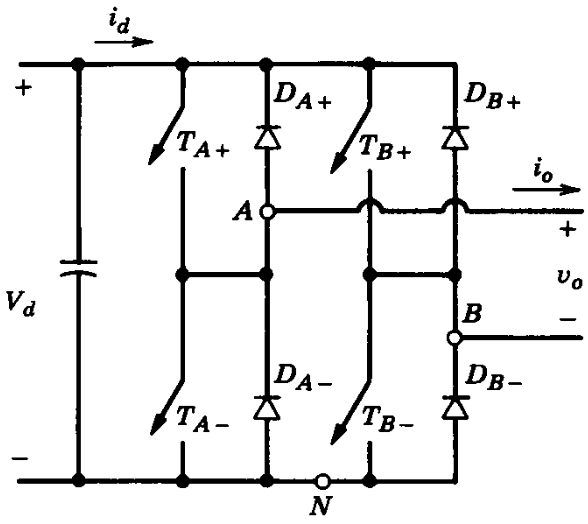
Chapter 6

DC-AC Inverters

6-1. Single-phase Bridge Inverters



a **blanking time** of a few μs after turn-off of one switch in a leg before the other in the same leg are turned on, otherwise a risk of re-conduction in the outgoing switch, giving a short-circuit.

Four combinations of switch states and the corresponding voltage levels:

1. T_{A+}, T_{B-} on: $\boldsymbol{v_{AN}} = \boldsymbol{V_d}$, $\boldsymbol{v_{BN}} = 0$;
   (T_{A-}, T_{B+} off) $\boldsymbol{v_o = V_d}$
2. T_{A-}, T_{B+} on: $\boldsymbol{v_{AN}} = 0$, $\boldsymbol{v_{BN}} = \boldsymbol{V_d}$;
   (T_{A+}, T_{B-} off) $\boldsymbol{v_o = -V_d}$
3. T_{A+}, T_{B+} on: $\boldsymbol{v_{AN}} = \boldsymbol{V_d}$, $\boldsymbol{v_{BN}} = \boldsymbol{V_d}$;
   (T_{A-}, T_{B-} off) $\boldsymbol{v_o} = 0$
4. T_{A-}, T_{B-} on: $\boldsymbol{v_{AN}} = 0$, $\boldsymbol{v_{BN}} = 0$;
   (T_{A+}, T_{B+} off) $\boldsymbol{v_o} = 0$

PWM with Bipolar Voltage Switching

Only one reference $v_{control}$ is used for TA and TB signals (two switch states)

1. T_{A+}, T_{B-} on: $\boldsymbol{v_{AN}} = \boldsymbol{V_d}$, $\boldsymbol{v_{BN}} = 0$;
   (T_{A-}, T_{B+} off) $\boldsymbol{v_o} = \boldsymbol{V_d}$
2. T_{A-}, T_{B+} on: $\boldsymbol{v_{AN}} = 0$, $\boldsymbol{v_{BN}} = \boldsymbol{V_d}$;
   (T_{A+}, T_{B-} off) $\boldsymbol{v_o} = -\boldsymbol{V_d}$

amplitude modulation ratio:

$$m_a = V_{control(peak)} / V_{tri(peak)}$$

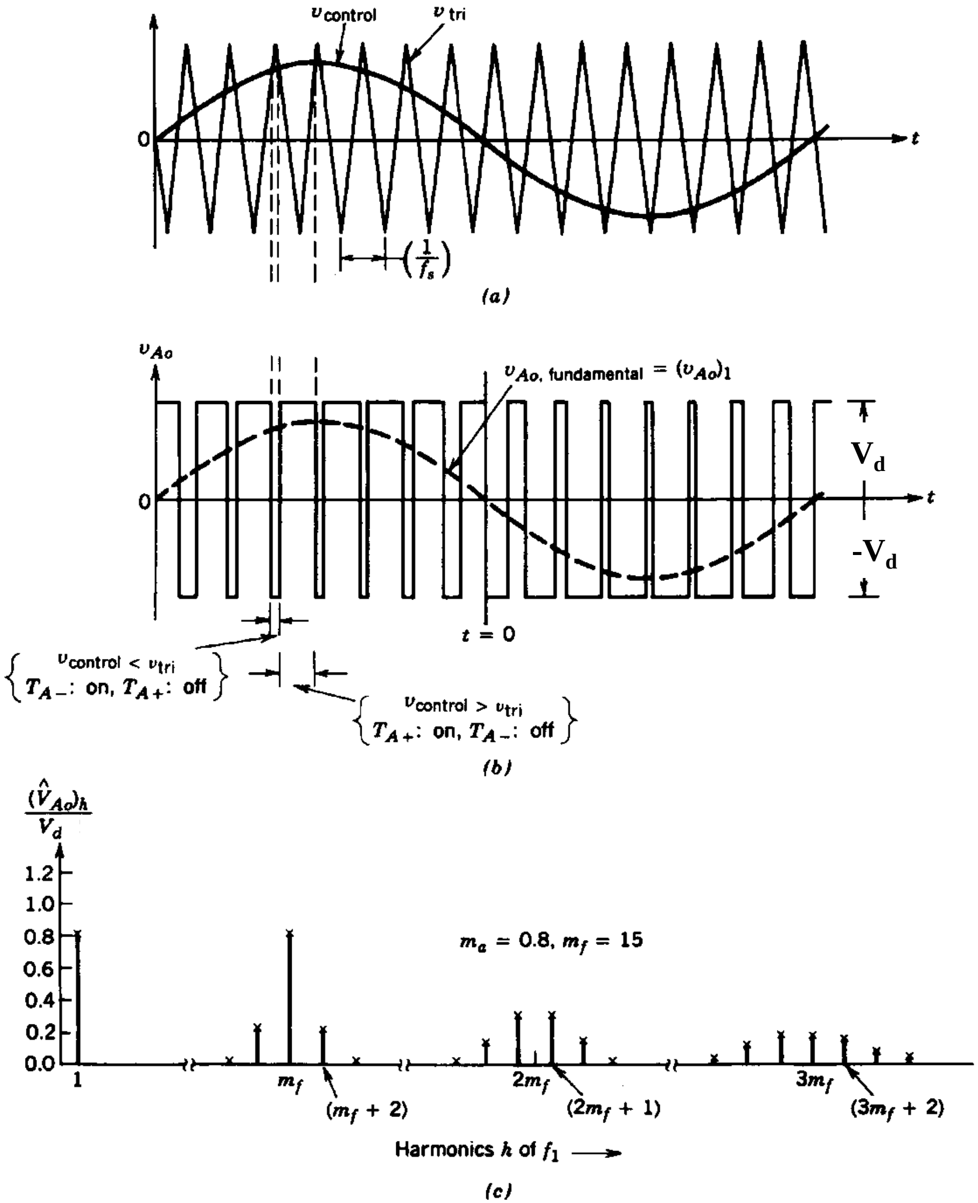
frequency modulation ratio:

$$m_f = f_s / f_1$$

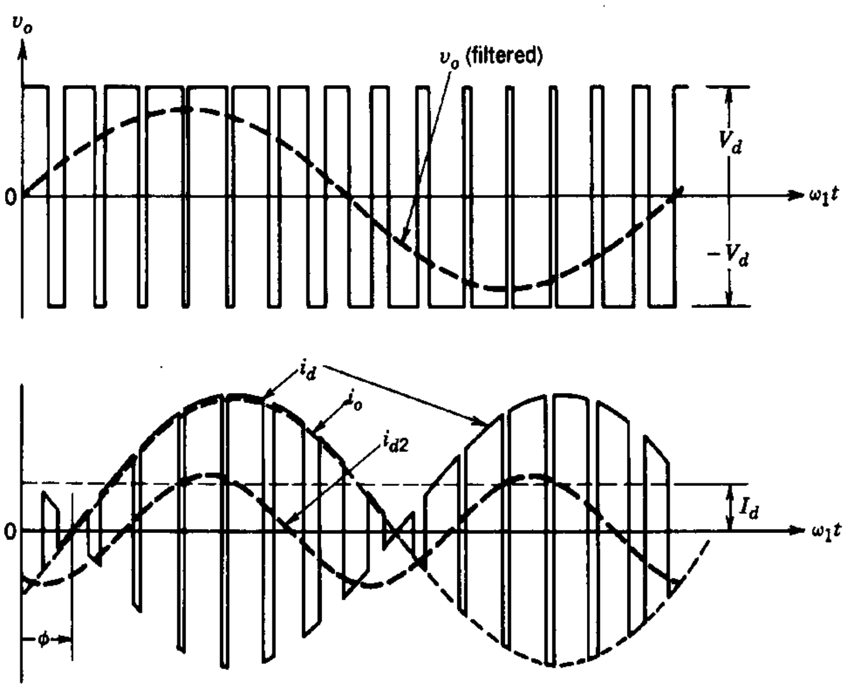
a. synchronous PWM
   – no subharmonics;

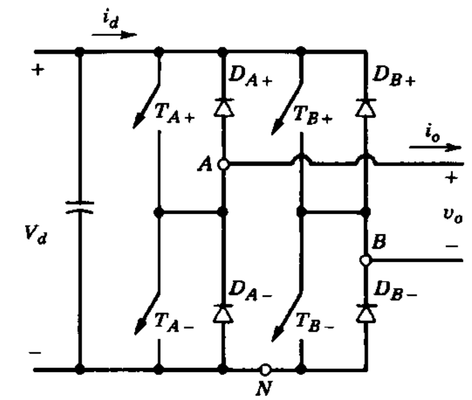
b. m_f an odd integer
   – no even harmonics;

c. harmonics appearing as sidebands centered around m_f and its multiples.



PWM with Bipolar Voltage Switching





1. T_{A+}, T_{B-} on: $\boldsymbol{v_{AN}} = \boldsymbol{V_d}$, $\boldsymbol{v_{BN}} = 0$;
   (T_{A-}, T_{B+} off) $\boldsymbol{v_o = V_d}$

   $\boldsymbol{i_o} > 0$ T_{A+}, T_{B-} conduct; $\boldsymbol{i_d = i_o}$
   $\boldsymbol{i_o} < 0$ D_{A+}, D_{B-} conduct; $\boldsymbol{i_d = i_o}$

2. T_{A-}, T_{B+} on: $\boldsymbol{v_{AN}} = 0$, $\boldsymbol{v_{BN}} = \boldsymbol{V_d}$;
   (T_{A+}, T_{B-} off) $\boldsymbol{v_o = -V_d}$

   $\boldsymbol{i_o} < 0$ T_{A-}, T_{B+} conduct; $\boldsymbol{i_d = -i_o}$
   $\boldsymbol{i_o} > 0$ D_{A-}, D_{B+} conduct; $\boldsymbol{i_d = -i_o}$

i_d consists of I_d, i_{d2} and the high-frequency components due to inverter switchings.

PWM with Bipolar Voltage Switching

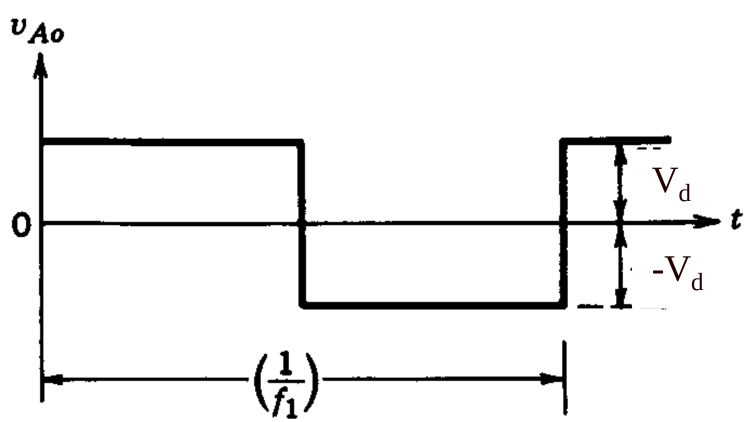
Linear $V_{o1max} = m_a V_d$

$m_a \leq 1$

Over-modulation $V_d < V_{o1max} < 4/\pi\, V_d$

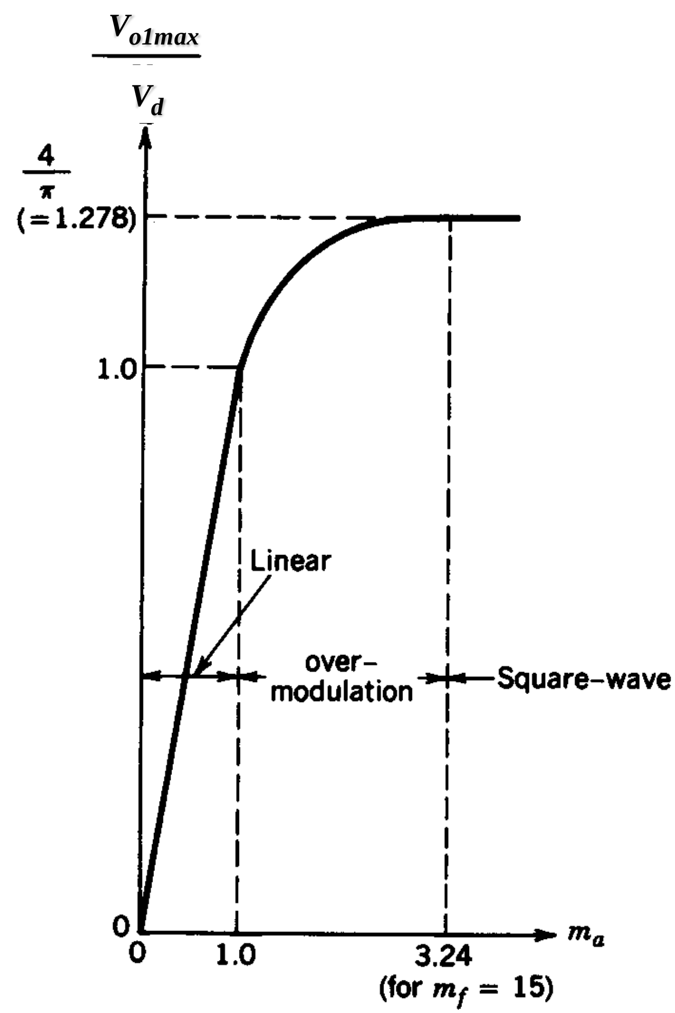
$m_a > 1$

Square-wave operation $V_{o1max} = 4/\pi\, V_d$

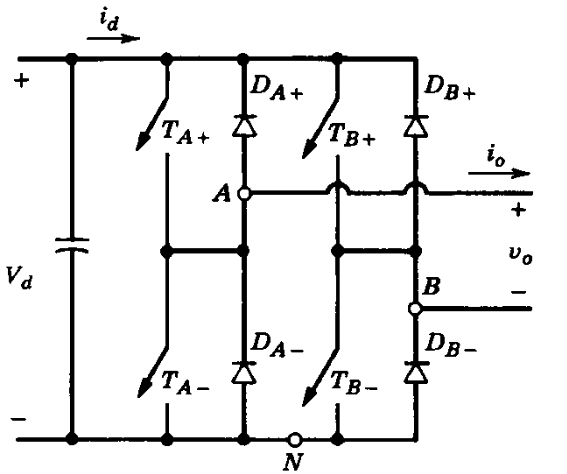


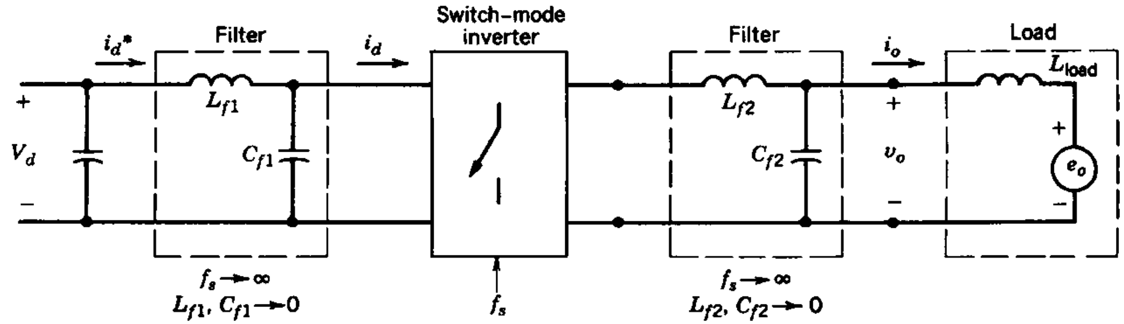
Square-Wave Mode of Operation

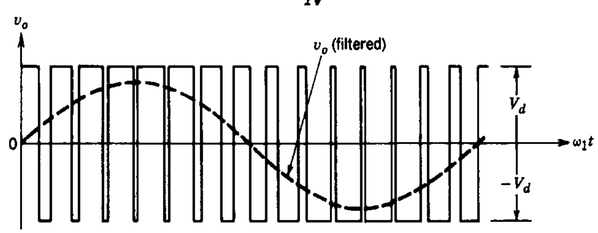
Output voltage Fundamental as a Function of m_a



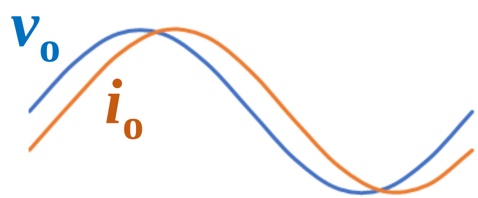
PWM with Bipolar Voltage Switching



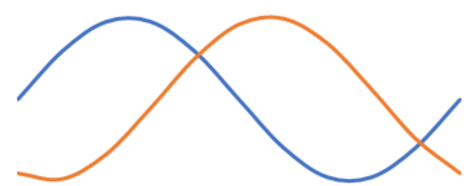




$0 < \theta < 90$

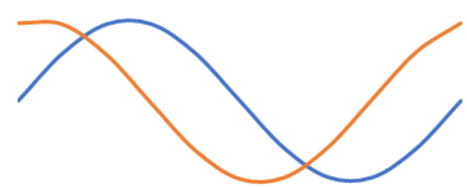


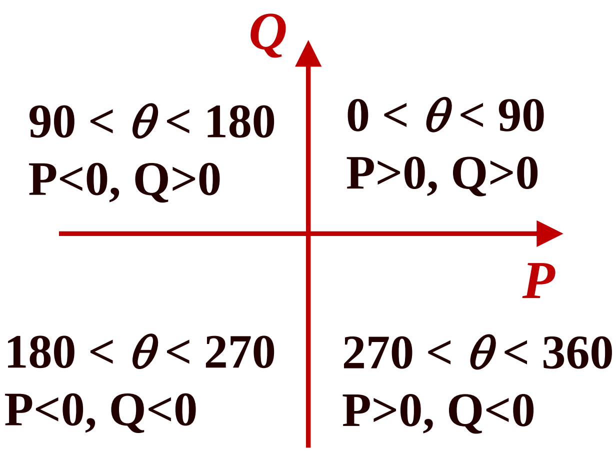
$90 < \theta < 180$



$180 < \theta < 270$

$270 < \theta < 360$





Four-quadrant operation

Single-Phase Inverter

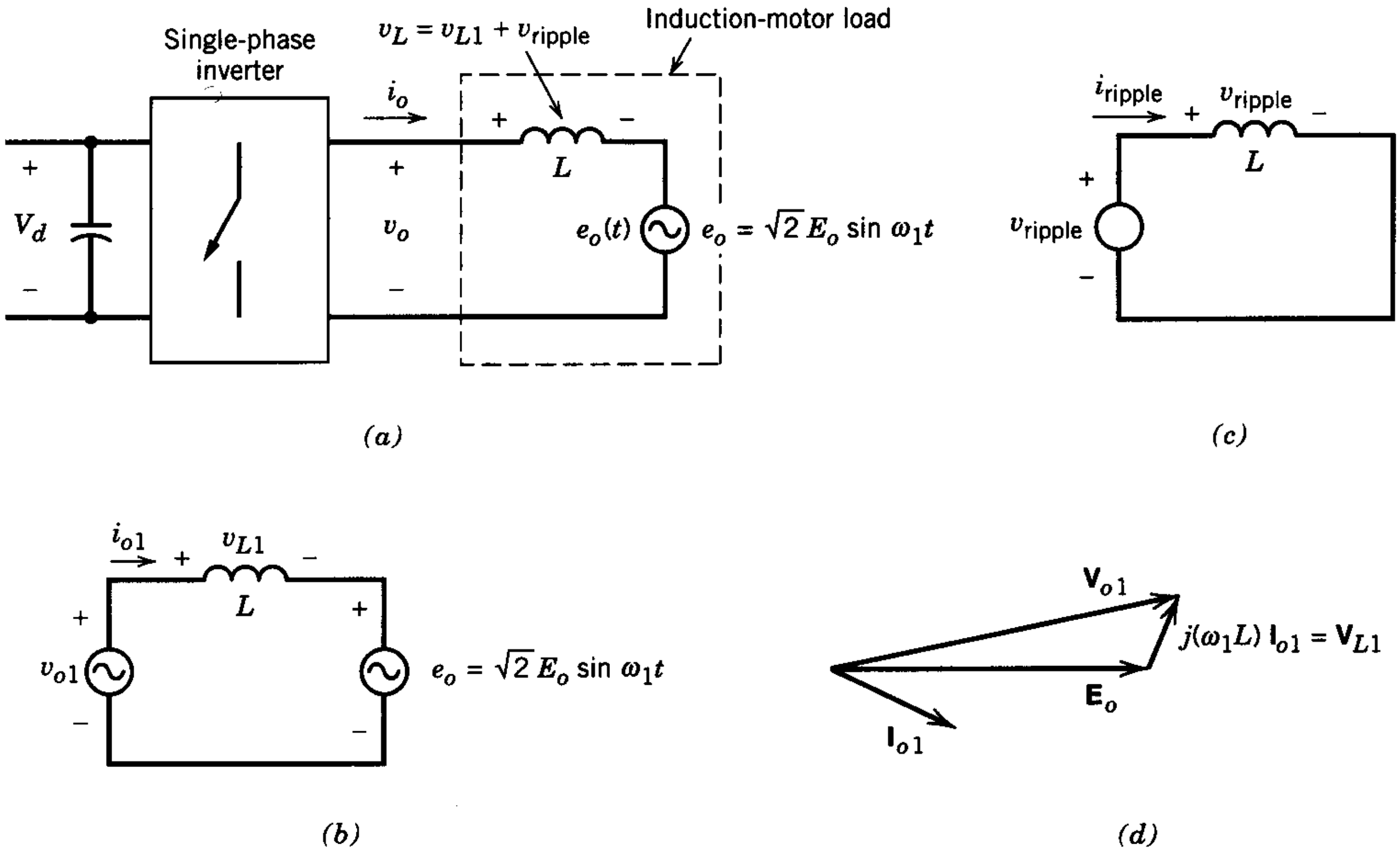
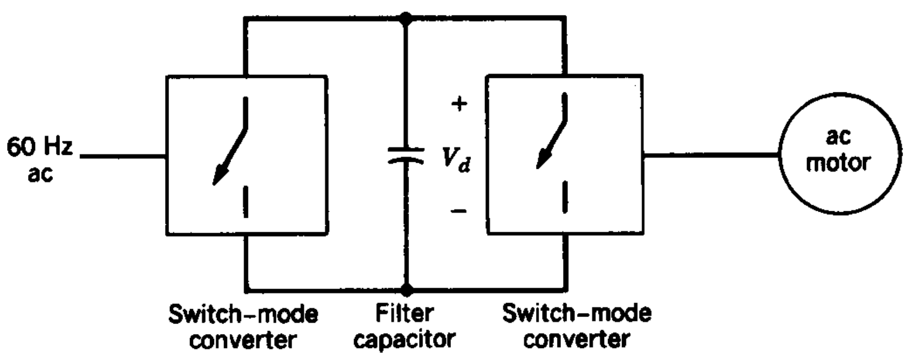


Figure 8-18 Single-phase inverter: (*a*) circuit; (*b*) fundamental-frequency components; (*c*) ripple frequency components; (*d*) fundamental-frequency phasor diagram.

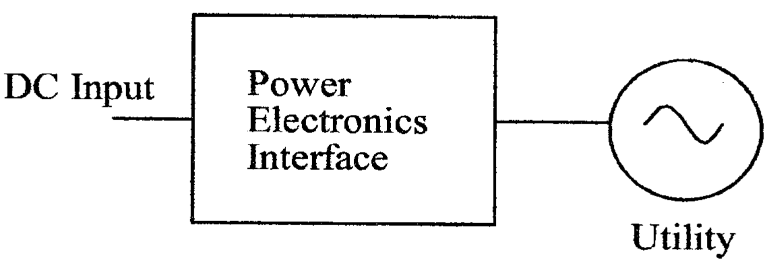
DC power source – DC-AC Inverters – an AC load

DC Voltage converted to Sinusoidal AC Voltage

* Switch-mode using fast switching devices, anti diode (GTO, IGBT, power MOSFET, etc.)
* Constant DC voltage source in DC side
* both output amplitude and frequency variable
* applications: AC motor drives and grid inverter



power flow bi-directional ac motor



Photovoltaic Systems

PWM with Unipolar Voltage Switching

Leg A:

$v_{control} > v_{tri}$ T_{A+} on $v_{AN} = V_d$;

(T_{A-} off)

$v_{control} < v_{tri}$ T_{A-} on $v_{AN} = 0$;

(T_{A+} off)

Leg B:

$-v_{control} > v_{tri}$ T_{B+} on $v_{BN} = V_d$;

(T_{B-} off)

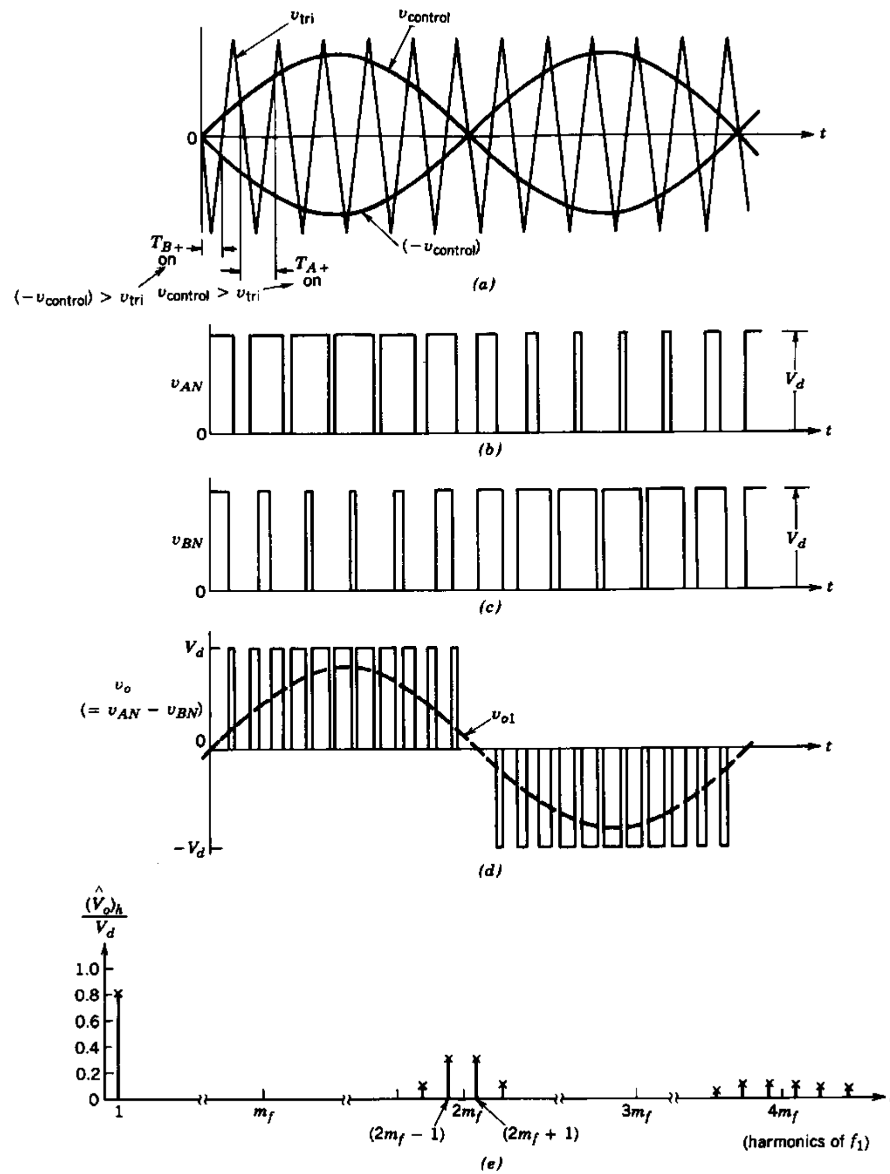
$-v_{control} < v_{tri}$ T_{B-} on $v_{BN} = 0$;

(T_{B+} off)

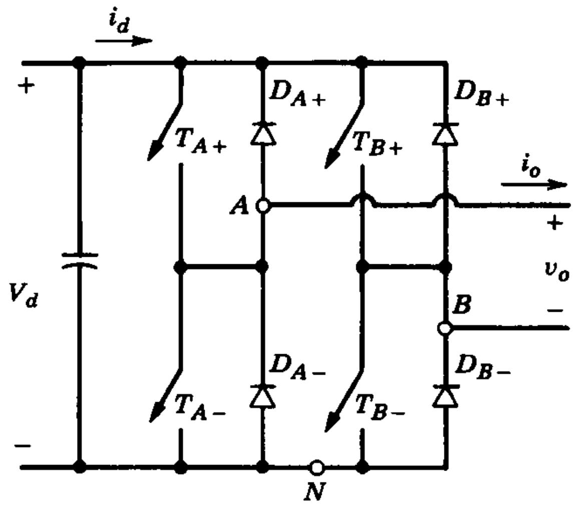
$$v_o = v_{AN} - v_{BN}$$

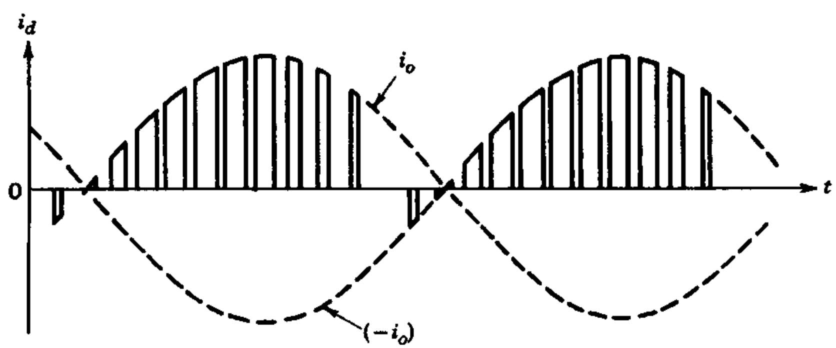
a. "effectively" doubling f_s

b. harmonic components around f_s are absent



PWM with Unipolar Voltage Switching





Leg A:

T_{A+} on $\quad \boldsymbol{i_o} > 0 \quad T_{A+}$ conducts; $\quad \boldsymbol{i_{d1} = i_o}$

$\boldsymbol{i_o} < 0 \quad D_{A+}$ conducts; $\quad \boldsymbol{i_{d1} = i_o}$

T_{A-} on $\quad \boldsymbol{i_o} < 0 \quad T_{A-}$ conducts; $\quad \boldsymbol{i_{d1} = 0}$

$\boldsymbol{i_o} > 0 \quad D_{A-}$ conducts; $\quad \boldsymbol{i_{d1} = 0}$

Leg B:

T_{B+} on $\quad \boldsymbol{i_o} < 0 \quad T_{B+}$ conducts; $\quad \boldsymbol{i_{d2} = -i_o}$

$\boldsymbol{i_o} > 0 \quad D_{B+}$ conducts; $\quad \boldsymbol{i_{d2} = -i_o}$

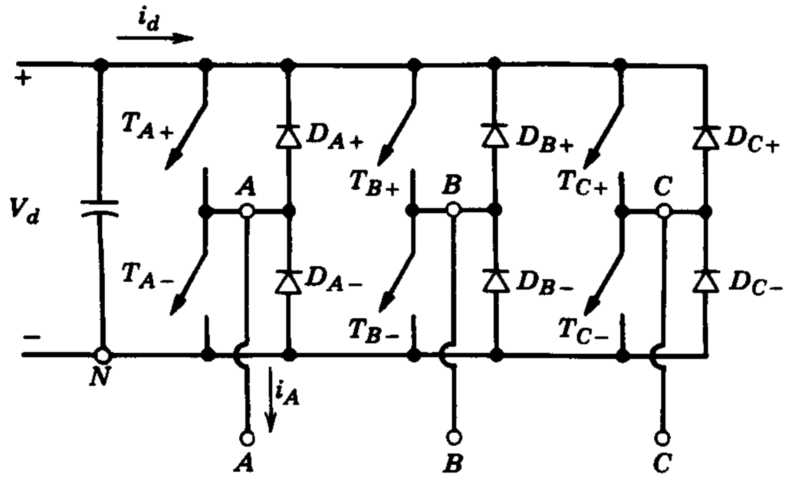
T_{B-} on $\quad \boldsymbol{i_o} > 0 \quad T_{B-}$ conducts; $\quad \boldsymbol{i_{d2} = 0}$

$\boldsymbol{i_o} < 0 \quad D_{B-}$ conducts; $\quad \boldsymbol{i_{d2} = 0}$

$$\boldsymbol{i_d = i_{d1} + i_{d2}}$$

i_d consists of I_d , i_{d2} and the high-frequency components due to inverter switchings.

6-2. Three-phase Bridge Inverters



switch states

and the corresponding voltage levels

$[T_{A+}, T_{B+}, T_{C+}, T_{A-}, T_{B-}, T_{C-}]$

= [0, 0, 0, 1, 1, 1] for V $[v_{AB}, v_{BC}, v_{CA}] = [0, 0, 0]$

= [1, 0, 0, 0, 1, 1] for V $[v_{AB}, v_{BC}, v_{CA}] = [V_d, 0, -V_d]$

= [0, 1, 0, 1, 0, 1] for V $[v_{AB}, v_{BC}, v_{CA}] = [-V_d, V_d, 0]$

= [1, 1, 0, 0, 0, 1] for V $[v_{AB}, v_{BC}, v_{CA}] = [0, V_d, -V_d]$

= [0, 0, 1, 1, 1, 0] for V $[v_{AB}, v_{BC}, v_{CA}] = [0, -V_d, V_d]$

= [1, 0, 1, 0, 1, 0] for V $[v_{AB}, v_{BC}, v_{CA}] = [V_d, -V_d, 0]$

= [0, 1, 1, 1, 0, 0] for V $[v_{AB}, v_{BC}, v_{CA}] = [-V_d, 0, V_d]$

= [1, 1, 1, 0, 0, 0] for V $[v_{AB}, v_{BC}, v_{CA}] = [0, 0, 0]$

Three-Phase PWM Waveforms

Leg A:

$v_{control,A} > v_{tri}$ T_{A+} on $v_{AN} = V_d$;

$v_{control,A} < v_{tri}$ T_{A-} on $v_{AN} = 0$;

Leg B:

$v_{control,B} > v_{tri}$ T_{B+} on $v_{BN} = V_d$;

$v_{control,B} < v_{tri}$ T_{B-} on $v_{BN} = 0$;

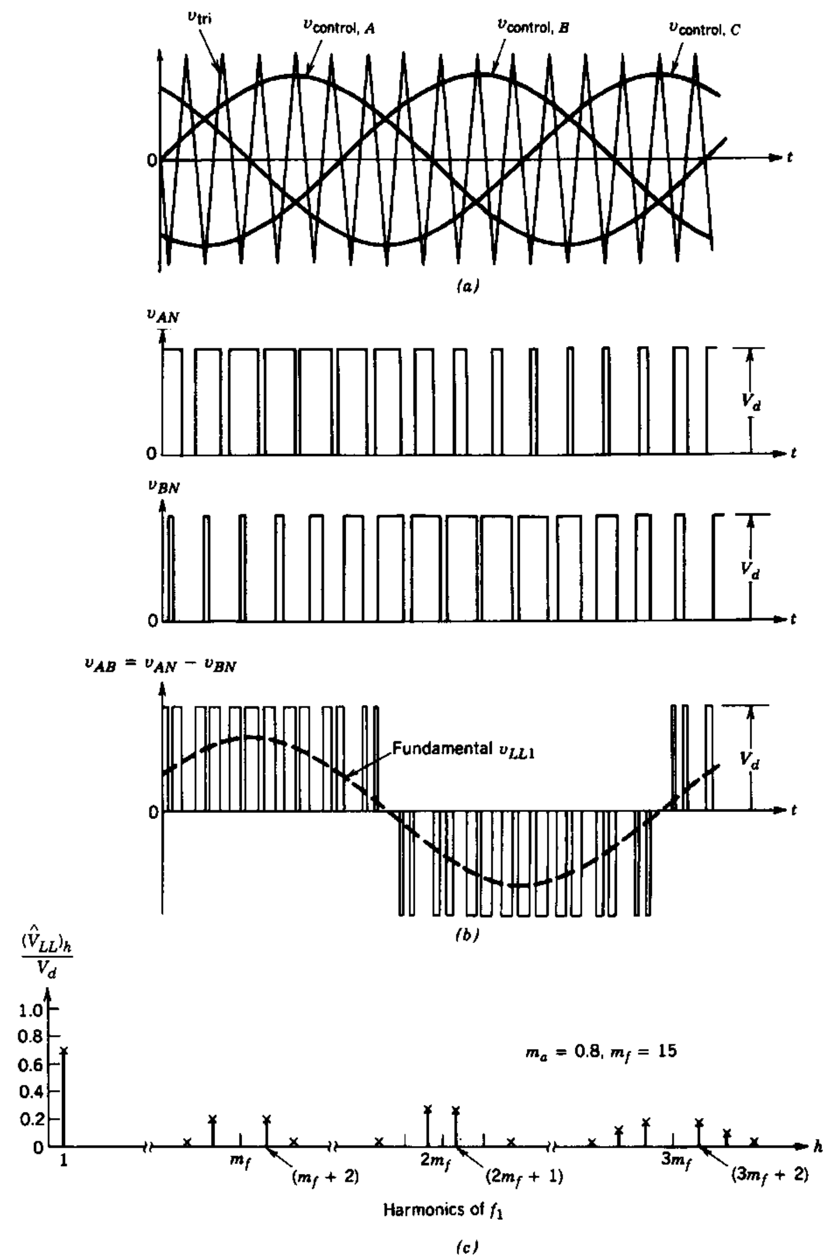
Leg C:

$v_{control,C} > v_{tri}$ T_{C+} on $v_{CN} = V_d$;

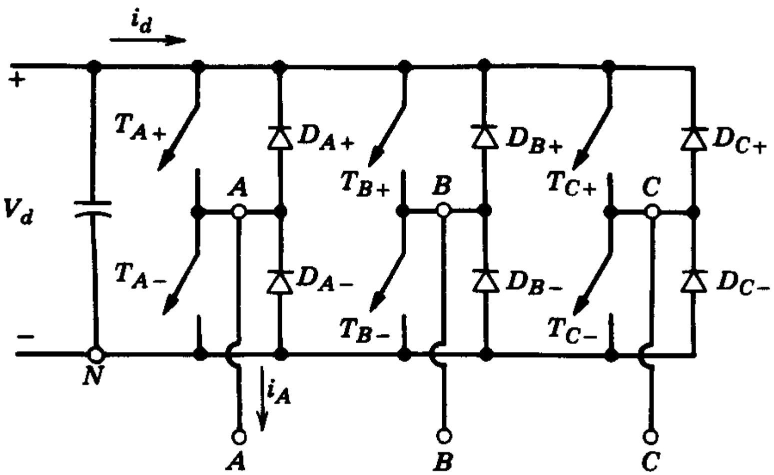
$v_{control,C} < v_{tri}$ T_{C-} on $v_{CN} = 0$;

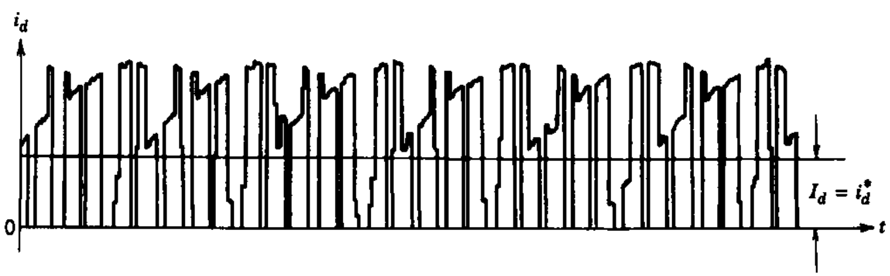
$$v_{AB} = v_{AN} - v_{BN}$$

m_f should be odd and a multiple of 3 to cancel out even harmonics and the harmonics at the odd multiples of m_f in the line-to-line voltage.



Three-Phase PWM Waveforms





The current consists of a DC component and the switching-frequency related harmonics.

Leg A:

T_{A+} on	$i_A > 0$	T_{A+} conducts;	$i_{d1} = i_A$
	$i_A < 0$	D_{A+} conducts;	$i_{d1} = i_A$
T_{A-} on	$i_A < 0$	T_{A-} conducts;	$i_{d1} = 0$
	$i_A > 0$	D_{A-} conducts;	$i_{d1} = 0$

Leg B:

T_{B+} on	$i_B > 0$	T_{B+} conducts;	$i_{d2} = i_B$
	$i_B < 0$	D_{B+} conducts;	$i_{d2} = i_B$
T_{B-} on	$i_B < 0$	T_{B-} conducts;	$i_{d2} = 0$
	$i_B > 0$	D_{B-} conducts;	$i_{d2} = 0$

Leg C:

T_{C+} on	$i_C > 0$	T_{C+} conducts;	$i_{d3} = i_C$
	$i_C < 0$	D_{C+} conducts;	$i_{d3} = i_C$
T_{C-} on	$i_C < 0$	T_{C-} conducts;	$i_{d3} = 0$
	$i_C > 0$	D_{C-} conducts;	$i_{d3} = 0$

$$i_d = i_{d1} + i_{d2} + i_{d3}$$

Three-Phase PWM Waveforms

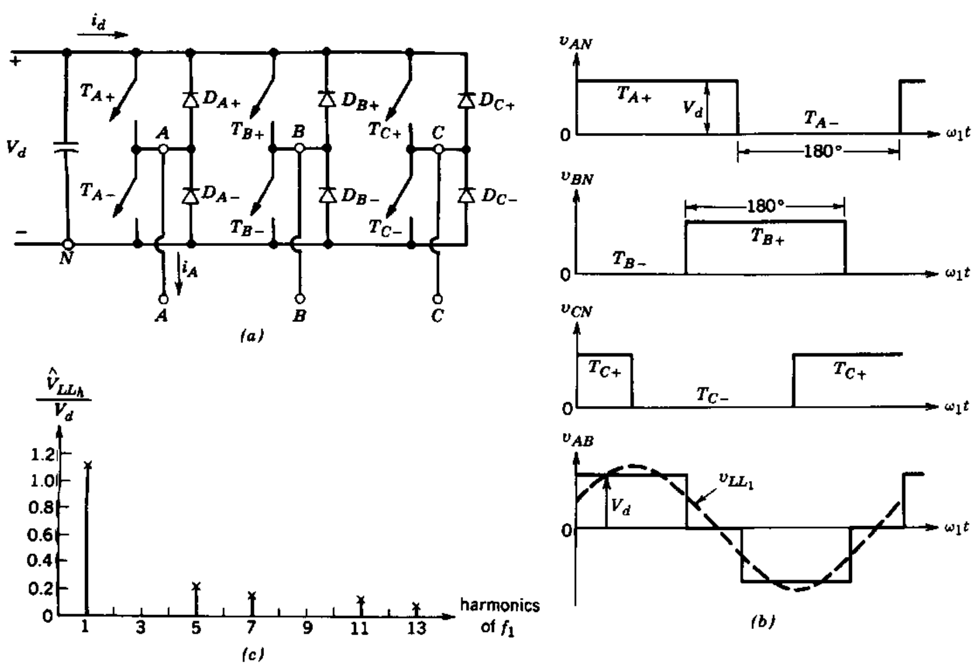
Linear $V_{LL1rms} = 0.612 m_a V_d$

$m_a \leq 1$

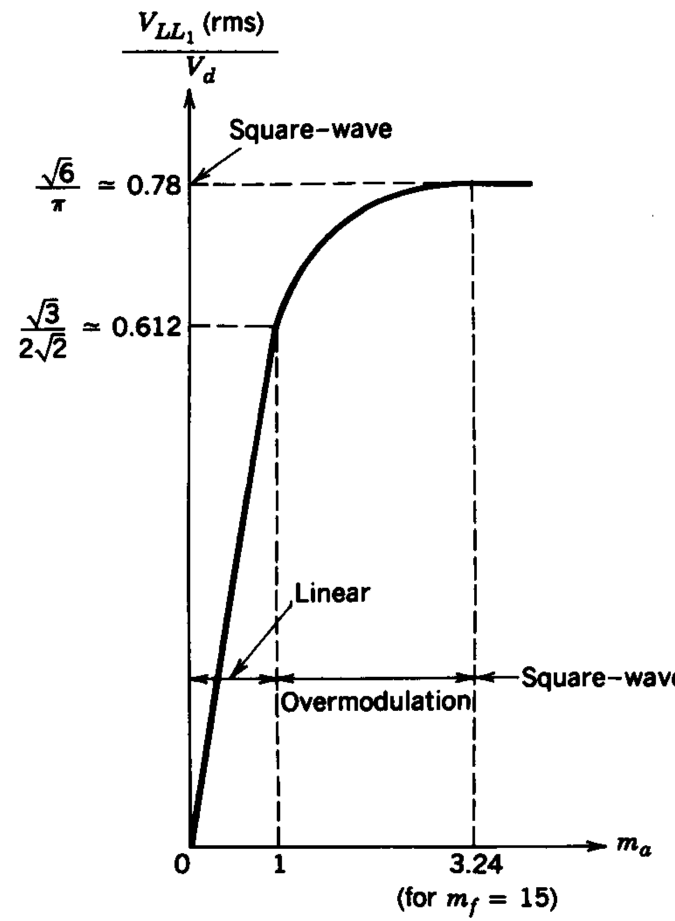
Over-modulation $0.612V_d < V_{LL1rms} < 0.78V_d$

$m_a > 1$

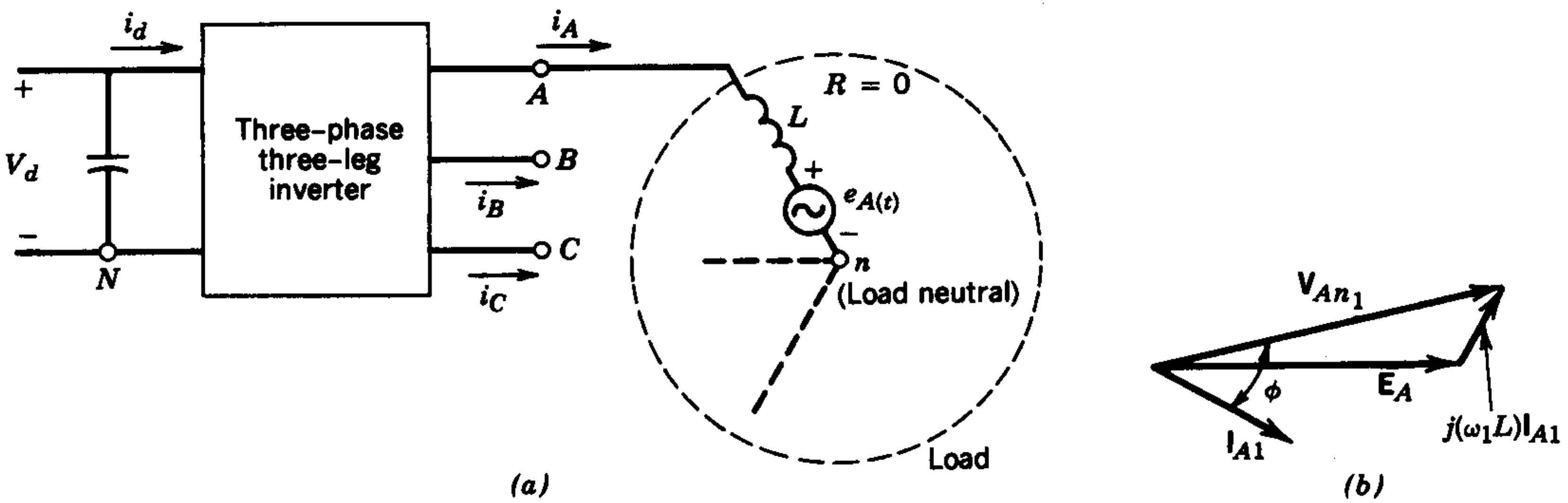
Square-wave operation $V_{LL1rms} = 0.78\ V_d$



Output voltage Fundamental as a Function of m_a

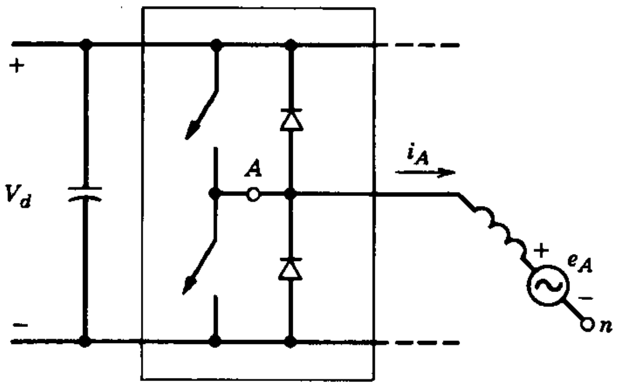


Fundamental Frequency

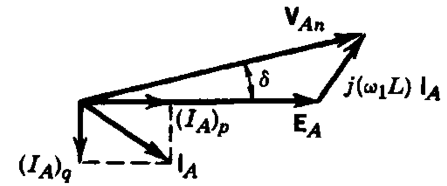


Analysis at the fundamental frequency can be done using phasors.

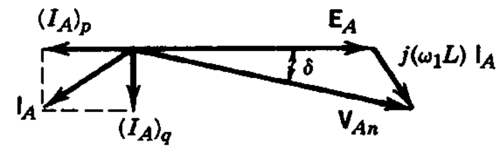
Transition from Inverter to Rectifier Mode



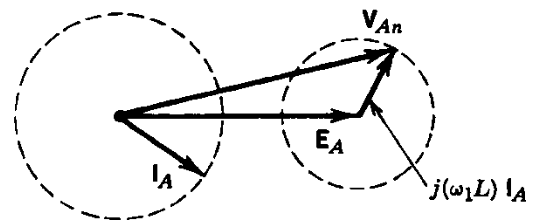
(a)



(b)

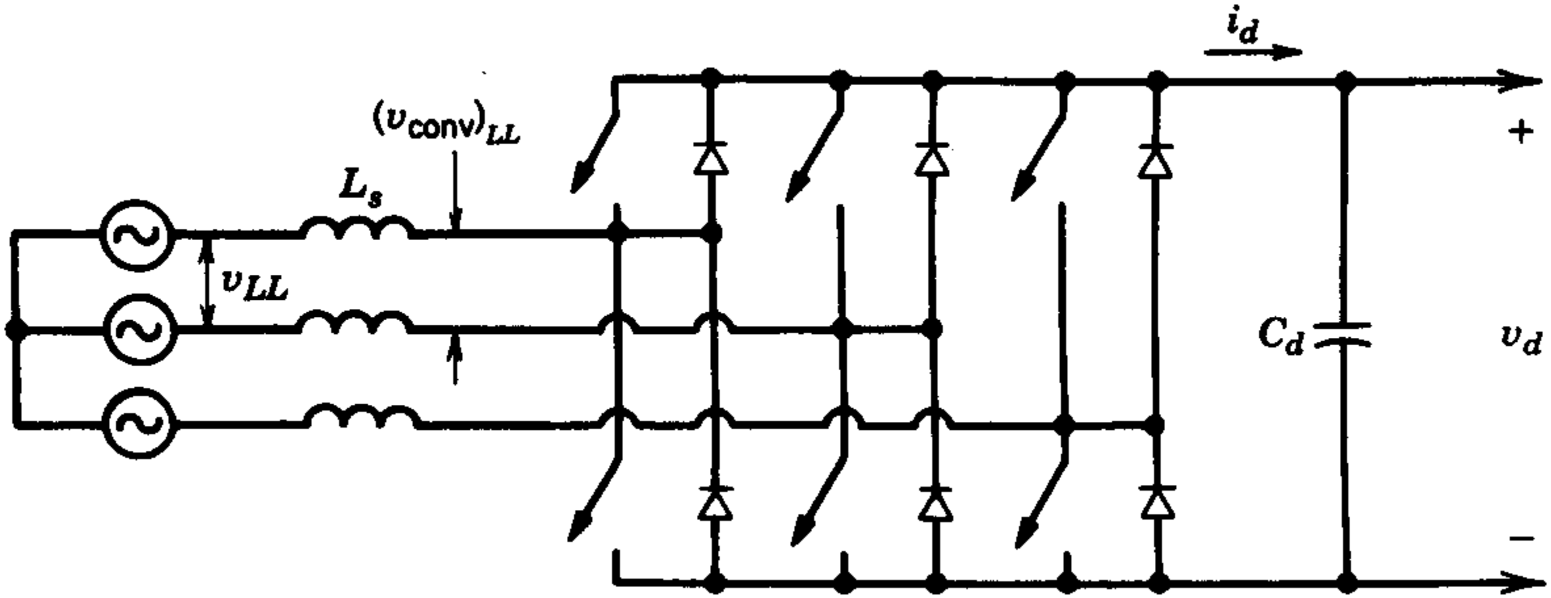


(c)

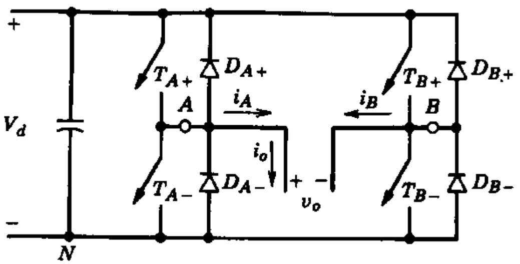


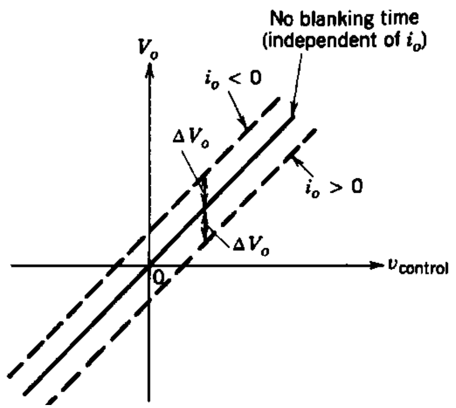
(d)

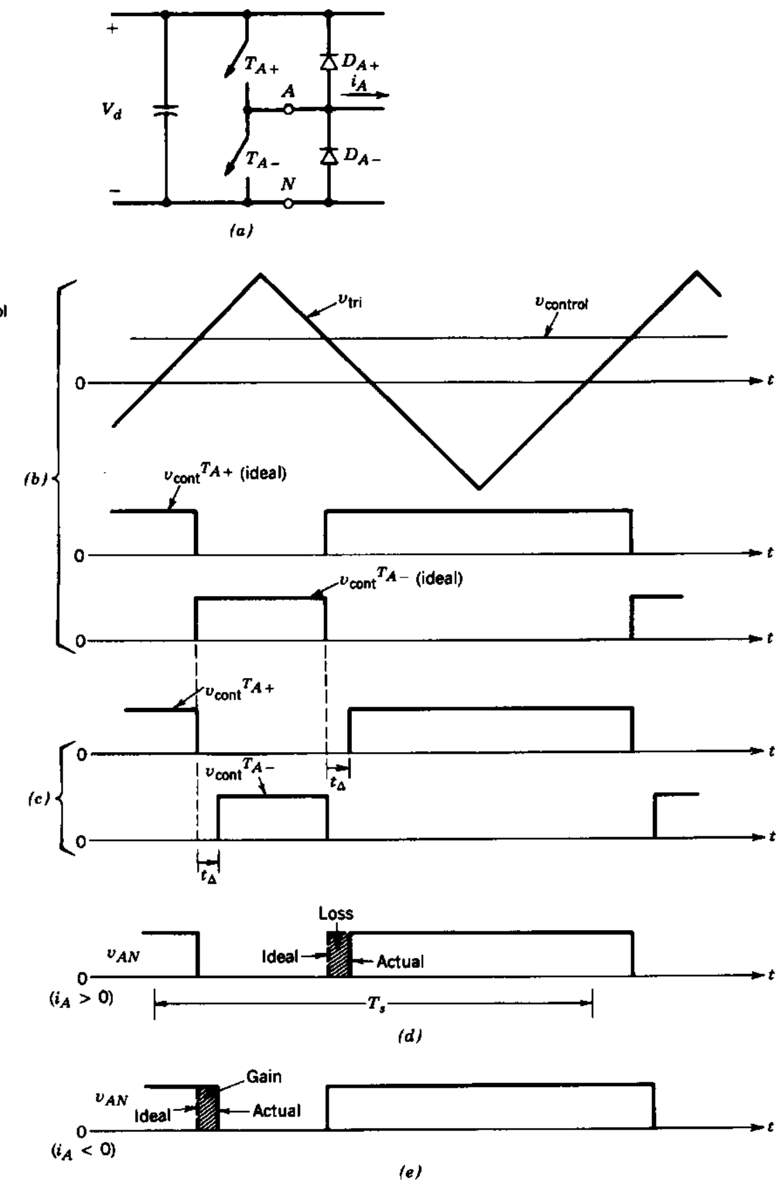
analysis based on the fundamental-frequency components


i_d
$(v_{conv})_{LL}$
L_s
v_{LL}
C_d
v_d
+
−

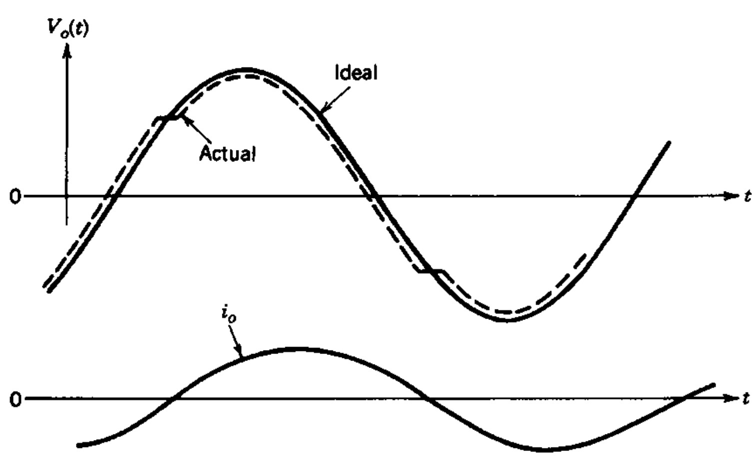
6-3. Effect of Blanking Time







Voltage jump when the current reverses direction



Summary:

- DC-AC inverter v.s. thyristor AC/DC inversion mode
- Switch states in DC/AC inverter (T, output voltage, current)
- Output voltage modulation method (waveforms)
- Output voltage and four-quadrant operation
- Frequency/amplitude modulation ratio: harmonics, over-modulation
- Required both for single-phase and three-phase DC-AC inverters

The End