EE-464 STATIC POWER CONVERSION-II

Three Phase Inverters

Ozan Keysan

keysan.me

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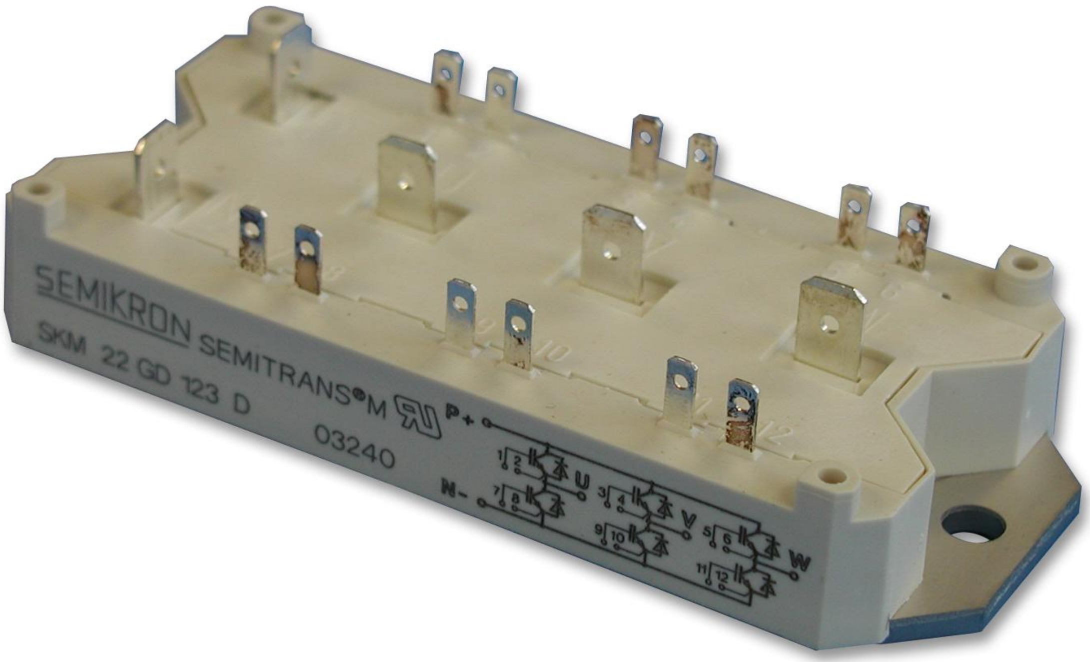
Three Phase Inverters

Different Sized Variable Frequency Drives (VFD)

Three Phase Inverters



Three Phase Voltage-Source Inverters

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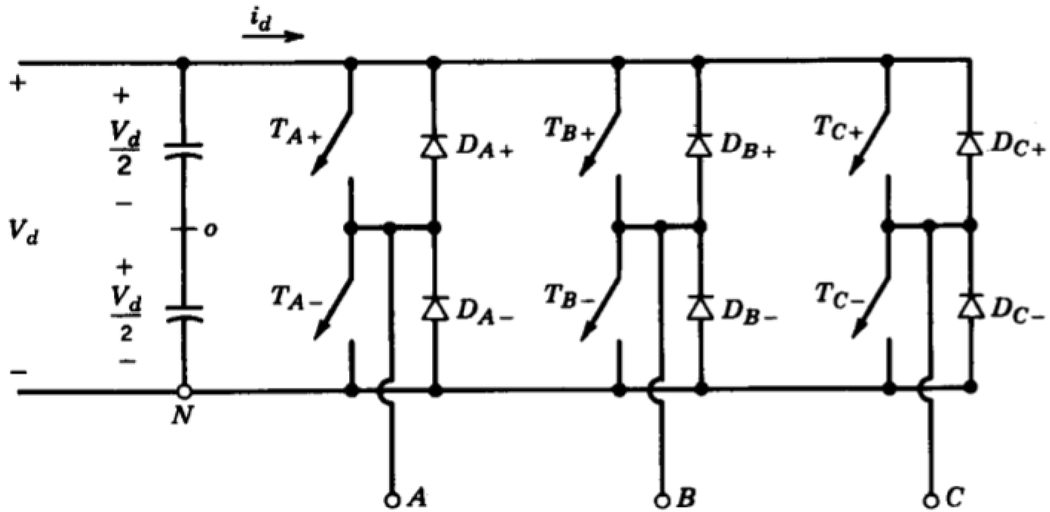

Three inverter legs are connected in parallel

Three Phase Voltage-Source Inverters

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- Do not close top and bottom switches at the same time

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Three Phase Voltage-Source Inverters

- Do not close top and bottom switches at the same time
- Point (o) is not needed put shown for simplicity in calculations
- Current can flow through the switch or anti-parallel diodes.

PWM Techniques

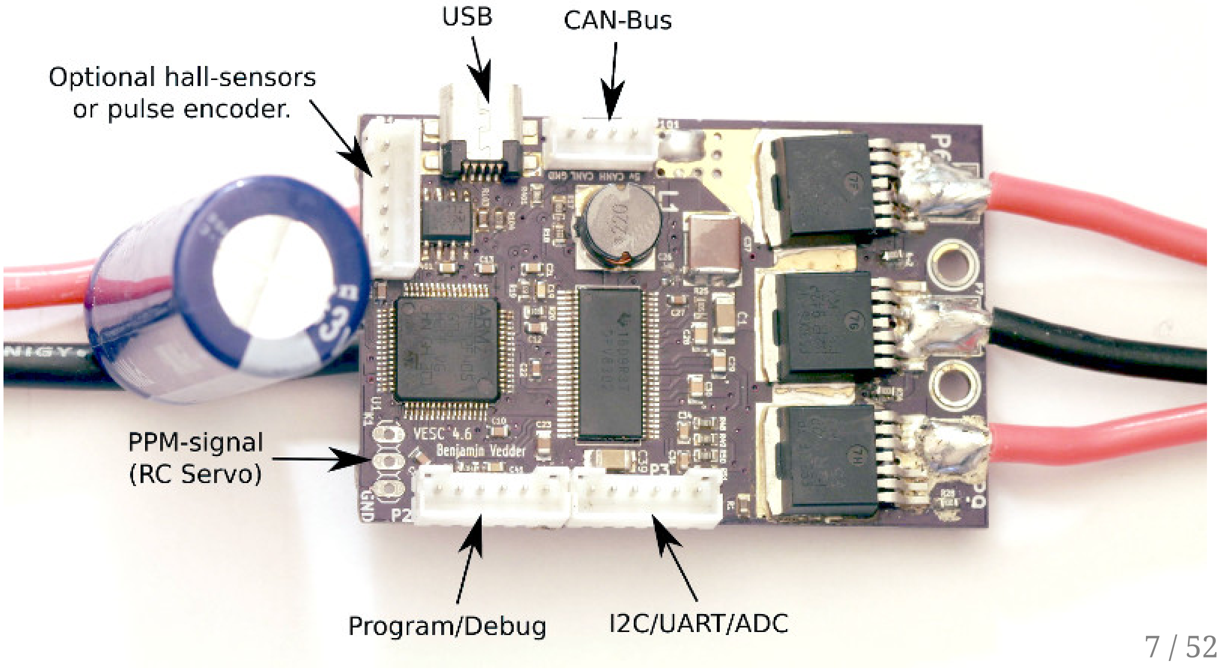
PWM Techniques

There are many different PWM techniques that will be covered:

- Square-wave (Six-step) PWM
- Sinusoidal PWM (SPWM)
- Hysteresis (Bang-Bang) Control
- Space-Vector PWM (SVPWM)
- Third harmonic injection

Six-Step Inverter

Commonly used in BLDC motor Drives



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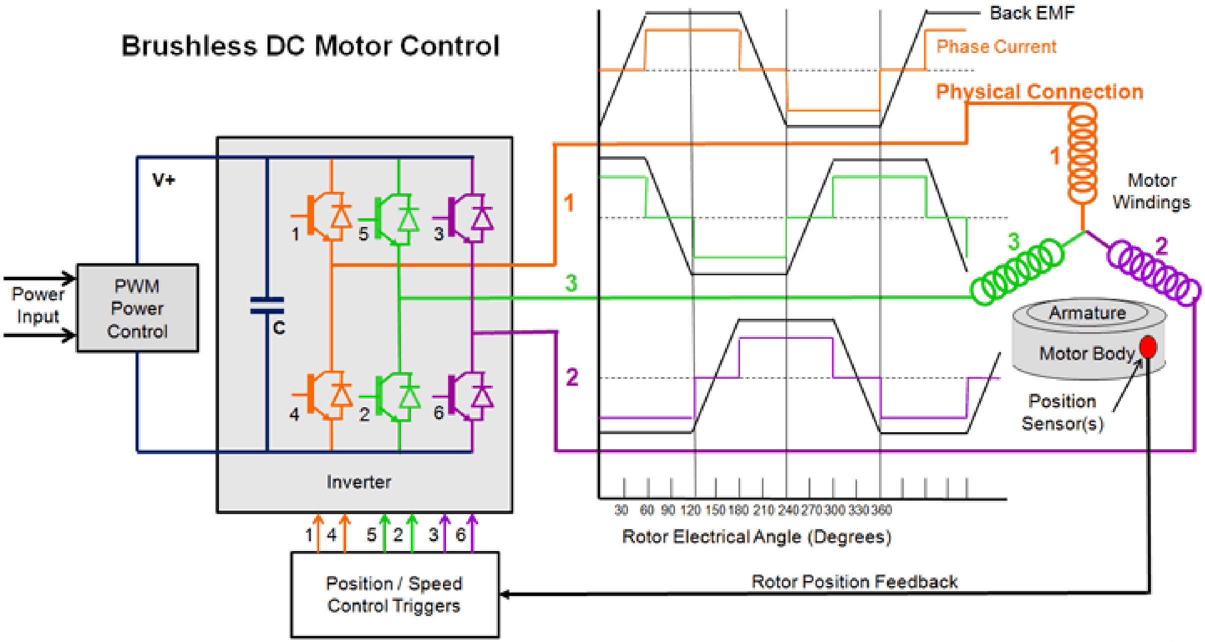
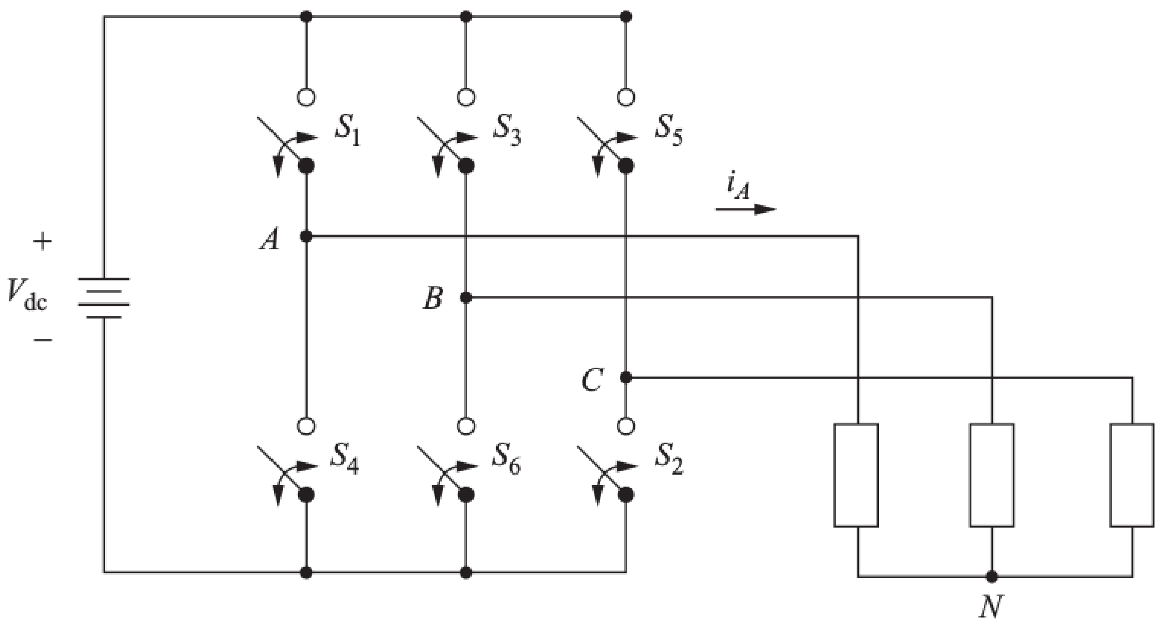


Six-Step Inverter

- Each switch has 50% duty ratio.
- Each leg has a phase difference of 120 degrees
- One switching action takes place at every 60 degrees

Six-Step Inverter



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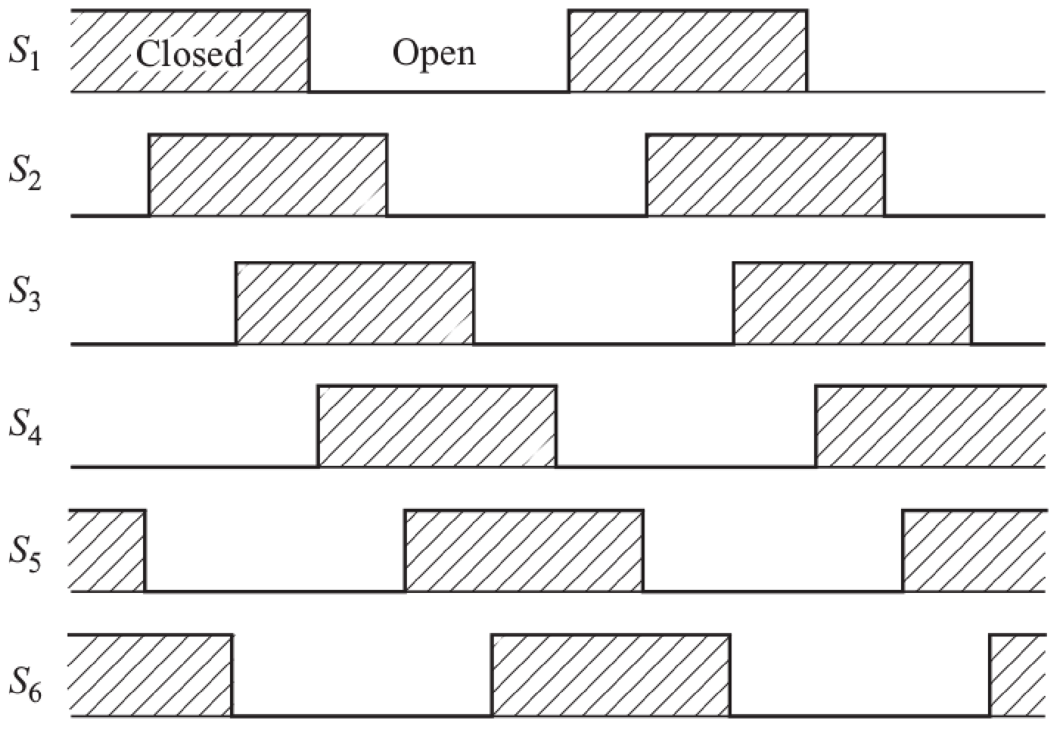
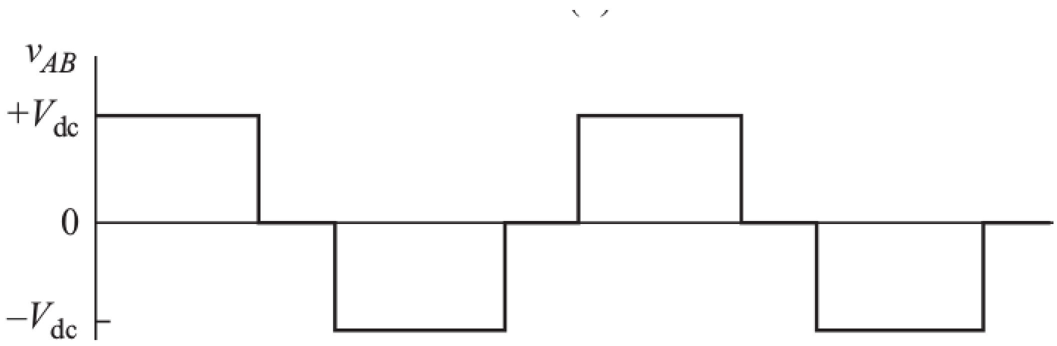
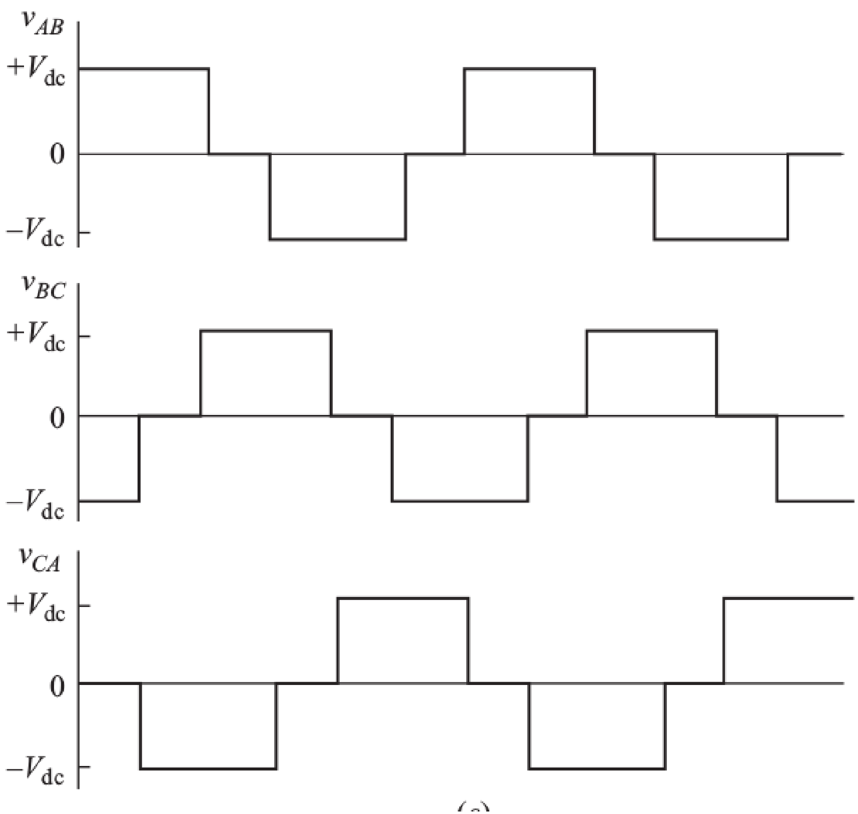


Six-Step Inverter

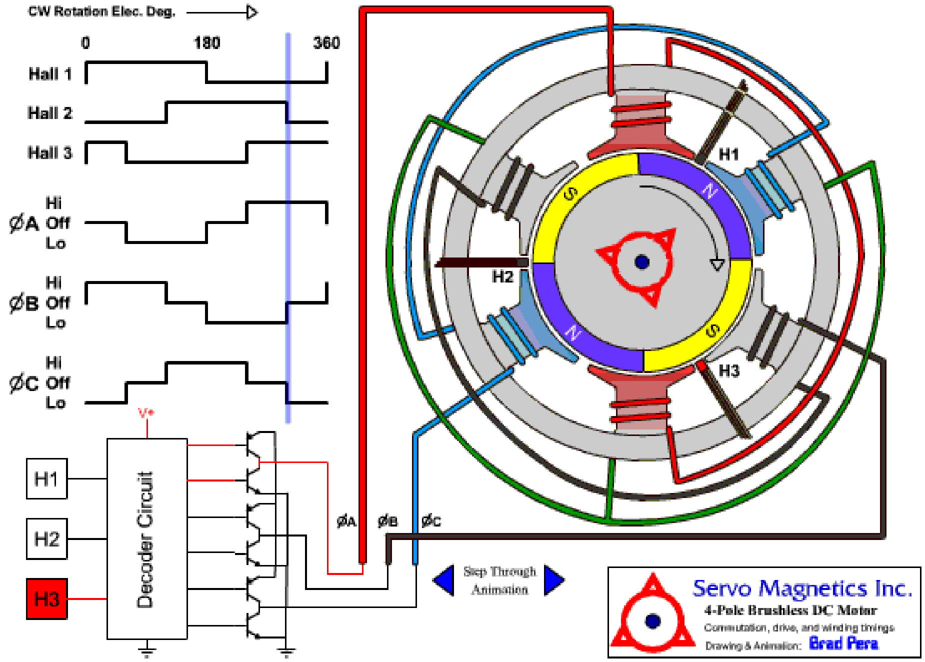
Line-to-line voltage: $V_{AB} = V_{A0} - V_{B0}$



Line-to-line voltages:

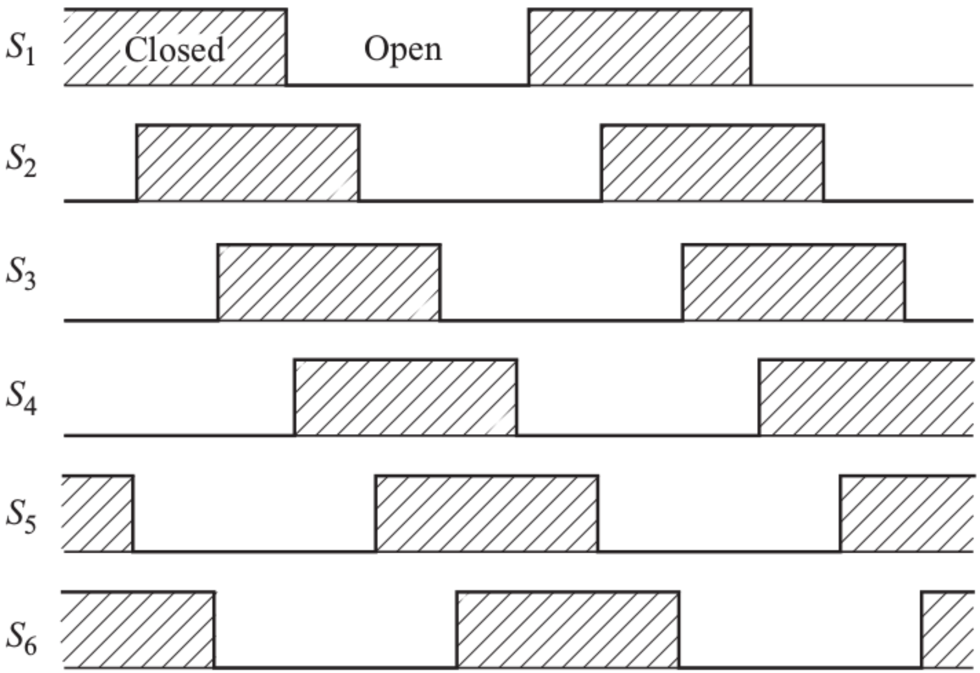


Square Wave Operation

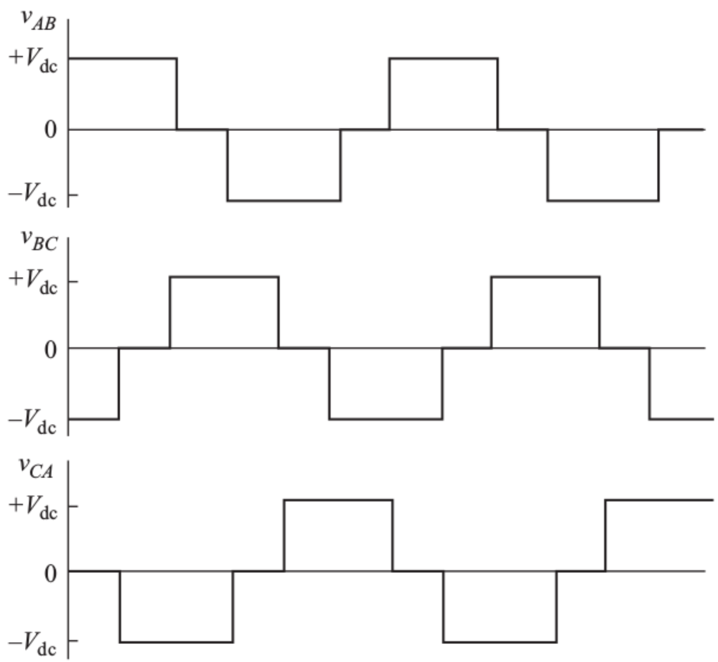


[BLDC Drive with square wave]

Switching Sequence

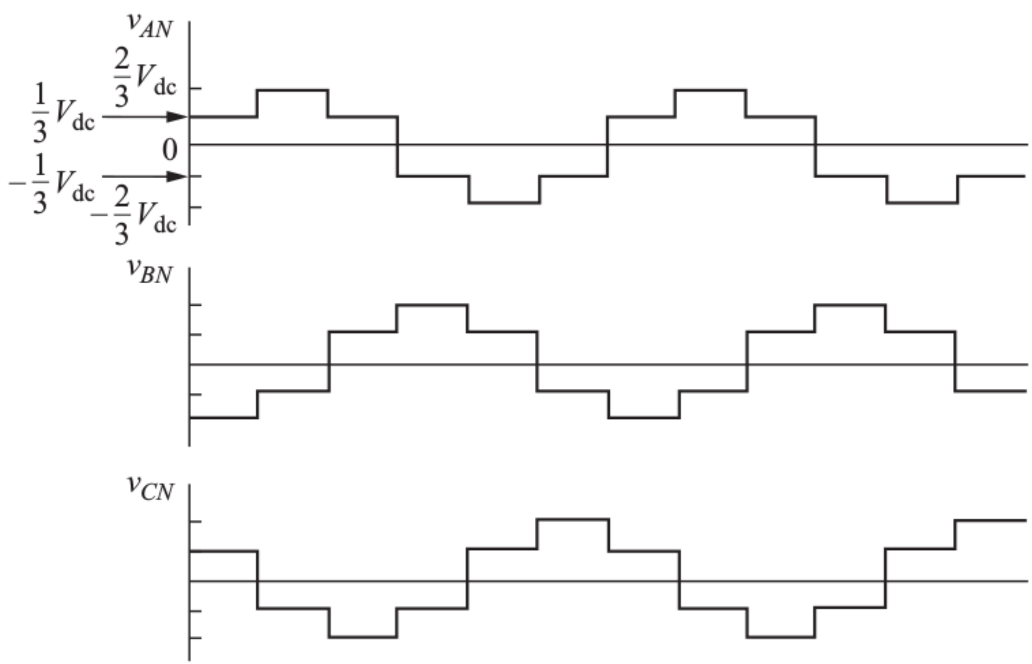


Line-to-Line Voltages



(c)

Equivalent Phase Voltages



Line-to-Line Harmonics

Fourier Coefficients

$$\hat{V}_{n,l-l} = \frac{1}{n}\frac{4}{\pi}V_{dc}cos(n\frac{\pi}{6})$$

For: $n = 6k \pm 1 = 1, 5, 7, 11, 13...$

- No even harmonics
- No third order harmonics

Line-to-Line Harmonics

RMS of the fundamental component?

$$V_{1,l-l,rms} = \frac{1}{\sqrt{2}}\frac{4}{\pi}V_{dc}\frac{\sqrt{3}}{2} = 0.78V_{dc}$$

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Harmonics RMS:

$$V_{n,l-l,rms} = \frac{1}{n}0.78V_{dc}$$

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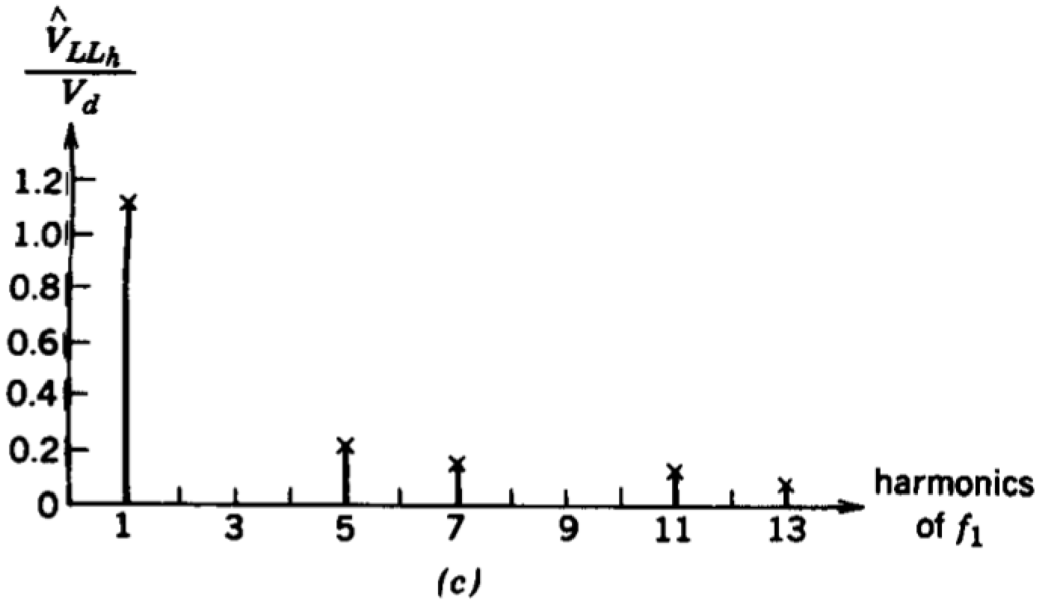
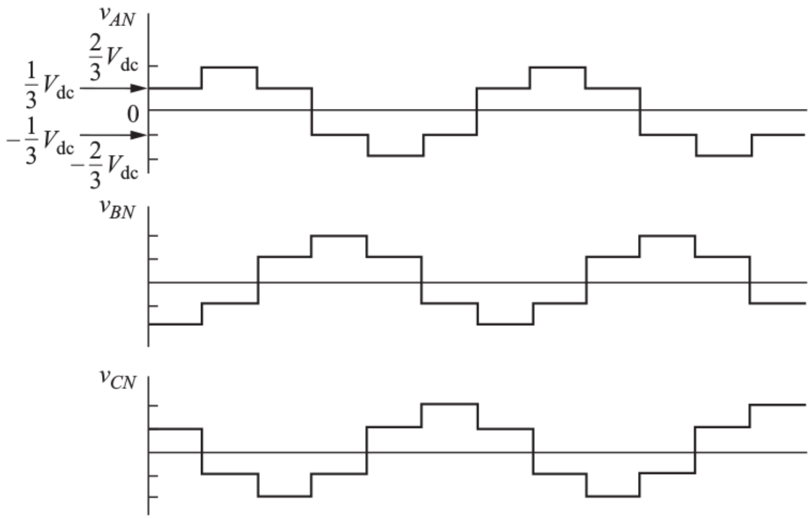
Line-to-Line Harmonics



Line-to-Neutral voltages:

Neutral point is floating



Voltage level changes every 60 degrees (that's why it's a six-step inverter!)

Line-to-Neutral Harmonics

Fourier Coefficients

$$\hat{V}_{n,l-N} = \frac{1}{n}\frac{2}{3\pi}V_{dc}(2 + cos(\frac{\pi n}{3}) - cos(\frac{2\pi n}{3})$$

For: $n = 6k \pm 1 = 1, 5, 7, 11, 13...$

Simpler Form

$$\hat{V}_{n,l-N} = \frac{1}{n}\frac{2}{\pi}V_{dc}$$

Line-to-Neutral Harmonics

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Example: (D. Hart . 8-12)

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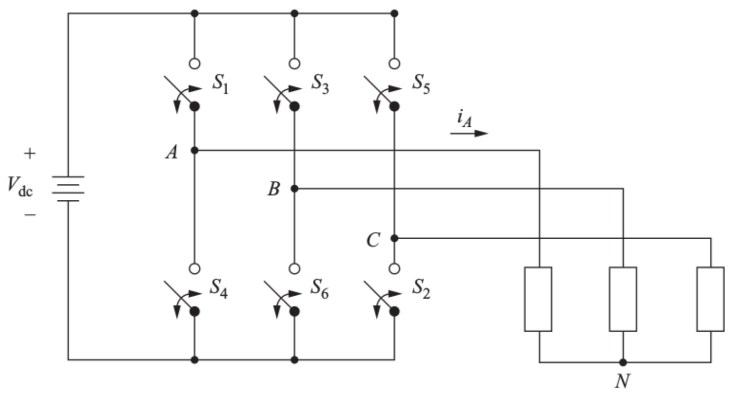
For the six-step three phase inverter shown below, Vin=100V, $f_{out} = 60Hz$. The load is Y-connected to load with a phase load of $R = 10\Omega, L = 20mH$.



Calculate the total harmonic distortion (THD) of the load current and voltage.

Example: (D. Hart . 8-12)

Amplitude for load current at each frequency:

$$I_n = \frac{V_{n,L-N}}{Z_n}$$

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Line-to-Neutral Harmonics

$$\hat{V}_{n,l-N} = \frac{1}{n}\frac{2}{\pi}V_{dc}$$

For: $n = 6k \pm 1 = 1, 5, 7, 11, 13...$

Table 8.7 Fourier Components for the Six-Step Inverter of Example 8-12

n	$V_{n,L\text{-}N}$ (V)	Z_n (Ω)	I_n (A)	$I_{n,\text{rms}}$ (A)
1	63.6	12.5	5.08	3.59
5	12.73	39.0	0.33	0.23
7	9.09	53.7	0.17	0.12
11	5.79	83.5	0.07	0.05
13	4.90	98.5	0.05	0.04

Voltage THD=

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Voltage THD=

$$\frac{\sqrt{\sum_{n=2}^{\infty} V_n{}^2}}{V_{1,rms}} \approx \frac{\sqrt{12.73^2 + 9.09^2 + 5.79^2 + 4.90^2}}{63.6} = 0.31 = 31\%$$

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Voltage Plot, Current Plot

Three Phase Voltage-Source Inverter

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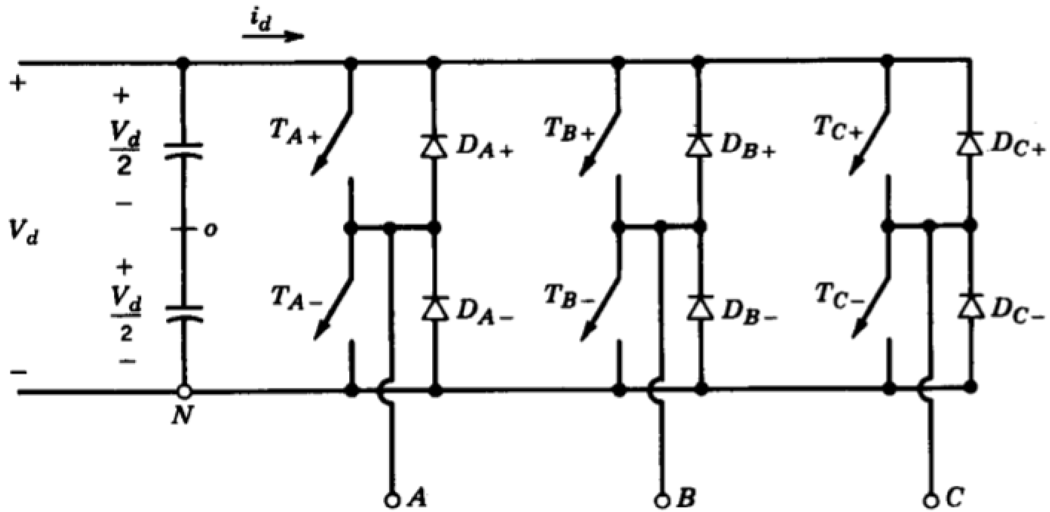

Sinusoidal PWM (SPWM)

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A triangular carrier wave is generated and compared with each phase.

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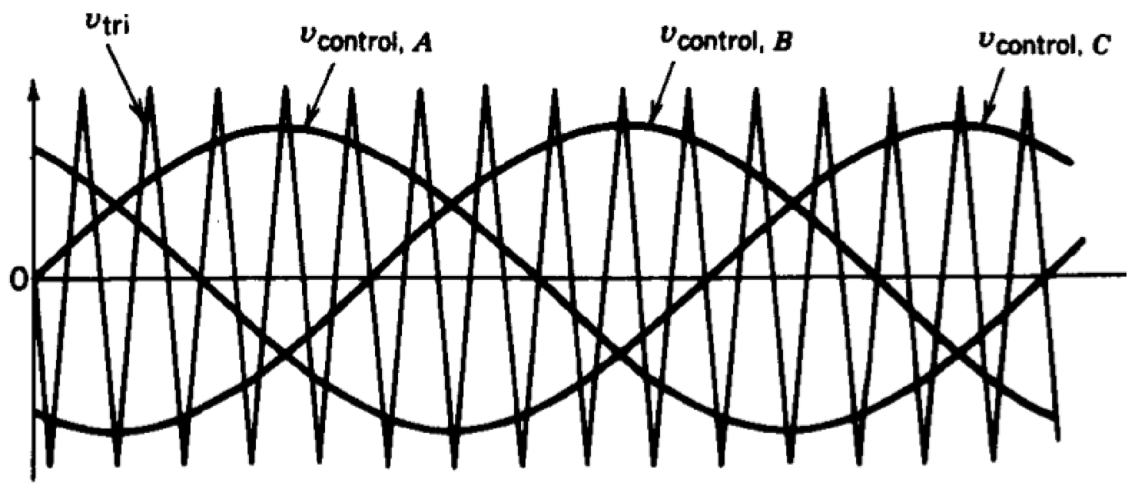

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Vd or 0 voltage is generated at V_{AN} depending on the comparison.

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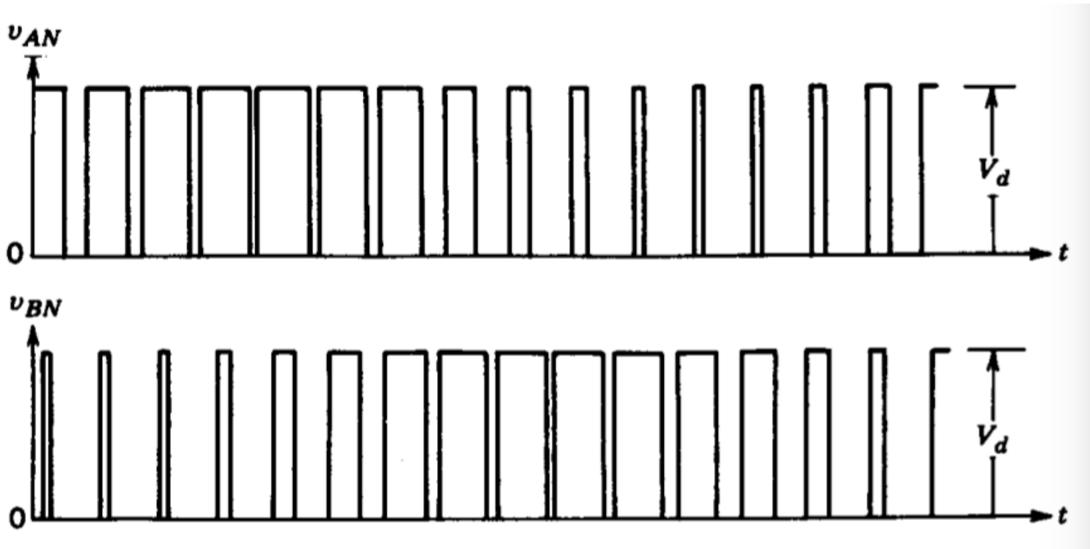

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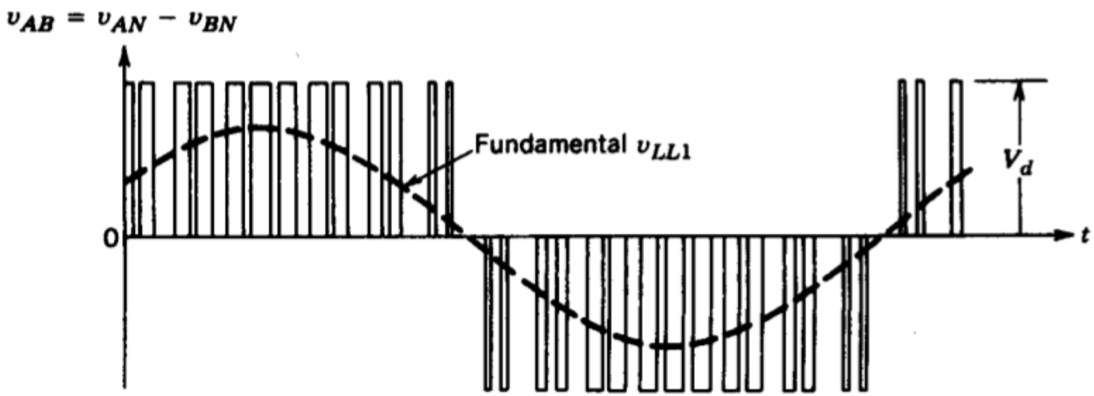

Sinusoidal PWM (SPWM)

Harmonics in the line voltage

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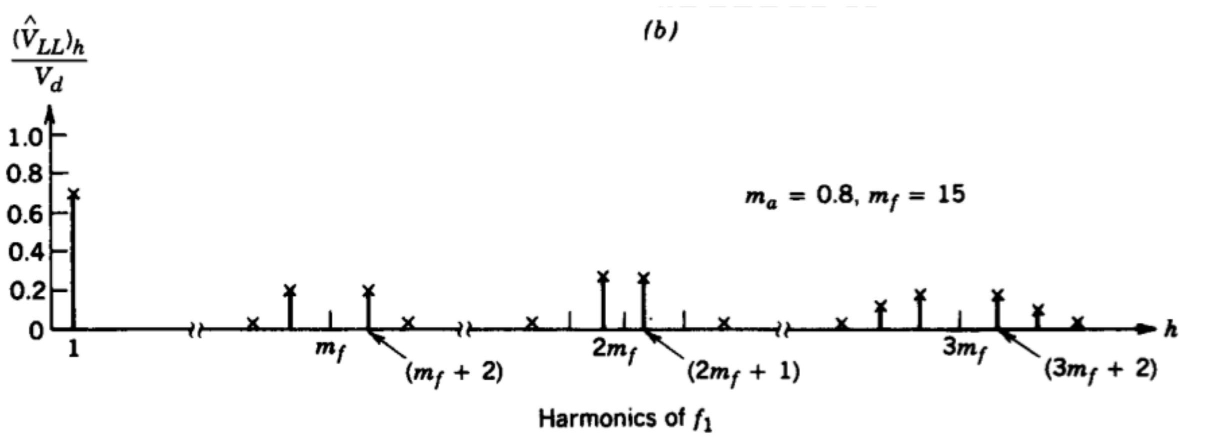
Harmonics in the line voltage



Harmonics at the side bands,

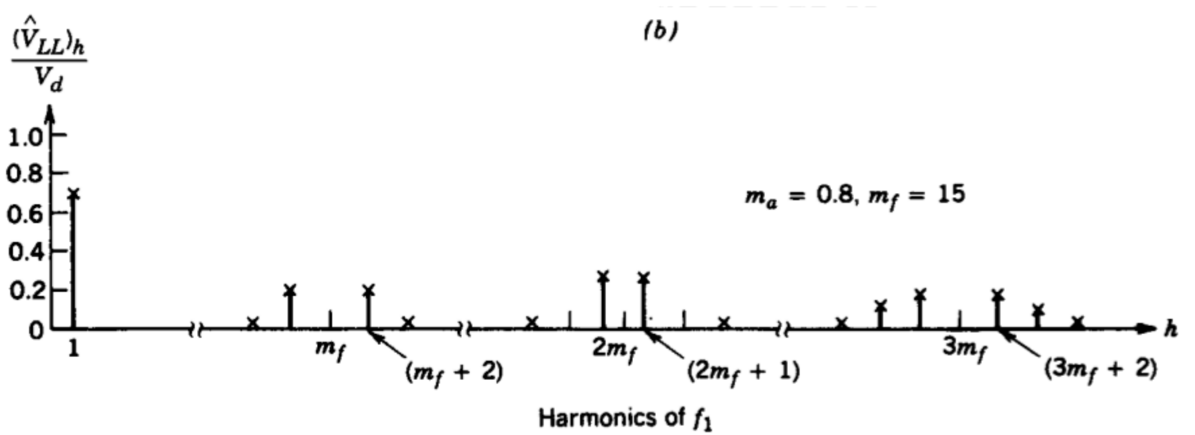
Like the unipolar but starts at mf.

Sinusoidal PWM (SPWM)

Harmonics in the line voltage

Sinusoidal PWM (SPWM)

Harmonics in the line voltage



If mf is small, it is better to use synchronized PWM, and mf should be an odd interger, preferably multiple of 3 to reduce harmonics.

Sinusoidal PWM (SPWM)

Harmonics in the line voltage

Sinusoidal PWM (SPWM)

Harmonics in the line voltage

Table 8-2 Generalized Harmonics of v_{LL} for a Large and Odd m_f That Is a Multiple of 3.

h \ m_a	0.2	0.4	0.6	0.8	1.0
1	*0.122*	*0.245*	*0.367*	*0.490*	*0.612*
$m_f \pm 2$	0.010	0.037	0.080	0.135	0.195
$m_f \pm 4$				0.005	0.011
$2m_f \pm 1$	0.116	0.200	0.227	0.192	0.111
$2m_f \pm 5$				0.008	0.020
$3m_f \pm 2$	0.027	0.085	0.124	0.108	0.038
$3m_f \pm 4$		0.007	0.029	0.064	0.096
$4m_f \pm 1$	0.100	0.096	0.005	0.064	0.042
$4m_f \pm 5$			0.021	0.051	0.073
$4m_f \pm 7$				0.010	0.030

Voltage Levels?

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Linear Region ($m_a < 1$)

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$$\hat{V}_{AN1} = m_a \frac{V_d}{2}$$

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$$\hat{V}_{AN1} = m_a \frac{V_d}{2}$$

$$V_{l-l,rms} = \frac{\sqrt{3}}{\sqrt{2}} m_a \frac{V_d}{2}$$

Voltage Levels?

Linear Region ($m_a < 1$)

$$\hat{V}_{AN1} = m_a \frac{V_d}{2}$$

$$V_{l-l,rms} = \frac{\sqrt{3}}{\sqrt{2}} m_a \frac{V_d}{2}$$

$V_{l-l,rms} = 0.612 V_d$ (max in linear region)

Voltage Levels?

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Overmodulation ($m_a > 1$)

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Square-Wave Operation?

Voltage Levels?

Overmodulation ($m_a > 1$)

Square-Wave Operation?

$$V_{l-l,rms} = \frac{\sqrt{3}}{\sqrt{2}} \frac{4}{\pi} m_a \frac{V_d}{2}$$

Voltage Levels?

Overmodulation ($m_a > 1$)

Square-Wave Operation?

$$V_{l-l,rms} = \frac{\sqrt{3}}{\sqrt{2}}\frac{4}{\pi}m_a\frac{V_d}{2}$$

$$V_{l-l,rms} = 0.78V_d$$

Voltage Levels?

Overmodulation ($m_a > 1$)

Square-Wave Operation?

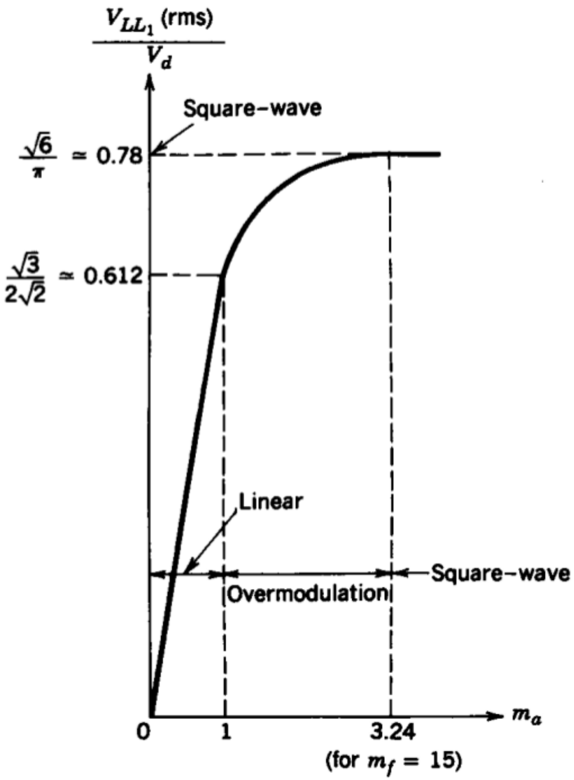
$$V_{l-l,rms} = \frac{\sqrt{3}}{\sqrt{2}}\frac{4}{\pi}m_a\frac{V_d}{2}$$

$$V_{l-l,rms} = 0.78V_d$$

$$V_{l-l,rms,h} = \frac{0.78}{h}V_d$$ for $h = 6n \pm 1$

Voltage Levels?

Voltage Levels?



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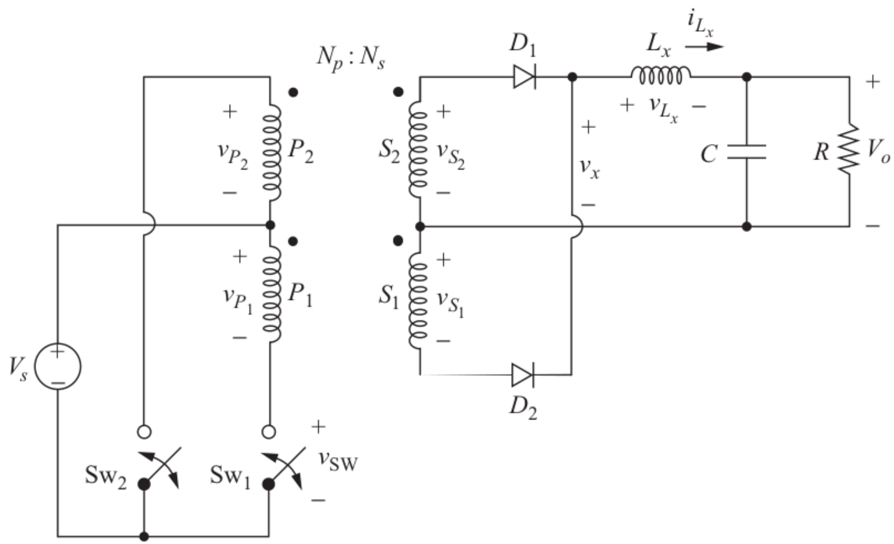
Harici Slaytlar

Push-Pull Inverter

Push-Pull Inverter

Similar to Push-Pull Converter



Push-Pull Inverter

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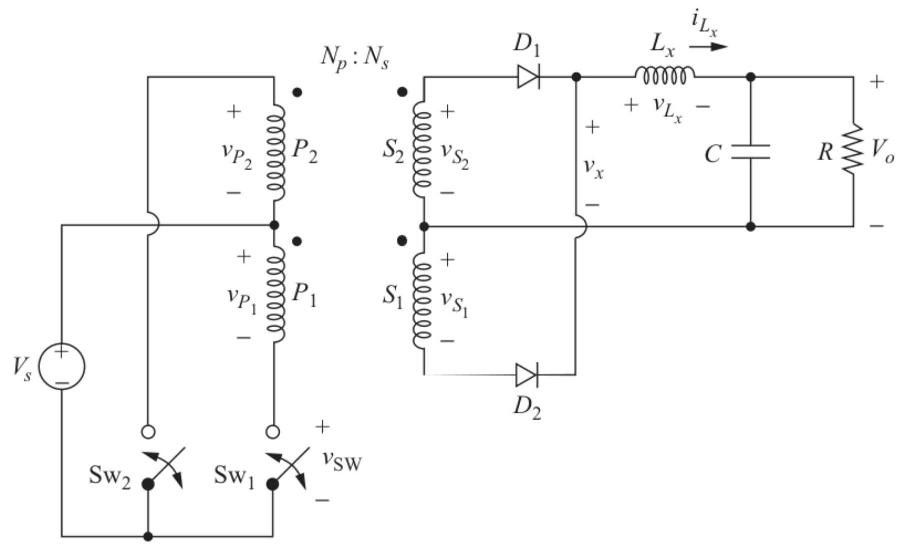
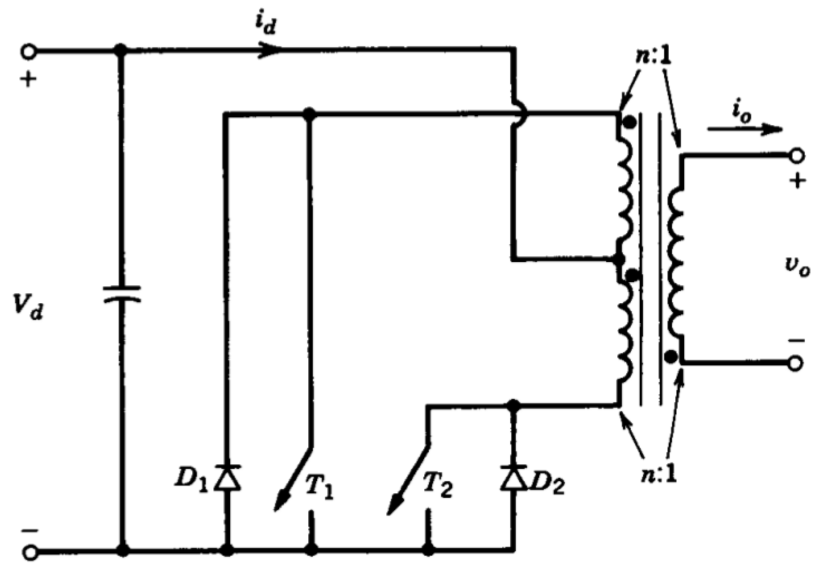


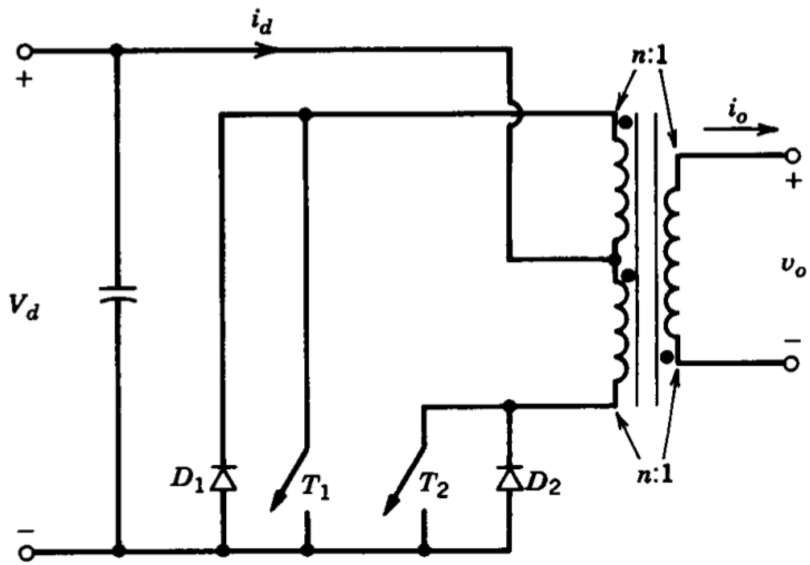
But without the rectifying diodes

Push-Pull Inverter

Push-Pull Inverter



Push-Pull Inverter



T1, T2 operates in sequence

Push-Pull Inverter

Push-Pull Inverter

Voltage output can be adjusted by the turns-ratio

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$$\hat{V}_{o1} = m_a \frac{V_d}{n}$$

Push-Pull Inverter

Advantages?

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- Only single transistor conduct at a time,

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Push-Pull Inverter

Advantages?

- Only single transistor conduct at a time,small voltage drop
- Especially important for low voltage applications (e.g. fed from a battery)
- There are a few PV applications as well
- Transistors have common ground (no isolation required for gate drives)

Push-Pull Inverter

Disadvantages?

Push-Pull Inverter

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- What is the required voltage rating of the transistors?

Push-Pull Inverter

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$$V_T = 2V_d$$

Therefore may not be practical for higher input voltages

Push-Pull Inverter

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- What is the required voltage rating of the transistors?

$$V_T = 2V_d$$

Therefore may not be practical for higher input voltages

- A good transformer, with high coupling is required (to reduce energy in the leakage inductance)

Switch Utilization in Single Phase Inverters

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Ratio of the output power to max. power capacity of the switches

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Assume highly inductive load, no current harmonics (just the fundamental)

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Assume highly inductive load, no current harmonics (just the fundamental)

$$= \frac{V_{o1} I_{o,max}}{q V_T I_T}$$

Switch Utilization in Single Phase Inverters

Ratio of the output power to max. power capacity of the switches

Assume highly inductive load, no current harmonics (just the fundamental)

$$= \frac{V_{o1} I_{o,max}}{q V_T I_T}$$

Maximum utilization occurs at square wave

Switch Utilization in Single Phase Inverters

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Half Bridge Inverter

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Voltage rating?

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$$V_T = V_{d,max}$$

Switch Utilization in Single Phase Inverters

Half Bridge Inverter

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$$V_T = V_{d,max}$$

Current rating?

Switch Utilization in Single Phase Inverters

Half Bridge Inverter

Voltage rating?

$$V_T = V_{d,max}$$

Current rating?

$$I_T = \sqrt{2} I_{o,max}$$

Switch Utilization in Single Phase Inverters

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Half Bridge Inverter

Output Voltage: $V_{o1,max} = \frac{4}{\pi\sqrt{2}}\frac{V_{d,max}}{2}$

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Max. Switch Utilization

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Half Bridge Inverter

Output Voltage: $V_{o1,max} = \frac{4}{\pi\sqrt{2}}\frac{V_{d,max}}{2}$

Max. Switch Utilization

q=2

$$= \frac{1}{2\pi} \approx 0.16$$

Switch Utilization in Full Bridge Inverter

Switch Utilization in Full Bridge Inverter

Voltage, Current Ratings?

Switch Utilization in Full Bridge Inverter

Voltage, Current Ratings?: Same with Half Bridge

Switch Utilization in Full Bridge Inverter

Voltage, Current Ratings?: Same with Half Bridge

q=

Switch Utilization in Full Bridge Inverter

Voltage, Current Ratings?: Same with Half Bridge

$q=4$

Switch Utilization in Full Bridge Inverter

Voltage, Current Ratings?: Same with Half Bridge

q=4

Voltage output =

Switch Utilization in Full Bridge Inverter

Voltage, Current Ratings?: Same with Half Bridge

q=4

Voltage output =twice of the half bridge

Switch Utilization in Full Bridge Inverter

Voltage, Current Ratings?: Same with Half Bridge

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Switch utilization=?

Switch Utilization in Full Bridge Inverter

Voltage, Current Ratings?: Same with Half Bridge

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Voltage output =twice of the half bridge

Switch utilization=?

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Switch Utilization in Push-Pull Inverter

Switch Utilization in Push-Pull Inverter

Voltage, Current Ratings?

Switch Utilization in Push-Pull Inverter

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$$V_T = 2V_{d,max}$$

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$$I_T = \sqrt{2}\frac{I_{o,max}}{n}$$

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Voltage, Current Ratings?

$$V_T = 2V_{d,max}$$

$$I_T = \sqrt{2}\frac{I_{o,max}}{n}$$

Output Voltage: $V_{o1,max} = \frac{4}{\pi\sqrt{2}}\frac{V_{d,max}}{n}$

Switch Utilization in Push-Pull Inverter

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$q = 2$

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Switch Utilization

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q =2

Switch Utilization

$$= \frac{1}{2\pi} \approx 0.16$$

Switch Utilization in Linear Region

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$$= \frac{1}{2\pi}\frac{\pi}{4}m_a = \frac{1}{8}m_a$$

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Linear Region

$= 0.125$ when $m_a = 1$