Power Converter Systems

Graduate Course EE8407

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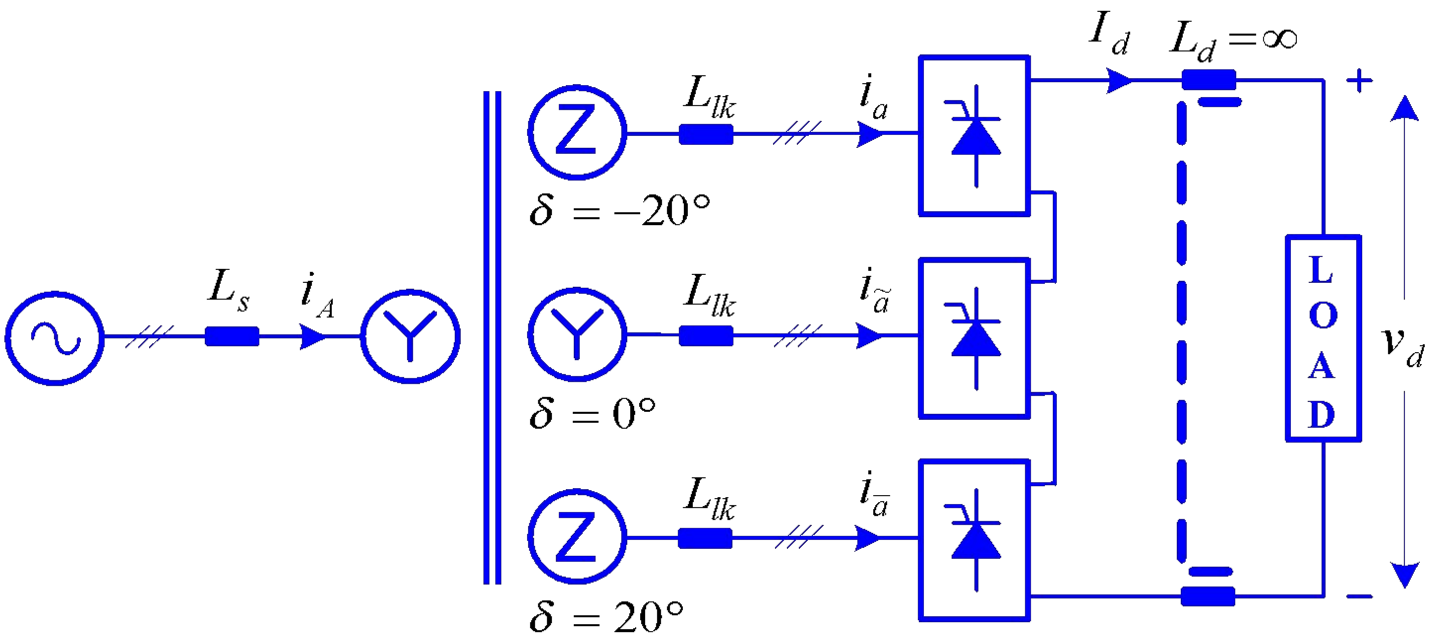
Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley - IEEE Press, 2006

Topic 4

Multi-pulse SCR Rectifiers



Multi-pulse SCR Rectifiers

Lecture Topics

- Six-pulse SCR Rectifier (Building Block)
- 12-, 18- and 24-pulse SCR Rectifiers
- THD and PF

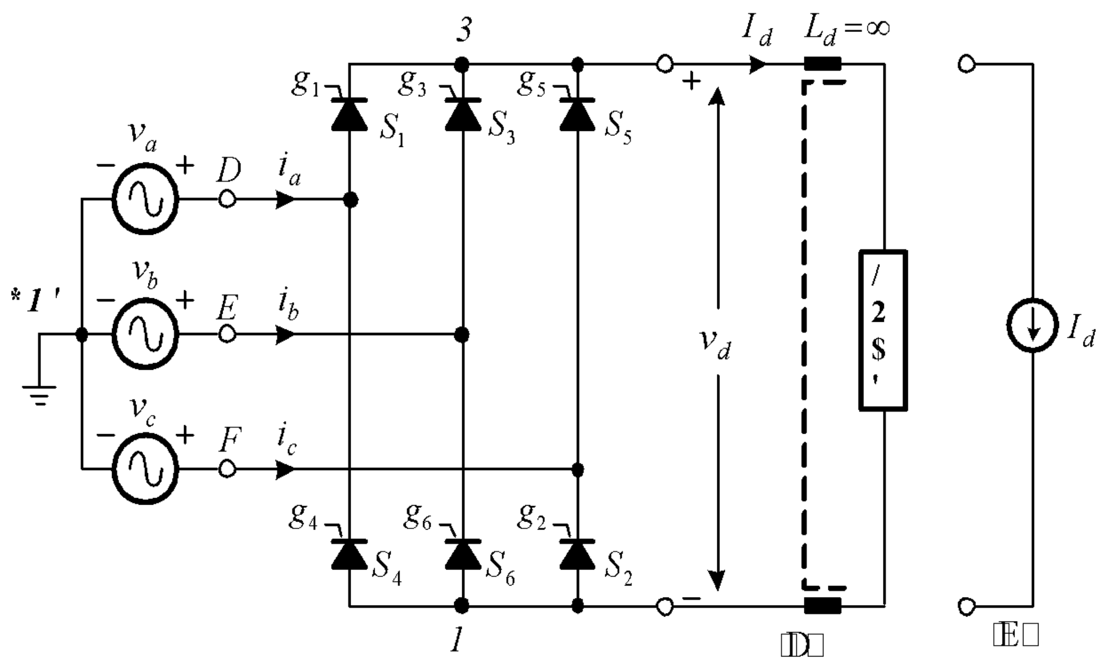
Multi-pulse SCR Rectifiers

Why Use Multi-pulse SCR Rectifiers?

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

Six-pulse SCR Rectifier

• Converter Configuration



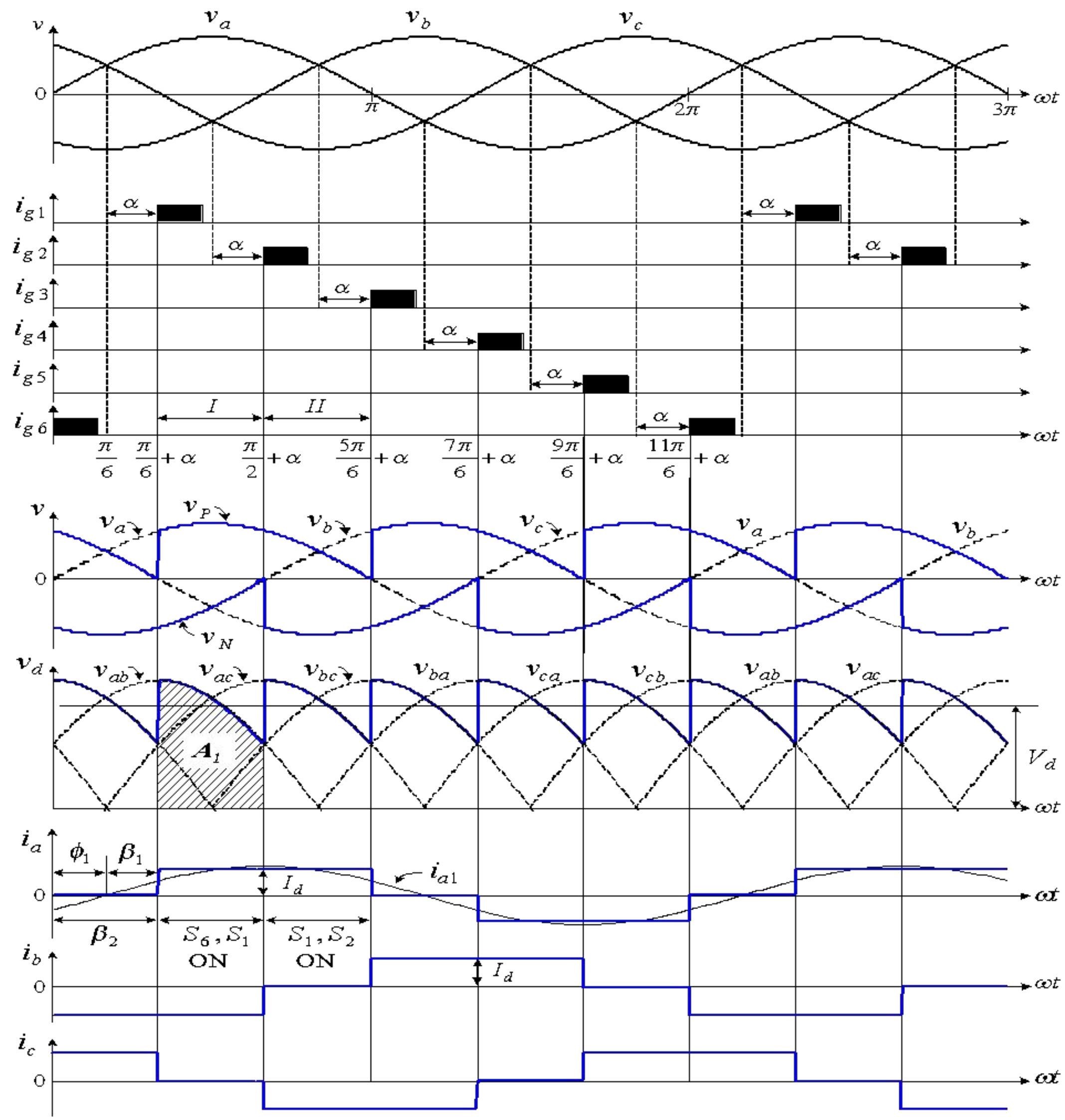
• **Assumption: 1) Ideal SCRs - no power loss**

2) $L_d = \infty \rightarrow$ dc current ripple free

• **Use constant current source I_d as a load**

Six-pulse SCR Rectifier

- **Waveforms**



- **Average dc voltage**

$$V_d = \frac{\text{area } \mathbf{A_1}}{\pi/3}$$

$$= \frac{1}{\pi/3}\int_{\pi/6+\alpha}^{\pi/2+\alpha} v_{ab}\, d(\omega t)$$

$$= \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha$$

$$\approx 1.35 V_{LL} \cos\alpha$$

Six-pulse SCR Rectifier

• Fourier Analysis

$$i_a = \frac{2\sqrt{3}}{\pi} I_d \left(\sin(\omega t - \phi_1) - \frac{1}{5}\sin 5(\omega t - \phi_1) - \frac{1}{7}\sin 7(\omega t - \phi_1) + \frac{1}{11}\sin 11(\omega t - \phi_1) \right.$$
$$\left. + \frac{1}{13}\sin 13(\omega t - \phi_1) - \frac{1}{17}\sin 17(\omega t - \phi_1) - \frac{1}{19}\sin 19(\omega t - \phi_1) + ... \right)$$

• RMS current

$$I_a = \left(\frac{1}{2\pi} \int_0^{2\pi} (i_a)^2 d(\omega t) \right)^{1/2} = \left(\frac{1}{2\pi} \left(\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} (I_d)^2 d(\omega t) + \int_{\frac{7\pi}{6}+\alpha}^{\frac{11\pi}{6}+\alpha} (-I_d)^2 d(\omega t) \right) \right)^{1/2}$$
$$= \sqrt{\frac{2}{3}} I_d = 0.816 I_d$$

• THD

$$THD = \frac{\sqrt{I_a^2 - I_{a1}^2}}{I_{a1}} = \frac{\sqrt{(0.816 I_d)^2 - (0.78 I_d)^2}}{0.78 I_d} = 0.311$$

Six-pulse SCR Rectifier

- **Power Factor (PF)**

  - **Displacement Power Factor**

$$\phi_1 = \beta_2 - \beta_1 = \alpha$$

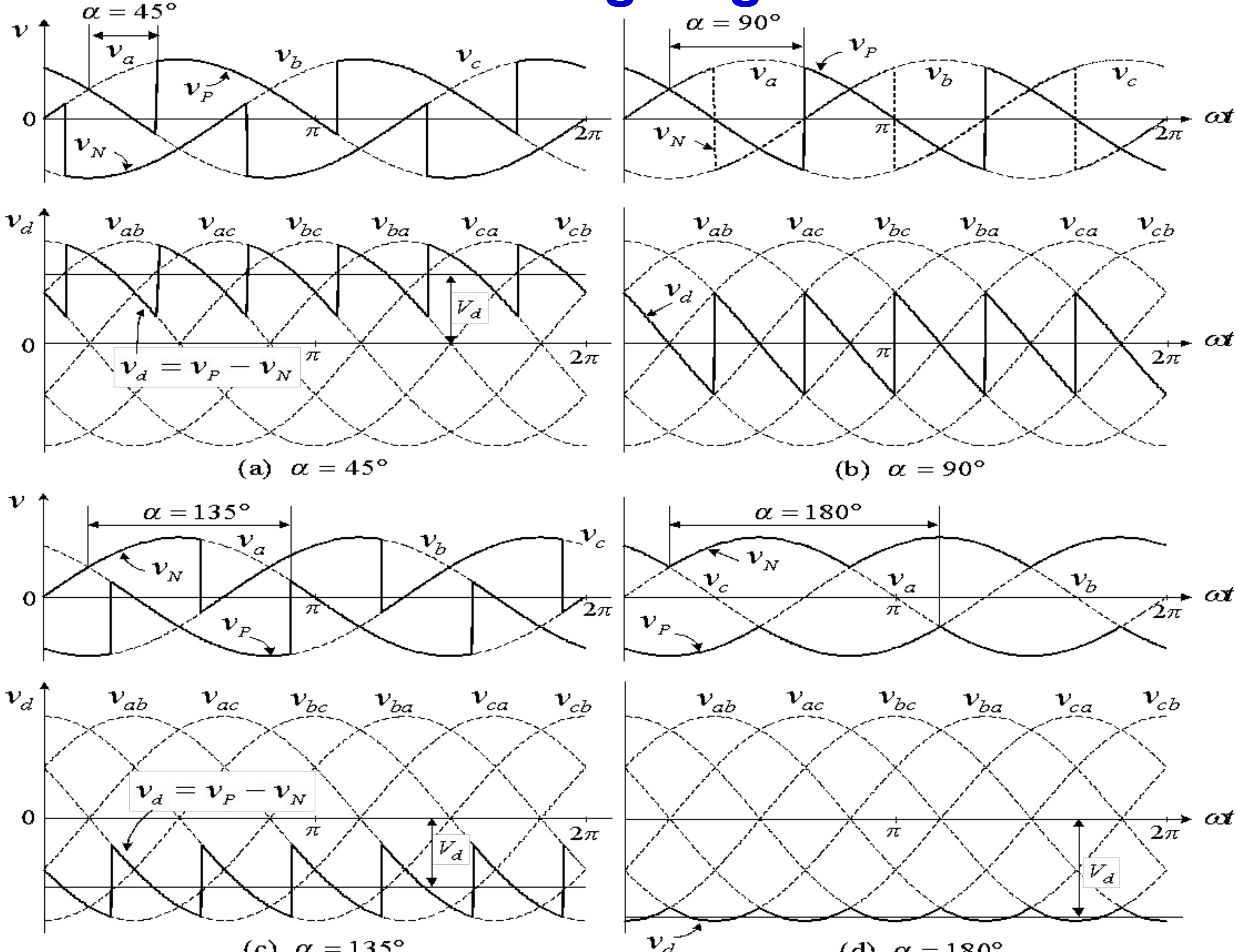
$$DPF = \cos\phi_1 = \cos\alpha$$

  - **Overall Power Factor**

$$PF = \frac{\cos\phi_1}{\sqrt{1 + THD^2}} = 0.955\cos\alpha$$

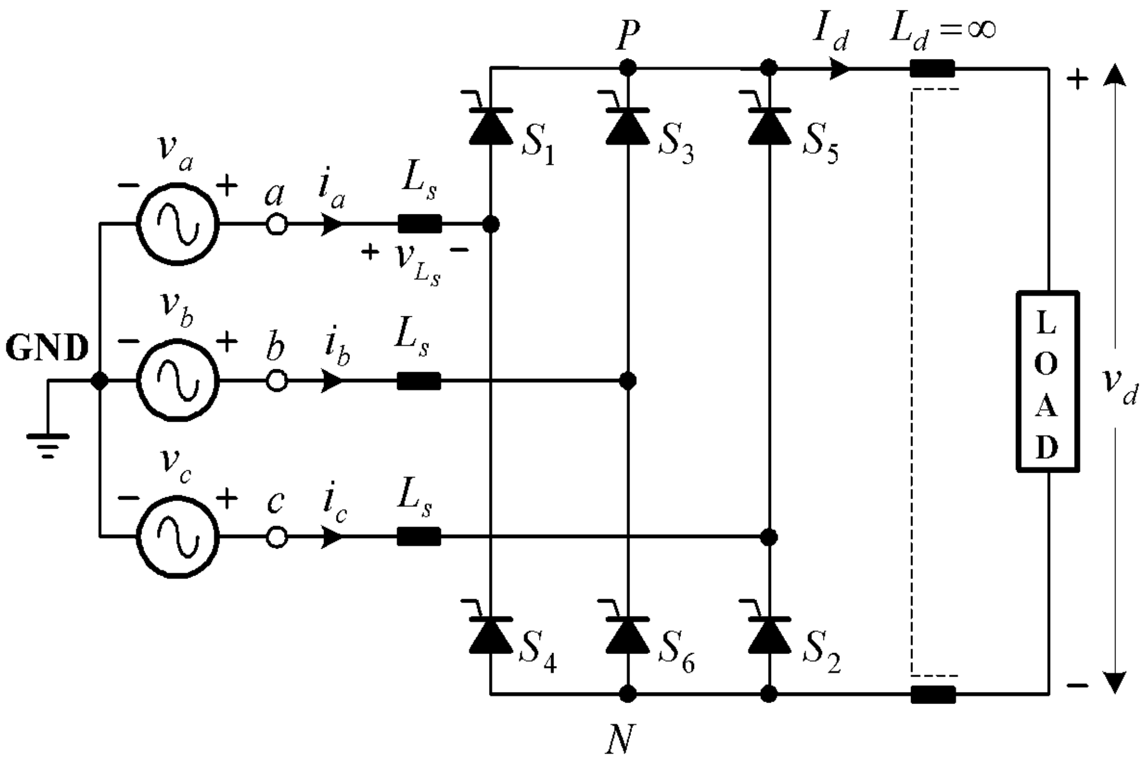
Six-pulse SCR Rectifier

- **Waveforms at Various Firing Angles**



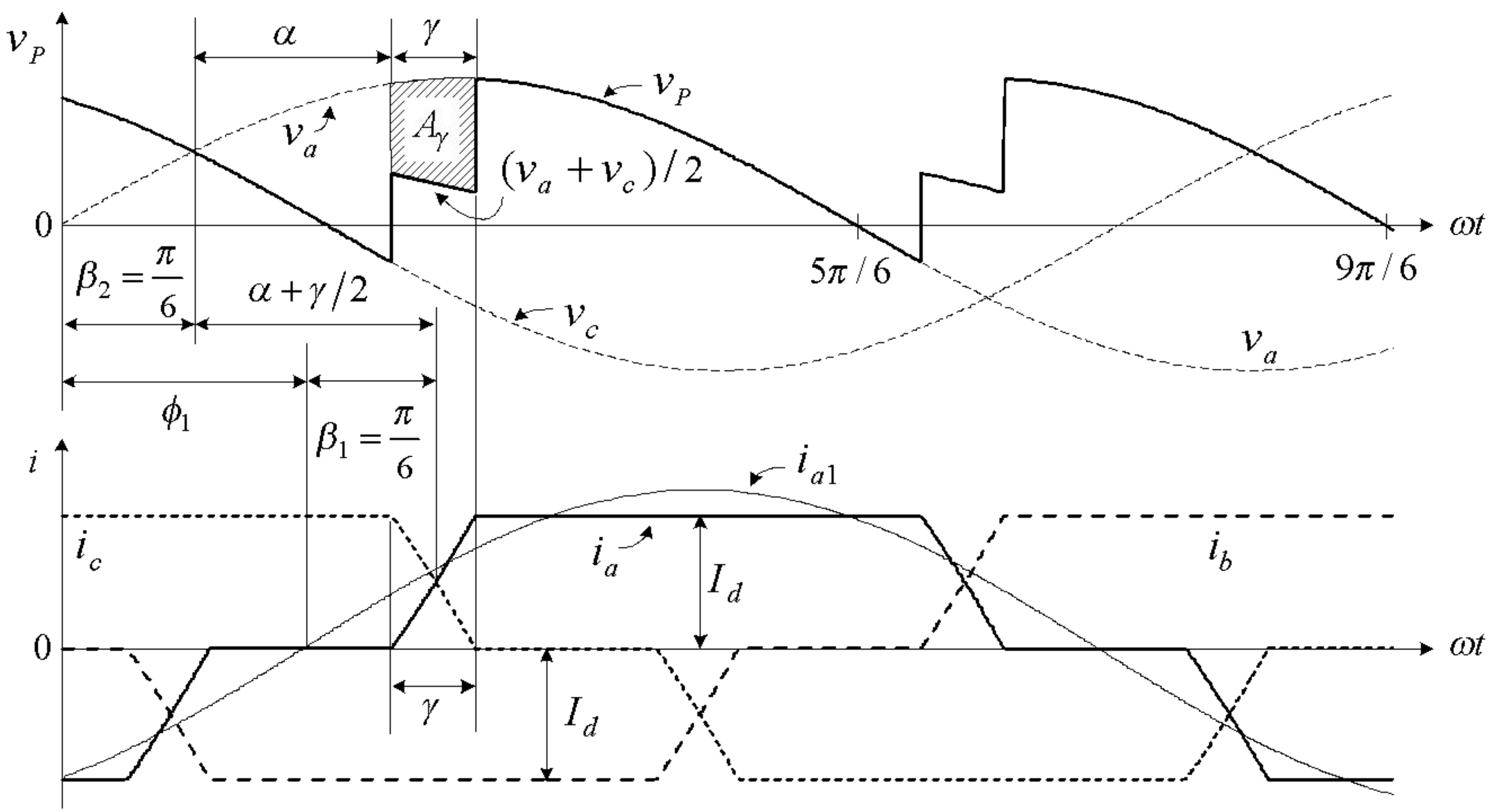
Six-pulse SCR Rectifier

- **Effect of Line Inductance L_s**



Six-pulse SCR Rectifier

- **Waveform During SCR Commutation**



Six-pulse SCR Rectifier

- **DC Voltage Reduction** (caused by commutation)

  - ***S_1 and S_5 on (during commutation)***

$$v_P = v_a - L_s \frac{di_a}{dt} = v_c - L_s \frac{di_c}{dt}$$

from which

$$v_P = \frac{v_a + v_c}{2} - \frac{L_s}{2}\left(\frac{di_a}{dt} + \frac{di_c}{dt}\right)$$

  - **Since $i_a + i_c = I_d$, and i_d is constant**

$$\frac{di_a}{dt} + \frac{di_c}{dt} = 0$$

from which

$$v_P = \frac{v_a + v_c}{2}$$

Six-pulse SCR Rectifier

- **DC Voltage Reduction**

  - **Shaded Area A_γ**

$$A_\gamma = \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha+\gamma} (v_a - v_P)\, d(\omega t)$$

  - **Since** $v_a - v_p = L_s (di_a / dt)$

$$A_\gamma = \int_0^{I_d} \omega L_s di_a = \omega L_s I_d$$

  - **Average dc voltage loss**

$$\Delta V = \frac{A_\gamma}{\pi / 3} = \frac{3\omega L_s}{\pi} I_d$$

  - **Average dc output voltage**

$$V_d = 1.35 V_{LL} \cos\alpha - \frac{3\omega L_s}{\pi} I_d$$

Six-pulse SCR Rectifier

- **Commutation Interval**

  - A_γ **can be rearranged as**

$$A_\gamma = \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha+\gamma} \frac{v_{ac}}{2} d(\omega t) = \frac{V_{LL}}{\sqrt{2}} \left(\cos\alpha - \cos(\alpha + \gamma) \right)$$

where $v_{ac} = \sqrt{2} V_{LL} \sin(\omega t - \frac{\pi}{6}) d(\omega t)$

  - **Substitute** $\omega L_s I_d$ **into the above equation**

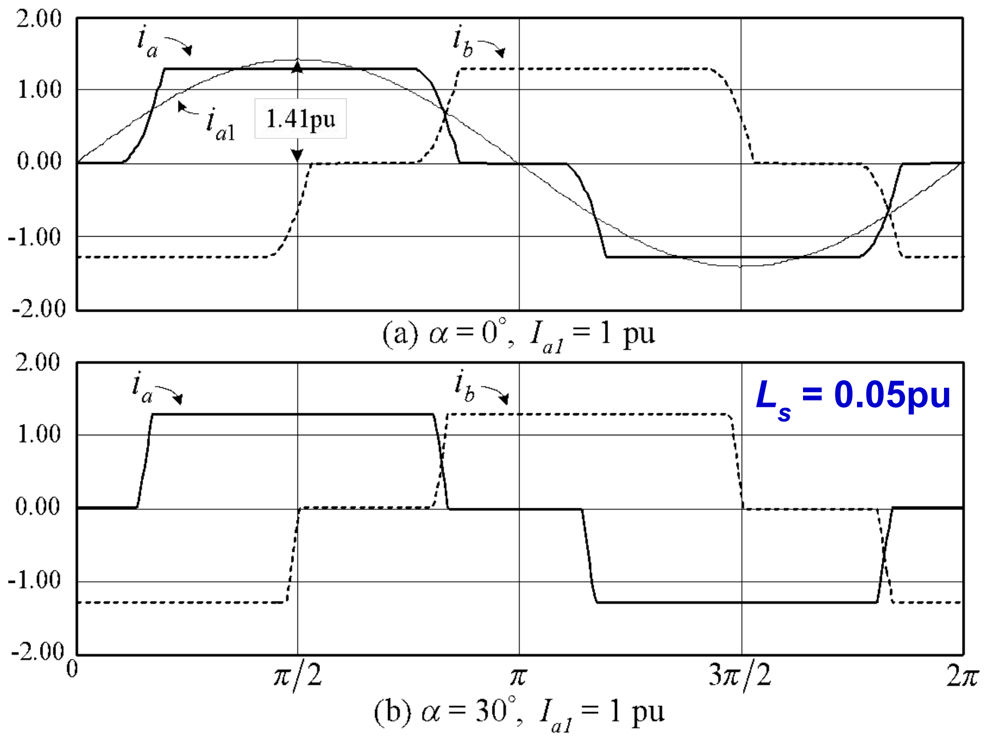
$$\omega L_s I_d = \frac{V_{LL}}{\sqrt{2}} \left(\cos\alpha - \cos(\alpha + \gamma) \right)$$

from which

$$\gamma = \cos^{-1}\left(\cos\alpha - \frac{\sqrt{2}\,\omega L_s}{V_{LL}} I_d \right) - \alpha$$

Six-pulse SCR Rectifier

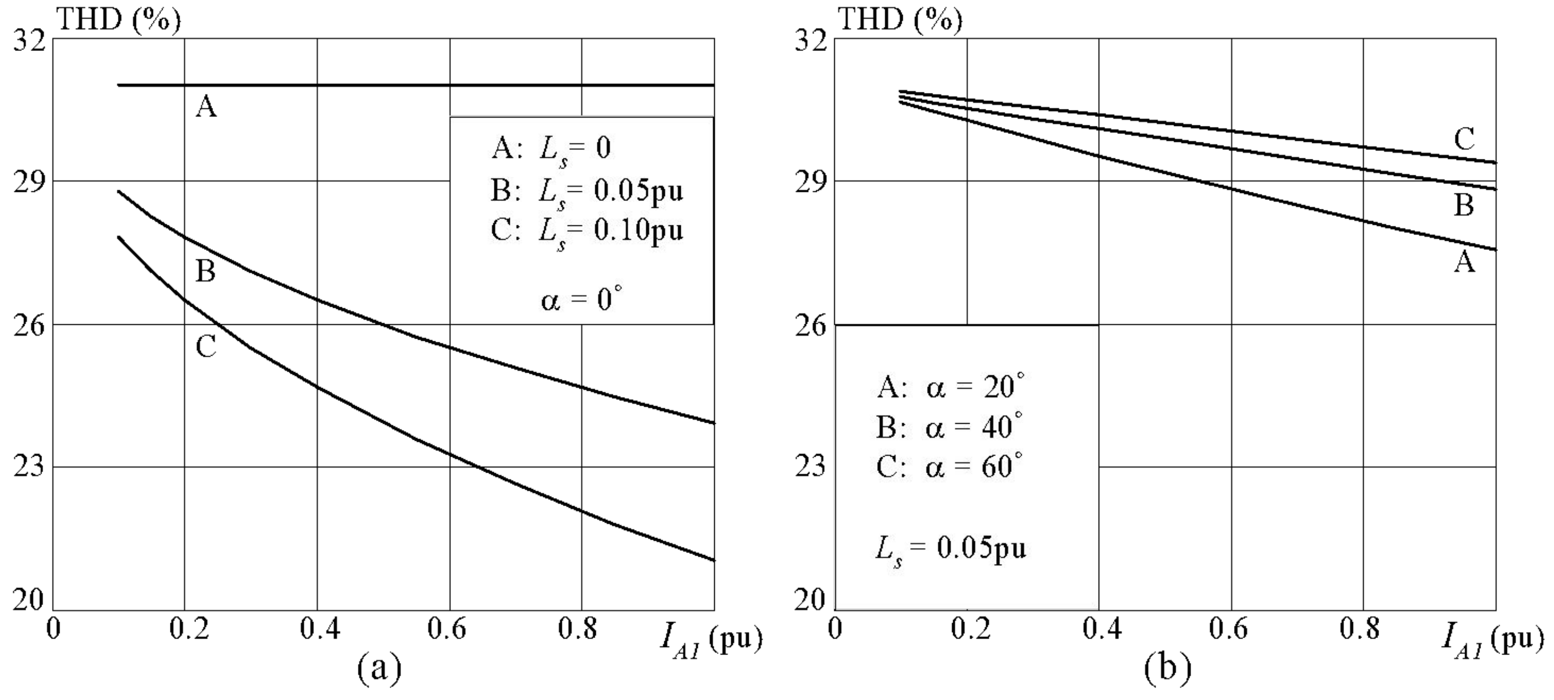
- **Line Current Waveforms**



Harmonics n	5	7	11	13	17	19	23	25	THD %
I_{an} / I_{a1} (%) $\alpha = 0°$	18.6	12.4	6.32	4.58	2.40	1.73	1.02	0.87	23.9
I_{an} / I_{a1} (%) $\alpha = 30°$	19.7	14.1	8.58	7.27	5.16	4.62	3.43	3.16	28.3

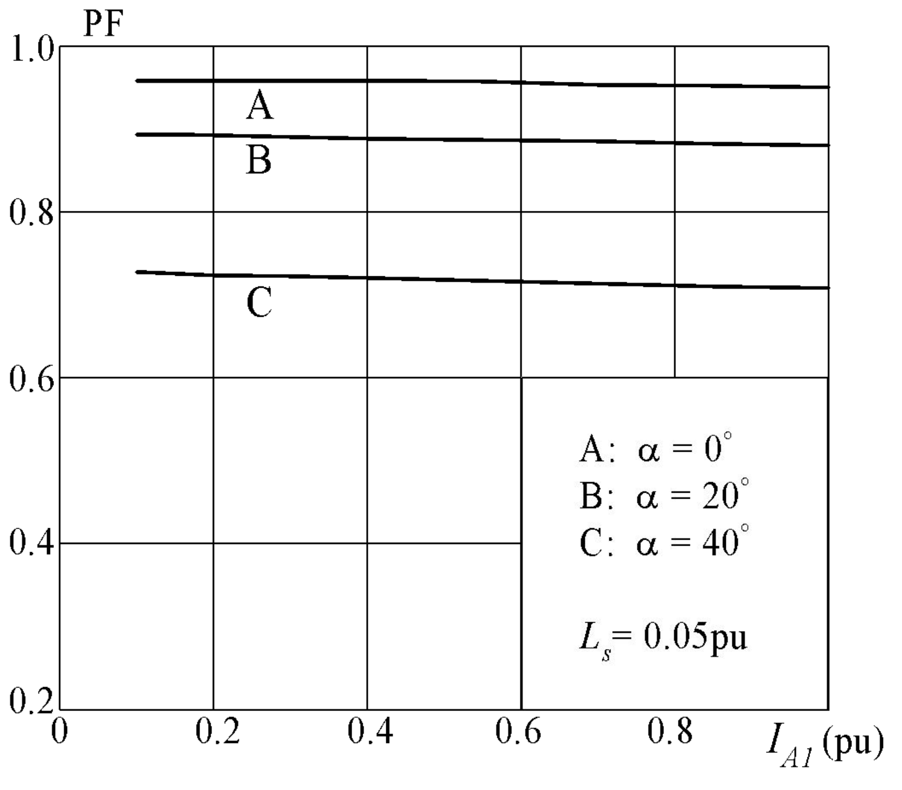
Six-pulse SCR Rectifier

- **Line Current THD**



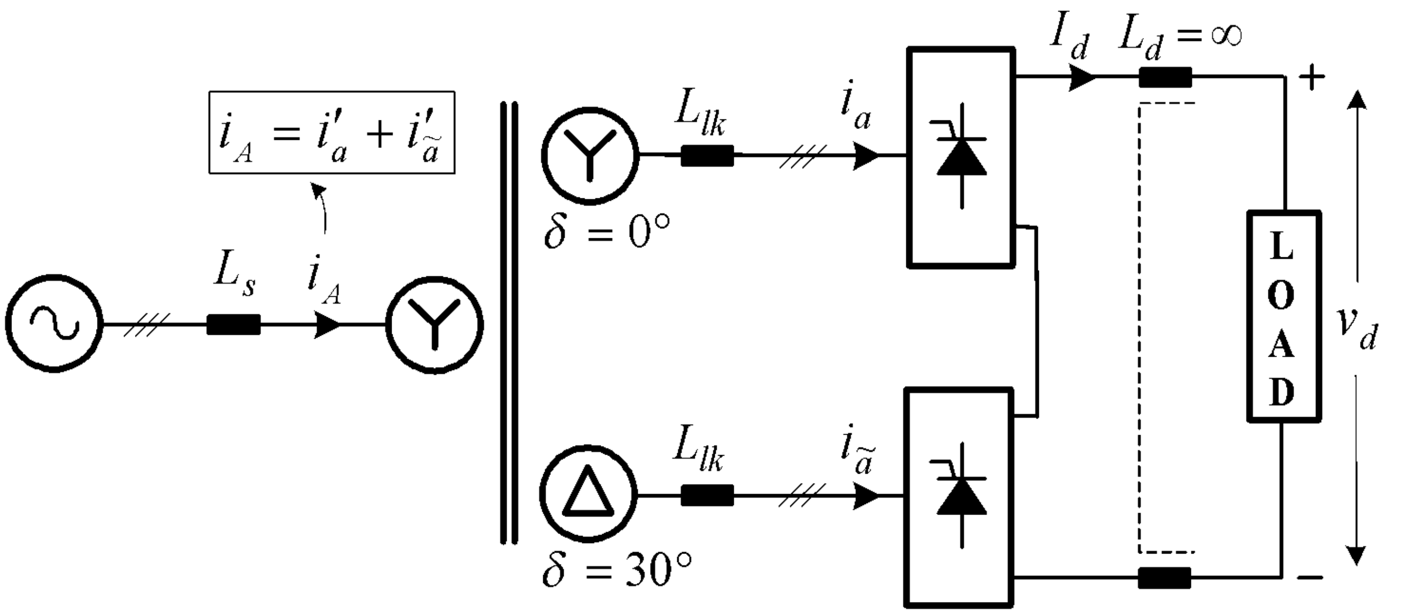
Six-pulse SCR Rectifier

- **Power Factor**



12-pulse SCR Rectifier

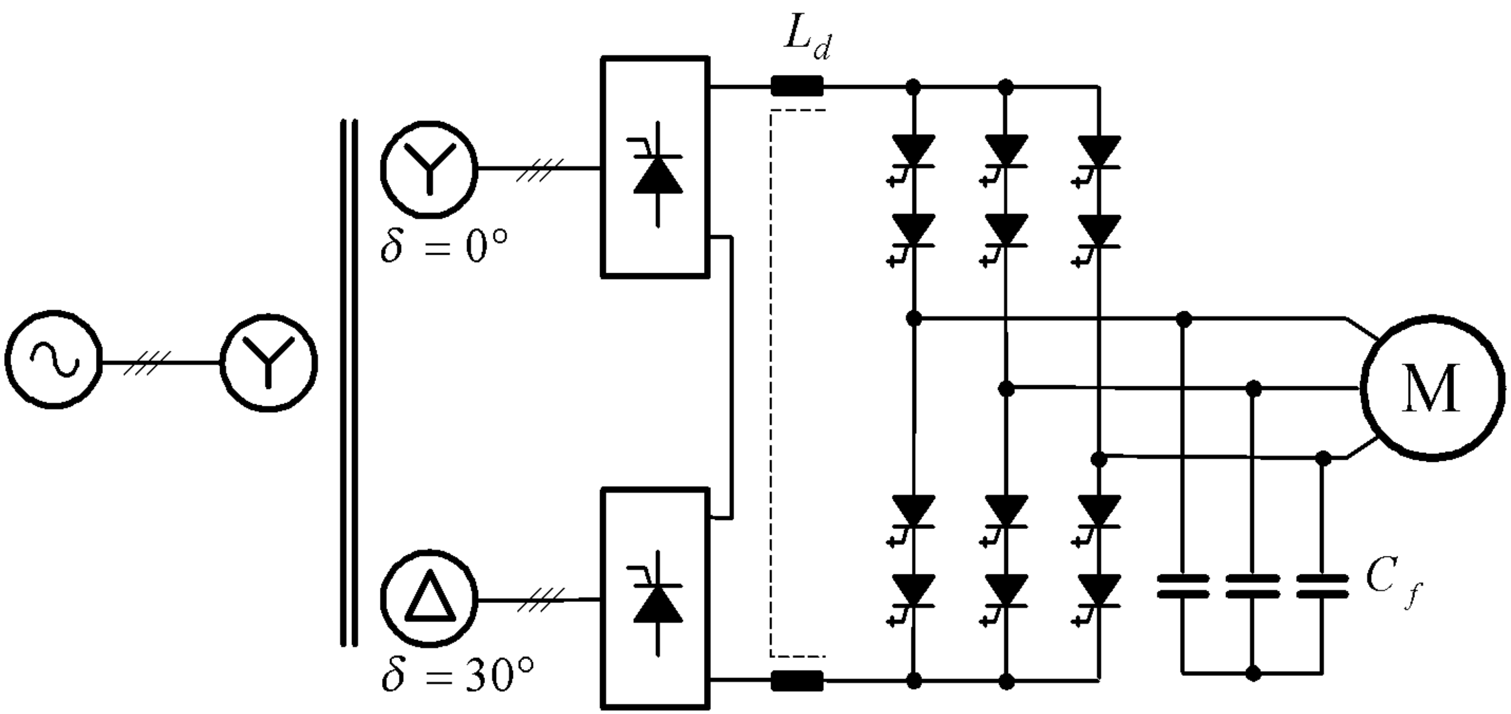
- Topology



- Main Benefits
  - Low line current THD
  - No SCRs in series

12-pulse SCR Rectifier

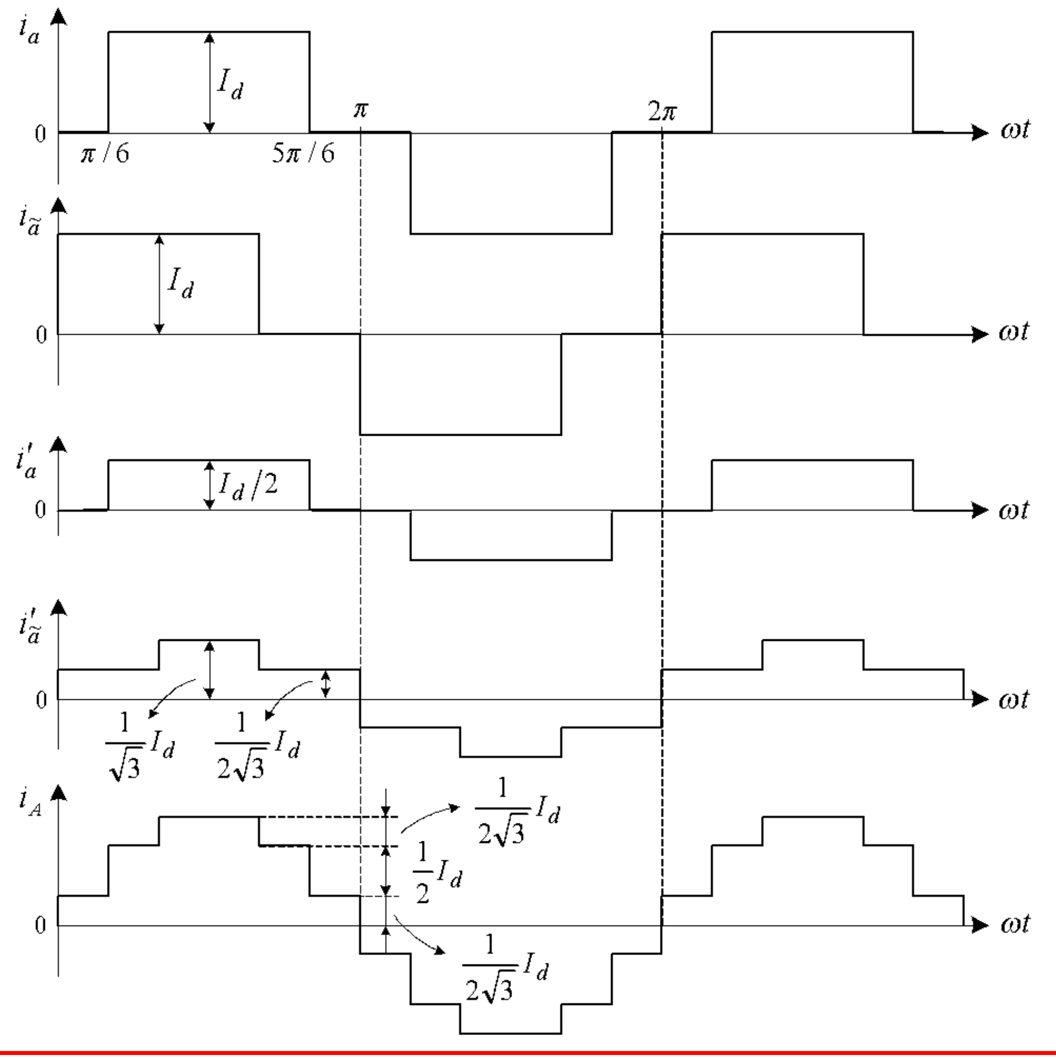
- **Application Example**



- **Used for current source inverter (CSI) fed drive**

12-pulse SCR Rectifier

- **Waveforms of Idealized Rectifier** *($L_s = L_{lk} = 0$)*



12-pulse SCR Rectifier

• Fourier Analysis

- **Secondary currents**

$$i_a = \frac{2\sqrt{3}}{\pi} I_d \left(\sin \omega t - \frac{1}{5}\sin 5\omega t - \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t - \frac{1}{17}\sin 17\omega t - \frac{1}{19}\sin 19\omega t + ... \right)$$

$$i_{\tilde{a}} = \frac{2\sqrt{3}}{\pi} I_d \left(\sin(\omega t + 30°) - \frac{1}{5}\sin 5(\omega t + 30°) - \frac{1}{7}\sin 7(\omega t + 30°) + \frac{1}{11}\sin 11(\omega t + 30°) + \frac{1}{13}\sin 13(\omega t + 30°) - \frac{1}{17}\sin 17(\omega t + 30°) - \frac{1}{19}\sin 19(\omega t + 30°) + ... \right)$$

12-pulse SCR Rectifier

- **Fourier Analysis (continued)**
  - **Secondary currents referred to the primary side**

$$i'_a = \frac{\sqrt{3}}{\pi} I_d \{\sin \omega t - \frac{1}{5}\sin 5\omega t - \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t - \frac{1}{17}\sin 17\omega t - \frac{1}{19}\sin 19\omega t + ...\}$$

$$i'_{\tilde{a}} = \frac{\sqrt{3}}{\pi} I_d \{\sin \omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t + \frac{1}{17}\sin 17\omega t + \frac{1}{19}\sin 19\omega t + ...\}$$

  - **Primary line current**

$$i_A = i'_a + i'_{\tilde{a}} = \frac{2\sqrt{3}}{\pi} I_d \{\sin \omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t + \frac{1}{23}\sin 23\omega t + \frac{1}{25}\sin 25\omega t + ...\}$$

12-pulse SCR Rectifier

- **Line Current THD**

  - **Secondary side**

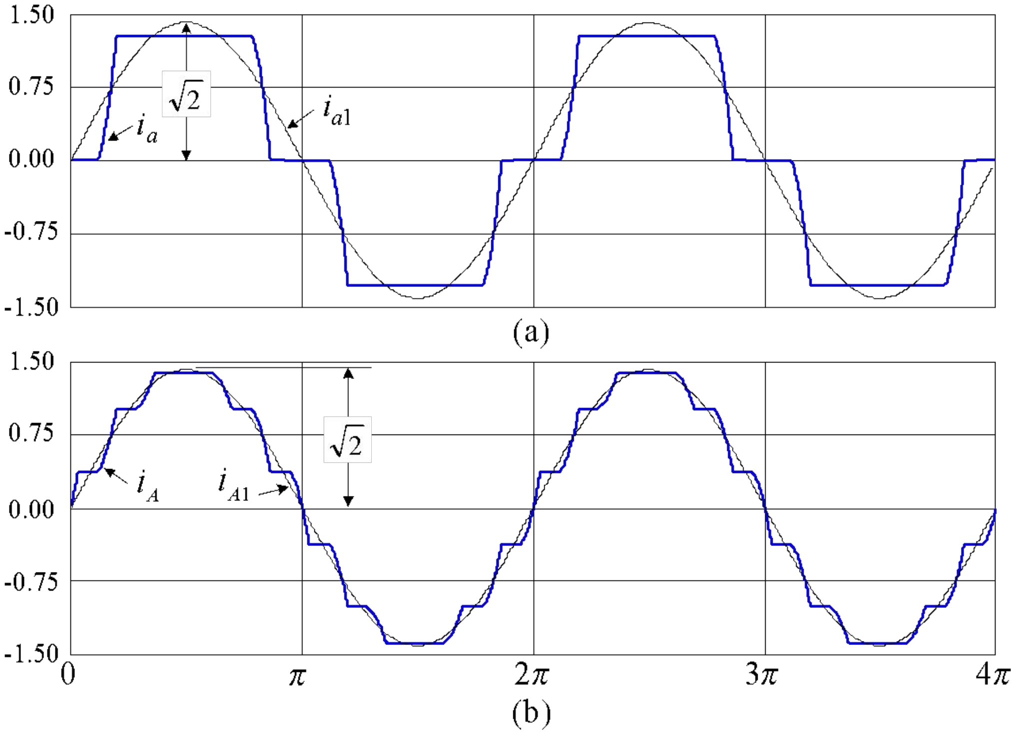
$$THD_{i_a} = \frac{\sqrt{I_a^2 - I_{a1}^2}}{I_{a1}} = \frac{\left(I_{a5}^2 + I_{a7}^2 + I_{a11}^2 + I_{a13}^2 + \ldots\right)^{1/2}}{I_{a1}} = 31.1\%$$

  - **Primary side**

$$THD_{i_A} = \frac{\sqrt{I_A^2 - I_{A1}^2}}{I_{A1}} = \frac{\left(I_{A11}^2 + I_{A13}^2 + I_{A23}^2 + I_{A25}^2 + \ldots\right)^{1/2}}{I_{A1}} = 15.3\%$$

12-pulse SCR Rectifier

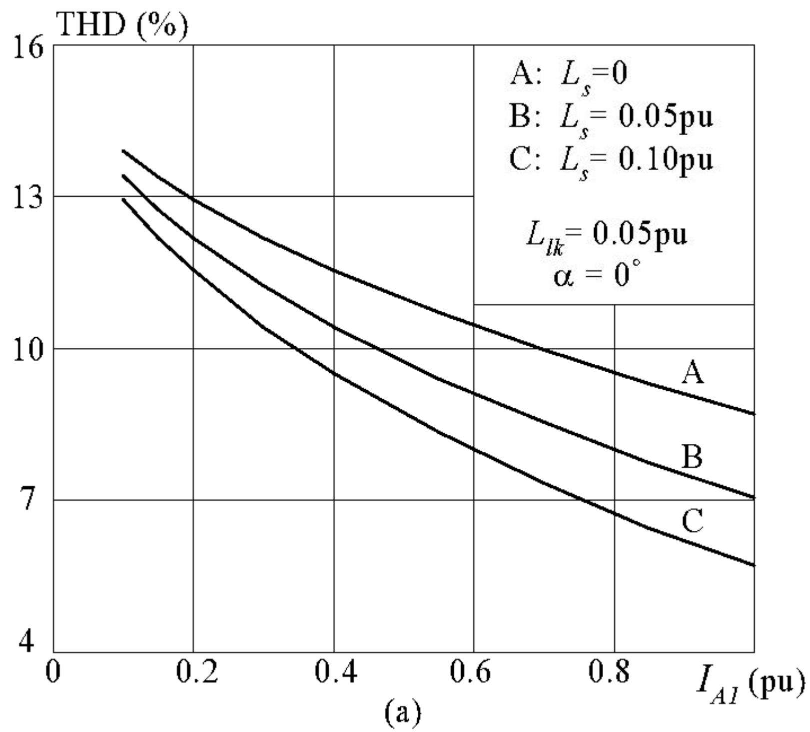
- **Line Current Waveform ($L_s \neq 0$)**

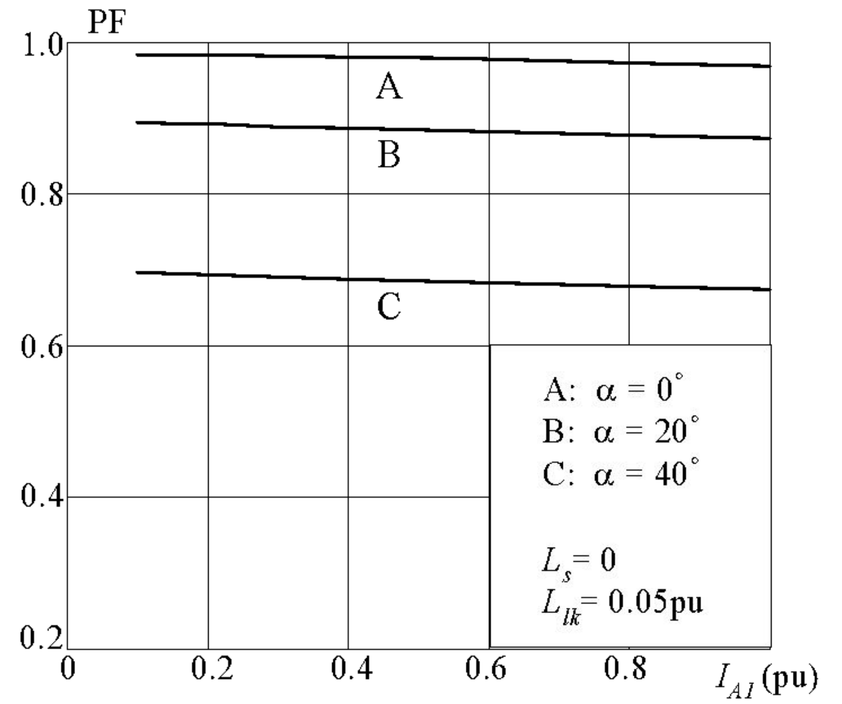


Harmonics n	5	7	11	13	17	19	23	25	THD (%)
I_{an} / I_{a1} (%)	18.8	12.7	6.78	5.05	2.77	2.01	1.01	0.75	24.6
I_{An} / I_{A1} (%)	0	0	6.78	5.05	0	0	1.01	0.75	8.61

12-pulse SCR Rectifier

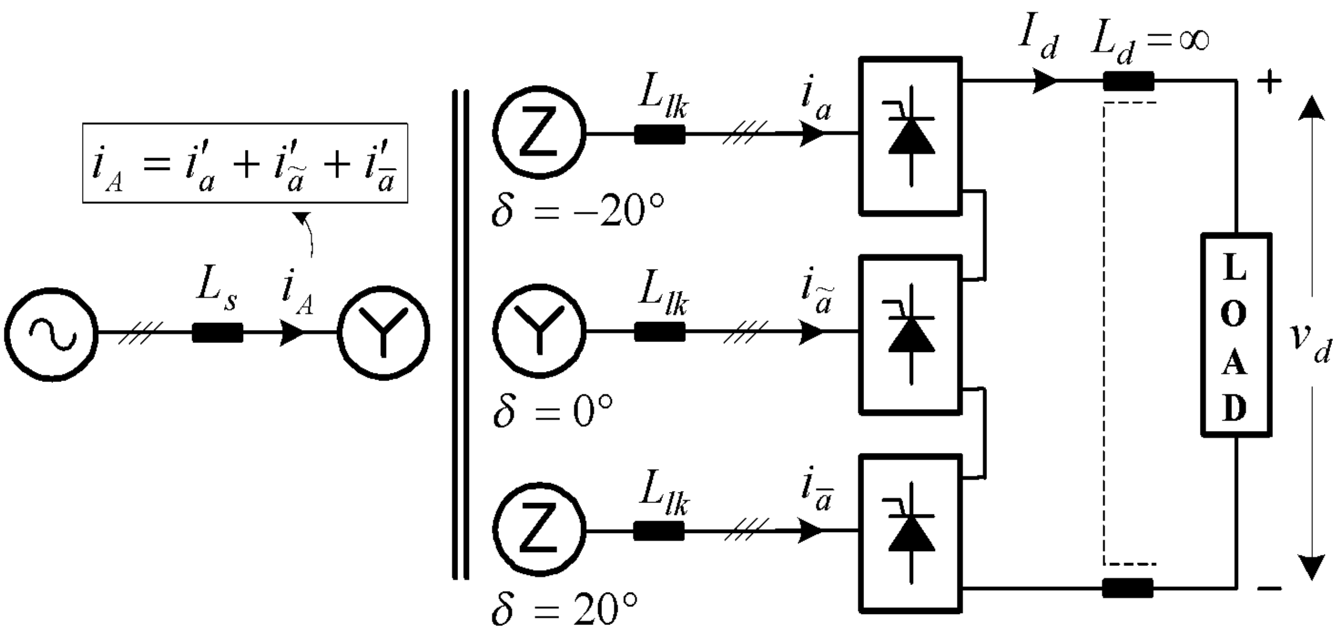
- **THD and PF**





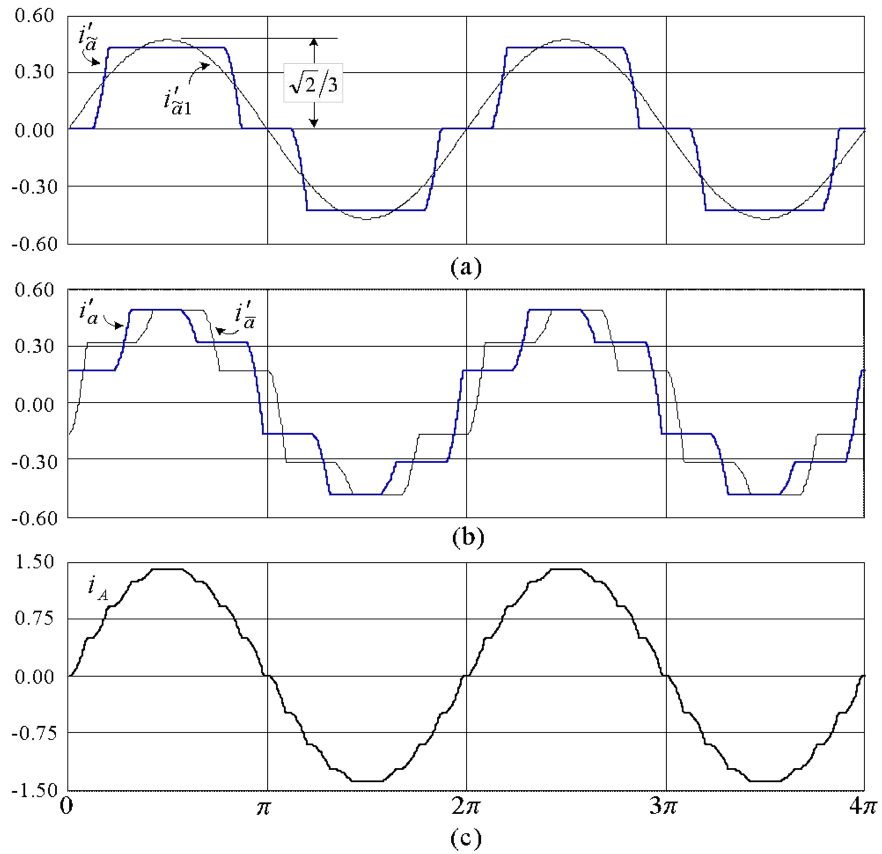
18-pulse SCR Rectifier

• Rectifier Configuration



18-pulse SCR Rectifier

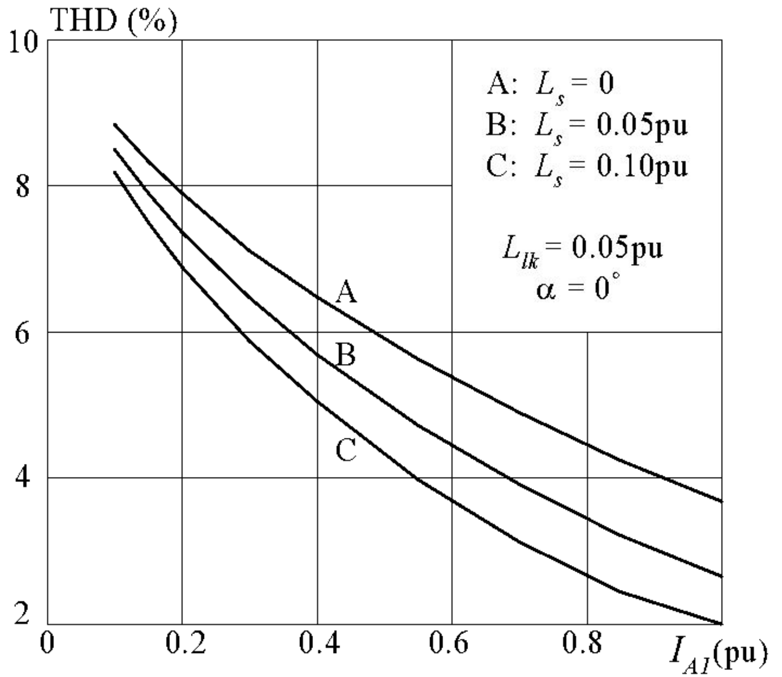
- **Waveforms**

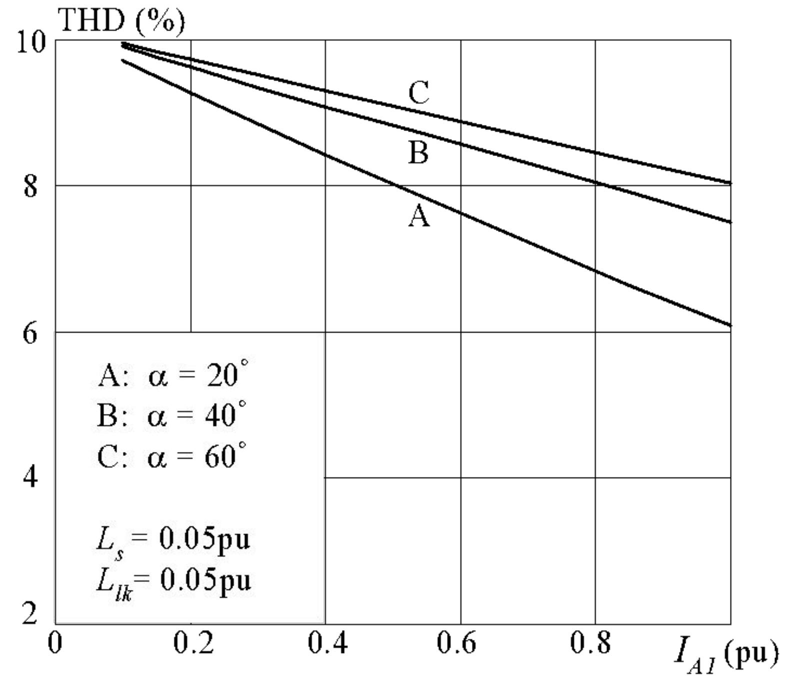


Harmonics n	5	7	11	13	17	19	23	25	THD (%)
I'_{an} / I'_{a1} (%)	18.8	12.7	6.78	5.05	2.77	2.01	1.01	0.75	24.6
I_{An} / I_{A1} (%)	0	0	0	0	2.77	2.01	0	0	3.54

18-pulse SCR Rectifier

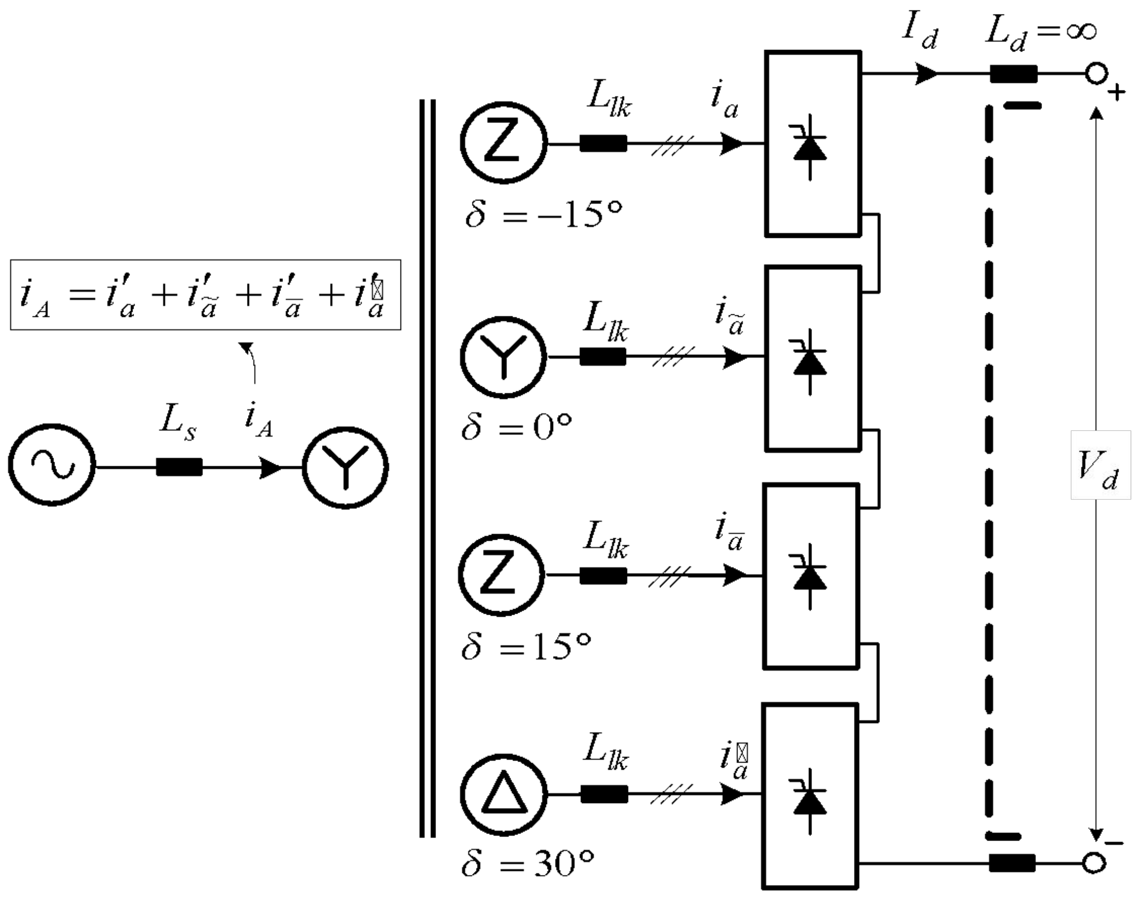
- **Line Current THD**





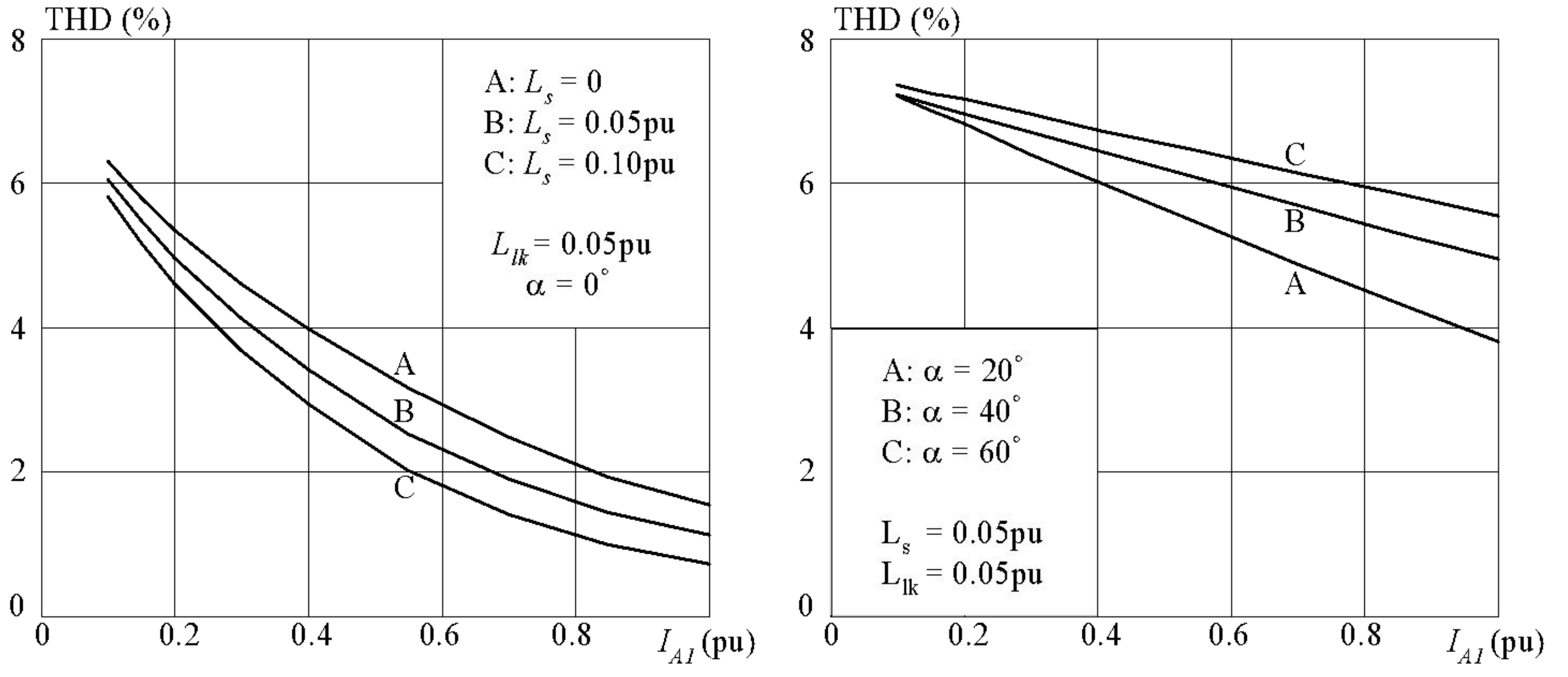
24-pulse SCR Rectifier

- **Rectifier Configuration**



24-pulse SCR Rectifier

- **Line Current THD**



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Thanks