Electric Vehicle (EE60082)

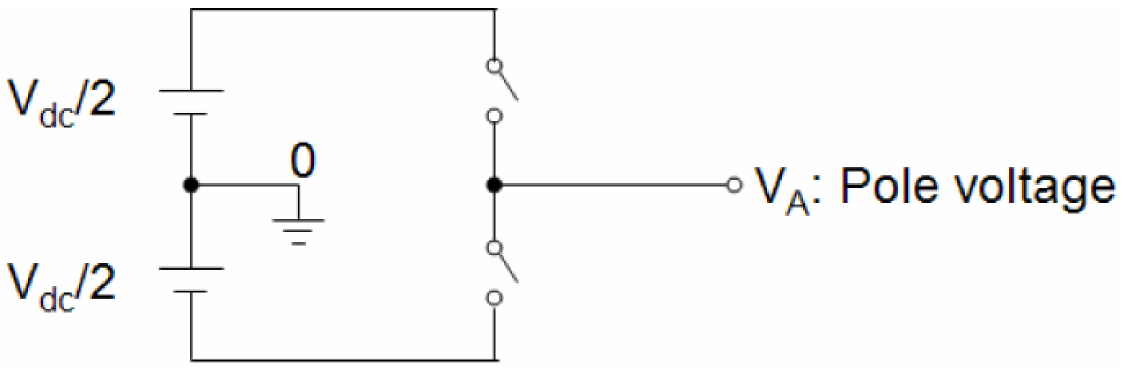
Lecture 9: Motor drive for EV (part 5)

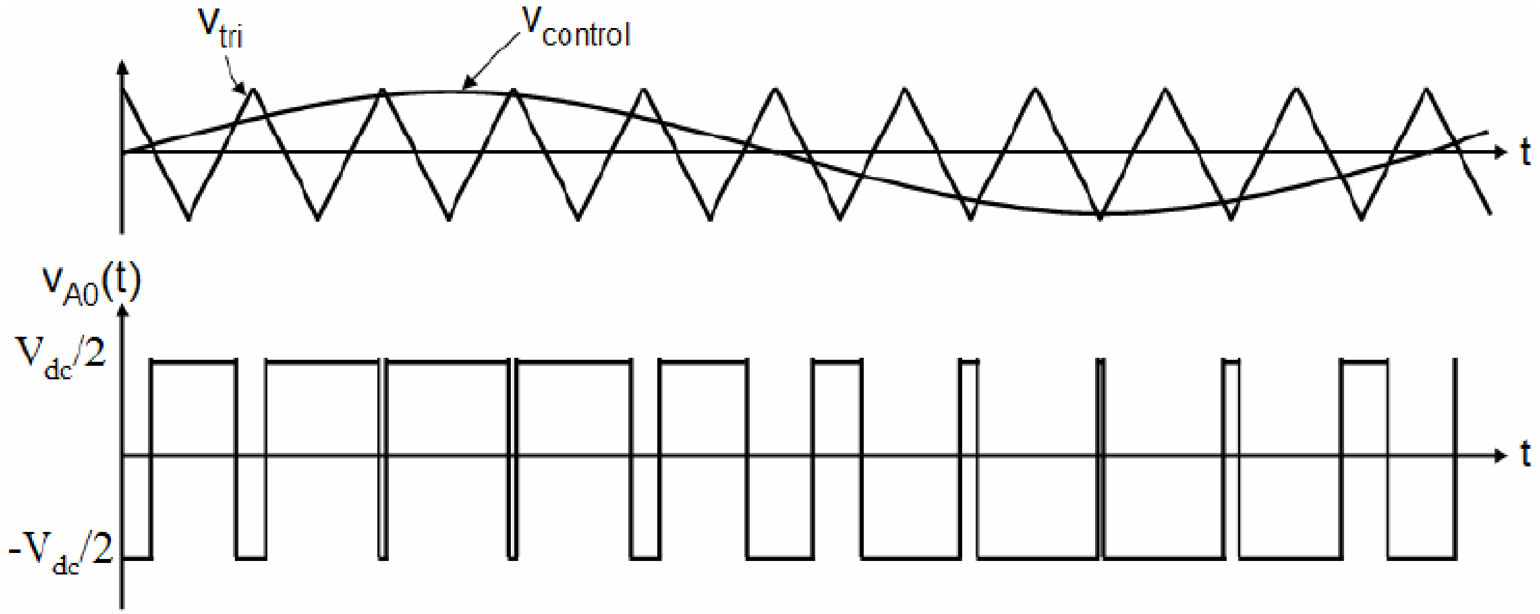
DR. SHIMUL K. DAM

ASSISTANT PROFESSOR,
DEPARTMENT OF ELECTRICAL ENGINEERING,
INDIAN INSTITUTE OF TECHNOLOGY (IIT), KHARAGPUR.

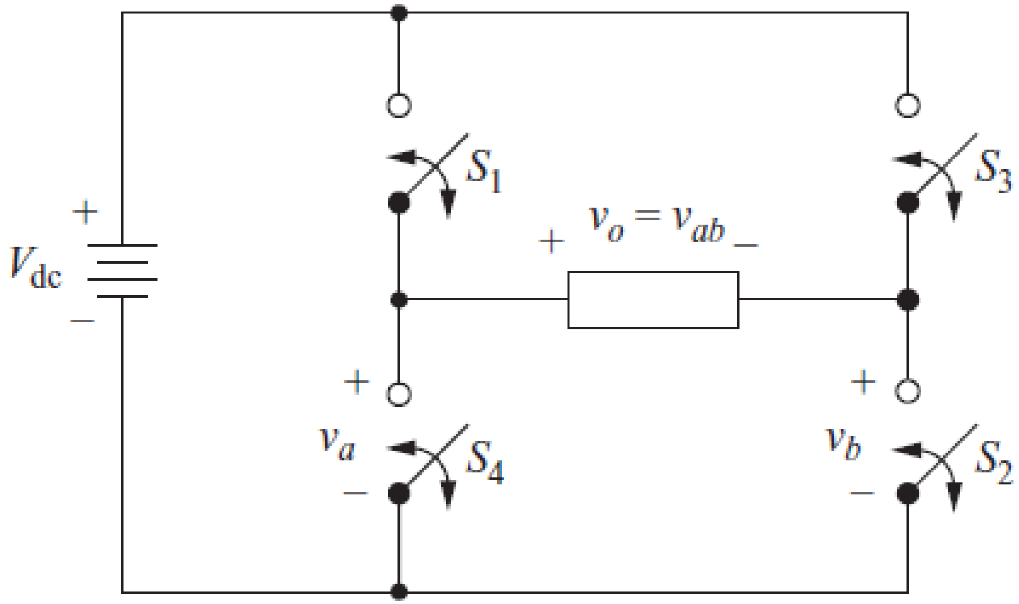
AC sources for AC Machines

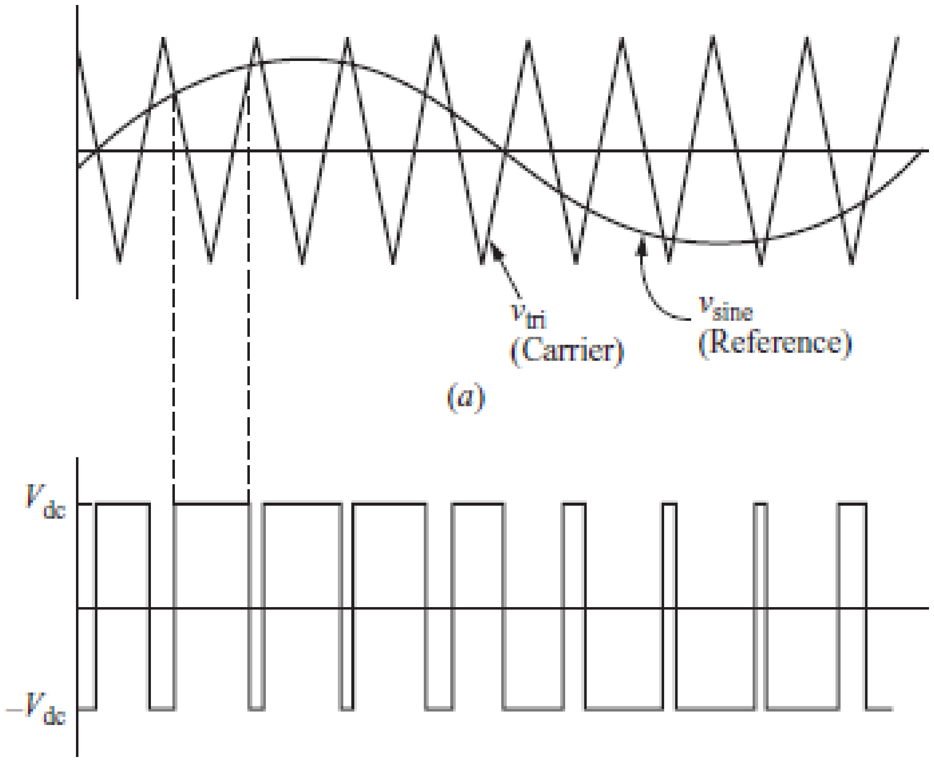
Generation of AC voltage(recap)





AC generation with H-bridge (recap)

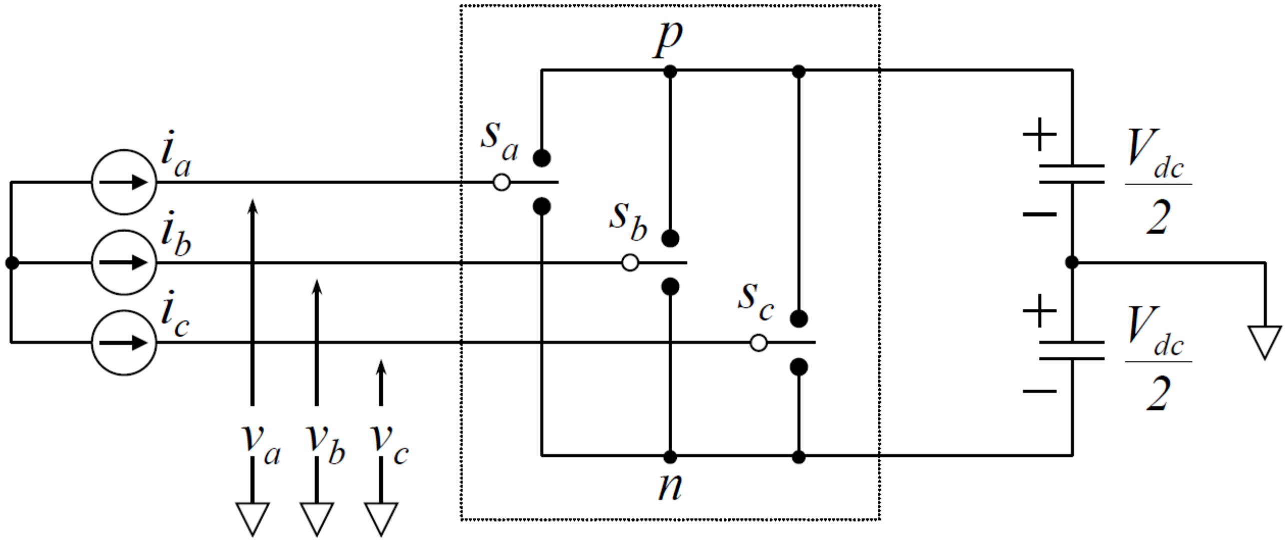


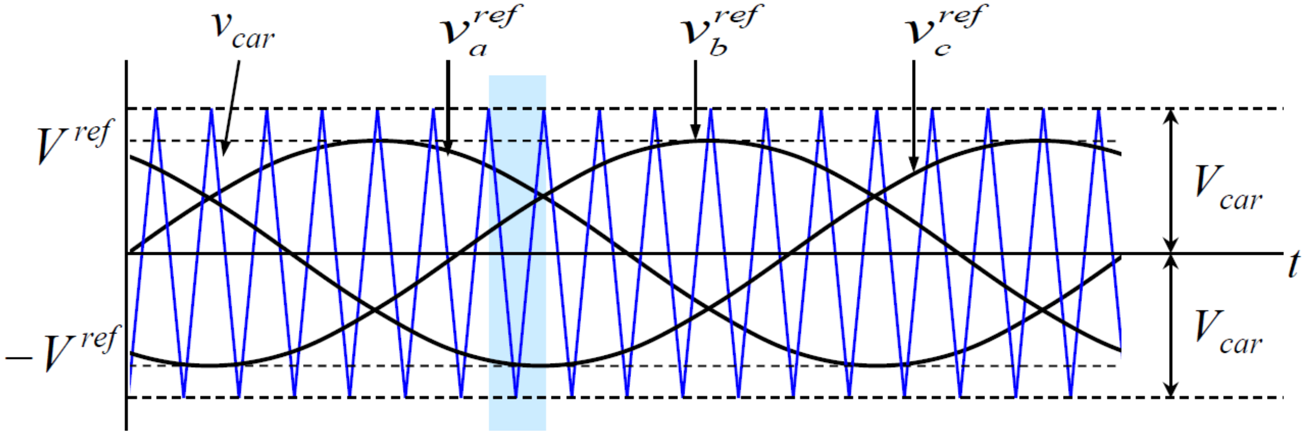


(a)

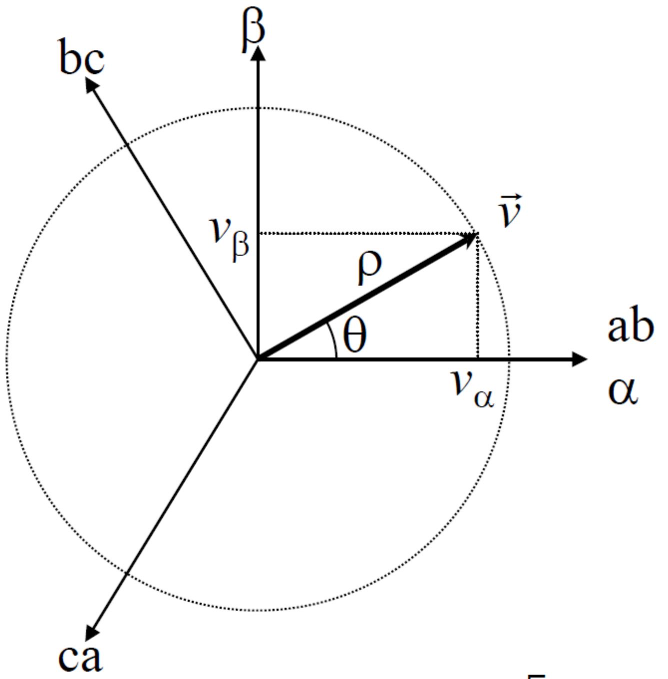
(b)

Three-phase voltage generation (recap)





Clarke's Transformation (recap)



$$T_{\alpha\beta/abc} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

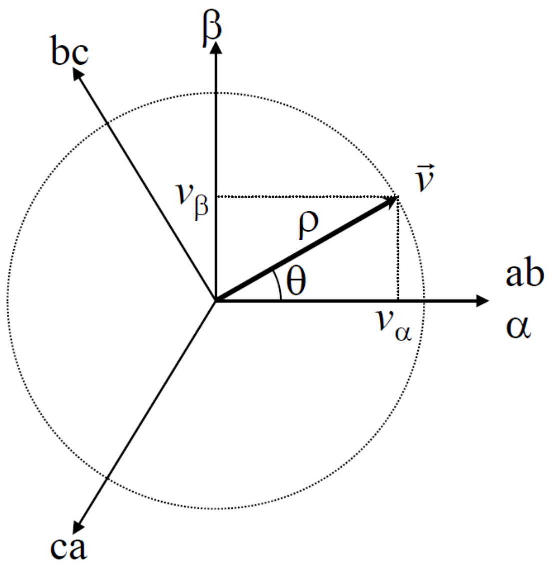
- A bit of history
  - Edith Clarke (1883-1959)
    - The first professional woman electrical engineer in US
    - first female professor of electrical engineering
    - first woman to deliver a paper at the *American Institute of Electrical Engineers (AIEE)*
    - first woman named as a fellow of AIEE

Space vector (recap)

$$T_{\alpha\beta/abc} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

$$\vec{v} = \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} = \begin{bmatrix} V_m \cos(\omega t) \\ V_m \cos(\omega t - 2\pi/3) \\ V_m \cos(\omega t + 2\pi/3) \end{bmatrix}$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = T_{\alpha\beta/abc} \cdot \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}$$

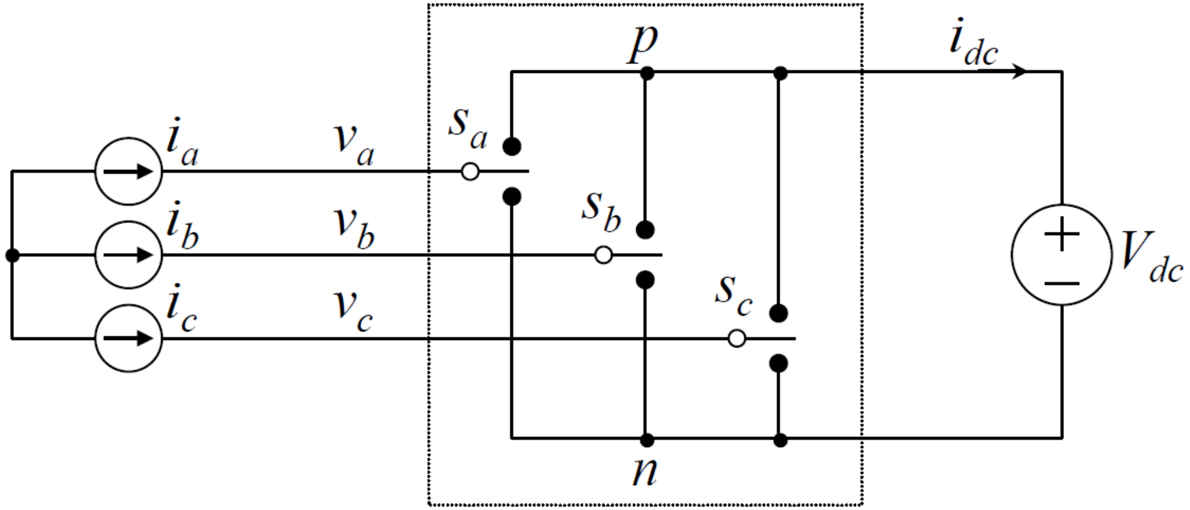


$$\vec{v} = \rho \cdot e^{j\theta}$$

$$\rho = \sqrt{v_\alpha^2 + v_\beta^2} \qquad \theta = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right)$$

$$\rho = \sqrt{\frac{3}{2}} \cdot V_m \,, \quad \theta = \omega t$$

Switching states (recap)



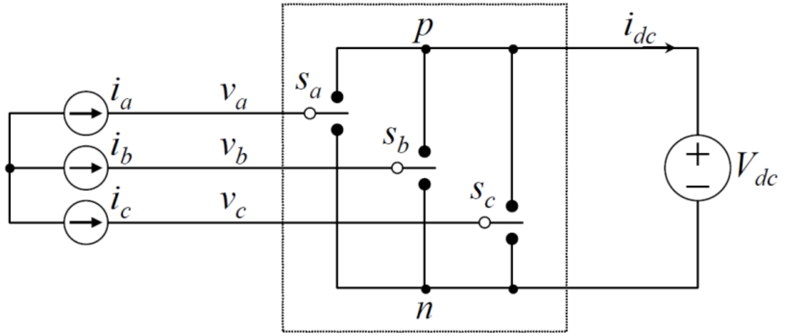
s_a	s_b	s_c	Switching state
0	0	0	*nnn*
0	0	1	*nnp*
0	1	0	*npn*
0	1	1	*npp*
1	0	0	*pnn*
1	0	1	*pnp*
1	1	0	*ppn*
1	1	1	*ppp*

Switching state	i_{dc}	v_{ab}	v_{bc}	v_{ca}
nnn	0	0	0	0
nnp	i_c	0	$-V_{dc}$	V_{dc}
npn	i_b	$-V_{dc}$	V_{dc}	0
npp	i_b+i_c	$-V_{dc}$	0	V_{dc}
pnn	i_a	V_{dc}	0	$-V_{dc}$
pnp	i_a+i_c	V_{dc}	$-V_{dc}$	0
ppn	i_a+i_b	0	V_{dc}	$-V_{dc}$
ppp	$i_a+i_b+i_c$	0	0	0

Space vector for state pnn (recap)

Switch state: pnn

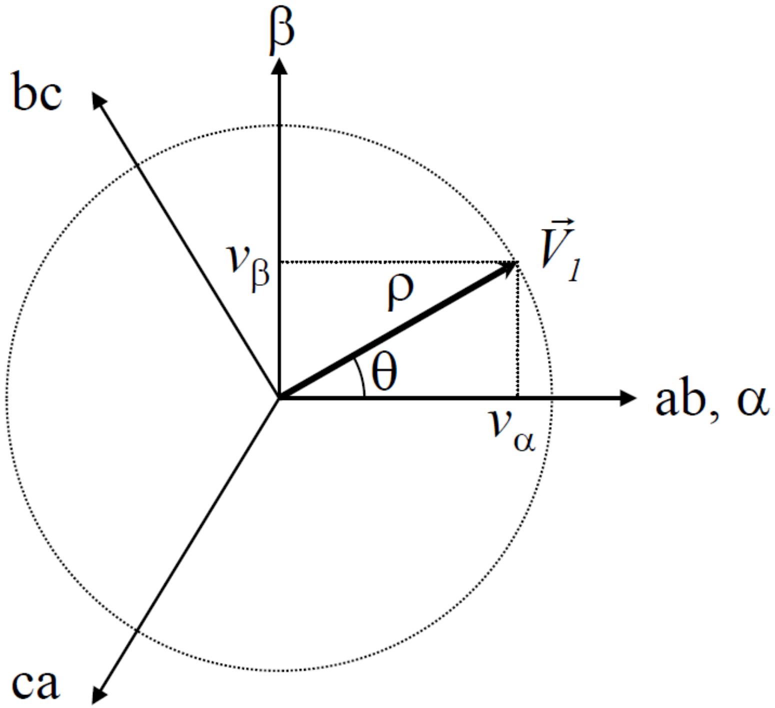
$$\vec{V}_{pnn} = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}_{pnn} = T_{\alpha\beta/abc} \cdot \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}_{pnn} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_{dc} \\ 0 \\ -V_{dc} \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{3}{2}} \cdot V_{dc} \\ \sqrt{\frac{1}{2}} \cdot V_{dc} \end{bmatrix}$$



$$\vec{V}_{pnn} = \vec{V}_1 = \rho \cdot e^{j\theta}$$

$$\rho = \sqrt{2} \cdot V_{dc}$$

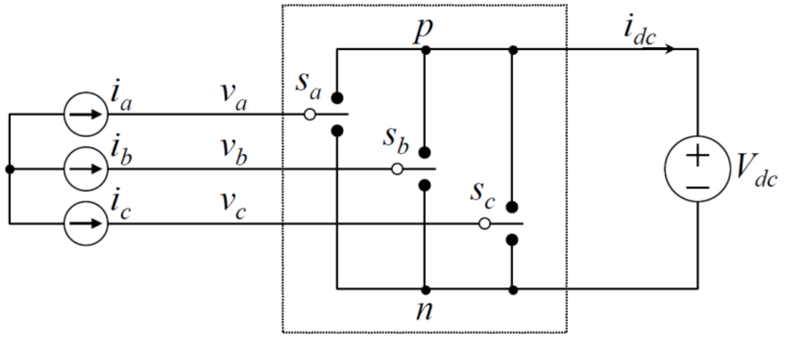
$$\theta = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right) = 30^\circ$$



Space vector for state ppn (recap)

Switch state: ppn

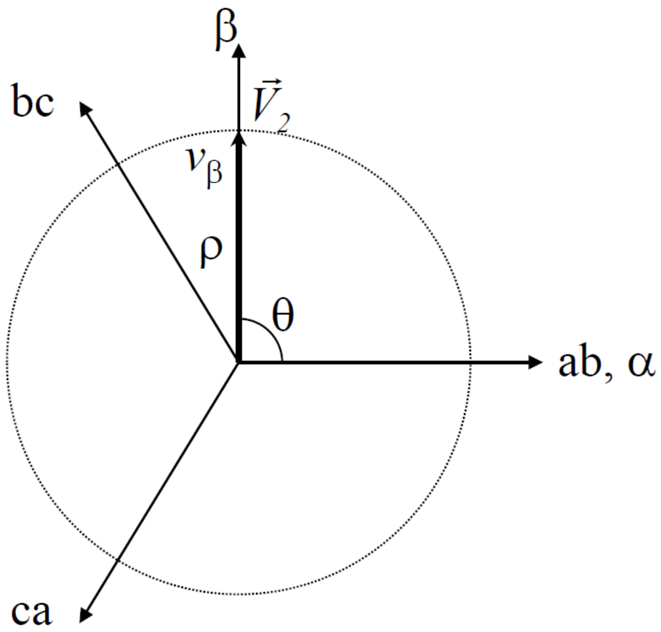
$$\vec{V}_{ppn} = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}_{ppn} = T_{\alpha\beta/abc} \cdot \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}_{ppn} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ V_{dc} \\ -V_{dc} \end{bmatrix} = \begin{bmatrix} 0 \\ \sqrt{2} \cdot V_{dc} \end{bmatrix}$$



$$\vec{V}_{ppn} = \vec{V}_2 = \rho \cdot e^{j\theta}$$

$$\rho = \sqrt{2} \cdot V_{dc}$$

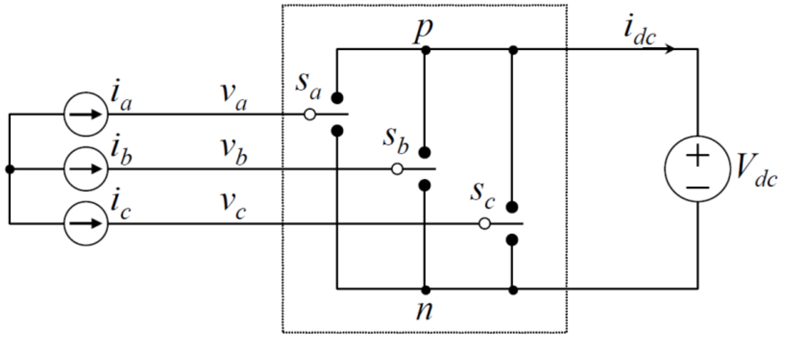
$$\theta = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right) = 90°$$



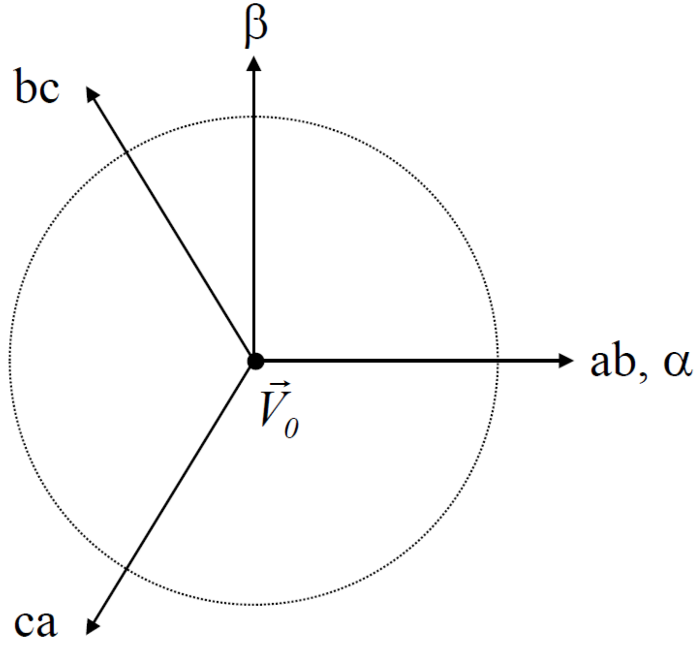
Space vector for state ppp (recap)

Switch state: ppp

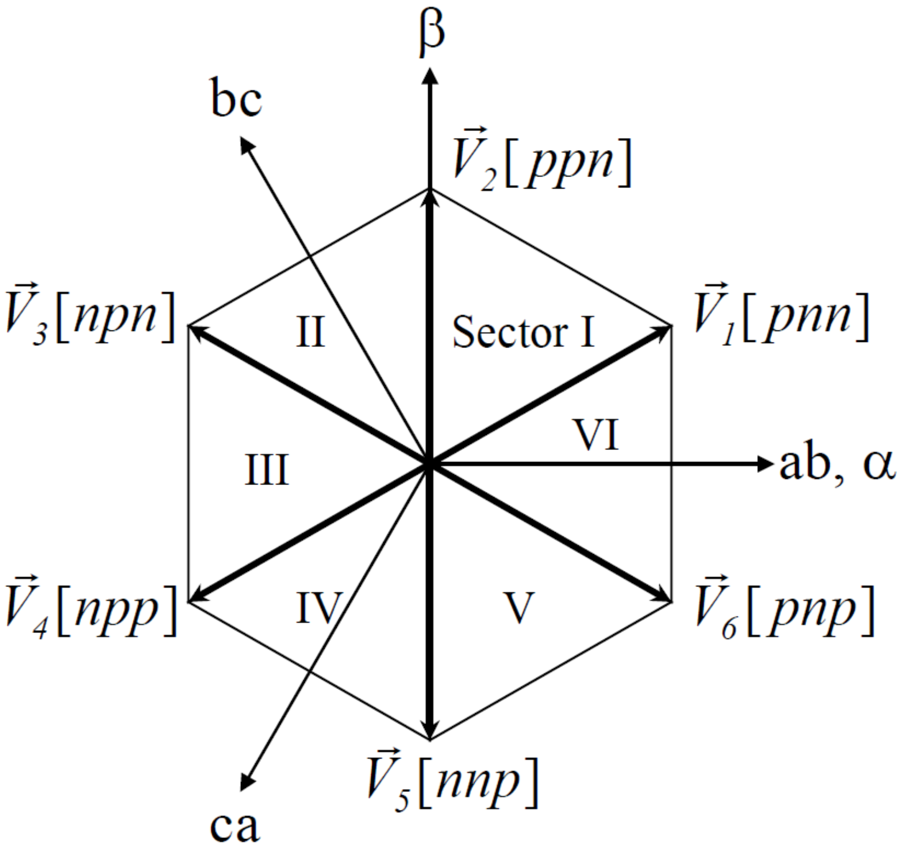
$$\vec{V}_{ppp} = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}_{ppp} = T_{\alpha\beta/abc} \cdot \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}_{ppp} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$



$$\vec{V}_{ppp} = \vec{V}_0 = 0$$



Switching State Vectors



$\vec{V}_0 = [ppp] = [nnn]$ at center point

	ρ	θ (°)
$\vec{V}_1[pnn]$	$\sqrt{2}\cdot V_{dc}$	30
$\vec{V}_2[ppn]$		90
$\vec{V}_3[npn]$		150
$\vec{V}_4[npp]$		-150
$\vec{V}_5[nnp]$		-90
$\vec{V}_6[pnp]$		-30
$\vec{V}_0[ppp]$	0	0
$\vec{V}_0[nnn]$		0

Vector synthesis (recap)

Step 1 : Choose desired switching state vectors to synthesize $\vec{V}_{ref}$

↓

Step 2 : Calculate the duty ratios of chosen switching state vectors

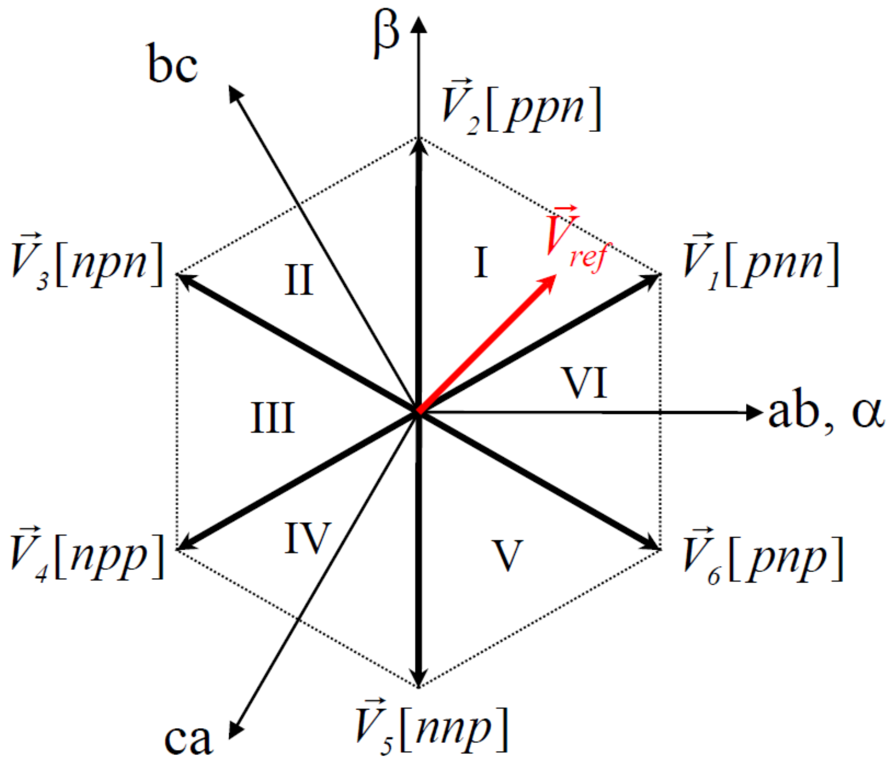
↓

Step 3 : Make the sequence of chosen switching state vectors

Vector selection (recap)

- Minimize the number of switching
- Minimize the harmonic distortion

☞ **Nearest Three Vectors (NTV)**

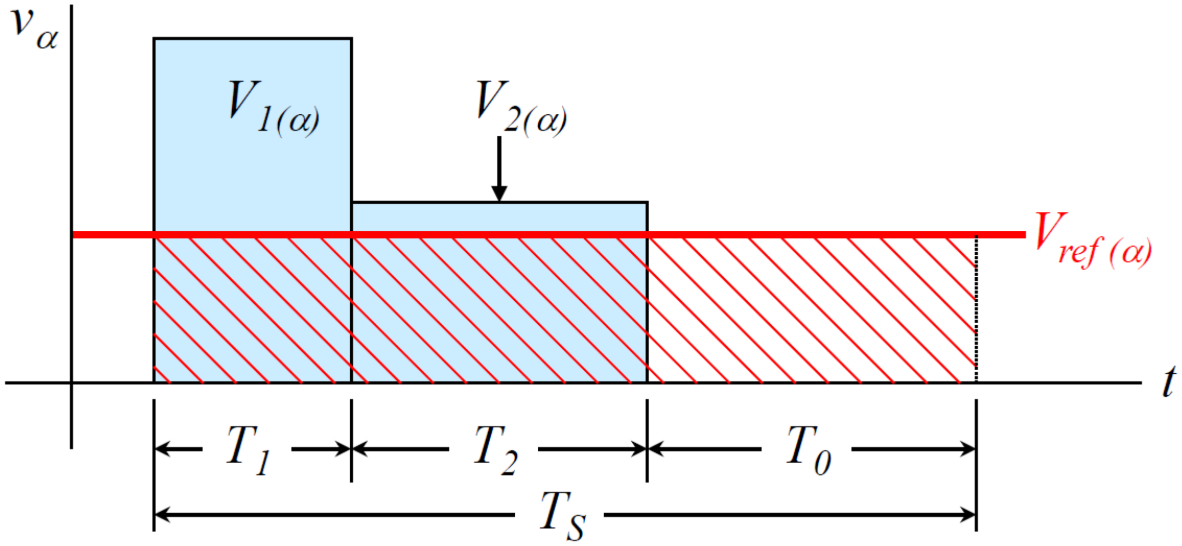


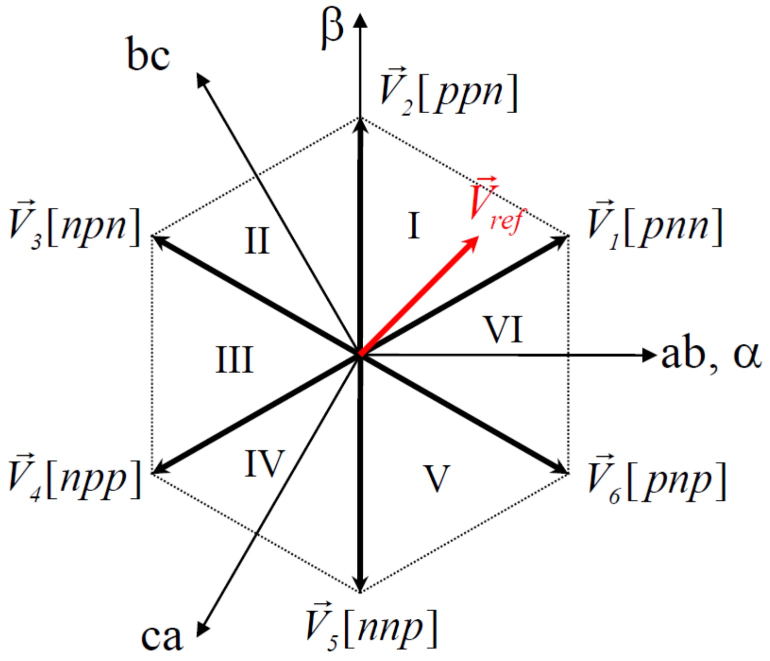
$\vec{V}_0 = [ppp] = [nnn]$ at center point

High frequency synthesis (recap)

$$\int_0^{T_S} \vec{V}_{ref}\, dt = \sum_i \left(\int_0^{T_i} \vec{V}_i\, dt \right), \qquad \sum_i T_i = T_S$$

For example $\displaystyle \int_0^{T_S} \vec{V}_{ref}\, dt = \int_0^{T_1} \vec{V}_1\, dt + \int_{T_1}^{T_1+T_2} \vec{V}_2\, dt + \int_{T_1+T_2}^{T_S} \vec{V}_0\, dt$





Total area of [light blue box] = Area of [red hatched box]

Duty ratio in sector I (recap)

From HF synthesis definition, $\int_0^{T_S} \vec{V}_{ref}\,dt = \int_0^{T_1} \vec{V}_1\,dt + \int_{T_1}^{T_1+T_2} \vec{V}_2\,dt + \int_{T_1+T_2}^{T_S} \vec{V}_0\,dt$

Assume $\vec{V}_{ref}$ is constant in T_S, $\vec{V}_{ref} \cdot T_S = \vec{V}_1 \cdot T_1 + \vec{V}_2 \cdot T_2$

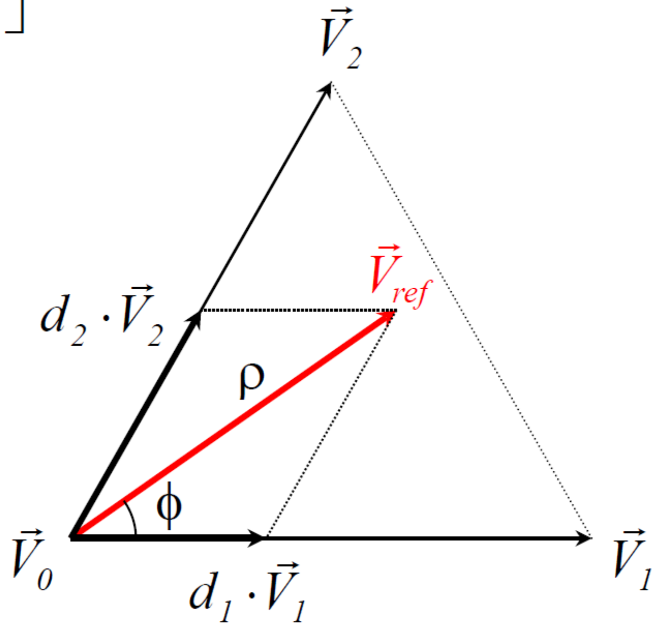
$$\rho \cdot \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix} \cdot T_S = \|V_1\| \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot T_1 + \|V_2\| \cdot \begin{bmatrix} \cos 60^\circ \\ \sin 60^\circ \end{bmatrix} \cdot T_2$$

where $\phi = \theta - 30^\circ$

$$\frac{T_1}{T_S} = d_1 = \frac{2}{\sqrt{3}} \cdot \frac{\rho}{\|V_1\|} \cdot \sin(60^\circ - \phi)$$

$$\frac{T_2}{T_S} = d_2 = \frac{2}{\sqrt{3}} \cdot \frac{\rho}{\|V_2\|} \cdot \sin\phi$$

$$d_0 = 1 - d_1 - d_2$$



Duty ratio in other sectors (recap)

☞ Other sectors have the same results of duty ratio.

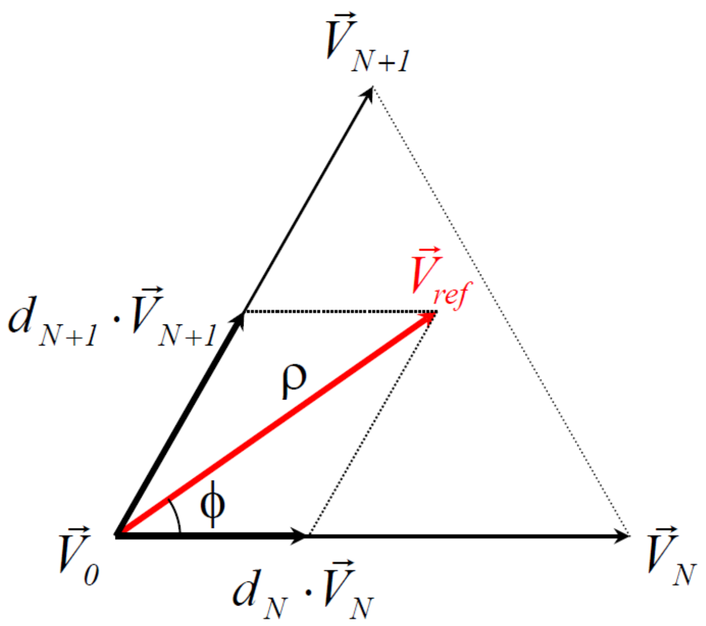
$$\frac{T_N}{T_S} = d_N = \frac{2}{\sqrt{3}} \cdot \frac{\rho}{\left\| V_N \right\|} \cdot \sin(60^\circ - \phi)$$

$$\frac{T_{N+1}}{T_S} = d_{N+1} = \frac{2}{\sqrt{3}} \cdot \frac{\rho}{\left\| V_{N+1} \right\|} \cdot \sin \phi$$

$$d_0 = 1 - d_N - d_{N+1}$$

where $\phi = \theta - (N-1) \cdot 60^\circ - 30^\circ$

$N : sector\ number\ (1 \sim 6)$



$$\vec{V}_{ref\,(steady-state)} = \rho \cdot e^{j\theta} = \sqrt{\frac{3}{2}} \cdot V_m \cdot e^{j\omega t}$$

Modulation index (recap)

For all the switching state vectors, $\left\|V_N\right\| = \sqrt{2} \cdot V_{dc}$ and $\rho = \sqrt{\frac{3}{2}} \cdot V_m$

$$d_N = \frac{V_m}{V_{dc}} \cdot \sin(60^\circ - \phi)$$

$$d_{N+1} = \frac{V_m}{V_{dc}} \cdot \sin\phi$$

$$d_0 = 1 - d_N - d_{N+1}$$

Define the modulation index $M = \frac{V_m}{V_{dc}}$

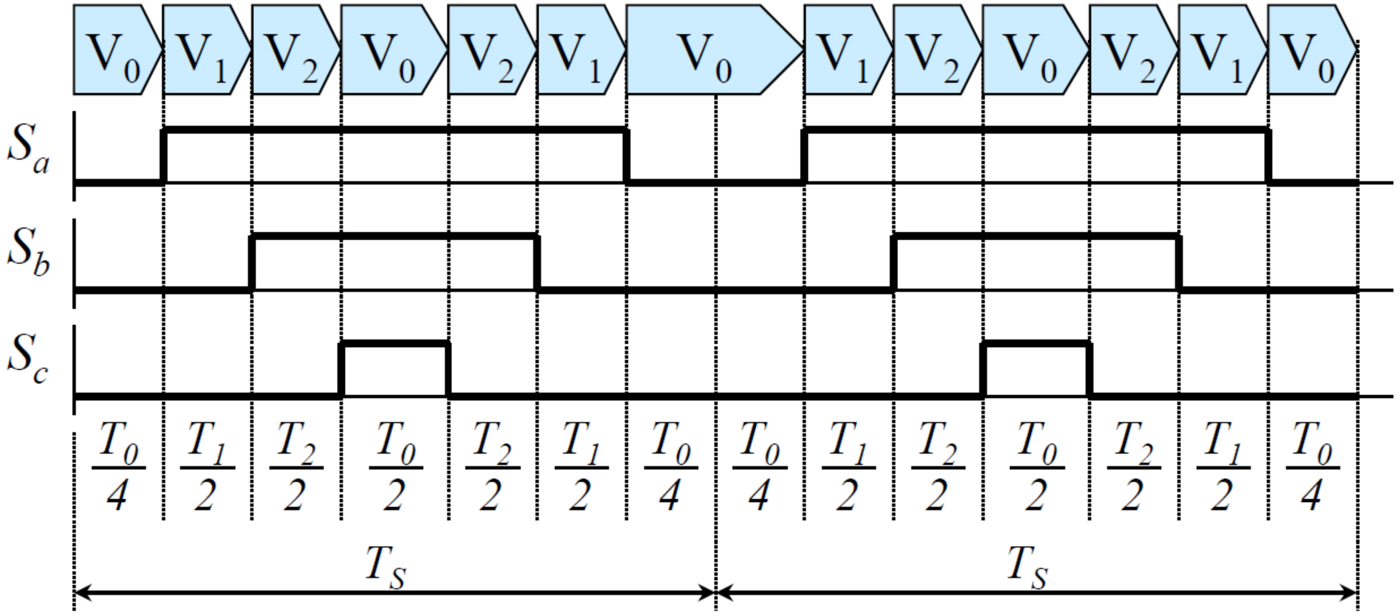
$$d_N = M \cdot \sin(60^\circ - \phi)$$

$$d_{N+1} = M \cdot \sin\phi$$

$$d_0 = 1 - d_N - d_{N+1}$$

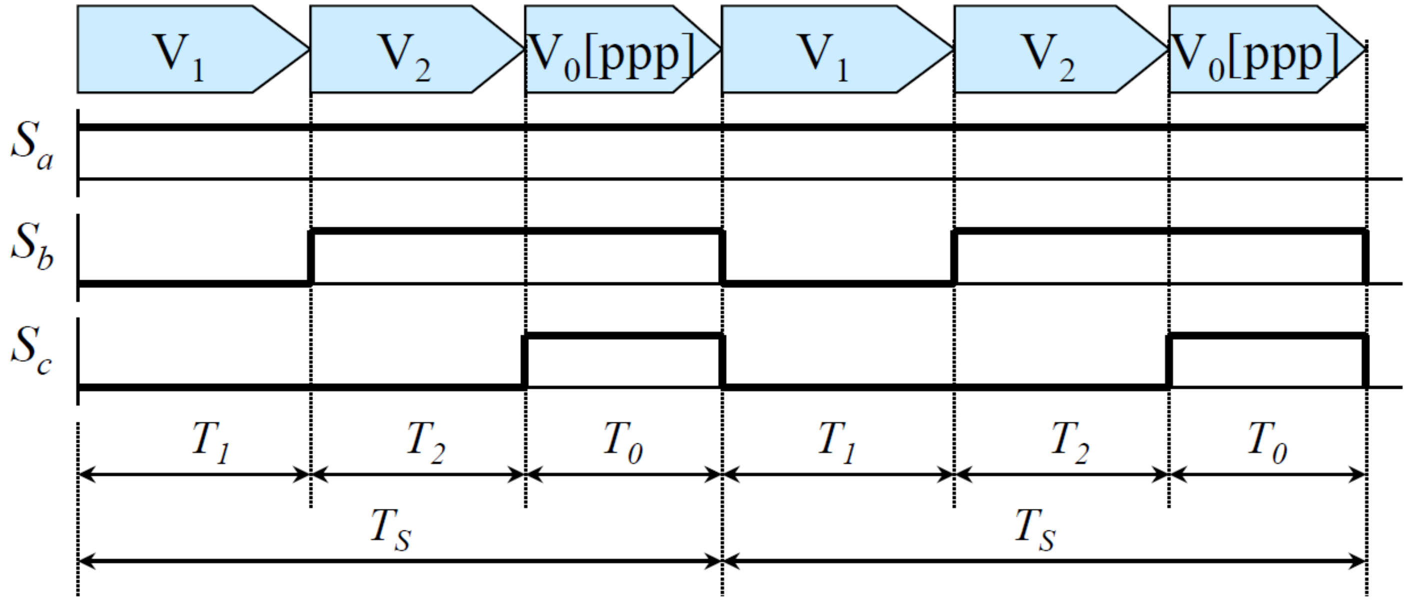
Vector sequence – 3ph, symmetric (recap)

- Use both zero switching state vectors
- Symmetrical sequence ⇨ Low THD
- Six commutations per switching cycle



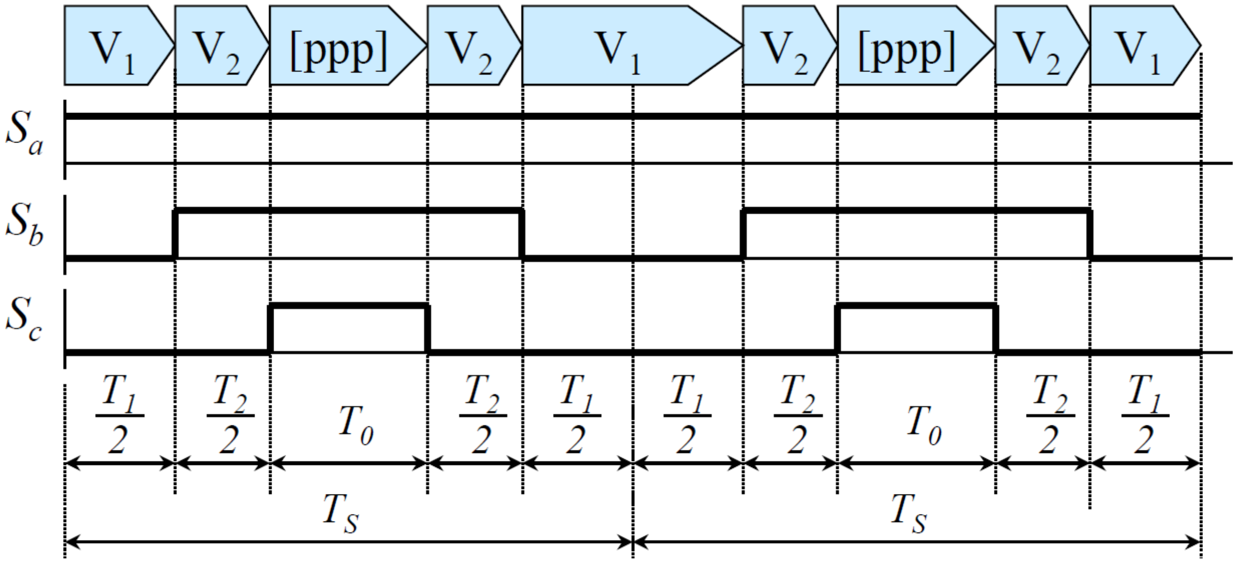
Vector sequence – 2ph, asymmetric (recap)

- Use a zero vector in one switching cycle $\begin{cases} \text{Sector I, III, V : [ppp]} \\ \text{Sector II, IV, VI : [nnn]} \end{cases}$
- Asymmetrical sequence
- Four commutations ⇒ Reduced switching losses



Vector sequence – 2ph, symmetric

- Use a zero vector in one switching cycle
  - Sector I, III, V : [ppp]
  - Sector II, IV, VI : [nnn]
- Symmetrical sequence → Low THD
- Four commutations → Reduced switching losses



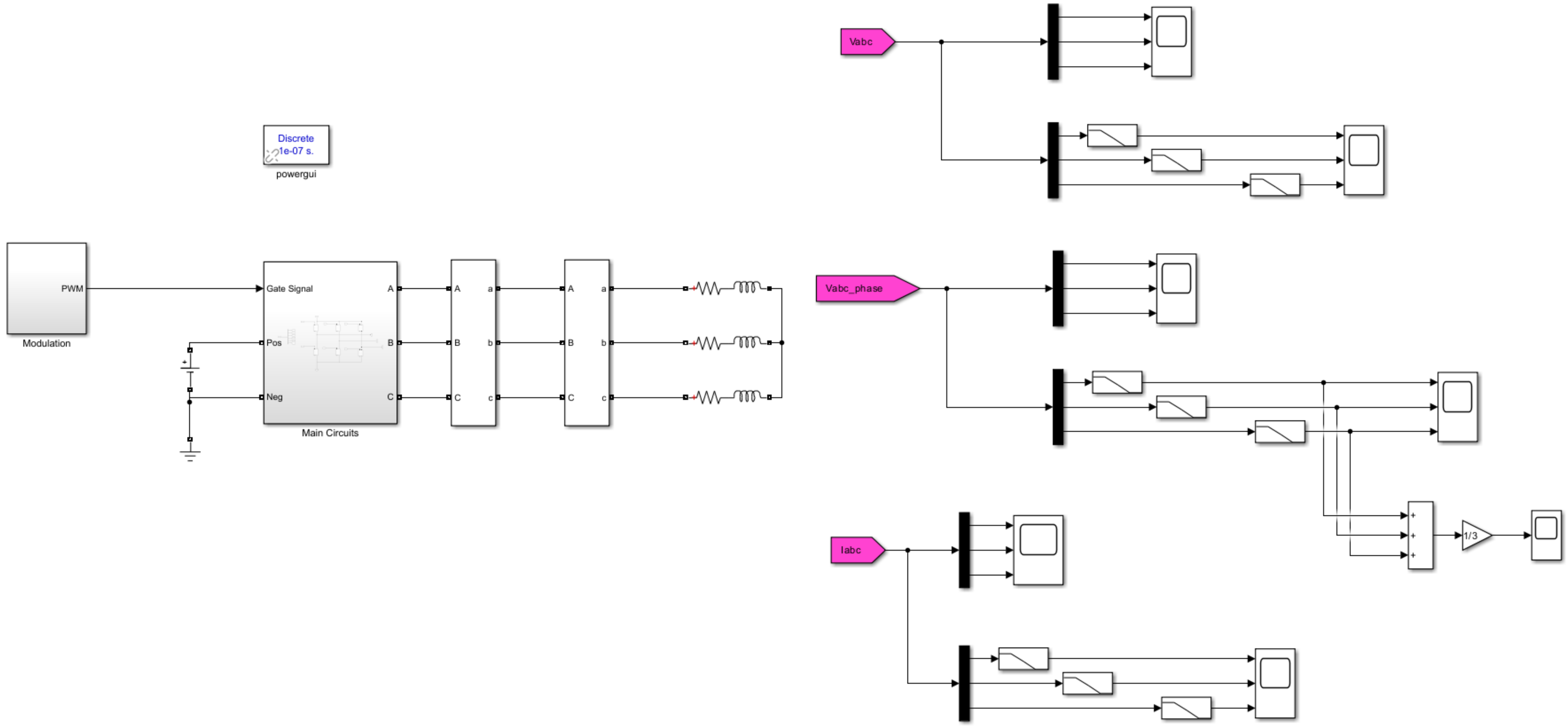
< Example in sector I >

AC volage generation with space vector

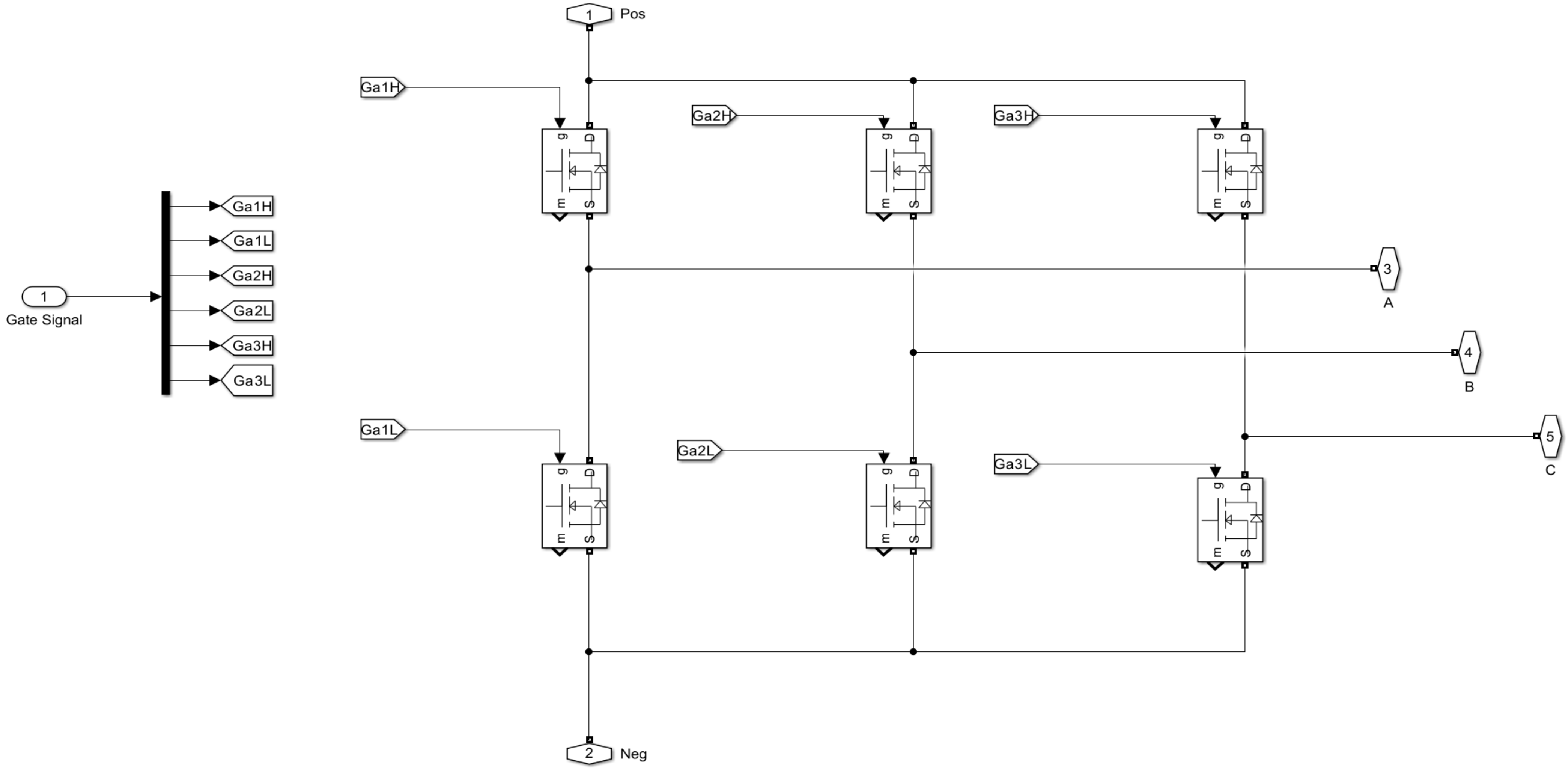
Example:

- DC voltage, Vdc = 400V
- Switching frequency, fsw = 100 kHz
- Line frequency, fline=100 Hz
- R-L load, 1Ω, 1µH

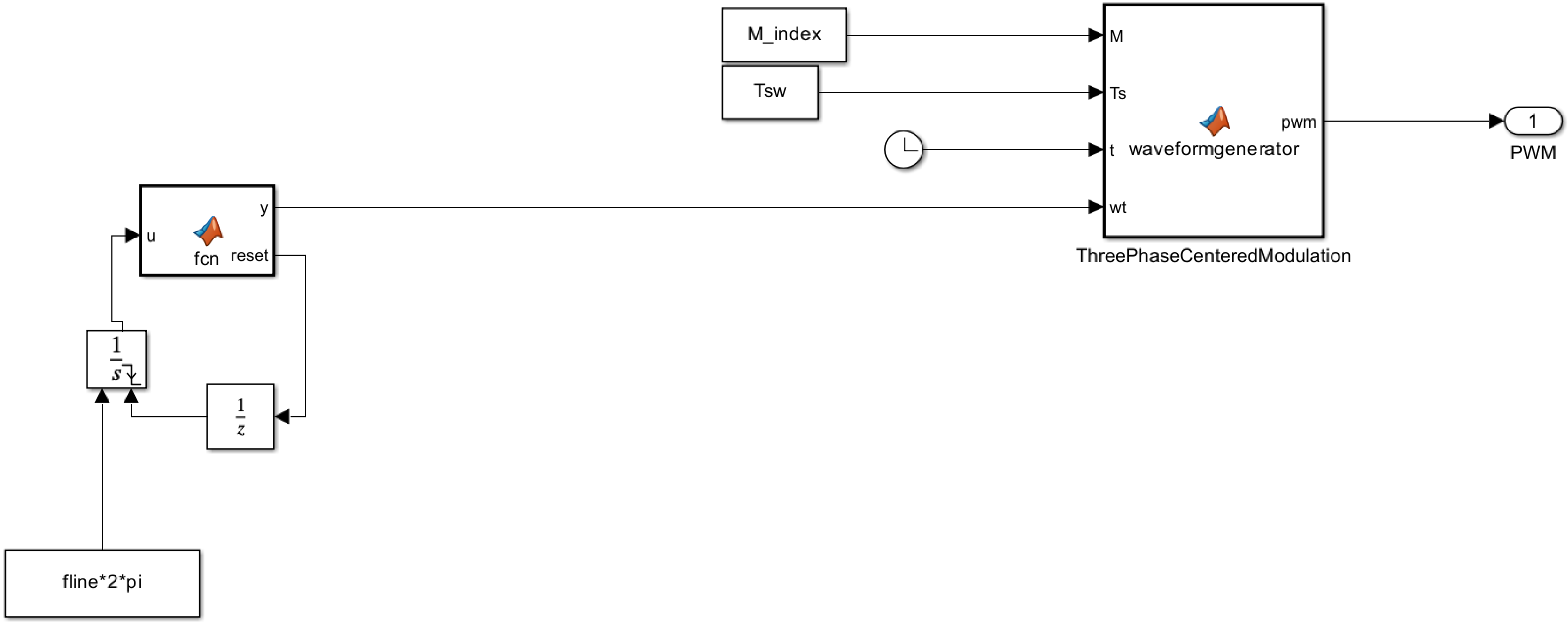
VSI simulation



VSI simulation



VSI simulation - modulation



VSI simulation - modulation

```matlab
% inputs: M=modulation index, Ts=switching period, t=simulation time,
% wt=fundamental angle
function pwm   = waveformgenerator(M,Ts,t,wt)

p=[1;0]; n=[0;1];
% find the current sector and relative angle phi

theta=rem((wt),2*pi)-pi/6;
if theta<0
    theta=theta+2*pi;
end

if theta<(pi/3)
    phi=theta; V1=[p;n;n]; V2=[p;p;n];          % sector 1
elseif theta<(2*pi/3)
    phi=theta-pi/3; V1=[p;p;n]; V2=[n;p;n];     % sector 2
elseif theta<(3*pi/3)
    phi=theta-2*pi/3; V1=[n;p;n]; V2=[n;p;p];   % sector 3
elseif theta<(4*pi/3)
    phi=theta-3*pi/3; V1=[n;p;p]; V2=[n;n;p];   % sector 4
elseif theta<(5*pi/3)
    phi=theta-4*pi/3; V1=[n;n;p]; V2=[p;n;p];   % sector 5
else
    phi=theta-5*pi/3; V1=[p;n;p]; V2=[p;n;n];   % sector 6
end

V0=[n;n;n];
V7=[p;p;p];

% find tine durations for vectors
T1=M*sin(pi/3-phi)*Ts;
T2=M*sin(phi)*Ts;
T0=Ts-T1-T2;
```

```matlab
% relative time in a switching period
tsec=rem(t,Ts);

% apply the vectors     -- for three phase centered modulation (0127-7210)
if tsec<T0/4
    pwm=V0;
elseif tsec<(T0/4+T1/2)
    pwm=V1;
elseif tsec<(T0/4+T1/2+T2/2)
    pwm=V2;
elseif tsec<(T0/4+T1/2+T2/2+T0/2)
    pwm=V7;
elseif tsec<(T0/4+T1/2+T2/2+T0/2+T2/2)
    pwm=V2;
elseif tsec<(T0/4+T1/2+T2/2+T0/2+T2/2+T1/2)
    pwm=V1;
else
    pwm=V0;
end
```

VSI simulation - modulation

Exercise:

Implement modulation with three phase symmetric (0127210) and two phase symmetric (01210) PWM

- Compare filtered voltage and current waveforms
- Compare common mode voltage waveforms
- Compare unfiltered current waveforms
- Which one is better?

Thank you!