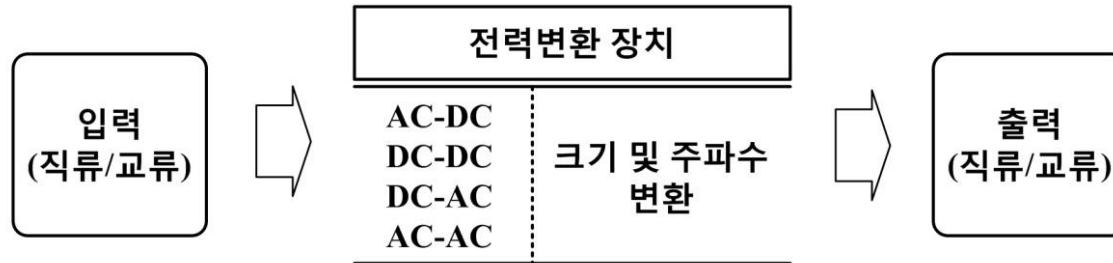


## 9장 인버터의 기초

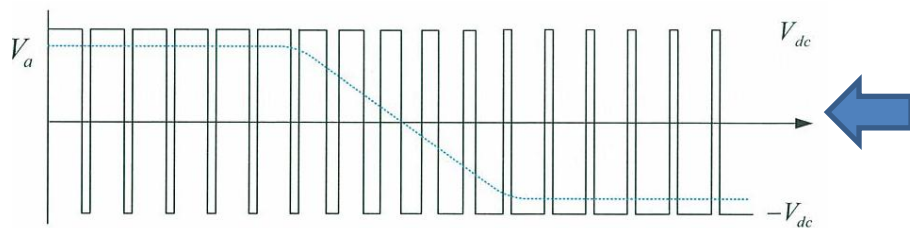
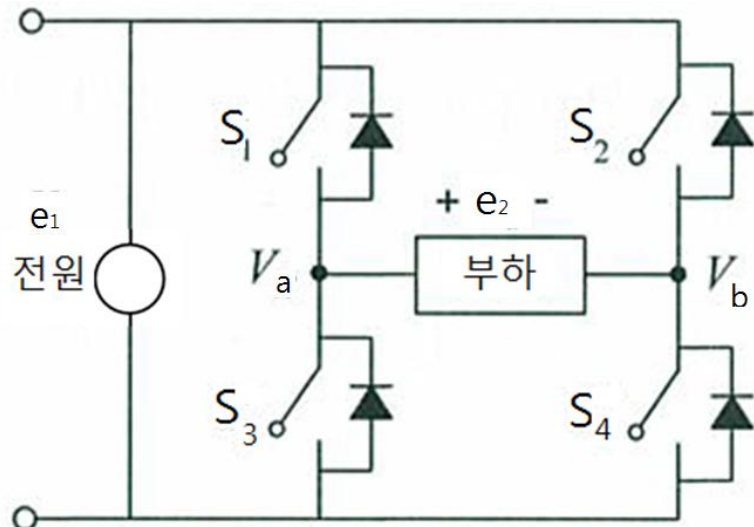
## 9-1 기초지식

# [1] 전력변환 장치의 종류



입력	AC	DC	DC	AC
기본 명칭	정류기	DC-DC 컨버터	인버터	AC-AC 컨버터
종류	다이오드 정류기 위상제어 정류기	DC 쇼퍼 Buck 컨버터 Forward 컨버터 Boost 컨버터 Buck-Boost 컨버터 Flyback 컨버터 Cuk 컨버터 Full-Bridge 컨버터	전류형 인버터 - PWM - 위상제어  전압형 인버터 - 6-Step - SPWM - SVPWM	변압기  사이클로 컨버터
출력	DC		AC	

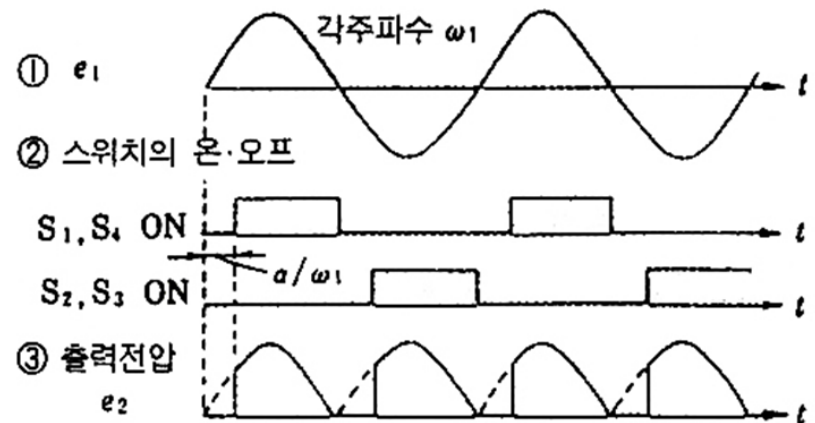
# [1] 전력변환 장치의 동작원리



바이폴라(bipolar) 스위칭 방식에서의 출력 전압

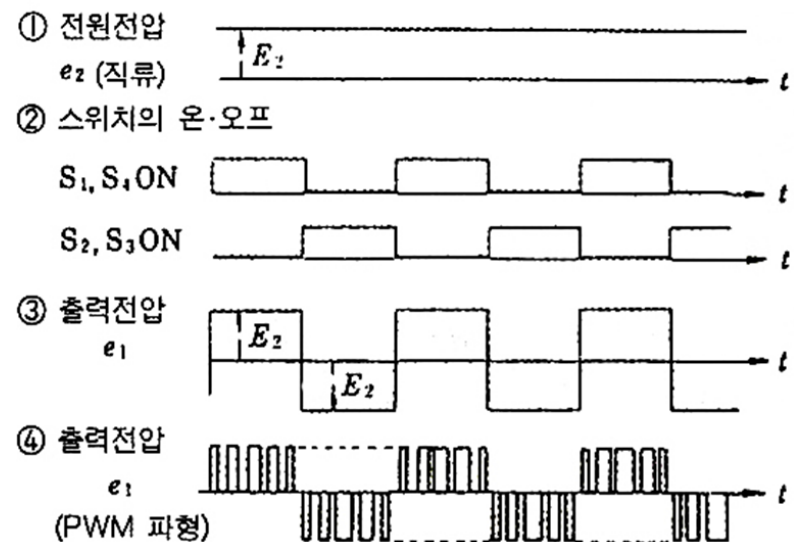
## (1) AC-DC (정류기)

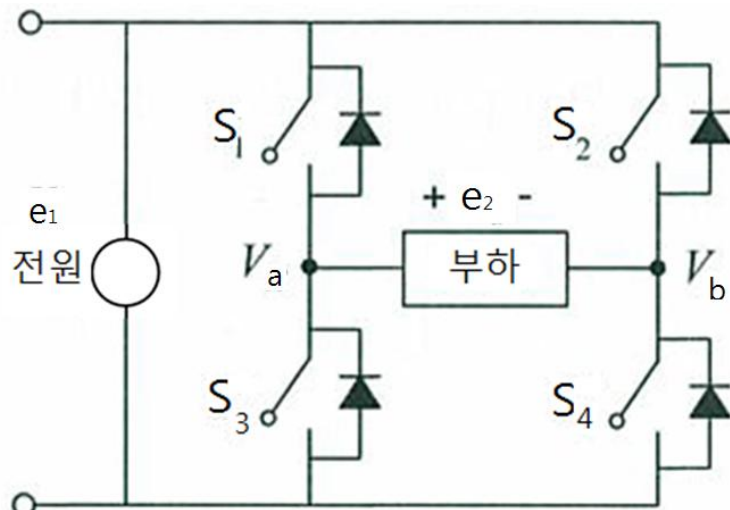
A-A'간 : 교류전원, B-B'간 : 출력전압



## (2) DC-DC (쇼퍼)

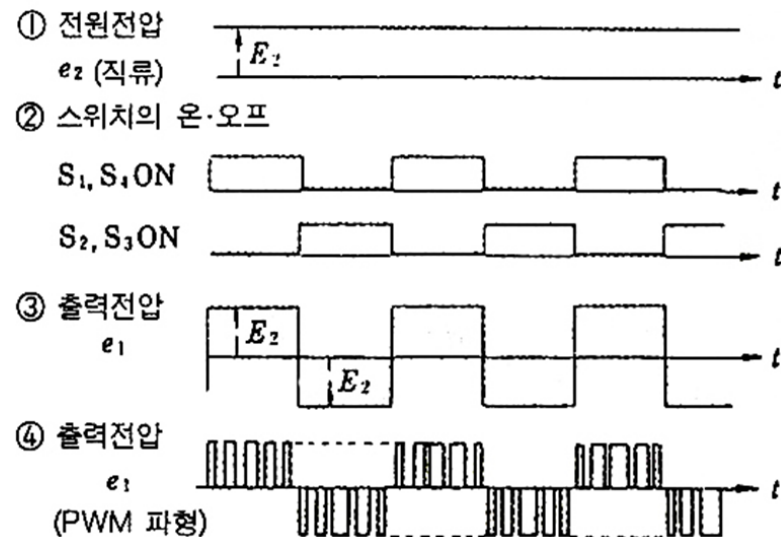
A-A'간 : 부하저항, B-B'간 : 출력전압





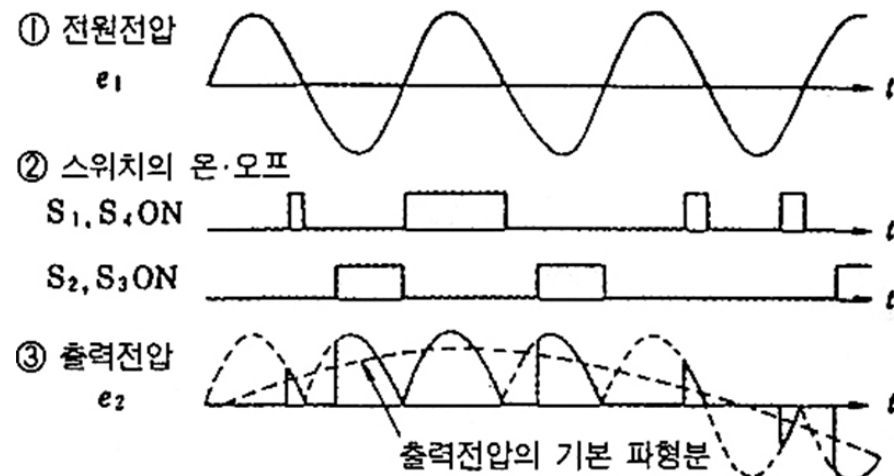
### (3) DC-AC (인버터)

A-A'간 : 부하저항, B-B'간 : 출력전압



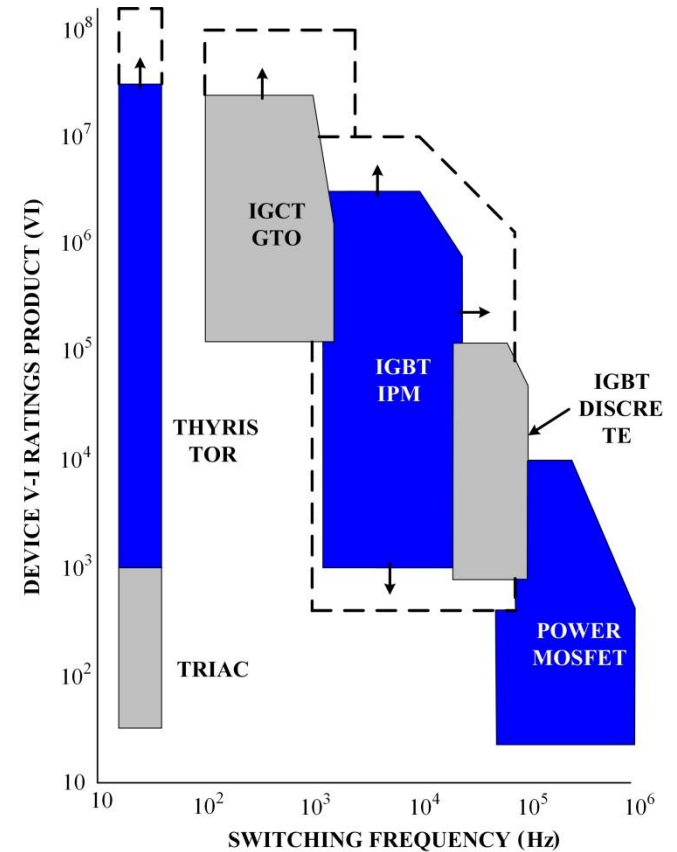
### (4) AC-AC (사이클로 컨버터)

A-A'간 : 교류전원, B-B'간 : 출력전압

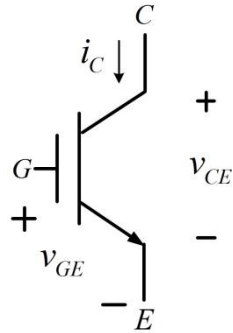


## [2] Switching 소자

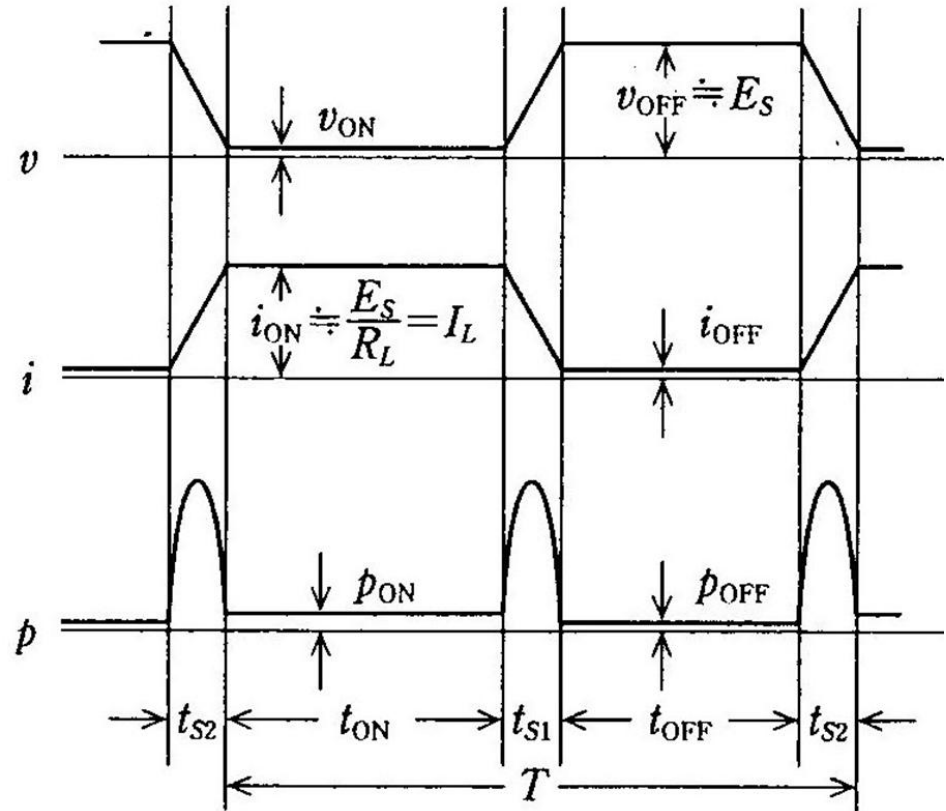
명칭	기호	이상적인 동작극성	특성
<b>Diode</b> (1955)			ON/OFF 제어 불가 매우 작은 ON 방향 전압 강하 단방향 전압 저지, 단방향 전류 소자
<b>Thyristor</b> (1958)			OFF 제어 불가 Gate의 전류펄스에 의하여 ON 제어 양방향 전압 저지, 단방향 전류 소자
<b>TRIAC</b> (1958)			OFF 제어 불가 SCR보다 Gate 전류에 대한 민감도가 떨어져서 OFF 시간이 길다. 양방향 전압 저지, 양방향 전류 소자
<b>GTO</b> (1980)			ON/OFF 제어 가능 ON 유지를 위한 Gate 전류가 낮음 음의 Gate 전류로 OFF 가능 양방향 전압 저지, 단방향 전류 소자
<b>BJT</b> (1975)			Base 전류에 의하여 ON 결정 Base 전류 크기에 따라 도통 전류 최대치 결정 단방향 전압 저지, 단방향 전류 소자
<b>MOSFET</b> (1975)			Gate와 Source 사이에 전압을 인가하여 ON/OFF 결정 ON시 도통전류에 따라 전압강하 변동 단방향 전압 저지, 단방향 전류 소자
<b>IGBT</b> (1985)			Gate와 Emitter 사이에 전압을 인가하여 구동하는 전압구동형 ON시 전압강하는 거의 일정 양방향 전압 저지, 단방향 전류 소자
<b>IGCT</b> (1996)			Gate에 도통 전류와 크기가 갖고 음의 전류를 흘려서 빠른 OFF 가능 IGBT보다 도통 시 전압강하가 낮다 양방향 전압 저지, 단방향 전류 소자



### [3] Switching Loss (스위칭 손실)



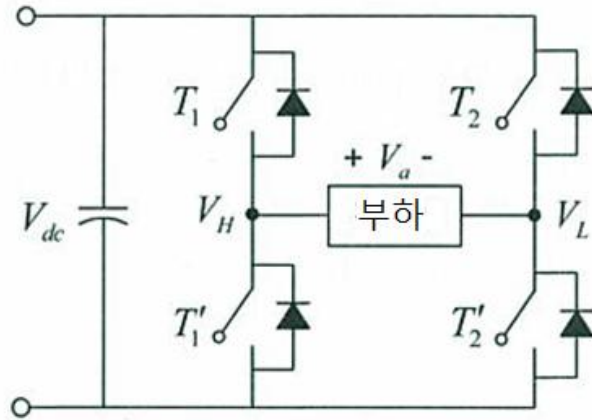
$v_{on}$ : 스위치 내부 전압강하  
 $i_{off}$ : 스위치 off시 누설전류  
 $P_{s1}$ : 스위치 on시 과도 손실  
 $P_{s2}$ : 스위치 off시 과도 손실



저항 부하의 경우

$$\text{스위칭 주기당 손실} = \frac{t_{on}}{T} v_{on} I_L + \frac{t_{off}}{T} E_s I_{off} + P_{s1} + P_{s2}$$

## [4] PWM (Pulse Width Modulation)



극전압

$$V_H = V_{dc} \text{ or } 0$$

$$V_L = V_{dc} \text{ or } 0$$

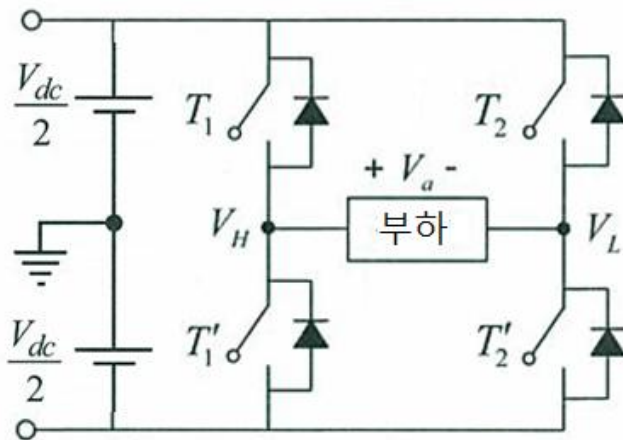
부하전압 ( $V_H - V_L$ )

(1)  $T_1, T'_2$  on

$$V_a = V_{dc}$$

(2)  $T_2, T'_1$  on

$$V_a = -V_{dc}$$



극전압

$$V_H = V_{dc}/2 \text{ or } -V_{dc}/2$$

$$V_L = V_{dc}/2 \text{ or } -V_{dc}/2$$

부하전압 ( $V_H - V_L$ )

(1)  $T_1, T'_2$  on

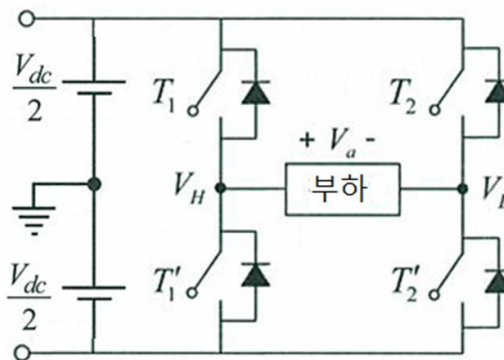
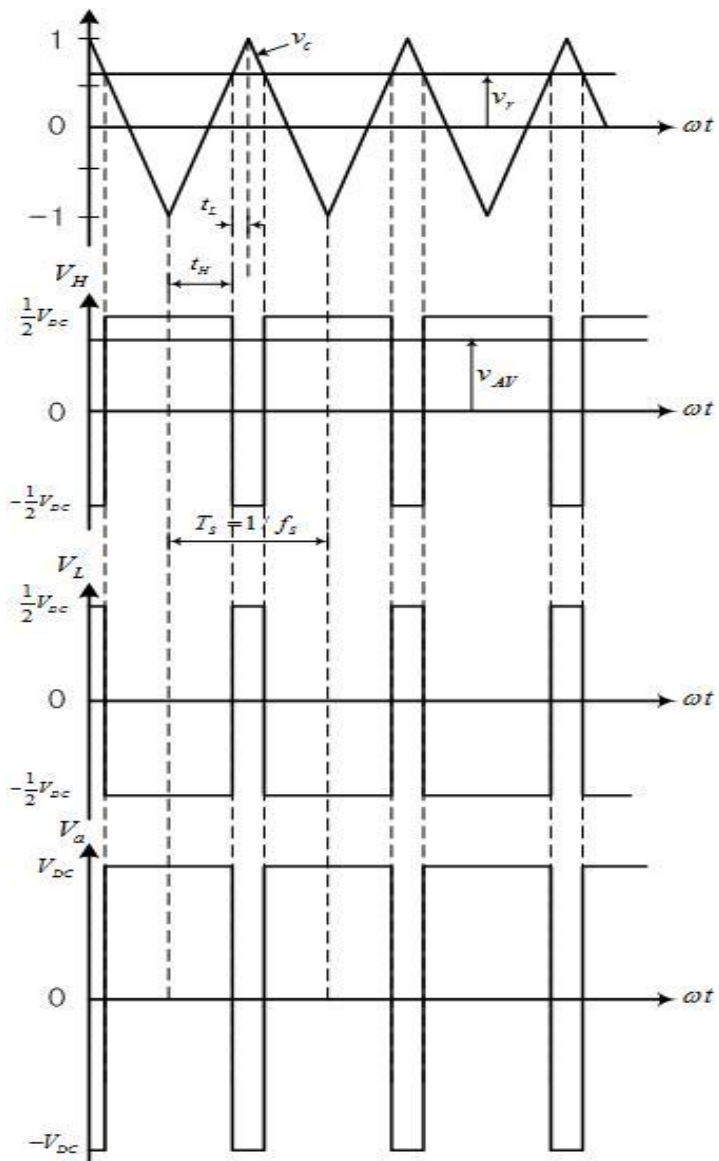
$$V_a = V_{dc}$$

(2)  $T_2, T'_1$  on

$$V_a = -V_{dc}$$



# (1) PWM (Pulse Width Modulation)의 평균전압 1



$$V_{H<AV>} = \frac{2t_H \times \left(\frac{V_{DC}}{2}\right) + 2t_L \times \left(-\frac{V_{DC}}{2}\right)}{T_S}$$

$$= \frac{V_{DC}}{T_S} (t_H - t_L)$$

$$\leftarrow \frac{v_r + 1}{t_H} = \frac{1 - v_r}{t_L}$$

$$\leftarrow t_H + t_L = \frac{T_S}{2}$$

$$V_{H<AV>} = \frac{V_{DC}}{2} v_r$$

$$V_{L<AV>} = \frac{2t_H \times \left(-\frac{V_{DC}}{2}\right) + 2t_L \times \left(+\frac{V_{DC}}{2}\right)}{T_S}$$

$$= -\frac{V_{DC}}{T_S} (t_H - t_L)$$

$$\leftarrow \frac{v_r + 1}{t_H} = \frac{1 - v_r}{t_L}$$

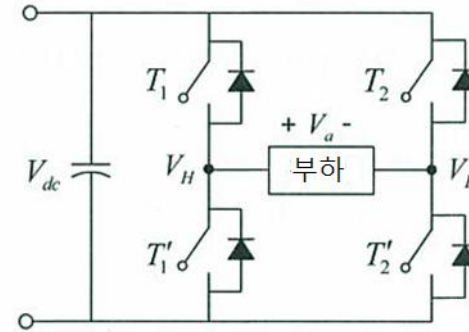
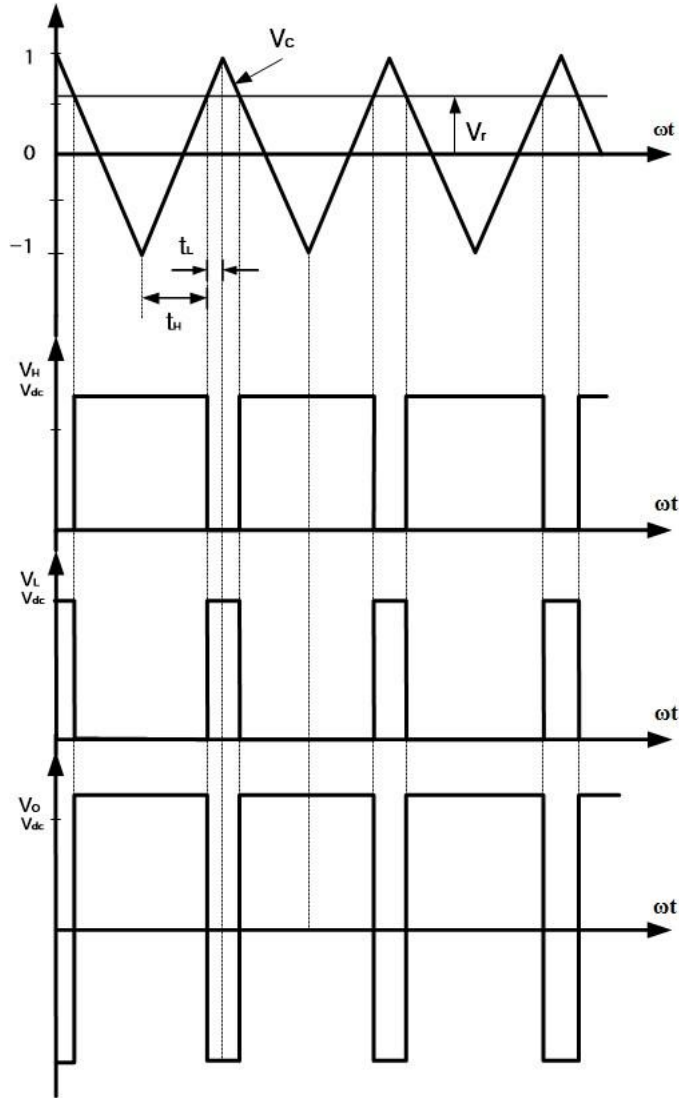
$$\leftarrow t_H + t_L = \frac{T_S}{2}$$

$$V_{L<AV>} = -\frac{V_{DC}}{2} v_r$$

$$V_{a<AV>} = V_{H<AV>} - V_{L<AV>} = V_{DC} v_r \quad (\text{단 } -1 \leq v_r \leq 1)$$

$$\text{여기서 } v_r = \frac{v_r^*}{V_{DC}}$$

## (2) PWM (Pulse Width Modulation)의 평균전압 2



$$V_{H<AV>} = \frac{2t_H \times (V_{DC})}{T_s}$$

$$= \frac{2V_{DC}}{T_s} t_H$$

$$\leftarrow \frac{v_r + 1}{t_H} = \frac{2}{\frac{1}{2}T_s} = \frac{4}{T_s}$$

$$V_{H<AV>} = \frac{V_{DC}}{2} (v_r + 1)$$

$$V_{L<AV>} = \frac{2t_L \times V_{DC}}{T_s}$$

$$= \frac{2V_{DC}}{T_s} t_L$$

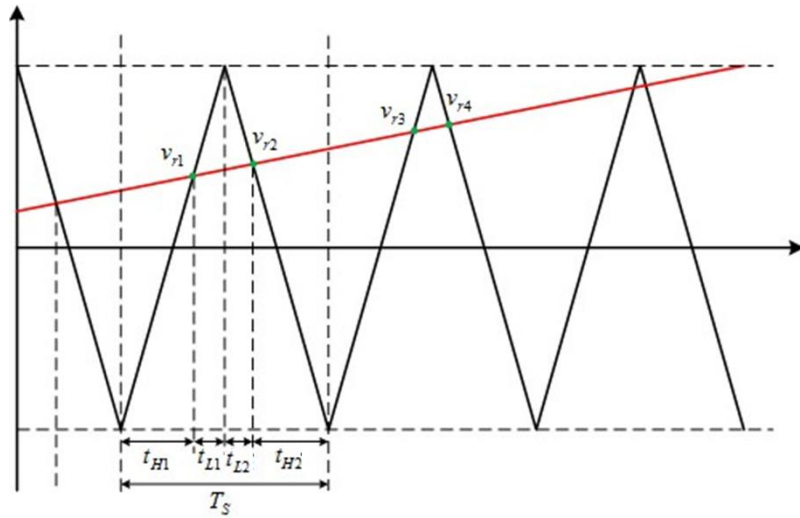
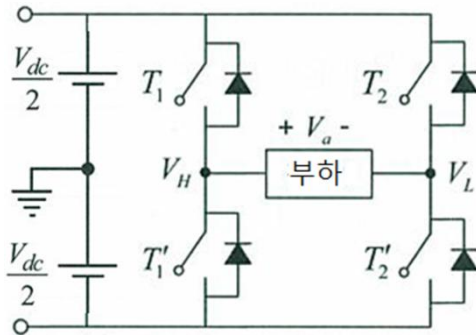
$$\leftarrow \frac{1 - v_r}{t_L} = \frac{2}{\frac{1}{2}T_s} = \frac{4}{T_s}$$

$$V_{L<AV>} = \frac{V_{DC}}{2} (1 - v_r)$$

$$V_{a<AV>} = V_{H<AV>} - V_{L<AV>} = V_{DC} v_r \quad (\text{단 } -1 \leq v_r \leq 1)$$

$$\text{여기서 } v_r = \frac{v_r^*}{V_{DC}}$$

### (3) PWM (Pulse Width Modulation)의 평균전압 3 (정현파)

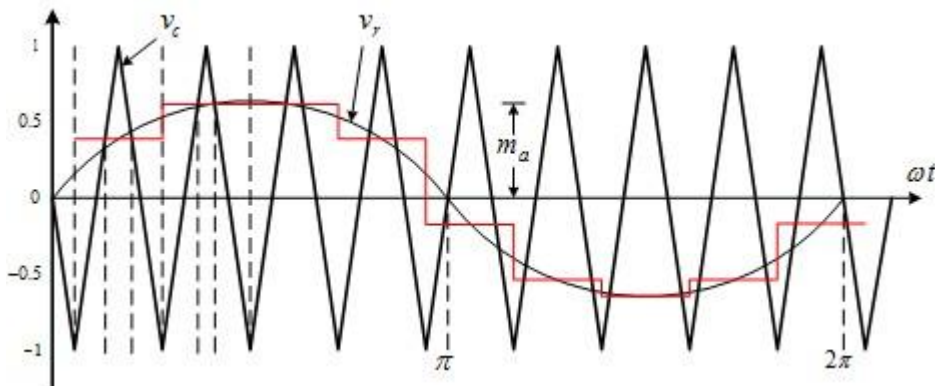


$$\begin{aligned}
 V_{H<AV>} &= \frac{t_{H1} \times \left(\frac{V_{DC}}{2}\right) + t_{L1} \times \left(-\frac{V_{DC}}{2}\right) + t_{L2} \times \left(-\frac{V_{DC}}{2}\right) + t_{H2} \times \left(\frac{V_{DC}}{2}\right)}{T_s} \\
 &= \frac{V_{DC}(t_{H1} - t_{L1})}{2T_s} + \frac{V_{DC}(t_{H2} - t_{L2})}{2T_s} = \frac{V_{DC}}{2} \left(\frac{v_{r1}}{2}\right) + \frac{V_{DC}}{2} \left(\frac{v_{r2}}{2}\right) \\
 &= \frac{V_{DC}}{2} \left(\frac{v_{r1} + v_{r2}}{2}\right) = \frac{V_{DC}}{2} v_{r<av>}
 \end{aligned}$$

$$\begin{aligned}
 V_{L<AV>} &= \frac{t_{H1} \times \left(-\frac{V_{DC}}{2}\right) + t_{L1} \times \left(+\frac{V_{DC}}{2}\right) + t_{L2} \times \left(+\frac{V_{DC}}{2}\right) + t_{H2} \times \left(-\frac{V_{DC}}{2}\right)}{T_s} \\
 &= \frac{-V_{DC}(t_{H1} - t_{L1})}{2T_s} - \frac{V_{DC}(t_{H2} - t_{L2})}{2T_s} = -\frac{V_{DC}}{2} \left(\frac{v_{r1}}{2}\right) - \frac{V_{DC}}{2} \left(\frac{v_{r2}}{2}\right) \\
 &= -\frac{V_{DC}}{2} \left(\frac{v_{r1} + v_{r2}}{2}\right) = -\frac{V_{DC}}{2} v_{r<av>}
 \end{aligned}$$

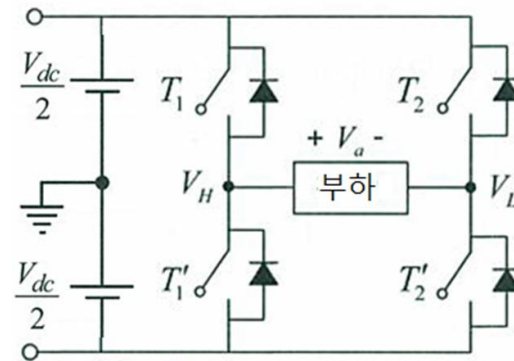
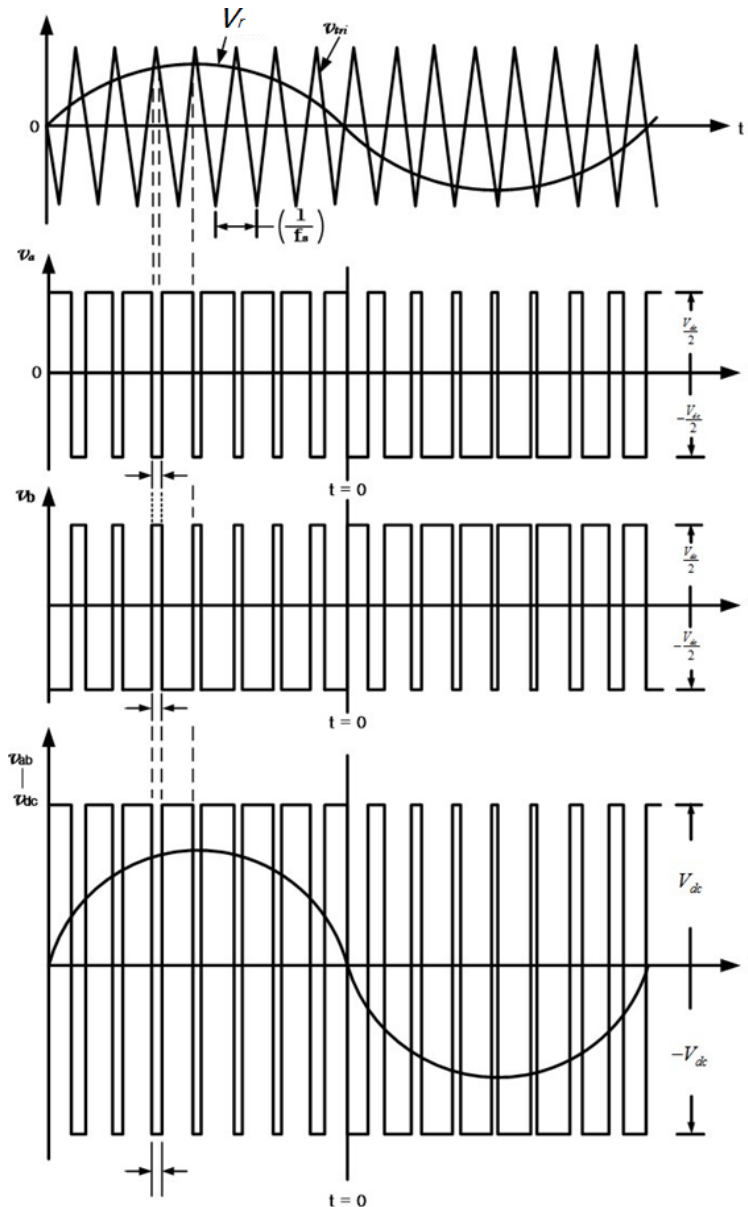
$$V_{a<AV>} = V_{H<AV>} - V_{L<AV>} = V_{DC} v_r \quad (\text{단 } -1 \leq v_r \leq 1)$$

여기서  $v_r = \frac{v_r^*}{V_{DC}}$



만일 반송파의 주파수가 기준파의 주파수에 비해 충분히 크다면 출력전압의 기본파 성분은 출력전압의 매 시간 간격  $T_s$  동안의 구간 평균값의 변화로 볼수 있다.

#### [4] 정현파 PWM 제어



$$m_a = \frac{\text{기준파의 진폭}}{\text{반송파의 진폭}}$$

$$m_f = \frac{\text{반송파의 주파수}}{\text{기준파의 주파수}} = \frac{f_c}{f}$$

$$v_r = m_a \sin \omega t \quad (\text{단, } 0 \leq m_a \leq 1)$$

$$V_{H<1>} = \frac{V_{DC}}{2} m_a \sin \omega t$$

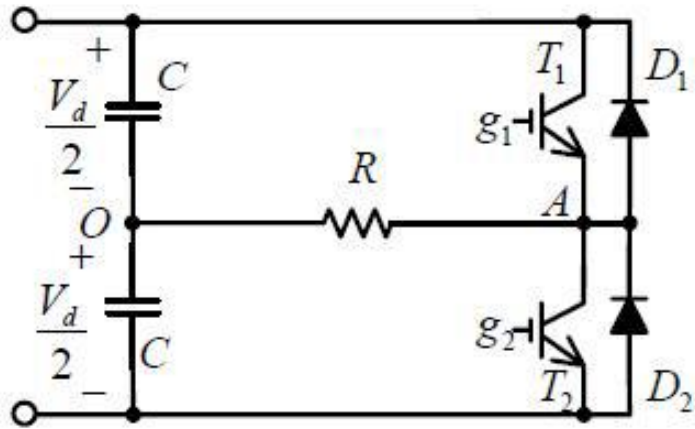
$$V_{L<1>} = -\frac{V_{DC}}{2} m_a \sin \omega t$$

$$V_{a<1>} = V_{H<1>} - V_{L<1>} = V_{DC} m_a \sin \omega t \quad (\text{단 } -1 \leq v_r \leq 1)$$

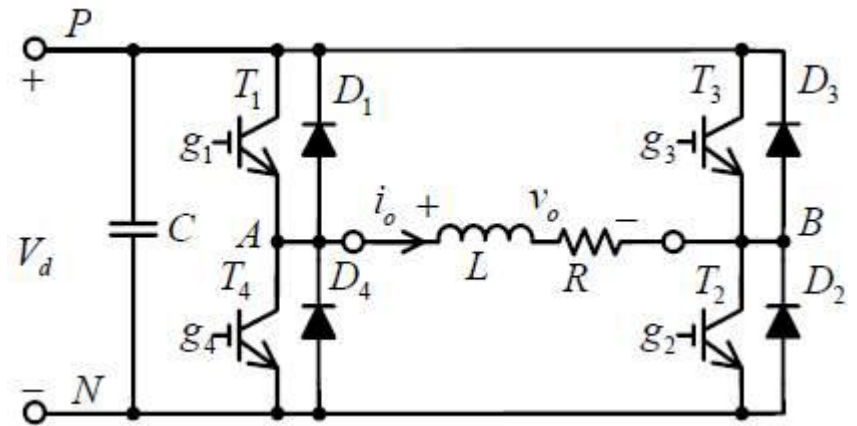
$$\text{여기서 } m_a = \frac{m_a^*}{V_{DC}}$$

## 9-2 단상 인버터

# [1] 인버터의 종류



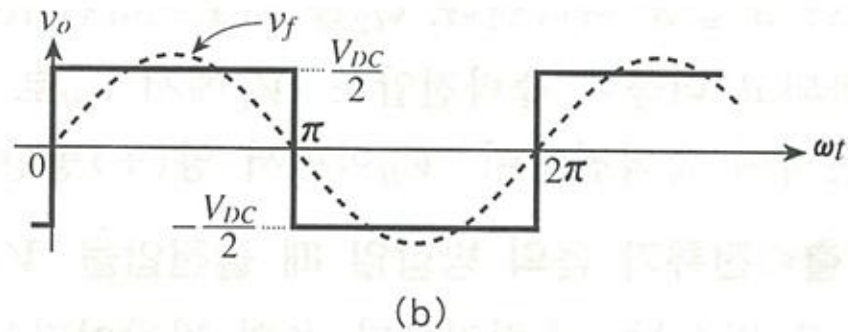
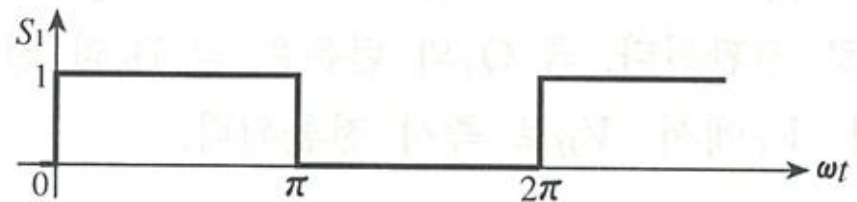
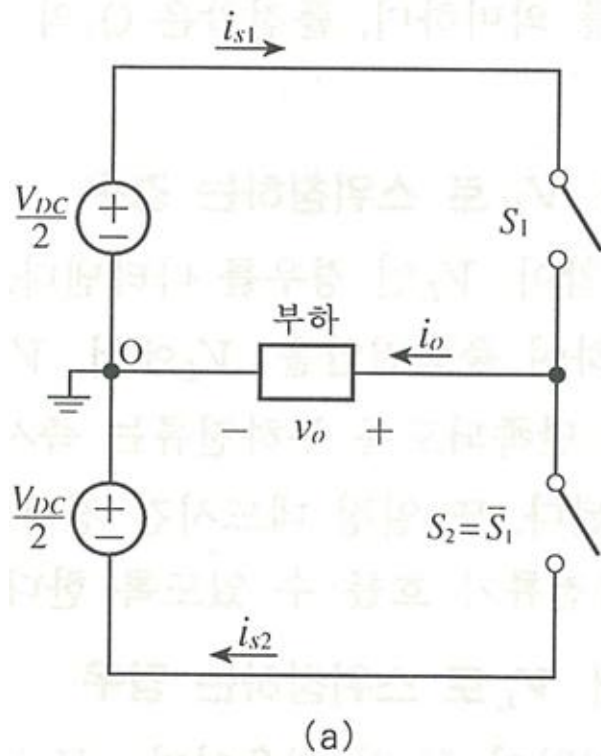
단상 Half Bridge Inv.



단상 Full Bridge Inv.

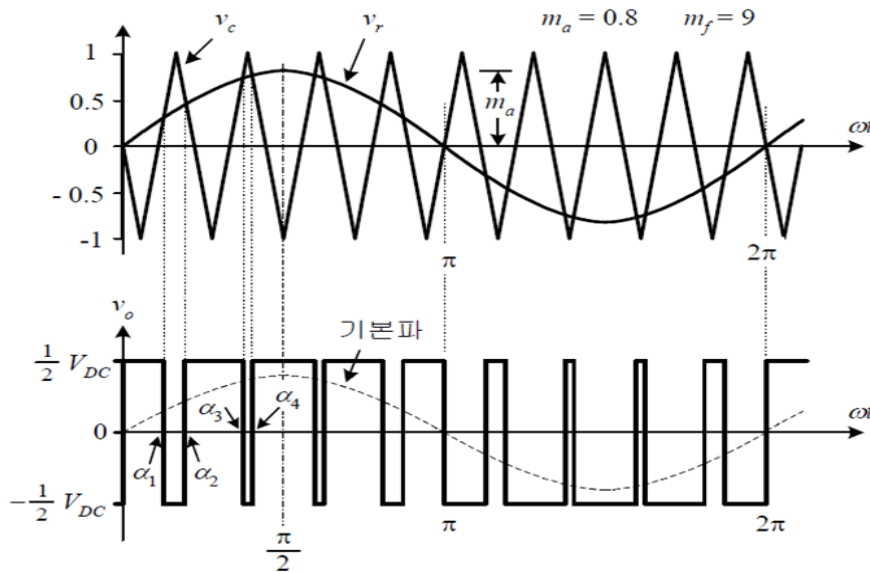
## [2] 단상 Half-bridge Inverter

### (1) 구형파 제어



기본파의 크기 :  $2V_{DC} / \pi$

## (2) PWM 제어



$$v_r = m_a \sin \omega t \quad (\text{단, } 0 \leq m_a \leq 1)$$

$$V_0 = \frac{V_{DC}}{2} m_a \sin \omega t$$

- 기준파 (선형변조):  $v_r = m_a \sin \omega t$  (단,  $0 \leq m_a \leq 1$ )
- 출력전압 기본파의 크기는  $m_a$ 에 비례하고, 주파수는 기준파의 주파수와 같다.
- 선형변조시 출력전압 기본파의 최대치는  $m_a=1$ 일 때  $V_{DC}/2$  이다.
- 정현파 PWM 제어로 얻을 수 있는 출력전압 기본파의 최대 크기는 구형파 제어되는 경우 ( $= 2V_{DC}/\pi$ )의 78.5%에 불과하다.



## 9-2 단상 Full-bridge Inverter

### (1) 구형파 제어

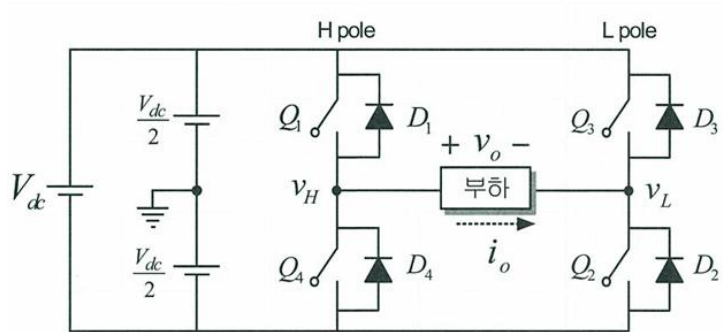
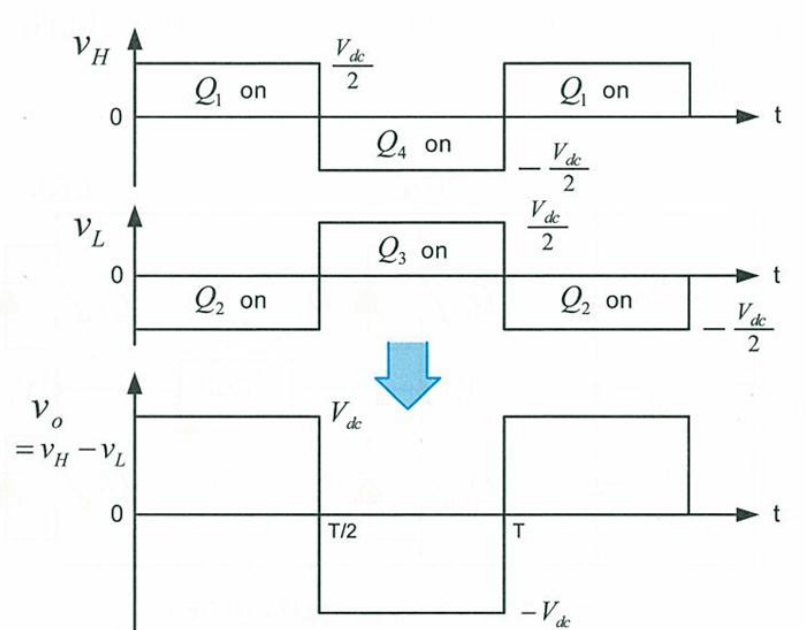


그림 7.11 단상 풀 브리지 인버터

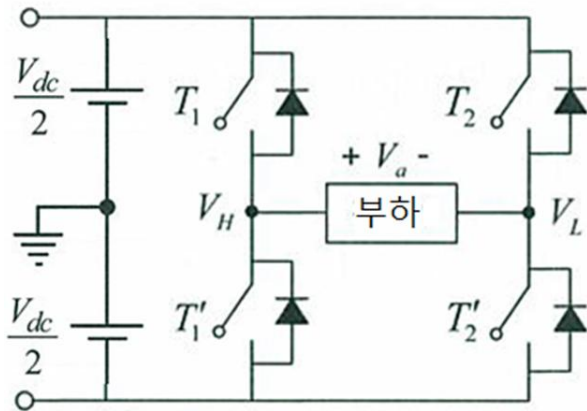
$$v_o = v_H - v_L$$



$$v_o = \frac{4 V_{dc}}{\pi} \sum_{n=1,3,5\dots}^{\infty} \frac{\sin n \omega t}{n}$$

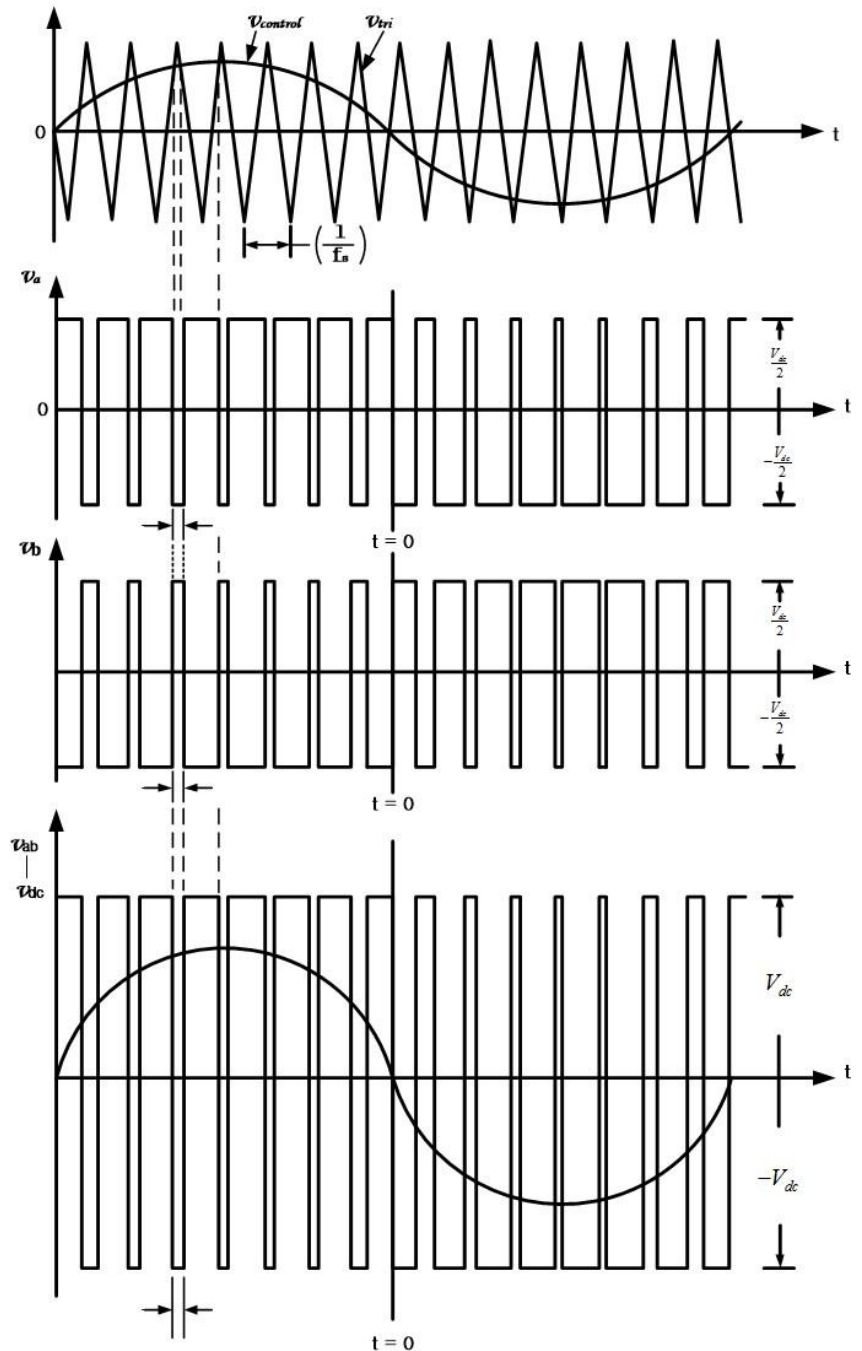
## (2) PWM 제어

### (A) bi-polar 방식

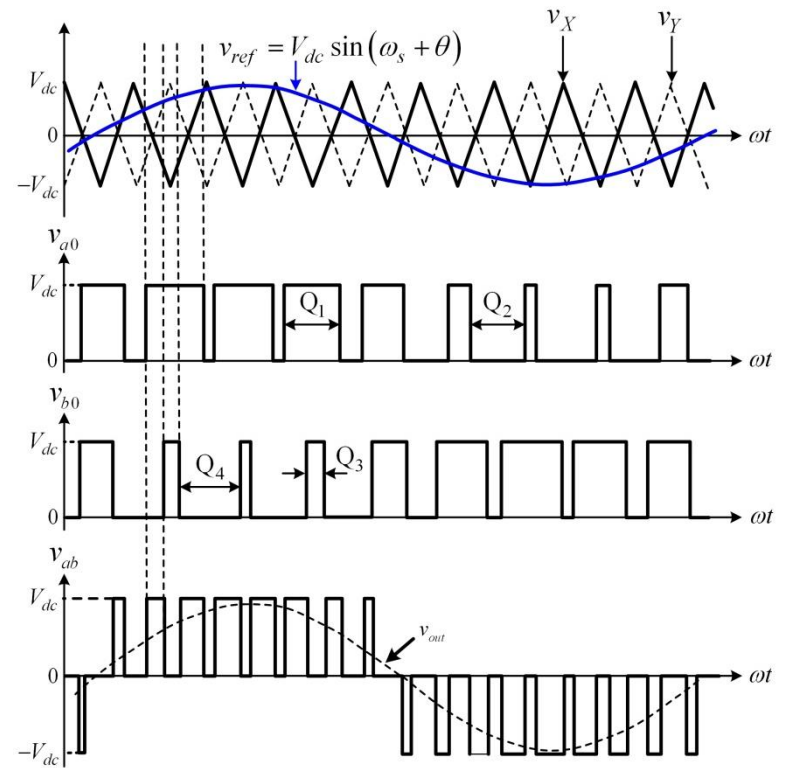
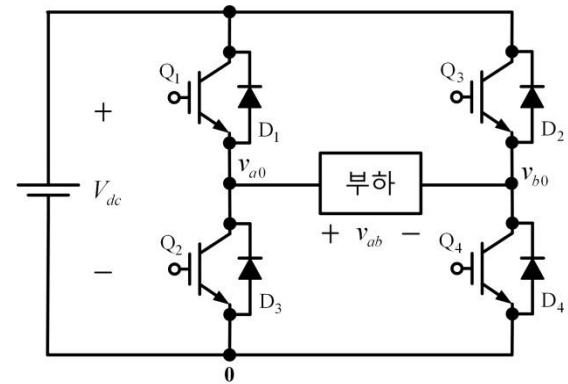
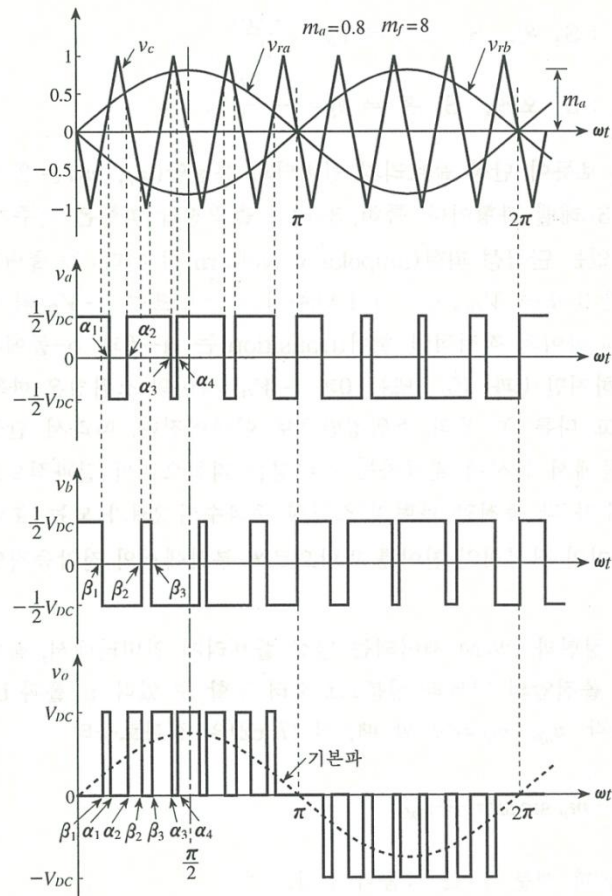
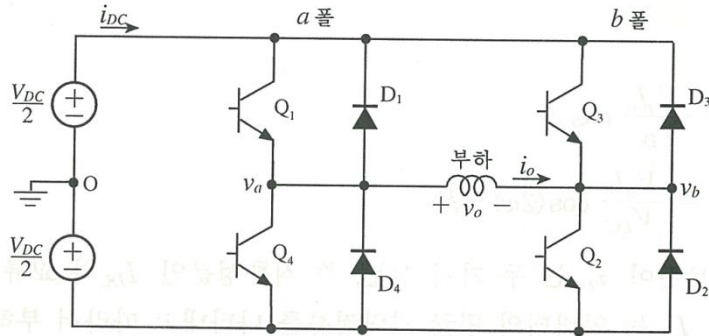


$$V_0 = V_{DC} m_a \sin \omega t$$

Half-bridge의 2배

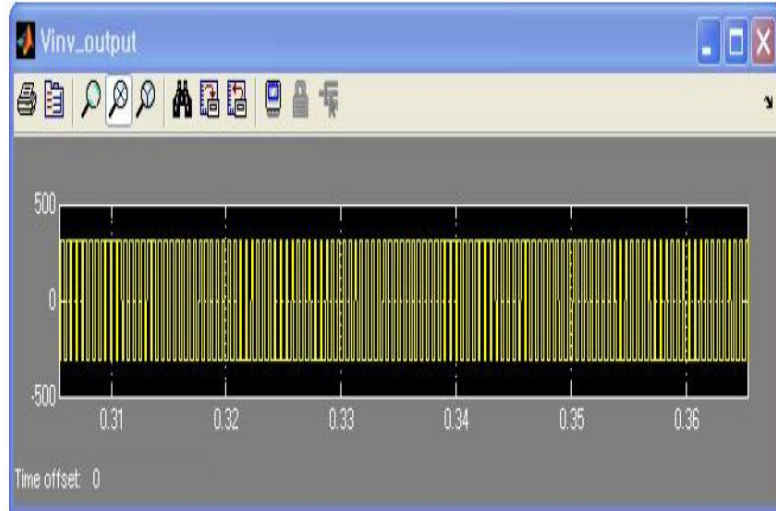
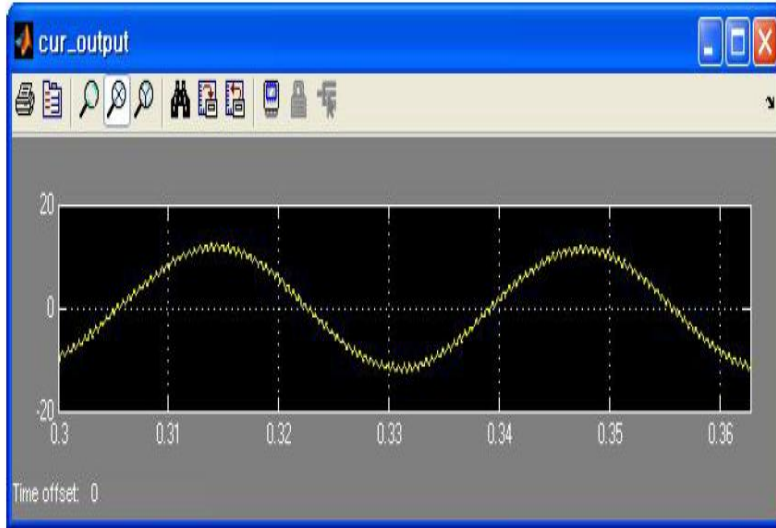


## (B) Uni-polar 방식

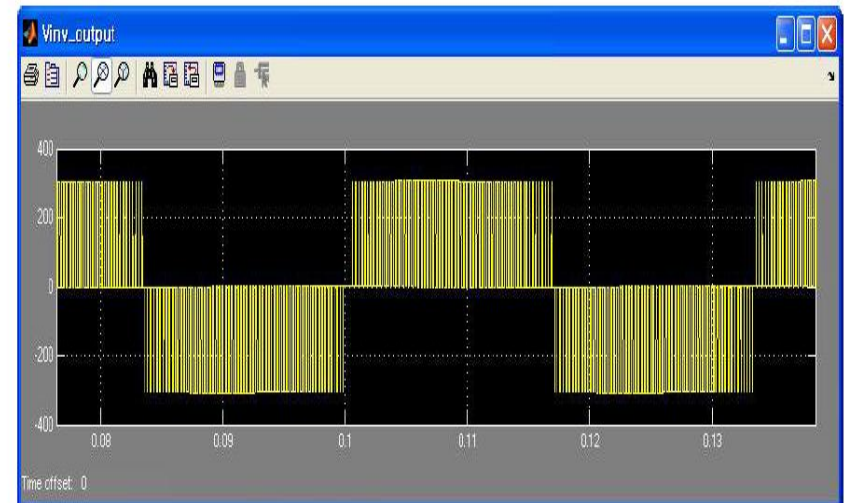
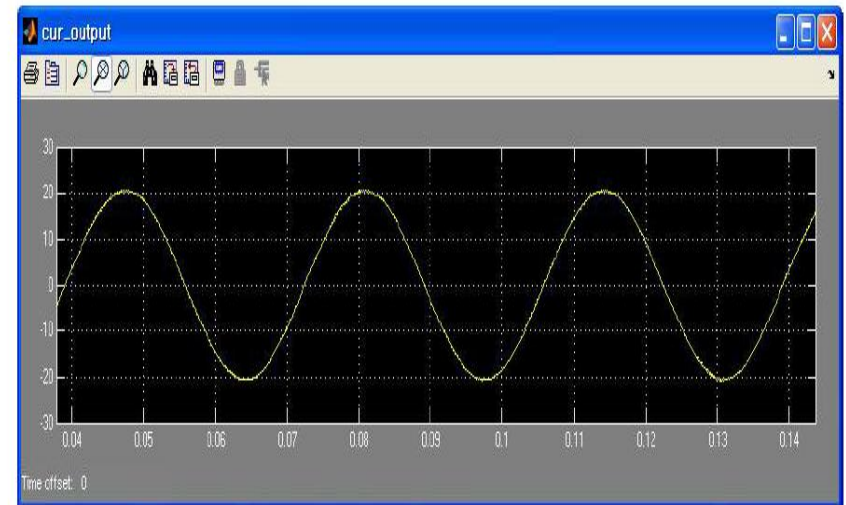


## (C) Uni-polar 방식과 bi-polar방식의 비교

선 전류(Phase current), 선간 전압 (line to line voltage)파형

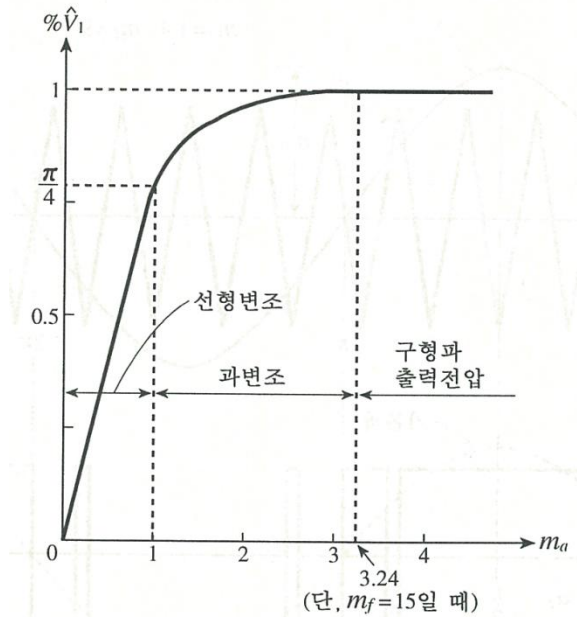
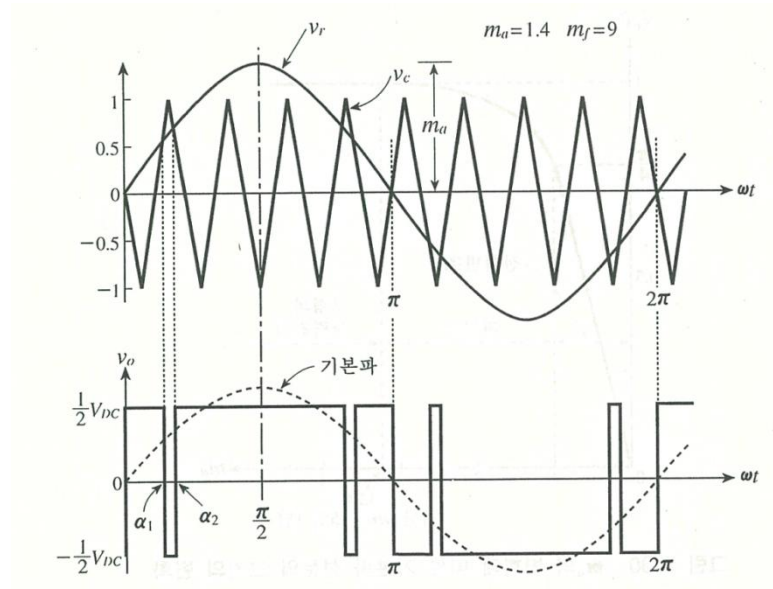


bi-polar방식



Uni-polar 방식

### (3) 과변조

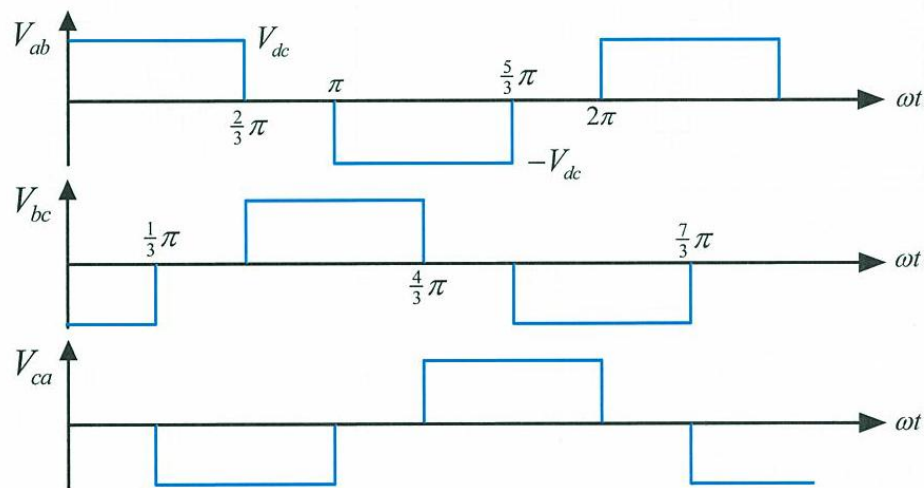
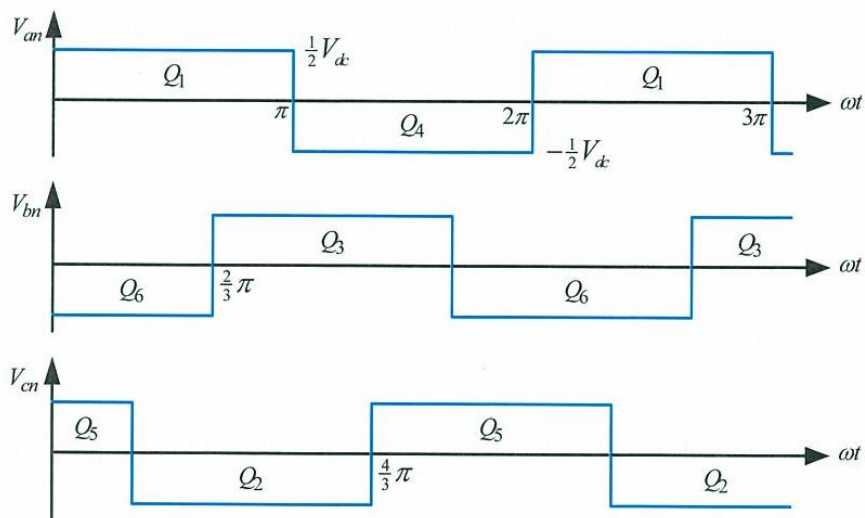
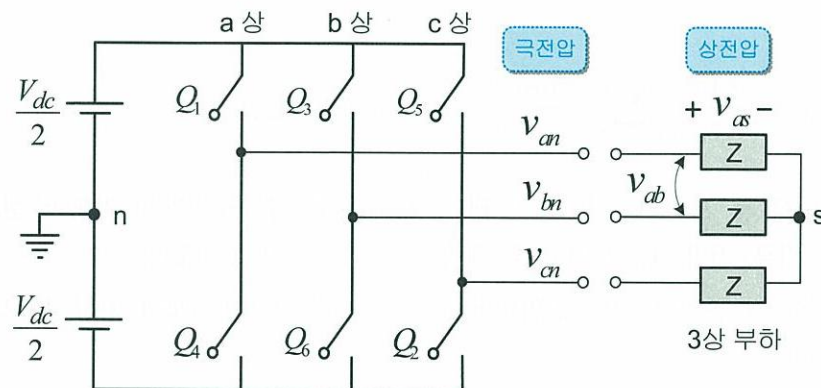


선형변조구간 : 
$$\frac{\text{선형구간의 기본파 최대치}}{\text{구형파의 기본파의 최대치}} = \frac{V_{DC}}{\frac{4}{\pi} V_{DC}} = \frac{\pi}{4}$$

## 9-3 3상 인버터

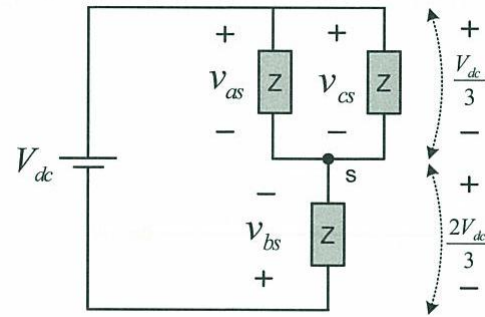
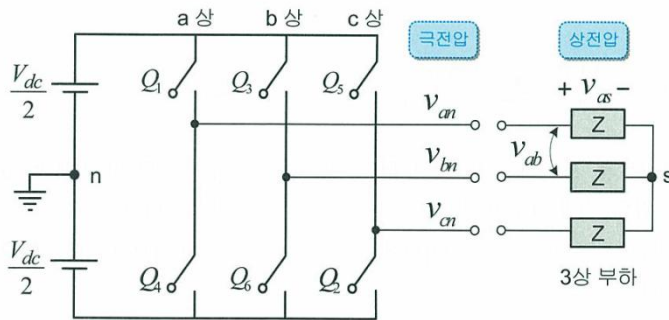
# [1] 6-step 제어

## (1) 극전압과 선간전압

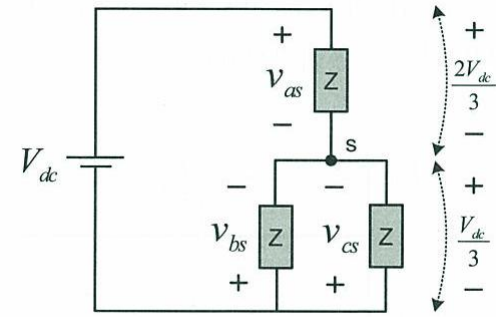




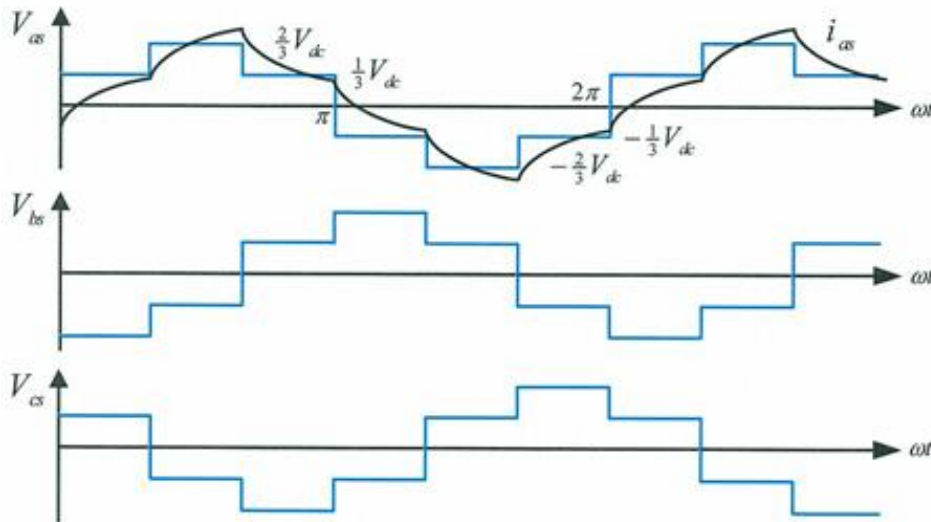
## (2) 극전압과 선간전압



(a) Q6, Q5, Q1 도통



(b) Q6, Q1, Q2 도통



$$v_{as} = \frac{2 V_{dc}}{\pi} \left[ \sin \omega t - \frac{1}{5} \sin 5 \omega t - \frac{1}{7} \sin 7 \omega t + \dots \right]$$



기본파 크기 :  $\frac{2}{\pi} V_{DC}$

6-스텝 인버터의 전압 파형



### (3) 스위치 상태별 전압특성

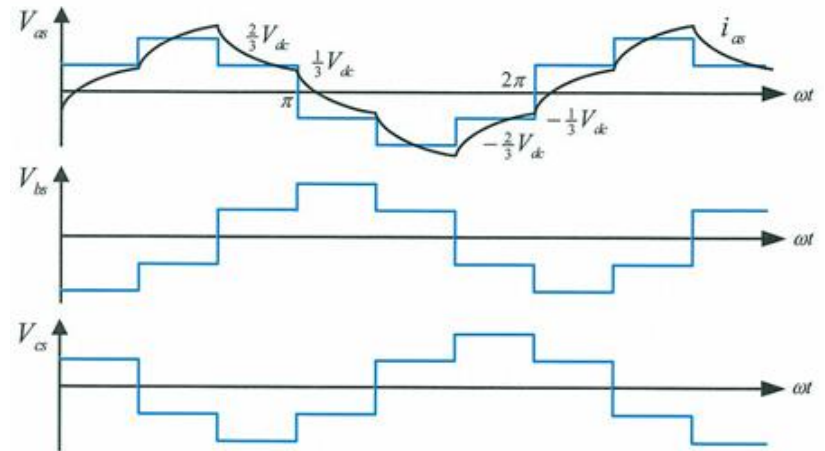
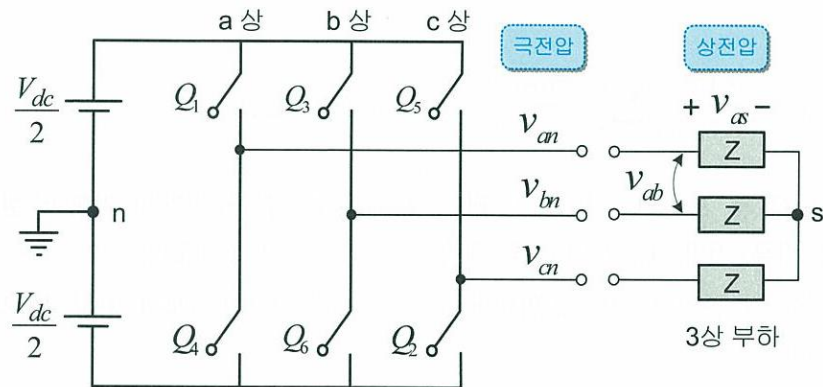
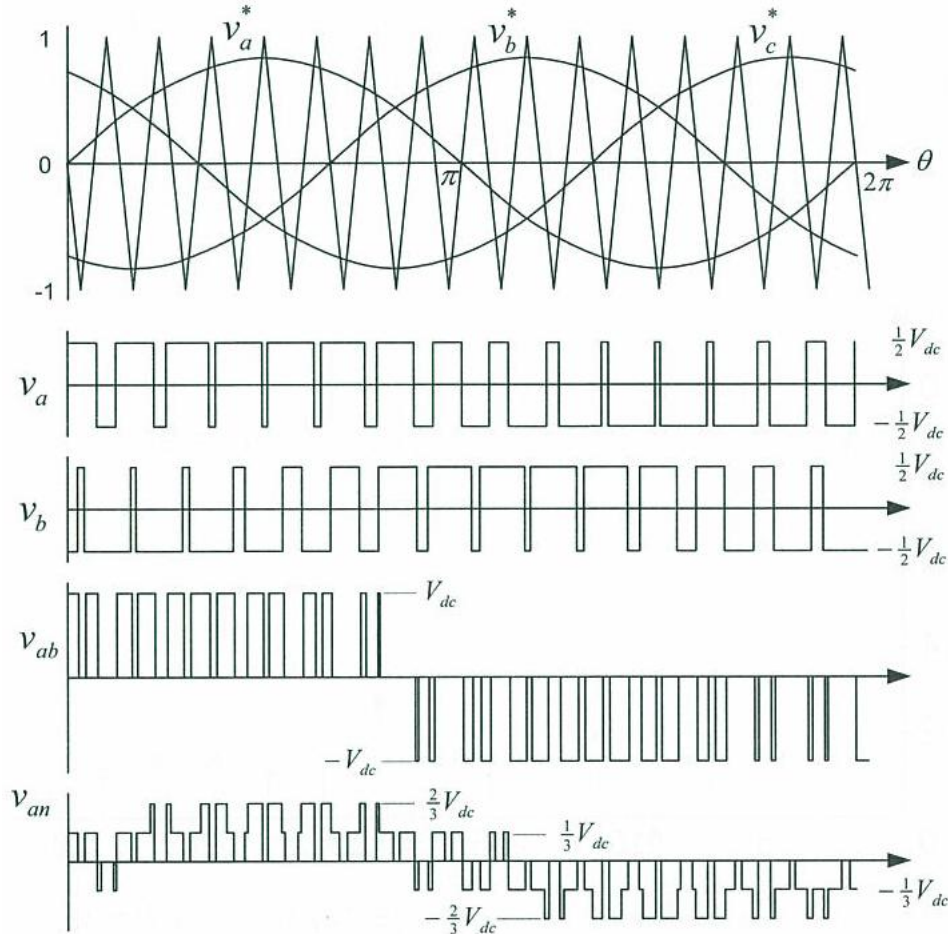


표 7.2 스위칭 상태에 따른 극전압과 상전압

스위치 상태			극전압			상전압(부하전압)		
$S_a$	$S_b$	$S_c$	$V_{an}$	$V_{bn}$	$V_{cn}$	$V_{as}$	$V_{bs}$	$V_{cs}$
0	0	0	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	0	0	0
0	0	1	$-V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$
0	1	0	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$
0	1	1	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$
1	0	0	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$
1	0	1	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$
1	1	0	$V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$
1	1	1	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	0	0	0

## [2] SPWM 제어 (Sine PWM)



$$\frac{\frac{2}{\pi} V_{DC}}{\frac{V_{DC}}{2}} = \frac{4}{\pi} = 1.273$$

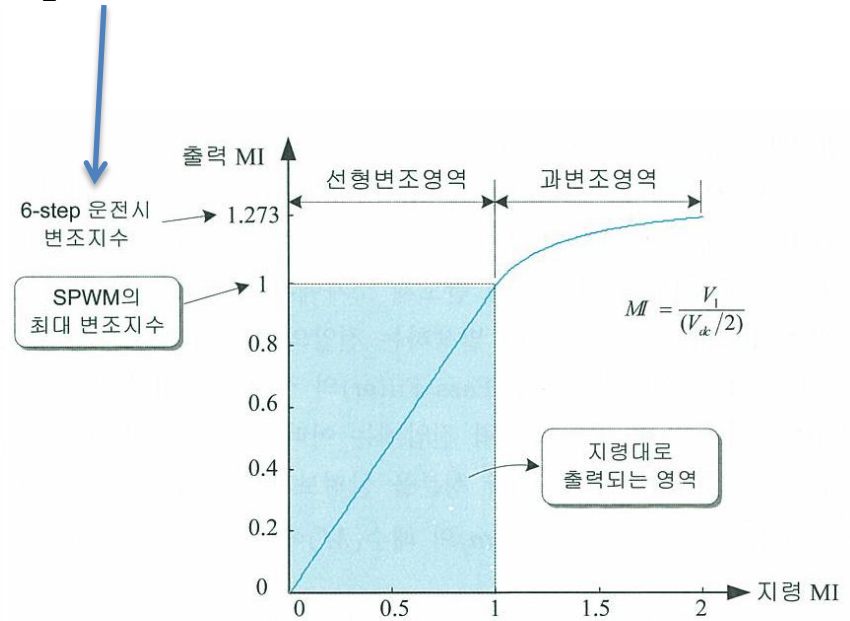
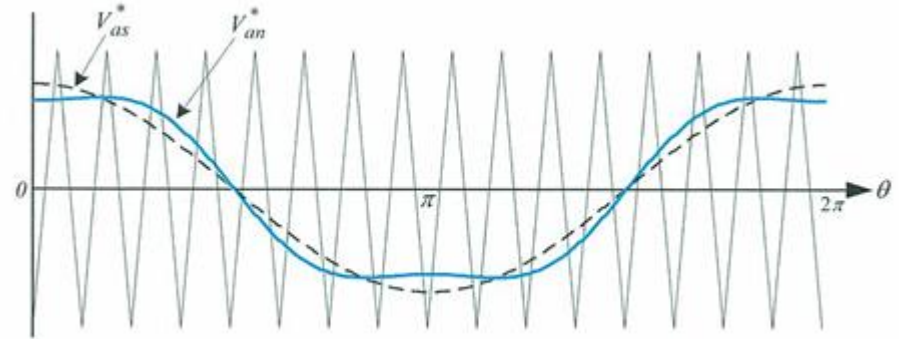
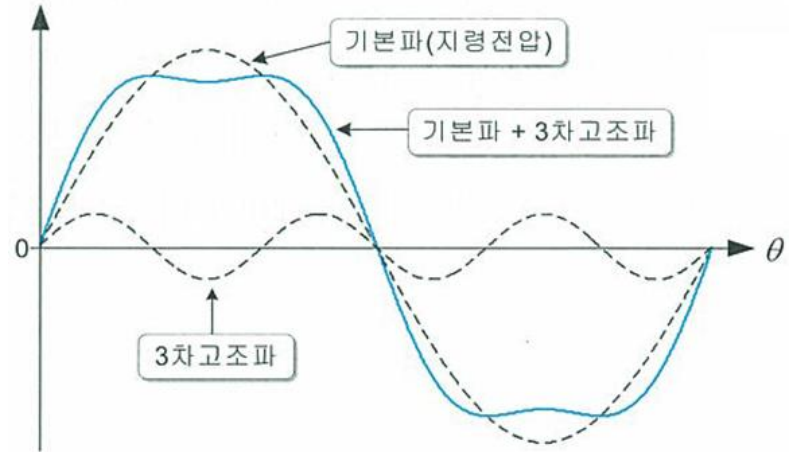
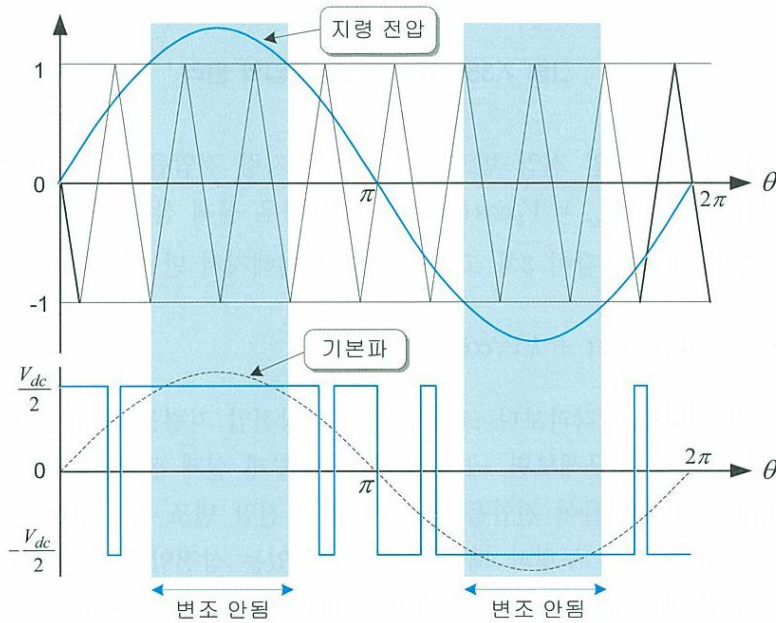


그림 7.29 SPWM 기법에서의 전압 변조 영역

■ 전압 변조 지수 (Modulation Index)  $MI = \frac{V_{1peak}}{\frac{V_{dc}}{2}}$

### [3] 3고조파 주입 전압 변조방식



$$V_{an} = V_1 \cos \omega t + k V_1 \cos (3\omega t) \Rightarrow K=1/6$$

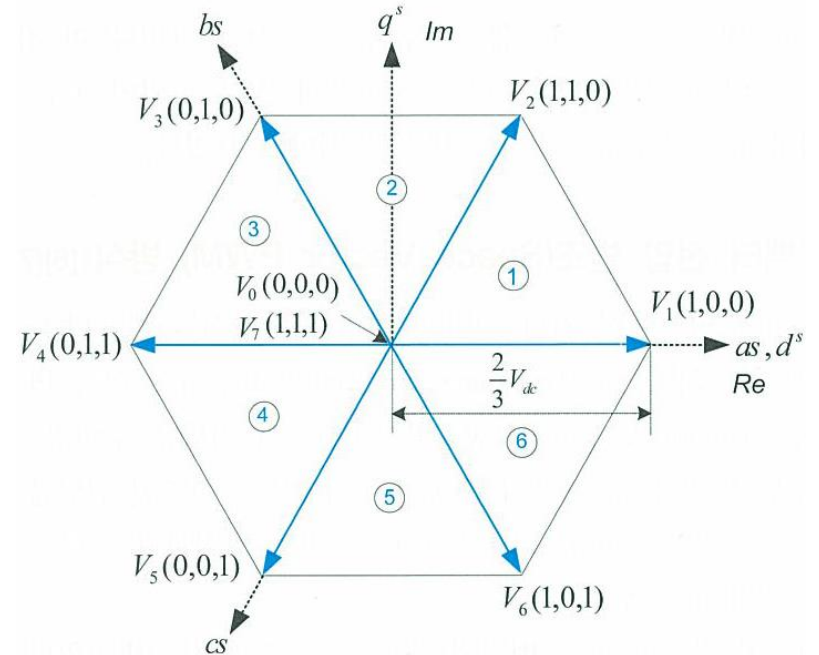
선형 변조 MI 가 최대 1.15배로 커짐

## [4] SVPWM (Space Vector PWM : 공간 벡터 변조법)

### (1) 원리

표 7.3 스위칭 상태에 따른 인버터의 공간 전압 벡터

스위칭 상태 $S_a$ $S_b$ $S_c$	상전압 $v_{as}$ $v_{bs}$ $v_{cs}$	공간 전압 벡터 $V_n$
0 0 0	0 0 0	$V_0 = 0/0^\circ$
1 0 0	$\frac{2}{3} V_{dc}$ $-\frac{1}{3} V_{dc}$ $-\frac{1}{3} V_{dc}$	$V_1 = \frac{2}{3} V_{dc}/0^\circ$
1 1 0	$\frac{1}{3} V_{dc}$ $\frac{1}{3} V_{dc}$ $-\frac{2}{3} V_{dc}$	$V_2 = \frac{2}{3} V_{dc}/60^\circ$
0 1 0	$-\frac{1}{3} V_{dc}$ $\frac{2}{3} V_{dc}$ $-\frac{1}{3} V_{dc}$	$V_3 = \frac{2}{3} V_{dc}/120^\circ$
0 1 1	$-\frac{2}{3} V_{dc}$ $\frac{1}{3} V_{dc}$ $\frac{1}{3} V_{dc}$	$V_4 = \frac{2}{3} V_{dc}/180^\circ$
0 0 1	$-\frac{1}{3} V_{dc}$ $-\frac{1}{3} V_{dc}$ $\frac{2}{3} V_{dc}$	$V_5 = \frac{2}{3} V_{dc}/240^\circ$
1 0 1	$\frac{1}{3} V_{dc}$ $-\frac{2}{3} V_{dc}$ $\frac{1}{3} V_{dc}$	$V_6 = \frac{2}{3} V_{dc}/300^\circ$
1 1 1	0 0 0	$V_7 = 0/0^\circ$



예로서 모드 2( $S_a=1, S_b=1, S_c=0$ )의 경우에 공간 전압 벡터  $V_2$ 를 구해보자.

- 공간 벡터 정의식 :  $V = \frac{2}{3}(v_{as} + a \cdot v_{bs} + a^2 \cdot v_{cs})$

$$= v_{as} + j \frac{1}{\sqrt{3}}(v_{bs} - v_{cs})$$

(여기서,  $a = e^{j\frac{2\pi}{3}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$ ,  $a^2 = e^{-j\frac{2\pi}{3}} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$ )

- 모드 2의 상전압 :  $v_{as} = \frac{1}{3} V_{dc}$ ,  $v_{bs} = \frac{1}{3} V_{dc}$ ,  $v_{cs} = -\frac{2}{3} V_{dc}$

→ 공간 전압 벡터  $V_2 = \left( \frac{1}{3} + j\frac{1}{\sqrt{3}} \right) V_{dc} = \frac{2}{3} V_{dc} \angle 60^\circ$



## (2) 스위칭 시간

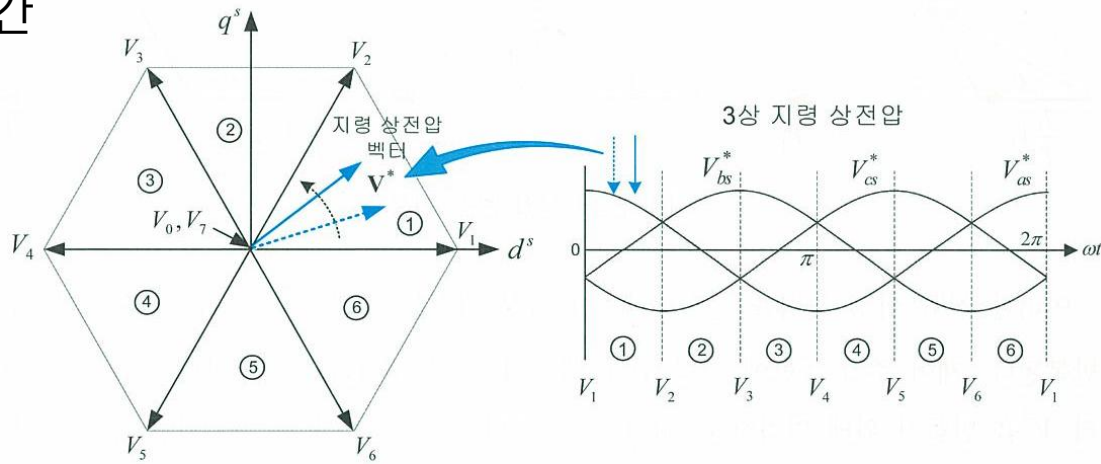
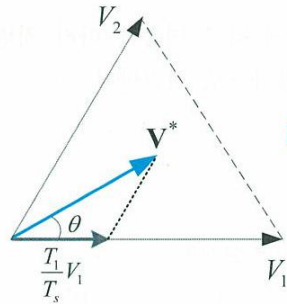
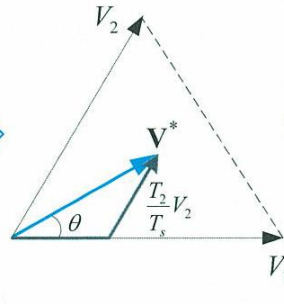


그림 7.38 지령 전압 벡터의 움직임

Step 1.  
유효 전압벡터 1 인가



Step 2.  
유효 전압벡터 2 인가



Step 3.  
영 전압 벡터 인가

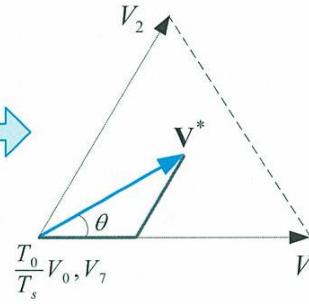
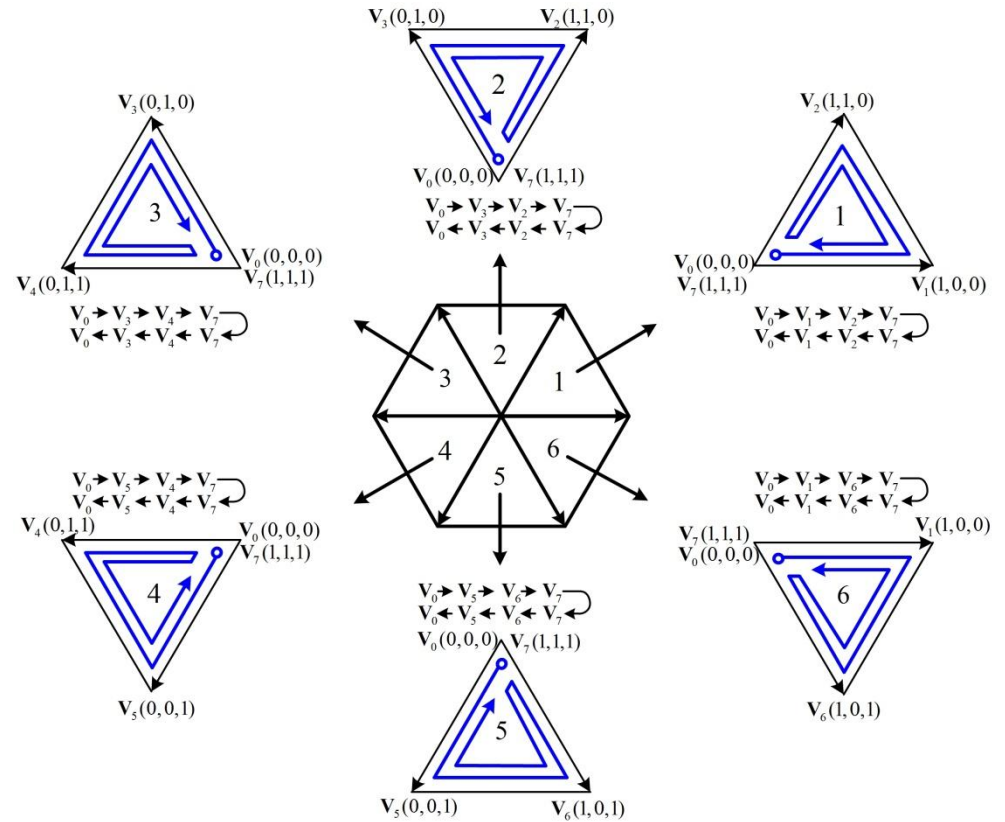
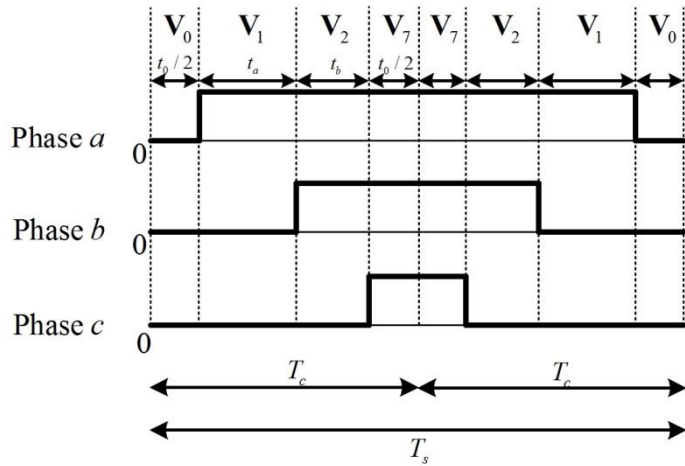
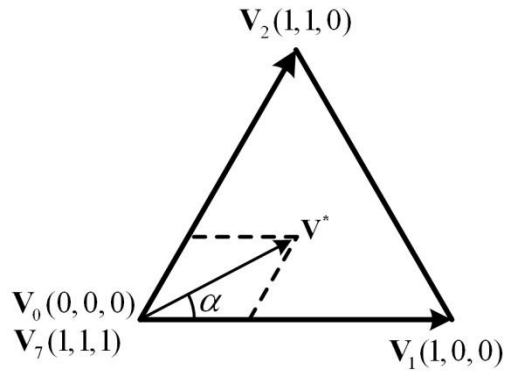


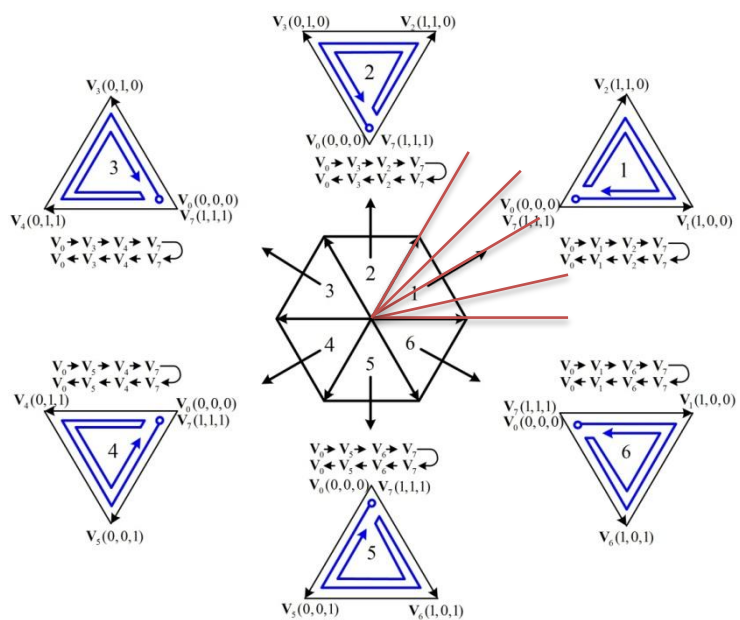
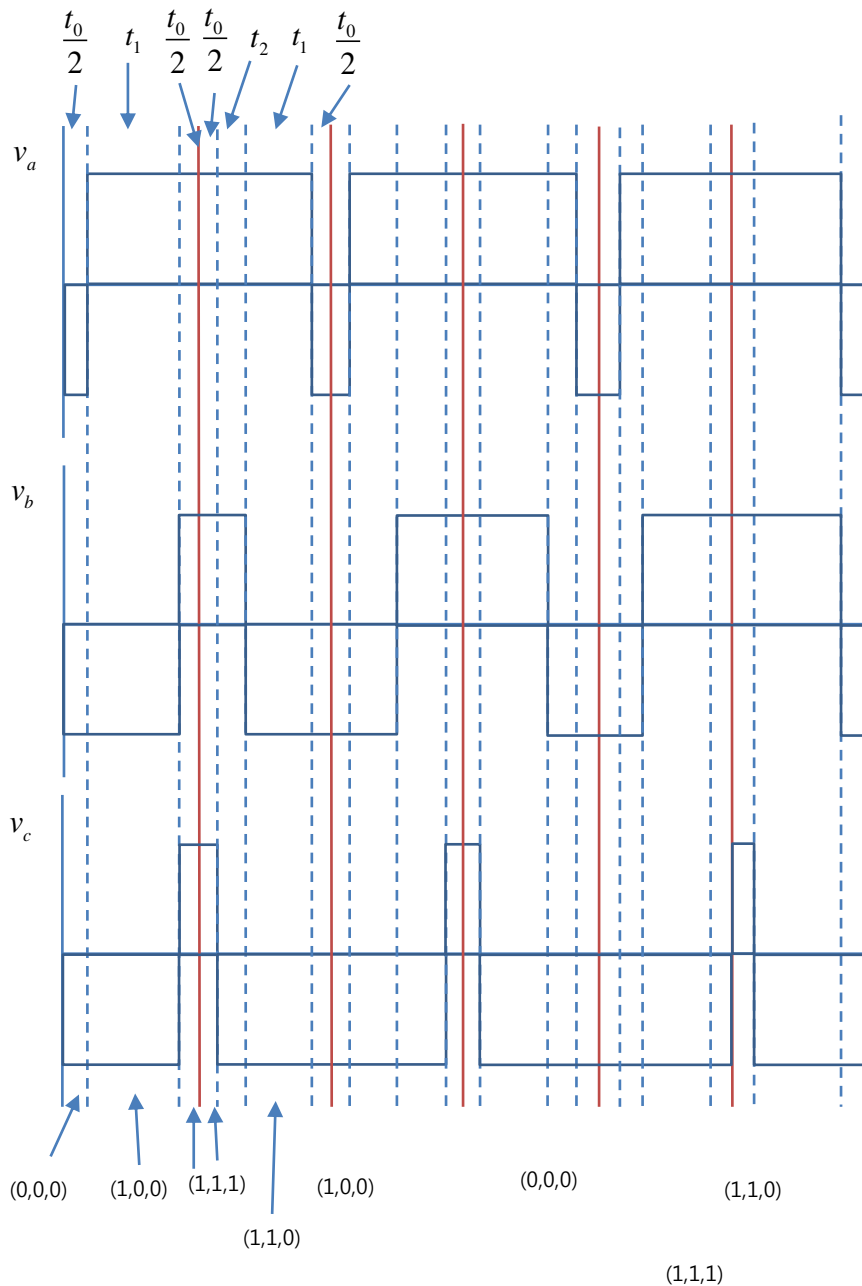
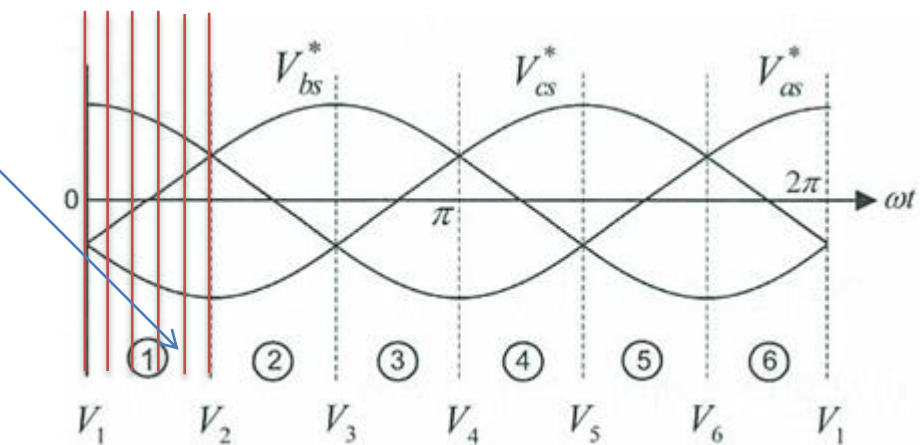
그림 7.39 전압 변조 과정

$$\int_0^{T_s} V^* dt = \int_0^{T_1} V_n dt + \int_{T_1}^{T_1+T_2} V_{n+1} dt + \int_{T_1+T_2}^{T_s} V_{0,7} dt$$

$$\Rightarrow \begin{aligned} T_1 &= \sqrt{3}T_s \frac{|V^*|}{V_{dc}} \left( \sin \frac{n\pi}{3} \cos \theta - \cos \frac{n\pi}{3} \sin \theta \right) \\ T_2 &= \sqrt{3}T_s \frac{|V^*|}{V_{dc}} \left( \sin \theta \cdot \cos \frac{n-1}{3}\pi - \cos \theta \cdot \sin \frac{n-1}{3}\pi \right) \end{aligned}$$

### (3) 스위칭 순서





[5] 각 PWM의 선형 변조 가능 전압

