

Power Converter Systems

Graduate Course EE8407

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Contact Info

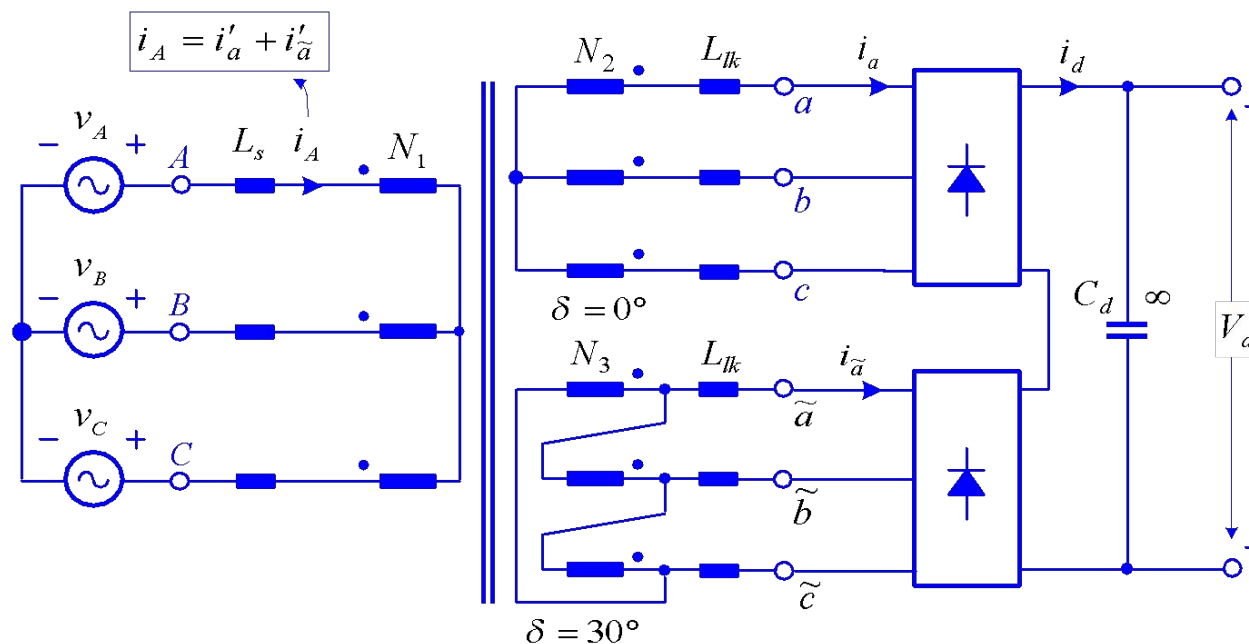
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Ryerson Campus

Topic 3

Multi-pulse Diode Rectifiers



Multi-pulse Diode Rectifiers

Lecture Topics

- **Six-pulse Diode Rectifier (Building Block)**
- **Series-type 12-, 18- and 24-pulse rectifiers**
- **Separate-type 12-, and 18-pulse rectifiers**

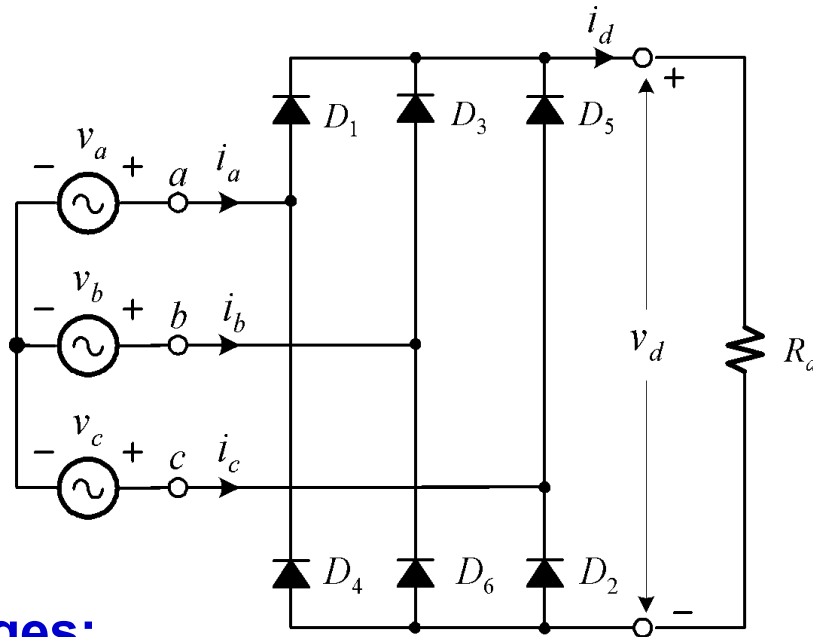
Multi-pulse Diode Rectifiers

Why Use Multipulse Diode Rectifiers?

- To reduce line current THD;
- To improve input power factor; and
- To avoid semiconductor devices in series.

Six-pulse Diode Rectifier

• Resistive Load



Supply Voltages:

$$v_a = \sqrt{2} V_{PH} \sin(\omega t)$$

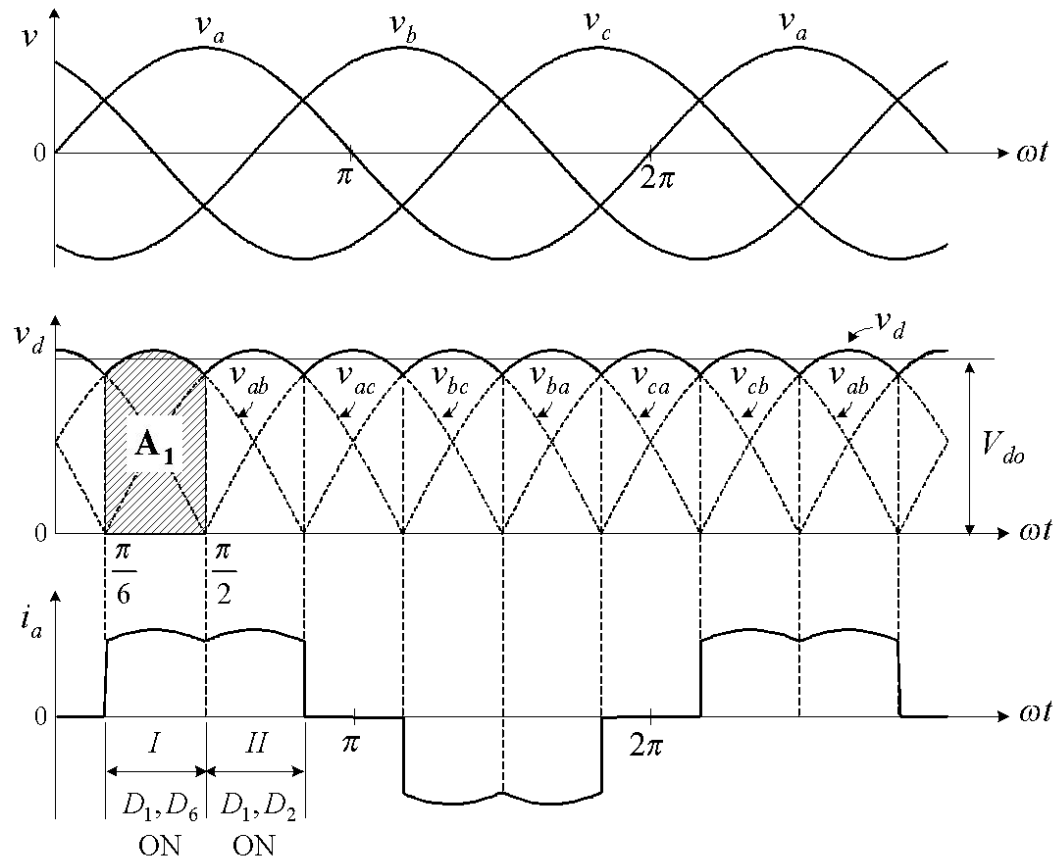
$$v_b = \sqrt{2} V_{PH} \sin(\omega t - 2\pi / 3)$$

$$v_c = \sqrt{2} V_{PH} \sin(\omega t - 4\pi / 3)$$

$$v_{ab} = v_a - v_b = \sqrt{2} V_{LL} \sin(\omega t + \pi / 6)$$

Six-pulse Diode Rectifier

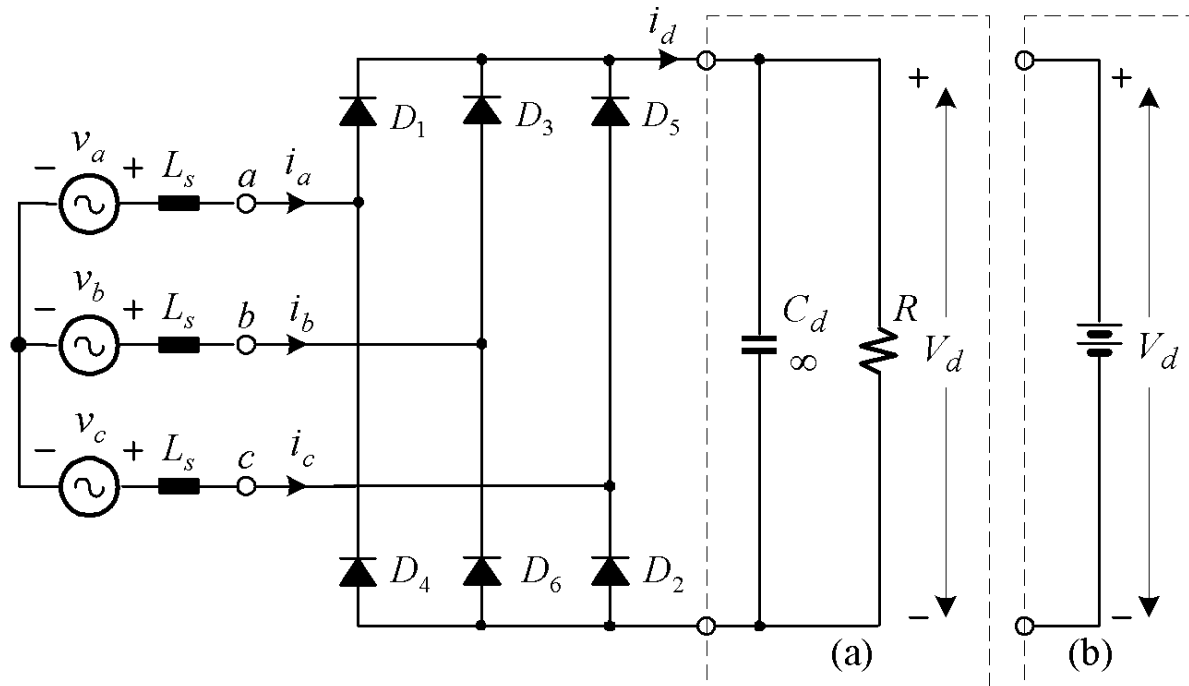
• Waveforms



$$V_{do} = \frac{\text{area } \mathbf{A}_1}{\pi/3} = \frac{1}{\pi/3} \int_{\pi/6}^{\pi/2} \sqrt{2} V_{LL} \sin(\omega t + \pi/6) d(\omega t) = \frac{3\sqrt{2}}{\pi} V_{LL} \approx 1.35 V_{LL}$$

Six-pulse Diode Rectifier

• Capacitive Load

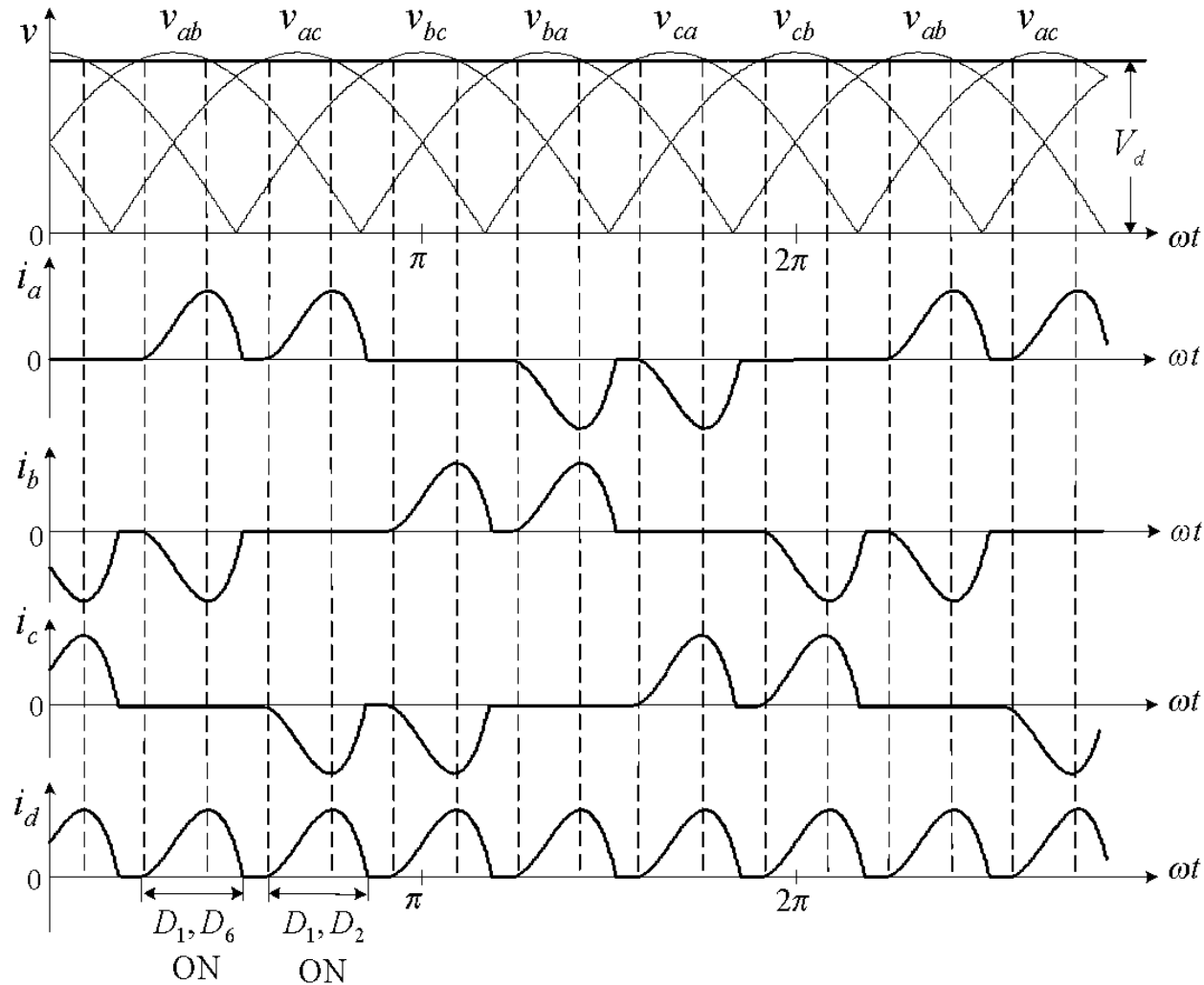


Assumption:

$$C_d = \infty \Rightarrow V_d = \text{constant}$$

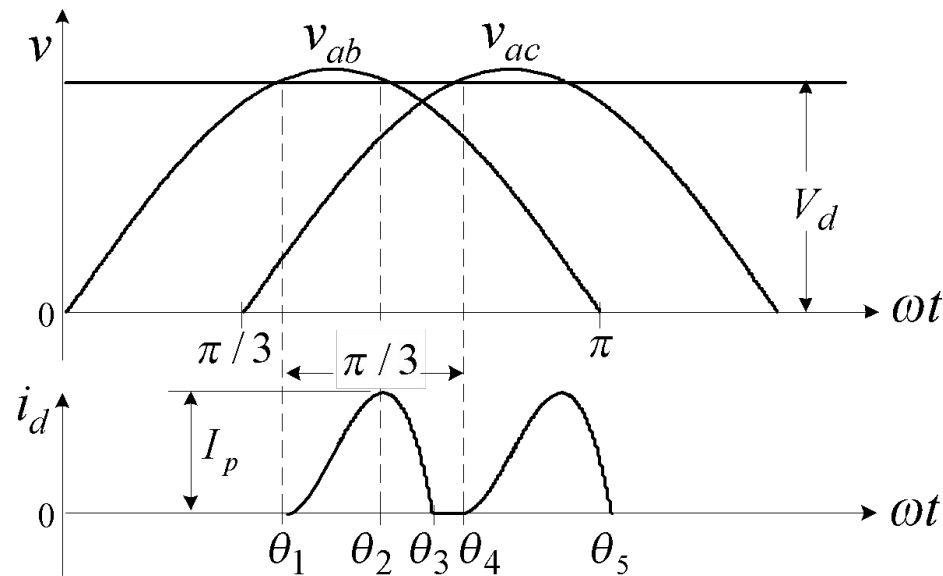
Six-pulse Diode Rectifier

• Waveforms



Six-pulse Diode Rectifier

• Discontinuous Current Operation

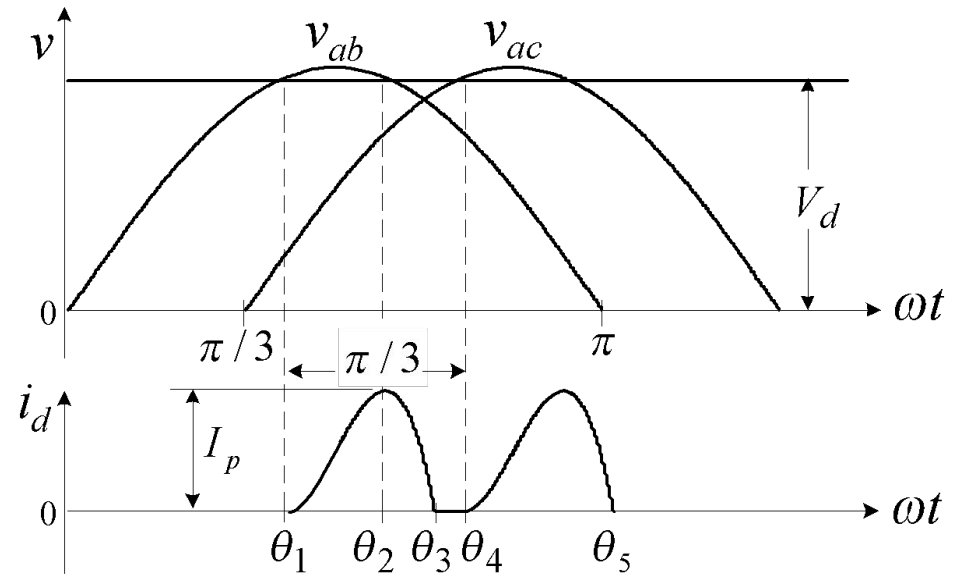
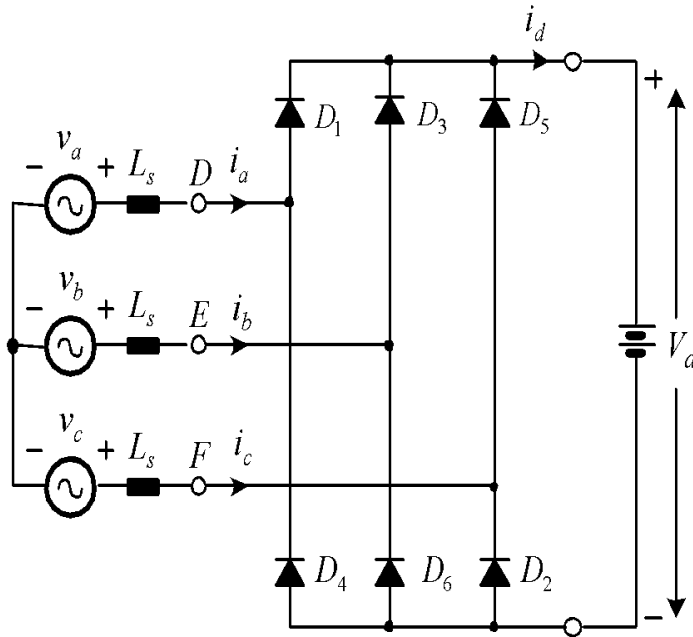


$$\theta_1 = \sin^{-1}\left(\frac{V_d}{\sqrt{2} V_{LL}}\right)$$

$$\theta_2 = \pi - \theta_1$$

Six-pulse Diode Rectifier

• Discontinuous Current Operation



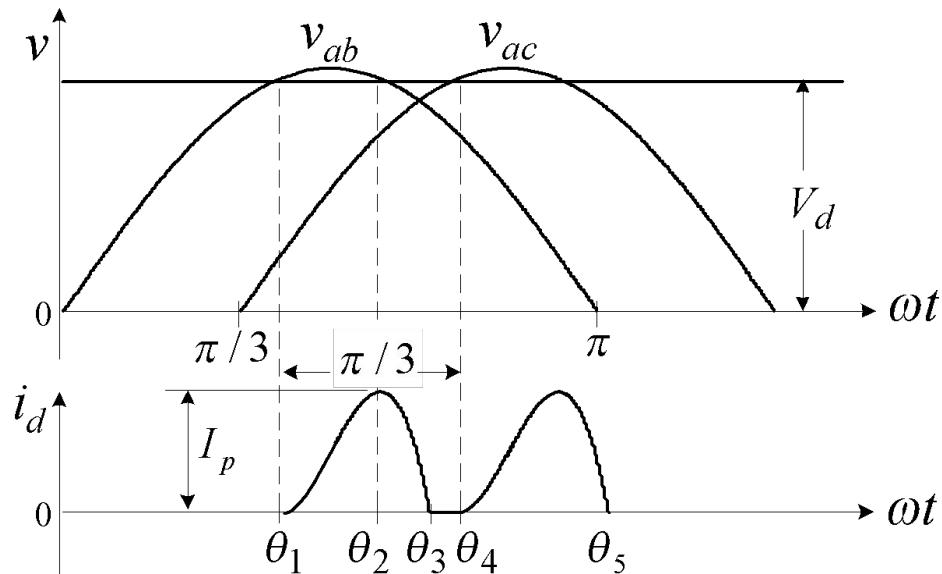
Differential Equation:
$$2L_s \frac{di_d}{dt} = v_{ab} - V_d \quad \theta_1 \leq \omega t < \theta_3$$

Solution:
$$i_d(\theta) = \frac{1}{2\omega L_s} \int_{\theta_1}^{\theta} (\sqrt{2}V_{LL} \sin(\omega t) - V_d) d(\omega t)$$

$$= \frac{1}{2\omega L_s} (\sqrt{2}V_{LL} (\cos\theta_1 - \cos\theta) + V_d(\theta_1 - \theta))$$

Six-pulse Diode Rectifier

• Discontinuous Current Operation



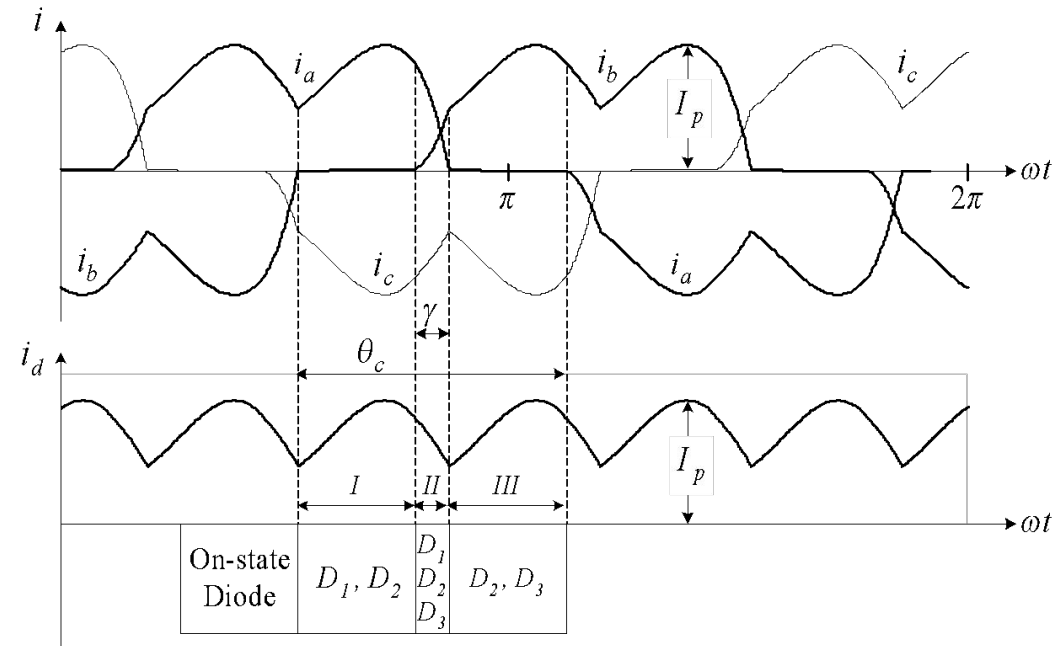
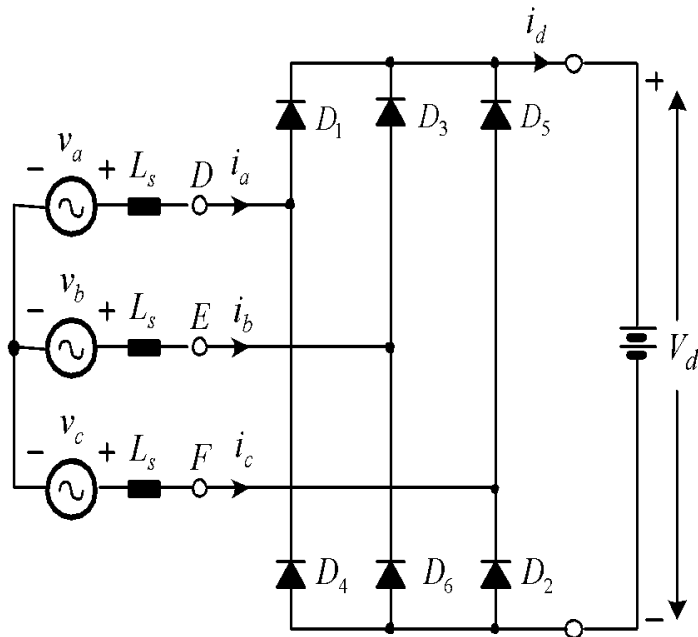
Peak dc current:
$$I_p = \frac{1}{2\omega L_s} (\sqrt{2}V_{LL}(\cos\theta_1 - \cos\theta_2) + V_d(\theta_1 - \theta_2))$$

Average dc current:
$$I_d = \frac{1}{\pi/3} \int_{\theta_1}^{\theta_3} i_d(\theta) d(\theta)$$

Voltage – theta relation:
$$\frac{V_d}{\sqrt{2}V_{LL}} = \frac{\cos\theta_1 - \cos\theta_3}{\theta_1 - \theta_3}$$

Six-pulse Diode Rectifier

• Continuous Current Operation



Note:

- With the increase of the load current, the rectifier will enter into continuous current operation.
- During commutation interval, three diodes are on.

Six-pulse Diode Rectifier

- Definition of Total Harmonic Distortion (THD)

Phase voltage (pure sine): $v_a = \sqrt{2} V_a \sin \omega_1 t$

Line current (distorted): $i_a = \sum_{n=1,2,3,\dots}^{\infty} \sqrt{2} I_{an} (\sin(\omega_n t) - \phi_n)$

RMS line current: $I_a = \left(\frac{1}{2\pi} \int_0^{2\pi} (i_a)^2 d(\omega t) \right)^{1/2} = \left(\sum_{n=1,2,3,\dots}^{\infty} I_{an}^2 \right)^{1/2}$

Line current THD: $THD = \frac{\sqrt{I_a^2 - I_{a1}^2}}{I_{a1}}$

Six-pulse Diode Rectifier

- Definition of Power Factor (PF)

Per-phase average (real) power:
$$P = \frac{1}{2\pi} \int_0^{2\pi} v_a \times i_a d(\omega t) = V_a I_{a1} \cos\phi_1$$

Per-phase apparent power:
$$S = V_a I_a$$

Total power factor (PF):
$$PF = \frac{P}{S} = \frac{V_a I_{a1} \cos\phi_1}{V_a I_a} = \frac{I_{a1}}{I_a} \cos\phi_1 = DF \times DPF$$

Distortion factor (DF):
$$DF = I_{a1} / I_a$$

Displacement power factor (DPF):
$$DPF = \cos\phi_1$$

PF = f (THD):
$$PF = \frac{DPF}{\sqrt{1 + THD^2}}$$

Six-pulse Diode Rectifier

• Per Unit System

Rated power, rated line-to-line voltage: S_R, V_R

Base voltage and frequency: $V_B = \frac{V_R}{\sqrt{3}}$ and $\omega_B = 2\pi f_1$

Base current and impedance: $I_B = \frac{S_R}{3V_B}$ and $Z_B = \frac{V_B}{I_B}$.

Base inductance and capacitance: $L_B = \frac{Z_B}{\omega_B}$ and $C_B = \frac{1}{\omega_B Z_B}$

Example

Rectifier ratings: 4160V, 60Hz, 2MVA.

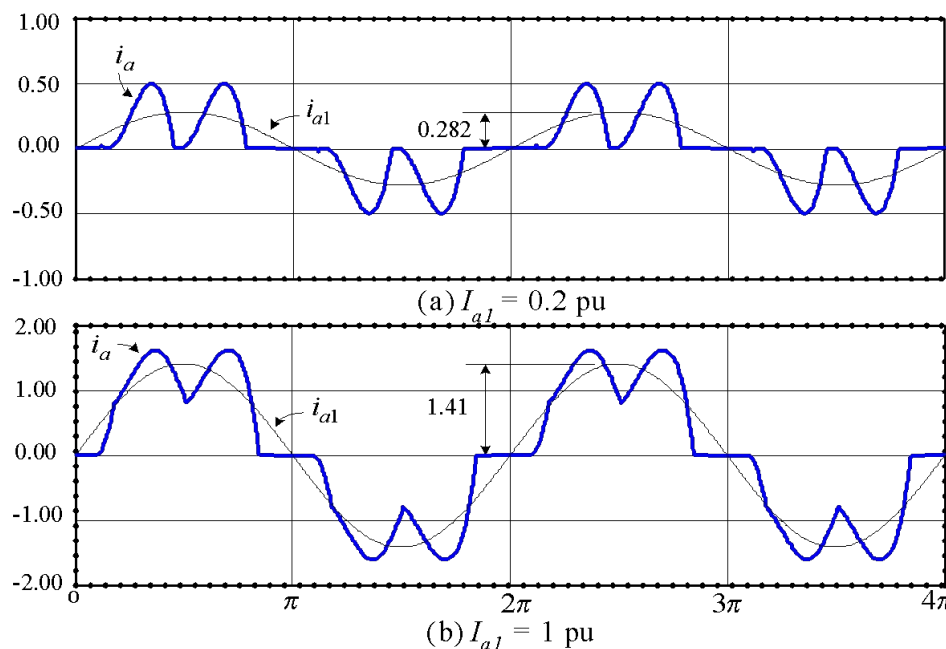
Base current = 277.6A, Base inductance = 22.9mH.

Line inductance = 2.29mH = 0.1pu

Line current = 138.8A = 0.5pu

Six-pulse Diode Rectifier

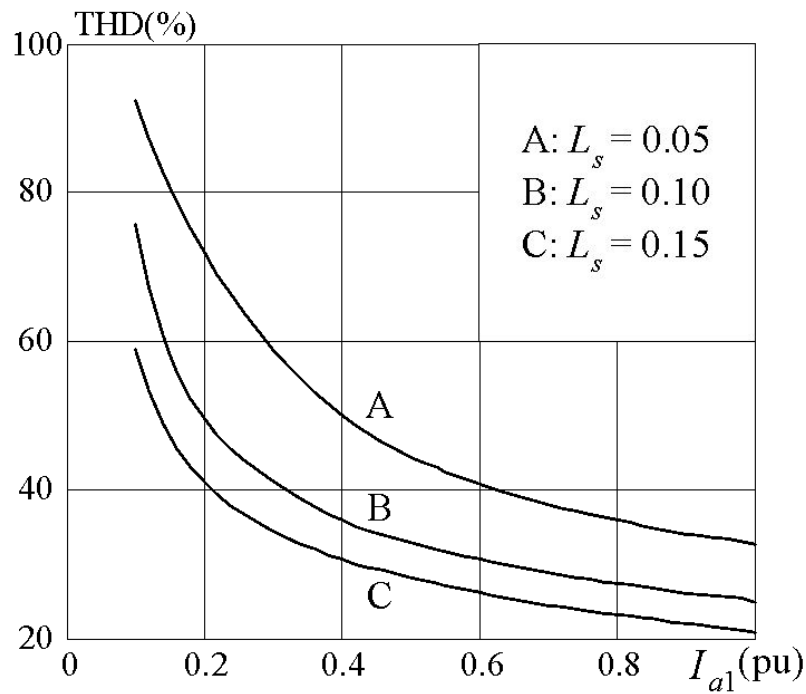
• Typical Waveforms / Harmonic Content



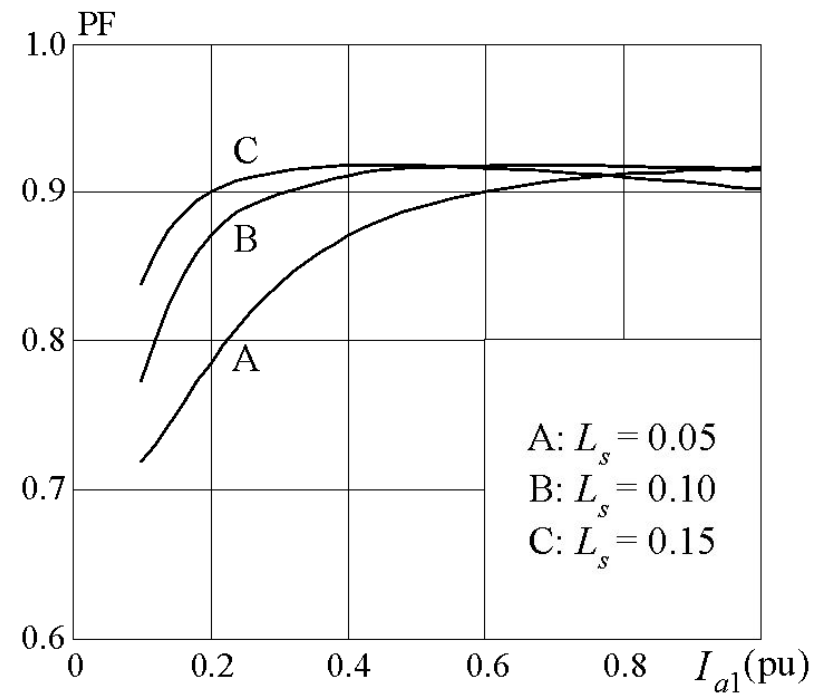
Harmonics n	5	7	11	13	17	19	23	25	THD (%)
I_{an} / I_{a1} (%) $I_{a1} = 0.2$ pu	63.4	38.7	8.99	8.64	4.22	3.61	2.48	2.02	75.7
I_{an} / I_{a1} (%) $I_{a1} = 1$ pu	30.4	8.79	6.31	3.40	2.30	1.89	1.04	1.03	32.7

Six-pulse Diode Rectifier

- THD and PF



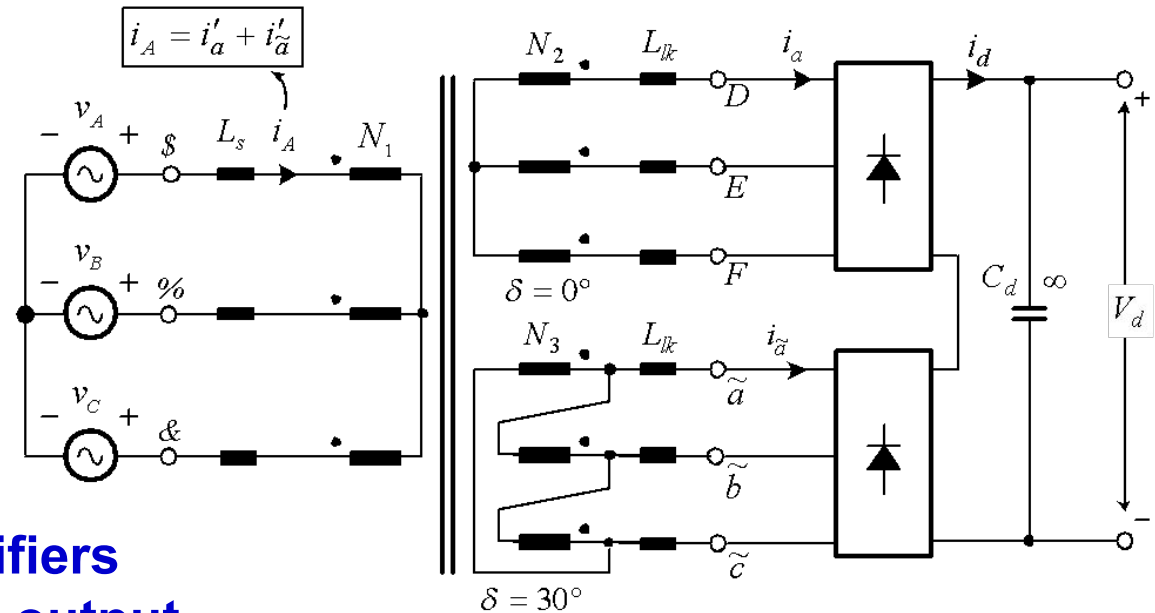
(a) THD



(b) PF

12-pulse Series-type Diode Rectifier

• Rectifier Topology



- **Series type:**
Two six-pulse rectifiers
are in series at the output.

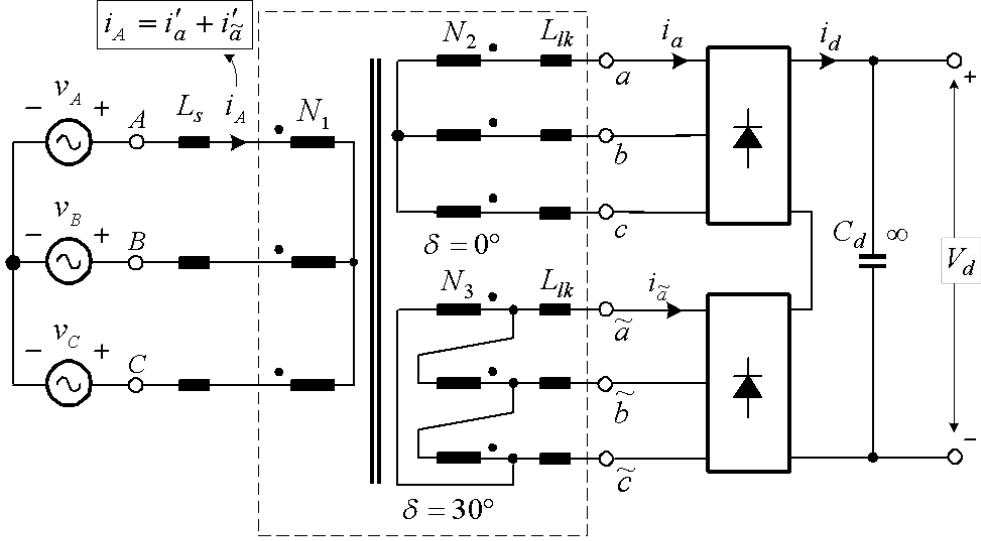
- **Phase shifting transformer:** $\delta = \angle V_{\tilde{a}\tilde{b}} - \angle V_{AB} = 30^\circ$

- **Secondary line-to-line voltage:** $V_{ab} = V_{\tilde{a}\tilde{b}} = V_{AB} / 2$

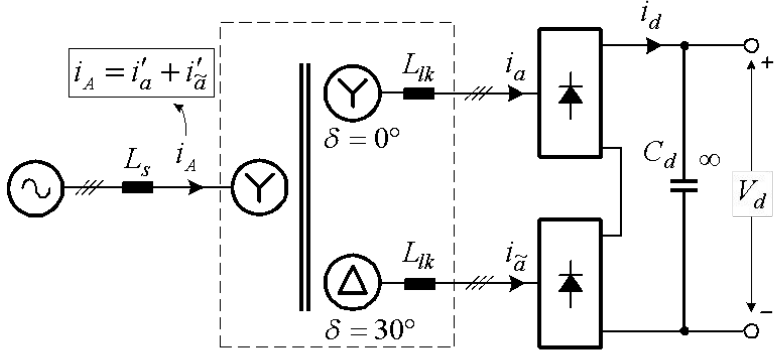
- **Turns ratio:** $\frac{N_1}{N_2} = 2$ and $\frac{N_1}{N_3} = \frac{2}{\sqrt{3}}$.

12-pulse Series-type Diode Rectifier

- Simplified Block Diagram



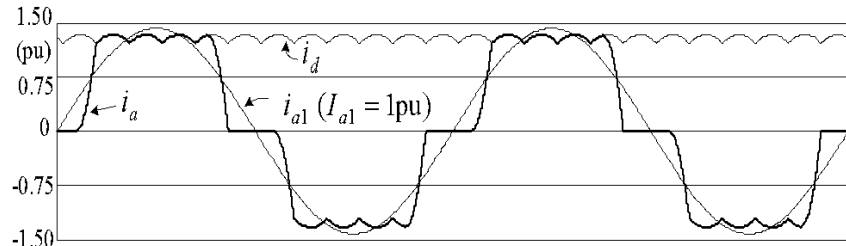
(a) 12-pulse diode rectifier



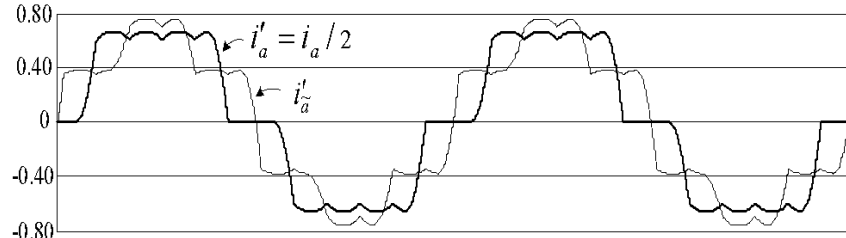
(b) Simplified diagram

12-pulse Series-type Diode Rectifier

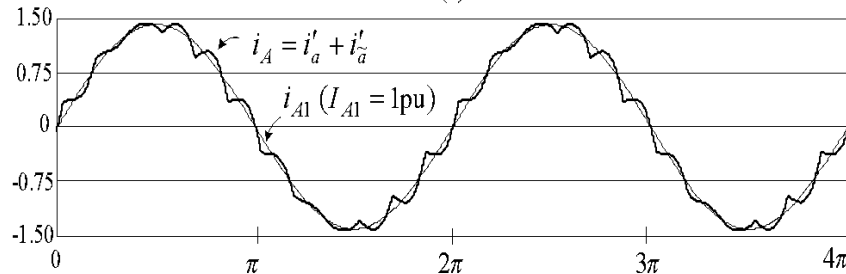
• Waveforms and FFT



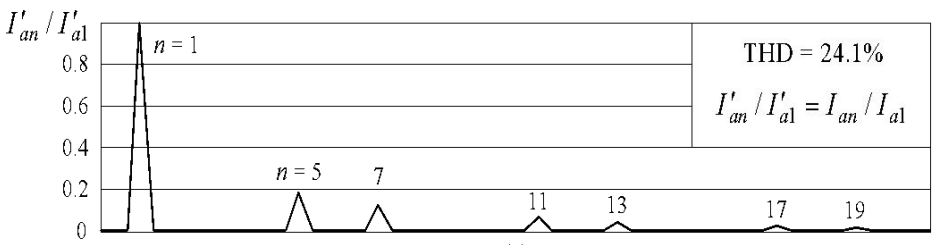
(a)



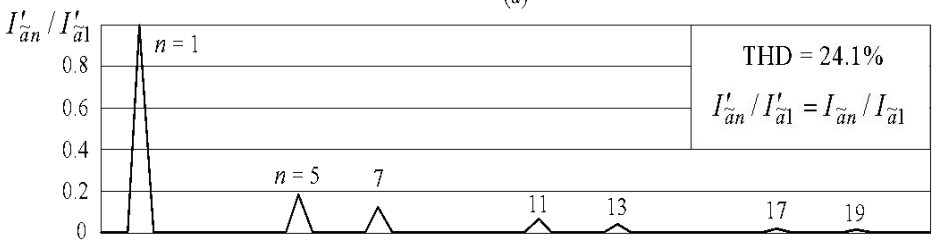
(b)



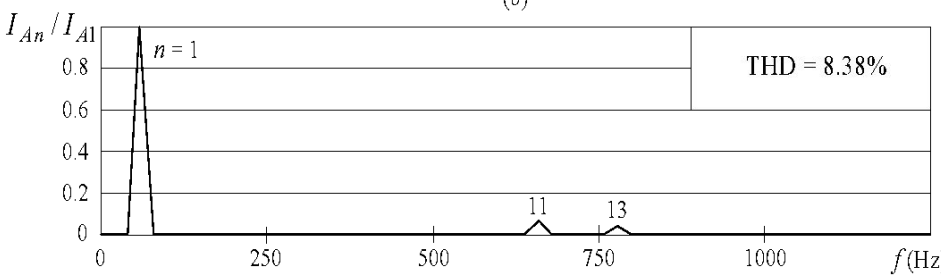
(c)



(a)



(b)

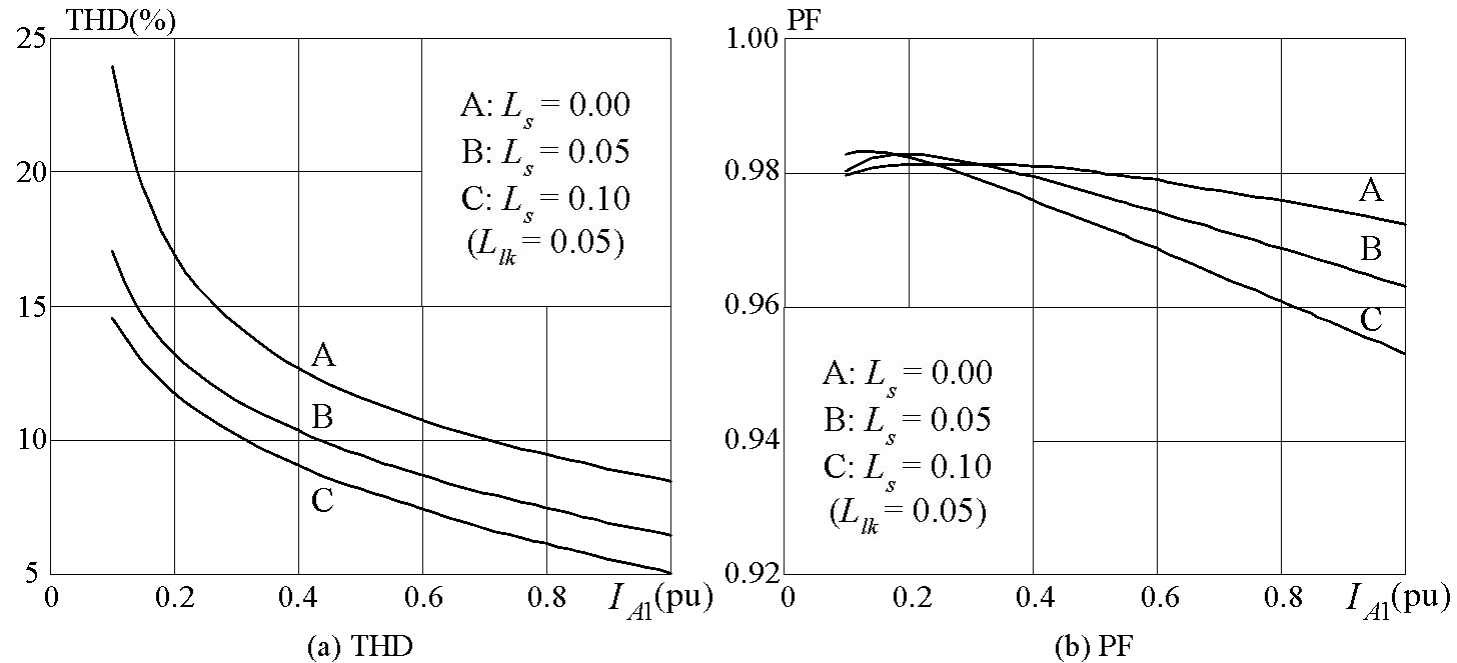


(c)

- No 5th or 7th harmonics in the line current.
- Primary line current THD: 8.38%

12-pulse Series-type Diode Rectifier

• THD and PF

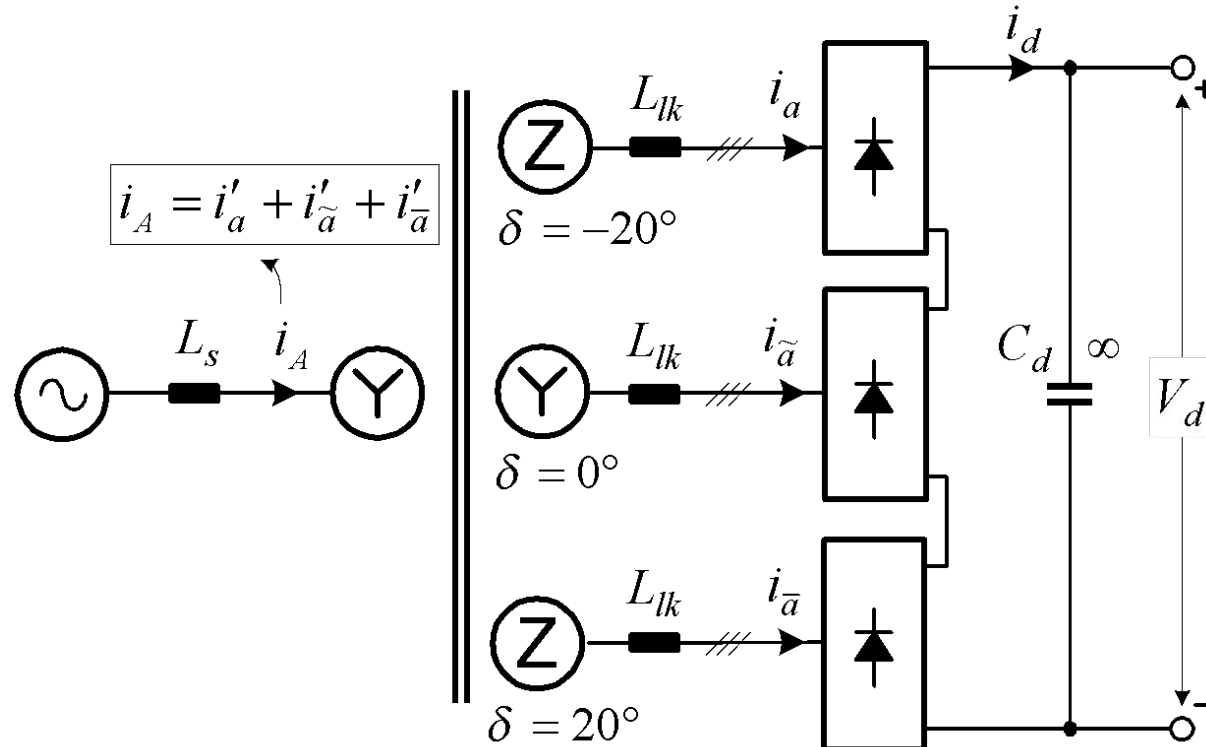


Comparison with six-pulse rectifier:

- THD is reduced; and
- PF is improved.

18-pulse Series-type Diode Rectifier

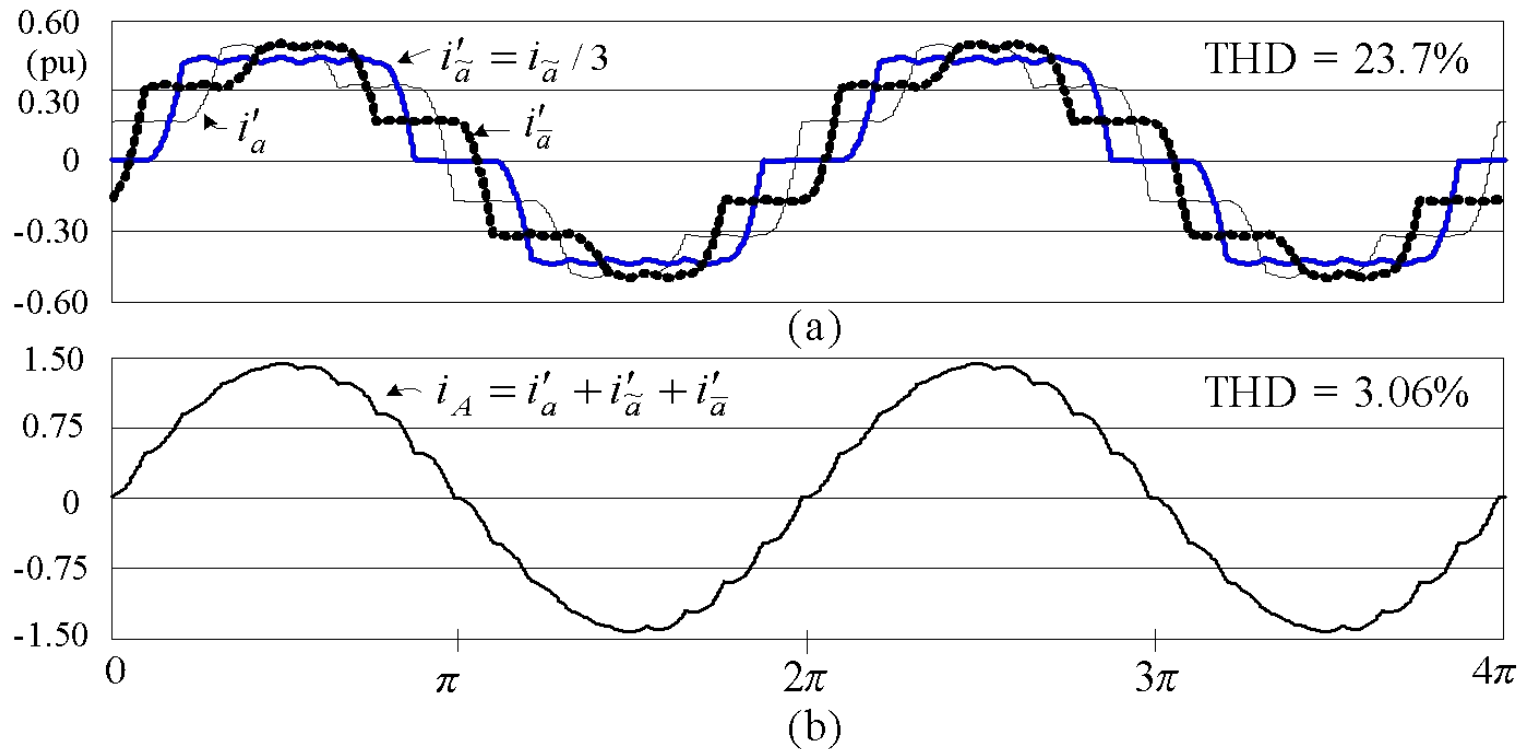
- Converter Topology



**Phase-Shifting
(Zigzag) Transformer**

18-pulse Series-type Diode Rectifier

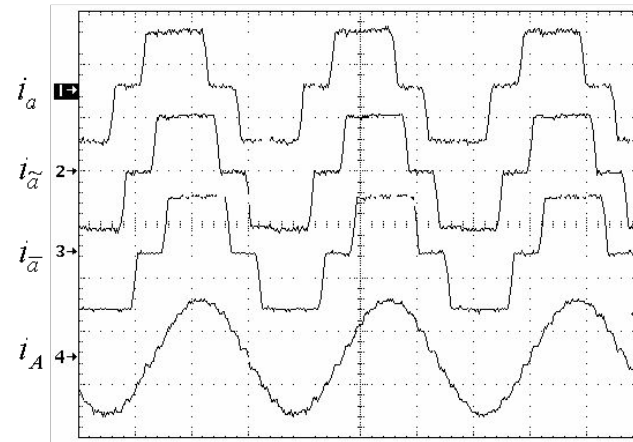
• Simulated Waveforms



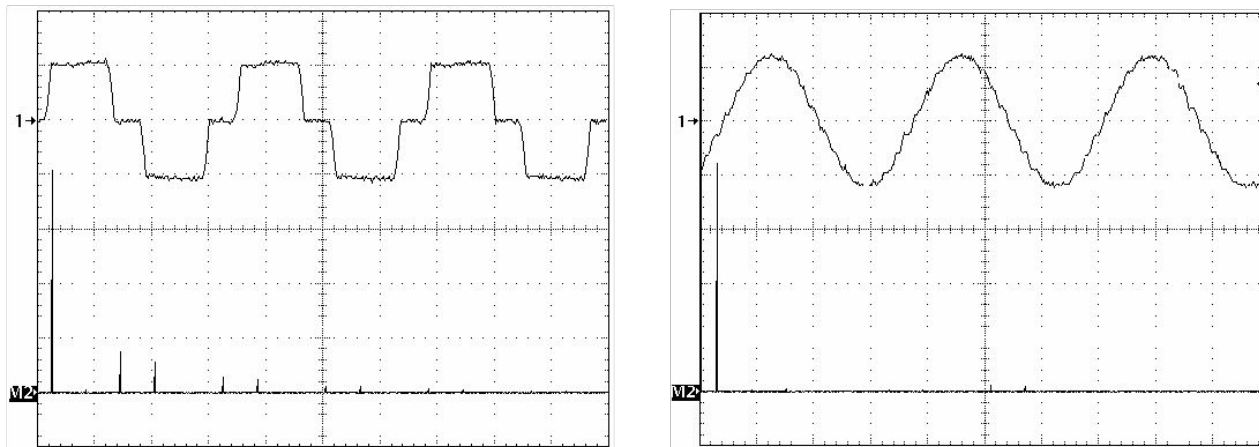
- No 5th, 7th, 11th, or 13th harmonics in the line current.
- Lowest harmonic: 17th
- Line current THD: 3.06%

18-pulse Series-type Diode Rectifier

- Measured Waveforms



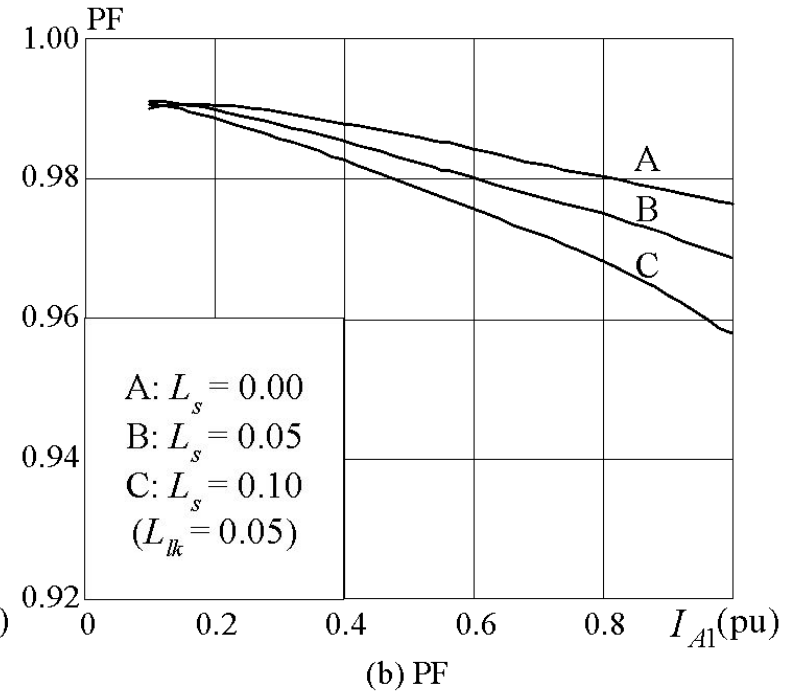
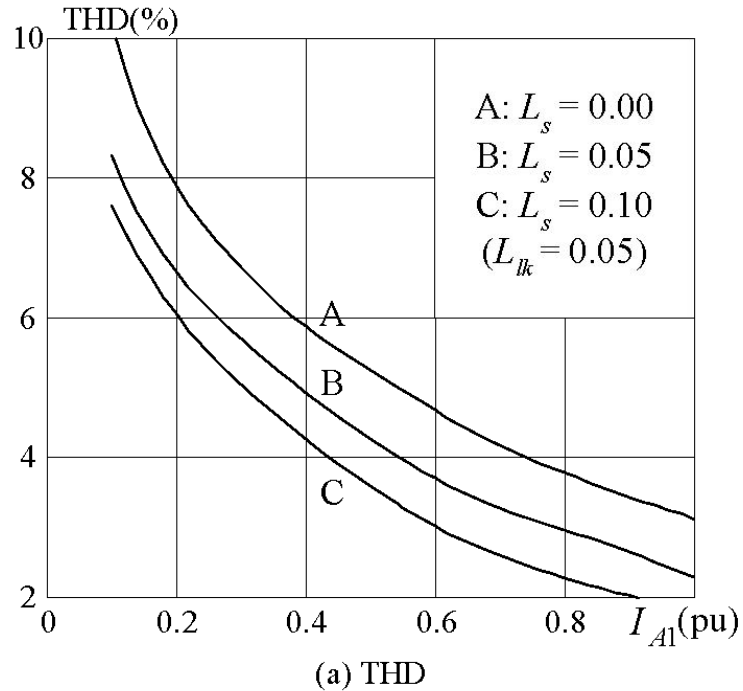
(a) Currents: $\sqrt{2}$ pu/div, 5ms/div



(b) Spectrum: $\sqrt{2}/5$ pu/div, 200Hz/div

18-pulse Series-type Diode Rectifier

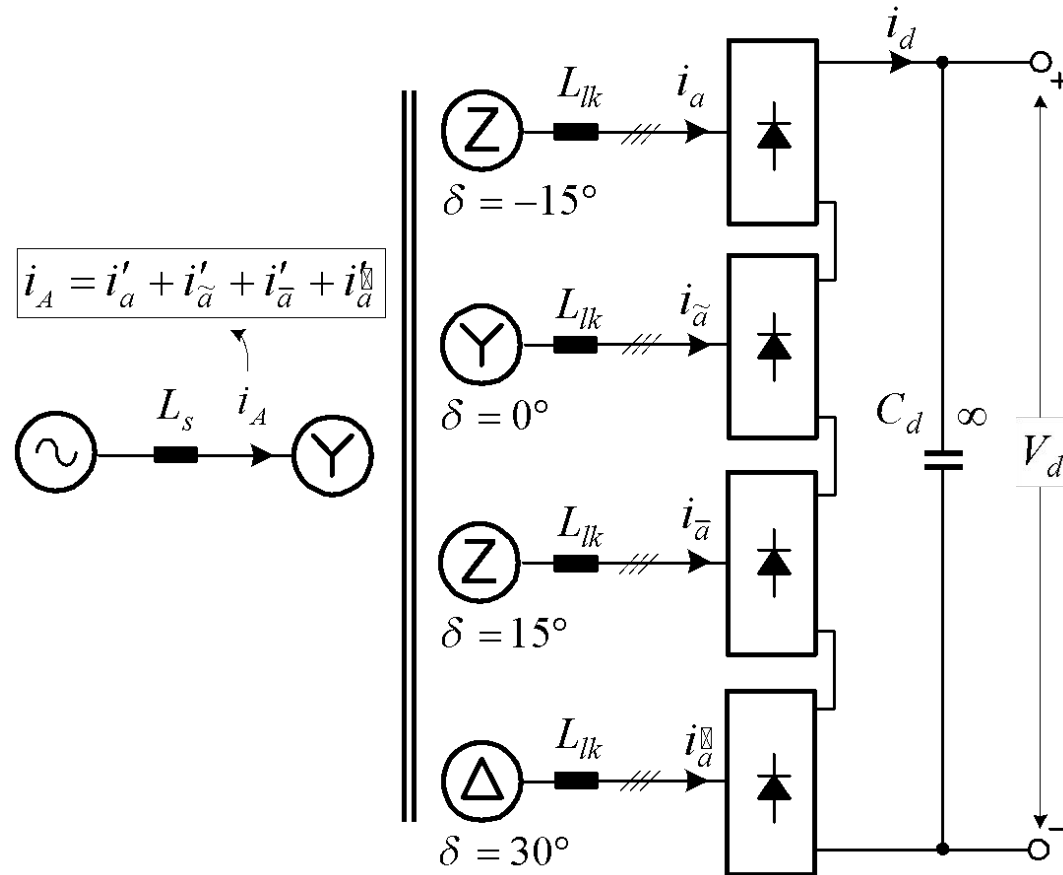
- THD and PF



**Comparison with 12-pulse:
Improved THD**

24-pulse Series-type Diode Rectifier

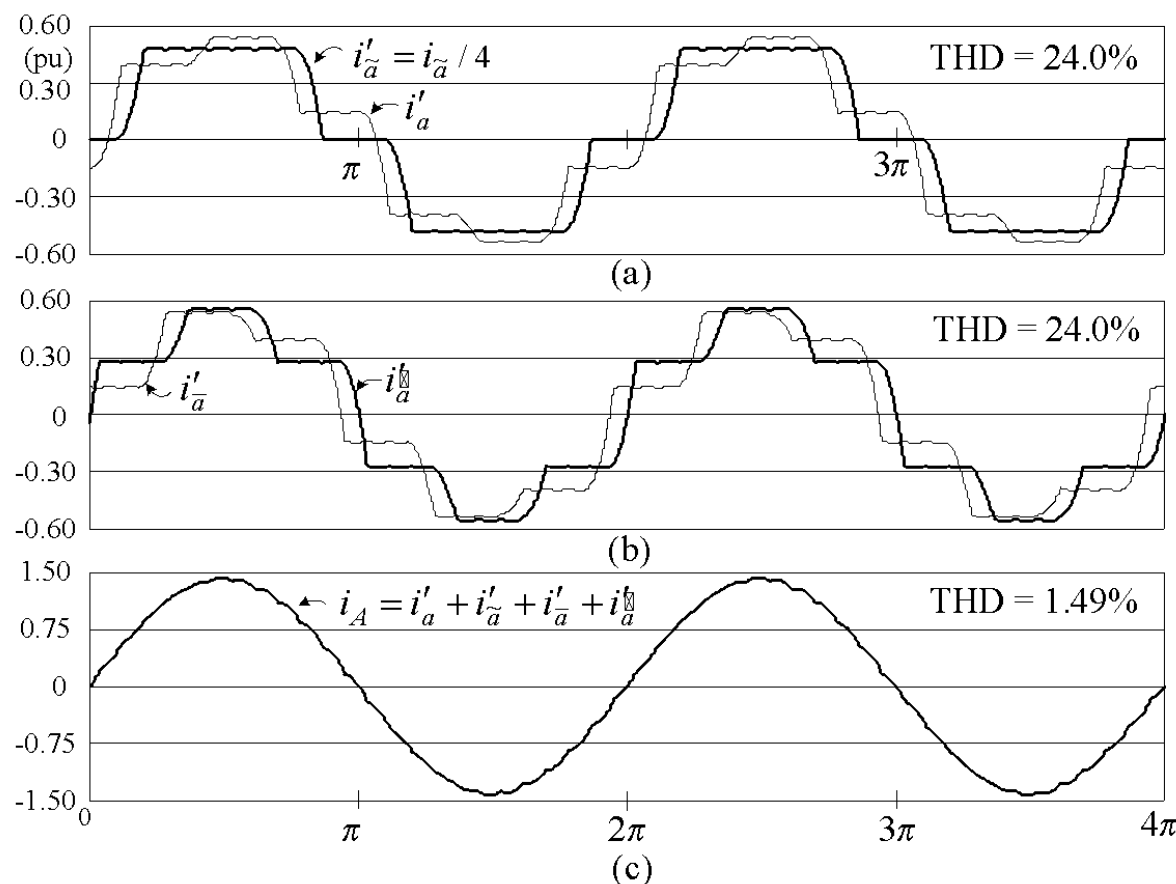
- Converter Topology



Phase-Shifting (Zigzag) Transformer

24-pulse Series-type Diode Rectifier

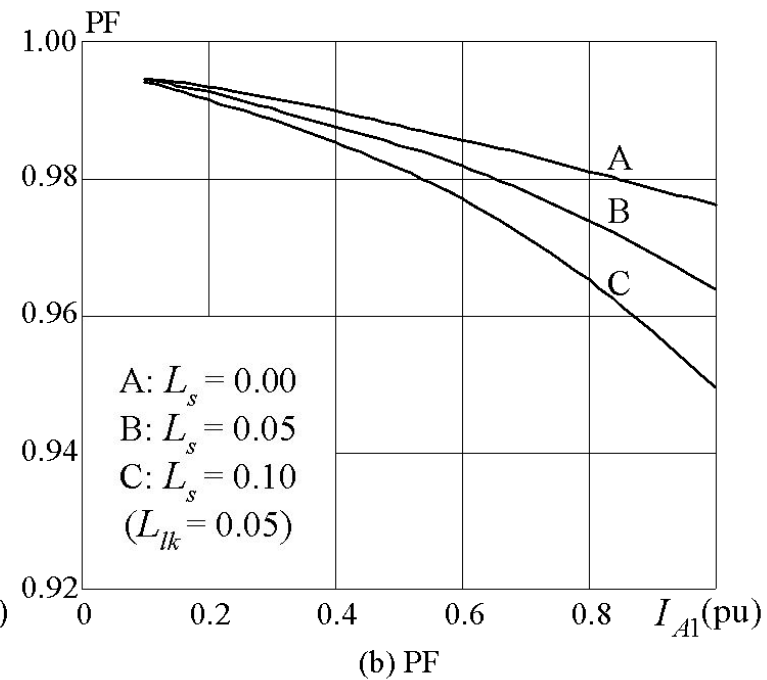
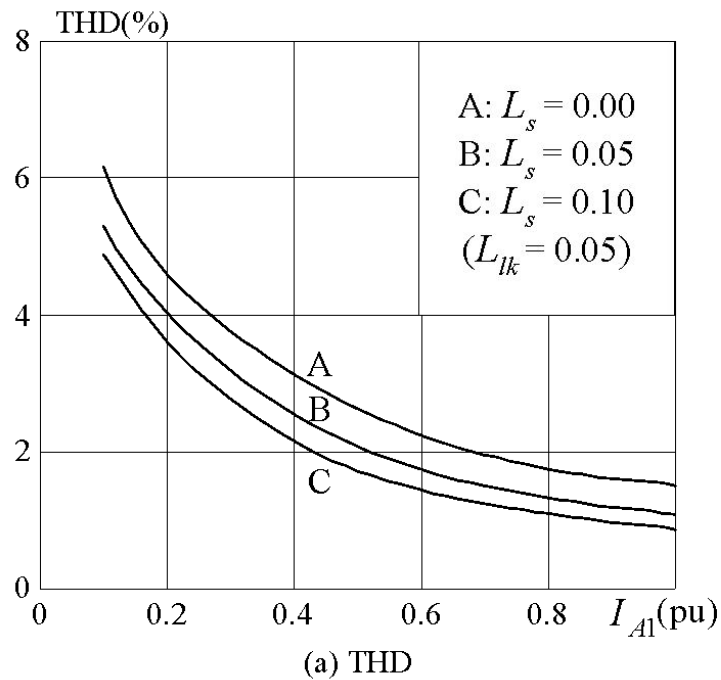
• Typical Waveforms



- Lowest line current harmonic: 23th
- THD: 1.49%

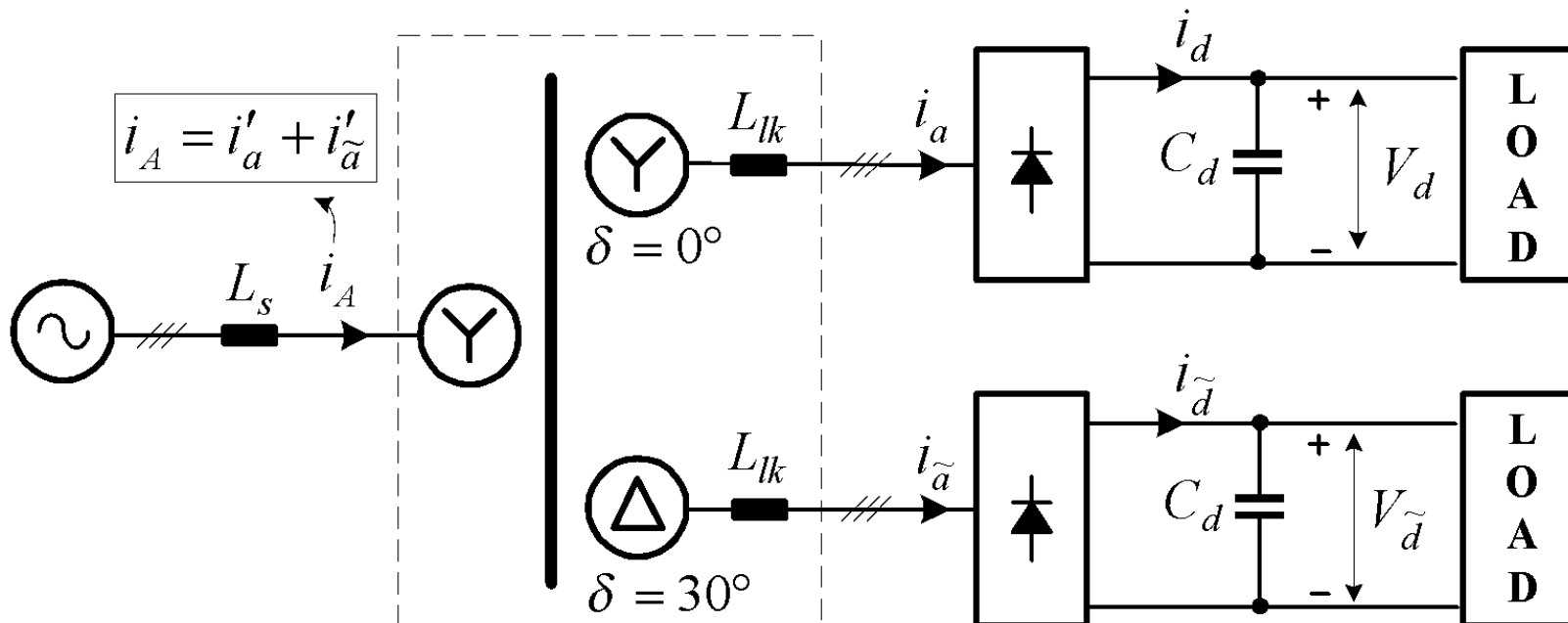
24-pulse Series-type Diode Rectifier

- THD and PF



12-pulse Separate-type Diode Rectifier

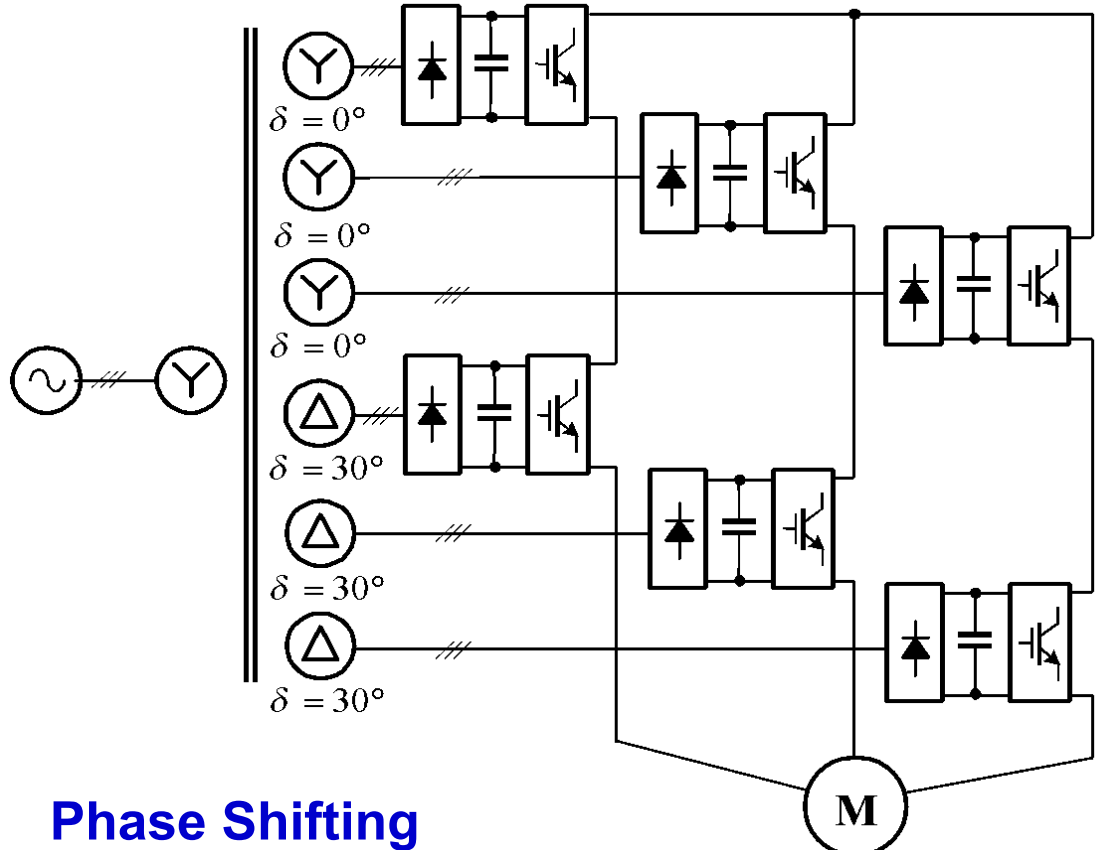
- Rectifier Topology



- Separate Type
Each six-pulse rectifier feeds a separate dc load.

12-pulse Separate-type Diode Rectifier

- Application Example

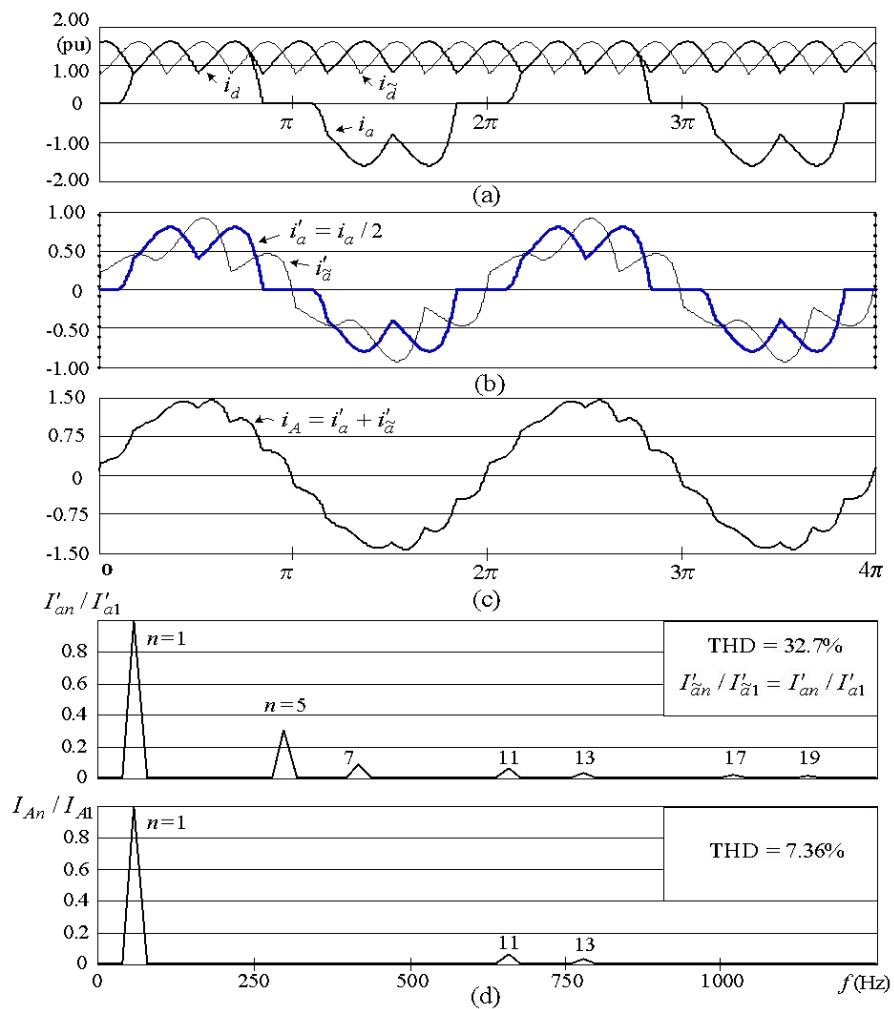


Phase Shifting Transformer

Multilevel Cascade H-bridge Inverter Fed Drive

12-pulse Separate-type Diode Rectifier

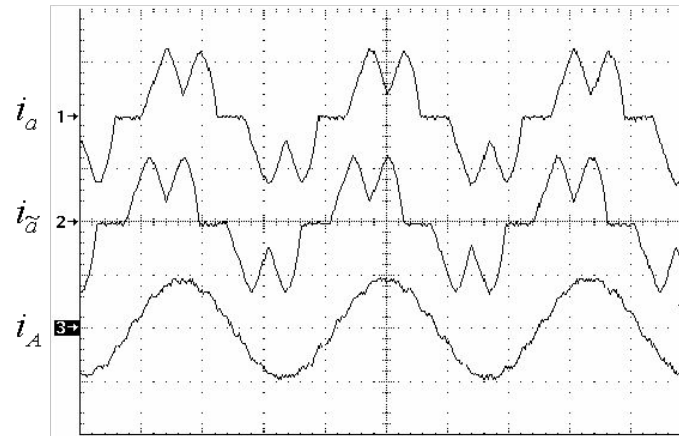
• Typical Waveforms



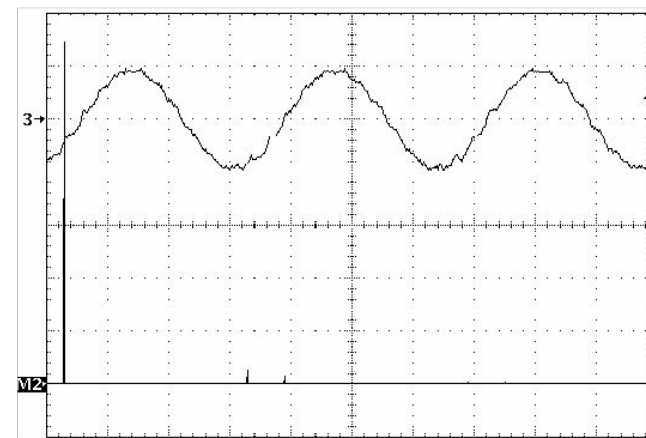
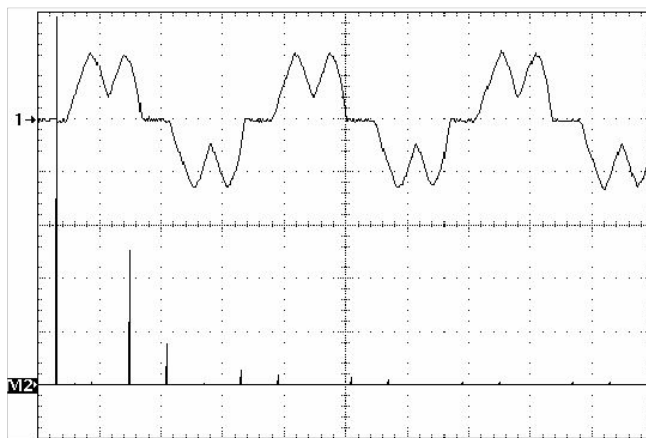
- Comparison with series-type:
 - DC current ripple: higher
 - Line current THD: close

12-pulse Separate-type Diode Rectifier

- Measured Waveforms



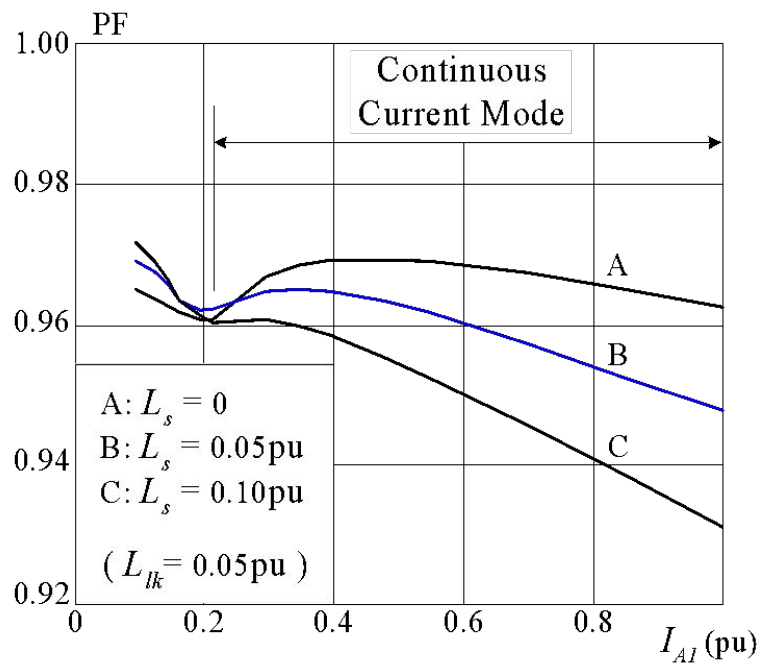
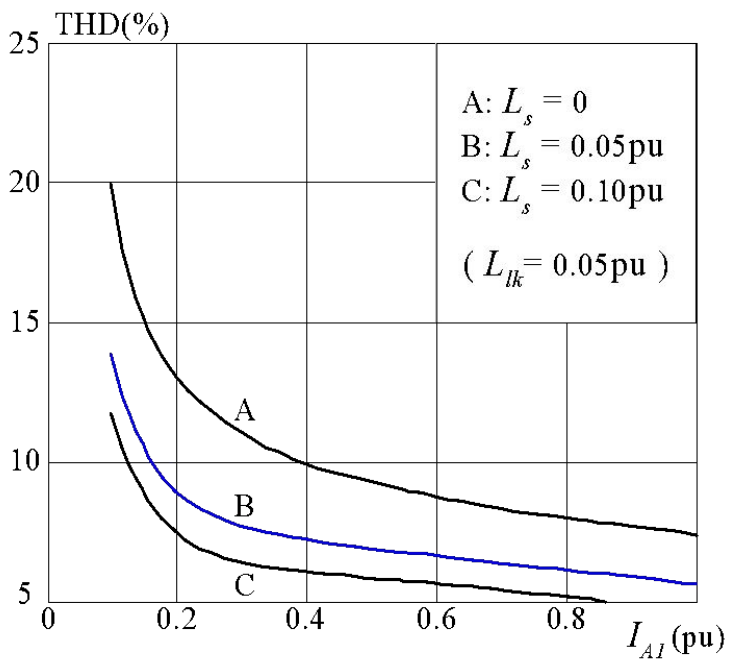
(a) Currents: $\sqrt{2}$ pu/div, 5ms/div



(b) Spectrum: $\sqrt{2}/10$ pu/div, 200Hz/div

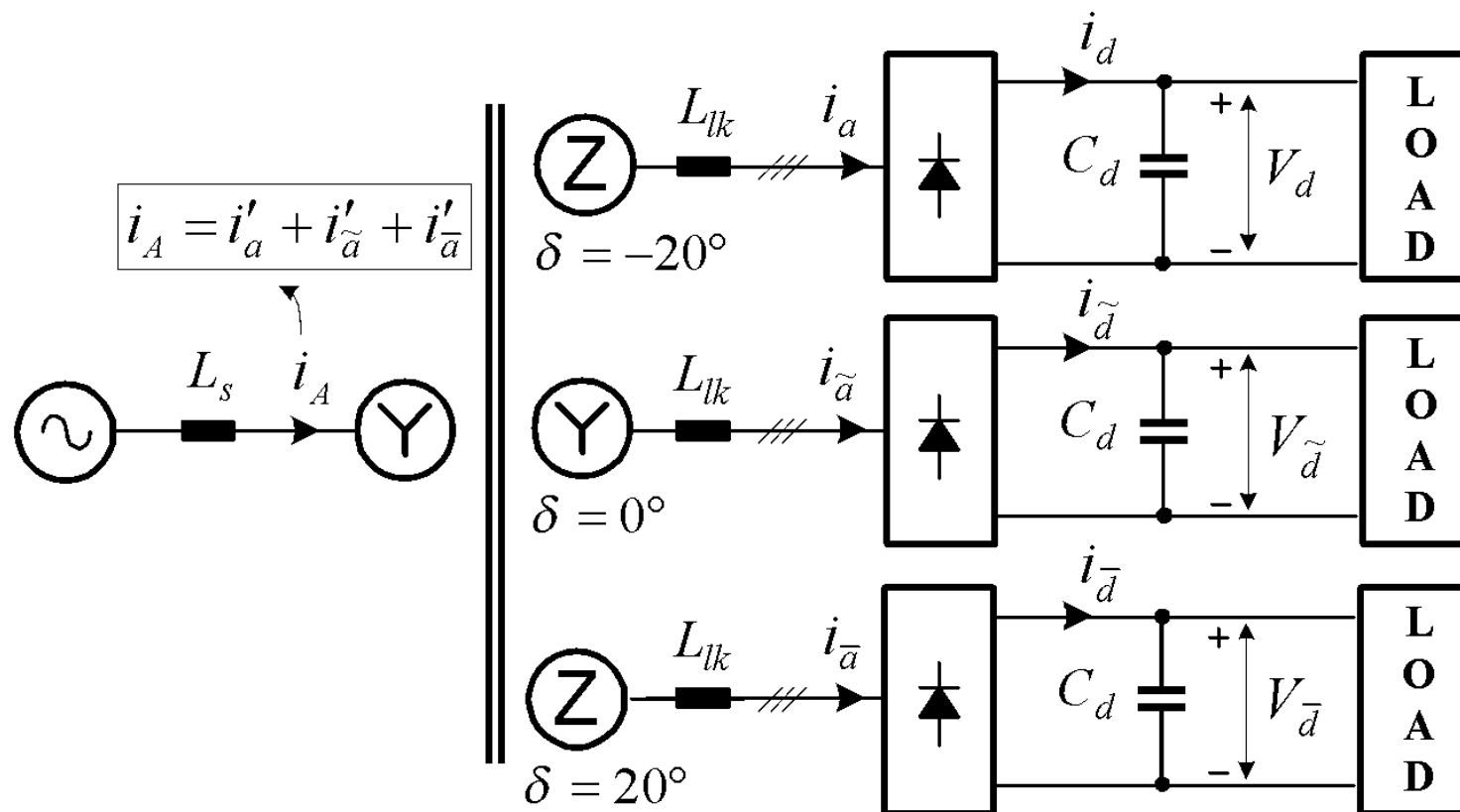
12-pulse Separate-type Diode Rectifier

- Line Current THD and Input PF



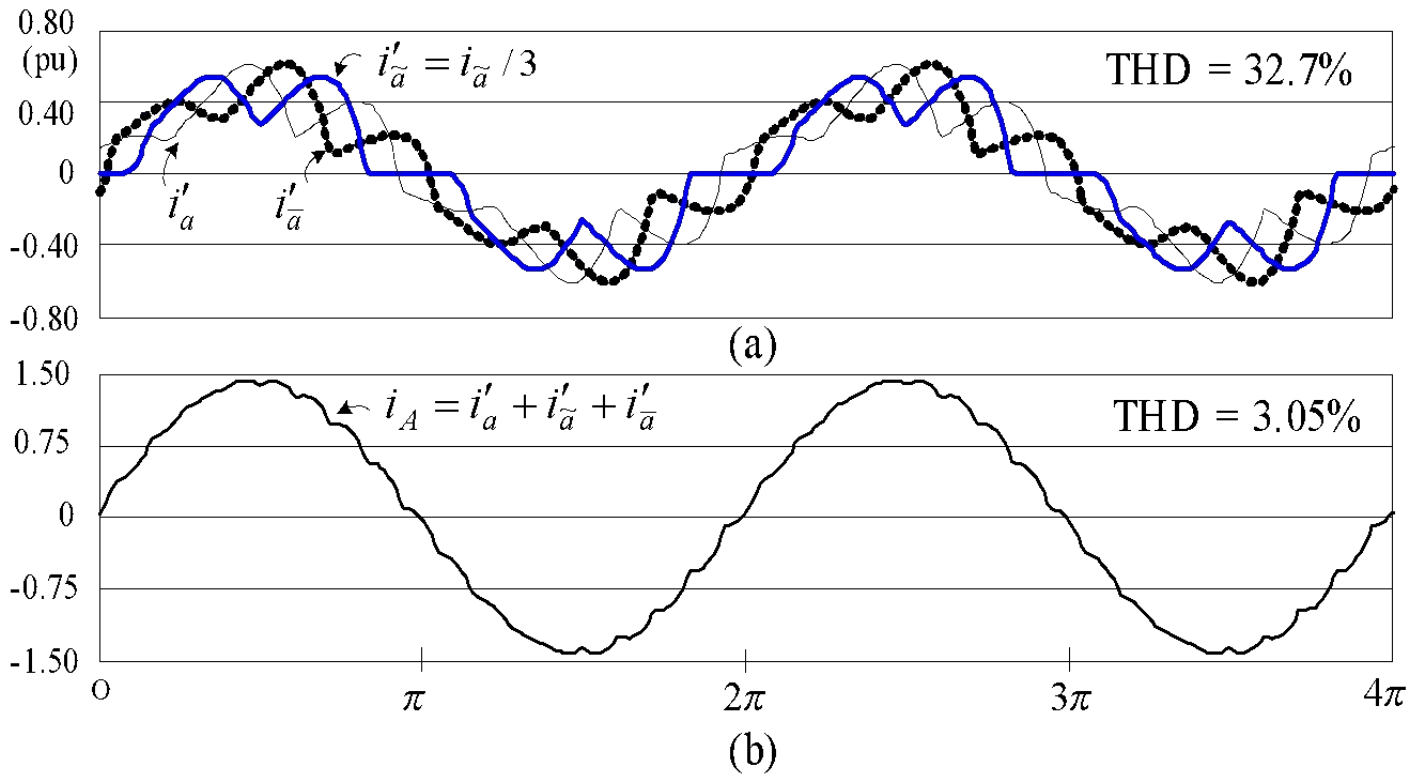
18-pulse Separate-type Diode Rectifier

• Rectifier Topology



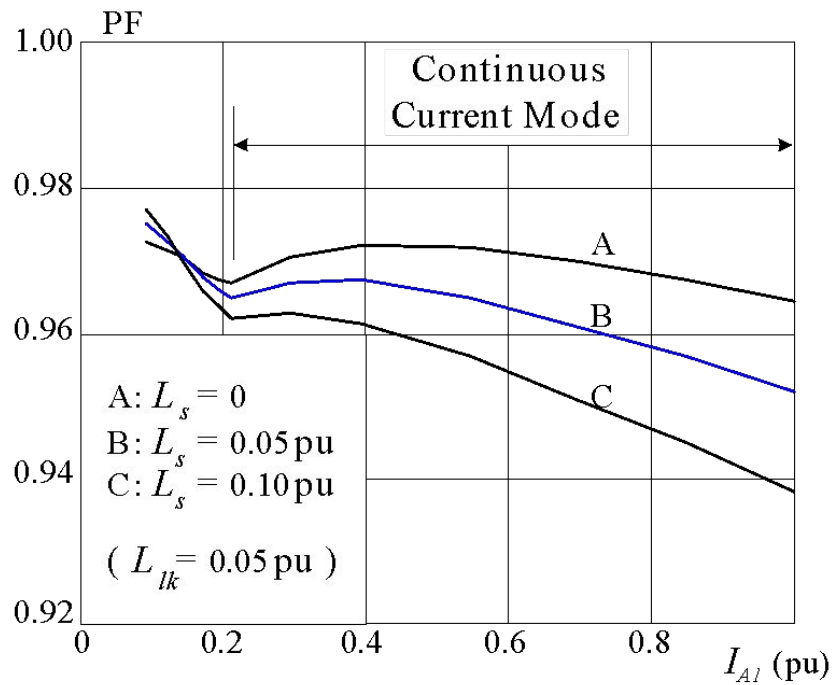
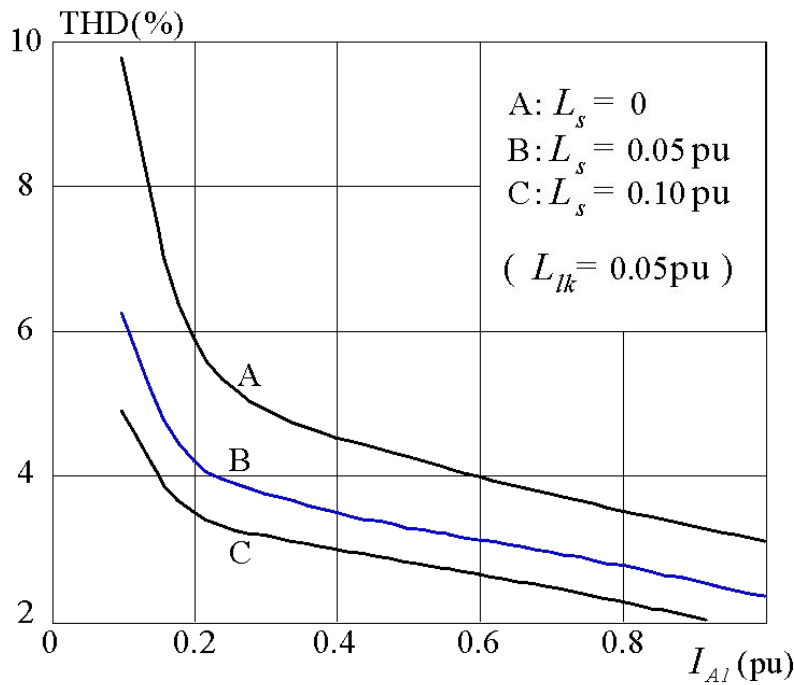
18-pulse Separate-type Diode Rectifier

• Simulated Waveforms



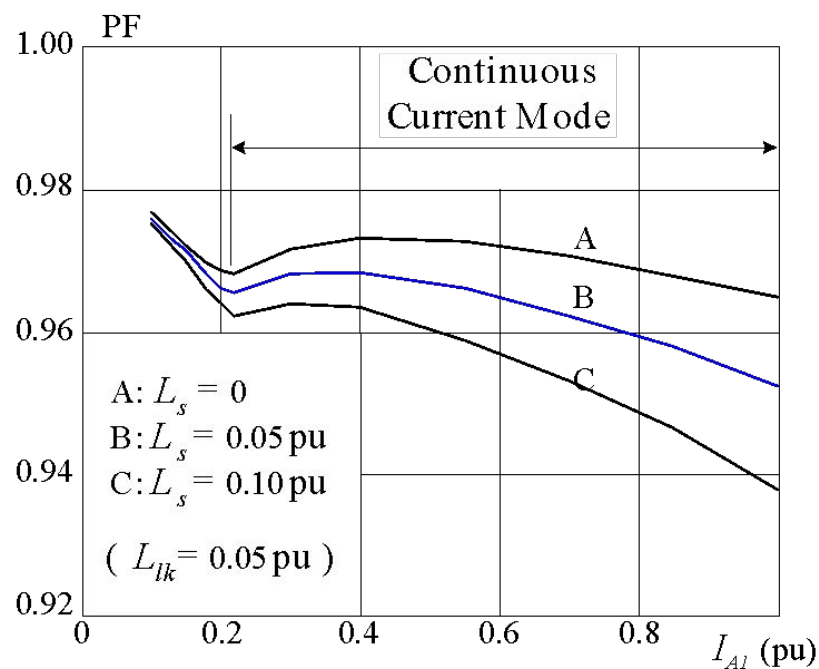
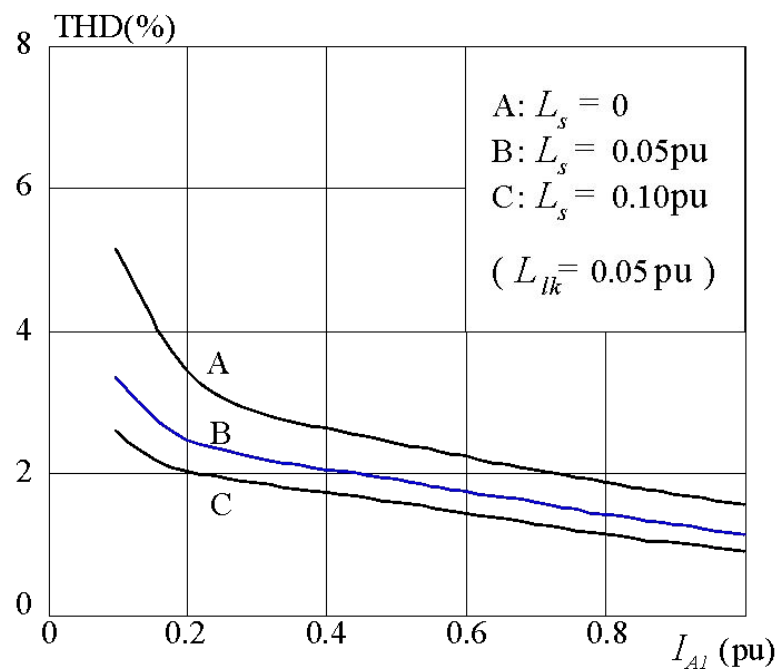
18-pulse Separate-type Diode Rectifier

• Line Current THD and Input PF



24-pulse Separate-type Diode Rectifier

• Line Current THD and Input PF





Thanks