METU EE7566
Electric Drives in Electric and Hybrid Electric Vehicles

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Office: C-107

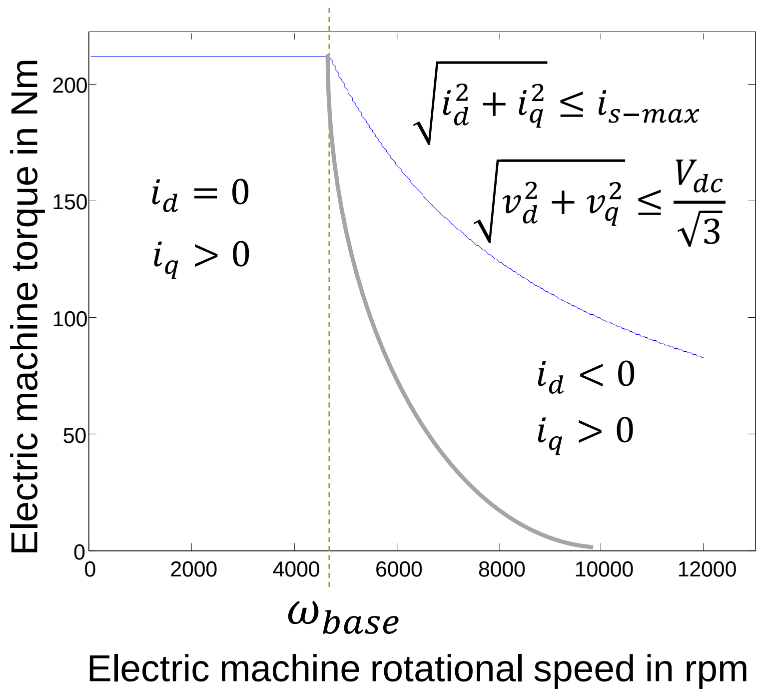
Content

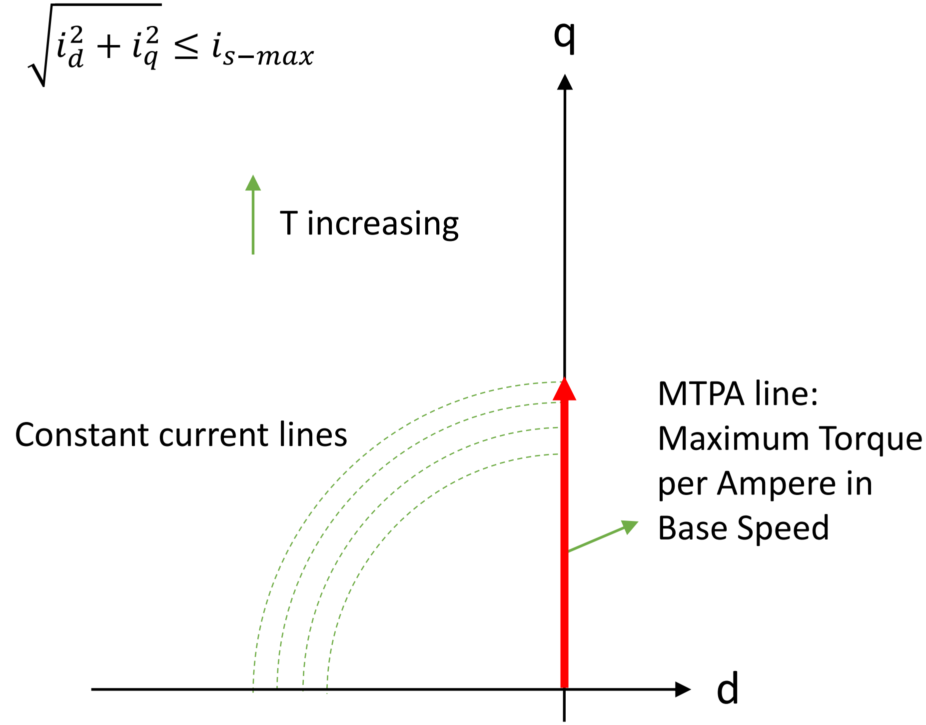
- MTPA Operation
- Field Oriented Control (FOC)
- 3-phase inverter modulation techniques
    - Sine-PWM
    - Space vector modulation

Maximum Torque per Ampere Operation in SMPMSM

$$T_{mech} = \frac{3}{2} pp \Psi_{mf}^{r} \, i_q$$

$$\sqrt{i_d^2 + i_q^2} \le i_{s-max}$$



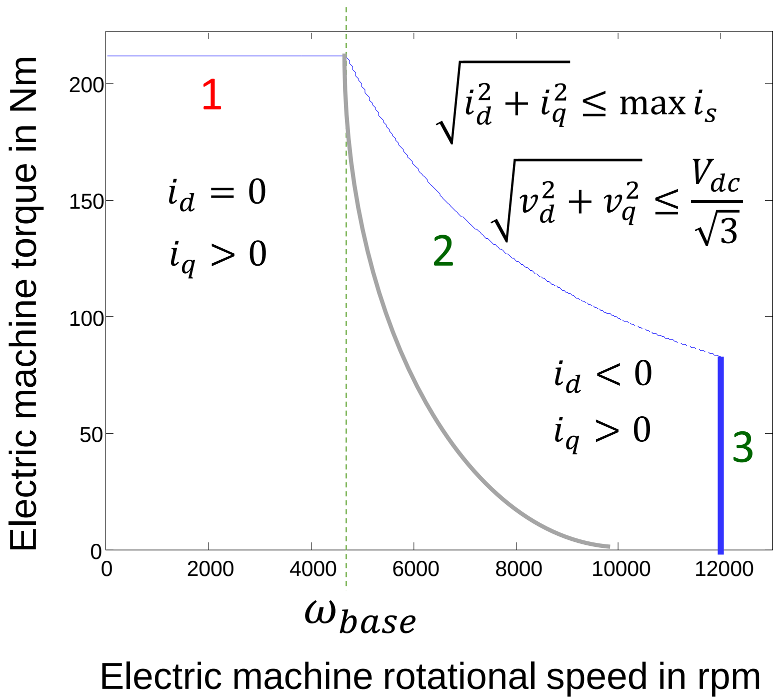


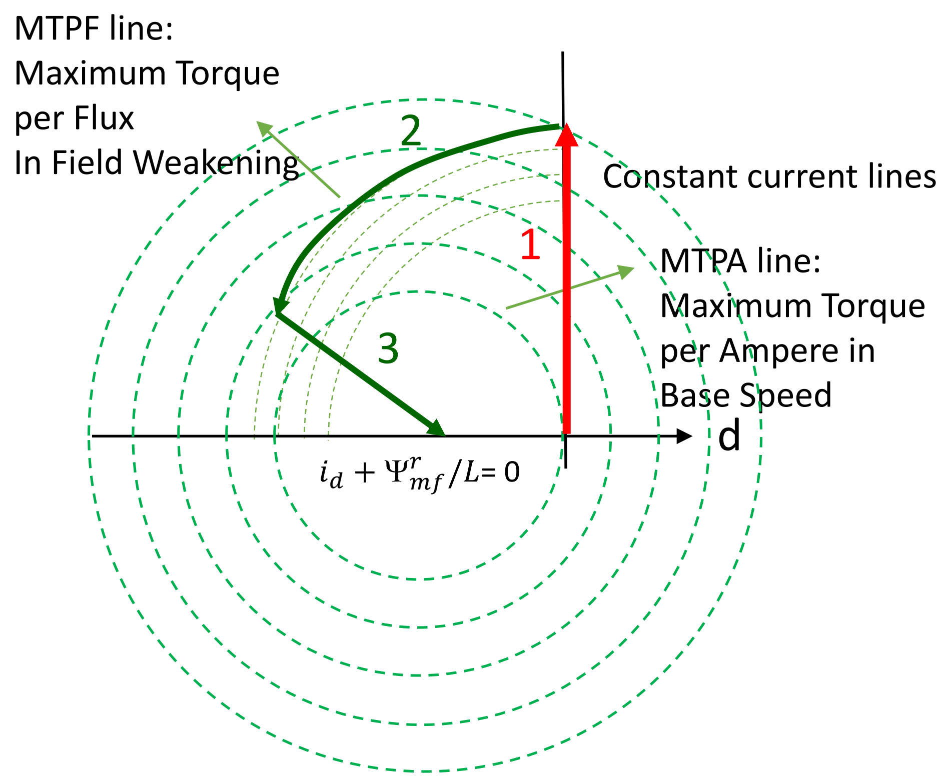
Maximum Flux per Ampere Operation in SMPMSM

$$T_{mech} = \frac{3}{2} pp \Psi_{mf}^{r} \, i_q$$

Stator flux limit: $\sqrt{\left(L_d i_d + \Psi_{mf}^{r}\right)^2 + \left(-L_q i_q\right)^2} = L\sqrt{\left(i_d + \Psi_{mf}^{r}/L\right)^2 + \left(-i_q\right)^2} \leq \frac{V_{dc}}{\omega\sqrt{3}}$

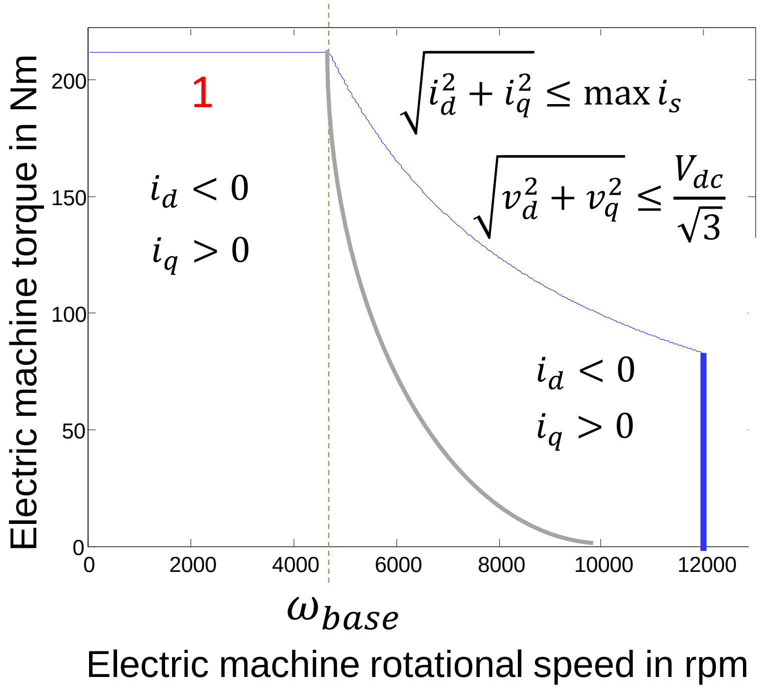
$for\ L_d = L_q = L$

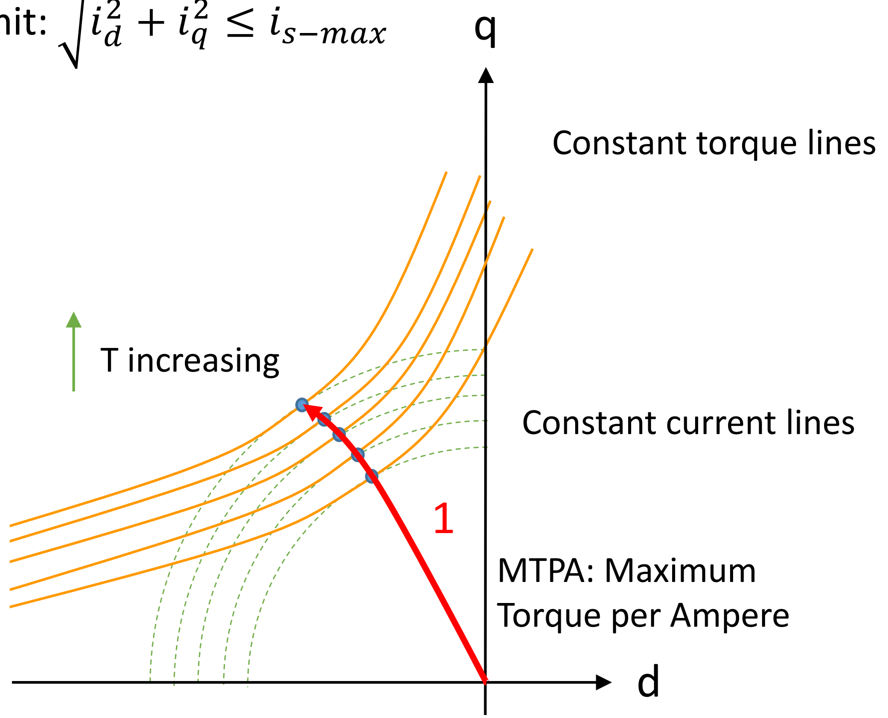




Maximum Torque per Ampere Operation in IPMSM

$T_{mech} = \frac{3}{2} pp \left(\Psi^r_{mf} - (L_q - L_d) i_d \right) i_q$ Current limit: $\sqrt{i_d^2 + i_q^2} \leq i_{s-max}$

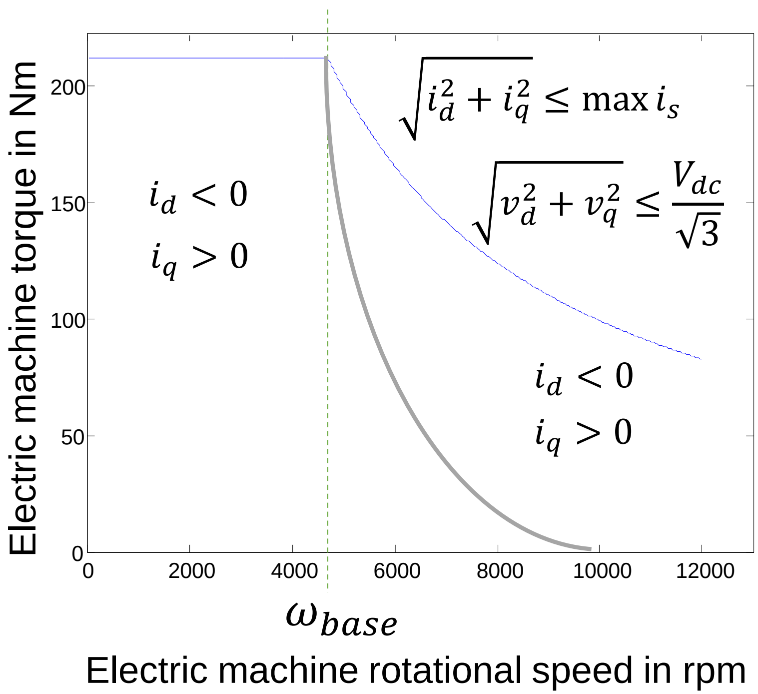




In base speed range, find minimum current that generated the torque desired.

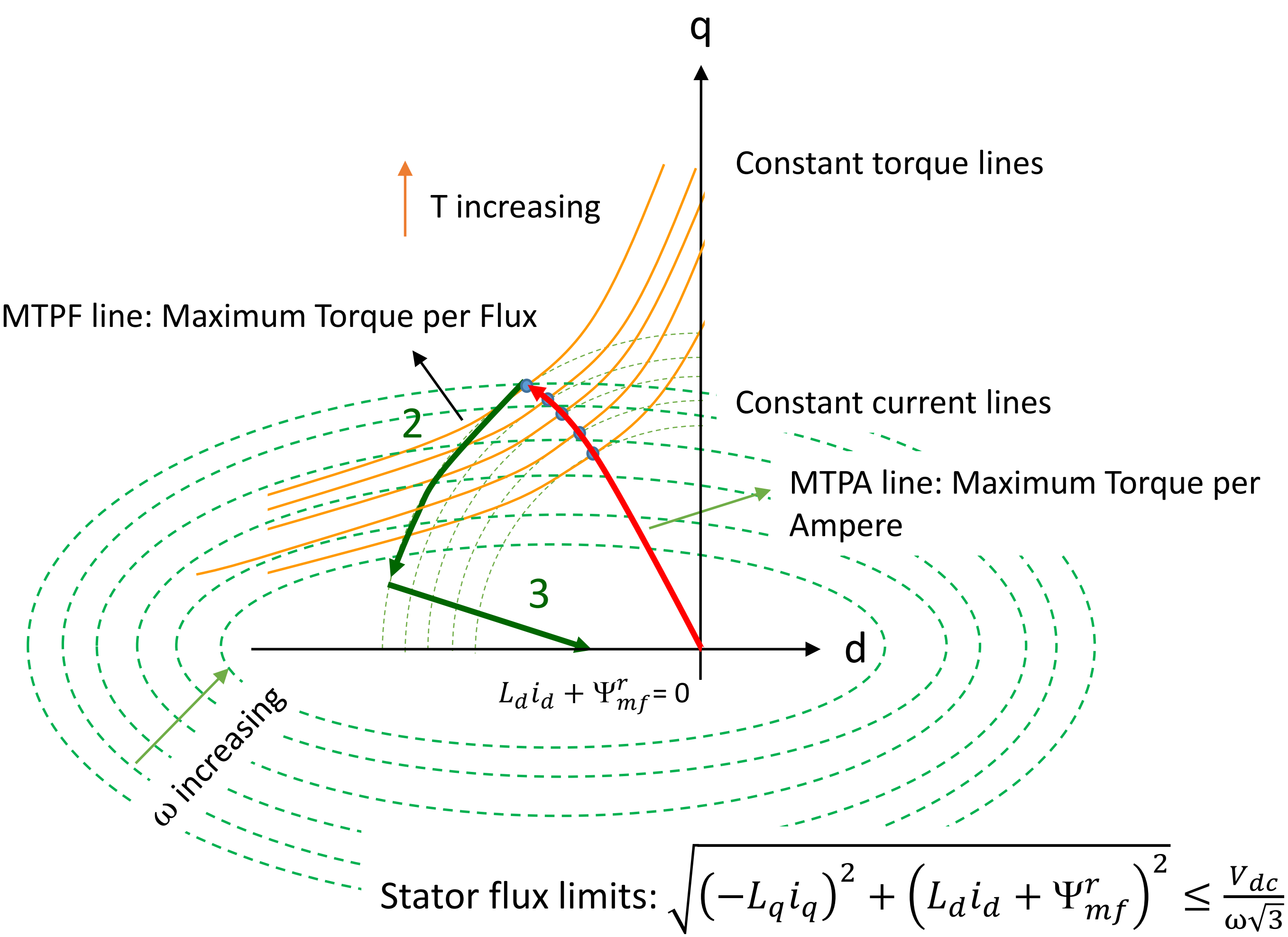
Maximum Torque per Ampere Operation in IPMSM

$$T_{mech} = \frac{3}{2} pp\, \Psi_{mf}^{r} i_q$$



In field weakening range, find minimum current that generated the torque desired within voltage limits.

Maximum Torque per Ampere Operation in IPMSM



Field Oriented Control

Main goal of the field oriented control is the high-dynamic control of SMs similar to dc machines. In dc machines, armature current is typically used to control torque and field current is used to control field at high speeds. We do not regulate field current to control torque due to larger time constants.

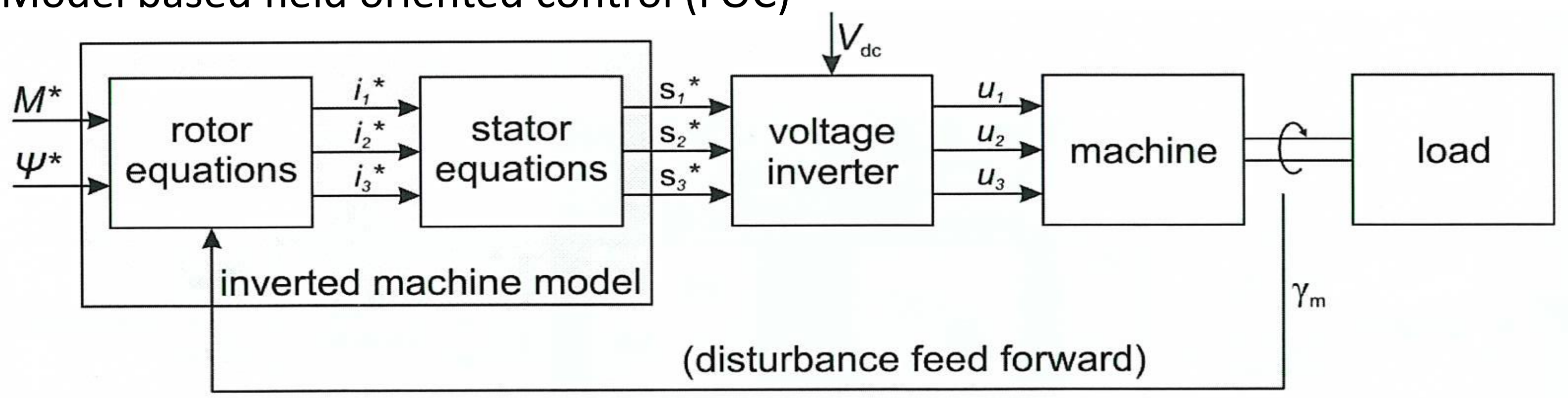
As we derived, q-component of stator current in rotor coordinates is the torque producing current component. Whereas, d-component of stator current in rotor coordinates is the filed producing current component.

i_d ➔ Producing stator flux in the direction of rotor flux (we can intensify and weaken rotor flux)

i_q ➔ Producing stator flux that is responsible for torque production

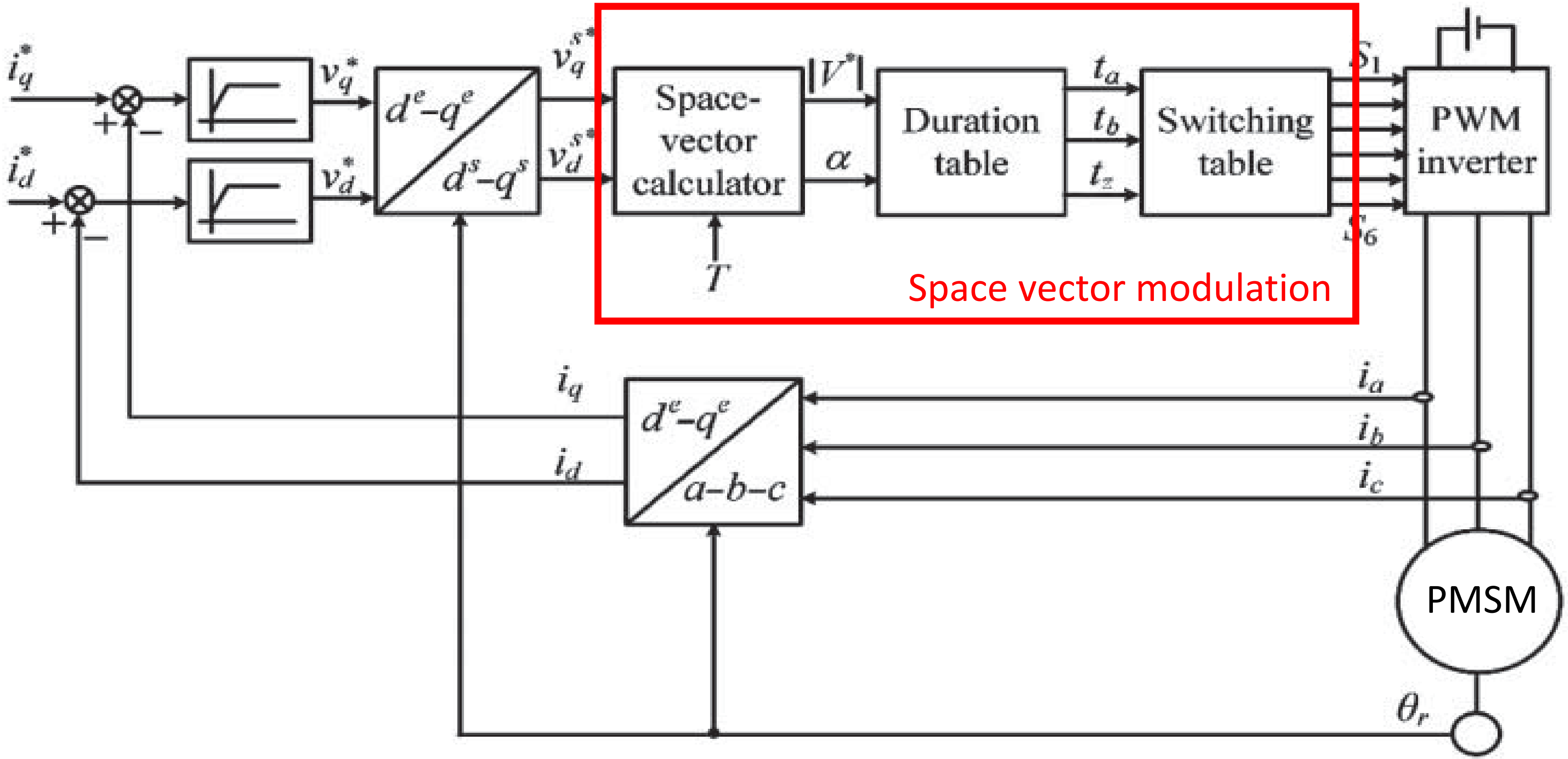
So, in dq coordinates, flux producing and torque producing components are decoupled.

Model based field oriented control (FOC)

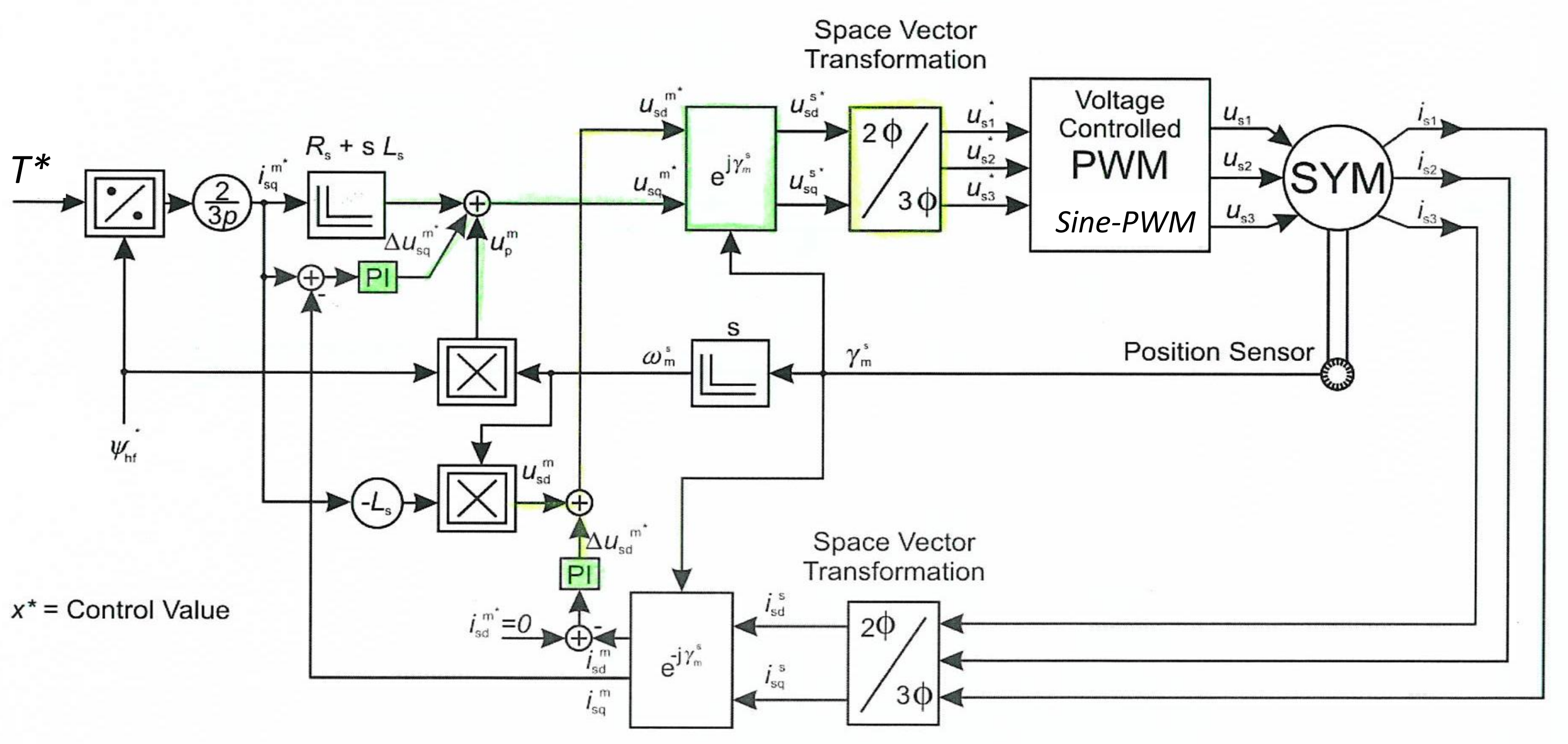


Field Oriented Control (FOC)

Aim: High dynamic control of synchronous machines similar to DC machines



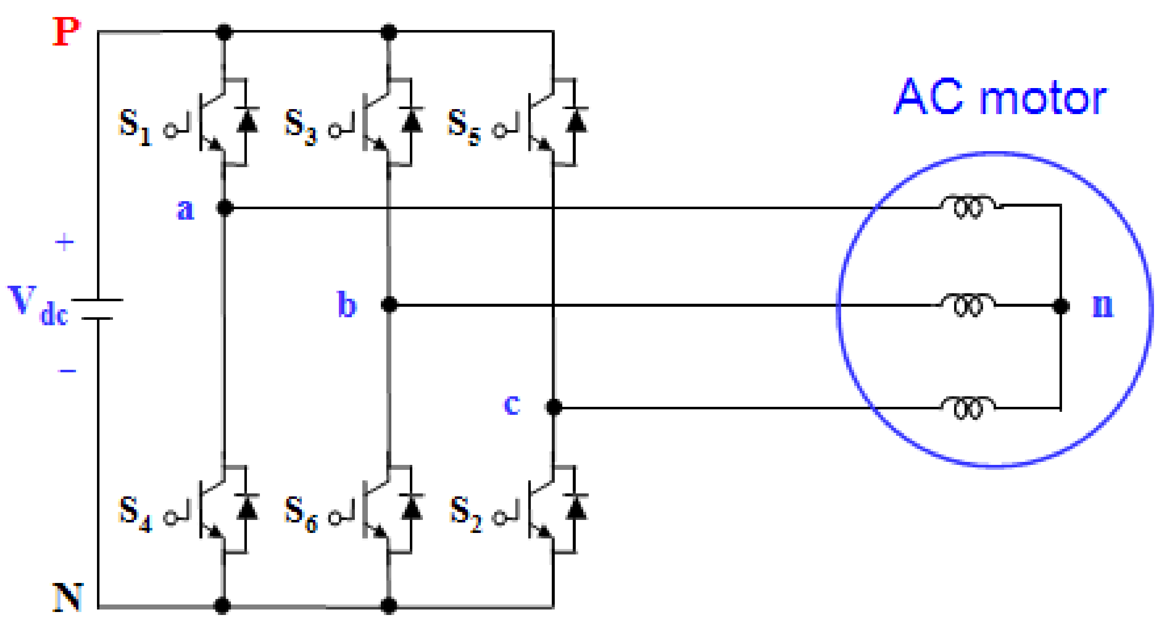
FOC of a Synchronous Machine with Sine-PWM



Modulation Techniques

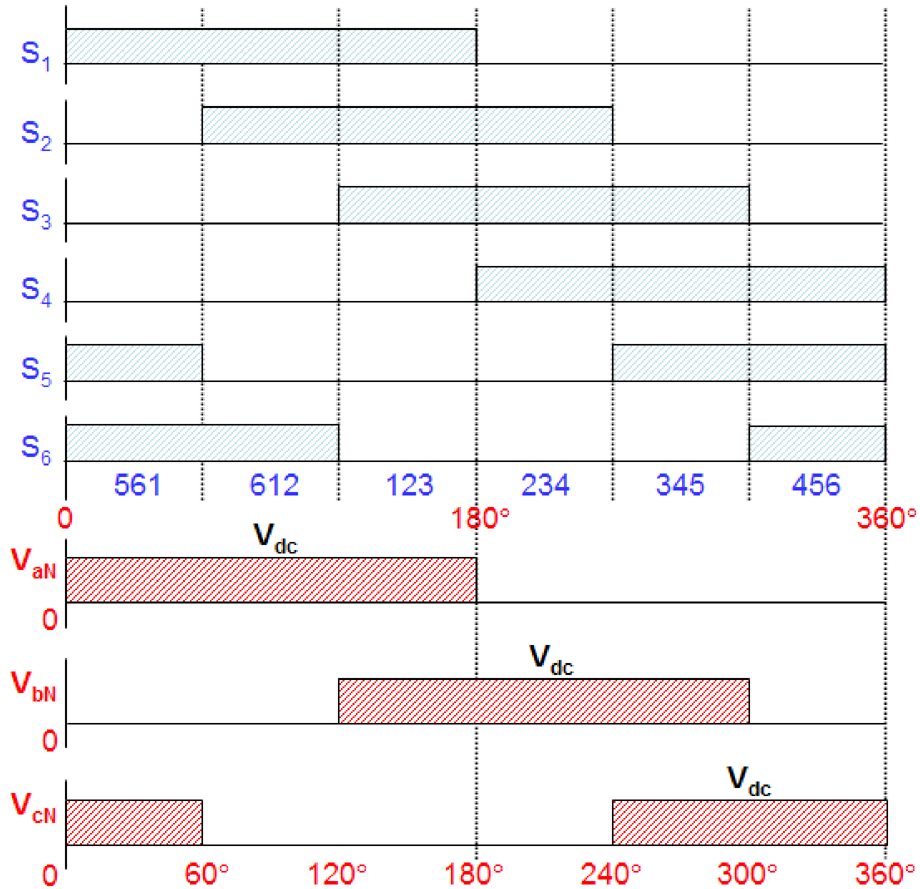
<u>Basic modulation techniques:</u>

- **Square-wave (six-step) operation**
- **Sinusoidal Pulse Width Modulation (Sine-PWM)**
- Hysteresis Current Control
- **Space Vector Modulation (SVM)**



Why switches are called that way?

Gating signals, switching sequence and line to negative voltages at six-step operation

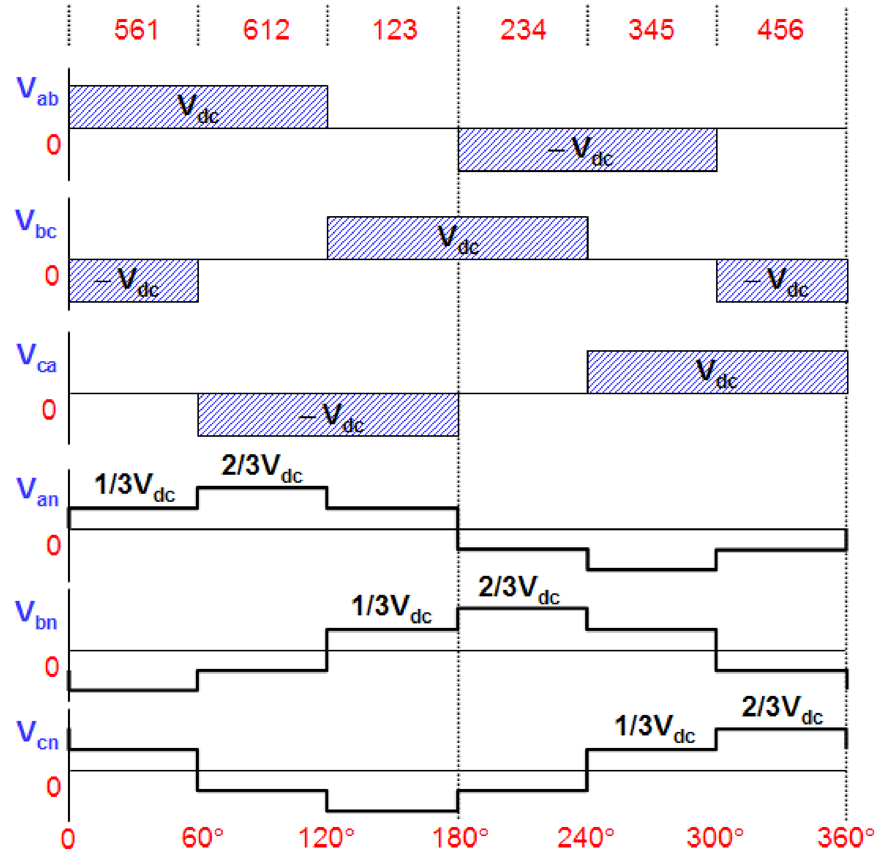


Waveforms of gating signals, switching sequence, line to negative voltages for six-step voltage source inverter.

Square-wave (Six-step) Operation

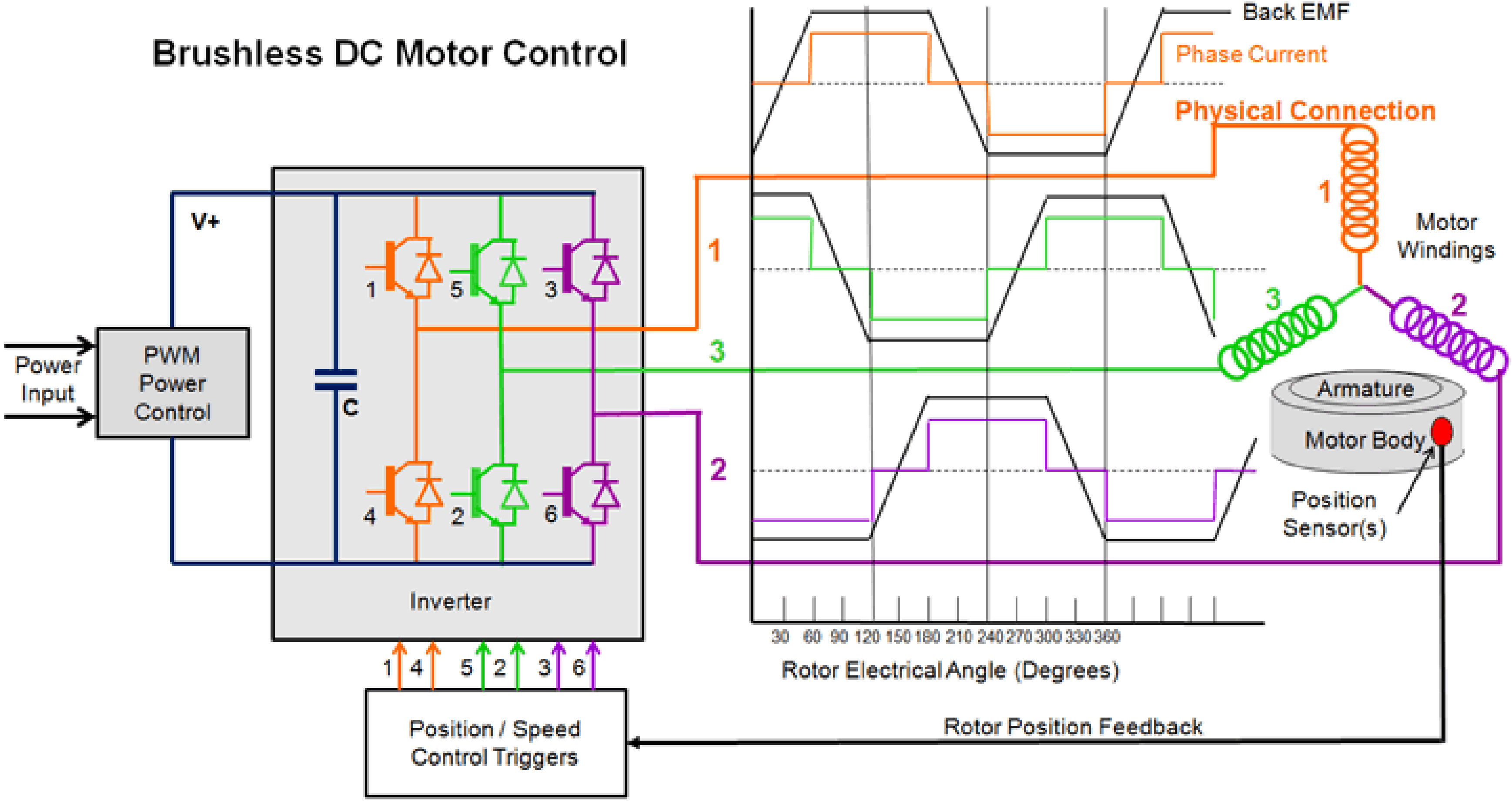
Line to line voltages (V_{ab}, V_{bc}, V_{ca}) and line to neutral voltages (V_{an}, V_{bn}, V_{cn})

- Line to line voltages
  - ⇨ $V_{ab} = V_{aN} - V_{bN}$
  - ⇨ $V_{bc} = V_{bN} - V_{cN}$
  - ⇨ $V_{ca} = V_{cN} - V_{aN}$
- Phase voltages
  - ⇨ $V_{an} = 2/3V_{aN} - 1/3V_{bN} - 1/3V_{cN}$
  - ⇨ $V_{bn} = -1/3V_{aN} + 2/3V_{bN} - 1/3V_{cN}$
  - ⇨ $V_{cn} = -1/3V_{aN} - 1/3V_{bN} + 2/3V_{cN}$

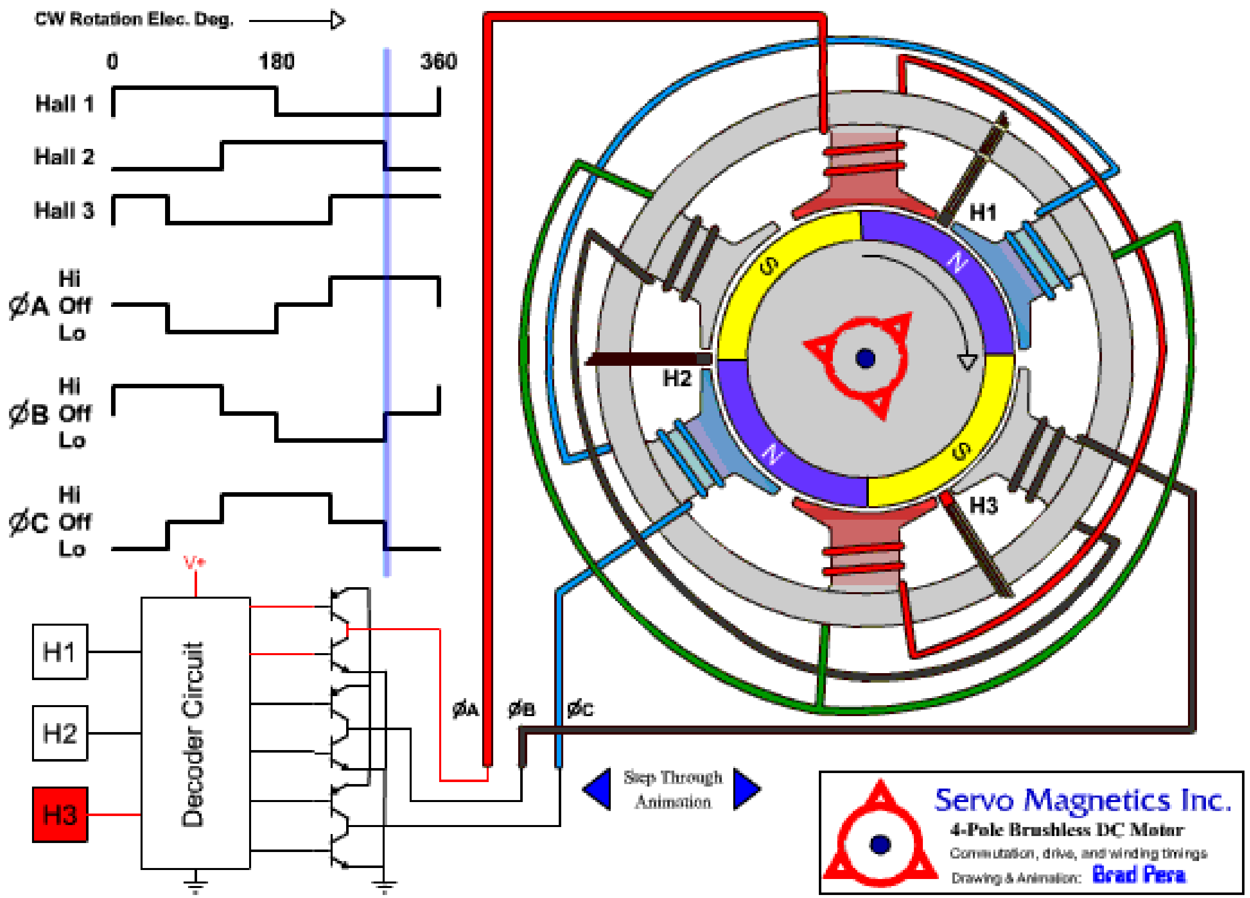


Waveforms of line to neutral (phase) voltages and line to line voltages for six-step voltage source inverter.

Square-wave (Six-step) Operation



Square-wave (Six-step) Operation



Square-wave (Six-step) Operation

Characteristics of Six-step VSI

- It is called “six-step inverter” because of the presence of six “steps” in the line to neutral (phase) voltage waveform

- Harmonics of order three and multiples of three are absent from both the line to line and the line to neutral voltages and consequently absent from the currents

- Output amplitude in a three-phase inverter can be controlled by only change of DC-link voltage (V_{dc})

➢ Amplitude of line to line voltages (V_{ab}, V_{bc}, V_{ca})

- Fundamental Frequency Component $(V_{ab})_1$

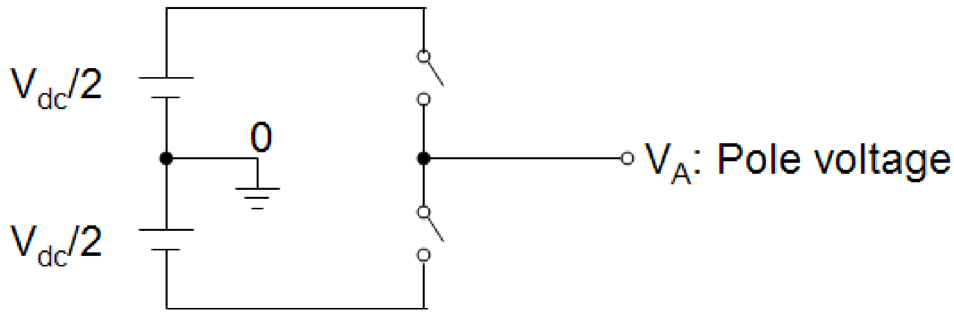
$$\mathbf{(V_{ab})_1(rms)} = \frac{\sqrt{3}}{\sqrt{2}}\frac{4}{\pi}\frac{V_{dc}}{2} = \frac{\sqrt{6}}{\pi}V_{dc} \approx 0.78V_{dc}$$

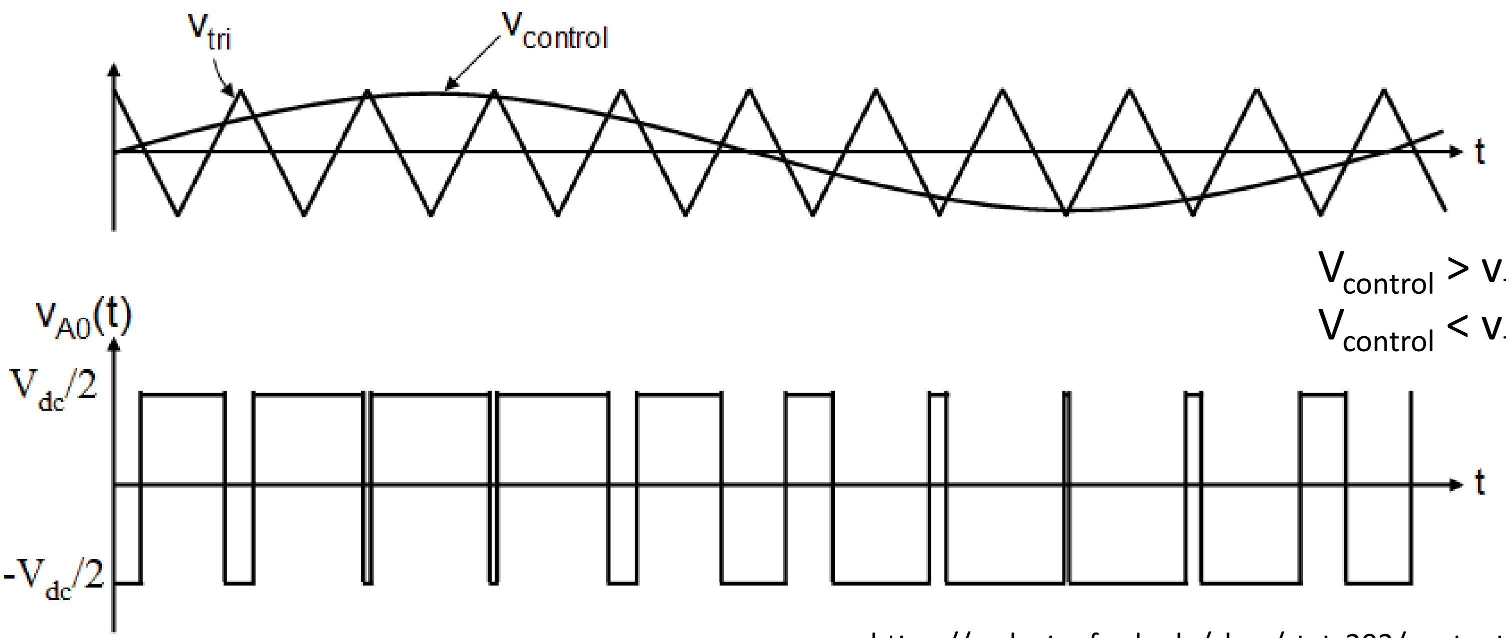
- Harmonic Frequency Components $(V_{ab})_h$

: amplitudes of harmonics decrease inversely proportional to their harmonic order

$$\mathbf{(V_{ab})_h(rms)} = \frac{0.78}{h}V_{dc} \quad \text{where,} \quad h = 6n \pm 1 \quad (n = 1, 2, 3, ...)$$

Sinusoidal Pulse Width Modulation (Sine-PWM)

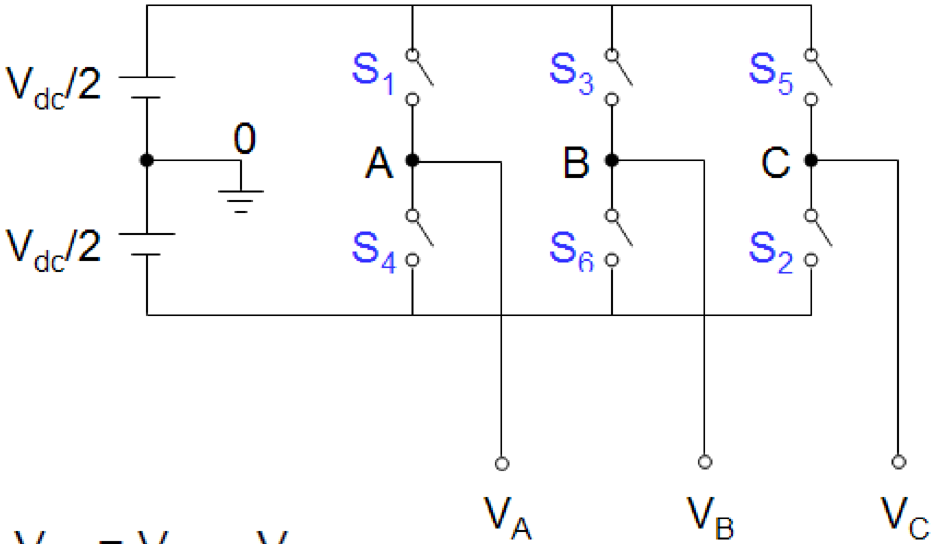




$V_{control} > v_{tri}$, $V_{A0} = V_{dc}/2$
$V_{control} < v_{tri}$, $V_{A0} = -V_{dc}/2$

https://web.stanford.edu/class/stats202/content/lec24-condensed.pdf

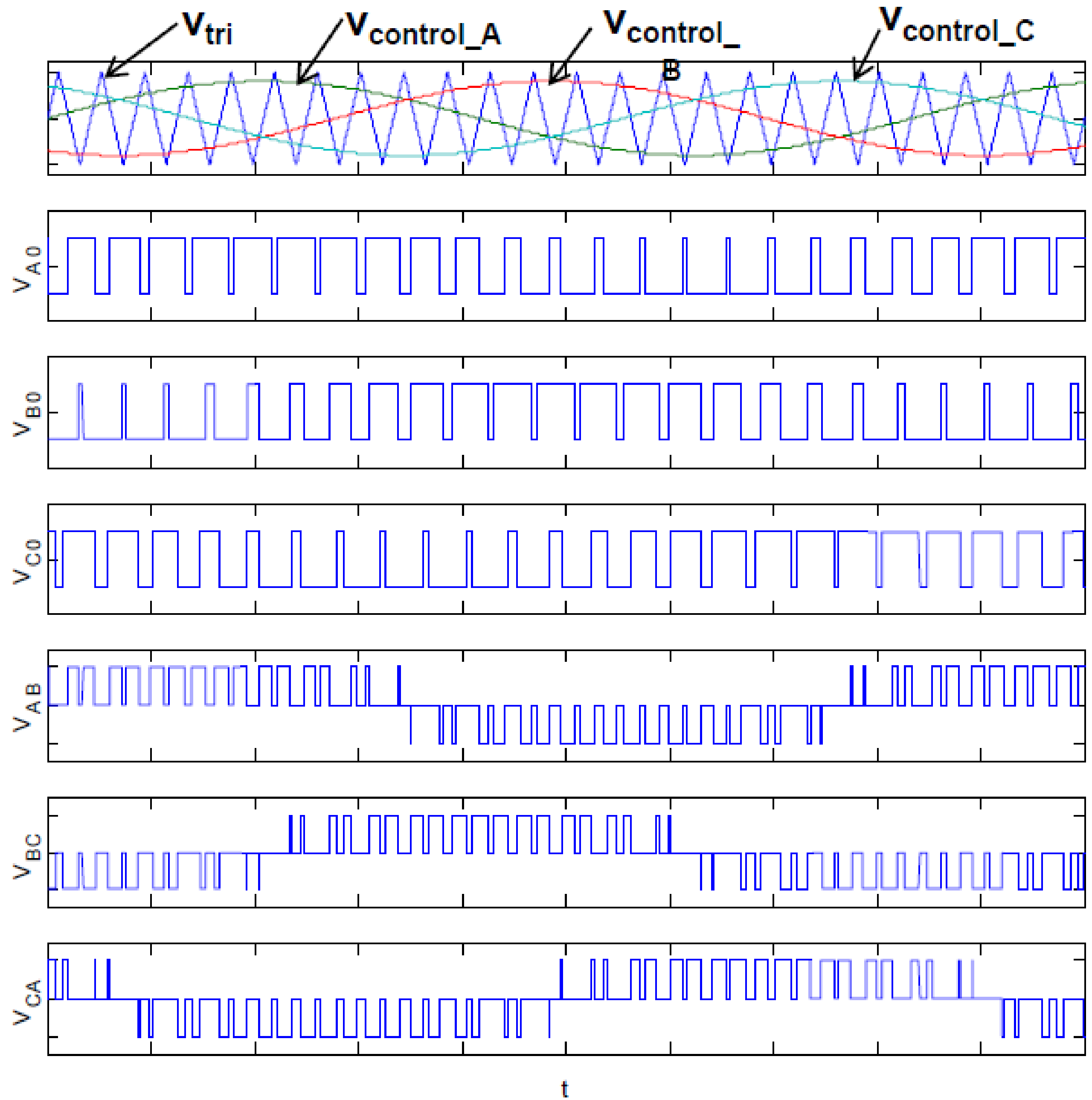
Sine-PWM



$$V_{AB} = V_{A0} - V_{B0}$$
$$V_{BC} = V_{B0} - V_{C0}$$
$$V_{CA} = V_{C0} - V_{A0}$$

Frequency of $v_{tri} = f_s$: switching frequency
Frequency of $v_{control} = f_1$: fundamental frequency

Sine-PWM



v_{tri}
$v_{control\_A}$
$v_{control\_B}$
$v_{control\_C}$
v_{A0}
v_{B0}
v_{C0}
v_{AB}
v_{BC}
v_{CA}
t

Sine-PWM

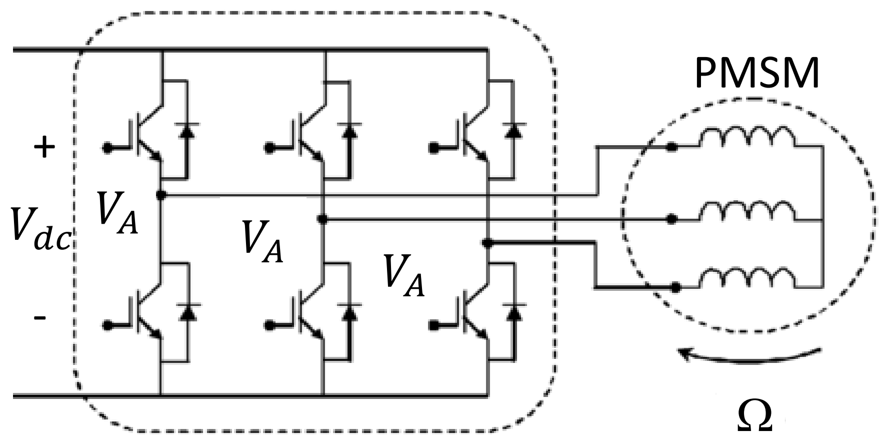
Disadvantages of PWM

- Increase of switching losses due to high PWM frequency
- EMI problems due to high-order harmonics
- Reduction of available voltage

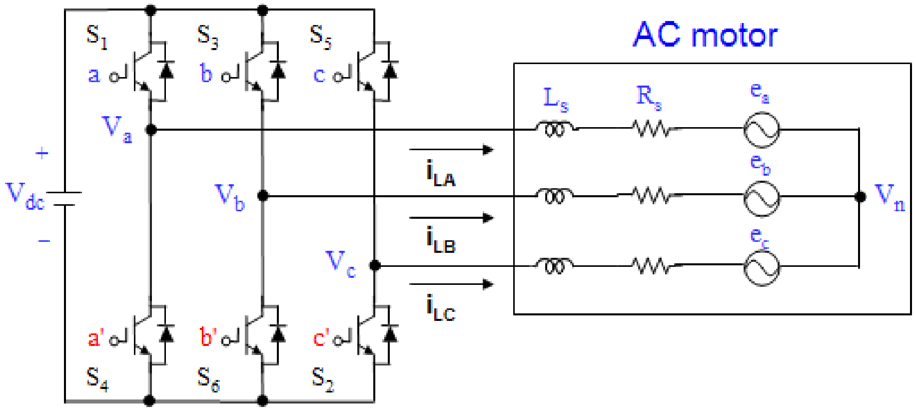
$$V_{AB} = V_A - V_B = \frac{V_{dc}}{2}\sin(\omega t) - \frac{V_{dc}}{2}\sin\left(\omega t - \frac{2\pi}{3}\right)$$

$$= \frac{\sqrt{3}\ V_{dc}}{2}\sin\left(\omega t + \frac{2\pi}{12}\right)$$

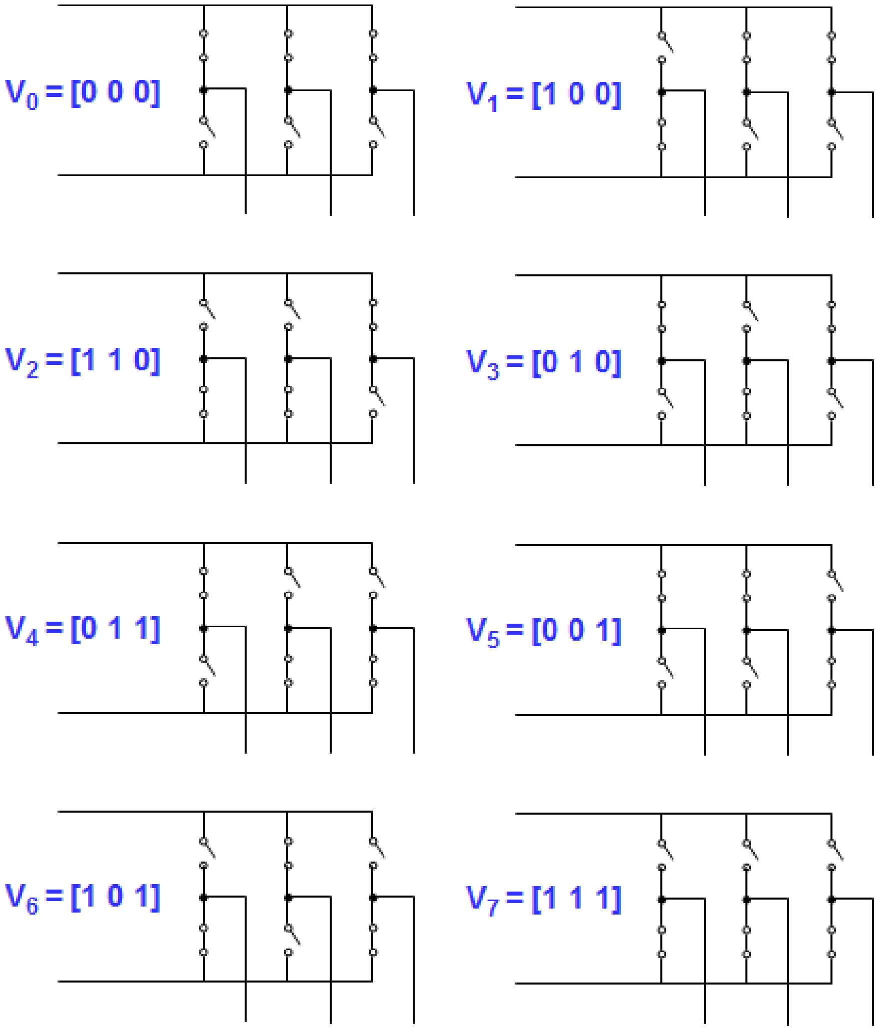
$$\hat{V}_{phase} = \frac{\sqrt{3}\ V_{dc}}{\sqrt{3}\ 2} = \frac{V_{dc}}{2}$$



Space Vector Pulse Width Modulation



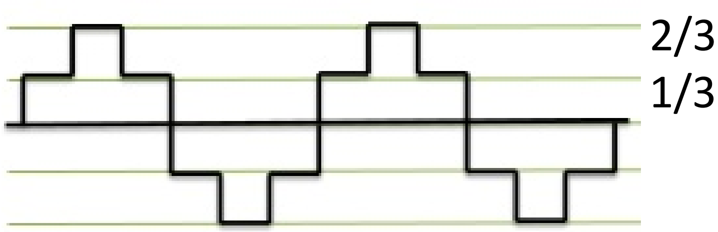
In 2-level 3-phase voltage source inverter (VSI), there are $2^3 = 8$ possible switching states $v_0 - v_7$.



Space Vector Pulse Width Modulation

Voltage Vectors	Line to neutral voltage			Line to line voltage		
	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0
V_1	2/3	-1/3	-1/3	1	0	-1
V_2	1/3	1/3	-2/3	0	1	-1
V_3	-1/3	2/3	-1/3	-1	1	0
V_4	-2/3	1/3	1/3	-1	0	1
V_5	-1/3	-1/3	2/3	0	-1	1
V_6	1/3	-2/3	1/3	1	-1	0
V_7	0	0	0	0	0	0

Voltage values must be multiplied with V_{dc}



Output of switching states, line to neutral (no PWM applied)

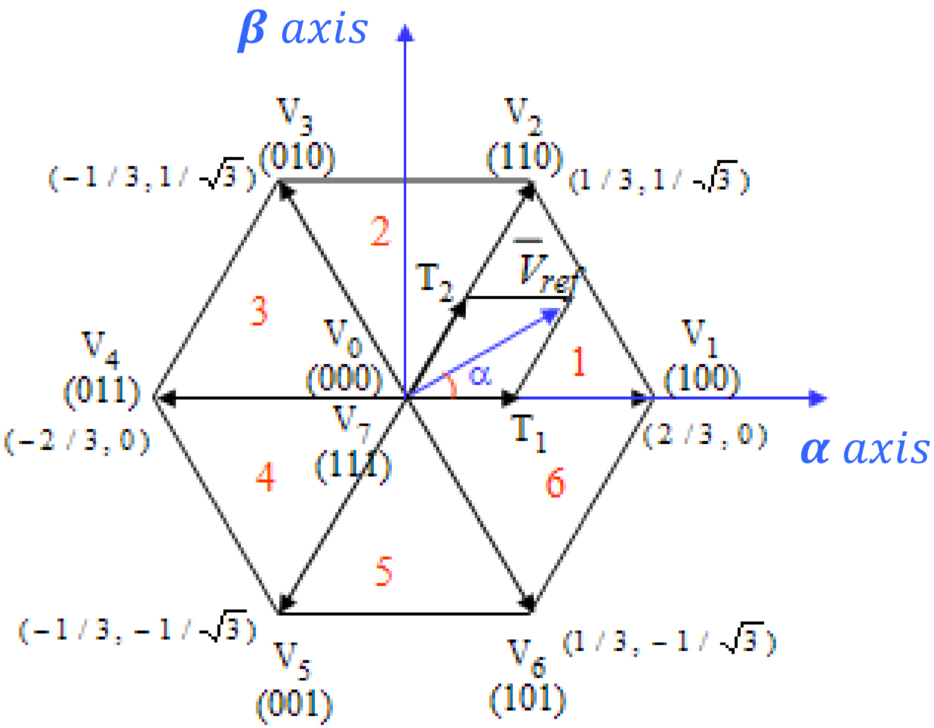
Space Vector Pulse Width Modulation

Voltage Vectors	Line to neutral voltage			Line to line voltage			$\alpha\beta$ voltage	
	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}	v_α	v_β
V_0	0	0	0	0	0	0	0	0
V_1	2/3	-1/3	-1/3	1	0	-1	$^2/_3$	0
V_2	1/3	1/3	-2/3	0	1	-1	$^1/_3$	$^{\sqrt{3}}/_3$
V_3	-1/3	2/3	-1/3	-1	1	0	$^{-1}/_3$	$^{\sqrt{3}}/_3$
V_4	-2/3	1/3	1/3	-1	0	1	$^{-2}/_3$	0
V_5	-1/3	-1/3	2/3	0	-1	1	$-^1/_3$	$^{-\sqrt{3}}/_3$
V_6	1/3	-2/3	1/3	1	-1	0	$^1/_3$	$^{-\sqrt{3}}/_3$
V_7	0	0	0	0	0	0	0	0

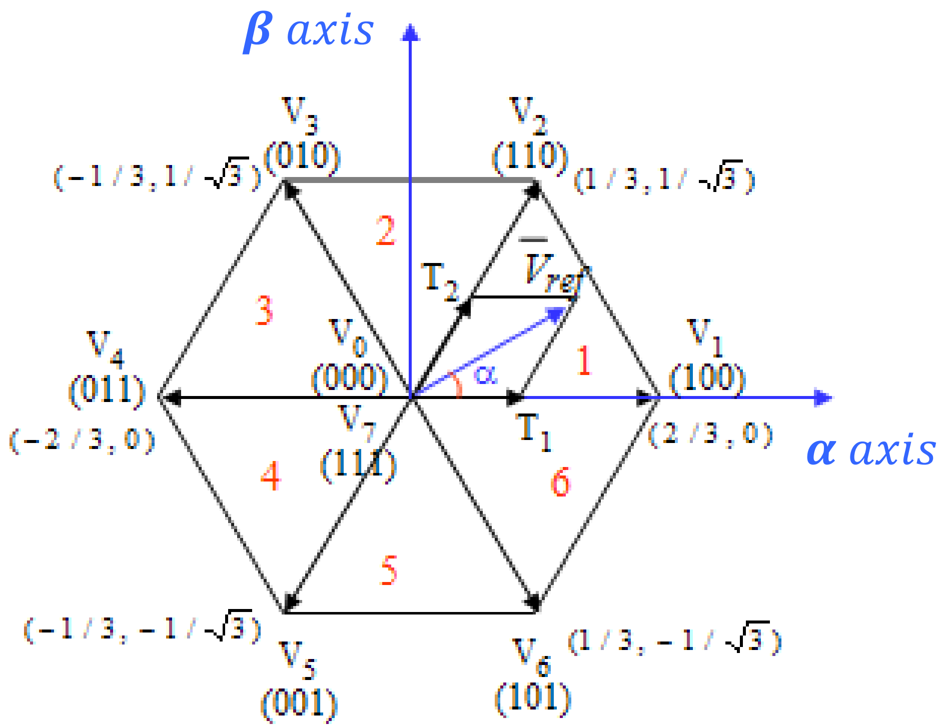
Voltage values must be multiplied with V_{dc}

Space Vector Pulse Width Modulation

$\alpha\beta$ voltage	
v_α	v_β
0	0
$^2/_3$	0
$^1/_3$	$^{\sqrt{3}}/_3$
$-^1/_3$	$^{\sqrt{3}}/_3$
$-^2/_3$	0
$-^1/_3$	$-^{\sqrt{3}}/_3$
$^1/_3$	$-^{\sqrt{3}}/_3$
0	0



Space Vector Pulse Width Modulation



- Treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency
- This PWM technique approximates the reference voltage v_{ref} by a combination of the eight switching patterns
- Coordinate transformation (abc reference frame to the stationary d-q frame)
- The vectors (V1 to V6) divide the plane into six sectors (each sector: 60 degrees)
- v_{ref} is generated usually by two adjacent non-zero vectors and two zero vectors.

- SV-PWM can be applied whenever sinusoidal output voltages needed to be generated, such a 3-phase balanced inductance load. So, here dq coordinates are defined for the modulation purposes.
- In AC machine drives, the dq axis defined for inverter control and dq axis of the rotor must be the same.

Space Vector Pulse Width Modulation

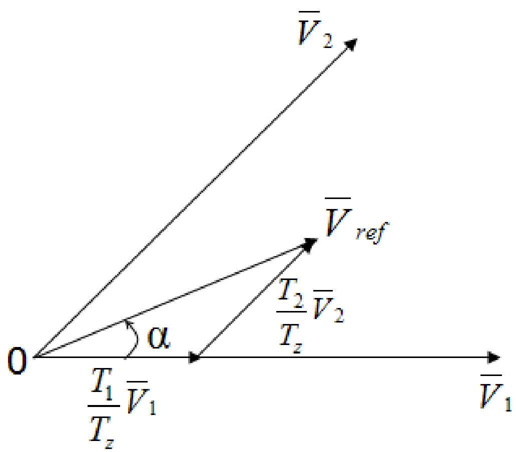
Realization of Space Vector PWM

Step 1: Determine v_{ref} $(amplitude\ and\ angle)$ from required v_d and v_q

$$v_{ref} = \sqrt{v_d^2 + v_q^2}$$

Step 2: Determine the sector and the applied vectors (i.e. v_1, v_2, v_0, v_7 in Sector 1)

Step 3: Determine time duration of non-zero space vectors, T_k and T_{k+1}

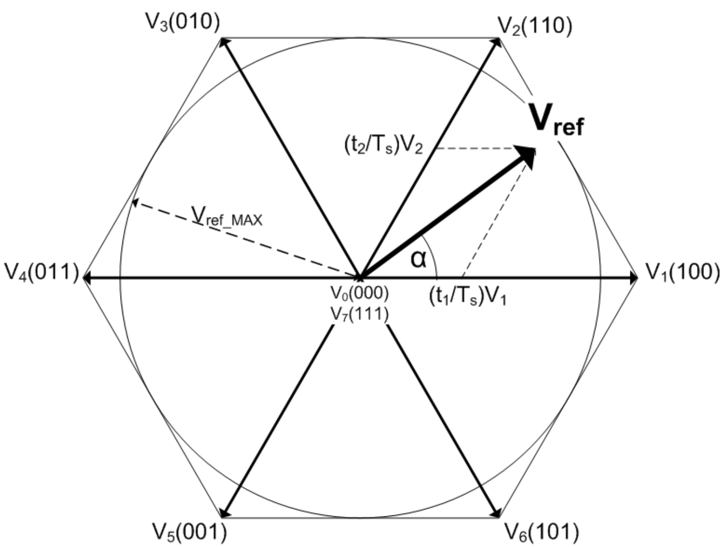


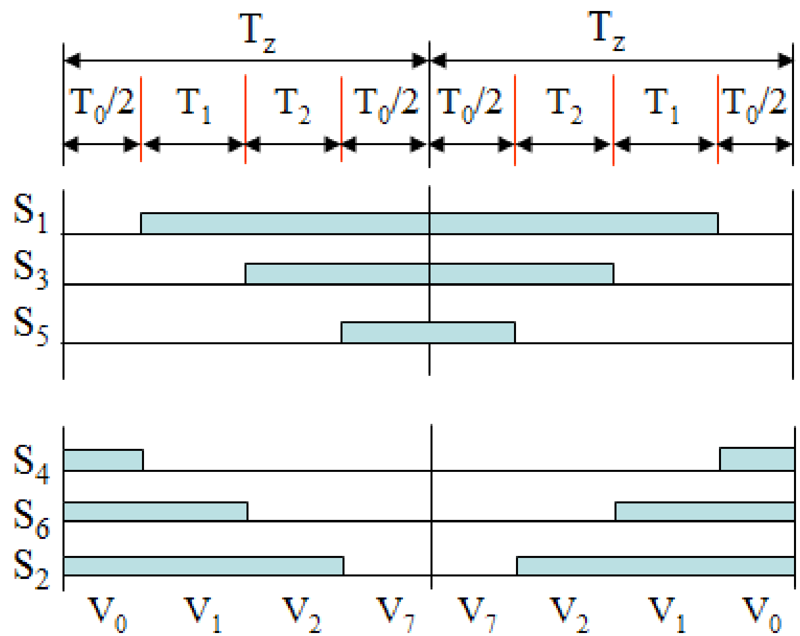
Step 4: Determine the duration of zero vectors $T_0 = T_7 = 1/2\ (T_z - (T_k + T_{k+1}))$

Step 5: Determine the switching time of each transistor conside (S1 to S6)

Repeat all these steps at each switching period, T_z

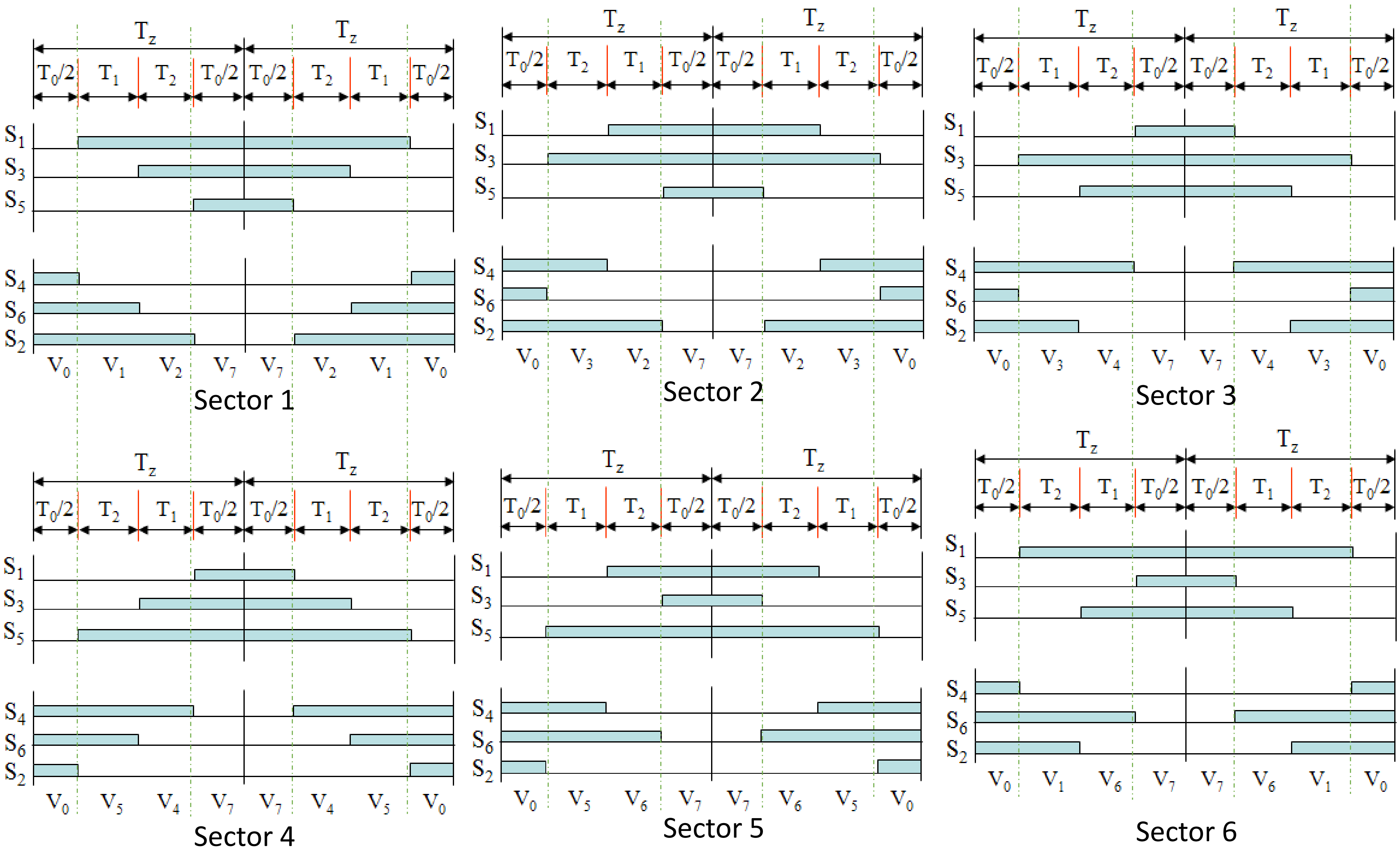
Space Vector Pulse Width Modulation





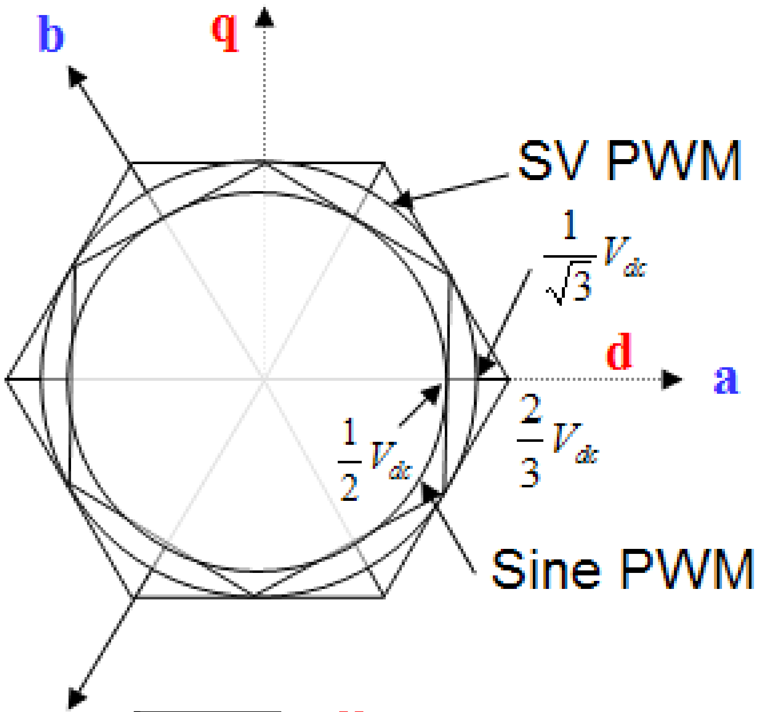
Sequence of the space vectors and the choice of zero vectors influence the number of switching (switching losses) and voltage harmonics.
Scheme shown above is usually employed.

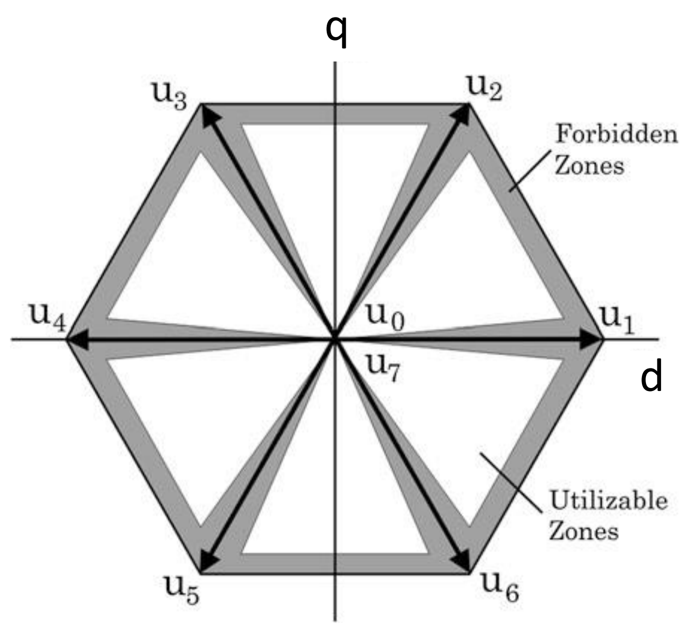
Space Vector Pulse Width Modulation



Selected vectors and their sequence in different sectorx, for SVPWM .

Actual Utilizable Voltage





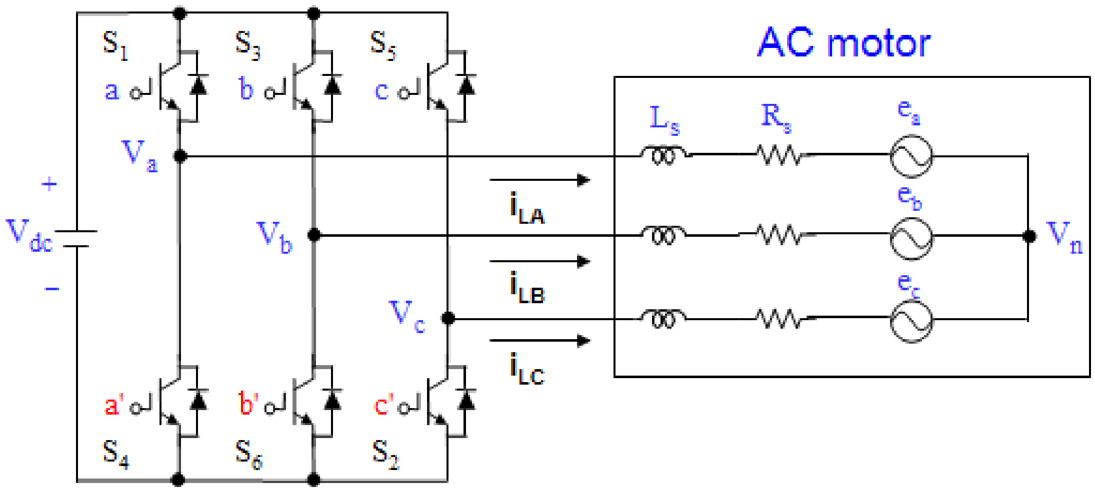
$$\sqrt{v_d^2 + v_q^2} \leq \frac{V_{dc}}{2} \text{ with Sine} - \text{PWM}$$

$$\sqrt{v_d^2 + v_q^2} \leq \frac{V_{dc}}{\sqrt{3}} \text{ with SVM}$$

Forbidden zones: The values either of T_k or of T_{k+1} become very small in the boundary zone between the sectors or near one of the non-zero vectors v_1-v_6.

N.P. Quang and J.-A. Dittrich, Vector Control of Three-Phase AC Machines, Power Systems

Dead Time in VSI



When an upper switch is turned on

- a, b or c is “1”

the corresponding lower switch is turned off

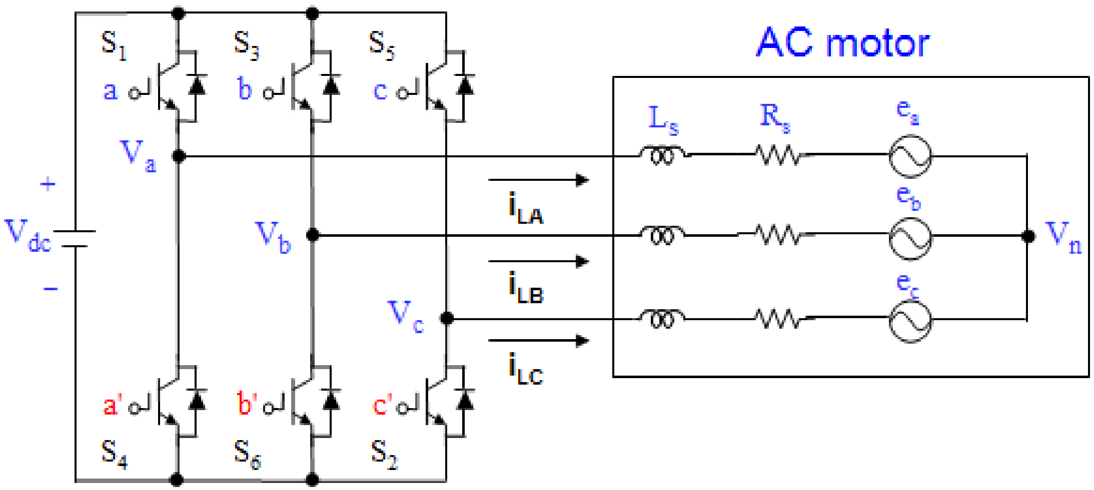
- a', b' or c' is “0”

However, finite turn-on and turn-off times of power switches must be considered.

- Dead-time

https://www.maximintegrated.com/en/app-notes/index.mvp/id/4266

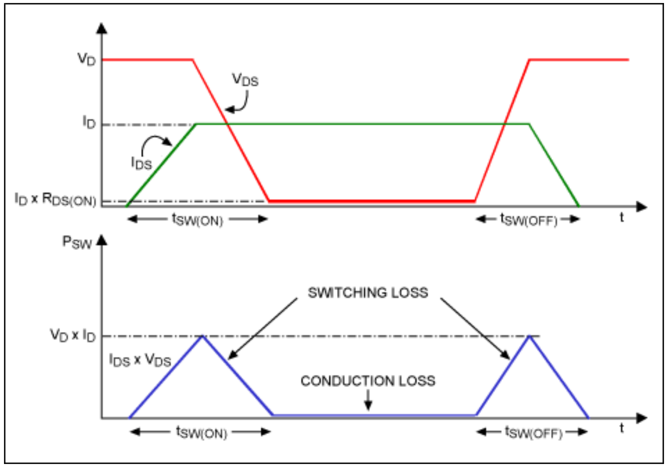
Dead Time in VSI

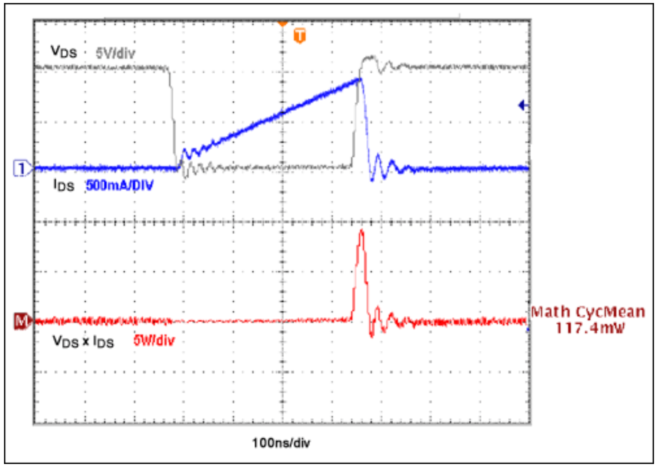


Dead time: Any solid-state switching device has a finite switching time, and the turn-off time of the device is of particular importance in most applications. In inverters, the finite turn-off time may cause a short circuit of the dc link at the instant of switchover between the two elements connected in series across the dc link. Thus, it is essential to insert a time delay in control signals in order to avoid the conduction overlap of the elements.

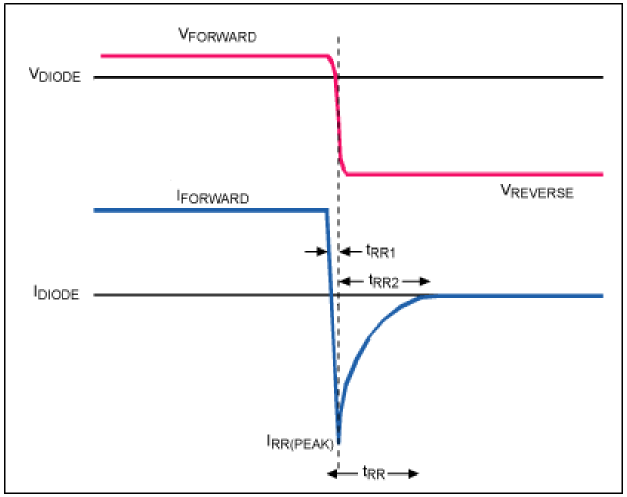
Dead-time effect: Although the time delay guarantees safe operation, it adversely affects the performance of the inverter. The time delay results in a momentary loss of control, and the inverter output voltage waveform deviates from that for which it is originally intended. Since this is repeated over and over for every switching operation, its detrimental effect may become significant in PWM inverters that operate in high switching frequency. This is known as the dead-time effect. Fast switching devices such as MOSFET, SIT, IGBT, etc., do not necessarily improve the situation because using them generally implies quite high switching frequency, and the cumulative effect of the time delay remains essentially the same. Therefore, irrelevant to the switching device to be used, a thorough understanding of the dead-time effect is important in improving the performance of PWM inverters.

Dead Time in VSI





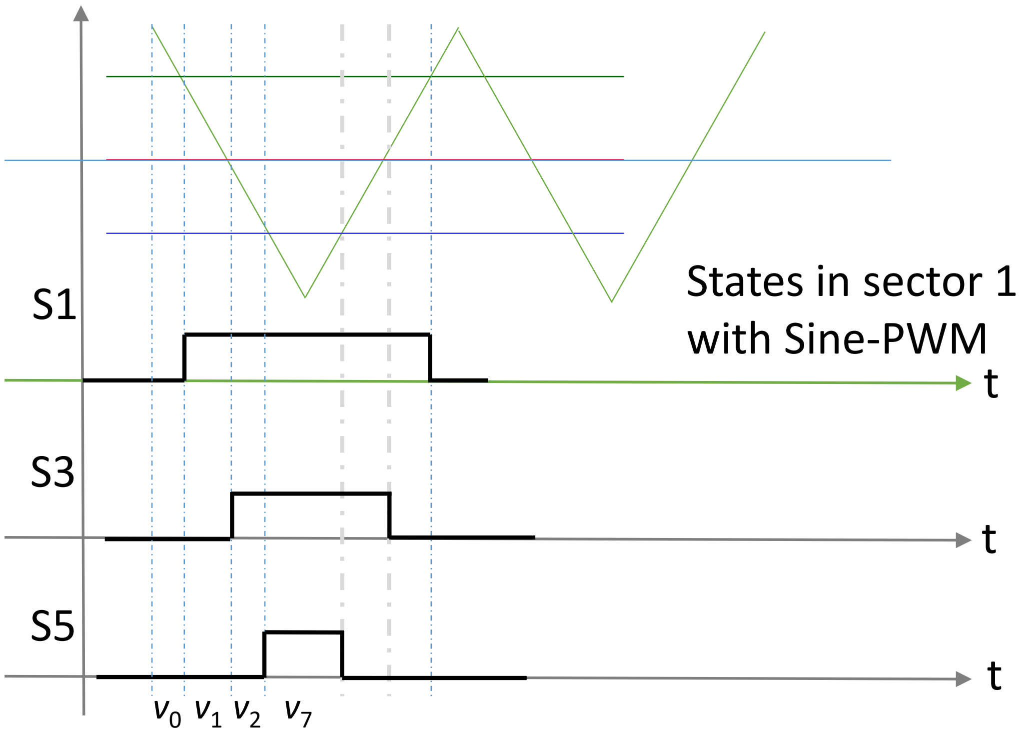
Switching and switching losses



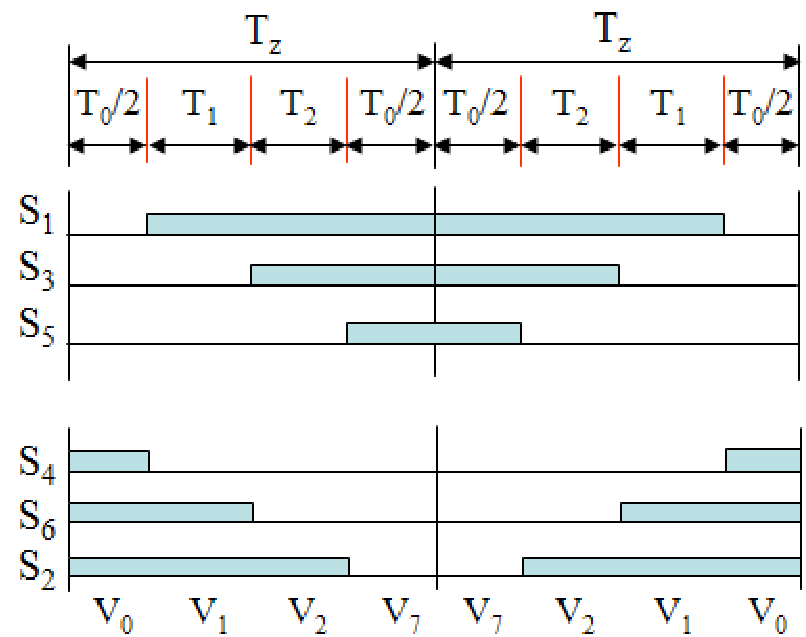
Turn-off of a diode

https://www.maximintegrated.com/en/app-notes/index.mvp/id/4266

Difference of Sine-PWM and SV-PWM



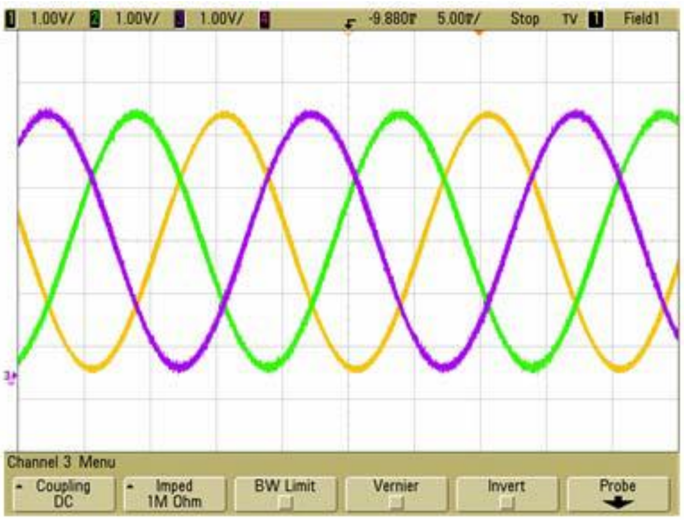
States in sector 1 with Sine-PWM



States in sector 1 with SV-PWM

- ✓ Sine-PWM minimizes the number of switching.
- ✓ Sine-PWM and the usually applied SV-PWM have the same sequences.
- ✓ Difference is the timings of zero-states, $T_0 \neq T_7$

Difference of Sine-PWM and SV-PWM

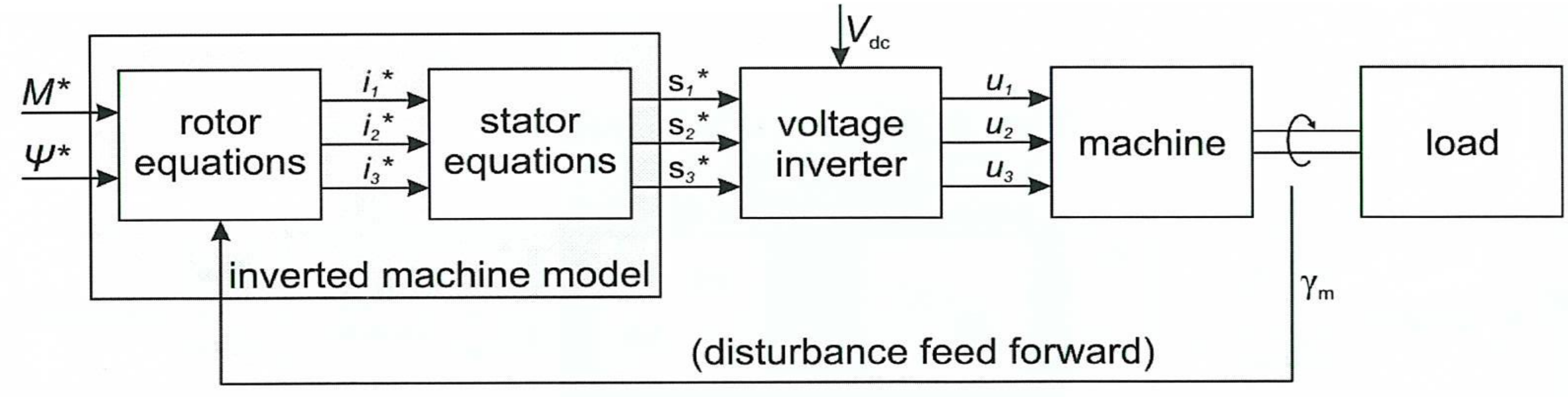


3-phase reference voltages with Sine-PWM

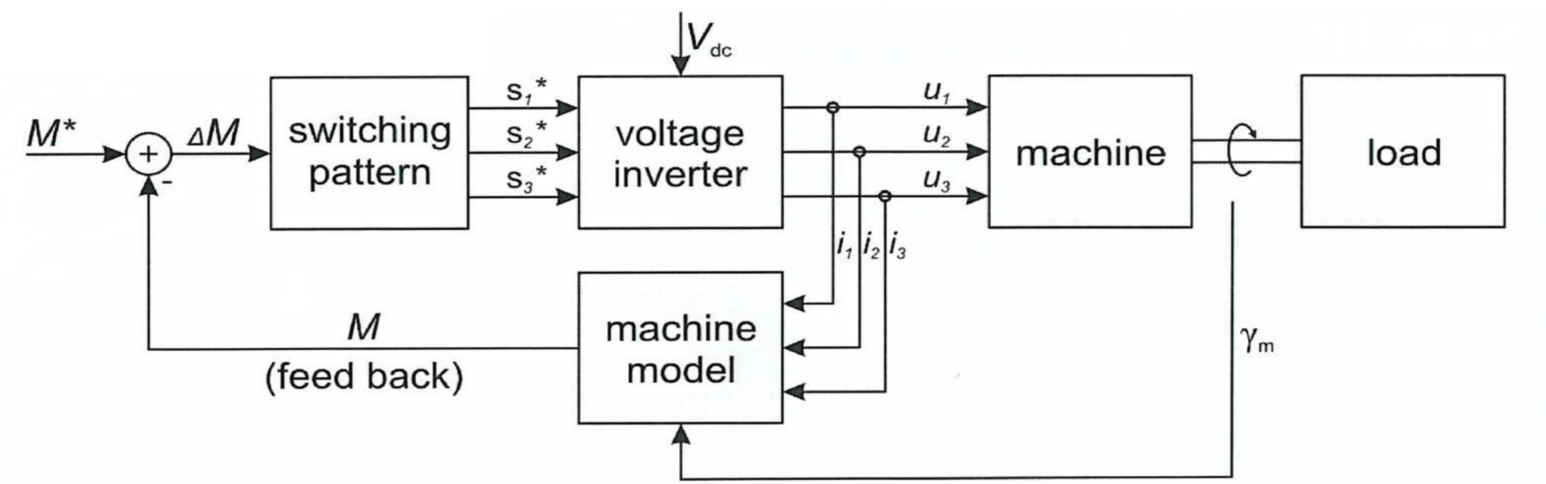
3-phase reference voltages with SV-PWM

FOC vs. DTC

Model based field oriented control (FOC)



Observer based direct torque control (DTC)



Current EM Technology in EVs

Electric machine types

Voltage levels

Power, speed and torque specs

Winding technology

Materials

Reading Assignment

[Electrical propulsion system design of Chevrolet Bolt battery electric vehicle]

F. Momen, K. Rahman, Y. Son and P. Savagian, "Electrical propulsion system design of Chevrolet Bolt battery electric vehicle," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-8.
doi: 10.1109/ECCE.2016.7855076

References

Pulse-Width Modulation (PWM) Techniques, Prof. Ali Keyhani

2nd Chapter of N.P. Quang and J.-A. Dittrich, Vector Control of Three-Phase AC Machines, Power Systems

Assigment Video:

Field-Oriented Control with Simulink, Part 1: What Is Field-Oriented Control?

Projects

Groups of 2 or 3

Project outputs

- 3-4 page project report in IEEE Journal format
- 15 min group presentation - Presentation time will be announced.

Some Possible Project Topics

1. Comparison of Inductances of IPMSM and SMPMSM
2. Effect of Number of Poles on IPMSM Performance
3. 5-Phase IPMSM Design
4. IPMSM Efficiency Map Calculation
5. Effect of Temperature on IPMSM Performance
6. Optimum Id-Iq Table Calculation for an IPMSM
7. Sensorless Control of an IPMSM
8. Performance Comparison of Sine-PWM vs. SVPWM
9. Inductance and Resistance Calculations of Hairpin Windings at Various Operating Points
10. Application of Wide Bandgap Switches in Traction Application - Advantages and Challenges
11. You can suggest some other topics.