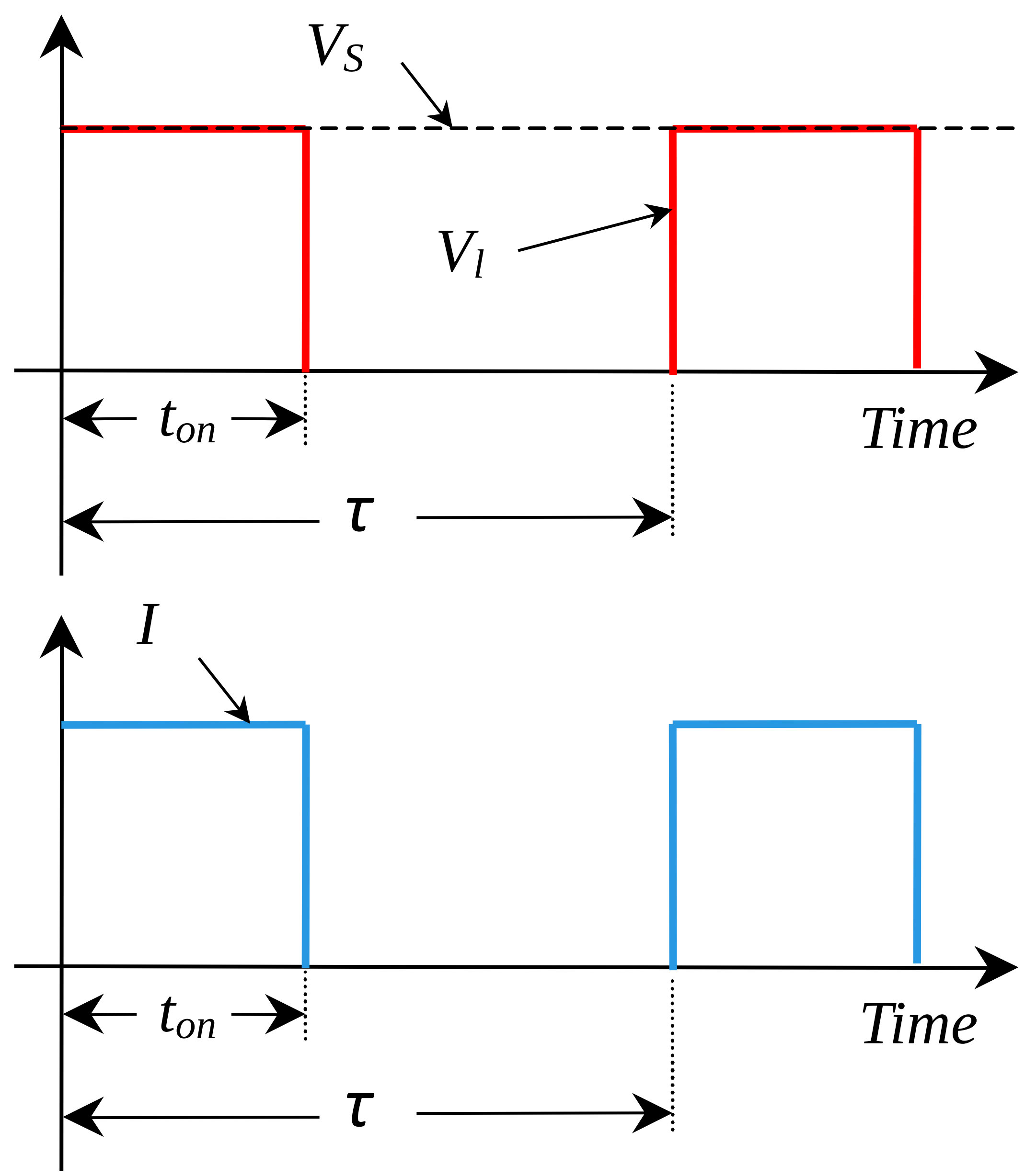
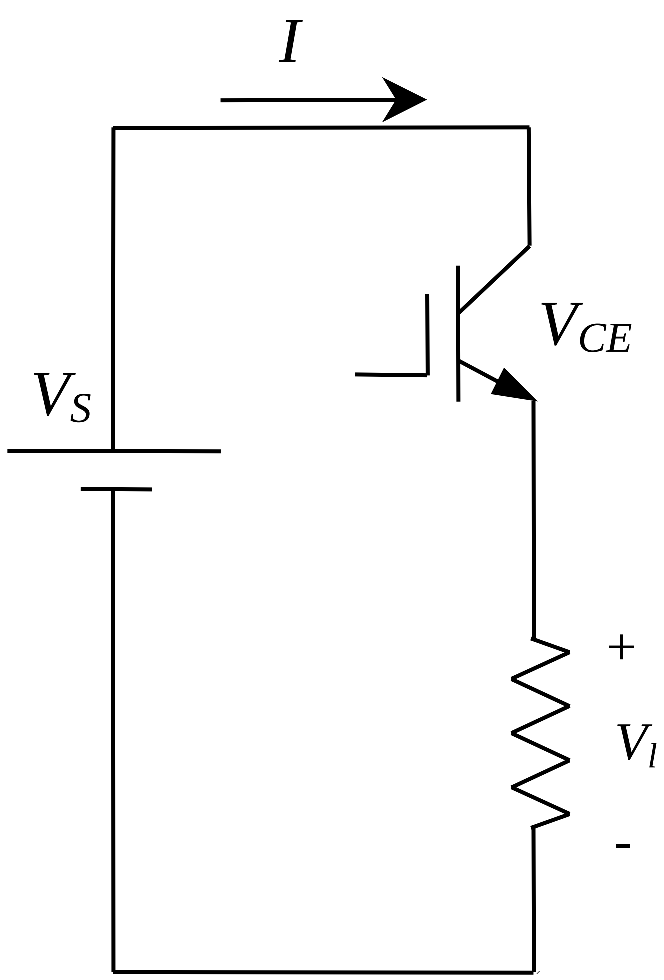
Step Down (Buck converter)





$$V_{ave} = \frac{1}{\tau} \int_0^{t_{on}} V_s \, dt = \frac{t_{on}}{\tau} V_s = K \, V_s$$

Example

$$f = 5\ kHz\ (switching\ \ frequency)$$

$$V_s = 12\ V;\ \ V_{ave} = 5\ V;\ \ t_{on} = ?$$

Solution

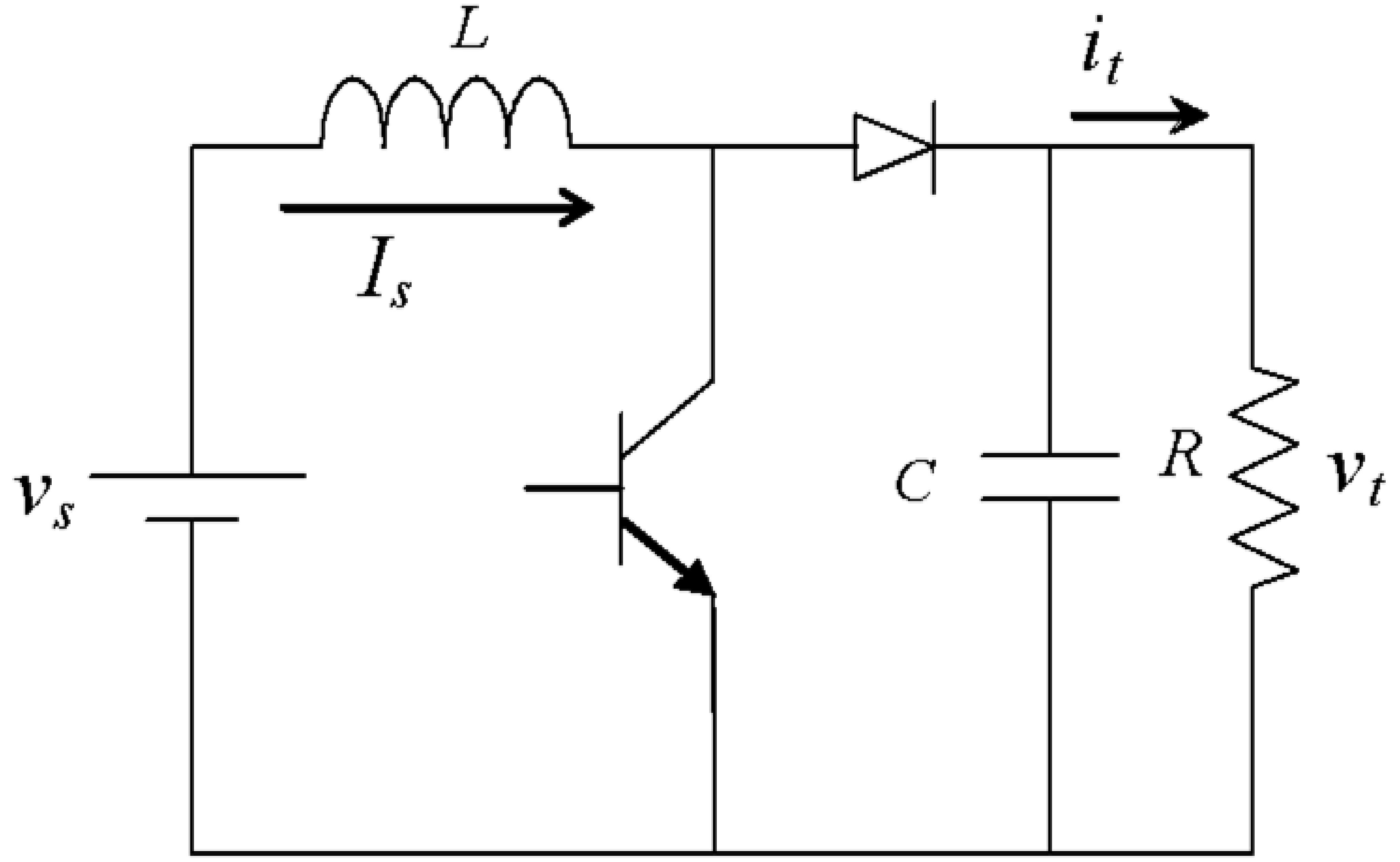
$$\tau = \frac{1}{f} = \frac{1}{5} = 0.2\ ms$$

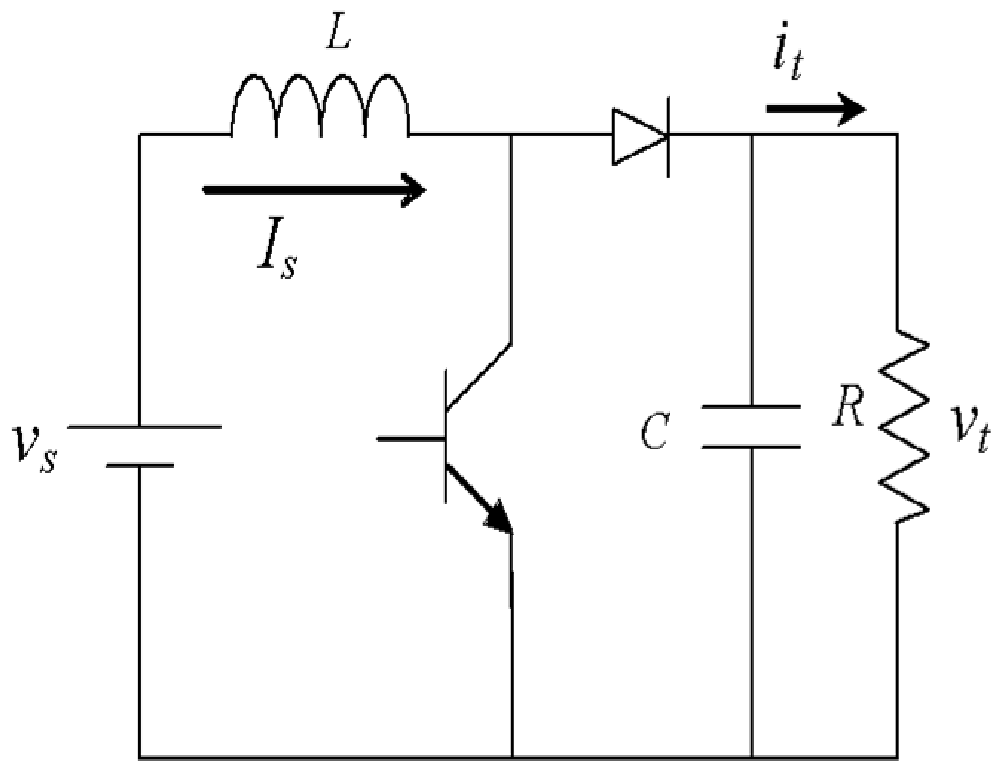
$$V_{ave} = \frac{t_{on}}{\tau} V_s = K\, V_s$$

$$K = \frac{5}{12} = 0.417$$

$$t_{on} = 0.417 \times 0.2 = 0.0834\ ms$$

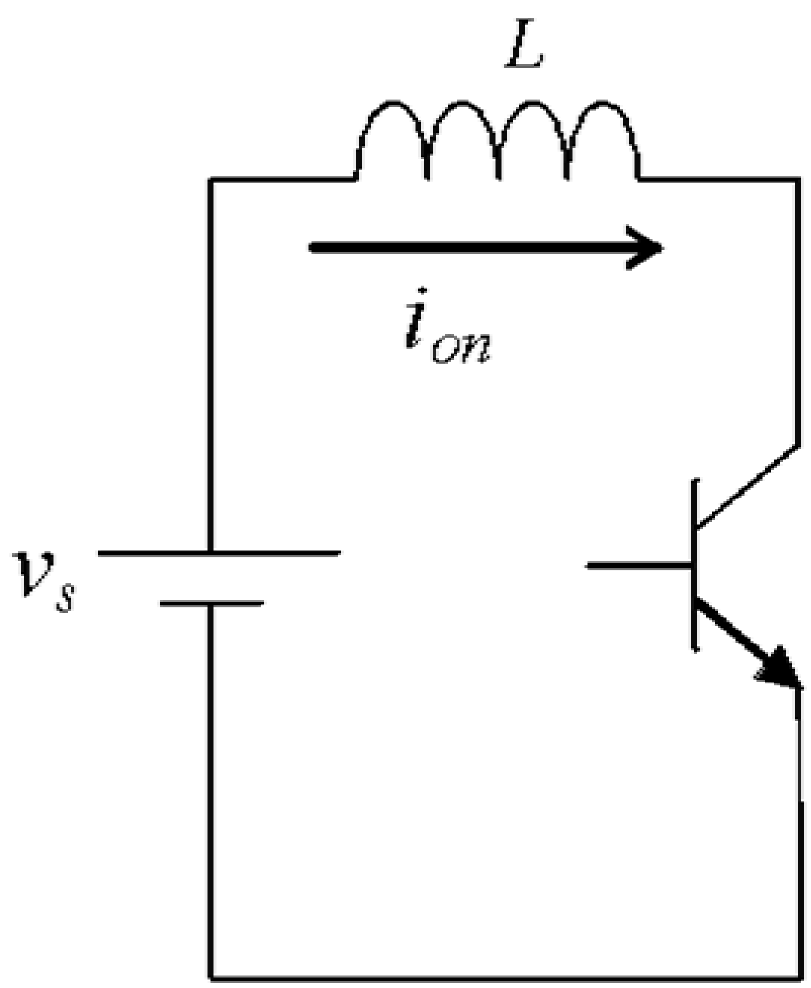
Step up (Boost converter)

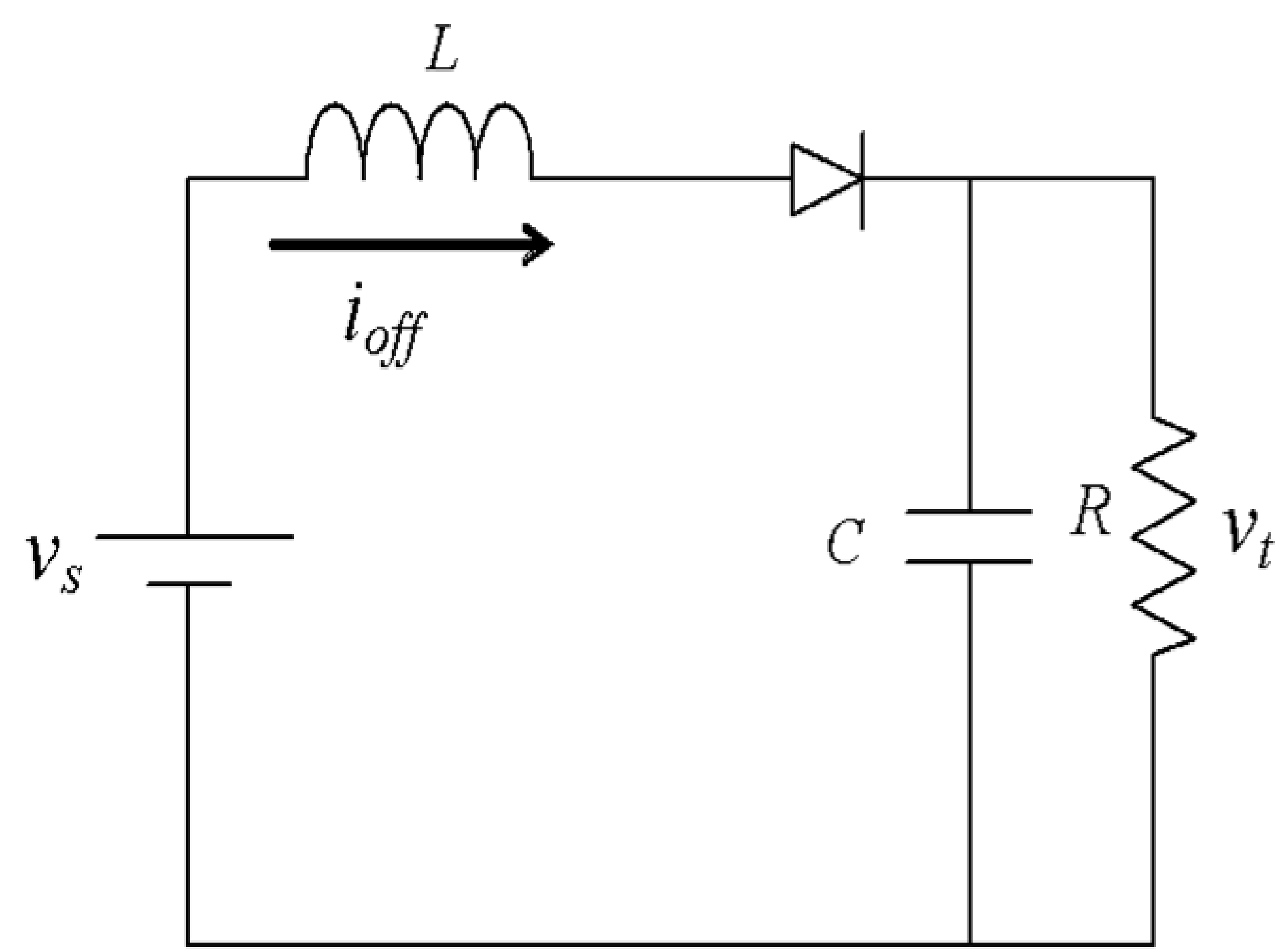


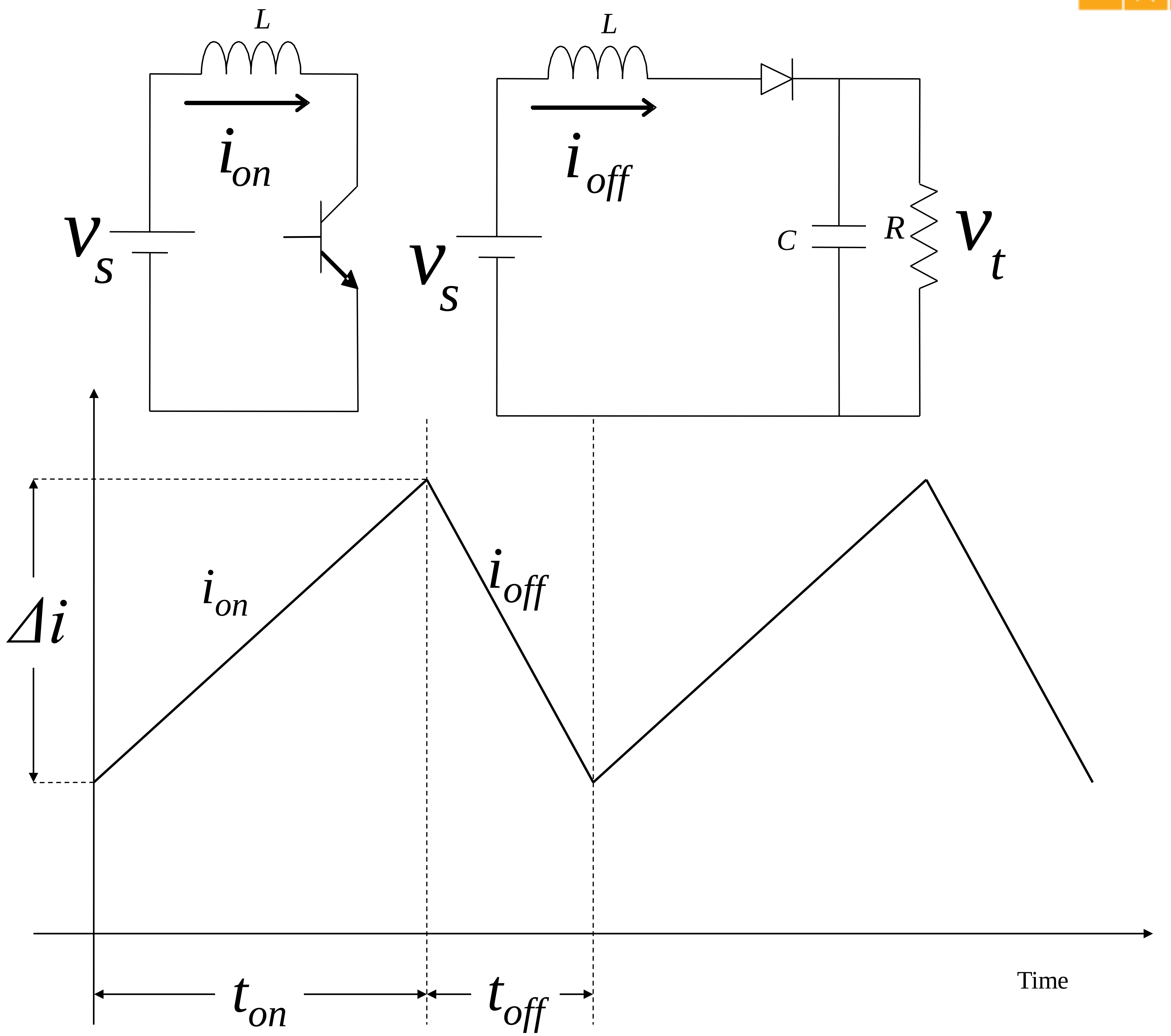


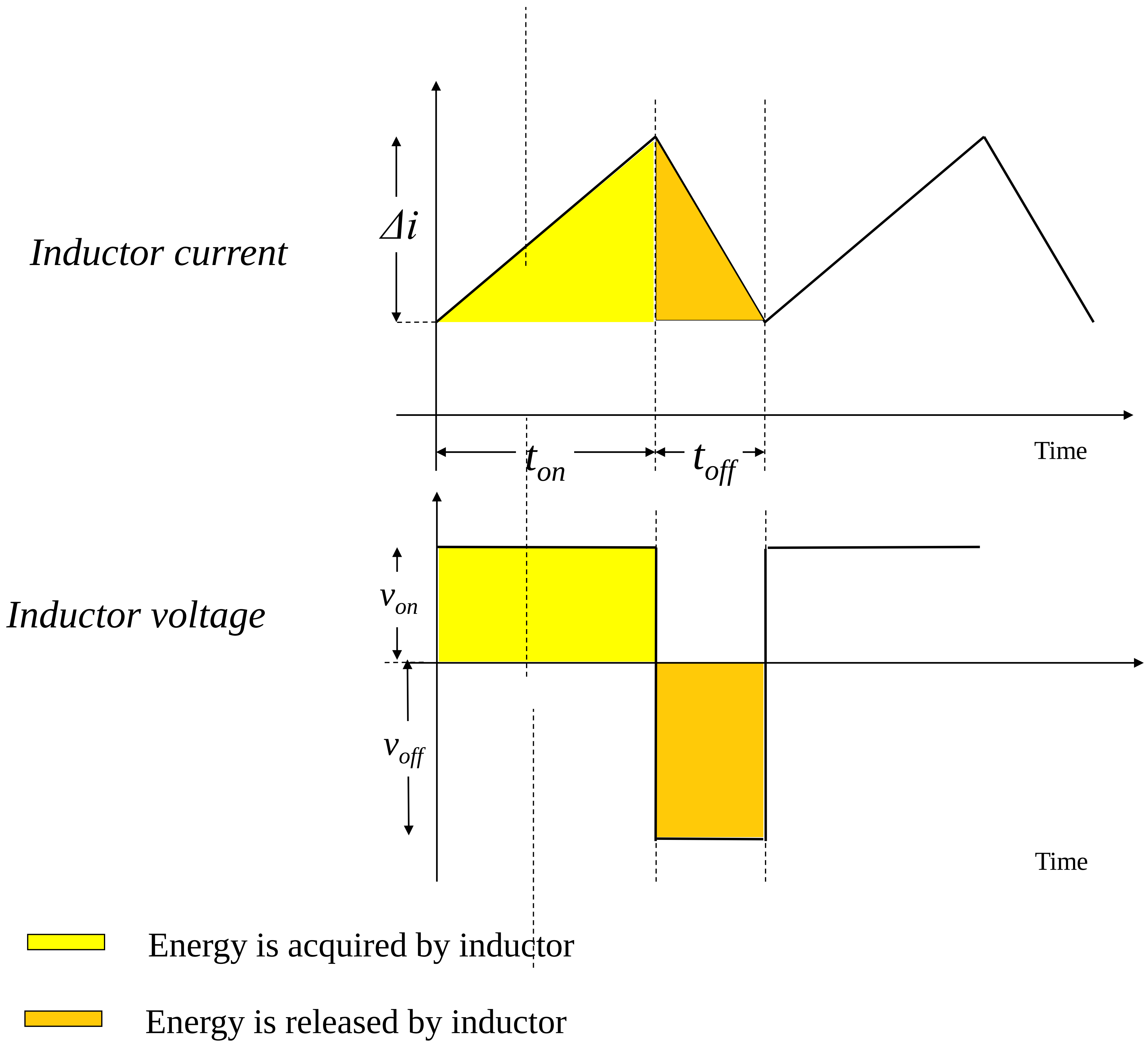
Keep in mind

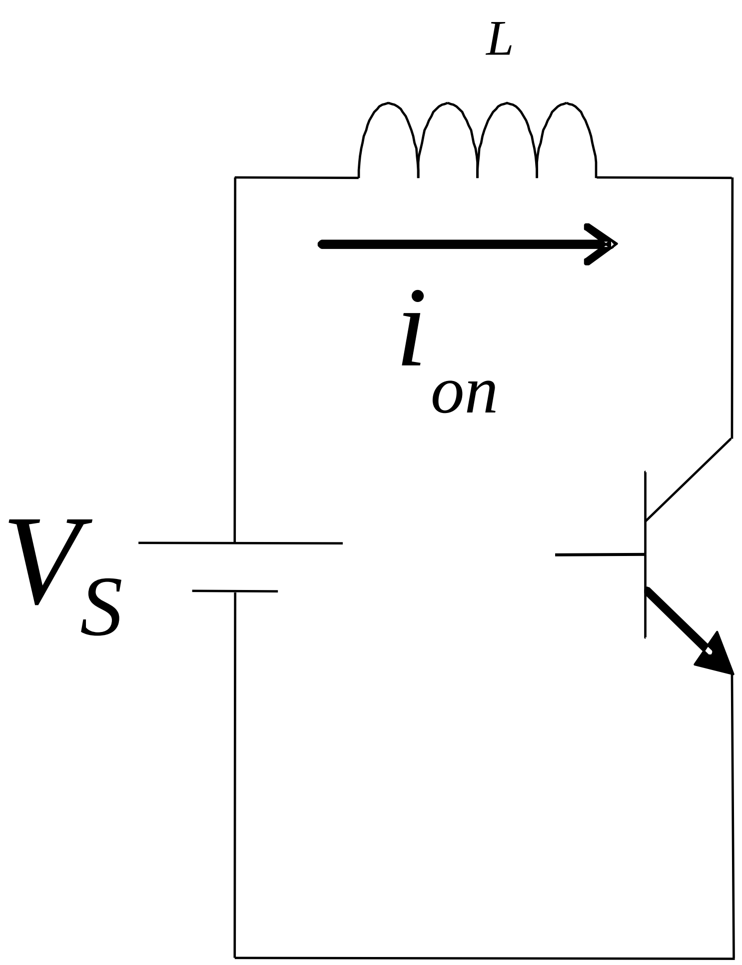
- Inductor current is unidirectional
- Inductor cannot permanently store energy
- Voltage across inductor reverses

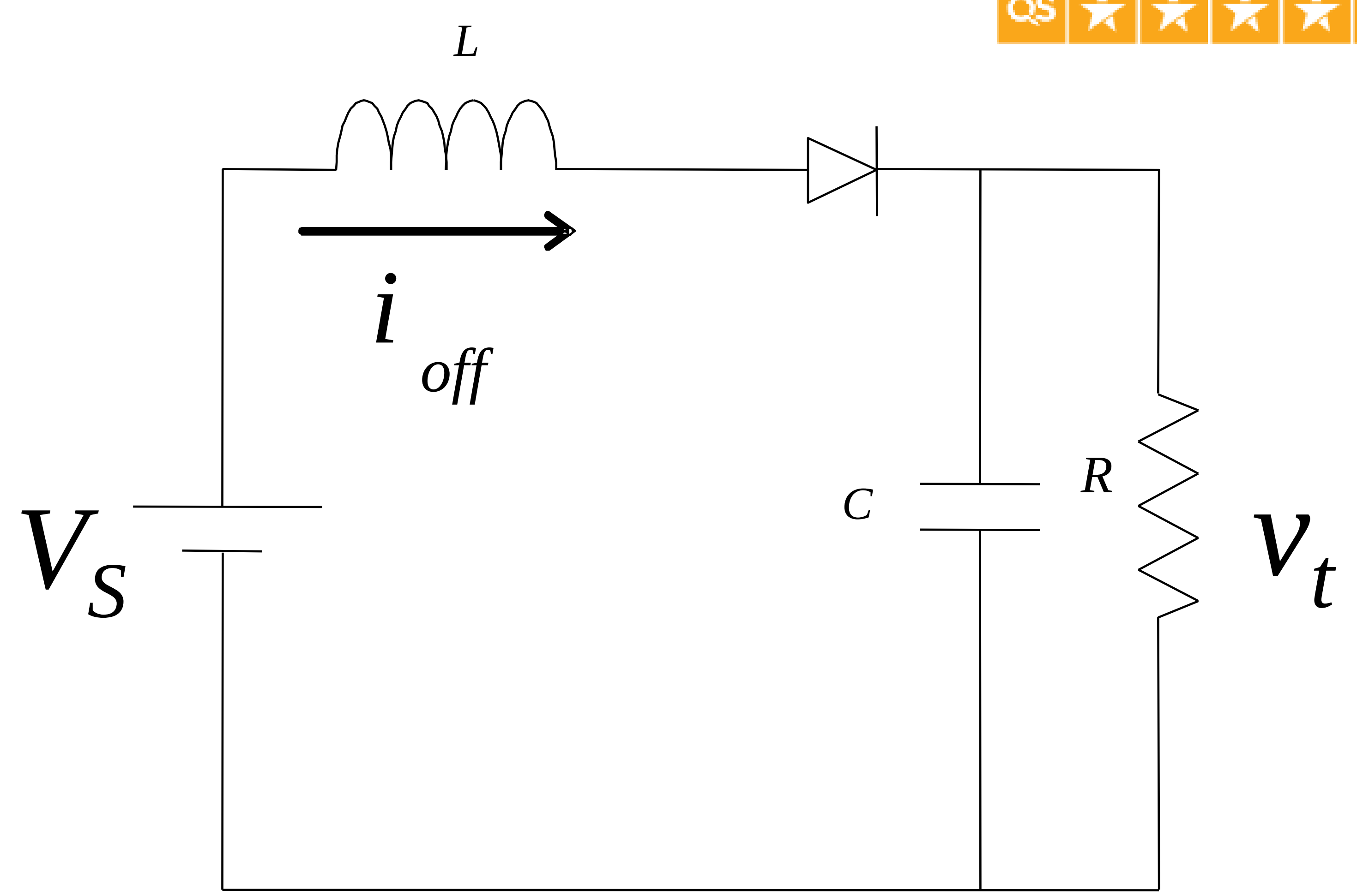





L
i_{on}
V_s
L
i_{off}
V_s
C
R
V_t
Δi
i_{on}
i_{off}
t_{on}
t_{off}
Time


Inductor current
Δi
t_{on}
t_{off}
Time
Inductor voltage
v_{on}
v_{off}
Time
Energy is acquired by inductor
Energy is released by inductor





$$V_L = L\frac{di}{dt} = L\,\frac{\Delta i_{on}}{t_{on}} = V_s$$

$$V_s = v_t - L\,\frac{\Delta i_{off}}{t_{off}}$$

At steady state $\Delta i_{on} = \Delta i_{off}$

$$v_t = V_s + L\,\frac{\Delta i_{off}}{t_{off}} = V_s\left(1 + \frac{t_{on}}{t_{off}}\right)$$

Example

- A Boost converter is used to step up 20V into 50V. The switching frequency of the transistor is 5kHz, and the load resistance is 10Ω. Compute the following:
  1. The value of the inductance that would limit the current ripple at the source side to 100mA
  2. The average current of the load
  3. The power delivered by the source
  4. The average current of the source

Solution

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Part 1

$$V_t = V_s\left(1+\frac{t_{on}}{t_{off}}\right)$$

$$50 = 20\left(1+\frac{t_{on}}{t_{off}}\right)$$

$$t_{on} = 1.5 * t_{off}$$

$$t_{on} + t_{off} = \frac{1}{f} = \frac{1}{5} = 0.2\ ms$$

$$t_{on} = 1.5 * t_{off} = 1.5 * (0.2 - t_{on})$$
$$= 0.12\ ms$$

$$V_L = L\,\frac{\Delta i_{on}}{t_{on}} = V_s$$

$$20 = L\,\frac{100}{0.12} \qquad\qquad L = 24\ \ mH$$

Part 2

$$I_t = \frac{V_t}{R} = \frac{50}{10} = 5\ \ A$$

Part 3

$$P = V_t * I_t = 50 * 5 = 250\ W$$

Part 4

$$I_s = \frac{P}{V_s} = \frac{250}{20} = 12.5\ \ A$$

Buck-Boost converter

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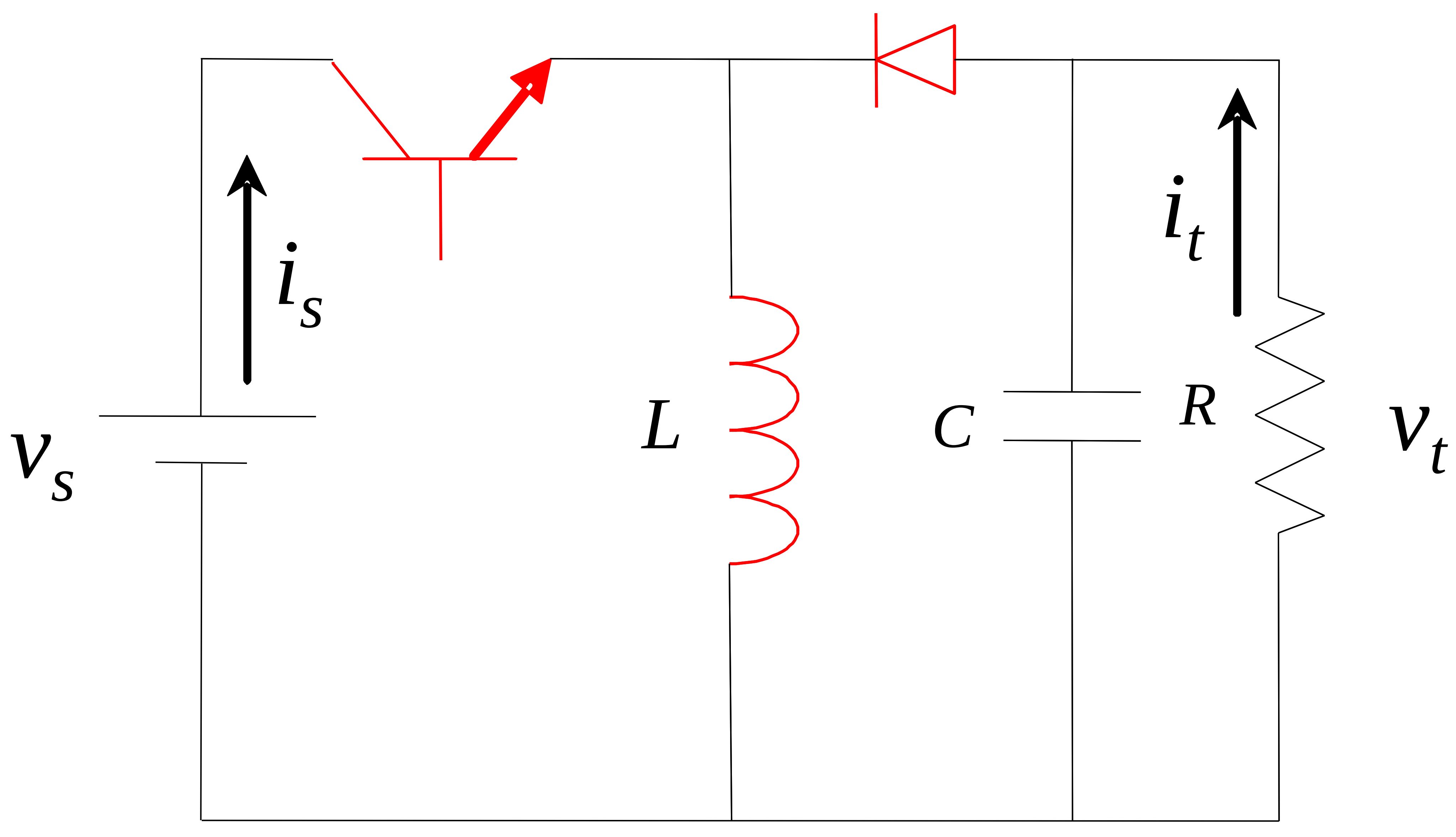
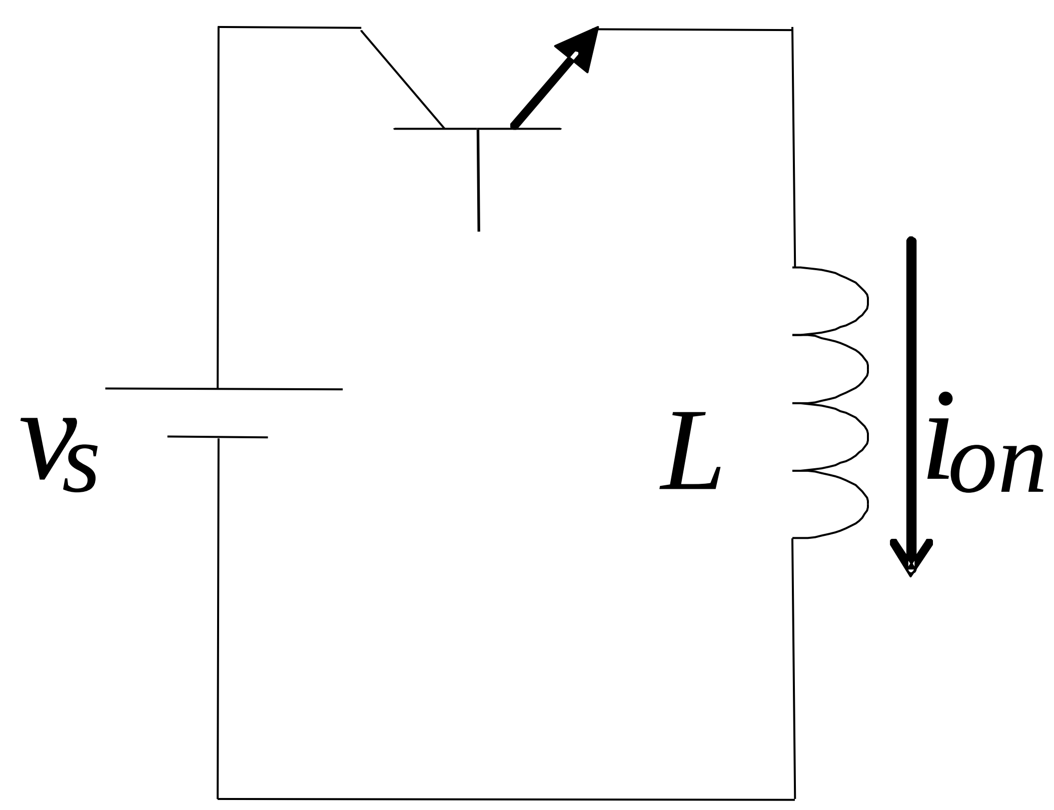
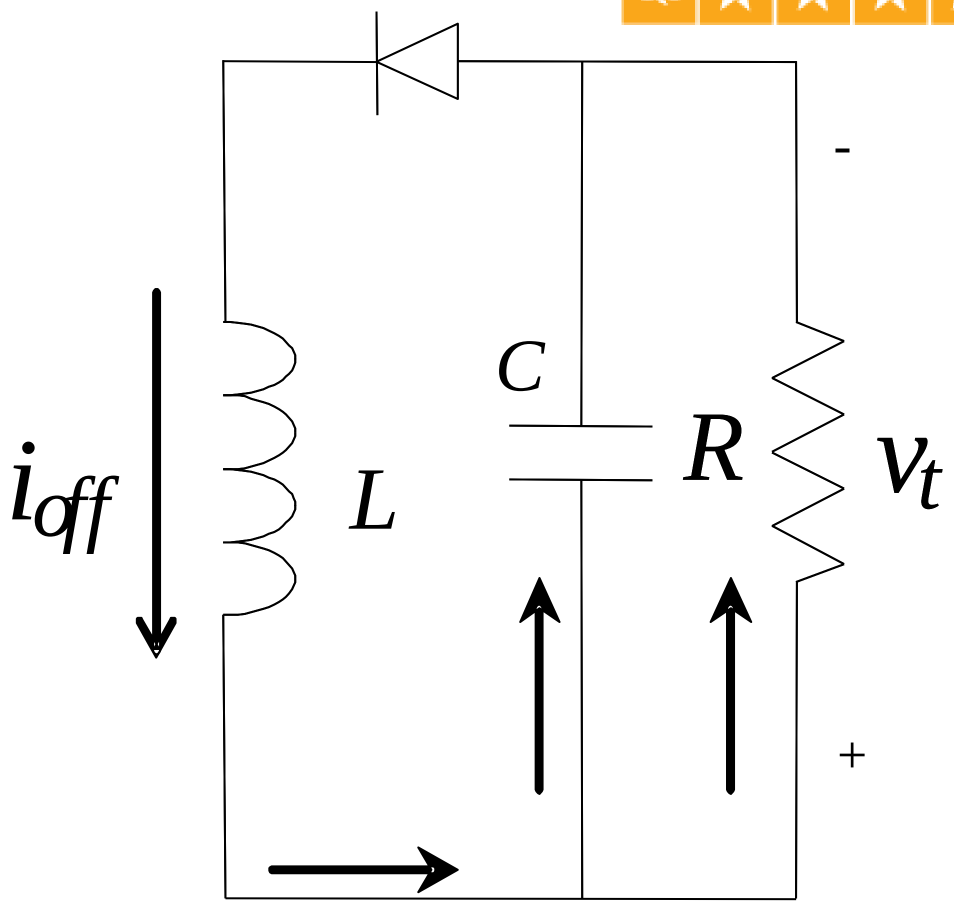






$$v_L = L\frac{\Delta i_{on}}{t_{on}} = v_s$$

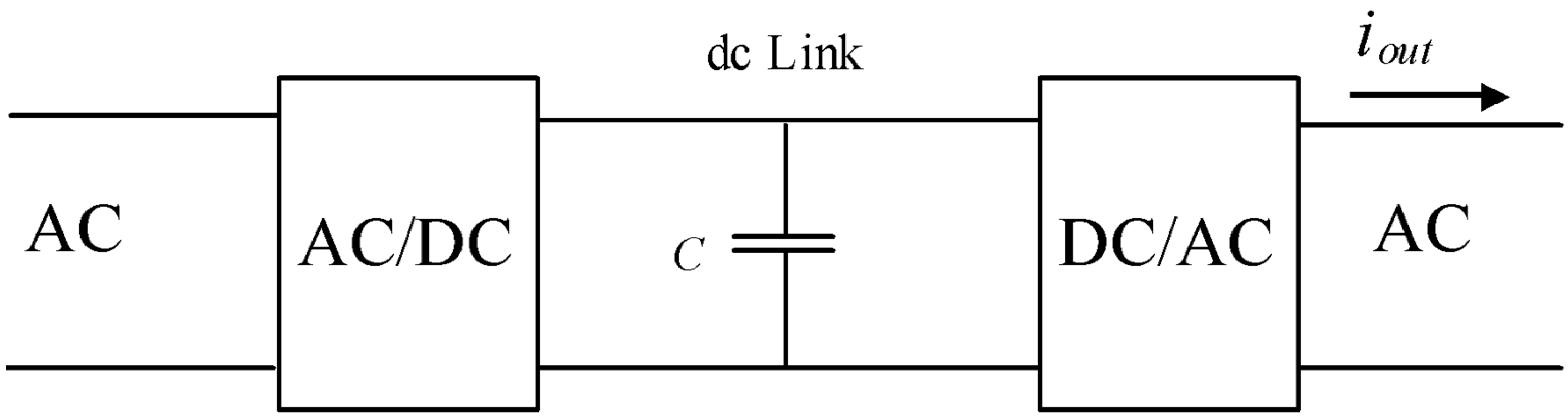
$$v_L = -L\frac{\Delta i_{off}}{t_{off}} = v_t$$

$$if \;\; \Delta i_{on} = \Delta i_{off}$$

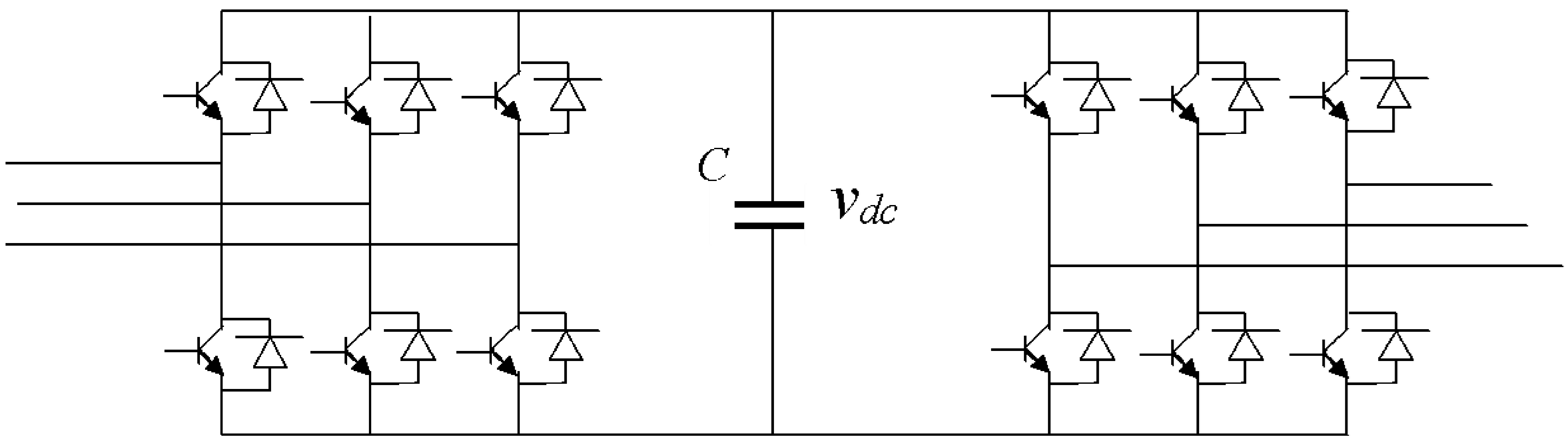
$$v_t = -v_s \frac{t_{on}}{t_{off}}$$

AC/AC Converters

AC/AC Converter



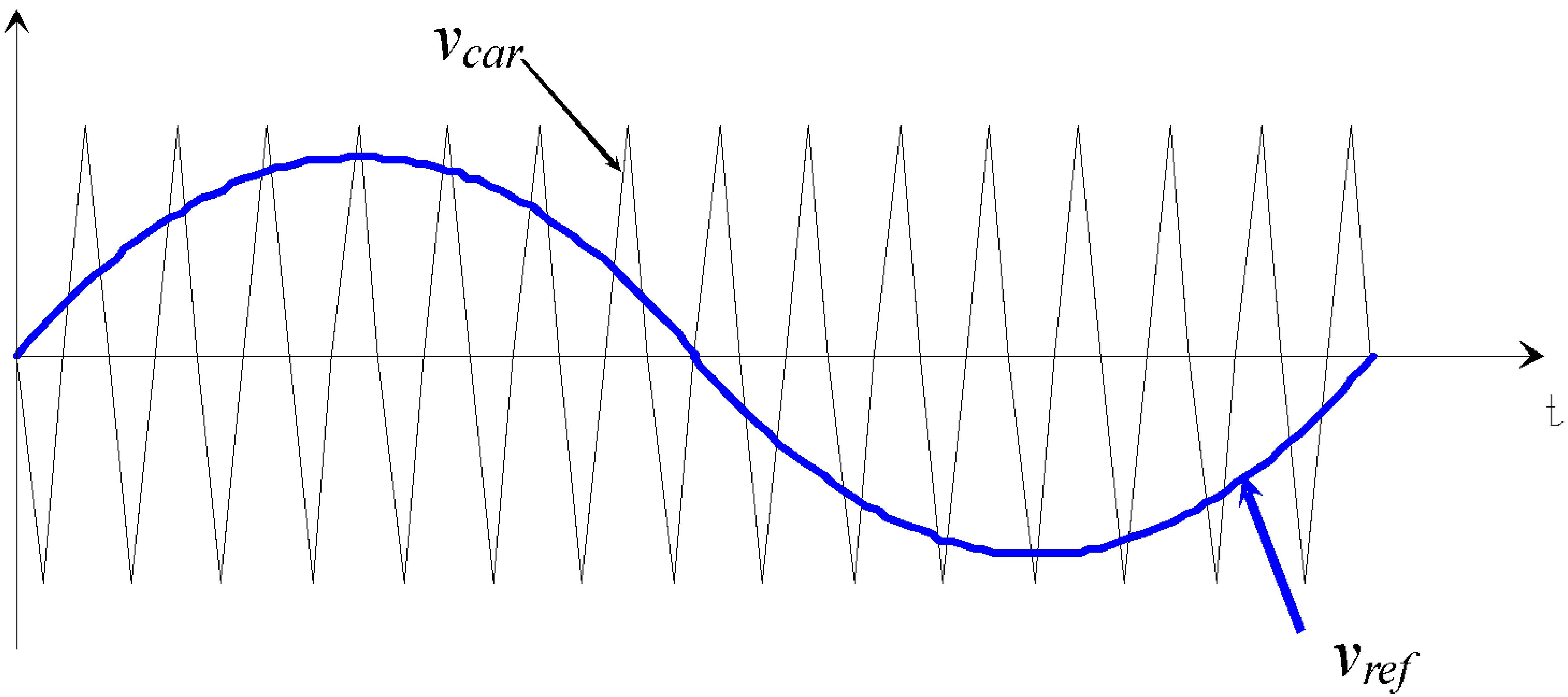
AC/DC Converter



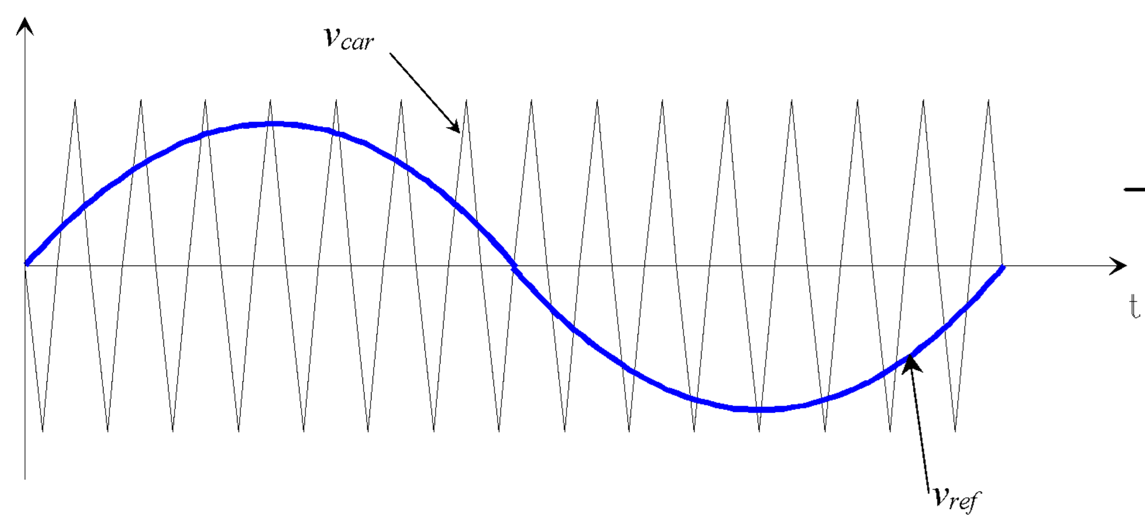
Control Parameters

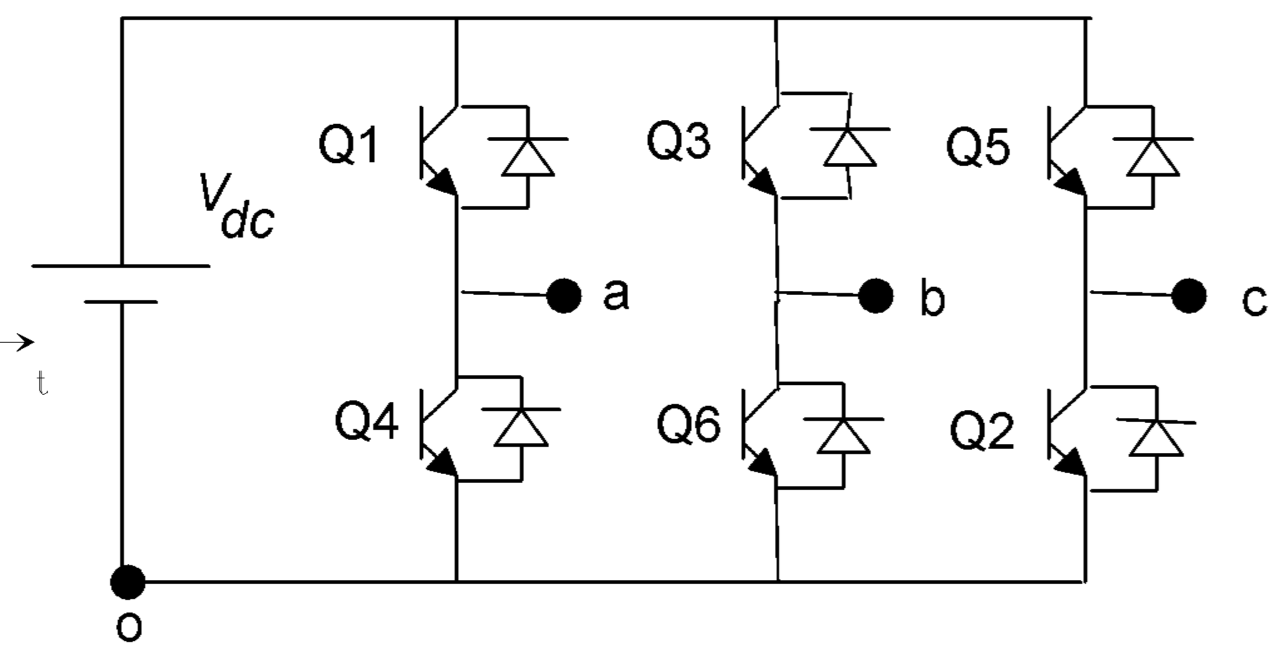
- *Frequency*
- *Voltage*
- *Phase shift*
- *Sequence*

Pulse-Width Modulation (PWM)



Switching of Phase a

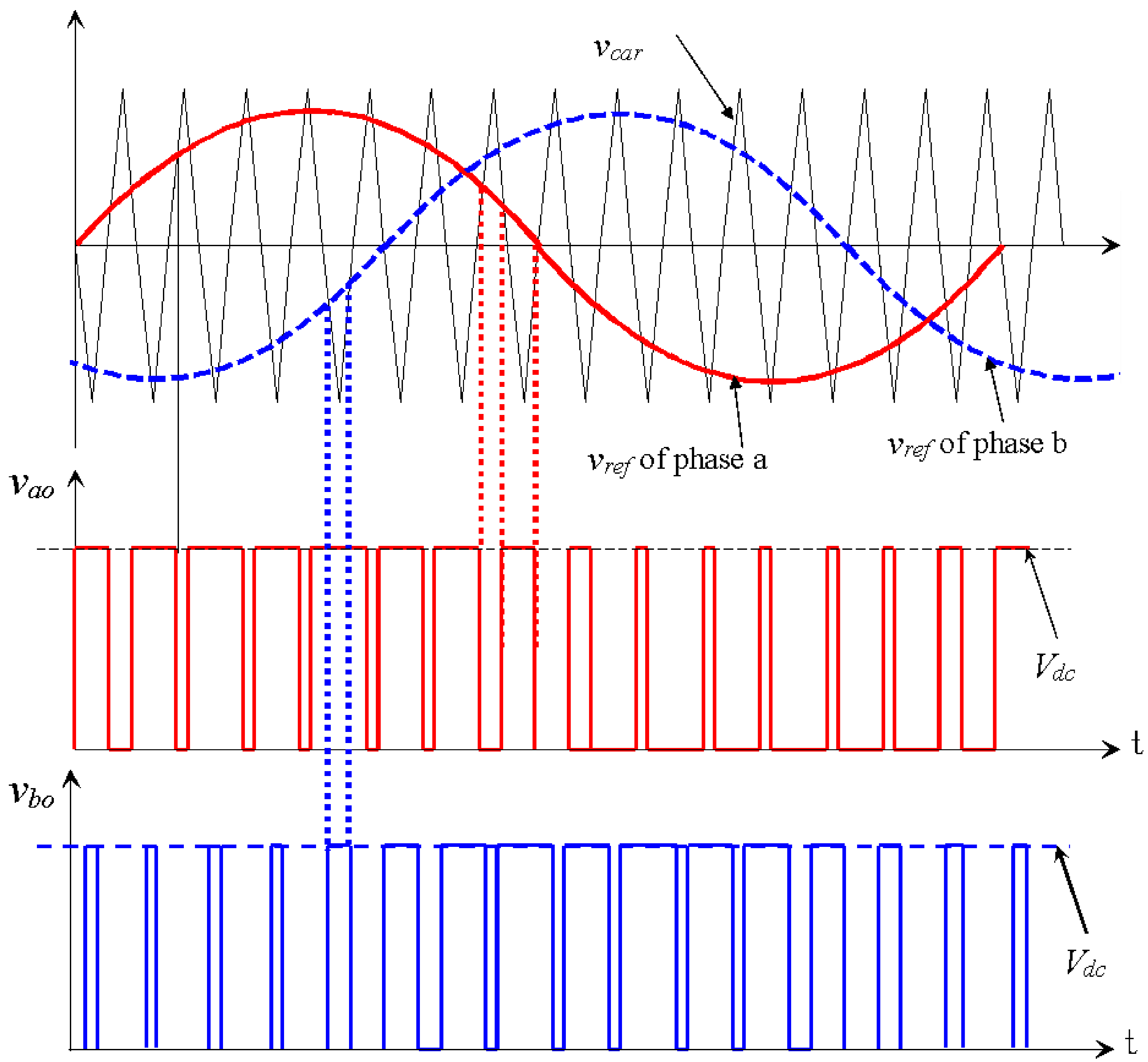


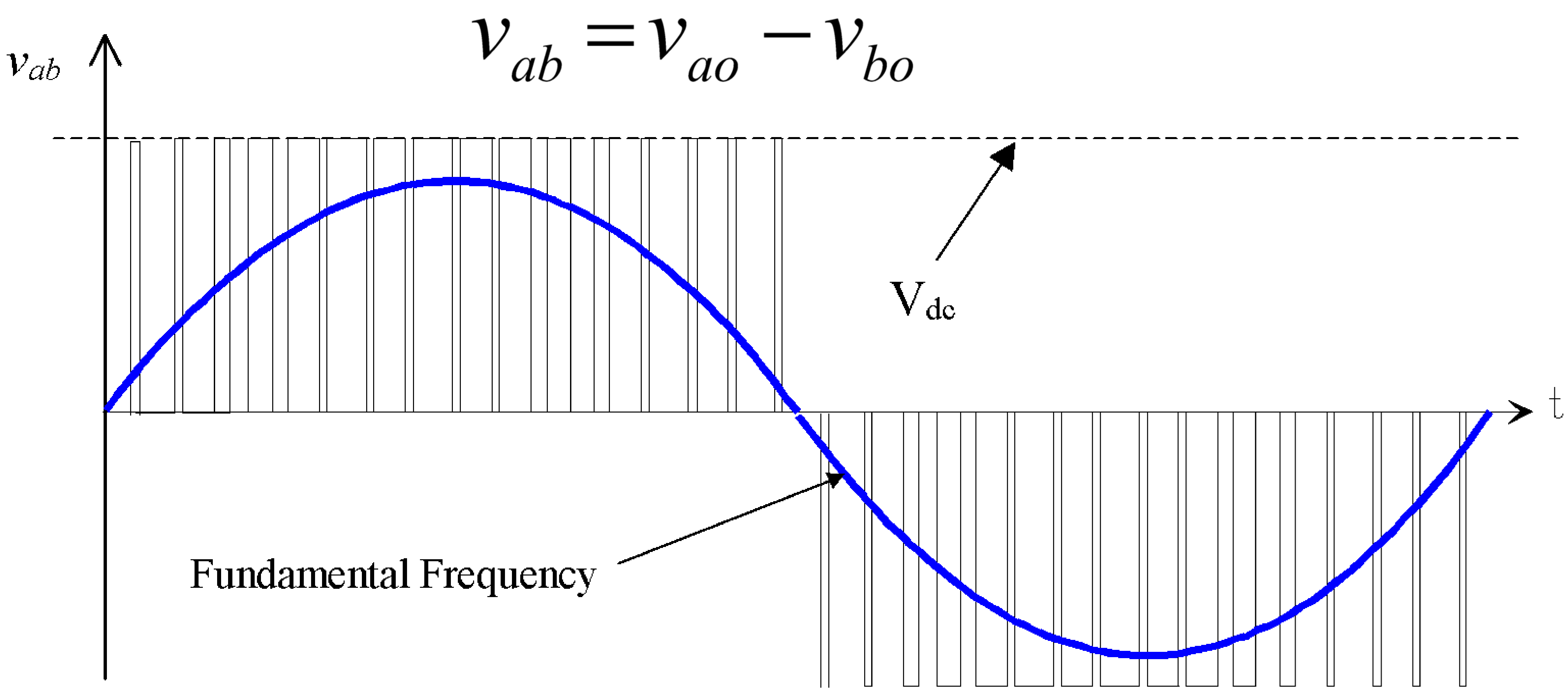


The switching rule

$$If\ \ v_{ref} > v_{car}\ \ Then\ \ \ Q_1\ is\ closed,\ Q_4\ is\ open \Rightarrow v_{ao} = V_{dc}$$

$$If\ \ v_{ref} < v_{car}\ \ Then\ \ \ Q_4\ is\ closed,\ Q_1\ is\ open \Rightarrow v_{ao} = 0$$


v_{car}
v_{ref} of phase a
v_{ref} of phase b
v_{ao}
V_{dc}
t
v_{bo}
V_{dc}
t



$$v_{ab}(t) = \sqrt{3}\; m_a \frac{V_{dc}}{2} \sin(2\pi f_s t) + \textit{Bessel harmonic terms}$$

$$m_a = \frac{V_{ref}}{V_{car}}$$ Amplitude Modulation

$$v_{ab}(t) = \sqrt{3}\ m_a\ \frac{V_{dc}}{2}\ \sin(2\pi f_s t)\ +\ \text{Bessel harmonic terms}$$

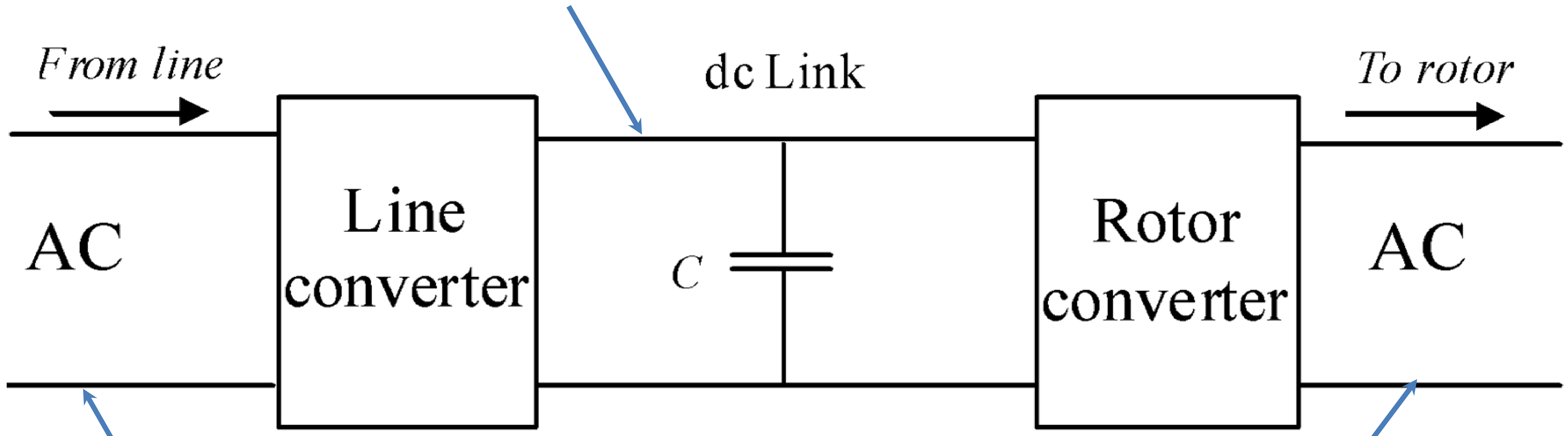
Ignore harmonics $$v_{ab}(t) = \sqrt{3}\ m_a\ \frac{V_{dc}}{2}\ \sin(2\pi f_s t)$$

Phase values $$v_{phase}(t) = m_a\ \frac{V_{dc}}{2}\ \sin(2\pi f_s t - 30^o)$$

rms of phase values $$V_{rms} = m_a\ \frac{V_{dc}}{2\sqrt{2}} = 0.354\, m_a\, V_{dc}$$

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_{max} \cos\alpha$$

$$\alpha = \alpha_{ab} - 60^o$$



$$v_{an-in} = V_{max} \sin\omega_1 t$$

$$v_{an-out} = m_a \frac{V_{dc}}{2} \sin(\omega_2 t)$$

$$V_{out-rms} = \frac{m_a}{2\sqrt{2}} V_{dc} = 0.585\ m_a V_{max} \cos\alpha$$

Control Parameters: Frequency

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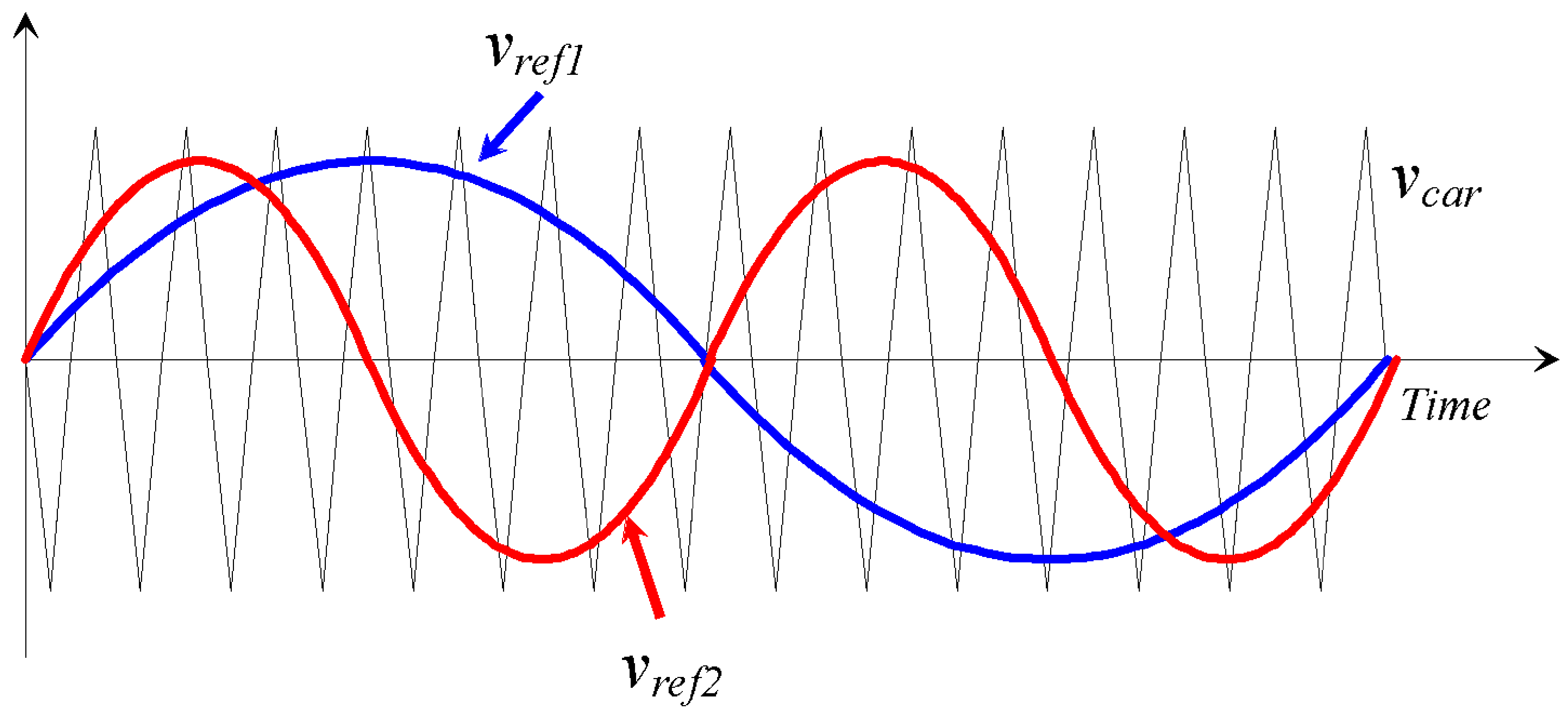
- *Frequency:* by adjusting the frequency of the reference waveform



Control Parameters: Voltage

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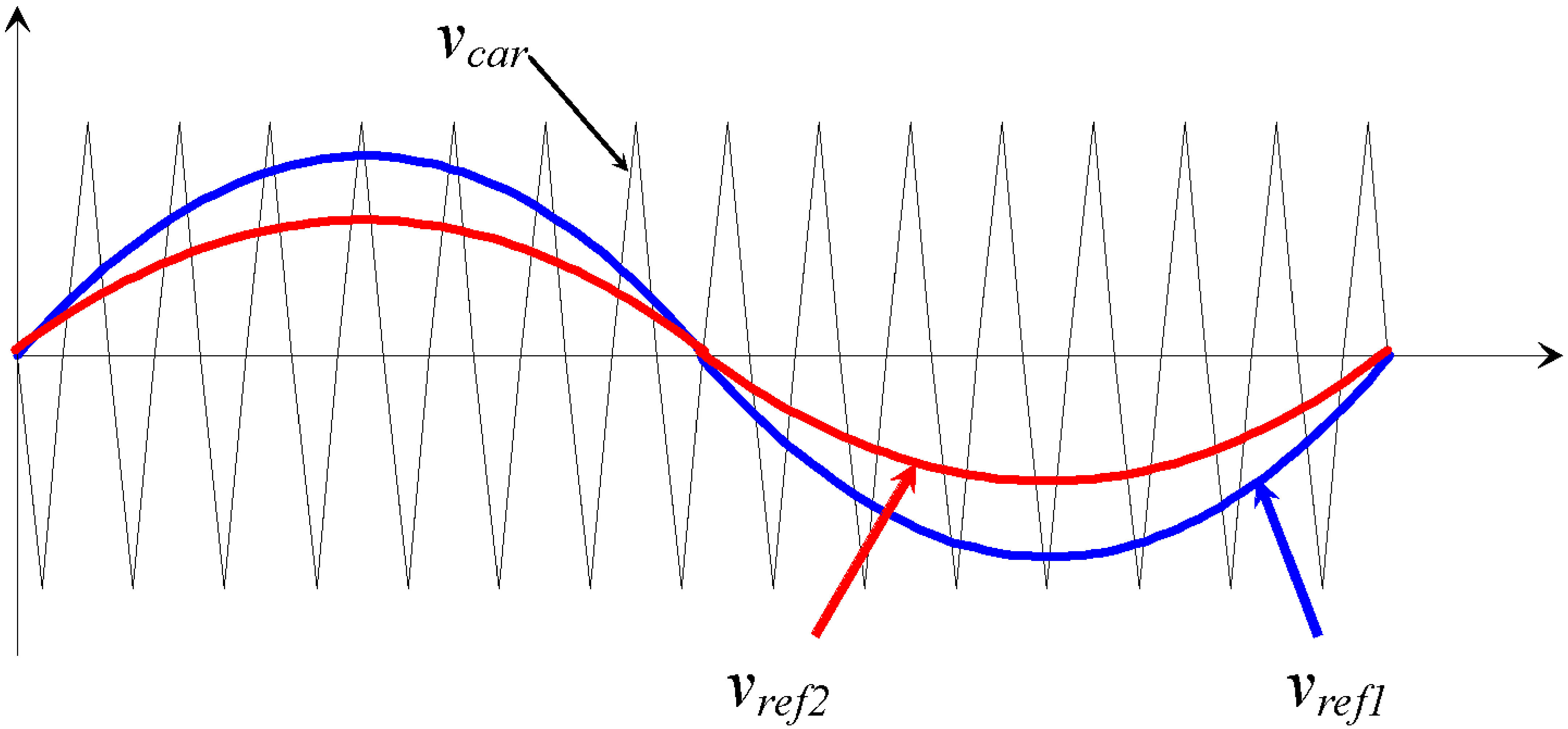
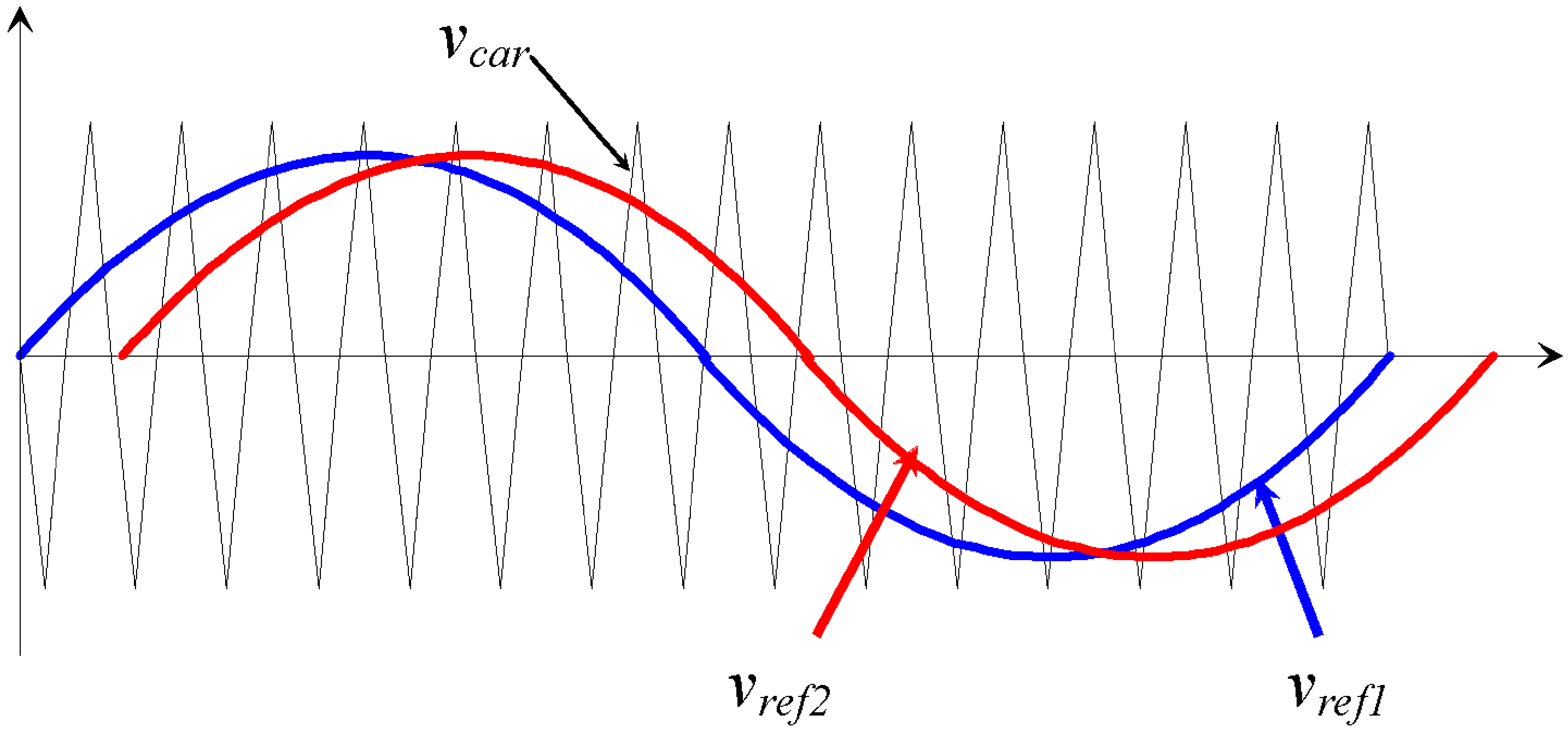
- *Voltage:* by adjusting the reference voltage and/or the triggering angle

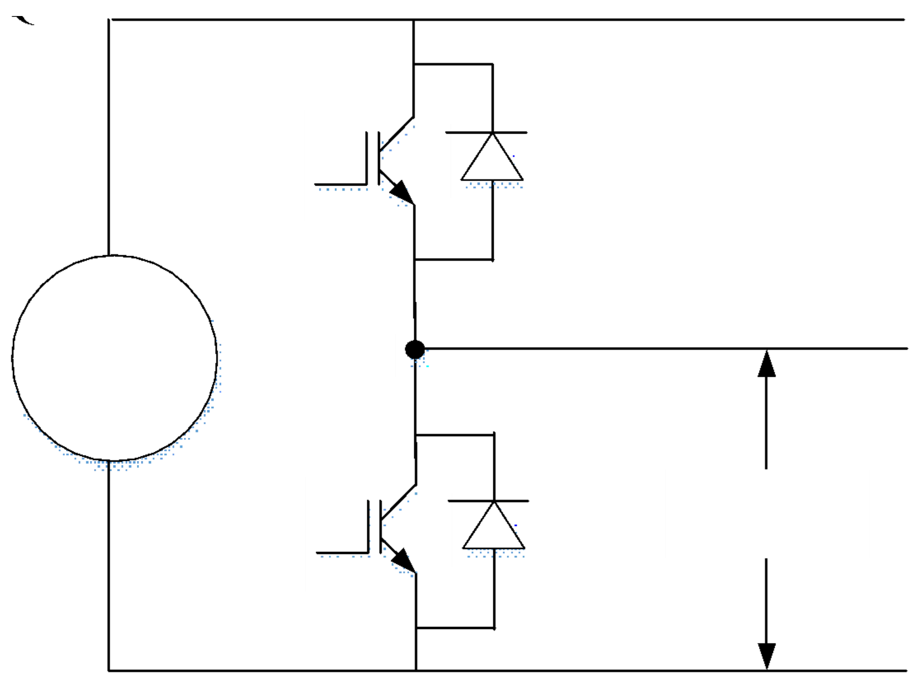


Control Parameters: Phase Shift

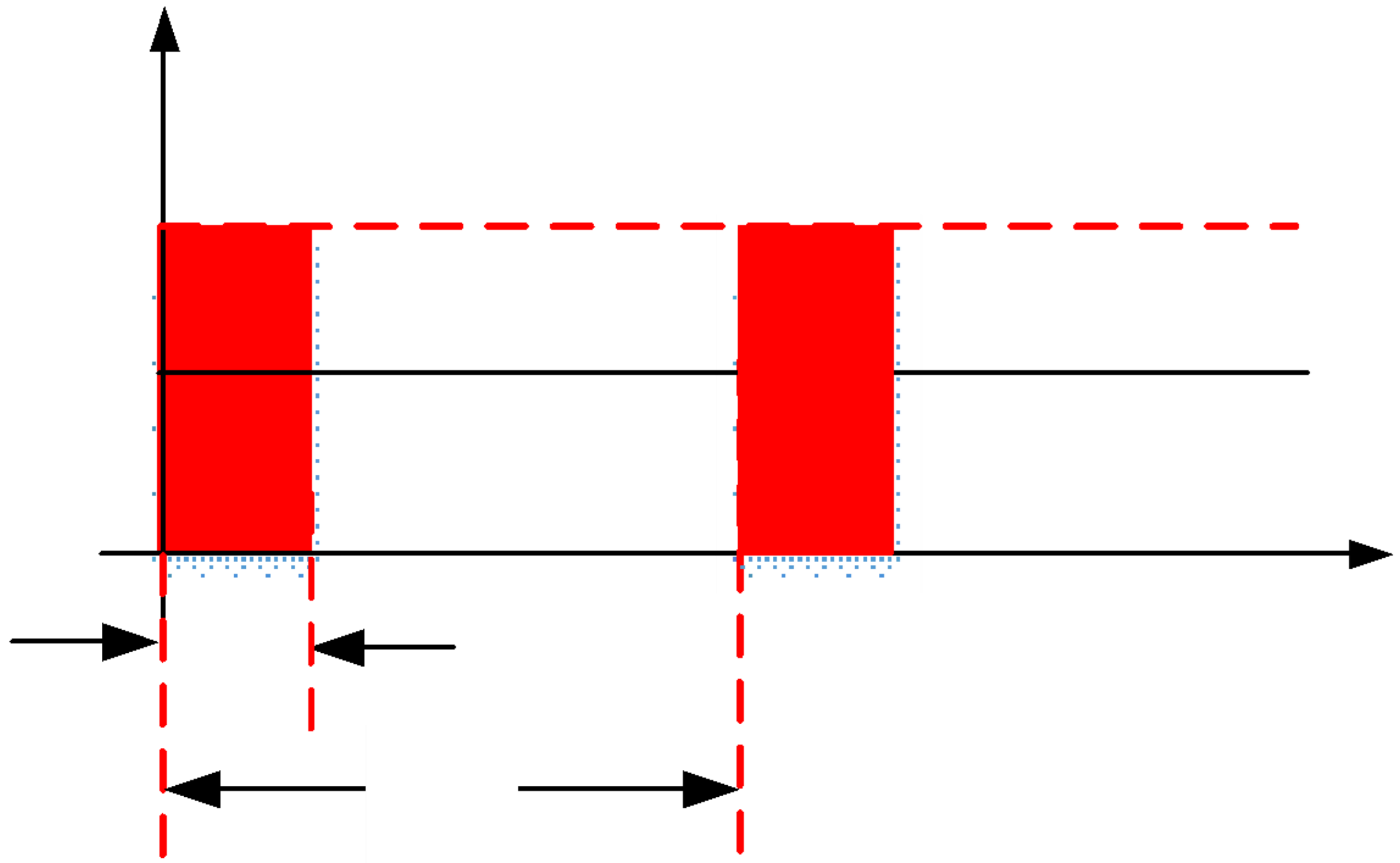
- *Phase shift:* by adjusting the phase sift of the reference waveform with respect to the line voltage



Reduced Harmonics PWM Technique



One cycle of high frequency carrier



when Q_4 is closed, $v_{ao} = 0$

when Q_1 is closed, $v_{ao} = V_{dc}$

$$v_{ao} \approx V_{ao} = m\, V_{dc} = \frac{t_{on}}{\tau} V_{dc} = t_{on}\, f\, V_{dc}$$

Reduced Harmonics PWM Technique

$$v_{ao} = m_a V_{dc}$$
$$v_{bo} = m_b V_{dc}$$
$$v_{co} = m_c V_{dc}$$

$$m_a = 0.5 + k \sin(2\pi f_s t)$$
$$m_b = 0.5 + k \sin\left(2\pi f_s t - \frac{2\pi}{3}\right)$$
$$m_c = 0.5 + k \sin\left(2\pi f_s t + \frac{2\pi}{3}\right)$$

$$k = \frac{V_{max-r}}{V_{max-car}}$$

Reduced Harmonics PWM Technique

$$m_a = 0.5 + k\sin(2\pi f_s t)$$

$$m_b = 0.5 + k\sin\left(2\pi f_s t - \frac{2\pi}{3}\right)$$

$$m_c = 0.5 + k\sin\left(2\pi f_s t + \frac{2\pi}{3}\right)$$

$$v_{ab} = v_{ao} - v_{bo} = m_a V_{dc} - m_b V_{dc} = \sqrt{3}\,k\,V_{dc}\sin\left(2\pi f_s t - \frac{\pi}{6}\right)$$

$$v_{bc} = v_{bo} - v_{co} = m_b V_{dc} - m_c V_{dc} = \sqrt{3}\,k\,V_{dc}\sin\left(2\pi f_s t - \frac{5\pi}{6}\right)$$

$$v_{ca} = v_{co} - v_{ao} = m_c V_{dc} - m_a V_{dc} = \sqrt{3}\,k\,V_{dc}\sin\left(2\pi f_s t + \frac{\pi}{2}\right)$$

Reduced Harmonics PWM Technique

$$v_{ab} = \sqrt{3}\, k\, V_{dc} \sin\left(2\pi f_s t - \frac{\pi}{6}\right)$$

$$v_{bc} = \sqrt{3}\, k\, V_{dc} \sin\left(2\pi f_s t - \frac{5\pi}{6}\right)$$

$$v_{ca} \sqrt{3}\, k\, V_{dc} \sin\left(2\pi f_s t + \frac{\pi}{2}\right)$$

$$v_{an} = k\, V_{dc} \sin(2\pi f_s t)$$

$$v_{bn} = k\, V_{dc} \sin\left(2\pi f_s t - \frac{2\pi}{3}\right)$$

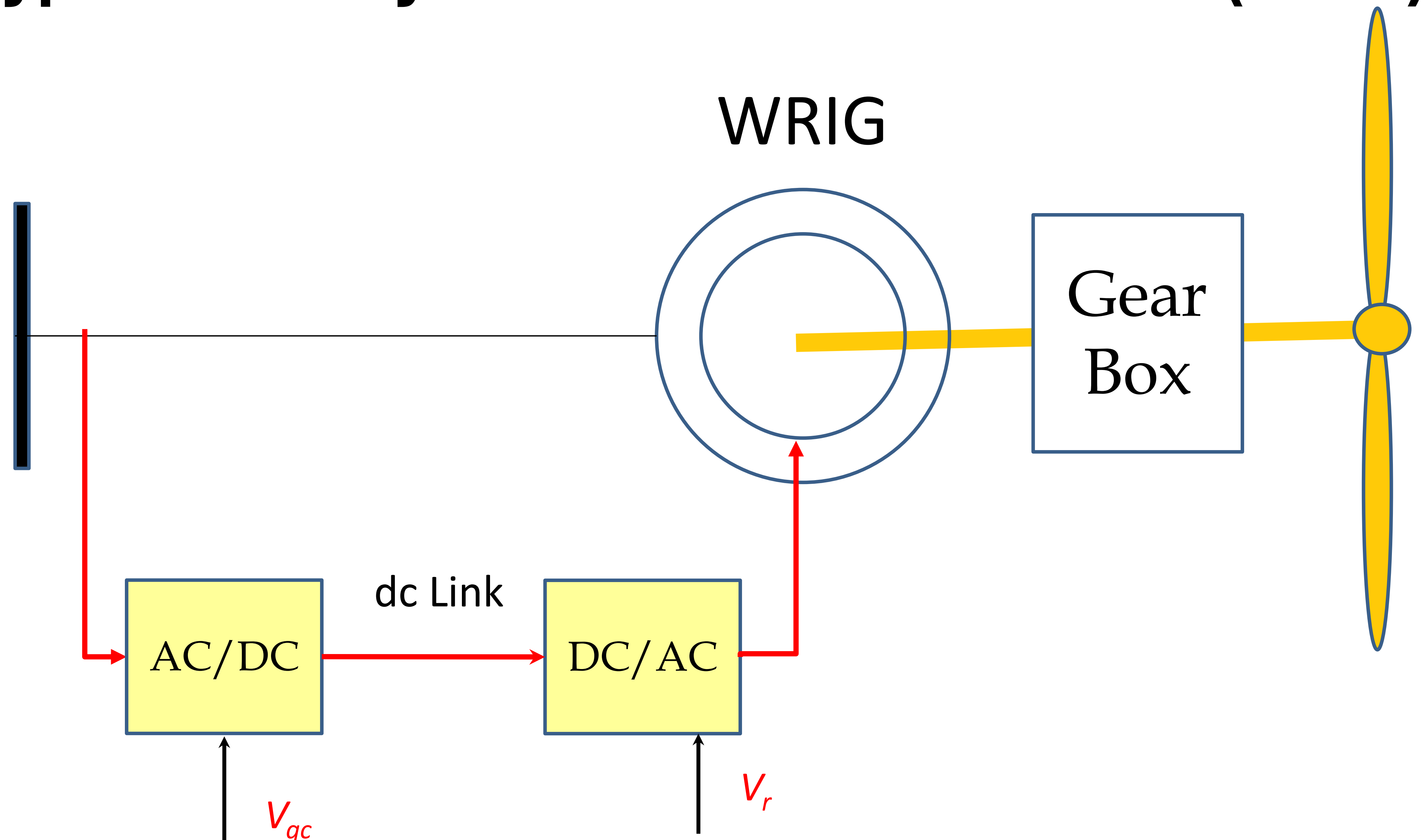
$$v_{cn} = k\, V_{dc} \sin\left(2\pi f_s t + \frac{2\pi}{3}\right)$$

$$\bar{V}_{an} = \frac{k\, V_{dc}}{\sqrt{2}} \angle 0^o$$

$$\bar{V}_{bn} = \frac{k\, V_{dc}}{\sqrt{2}} \angle -120^o$$

$$\bar{V}_{cn} = \frac{k\, V_{dc}}{\sqrt{2}} \angle 120^o$$

Type 3: Doubly Fed Induction Generator (DFIG)



Controls

- DC link voltage
- Reactive power (in some applications)

Controls

- Electromagnetic torque
- Speed (extracted power)
- Terminal voltage of generator
- Reactive power

Key Features of DFIG

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- The capacitor connected on the DC bus acts as a filter and a voltage source.
- The control system generates the control signals V_r and V_{gc}.
- The frequency of the injected voltage to the rotor is equal to the desired slip frequency

$$f_r = s_{new} f$$

- The rotor will eventually rotate at the new speed

Website

Use the course website:	To check for announcements
	To get copies of the lecture slides and other material
	To get the homework and project assignments

https://lms.ttu.edu.jo/

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