EE-464 STATIC POWER CONVERSION-II

Other PWM Techniques

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Hysteresis (Bang-Bang) PWM

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You already implemented in the first semester

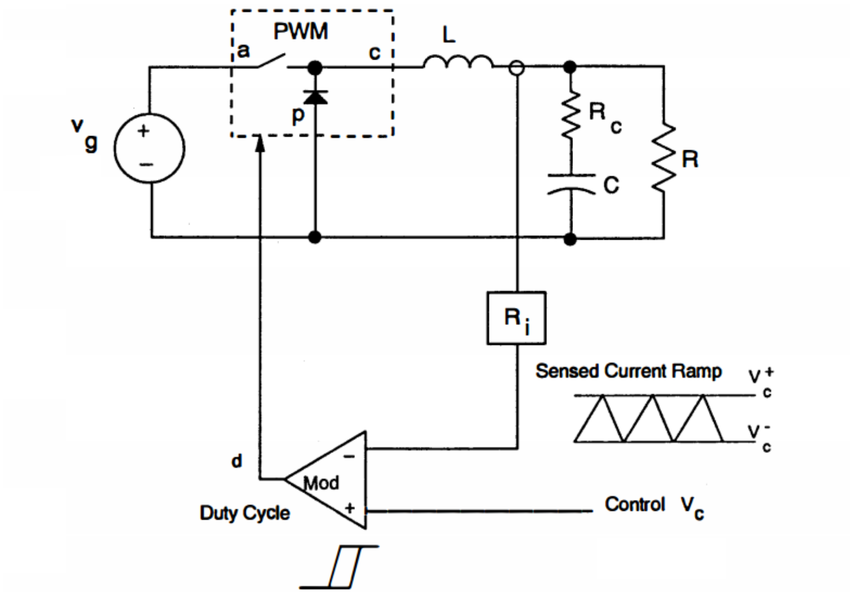
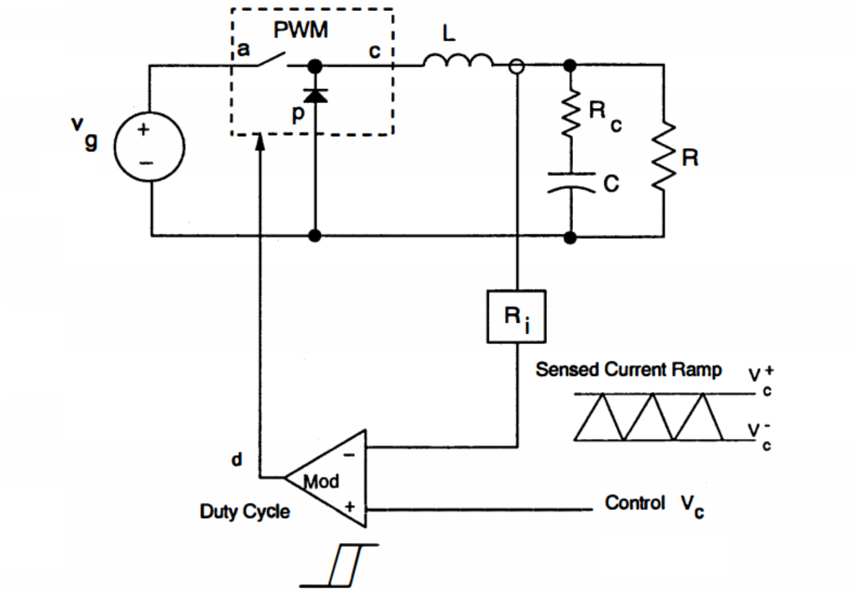


Figure 2.2. ***Buck Converter with Hysteretic Current-Mode Control:*** *A control sig-*

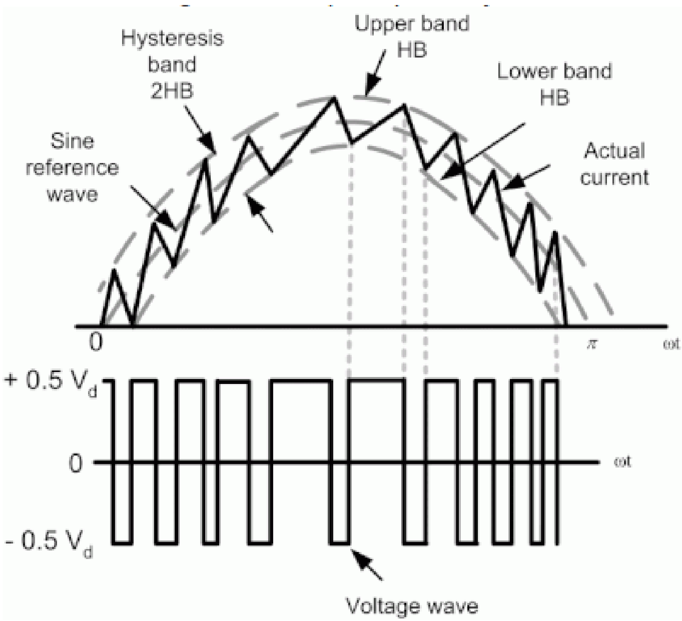
Hysteresis (Bang-Bang) PWM

If your current is higher than your reference, reduce the current (switch off), if not increase the current (Switch ON)



Hysteresis (Bang-Bang) PWM

For an inverter, just change your reference current to a sinusoidal waveform instead of a constant reference.



Hysteresis (Bang-Bang) PWM

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- The switching frequency is varying

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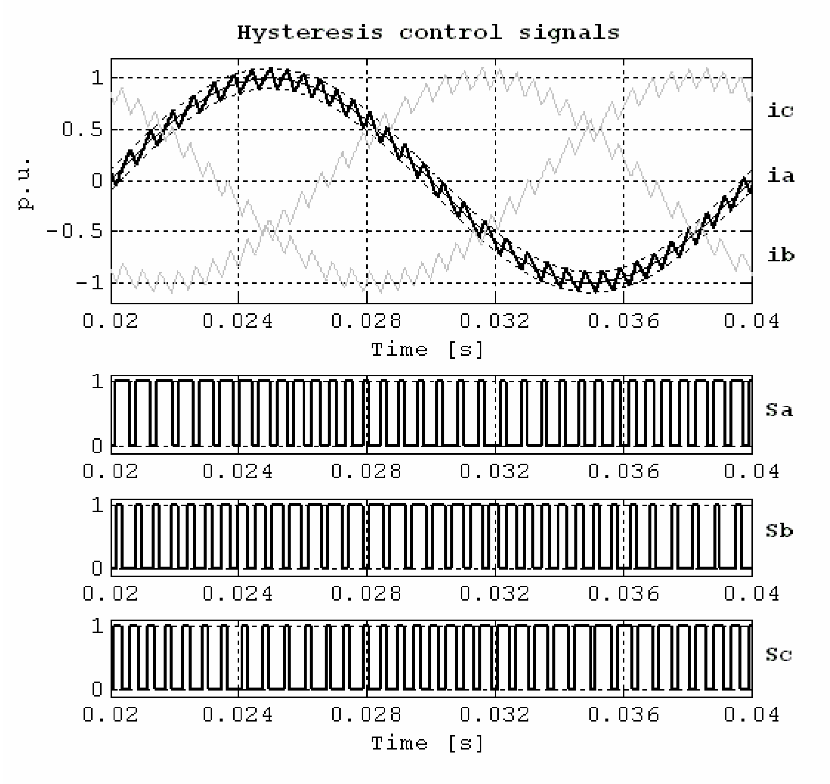
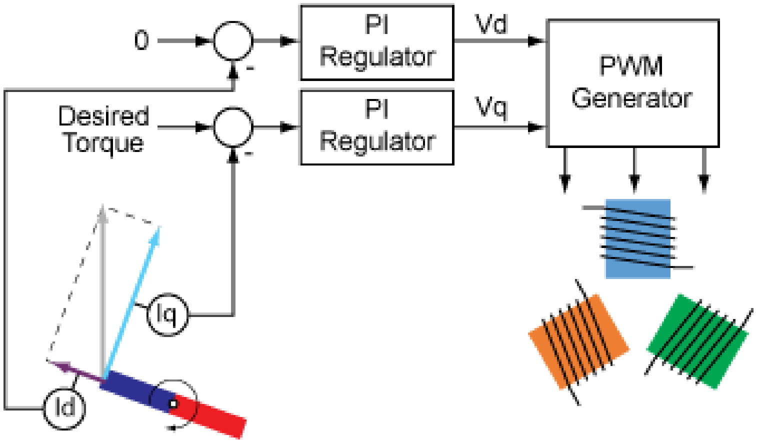
- Difficult to design filter (because of varying fs)
- Can induce side-band harmonics
- Simple control and implementation

Hysteresis (Bang-Bang) PWM



Field Oriented Control (FOC) in Electrical Machines



- [What is FOC?]
- [Field oriented Control of PM Motors]

How to aim to a moving target?

How to aim to a moving target?

Some Useful Mathematical Tools

Some Useful Mathematical Tools

- Clarke Transformation
- Park Transformation

Clarke Transformation

(a-b-c) to $\alpha\beta$ Transformation

From three-phase to two orthogonal phase transformation

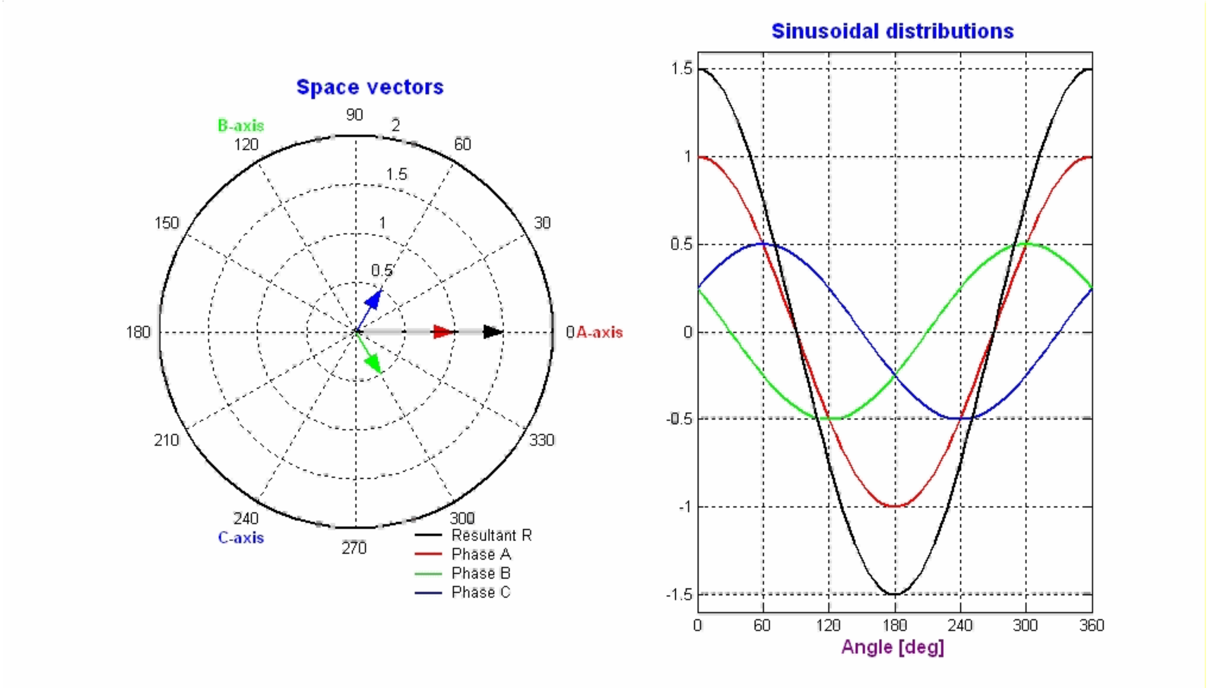
Clarke Transformation

(a-b-c) to $\alpha\beta$ Transformation

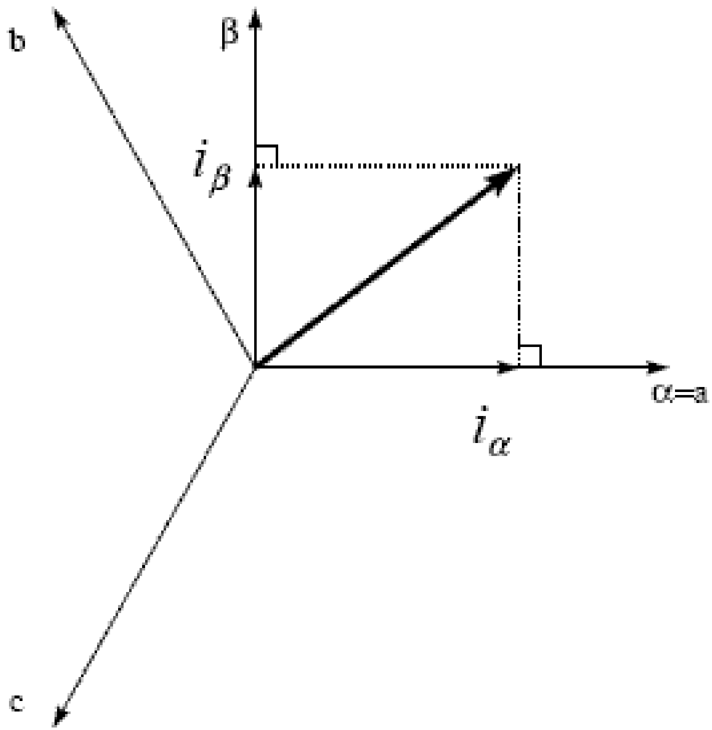
From three-phase to two orthogonal phase transformation

Main Idea: In a balanced three-phase system, $I_a + I_b + I_c = 0$ so there is redundant information and system can be reduced to two variables.

How do you define the resultant (black) phasor?



Clarke Transformation



Clarke Transformation

$$i_{\alpha\beta}(t) = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix}$$

Park Transformation in Space

i.e. [Interstellar - Docking Scene]

Park Transformation

Park Transformation

From stationary frame to rotationary frame

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From stationary frame to rotationary frame

Instead of dealing with sinusoidal signals, just use the magnitudes.

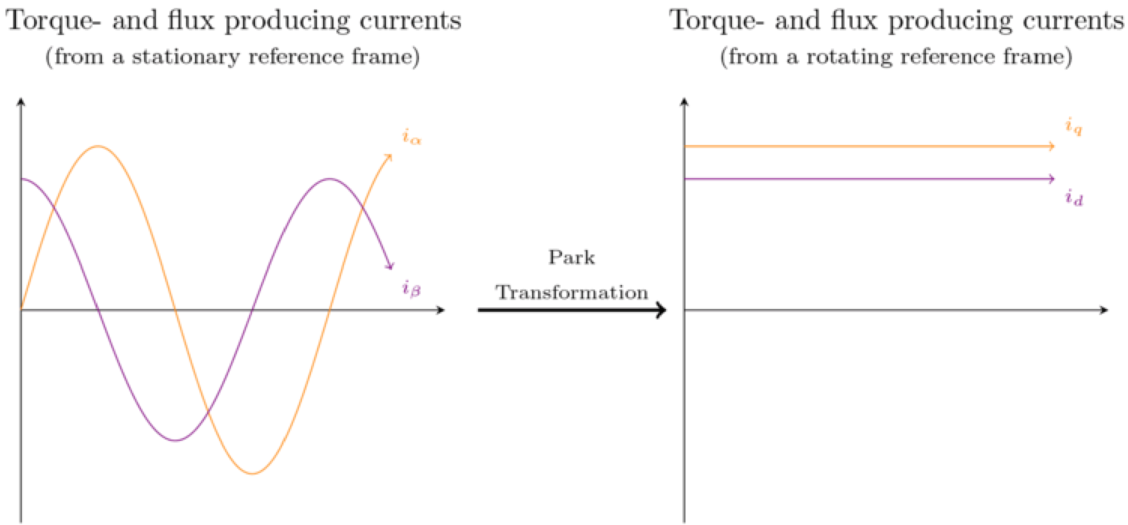
Park Transformation

From stationary frame to rotationary frame

Instead of dealing with sinusoidal signals, just use the magnitudes.

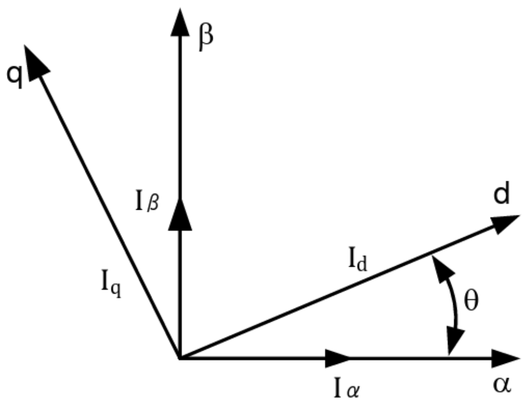
When reconstructing signals use the rotor position information

Park Transformation

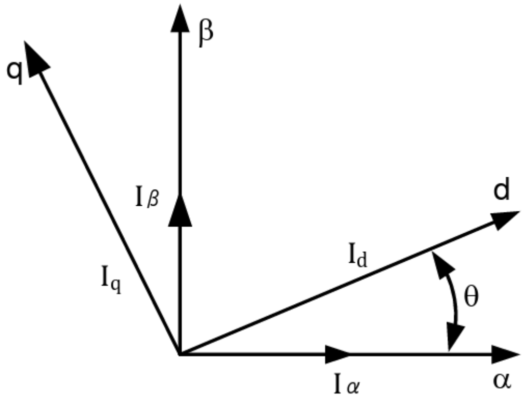


Park Transformation

Park Transformation

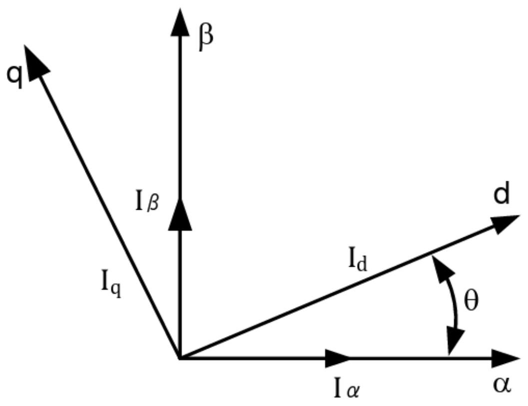


Park Transformation



$$I_d = I_\alpha cos(\theta) + I_\beta sin(\theta)$$

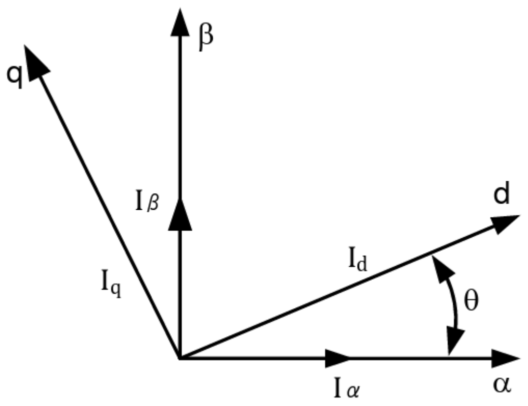
Park Transformation



$$I_d = I_\alpha cos(\theta) + I_\beta sin(\theta)$$

$$I_q = I_\beta cos(\theta) - I_\alpha sin(\theta)$$

Park Transformation



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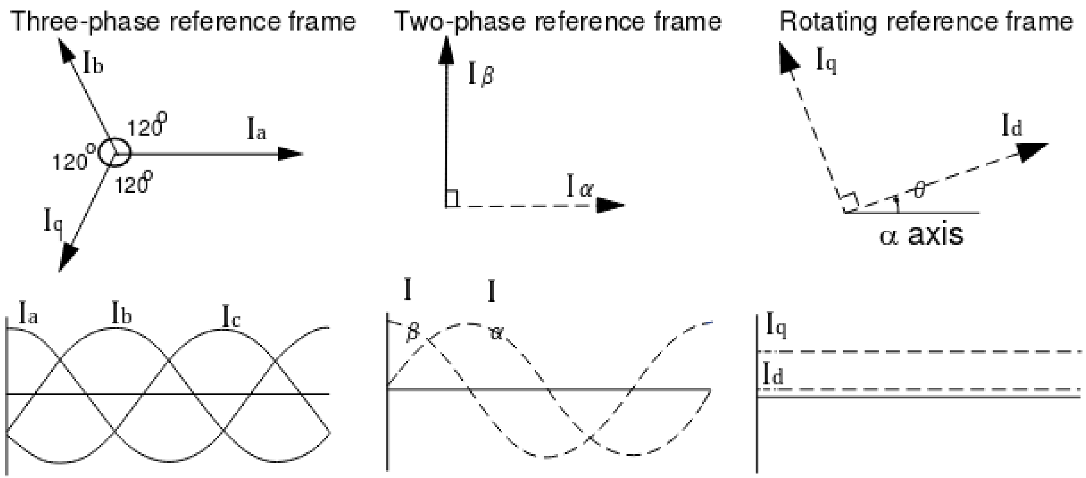
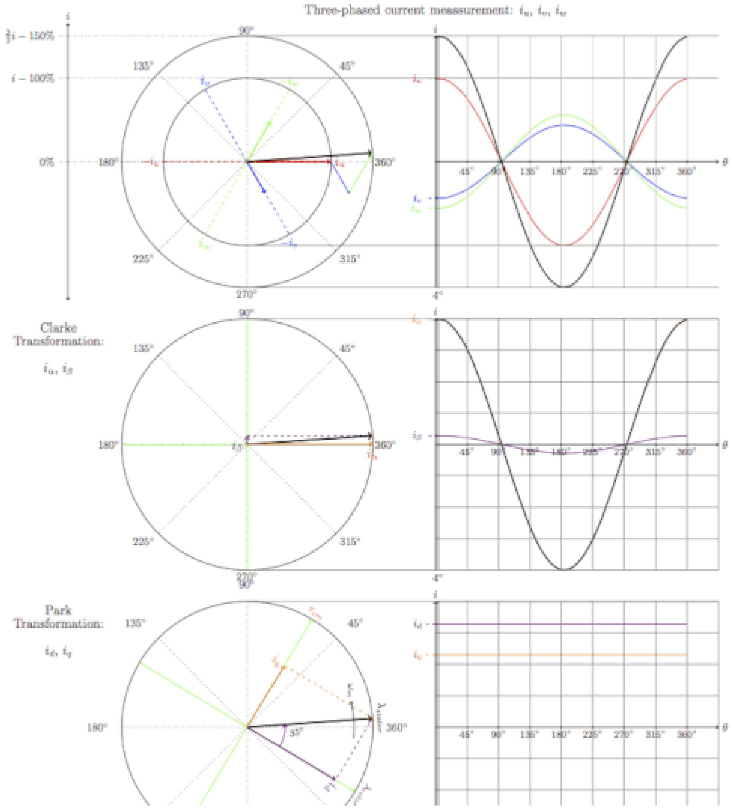
$$I_q = I_\beta cos(\theta) - I_\alpha sin(\theta)$$

Reference Frames



Clarke and Park Transformations



Torque and Flux Control

Id: Proportional to flux in the air-gap

Iq: Proportional to torque generated

Inverse Transforms

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Required to apply reference voltage and current waveforms (sinusoidals)

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Required to apply reference voltage and current waveforms (sinusoidals)

- Inverse Park Transform
- Inverse Clarke Transform

Inverse Park Transform

Inverse Park Transform

From rotation frame to stationary frame

Inverse Park Transform

From rotation frame to stationary frame

$$I_\alpha = I_d cos(\theta) - I_q sin(\theta)$$

Inverse Park Transform

From rotation frame to stationary frame

$$I_\alpha = I_d cos(\theta) - I_q sin(\theta)$$

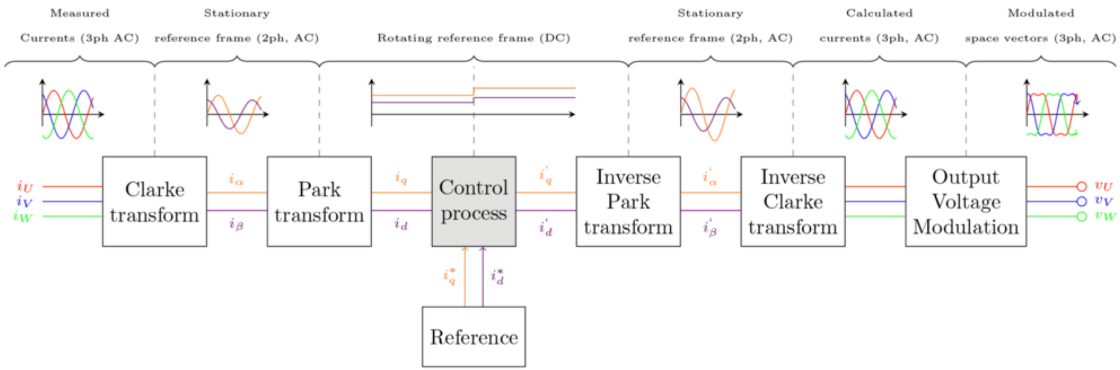
$$I_\beta = I_q cos(\theta) + I_d sin(\theta)$$

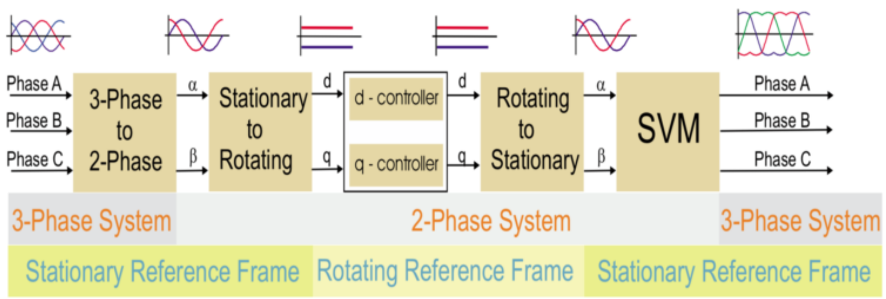
Inverse Clarke Transform

From two-axis orthogonal plane to 3-phase stationary frame.

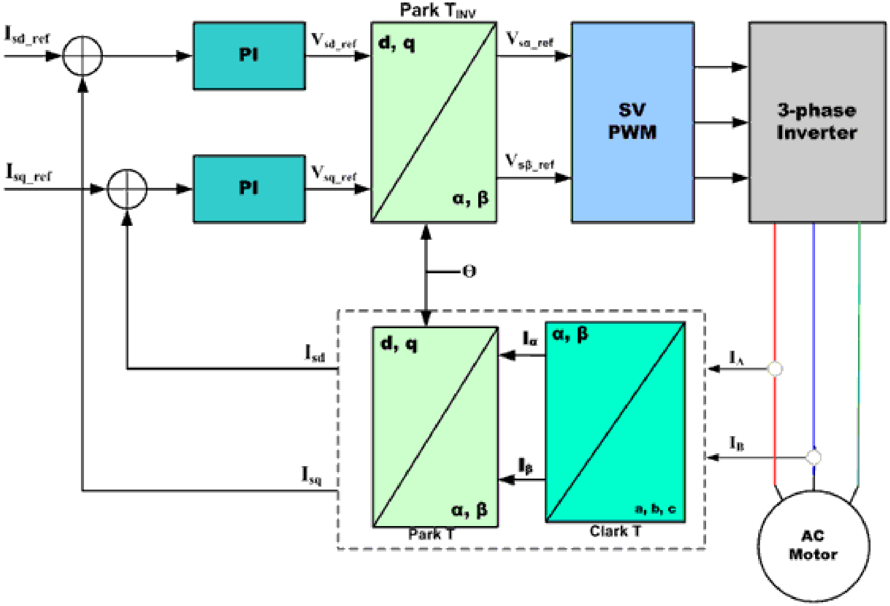
α, β -> **a, b, c**
$i_a = i_\alpha$ $i_b = -\frac{1}{2} \cdot i_\alpha + \frac{\sqrt{3}}{2} \cdot i_\beta$ $ic = -\frac{1}{2} \cdot i_\alpha - \frac{\sqrt{3}}{2} \cdot i_\beta$

Whole Workflow

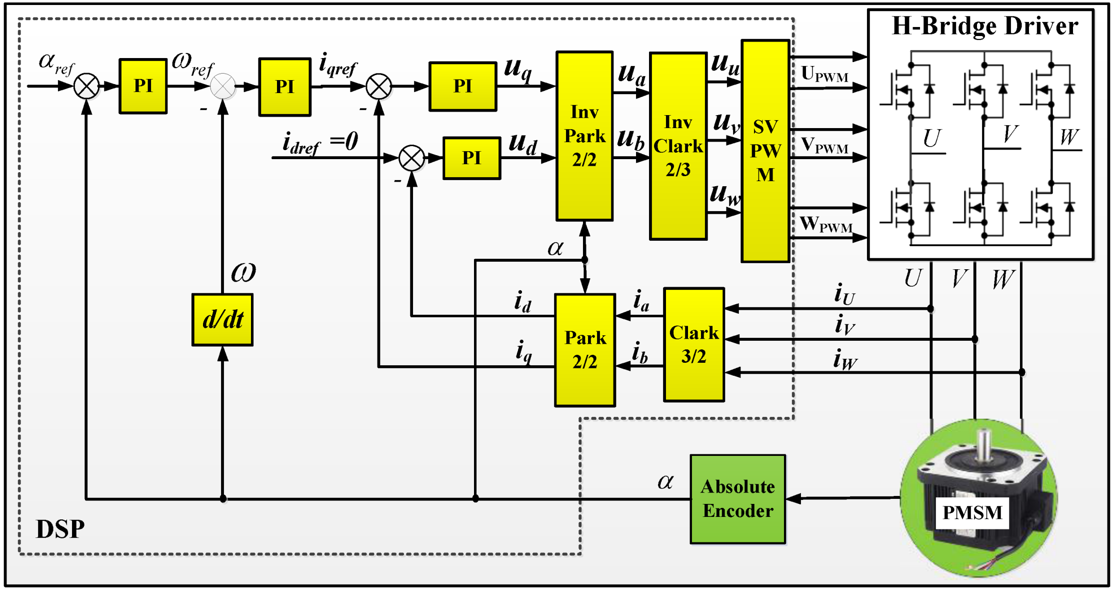




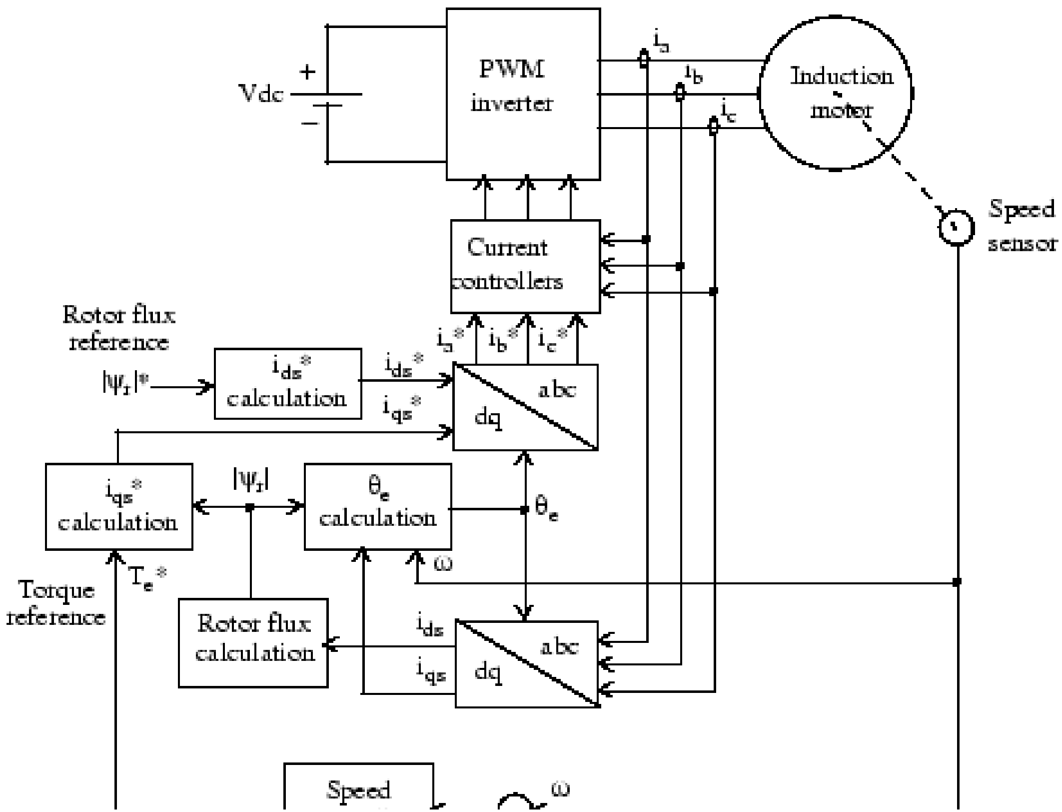
Classical Vector Control Diagram



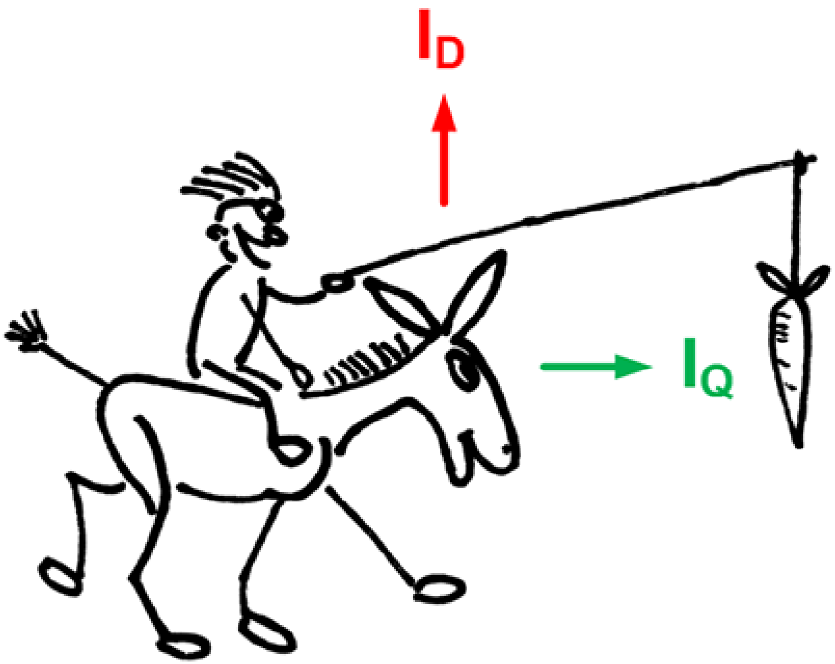
Vector Control in PMSM



Vector Control in Induction Motors



Summary



Further Reading

Vector Control for Dummies

What is Field Oriented Control?

Field Oriented Control

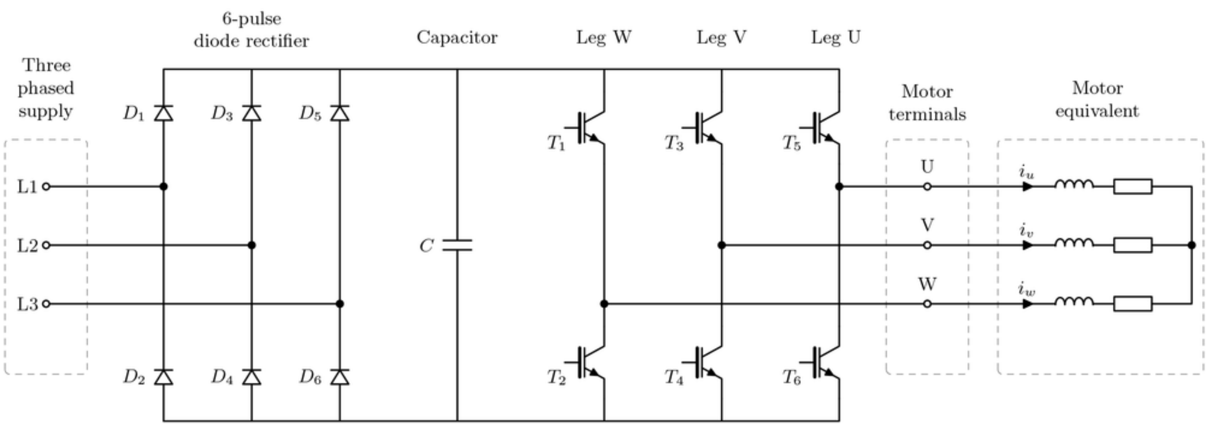
Field Oriented Control of AC Motors

Sensorless PMSM Field Oriented Control

Space Vector PWM

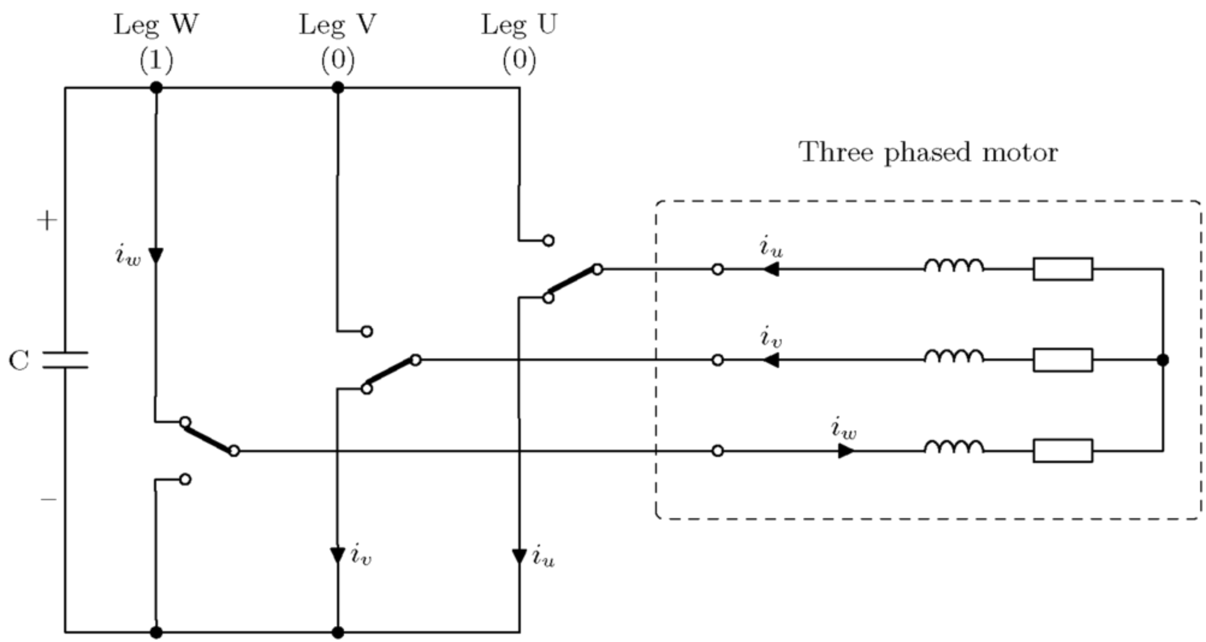
3-Phase Two-Level Inverter

3-Phase Two-Level Inverter



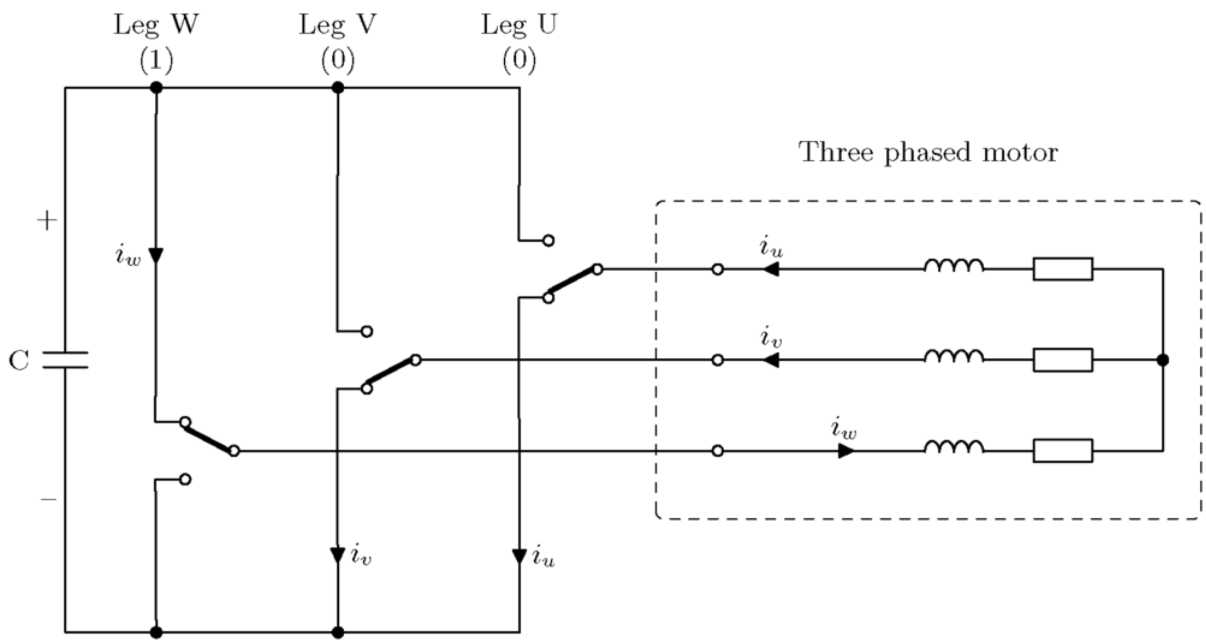
Anti-parallel diodes are not shown.

3-Phase Two-Level Inverter



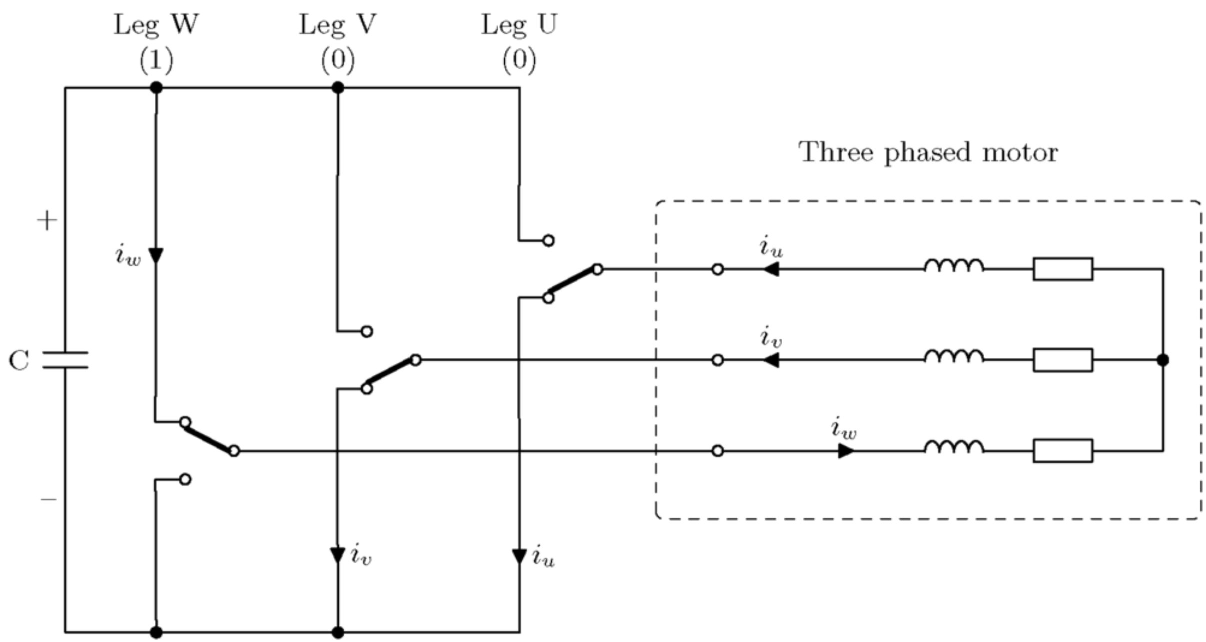
Each leg has two positions:

3-Phase Two-Level Inverter



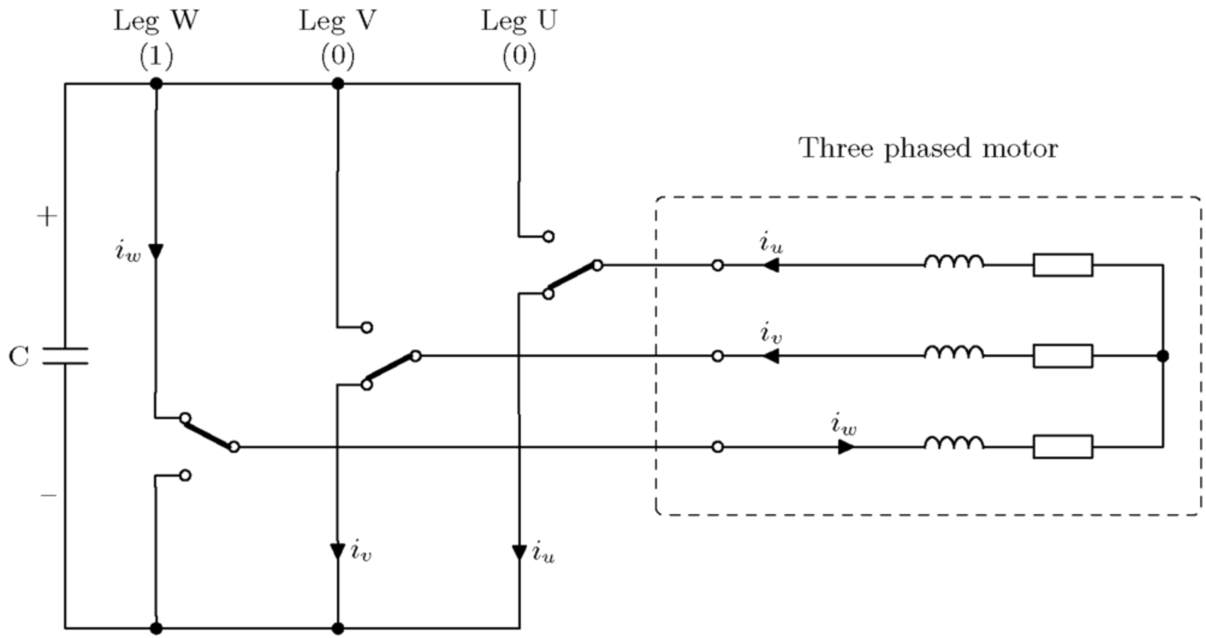
Each leg has two positions: top switch closed (1)

3-Phase Two-Level Inverter



Each leg has two positions:

3-Phase Two-Level Inverter



Each leg has two positions: bottom switch closed (0)

Voltage Vectors

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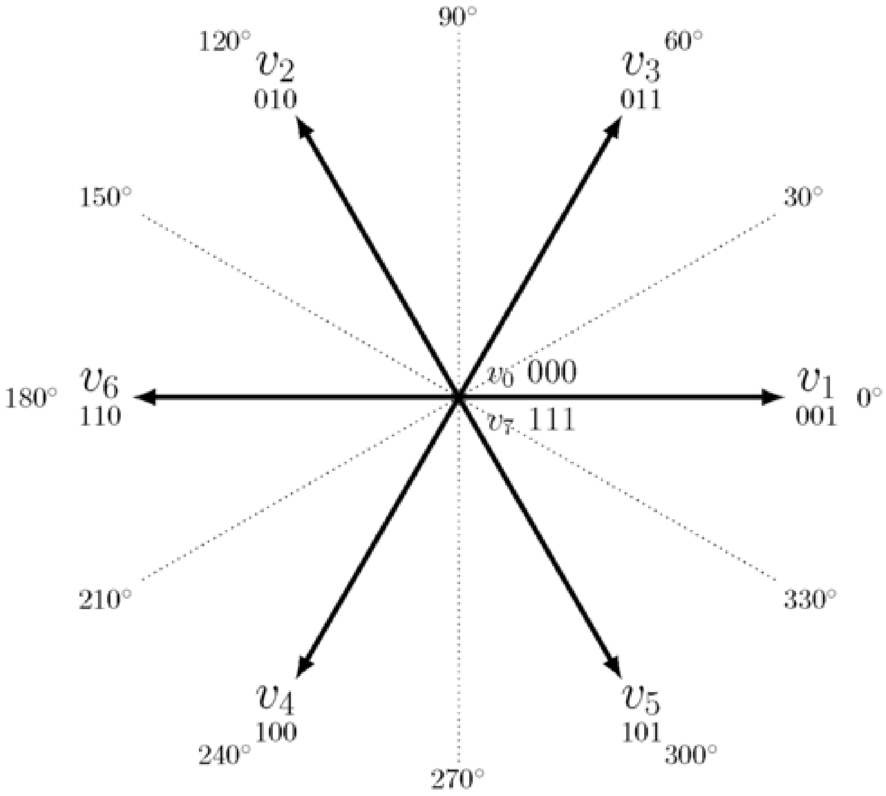


000 - v_0 (zero vector)

001 - v_1 (Phase +U)

010 - v_2 (Phase +V)

011 - v_3 (Phase -W)

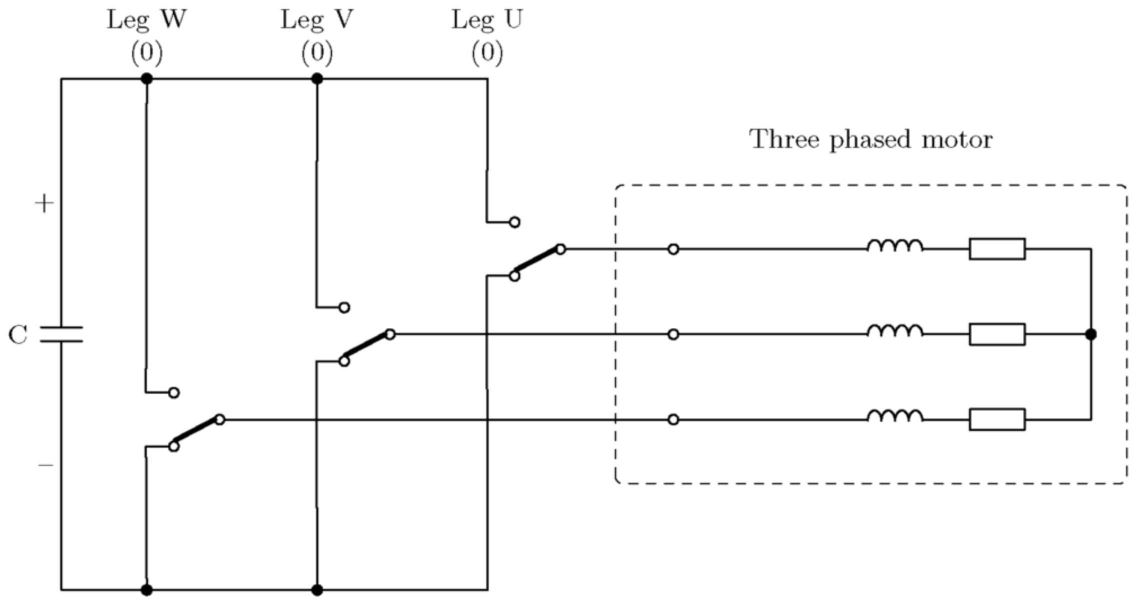
100 - v_4 (Phase +W)

101 - v_5 (Phase -V)

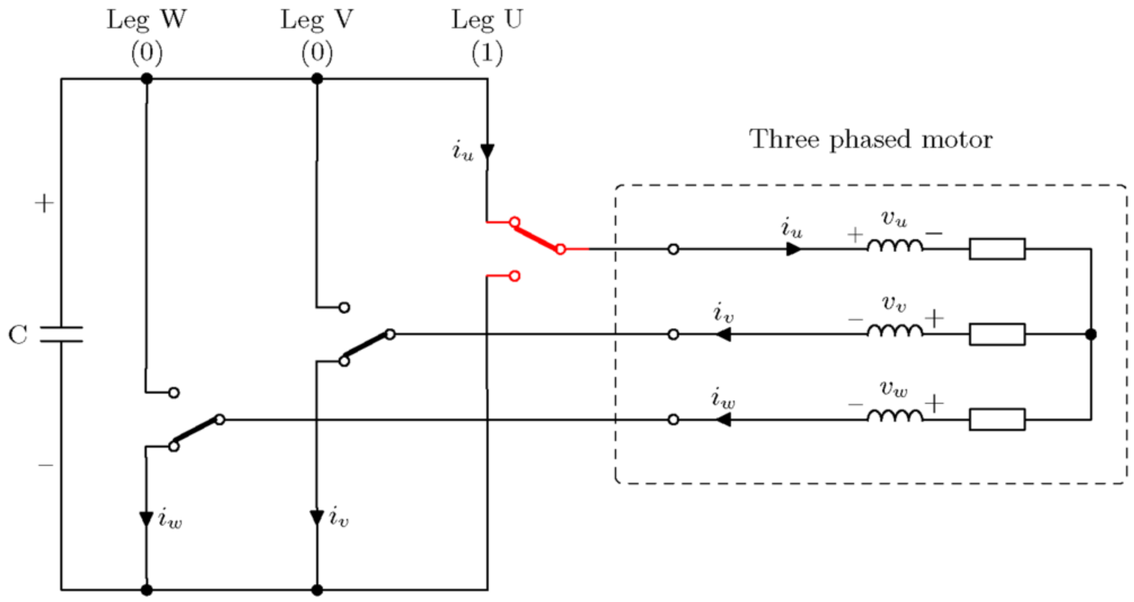
110 - v_6 (Phase -U)

111 - v_7 (zero vector)

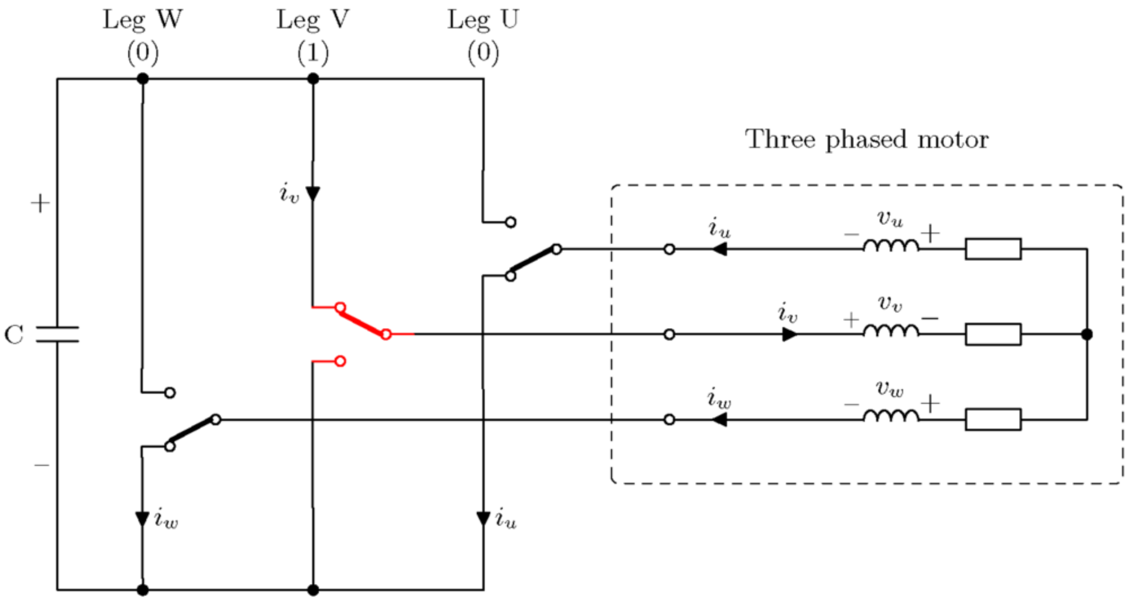
Voltage Vectors: V0



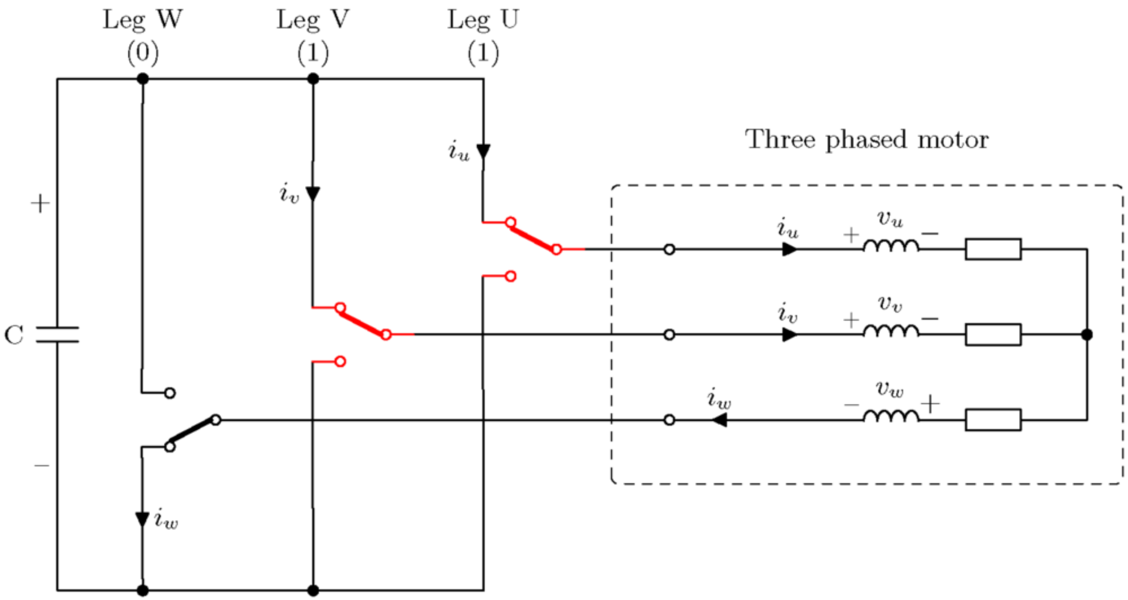
Voltage Vectors: V1



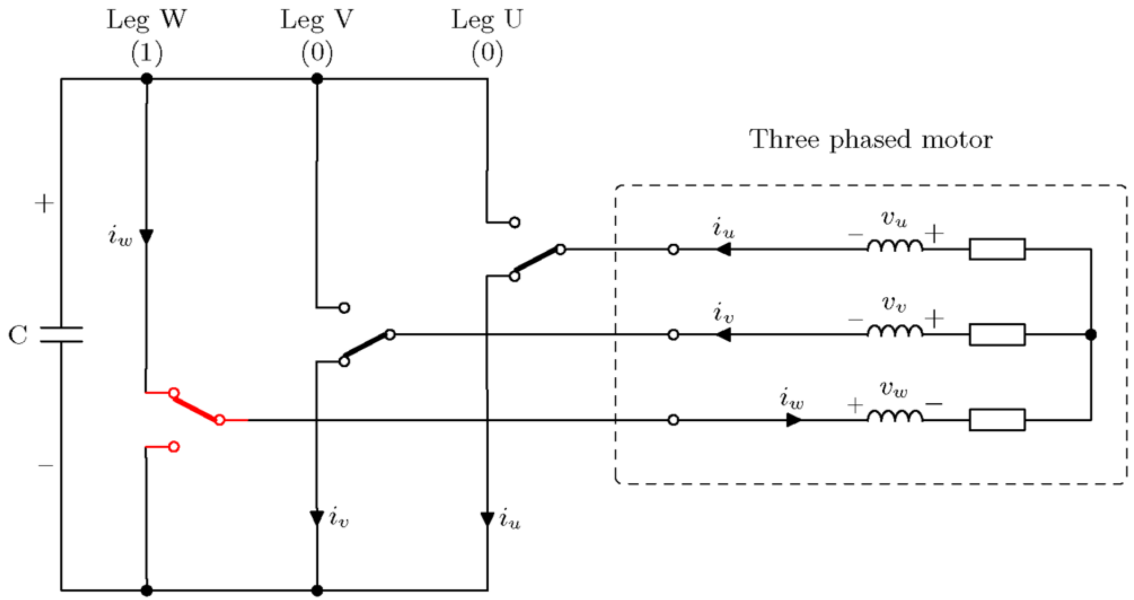
Voltage Vectors: V2



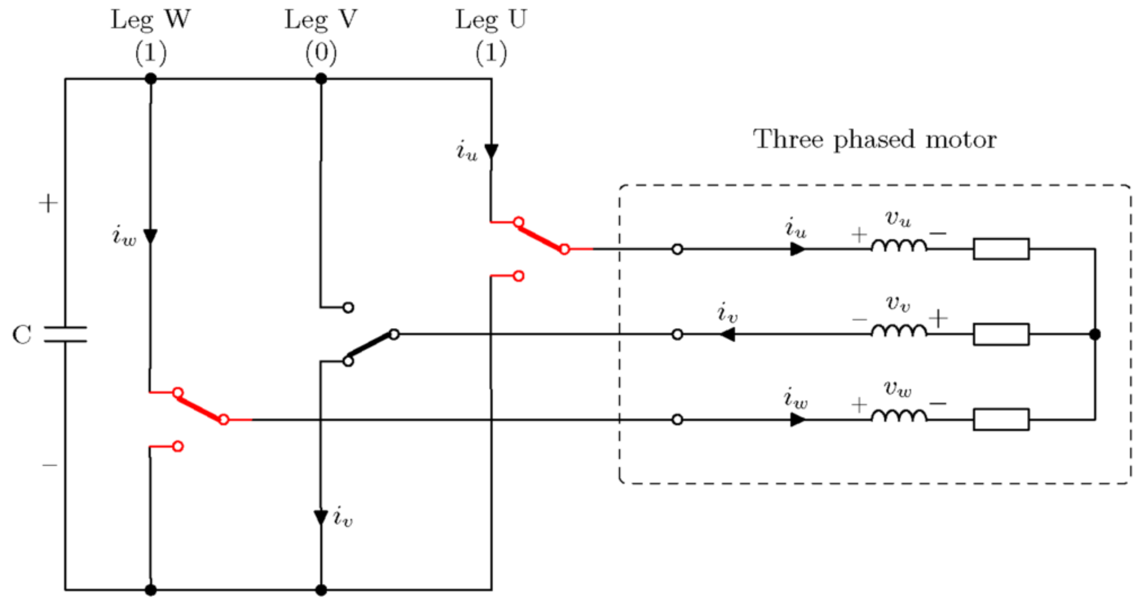
Voltage Vectors: V3



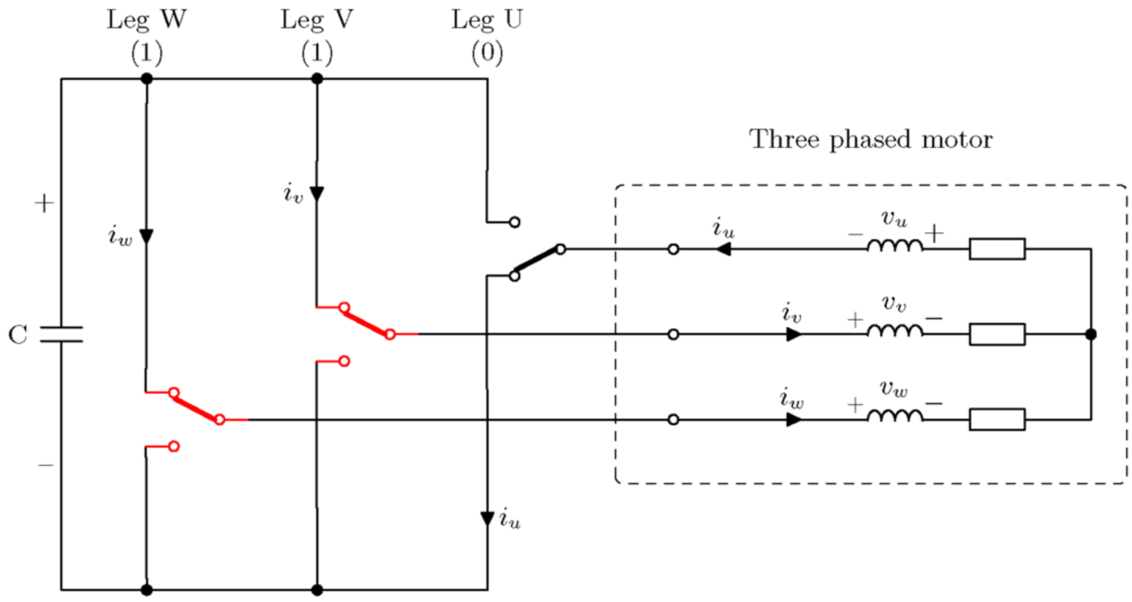
Voltage Vectors: V4



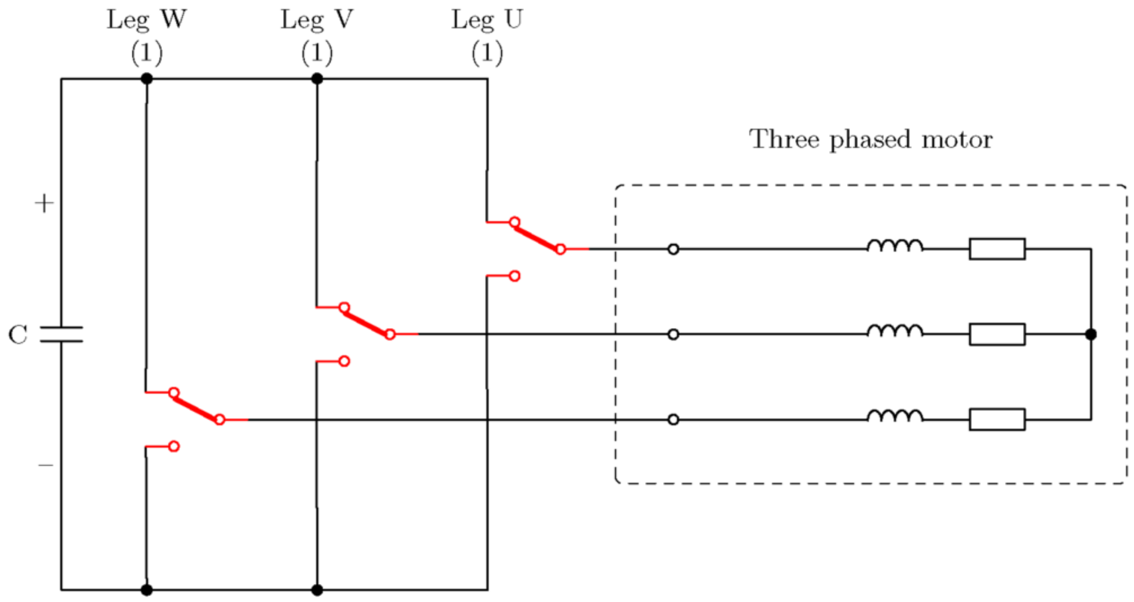
Voltage Vectors: V5



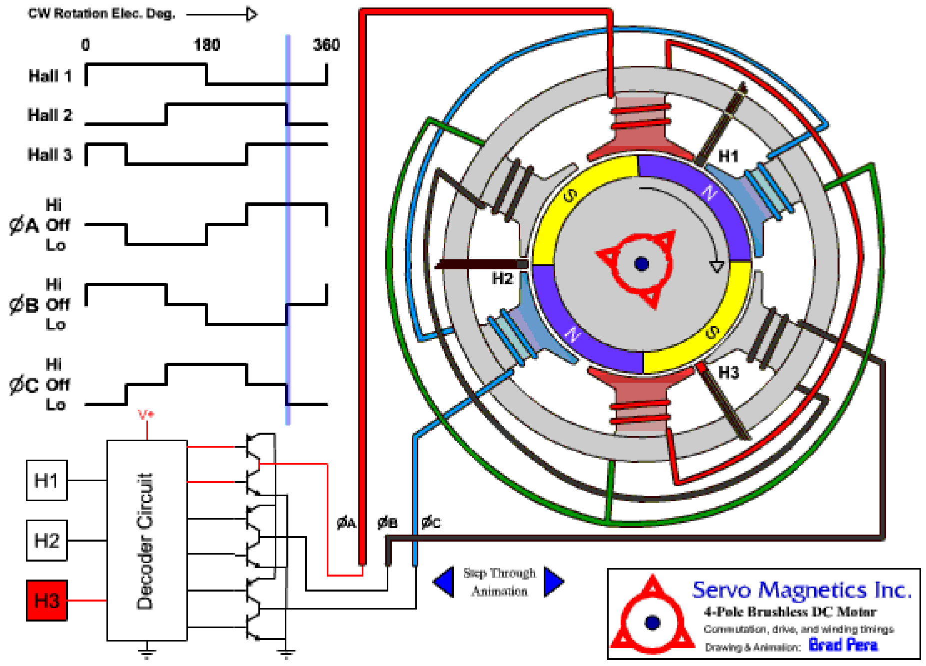
Voltage Vectors: V6



Voltage Vectors: V7



Square Wave Operation



[BLDC Drive with square wave]

What about the vectors in between?

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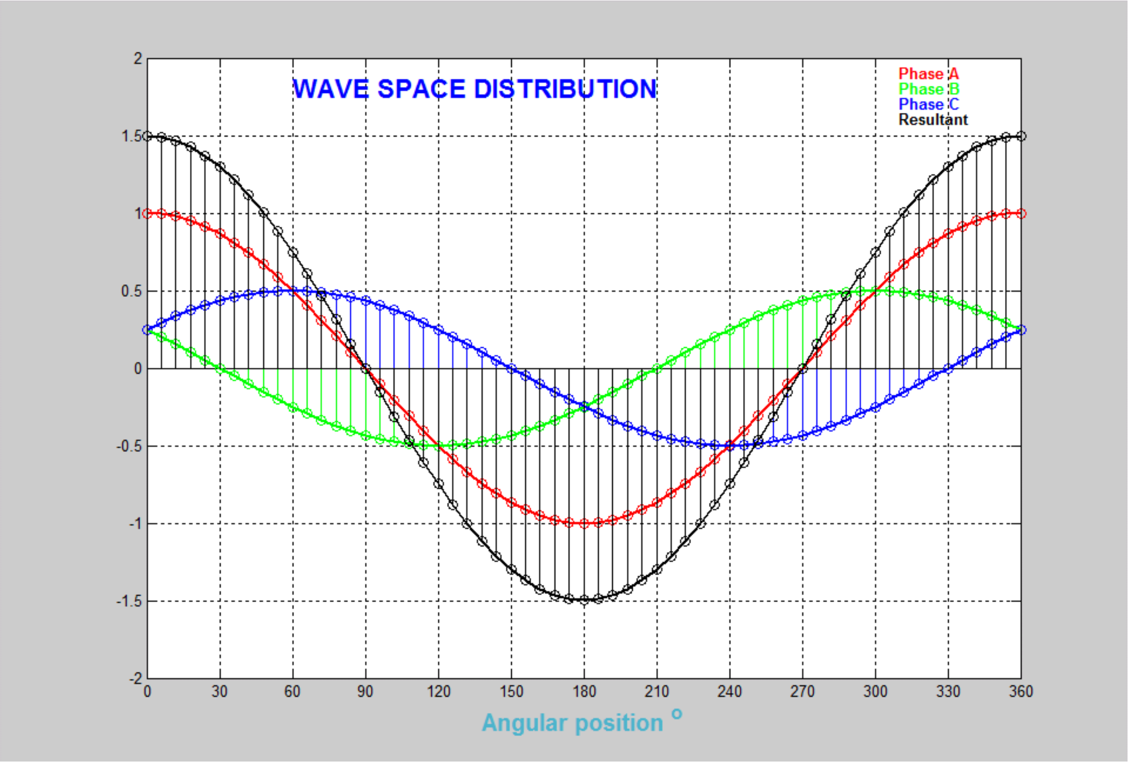

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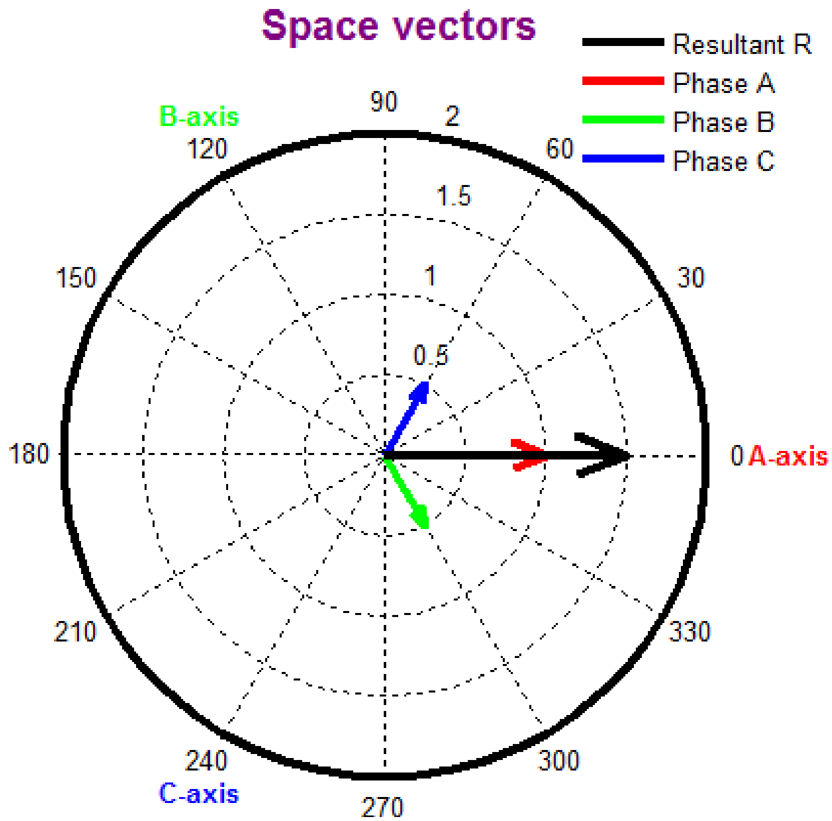

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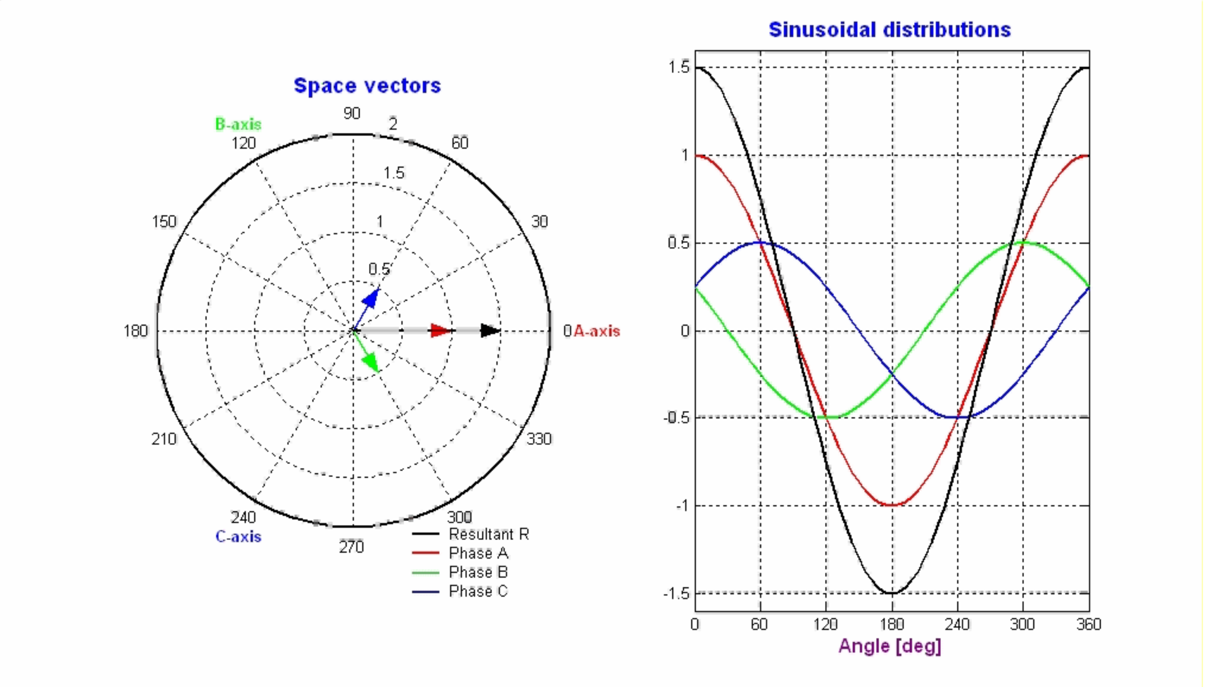
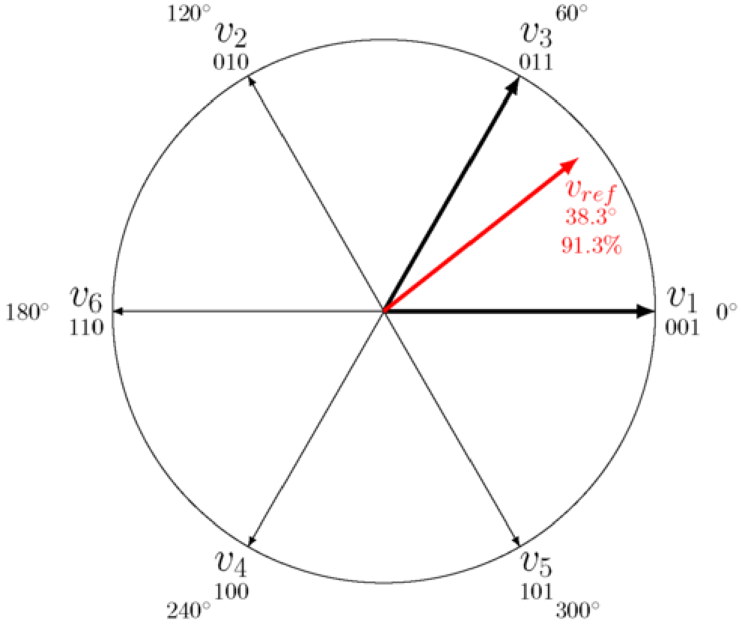


Voltage Synthesizing



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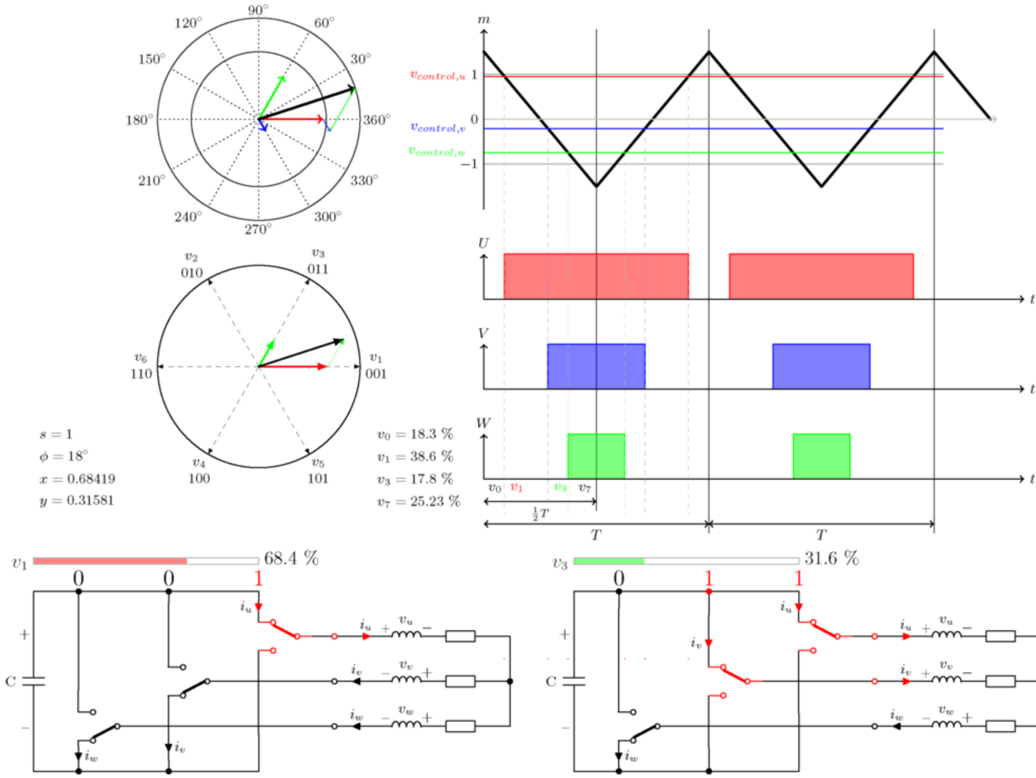
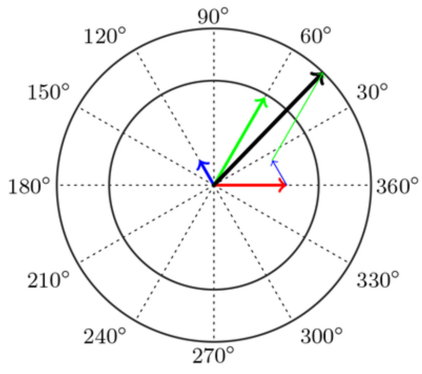
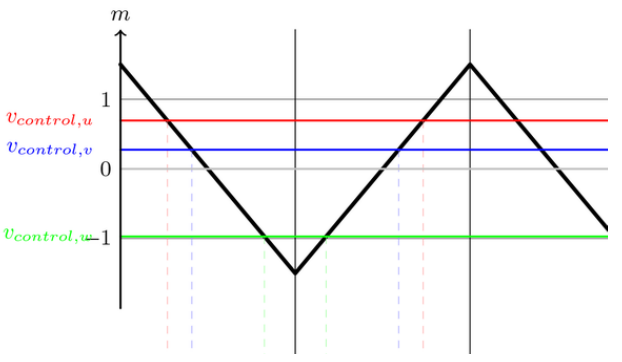


PWM Generation





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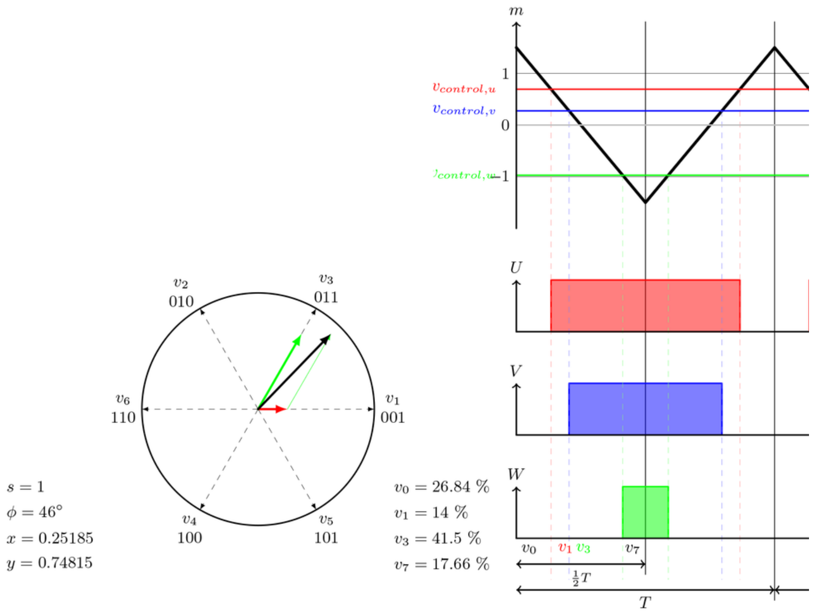


Switching Sequence: 000-001-011-111

PWM Generation

Switching Sequence:

- Zero Vector (000)

PWM Generation

Switching Sequence:

- Zero Vector (000)
- Basic Vector (i.e. 001)

PWM Generation

Switching Sequence:

- Zero Vector (000)
- Basic Vector (i.e. 001)
- Basic Vector (i.e. 011)

PWM Generation

Switching Sequence:

- Zero Vector (000)
- Basic Vector (i.e. 001)
- Basic Vector (i.e. 011)
- Zero Vector (i.e. 111)

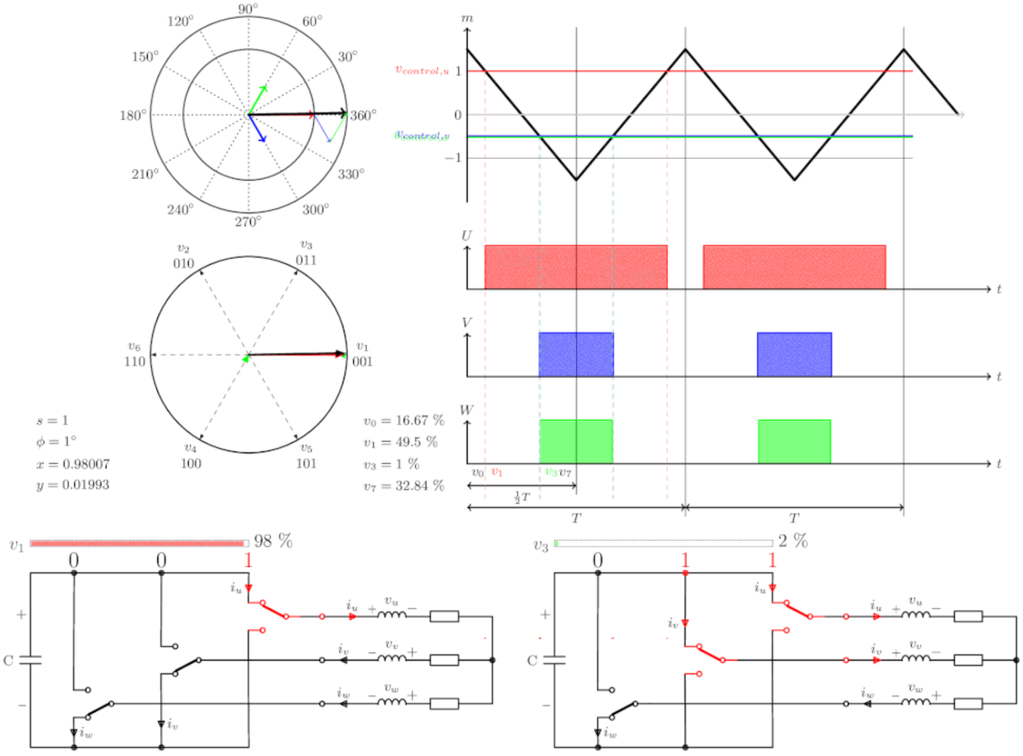
PWM Generation

Switching Sequence:

- Zero Vector (000)
- Basic Vector (i.e. 001)
- Basic Vector (i.e. 011)
- Zero Vector (i.e. 111)

  Only one switch position is changed at each step!

PWM Generation



SPWM vs SVPWM

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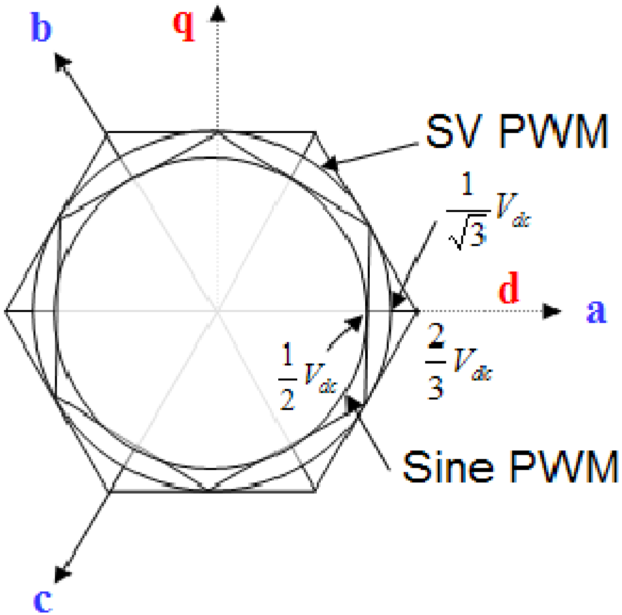

Phase Voltages

SPWM vs SVPWM

SPWM vs SVPWM

- Space Vector PWM generates less harmonic distortion

SPWM vs SVPWM

- Space Vector PWM generates less harmonic distortion
- Space Vector PWM utilizes input voltage more $1/2$ vs $1/\sqrt{3}$ (15% more)

What is the max. possible phase voltage with SPWM (Sinusoidal PWM)?

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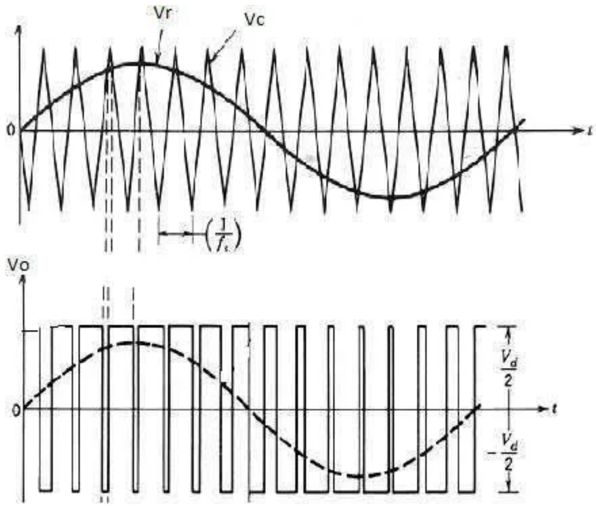

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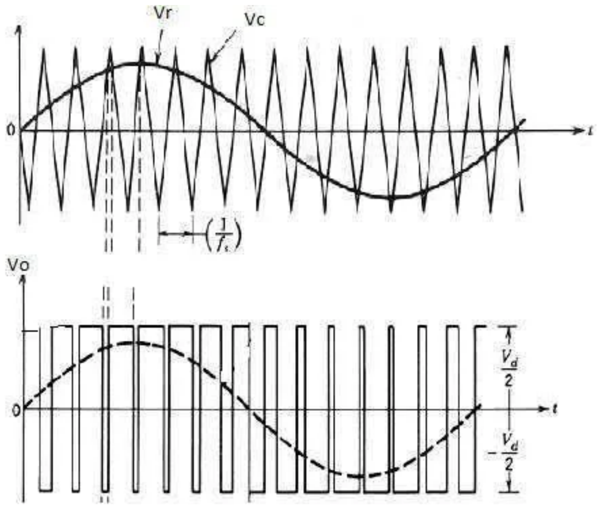

$$\hat{V}_{p-n} = \frac{V_{DC}}{2}$$

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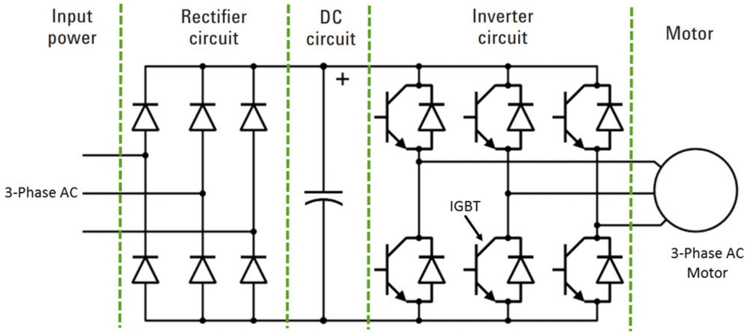
The inverter is connected to 400 V_{l-l} grid with a 3-ph diode rectifier:



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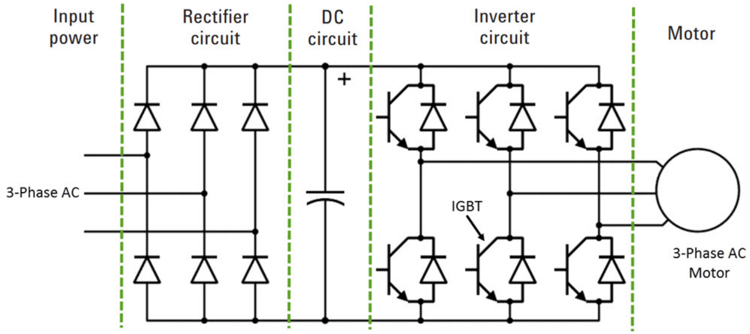

$$V_{DC} =$$

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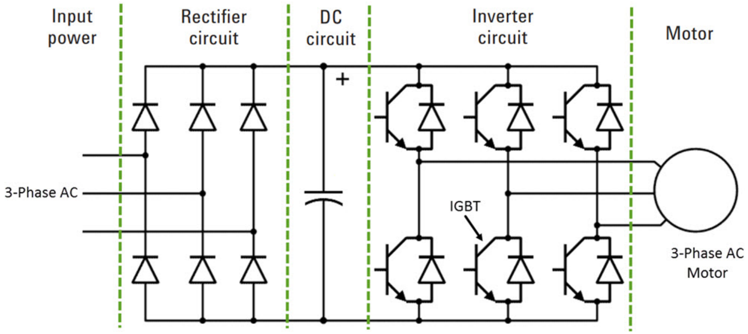

$$V_{DC} = \frac{3\sqrt{2}}{\pi} V_{l-l}$$

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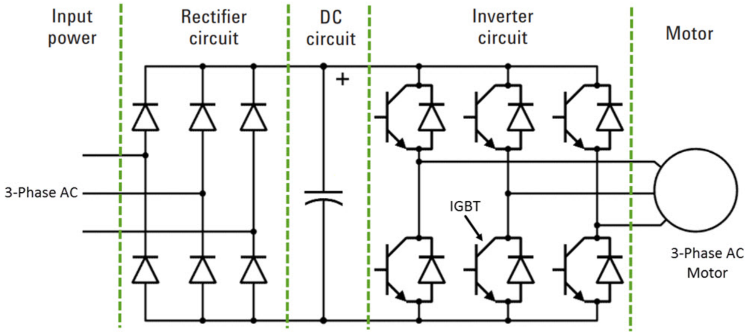

$$V_{DC} = \frac{3\sqrt{2}}{\pi} V_{l-l} = 1.35 V_{l-l} = 540V$$

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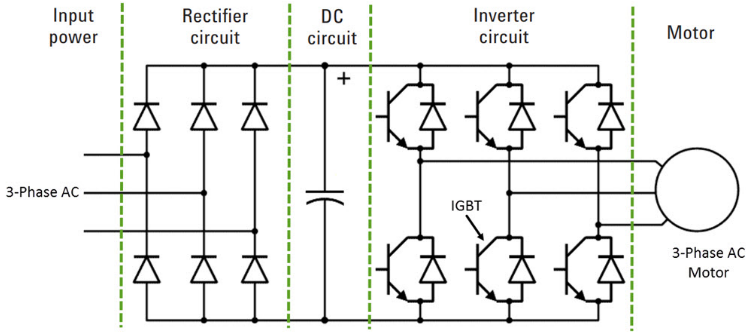

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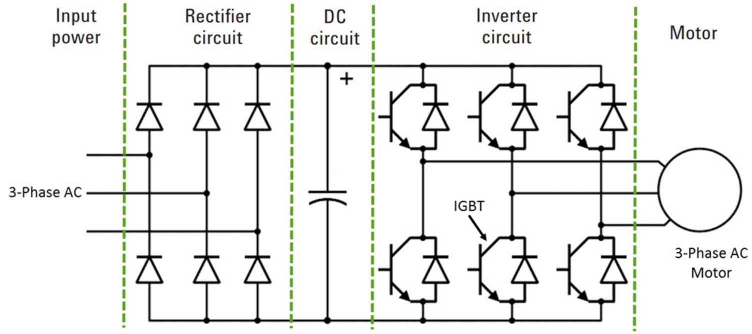
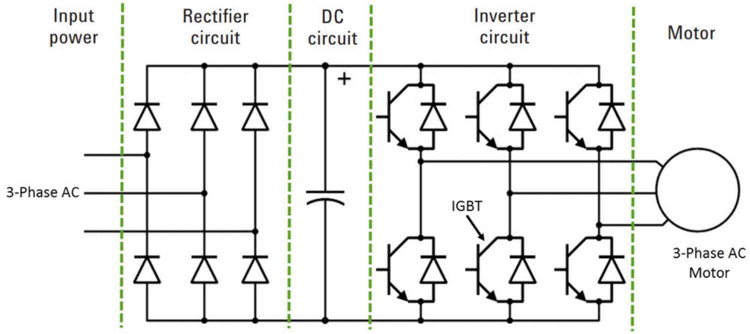


Maximum motor phase voltage:

What is the max. possible phase voltage with SPWM (Sinusoidal PWM)?



Maximum motor phase voltage:

$$V_{phase-rms} = \frac{V_{DC}}{2\sqrt{2}} = 190V$$

which is quite low for standard motors!

How can you increase the output voltage beyond the DC-link voltage limit?

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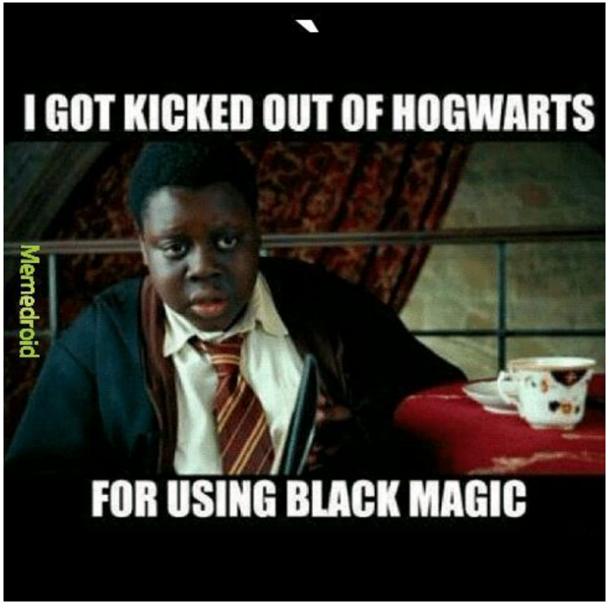
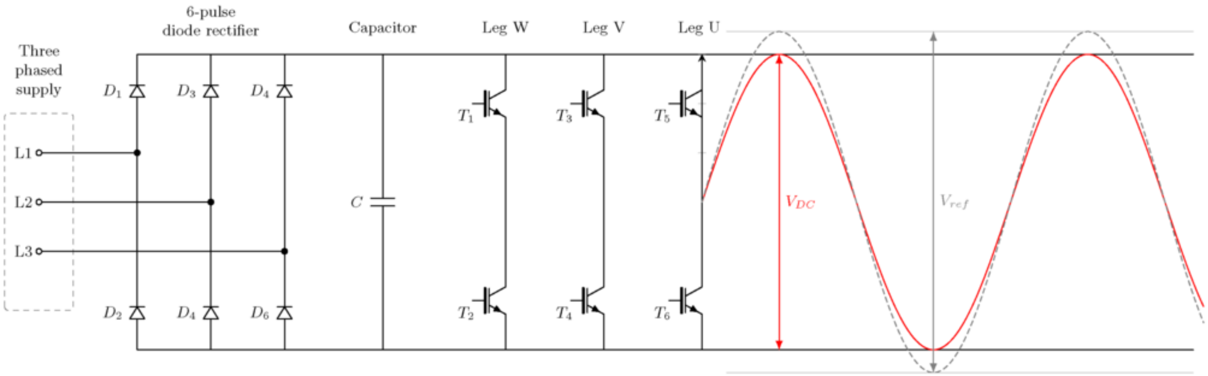


Third Harmonic Injection (THIPWM)

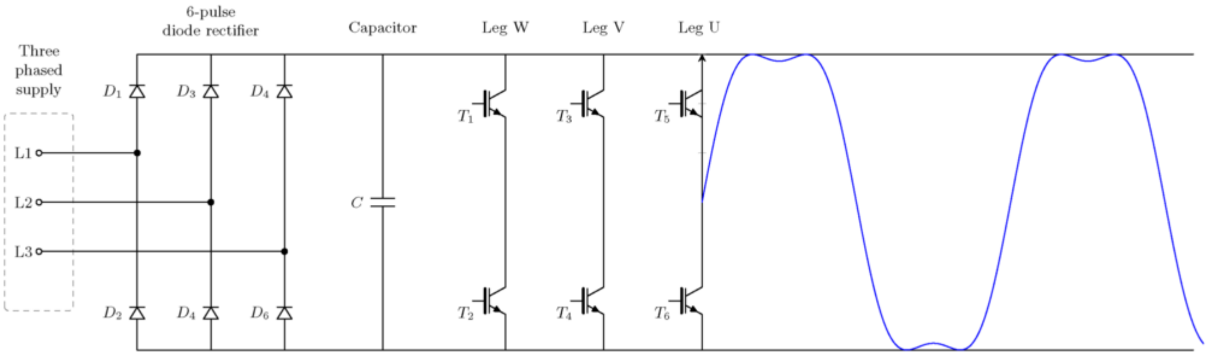
Third Harmonic Injection (THIPWM)

A sinusoidal reference voltage output:



Third Harmonic Injection (THIPWM)

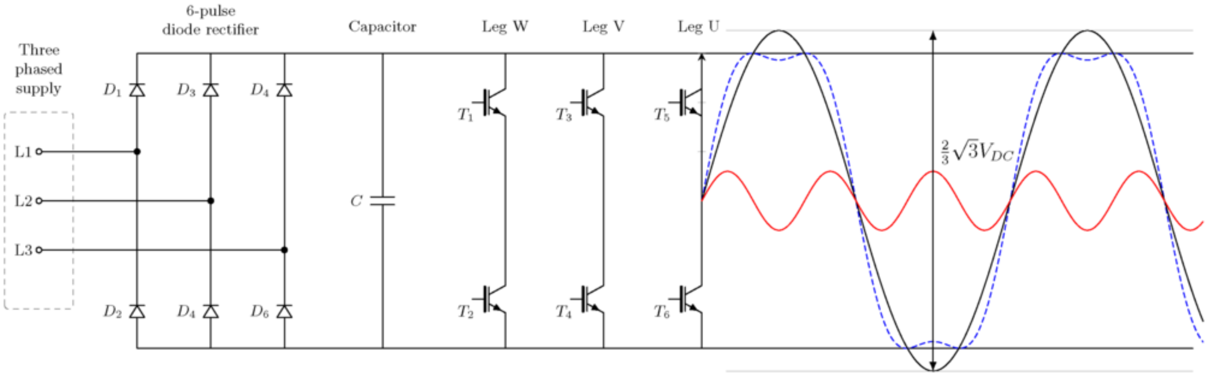
Assume you apply a waveform like that:



which composes of the fundamental and a third-harmonic component

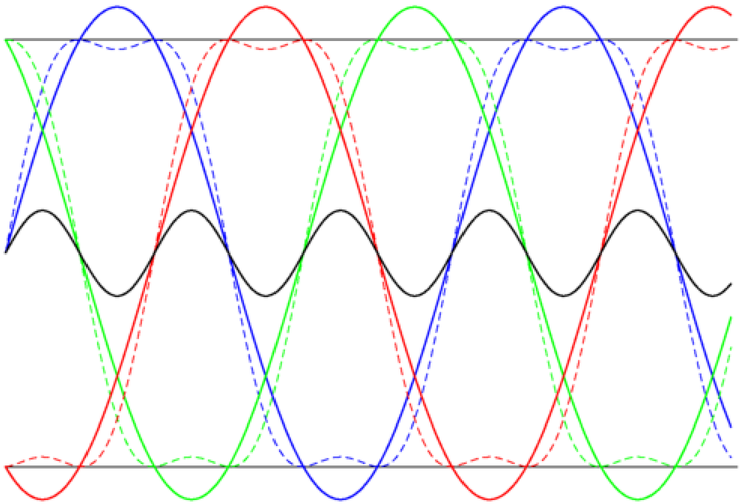
Third Harmonic Injection (THIPWM)

Such that $V = \frac{V_{DC}}{2}$ at $\pi/3$



Third Harmonic Injection (THIPWM)

What is the phase voltage?



Third harmonic cancels itself (common-mode voltage), the potential of the neutral votlage is oscillating, but the winding doesn't see this change and observe a pure sinusoidal.

Third Harmonic Injection (THIPWM)

What is the phase voltage?

THIPWM: $V_{phase-rms} = \frac{V_{DC}}{\sqrt{6}} = 220V$

Third Harmonic Injection (THIPWM)

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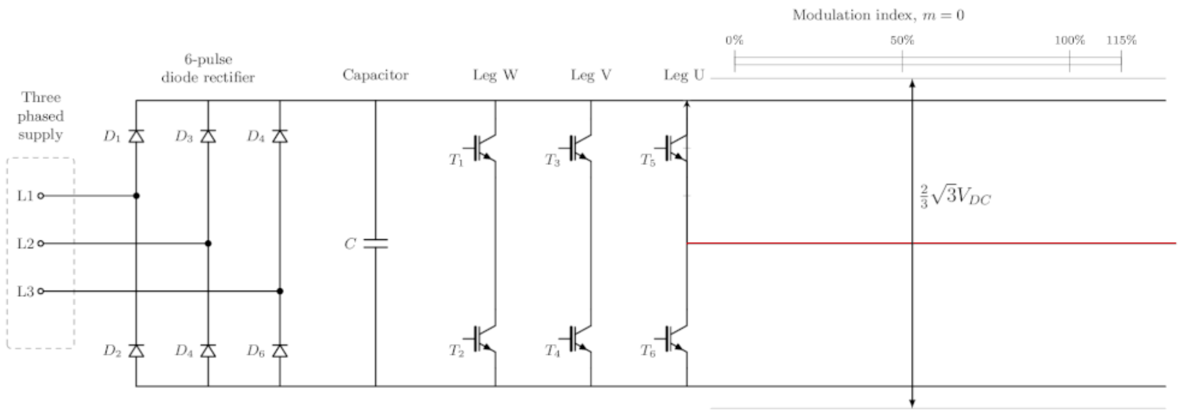
%15 higher than SPWM

$$(V_{phase-rms} = \frac{V_{DC}}{2\sqrt{2}} = 190V)$$

Third Harmonic Injection (THIPWM)



How about SVPWM?

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$$\hat{V_n} = \frac{2}{3} V_{DC}$$

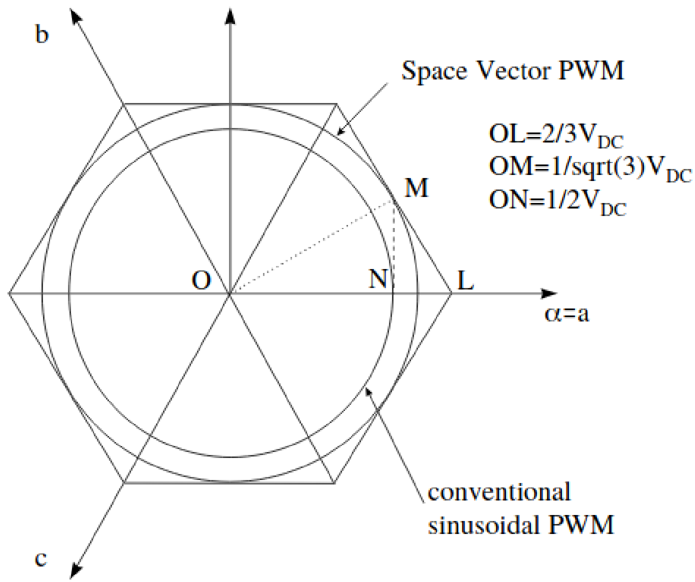
What if two adjacent vectors are applied for %50, %50?

$$= \frac{2}{3} V_{DC} \frac{\sqrt{3}}{2} = \frac{1}{\sqrt{3}} V_{DC}$$

Same with THIPWM: $V_{ph,rms} = \frac{1}{\sqrt{6}} V_{DC} = 220V$

How about SVPWM?

Magnitude comparison of SPWM and SVPWM



Magnitude comparison of SPWM and SVPWM

Space Vector (SVPWM)

Max. $V_{l-l,rms} = \sqrt{3}\frac{\frac{V_{dc}}{\sqrt{3}}}{\sqrt{2}}$

Magnitude comparison of SPWM and SVPWM

Space Vector (SVPWM)

Max. $V_{l-l,rms} = \sqrt{3}\frac{\frac{V_{dc}}{\sqrt{3}}}{\sqrt{2}} = \frac{V_{dc}}{\sqrt{2}} = 0.707V_{dc}$

Magnitude comparison of SPWM and SVPWM

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Sinusoidal (SPWM)

Magnitude comparison of SPWM and SVPWM

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Sinusoidal (SPWM)

Max. $V_{l-l,rms} = \sqrt{3}\frac{\frac{V_{dc}}{2}}{\sqrt{2}}$

Magnitude comparison of SPWM and SVPWM

Space Vector (SVPWM)

Max. $V_{l-l,rms} = \sqrt{3}\frac{\frac{V_{dc}}{\sqrt{3}}}{\sqrt{2}} = \frac{V_{dc}}{\sqrt{2}} = 0.707V_{dc}$

Sinusoidal (SPWM)

Max.

$$V_{l-l,rms} = \sqrt{3}\frac{\frac{V_{dc}}{2}}{\sqrt{2}} = \frac{\sqrt{3}V_{dc}}{2\sqrt{2}} = 0.612V_{dc}$$

SVPWM is %15 higher than SPWM

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