Power Converter Systems

Graduate Course EE8407

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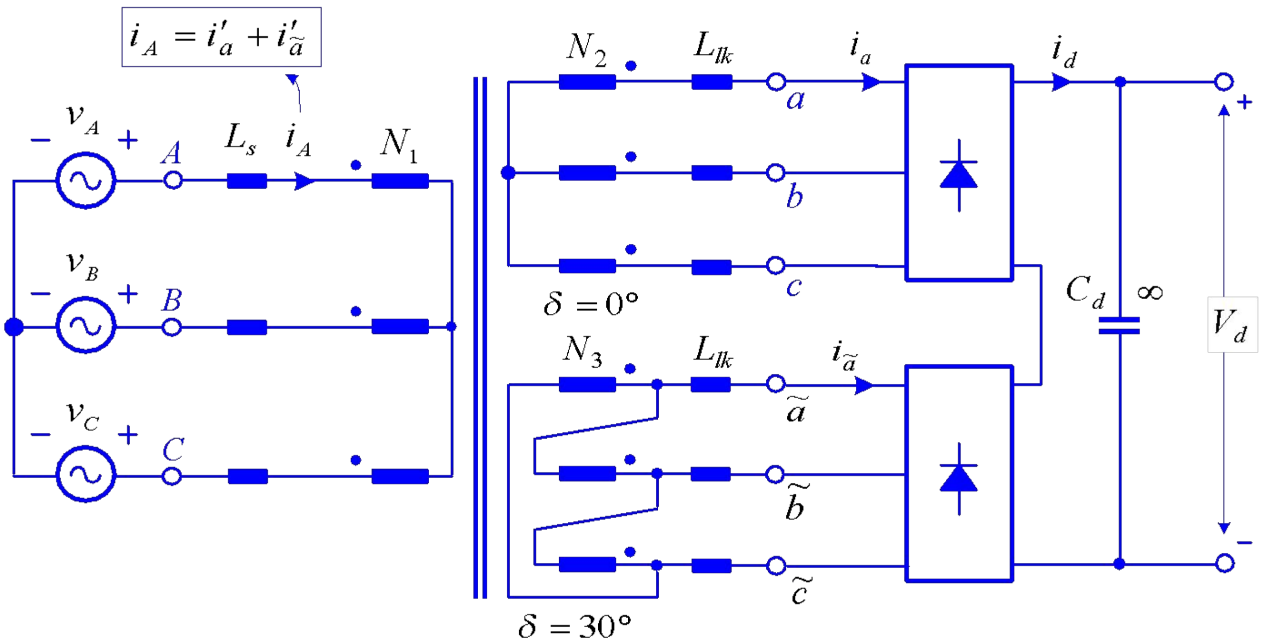
Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley - IEEE Press, 2006

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

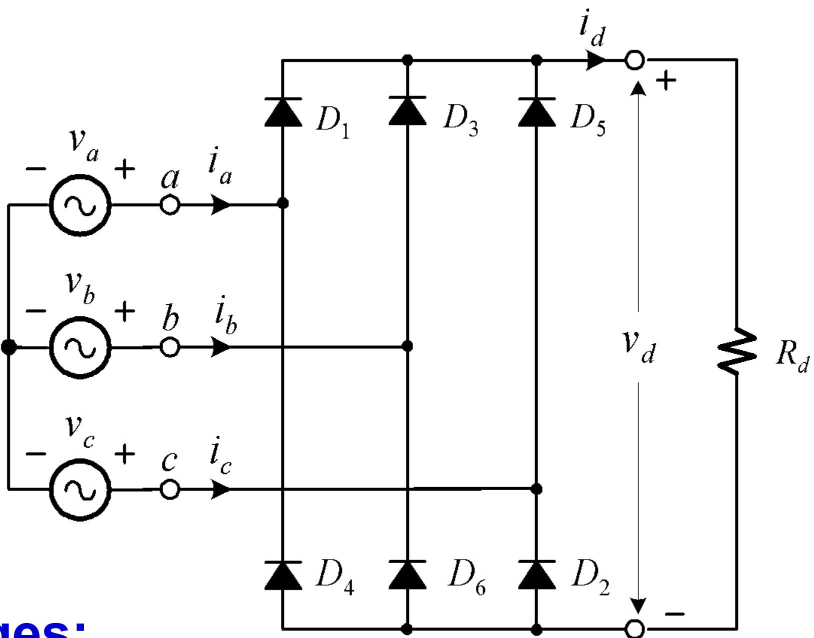
Multi-pulse Diode Rectifiers

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:

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

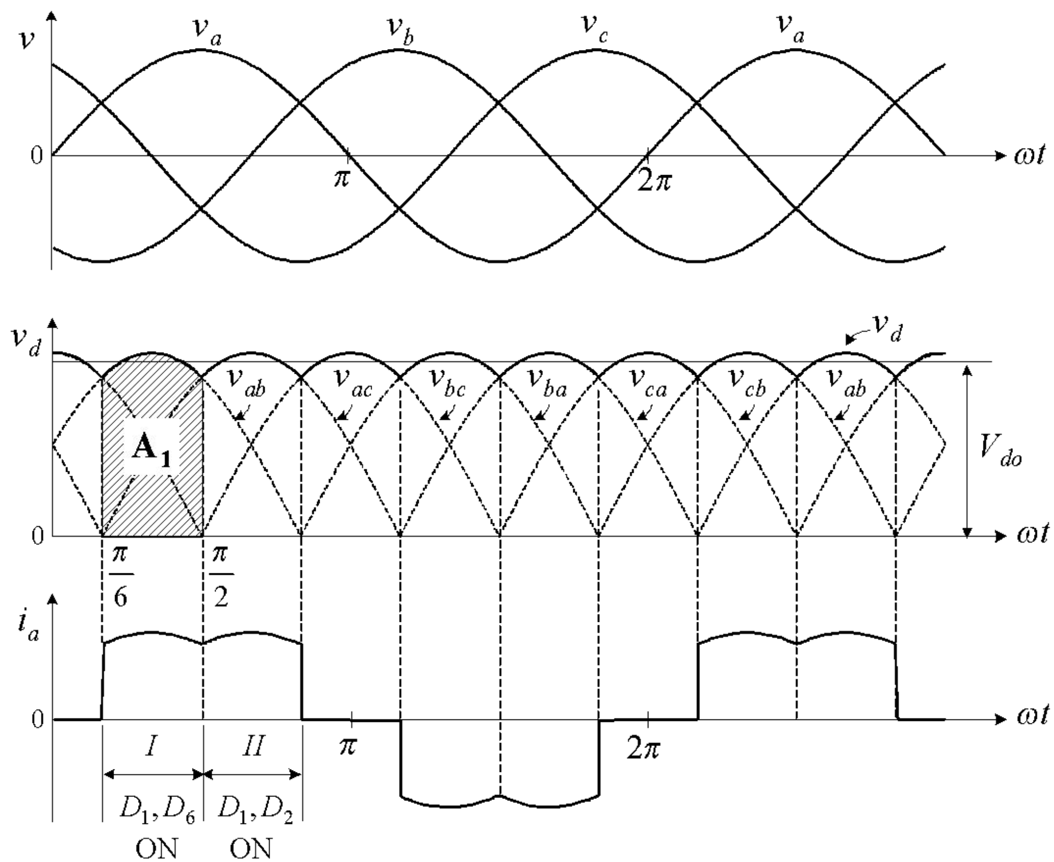
$$v_b = \sqrt{2}\,V_{PH}\sin(\omega t - 2\pi/3)$$

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

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

Six-pulse Diode Rectifier

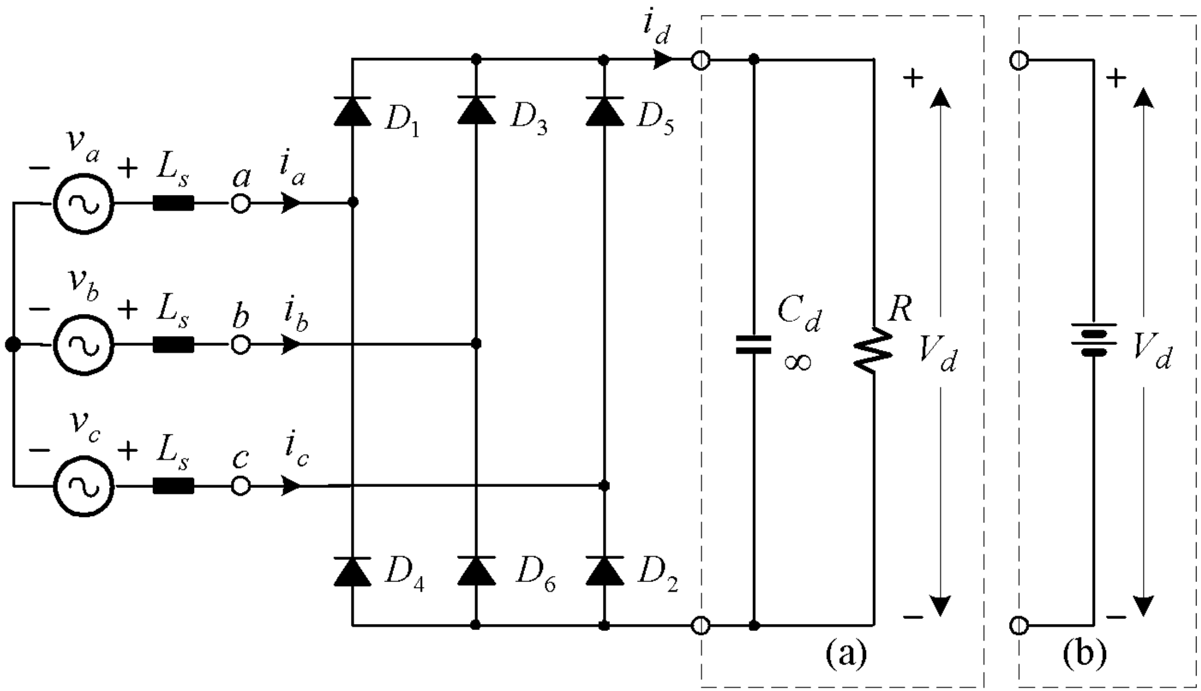
- **Waveforms**



$$V_{do} = \frac{\text{area } \mathbf{A_1}}{\pi/3} = \frac{1}{\pi/3}\int_{\pi/6}^{\pi/2}\sqrt{2}V_{LL}\sin(\omega t + \pi/6)\,d(\omega t) = \frac{3\sqrt{2}}{\pi}V_{LL} \approx 1.35V_{LL}$$

Six-pulse Diode Rectifier

- **Capacitive Load**

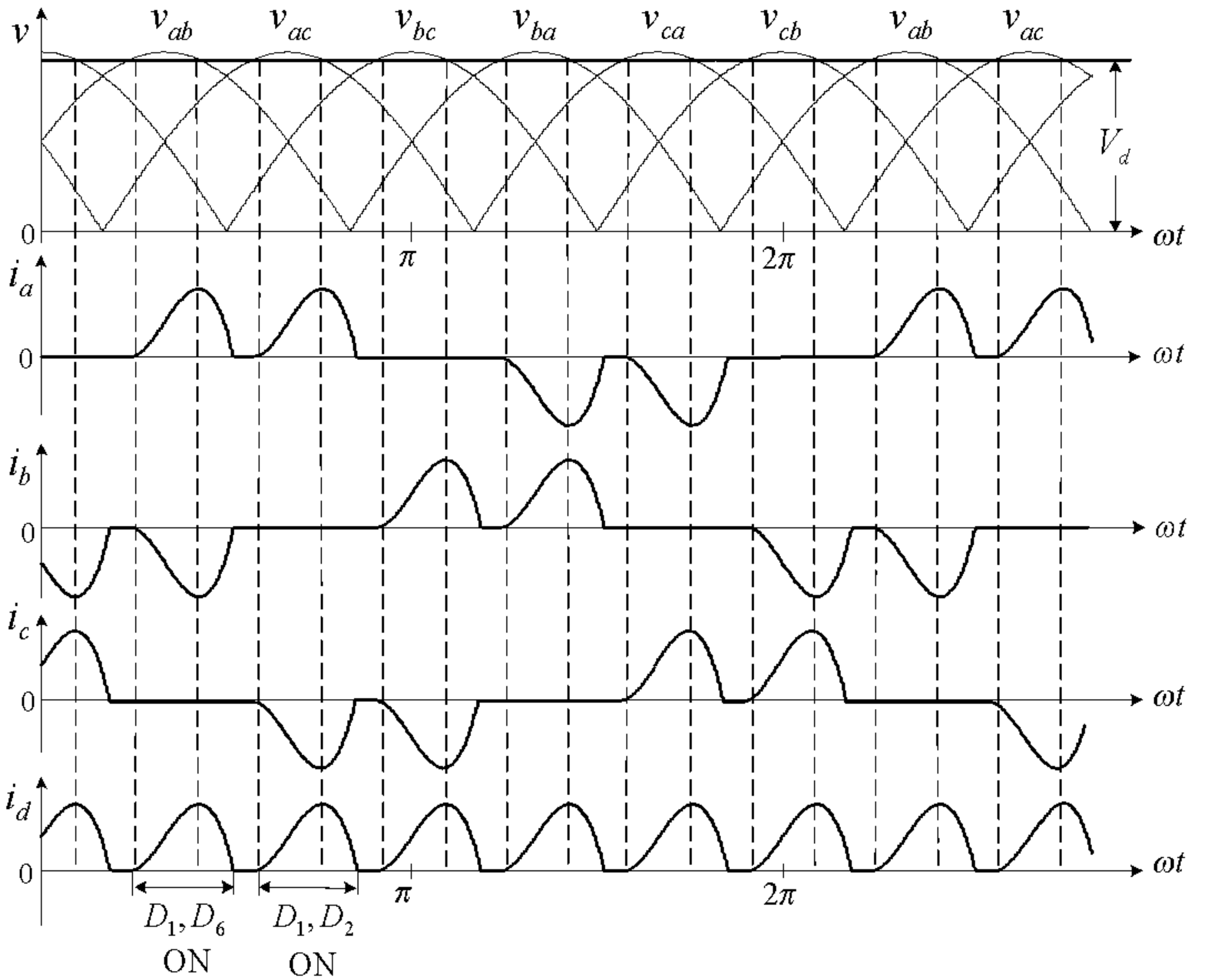


Assumption:

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

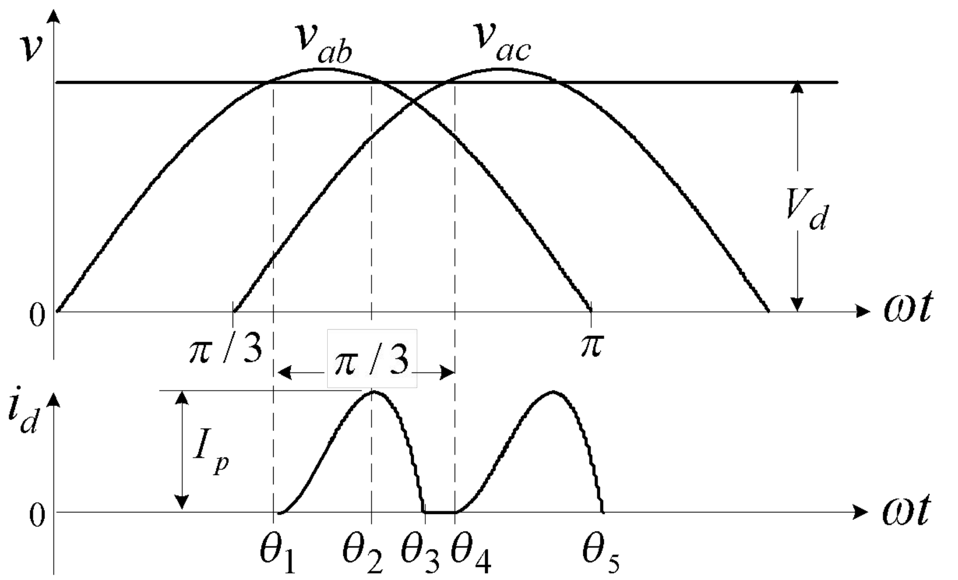
Six-pulse Diode Rectifier

- **Waveforms**



Six-pulse Diode Rectifier

- **Discontinuous Current Operation**

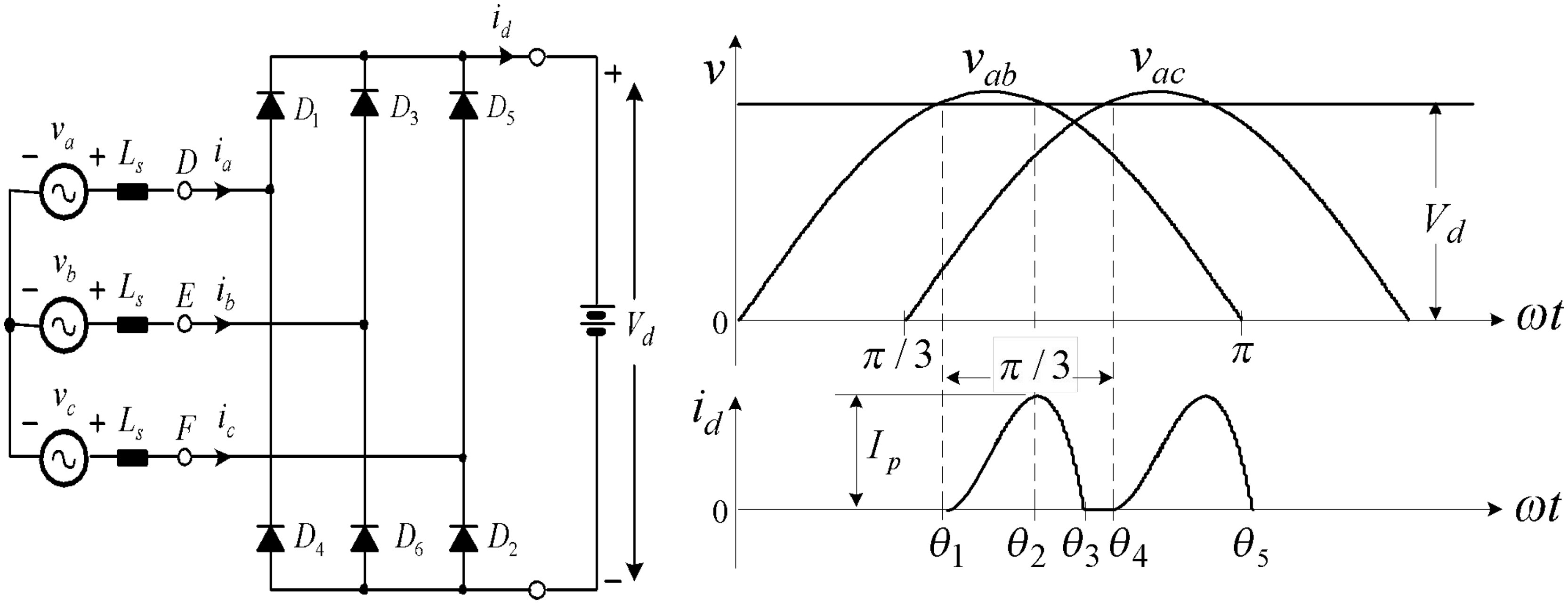


$$\theta_1 = \sin^{-1}\left(\frac{V_d}{\sqrt{2}\,V_{LL}}\right)$$

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

Six-pulse Diode Rectifier

- **Discontinuous Current Operation**



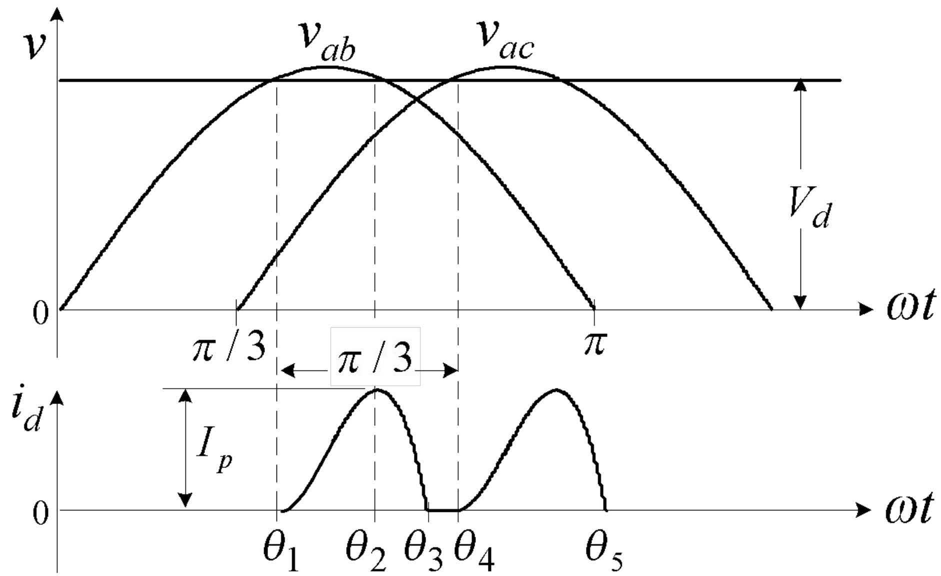
Differential Equation: $$2L_s \frac{d\,i_d}{dt} = v_{ab} - V_d \qquad \theta_1 \le \omega t < \theta_3$$

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

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

Six-pulse Diode Rectifier

• **Discontinuous Current Operation**



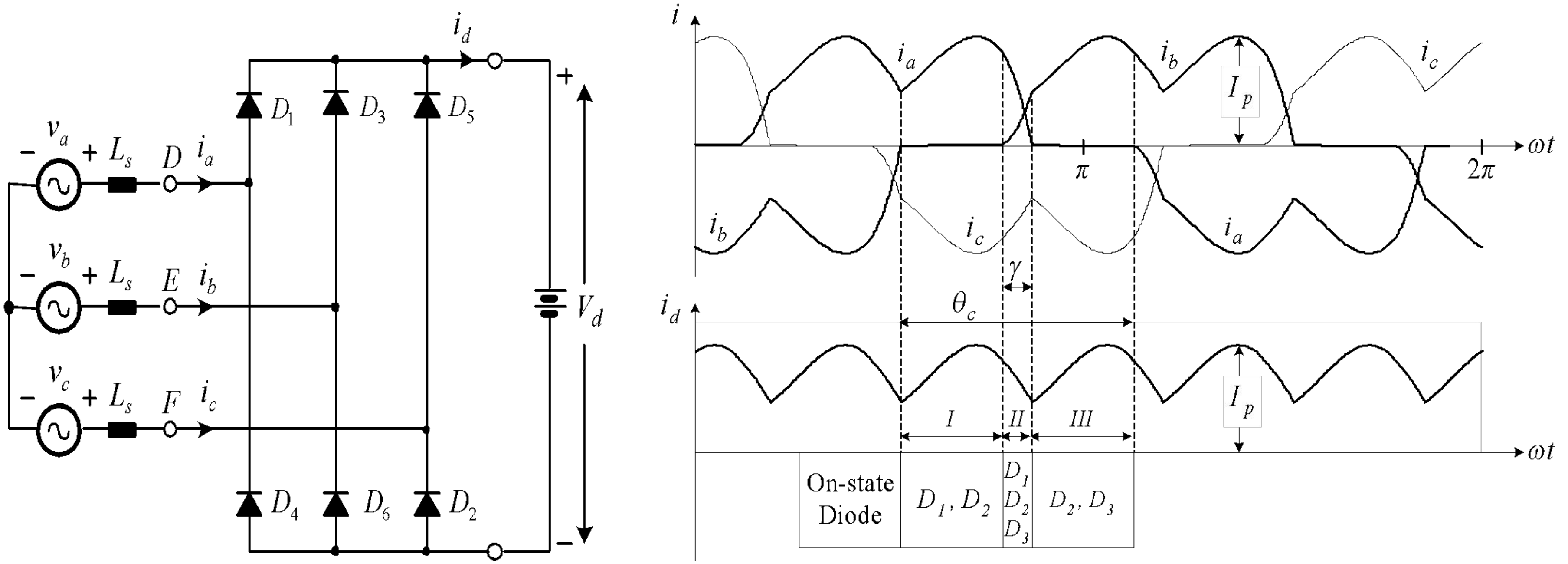
Peak dc current: $$I_p = \frac{1}{2\omega L_s}\left(\sqrt{2}V_{LL}\left(\cos\theta_1 - \cos\theta_2\right) + V_d\left(\theta_1 - \theta_2\right)\right)$$

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): $$i_a = \sum_{n=1,2,3,\ldots}^{\infty} \sqrt{2} I_{an} \left(\sin (\omega_n t) - \phi_n \right)$$

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

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 lint-to-line voltage: S_R, V_R

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

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

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

Example

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

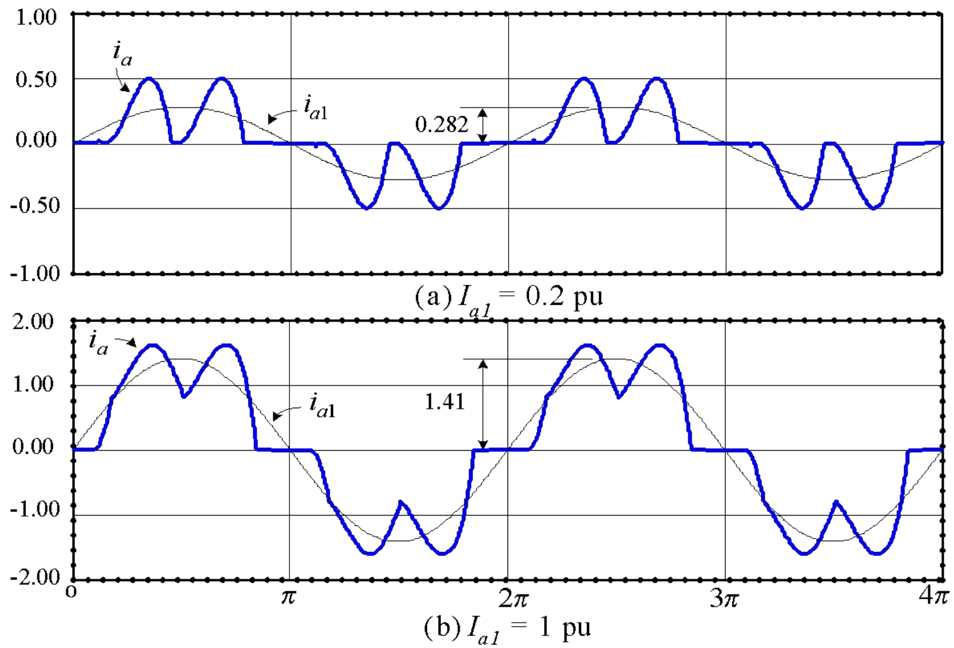
Base current = 277.6A, Base inductance = 22.9mH.

Line inductance = 2.29mH = 0.1pu

Line current = 138.8A = 0.5pu

Six-pulse Diode Rectifier

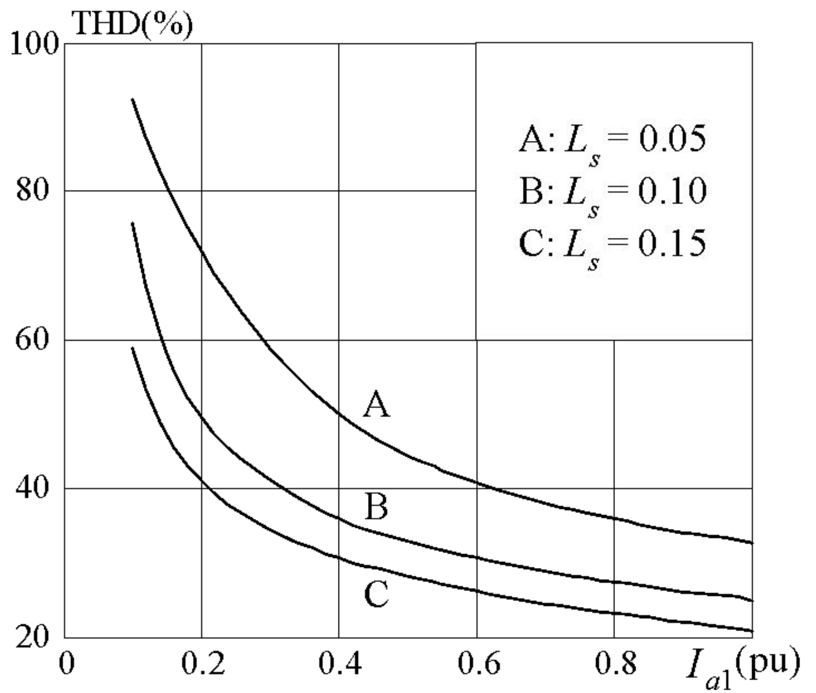
• Typical Waveforms / Harmonic Content



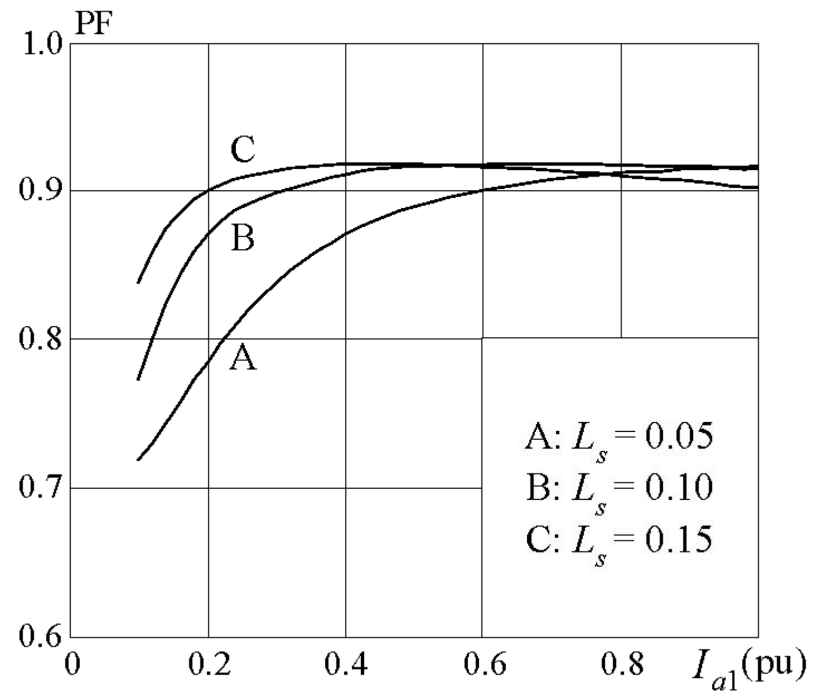
Harmonics n	5	7	11	13	17	19	23	25	THD (%)
I_{an} / I_{a1} (%) $I_{a1} = 0.2\text{pu}$	63.4	38.7	8.99	8.64	4.22	3.61	2.48	2.02	75.7
I_{an} / I_{a1} (%) $I_{a1} = 1\text{pu}$	30.4	8.79	6.31	3.40	2.30	1.89	1.04	1.03	32.7

Six-pulse Diode Rectifier

- **THD and PF**



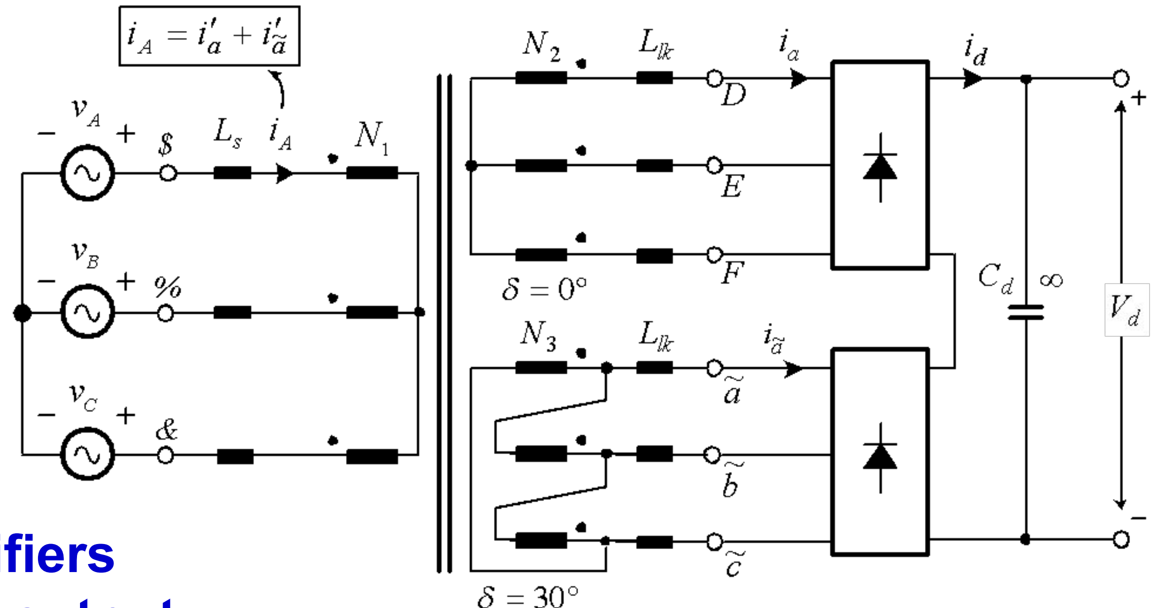
(a) THD



(b) PF

12-pulse Series-type Diode Rectifier

- **Rectifier Topology**



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

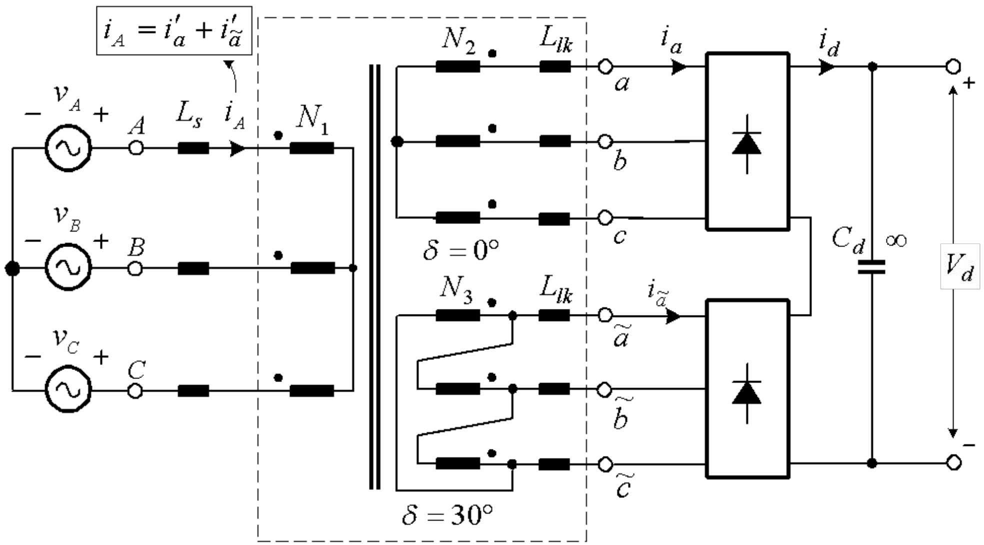
- **Phase shifting transformer:** $\delta = \angle V_{\tilde{a}\tilde{b}} - \angle V_{AB} = 30°$

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

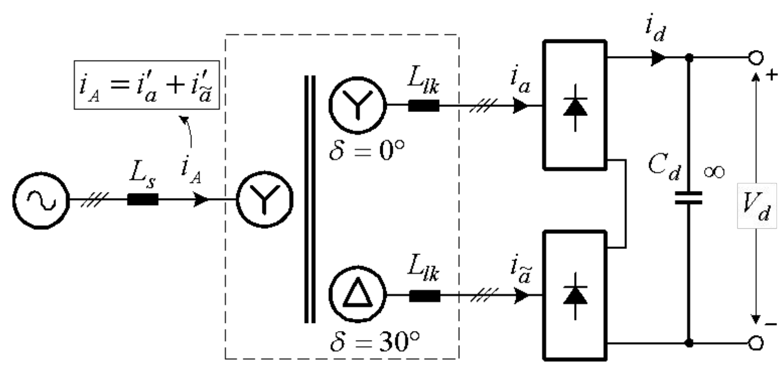
- **Turns ratio:** $\dfrac{N_1}{N_2} = 2$ and $\dfrac{N_1}{N_3} = \dfrac{2}{\sqrt{3}}.$

12-pulse Series-type Diode Rectifier

- Simplified Block Diagram



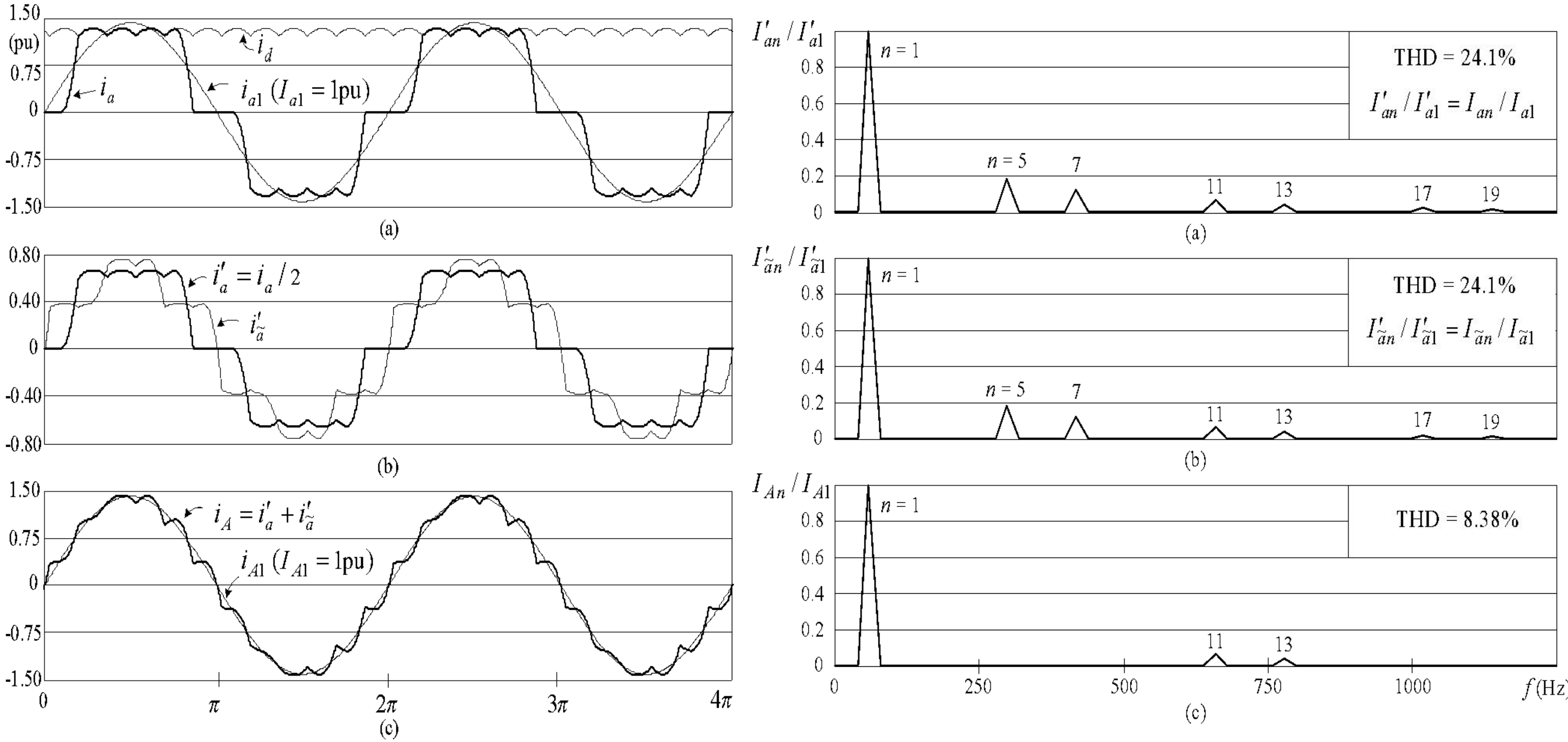
(a) 12-pulse diode rectifier



(b) Simplified diagram

12-pulse Series-type Diode Rectifier

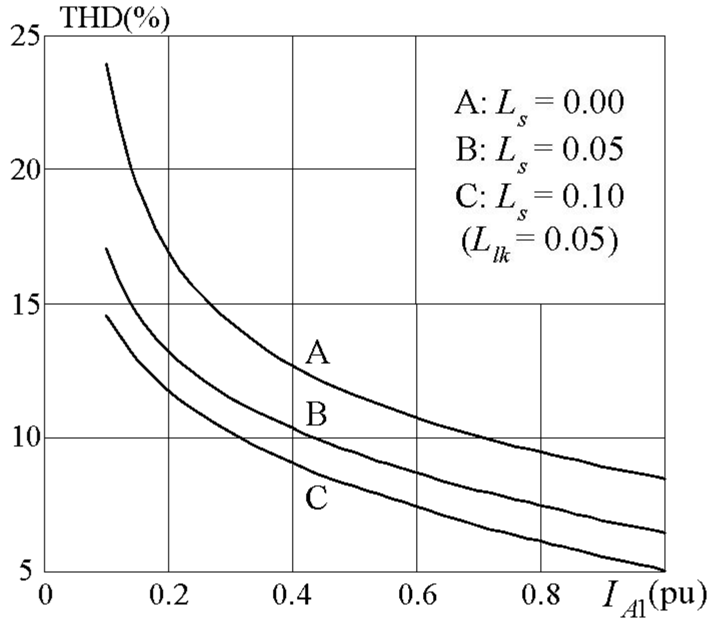
- **Waveforms and FFT**



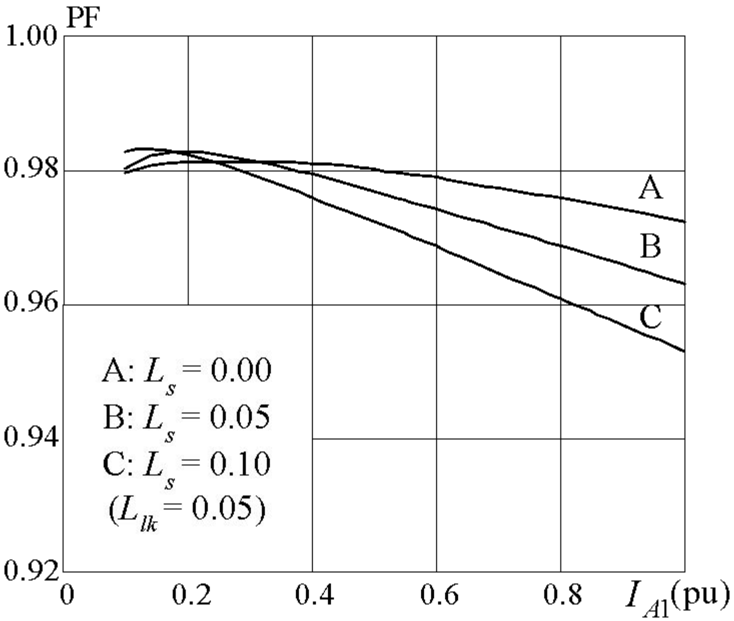
- **No 5th or 7th harmonics in the line current.**
- **Primary line current THD: 8.38%**

12-pulse Series-type Diode Rectifier

- **THD and PF**



(a) THD



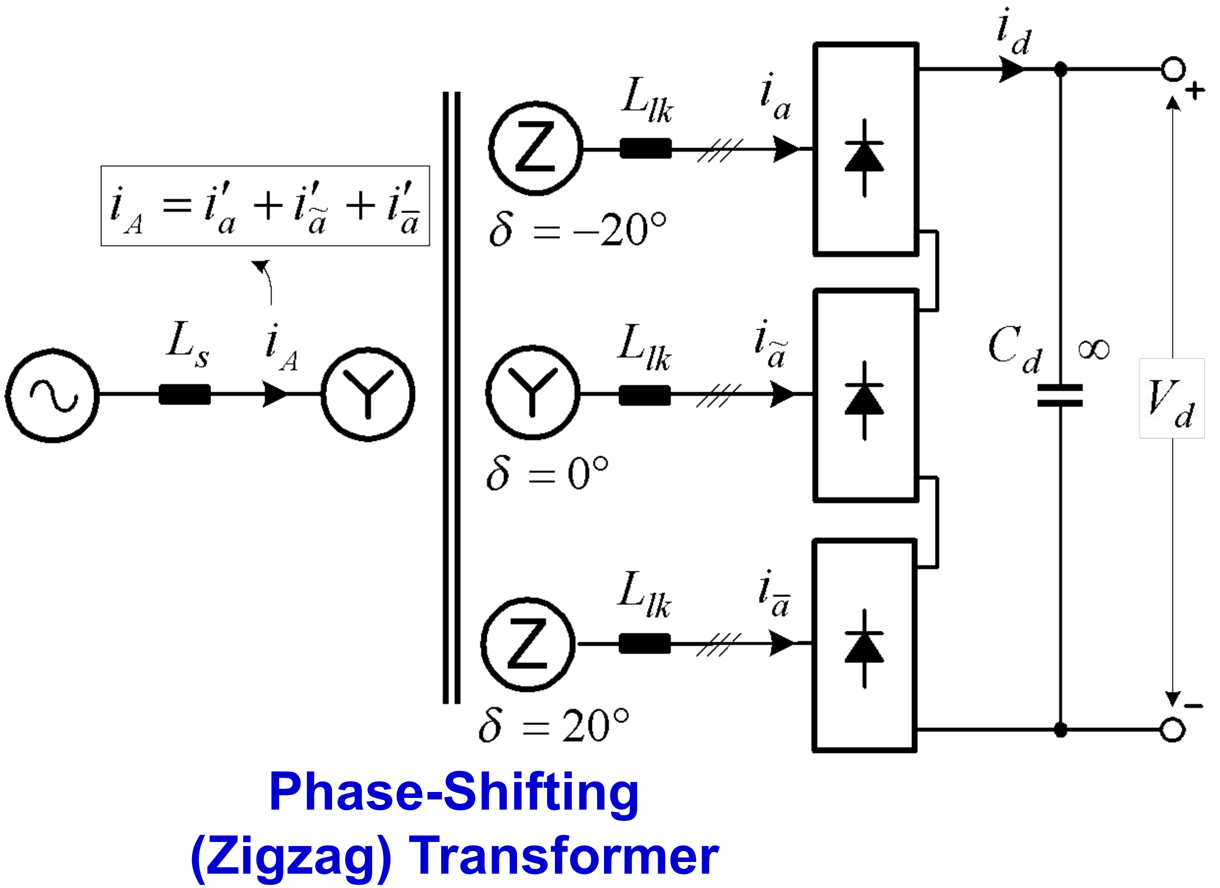
(b) PF

Comparison with six-pulse rectifier:

- **THD is reduced; and**
- **PF is improved.**

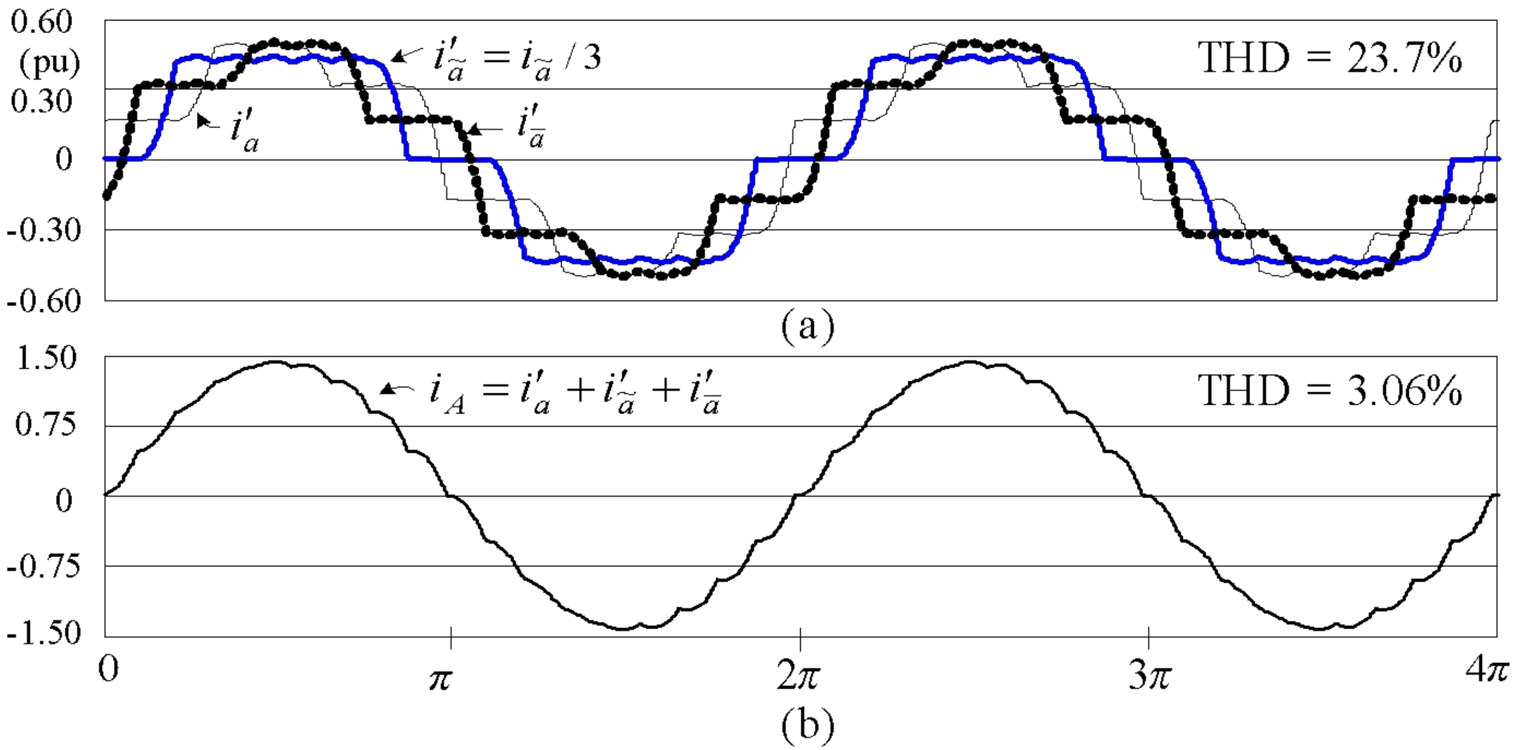
18-pulse Series-type Diode Rectifier

- **Converter Topology**



18-pulse Series-type Diode Rectifier

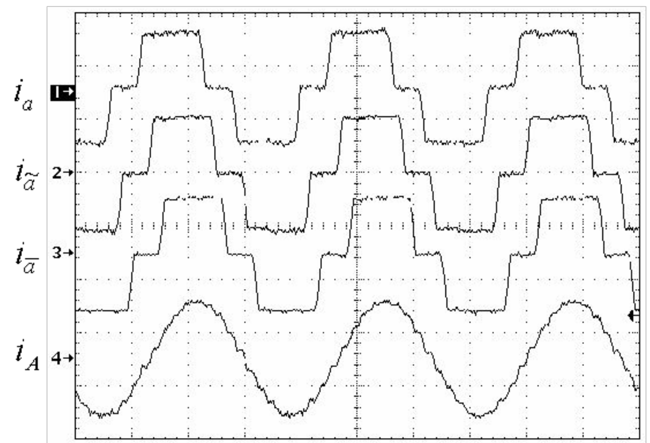
- **Simulated Waveforms**



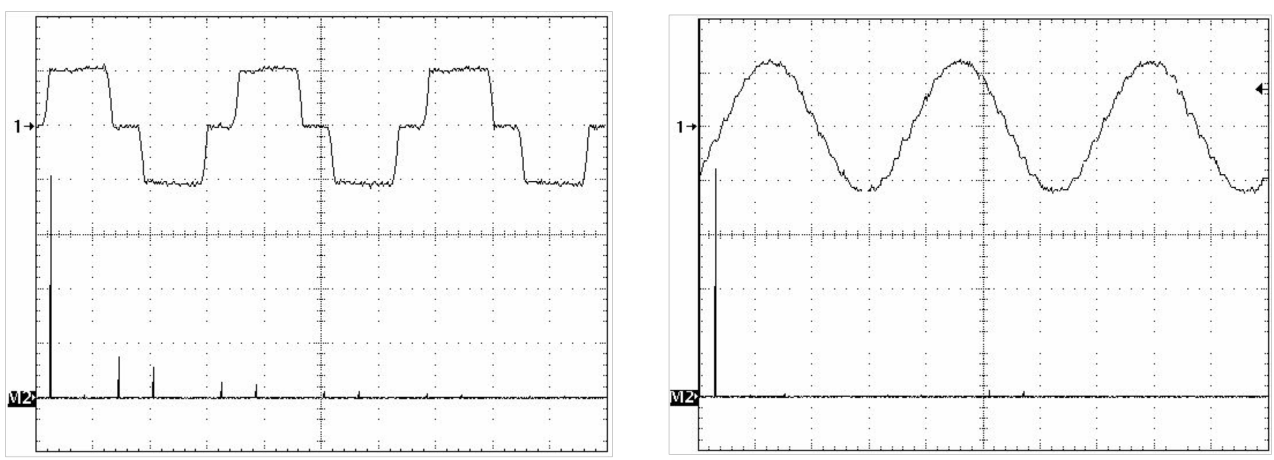
- **No 5th, 7th, 11th, or 13th harmonics in the line current.**
- **Lowest harmonic: 17th**
- **Line current THD: 3.06%**

18-pulse Series-type Diode Rectifier

- **Measured Waveforms**



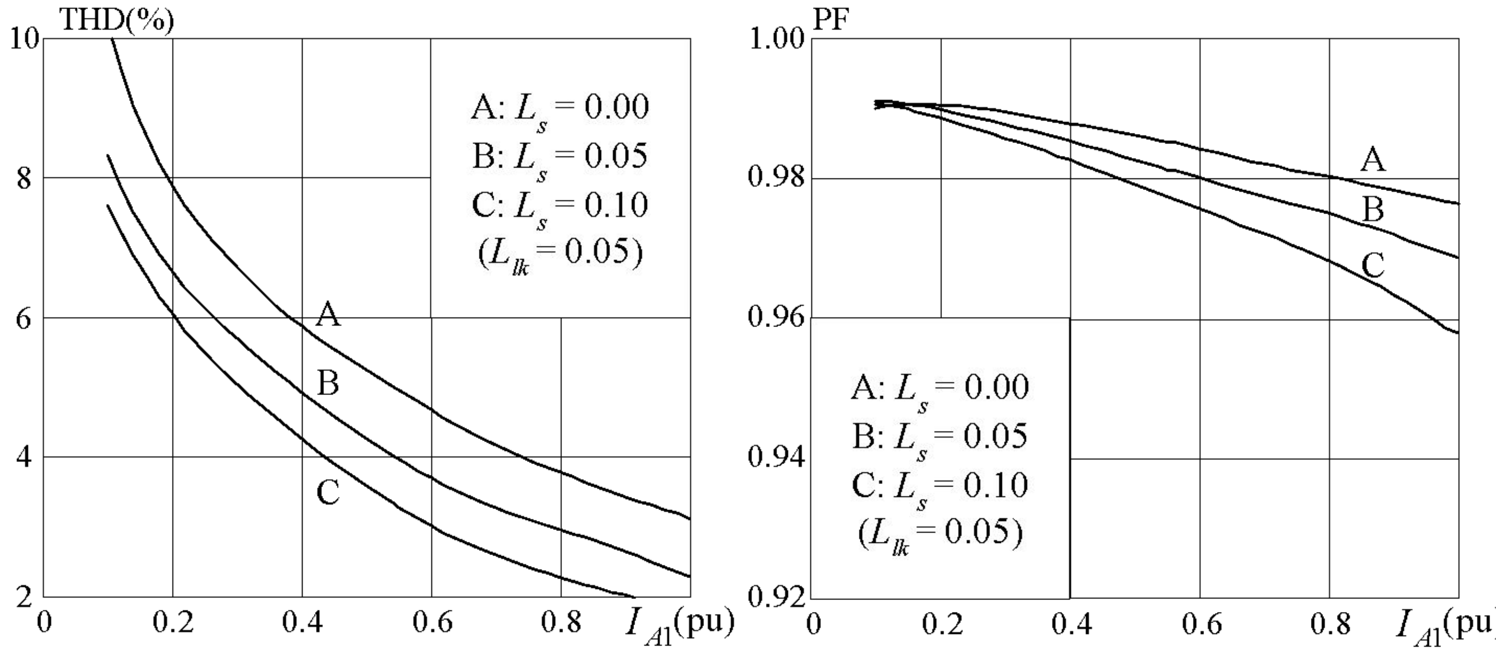
(a) Currents: $\sqrt{2}$ pu/div, 5ms/div



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

18-pulse Series-type Diode Rectifier

- **THD and PF**

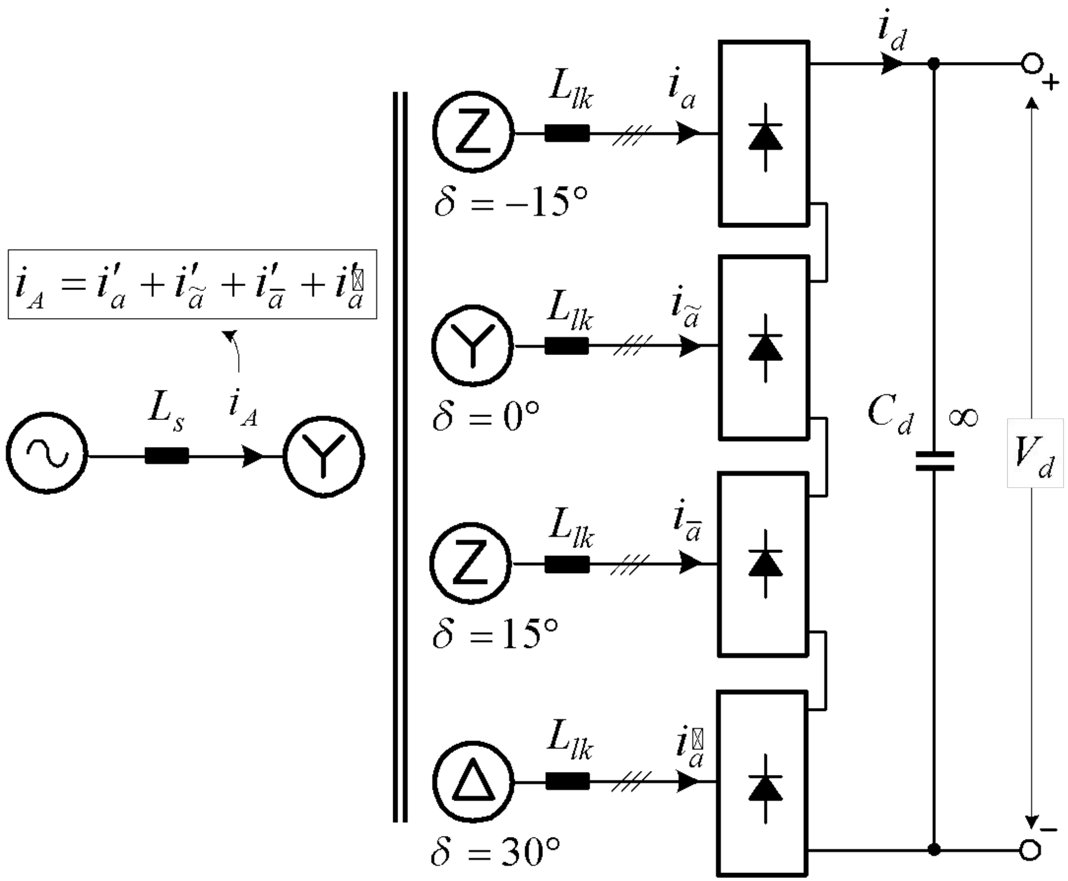


(a) THD (b) PF

Comparison with 12-pulse: Improved THD

24-pulse Series-type Diode Rectifier

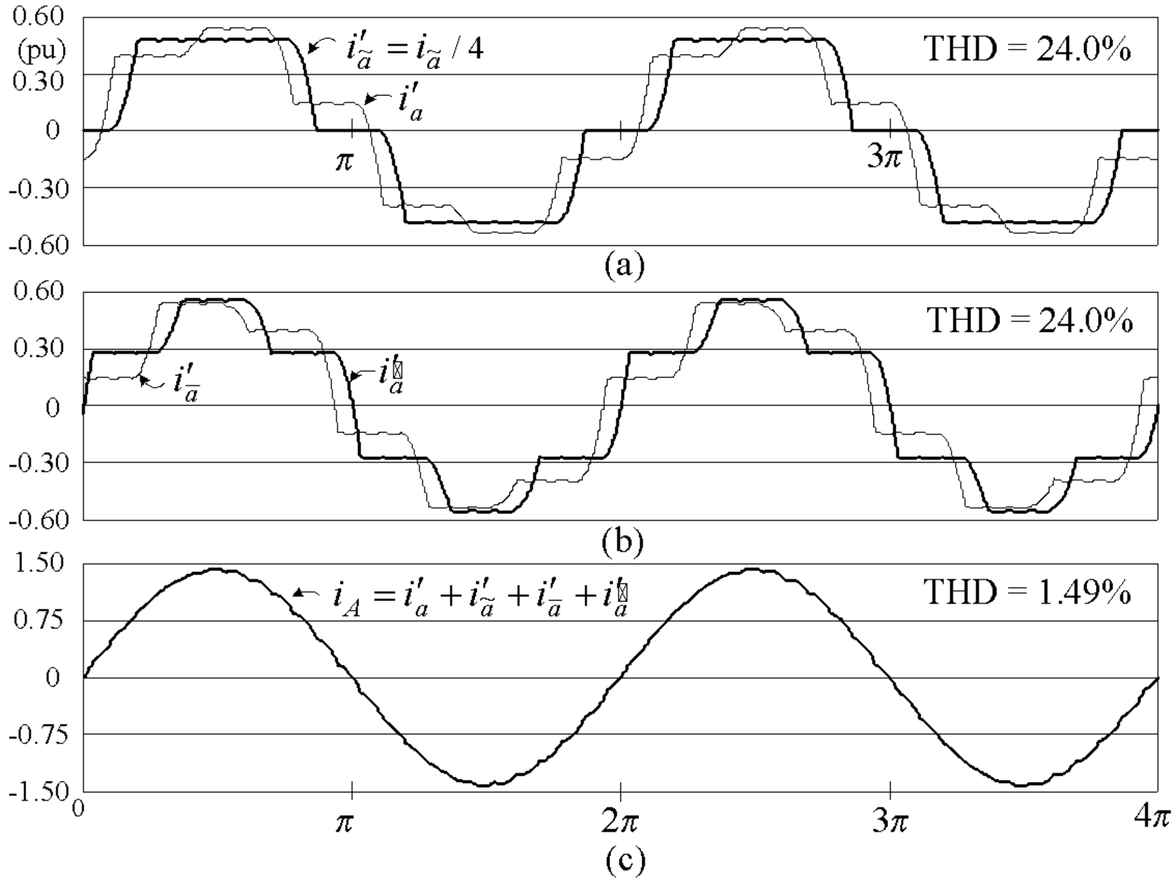
- **Converter Topology**



Phase-Shifting (Zigzag) Transformer

24-pulse Series-type Diode Rectifier

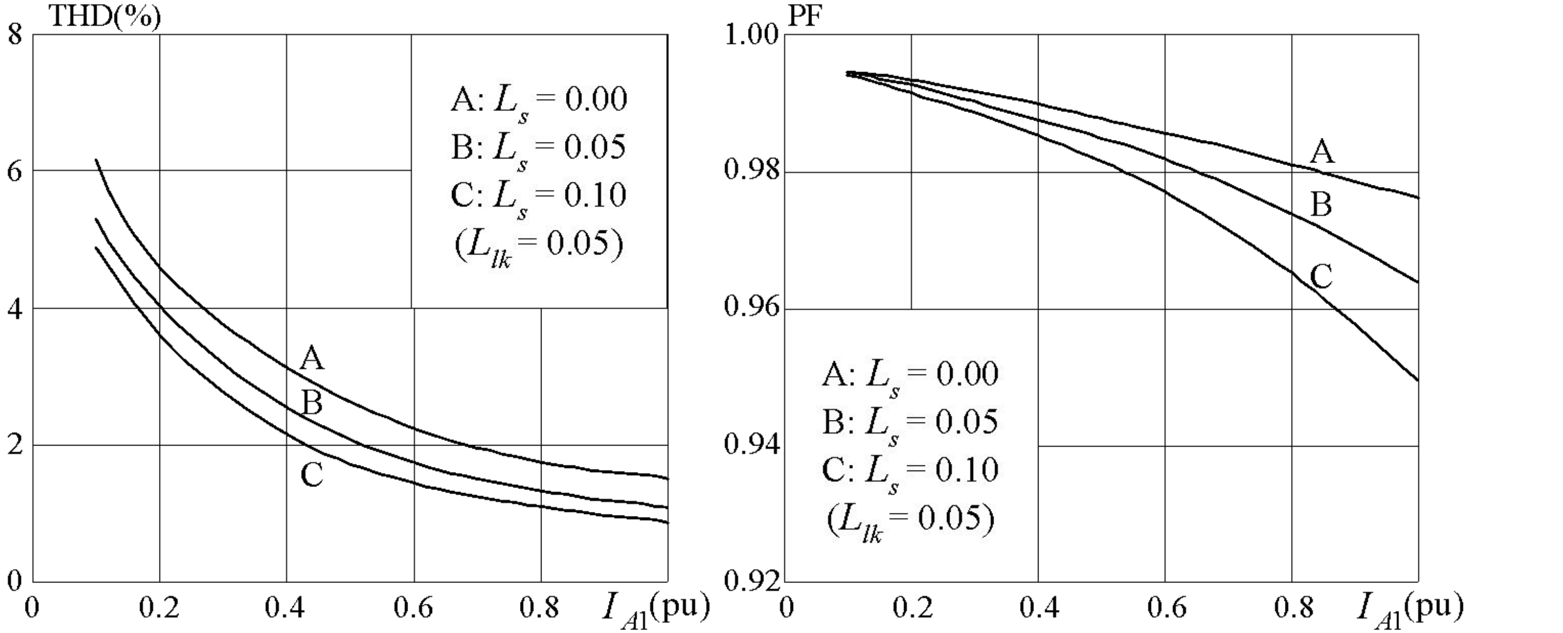
- **Typical Waveforms**



- **Lowest line current harmonic: 23^{th}**
- **THD: 1.49%**

24-pulse Series-type Diode Rectifier

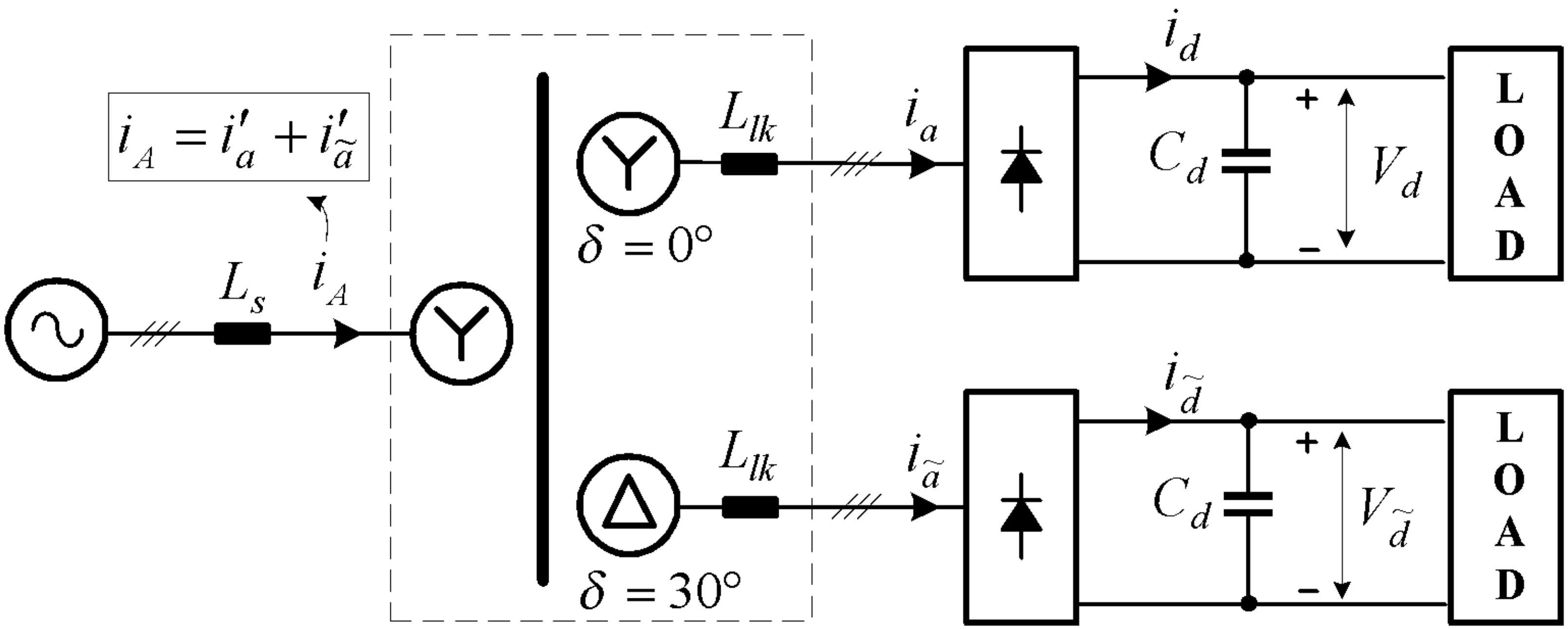
- **THD and PF**



(a) THD (b) PF

12-pulse Separate-type Diode Rectifier

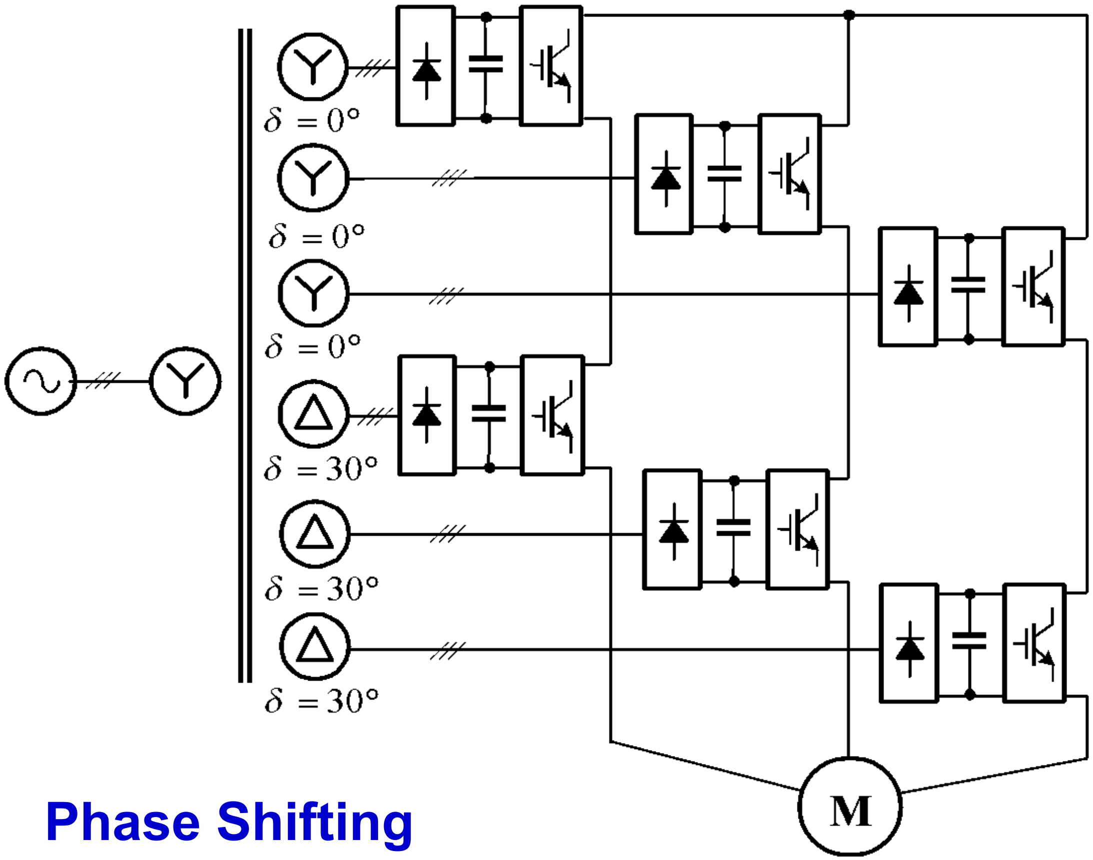
- **Rectifier Topology**



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

12-pulse Separate-type Diode Rectifier

- **Application Example**

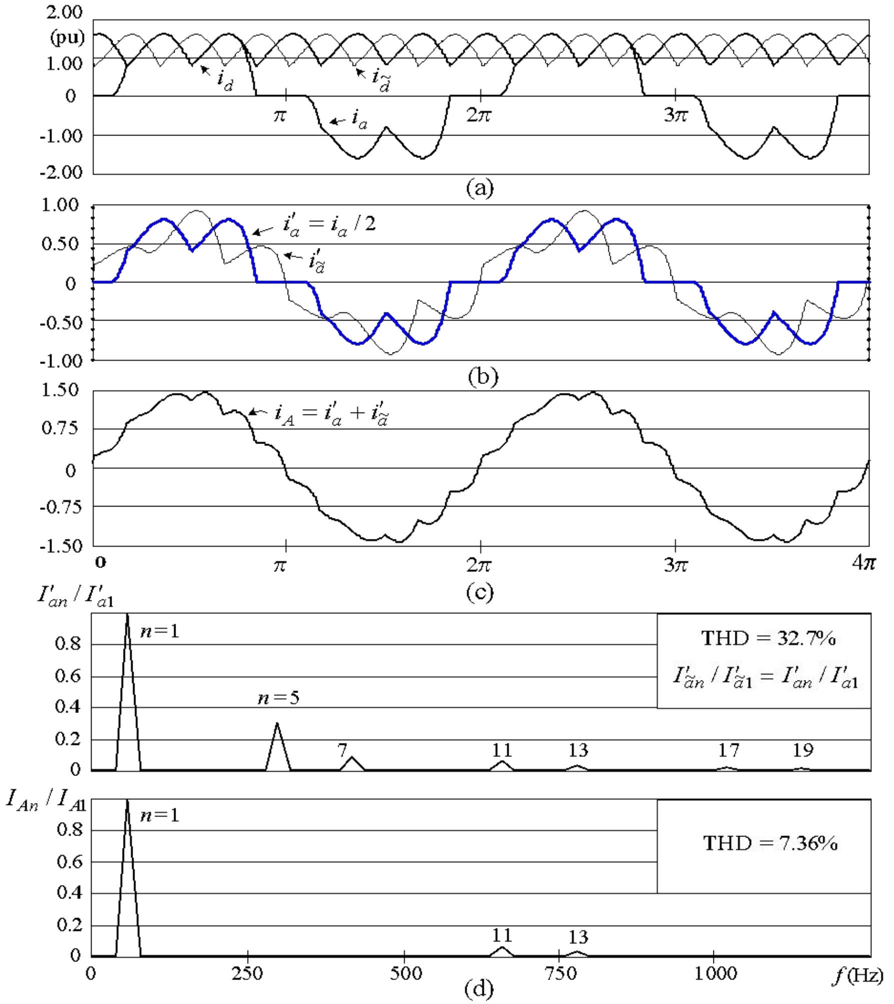


Phase Shifting Transformer

Multilevel Cascade H-bridge Inverter Fed Drive

12-pulse Separate-type Diode Rectifier

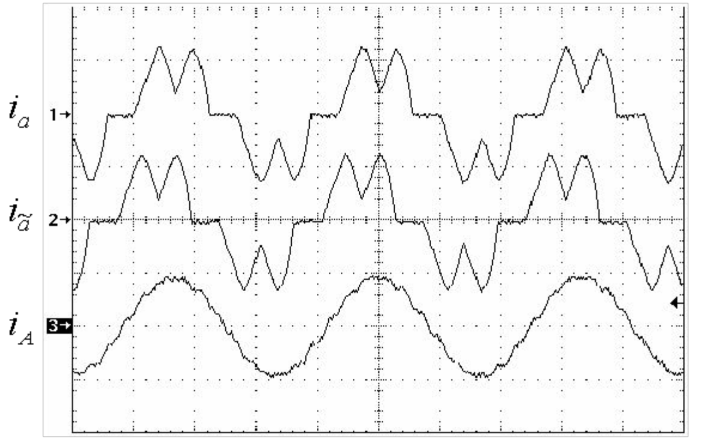
- **Typical Waveforms**



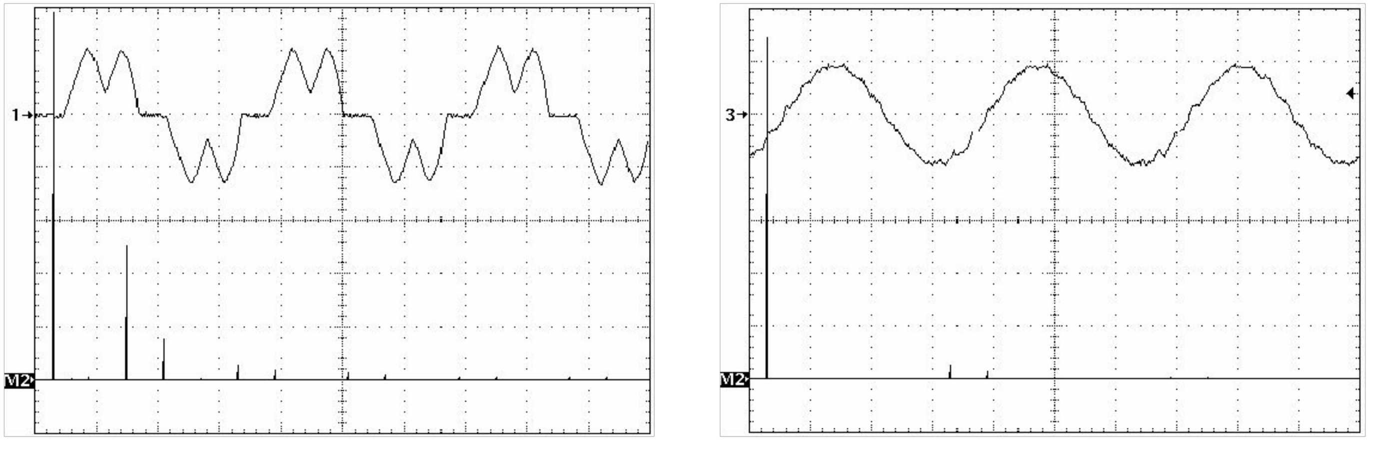
- **Comparison with series-type:**
  - DC current ripple: higher
  - Line current THD: close

12-pulse Separate-type Diode Rectifier

- **Measured Waveforms**



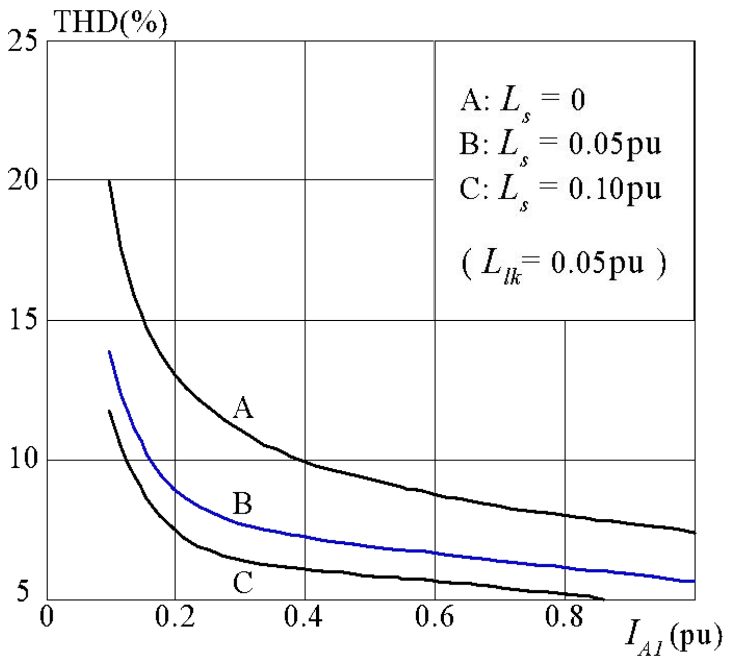
(a) Currents: $\sqrt{2}$ pu/div, 5ms/div

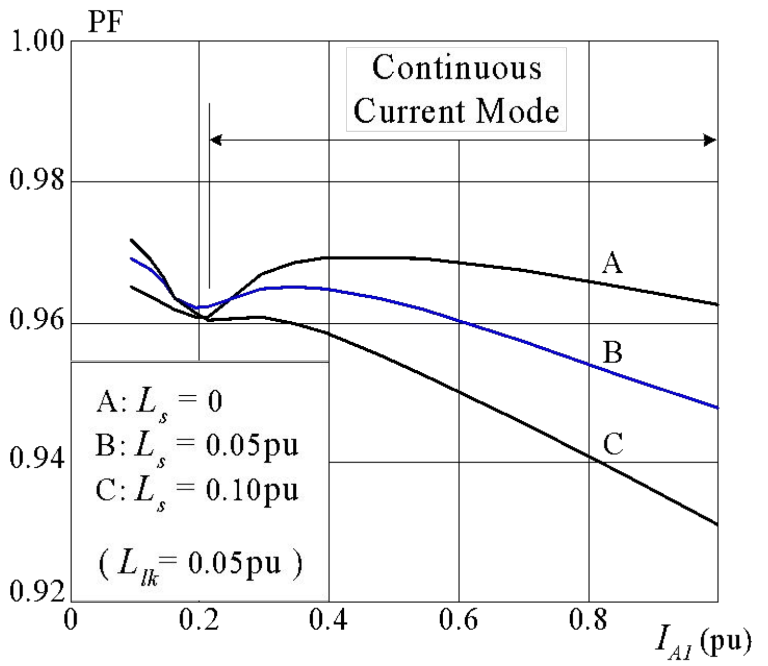


(b) Spectrum: $\sqrt{2}/10$ pu/div, 200Hz/div

12-pulse Separate-type Diode Rectifier

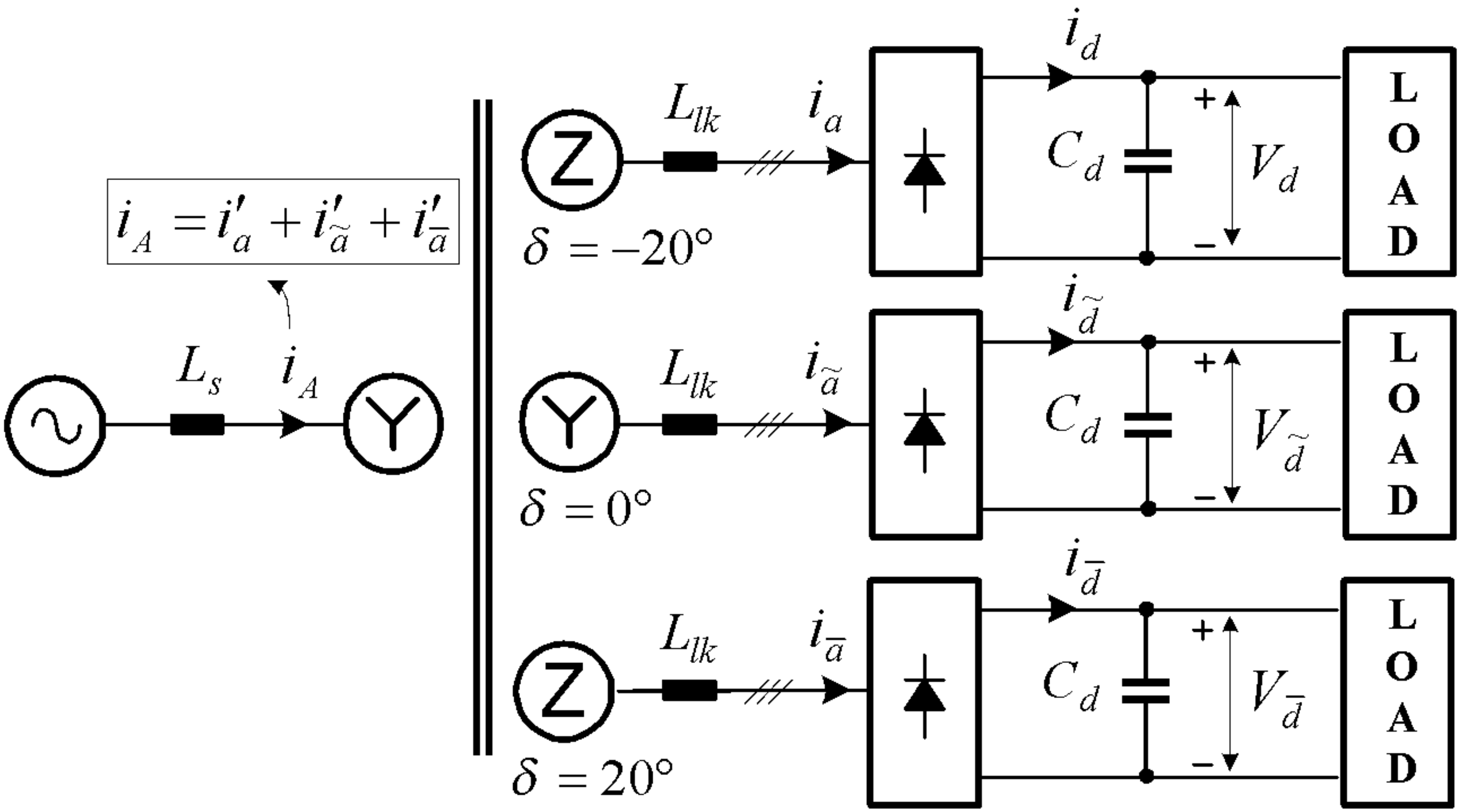
- **Line Current THD and Input PF**





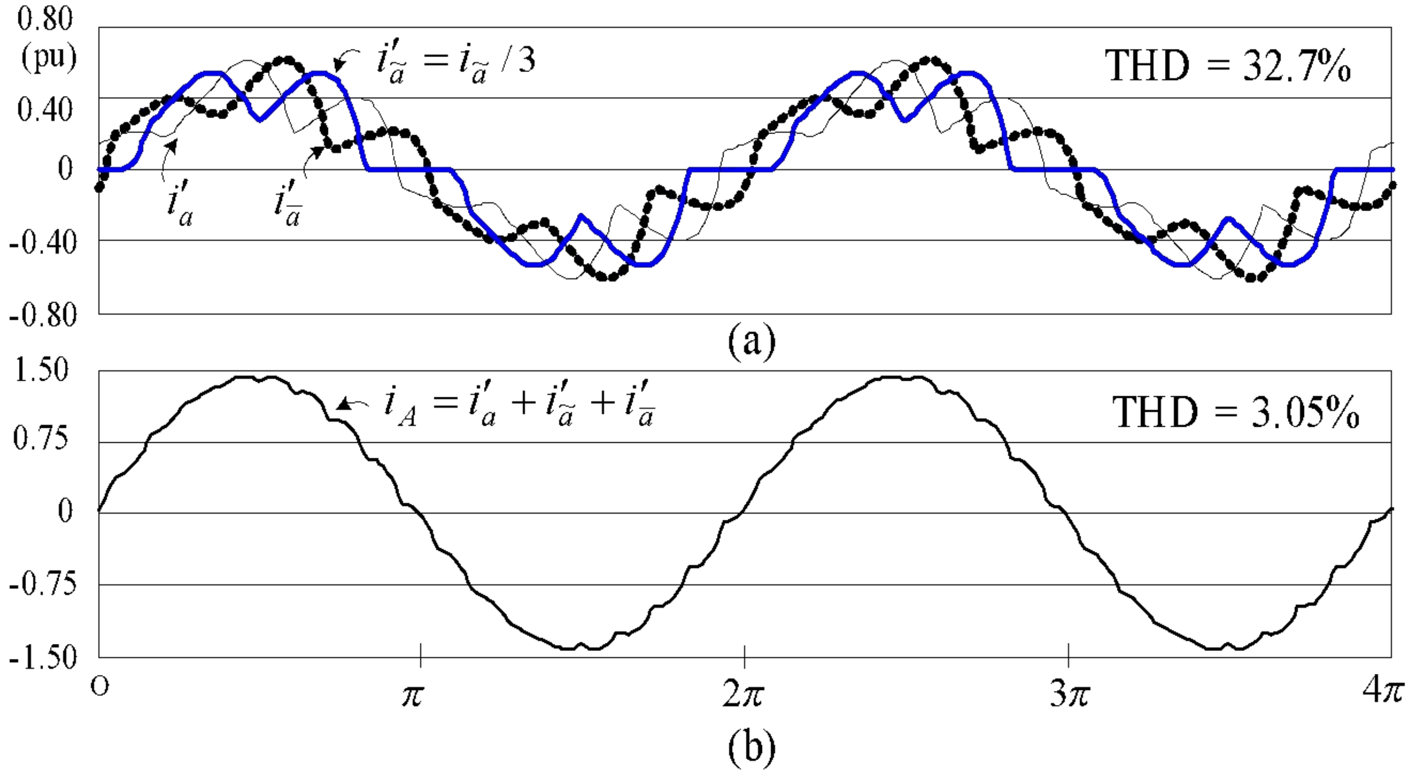
18-pulse Separate-type Diode Rectifier

- Rectifier Topology



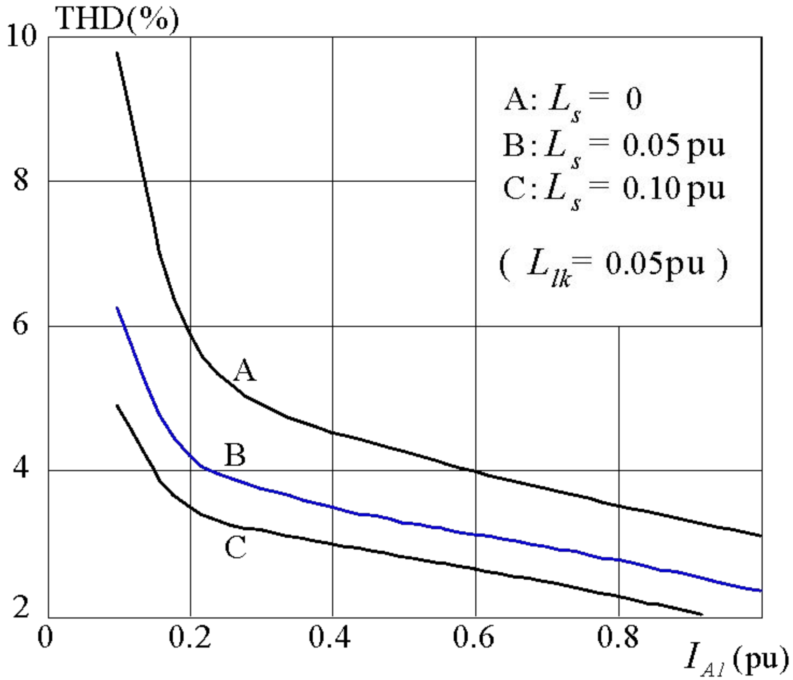
18-pulse Separate-type Diode Rectifier

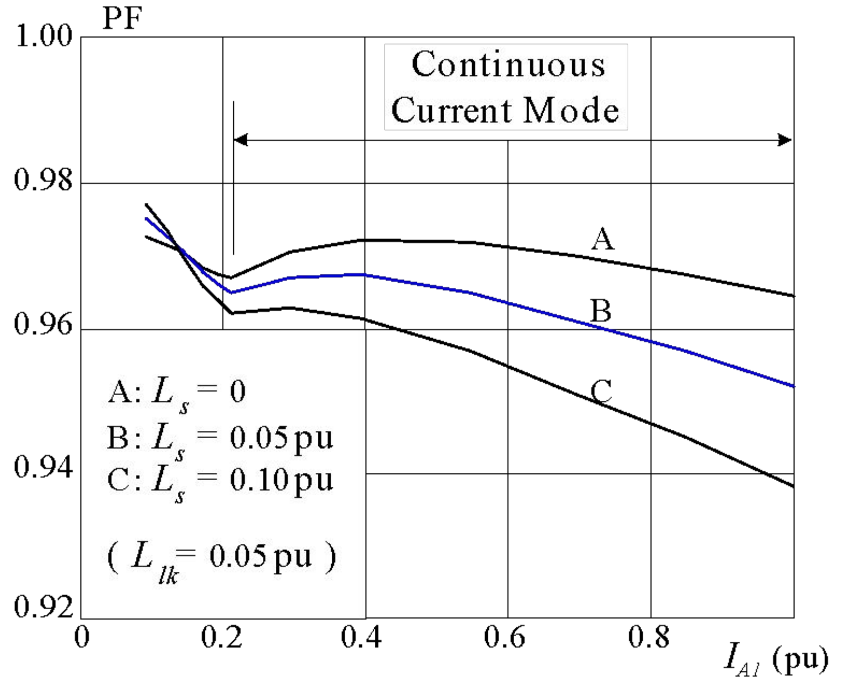
- **Simulated Waveforms**



18-pulse Separate-type Diode Rectifier

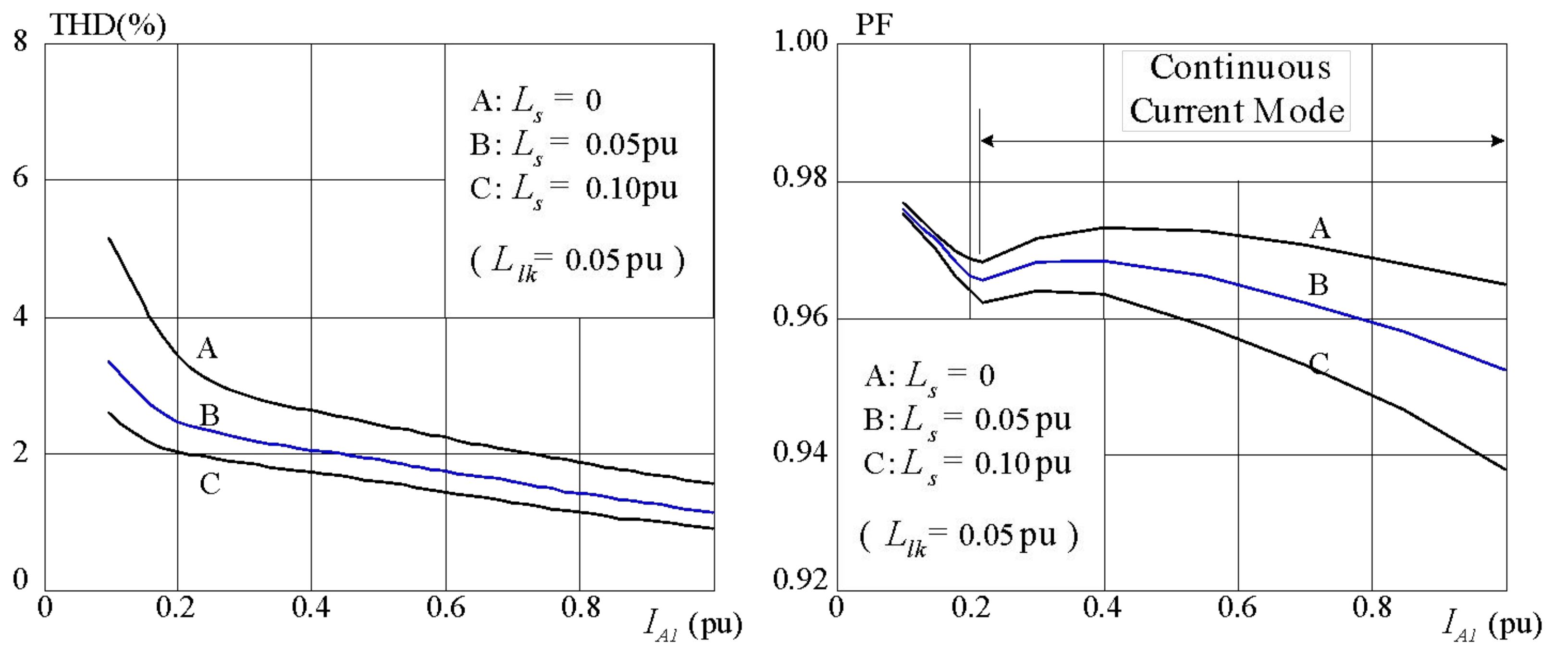
- **Line Current THD and Input PF**





24-pulse Separate-type Diode Rectifier

- **Line Current THD and Input PF**



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Thanks