Chapter 7

Power Supplies for AC Drives

Power Supplies for Adjustable Speed AC Drives

แบ่งออกเป็น

1) Voltage Source ..... จ่ายแรงดัน V, ω, ϕ ใดๆได้

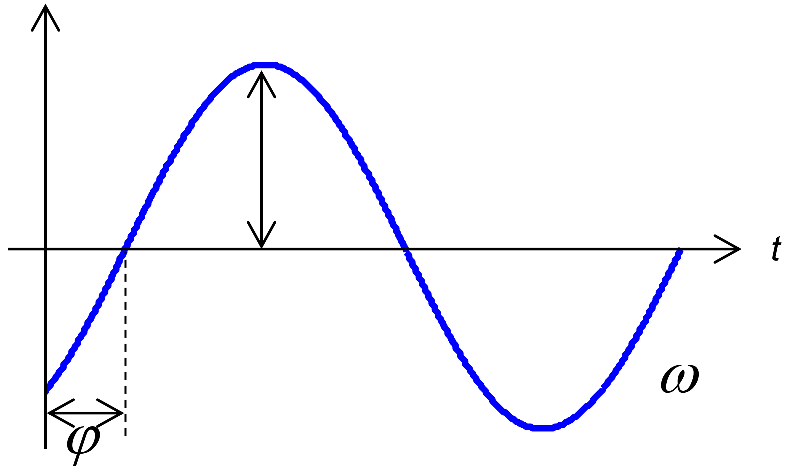
- *Six-Step Inverters*
- *PWM Inverters*
- *Cycloconverters*

Voltage Source Inverter (VSI)

AC (50 Hz) → DC → AC

-MW range

AC (50 Hz) → AC



2) Current Source ..... จ่ายกระแส I, ω, ϕ ใดๆได้

- *Current Source Inverter [CSI]*
- *Current-Controlled Inverter [VSI+Current Feedback]*

current control Inverter

(-Regulated) [CCI, CRI]

current regulated Inverter

- *Hysteresis Current Control*
- *PI Current Control*

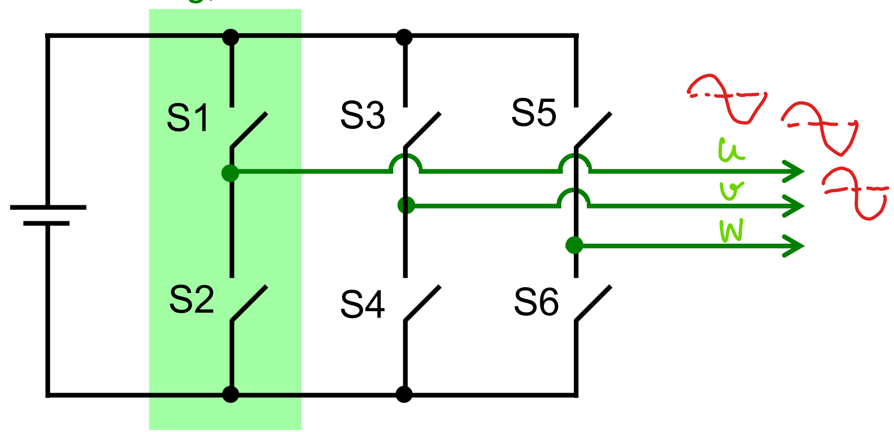
Six-Step Inverters

โครงสร้างวงจรของ VSI

Leg, Arm

DC Bus

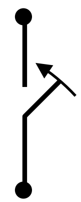
แหล่งจ่ายไฟตรง



S1, S2 : ON พร้อมกันไม่ได้

S3, S4 : ON พร้อมกันไม่ได้

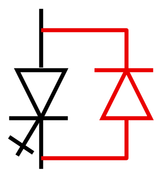
S5, S6 : ON พร้อมกันไม่ได้

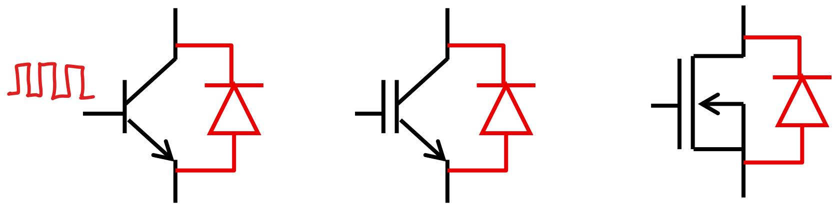


= Power Devices ที่ ON/OFF ได้ตามสัญญาณขับนำ

S_1 & S_2 = T ⇒ Shoot Through

Anti-Parallel Diode





~~Thyristor~~ IGCT GTO ~~BJT~~ IGBT MOSFET

$\underbrace{\text{IGCT} \quad \text{GTO}}_{\text{High Power}}$

$\underbrace{\text{BJT} \quad \text{IGBT} \quad \text{MOSFET}}_{\text{Medium-Low Power}}$

GTO: Gate Turn-Off Thyristors

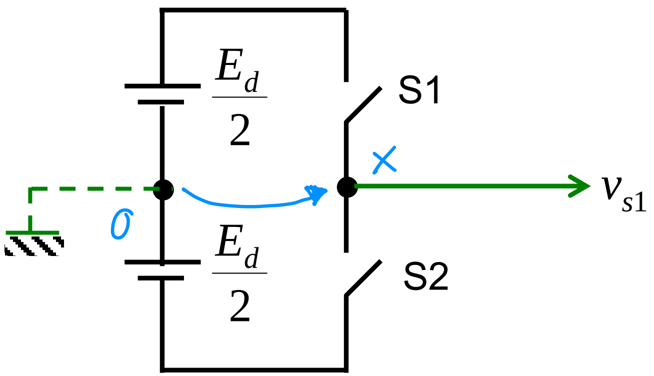
IGCT: Integrated Gate commutated Thyristors

BJT: Bipolar Junction Transistors

MOSFET:

IGBT: Insulated Gate Bipolar Transistors

<u>การทำงาน</u>



E_d: แรงดันที่ DC Bus

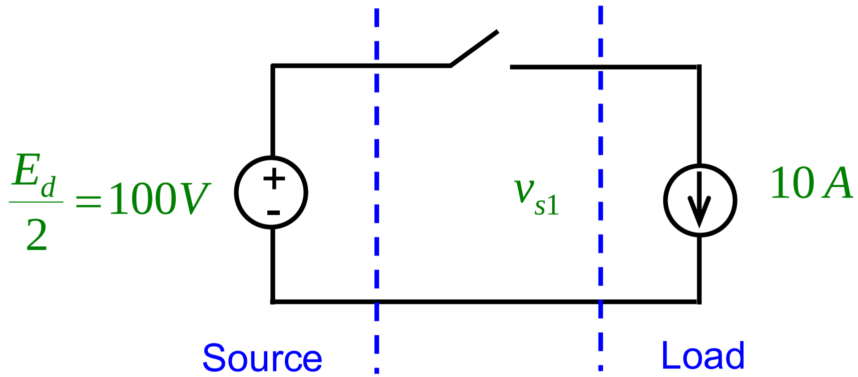
- S1 = ON (S2 = OFF)

$$v_{s1-0} = +E_d/2$$

- S1 = OFF (S2 = ON)

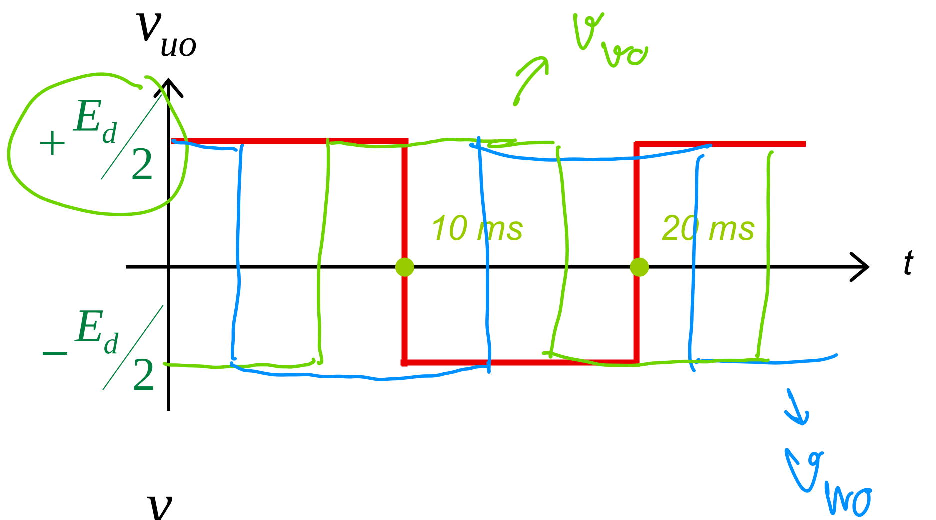
$$v_{s1-0} = -E_d/2$$

- แรงดันขาออกจะถูกกำหนดโดยสภาวะของสวิตซ์
- กระแสใน DC Bus จะถูกกำหนดโดยสภาวะของสวิตซ์เช่นกัน

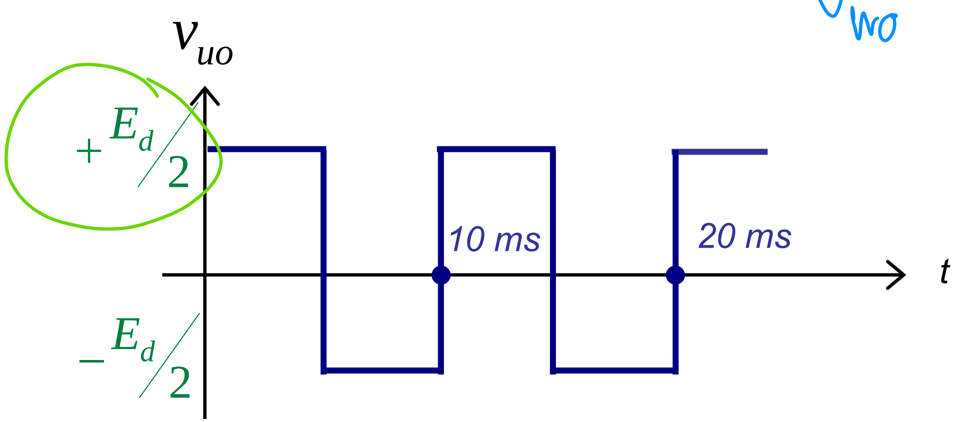


สำหรับ Six-Step Inverter

- S1, S3, S5 จะมีช่วงในการ ON = 180^{o}
- โดยช่วงการ ON ของ S1, S3, S5 จะ shift phase กัน 120^{o}

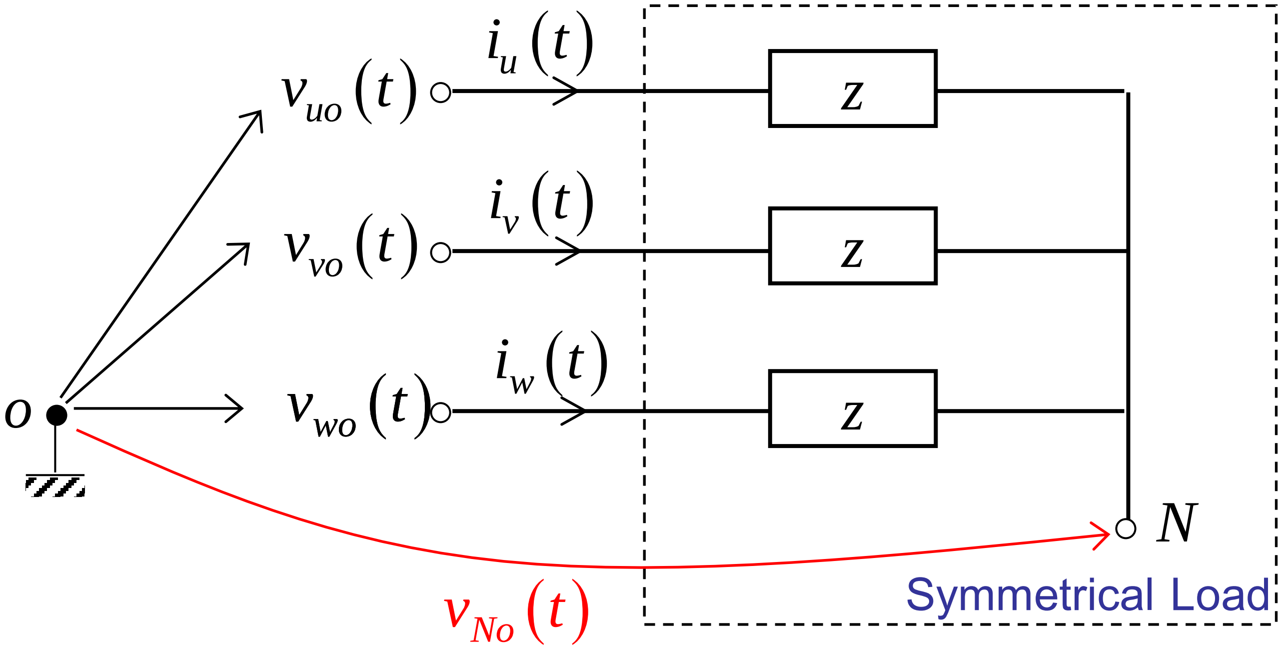


50 Hz



100 Hz

- ปรับได้แต่ความถี่ และมุมเฟส ω φ
- ไม่สามารถปรับขนาดแรงดันได้ V หากต้องการปรับขนาดแรงดันต้องเปลี่ยน E_d



สมการ

<KVL>

$$\begin{cases} v_{uo}(t) = z \cdot i_u(t) + v_{No}(t) \\ v_{vo}(t) = z \cdot i_v(t) + v_{No}(t) \\ v_{wo}(t) = z \cdot i_w(t) + v_{No}(t) \end{cases}$$

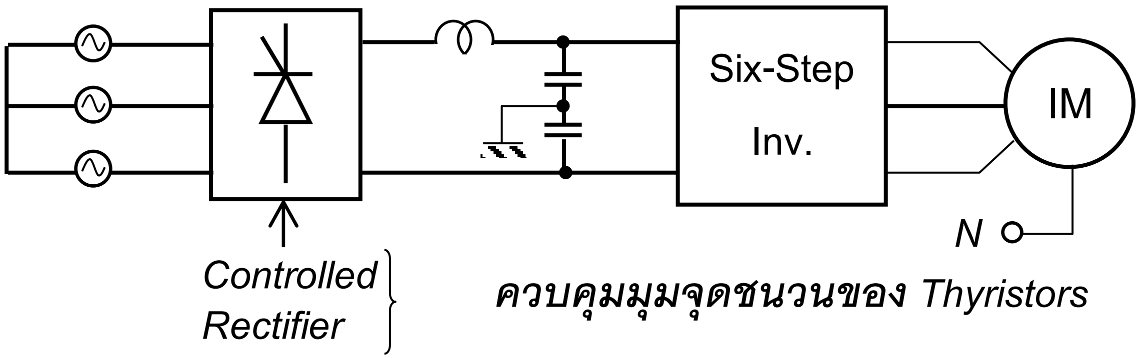
<KCL>

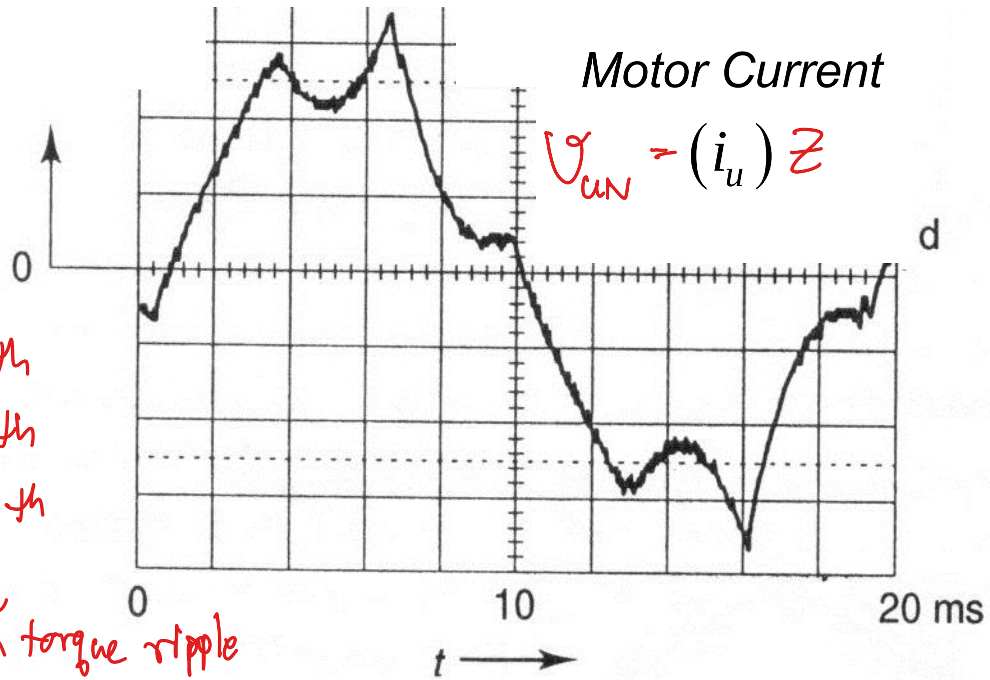
$$\{ \; i_u(t) + i_v(t) + i_w(t) = 0$$

$$v_{uo}(t) + v_{vo}(t) + v_{wo}(t) = 3v_{No}(t)$$

$$\boxed{v_{No}(t) = \frac{1}{3}\left[v_{uo}(t) + v_{vo}(t) + v_{wo}(t)\right]}$$

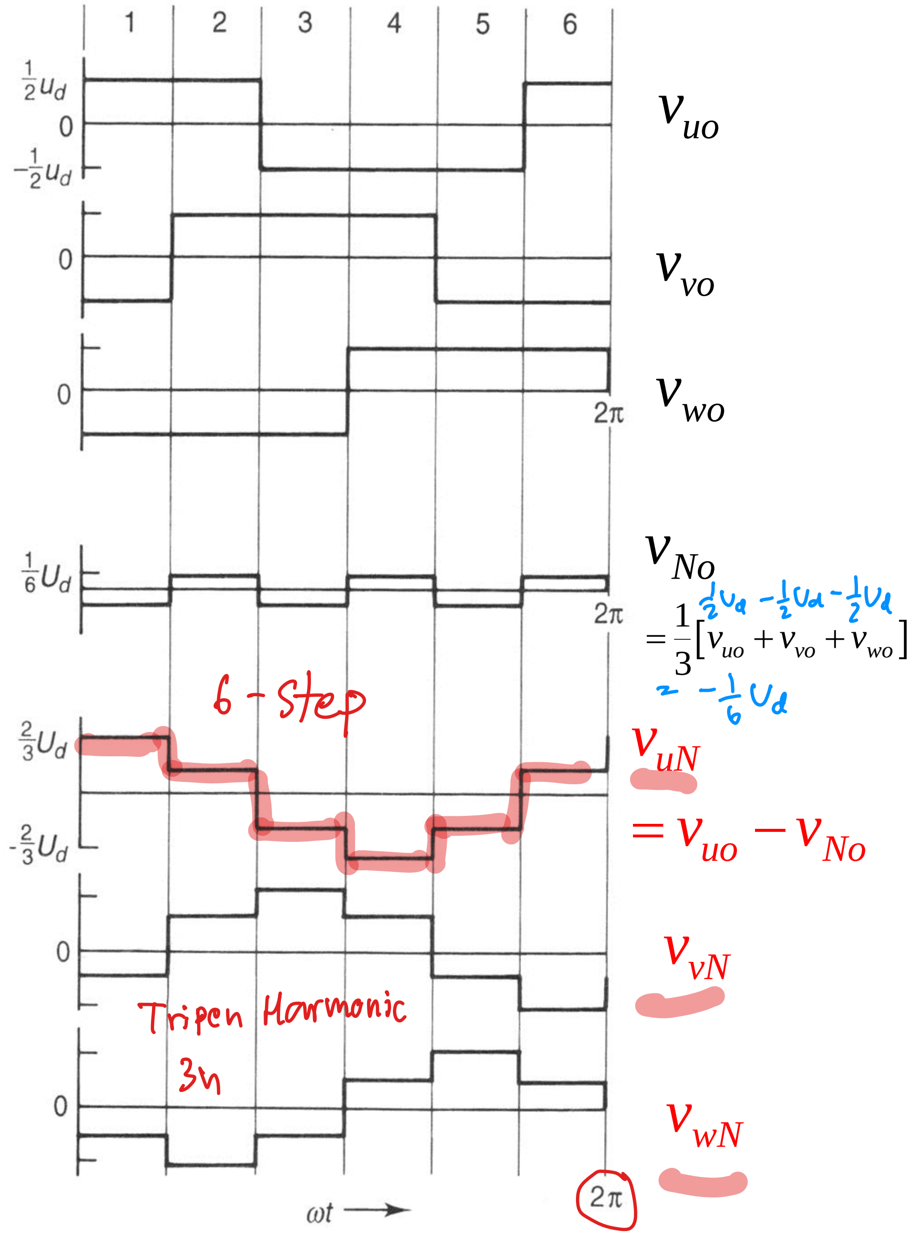
■ การปรับขนาดต้องทำในส่วน
วงจรเรียงกระแสโดยปรับแรงดัน DC BUS





$v_{uN} = (i_u) Z$

5th, 7th, nth → เกิด torque ripple



$\frac{1}{2}U_d - \frac{1}{2}U_d - \frac{1}{2}U_d$

$= -\frac{1}{6}U_d$

6-step

Tripen Harmonic 3n

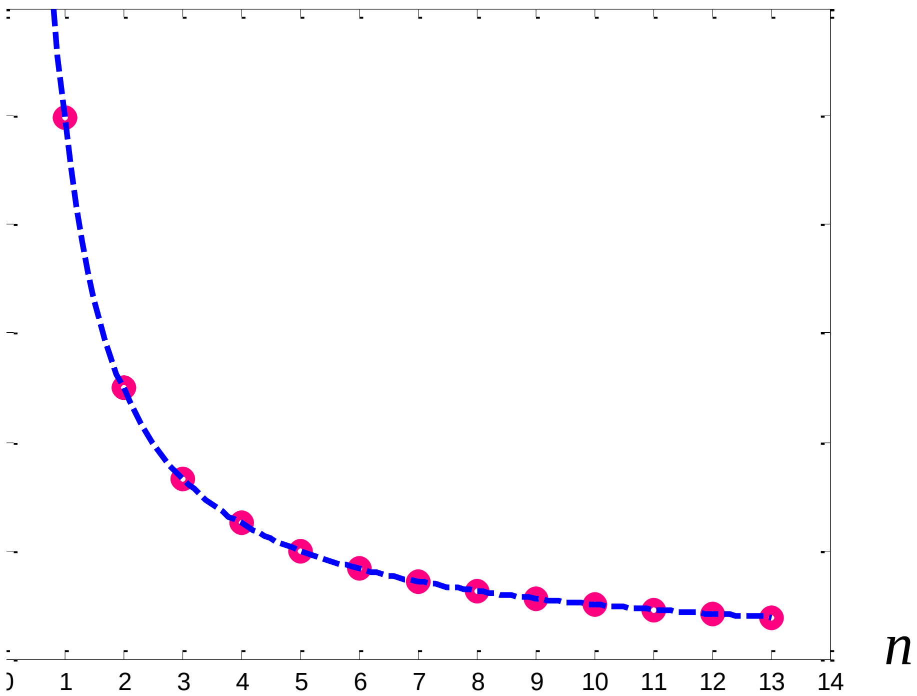
$V_{NO} \Rightarrow 3n$ Tripen Harmonic

$$v_{uo} = \frac{4}{\pi}\cdot\frac{E_d}{2}\cdot\sum_{n=1,3,\ldots}\frac{1}{n}\cdot\sin\left[n\omega t\right]$$

$$v_{vo} = \frac{4}{\pi}\cdot\frac{E_d}{2}\cdot\sum_{n=1,3,\ldots}\frac{1}{n}\cdot\sin\left[n\left(\omega t-\frac{2\pi}{3}\right)\right]$$

$$v_{wo} = \frac{4}{\pi}\cdot\frac{E_d}{2}\cdot\sum_{n=1,3,\ldots}\frac{1}{n}\cdot\sin\left[n\left(\omega t+\frac{2\pi}{3}\right)\right]$$

$|V_n|$



- ✔ จำนวนครั้งของ Switching น้อย
- ✔ ไม่ต้องใช้ Power Devices ที่เร็ว
- ✘ Harmonics สูง/Torque Ripple

Triplen Harmonics

$$v_{No} = \frac{4}{\pi}\cdot\frac{E_d}{2}\cdot\sum_{n=3,9,15,\dots}\frac{1}{n}\cdot\sin[n\omega t]$$

Phase Voltage

$$v_{uN} = \frac{4}{\pi}\cdot\frac{E_d}{2}\cdot\sum_{n=1,5,7,\dots}\frac{1}{n}\cdot\sin[n\omega t]$$

$$n = \begin{cases} 6m-1 & ; m = 1,2,3,\dots \\ 6m+1 & ; m = 0,1,2,\dots \end{cases}$$

$$v_{uN1} = \frac{4}{\pi}\frac{Ed}{2}\frac{1}{1}\sin\omega t$$

$$RMS = \frac{4}{\pi}\frac{Ed}{2}\times\frac{1}{\sqrt{2}}$$

ค่า R.M.S. ของแรงดันเฟส $= \dfrac{\sqrt{2}}{\pi}E_d$

ค่า R.M.S. ของแรงดัน line-line $= \dfrac{\sqrt{6}}{\pi}E_d$

(องค์ประกอบหลักมูล) $n=1$

fundemental

$V_{LL} = \sqrt{3}\,V_\phi$

b) Pulse Width-Modulation Inverters (PWM Inverters)

- ลด Harmonics ที่ความถี่ต่ำของ Six-Step Inverter
- ใช้การปรับ duty cycle (อัตราส่วน $\dfrac{\text{Ton ของ S1}}{\text{Ton+Toff ของ S1}}$)

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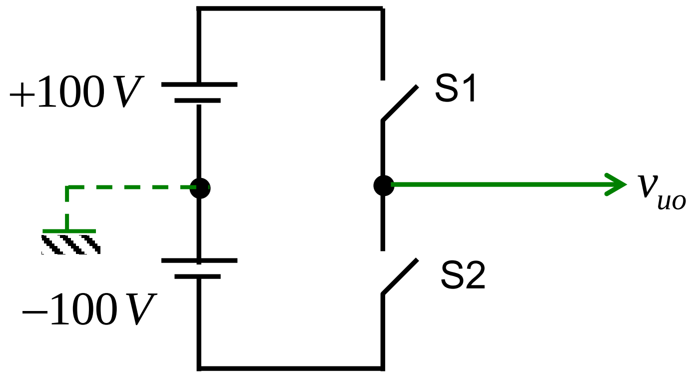
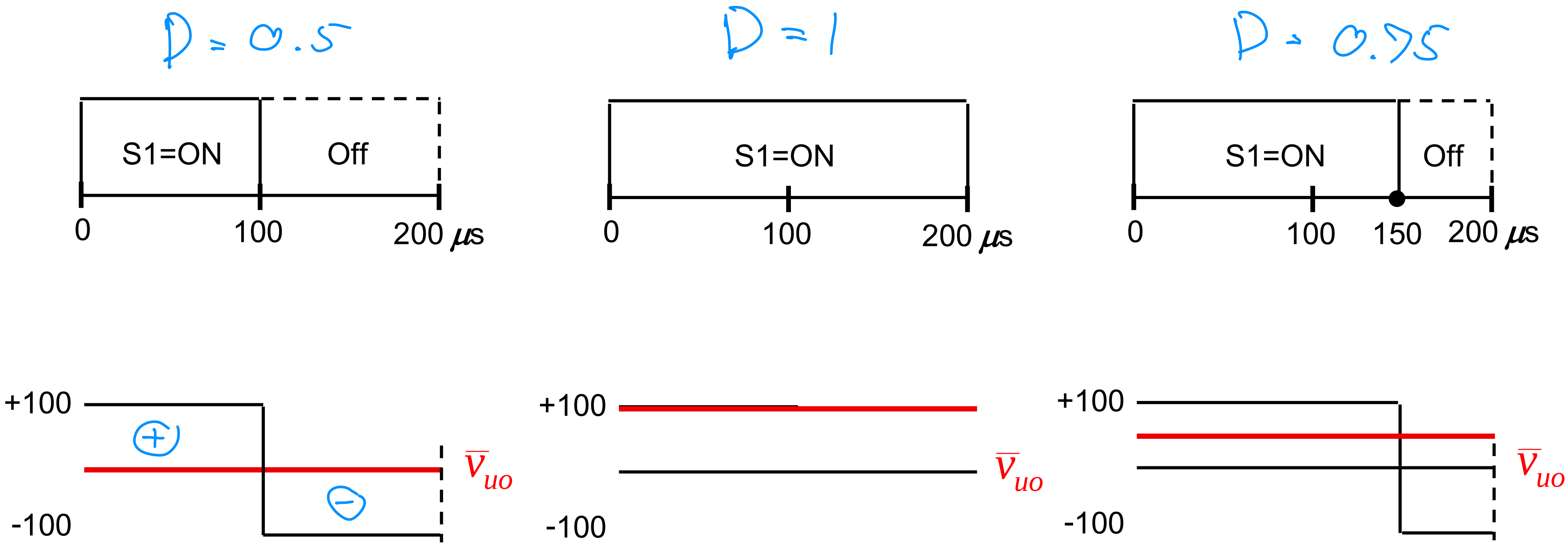


ให้ค่าเฉลี่ยแรงดันมีค่าตามต้องการ

Ex $E_d = 200\,V;\ T = 200\,\mu s$

$$\therefore v_{uo} = \begin{cases} +100\,V \\ -100\,V \end{cases}$$

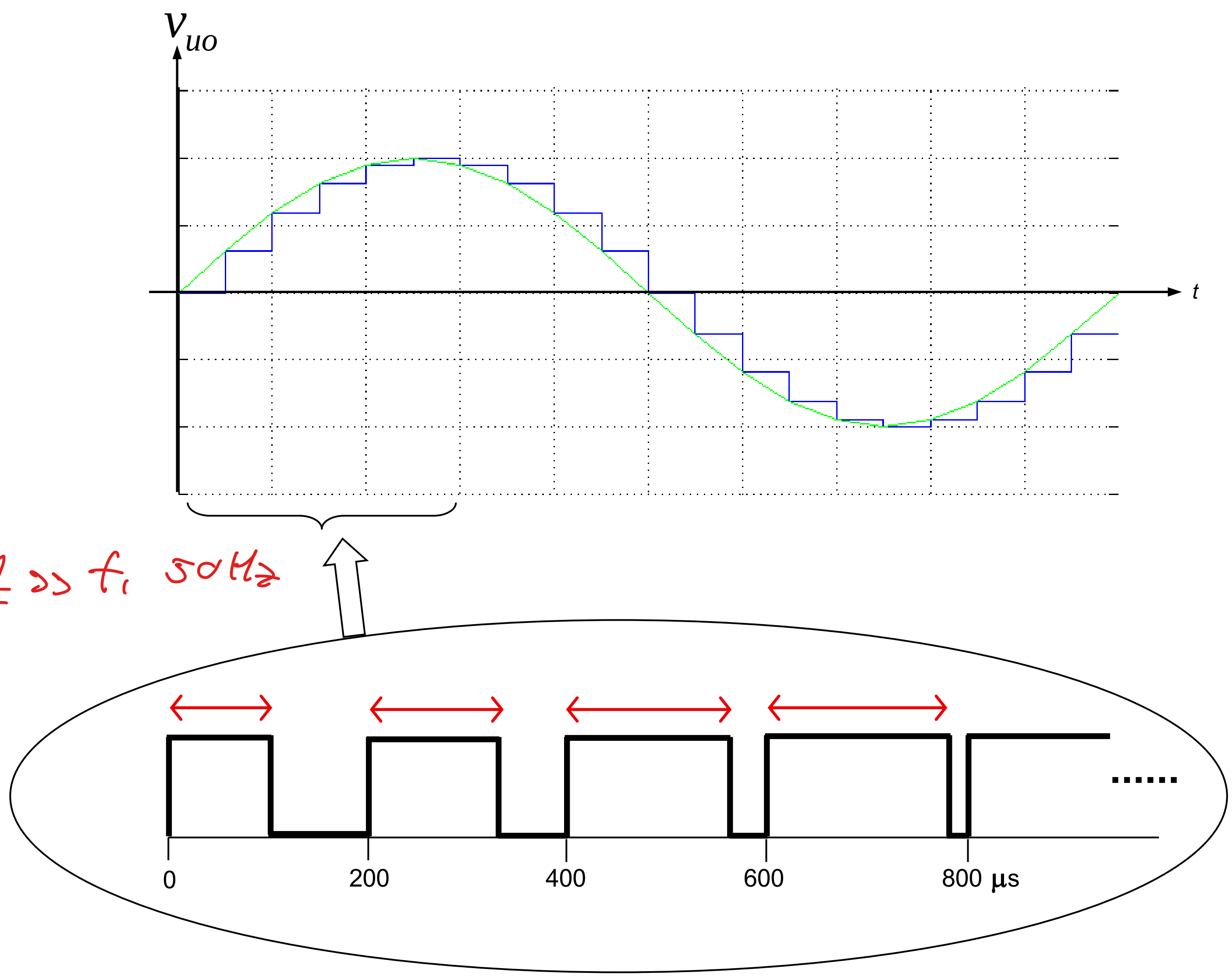


$\bar{v}_{uo} = 0\,V$ $\quad$ $\bar{v}_{uo} = +100\,V$ $\quad$ $\bar{v}_{uo} = +50\,V$

เราสามารถปรับค่าเฉลี่ยของแรงดันได้อย่างต่อเนื่องระหว่างค่า

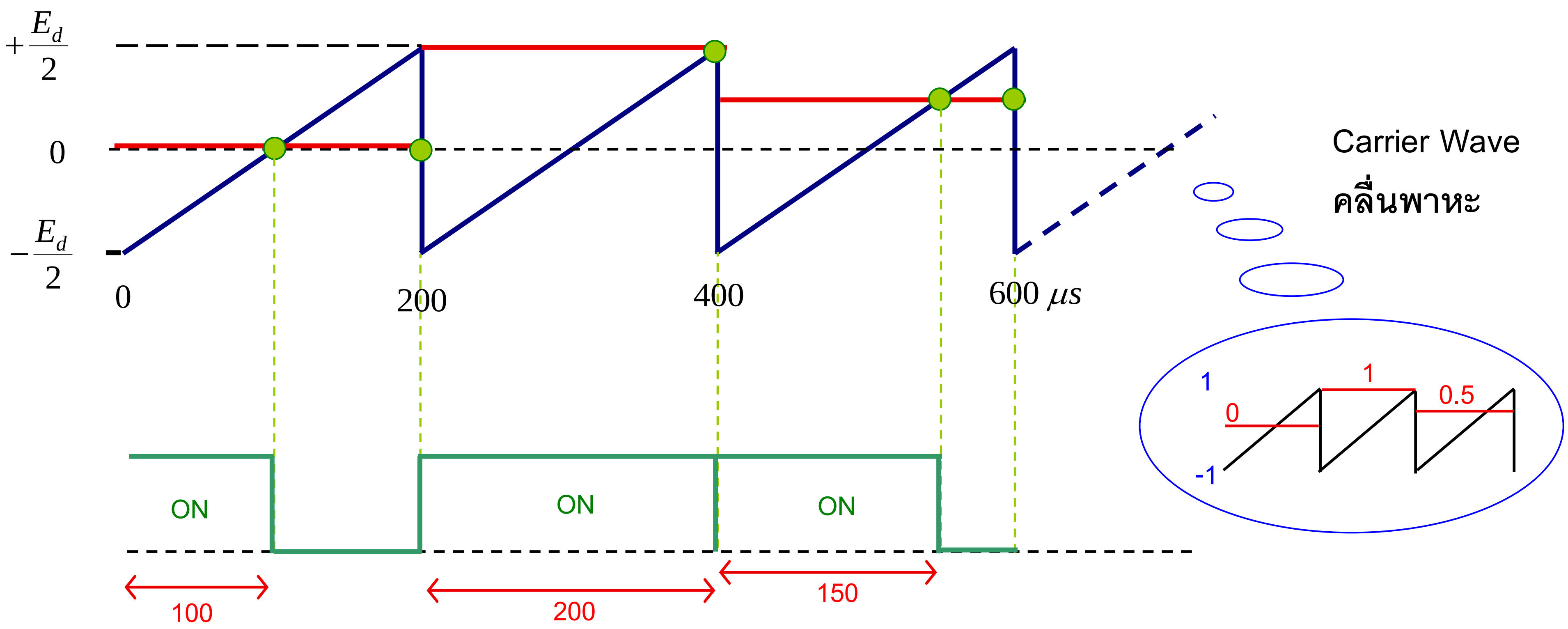
$$+\frac{E_d}{2} \sim -\frac{E_d}{2} \quad \left(+100V \sim -100V\right)$$

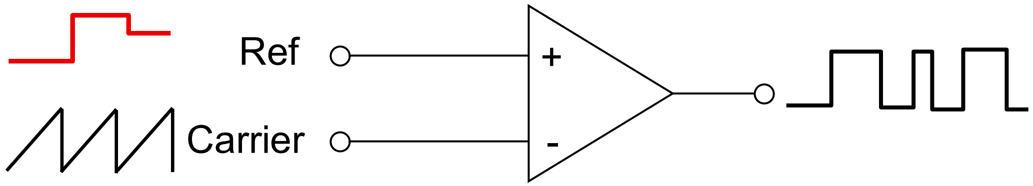
- ถ้าเราเปลี่ยนค่าเฉลี่ย $\overline{v}_{uo}$ ไปทุก ๆ Cycle ก็จะได้รูปคลื่นแรงดันออกที่มีค่าเฉลี่ยตามต้องการได้



$f_{sw} = \frac{1}{T} >> f_1$ 50Hz

วิธีการหาตำแหน่งเวลาการสวิตช์

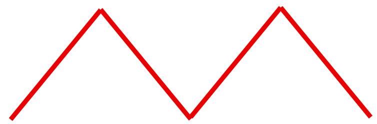




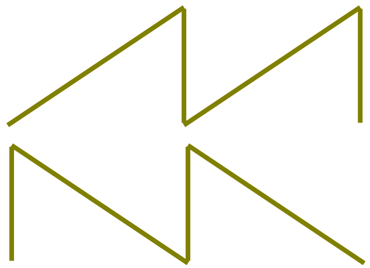
Pulse-Width Modulation (PWM)

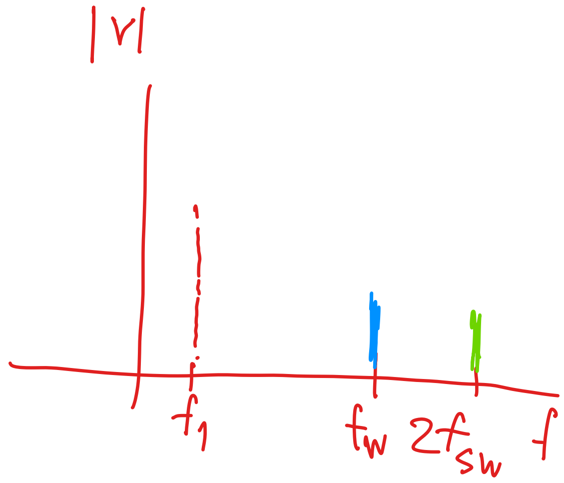
■ ชนิดของ Carrier Wave

1) สามเหลี่ยม (Triangular)

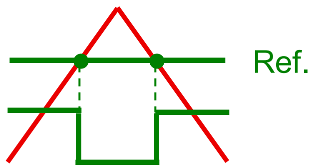


2) ฟันเลื่อย (Saw Tooth)





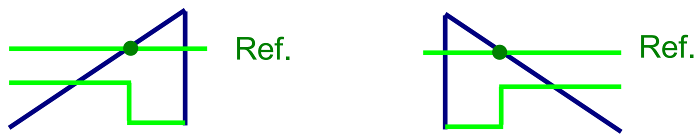
Double Edge Modulation

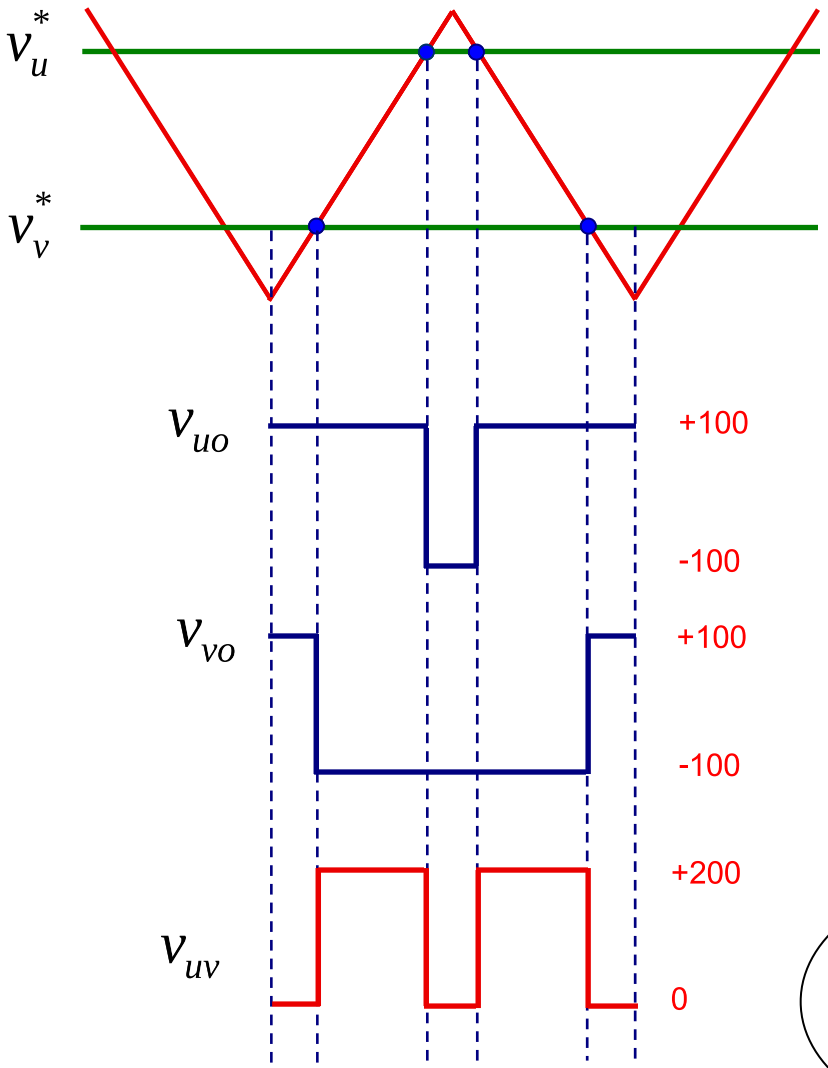


การกระจายของ Harmonics จะย้ายไปอยู่ที่ความถี่ $2\cdot f_{sw}$

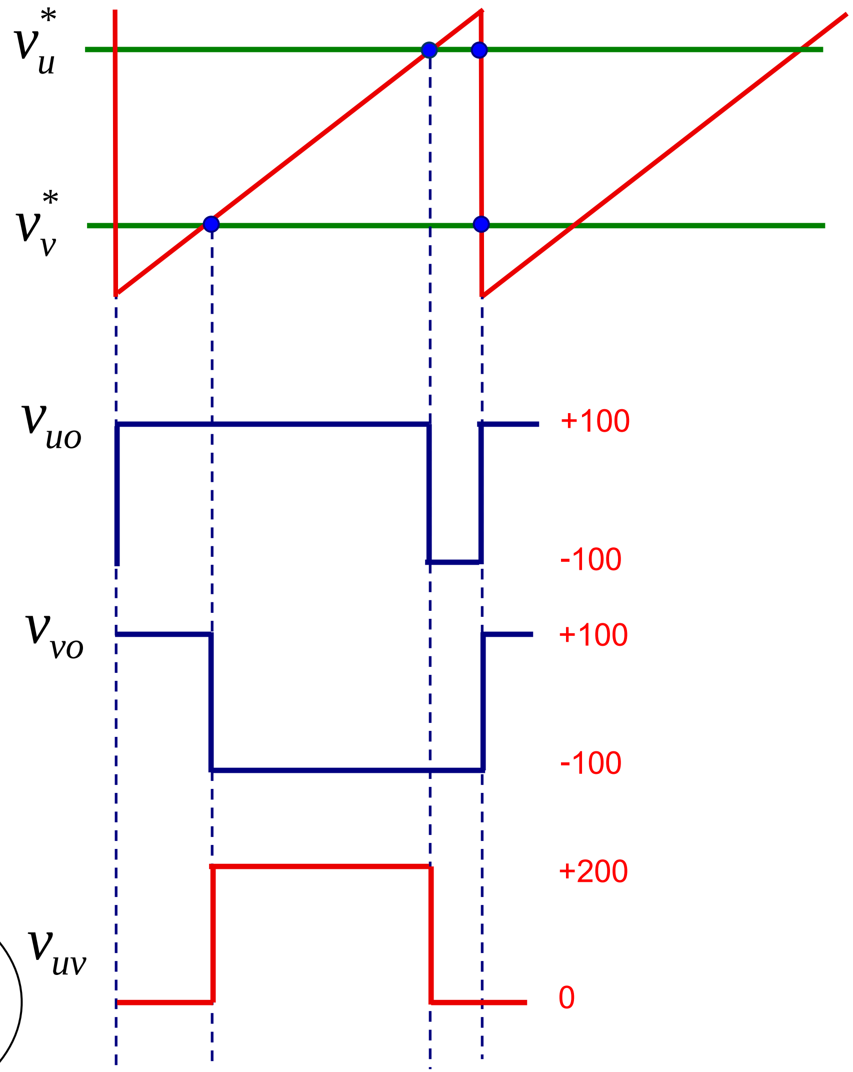
ยิ่งไกล ยิ่งดี

Single Edge Modulation





จำนวน pulse
เป็น 2 เท่า

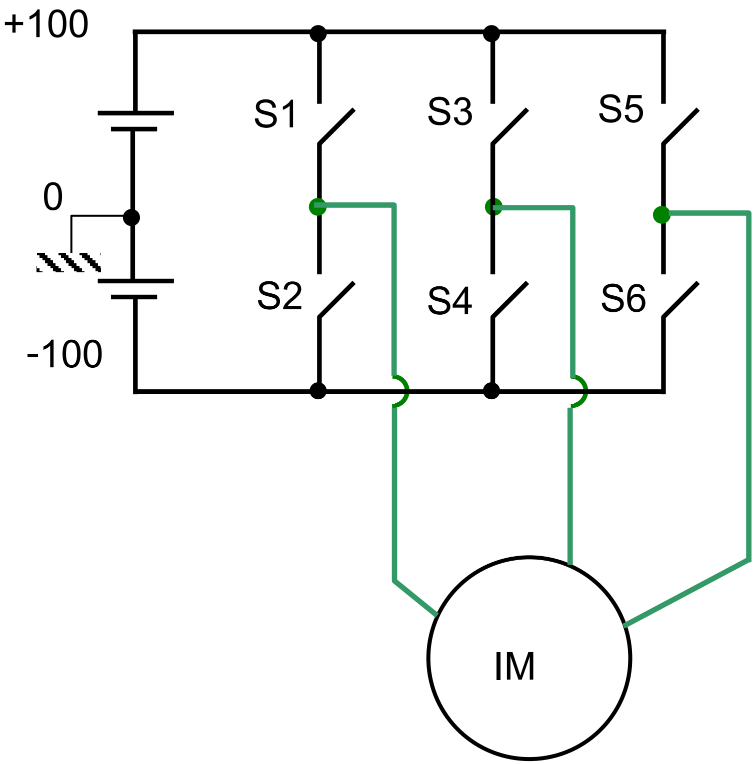


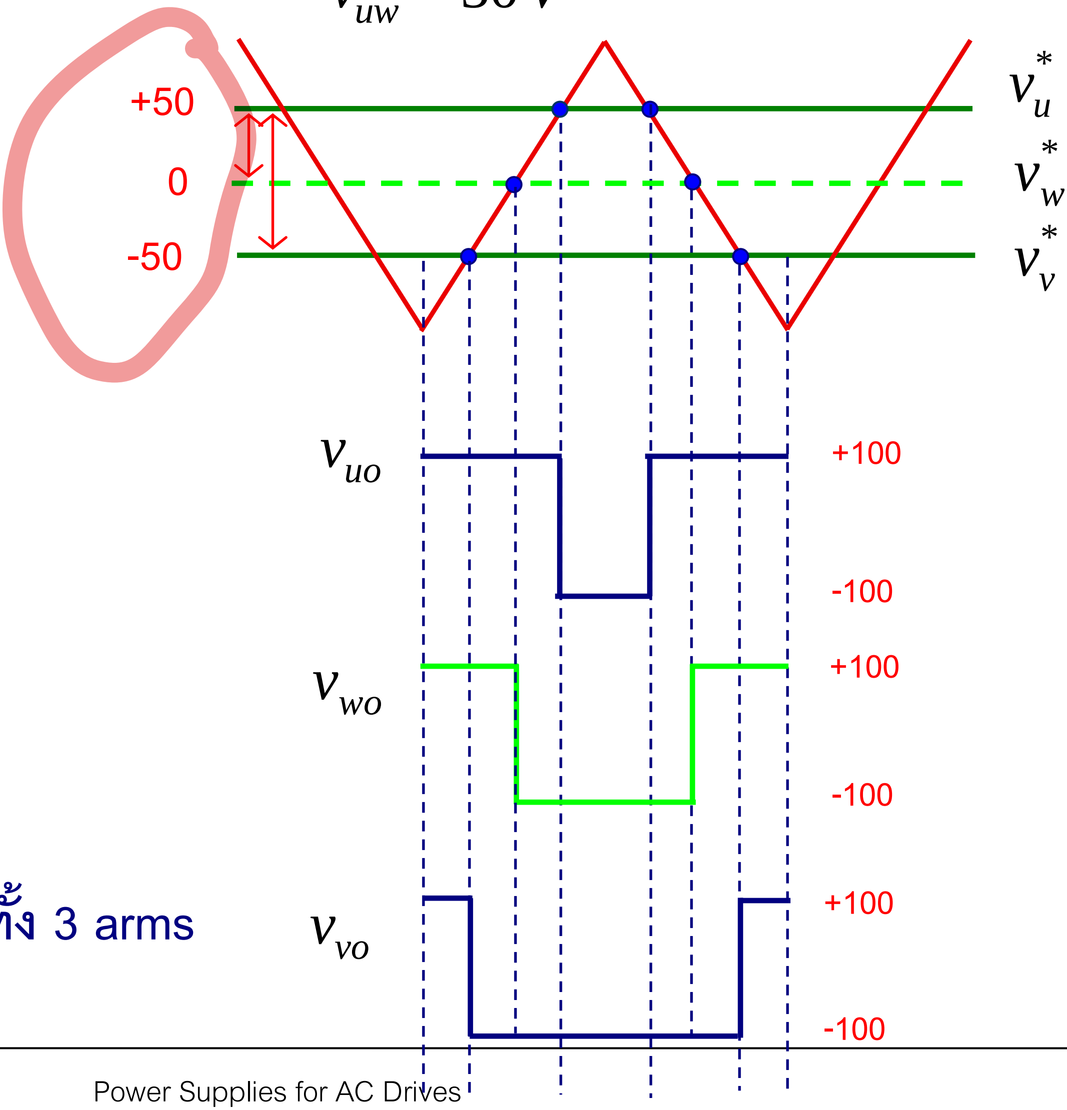
- จำนวน ARM ที่ถูก modulated

แรงดัน line-to-line เป็นตัวกำหนดกระแสในมอเตอร์

ex $v_{uv} = 100\,V$

$v_{uw} = 50\,V$

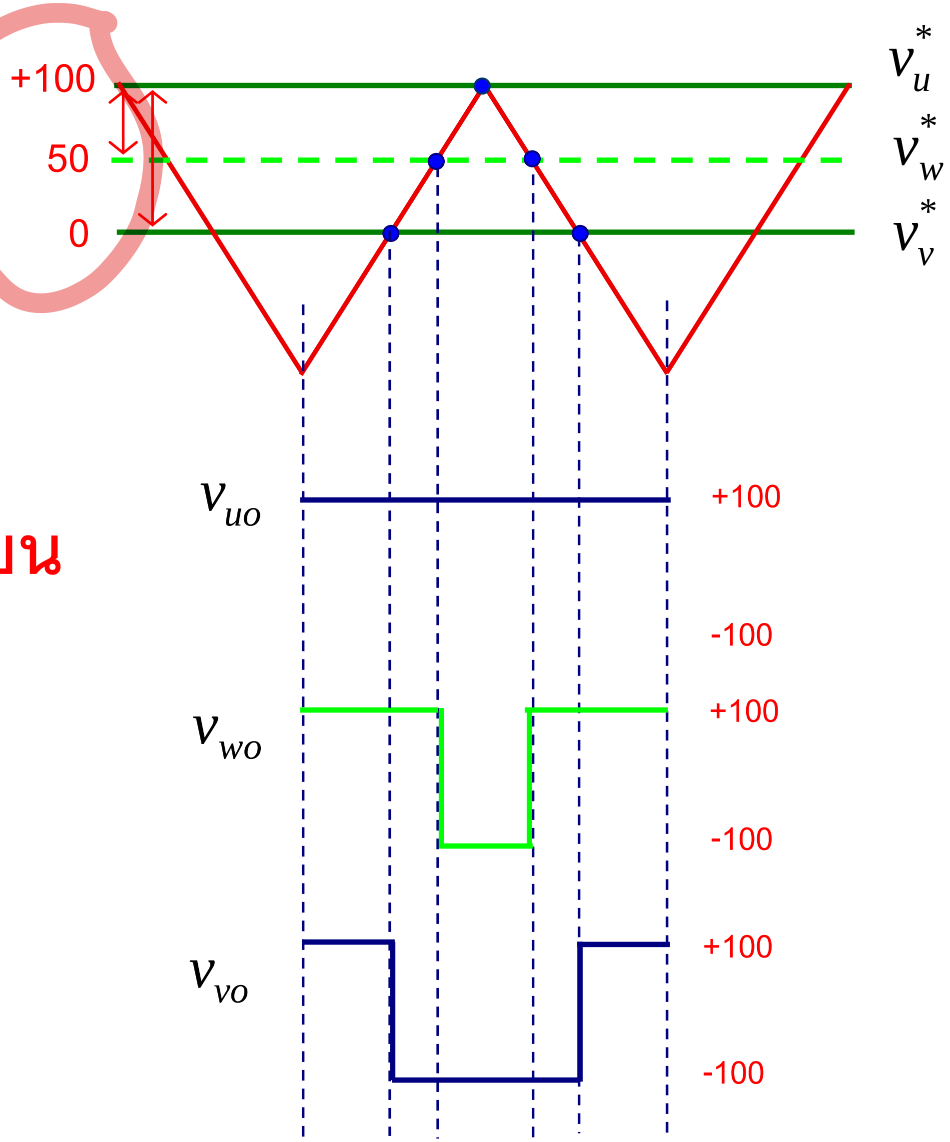




มีการสวิตช์ ON-OFF ทั้ง 3 arms

v, w u On ค้าง

- 2 arms modulation
- Line-to-line voltage modulation



มีการสวิตช์เพียง 2/3 ของกรณีบน

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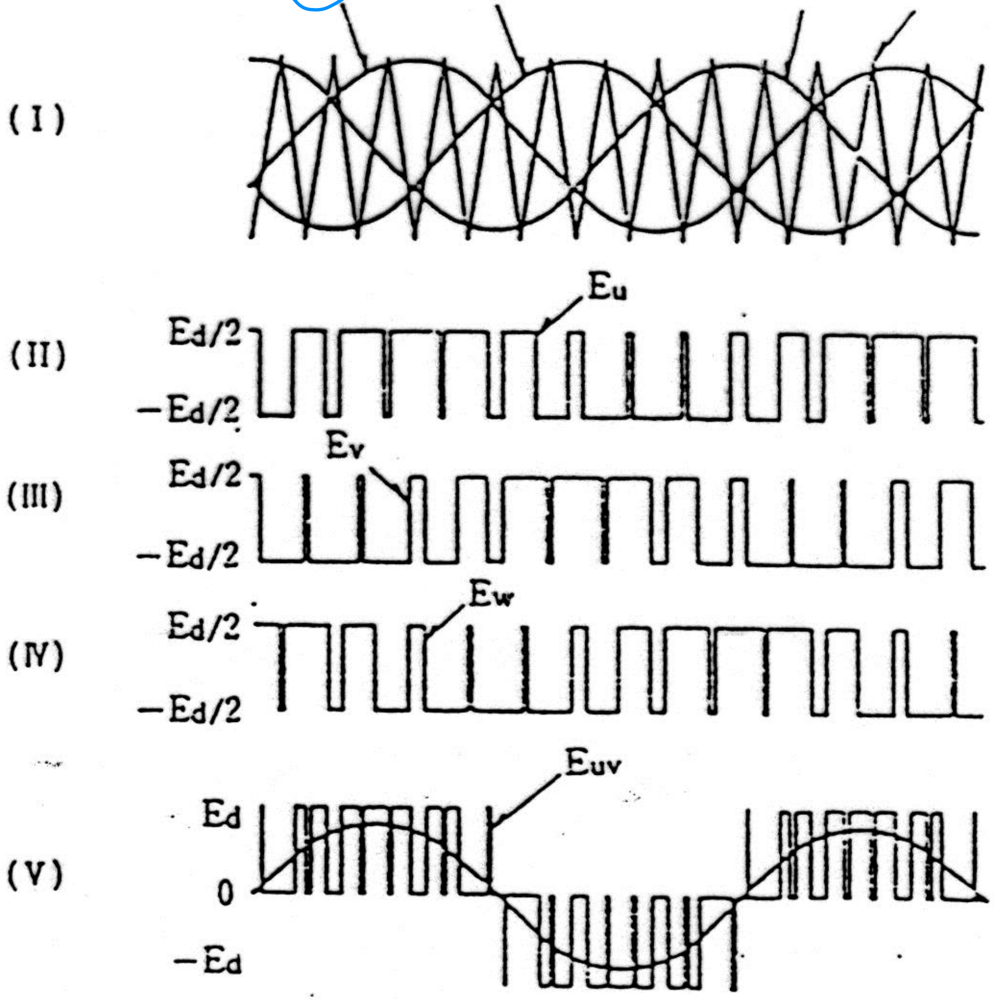
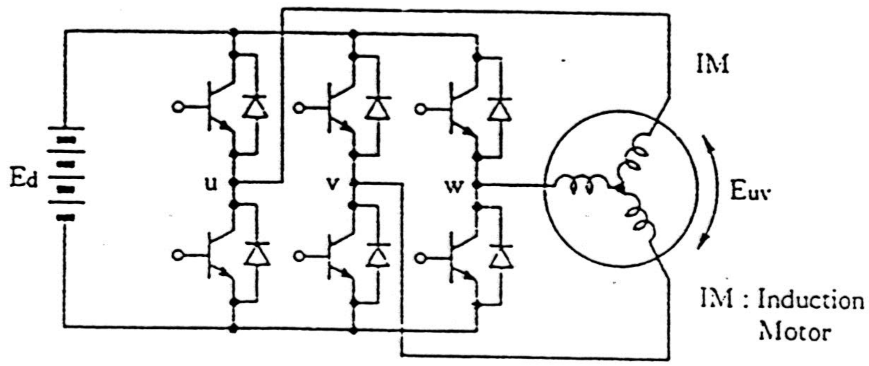
ลด Switching Losses ได้ 1/3

Sinusoidal Modulation

v_{uo} v_{vo} $v_{wo} = v_{uN} + v_{No}$ (→ 0)



(a) PWM signal based on sinusoidal modulation.



(b) Three-phase half bridge inverter.

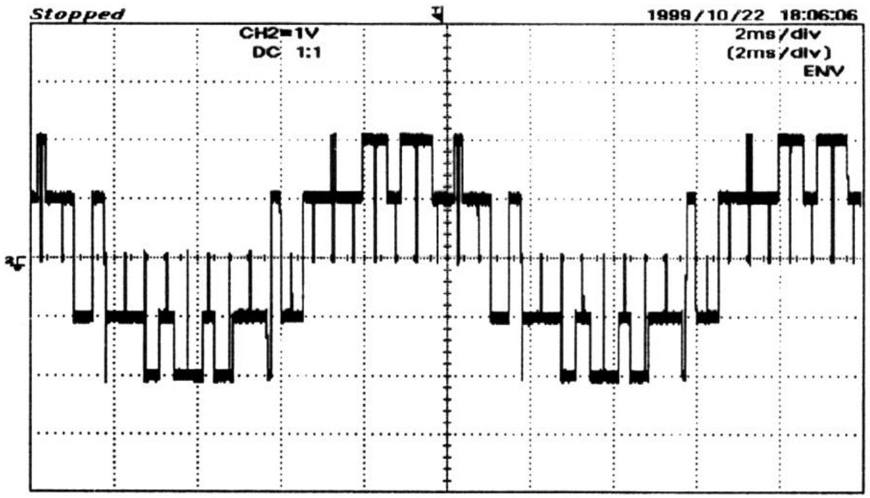
Sinusoidal-triangular wave form comparison method.

u_d, u_q $\quad e^{j\theta} \rightarrow \quad u_\alpha$, u_β $\quad \xrightarrow{2/3} \quad$ $u \sim$, $v \sim$, $w \sim$

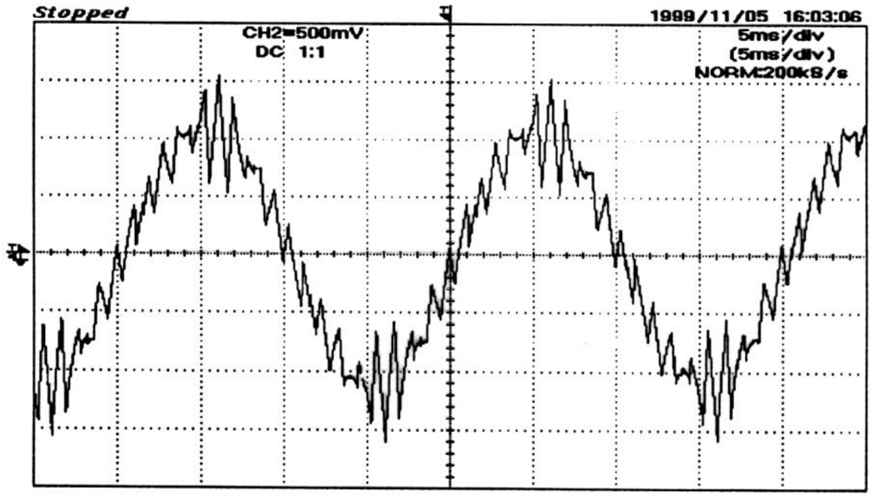
v^*_{uN}

v^*_{vN}

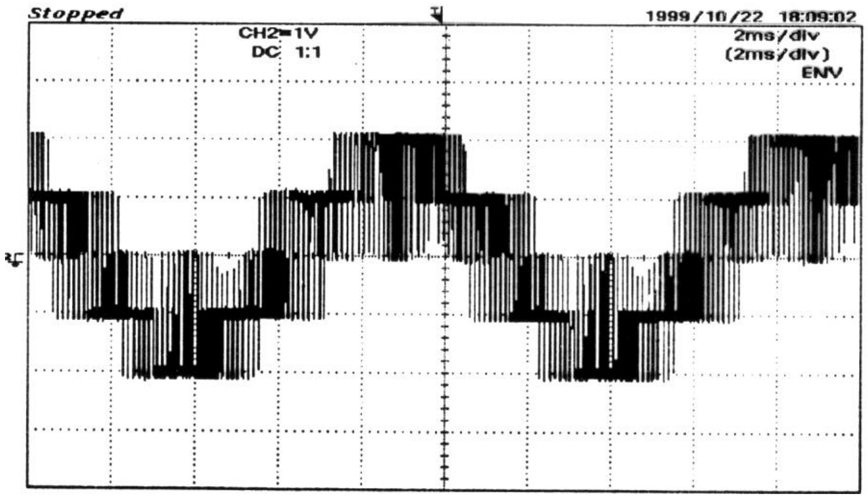
v^*_{wN}



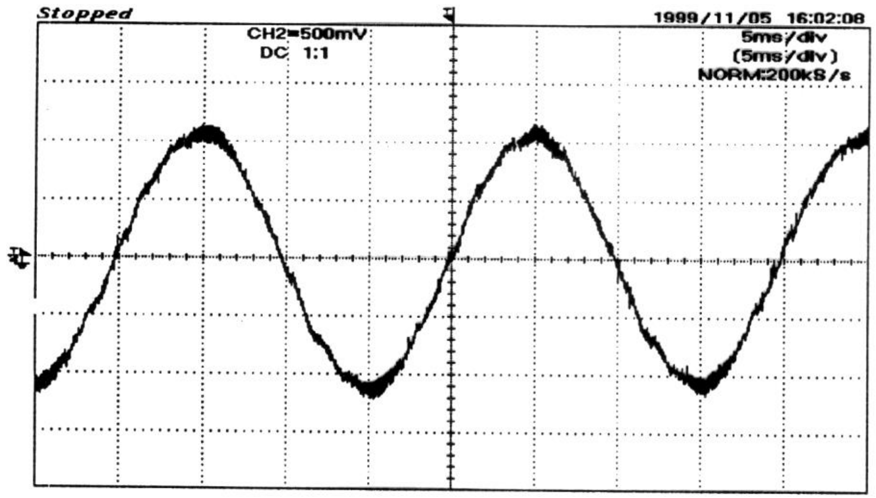
รูปคลื่นแรงดันมอเตอร์ที่ความถี่การสวิตช์ 1 kHz (1 ms)



รูปคลื่นกระแสสเตเตอร์ที่ความถี่การสวิตช์ 1 kHz

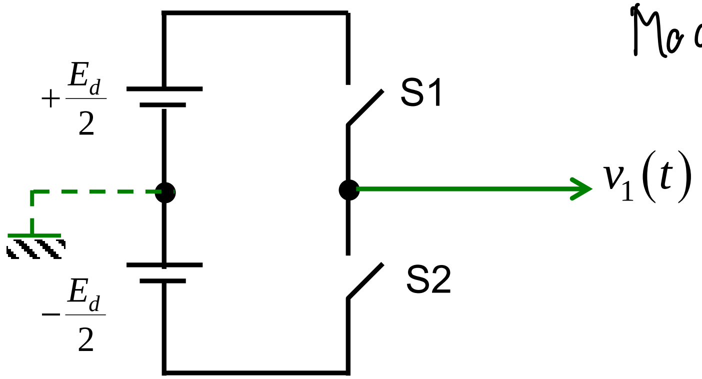


รูปคลื่นแรงดันมอเตอร์ที่ความถี่การสวิตช์ 8 kHz (125 μs)



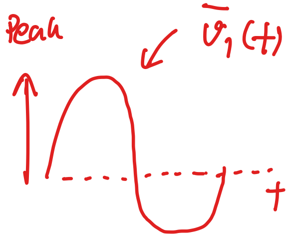
รูปคลื่นกระแสสเตเตอร์ที่ความถี่การสวิตช์ 16 kHz

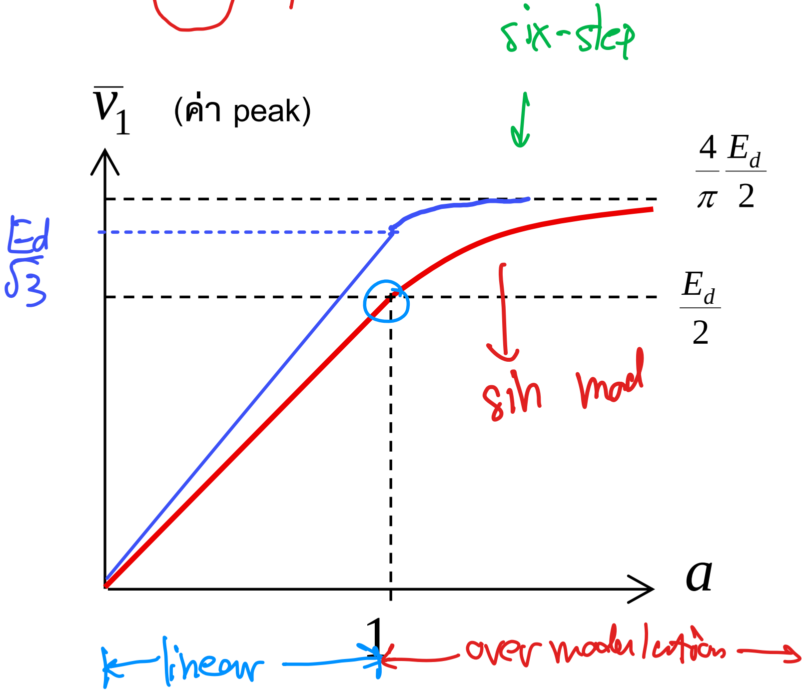
Note $v_1(t)$ เป็นแรงดันเทียบกับจุดกึ่งกลางของ DC Bus

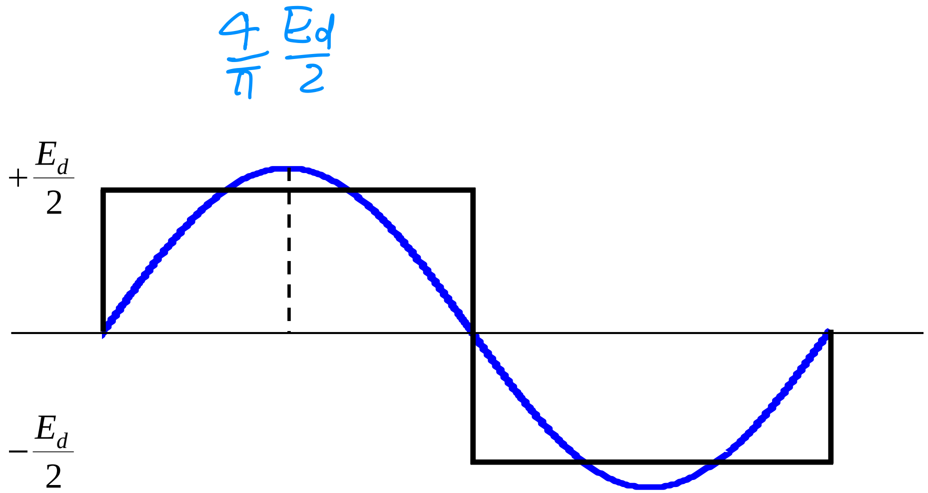


Modulation index

$$a \triangleq \frac{v_1^*}{E_d/2}$$







Space Vector PWM

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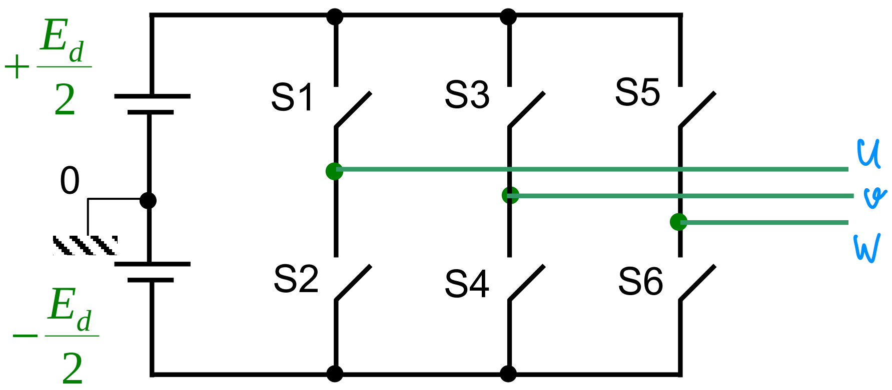
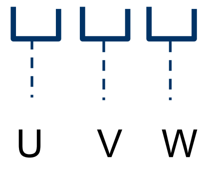
- การทำ PWM ในมุมมอง "Space Vector" → ให้ค่าเฉลี่ย "Space Vector" เท่ากัน

Voltage (Space) Vector ที่ Inverter สร้างได้



Symbol : "1" → upper switch "ON"

"0" → lower switch "ON"

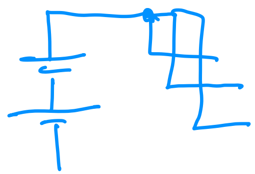


Ex "1 0 0" S1 = ON, S4 = S6 = ON

✱ States ของ Inverter มีด้วยกันทั้งหมด = 2^3 = 8 รูปแบบ

Active Vectors $\begin{cases} 1\ 0\ 0 \quad 0\ 1\ 0 \quad 0\ 0\ 1 \\ 0\ 1\ 1 \quad 1\ 0\ 1 \quad 1\ 1\ 0 \end{cases}$

111



L-L = 0

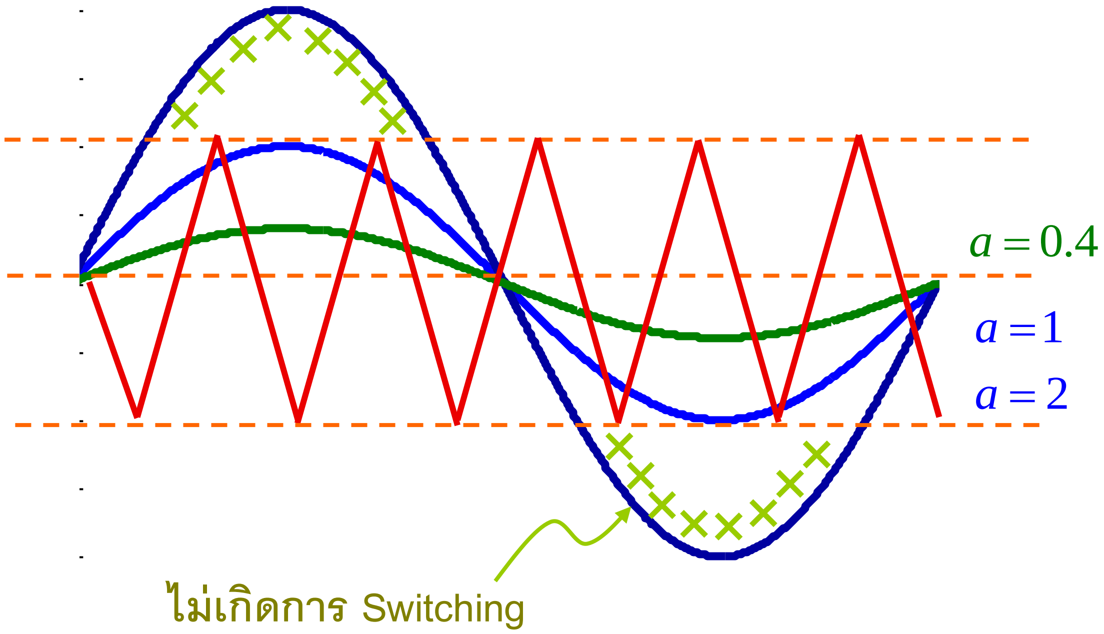
Zero Vectors $\{1\ 1\ 1 \quad 0\ 0\ 0$

สำหรับกรณี 3 ϕ : แรงดัน line-to-line จะมี Harmonics เป็นดังนี้

$$\omega_o \quad : \quad \sqrt{3}\cdot a \cdot \frac{E_d}{2}$$

$$n\omega_s \pm k\omega_o \quad : \quad \sqrt{3}\cdot \frac{4}{n\pi}\cdot \frac{E_d}{2}\cdot J_k\left(\frac{an\pi}{2}\right) \quad ; \quad \begin{matrix} n = 1,3,5\ldots & k = 0,2,4,8,10,\ldots \\ n = 2,4,6\ldots & k = 1,5,7,11,13,\ldots \end{matrix}$$

โดยทั่วไปเราเรียก "a" = Modulation Index $(0 \le a \le 1)$

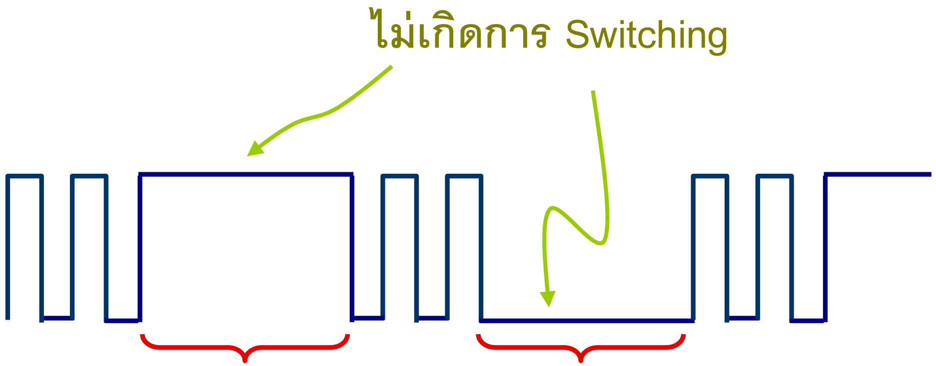


$a > 1$ ก็สามารถทำได้

⇩

Overmodulation

Overmodulation

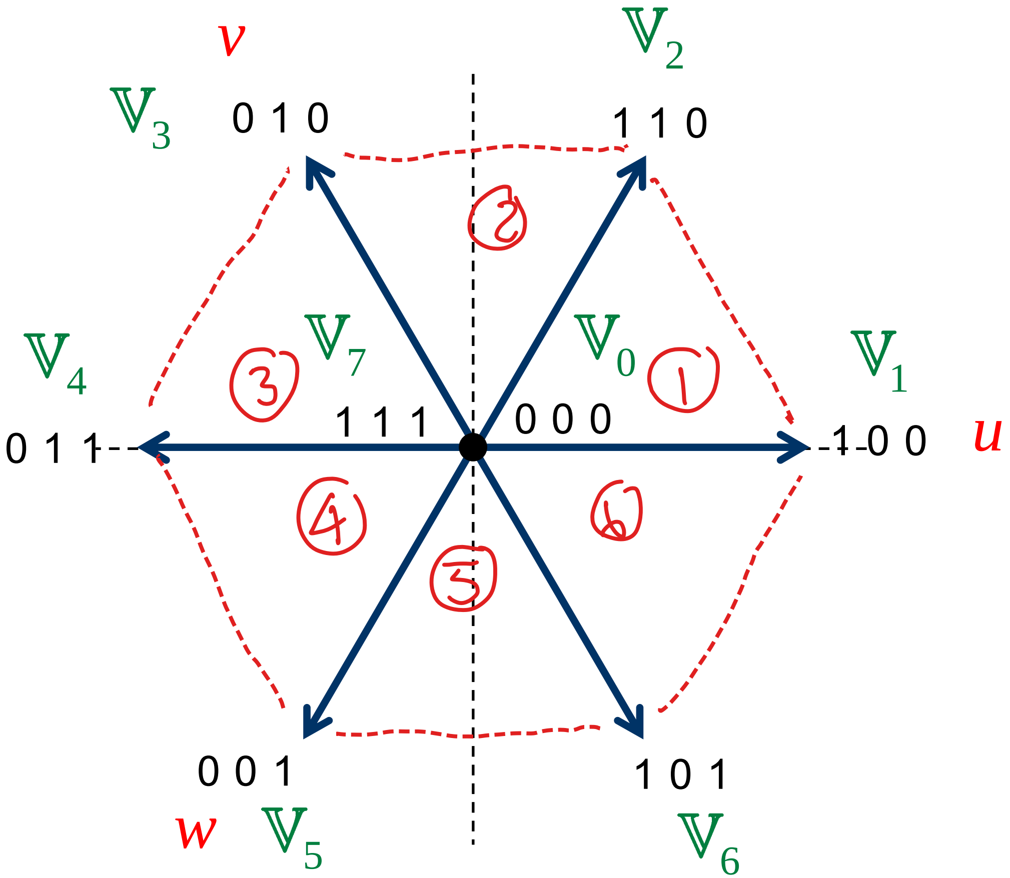


- ✘ Pulse Dropping Phenomena
- ✘ เกิด Harmonics อันดับต่ำ
- ✓ ให้แรงดันเฉลี่ยสูงขึ้น
- $a = \infty$ จะกลายเป็น Six-Step Inverter

Power - Variant

"1 0 0" : $v_{uo} = \frac{E_d}{2}, \quad v_{vo} = -\frac{E_d}{2}, \quad v_{wo} = -\frac{E_d}{2}$

คิดเป็น Space Vector



$$\mathbb{V}_1 = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} 1 \\ -1 \\ -1 \end{bmatrix} \cdot \frac{E_d}{2}$$

$\times\sqrt{\frac{2}{3}}$ for Power Invariant

$$= \begin{bmatrix} 2 \\ 0 \end{bmatrix} \cdot \frac{E_d}{2} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot E_d$$

"1 1 0" : $\begin{cases} v_{uo} = E_d/2 \\ v_{vo} = E_d/2 \\ v_{wo} = -E_d/2 \end{cases}$

$$\therefore \mathbb{V}_2 = \begin{bmatrix} 1/2 \\ \sqrt{3}/2 \end{bmatrix} \cdot E_d$$

"0 0 0" $\therefore \mathbb{V}_0 = 0$; "1 1 1" $\therefore \mathbb{V}_7 = 0$

แนวคิด (1) ต้องการ $\begin{bmatrix} v_{uN} \\ v_{vN} \\ v_{wN} \end{bmatrix} \Rightarrow \mathbb{V}^*$ (Space Vector)

(2) เลือกรูปแบบการใช้ $\mathbb{V}_0 \sim \mathbb{V}_7$ ภายในคาบเวลาการสวิตช์ (Carrier/Switching Period) ให้ $\overline{\mathbb{V}} = \mathbb{V}^*$

ถ้า $v_{uN} + v_{vN} + v_{wN} = 0$ จะได้ $\overline{v}_{uN} = v_{uN}$; $\overline{v}_{vN} = v_{vN}$; $\overline{v}_{wN} = v_{wN}$

กรณีทั่วไป

(1) เลือก Vector ที่ใช้ในการสวิตช์ โดยดูว่า $\mathbb{V}^*$ ตกอยู่ที่ Sector ใด ⟶ เลือก Vector ที่ประกอบเป็น Sector นั้น (รวม $\mathbb{V}_0, \mathbb{V}_7$ ด้วย)

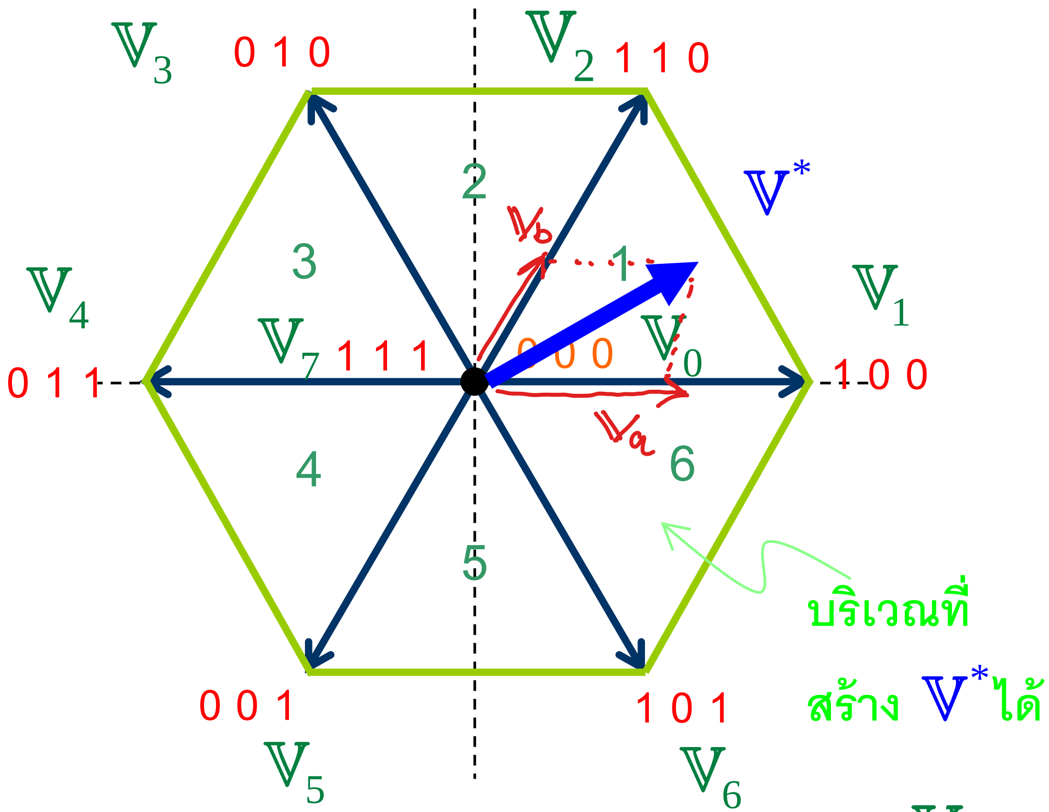
Sec. 1 = $\mathbb{V}_1, \mathbb{V}_2, \mathbb{V}_0, \mathbb{V}_7$ Sec. 4 = $\mathbb{V}_4, \mathbb{V}_5, \mathbb{V}_0, \mathbb{V}_7$

Sec. 2 = $\mathbb{V}_2, \mathbb{V}_3, \mathbb{V}_0, \mathbb{V}_7$ Sec. 5 = $\mathbb{V}_5, \mathbb{V}_6, \mathbb{V}_0, \mathbb{V}_7$

Sec. 3 = $\mathbb{V}_3, \mathbb{V}_4, \mathbb{V}_0, \mathbb{V}_7$ Sec. 6 = $\mathbb{V}_6, \mathbb{V}_1, \mathbb{V}_0, \mathbb{V}_7$

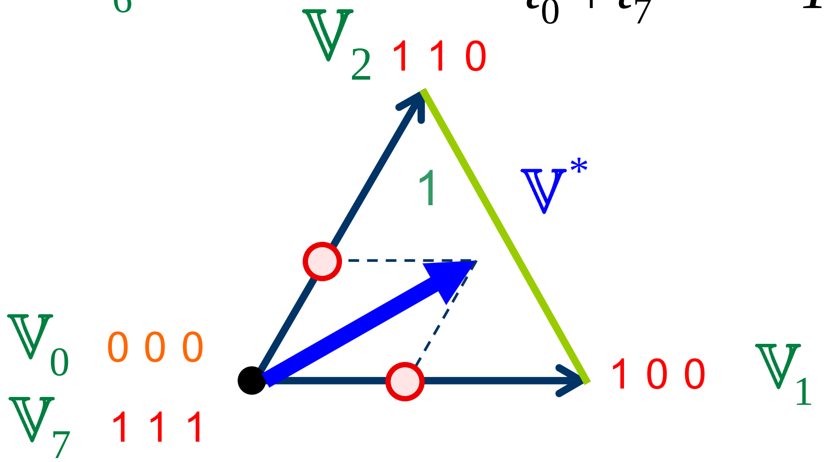
(2) แตก $\mathbb{V}^*$ เป็นองค์ประกอบในแนว Vector ที่เลือก $\mathbb{V}^* = \mathbb{V}_a + \mathbb{V}_b$

$|\mathbb{V}_1| = |\mathbb{V}_2|$

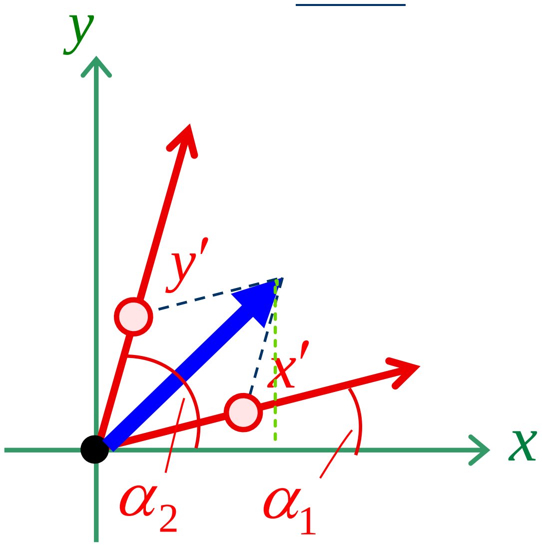


$$\begin{cases} t_a = \dfrac{|\mathbb{V}_a|}{|\mathbb{V}_1|} \times T \le T & \text{on } \mathbb{V}_a \\ t_b = \dfrac{|\mathbb{V}_b|}{|\mathbb{V}_2|} \times T \le T & \text{on } \mathbb{V}_b \\ t_{zero} = T - t_a - t_b \ge 0 & \text{; Zero Vectors} \end{cases}$$

$$t_0 + t_7 = T - t_a - t_b$$



การคำนวณหาค่า t_a, t_b



$\alpha_2 = \alpha_1 + 60^o$

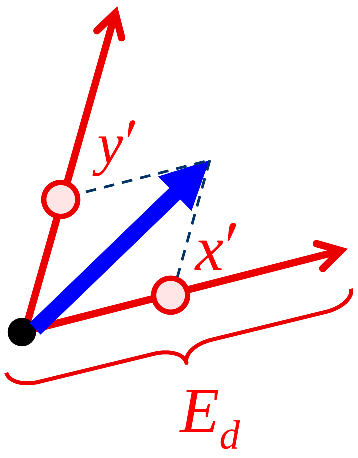
กำหนดให้ $\mathbb{V}^* = \begin{bmatrix} x \\ y \end{bmatrix} \quad (x + jy)$

$$\begin{aligned} x &= x'\cos\alpha_1 + y'\cos\alpha_2 \\ y &= x'\sin\alpha_1 + y'\sin\alpha_2 \end{aligned}$$

$$\therefore \begin{bmatrix} x' \\ y' \end{bmatrix} = \frac{1}{\underbrace{\left(\cos\alpha_1\sin\alpha_2 - \cos\alpha_2\sin\alpha_1\right)}_{\sin(\alpha_2-\alpha_1)}} \cdot \begin{bmatrix} \sin\alpha_2 & -\cos\alpha_2 \\ -\sin\alpha_1 & \cos\alpha_1 \end{bmatrix} \times \begin{bmatrix} x \\ y \end{bmatrix}$$

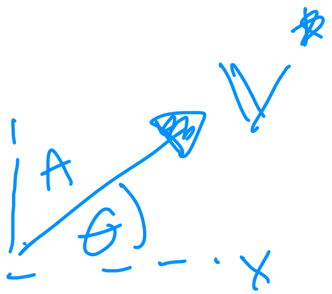
$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \frac{2}{\sqrt{3}} \cdot \begin{bmatrix} \sin\alpha_2 & -\cos\alpha_2 \\ -\sin\alpha_1 & \cos\alpha_1 \end{bmatrix} \times \begin{bmatrix} x \\ y \end{bmatrix} \quad **$$

$$\begin{bmatrix} \dfrac{t_a}{T} \\ \dfrac{t_b}{T} \end{bmatrix} = \begin{bmatrix} \dfrac{x'}{E_d} \\ \dfrac{y'}{E_d} \end{bmatrix} = \frac{2}{\sqrt{3}E_d} \cdot \begin{bmatrix} \sin\alpha_2 & -\cos\alpha_2 \\ -\sin\alpha_1 & \cos\alpha_1 \end{bmatrix} \times \begin{bmatrix} x \\ y \end{bmatrix}$$



กำหนดให้ $\begin{cases} x = A\cos\theta \\ y = A\sin\theta \end{cases}$

$$\begin{bmatrix} \dfrac{t_a}{T} \\ \dfrac{t_b}{T} \end{bmatrix} = \frac{2A}{\sqrt{3}E_d} \cdot \begin{bmatrix} \sin(\alpha_2 - \theta) \\ \sin(\theta - \alpha_1) \end{bmatrix}$$



$$= \frac{2A}{\sqrt{3}E_d} \cdot \begin{bmatrix} \sin\left(\alpha_1 + \dfrac{\pi}{3} - \theta\right) \\ \sin(\theta - \alpha_1) \end{bmatrix} \quad **$$

$\theta \rightarrow \alpha_1, \alpha_2$

<u>สำหรับ Sector 1</u>

$$\alpha_1 = 0, \alpha_2 = \pi/3 \quad ; \quad 0 \le \theta < \pi/3 \quad [\mathbb{V}_1, \mathbb{V}_2, \mathbb{V}_0, \mathbb{V}_7]$$

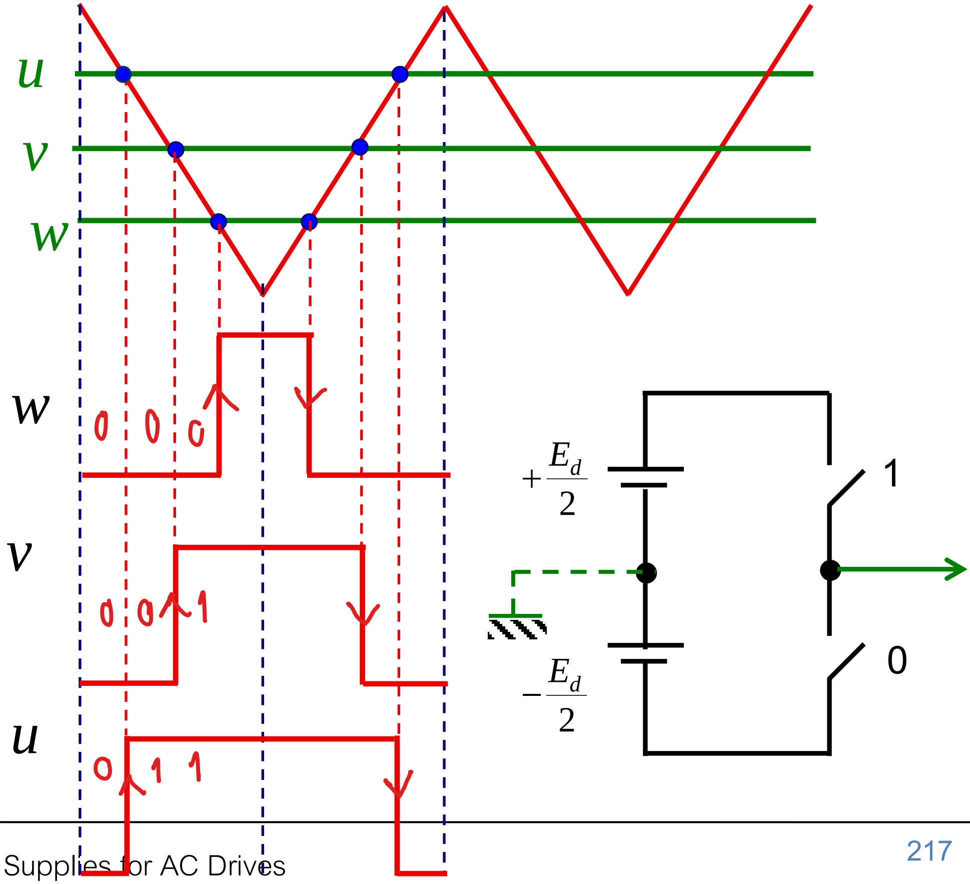
$$\begin{array}{cccc} \updownarrow & \updownarrow & \updownarrow & \updownarrow \\ t_1 & t_2 & t_0 & t_7 \end{array}$$

$$\begin{bmatrix} \frac{t_a}{T} \\ \frac{t_b}{T} \end{bmatrix} = \frac{2A}{\sqrt{3}E_d} \cdot \begin{bmatrix} \sin\left(\frac{\pi}{3} - \theta\right) \\ \sin(\theta) \end{bmatrix}$$

$$\begin{cases} t_1 = t_a \ ; \ t_2 = t_b \\ T = t_1 + t_2 + t_o + t_7 \\ t_0 = t_7 \end{cases}$$

<u>การเรียงลำดับ Vector (Double Edge Modulation)</u>

t		u	v	w
$t_0/2$	$\mathbb{V}_0$	0	0	0
$t_1/2$	$\mathbb{V}_1$	1	0	0
$t_2/2$	$\mathbb{V}_2$	1	1	0
$t_7/2$	$\mathbb{V}_7$	1	1	1
$t_7/2$	$\mathbb{V}_7$	1	1	1
$t_2/2$	$\mathbb{V}_2$	1	1	0
$t_1/2$	$\mathbb{V}_1$	1	0	0
$t_0/2$	$\mathbb{V}_0$	0	0	0



$$
\begin{aligned}
\bar{v}_{uo} &= \frac{t_1+t_2}{T}\cdot\frac{E_d}{2} = \frac{A}{\sqrt{3}}\left[2\sin\frac{\pi}{6}\cdot\cos\left(\frac{\pi}{6}-\theta\right)\right] \\
&= \frac{A}{\sqrt{3}}\cos\left(\theta-\frac{\pi}{6}\right)
\end{aligned}
$$

$$
\begin{aligned}
\bar{v}_{vo} &= \frac{t_2-t_1}{T}\cdot\frac{E_d}{2} = \frac{A}{\sqrt{3}}\left[2\cos\frac{\pi}{6}\cdot\sin\left(\theta-\frac{\pi}{6}\right)\right] \\
&= A\sin\left(\theta-\frac{\pi}{6}\right) = A\cos\left(\theta-\frac{2\pi}{3}\right)
\end{aligned}
$$

$$
\begin{aligned}
\bar{v}_{wo} &= -\frac{(t_1+t_2)}{T}\cdot\frac{E_d}{2} = -\frac{A}{\sqrt{3}}\cdot\cos\left(\theta-\frac{\pi}{6}\right) \\
&= -\bar{v}_{uo}
\end{aligned}
$$

$$\overline{v}_{u0} = \frac{1}{T}\left(\frac{t_0}{2}\left(-\frac{E_d}{2}\right) + \frac{t_1}{2}\left(\frac{E_d}{2}\right) + \frac{t_2}{2}\left(\frac{E_d}{2}\right) + \frac{t_7}{2}\left(\frac{E_d}{2}\right) + \frac{t_7}{2}\left(\frac{E_d}{2}\right) + \frac{t_2}{2}\left(\frac{E_d}{2}\right) + \frac{t_1}{2}\left(\frac{E_d}{2}\right) + \frac{t_0}{2}\left(-\frac{E_d}{2}\right)\right)$$

$t_0/2$

$t_1/2$

$t_2/2$

$t_7/2$

$t_7/2$

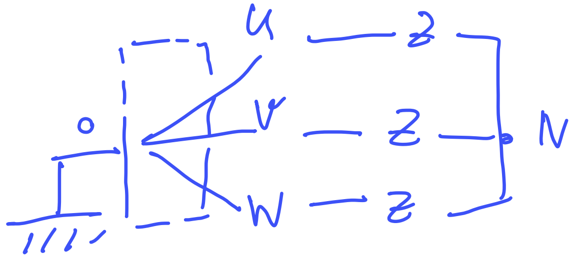
$t_2/2$

$t_1/2$

$t_0/2$

$$t_0 = t_7 \Rightarrow \overline{v}_{u0} = \frac{1}{T}(t_1 + t_2)\frac{E_d}{2}$$

Power Variant $\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$



จาก $\begin{pmatrix} x \\ y \end{pmatrix} = A\begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \leftrightarrow \begin{cases} v_{un} = \frac{2}{3}A\cos\theta \\ v_{vn} = \frac{2}{3}A\cos\left(\theta - \frac{2\pi}{3}\right) \\ v_{wn} = \frac{2}{3}A\cos\left(\theta + \frac{2\pi}{3}\right) \end{cases}$

$\bar{v}_{No} = \frac{1}{3}\left(\bar{v}_{uo} + \bar{v}_{vo} + \bar{v}_{wo}\right)$

Zero Sequence Voltage

$$\bar{v}_{No} = \frac{1}{3}\bar{v}_{vo} = \frac{A}{3}\cos\left(\theta - \frac{2\pi}{3}\right) = \frac{1}{2}v_{vN}$$

พบว่า การทำ Space Vector PWM แบบ Double Edge Modulation

= การบวกแรงดัน Zero Sequence Voltage $\frac{1}{2}v_{vN}$ เข้าไปในทุกเฟส (ของการทำ PWM โดยใช้ triangular carrier wave)

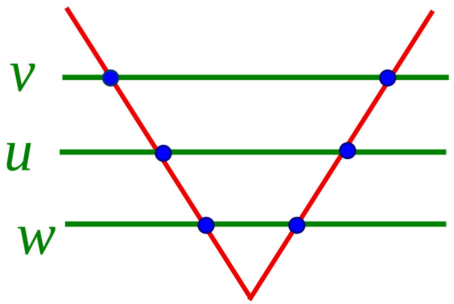
$$v_{v0} = v_{vN} + v_{N0} = v_{vN} + \frac{1}{2} v_{vN} = A\cos\left(\theta - \frac{2\pi}{3}\right) = \bar{v}_{v0}$$

สำหรับ Sector 2

$$\alpha_1 = \pi/3,\ \alpha_2 = 2\pi/3 \quad ; \quad \pi/3 \le \theta \le 2\pi/3 \quad [\mathbb{V}_2, \mathbb{V}_3, \mathbb{V}_0, \mathbb{V}_7]$$

$$\begin{bmatrix} \frac{t_2}{T} \\ \frac{t_3}{T} \end{bmatrix} = \frac{2A}{\sqrt{3}E_d} \cdot \begin{bmatrix} \sin\left(\frac{2\pi}{3} - \theta\right) \\ \sin\left(\theta - \frac{\pi}{3}\right) \end{bmatrix}$$

t		u	v	w
$t_0/2$	$\mathbb{V}_0$	0	0	0
$t_3/2$	$\mathbb{V}_3$	0	1	0
$t_2/2$	$\mathbb{V}_2$	1	1	0
$t_7/2$	$\mathbb{V}_7$	1	1	1
$t_7/2$	$\mathbb{V}_7$	1	1	1
$t_2/2$	$\mathbb{V}_2$	1	1	0
$t_3/2$	$\mathbb{V}_3$	0	1	0
$t_0/2$	$\mathbb{V}_0$	0	0	0



$$\bar{v}_{No} = \frac{1}{3}\bar{v}_{uo} = \frac{A}{3}\cos\theta = \frac{1}{2}v_{uN}$$

$$\bar{v}_{uo} = \frac{t_2 - t_3}{T} \cdot \frac{E_d}{2} = \frac{A}{\sqrt{3}}\left[2\cos\frac{\pi}{6} \cdot \sin\left(\frac{\pi}{2} - \theta\right)\right] = A\cos\theta$$

$$\bar{v}_{vo} = \frac{t_2 + t_3}{T} \cdot \frac{E_d}{2} = \frac{A}{\sqrt{3}}\left[2\sin\frac{\pi}{6} \cdot \cos\left(\frac{\pi}{2} - \theta\right)\right] = \frac{A}{\sqrt{3}}\sin\theta$$

$$\bar{v}_{wo} = -\frac{(t_2 + t_3)}{T} \cdot \frac{E_d}{2} = -\bar{v}_{vo} = -\frac{A}{\sqrt{3}}\sin\theta$$

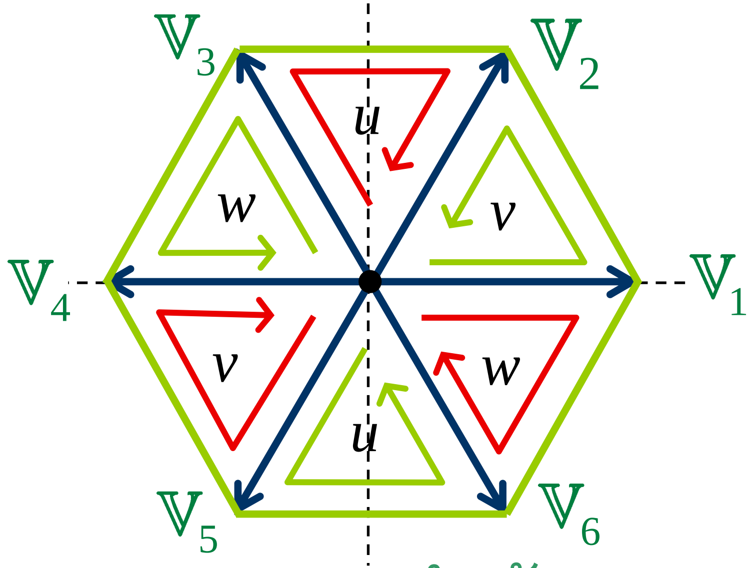
สำหรับ Sector 3 $[\mathbb{V}_3, \mathbb{V}_4, \mathbb{V}_0, \mathbb{V}_7]$ Sequence: $\mathbb{V}_0 \to \mathbb{V}_3 \to \mathbb{V}_4 \to \mathbb{V}_7 \to \mathbb{V}_7 \to \mathbb{V}_4 \to \mathbb{V}_3 \to \mathbb{V}_0$

$$\bar{v}_{uo} = +\frac{A}{\sqrt{3}}\cos\left(\theta + \frac{\pi}{6}\right)$$

$$\bar{v}_{vo} = -\frac{A}{\sqrt{3}}\cos\left(\theta + \frac{\pi}{6}\right) = -\bar{v}_{uo}$$

$$\bar{v}_{wo} = A\cos\left(\theta + \frac{2\pi}{3}\right)$$

$$\bar{v}_{No} = \frac{A}{3}\cos\left(\theta + \frac{2\pi}{3}\right) = \frac{1}{2}v_{wN}$$



สำหรับ Sector 4

$$\bar{v}_{uo} = +\frac{A}{\sqrt{3}}\cos\left(\theta - \frac{\pi}{6}\right)$$

$$\bar{v}_{vo} = A\cos\left(\theta - \frac{2\pi}{3}\right)$$

$$\bar{v}_{wo} = -\frac{A}{\sqrt{3}}\cos\left(\theta - \frac{\pi}{6}\right) = \bar{v}_{uo}$$

$$\bar{v}_{No} = \frac{A}{3}\cos\left(\theta - \frac{2\pi}{3}\right) = \frac{1}{2}v_{vN}$$

สำหรับ Sector 5

$$\bar{v}_{uo} = A\cos\theta$$

$$\bar{v}_{vo} = \frac{A}{\sqrt{2}}\sin\theta$$

$$\bar{v}_{wo} = -\frac{A}{\sqrt{3}}\sin\theta = -\bar{v}_{uo}$$

$$\bar{v}_{No} = \frac{A}{3}\cos\theta = \frac{1}{2}v_{uN}$$

สำหรับ Sector 6

$$\bar{v}_{uo} = \frac{A}{\sqrt{3}}\cos\left(\theta + \frac{\pi}{6}\right)$$

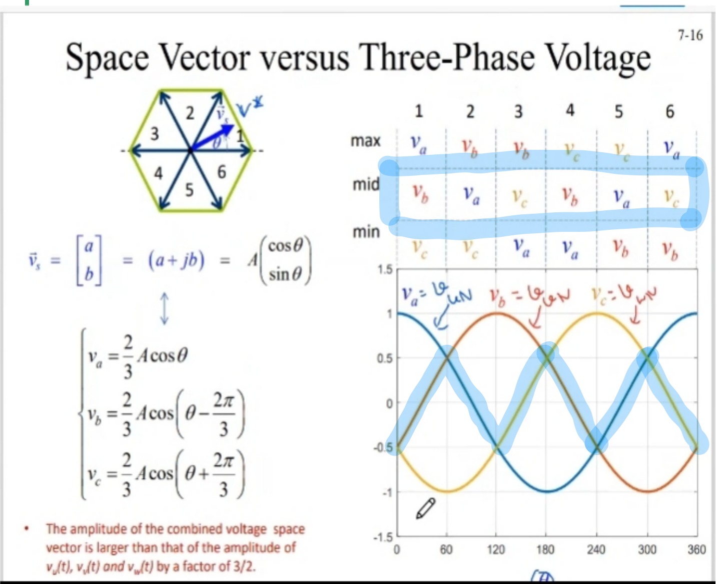
$$\bar{v}_{vo} = -\frac{A}{\sqrt{3}}\cos\left(\theta + \frac{\pi}{6}\right) = -\bar{v}_{uo}$$

$$\bar{v}_{wo} = A\cos\left(\theta + \frac{2\pi}{3}\right)$$

$$\bar{v}_{No} = \frac{A}{3}\cos\left(\theta + \frac{2\pi}{3}\right) = \frac{1}{2}v_{wN}$$

<u>สรุป</u> แรงดัน Zero Vector $\overline{v}_{No}$ ที่บวกเข้าไปใน (v_{uN}, v_{vN}, v_{wN}) จะเปลี่ยนไปตามสมการ

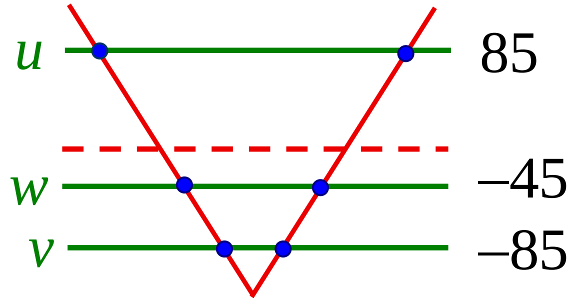
$$\boxed{\overline{v}_{No} = \frac{1}{2} Median(v_{uN}, v_{vN}, v_{wN})}$$

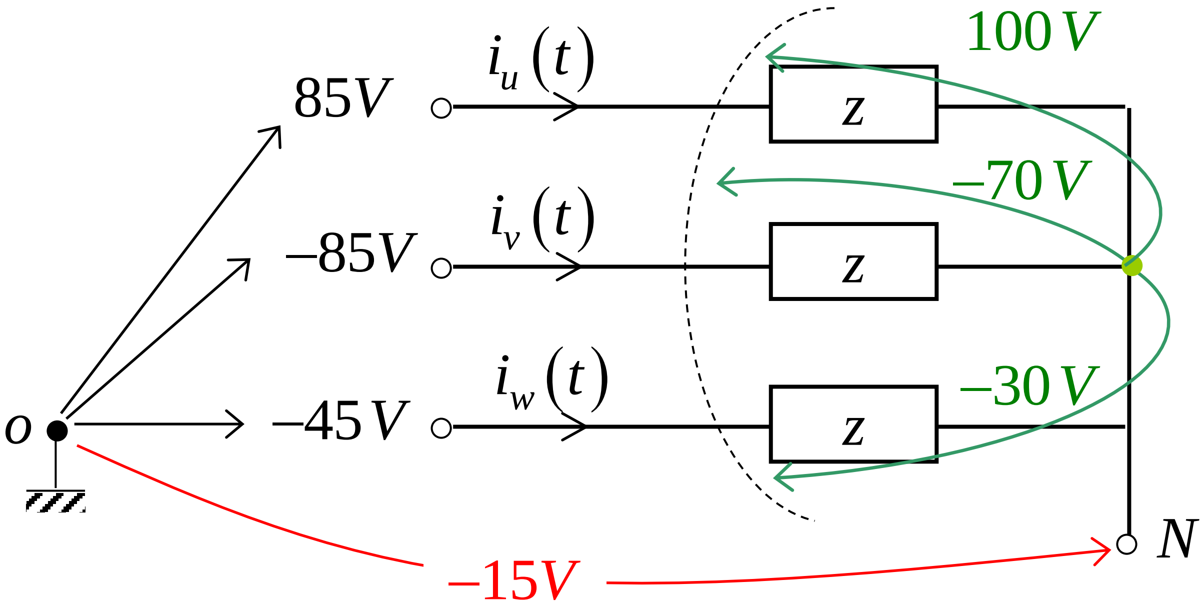


$$\boxed{\begin{aligned} \overline{v}_{uo} &= v_{uN} + \overline{v}_{No} \\ \overline{v}_{vo} &= v_{vN} + \overline{v}_{No} \\ \overline{v}_{wo} &= v_{wN} + \overline{v}_{No} \end{aligned}}$$

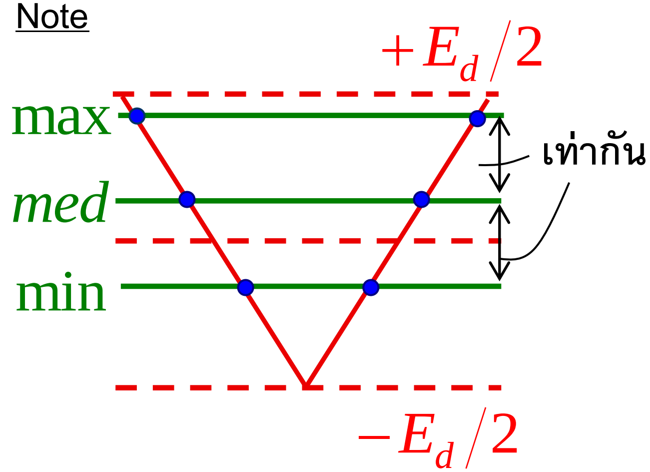
Ex ต้องการสร้าง
$$\begin{cases} v_{uN} = 100V \\ v_{vN} = -70V \\ v_{wN} = -30V \end{cases} \rightarrow \quad \overline{v}_{No} = \frac{1}{2}(-30) = -15V$$

$$\therefore \begin{cases} v_{uo} = 100+(-15) = 85 \\ v_{vo} = -70+(-15) = -85 \\ v_{wo} = -30+(-15) = -45 \end{cases}$$





Note



เปรียบเทียบการทำ Space Vector PWM

1.48

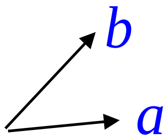
v_{uN}, v_{vN}, v_{wN}

↓

v_x, v_y

↓

Check Sector



↓

แตก v_a, v_b

↓

t_a, t_b, t_o, t_7

↓

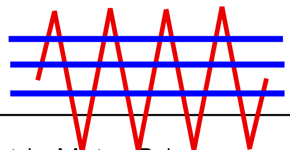
กำหนด Sequence v_0, v_7, v_a, v_b

↓

คำนวณหา $\overline{v}_{uo}, \overline{v}_{vo}, \overline{v}_{wo}$

↓

เปรียบเทียบ



v_{uN}, v_{vN}, v_{wN}

↓

Check หา Median (u,v,w)

↓

กำหนด $\overline{v}_{No} = \frac{1}{2} Median$

↓

คำนวณหา

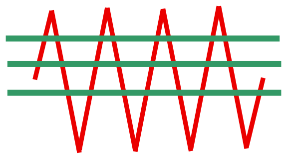
$$\overline{v}_{uo} = v_{uN} + \overline{v}_{No}$$

$$\overline{v}_{vo} = v_{vN} + \overline{v}_{No}$$

$$\overline{v}_{wo} = v_{wN} + \overline{v}_{No}$$

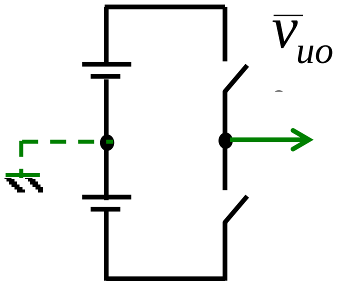
↓

เปรียบเทียบ



ต้องการสร้าง

$$\begin{bmatrix} v_{uN}^{*}(t) \\ v_{vN}^{*}(t) \\ v_{wN}^{*}(t) \end{bmatrix} \xrightarrow{\text{Sinusoidal PWM}} \begin{bmatrix} \bar{v}_{uo}(t) = v_{uN}^{*}(t) \\ \bar{v}_{vo}(t) = v_{vN}^{*}(t) \\ \bar{v}_{wo}(t) = v_{wN}^{*}(t) \end{bmatrix}$$



คิดแยกทีละเฟส

$* : command$

$$\underline{v}^{*}(t) \Rightarrow \begin{bmatrix} \bar{v}_{u0}(t) \\ \bar{v}_{v0}(t) \\ \bar{v}_{w0}(t) \end{bmatrix} \Rightarrow \underline{\bar{v}}(t) = \underline{v}^{*}(t)$$

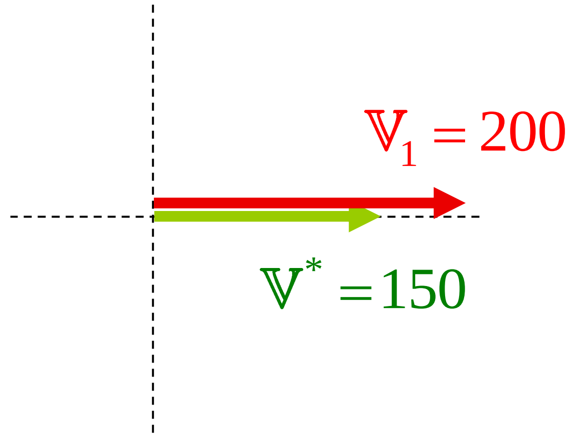
$$\Updownarrow$$

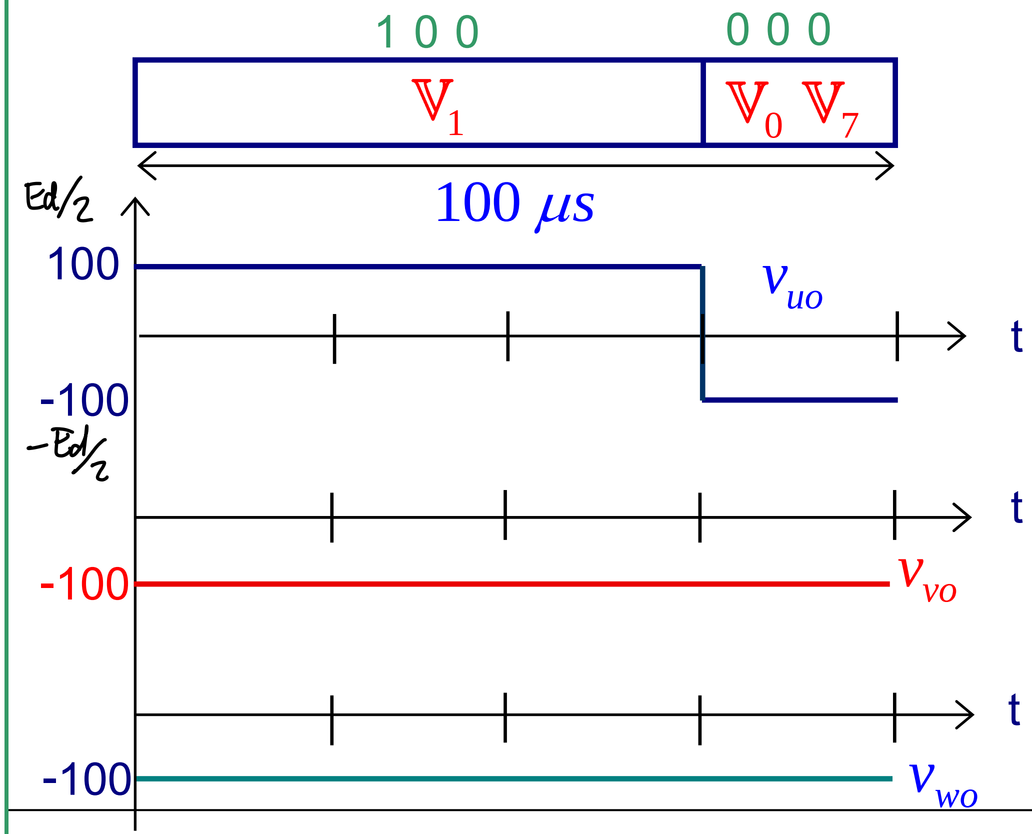
$$\begin{cases} \bar{v}_{uN}(t) = v_{uN}^{*}(t) \\ \bar{v}_{vN}(t) = v_{vN}^{*}(t) \\ \bar{v}_{wN}(t) = v_{wN}^{*}(t) \end{cases}$$

[ex] $E_d = 200\,V, \quad T = 100\,\mu s \quad [\,f_{sw} = 10\,kHz\,]$

ต้องการ $\begin{cases} v_{uN} = 100V \\ v_{vN} = -50V \\ v_{wN} = -50V \end{cases} \Rightarrow \mathbb{V}^* = \begin{bmatrix} 150 \\ 0 \end{bmatrix}$

$\left(\sum = 0\right)$





$\begin{cases} \bar{v}_{uo} = 50\,V \\ \bar{v}_{vo} = -100\,V \\ \bar{v}_{wo} = -100\,V \end{cases}$

$\boxed{\bar{v}_{No} = -50V}$

จงใจเลือก ↗ +

$\begin{cases} \bar{v}_{uN} = 100\,V \\ \bar{v}_{vN} = -50\,V \\ \bar{v}_{wN} = -50\,V \end{cases}$

Note
ไม่เท่ากัน !!

$v_{uN} = 100\text{ V}$

$v_{vN} = -50\text{ V}$

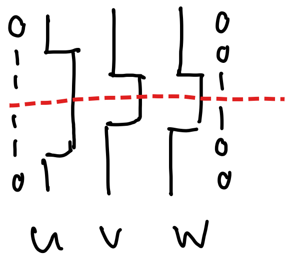
$v_{wN} = -50\text{ V}$

$$\Rightarrow v_{N0} = \frac{1}{2}\text{Med}\{100, -50, -50\} = \frac{1}{2}\{-50\} = -25\text{ V}$$

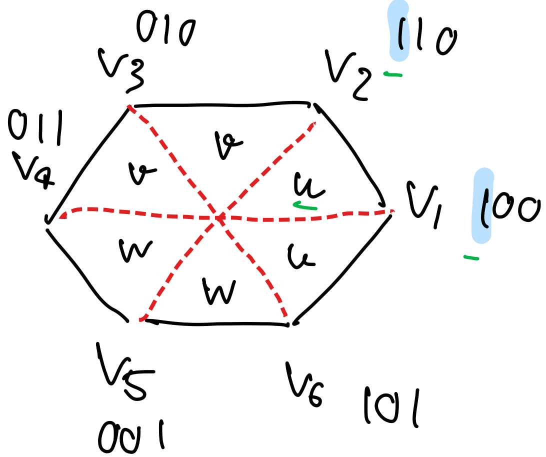
$\therefore\ v_{u0} = 100 - 25 = 75\text{ V}$

$v_{v0} = -50 - 25 = -75\text{ V}$

$v_{w0} = -50 - 25 = -75\text{ V}$



ON ตัว

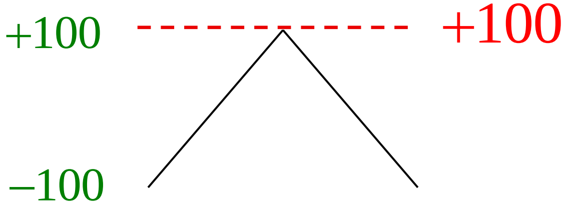


แบบ PWM เดิม

- $v_{uN} = 100$ → $\bar{v}_{uo} = 100\,V$

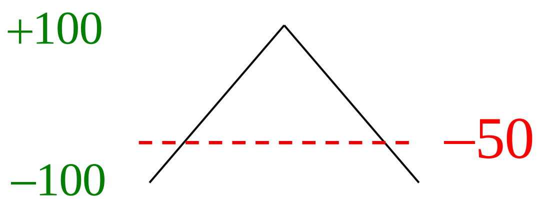
1

100 μs



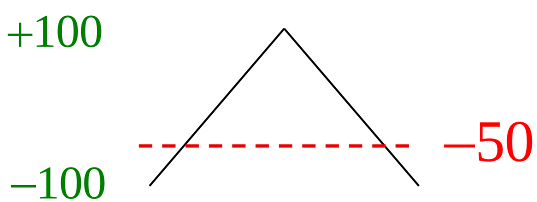
- $v_{vN} = -50$ → $\bar{v}_{vo} = -50\,V$

1	0
25 μs	75 μs



- $v_{wN} = -50$ → $\bar{v}_{wo} = -50\,V$

1	0
25 μs	75 μs



$\therefore$

$\mathbb{V}_7$	$\mathbb{V}_1$
111	100
25 μs	75 μs

$\bar{v}_{No} = 0$

เงื่อนไขแรงดันในแต่ละ Sector

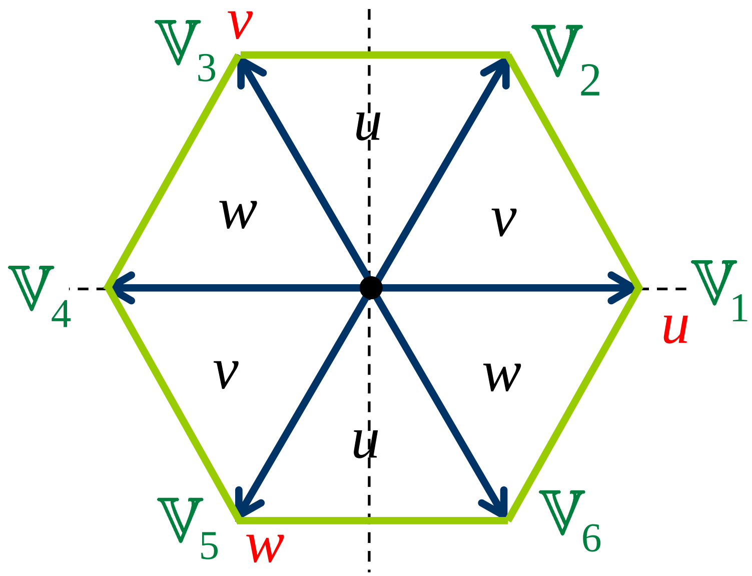
Sector 1

U
V
W

$U > 0$

$V > 0$ หรือ $V < 0$ ก็ได้ แต่ $W < V < U$

$W < 0$



Sector 2

V
U
W

Sector 3

V
W
U

Sector 4

W
V
U

Sector 5

W
U
V

Sector 6

U
W
V

Note: ในกรณีที่

$$v_{uN} + v_{vN} + v_{wN} \neq 0,$$ การทำ space vector PWM จะได้

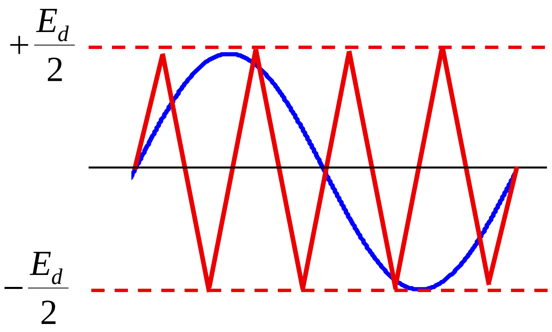
General Form:

$$\boxed{\bar{v}_{No} = -\frac{1}{2}\left[\max\left(v_{uN}, v_{vN}, v_{wN}\right) + \min\left(v_{uN}, v_{vN}, v_{wN}\right)\right]}$$

A = Varying Amplitude

กรณีที่คำสั่งเป็น Sinusoid

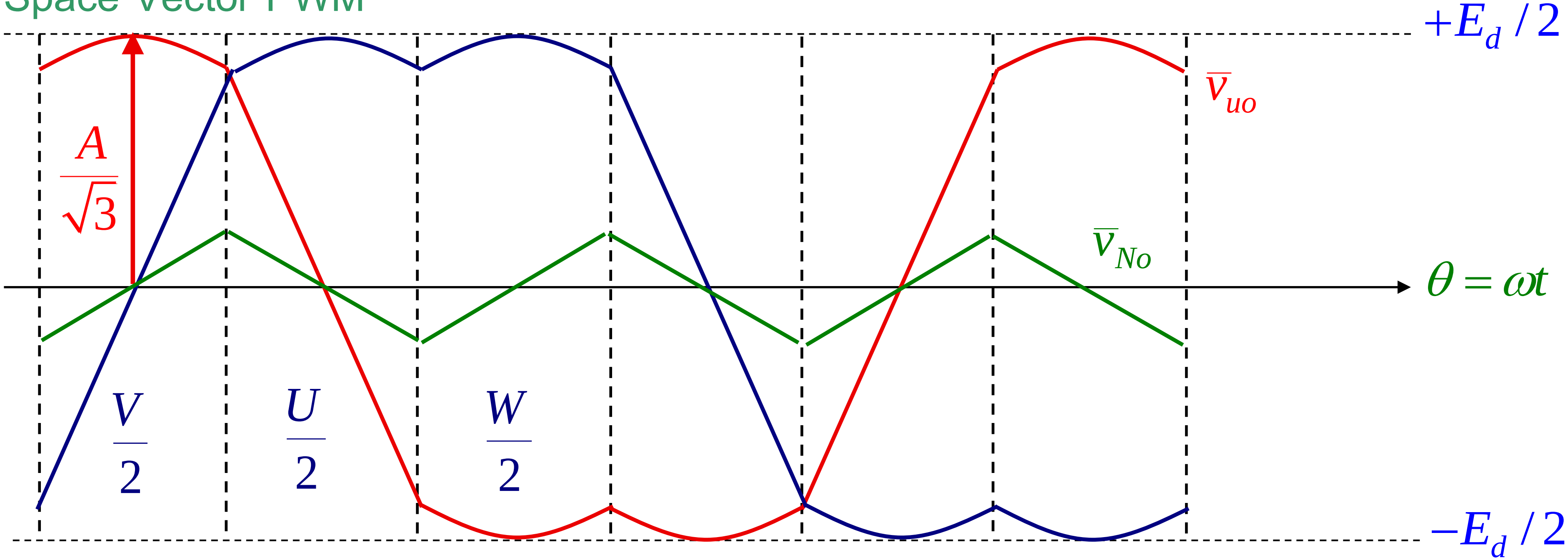
- Sinusoidal PWM



Max. modulation index a=1

Peak $v_{un} = \boxed{\frac{E_d}{2}}$

- Space Vector PWM



$$v_{uN} = \frac{2}{3} A \cdot \cos\theta$$

$$v_{uN} + v_{NO} = v_{uo}$$

$$\bar{v}_{u0} = \frac{A}{\sqrt{3}} \cdot \cos\left(\theta - \frac{\pi}{6}\right) \quad ; \ 0 < \theta < \frac{\pi}{3}$$

$$= A \cdot \cos\theta \quad ; \ \frac{\pi}{3} < \theta < \frac{2\pi}{3}$$

$$= \frac{A}{\sqrt{3}} \cdot \cos\left(\theta + \frac{\pi}{6}\right) \quad ; \ \frac{2\pi}{3} < \theta < \pi$$

$$= \frac{A}{\sqrt{3}} \cdot \cos\left(\theta - \frac{\pi}{6}\right) \quad ; \ \pi < \theta < \frac{4\pi}{3}$$

$$= A \cdot \cos\theta \quad ; \ \frac{4\pi}{3} < \theta < \frac{5\pi}{3}$$

$$= \frac{A}{\sqrt{3}} \cdot \cos\left(\theta + \frac{\pi}{6}\right) \quad ; \ \frac{5\pi}{3} < \theta < 2\pi$$

$$\therefore \quad \max \frac{A}{\sqrt{3}} = \frac{E_d}{2}$$

$$\therefore \quad A = \frac{\sqrt{3}}{2} E_d$$

$$\text{Peak } v_{uN} = \frac{2}{3} \times \frac{\sqrt{3}}{2} E_d = \boxed{\frac{E_d}{\sqrt{3}}}$$

Sine mod $\frac{Ed}{2}$

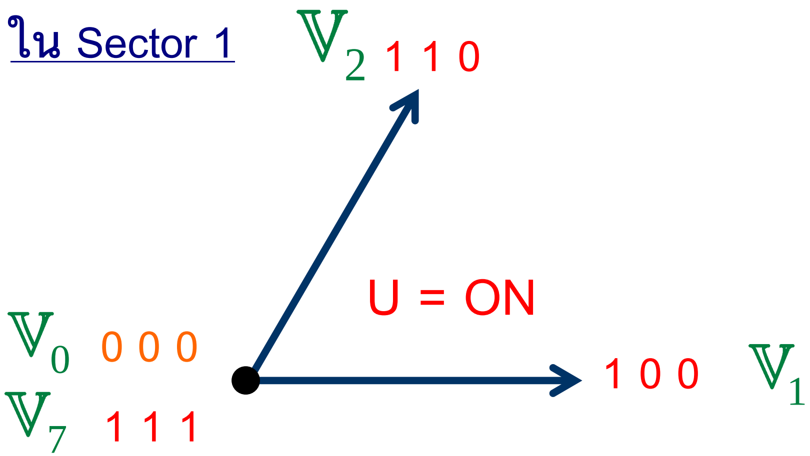
	Phase	V_{L-L}
sin Mod	$\frac{E_d}{2}$	$\sqrt{3}\,\frac{E_d}{2} = 0.866\,E_d$
space Vector Mod	$\frac{E_d}{\sqrt{3}}$	$\sqrt{3}\left(\frac{E_d}{\sqrt{3}}\right) = E_d$

~ 14%

2 arms modulation

ใน 1 คาบ carrier wave จะมีเพียง 2 arms (เฟส) เท่านั้นที่มีการสวิตช์

ใน Sector 1

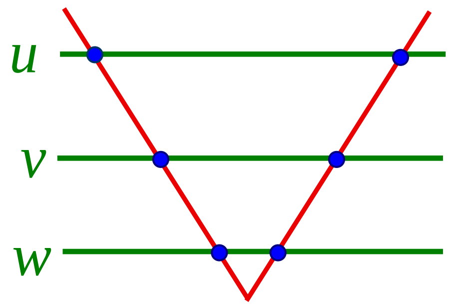


t		u	v	w
$t_0/2$	$\mathbb{V}_7$	1	1	1
$t_2/2$	$\mathbb{V}_2$	1	1	0
$t_1/2$	$\mathbb{V}_1$	1	0	0
$t_1/2$	$\mathbb{V}_1$	1	0	0
$t_2/2$	$\mathbb{V}_2$	1	1	0
$t_0/2$	$\mathbb{V}_7$	1	1	1

เดิม : $\mathbb{V}_0 - \mathbb{V}_1 - \mathbb{V}_2 - \mathbb{V}_7 - \mathbb{V}_7 - \mathbb{V}_2 - \mathbb{V}_1 - \mathbb{V}_0$

⇩ เลือกใช้เฉพาะ $\mathbb{V}_7$ ไม่ใช้ $\mathbb{V}_0$

$$\mathbb{V}_7 - \mathbb{V}_2 - \mathbb{V}_1 - \mathbb{V}_1 - \mathbb{V}_2 - \mathbb{V}_7$$



$$\boxed{\bar{v}_{uo} = +\frac{E_d}{2}} \quad + v_{uN} - v_{uN}$$

$$\bar{v}_{vo} = \frac{E_d}{2} - 2\cdot\frac{t_1}{T}\cdot\frac{E_d}{2}$$

$$= \frac{E_d}{2} - \frac{2A}{\sqrt{3}E_d}\cdot\sin\left(\frac{\pi}{3}-\theta\right)\cdot E_d$$

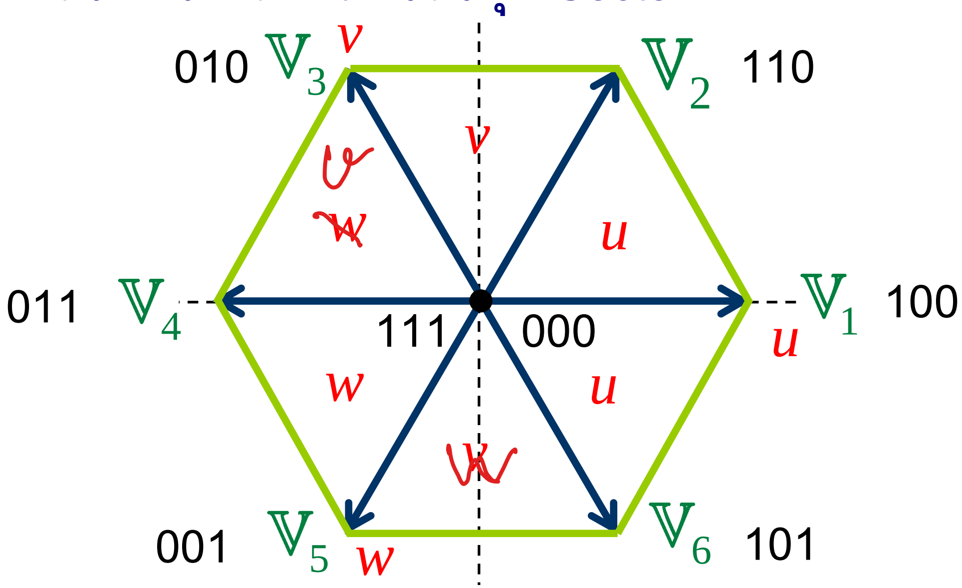
$$= \frac{E_d}{2} + \underbrace{\frac{2A}{\sqrt{3}}\cdot\cos\left(\theta - \frac{5\pi}{6}\right)}_{v_{vN} - v_{uN}}$$

$$\bar{v}_{wo} = \frac{E_d}{2} - 2\cdot\frac{(t_1+t_2)}{T}\cdot\frac{E_d}{2}$$

$$= \frac{E_d}{2} + \underbrace{\frac{2A}{\sqrt{3}}\cdot\cos\left(\theta + \frac{5\pi}{6}\right)}_{v_{wN} - v_{uN}}$$

$$\bar{v}_{No} = \frac{E_d}{2} - \underbrace{\frac{2}{3}A\cos\theta}_{v_{uN}}$$

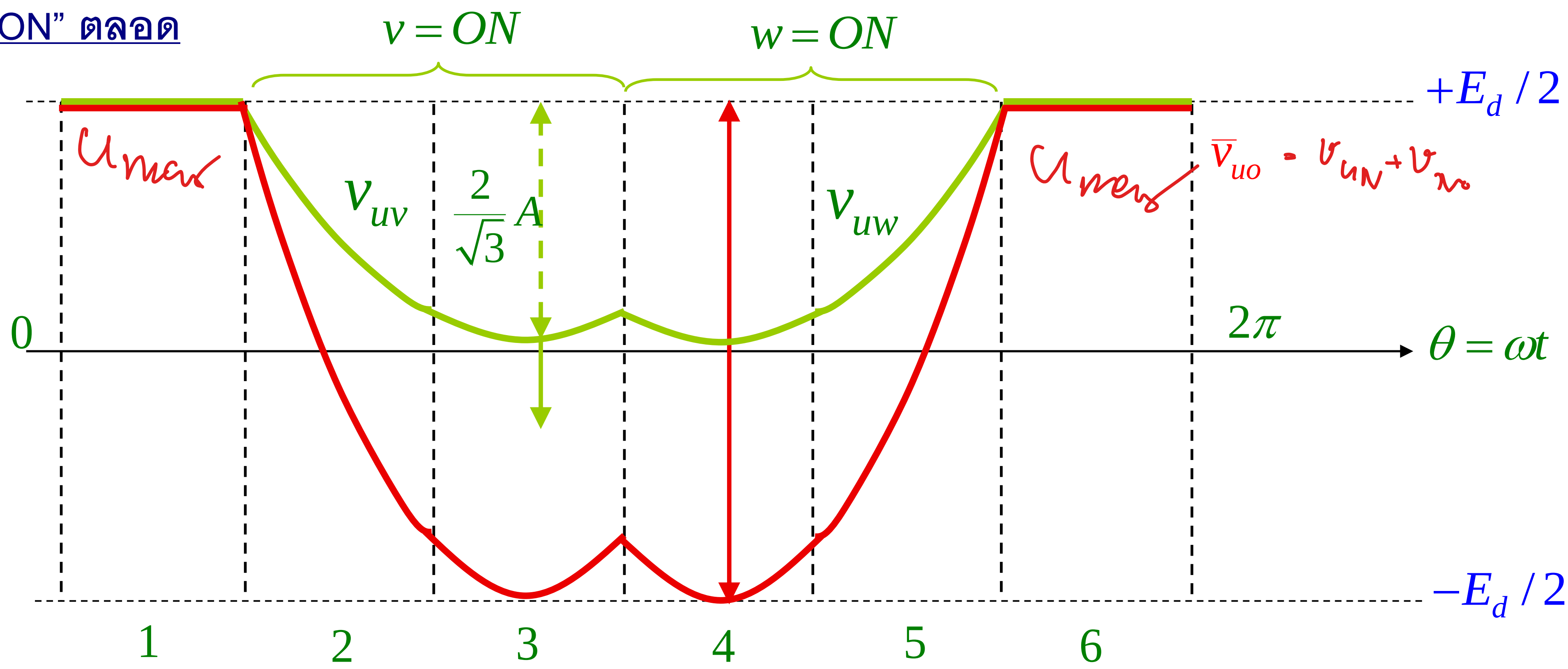
คิดในทำนองเดียวกันในทุก Sector



Sector 2

$$\begin{cases} \bar{v}_{uo} = \dfrac{E_d}{2} + \underbrace{v_{uN} - v_{vN}}_{\frac{2A}{\sqrt{3}}\cos\left(\theta+\frac{\pi}{6}\right)} \\ \bar{v}_{vo} = \dfrac{E_d}{2} \\ \bar{v}_{wo} = \dfrac{E_d}{2} + v_{wN} - v_{vN} \\ \bar{v}_{No} = \dfrac{E_d}{2} - v_{vN} \end{cases}$$

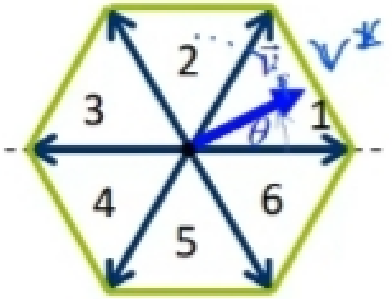
"ON" ตลอด



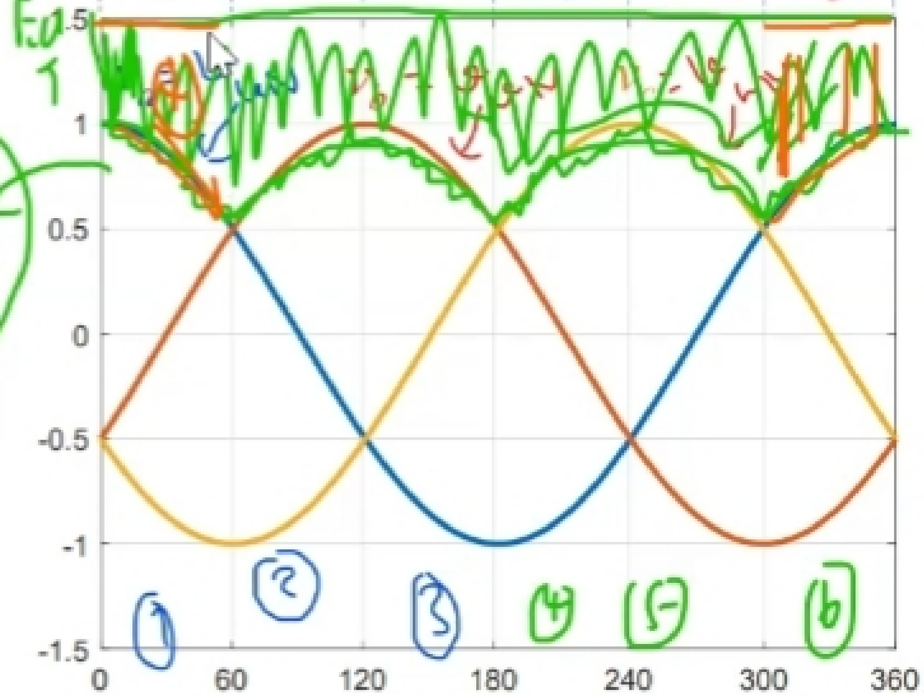
ที่ max. modulation $\quad \frac{2A}{\sqrt{3}} = E_d \rightarrow A = \frac{\sqrt{3}}{2}E_d$

$\therefore$ ค่า Peak $v_{uN} = \frac{2}{3}A = \boxed{\frac{E_d}{\sqrt{3}}}$

Space Vector versus Three-Phase Voltage



	1	2	3	4	5	6
max	v_a	v_b	v_b	v_c	v_c	v_a
mid	v_b	v_a	v_c	v_b	v_a	v_c
min	v_c	v_c	v_a	v_a	v_b	v_b



$$\vec{v}_s = \begin{bmatrix} a \\ b \end{bmatrix} = (a + jb) = A\begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}$$

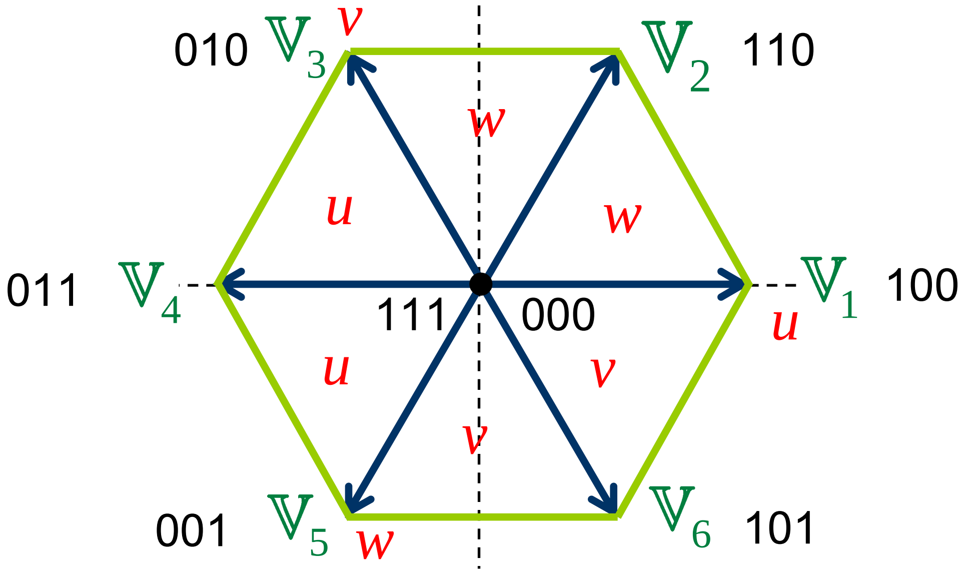
$$\updownarrow$$

$$\begin{cases} v_a = \dfrac{2}{3}A\cos\theta \\ v_b = \dfrac{2}{3}A\cos\left(\theta - \dfrac{2\pi}{3}\right) \\ v_c = \dfrac{2}{3}A\cos\left(\theta + \dfrac{2\pi}{3}\right) \end{cases}$$

- The amplitude of the combined voltage space vector is larger than that of the amplitude of

“OFF” ตลอด

Sector 1



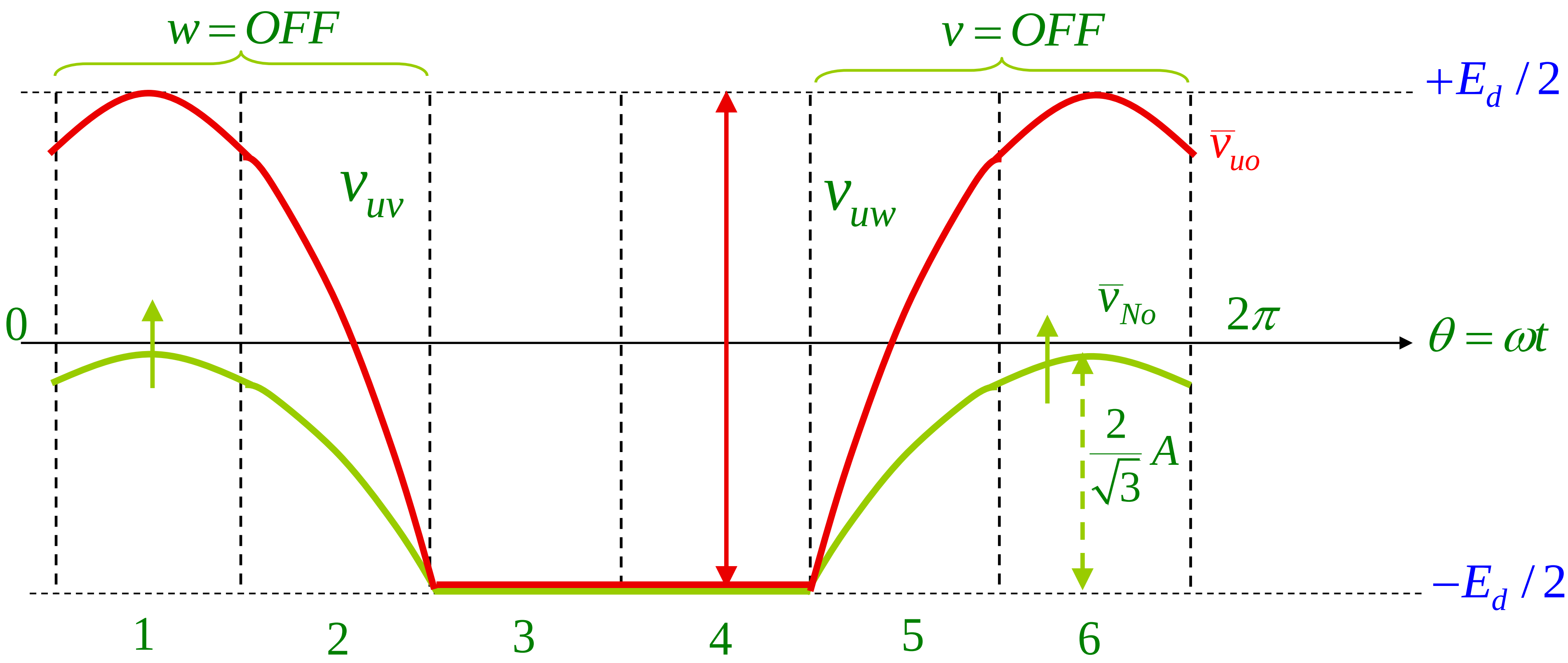
$$
\begin{cases}
\bar{v}_{uo} = -\dfrac{E_d}{2} + v_{uN} - v_{wN} \\
\bar{v}_{vo} = -\dfrac{E_d}{2} + v_{vN} - v_{wN} \\
\bar{v}_{wo} = -\dfrac{E_d}{2} \\
\bar{v}_{No} = -\dfrac{E_d}{2} - v_{wN}
\end{cases}
$$

$$\mathbb{V}_0 - \mathbb{V}_1 - \mathbb{V}_2 - \mathbb{V}_2 - \mathbb{V}_1 - \mathbb{V}_0$$

		u	v	w
$t_1/2$	$\mathbb{V}_0$	0	0	0
$t_1/2$	$\mathbb{V}_1$	1	0	0
$t_2/2$	$\mathbb{V}_2$	1	1	0
$t_2/2$	$\mathbb{V}_2$	1	1	0
$t_1/2$	$\mathbb{V}_1$	1	0	0
$t_0/2$	$\mathbb{V}_0$	0	0	0

→ OFF mode

@ sector 1



สรุป 2 arms modulation

กรณี “ON” ตลอด $\nearrow V_{\text{ว}}$

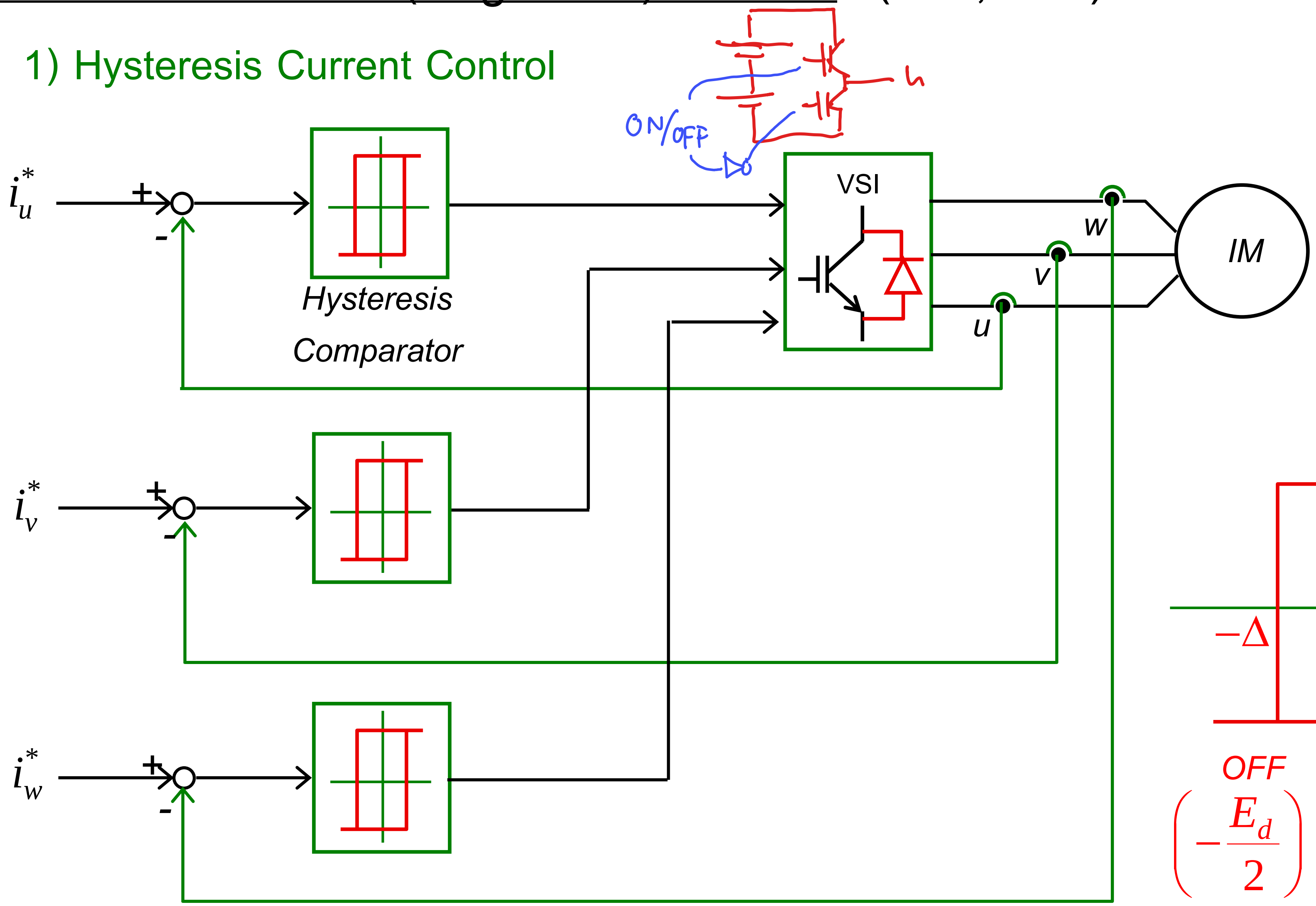
$$\bar{v}_{No} = \frac{E_d}{2} - \max\left[v_{uN}, v_{vN}, v_{wN}\right]$$

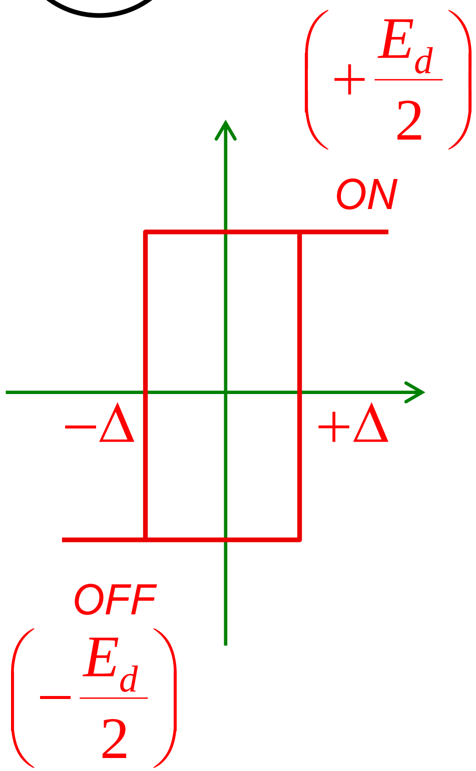
กรณี “OFF” ตลอด $\nearrow V_{\text{o}}$

$$\bar{v}_{No} = -\frac{E_d}{2} - \min\left[v_{uN}, v_{vN}, v_{wN}\right]$$

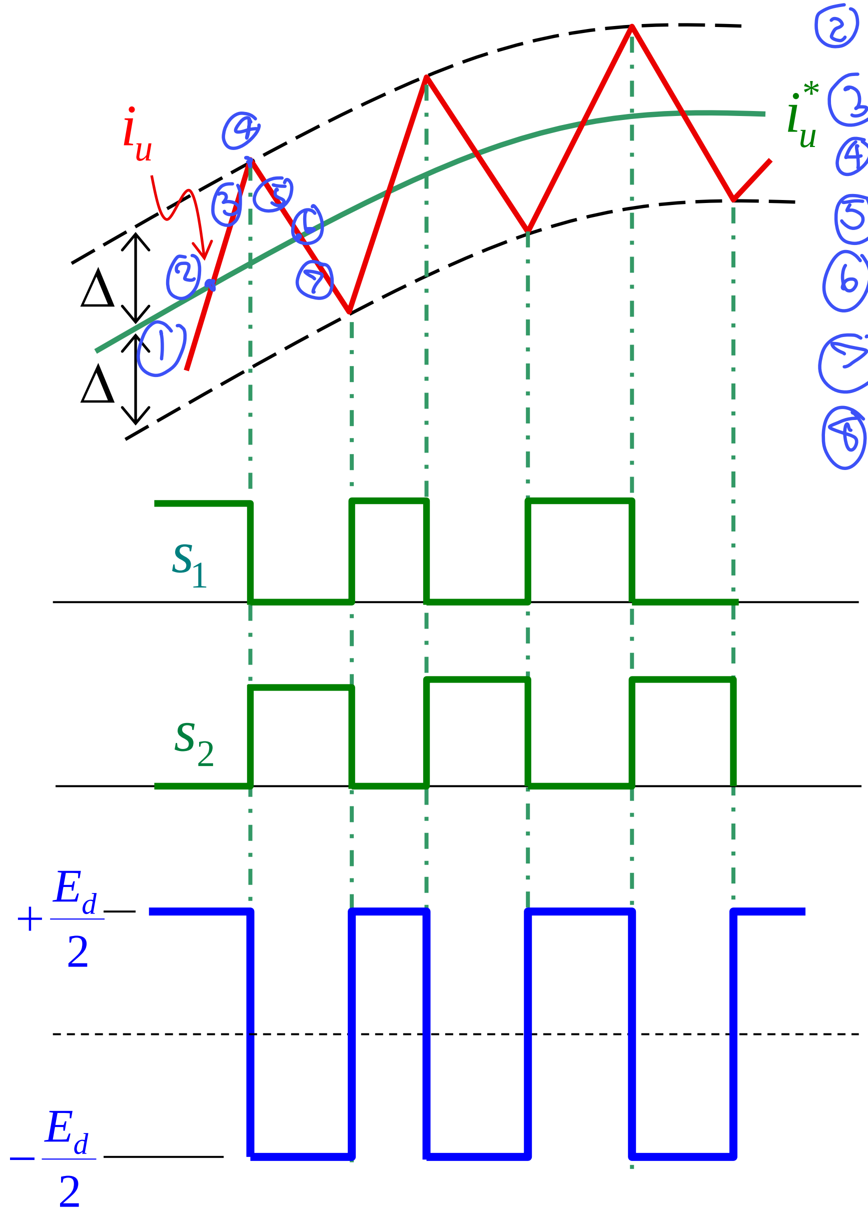
Current-Controlled (Regulated) Inverter (CCI, CRI)

1) Hysteresis Current Control

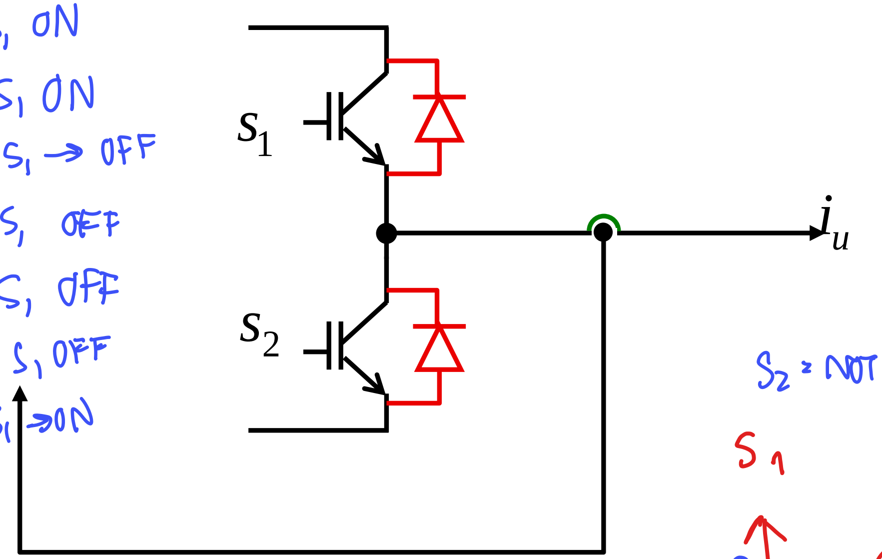




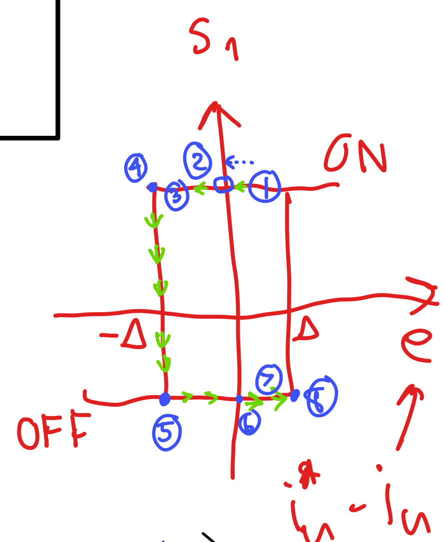
- ไม่มีการทำ PWM
- สัญญาณออกของ Hysteresis Comparator เป็น Switching Signal โดยตรง
- ไม่มี Carrier Frequency…… Switching Frequency ไม่คงที่
- เหมาะกับ Analog มากกว่า Digital
- Response เร็ว

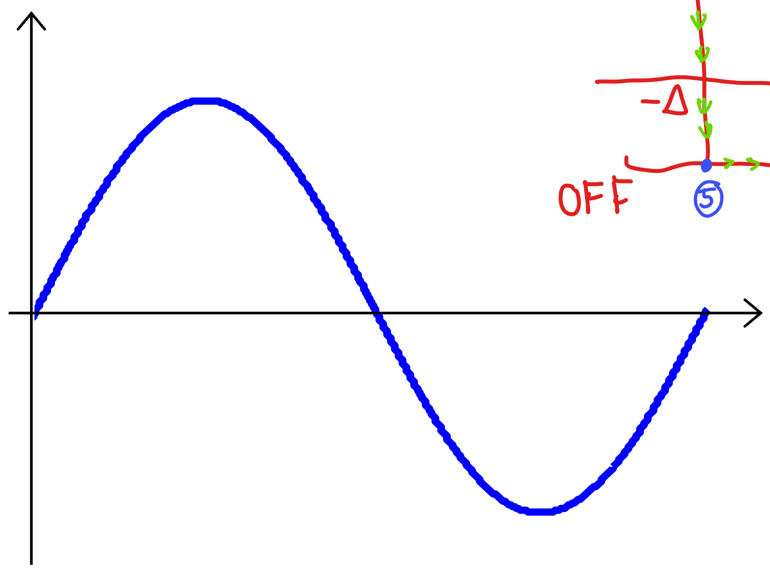


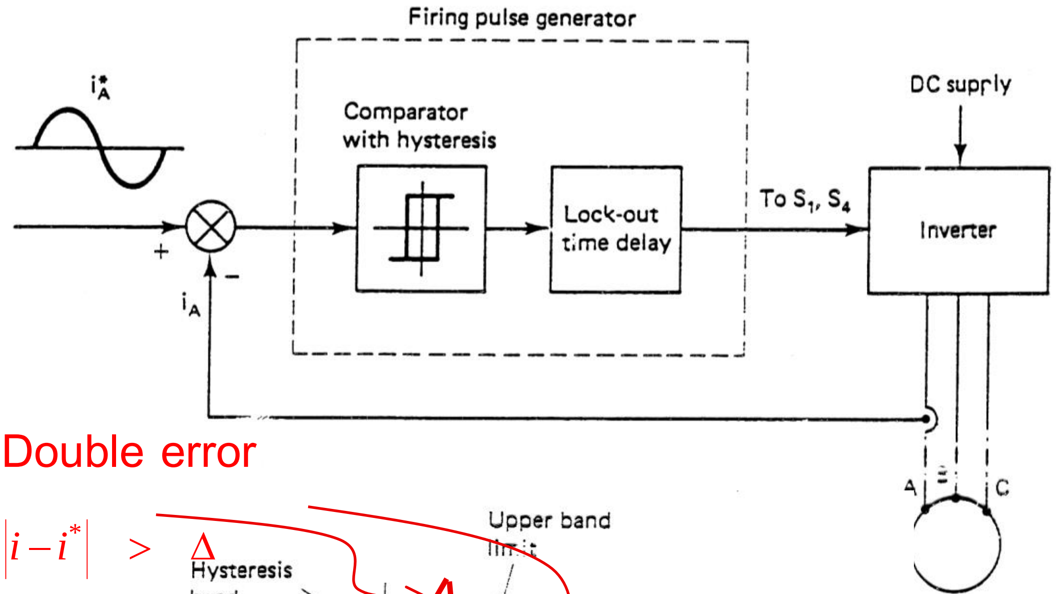
1 $e>0$: S_1 ON
2 $e=0$: S_1 ON
3 $e<0$ S_1 ON
4 $e=-\Delta$ $S_1 \rightarrow$ OFF
5 $e<0$ S_1 OFF
6 $e=0$ S_1 OFF
7 $e>0$ S_1 OFF
8 $e=\Delta$ $S_1 \rightarrow$ ON



$S_2 = \text{NOT}(S_1)$

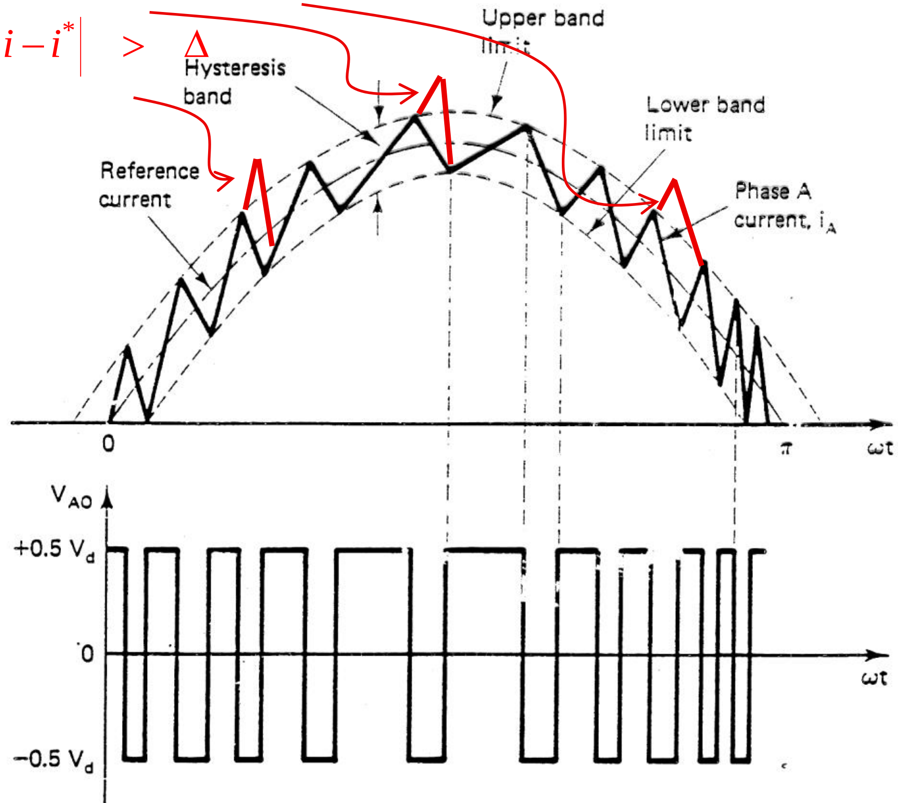


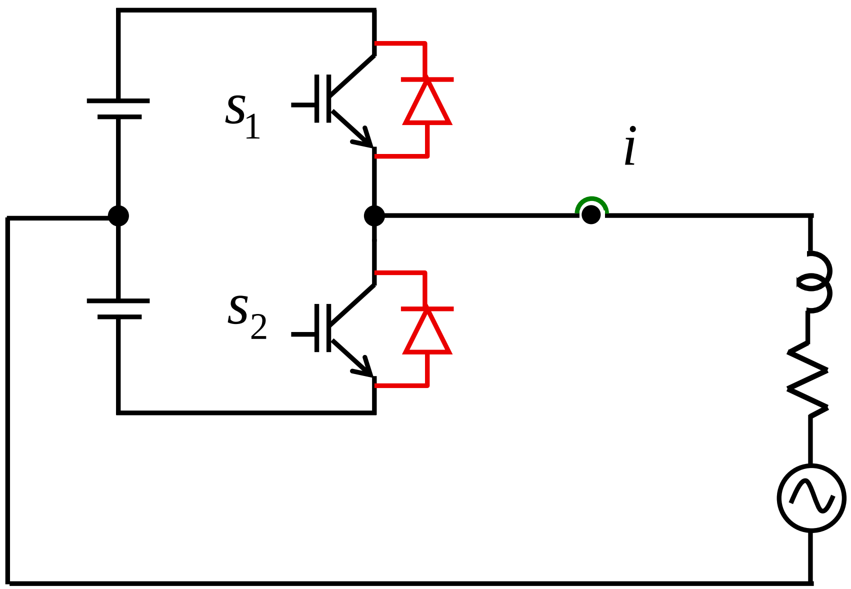




Double error

$|i - i^*| \; > \; \Delta$





ถ้าเป็น single phase

- Error ของ กระแส

$$|i - i^*| \;\le\; \Delta$$

แต่ในกรณี 3 phase

- $|i - i^*| \;\le\; 2\Delta$

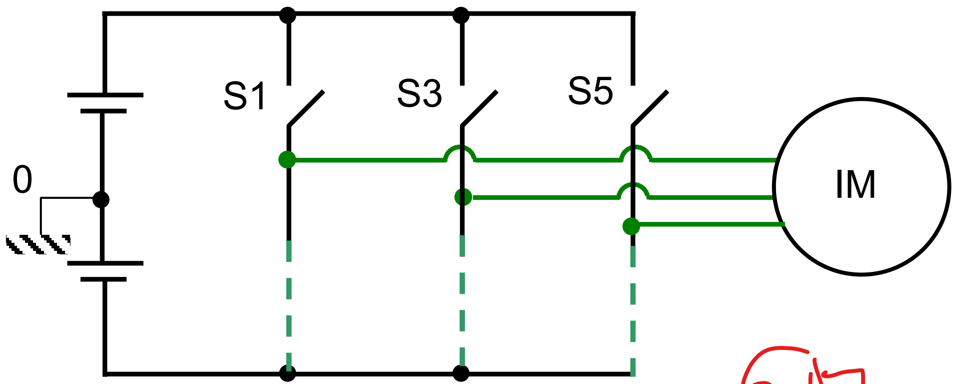
- กรณี 3 ϕ ถึงแม้ S1=ON ก็ไม่ได้หมายความว่ากระแสในเฟส u จะเพิ่ม … ถ้า ~~S2~~ S3 = S5 = ON ด้วย → Zero Vector → กระแสควบคุมไม่ได้

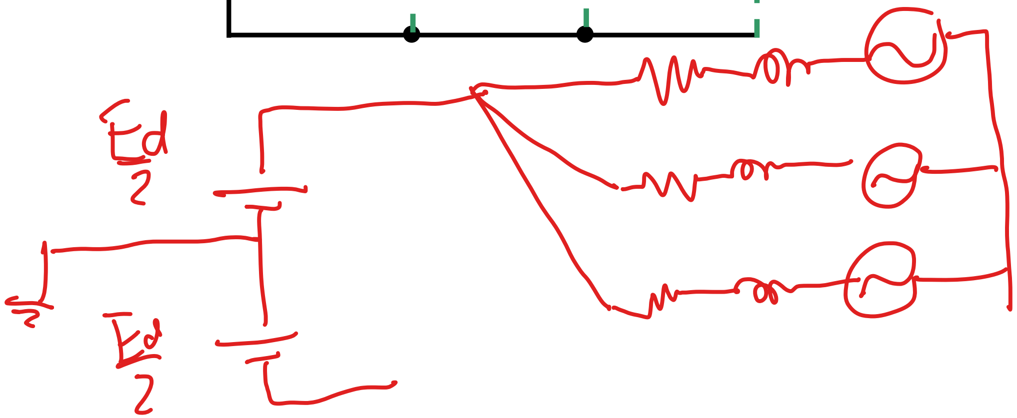
↓

เปลี่ยนแปลงตามแรงเคลื่อนเหนี่ยวนำภายในมอเตอร์

↓

อาจทะลุเกิน Band ของ Hysteresis Comparator ได้

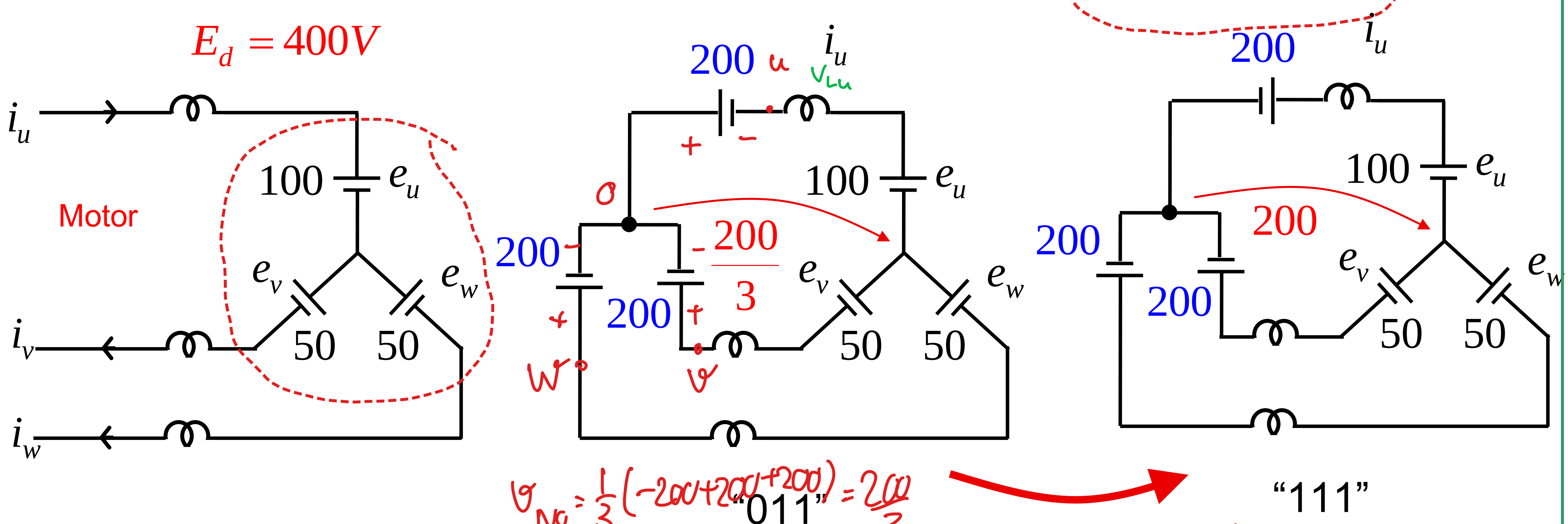




Ex. Inverter อยู่ในสถานะ " 0 1 1" แล้ว i_u ลดลงมาชนขอบ Hysteresis $\longrightarrow$ Inverter เปลี่ยนสถานะเป็น "1 1 1" ที่ $t = t_o$

$$t = t_o \begin{cases} i_u = 2 - \Delta \\ i_v = -1 + \Delta/2 \\ i_w = -1 + \Delta/2 \end{cases} \qquad \begin{cases} i_u^* = 2 \\ i_v^* = -1 \\ i_w^* = -1 \end{cases} \qquad \begin{aligned} e_u &= 100 \\ e_v &= -50 \\ e_w &= -50 \end{aligned}$$

$E_d = 400V$



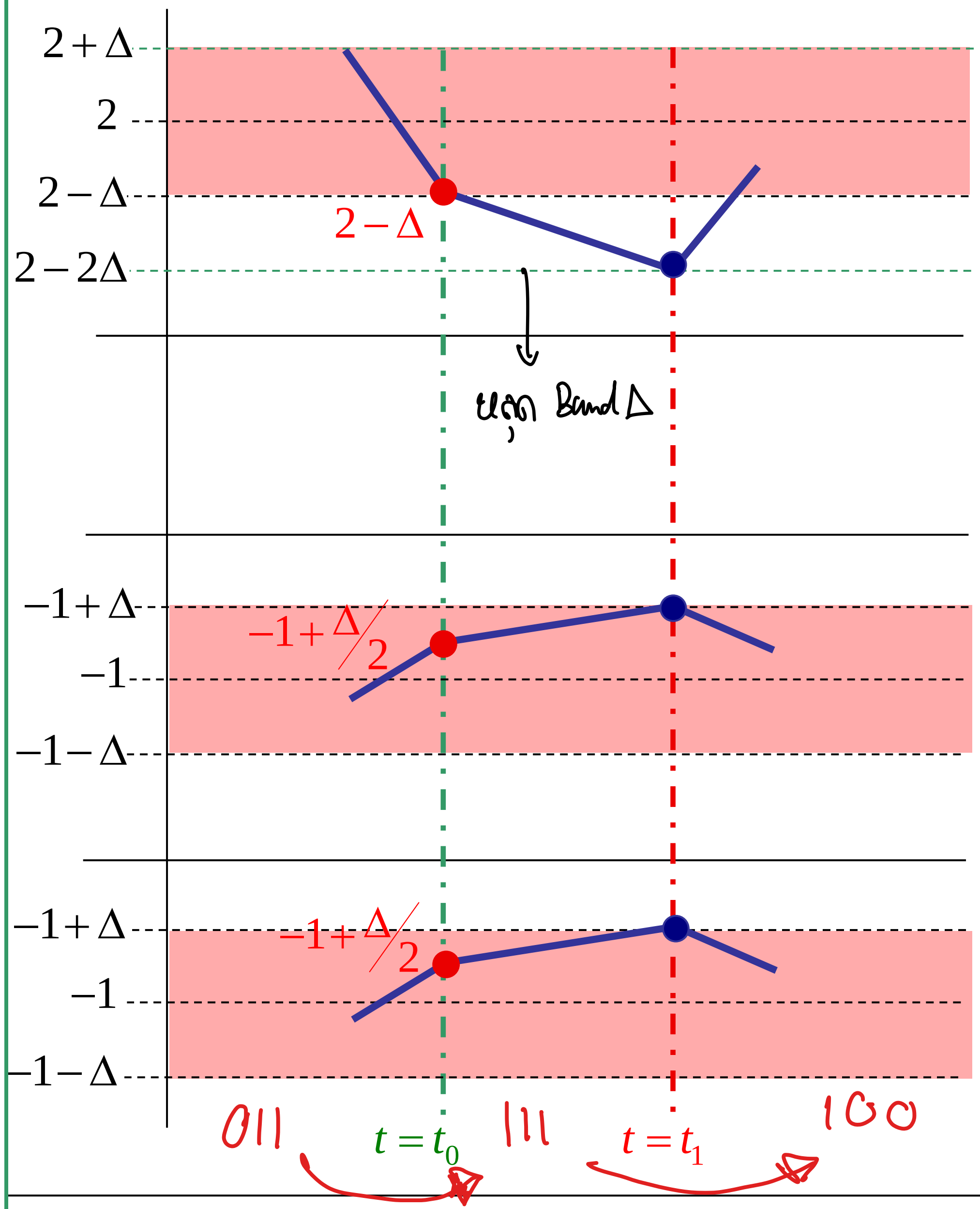
$v_{NO} = \frac{1}{3}(-200+200+200) = \frac{200}{3}$

$V_{NO} = \frac{1}{3}(200+200+200) = 200$

$L\frac{di_u}{dt} + e_u + v_{NO} - V_{uo} = 0$

$$\underbrace{\begin{aligned} \frac{d\,i_u}{dt} &= \frac{1}{L}\left(-\frac{800}{3} - 100\right) \\ \frac{d\,i_v}{dt} &= \frac{1}{L}\left(+\frac{400}{3} + 50\right) \\ \frac{d\,i_w}{dt} &= \frac{1}{L}\left(+\frac{400}{3} + 50\right) \end{aligned}}_{0 \le t \le t_o} \quad \Rightarrow \quad \underbrace{\begin{aligned} \frac{d\,i_u}{dt} &= -\frac{1}{L}100 \\ \frac{d\,i_v}{dt} &= \frac{1}{L}\cdot 50 \\ \frac{d\,i_w}{dt} &= \frac{1}{L}\cdot 50 \end{aligned}}_{t > t_o}$$

"011" "111"



ที่ $t=t_1$ "100"

- i_w, i_v เพิ่มขึ้น $\frac{\Delta}{2}$

$$\left(-1+\frac{\Delta}{2} \rightarrow -1+\Delta\right)$$

- i_u ลดลง Δ

$$\left(+2-\Delta \rightarrow +2-2\Delta\right)$$

ที่ $t>t_1$

$$\frac{d\,i_u}{dt} = +\frac{1}{L}\left(\frac{800}{3}-100\right) > 0$$

$$\frac{d\,i_v}{dt} = \frac{1}{L}\left(-\frac{400}{3}+50\right) < 0$$

$$\frac{d\,i_w}{dt} = \frac{1}{L}\left(-\frac{400}{3}+50\right) < 0$$

Current Error ใน Space Vector

สมการของ Error :
$$\begin{cases} \Delta i_u = i_u^* - i_u \\ \Delta i_v = i_v^* - i_v \\ \Delta i_w = i_w^* - i_w \end{cases}$$

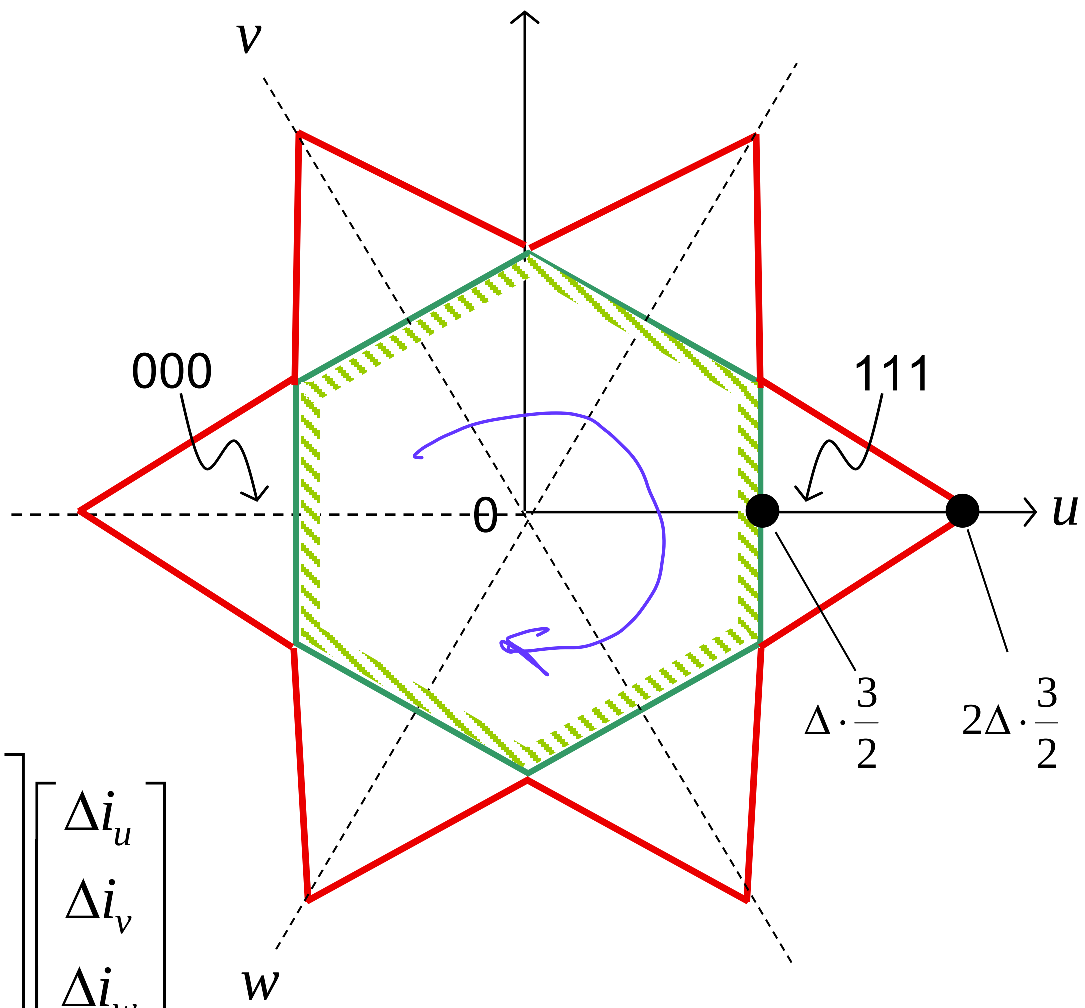
เงื่อนไข

1. $\Delta i_u + \Delta i_v + \Delta i_w = 0$

2. $|\Delta i_u| < \Delta$

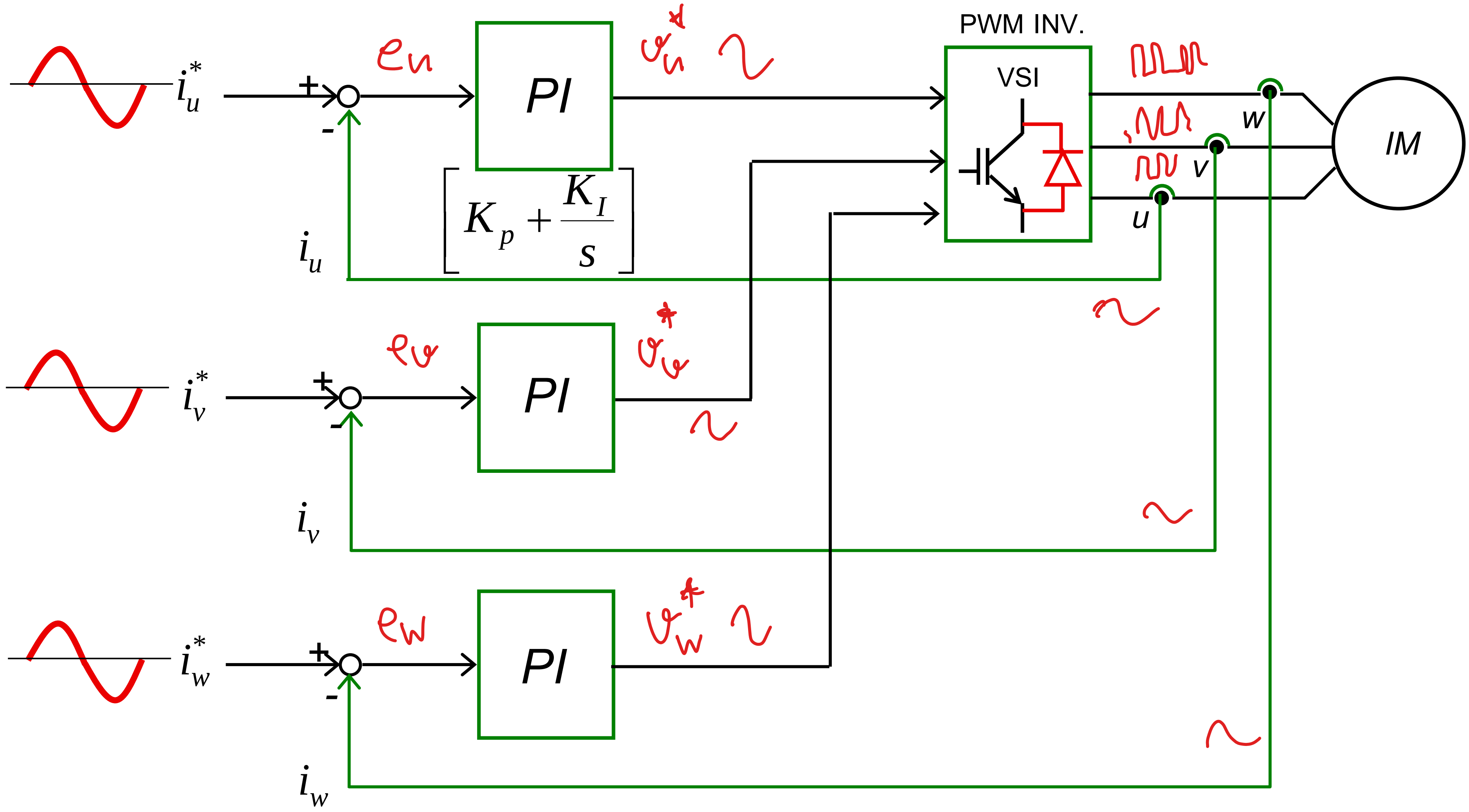
   $|\Delta i_v| < \Delta$

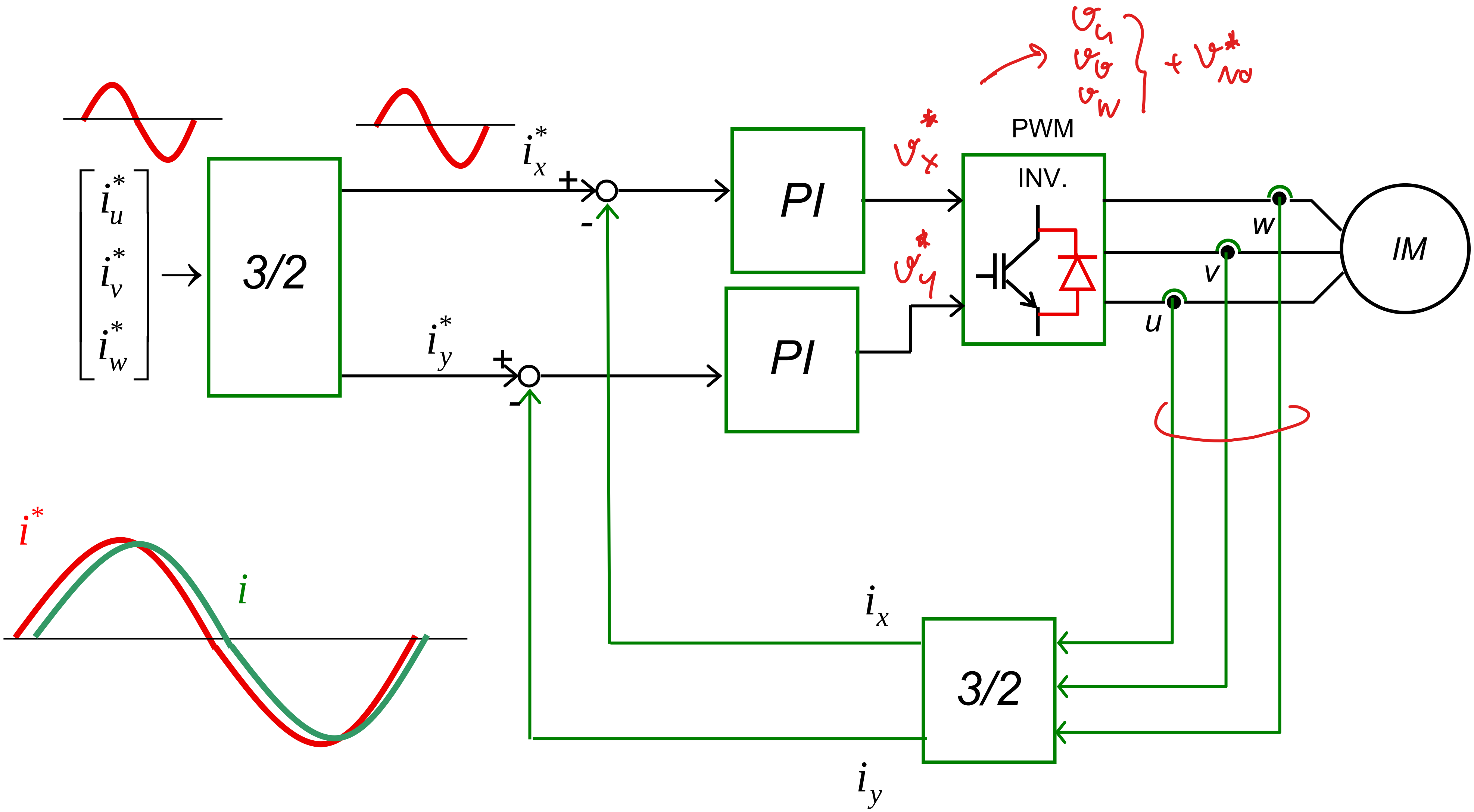
   $|\Delta i_w| < \Delta$



Space Vector $$\Delta \underline{i} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \Delta i_u \\ \Delta i_v \\ \Delta i_w \end{bmatrix}$$

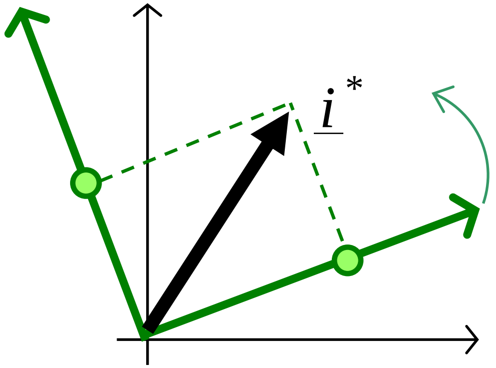
PI Current Control on Stator Frame





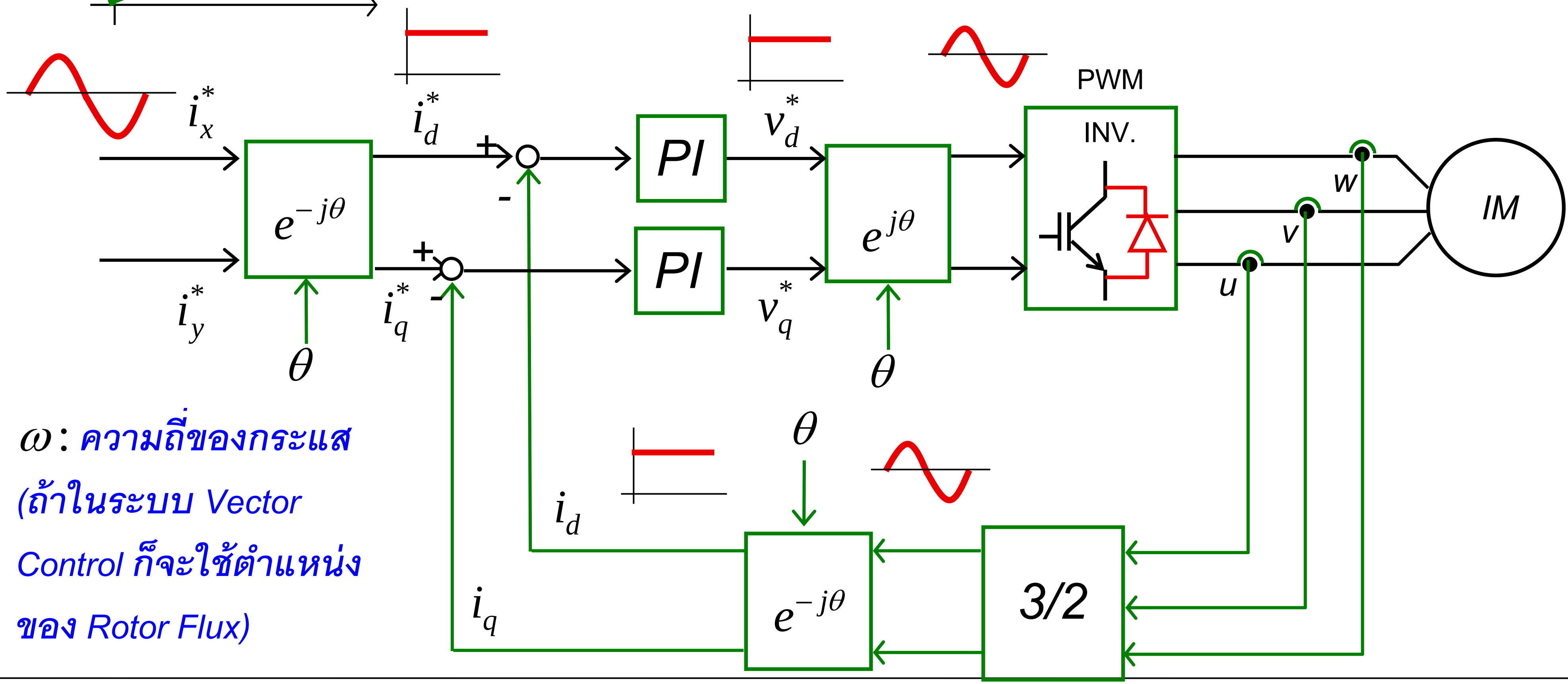
✘ : PI controller กำจัด steady-state error ได้เฉพาะกรณี i^* = DC

PI Current Control on Synchronously Rotating Reference Frame

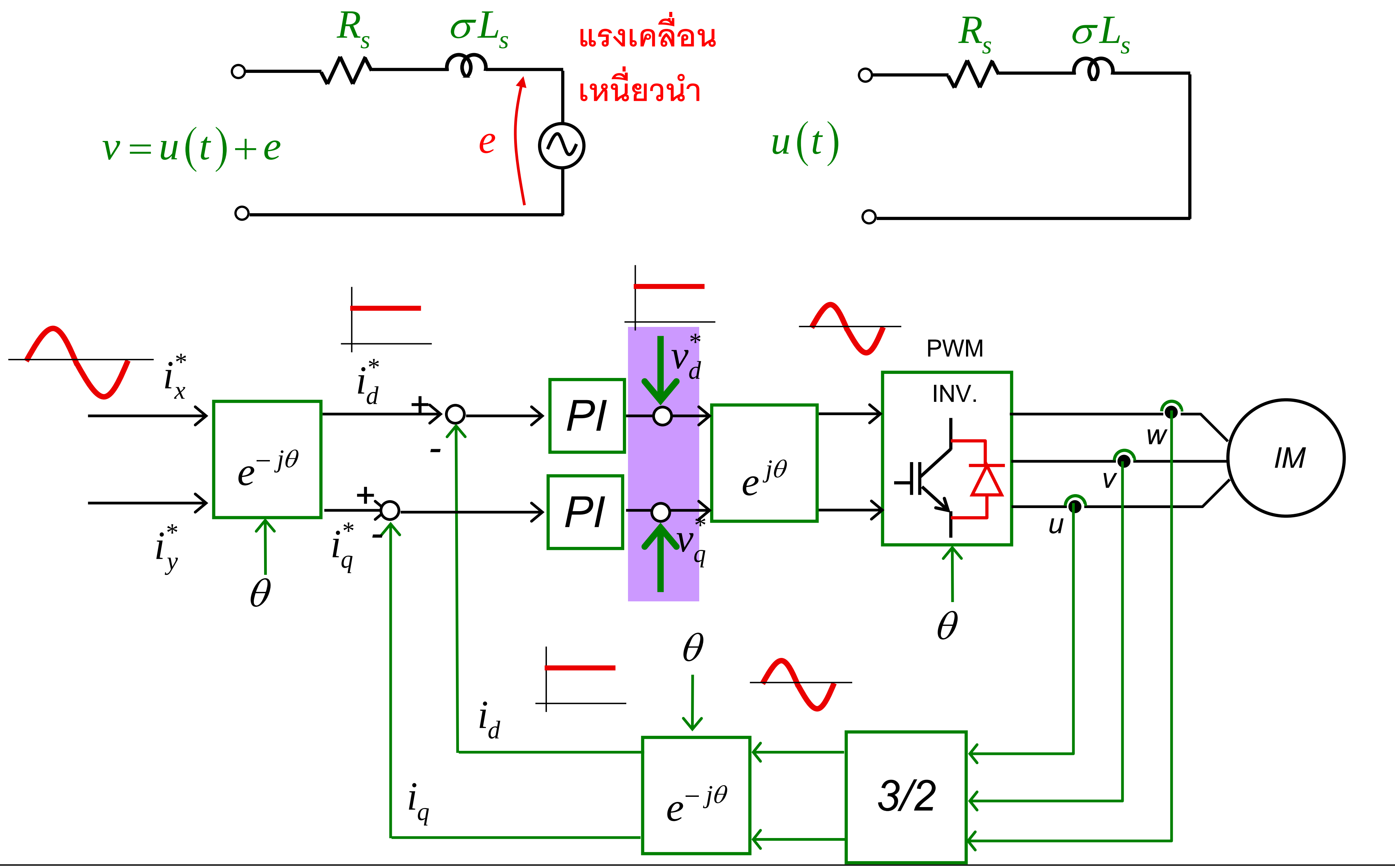


– $\underline{i}^*$ จะกลายเป็น DC Component บนแกนอ้างอิงหมุน

∴ steady-state error =0 !!



ω: ความถี่ของกระแส (ถ้าในระบบ Vector Control ก็จะใช้ตำแหน่งของ Rotor Flux)


R_s
σL_s
แรงเคลื่อน
เหนี่ยวนำ
$v = u(t) + e$
e
R_s
σL_s
$u(t)$
i_x^*
i_y^*
$e^{-j\theta}$
θ
i_d^*
i_q^*
PI
PI
v_d^*
v_q^*
$e^{j\theta}$
PWM
INV.
θ
IM
w
v
u
θ
i_d
i_q
$e^{-j\theta}$
3/2