Lecture Notes

Heat Sinks and Component Temperature Control

Need for Component Temperature Control

- All components, capacitors, inductors and transformers, and semiconductor devices and circuits have maximum operating temperatures specified by manufacturer.
  - Component reliability decreases with increasing temperature.Semiconductor failure rate doubles for every 10 - 15 °C increase in temperature above 50 °C (approx. rule-of-thumb).
- High component operating temperatures have undesirable effects on components.

Capacitors

Electrolyte evaporation rate increases significantly with temperature increases and thus shortens lifetime.

Magnetic Components

- Losses (at constant power input) increase above 100 °C
- Winding insulation (lacquer or varnish) degrades above 100 °C

Semiconductors

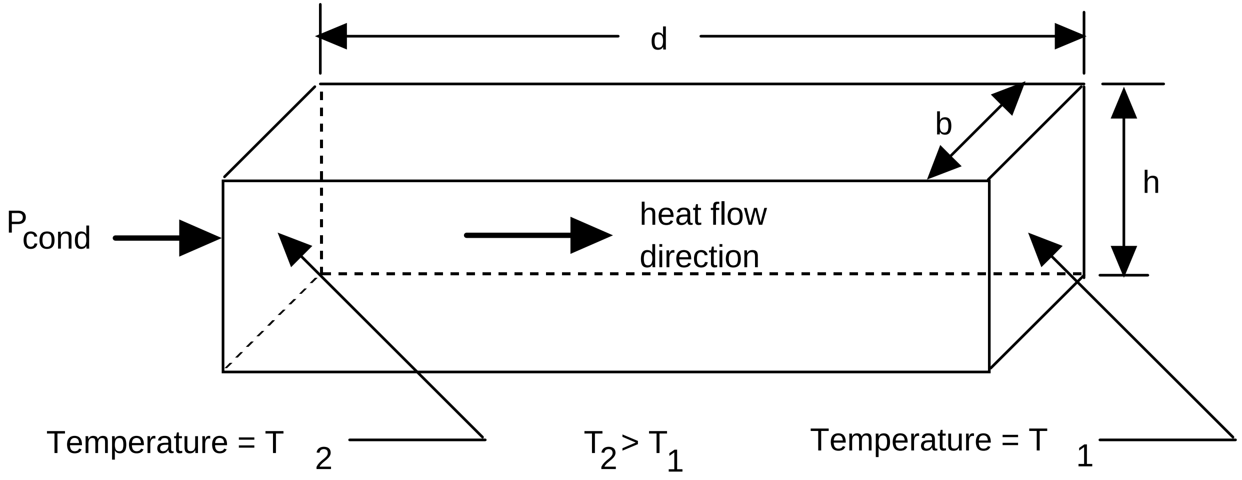
- Unequal power sharing in paralleled or series-connected devices.
- Reduction in breakdown voltage in some devices.
- Increase in leakage currents.
- Increase in switching times.

Temperature Control Methods

- Control voltages across and current through components via good design practices.
  - Snubbers may be required for semiconductor devices.
  - Free-wheeling diodes may be needed with magnetic components.
- Use components designed to maximize heat transfer via convection and radiation from component to ambient.
  - Short heat flow paths from interior to component surface and large component surface area.
- Component user has responsibility to properly mount temperature-critical components on heat sinks.
  - Apply recommended torque on mounting bolts and nuts and use thermal grease between component and heat sink.
  - Properly design system layout and enclosure for adequate air flow such that heat sinks can operate properly to dissipate heat to the ambient.

Heat Conduction Thermal Resistance

- Generic geometry of heat flow via conduction

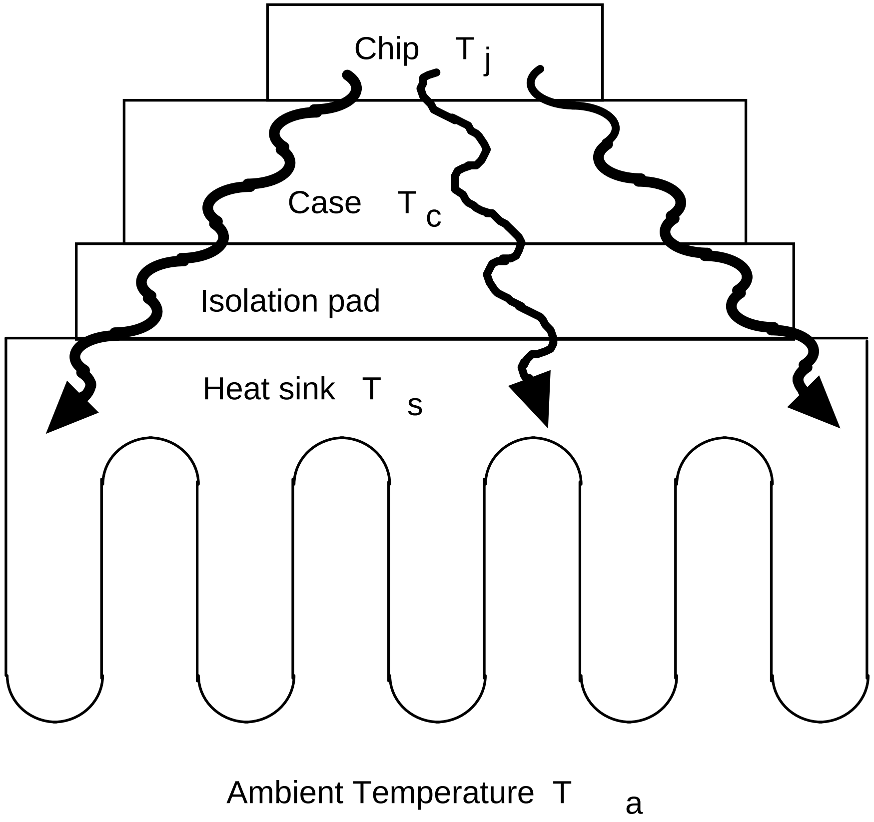


- Heat flow P_{cond} [W/m^2] = $\lambda A (T_2 - T_1) / d \quad = \quad (T_2 - T_1) / R_{\theta cond}$

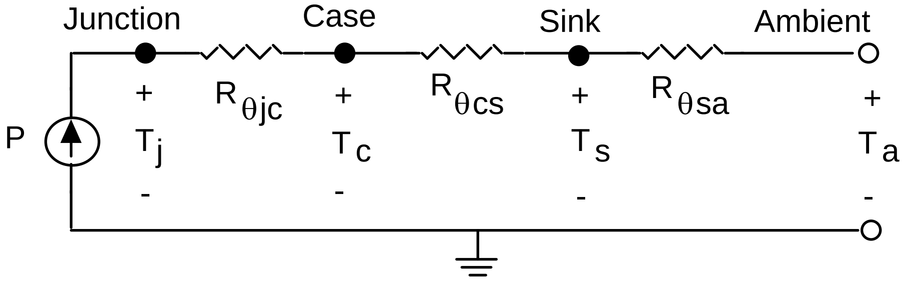
- Thermal resistance $R_{\theta cond} = d / [\lambda A]$
  - Cross-sectional area A = hb
  - λ = Thermal conductivity has units of W-m^{-1}-°C^{-1} (λ_{Al} = 220 W-m^{-1}-°C^{-1}).
  - Units of thermal resistance are °C/W

Thermal Equivalent Circuits

- Heat flow through a structure composed of layers of different materials.



- Thermal equivalent circuit simplifies calculation of temperatures in various parts of structure.



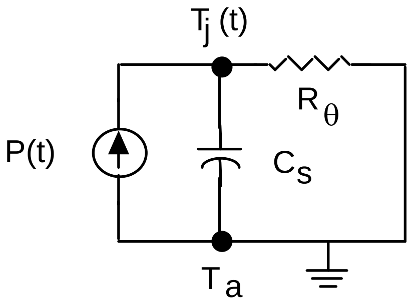
- $T_i = P_d\,(R_{\theta jc} + R_{\theta cs} + R_{\theta sa}) + T_a$

- If there parallel heat flow paths, then thermal resistances of the parallel paths combine as do electrical resistors in parallel.

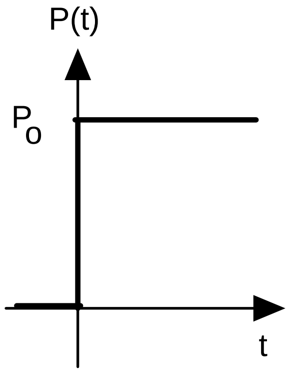
Transient Thermal Impedance

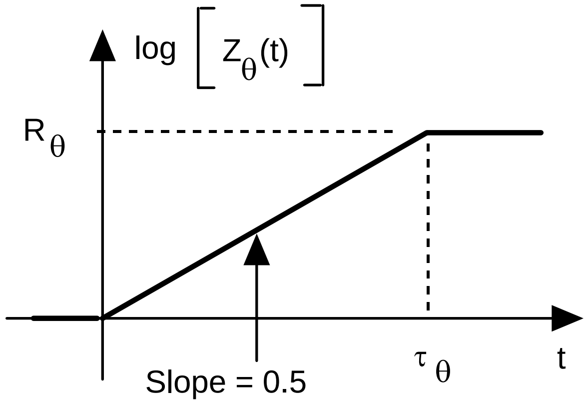
- Heat capacity per unit volume $C_v = dQ/dT$ [Joules /°C] prevents short duration high power dissipation surges from raising component temperature beyond operating limits.

- Transient thermal equivalent circuit. $C_s = C_v V$ where V is the volume of the component.



- Transient thermal impedance $Z_\theta(t) = [T_j(t) - T_a]/P(t)$





- $\tau_\theta = \pi R_\theta C_s /4$ = thermal time constant

- $T_j(t = \tau_\theta) = 0.833\ P_o R_\theta$

Heat Sinks

- Aluminum heat sinks of various shapes and sizes widely available for cooling components.
  - Often anodized with black oxide coating to reduce thermal resistance by up to 25%.
  - Sinks cooled by natural convection have thermal time constants of 4 - 15 minutes.
  - Forced-air cooled sinks have substantially smaller thermal time constants, typically less than one minute.
- Choice of heat sink depends on required thermal resistance, $R_{\theta sa}$, which is determined by several factors.
  - Maximum power, P_{diss}, dissipated in the component mounted on the heat sink.
  - Component's maximum internal temperature, $T_{j,max}$
  - Component's junction-to-case thermal resistance, $R_{\theta jc}$.
  - Maximum ambient temperature, $T_{a,max}$.
- $R_{\theta sa} = \{T_{j,max} - T_{a,max}\}P_{diss} - R_{\theta jc}$
  - P_{diss} and $T_{a,max}$ determined by particular application.
  - $T_{j,max}$ and $R_{\theta jc}$ set by component manufacturer.

Radiative Thermal Resistance

- Stefan-Boltzmann law describes radiative heat transfer.
  - $P_{rad} = 5.7\text{x}10^{-8}\,EA\,[(T_s)^4 - (T_a)^4]$; $[P_{rad}] = [\text{watts}]$
  - E = emissivity; black anodized aluminum E = 0.9 ; polished aluminum E = 0.05
  - A = surface area $[m^2]$through which heat radiation emerges.
  - T_s = surface temperature [°K] of component. T_a = ambient temperature [°K].

- $(T_s - T_a)/\text{Prad} = R_{\theta,rad} = [T_s - T_a][5.7EA\,\{(T_s/100)^4 - (T_a/100)^4\}]^{-1}$

- Example - black anodized cube of aluminum 10 cm on a side. $T_s = 120$ °C and

  $T_a = 20$ °C
  - $R_{\theta,rad} = [393 - 293][(5.7)(0.9)(6\text{x}10\text{-}2)\{(393/100)^4 - (293/100)^4\}]^{-1}$
  - $R_{\theta,rad} = 2.2$ °C/W

Convective Thermal Resistance

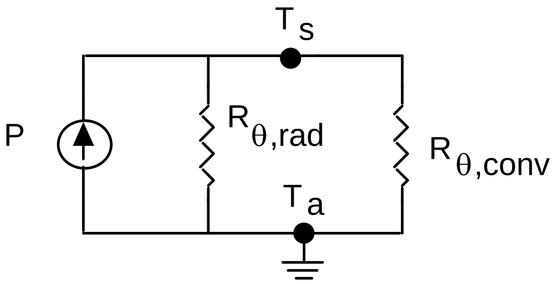
- P_{conv} = convective heat loss to surrounding air from a vertical surface at sea level having a height d_{vert} [in meters] less than one meter.
  - $P_{conv} = 1.34\ A\ [Ts - Ta]^{1.25}\ d_{vert}^{-0.25}$
  - A = total surface area in [m^2]
  - T_s = surface temperature [°K] of component. T_a = ambient temperature [°K].

- $[T_s - T_a]/P_{conv} = R_{\theta,conv} = [T_s - T_a]\ [d_{vert}]^{0.25}[1.34\ A\ (T_s - T_a)^{1.25}]^{-1}$
  - $R_{\theta,conv} = [d_{vert}]^{0.25}\ \{1.34\ A\ [T_s - T_a]^{0.25}\}^{-1}$

- Example - black anodized cube of aluminum 10 cm on a side. T_s = 120 °C and T_a = 20 °C.
  - $R_{\theta,conv} = [10^{-1}]0.25([1.34]\ [6x10^{-2}]\ [120 - 20]^{0.25})^{-1}$
  - $R_{\theta,conv} = 2.2$ °C/W

Combined Effects of Convection and Radiation

- Heat loss via convection and radiation occur in parallel.
  - Steady-state thermal equivalent circuit



  - $R_{\theta,sink} = R_{\theta,rad} R_{\theta,conv} / [R_{\theta,rad} + R_{\theta,conv}]$

- Example - black anodized aluminum cube 10 cm per side
  - $R_{\theta,rad} = 2.2$ °C/W and $R_{\theta,conv} = 2.2$ °C/W
  - $R_{\theta,sink} = (2.2)(2.2)/(2.2 + 2.2) = 1.1$ °C/W

Switch-Mode DC-AC Inverter

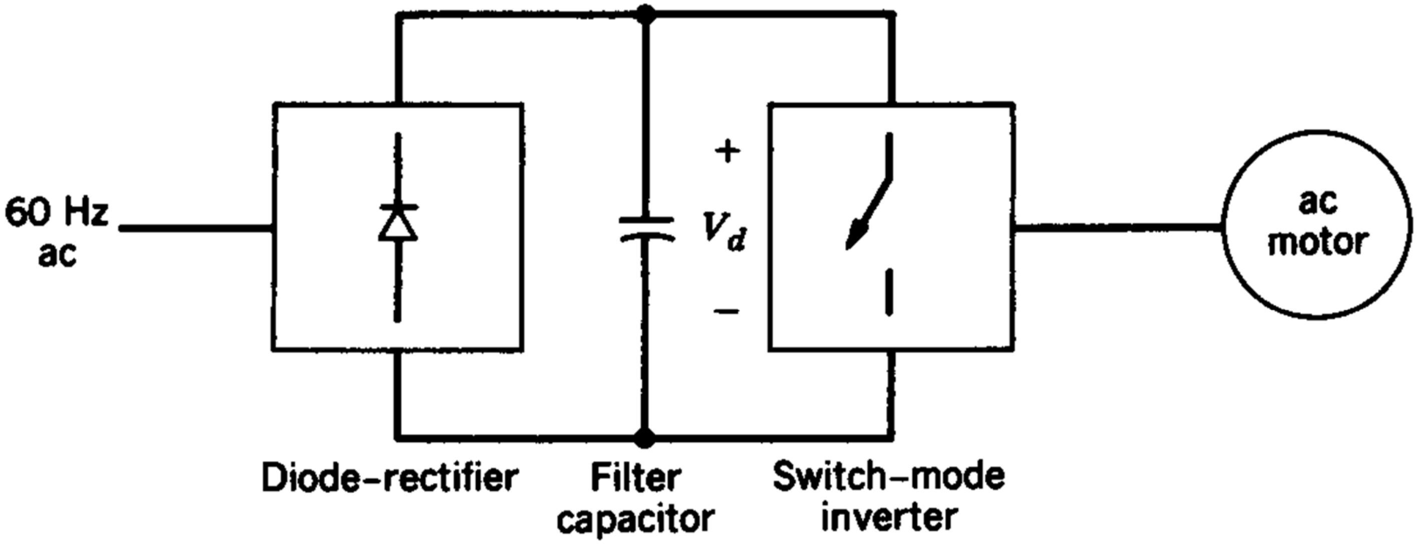


Figure 8-1 Switch-mode inverter in ac motor drive.

- Block diagram of a motor drive where the power flow is unidirectional

One Leg of a Switch-Mode DC-AC Inverter

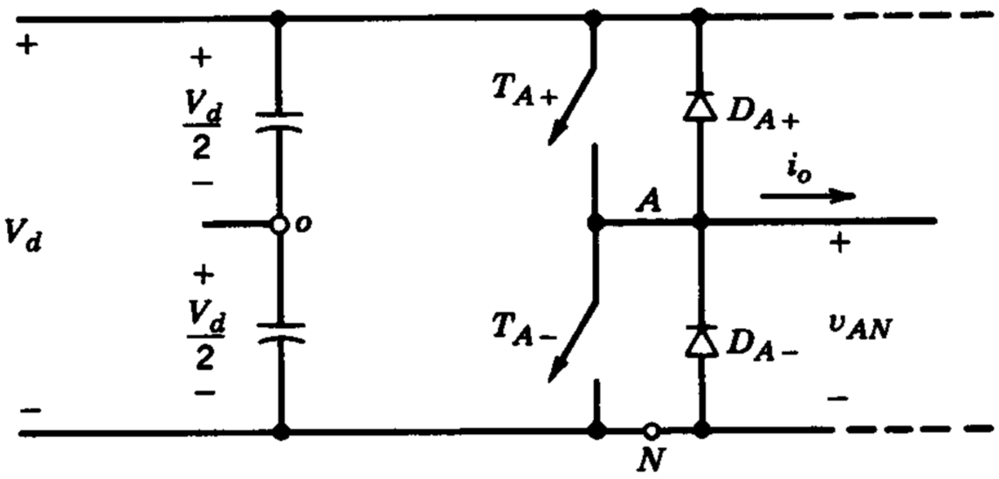


Figure 8-4 One-leg switch-mode inverter.

- The mid-point shown is fictitious

Synthesis of a Sinusoidal Output by PWM

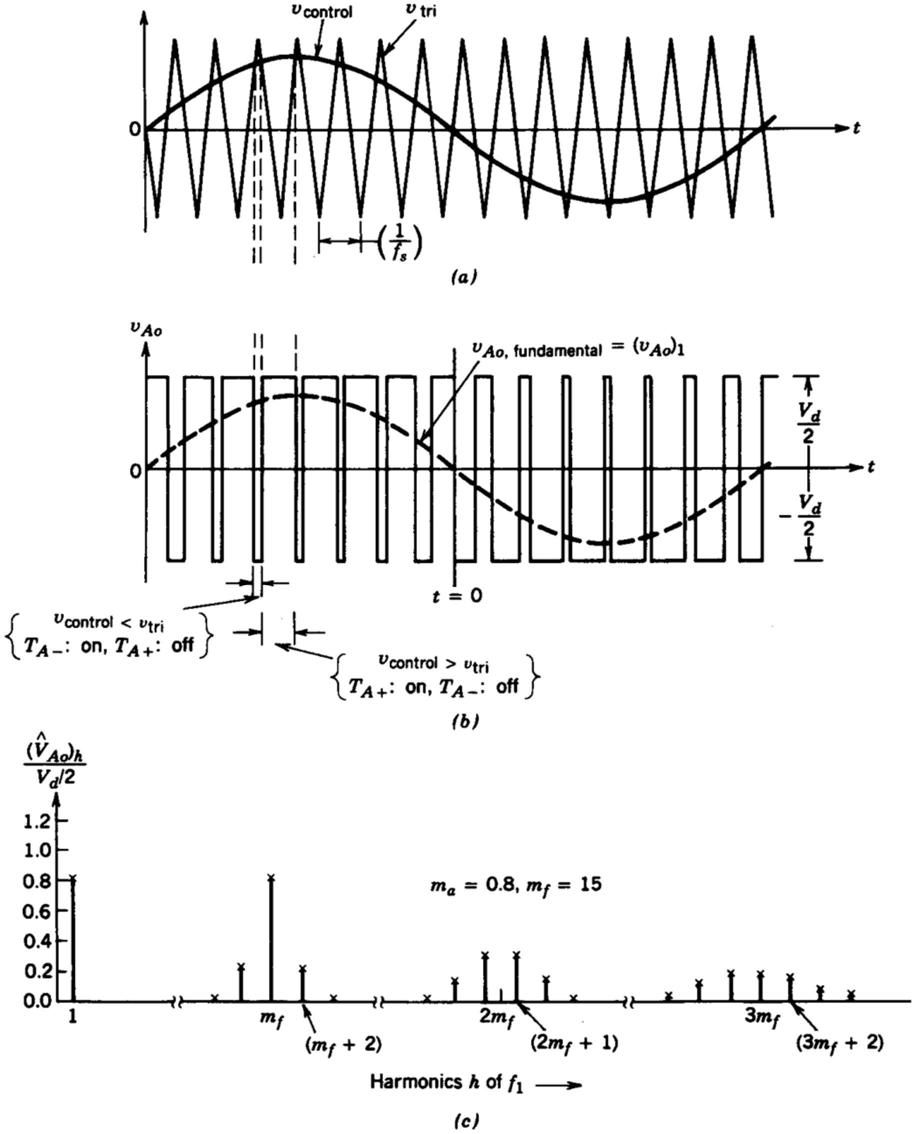


Figure 8-5 Pulse-width modulation.

Details of a Switching Time Period

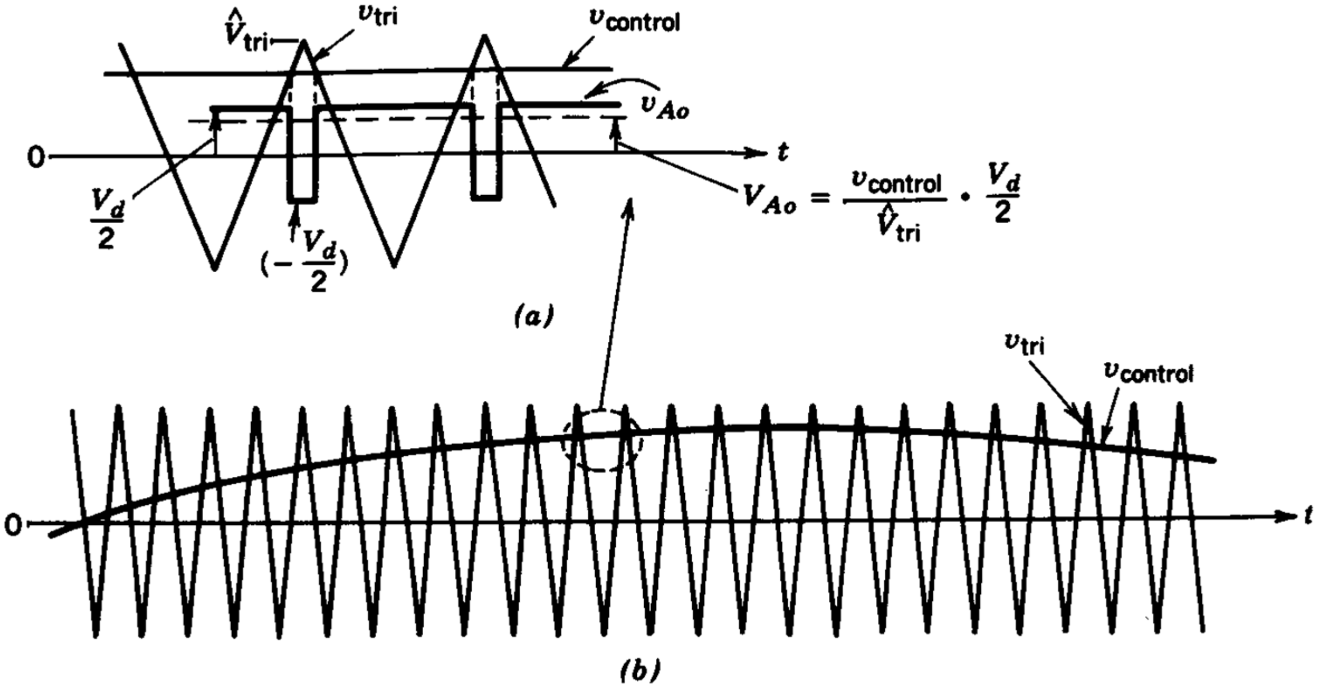


Figure 8-6 Sinusoidal PWM.

- Control voltage can be assumed constant during a switching time-period

Harmonics in the DC-AC Inverter Output Voltage

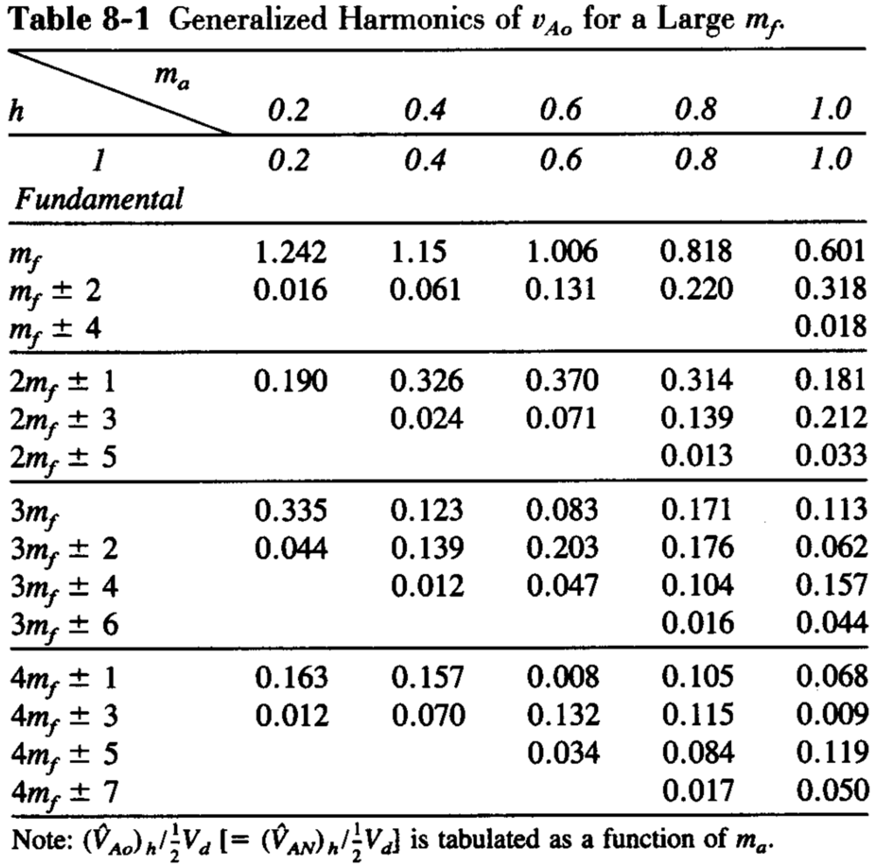


Table 8-1 Generalized Harmonics of v_{Ao} for a Large m_f.

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.

- Harmonics appear around the carrier frequency and its multiples

Output voltage Fundamental as a Function of the Modulation Index

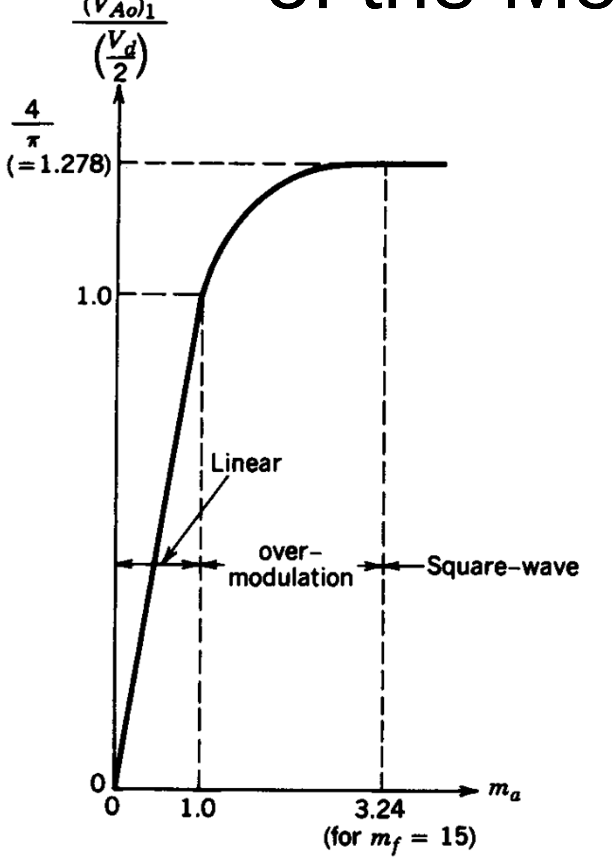


Figure 8-8 Voltage control by varying m_a.

- Shows the linear and the over-modulation regions; square-wave operation in the limit

Square-Wave Mode of Operation

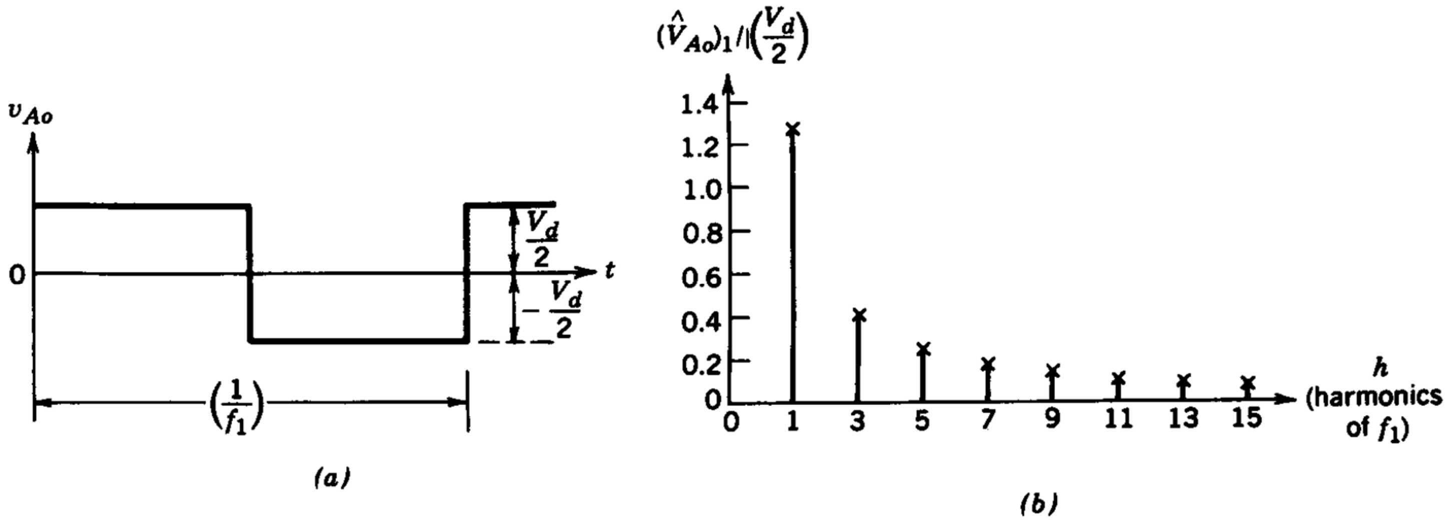


Figure 8-9 Square-wave switching.

- Harmonics are of the fundamental frequency

Harmonics due to Over-modulation

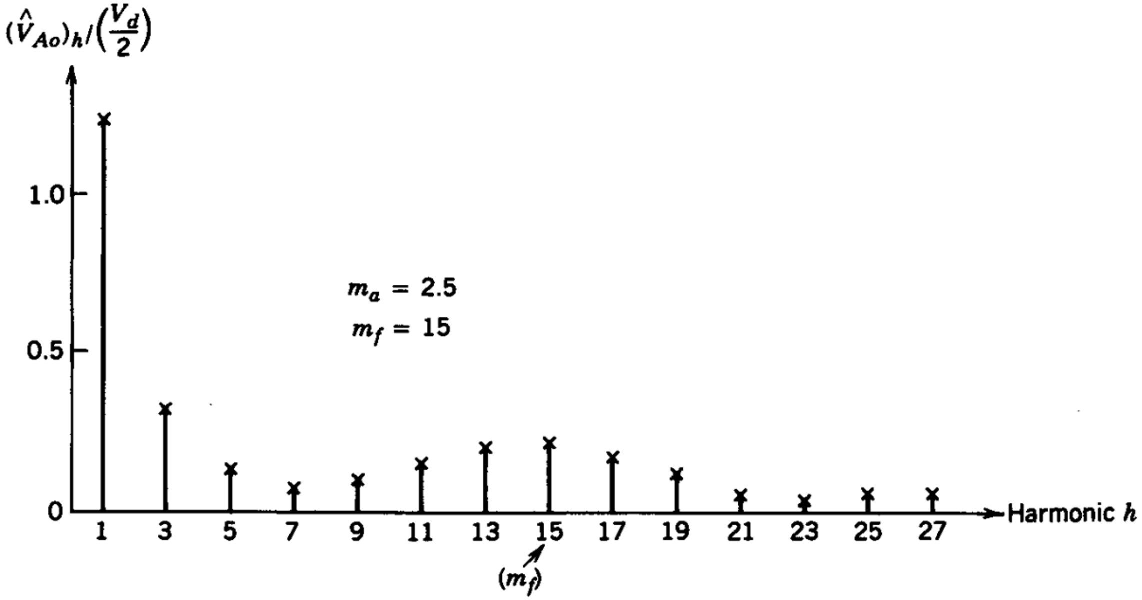


Figure 8-7 Harmonics due to overmodulation; drawn for $m_a = 2.5$ and $m_f = 15$.

- These are harmonics of the fundamental frequency

Half-Bridge Inverter

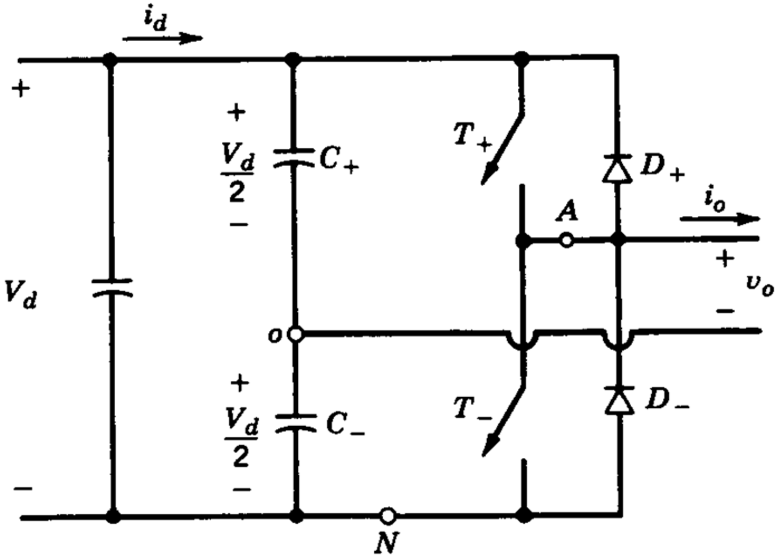


Figure 8-10 Half-bridge inverter.

- Capacitors provide the mid-point

Single-Phase Full-Bridge DC-AC Inverter

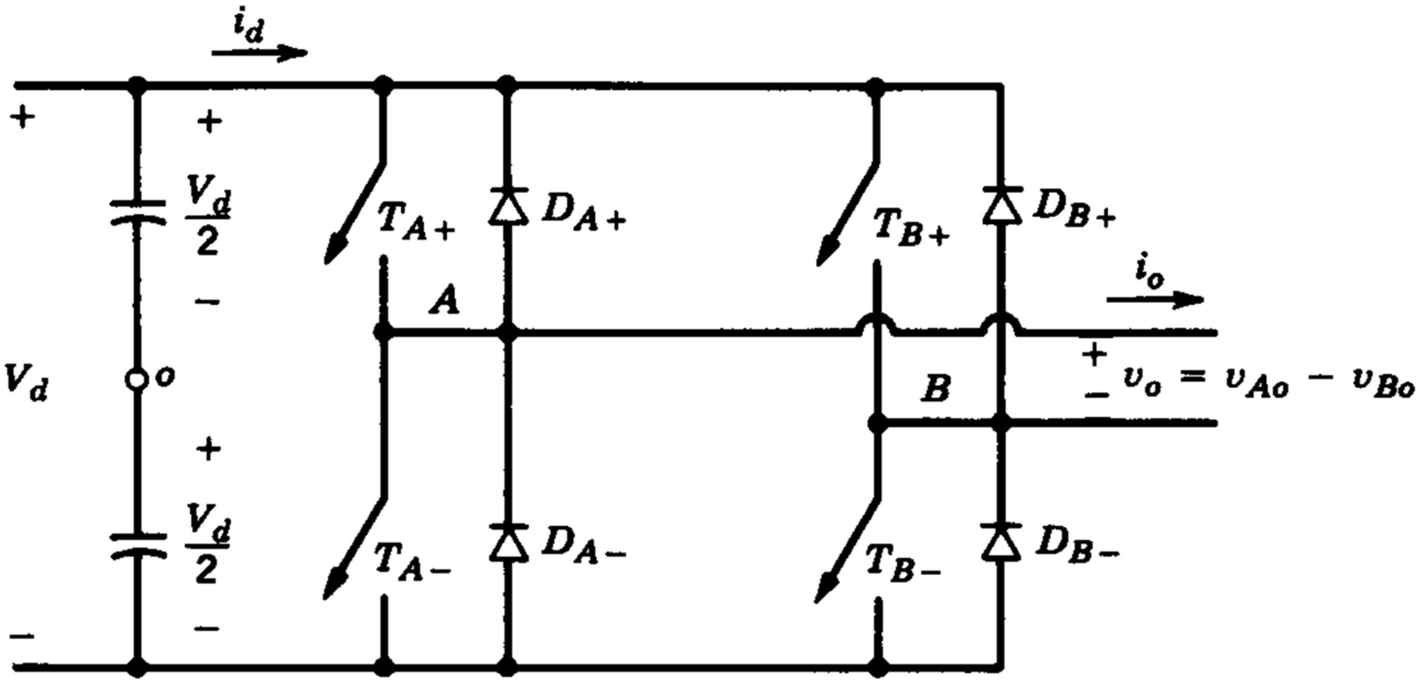


Figure 8-11 Single-phase full-bridge inverter.

- Consists of two inverter legs

PWM to Synthesize Sinusoidal Output

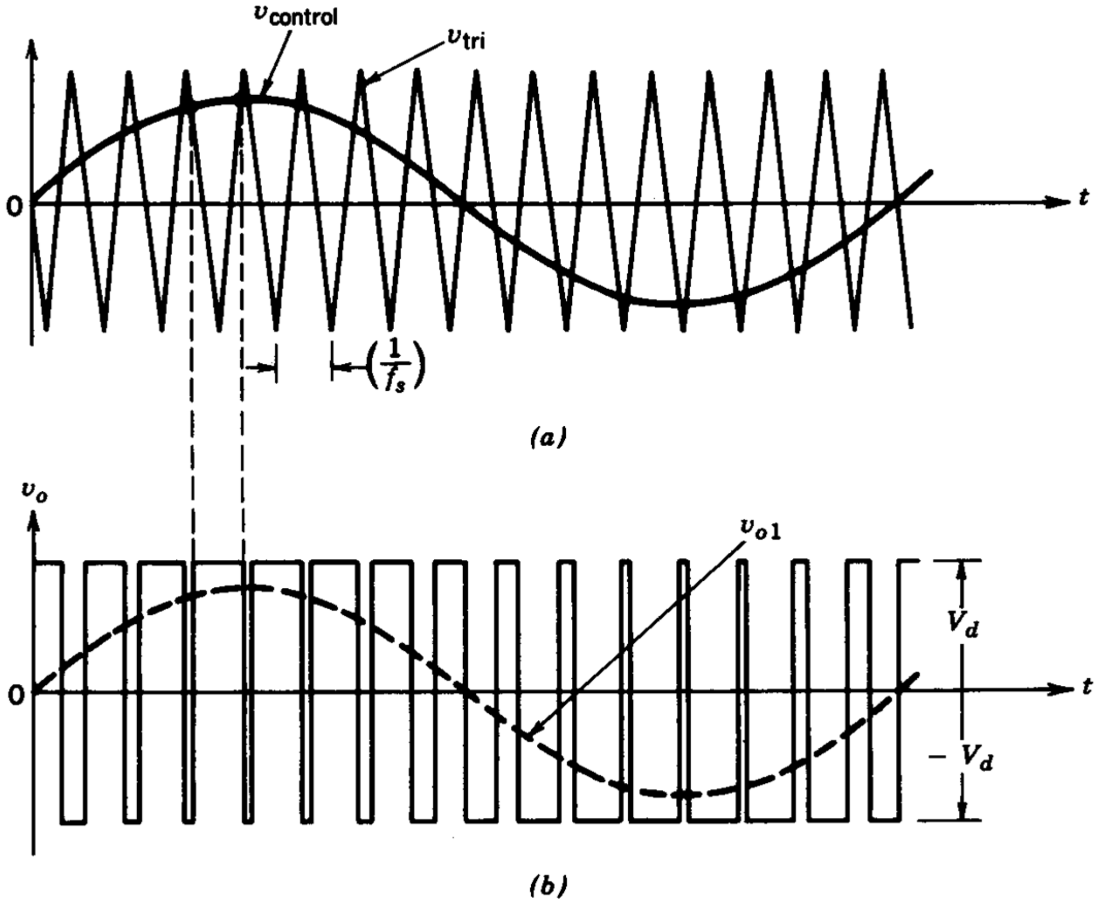


Figure 8-12 PWM with bipolar voltage switching.

- The dotted curve is the desired output; also the fundamental frequency