Electric Vehicle (EE60082)

Lecture 10: Motor drive for EV (part 6)

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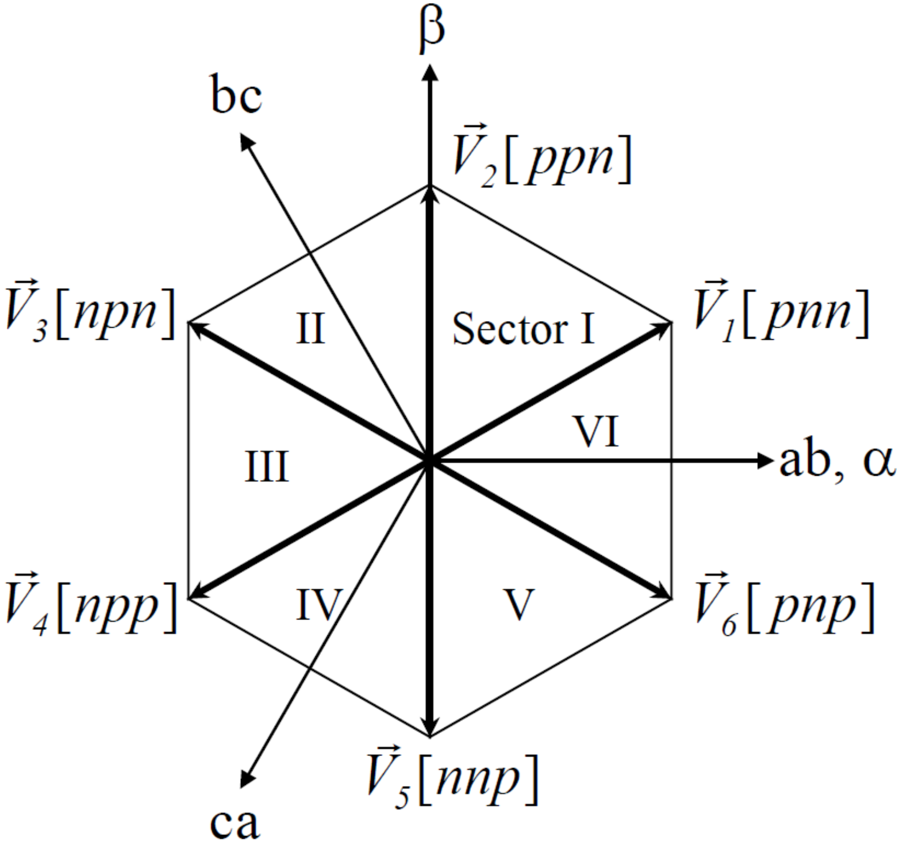
Switching State Vectors (recap)



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

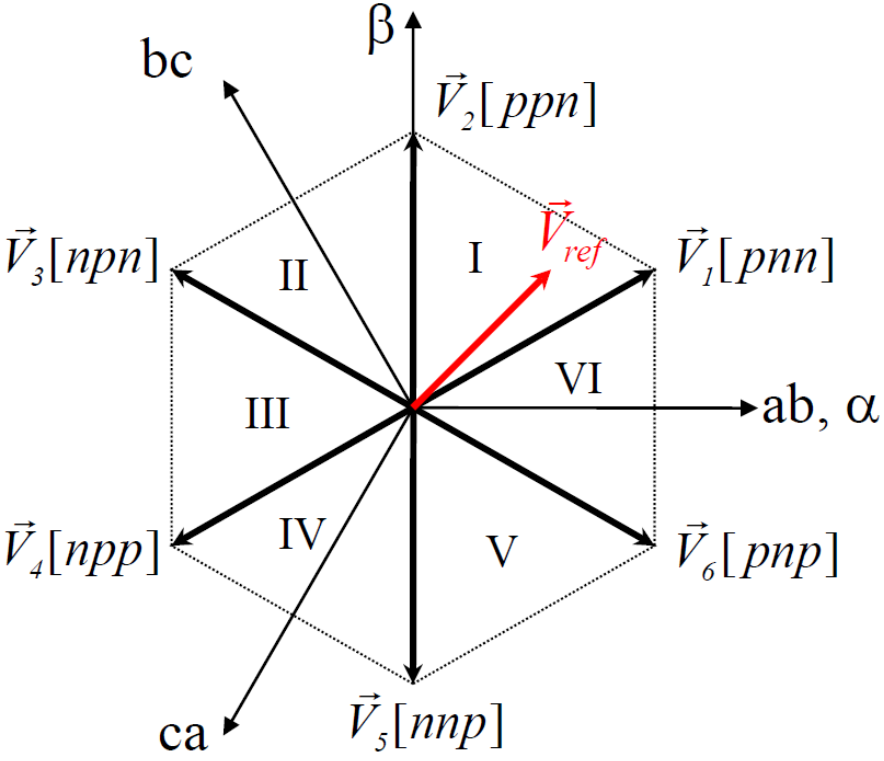
↓

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)**

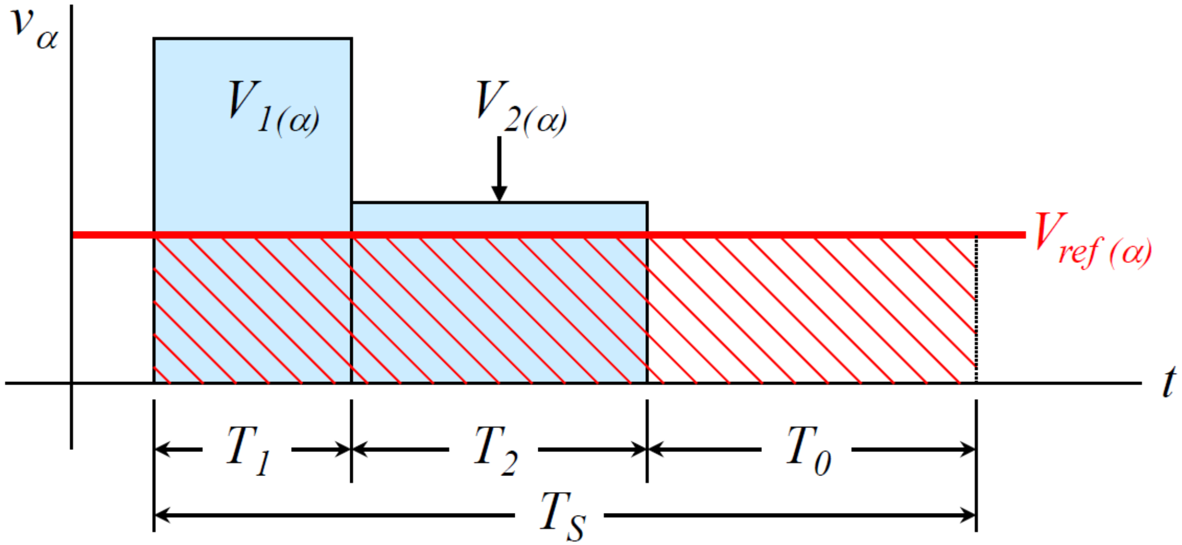


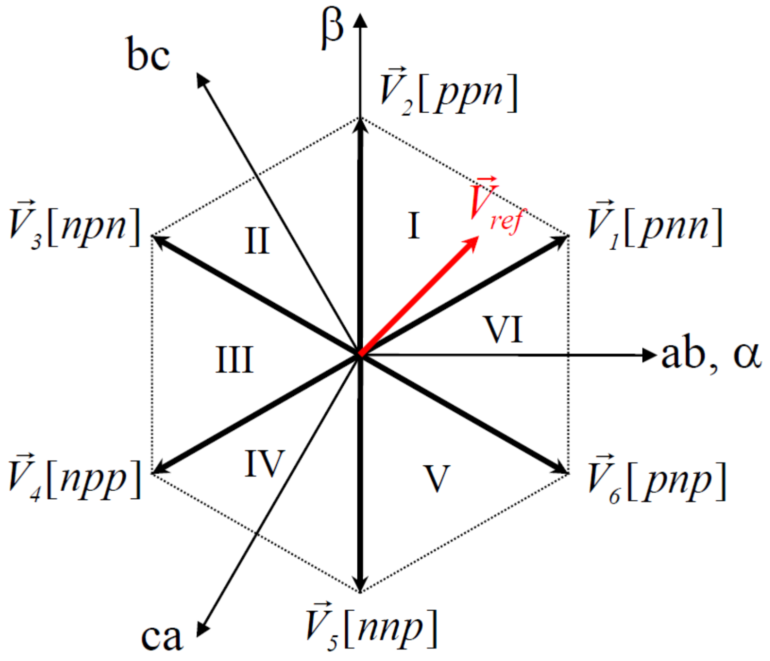
$\vec{V}_0 = [ppp] = [nnn]$ at center point

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





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

Total area of [blue box] = Area of [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, $\vec{V}_{ref} \cdot T_S = \vec{V}_1 \cdot T_1 + \vec{V}_2 \cdot T_2$

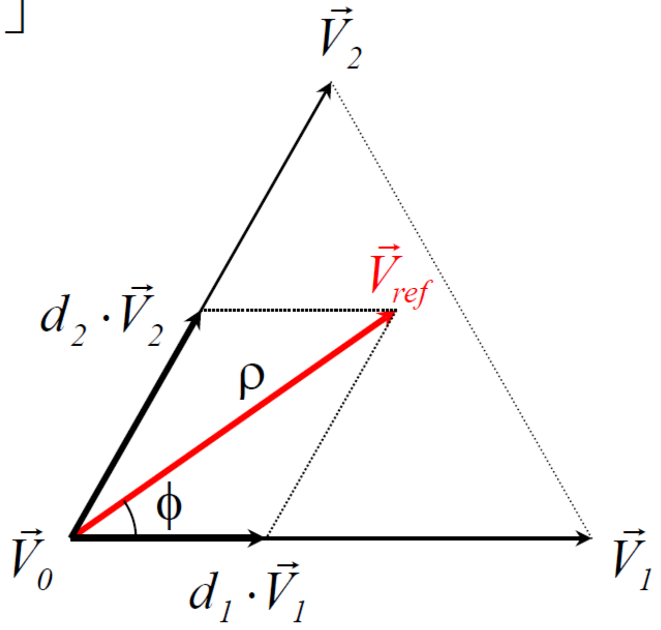
$$\rho \cdot \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix} \cdot T_S = \|V_1\| \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot T_1 + \|V_2\| \cdot \begin{bmatrix} \cos 60^\circ \\ \sin 60^\circ \end{bmatrix} \cdot T_2$$

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.

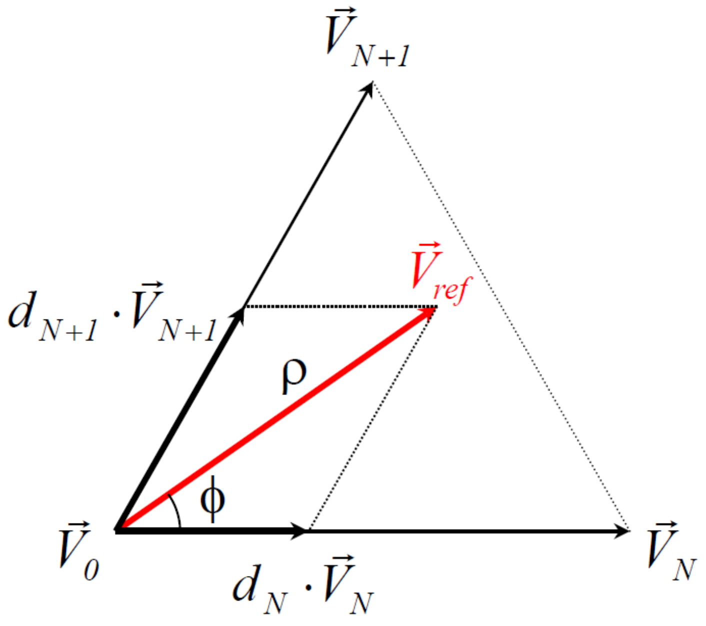
$$\frac{T_N}{T_S} = d_N = \frac{2}{\sqrt{3}} \cdot \frac{\rho}{\|V_N\|} \cdot \sin(60° - \phi)$$

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

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

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

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

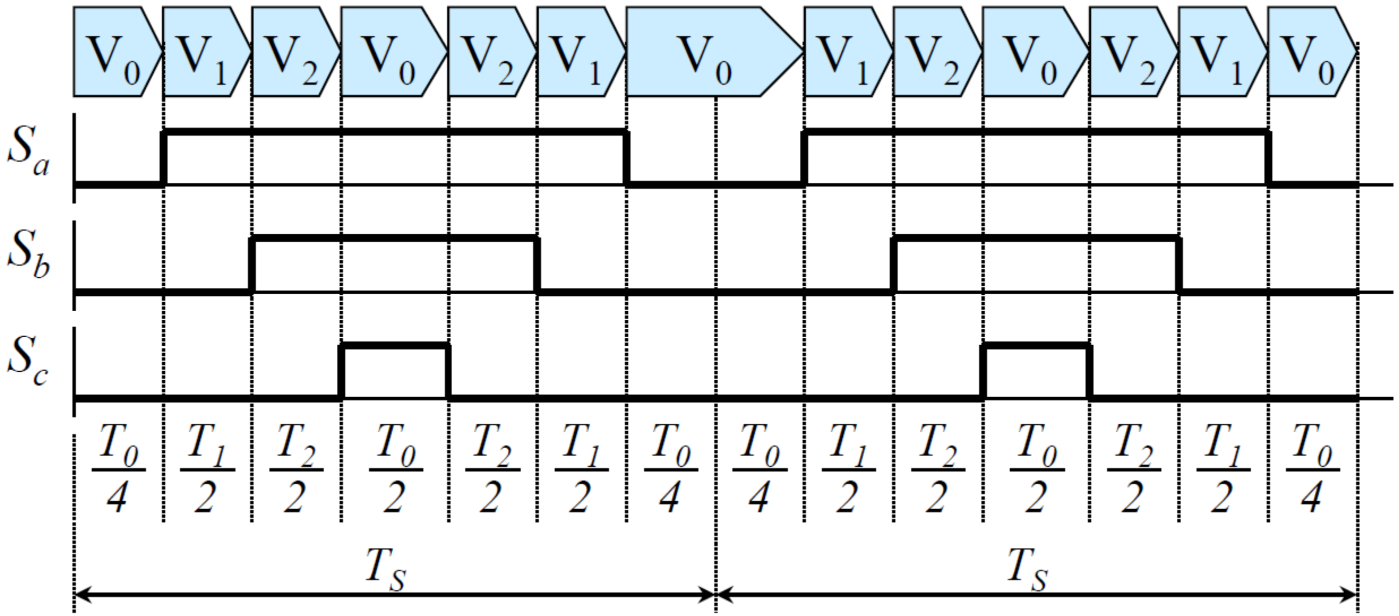
$$d_N = M \cdot \sin(60^\circ - \phi)$$

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

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

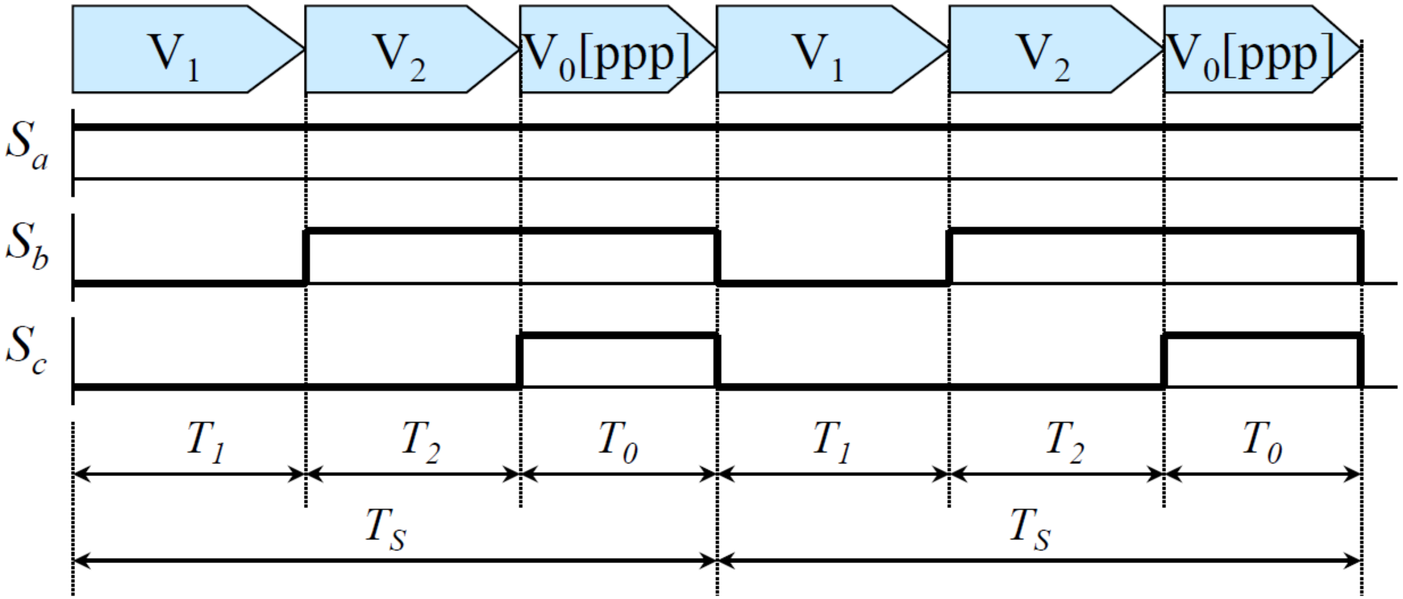
Vector sequence – 3ph, symmetric (recap)

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



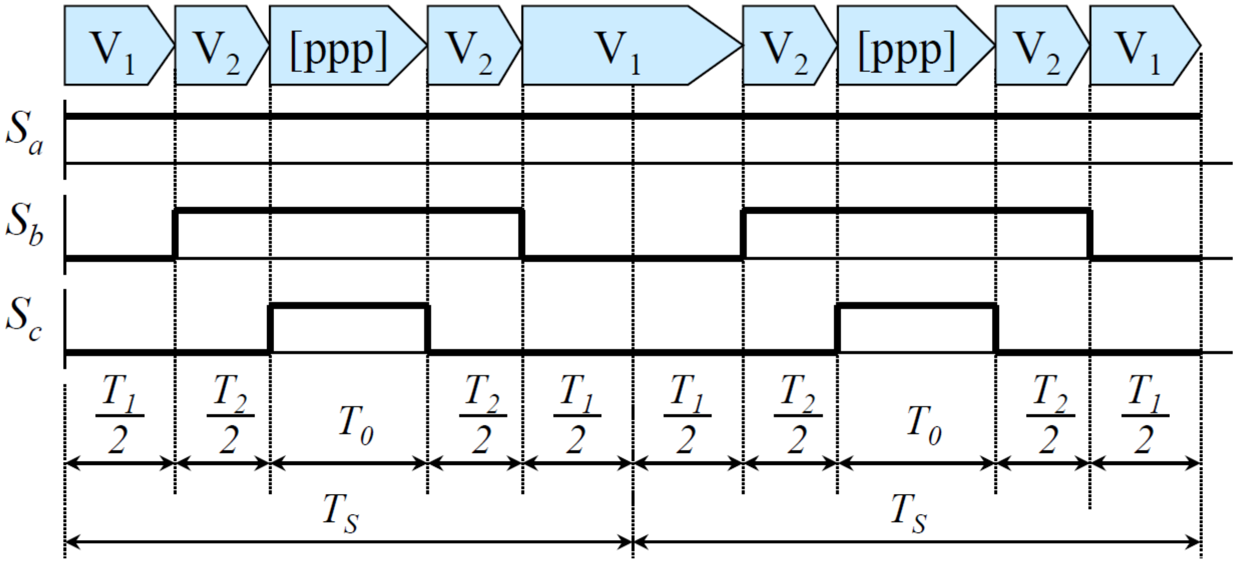
Vector sequence – 2ph, asymmetric (recap)

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



Vector sequence – 2ph, symmetric (recap)

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



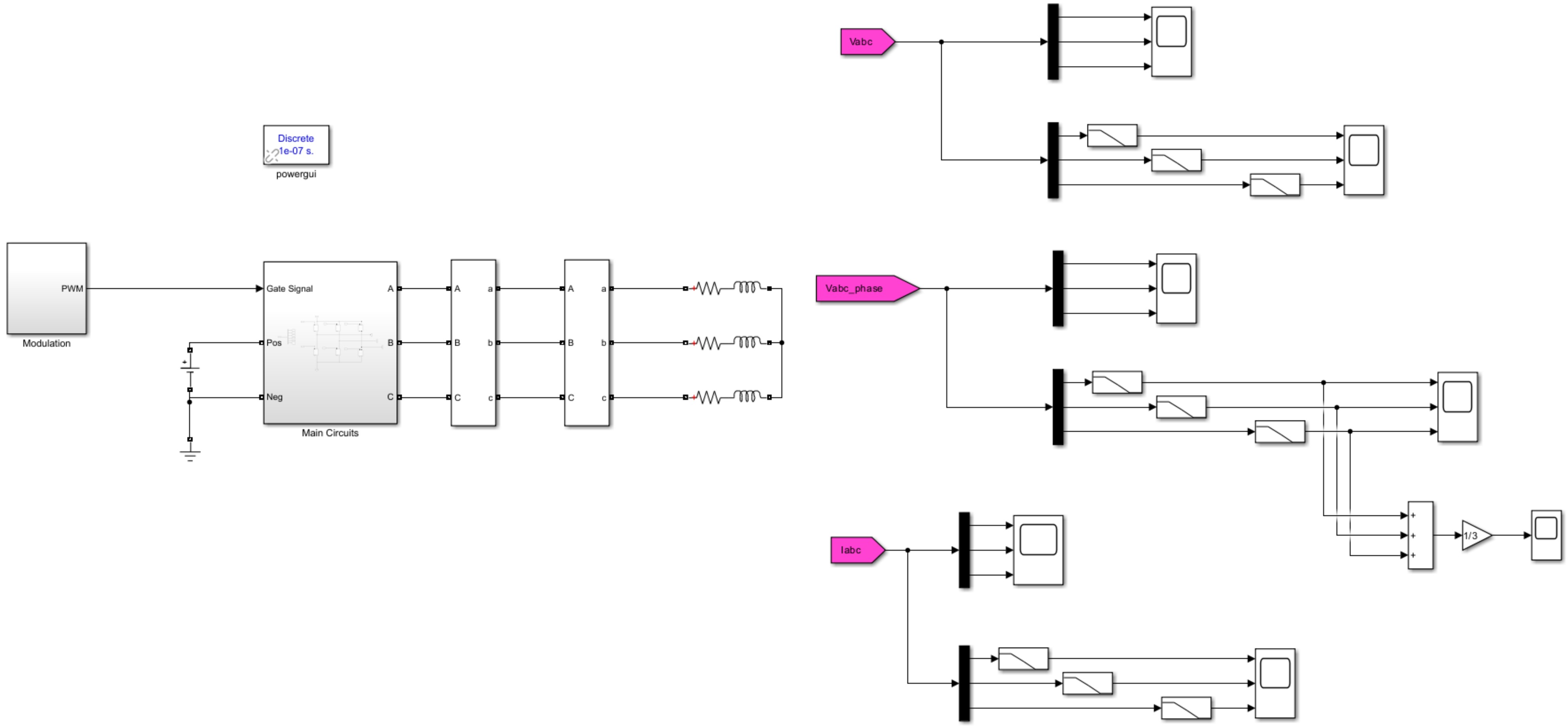
< Example in sector I >

AC volage generation with space vector (recap)

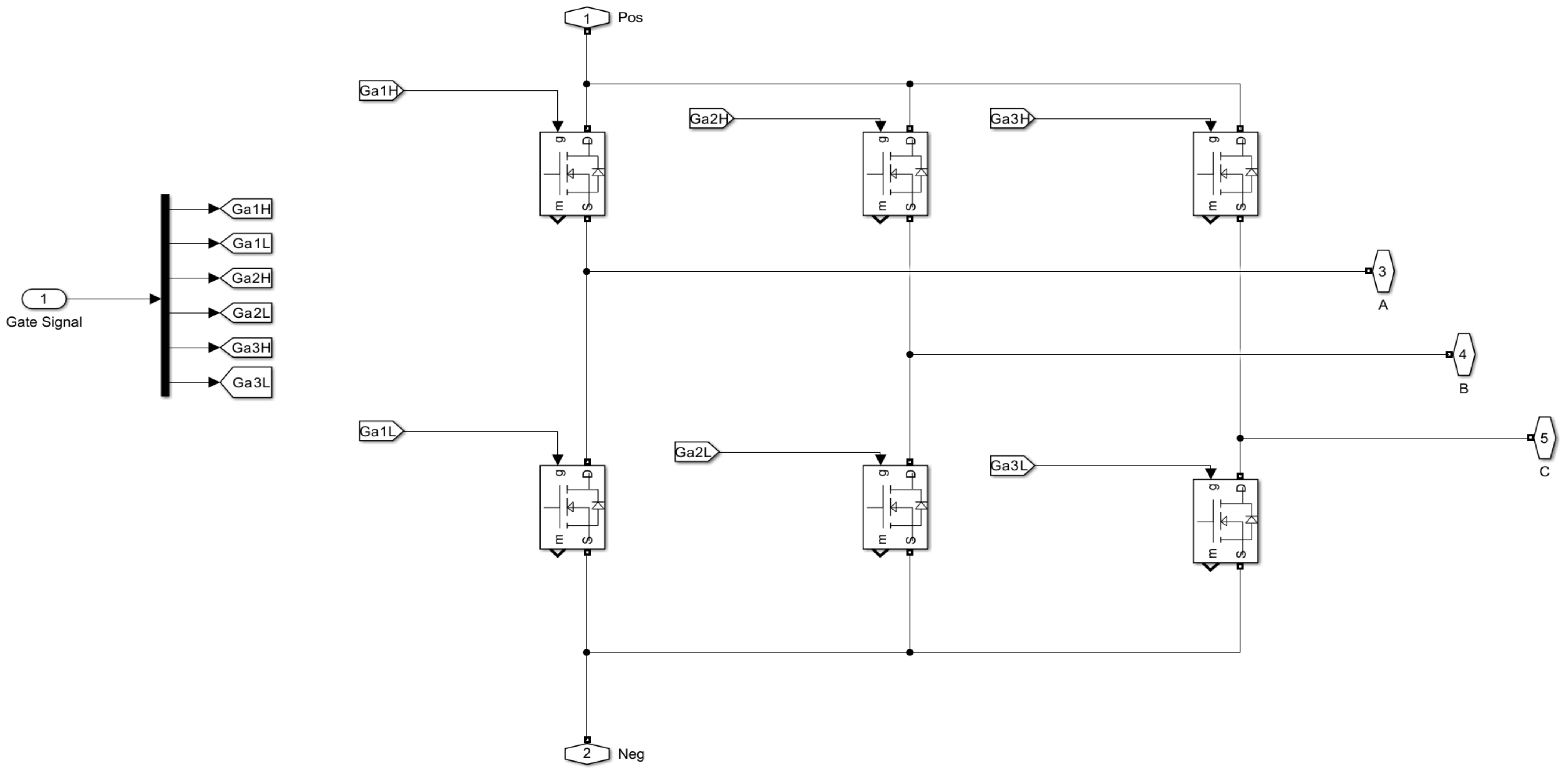
Example:

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

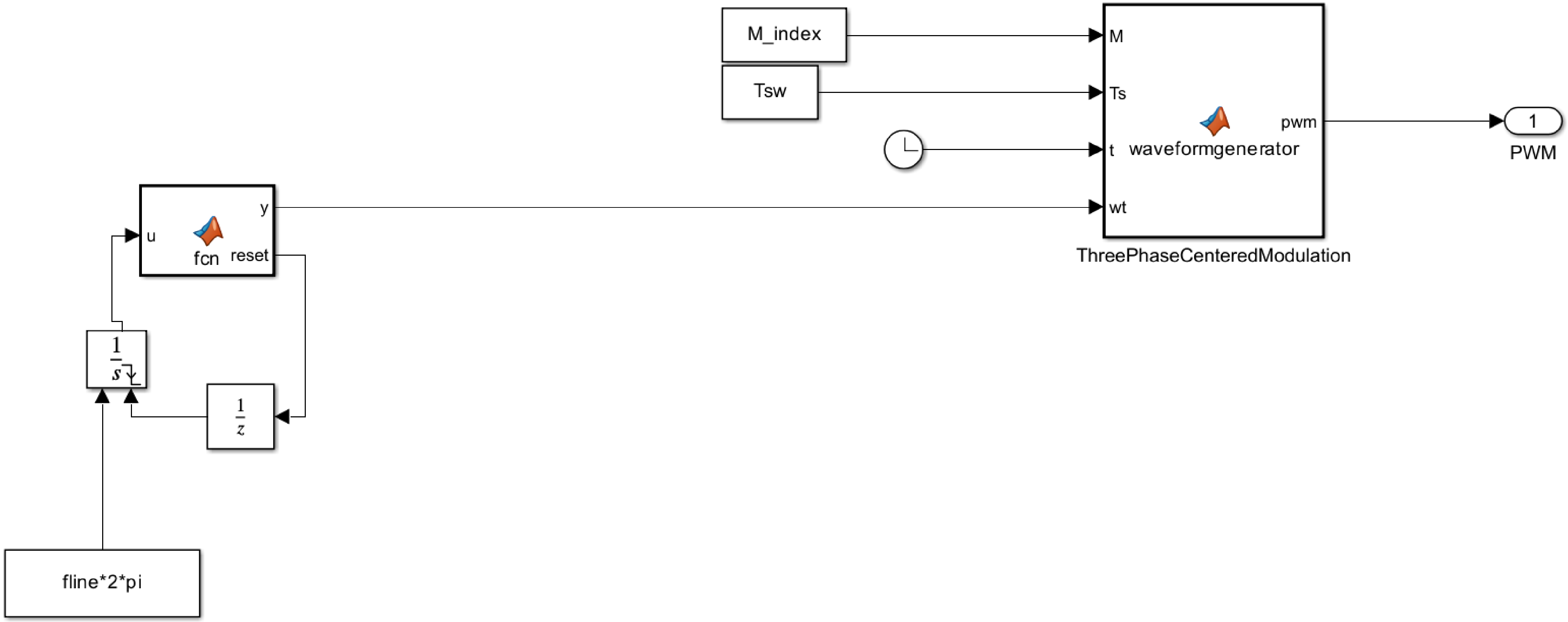
VSI simulation (recap)



VSI simulation (recap)



VSI simulation - modulation (recap)



VSI simulation - modulation (recap)

```
% 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;
```

```
% 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 (recap)

Exercise:

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

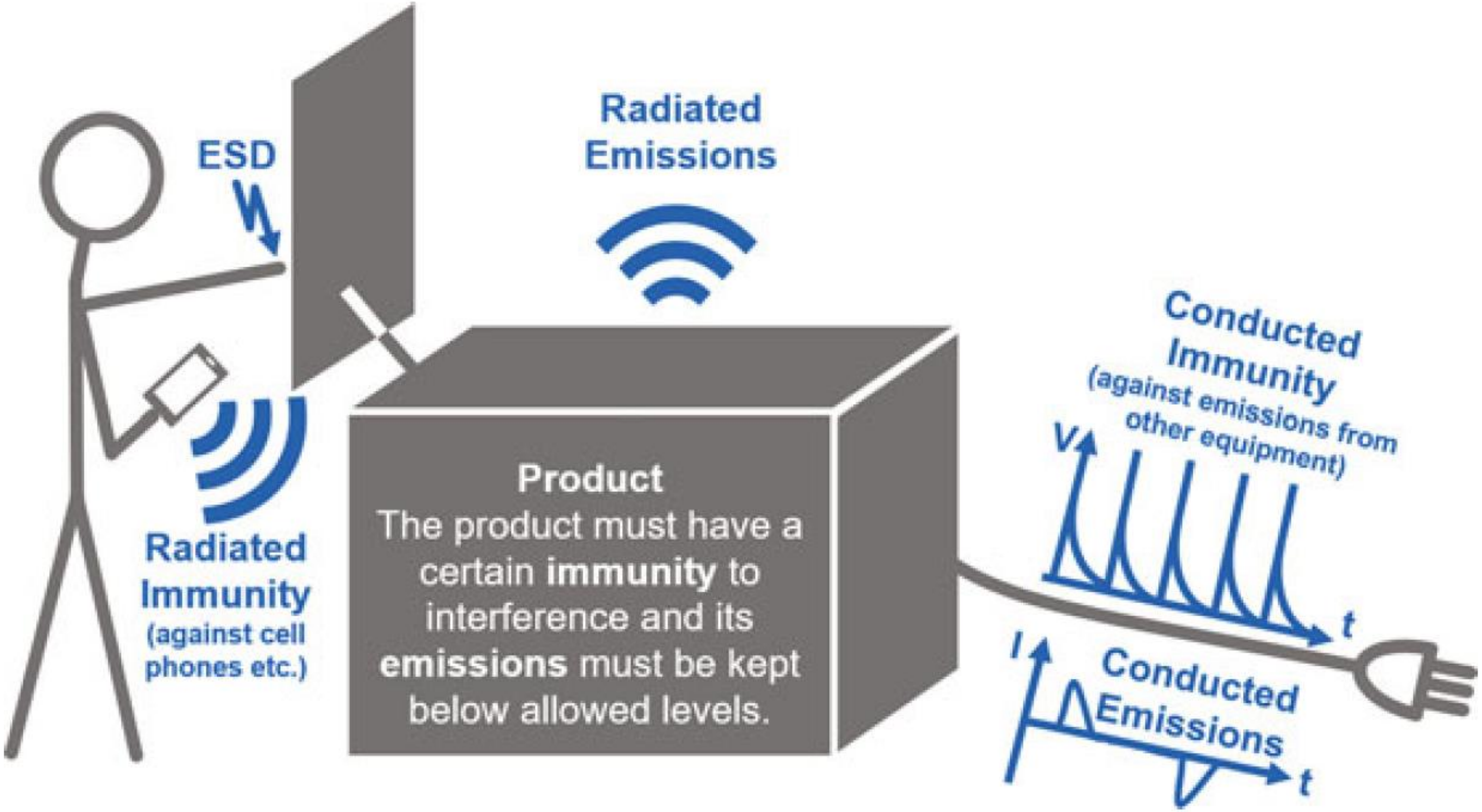
- Compare filtered voltage and current waveforms
- Compare common mode voltage waveforms
- Compare unfiltered current waveforms
- Which one is better?

Electromagnetic Interference

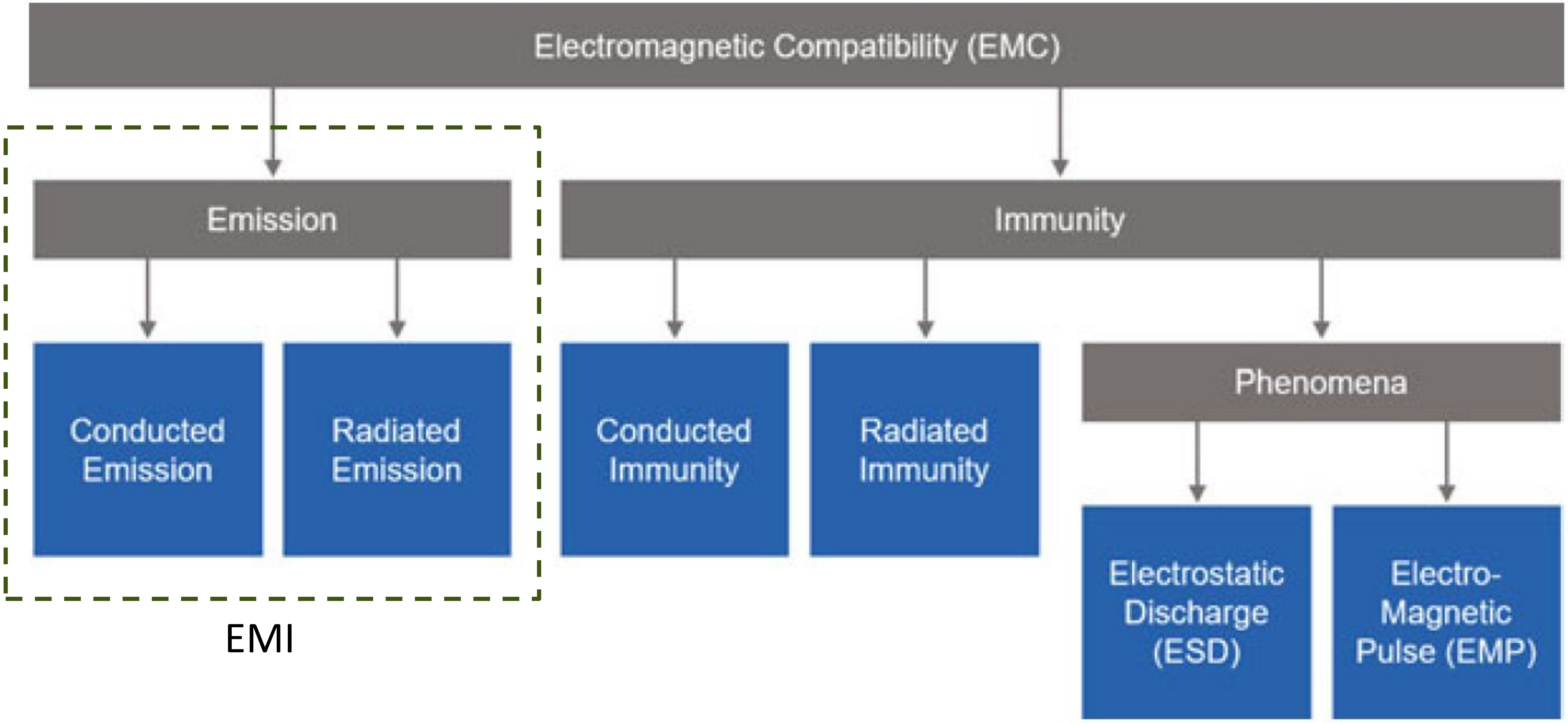
- In 1992, a woman died because pacemaker failure when the technicians turned on their radio transmitter to ask for advice

- Another example is the explosion of the Texaco refinery in Milford Haven UK, on the 24th of July 1994,
  - which was caused by an electrical storm giving rise to power surges
  - tripped out a number of pump motors while leaving others running.
  - The explosion led to 26 people being sustainably injured and damage of £48 million .

Electromagnetic Interference



Electromagnetic Compatibility (EMC)



Electromagnetic emissions

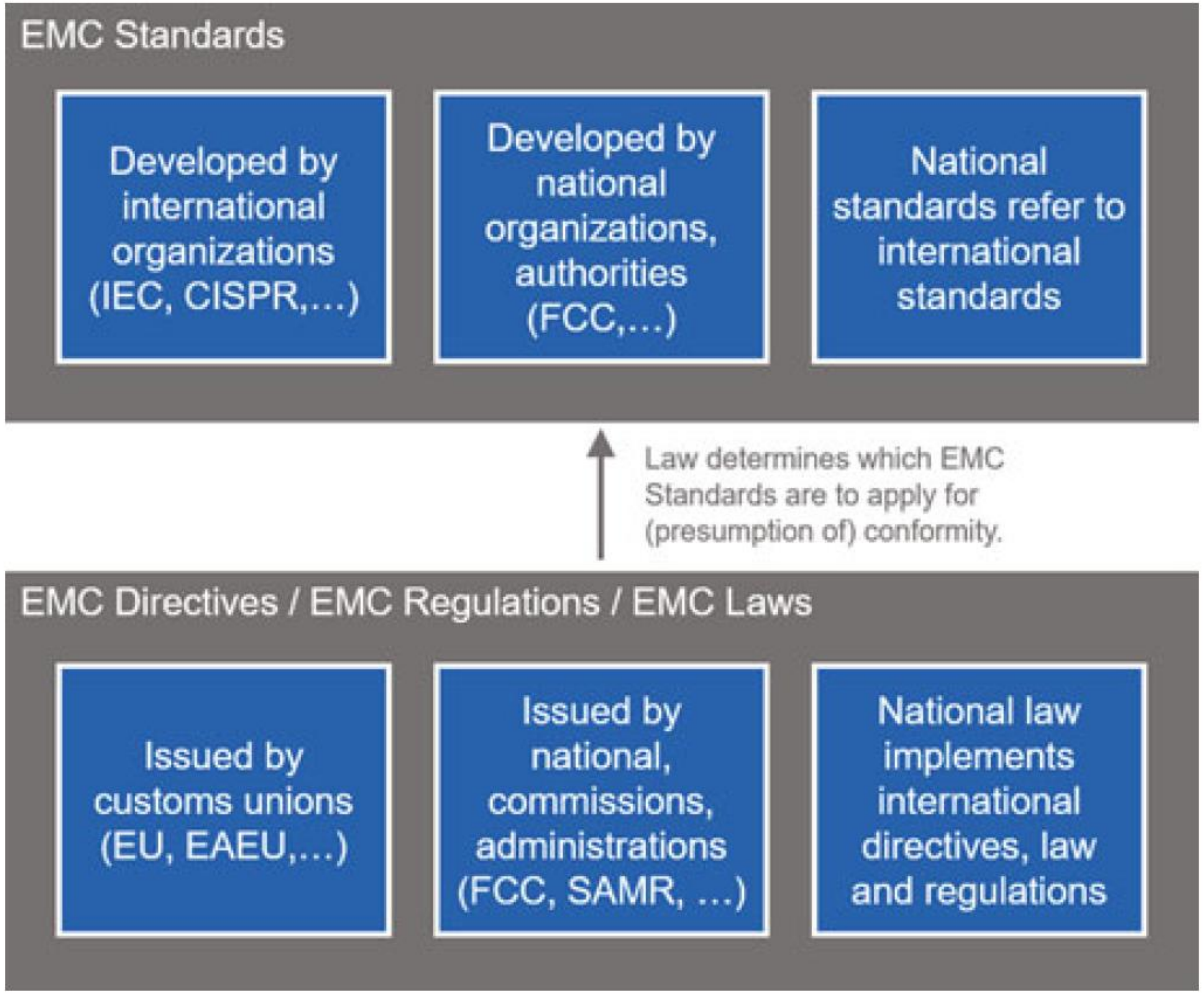
- Reduce Conducted emissions
  - Radio frequency conducted emissions
    - To prevent connected cables from radiating and
    - To avoid the interference of connected equipment
  - Harmonics
    - To prevent distortion of public mains supply
  - Flickers
    - to avoid unsteadiness
- Reduce Radiated emissions
  - To prevent disturbance of nearby electrical and electromechanical equipment

EMI standards

- Conducted EMI standards
  - measurement done on the connecting cables
  - Frequency range depends on products and standards to comply
    - 150 kHz to 30MHz (CISPR 32 and FCC 47)

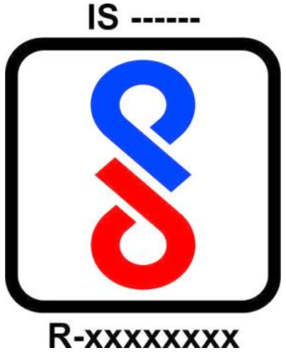
- Radiated EMI standards
  - measured in an anechoic or semi-anechoic chamber or at an open area test site (OATS).
  - frequency range depends on products and standards to comply
    - 30MHz to 6 GHz (CISPR 32)
    - 30MHz up to 40 GHz (FCC 47)

EMC regulations

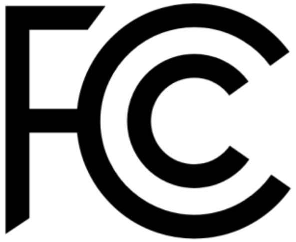


EMC compliance mark

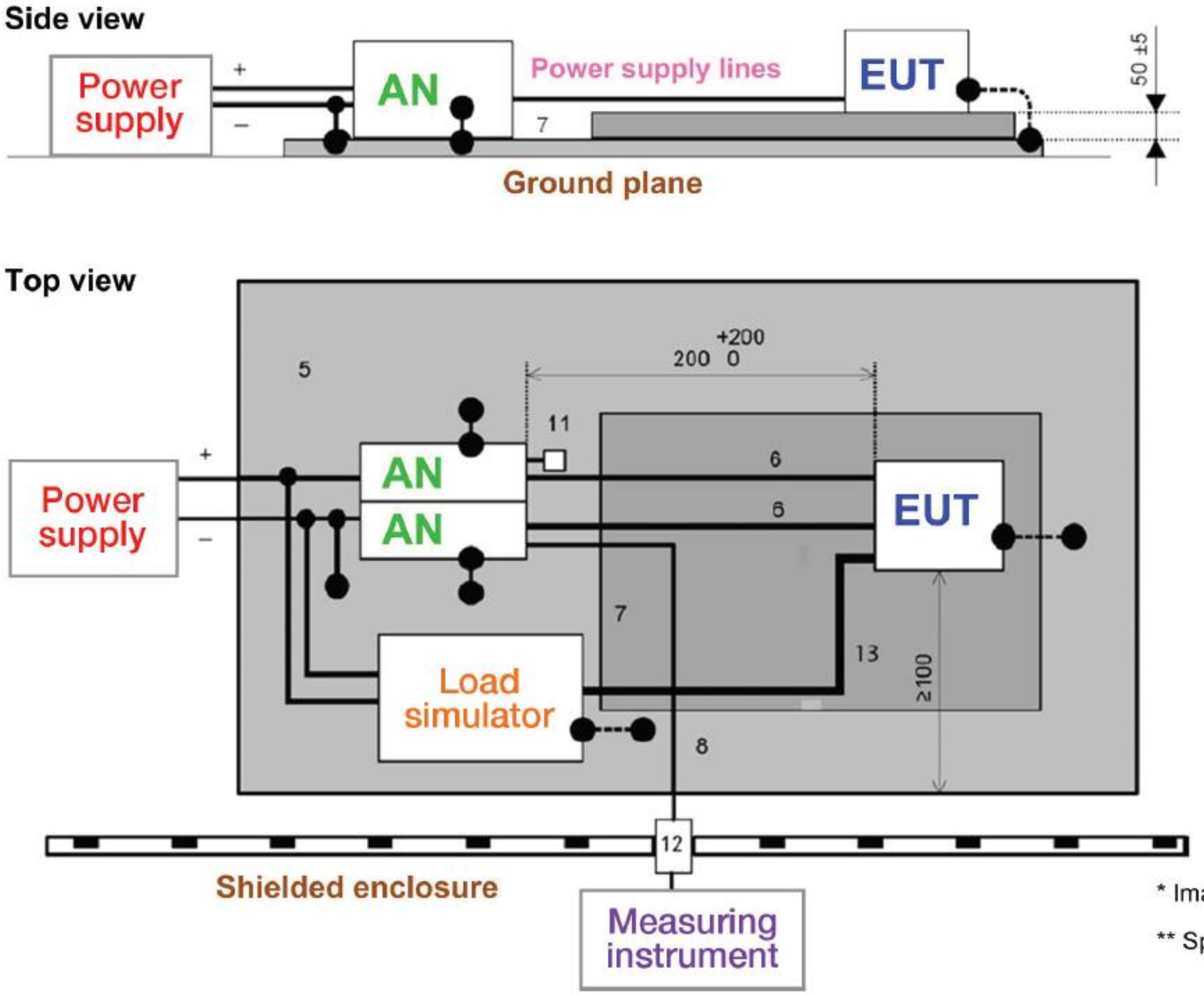
- Bureau of Indian Standards (BIS) mandates Compulsory Registration Scheme (CRS)
  - BIS CRS Mark



- For imported products, following marks are recognized,
  - CE Mark (Europe)
  - FCC Mark (USA)



CISPR 25 EMI test setup



5 = Reference ground plane

6 = Power supply lines

7 = Low relative permittivity support, $\varepsilon_R \leq 1.4$

8 = High-quality 50-Ω coaxial cable,

11 = 50 Ω load termination

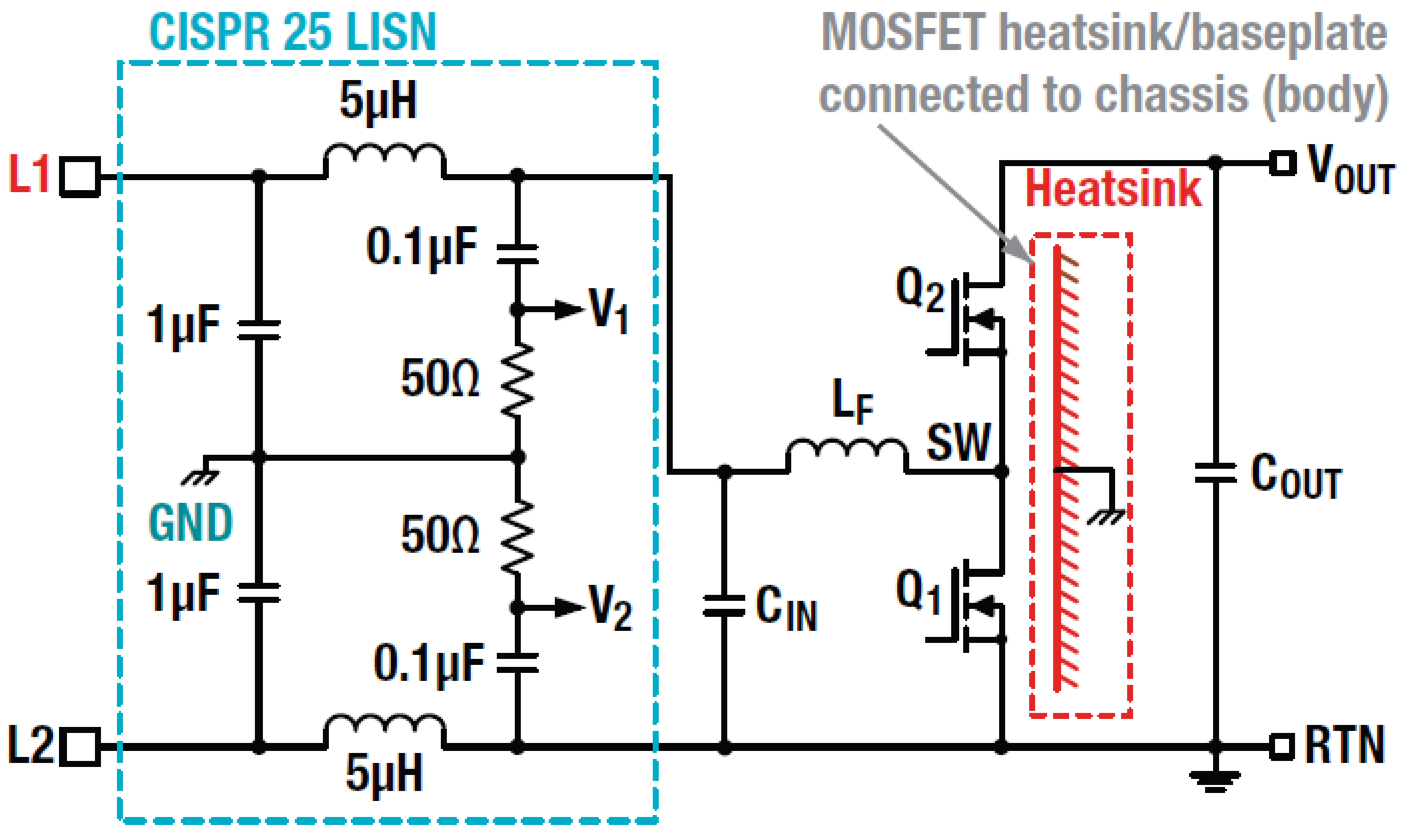
12 = Bulkhead connector

13 = Test harness (excluding power lines)

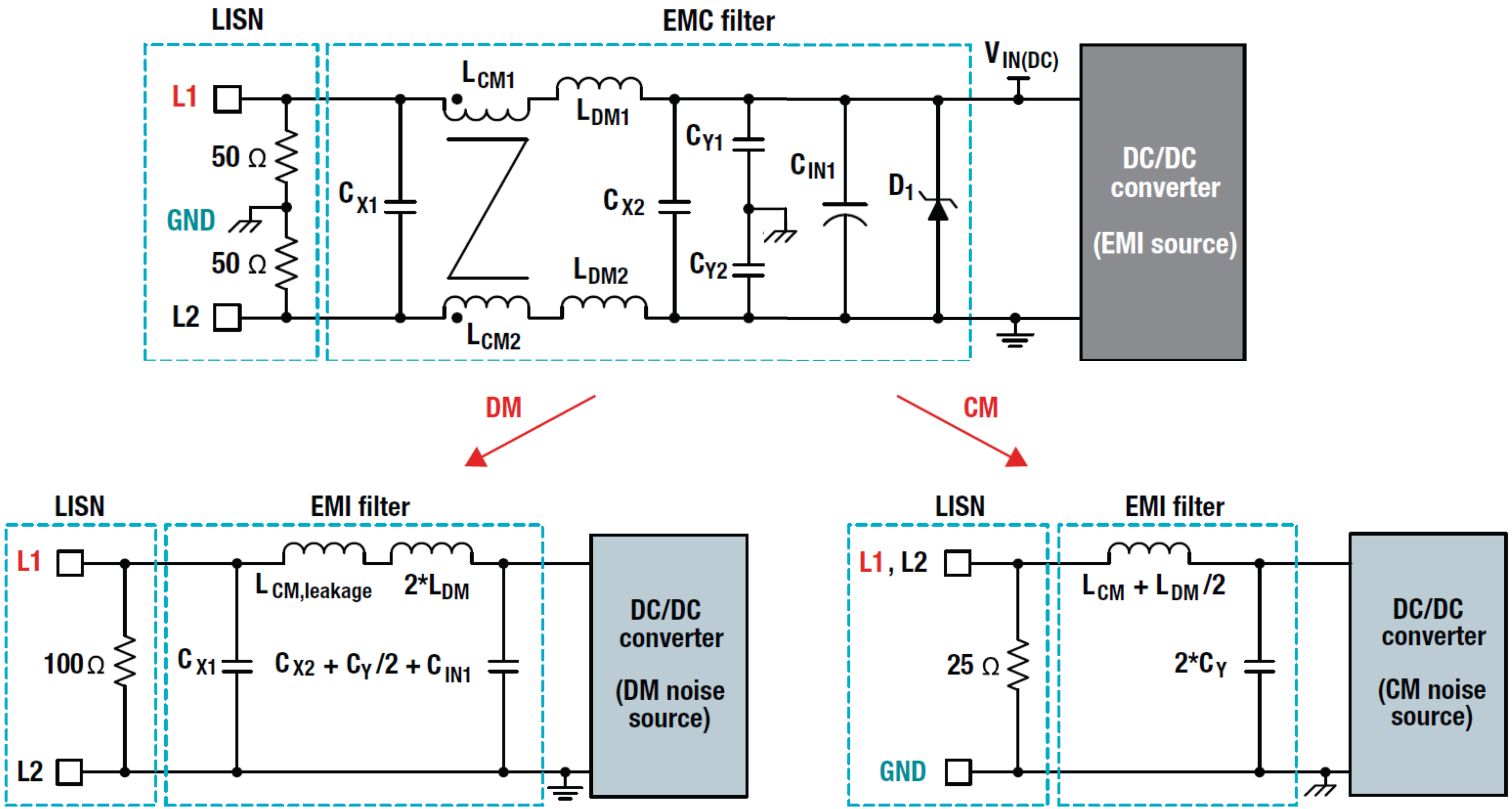
* Image adapted from CISPR 25 ed. 4 specification

** Spatial distances in mm

CISPR 25 EMI test example

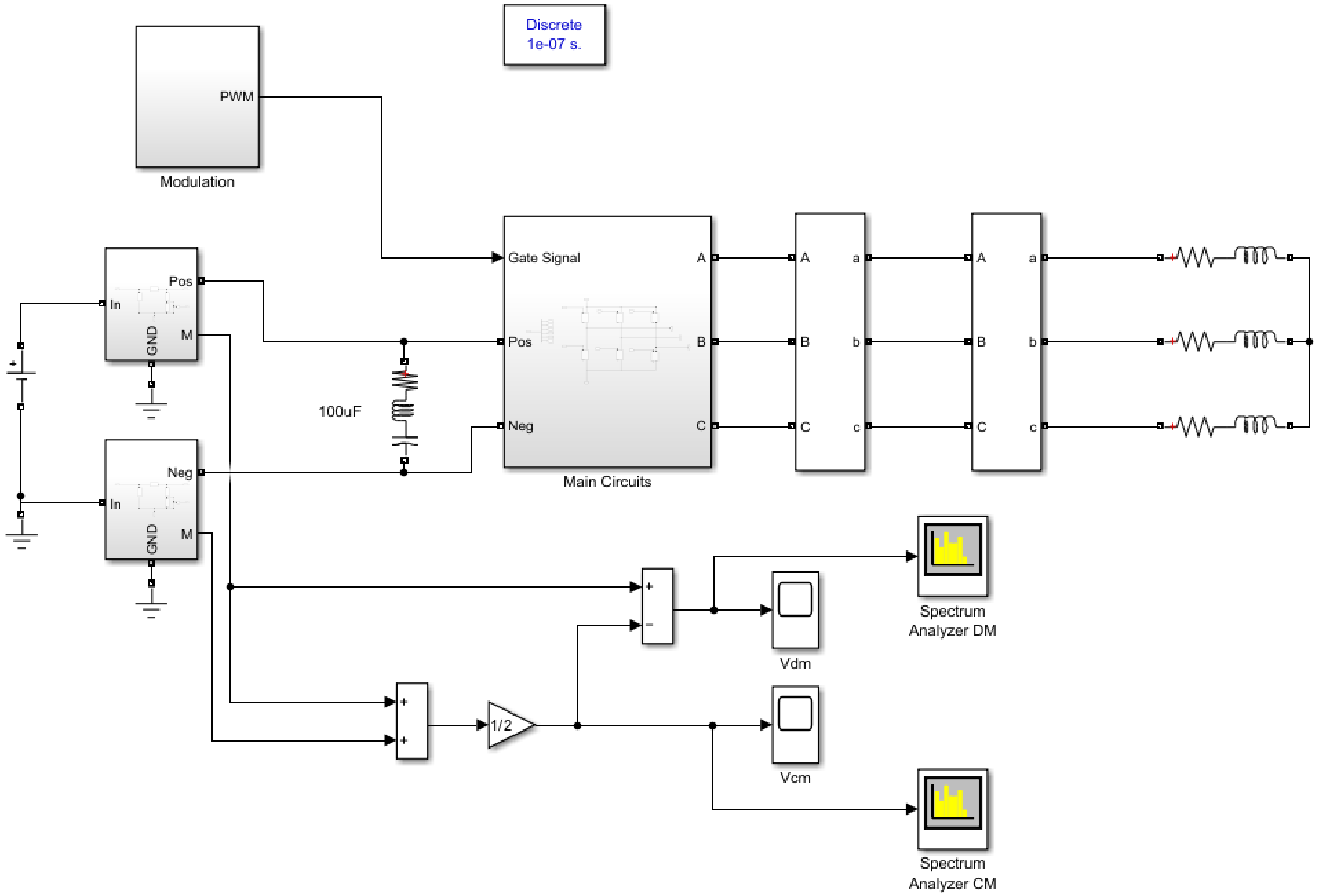


EMI Filter

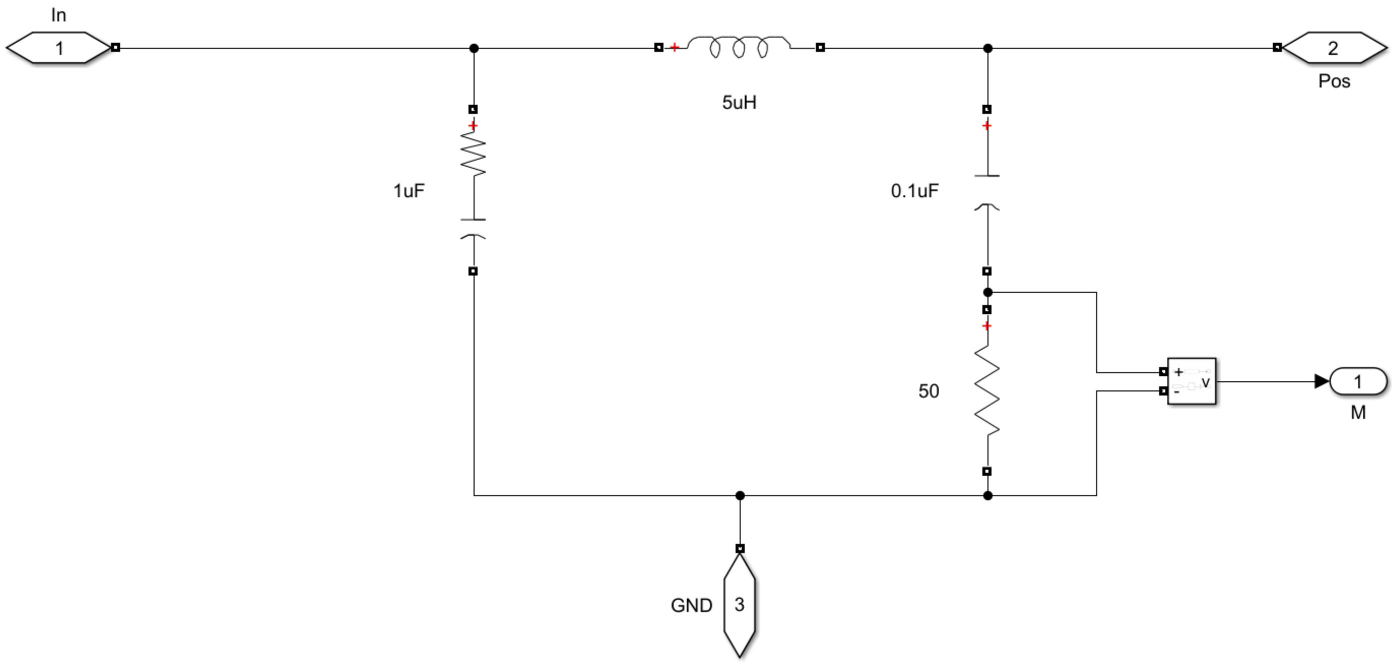


LISN
EMC filter
L1
50 Ω
GND
50 Ω
L2
C_{X1}
L_{CM1}
L_{DM1}
L_{CM2}
L_{DM2}
C_{X2}
C_{Y1}
C_{Y2}
C_{IN1}
D_1
$V_{IN(DC)}$
DC/DC converter
(EMI source)
DM
CM
LISN
EMI filter
L1
100 Ω
L2
C_{X1}
$L_{CM,leakage}$
$2*L_{DM}$
$C_{X2} + C_Y/2 + C_{IN1}$
DC/DC converter
(DM noise source)
LISN
EMI filter
L1, L2
25 Ω
GND
$L_{CM} + L_{DM}/2$
$2*C_Y$
DC/DC converter
(CM noise source)

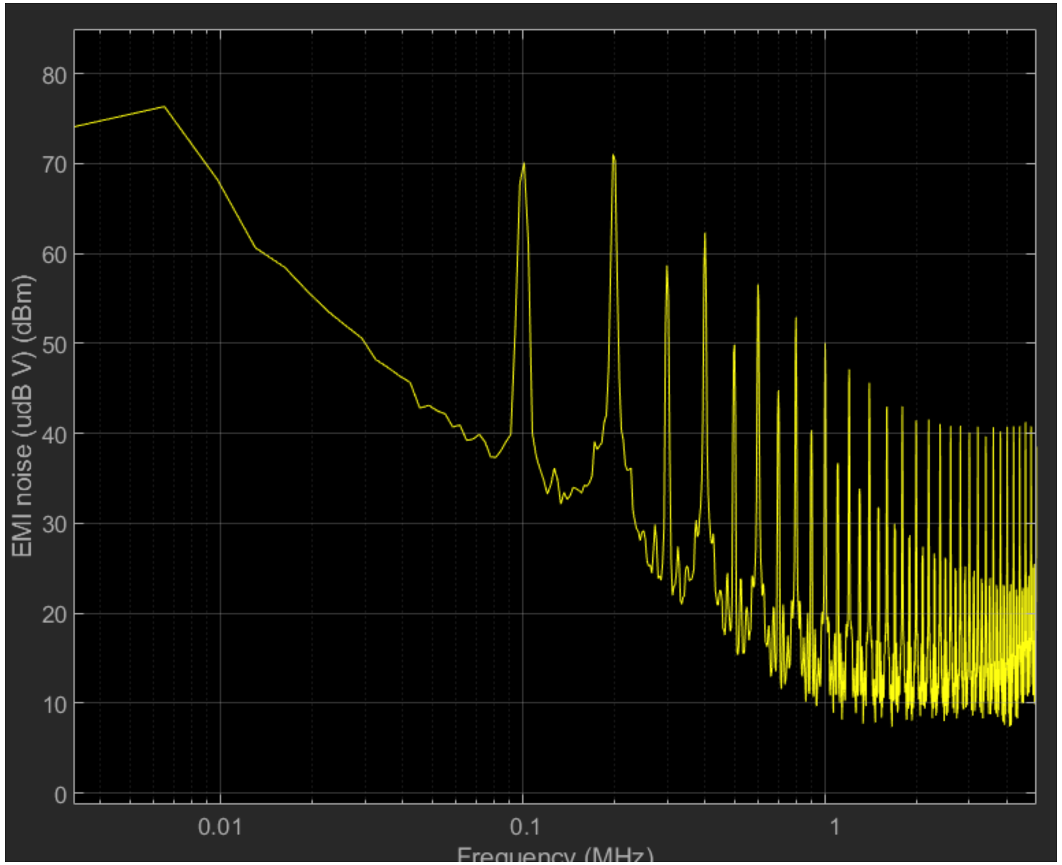
EMI noise simulation



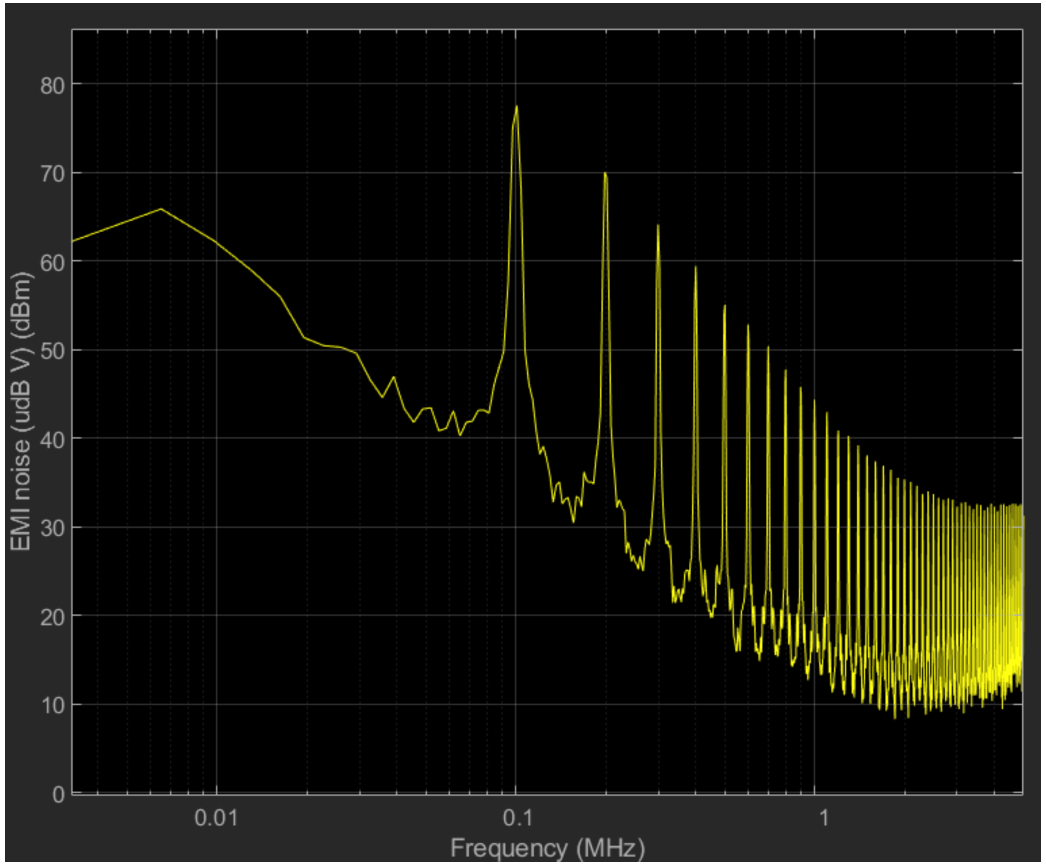
LISN model



EMI DM noise comparison



3-ph symmetric SVPWM



2-ph symmetric SVPWM

Thank you!