

# Power Converter Systems

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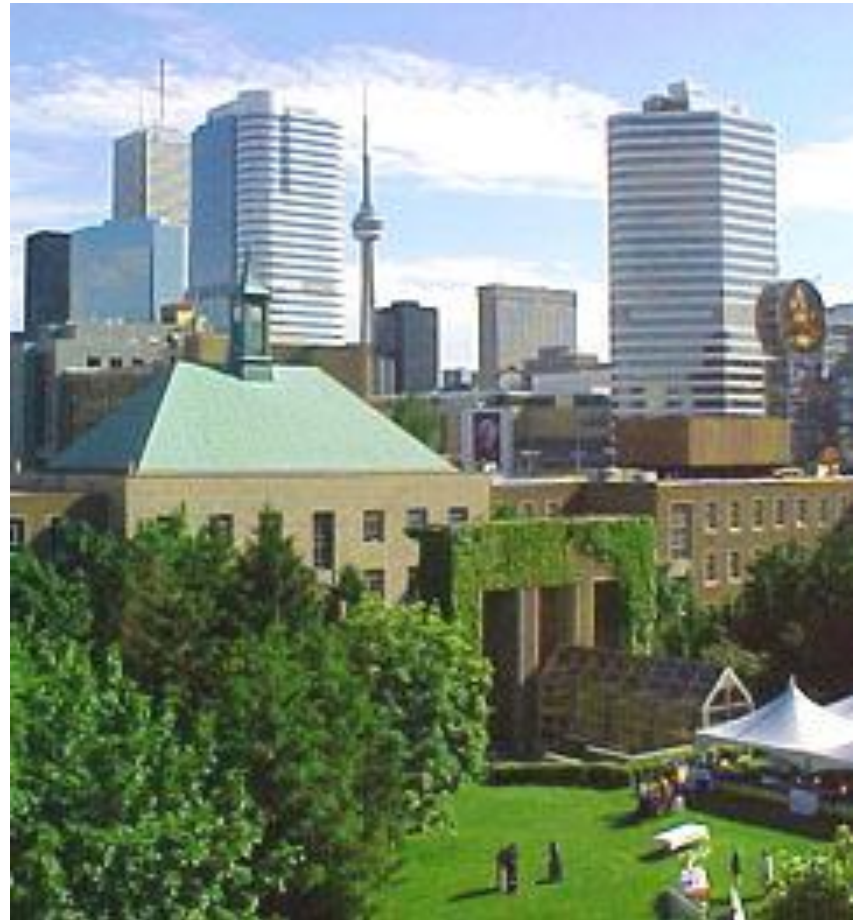
## Graduate Course EE8407

**Bin Wu** PhD, PEng

**Professor**  
ELCE Department  
Ryerson University

### Contact Info

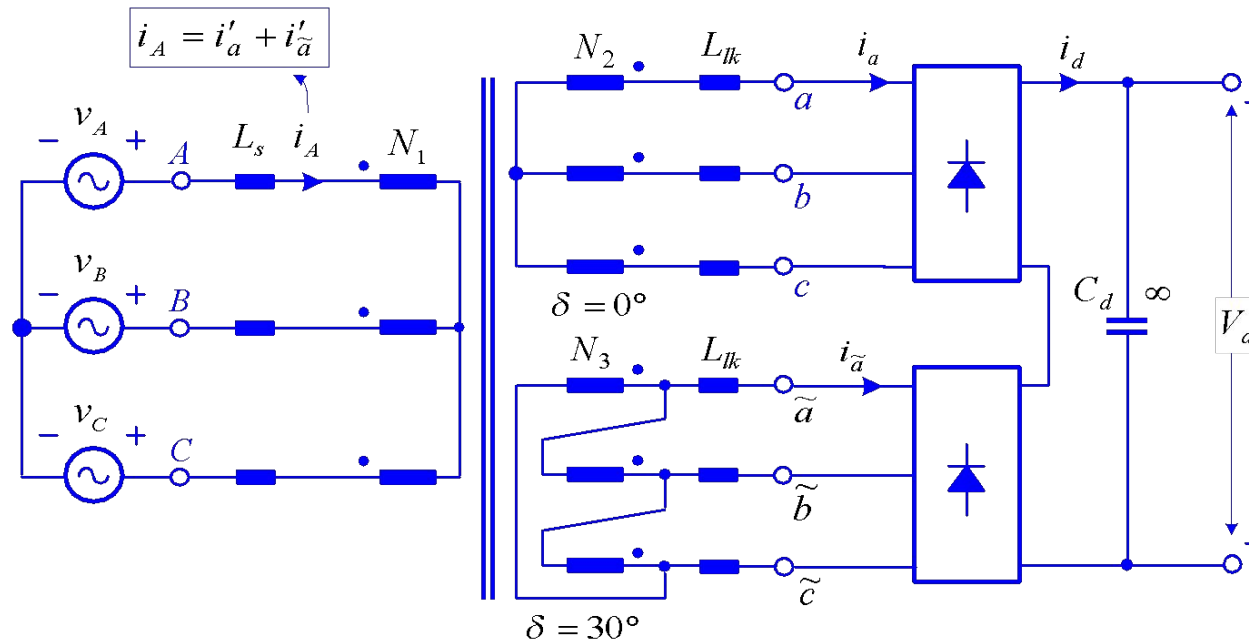
Office: ENG328  
Tel: (416) 979-5000 ext: 6484  
Email: [bwu@ee.ryerson.ca](mailto:bwu@ee.ryerson.ca)  
<http://www.ee.ryerson.ca/~bwu/>



**Ryerson Campus**

# Topic 3

## Multi-pulse Diode Rectifiers



# Multi-pulse Diode Rectifiers

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## 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

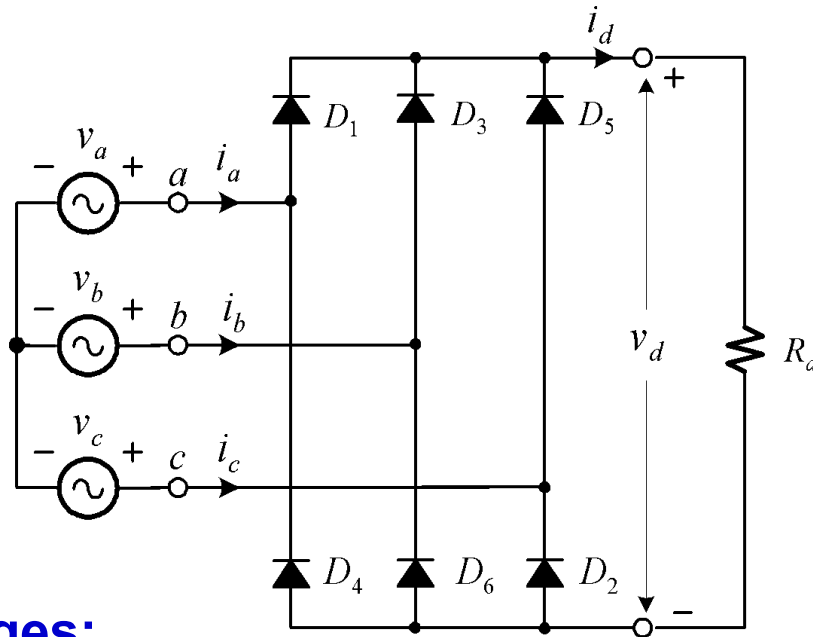
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## Why Use Multipulse Diode Rectifiers?

- 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:

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

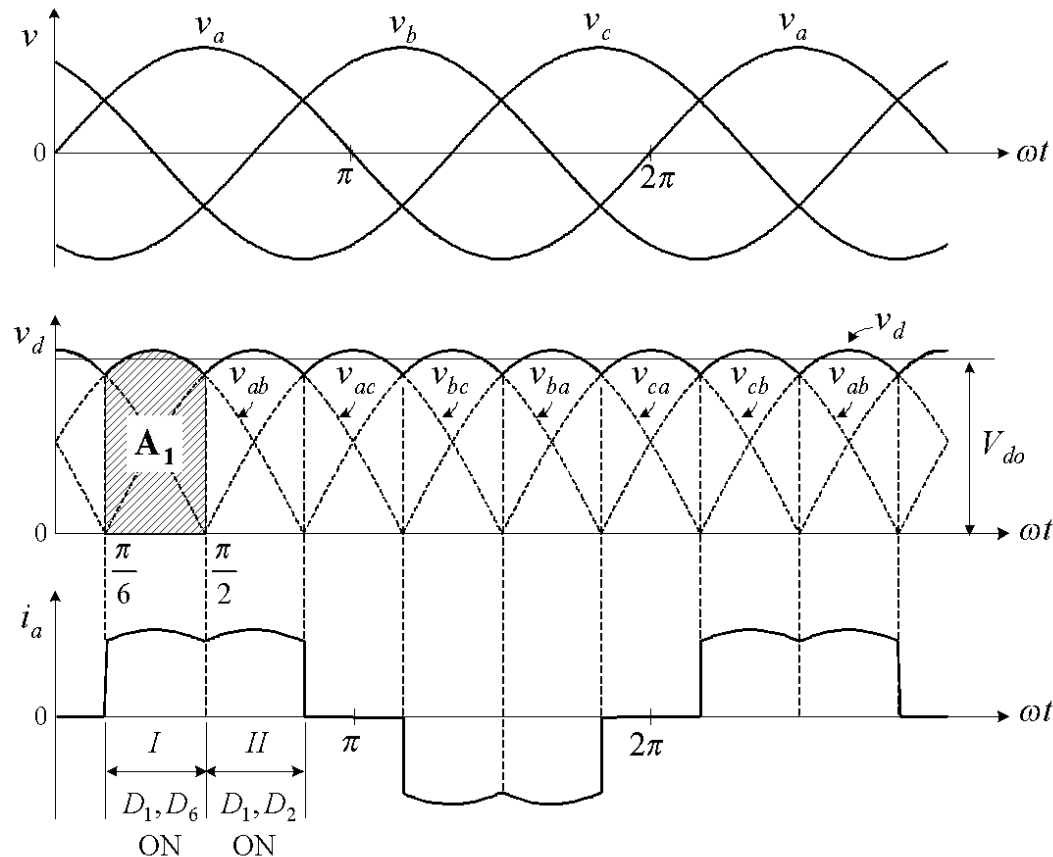
$$v_b = \sqrt{2} V_{PH} \sin(\omega t - 2\pi / 3)$$

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

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

# Six-pulse Diode Rectifier

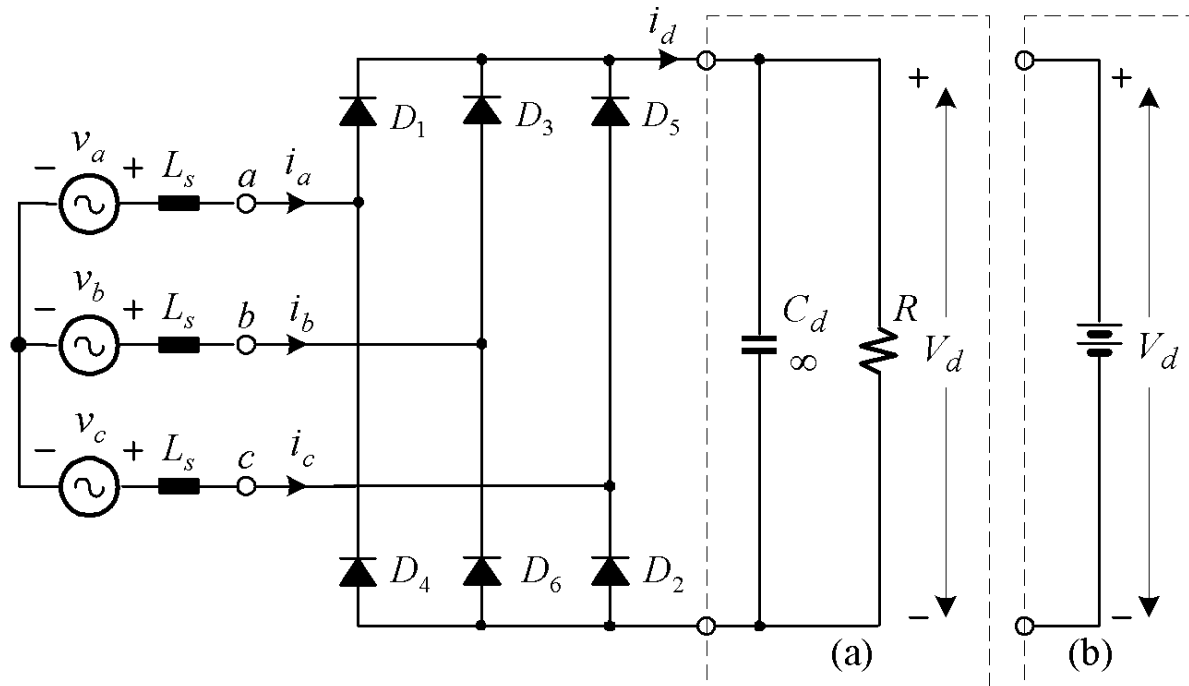
## • Waveforms



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

# Six-pulse Diode Rectifier

## • Capacitive Load

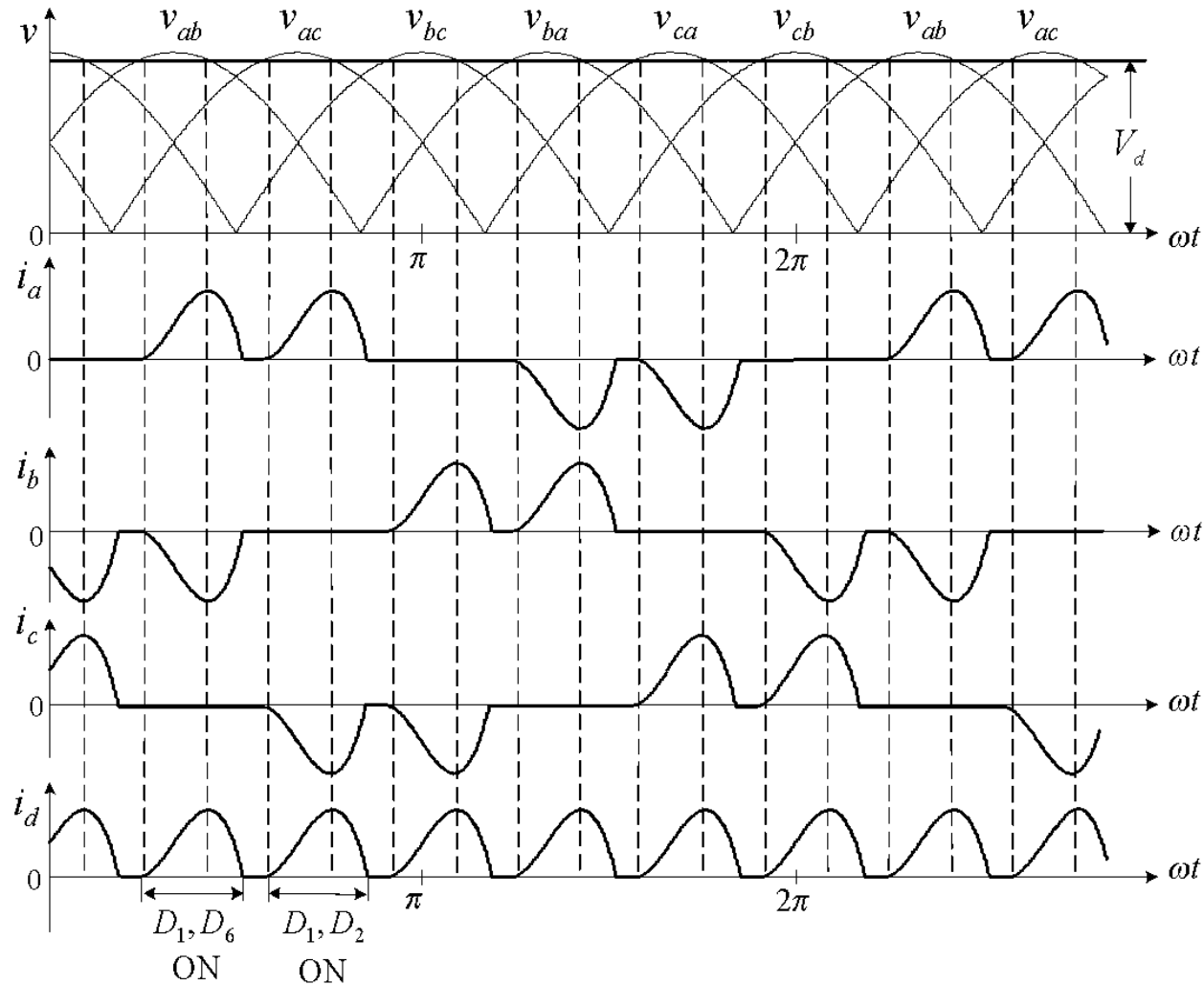


### Assumption:

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

# Six-pulse Diode Rectifier

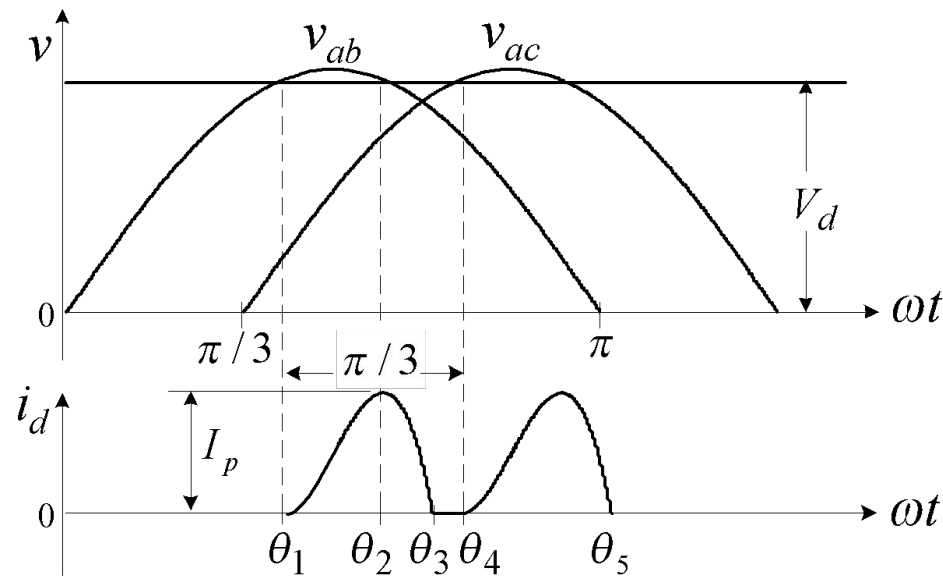
## • Waveforms





# Six-pulse Diode Rectifier

## • Discontinuous Current Operation

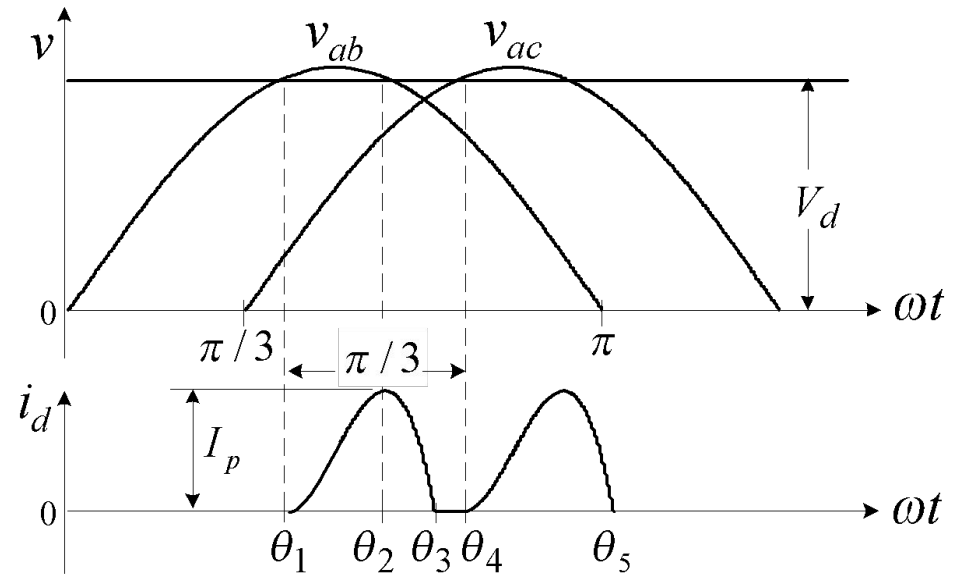
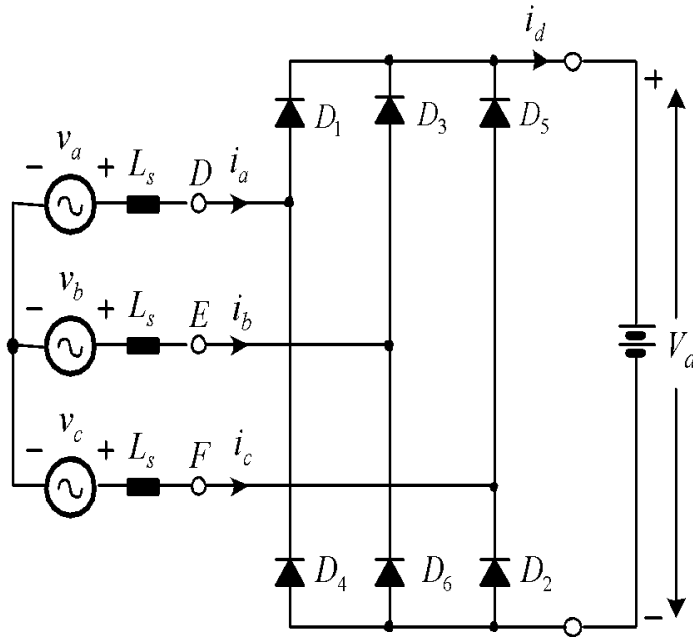


$$\theta_1 = \sin^{-1}\left(\frac{V_d}{\sqrt{2} V_{LL}}\right)$$

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

# Six-pulse Diode Rectifier

## Discontinuous Current Operation



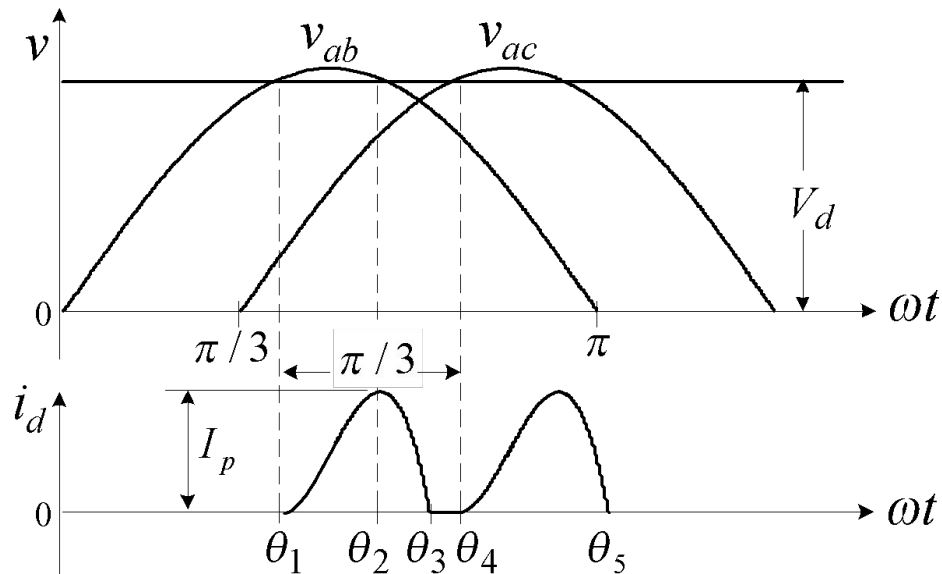
**Differential Equation:** 
$$2L_s \frac{di_d}{dt} = v_{ab} - V_d \quad \theta_1 \leq \omega t < \theta_3$$

**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



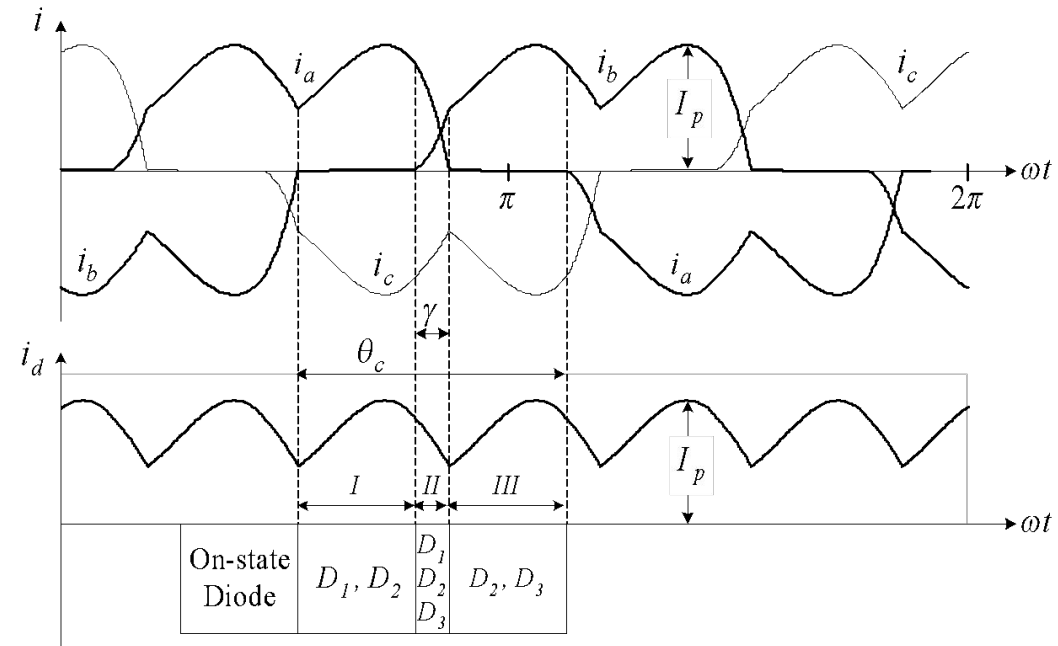
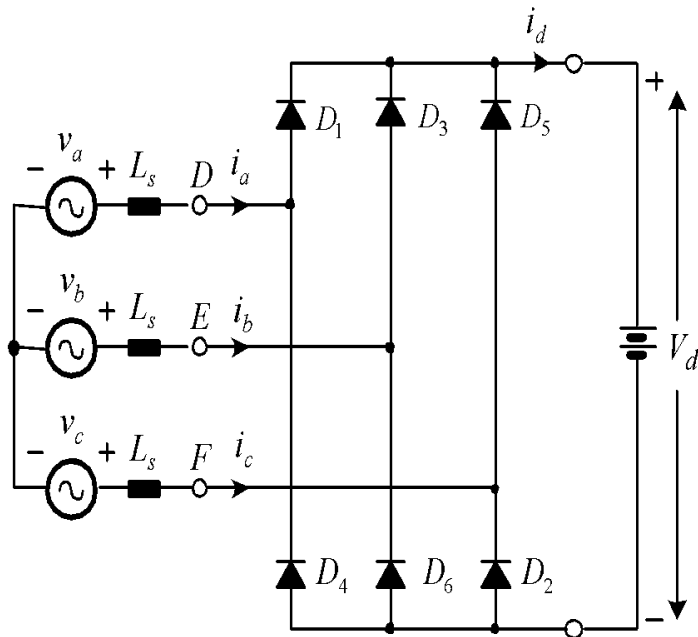
**Peak dc current:** 
$$I_p = \frac{1}{2\omega L_s} (\sqrt{2}V_{LL}(\cos\theta_1 - \cos\theta_2) + V_d(\theta_1 - \theta_2))$$

**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

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- 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

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- 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

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## • 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.

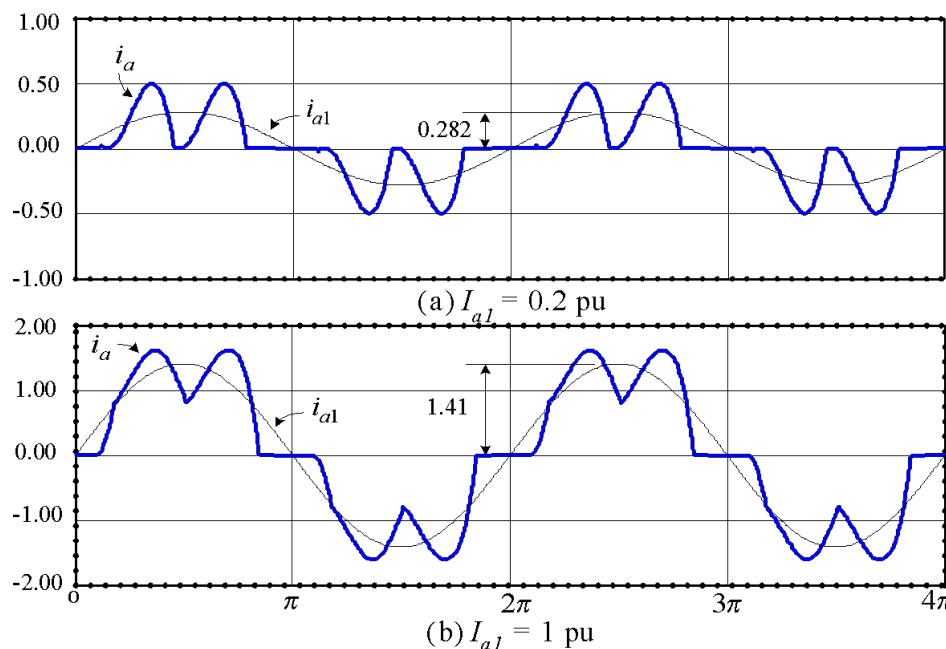
Base current = 277.6A, Base inductance = 22.9mH.

Line inductance = 2.29mH = 0.1pu

Line current = 138.8A = 0.5pu

# Six-pulse Diode Rectifier

## • Typical Waveforms / Harmonic Content

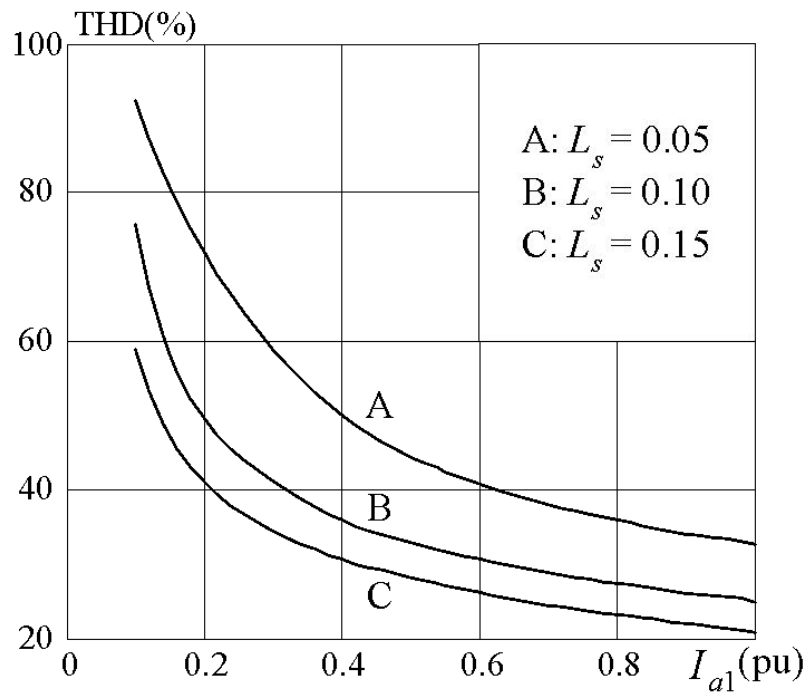


Harmonics $n$	5	7	11	13	17	19	23	25	THD (%)
$I_{an} / I_{a1}$ (%) $I_{a1} = 0.2$ pu	63.4	38.7	8.99	8.64	4.22	3.61	2.48	2.02	75.7
$I_{an} / I_{a1}$ (%) $I_{a1} = 1$ pu	30.4	8.79	6.31	3.40	2.30	1.89	1.04	1.03	32.7

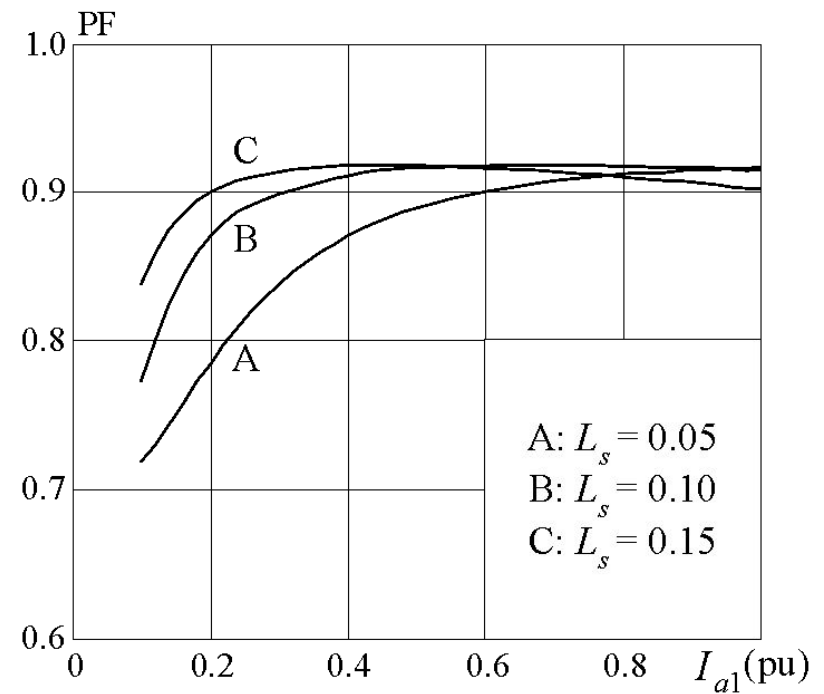


# Six-pulse Diode Rectifier

- THD and PF



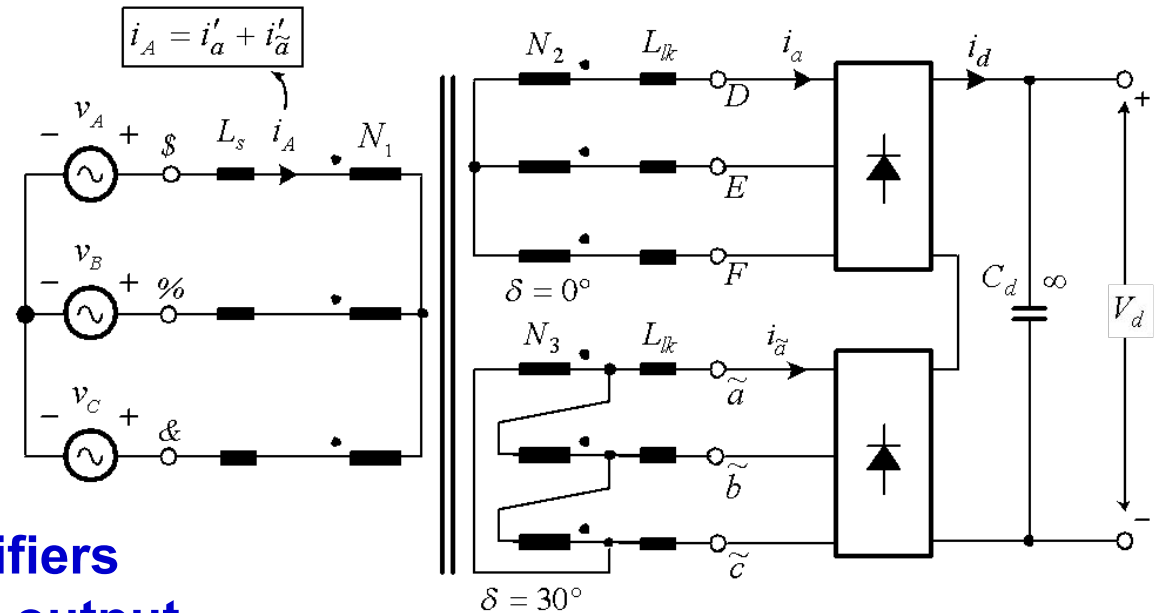
(a) THD



(b) PF

# 12-pulse Series-type Diode Rectifier

## • Rectifier Topology



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

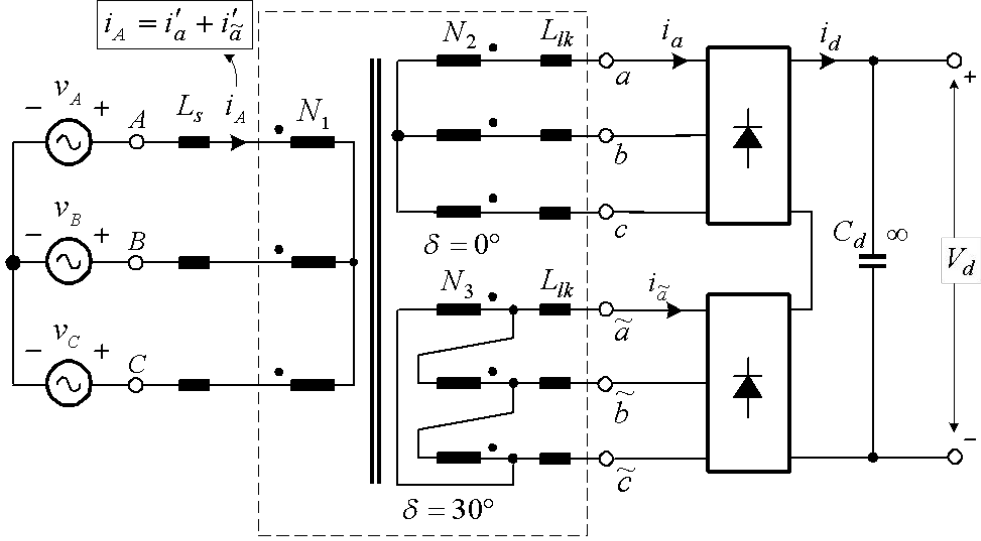
- **Phase shifting transformer:**  $\delta = \angle V_{\tilde{a}\tilde{b}} - \angle V_{AB} = 30^\circ$

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

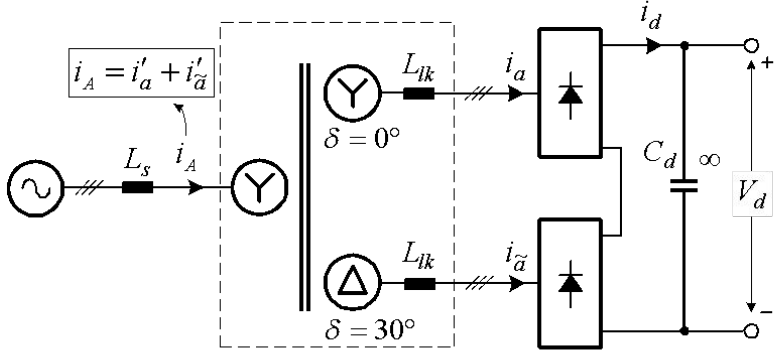
- **Turns ratio:**  $\frac{N_1}{N_2} = 2$  and  $\frac{N_1}{N_3} = \frac{2}{\sqrt{3}}$ .

# 12-pulse Series-type Diode Rectifier

- Simplified Block Diagram



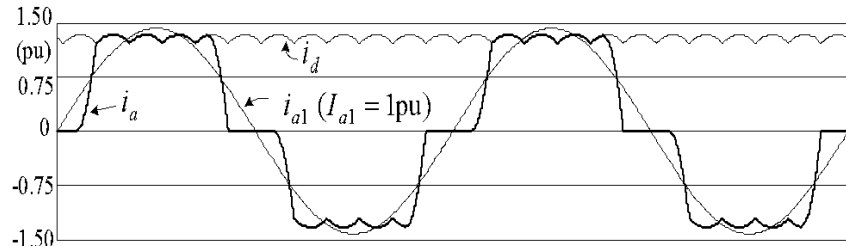
(a) 12-pulse diode rectifier



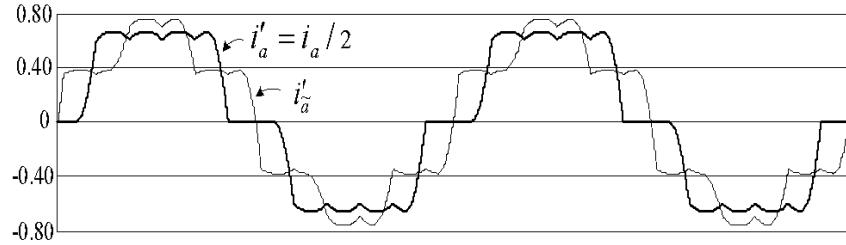
(b) Simplified diagram

# 12-pulse Series-type Diode Rectifier

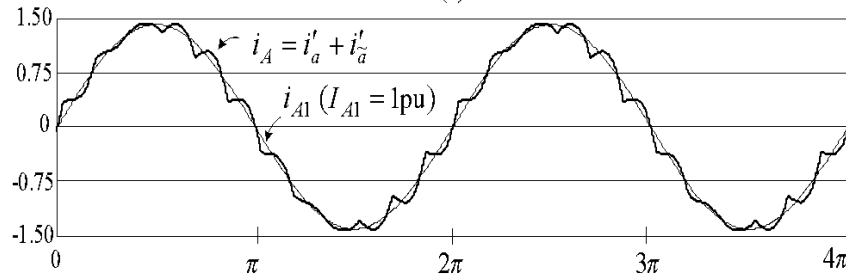
## • Waveforms and FFT



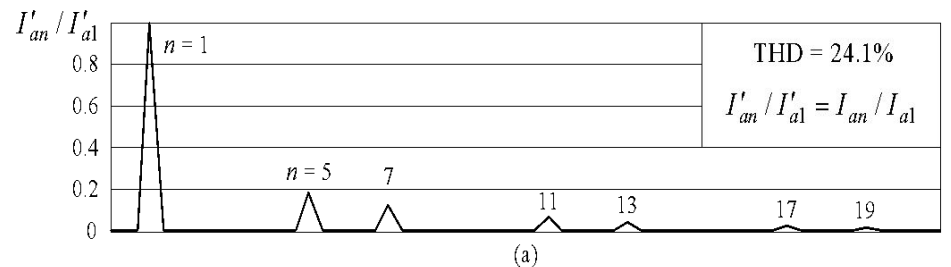
(a)



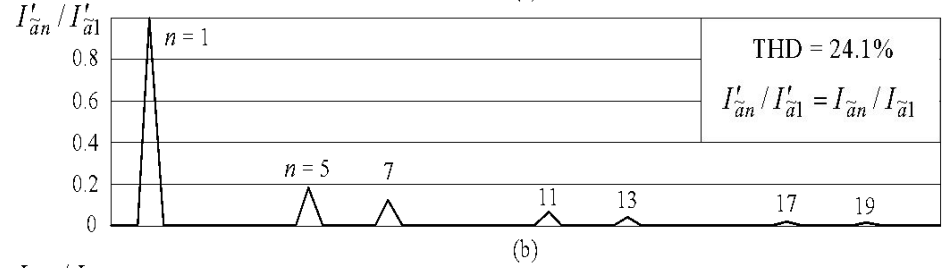
(b)



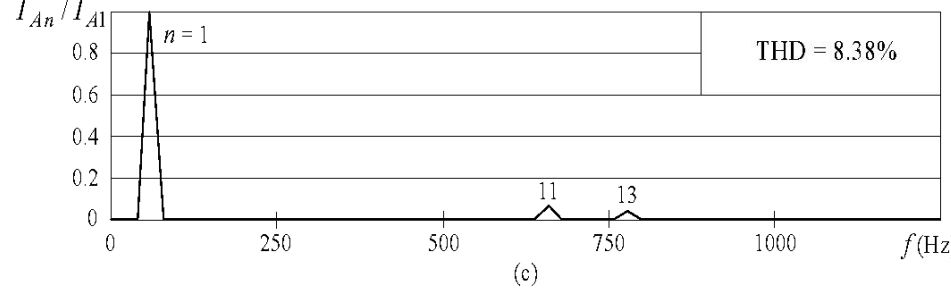
(c)



(a)



(b)

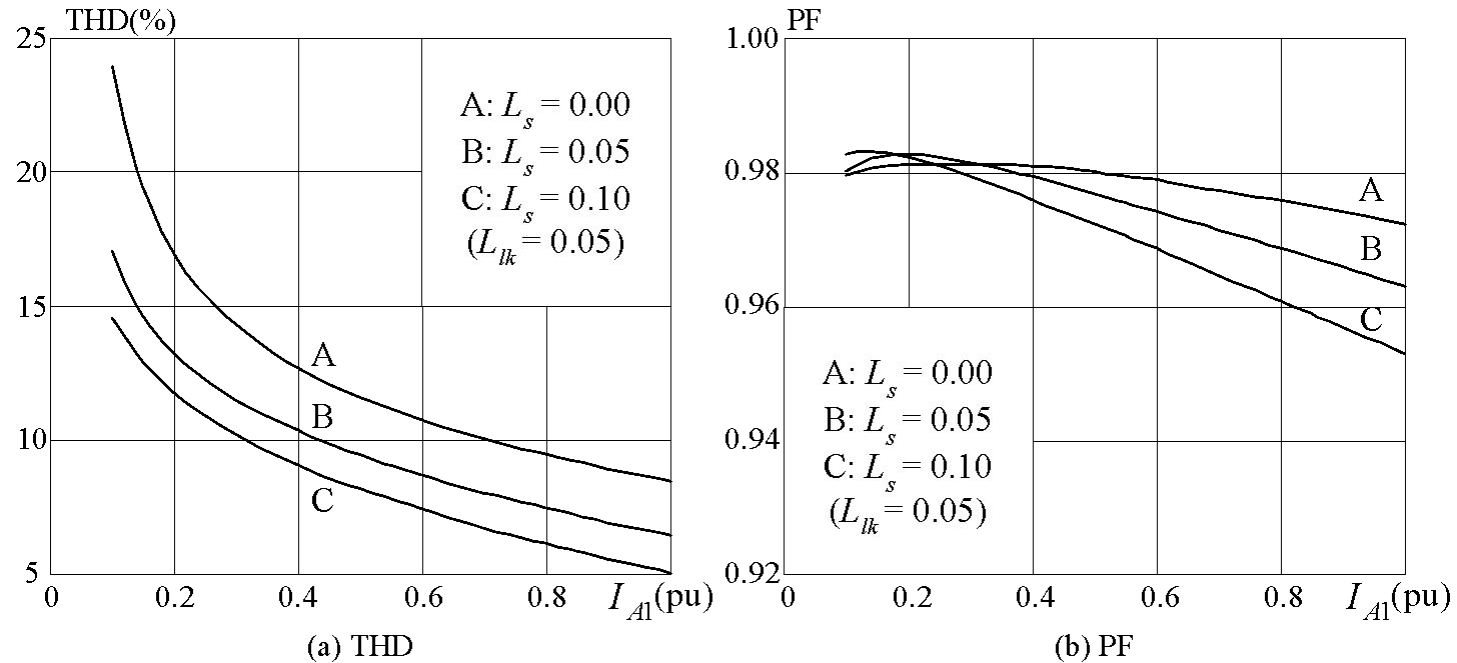


(c)

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

# 12-pulse Series-type Diode Rectifier

## • THD and PF

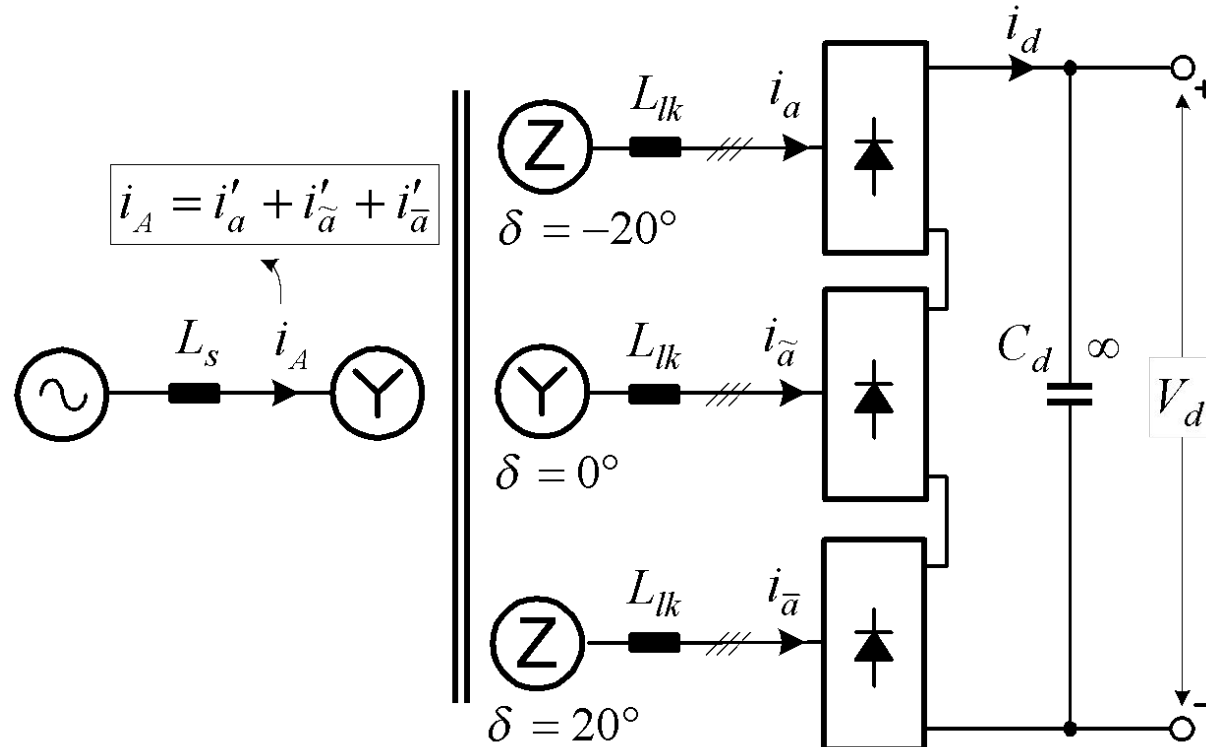


### Comparison with six-pulse rectifier:

- THD is reduced; and
- PF is improved.

# 18-pulse Series-type Diode Rectifier

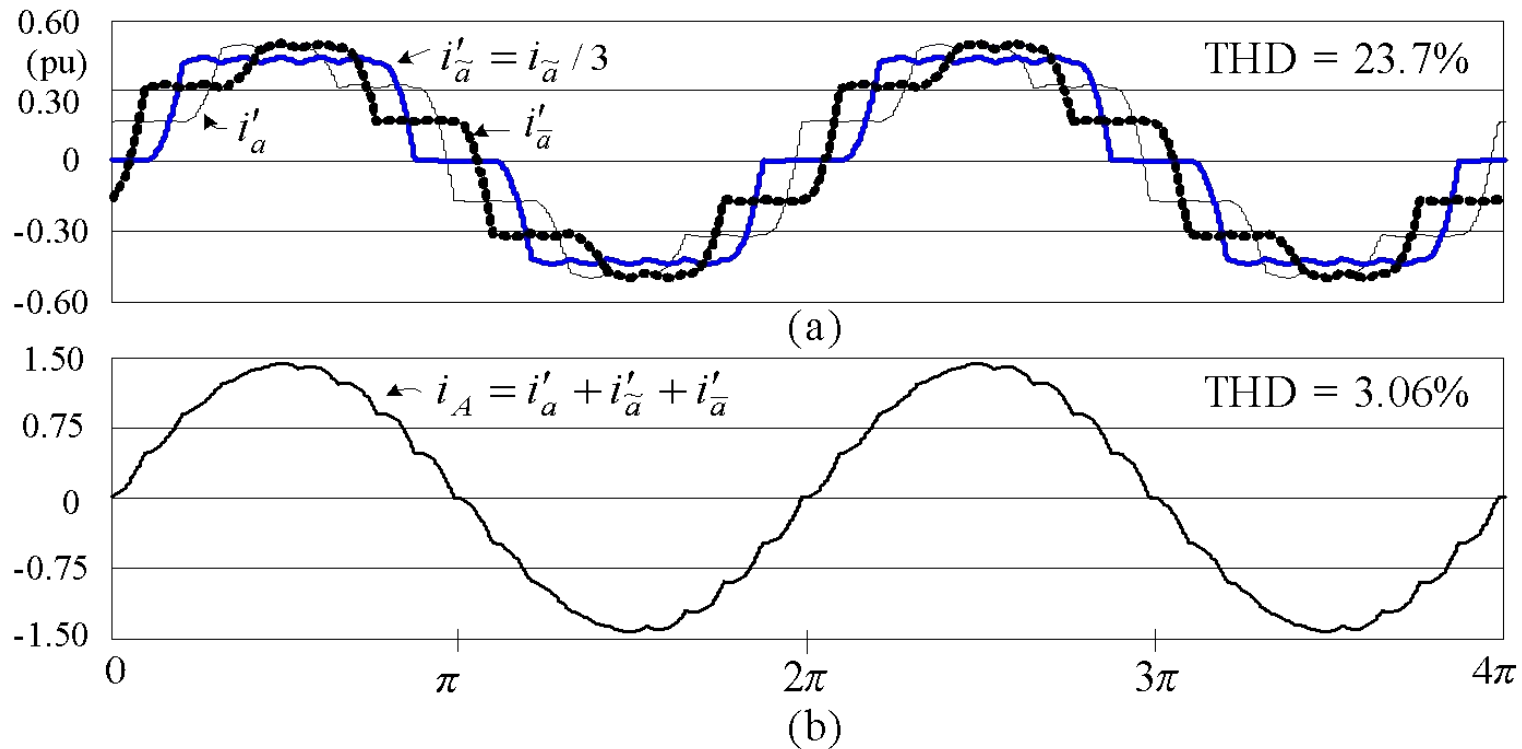
## • Converter Topology



**Phase-Shifting  
(Zigzag) Transformer**

# 18-pulse Series-type Diode Rectifier

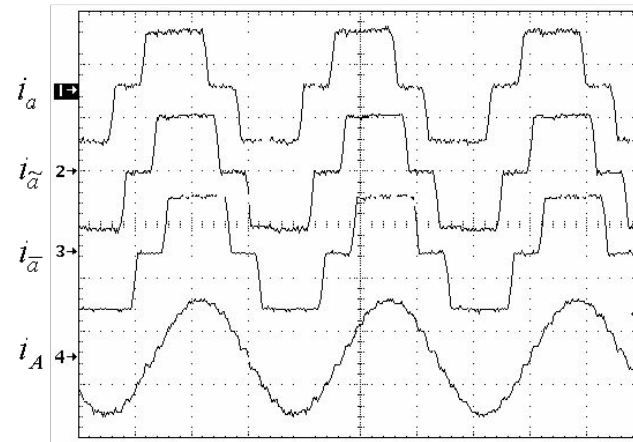
## • Simulated Waveforms



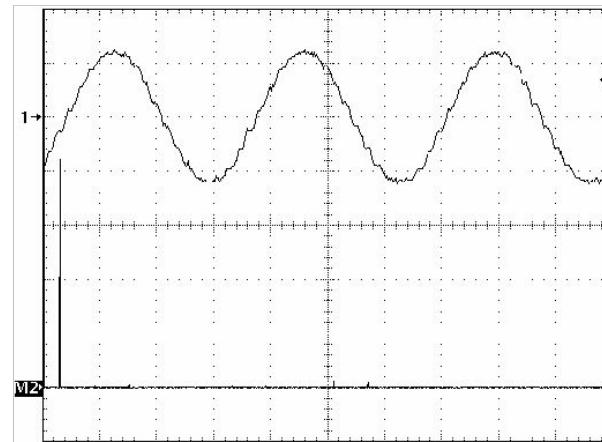
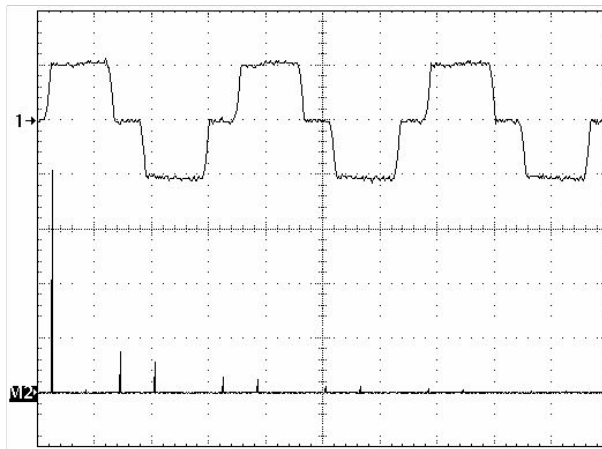
- No 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup>, or 13<sup>th</sup> harmonics in the line current.
- Lowest harmonic: 17<sup>th</sup>
- Line current THD: 3.06%

# 18-pulse Series-type Diode Rectifier

## • Measured Waveforms



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

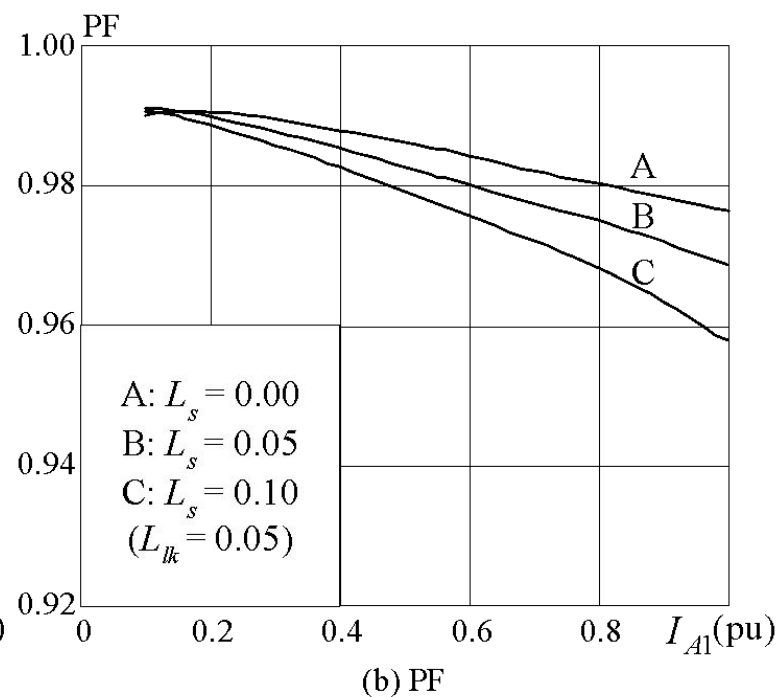
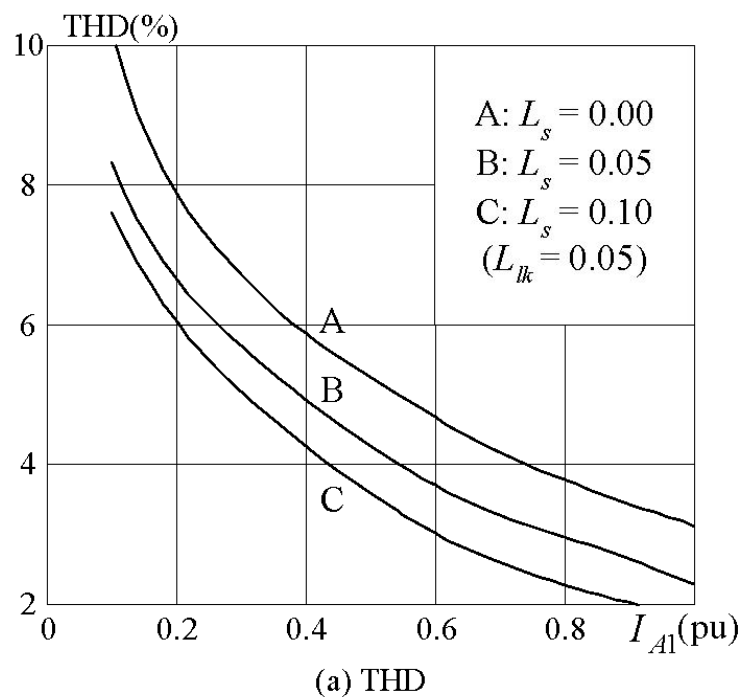


(b) Spectrum:  $\sqrt{2}/5$  pu/div, 200Hz/div



# 18-pulse Series-type Diode Rectifier

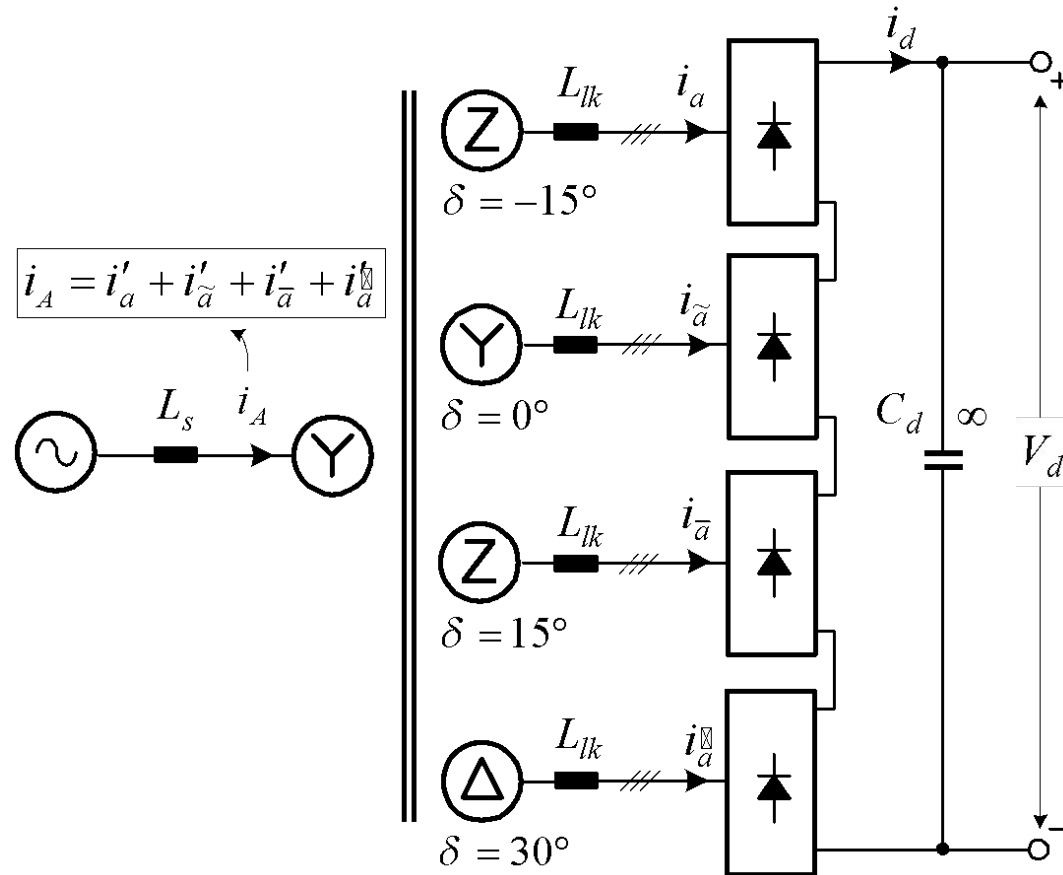
## • THD and PF



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

# 24-pulse Series-type Diode Rectifier

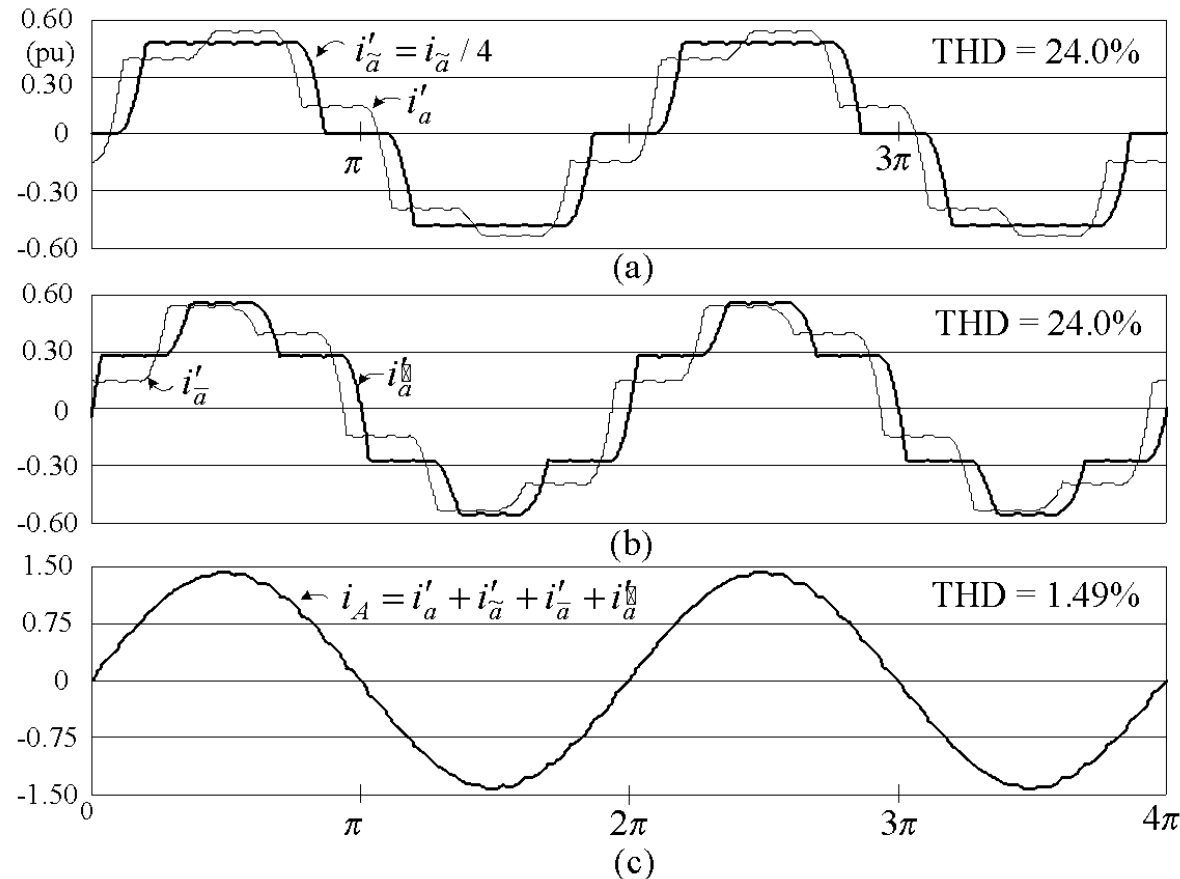
- Converter Topology



## Phase-Shifting (Zigzag) Transformer

# 24-pulse Series-type Diode Rectifier

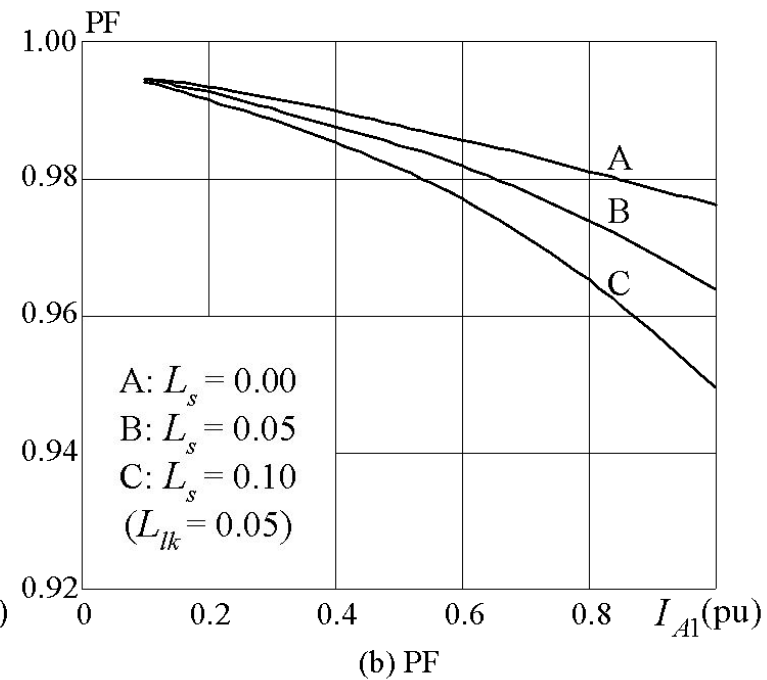
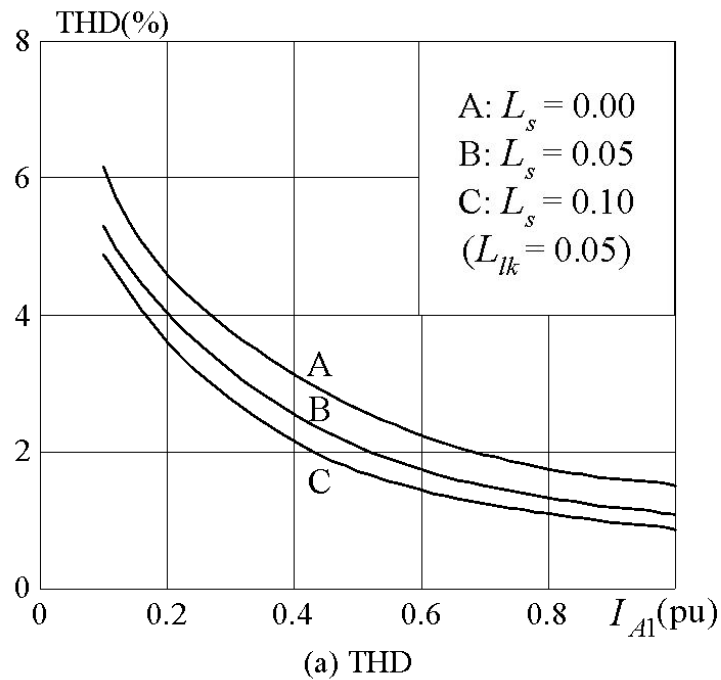
## • Typical Waveforms



- Lowest line current harmonic: 23<sup>th</sup>
- THD: 1.49%

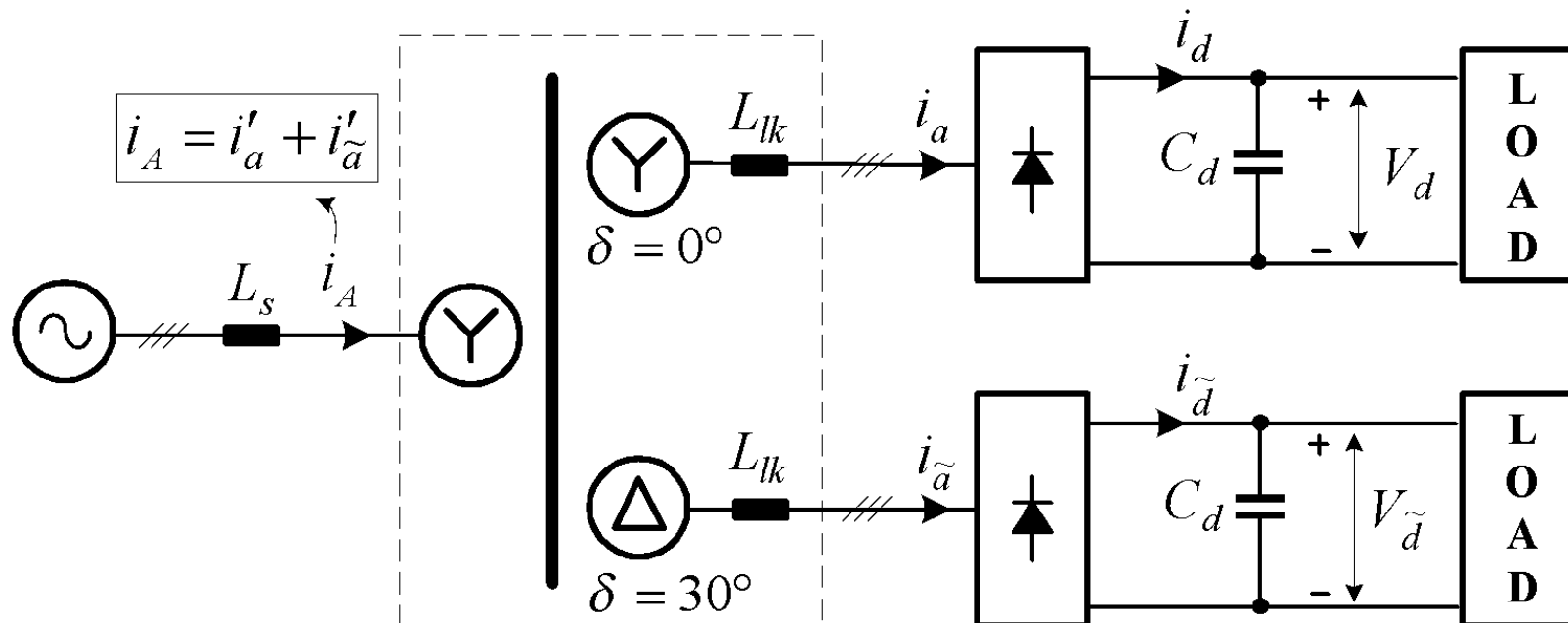
# 24-pulse Series-type Diode Rectifier

- THD and PF



# 12-pulse Separate-type Diode Rectifier

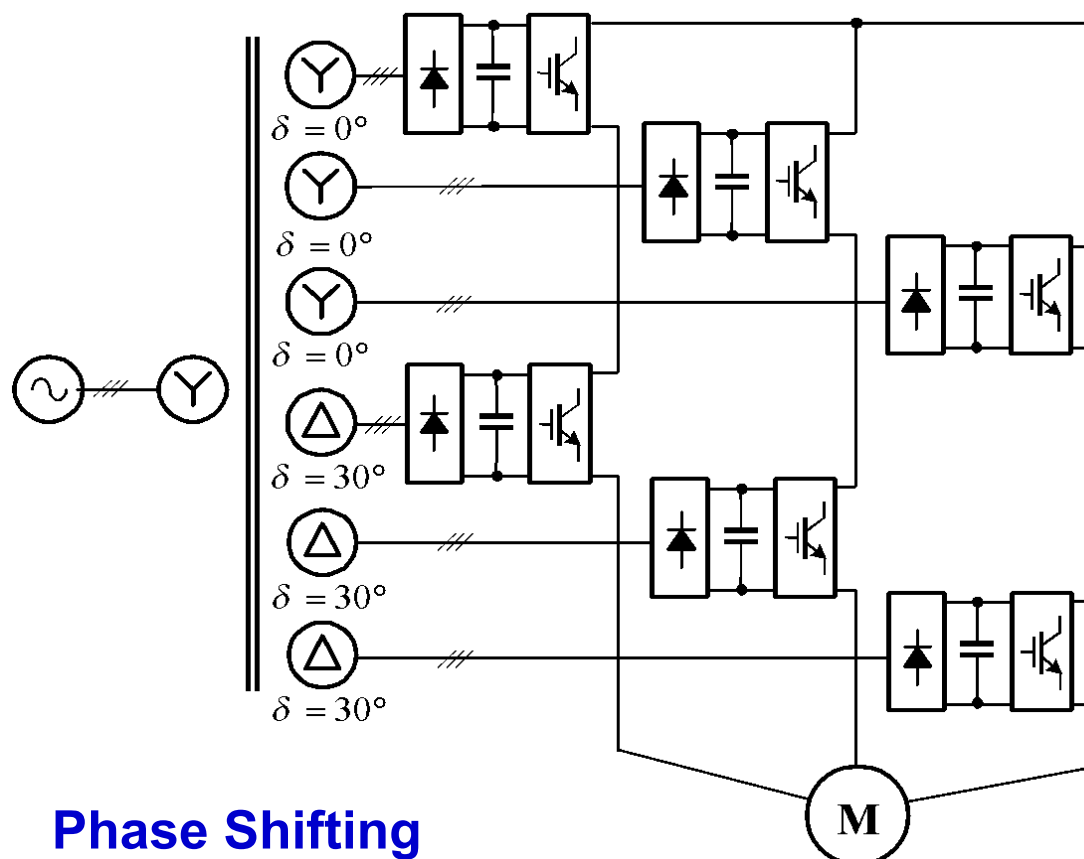
- Rectifier Topology



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

# 12-pulse Separate-type Diode Rectifier

- Application Example

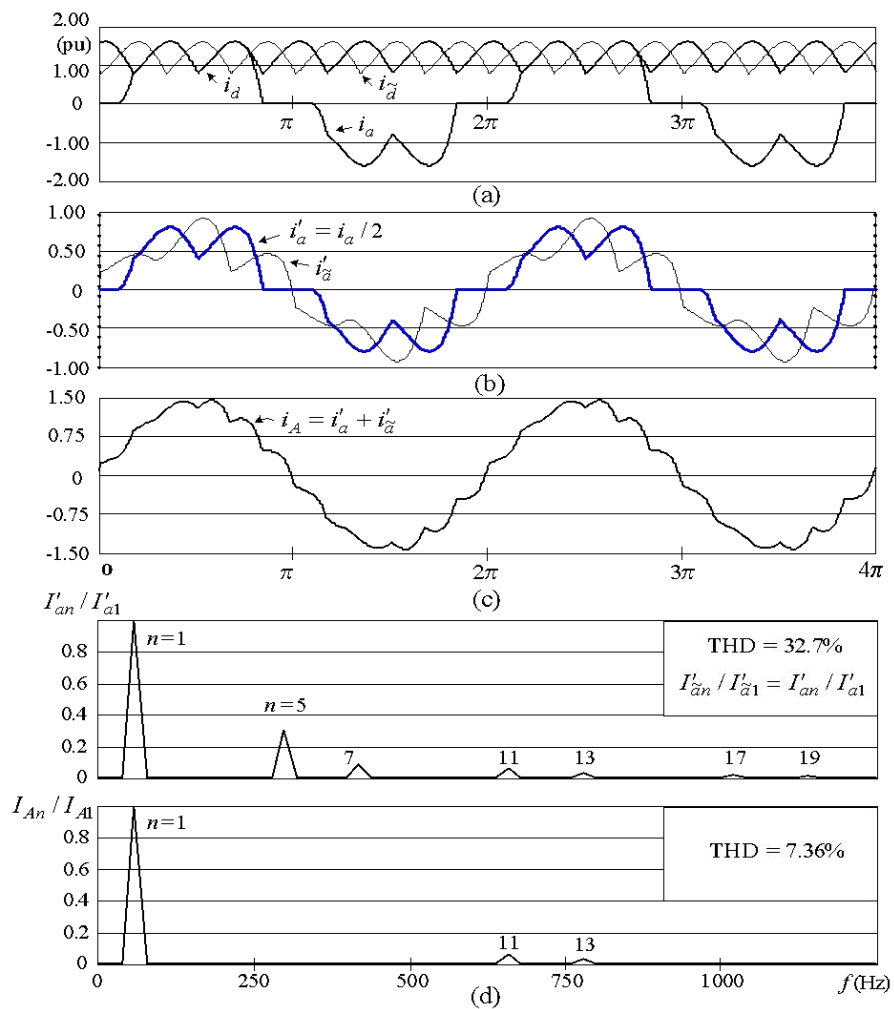


**Phase Shifting  
Transformer**

**Multilevel Cascade  
H-bridge Inverter Fed Drive**

# 12-pulse Separate-type Diode Rectifier

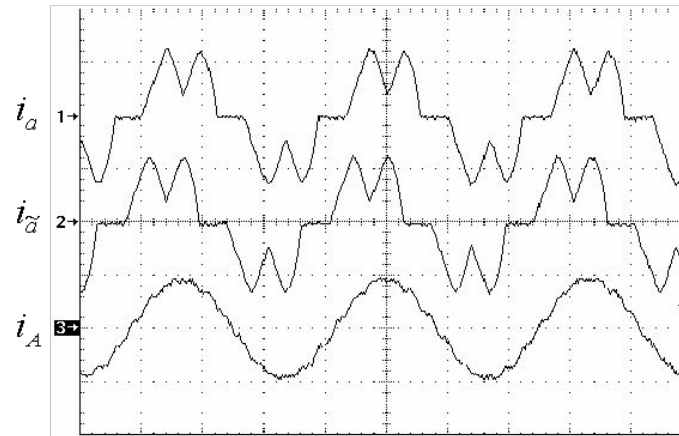
## • Typical Waveforms



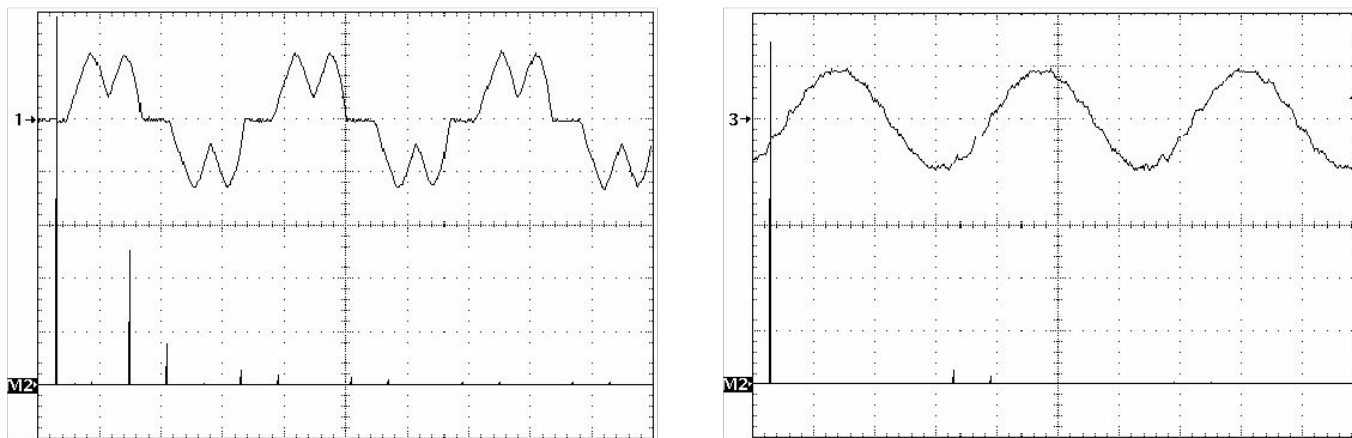
- Comparison with series-type:
  - DC current ripple: higher
  - Line current THD: close

# 12-pulse Separate-type Diode Rectifier

- Measured Waveforms



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

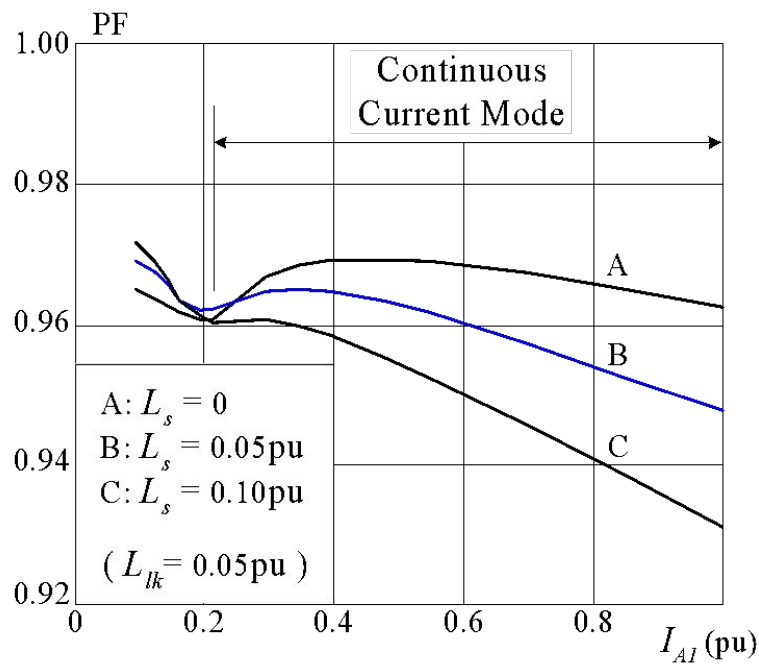
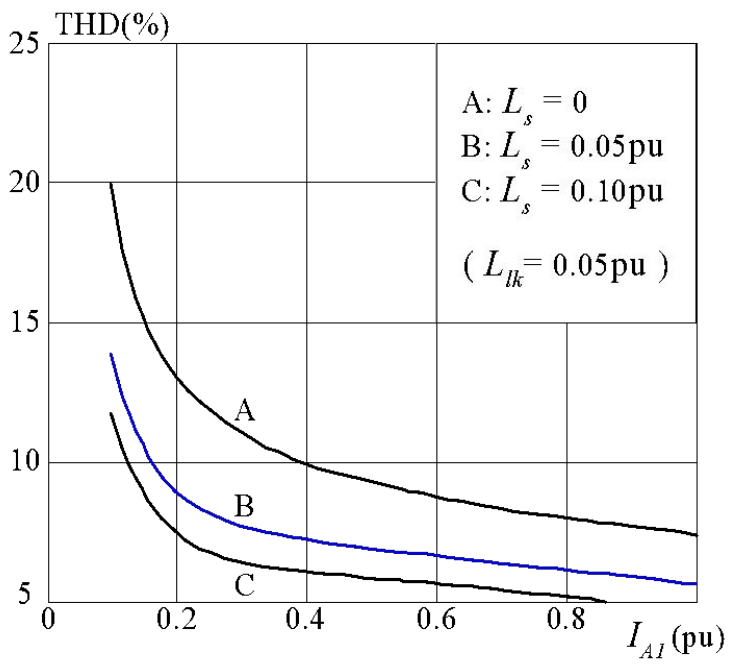


(b) Spectrum:  $\sqrt{2}/10$  pu/div, 200Hz/div



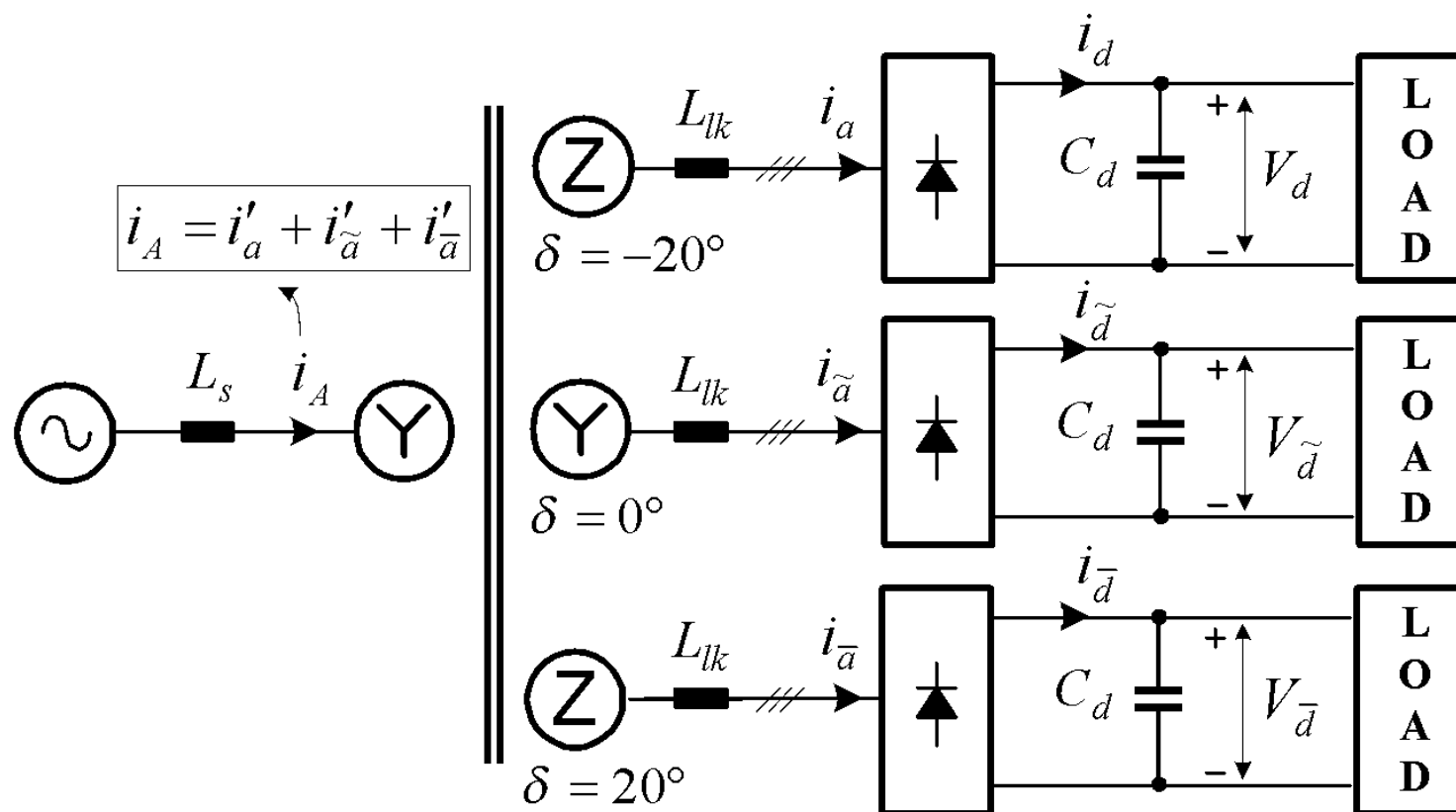
# 12-pulse Separate-type Diode Rectifier

- Line Current THD and Input PF



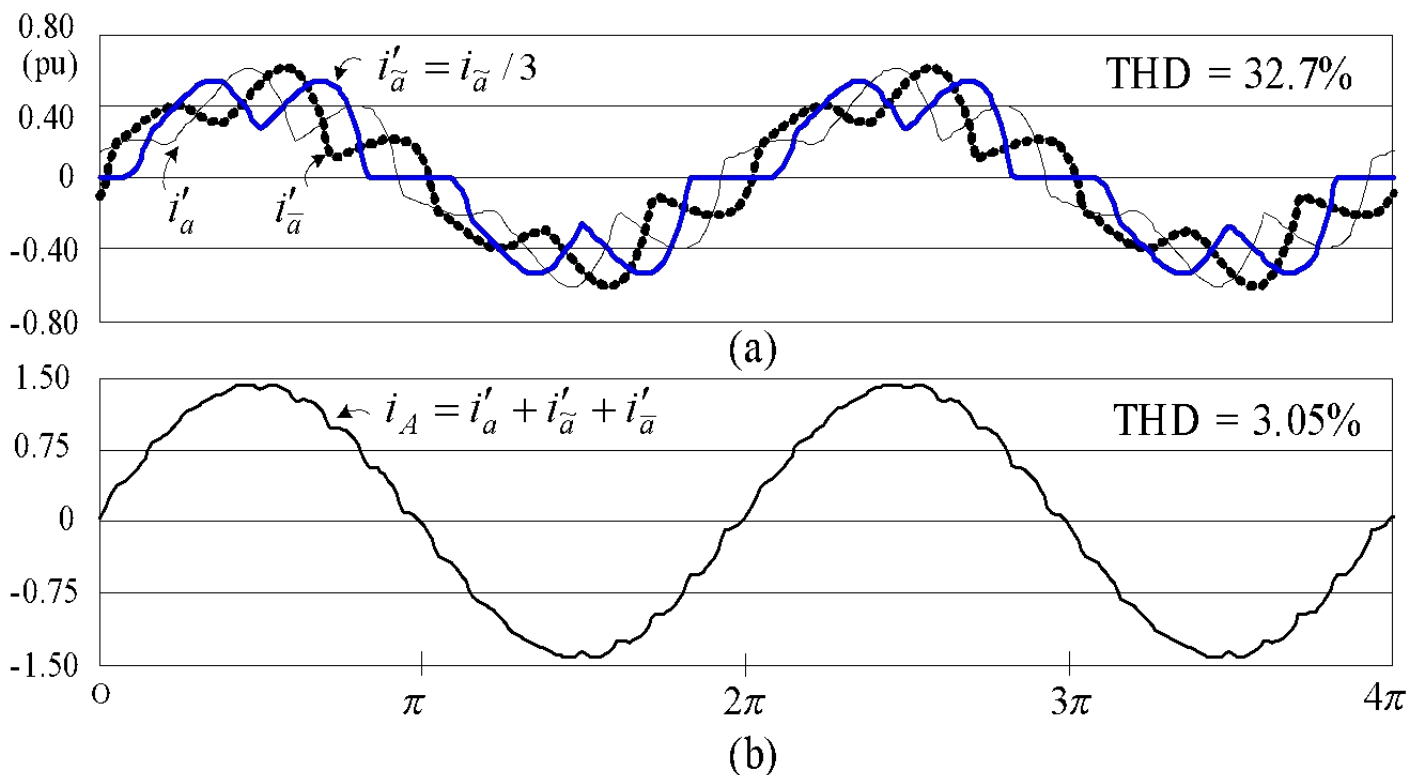
# 18-pulse Separate-type Diode Rectifier

## • Rectifier Topology



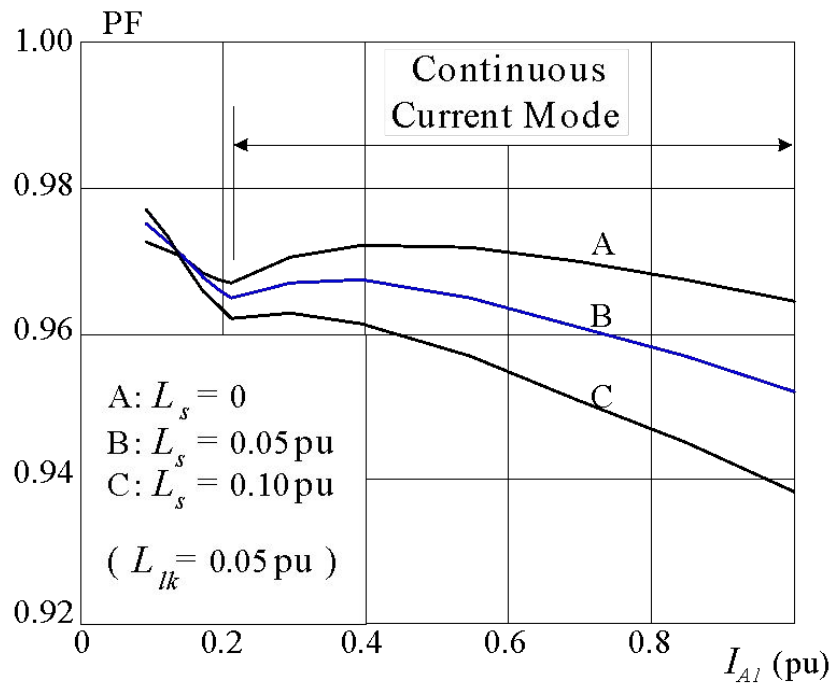
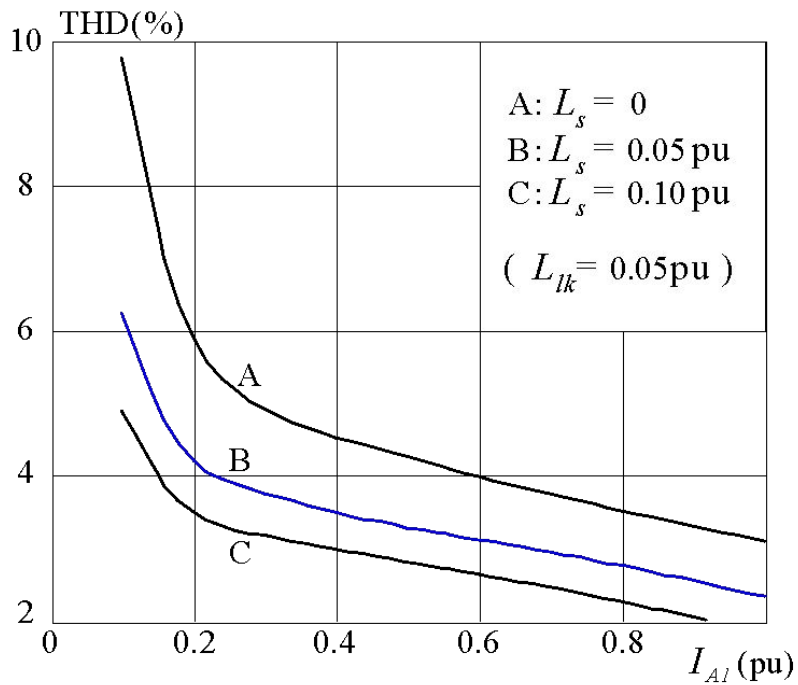
# 18-pulse Separate-type Diode Rectifier

## • Simulated Waveforms



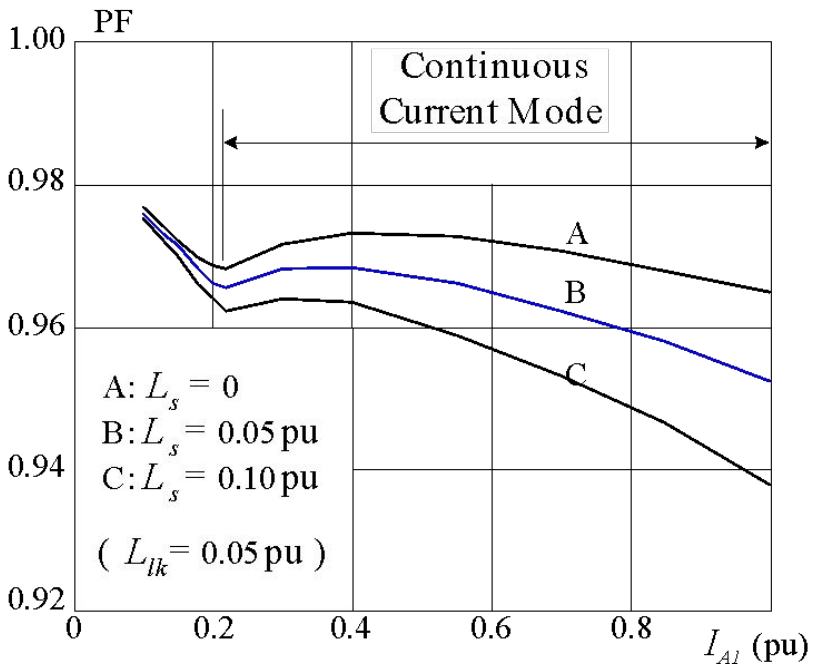
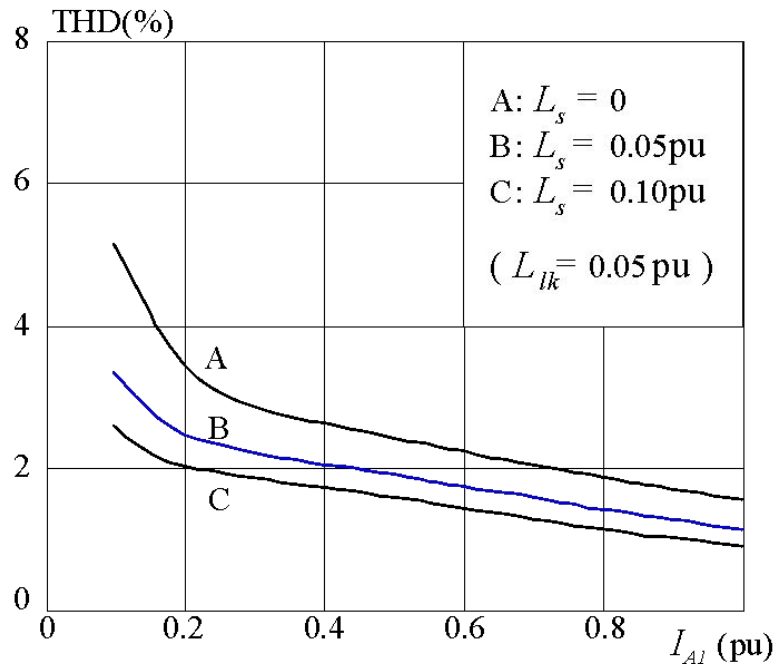
# 18-pulse Separate-type Diode Rectifier

## • Line Current THD and Input PF



# 24-pulse Separate-type Diode Rectifier

- Line Current THD and Input PF





Thanks