EE-464 STATIC POWER CONVERSION-II

DC/AC Converters (Inverters)

Ozan Keysan

keysan.me

Office: C-113 • Tel: 210 7586

DC/AC Converters

DC/AC Converters

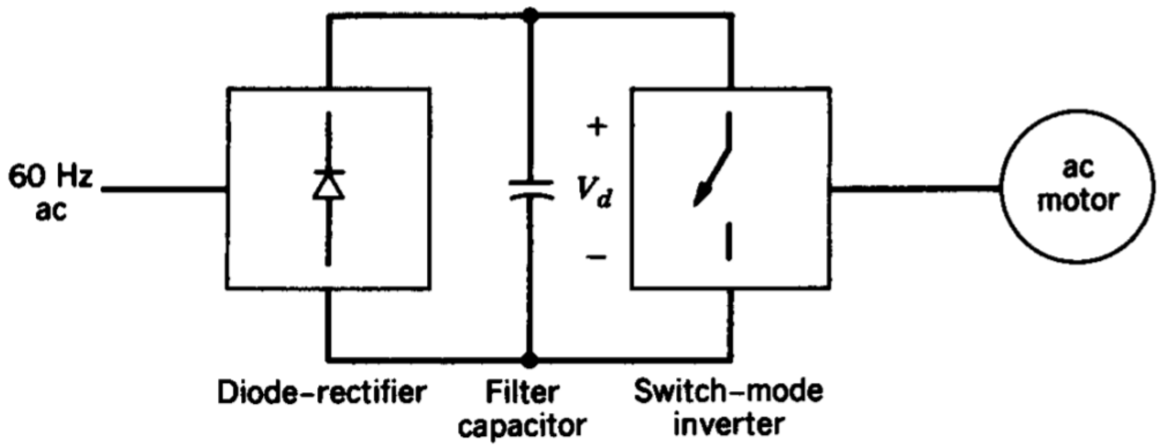
Inverters

Block Diagram

AC Motor drive with unidirectional power flow

Block Diagram

AC Motor drive with unidirectional power flow

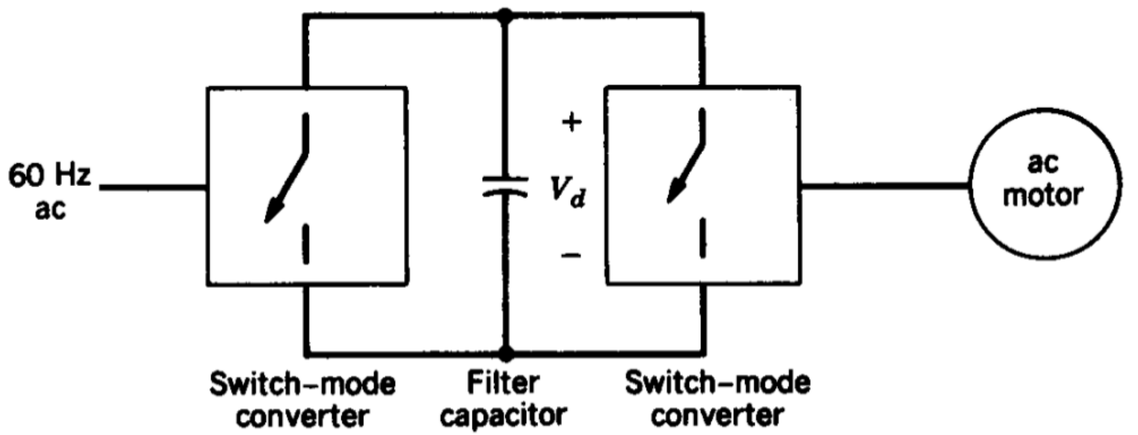


Block Diagram

AC Motor drive with bidirectional power flow

Block Diagram

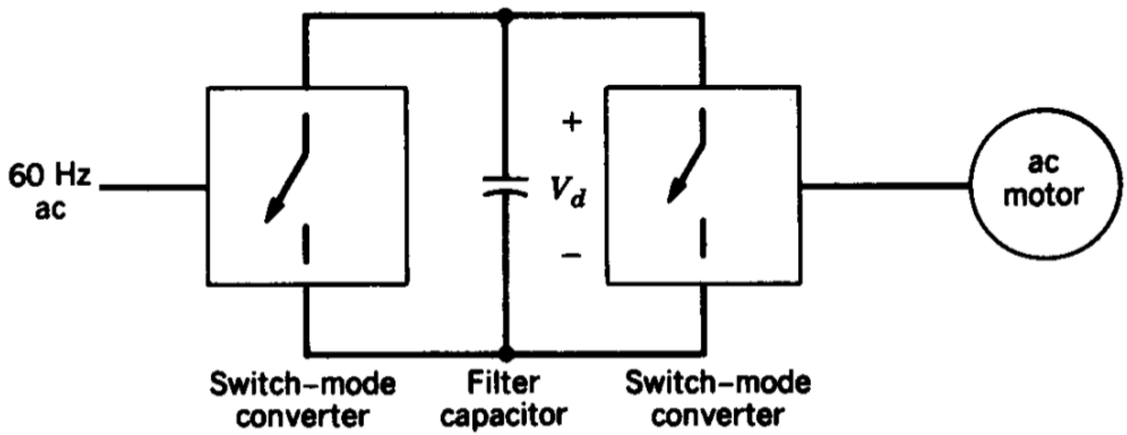
AC Motor drive with bidirectional power flow



Back-to-Back Converter, Active Front-End Converter, Variable Frequency Drive (VFD)

Block Diagram

AC Motor drive with bidirectional power flow



Back-to-Back Converter, Active Front-End Converter, Variable Frequency Drive (VFD)

PWM Generation

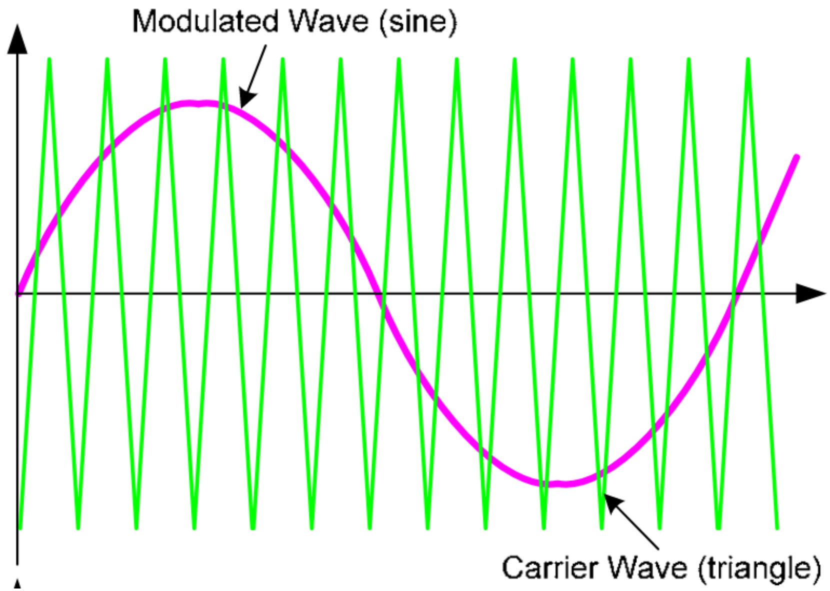
PWM Generation

Sinusoidal PWM (SPWM)

- The most common type
- There are many different PWM techniques (wait 2 weeks)

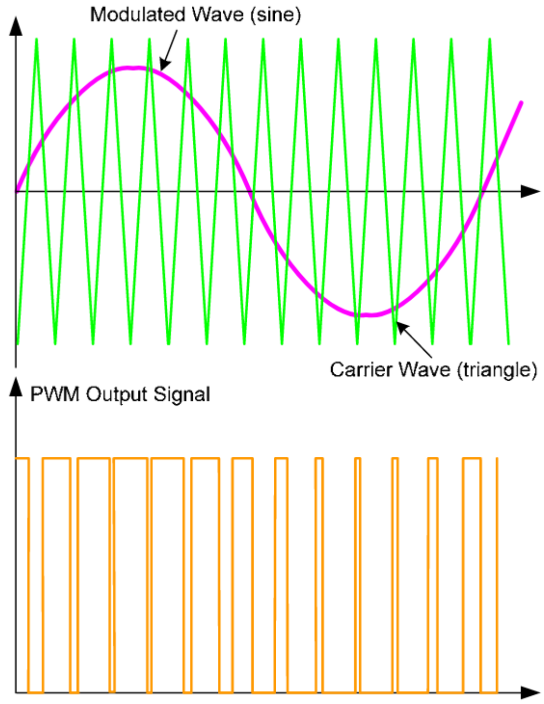
Sinusoidal PWM (SPWM)

Compare a sinusoidal wave with a carrier triangular wave



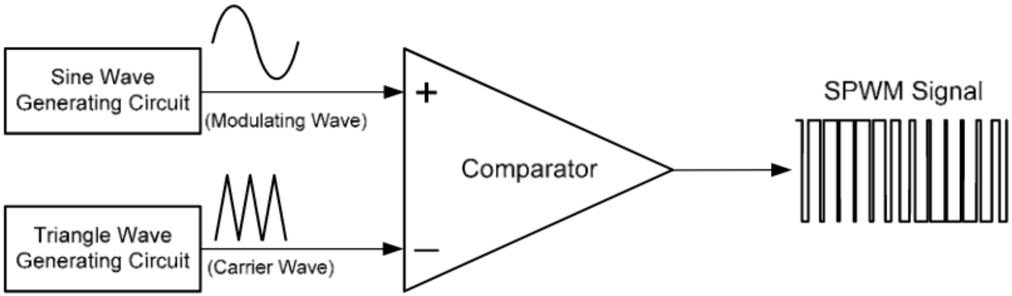
Sinusoidal PWM

Sinusoidal PWM



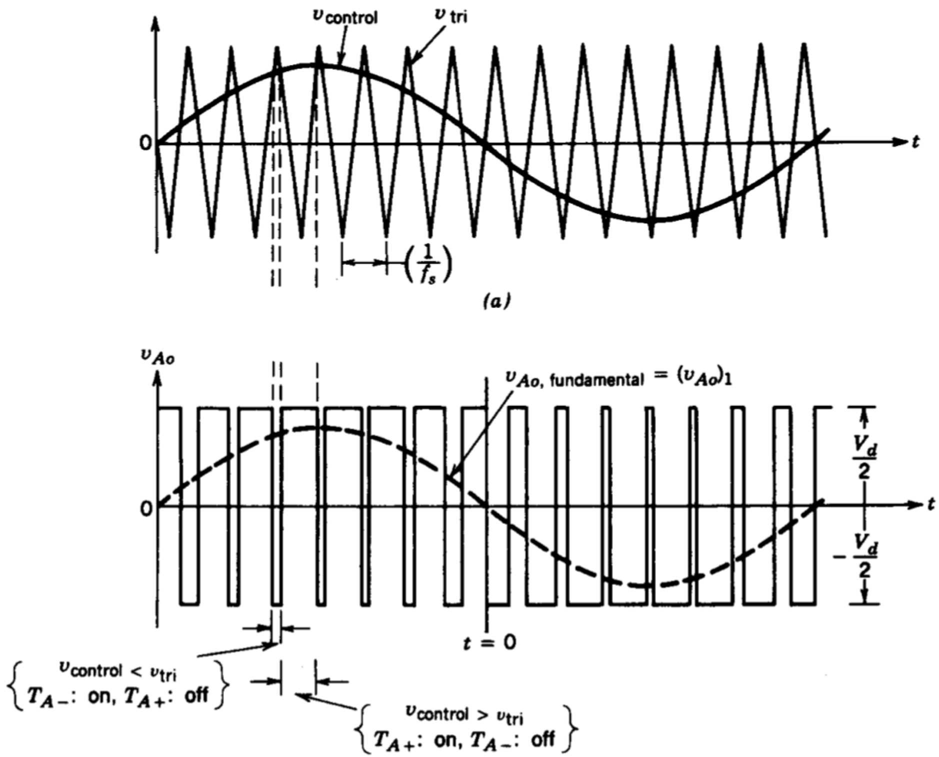
Sinusoidal PWM

Sinusoidal PWM



Analog generation of SPWM

PWM in one leg inverter



Some Definitions

Some Definitions

Frequency Modulation Ratio

Some Definitions

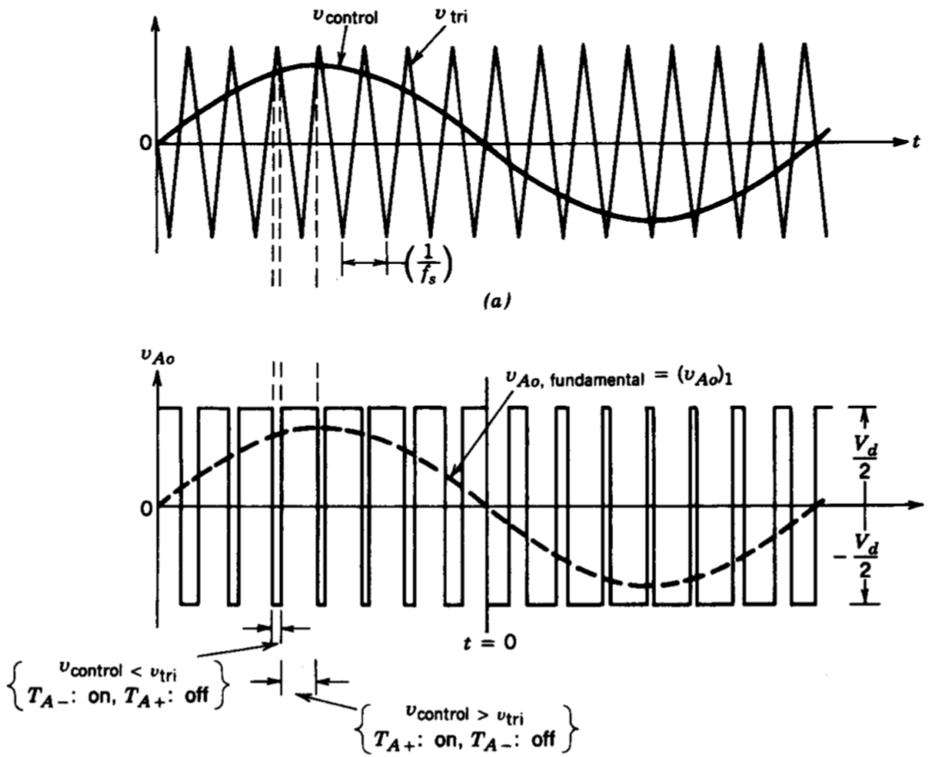
Frequency Modulation Ratio

$$m_f = \frac{f_s}{f_1}$$

f_s : Switching frequency

f_1 : Fundamental frequency of AC output

What is m_f for this case?



m_f selection

m_f selection

Preferred to have a high value ($m_f > 21$)

- i.e 2 kHz for 50 Hz: $m_f = 40$

m_f selection

Preferred to have a high value ($m_f > 21$)

- i.e 2 kHz for 50 Hz: $m_f = 40$
- May not be possible for larger power applications

m_f selection

Preferred to have a high value ($m_f > 21$)

- i.e 2 kHz for 50 Hz: $m_f = 40$
- May not be possible for larger power applications
- Be aware of audible noise (not only fs, but also its harmonics)

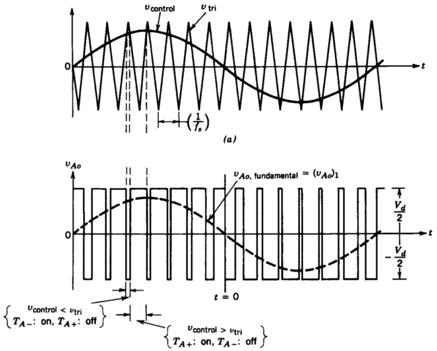
m_f selection

Preferred to have a high value ($m_f > 21$)

- i.e 2 kHz for 50 Hz: $m_f = 40$
- May not be possible for larger power applications
- Be aware of audible noise (not only fs, but also its harmonics)
- Asynchronous PWM can be used but not preferred

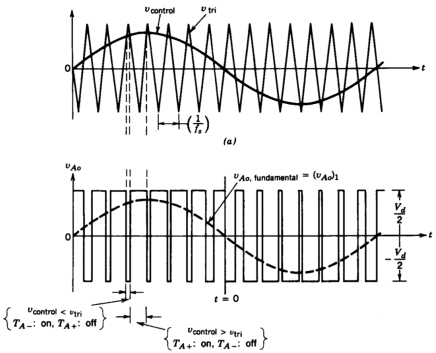
Synchronous PWM

f_s is an integer multiple of f_1



Synchronous PWM

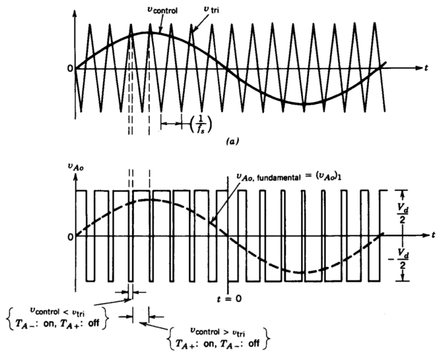
f_s is an integer multiple of f_1



- m_f is integer

Synchronous PWM

f_s is an integer multiple of f_1



- m_f is integer
- If not (asynchronous PWM), subharmonics of f_1 is generated

m_f selection

m_f selection

Small Frequency Modulation ($m_f < 21$)

- Synchronous PWM should be used

m_f selection

Small Frequency Modulation ($m_f < 21$)

- Synchronous PWM should be used
- m_f should be an odd integer

Some Definitions

Some Definitions

Modulation Index

Some Definitions

Modulation Index

(Amplitude Modulation Ratio)

Some Definitions

Modulation Index

(Amplitude Modulation Ratio)

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{triangle}}$$

Some Definitions

Modulation Index

(Amplitude Modulation Ratio)

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{triangle}}$$

Linear region: $m_a < 1$

Some Definitions

Modulation Index

(Amplitude Modulation Ratio)

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{triangle}}$$

Linear region: $m_a < 1$

Overmodulation: $m_a > 1$

Linear Region

Linear Region

Fundamental voltage magnitude varies linearly with m_a

Linear Region

Fundamental voltage magnitude varies linearly with m_a

$$\hat{V}_{ao1} = m_a \frac{V_d}{2}$$

Linear Region

Fundamental voltage magnitude varies linearly with m_a

$$\hat{V}_{ao1} = m_a \frac{V_d}{2}$$

$$V_{ao} = \frac{v_{control}}{\hat{V}_{triangle}} \frac{V_d}{2}$$

Linear Region

Fundamental voltage magnitude varies linearly with m_a

$$\hat{V}_{ao1} = m_a \frac{V_d}{2}$$

$$V_{ao} = \frac{v_{control}}{\hat{V}_{triangle}} \frac{V_d}{2}$$

Other harmonics does NOT change linearly with $\hat{V}_{ao1}$

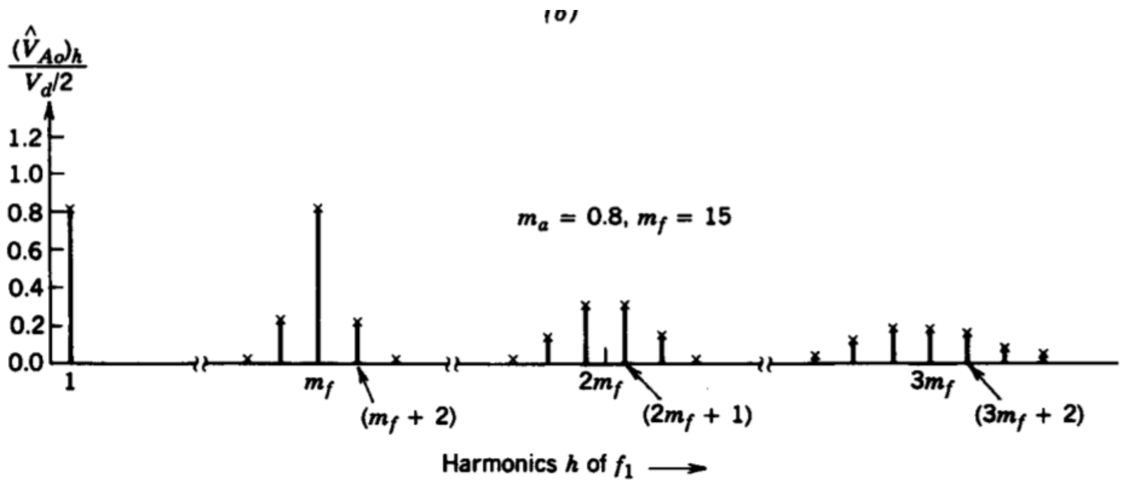
PWM Harmonics

PWM Harmonics

FFT in linear region

PWM Harmonics

FFT in linear region



Notice the sidebands

PWM Harmonics

PWM Harmonics

Table 8-1 Generalized Harmonics of v_{Ao} for a Large m_f.

h \ m_a	*0.2*	*0.4*	*0.6*	*0.8*	*1.0*
1 *Fundamental*	*0.2*	*0.4*	*0.6*	*0.8*	*1.0*
m_f	1.242	1.15	1.006	0.818	0.601
$m_f \pm 2$	0.016	0.061	0.131	0.220	0.318
$m_f \pm 4$					0.018
$2m_f \pm 1$	0.190	0.326	0.370	0.314	0.181
$2m_f \pm 3$		0.024	0.071	0.139	0.212
$2m_f \pm 5$				0.013	0.033
$3m_f$	0.335	0.123	0.083	0.171	0.113
$3m_f \pm 2$	0.044	0.139	0.203	0.176	0.062
$3m_f \pm 4$		0.012	0.047	0.104	0.157
$3m_f \pm 6$				0.016	0.044
$4m_f \pm 1$	0.163	0.157	0.008	0.105	0.068
$4m_f \pm 3$	0.012	0.070	0.132	0.115	0.009
$4m_f \pm 5$			0.034	0.084	0.119
$4m_f \pm 7$				0.017	0.050

Note: $(\hat{V}_{Ao})_h / \frac{1}{2} V_d$ [$= (\hat{V}_{AN})_h / \frac{1}{2} V_d$] is tabulated as a function of m_a.

PWM Harmonics

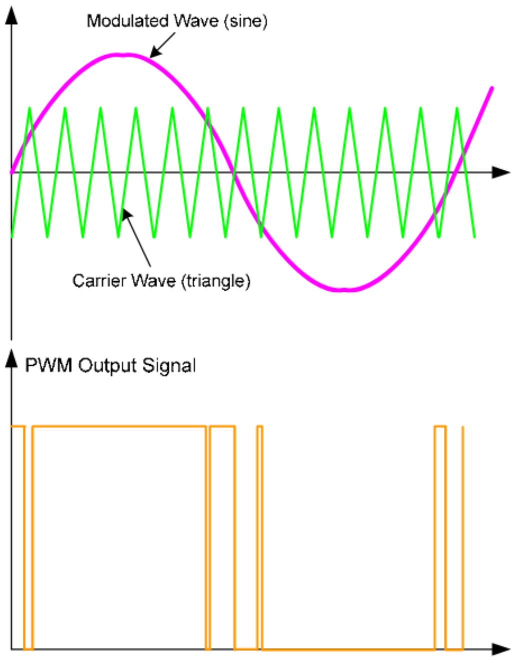
Advantages of choosing m_f as odd integer:

- Results in odd symmetry ($f(-t) = -f(t)$)
- Results in half-wave symmetry ($f(t) = -f(t + T/2)$)
- No even harmonics are present
- Only sine components exist (no cosine harmonics component)

Over-modulation in SPWM

Over-modulation in SPWM

Control signals gets bigger than the triangle waveform



Over-modulation in SPWM

Possible to create higher magnitude, but induce harmonics of f_1

Over-modulation in SPWM

Possible to create higher magnitude, but induce harmonics of f_1

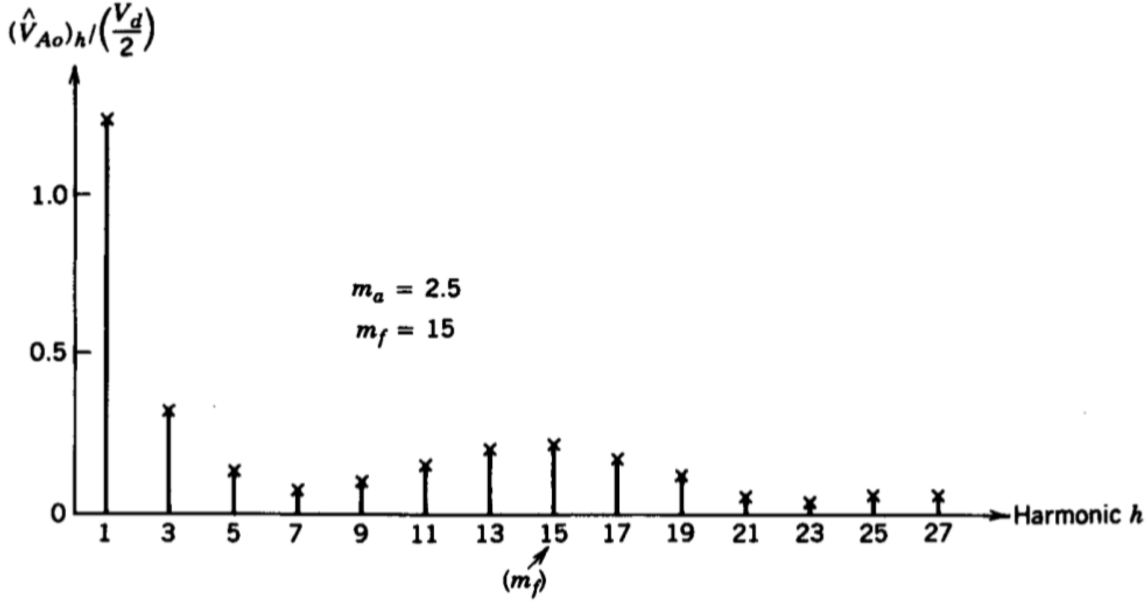


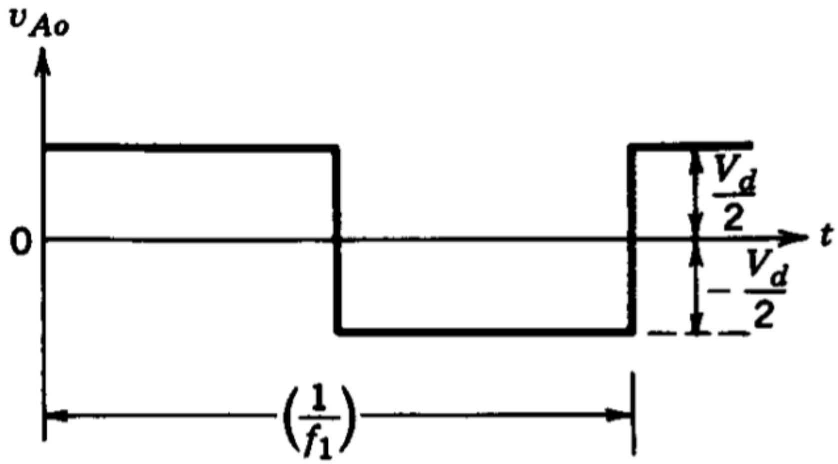
Figure 8-7 Harmonics due to overmodulation; drawn for $m_a = 2.5$ and $m_f = 15$.

Over-modulation in SPWM

Worst Case?:

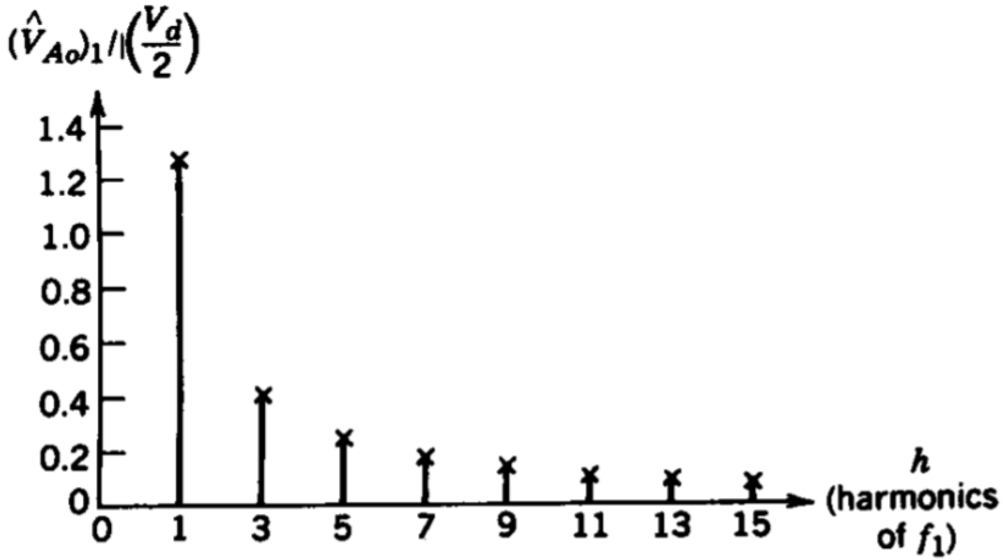
Over-modulation in SPWM

Worst Case?:Square Wave



Over-modulation in SPWM

Square Wave Harmonics



Over-modulation in SPWM

Square Wave Peak Voltage?

Over-modulation in SPWM

Square Wave Peak Voltage?

$$\hat{V}_{ao1} = \frac{4}{\pi}\frac{V_d}{2} = 1.273\frac{V_d}{2}$$

Over-modulation in SPWM

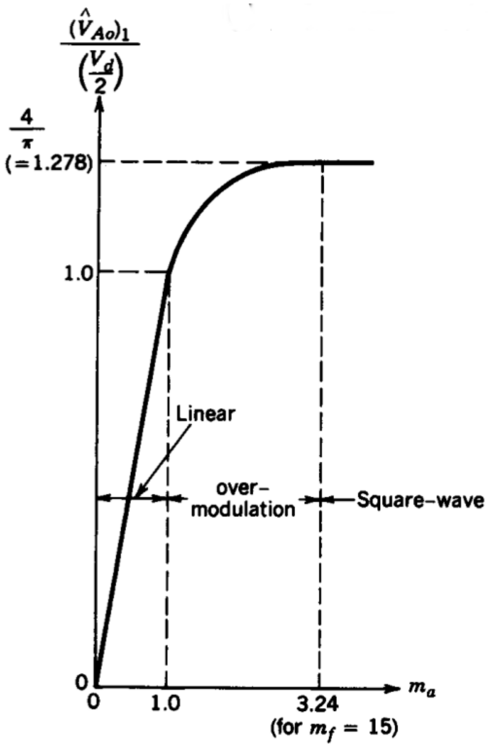
Square Wave Peak Voltage?

$$\hat{V}_{ao1} = \frac{4}{\pi}\frac{V_d}{2} = 1.273\frac{V_d}{2}$$

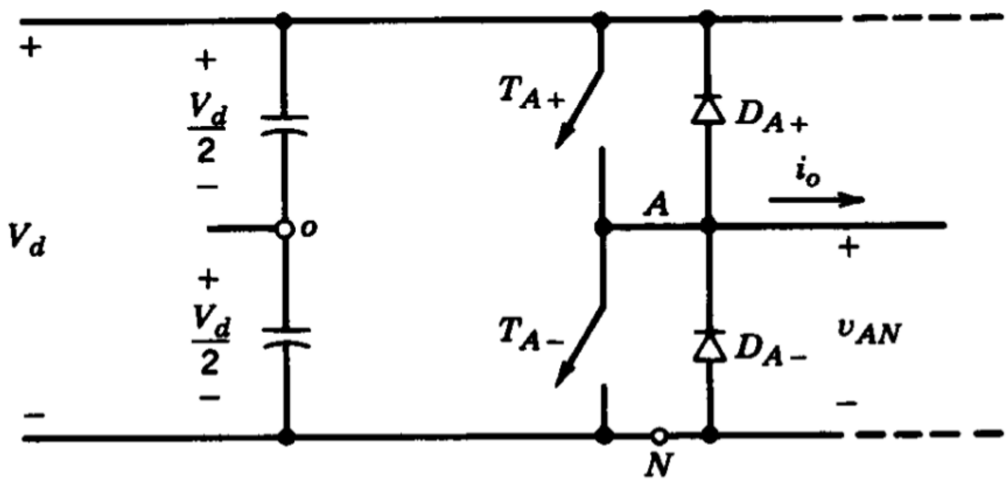
Fundamental harmonics:

$$\hat{V}_{aoh} = \frac{\hat{V}_{ao1}}{h}$$

Over-modulation Index Variation

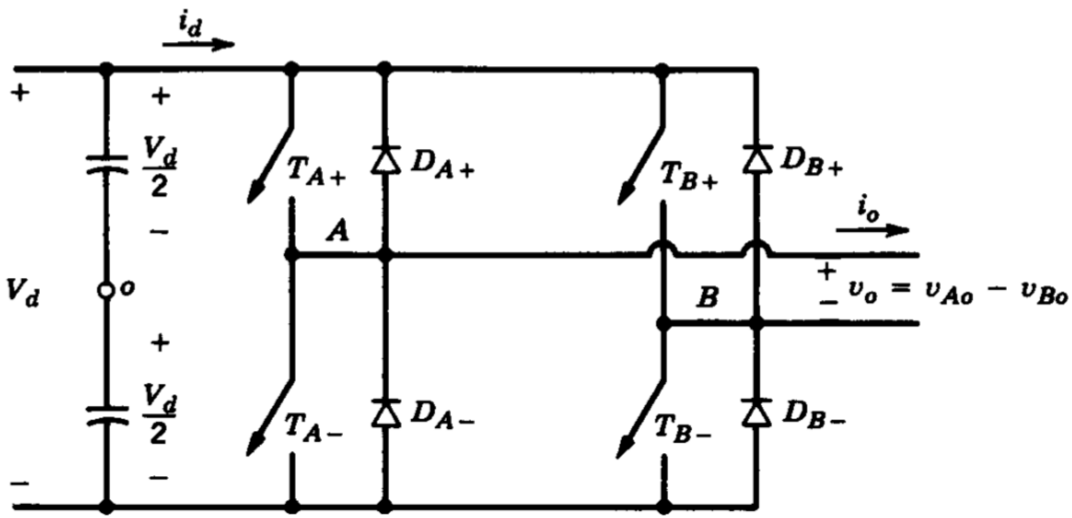


Single-Phase Half-Bridge Inverter



In order to have equal capacitor voltage, io cannot have a DC component

Single-Phase Full-Bridge Inverter



Voltage level is twice of the half bridge inverter

Bipolar PWM

Same with the full-bridge DC/DC converter

Bipolar PWM

Same with the full-bridge DC/DC converter

T_{A+} and T_{B-} are turn on and off together

Bipolar PWM

Same with the full-bridge DC/DC converter

T_{A+} and T_{B-} are turn on and off together

T_{A-} and T_{B+} are complimentary of T_{A+} and T_{B-}

Bipolar PWM

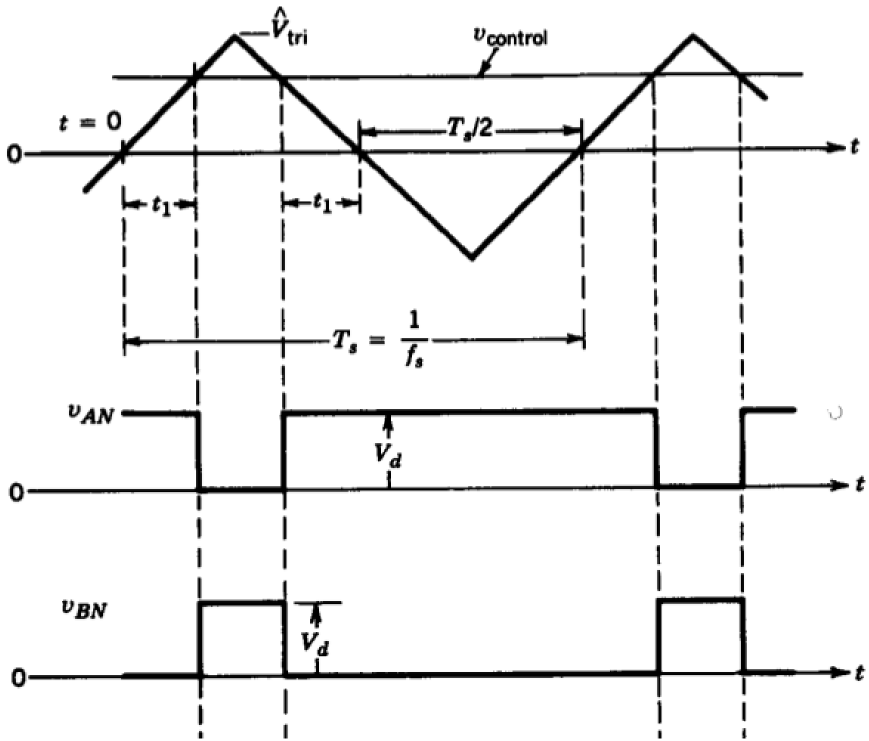
Same with the full-bridge DC/DC converter

T_{A+} and T_{B-} are turn on and off together

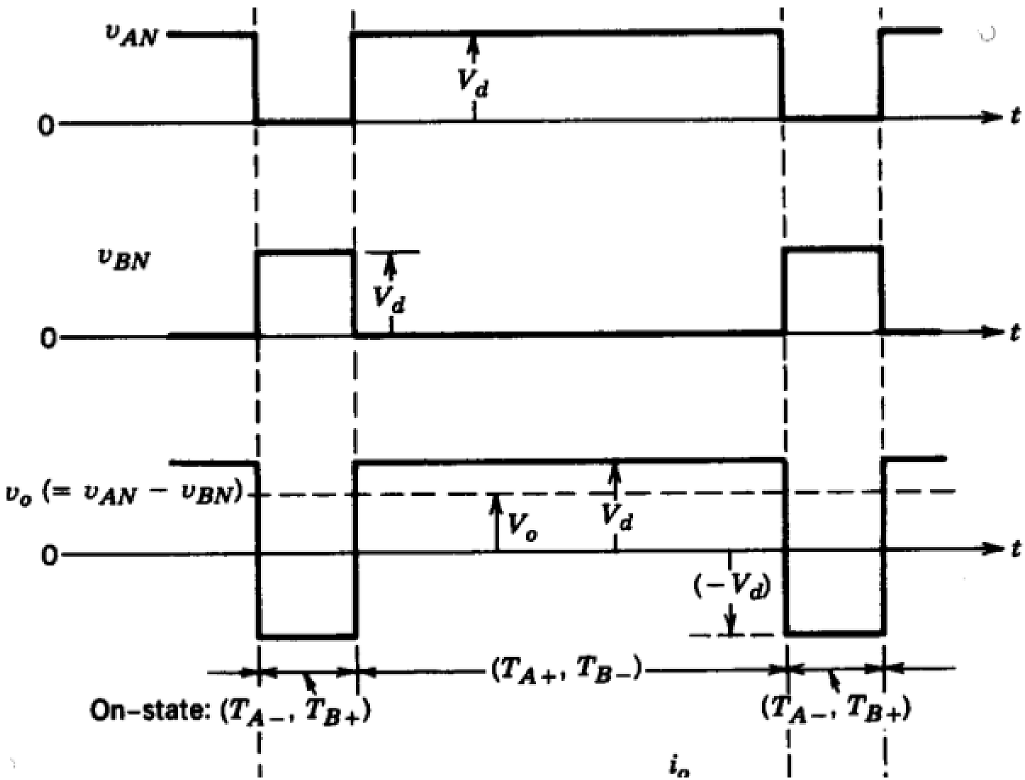
T_{A-} and T_{B+} are complimentary of T_{A+} and T_{B-}

Can give V_d or $-V_d$

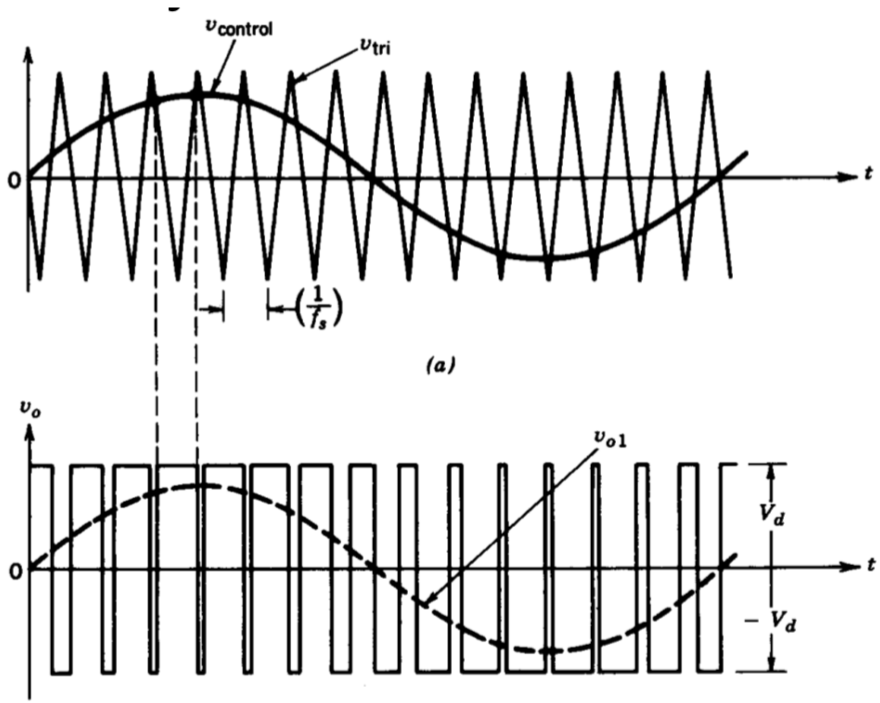
Bi-polar Voltage Switching



Bi-polar Voltage Switching



Bi-polar PWM



Bi-polar PWM

Voltage level is twice of the half bridge inverter

Bi-polar PWM

Voltage level is twice of the half bridge inverter

Linear Region

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

Bi-polar PWM

Voltage level is twice of the half bridge inverter

Linear Region

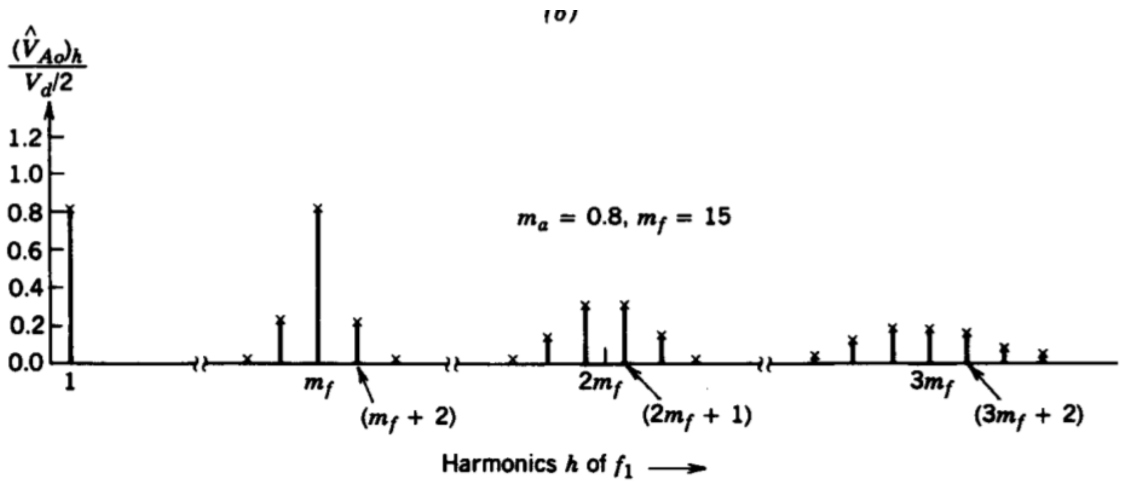
$$\hat{V}_{o1} = m_a V_d$$

Over-modulation

$$V_d < \hat{V}_{o1} < \frac{4}{\pi} V_d$$

Bi-polar PWM

Same harmonics



Unipolar PWM

Same with the full-bridge DC/DC converter

T_{A+} and T_{B+} are controlled seperately

T_{A-} and T_{B-} are complimetary of T_{A+} and T_{B+}

Unipolar PWM

Same with the full-bridge DC/DC converter

T_{A+} and T_{B+} are controlled seperately

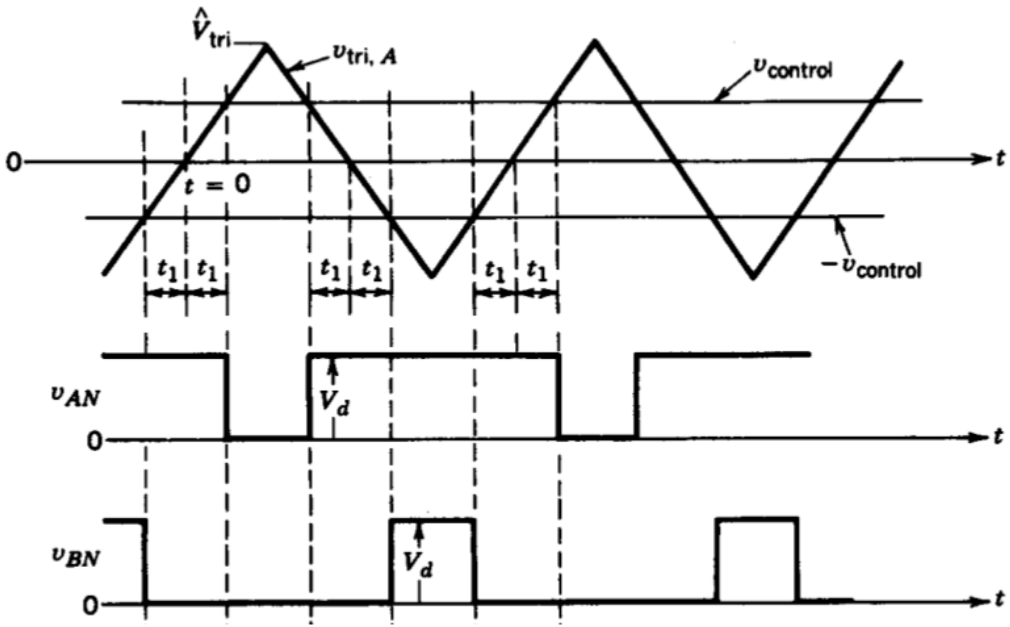
T_{A-} and T_{B-} are complimetary of T_{A+} and T_{B+}

Can give $V_d, 0, -V_d$

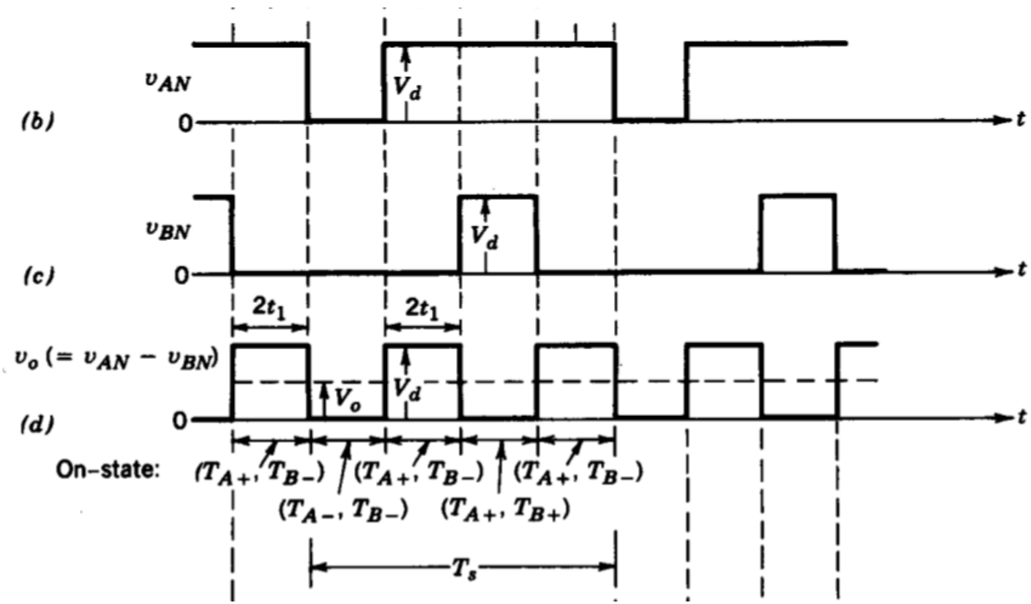
$V_o = 0$ if T_{A+} and T_{B+} are ON

$V_o = 0$ if T_{A-} and T_{B-} are ON

Uni-polar Voltage Switching

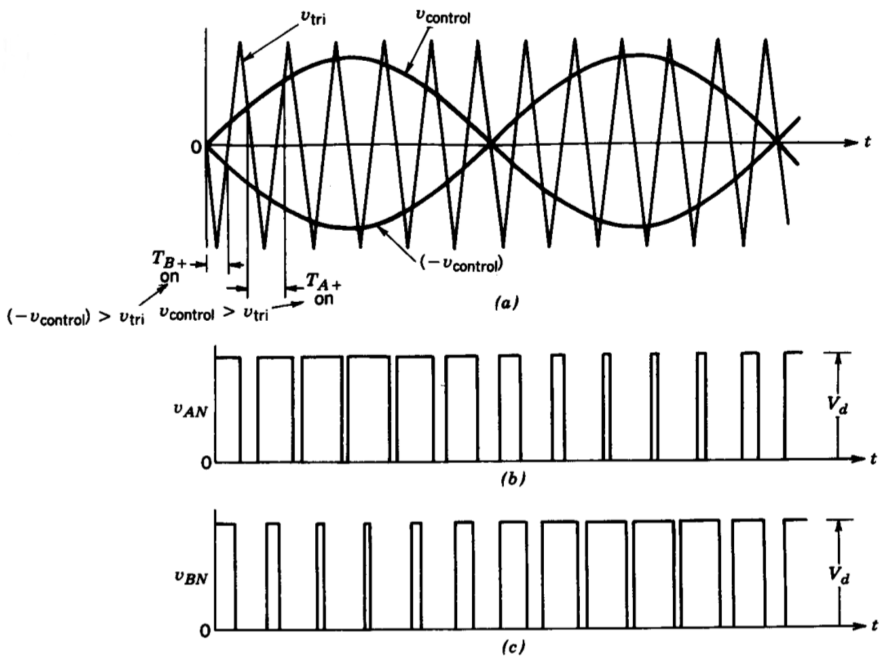


Uni-polar Voltage Switching



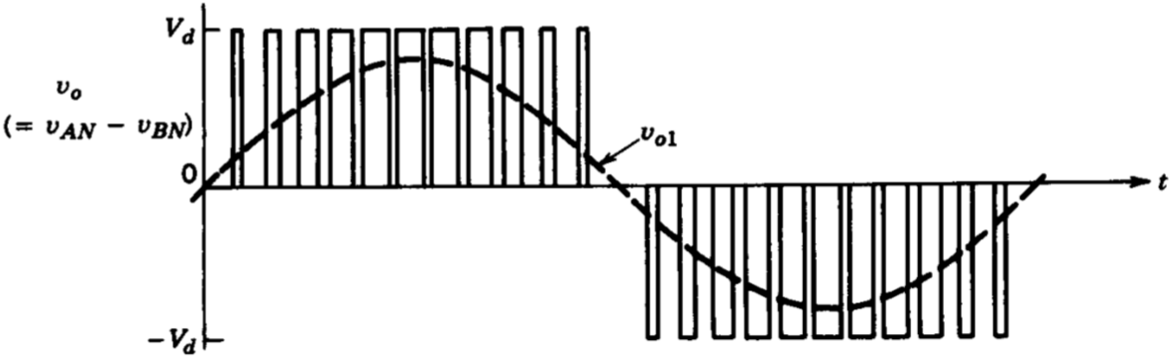
Uni-polar PWM Sine Output

Uni-polar PWM Sine Output



Uni-polar PWM Sine Output

Uni-polar PWM Sine Output



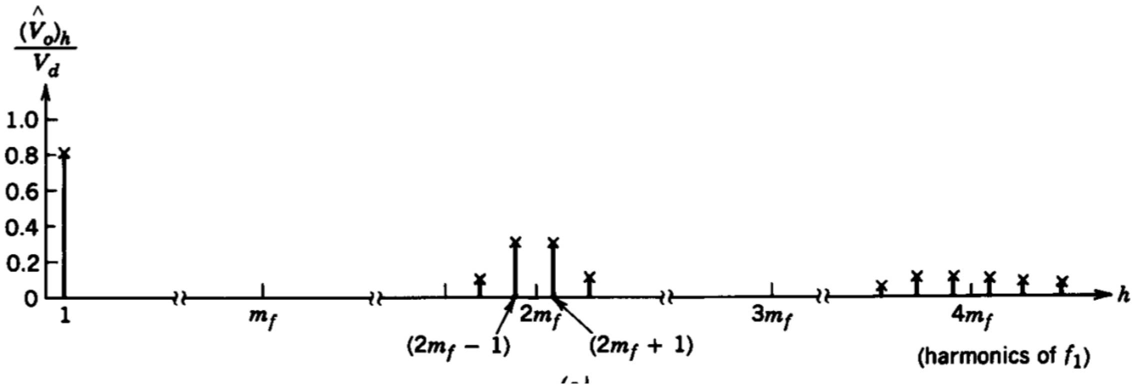
Uni-polar PWM Harmonics

Uni-polar PWM Harmonics

Harmonics of twice the switching frequency.

Uni-polar PWM Harmonics

Harmonics of twice the switching frequency.



Harmonics Comparison

Bipolar PWM

Table 8-3 Normalized Fourier Coefficients V_n/V_{dc} for Bipolar PWM

	m_a=1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
$n=1$	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10
$n=m_f$	0.60	0.71	0.82	0.92	1.01	1.08	1.15	1.20	1.24	1.27
$n=mf\pm2$	0.32	0.27	0.22	0.17	0.13	0.09	0.06	0.03	0.02	0.00

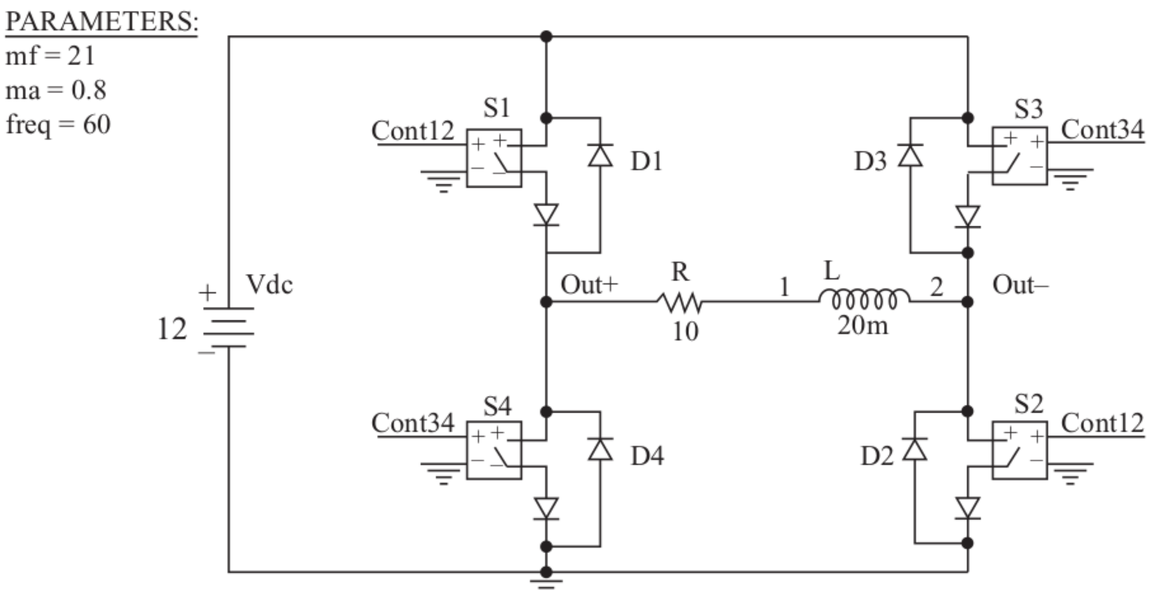
Unipolar PWM

Table 8-5 Normalized Fourier Coefficients V_n/V_{dc} for Unipolar PWM in Fig. 8-18

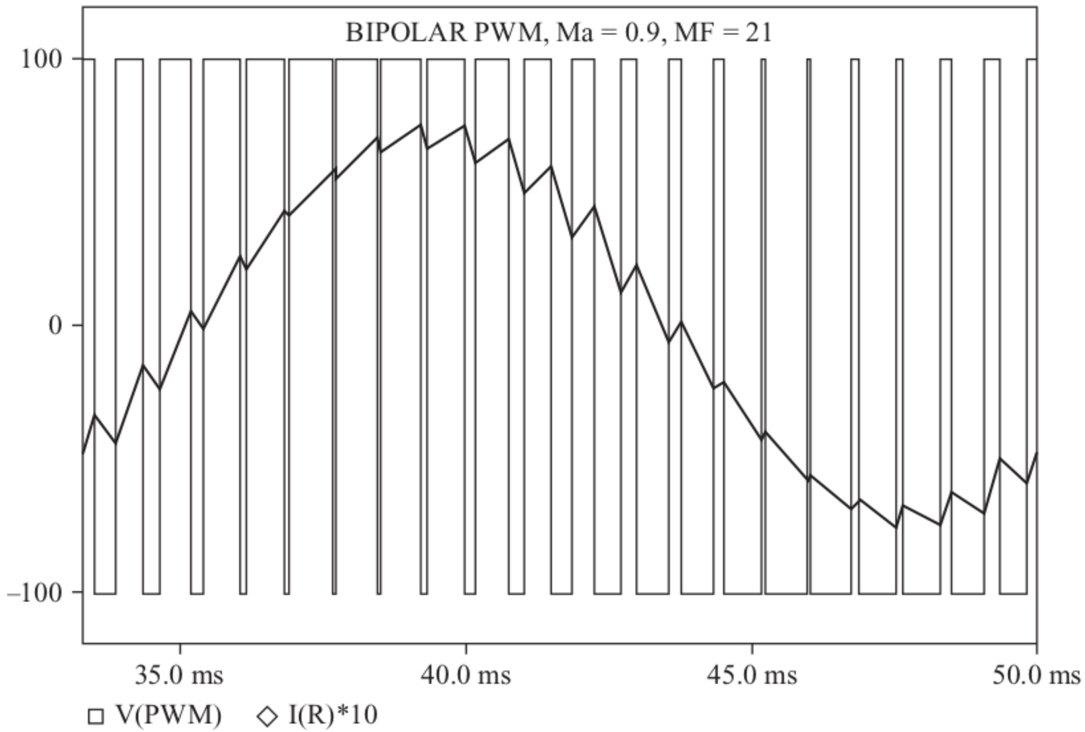
	m_a=1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
$n=1$	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10
$n=2m_f\pm1$	0.18	0.25	0.31	0.35	0.37	0.36	0.33	0.27	0.19	0.10
$n=2m_f\pm3$	0.21	0.18	0.14	0.10	0.07	0.04	0.02	0.01	0.00	0.00

Inverter Connected to R-L Load

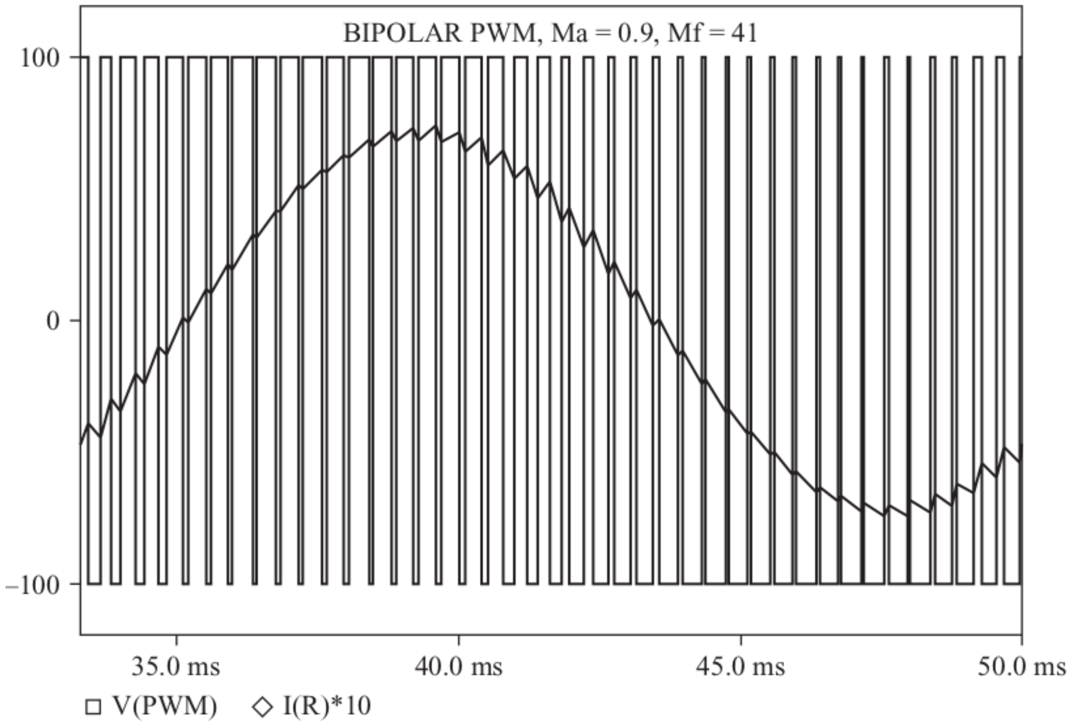
Inverter Connected to R-L Load



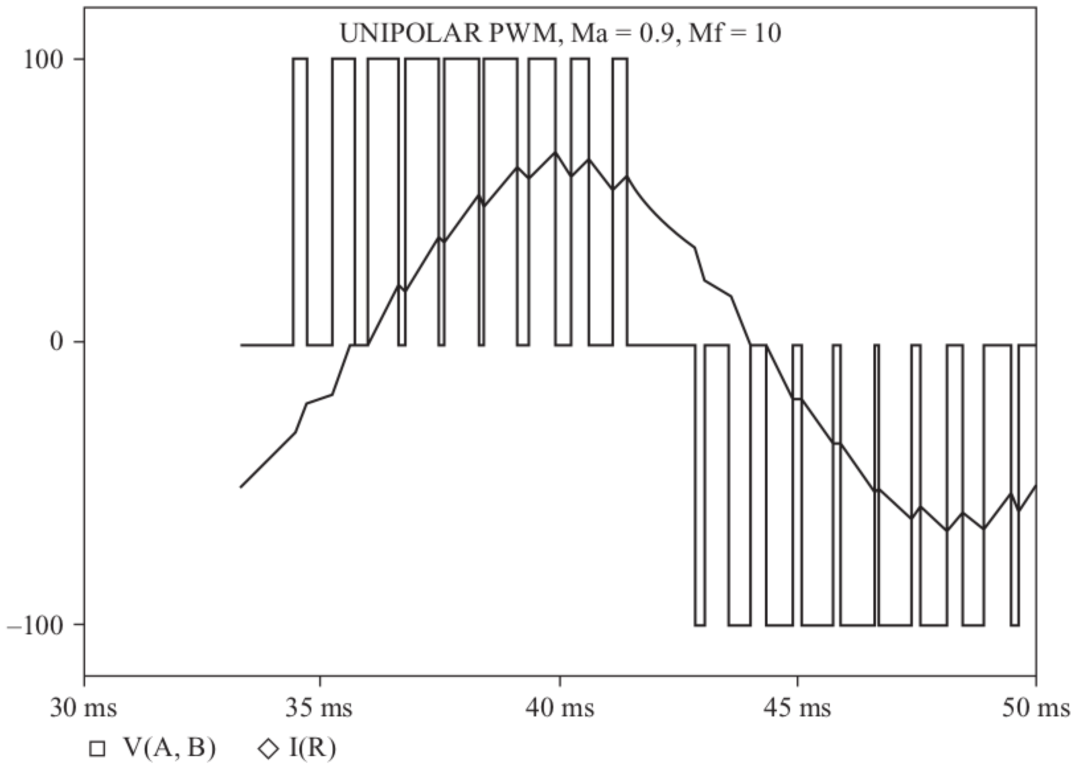
Inverter Connected to R-L Load



Inverter Connected to R-L Load



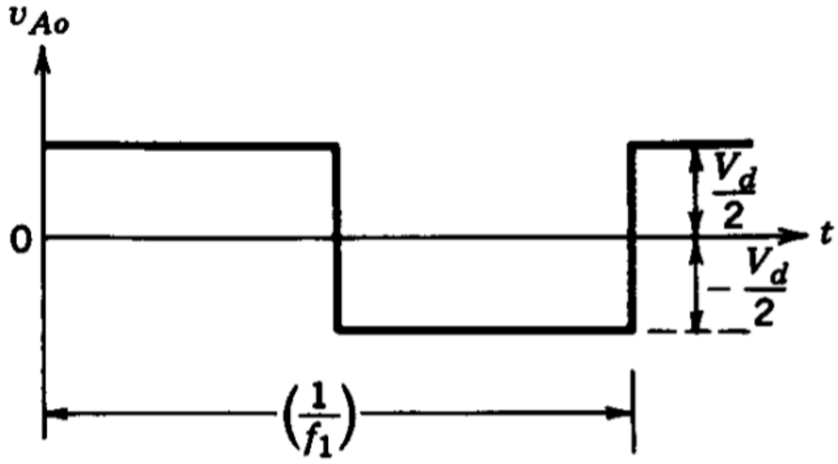
Inverter Connected to R-L Load



Sinusoidal Generation by Voltage Shift

Sinusoidal Generation by Voltage Shift

Generate Square wave with controllable off periods

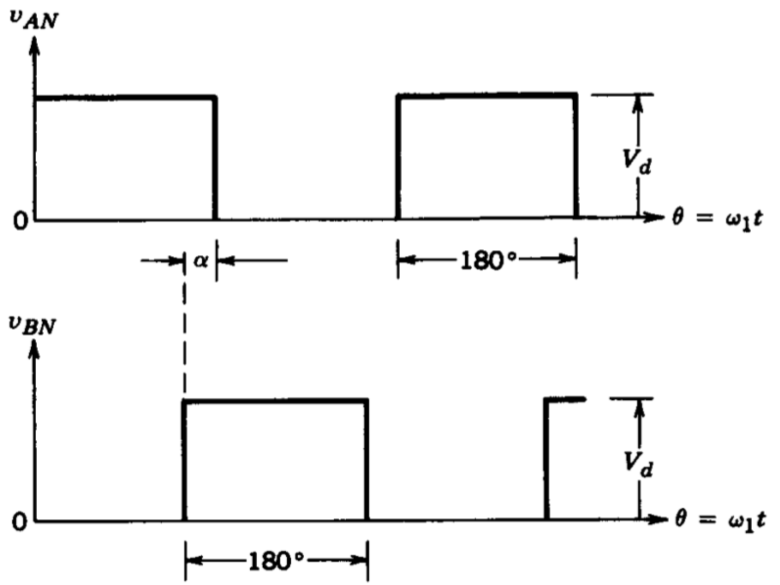


Sinusoidal Generation by Voltage Shift

Sinusoidal Generation by Voltage Shift

Generate Square wave with controllable off periods

Van and Vbn has overlapping regions

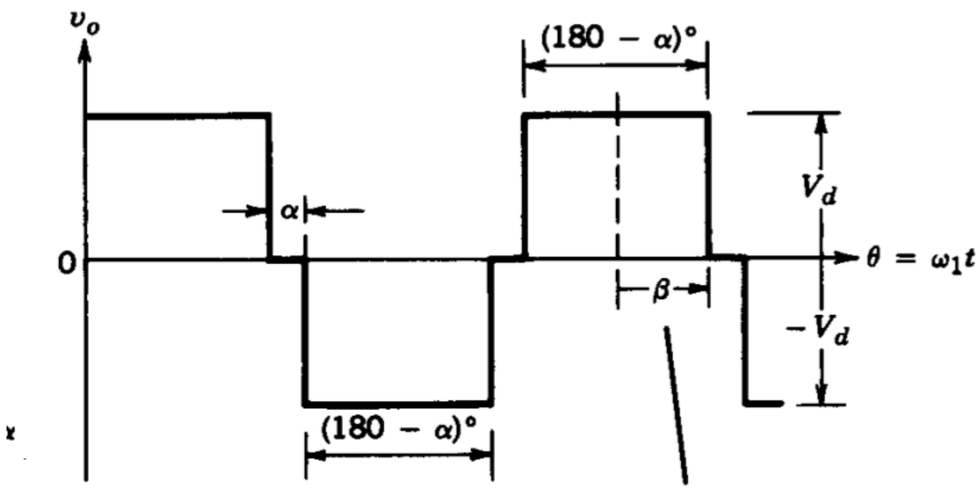


Sinusoidal Generation by Voltage Shift

Sinusoidal Generation by Voltage Shift

Generate Square wave with controllable off periods

Van and Vbn has overlapping regions



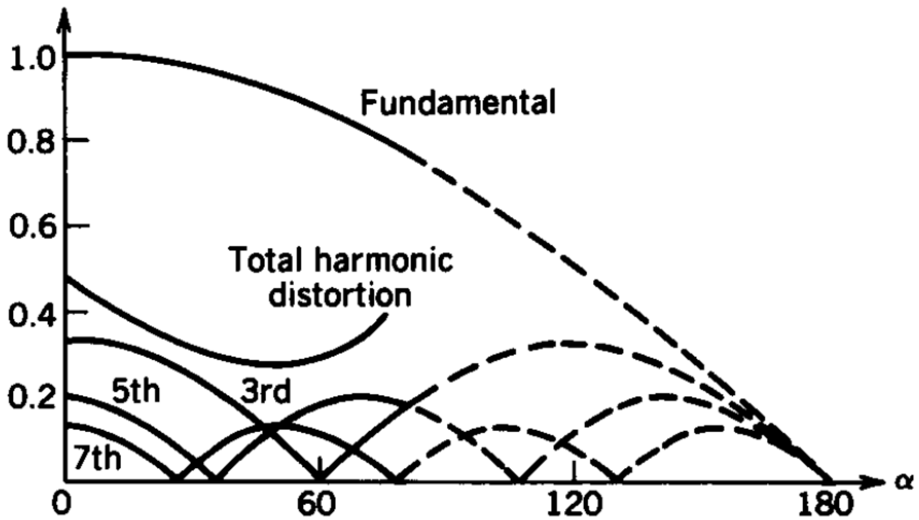
$$\beta = \frac{(180 - \alpha)°}{2} = (90 - \frac{\alpha}{2})°$$

Sinusoidal Generation by Voltage Shift

What about harmonics?

Sinusoidal Generation by Voltage Shift

What about harmonics?



For curious students: SHE: [Selective Harmonic Elimination]

Example:

Example:

Example 8.8 (Daniel W. Hart-Power Electronics)

Table 8-4 Fourier Series Quantities for the PWM Inverter of Example 8-8

n	$f_{n\,(Hz)}$	V_n (V)	Z_n (Ω)	I_n (A)	$I_{n,\text{rms}}$ (A)	P_n (W)
1	60	80.0	12.5	6.39	4.52	204.0
19	1140	22.0	143.6	0.15	0.11	0.1
21	1260	81.8	158.7	0.52	0.36	1.3
23	1380	22.0	173.7	0.13	0.09	0.1

You can download this presentation from:
keysan.me/ee464