Electric Vehicle (EE60082)

Lecture 8: Motor drive for EV (part 4)

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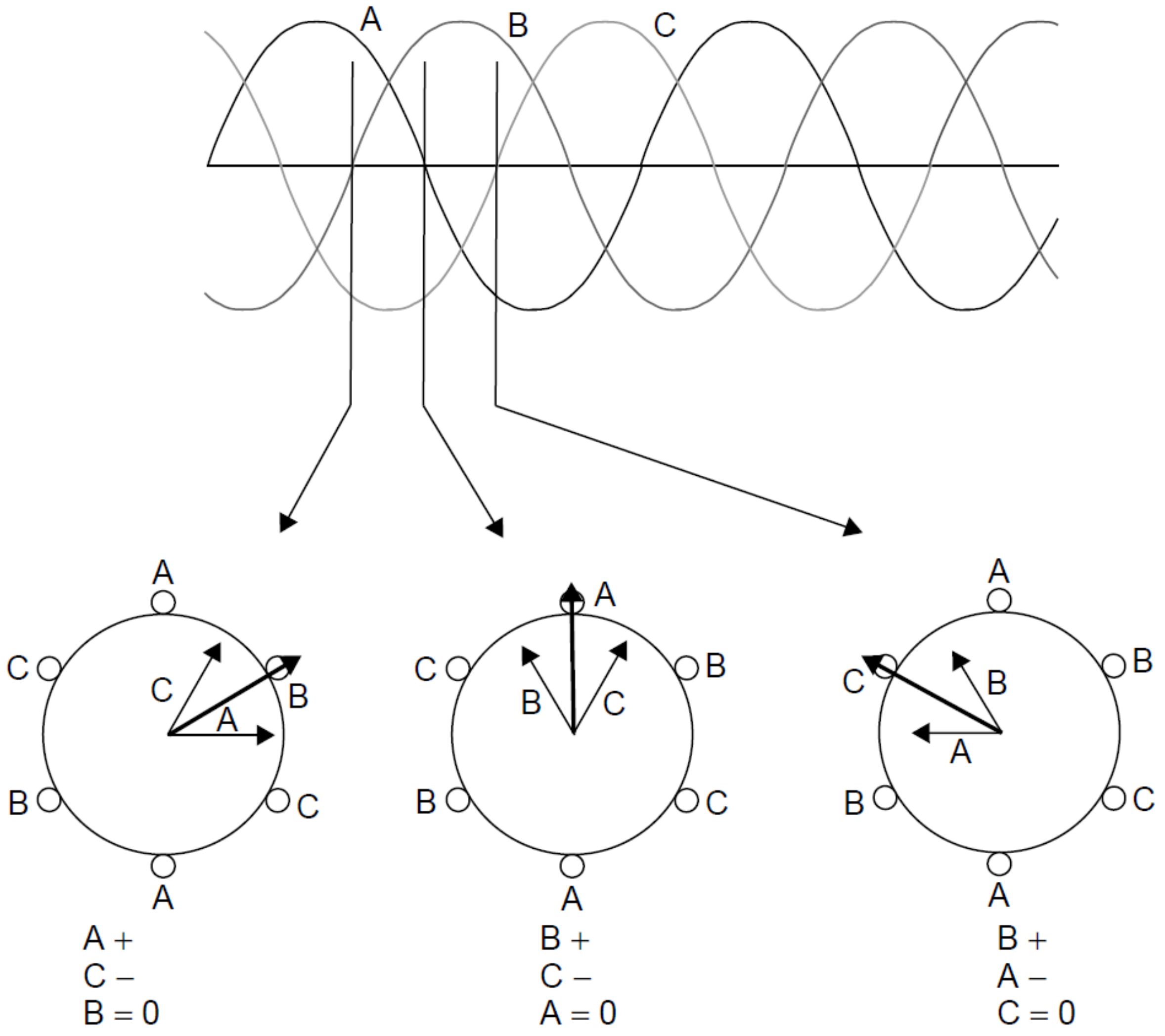
Traction motors for EV (recap)

Commonly used motors:

- Brushed DC motor
- Brushless DC motor (BLDC)
- Induction motor
- Permanent magnet synchronous motor (PMSM)
- Switched reluctance motor (SRM)

AC Machines

Rotating magnetic field (recap)



$$n_s = \frac{60f}{p}$$

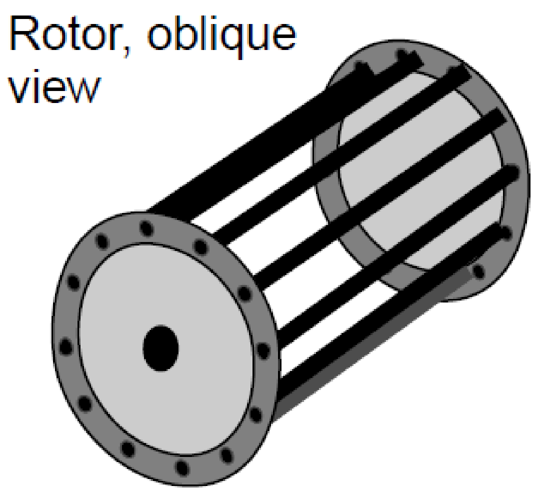
$$\omega_s = \frac{2\pi n_s}{60}$$

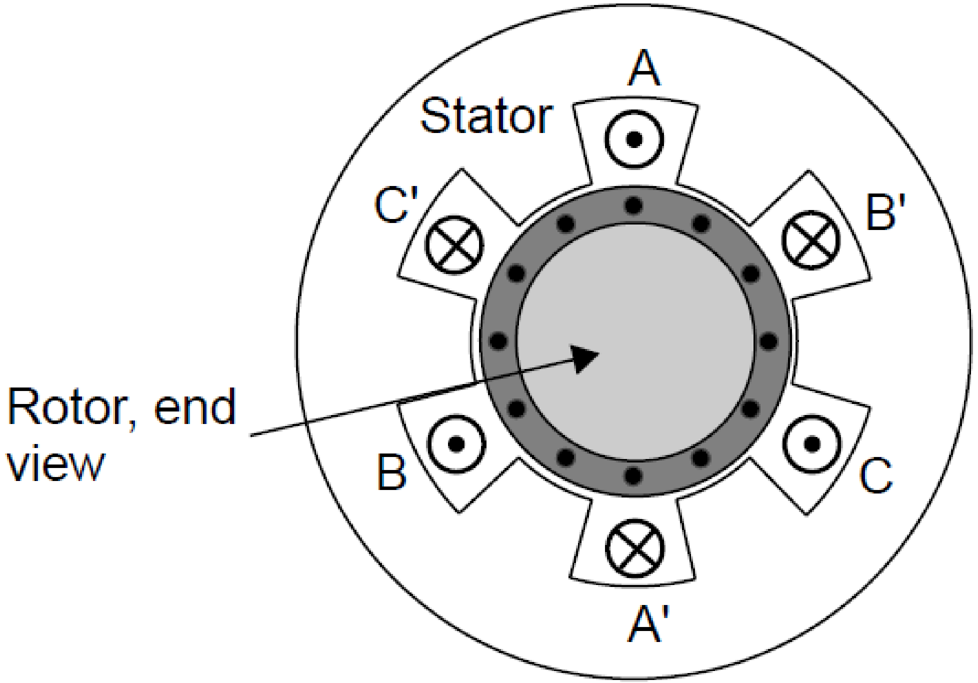
Synchronous speed (recap)

Assume the wheel radius is 0.25m. The final drive ratio is 1, i.e., gearless. f=50Hz is the rated frequency.

Pole pair	Synchronous speed (rpm)	Vehicle speed (kmph)
1	3000	282
2	1500	141
3	1000	94
4	750	70
5	600	56
6	500	47

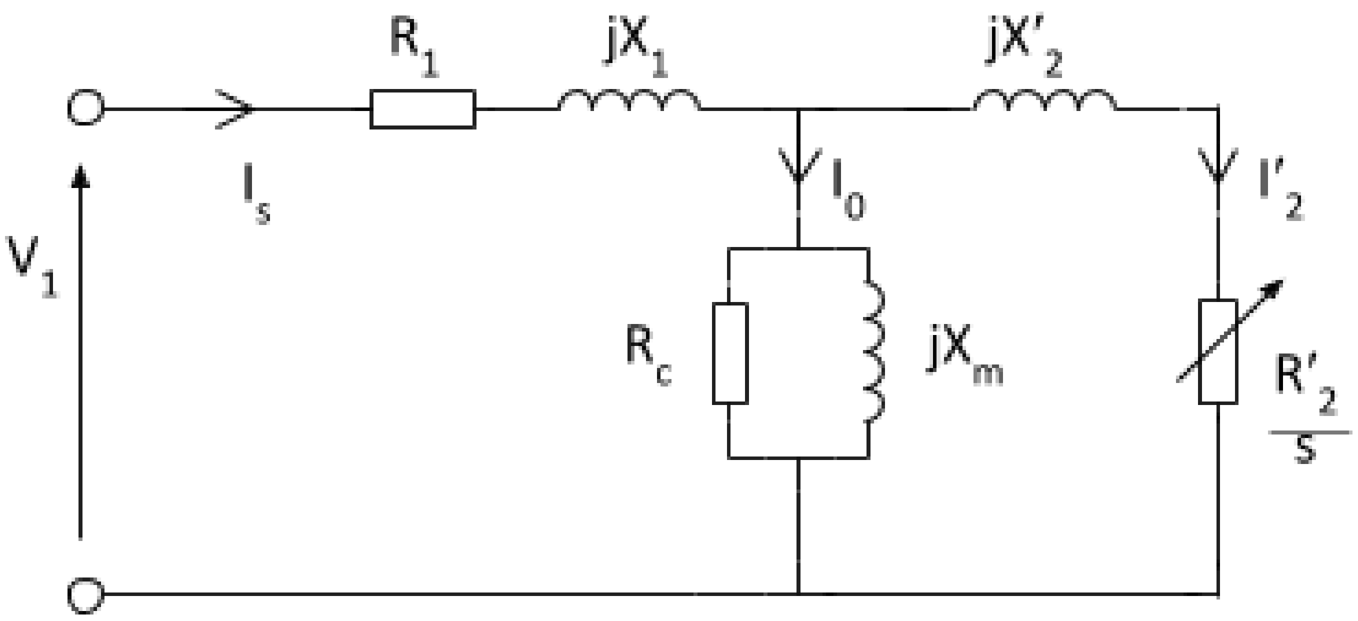
Induction motor construction (recap)





Equivalent circuit (recap)

When the load is heavy…

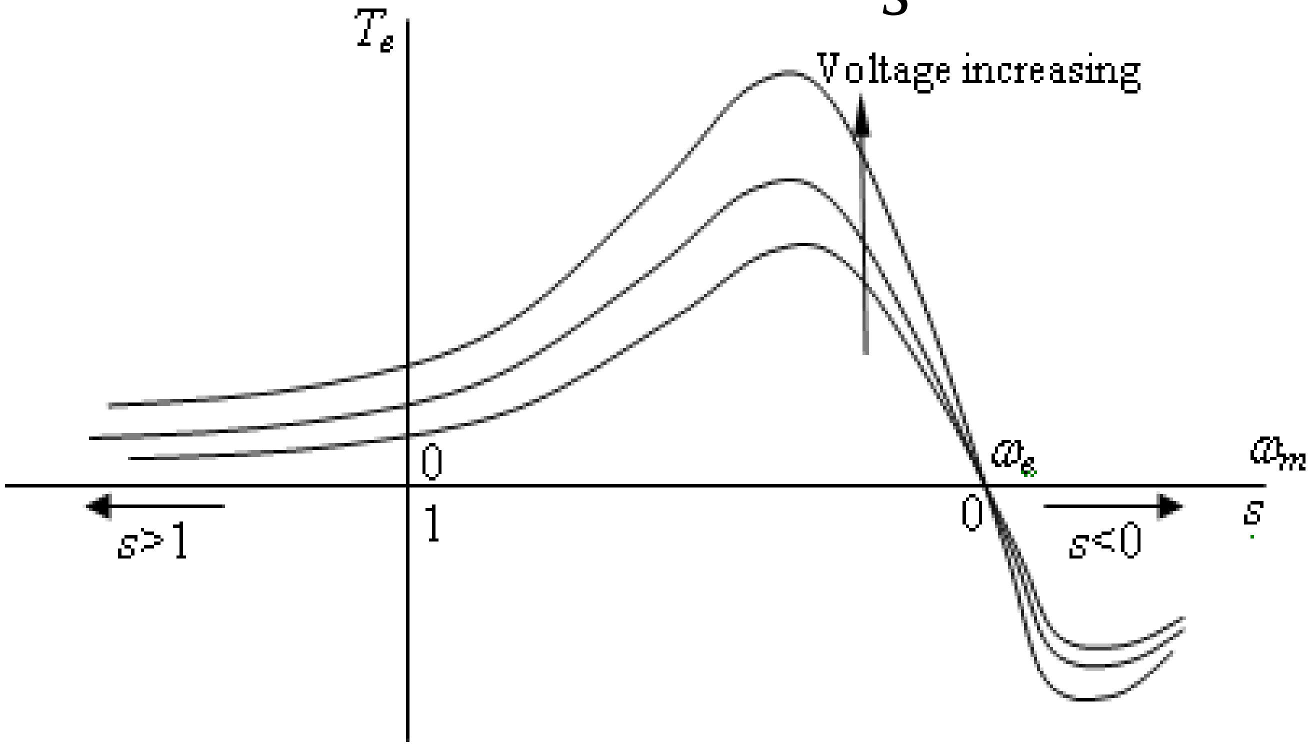


$$P_o = \left| \frac{V_1}{R_1 + R_2^{'}/s + jX_1 + jX_2^{'}} \right|^2 R_2^{'}(1-s)/s$$

$$P_o = \frac{R_2^{'}V_1^2}{(R_1 + R_2^{'}/s)^2 + (X_1 + X_2^{'})^2} \frac{1-s}{s}$$

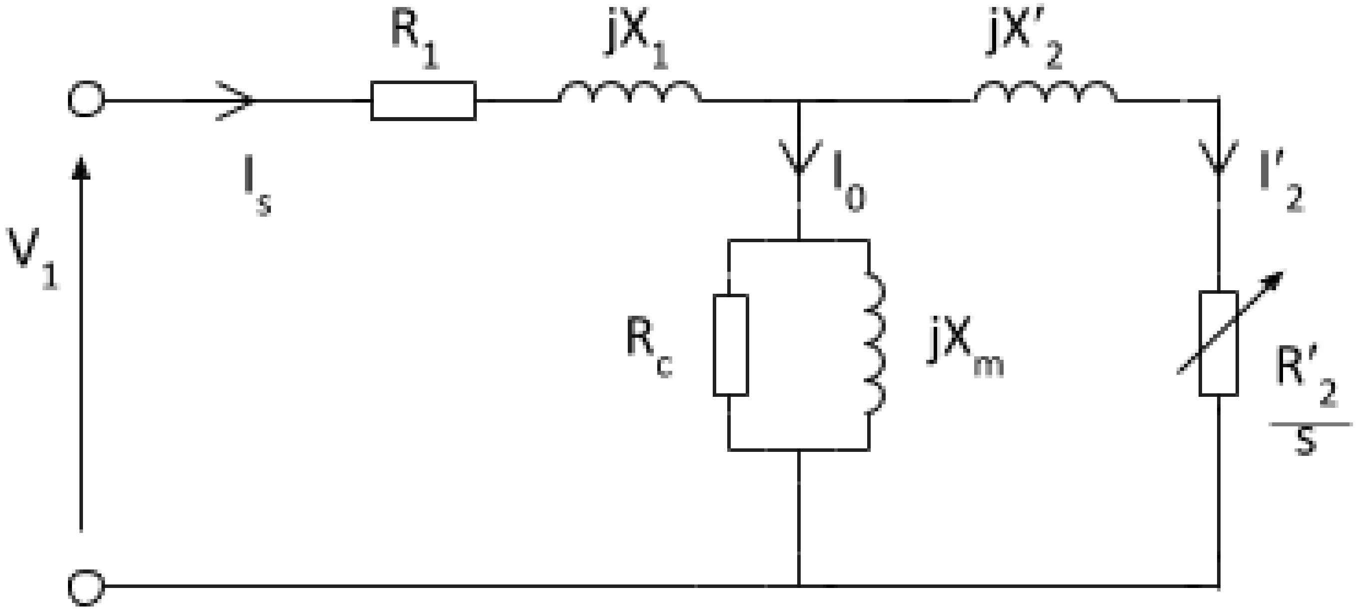
Voltage control (recap)

$$T = \frac{R_2' V_1^2}{s\{R_1^2 + (X_1 + X_2')^2\} + \frac{R_2'^{\,2}}{s} + 2R_1R_2'} \frac{1}{\omega_s}$$



V/F control

Ignore the stator loss.

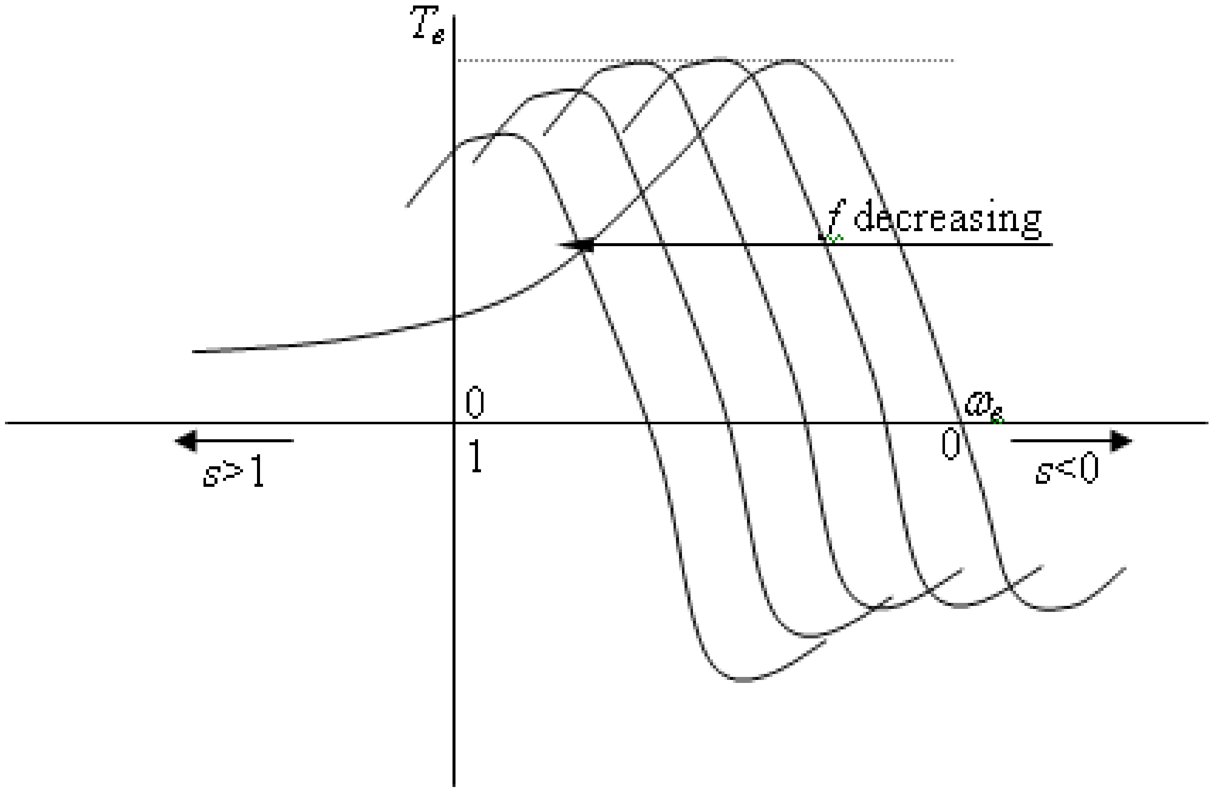


$$V_1 = j\omega_s L_m I_0 \qquad V_1 = j2\pi f_s \psi_m \qquad \frac{V_1}{f_s} = j2\pi\psi_m$$

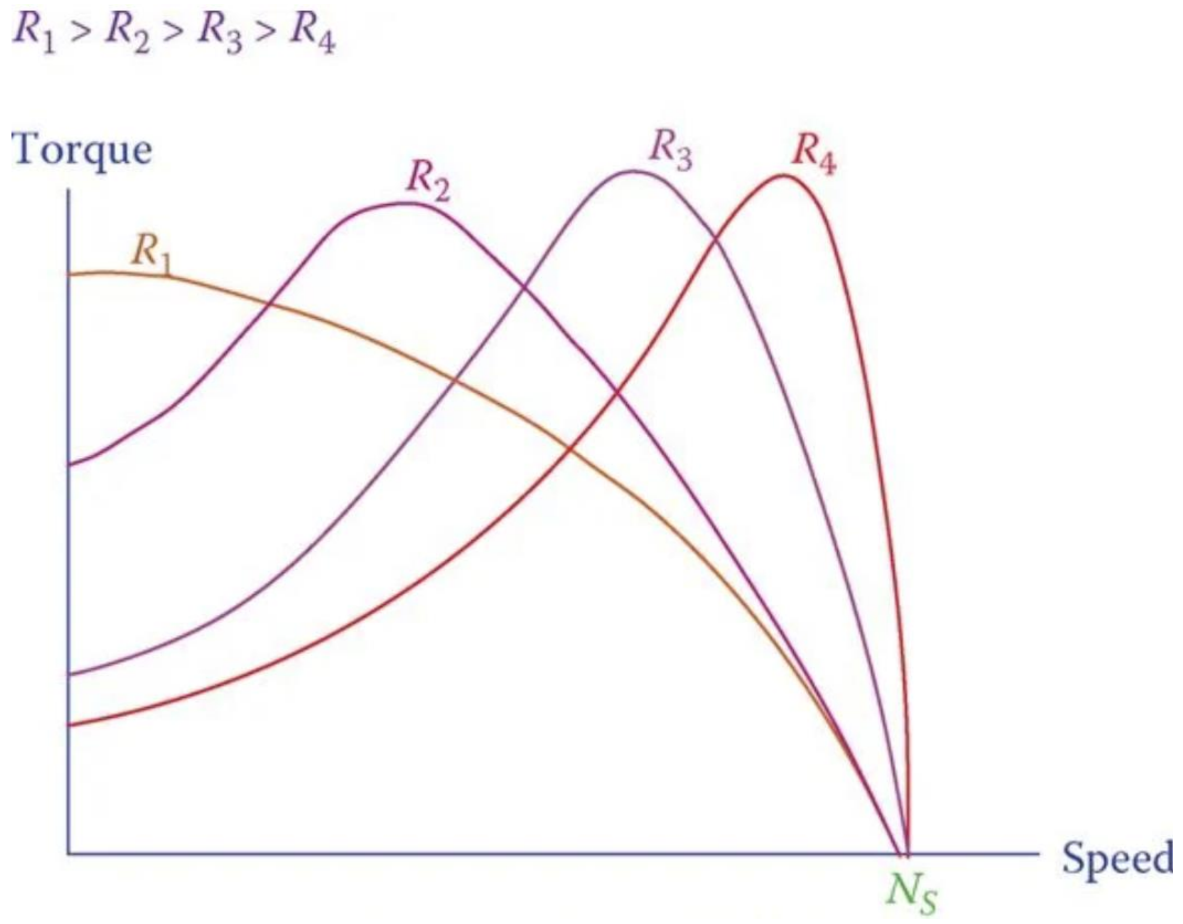
To avoid potential saturation, VVVF control is used.

Frequency control (recap)

$$T = \frac{R_2^{'} V_1^2}{s\{R_1^2 + (X_1 + X_2^{'})^2\} + \frac{R_2^{'2}}{s} + 2R_1 R_2^{'}} \frac{1}{\omega_s}$$



Design for higher starting torque (recap)

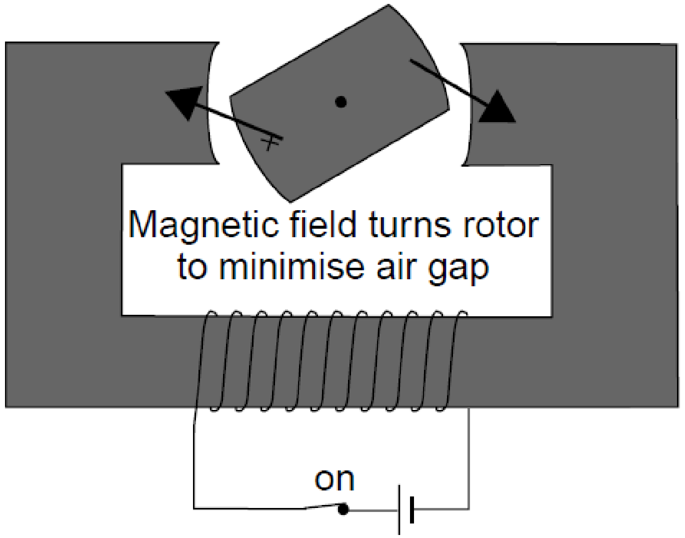


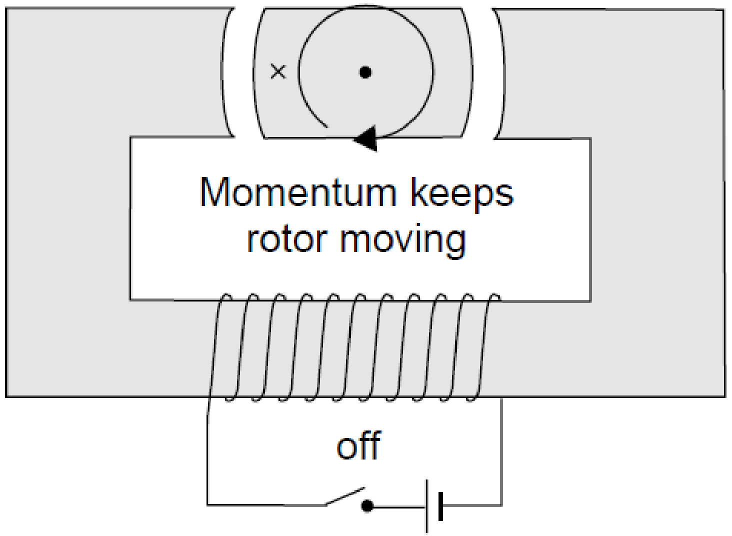
Induction motor- advantages and limitations (recap)

- Advantages:
  - Simple construction
    - harsh environments with minimal maintenance
  - no permanent magnet
    - Lower cost
    - No need for rear-earth elements
  - Self-starting
    - No special arrangement needed for starting
  - minimal noise and vibration
  - can be designed for a wide range of power outputs

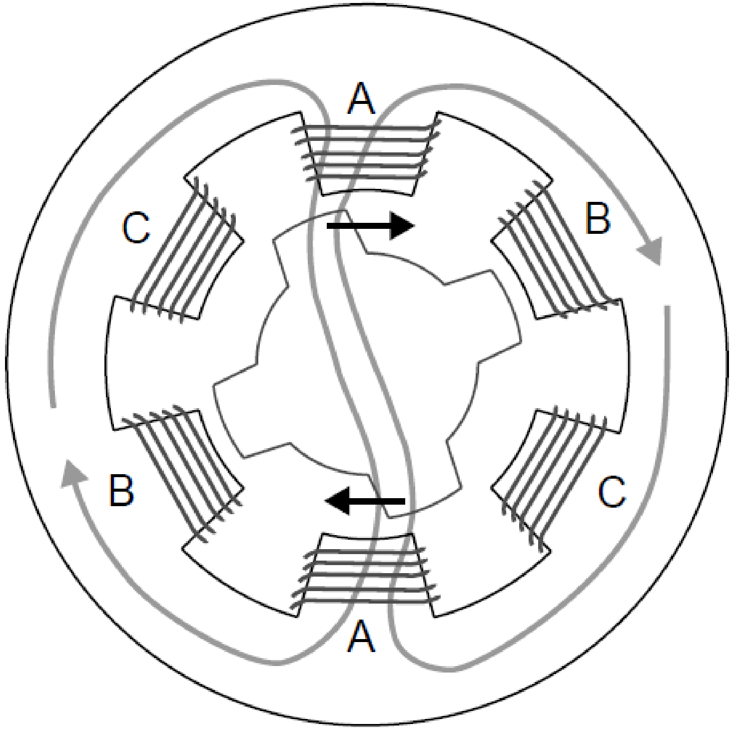
- Drawbacks:
  - Losses in rotor
    - Relatively lower efficiency
    - Heating in rotor
  - Complicated torque and speed control
    - complex controller required
  - High in-rush current
    - When DOL starter used
  - Lower starting torque

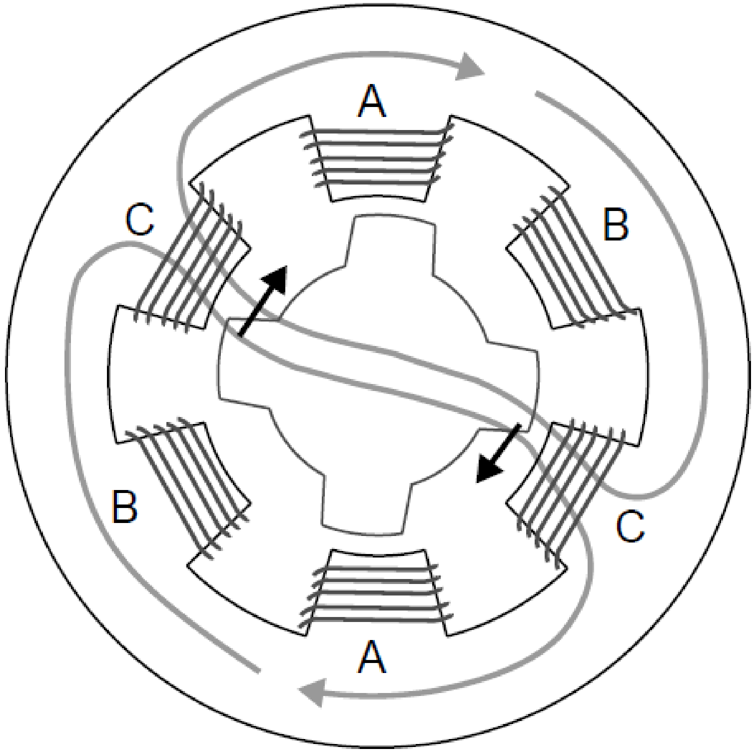
Switched reluctance motor (SRM)





SRM structure



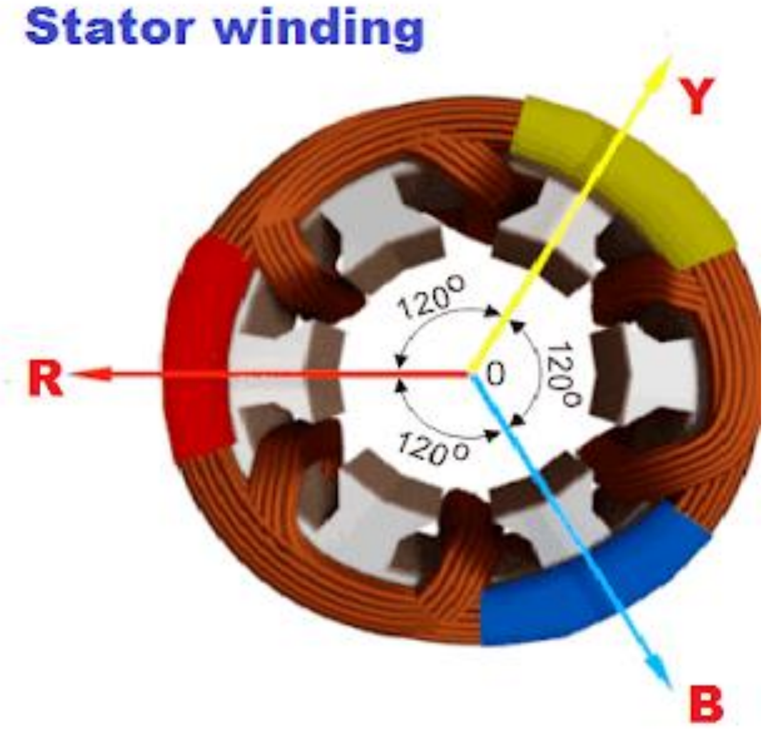


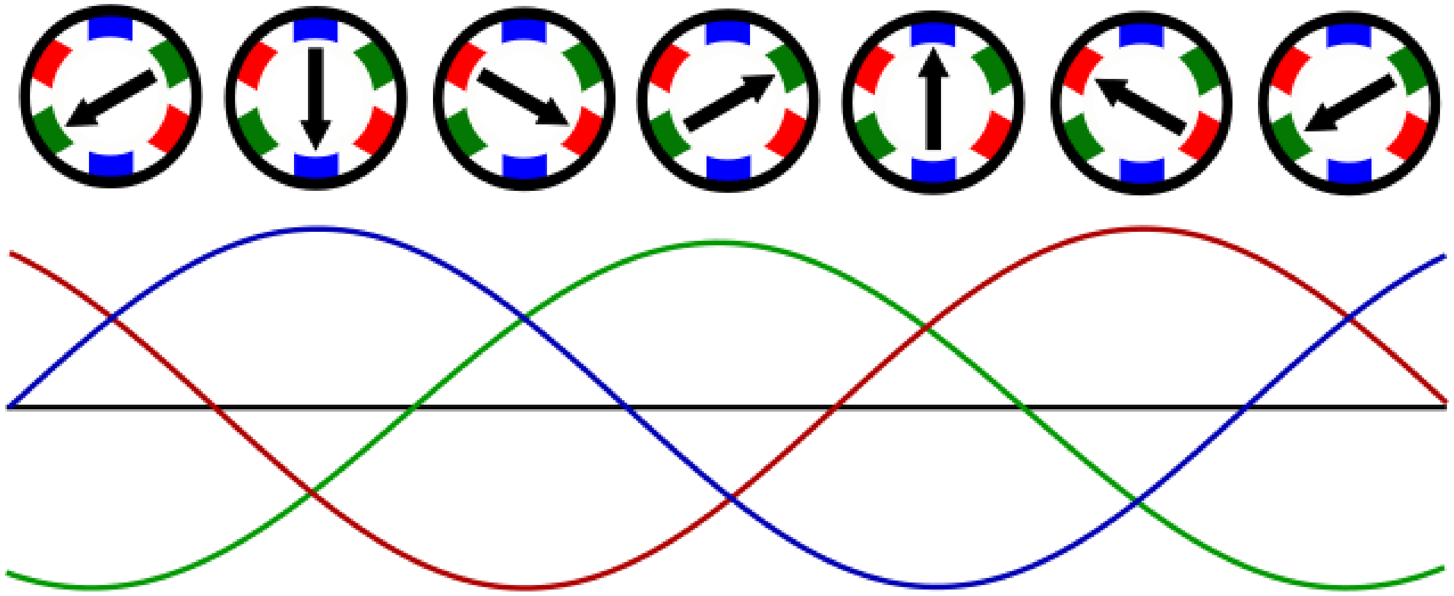
SRM-advantages and limitations

- Advantages:
  - Simple rotor
    - Rugged construction
    - minimal maintenance
  - no permanent magnet
    - Lower cost
    - No need for rear-earth elements
  - No current in rotor
    - No conduction loss in rotor
  - Good for high speed applications

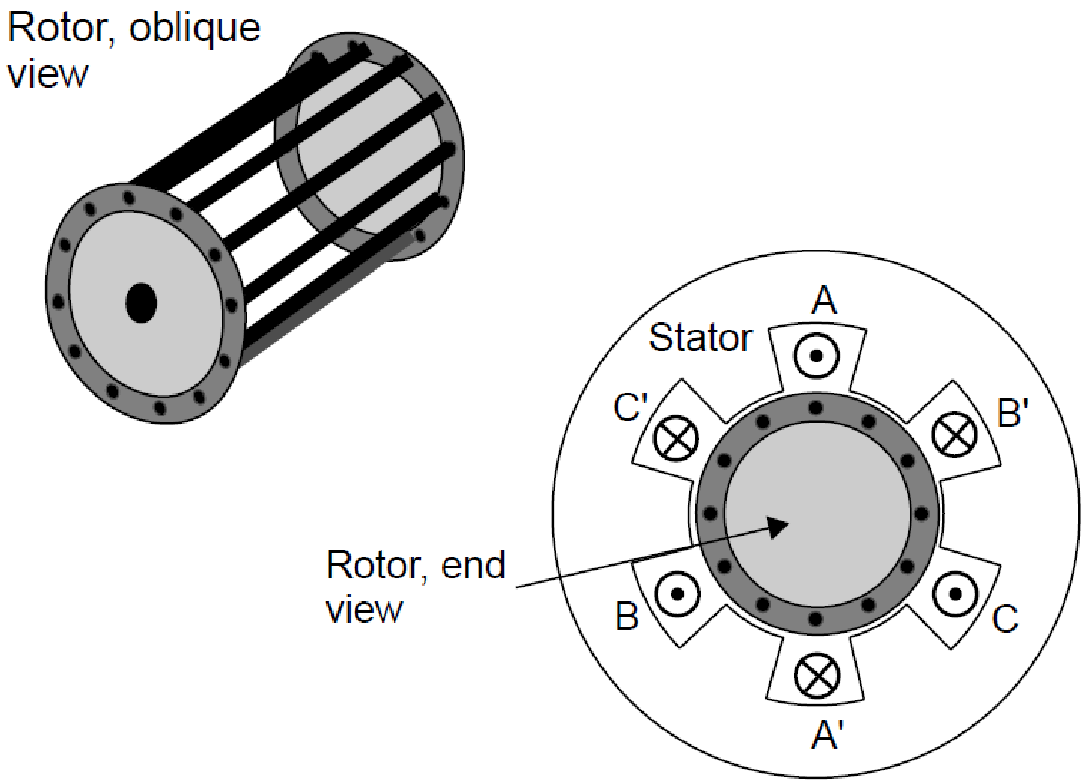
- Drawbacks:
  - Higher torque ripple
    - Noisy
  - Complicated control
    - complex controller required
  - Need for accurate position sensing
    - Costly sensors

Rotating magnetic field

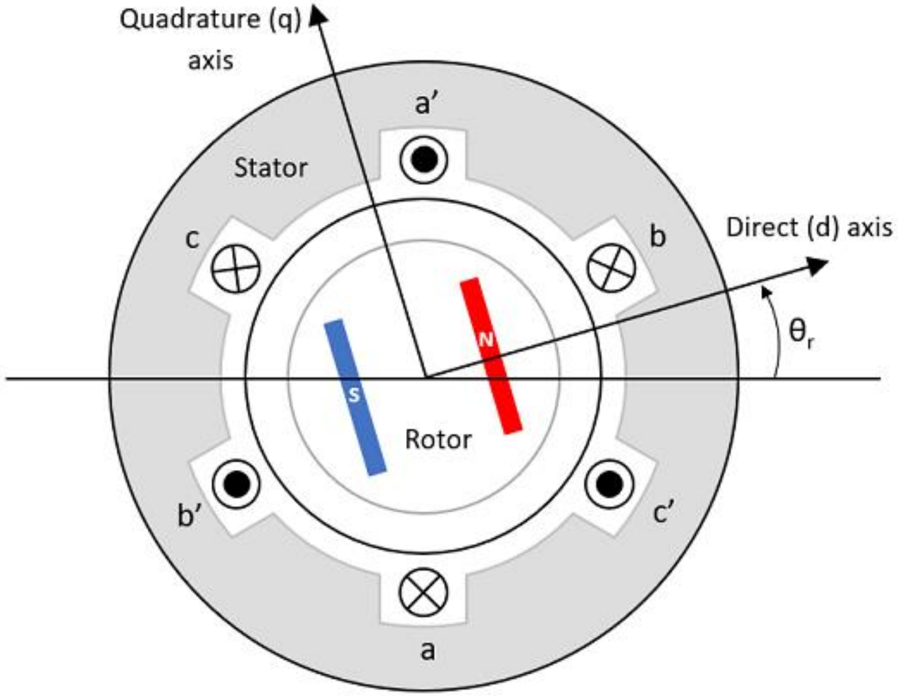




Permanent Magnet Synchronous Machine (PMSM)

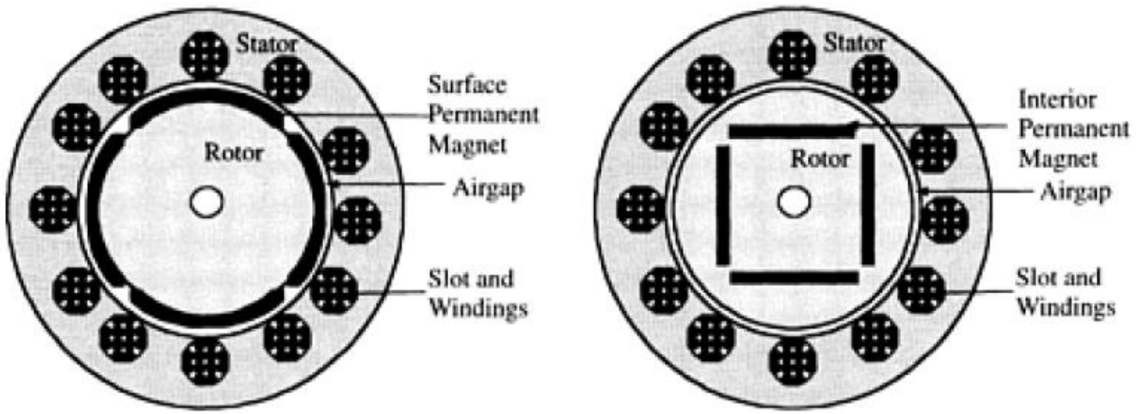


Induction motor

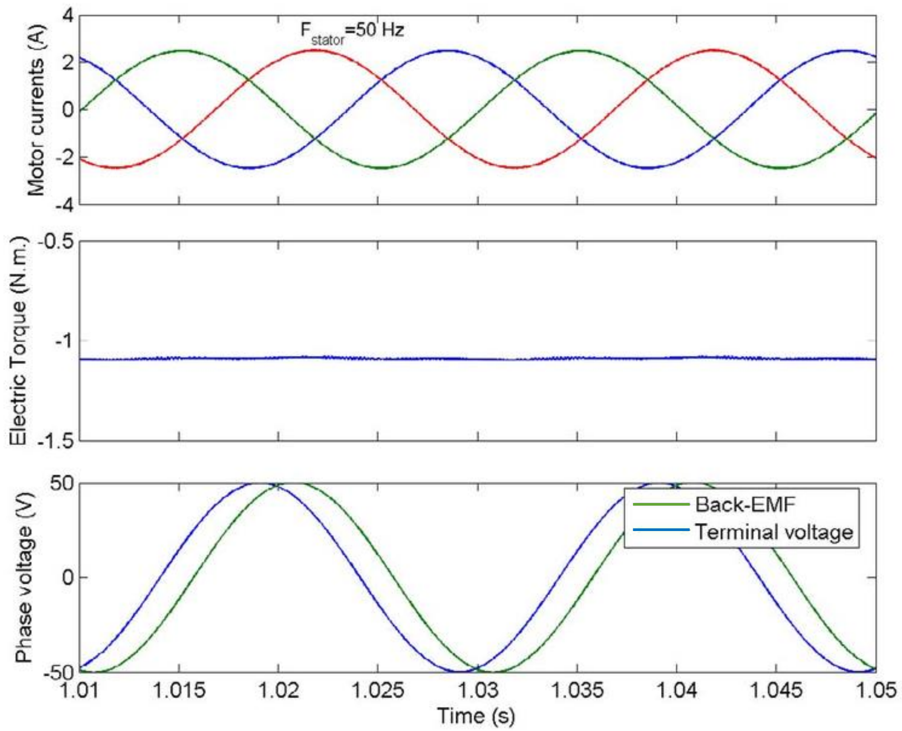


PMSM motor

PMSM induced voltage

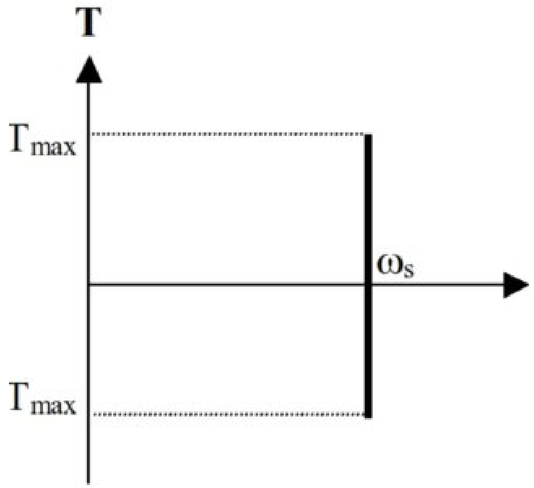


Surface mount and interior mount magnets



Speed control

Torque-speed characteristics



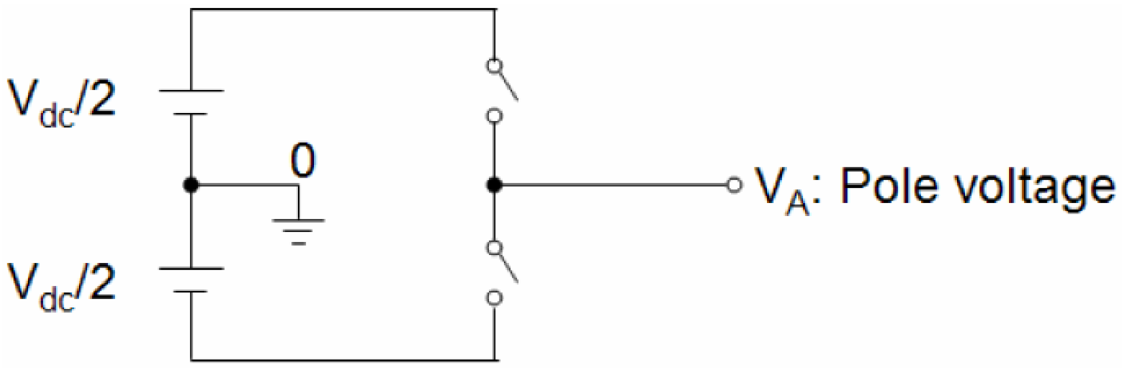
- How to start the motor?
  - Damper winding
  - Auxiliary motor
  - Using control (VFD)

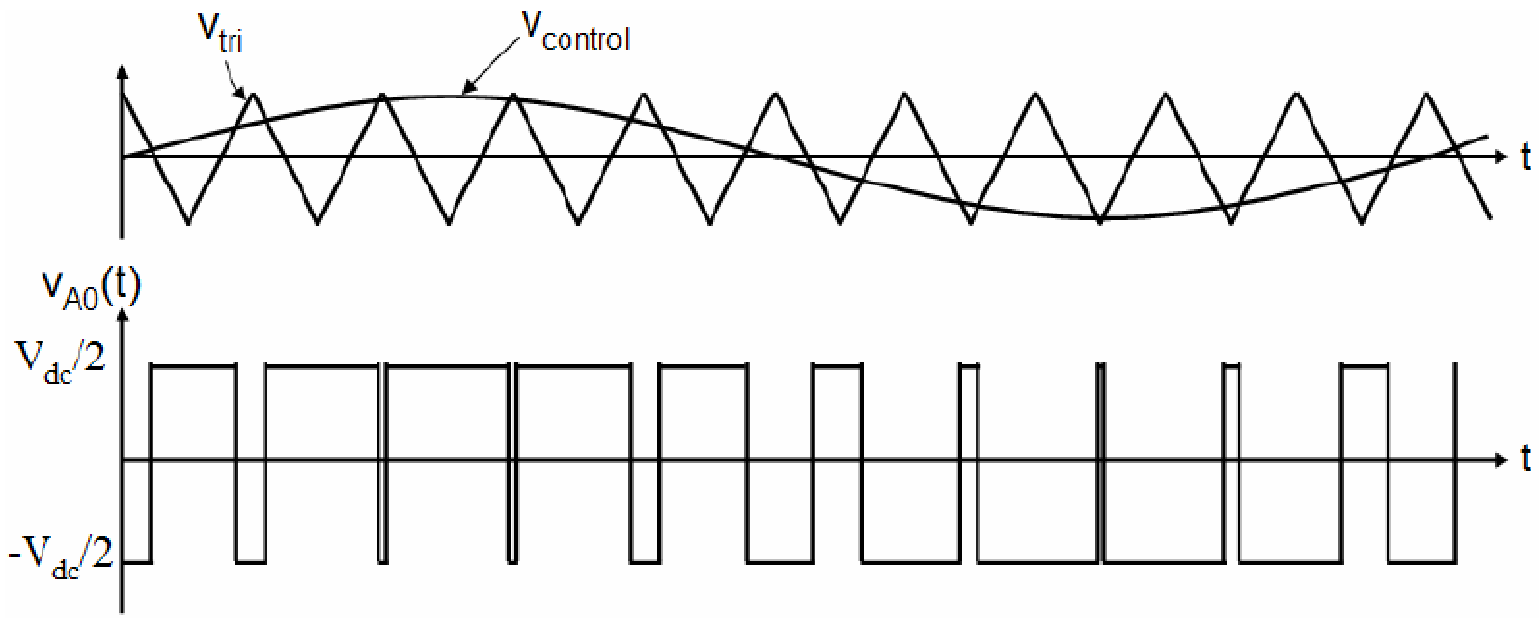
PMSM-advantages and limitations

- Advantages:
  - Higher power density
    - More flux due to permeant magnet
  - Higher efficiency
    - No conduction loss in rotor
  - Smooth torque
    - No conduction loss in rotor
  - Easier thermal management
- Drawbacks:
  - Higher cost
    - Costly permanent magnets
  - Risk of demagnetization
    - when exposed to higher temperature and reverse magnetic field
  - Complex control
  - Hazardous fault condition

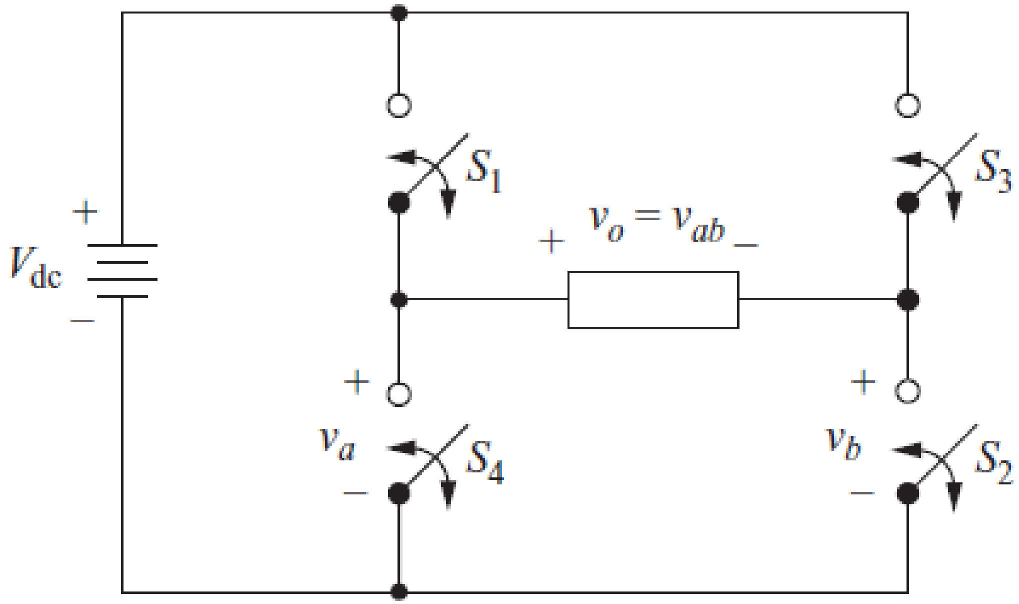
AC sources for AC Machines

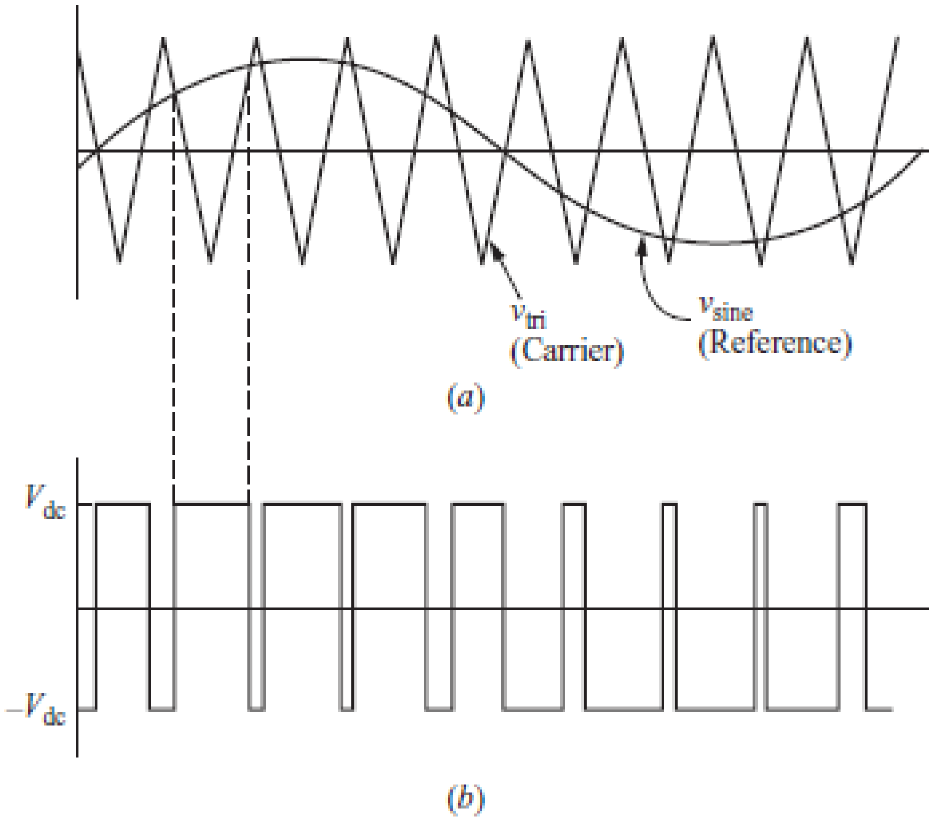
Generation of AC voltage



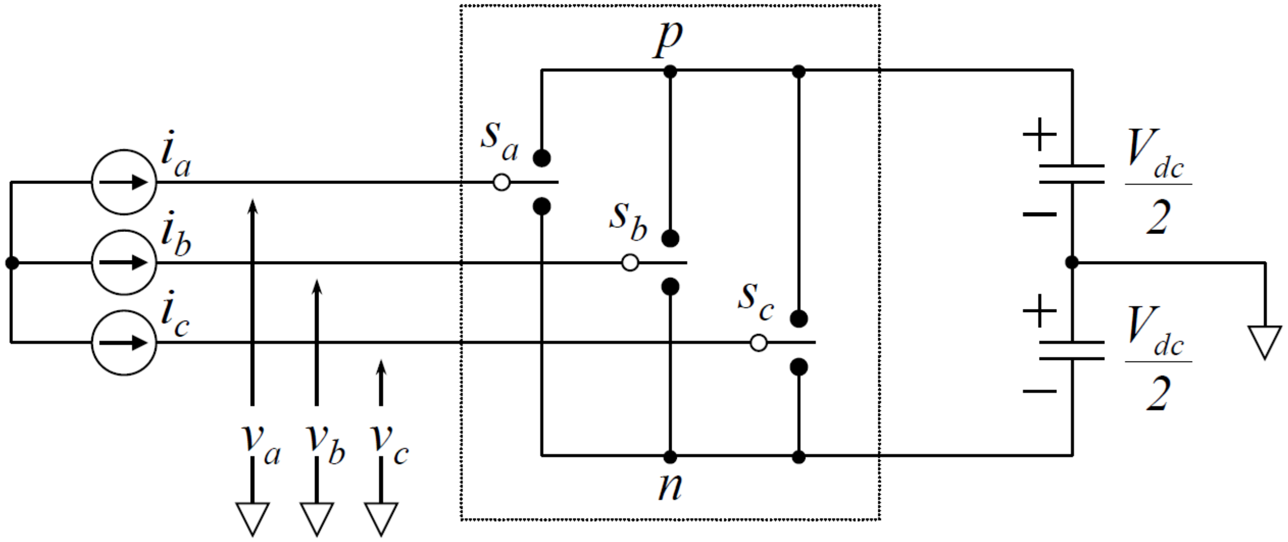


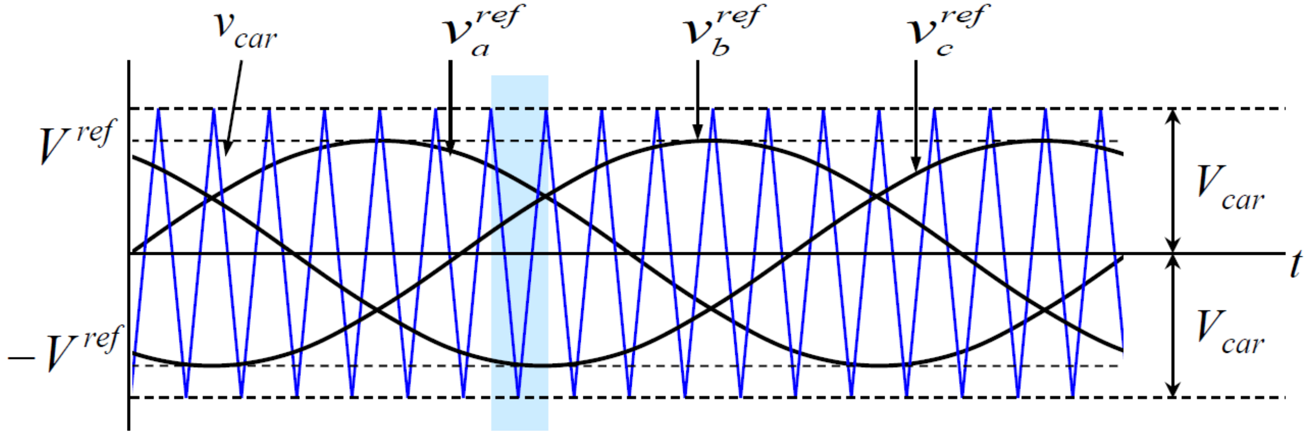
AC generation with H-bridge



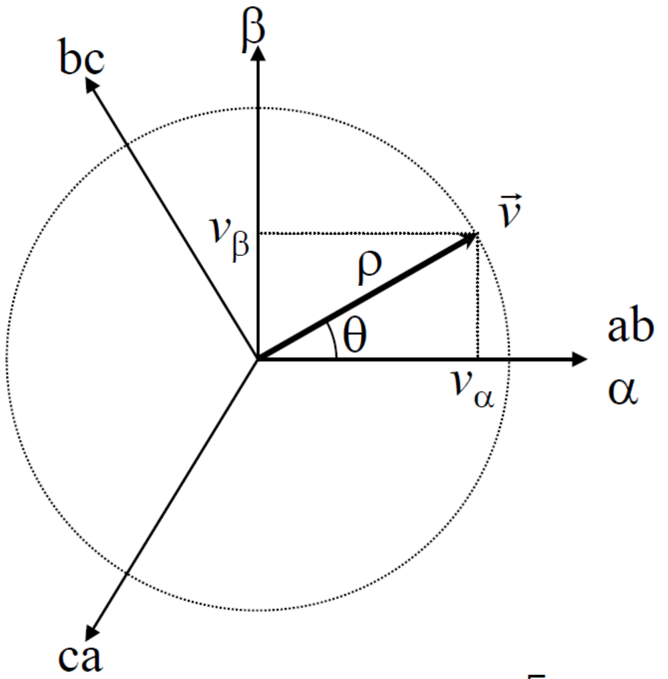


Three-phase voltage generation





Clarke's Transformation



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

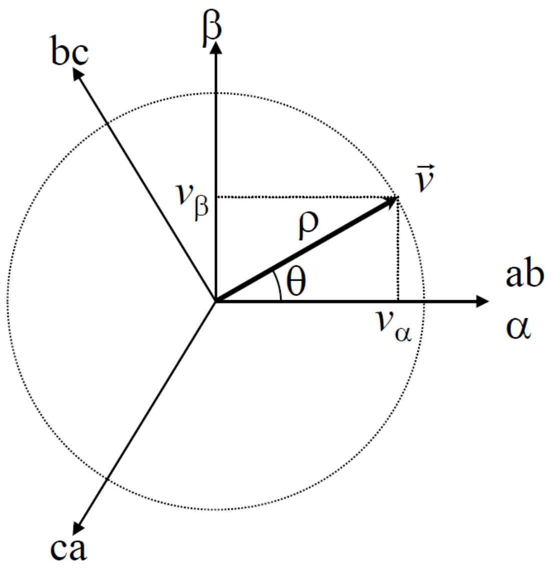
- A bit of history
  - Edith Clarke (1883-1959)
    - The first professional woman electrical engineer in US
    - first female professor of electrical engineering
    - first woman to deliver a paper at the *American Institute of Electrical Engineers (AIEE)*
    - first woman named as a fellow of AIEE

Space vector

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

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

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

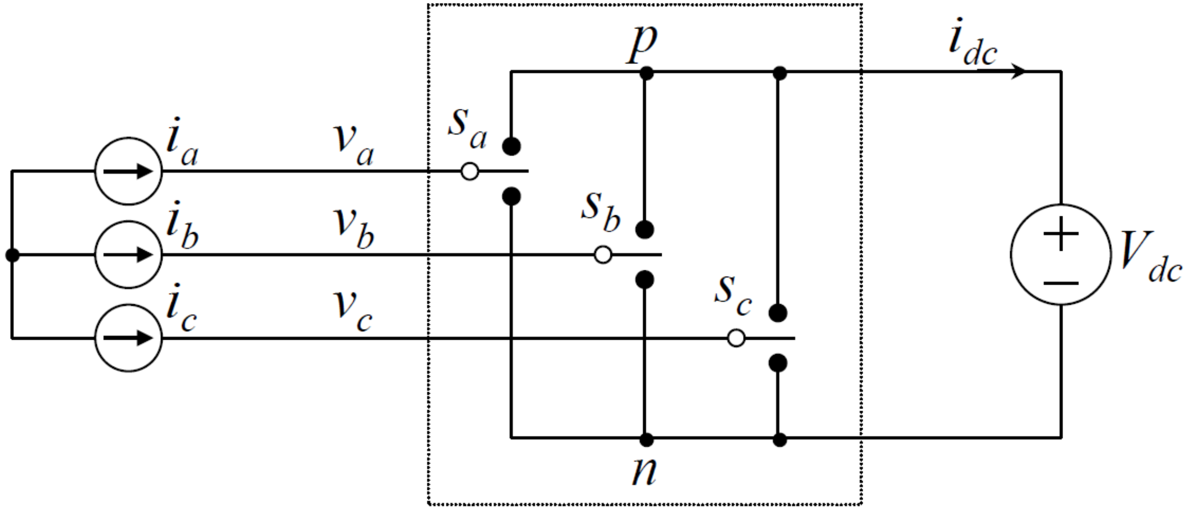


$$\vec{v} = \rho \cdot e^{j\theta}$$

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

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

Switching states



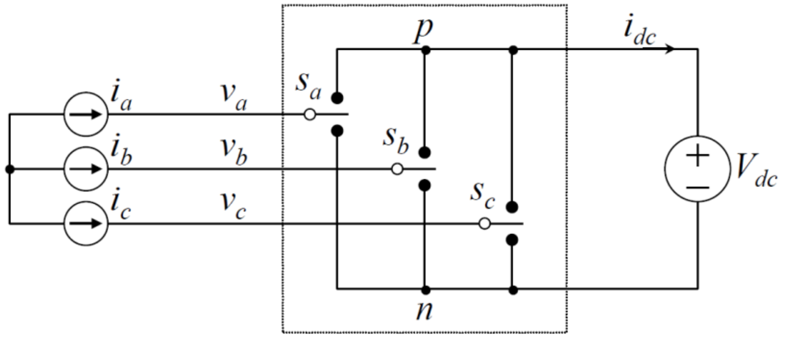
s_a	s_b	s_c	Switching state
0	0	0	*nnn*
0	0	1	*nnp*
0	1	0	*npn*
0	1	1	*npp*
1	0	0	*pnn*
1	0	1	*pnp*
1	1	0	*ppn*
1	1	1	*ppp*

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

Switch state: pnn

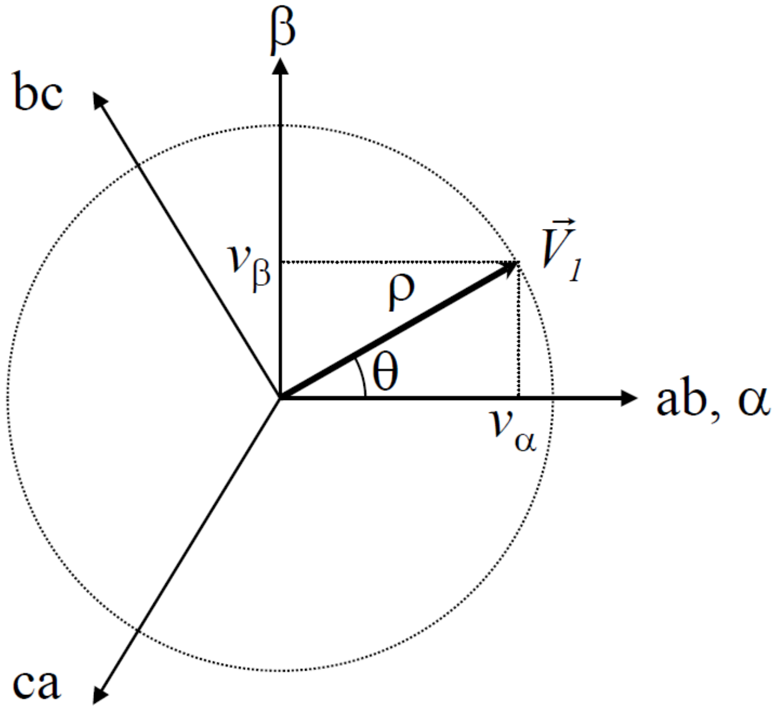
$$\vec{V}_{pnn} = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}_{pnn} = T_{\alpha\beta/abc} \cdot \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}_{pnn} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}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



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

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

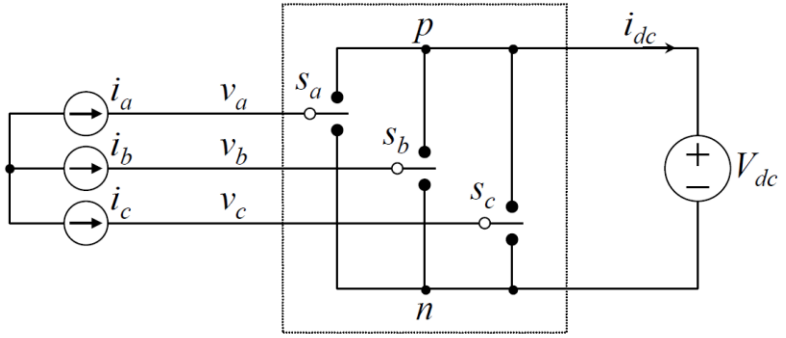
$$\theta = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right) = 30^\circ$$



Space vector for state ppn

Switch state: ppn

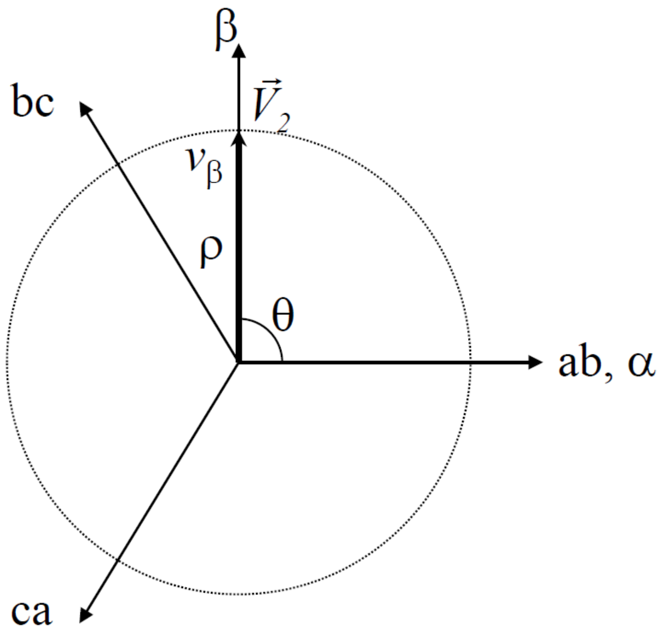
$$\vec{V}_{ppn}=\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}_{ppn}=T_{\alpha\beta/abc}\cdot\begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}_{ppn}=\sqrt{\frac{2}{3}}\cdot\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\cdot\begin{bmatrix}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



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

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

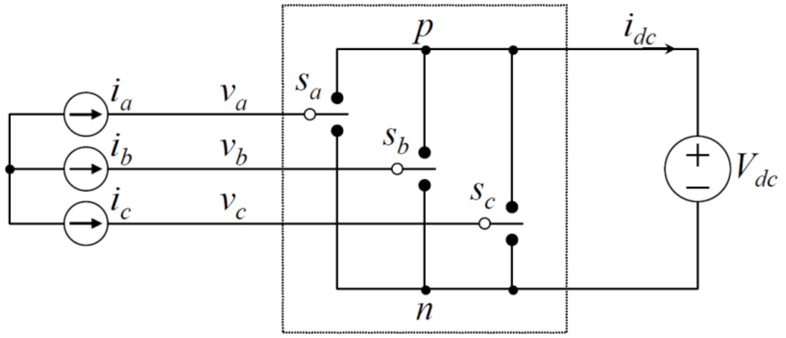
$$\theta=\tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right)=90°$$



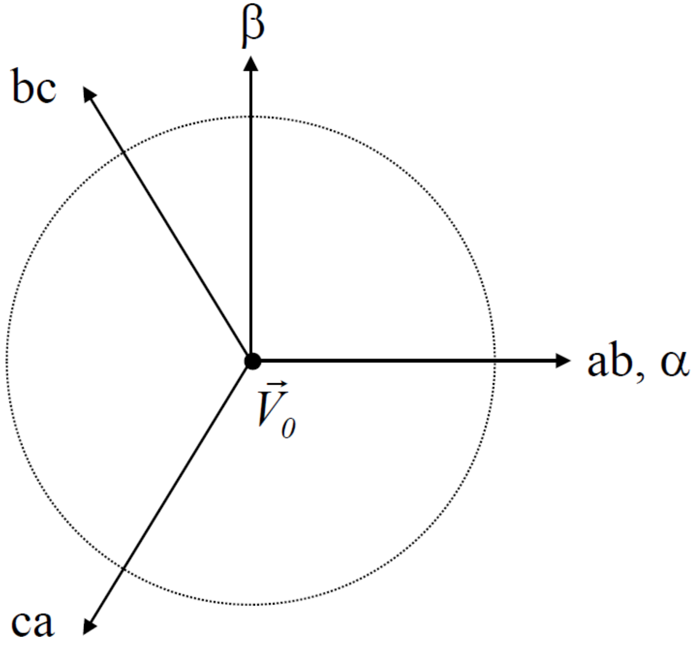
Space vector for state ppp

Switch state: ppp

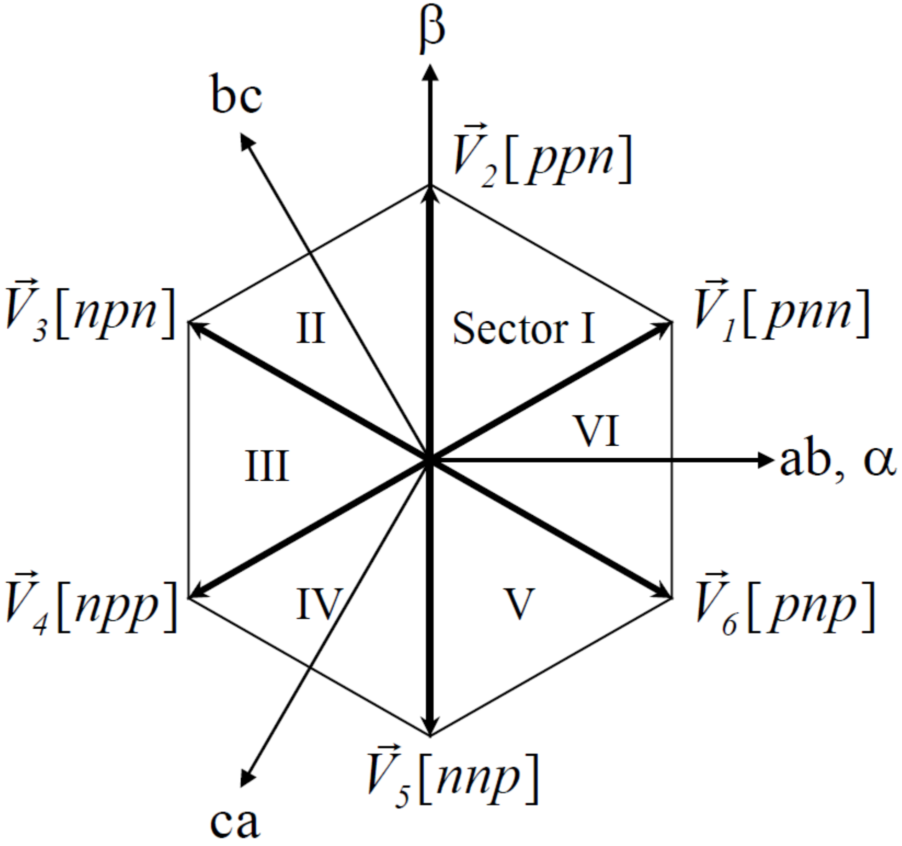
$$\vec{V}_{ppp} = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}_{ppp} = T_{\alpha\beta/abc} \cdot \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix}_{ppp} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}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



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



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

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

↓

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

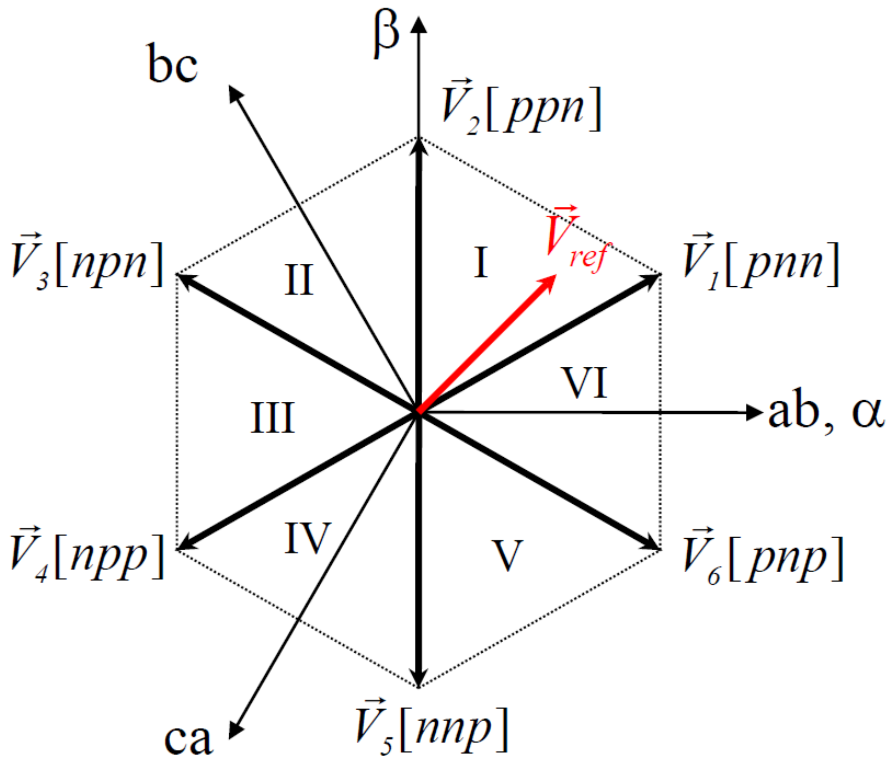
↓

Step 3 : Make the sequence of chosen switching state vectors

Vector selection

- Minimize the number of switching
- Minimize the harmonic distortion

☞ **Nearest Three Vectors (NTV)**

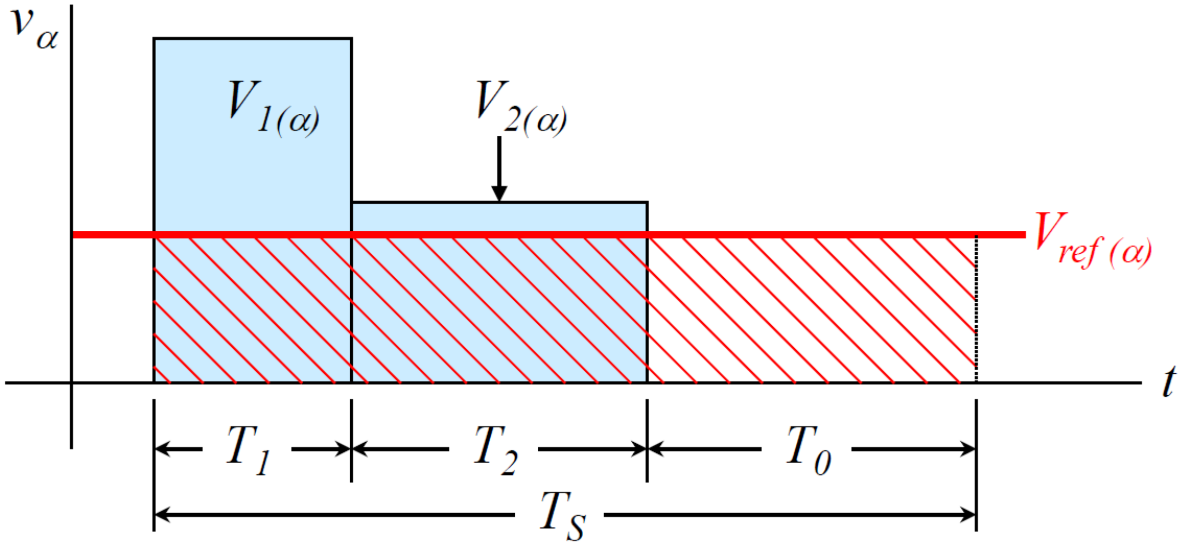


$\vec{V}_0 = [ppp] = [nnn]$ at center point

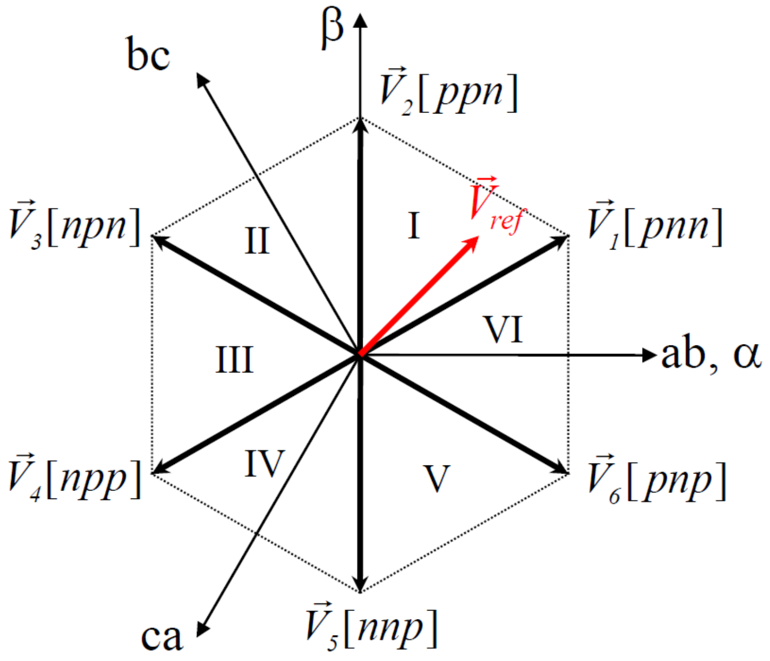
High frequency synthesis

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

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



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



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

Duty ratio in sector I

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

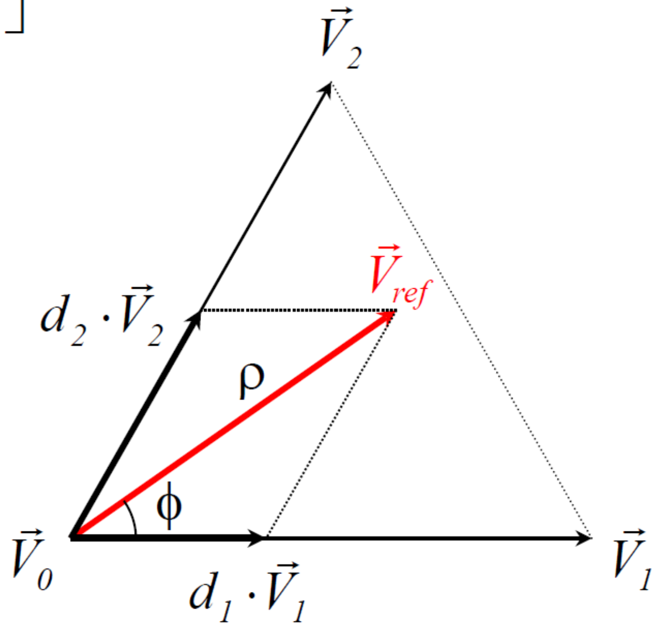
$$\rho \cdot \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix} \cdot T_S = \|V_1\| \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot T_1 + \|V_2\| \cdot \begin{bmatrix} \cos 60^\circ \\ \sin 60^\circ \end{bmatrix} \cdot T_2$$

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

☞ Other sectors have the same results of duty ratio.

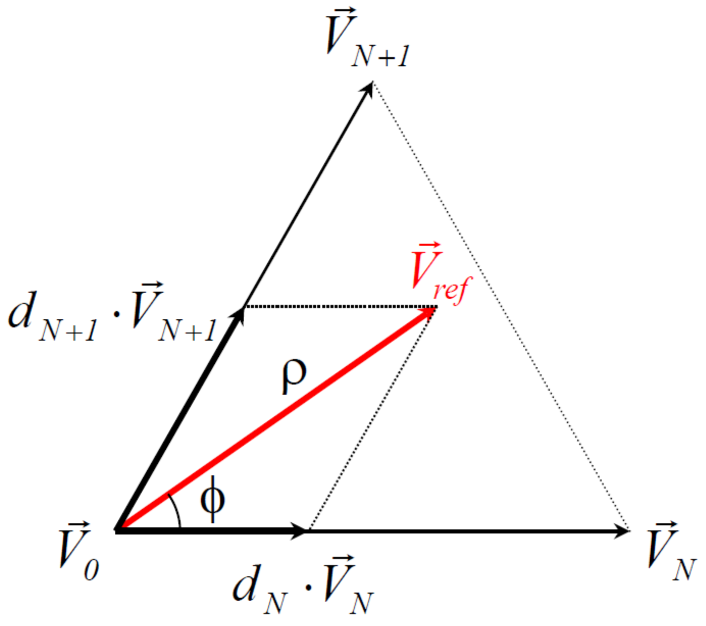
$$\frac{T_N}{T_S} = d_N = \frac{2}{\sqrt{3}} \cdot \frac{\rho}{\|V_N\|} \cdot \sin(60^\circ - \phi)$$

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

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

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

N : *sector number (1 ~ 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

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 $M = \frac{V_m}{V_{dc}}$

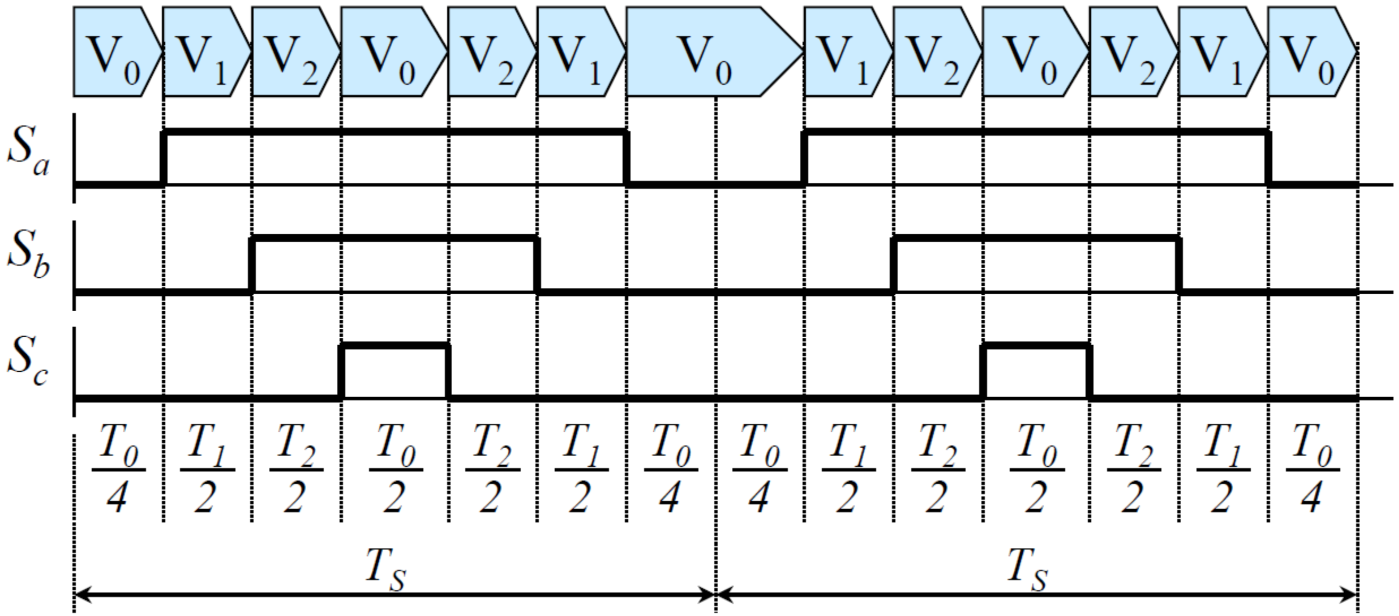
$$d_N = M \cdot \sin(60^\circ - \phi)$$

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

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

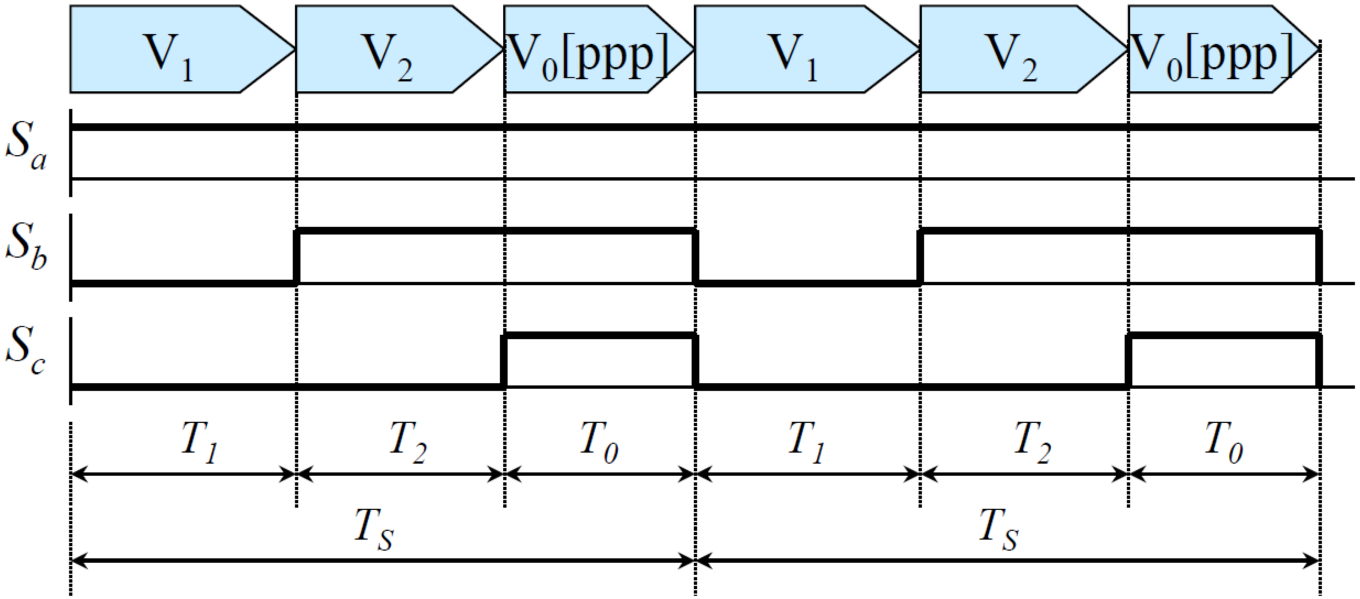
Vector sequence – 3ph, symmetric

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



Vector sequence – 2ph, symmetric

- 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



Thank you!