Lecture 03 -

AC-DC 컨버터 (I)

-다이오드 정류기-

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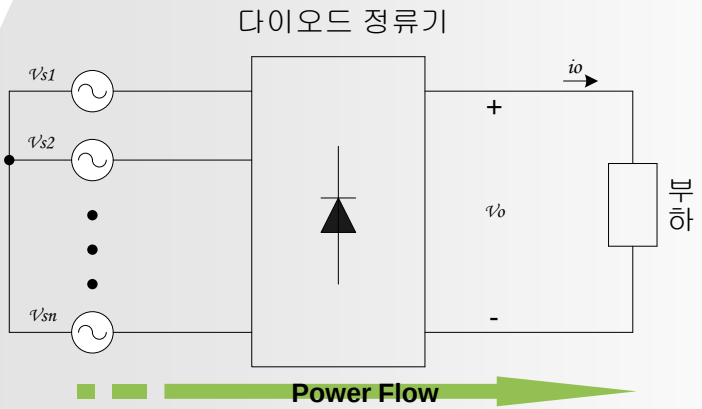
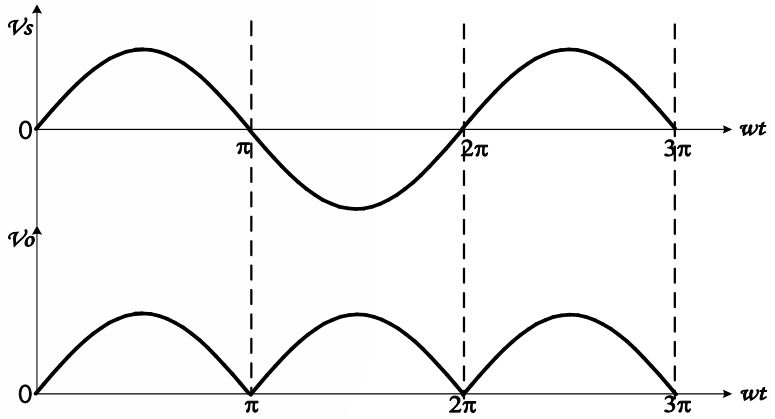
다이오드 정류회로

❖ 정류기 (Rectifier)의 기능 : AC ➔ DC



$$v_o = |v_S|$$



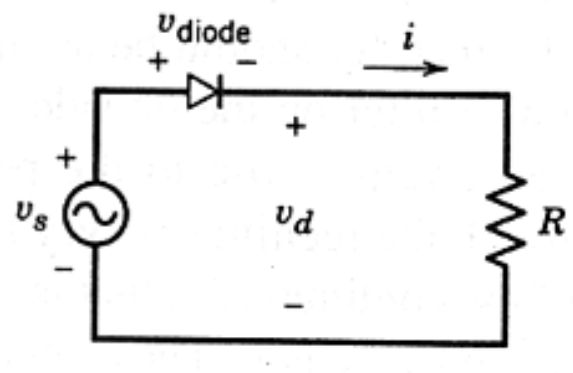
- **Input**
  - ✓ 전압 : 정현파 (given)
  - ✓ 전류 : 구형파
- **Output**
  - ✓ 전압 : 직류+교류
  - ✓ 전류 : 직류로 간주

입력전류 & 출력전압이 중요! ➔ Fourier Series로 해석

- **AC-DC Conversion**
  - ✓ Diode Rectifier (Diode)
  - ✓ Phase Controlled Rectifier (Thyristor)
  - ✓ PWM Converter (IGBT)
- **AC-DC Diode Rectifier**
  - ✓ 1상한 동작 (전원→부하)
  - ✓ 출력전압 제어 불가능
  - ✓ 입력전압에 의해 출력전압 결정

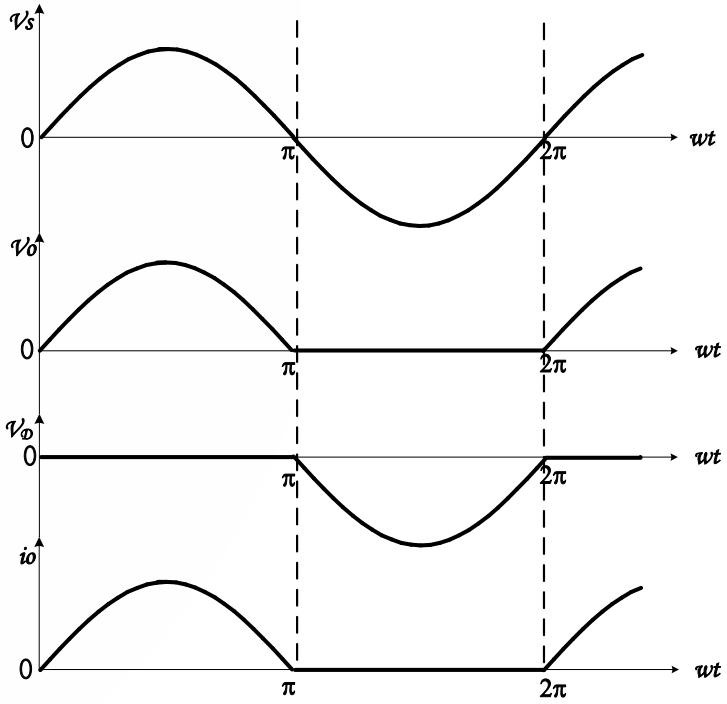
단상 반파 정류회로 – R 부하 (I)

❖ Circuit & Waveform



$$v_s = \sqrt{2}V \sin \omega t$$

$$KVL : v_s = v_D + v_o$$



i) $0 \le \omega t < \pi$

$\rightarrow Forward\ \ bias$

$$v_o = v_s = \sqrt{2}V \sin \omega t$$

$$i_o = \frac{v_o}{R} \approx \frac{v_s}{R} = \frac{V_m}{R} \sin \omega t$$

$(on - drop\ 무시)$

ii) $\pi \le \omega t < 2\pi$

$\rightarrow Reverse\ vias$

$$v_o = 0, \quad i_o = 0$$

$$v_D = v_s$$

단상 반파 정류회로 – R 부하 (II)

❖ Analysis

- **Average value**

$$v_{o,avg} = \frac{1}{T}\int_0^T v_o dt = \frac{1}{2\pi}\int_0^{\pi} V_m \sin\omega t \cdot d\omega t = \frac{v_m}{\pi}$$

$$i_{o,avg} = \frac{1}{T}\int_0^T i_o dt = \frac{v_{o,avg}}{R}$$

- **RMS value**

$$v_{o,rms} = \sqrt{\frac{1}{T}\int_0^T v_o^2 dt} = \frac{v_m}{2}$$

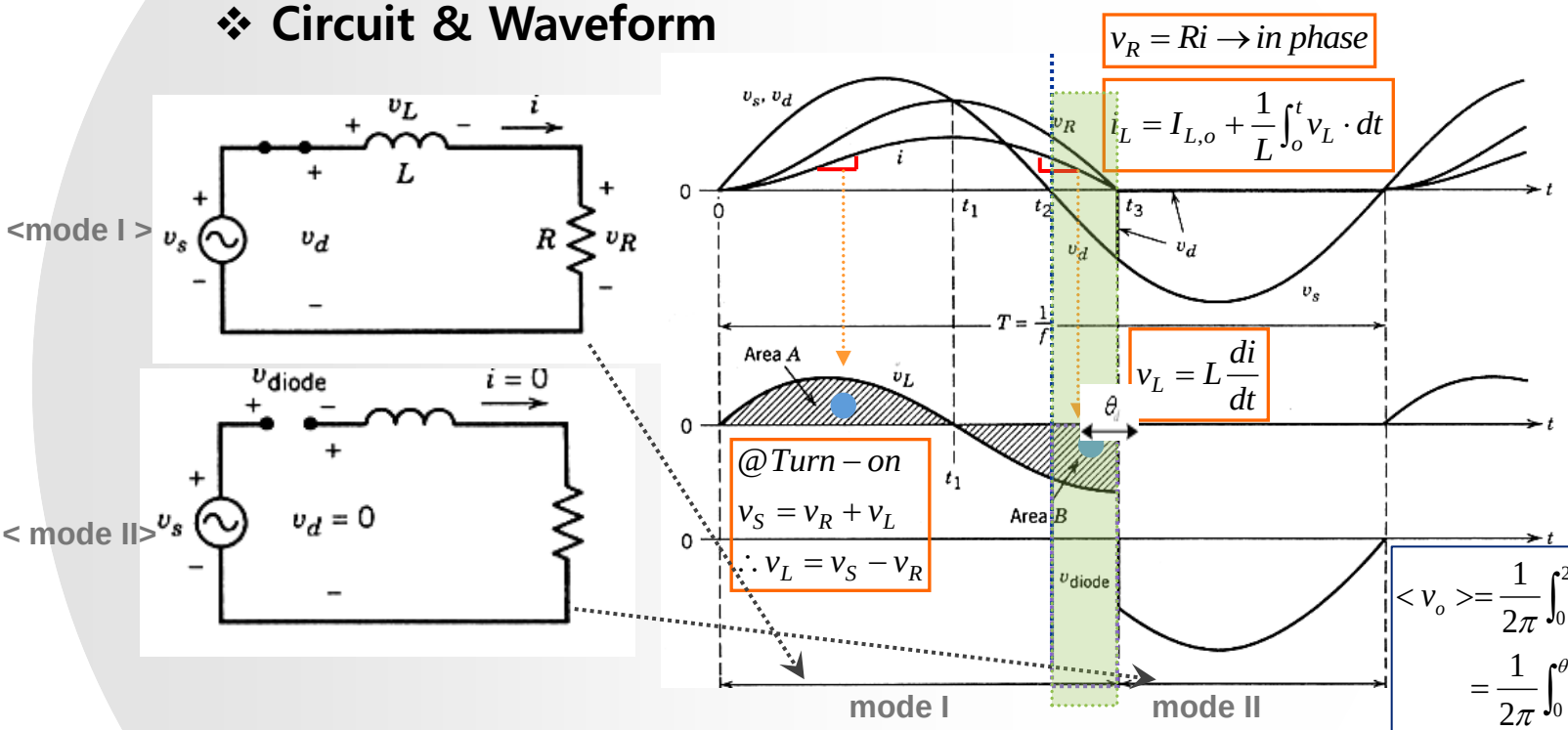
$$i_{o,rms} = \sqrt{\frac{1}{T}\int_0^T i_o^2 dt} = \frac{v_m}{2R}$$

- **Average power**

$$P_{avg} = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{2\pi}\int_0^{2\pi} v_o i_o \cdot d\omega t = \frac{V_m^2}{2R} = \frac{v_{rms}^2}{R}$$

단상 반파 정류회로 – RL 부하 (I)

❖ Circuit & Waveform



$$< v_o >= \frac{1}{2\pi}\int_0^{2\pi} v_o\, d(\omega t)$$

$$= \frac{1}{2\pi}\int_0^{\theta_2} \sqrt{2}V \sin\omega t\, d(\omega t)$$

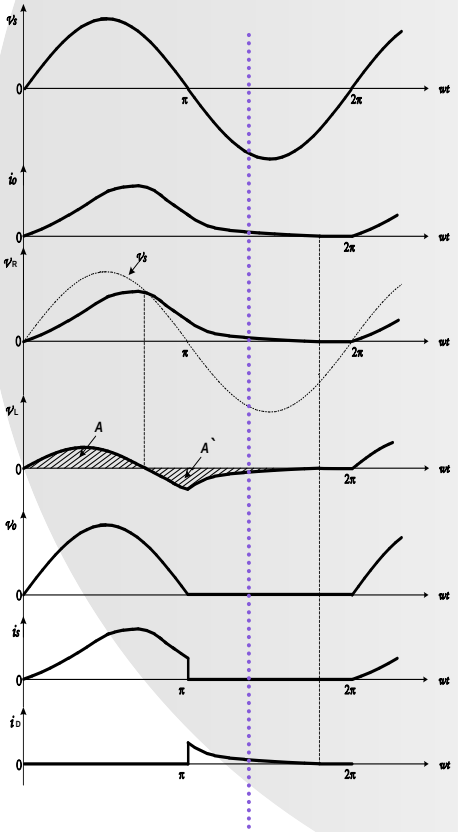
$$= \frac{\sqrt{2}V}{2\pi}(1-\cos\theta_2)$$

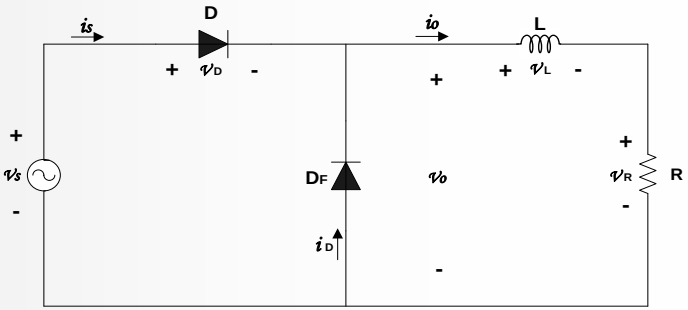
$$= \frac{1-\cos\theta_2}{2} < v_o >_R$$

$$L \rightarrow \infty\ ;\quad \theta_2 \rightarrow 2\pi\ ;\quad < v_o > \rightarrow 0$$

단상 반파 정류회로 – RL 부하 (II)

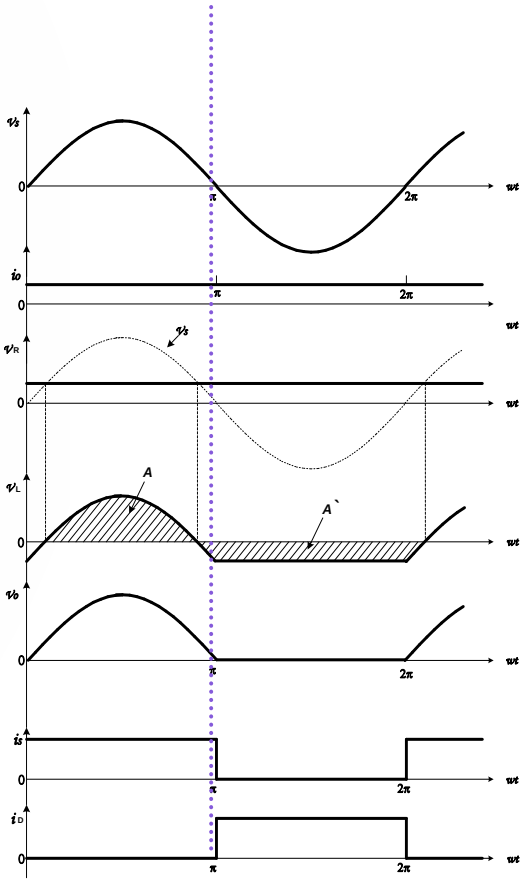
❖ Freewheeling Diode





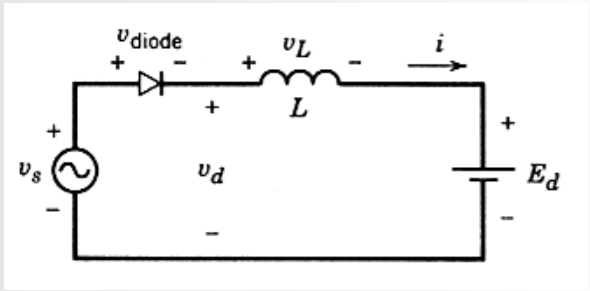
$$< v_o >= \frac{\sqrt{2}V}{\pi}$$

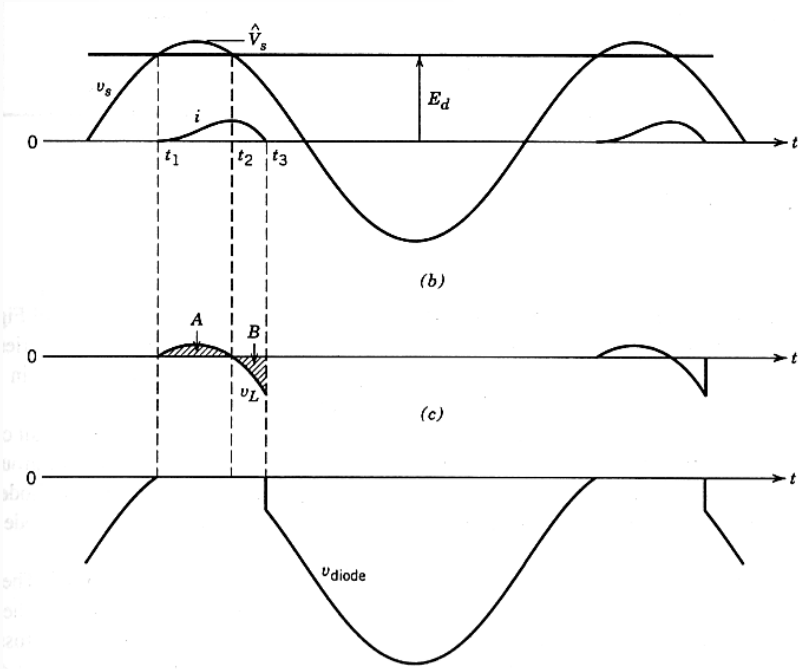
- io의 감소시간은 R-L 회로의 시정수 τ(=L/R)에 따라 결정



단상 반파 정류회로 – Motor 부하

❖ Design of Diode Rectifier



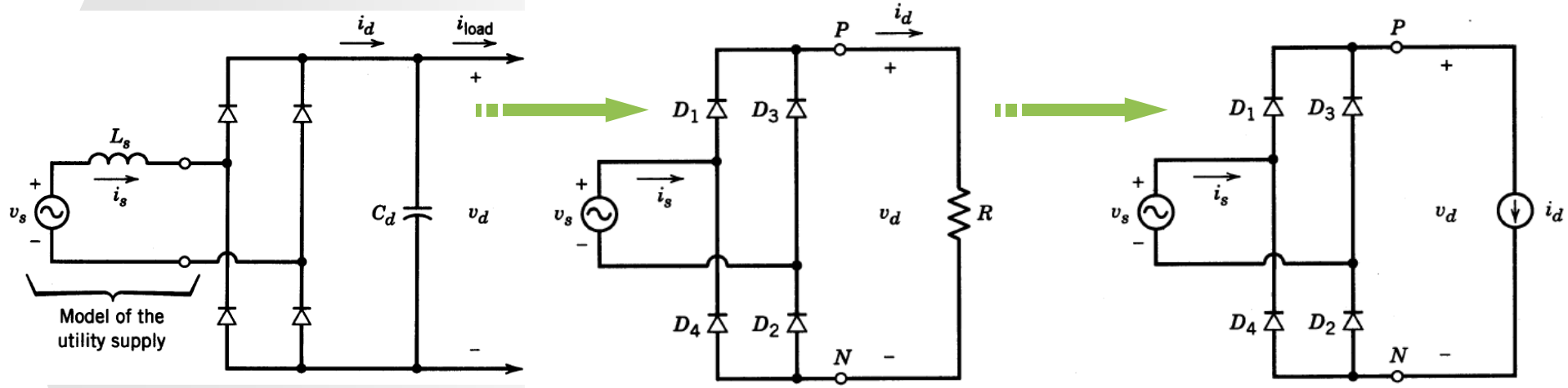


• 입력전압이 부하 기전력 초과 시부터 전류 흐르기 시작하여 입력전압보다 낮아지기 전까지 전류 계속 흐름 (L의 저장 에너지 방출이 끝날 때 까지)

• L이 없다면 입력전압이 Cap 전압보다 큰 경우만 전류 발생 → 비선형 전류 (가전기기)

단상 전파 정류회로 (I)

❖ Single-Phase Diode Rectifier Bridge



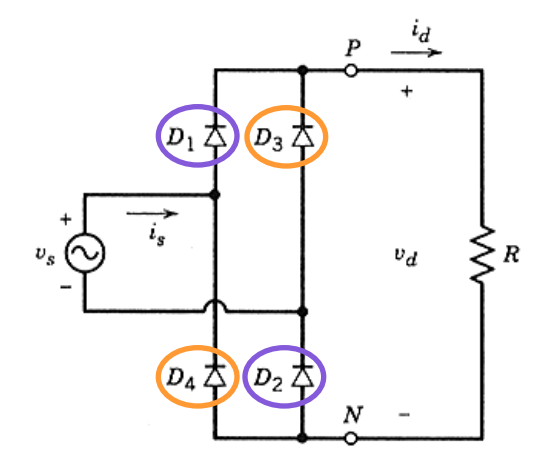
Practical circuit　　Analysis circuit I　　Analysis circuit II

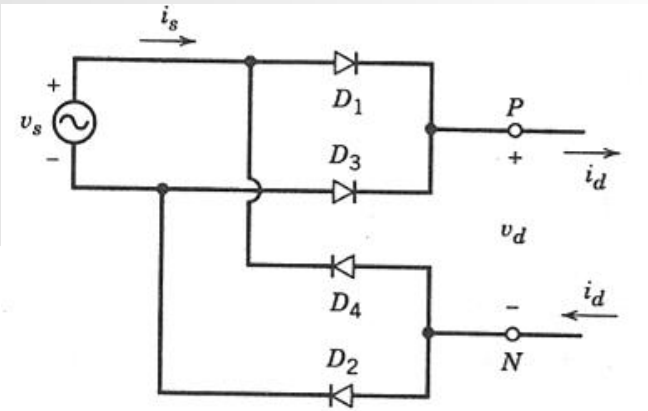
- 실제 다이오드 정류기의 등가회로는 계통 전원의 리액턴스 성분과 필터링 및 에너지 저장을 위한 DC Link Capacitor로 구성됨
- 해석을 위해 전원의 리액턴스와 출력 커패시터는 무시
- 부하는 전류원으로 가정 (ripple-free dc current → very big inductive load)

단상 전파 정류회로 (II)

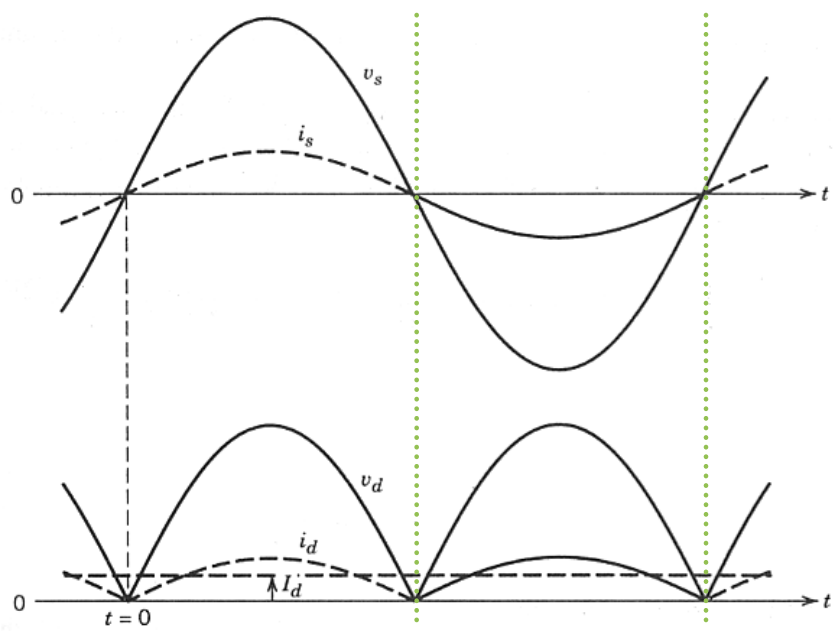
❖ Waveforms with a purely resistive load

▪ Circuit





▪ Waveform



- D1-D2 ON during positive V_s
- D3-D4 ON during negative V_s

단상 전파 정류회로 (III)

❖ **Waveforms with a purely resistive load**

▪ **Analysis**

$< Output\ Voltage >$

$$v_{o,avg} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \cdot d\omega t$$

$$= \frac{2}{\pi} V_m$$

$$= \frac{2\sqrt{2}}{\pi} v_{rms}$$

$$\approx 0.9 v_{rms}$$

$< Output\ Current >$

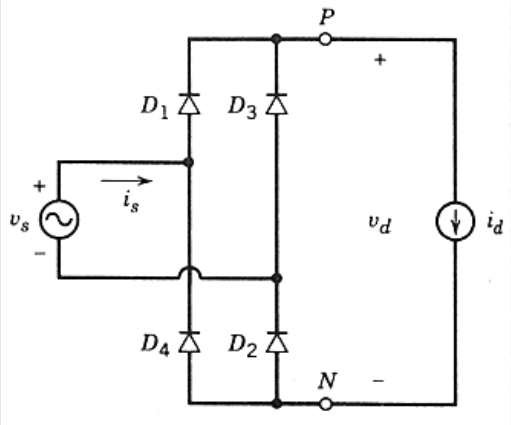
$$0 \le \omega t \le \pi : \quad i_o = \frac{v_o}{R} = \frac{v_s}{R} = \frac{V_m \sin\omega t}{R}$$

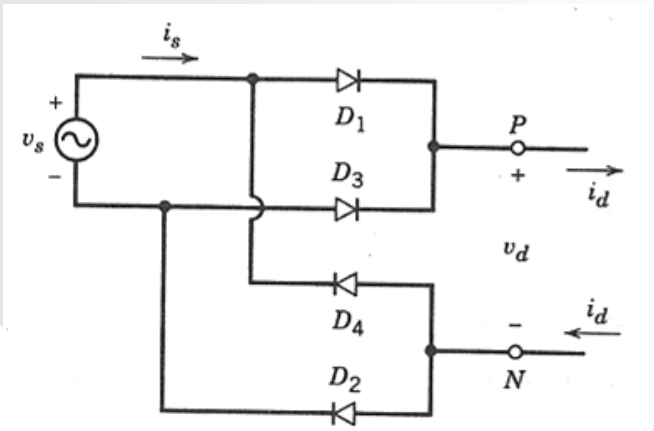
$$\pi \le \omega t \le 2\pi : i_o = \frac{v_o}{R} = \frac{-v_s}{R} = \frac{-V_m \sin\omega t}{R}$$

단상 전파 정류회로 (IV)

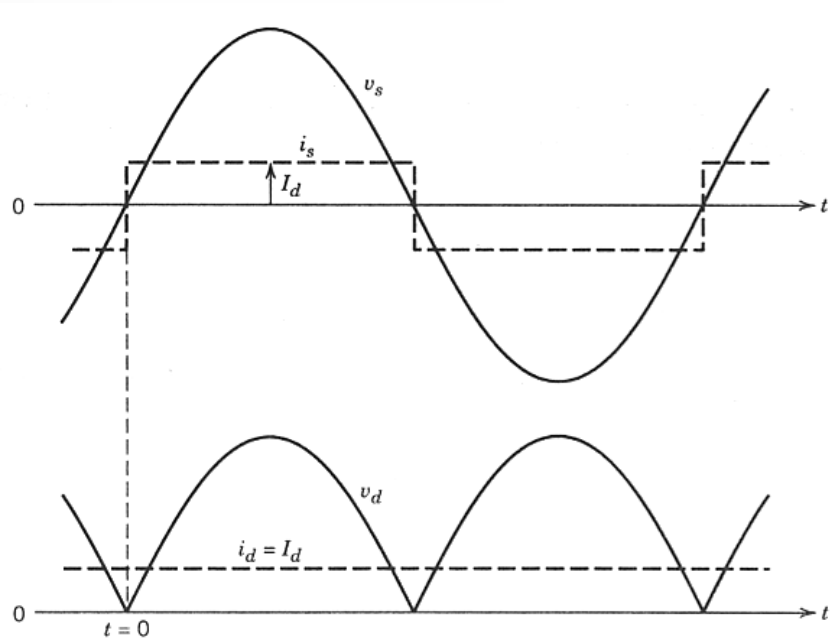
❖ Waveforms with a purely dc current at output

▪ Circuit





▪ Waveform

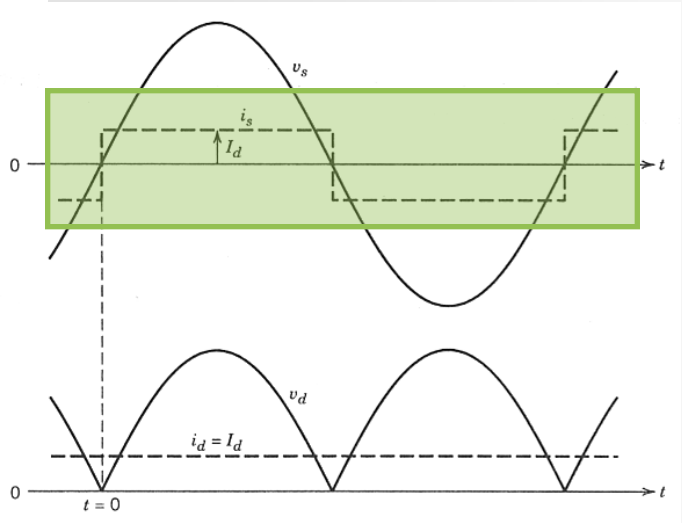


▪ 두 경우 모두 DC 출력전압의 파형은 동일

단상 전파 정류회로 (V)

❖ Waveforms with a purely dc current at output

▪ Analysis



< Input Voltage & Current >

$$v_s = V_m \sin \omega t$$

$$i_s = \frac{1}{2} a_o + \sum a_n \cos n\omega t + \sum b_n \sin n\omega t$$

where, input current is odd function

$$\rightarrow a_o = 0,\ a_n = 0$$

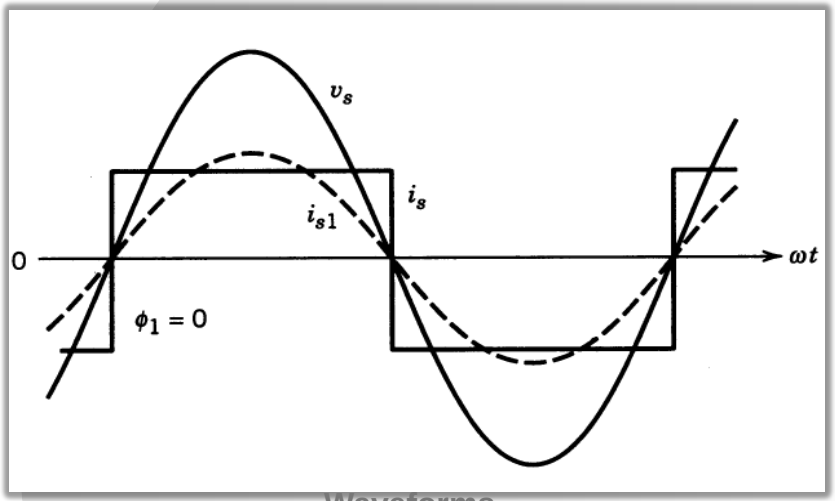
$$\therefore i_s = \sum b_n \sin n\omega t$$

$$\text{where, } b_n = \frac{2}{T}\int_0^T i_s \sin n\omega t \cdot d\omega t$$

$$\therefore i_s = \sum_{odd} \frac{4}{\pi} I_d \frac{1}{n} \sin n\omega t$$

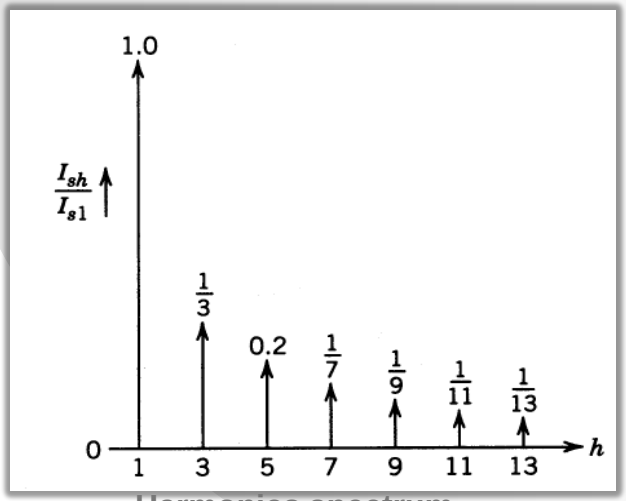
$$= \frac{4I_d}{\pi}\left(\sin \omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t + \cdots + \frac{1}{n}\sin n\omega t \right)$$

단상 전파 정류회로 (VI)



Waveforms

- 이상적으로 출력 전류가 완전한 DC일 경우, 입력 전류는 구형파로 나타남



Harmonics spectrum

- 입력전류에 대해 푸리에 급수 전개하여 고조파 분석하면 홀수배수 고조파 나타남

- **Power (seen at the source)**

$$P_{avg} = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T v(t)\cdot i(t)dt$$

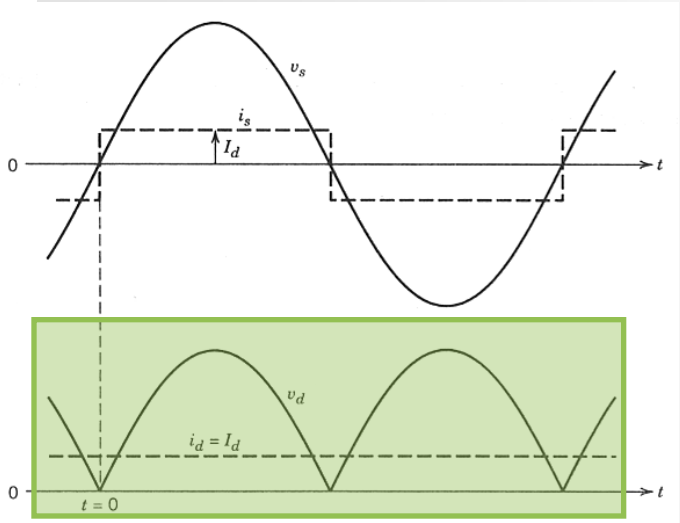
$$= V_m \frac{2}{\pi} I_d \approx V_m \left(\frac{I_{s1}}{2}\right)$$

$$\because \hat{I}_{s1} = \frac{4I_d}{\pi}$$

단상 전파 정류회로 (VII)

❖ Waveforms with a purely dc current at output

- **Analysis**



< Output Voltage & Current >

$$i_{dc} = I_d \ (constant)$$

$$v_{dc(\omega t)} = \frac{1}{2}a_o + \sum a_n \cos n\omega t + \sum b_n \sin n\omega t$$

where, output voltage is even function

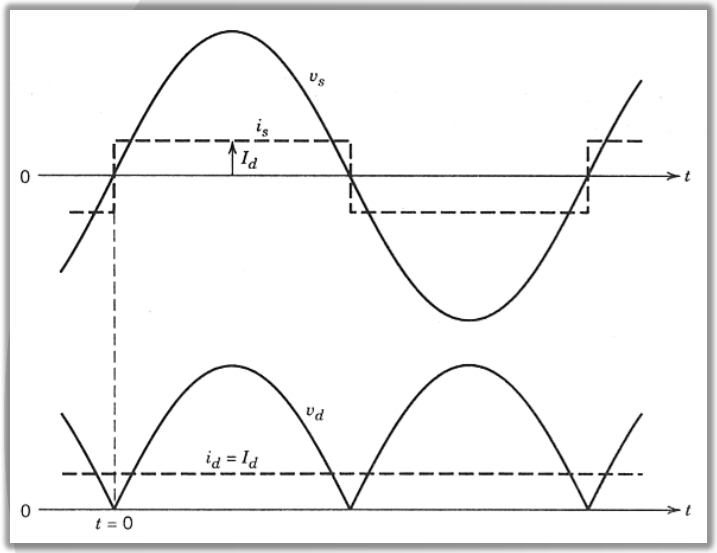
$$\rightarrow b_n = 0$$

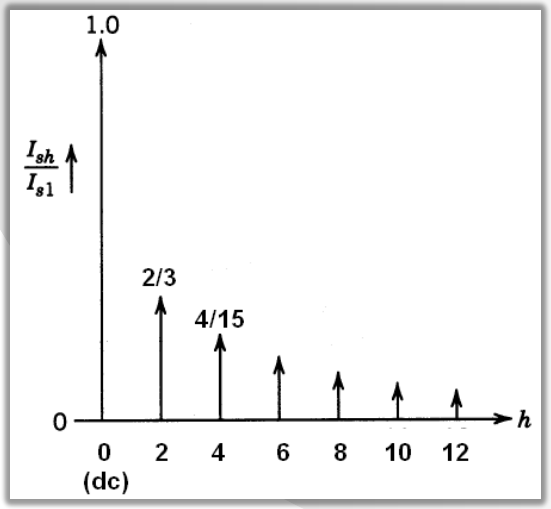
$$\therefore v_{dc(\omega t)} = \frac{1}{2}a_o + \sum a_n \cos n\omega t$$

$$where,\ a_n = \frac{2}{T}\int_0^T V_m \sin \omega t \cdot d\omega t = -\frac{4}{\pi}\frac{1}{n^2-1}V_m$$

$$\therefore v_{dc(\omega t)} = \frac{2V_m}{\pi} - \frac{4V_m}{\pi}\left(\frac{1}{3}\cos 2\omega t + \frac{1}{15}\cos 4\omega t + \cdots + \frac{1}{n^2-1}\cos n\omega t\right)$$

단상 전파 정류회로 (VIII)





- 출력전류는 완전한 DC로 가정, 출력전압은 저항부하와 동일하게 sine-wave에 절대값을 취한 형태로 나타남

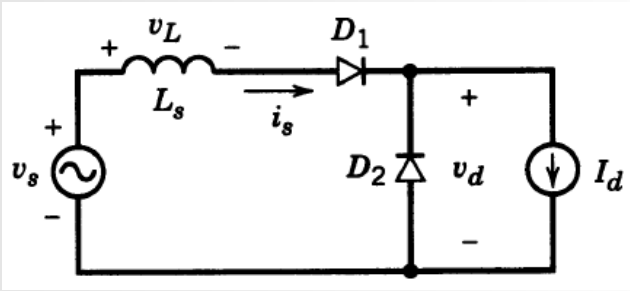
- 출력전압에 대해 푸리에 급수 전개하여 고조파 분석하면 짝수배수 고조파 나타남

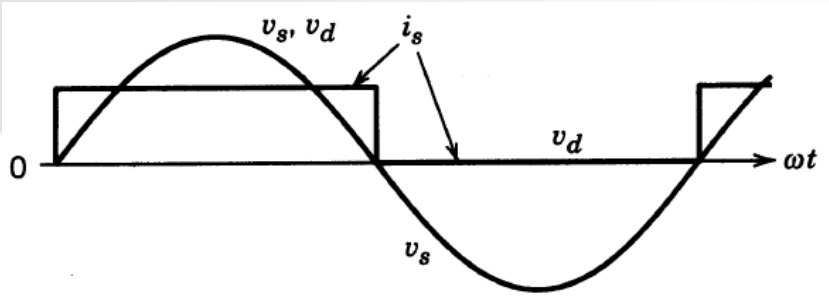
Power (seen at the load)

$$P_{avg} = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T (V_m \sin \omega t) I_d \cdot dt$$
$$= V_{avg} \cdot I_d$$

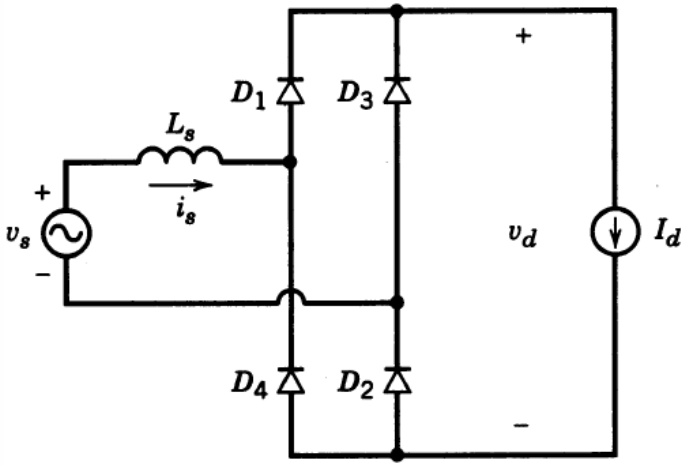
단상 전파 정류회로 (IX)

❖ Diode Rectifier Bridge Analysis with AC side Inductance & Understanding Current Commutation





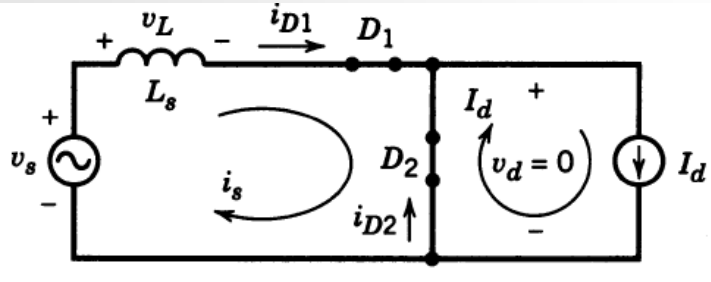
▪ 전원 인덕턴스 L_s=0으로 가정



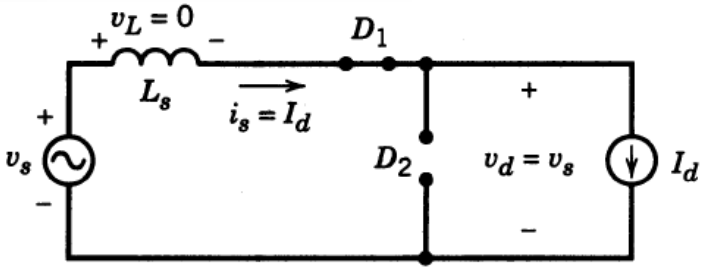
▪ 출력전류는 완전한 DC로 가정
▪ 전원 인덕턴스 L_s가 존재할 경우 각 부 파형 고찰
▪ Commutation

단상 전파 정류회로 (X)

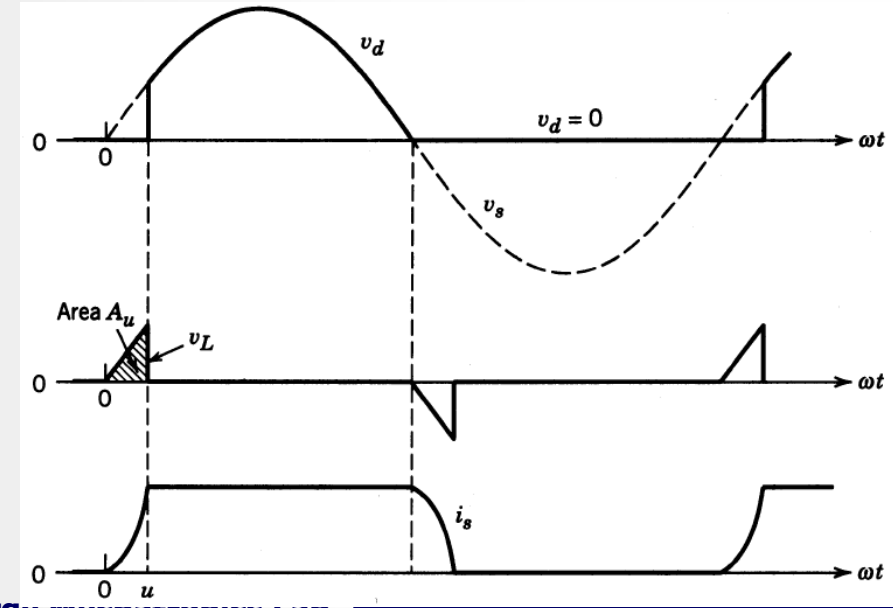
❖ Understanding Current Commutation (cont.)



▪ 전류 Commutation중인 등가회로

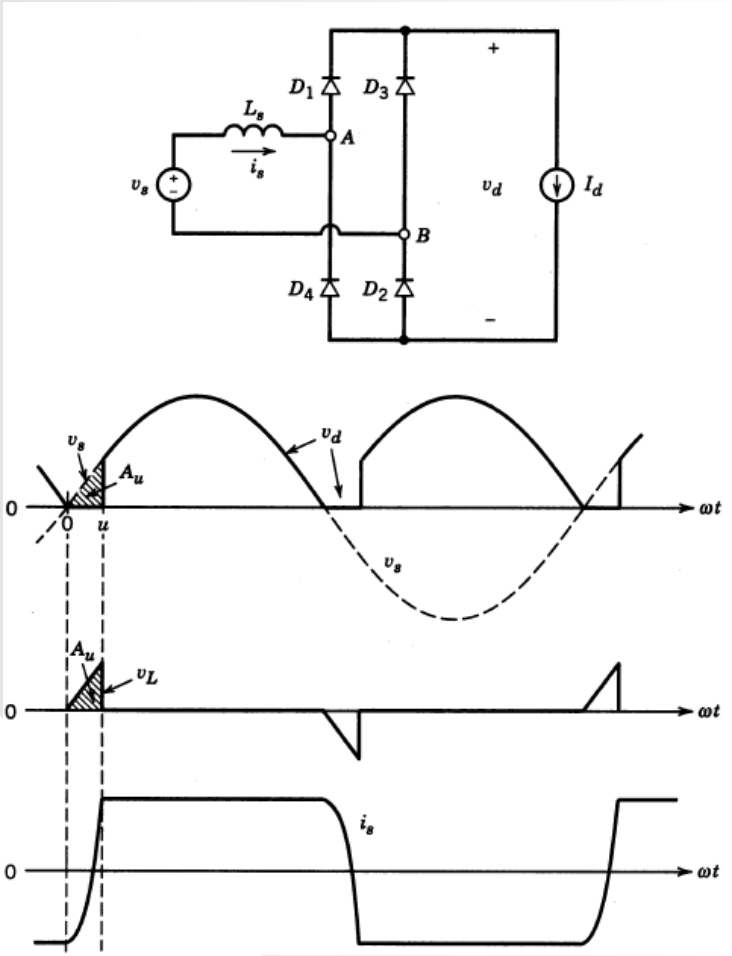


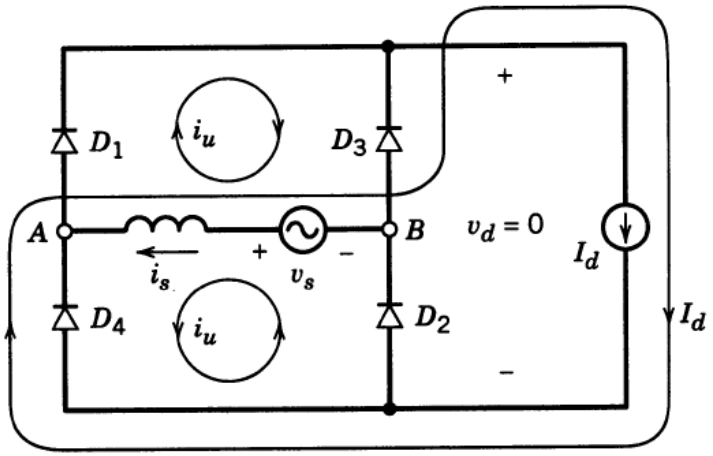
▪ Commutation 후 등가회로



단상 전파 정류회로 (XI)

❖ Current Commutation in Full-Bridge Rectifier

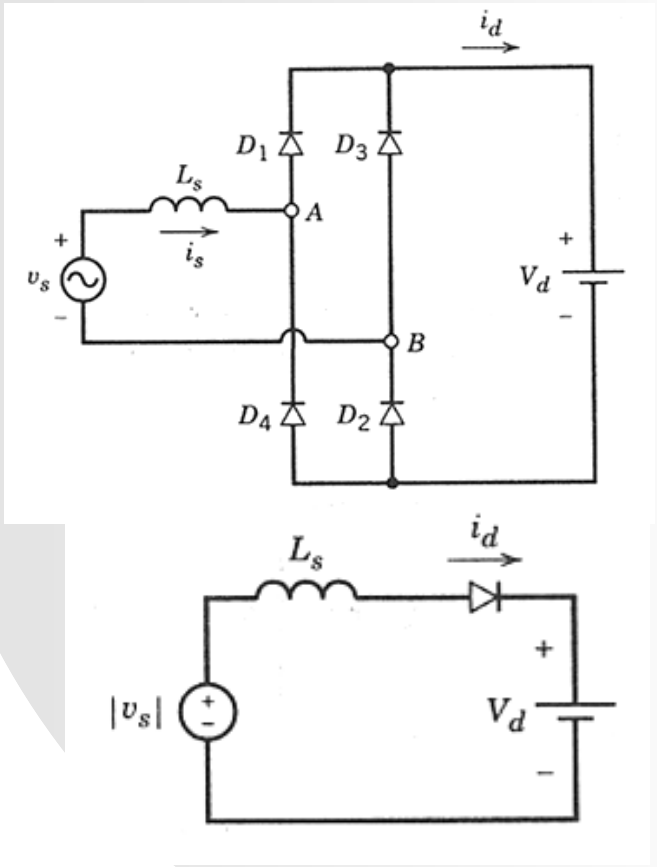


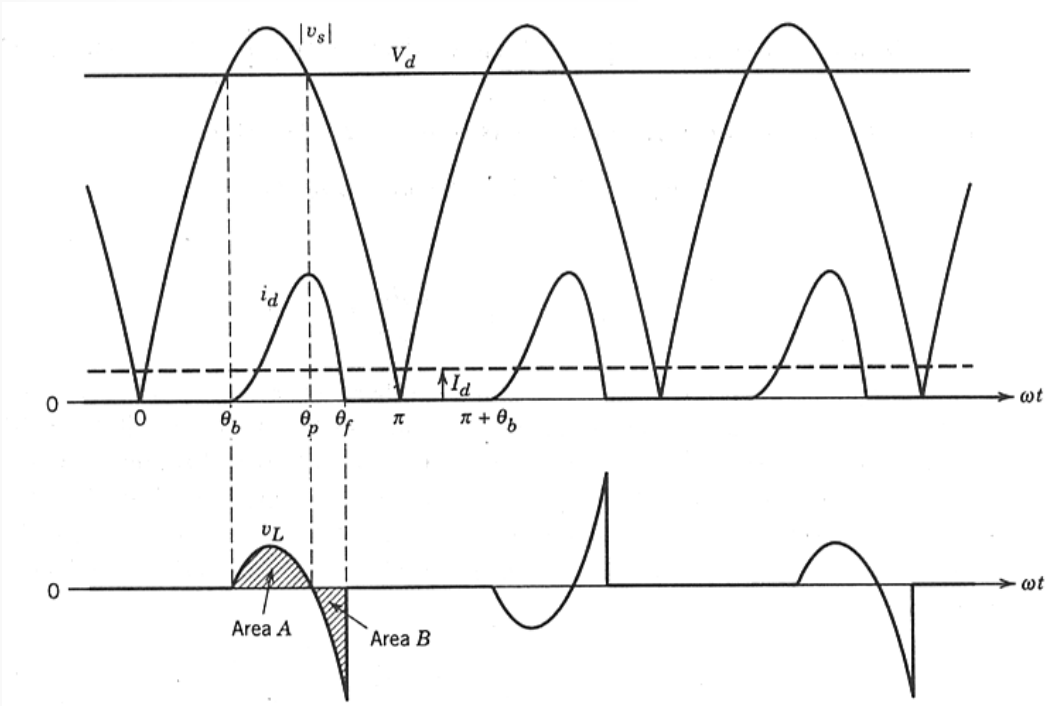


▪ 단상 전파 정류기에서의 전류 커뮤테이션

단상 전파 정류회로 (XII)

❖ **Rectifier with a dc-side voltage**

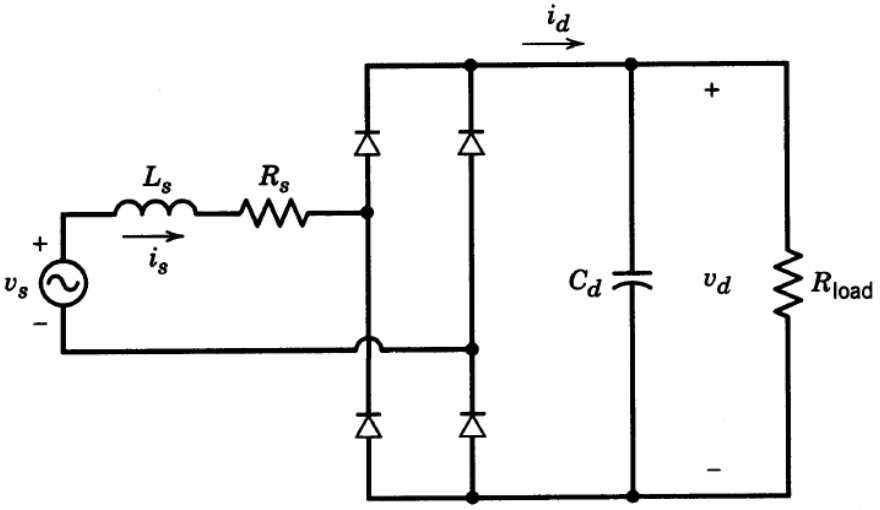


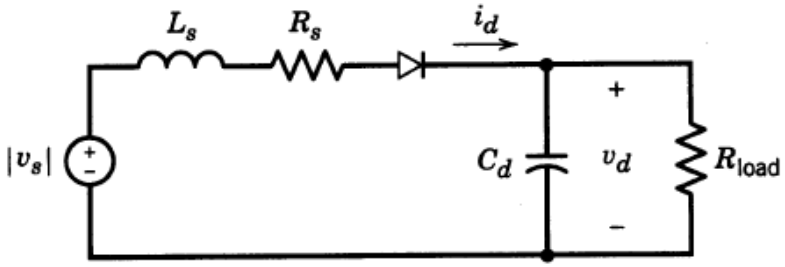


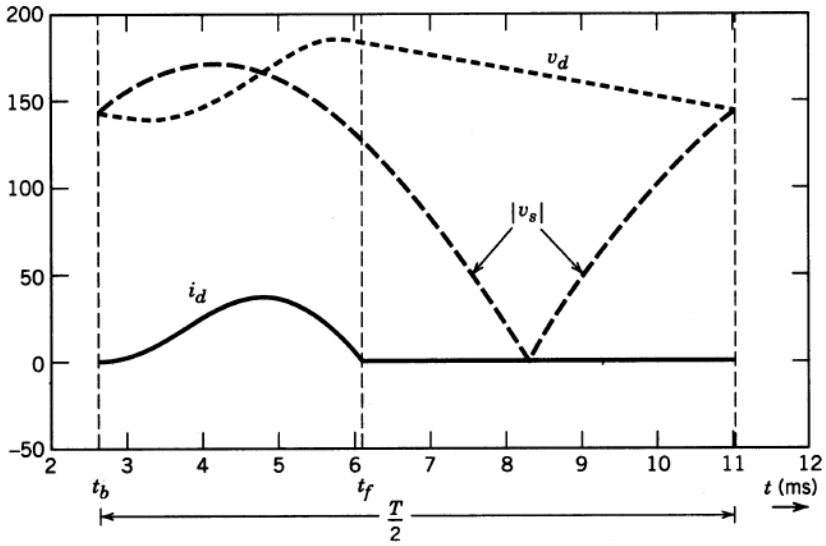
- 전류는 Vs가 Vd보다 커질때 부터 흐르기 시작
- 전원에 L_s가 존재할 때와 같은 패턴의 전류 흐름

단상 전파 정류회로 (XIII)

❖ Diode Rectifier with a Capacitor Filter – Practical Circuit

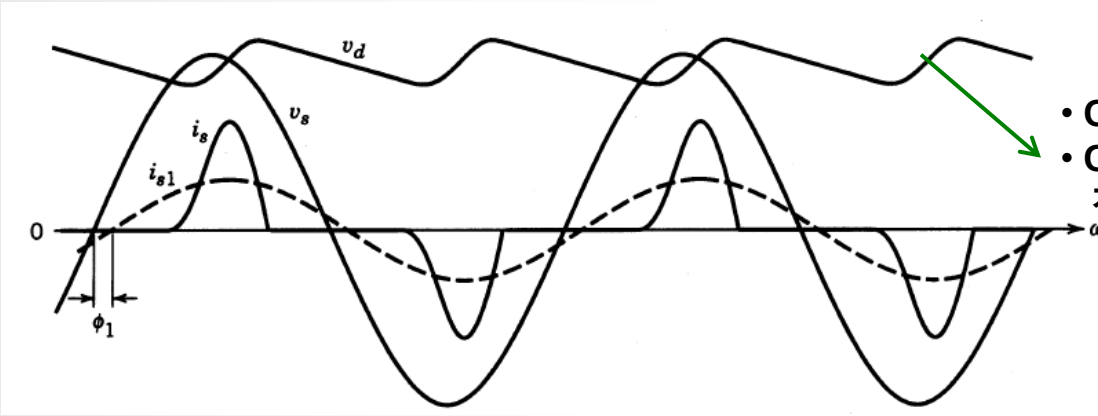






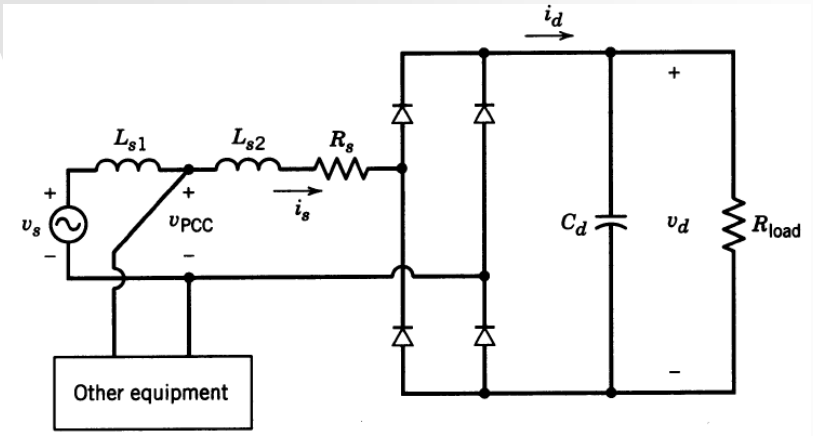
단상 전파 정류회로 (XIV)

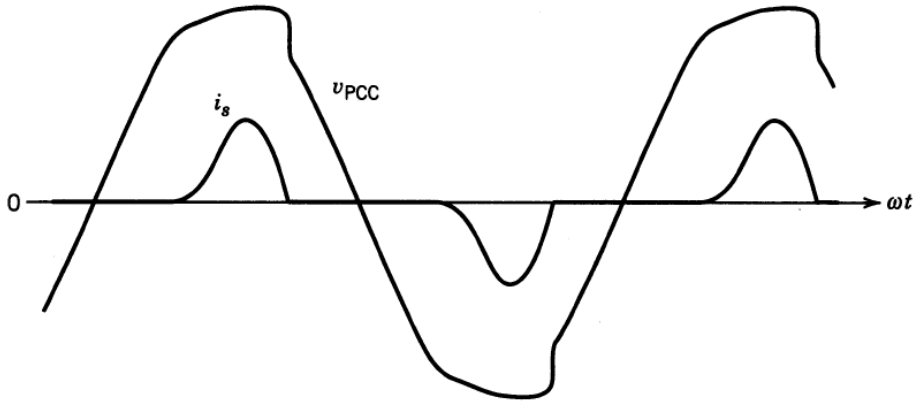
❖ Diode Rectifier with a Capacitor Filter – Waveforms



- C의 영향으로 DC전압이 됨
- C값이 커질수록 리플이 작아짐

● Nonlinear Current



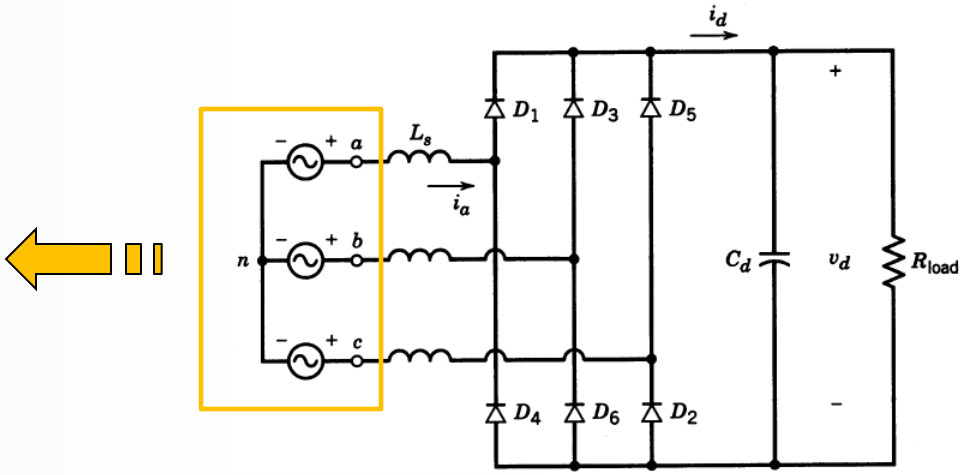


● Line Voltage Distortion

3상 다이오드 정류회로

❖ 3-phase system

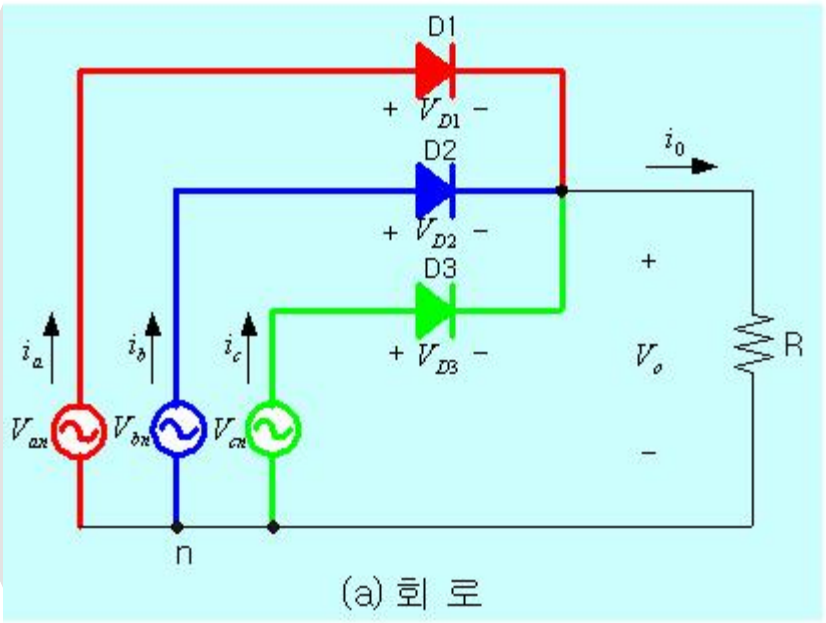
$$v_a = V_m \sin \omega t$$
$$v_b = V_m \sin(\omega t + 120°)$$
$$v_c = V_m \sin(\omega t - 120°)$$



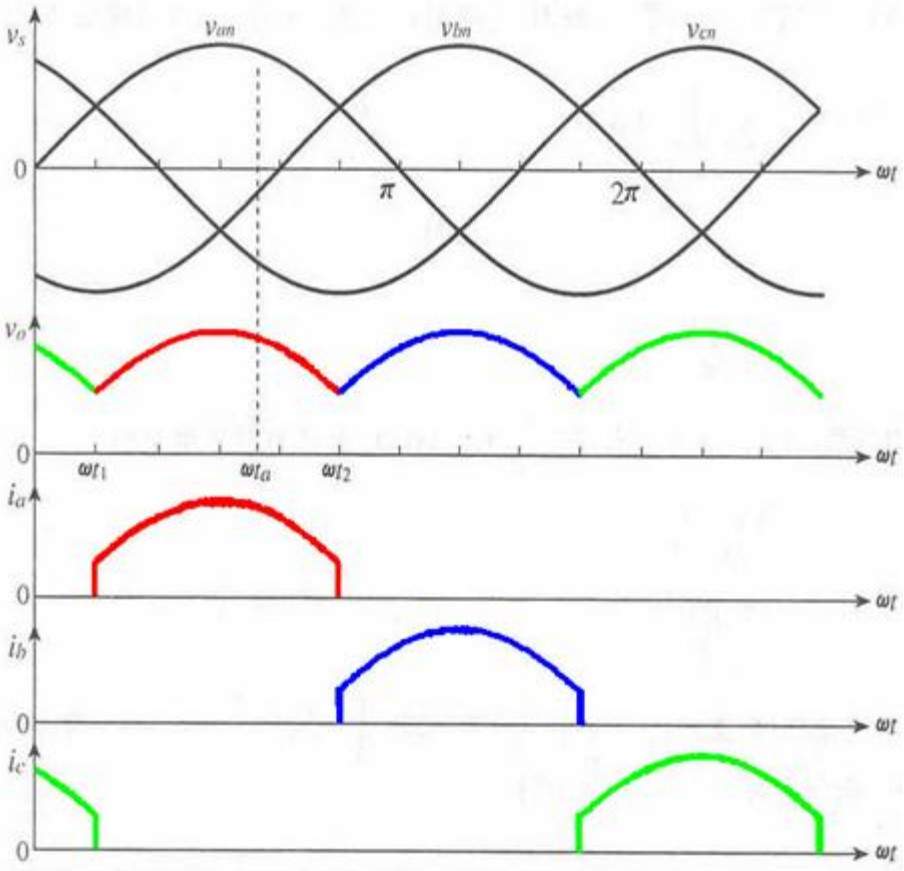
❖ Relation between phase and line-to-line voltage at 3ph system

$$v_{ab} = \sqrt{3} v_{an} \angle 30°$$
$$v_{bc} = \sqrt{3} v_{bn} \angle 30°$$
$$v_{ca} = \sqrt{3} v_{cn} \angle 30°$$

3상 반파 다이오드 정류기 (I)



(a) 회 로



(b) 파 형

3상 반파 다이오드 정류기 (II)

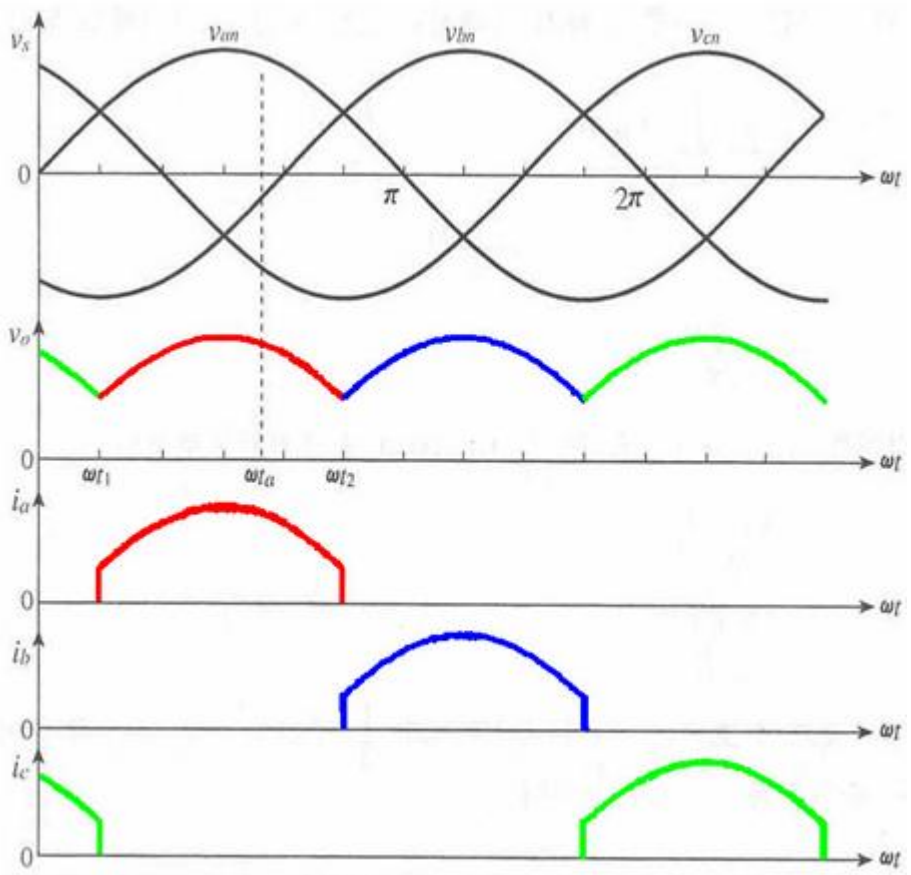
$$< v_o > = \frac{3}{2\pi}\int_{\omega t_1}^{\omega t_2} v_{an}\, dt$$

$$= \frac{3}{2\pi}\int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} \sqrt{2}V \sin\omega t d(\omega t)$$

$$= \frac{3\sqrt{6}V}{2\pi}$$

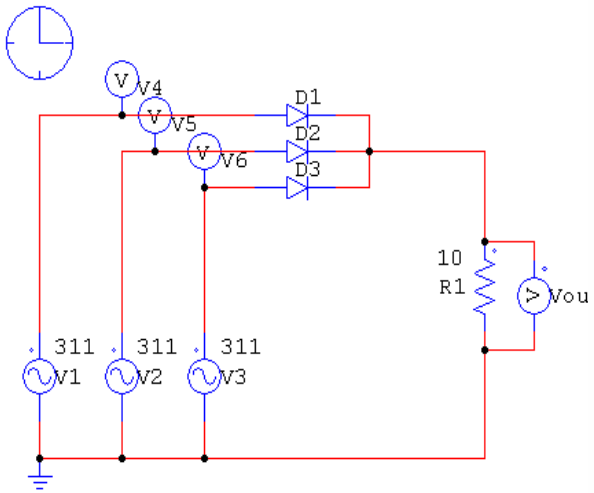
$$< i_o > = \frac{< v_o >}{R}$$

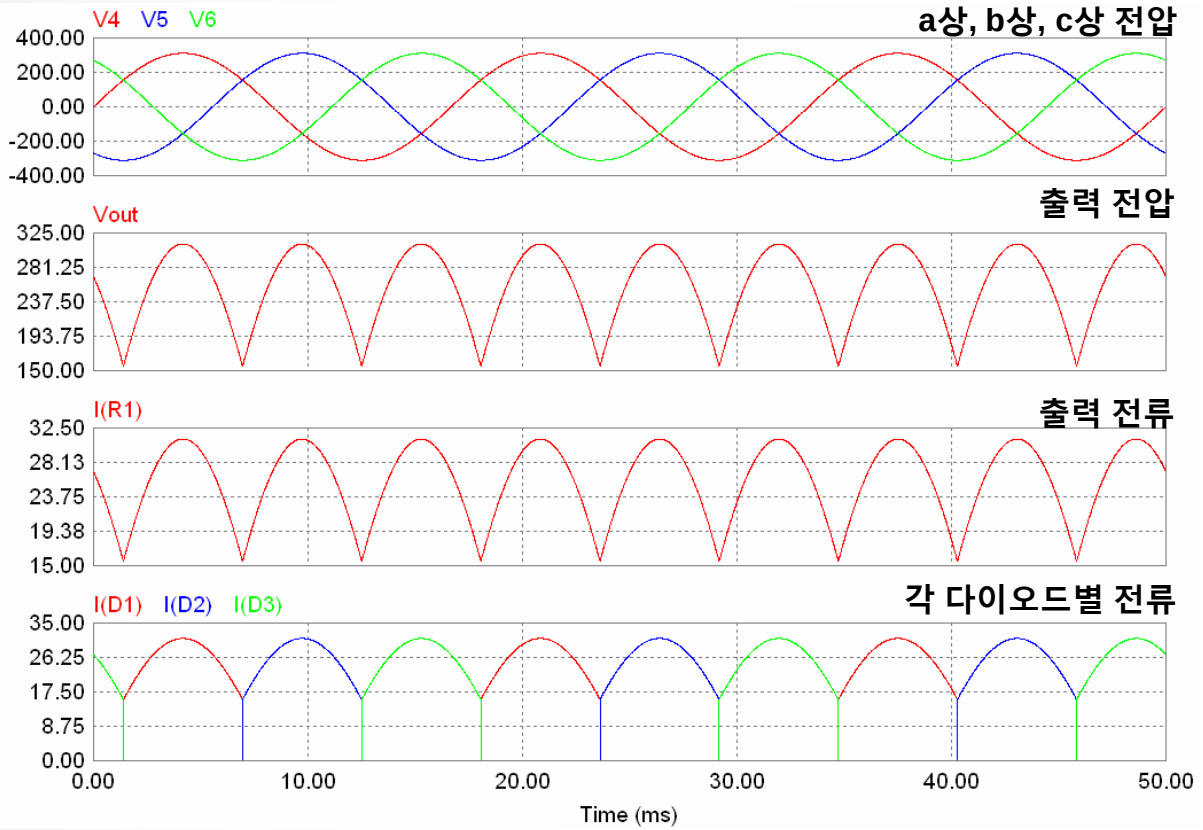
$$I_o = \sqrt{\frac{3}{2\pi}\int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} (\frac{\sqrt{2}V \sin\omega t}{R})^2 d(\omega t)}$$



3상 반파 다이오드 정류기 (III)

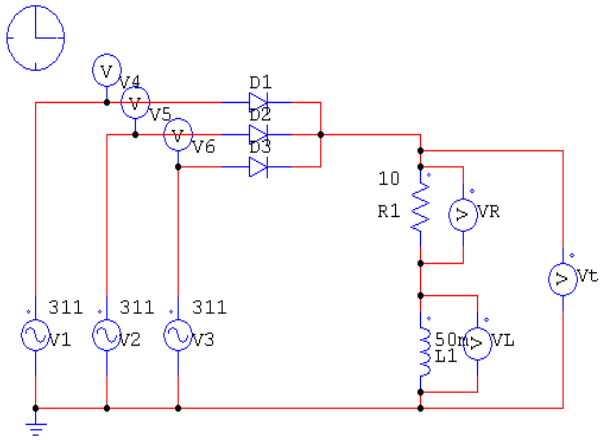
❖ with Resistive load

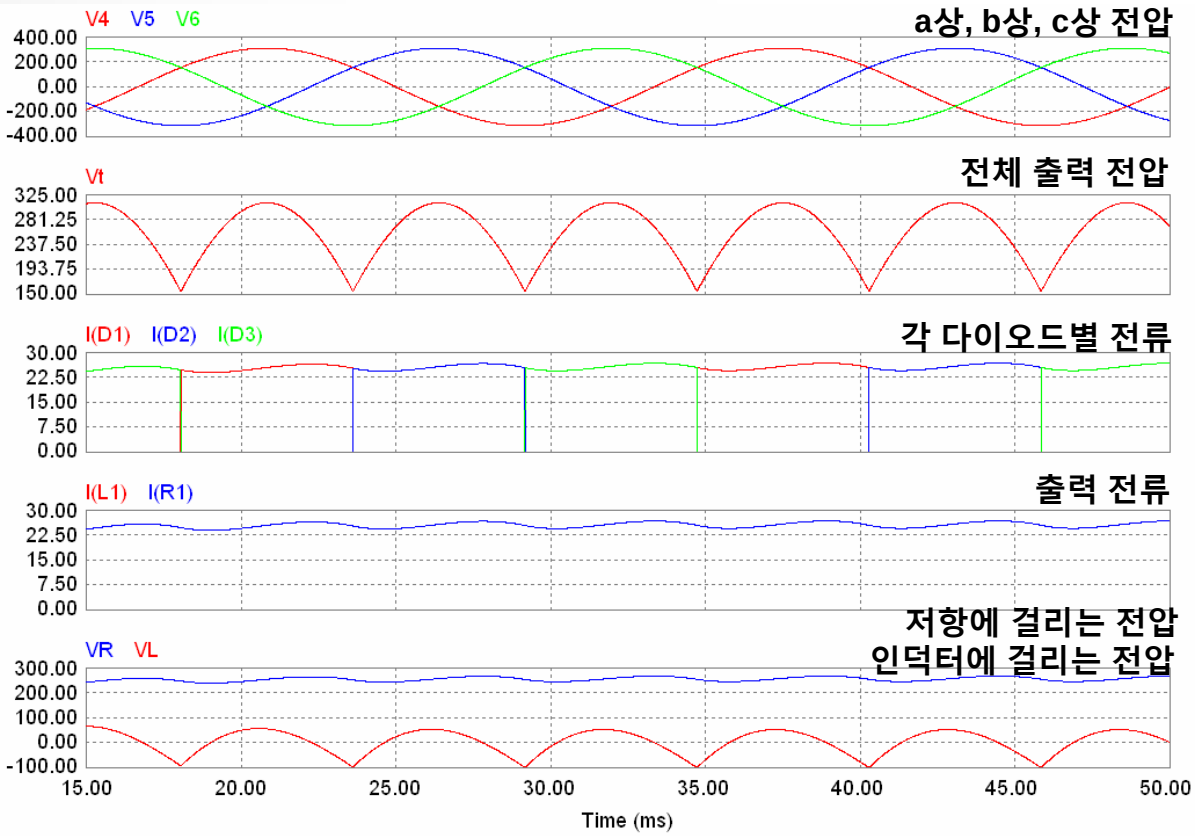




3상 전파 다이오드 정류기 (I)

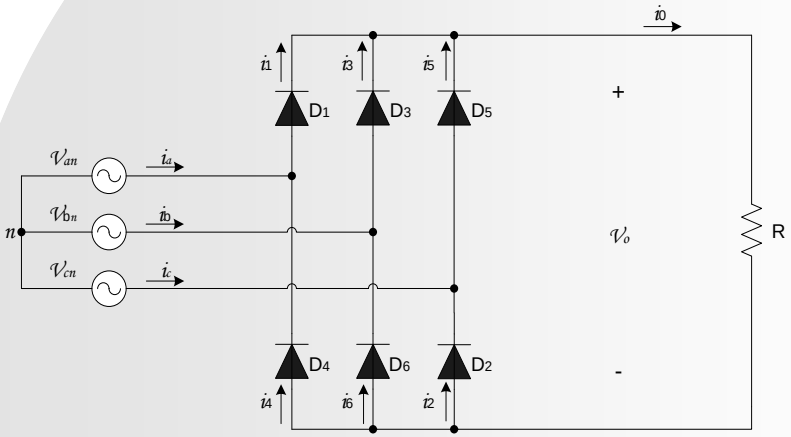
❖ with Inductive load



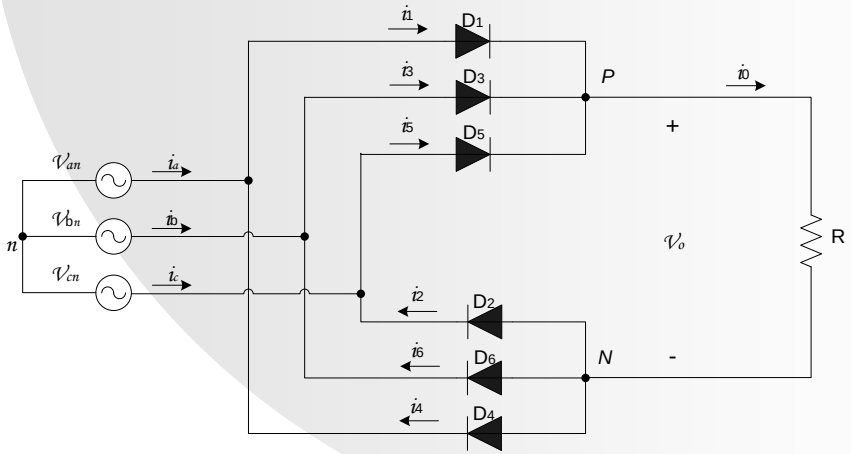


3상 전파 다이오드 정류기 (II)

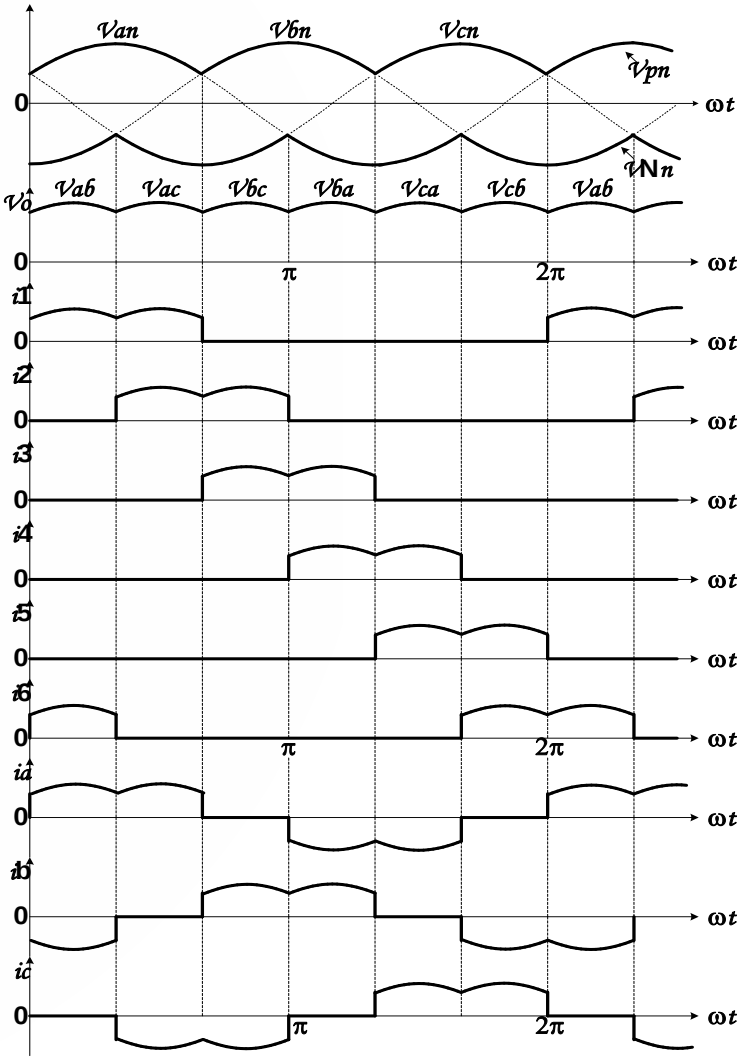
❖ Circuit



$$v_o = v_{Pn} - v_{Nn}$$



❖ Waveforms



3상 전파 다이오드 정류기 (III)

❖ Analysis

- Diode D1 ON 조건 : $v_{ab} > 0 \ \& \ v_{ac} > 0 \ (v_{ac} = -v_{ca})$
- Diode D2 ON 조건 : $v_{ca} < 0 \ \& \ v_{bc} < 0$
- Diode D3 ON 조건 : $v_{bc} > 0 \ \& \ v_{ba} > 0$
- Diode D4 ON 조건 : $v_{ab} < 0 \ \& \ v_{ac} < 0$
- Diode D5 ON 조건 : $v_{ca} > 0 \ \& \ v_{cb} > 0$
- Diode D6 ON 조건 : $v_{ba} < 0 \ \& \ v_{bc} < 0$
- Diode D1 ~ D6 까지 ON 조건 해석하면 ➔ 최대값과 최소값을 갖는 구간의 다이오드 ON 됨
- 각 diode는 120도씩 ON
- D1 → D2 → D3 → D4 → D5 → D6 순으로 60도 마다 sequencelly turn-ON
- 60도 구간 모드별로 2개의 diode pair가 도통됨
    - D1, D3, D5 중 1ea + D4, D6, D2 중 1ea :

3상 전파 다이오드 정류기 (IV)

❖ Analysis

▪ 직류 출력전압 :

$$\begin{aligned} v_{dc} &= v_{d1} - v_{d2} \\ &= v_{an} - v_{bn} = v_{ab} \\ &= v_{an} - v_{cn} = v_{ac} \\ &= v_{bn} - v_{cn} = v_{bc} \\ &= v_{bn} - v_{an} = v_{ba} \\ &= v_{cn} - v_{an} = v_{ca} \\ &= v_{cn} - v_{bn} = v_{cb} \end{aligned}$$

▪ 입력전류 :

$$\begin{aligned} i_a &\rightarrow pos : D1 \\ &\quad neg : D4 \\ i_b &\rightarrow pos : D3 \\ &\quad neg : D6 \\ i_c &\rightarrow pos : D5 \\ &\quad neg : D2 \end{aligned}$$

- 각 다이오드 전류에 Id 전류 흐름 (KCL)
- 스위치는 한 개씩 턴-온 되기 때문

3상 전파 다이오드 정류기 (V)

❖ Analysis

▪ 직류 출력전압 평균값 :

$$v_{dc,avg} = \frac{1}{\pi/3}\int_0^{\frac{\pi}{3}} v_{ab}\, d\omega t$$

$$= \frac{3}{\pi}\int_0^{\frac{\pi}{3}} \sqrt{2}V_{L-L}\sin\left(\omega t - \frac{\pi}{3}\right) d\omega t$$

$$= \frac{3\sqrt{2}}{\pi}V_{L-L} \quad (V_{L-L} : line-to-line\, voltage\, RMS)$$

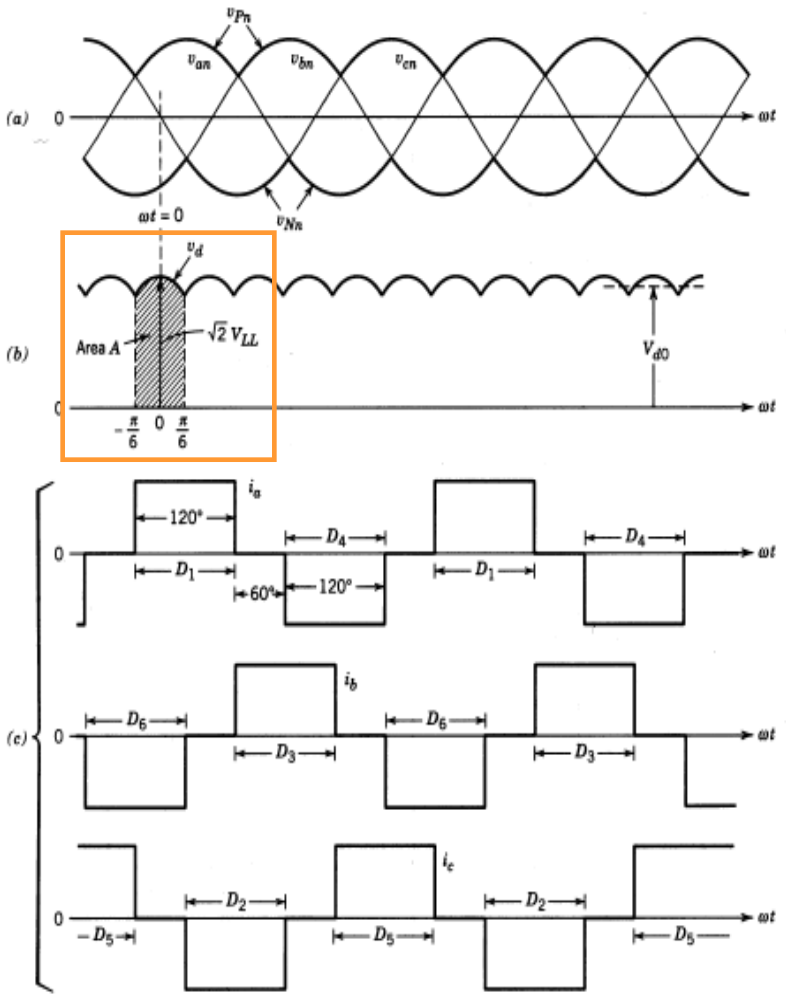
$$\approx 1.35V_{L-L}$$

▪ 출력전압 고조파

$$v_{DC} = \frac{3\sqrt{2}}{\pi}V_L\left(1 + \frac{2}{35}\cos 6\omega t - \frac{2}{143}\cos 12\omega t + \ldots\right)$$

✓ 단상 : 2n차 (even harmonics)

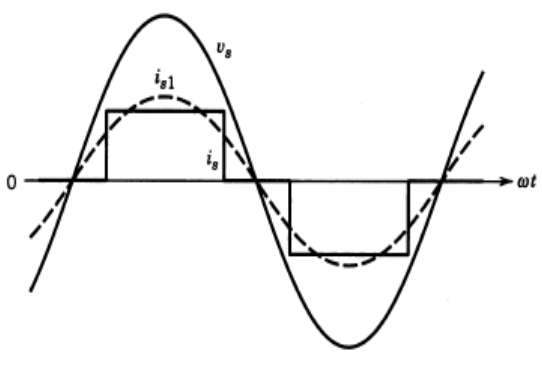
✓ 3상 : 6n차 harmonics

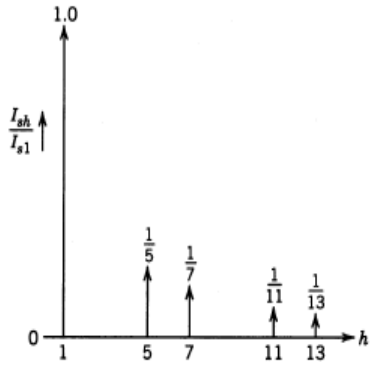


3상 전파 다이오드 정류기 (VI)

❖ Analysis

- 입력전류 고조파 :



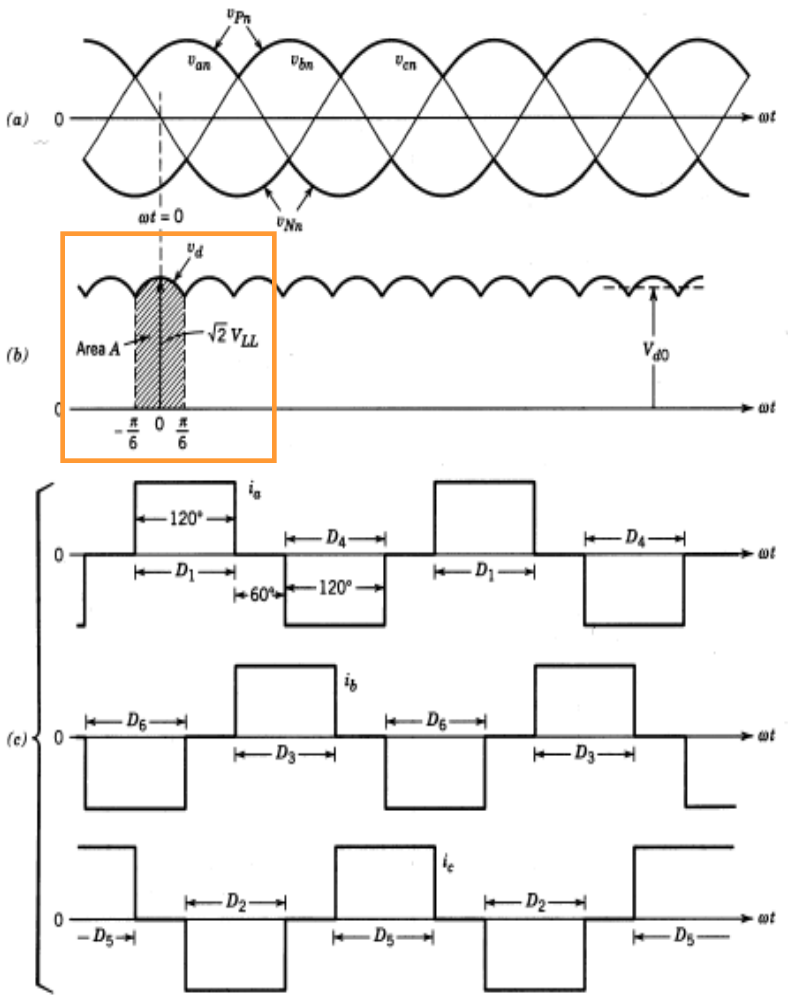


✓ $$i_a = \frac{2\sqrt{3}}{\pi} I_d [\sin \omega t - \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t - ...]$$

✓ 단상 : odd harmonics

✓ 3상 : odd harmonics – 3배수 고조파

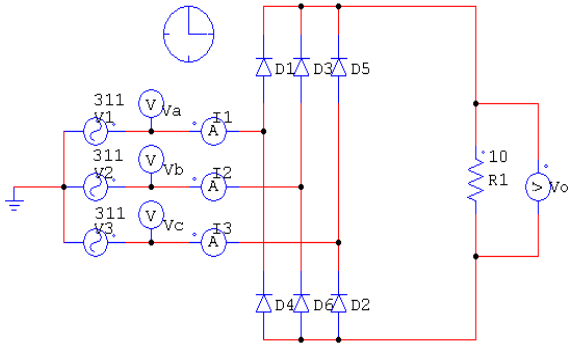
✓ 3상 다이오드 정류기가 3상 4선식 시스템에 연결된 경우 3배수 고조파 없음



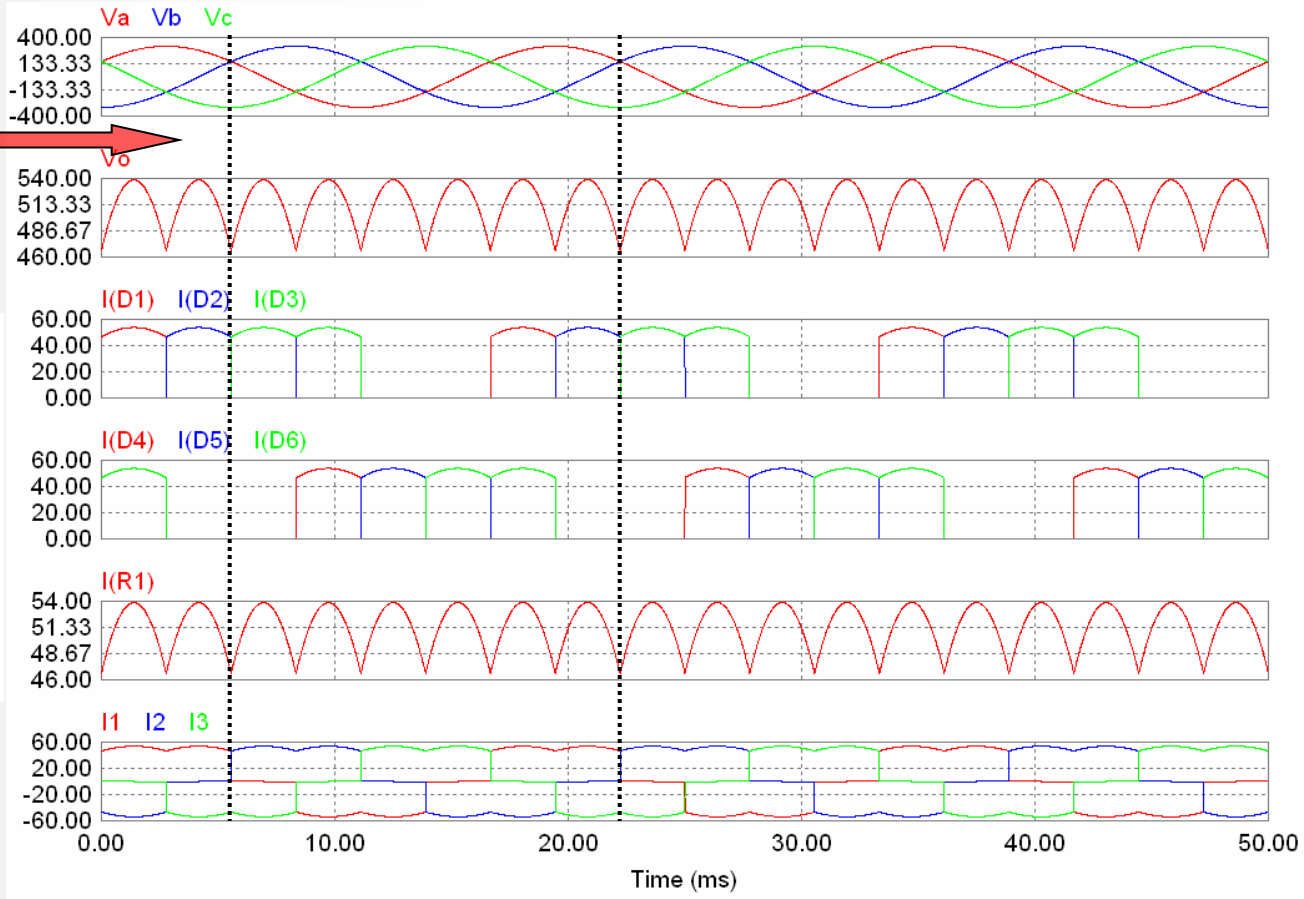
3상 전파 다이오드 정류기 (VII)

❖ Simulation

- 리플주파수
  - 3배
- 리플크기
  - Capacitor가 없으므로 큰 리플

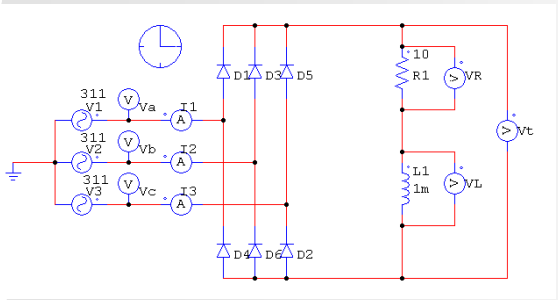


- R부하만 있을 때



3상 전파 다이오드 정류기 (VIII)

❖ Simulation



▪ R-L부하일 때