Accionamentos Electromecânicos

Componentes de Electrónica de Potência

Bobines: revisão de Electromagnetismo

$$B = \mu H$$

$$\iiint_V B\,dA = 0$$

$$\phi = \iint_{A_C} B\,dA \Rightarrow \phi = BA_C$$

Fluxo magnético

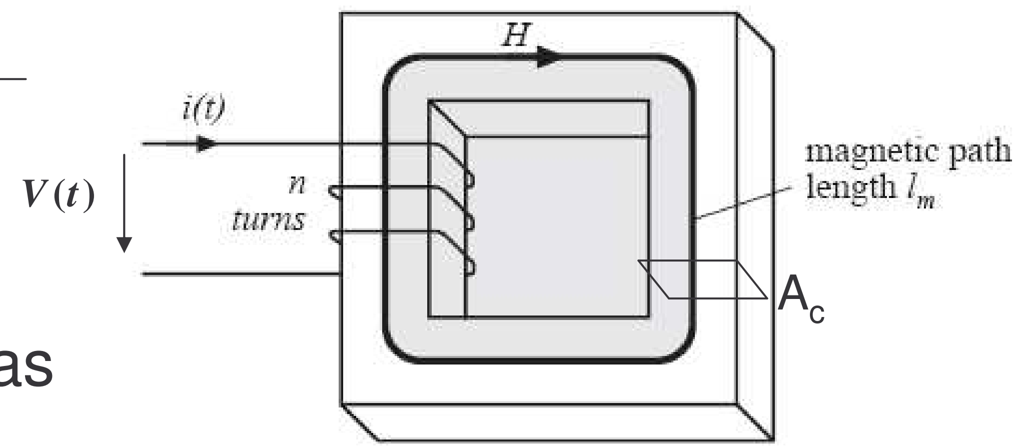
***B* – densidade de fluxo**

Lei de *Faraday*

$$V(t) = \frac{\partial \phi(t)}{\partial t} = A_C \frac{\partial B(t)}{\partial t}$$

$$V(t) = A_C N \frac{\partial B(t)}{\partial t}$$

N-espiras



Lei de *Ampere*

$$\oint_{lm} H\,dl = \sum I \Rightarrow H l_m = NI$$

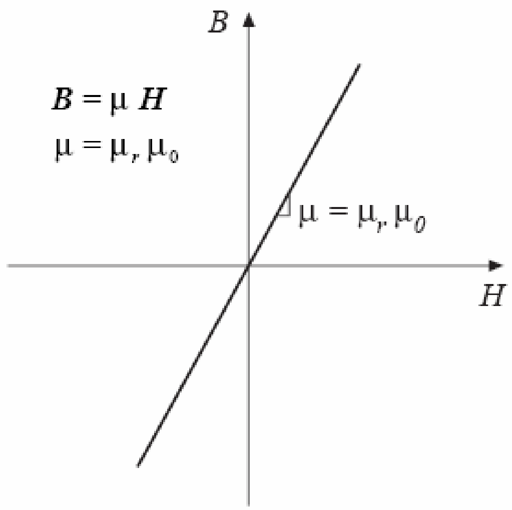
$$H = \frac{NI}{l_m} \rightarrow B = \mu \frac{NI}{l_m}$$

$$V(t) = \frac{A_C N \mu N}{l_m} \frac{\partial i(t)}{\partial t} = \underbrace{\frac{A_C \mu}{l_m}}_{A_L} N^2 \frac{\partial i(t)}{\partial t}$$

$$V(t) = L \frac{\partial i(t)}{\partial t} \Rightarrow L = \frac{A_C \mu N^2}{l_m} = A_L N^2$$

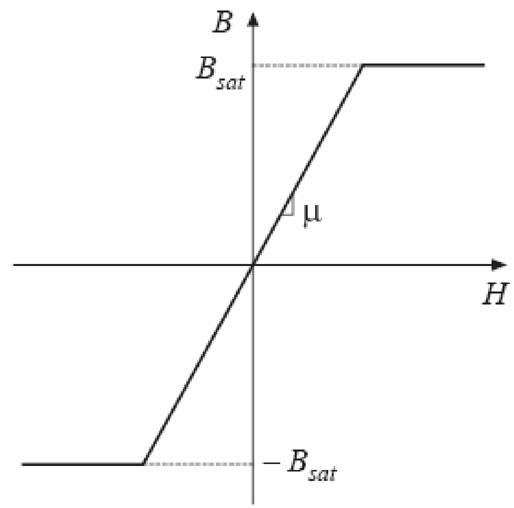
Modelização dos materiais magnéticos

No hysteresis or saturation



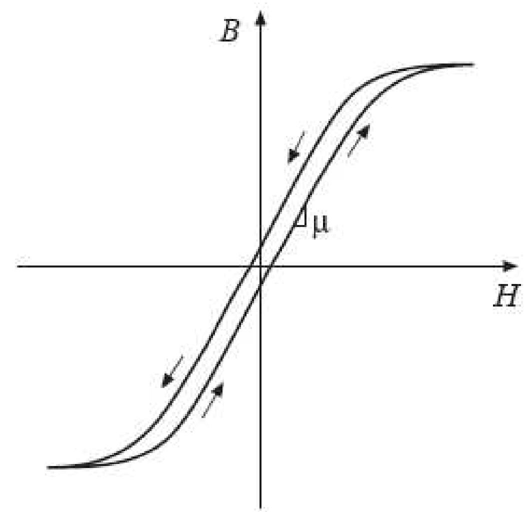
Typical $\mu_r = 10^3 - 10^5$

Saturation, no hysteresis



Typical $B_{sat} =$ 0.3-0.5T, ferrite
0.5-1T, powdered iron
1-2T, iron laminations

A magnetic core material



Highly nonlinear, with hysteresis and saturation

$$B = \begin{cases} B_{sat} & \text{for } H \geq B_{sat}/\mu \\ \mu H & \text{for } |H| < B_{sat}/\mu \\ -B_{sat} & \text{for } H \leq B_{sat}/\mu \end{cases}$$

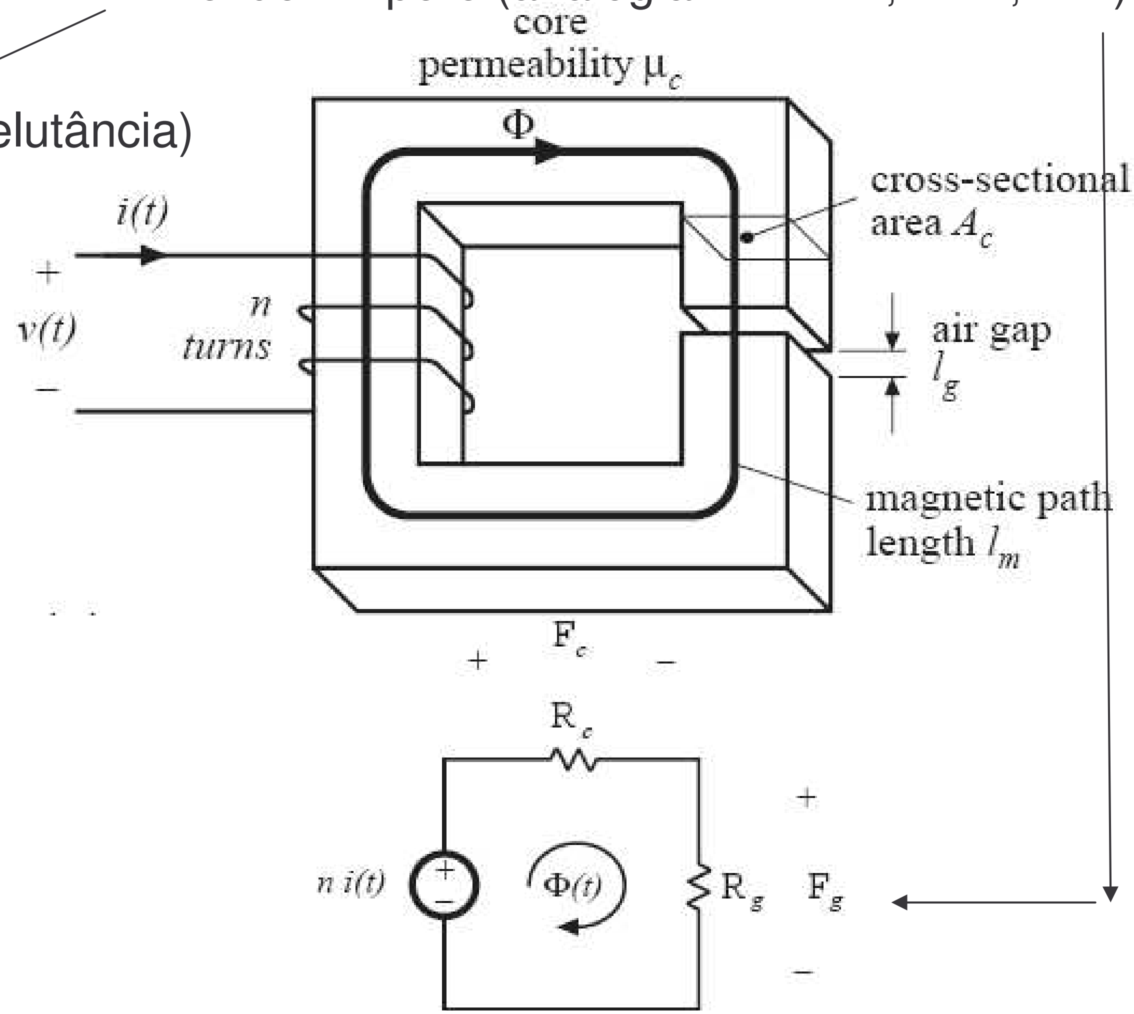
$$I_{SAT} = \frac{B_{SAT} l_m}{\mu N}$$

Força magnetomotriz - MMF

$$\boldsymbol{F} = \int_{x1}^{x2} \boldsymbol{Hdl} = \boldsymbol{Hl} = \boldsymbol{NI}$$

Lei de Ampére (analogia: F=NI=V, R=R, I=Φ)

$$\boldsymbol{F} = \frac{\boldsymbol{l}}{\mu A_C}\phi \rightarrow \boldsymbol{R} = \frac{\boldsymbol{l}}{\mu A_C}$$ (relutância)



$$F_C + F_g = NI$$

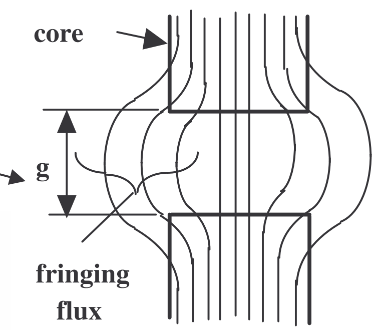
$$\phi(R_C + R_g) = NI$$

$$R_C = \frac{lm}{\mu A_C}$$

$$R_g = \frac{\lg}{\mu_o A_C}$$

$$L = \frac{N^2}{R_C + R_g}$$

No cálculo de R_g há que considerar o frangeamento

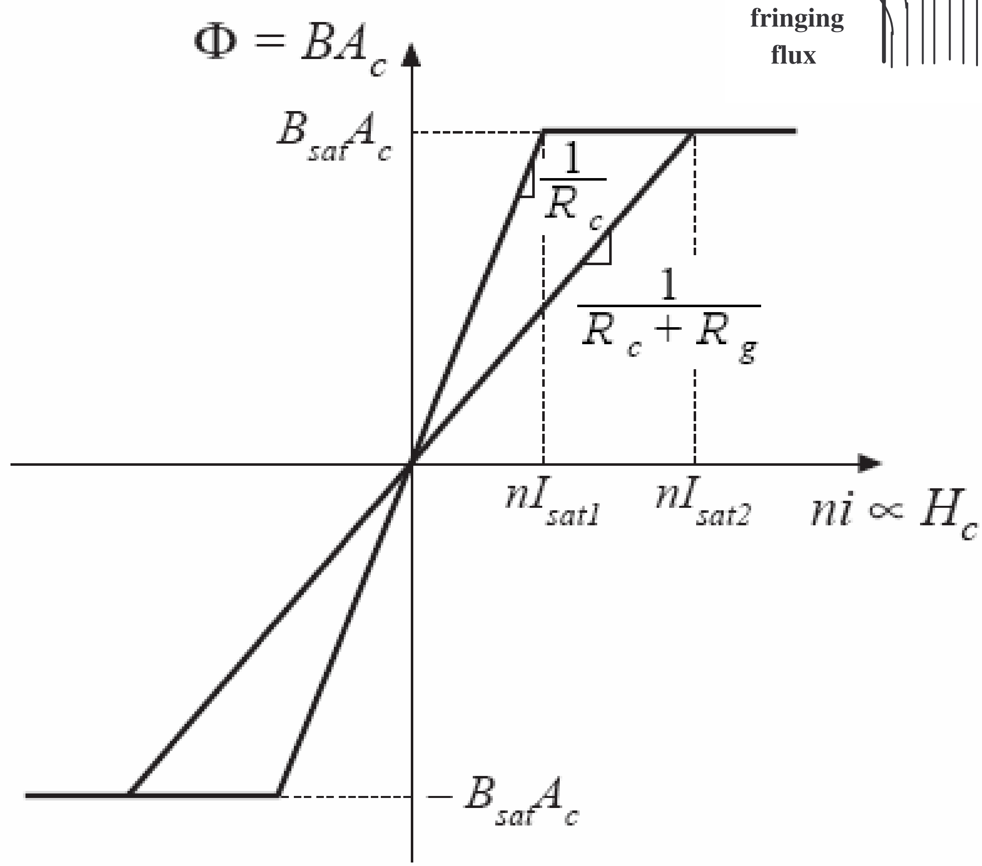


$$n\,i = \Phi\left(R_c + R_g\right)$$

$$L = \frac{n^2}{R_c + R_g}$$

$$\Phi_{sat} = B_{sat}A_c$$

$$I_{sat} = \frac{B_{sat}A_c}{n}\left(R_c + R_g\right)$$

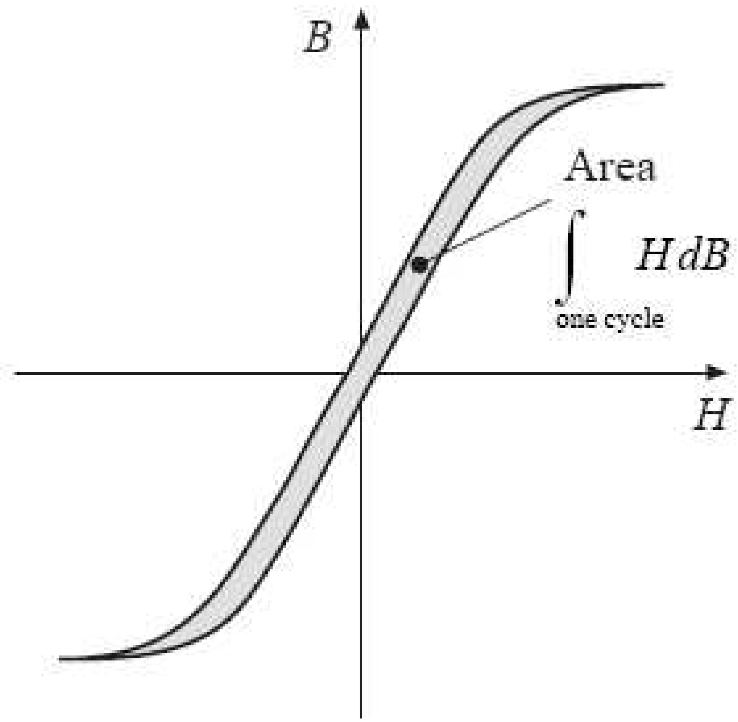


Effect of air gap:

- decrease inductance
- increase saturation current
- inductance is less dependent on core permeability

Perdas:

$$W = \left(A_c l_m\right) \int_{\text{one cycle}} H\,dB$$



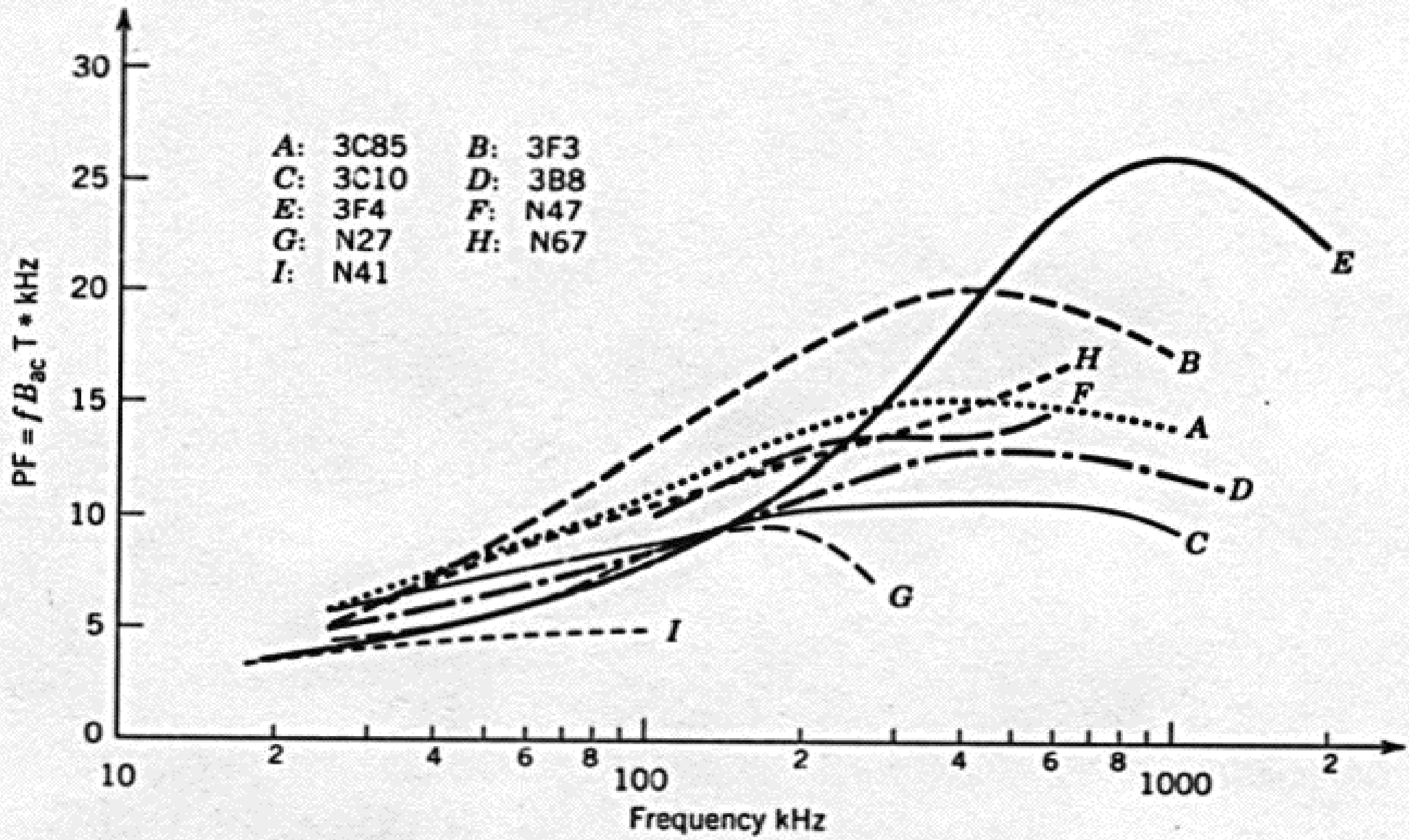
The term $A_c l_m$ is the volume of the core, while the integral is the area of the B-H loop.

(energy lost per cycle) = (core volume) (area of B-H loop)

$$P_H = \left(f\right)\left(A_c l_m\right) \int_{\text{one cycle}} H\,dB$$

Hysteresis loss is directly proportional to applied frequency

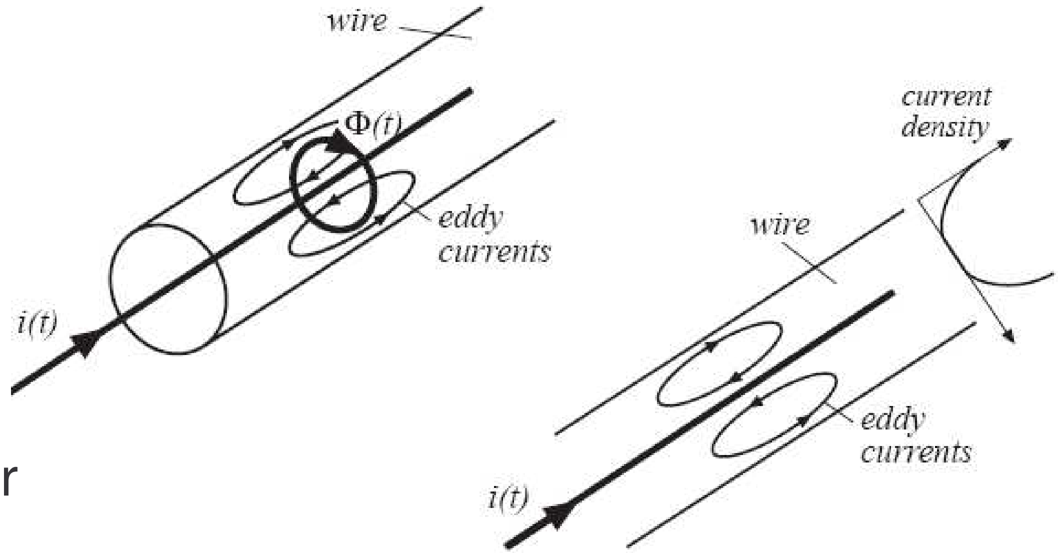
Perdas no ferro para diferentes materiais (ferrites)



Perdas no fio

$$R_{DC} = \rho \frac{l}{S}$$

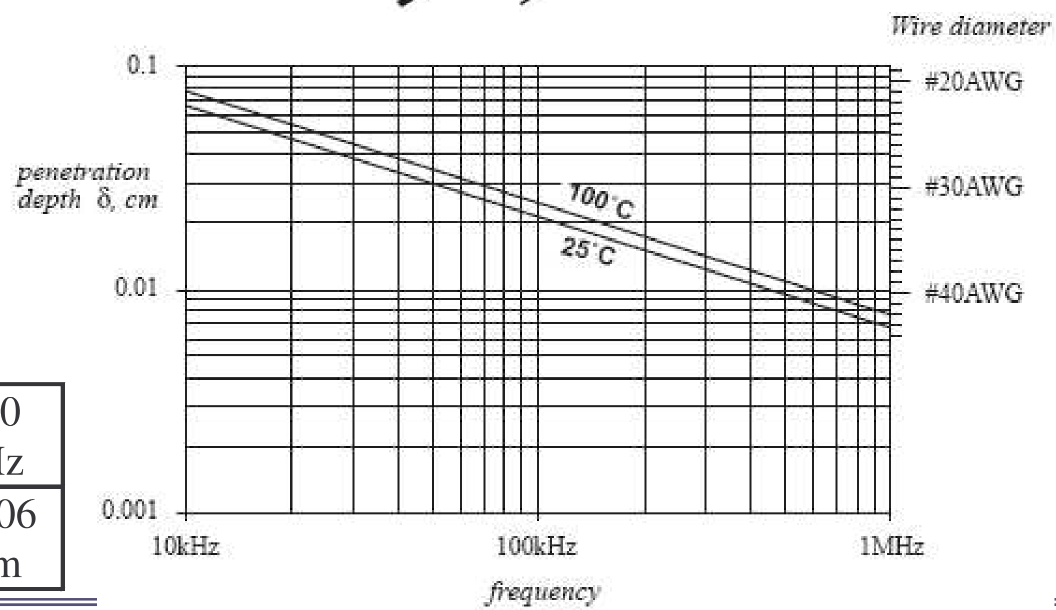
$$P_{CU} = I_{RMS}^2 R_{DC}$$



$$\delta = \sqrt{\frac{\rho}{\pi \mu F}}$$ Efeito pelicular

$$\delta = \frac{7.5}{\sqrt{F}} cm$$ cobre

$$R_{AC} = \frac{d}{\delta} R_{DC}$$



Frequency	50 Hz	5 kHz	20 kHz	500 kHz
Skin Depth	10.6 mm	1.06 mm	0.53 mm	0.106 mm

Projecto de bobinas

A eficiência dos conversores electrónicos de potência depende do dimensionamento adequado das bobinas. Os requisitos impostos às bobinas podem ser expressos em função de 3 parâmetros:

- A corrente contínua à qual a bobina deve servir de suporte (**IL**).
- O tremor da corrente como percentagem de **IL** (**Δie**).
- O rendimento da bobina em função das perdas no cobre (**Pcu**).

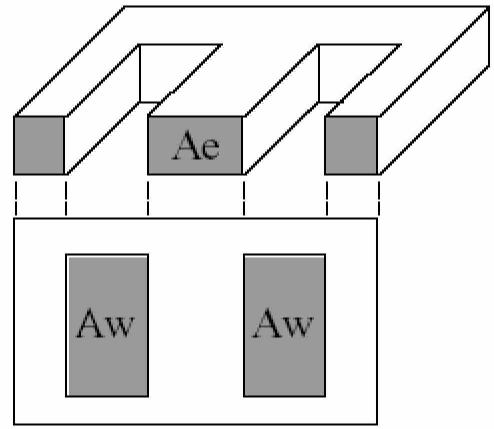
<u>Objectivos do projecto:</u>

- Menor núcleo que satisfaz as exigências.
- Número de espiras (**N**).
- A secção do fio de cobre a utilizar (**Acu**).
- O comprimento do entreferro (**lg**).

Critério: Via produto das áreas **Ap** = **Ae** . **Aw**

Ae = área do núcleo
Aw = área do cobre

A densidade de corrente é adoptada como parâmetro de projecto.



Jtípico 2-3 A/mm²
Jmax 10 A/mm².
Bmáx Densidade máxima do fluxo
Ku Factor de ocupação da janela de cobre. Típico 0.3 a 0.5.

O numero de espiras vem dado por

$$N = \frac{L \cdot IL_{max}}{B_{max} \cdot Ae} \qquad (1)$$

e a área de cobre por

$$Ku \cdot Aw = \frac{N \cdot IL}{J} \qquad (2)$$

O produto das áreas AP permite dimensionar o núcleo para uma dada aplicação.

$$Ap = Ae \cdot Aw = \frac{L \cdot IL^2}{B \cdot J \cdot Ku} \qquad (3)$$

tendo em conta que a densidade de corrente obtém-se por

$$J = \frac{IL}{Acu} \qquad (4)$$

2. Passos de projecto para bobinas

O projecto de uma bobina passa pelos seguintes passos:

1 - Escolha do núcleo:
Ap' ≥ Ap = Ae . Aw

2 - Determinação do nº espiras:

$$N' \geq N = \frac{L \cdot IL_{max}}{B_{max} \cdot Ae} \qquad (5)$$

3 - Determinação de Acu: $Acu = \frac{IL}{J}$ (6)

seguidamente verifica-se se o fio cabe todo na janela Aw

Ku.Aw ≥ N'.Acu' => Acu' ≥ Acu

o diâmetro do fio D vem calculado por: $D = \sqrt{\frac{4.Acu}{\pi}}$

4 - Determinação do comprimento do fio do enrolamento:

$$Lt = t.N' \qquad (7)$$

t - Comprimento de uma espira média

5 - Determinação de Pcu:

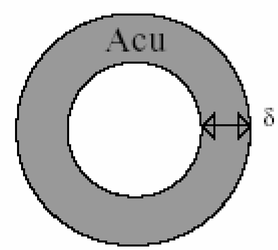
$$Pcu = \mathrm{Re} \cdot IL^2 = \rho \frac{N' \cdot t \cdot IL^2}{Acu} = \rho \frac{N'^2 \cdot t \cdot IL^2}{Ku \cdot Aw} \qquad (8)$$

com ρ = 1.724μΩ/cm

Ter em conta o efeito pelicular $\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$ (9)

$$Acu = \frac{\pi . D^2}{4} - \frac{\pi .(D - 2.\delta)^2}{4}$$

μ = μo e σ = 1/ρ



6 - Determinação do entreferro:

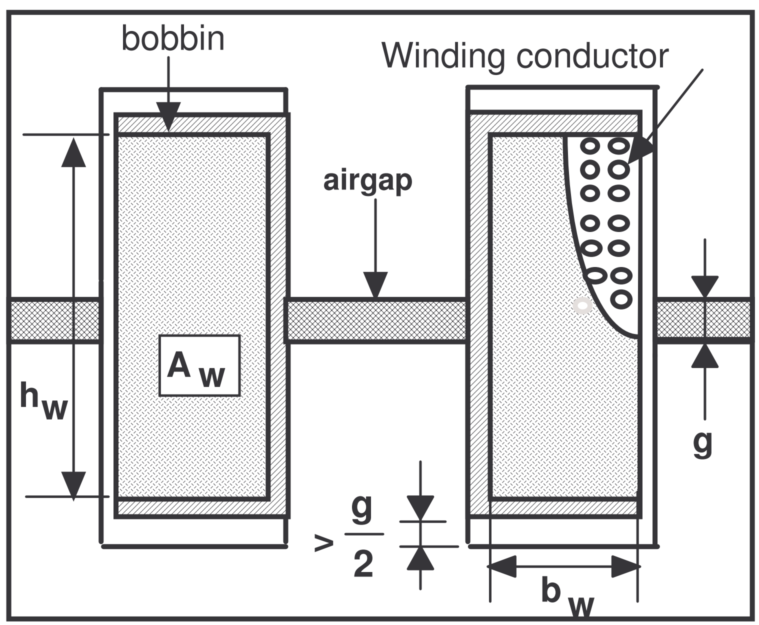
$$lg \approx \frac{N'^2 \mu o \cdot Ag}{L} \approx \frac{N'^2 \mu o \cdot Ae}{L} \qquad (10)$$

$$\mu o = 4\pi \cdot 10^{-7}$$

7 - Determinação das perdas no ferro < 10 mW/cm^2.
Recorrer aos gráficos dados pelo fabricante.

Pm = Ve(Bmax)
Ve - Volume do material magnético

Correcção devido à dispersão no entreferro:



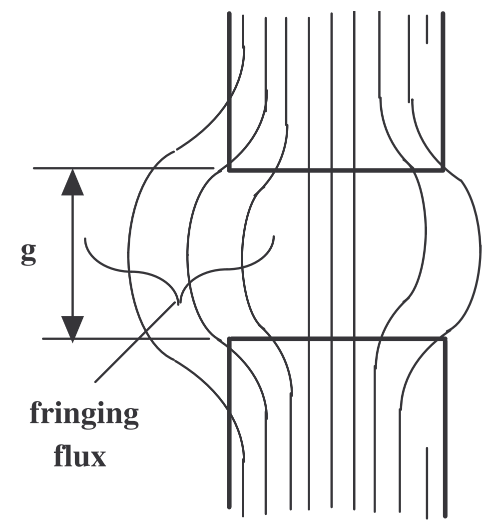


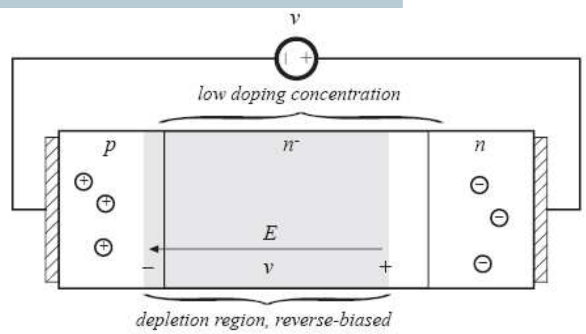
Tabela de fios:

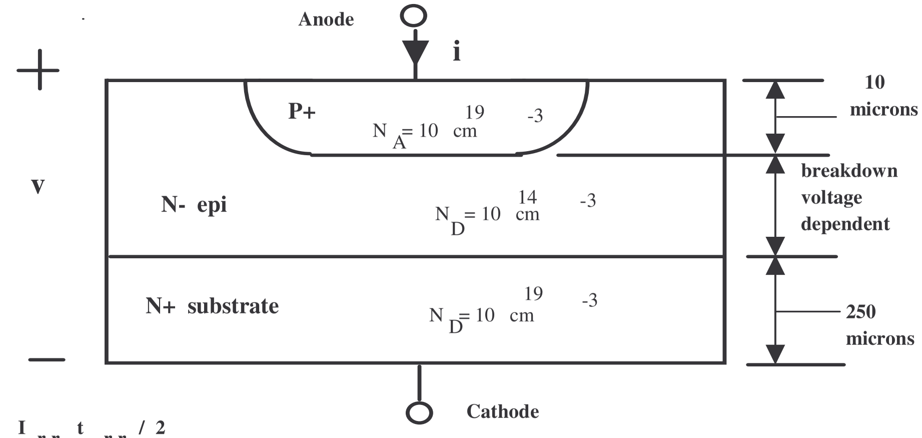
Table F–2 Wire Table — IEC R40

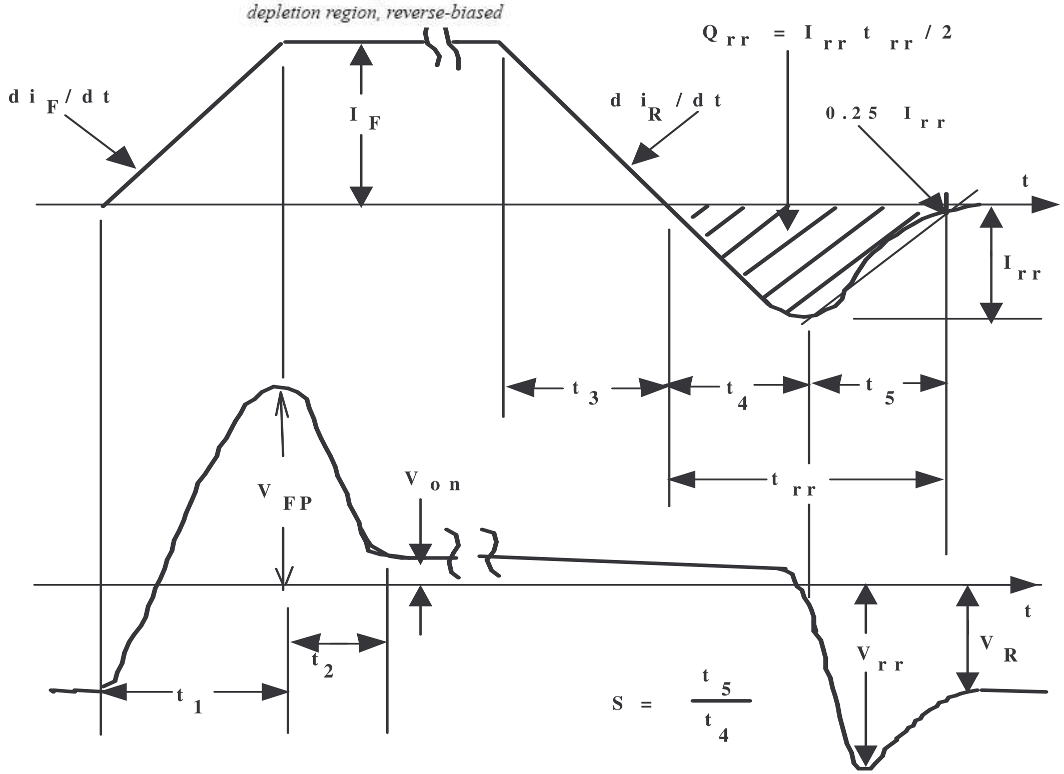
Copper Diameter	Maximum Overall Diameter — Insulated Wire			Current Capability*
	Grade 1	Grade 2	Grade 3	
(mm)	(mm)	(mm)	(mm)	(A)
2.650	2.730	2.772	2.811	11.66
2.360	2.438	2.478	2.516	9.25
2.120	2.196	2.235	2.272	7.46
1.900	1.974	2.012	2.048	6.00
1.700	1.772	1.809	1.844	4.80
1.500	1.570	1.606	1.640	3.74
1.320	1.388	1.422	1.455	2.89
1.180	1.246	1.279	1.311	2.31
1.060	1.124	1.157	1.188	1.87
0.950	1.012	1.044	1.074	1.50
0.850	0.909	0.939	0.968	1.20
0.750	0.805	0.834	0.861	0.93
0.670	0.722	0.749	0.774	0.702
0.600	0.649	0.674	0.698	0.598
0.530	0.576	0.600	0.623	0.467
0.475	0.519	0.541	0.562	0.375
0.425	0.466	0.488	0.508	0.300
0.375	0.414	0.434	0.453	0.234
0.335	0.372	0.391	0.408	0.186
0.300	0.334	0.352	0.369	0.149
0.265	0.297	0.314	0.330	0.117
0.236	0.267	0.283	0.298	0.092
0.212	0.240	0.254	0.268	0.075
0.190	0.216	0.228	0.240	0.060
0.170	0.194	0.205	0.217	0.048
0.150	0.171	0.182	0.193	0.037
0.132	0.152	0.162	0.171	0.029
0.118	0.136	0.145	0.154	0.023
0.106	0.123	0.132	0.140	0.019
0.095	0.111	0.119	0.126	0.015
0.085	0.100	0.107	0.114	0.012
0.075	0.089	0.095	0.102	0.009

*Based on a current density of 2.11 A/mm^2 (1000 circular mils/A).

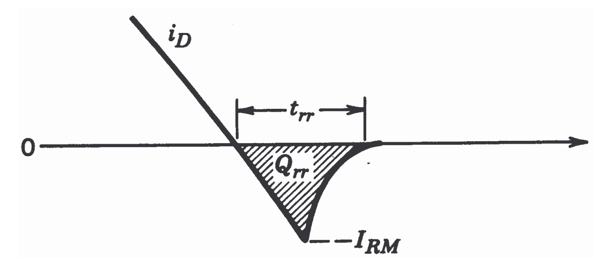
Diodos de potência







Trr – tempo de recuperação inversa



Diodo *Schottky*

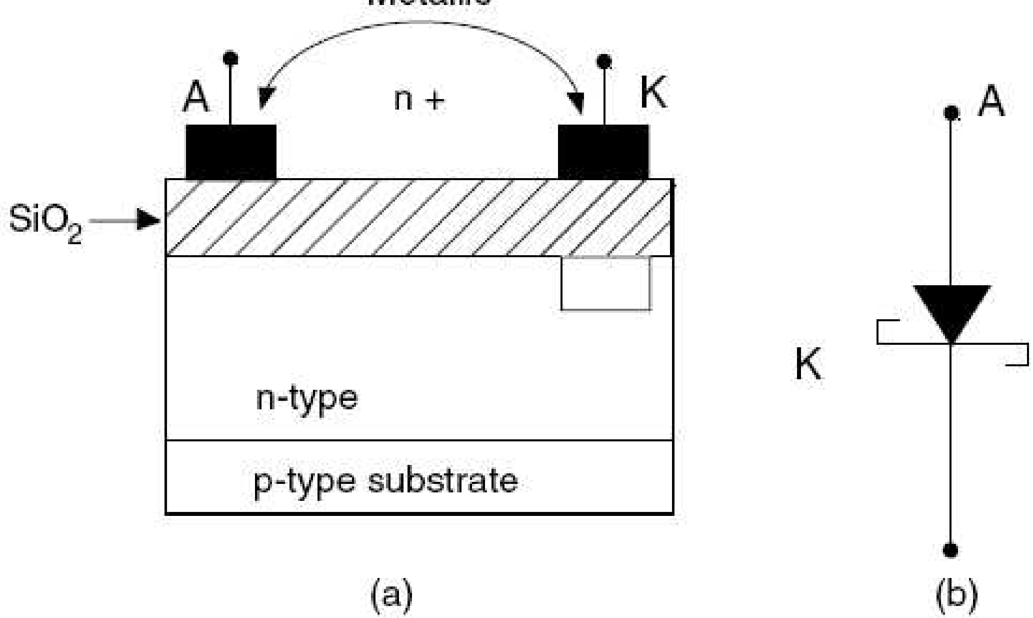
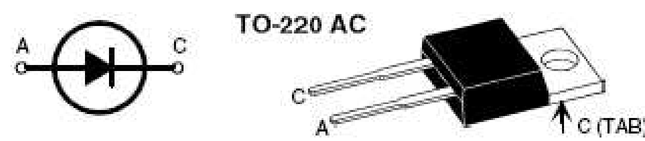


Diagram (a) and symbol (b) of the Schottky diode.

$I_{FAV} = 20\ A$
$V_{RRM} = 15\ V$
$V_F = 0.33\ V$



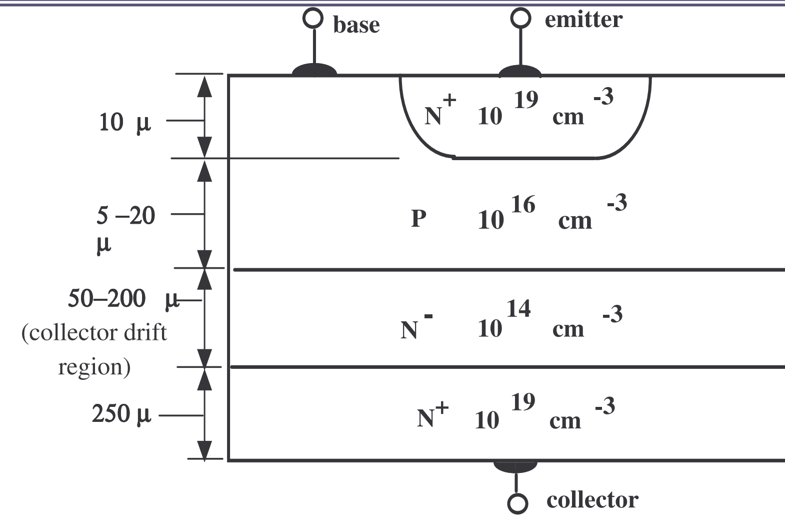
A = Anode, C = Cathode , TAB = Cathode

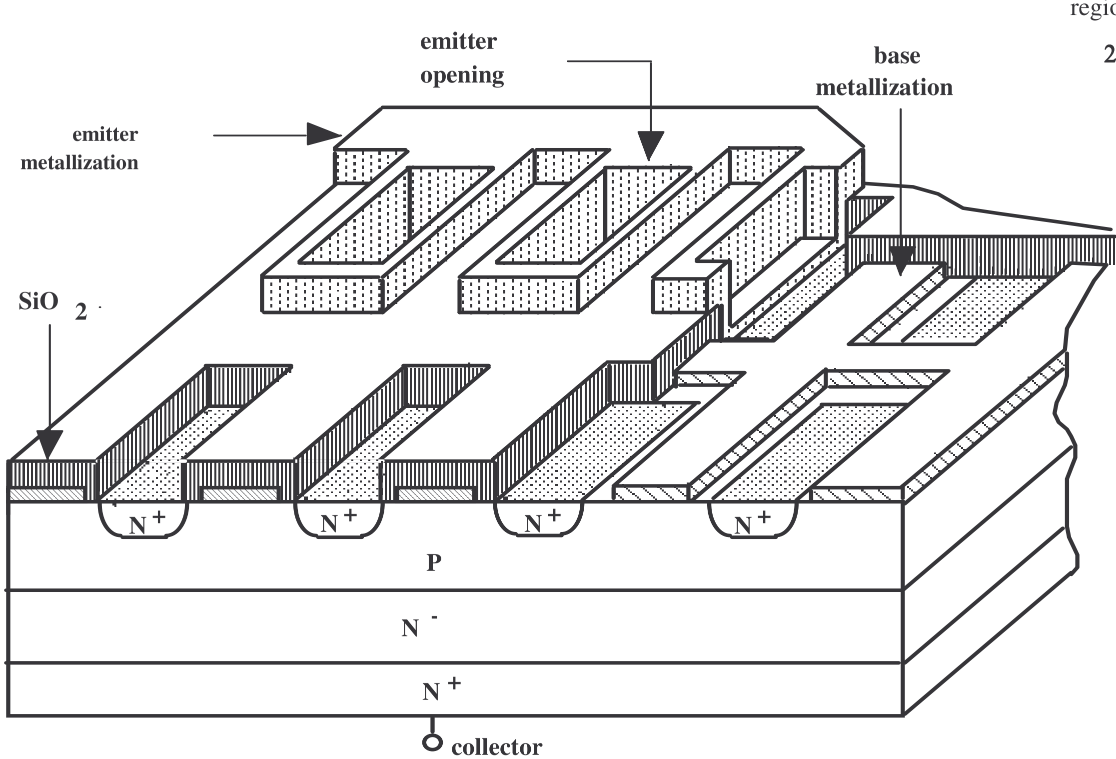
Tensão de disrupção = 100 – 200V

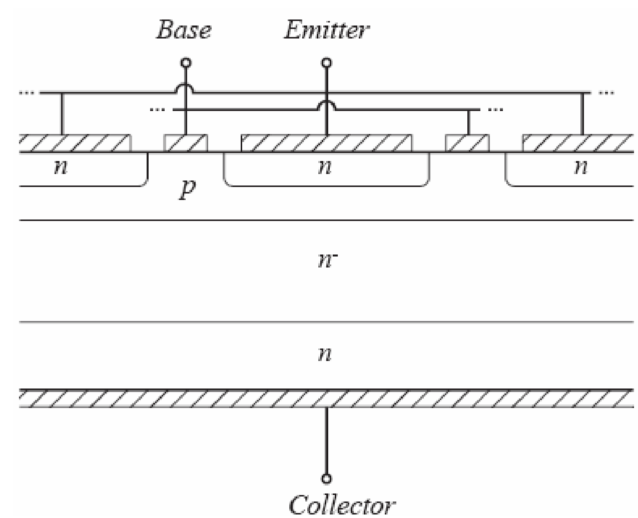
Part number	Rated max voltage	Rated avg current	V_F (typical)	t_r (max)
Fast recovery rectifiers				
1N3913	400V	30A	1.1V	400ns
SD453N25S20PC	2500V	400A	2.2V	2μs
Ultra-fast recovery rectifiers				
MUR815	150V	8A	0.975V	35ns
MUR1560	600V	15A	1.2V	60ns
RHRU100120	1200V	100A	2.6V	60ns
Schottky rectifiers				
MBR6030L	30V	60A	0.48V	
444CNQ045	45V	440A	0.69V	
30CPQ150	150V	30A	1.19V	

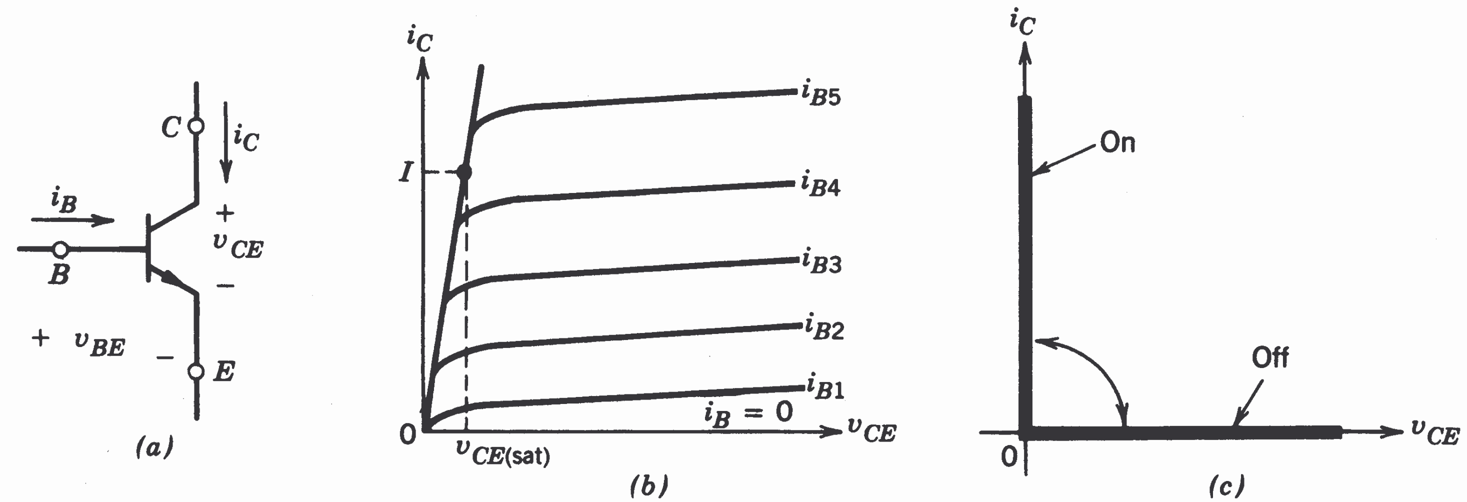
Transístor bipolar de potência

Basic Geometry of Power BJTs

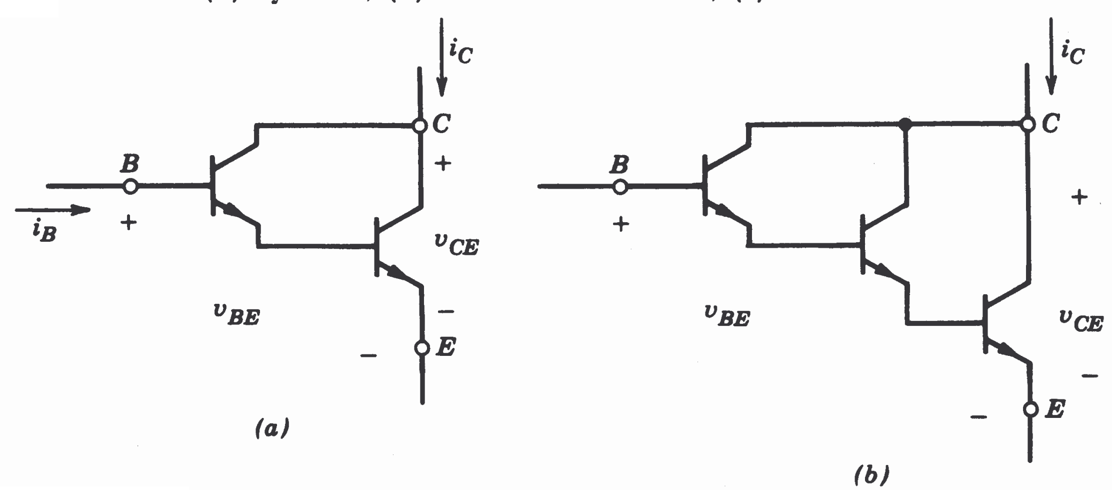




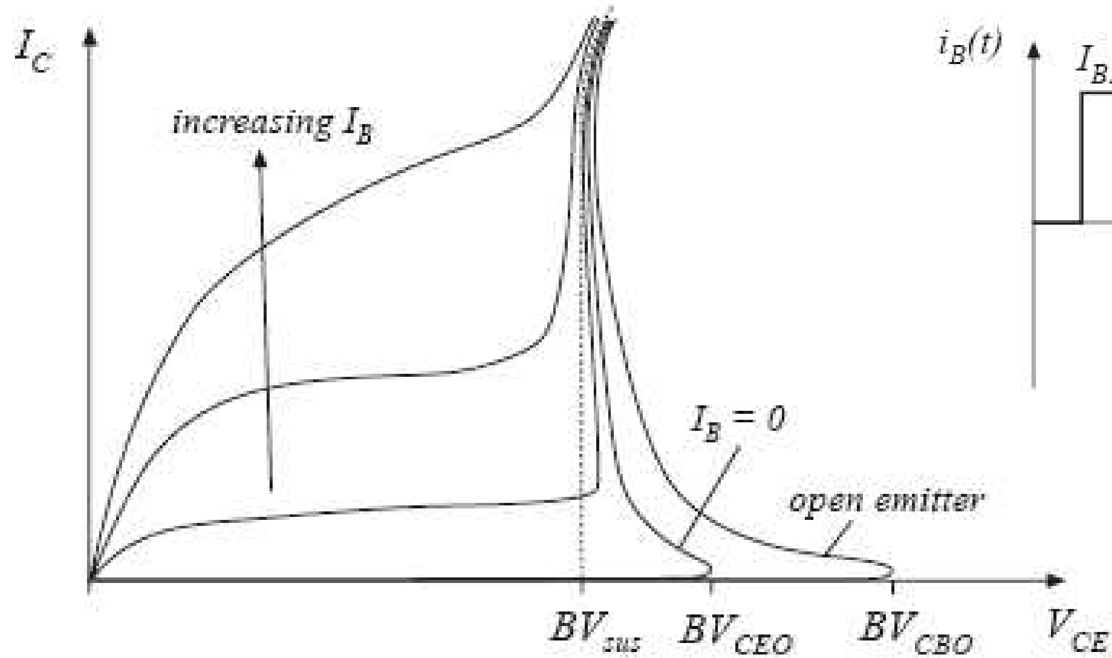




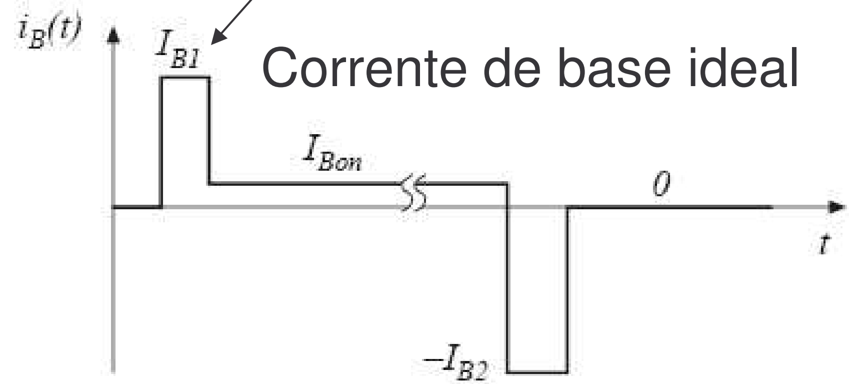
A BJT: (*a*) symbol, (*b*) *i*–*v* characteristics, (*c*) idealized characteristics.



Darlington configurations: (*a*) Darlington, (*b*) triple Darlington.



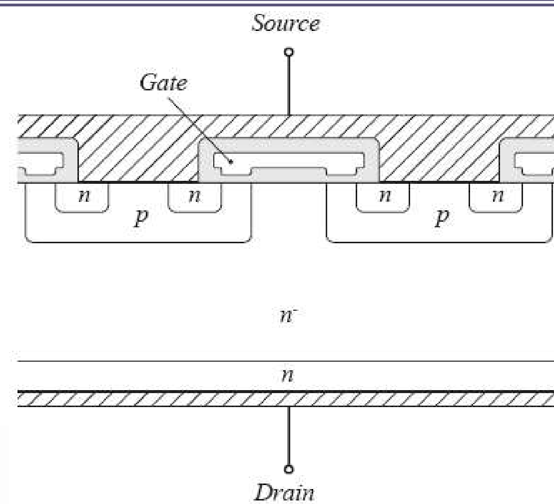
Impulso para ligar

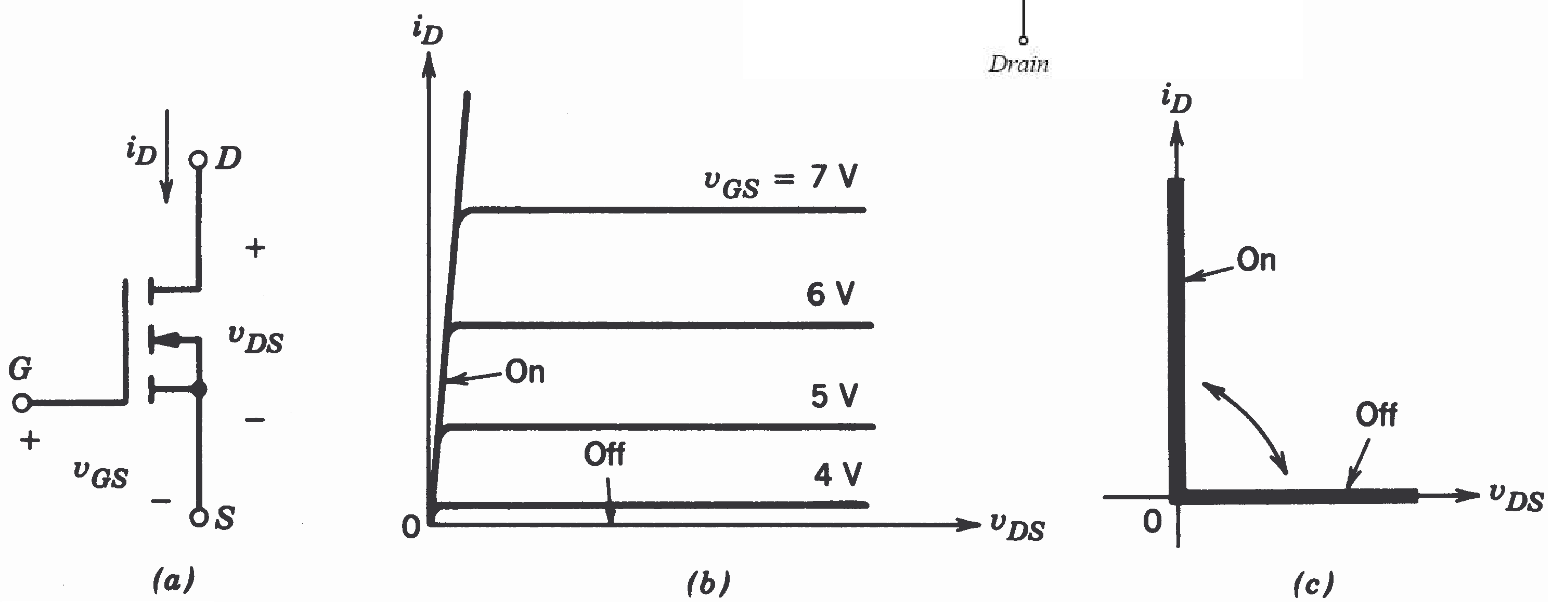


Corrente de base ideal

Impulso para desligar

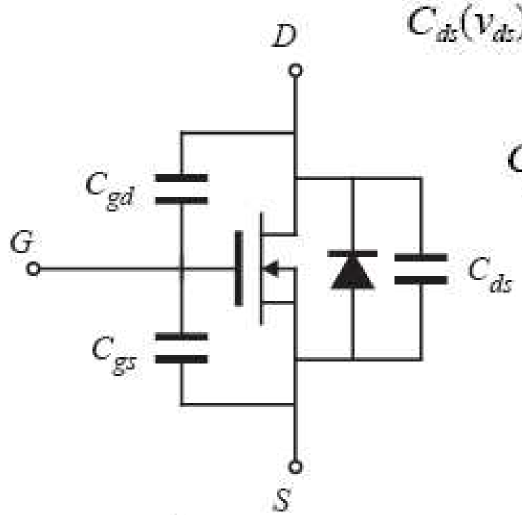
MOSFET de potência





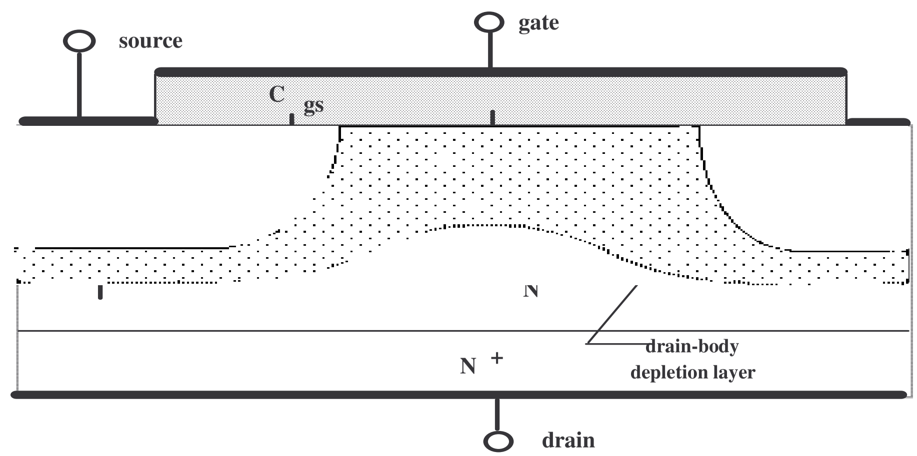
N-channel MOSFET: (*a*) symbol, (*b*) *i*–*v* characteristics, (*c*) idealized characteristics.

Conversores DC-DC ACCIONAMENTOS ELECTROMECÂNICOS

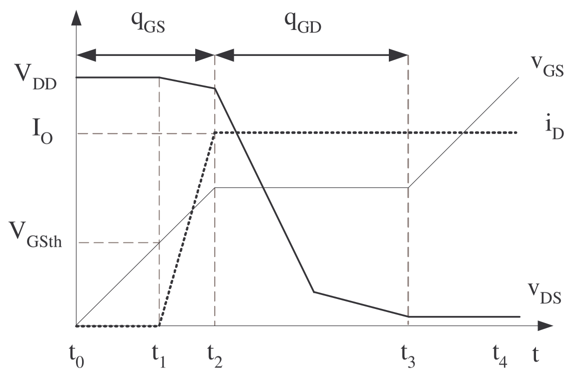


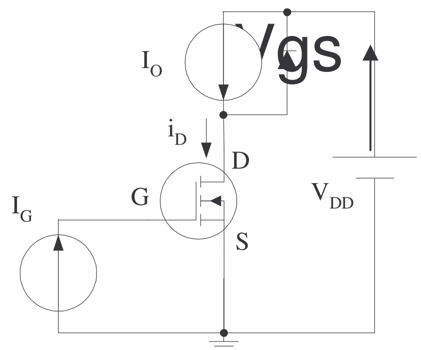
$$C_{ds}(v_{ds}) \approx C_0\sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0'}{\sqrt{v_{ds}}}$$

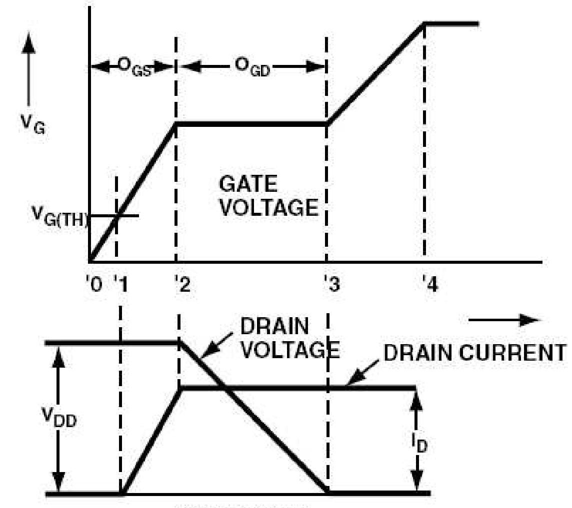
$$C_{ds}(v_{ds}) = \frac{C_0}{\sqrt{1+\frac{v_{ds}}{V_0}}}$$

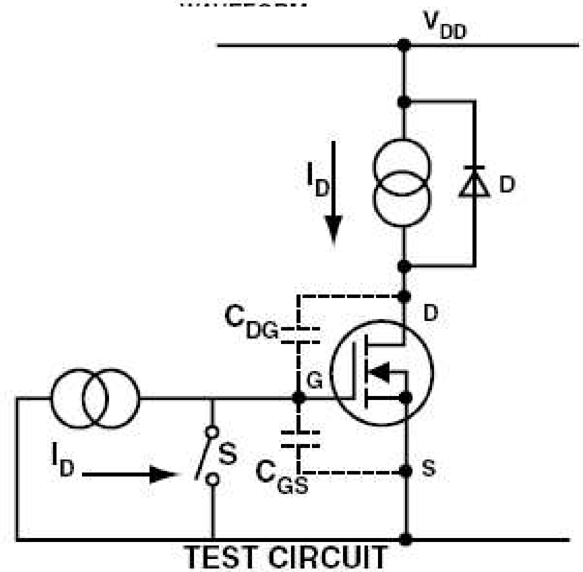


Part number	Rated max voltage	Rated avg current	R_{on}	Q_g (typical)
IRFZ48	60V	50A	0.018Ω	110nC
IRF510	100V	5.6A	0.54Ω	8.3nC
IRF540	100V	28A	0.077Ω	72nC
APT10M25BNR	100V	75A	0.025Ω	171nC
IRF740	400V	10A	0.55Ω	63nC
MTM15N40E	400V	15A	0.3Ω	110nC
APT5025BN	500V	23A	0.25Ω	83nC
APT1001RBNR	1000V	11A	1.0Ω	150nC



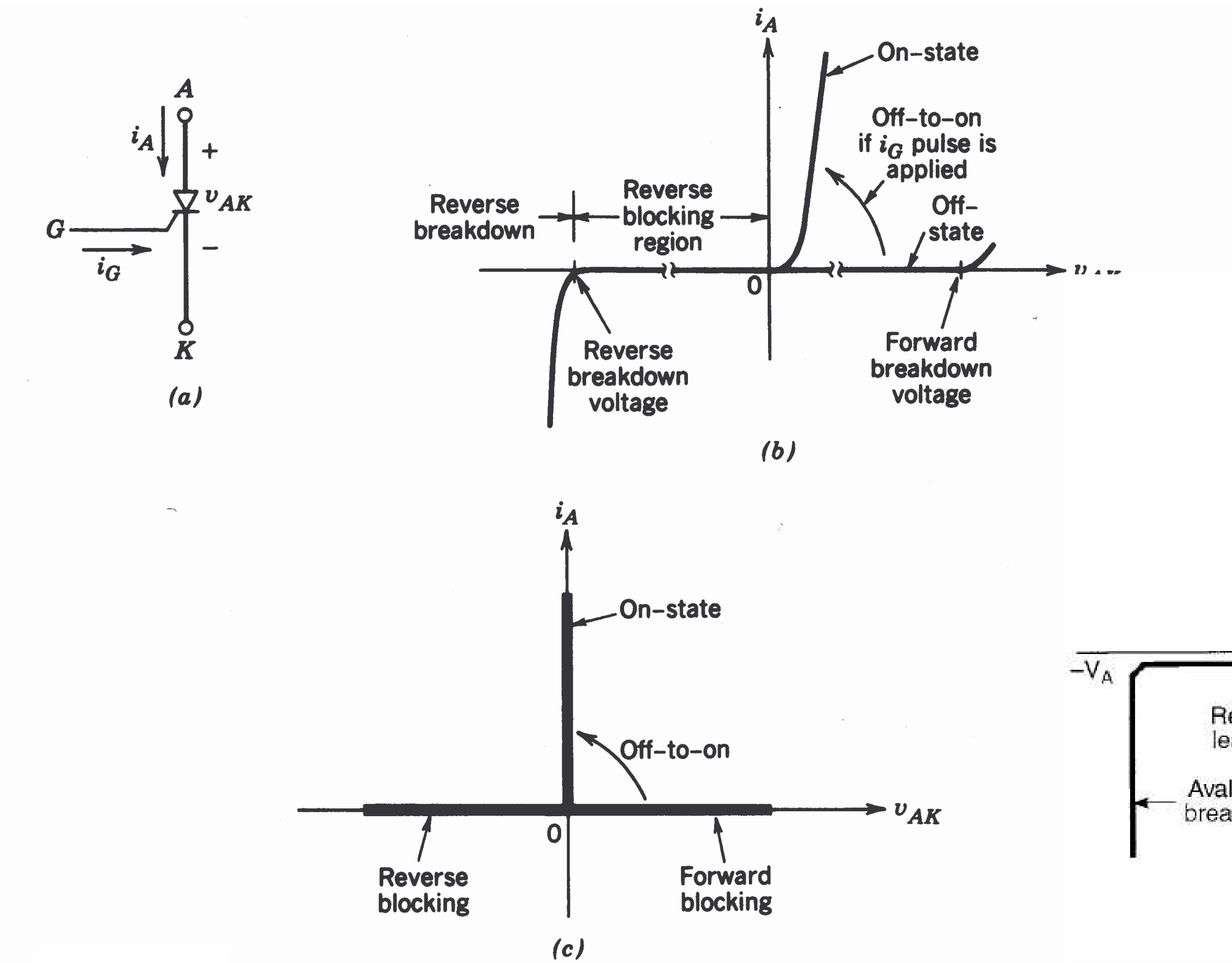




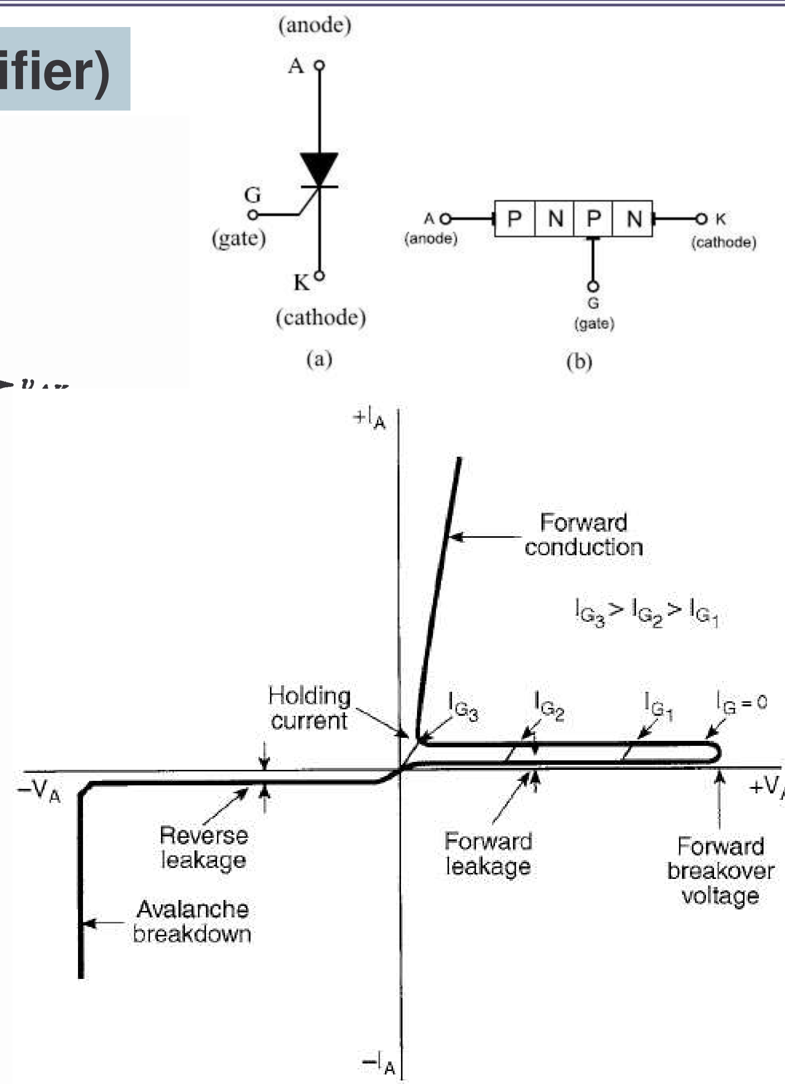


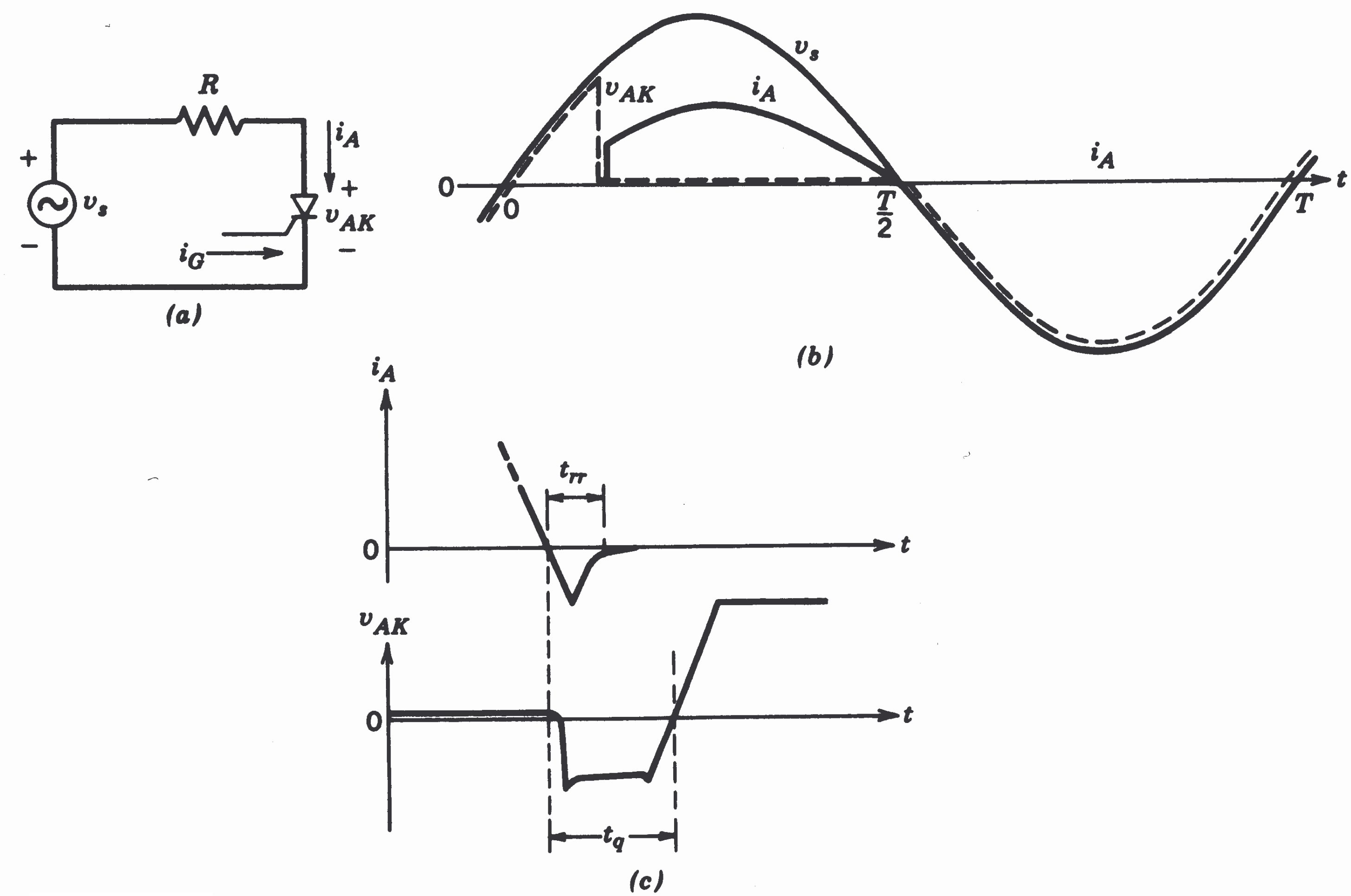
Intervalo temporal	Zona de Funcionamento	Acção em curso
$[t_0, t_1]$	Corte	Funcionamento como interruptor aberto ($V_{GS}<V_{GSth}$), C_{GS} está a carregar.
$[t_1, t_2]$	Saturação	A corrente de saída aumenta até I_O.
$[t_2, t_3]$	Saturação	C_{DG} descarrega, à medida que V_{DS} diminui.
$[t_3, t_4]$	Tríodo	Zona de tríodo do MOSFET, este funciona como interruptor fechado com resistência interna R_{DSon}.

Thyristor (SCR, Silicon Controlled Rectifier)



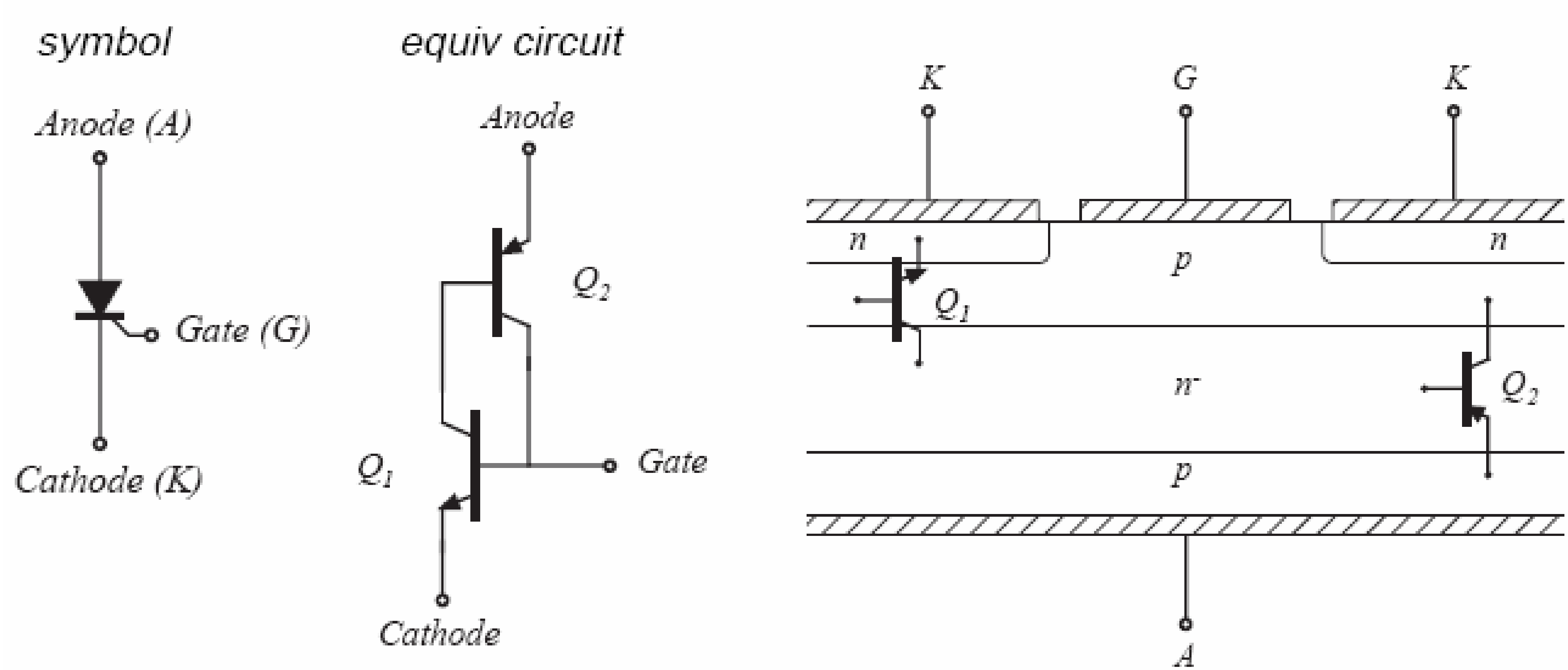
Thyristor: (a) symbol, (b) i–v characteristics, (c) idealized characteristics.



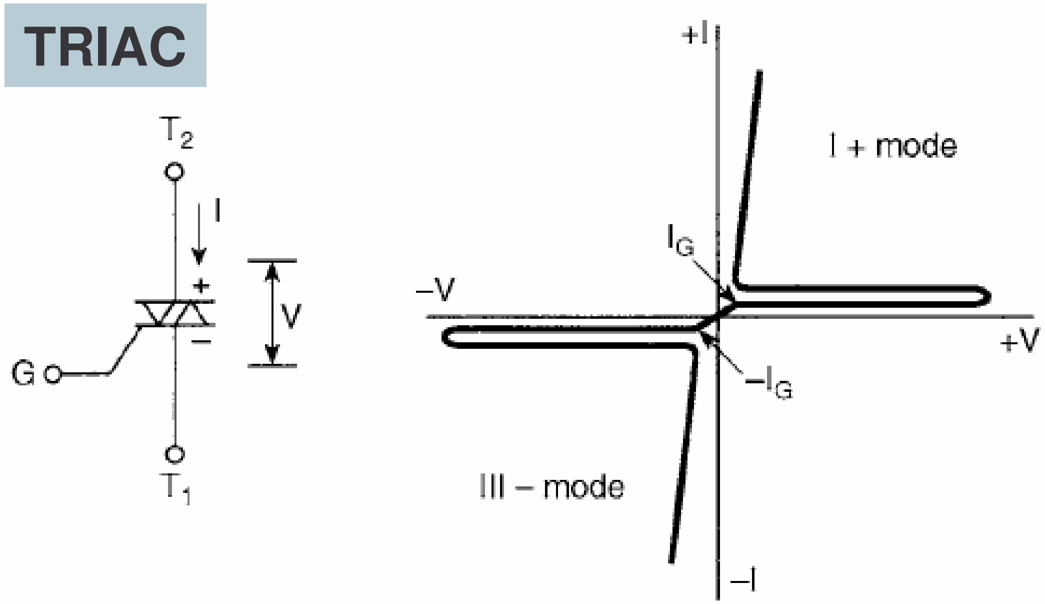


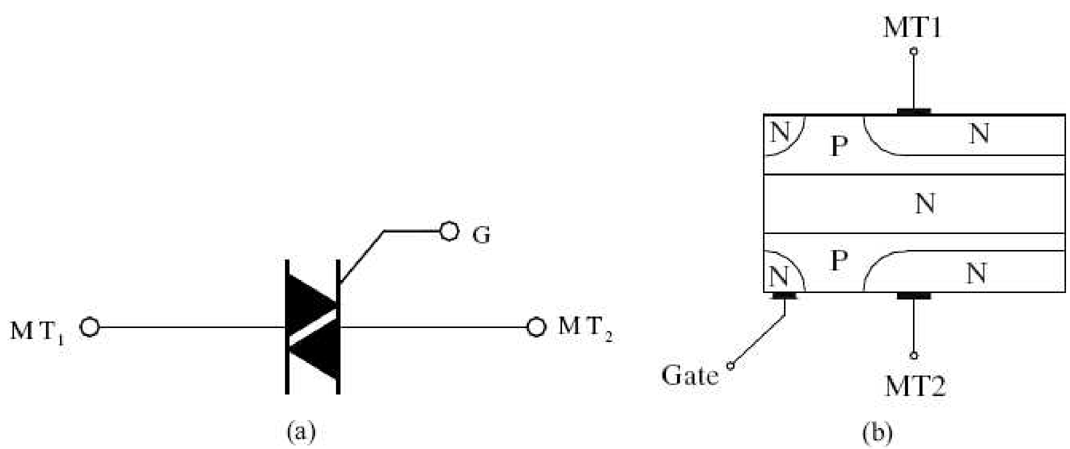
Thyristor: (*a*) circuit, (*b*) waveforms, (*c*) turn-off time interval t_q.

The SCR


symbol
Anode (A)
Gate (G)
Cathode (K)
equiv circuit
Anode
Q2
Q1
Gate
Cathode
construction
K
G
K
n
p
n
Q1
n-
Q2
p
A

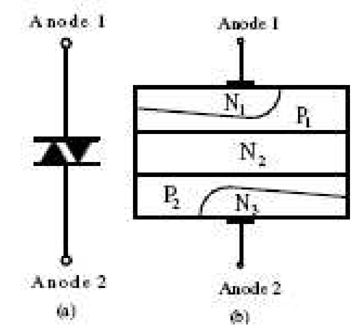
TRIAC

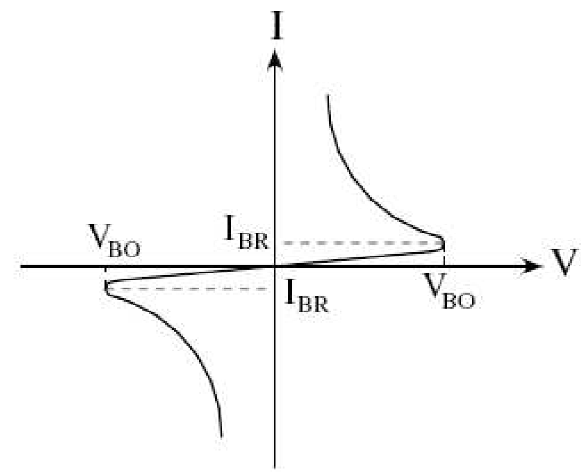




Funciona em 2 quadrantes

DIAC





V_{BO} = 20-30V

GTO- Gate Turn Off

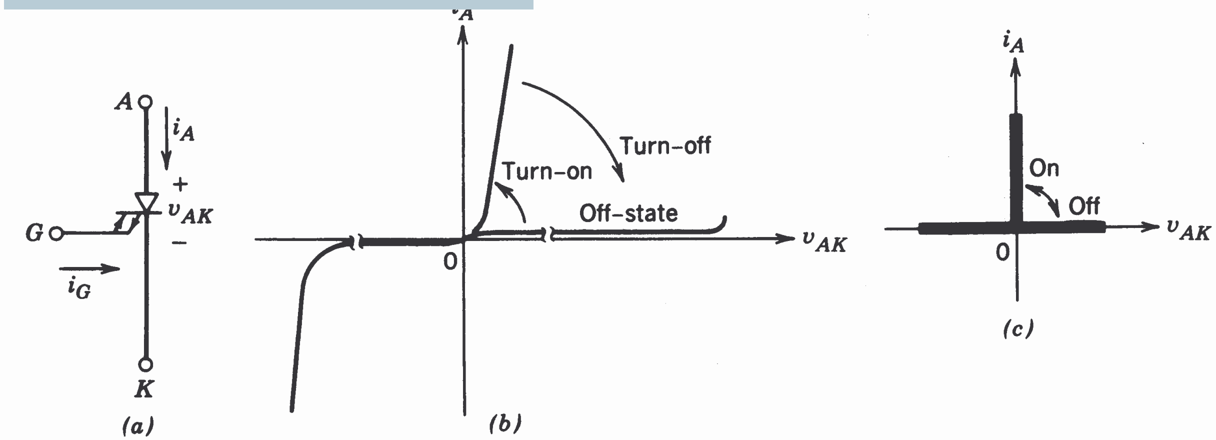
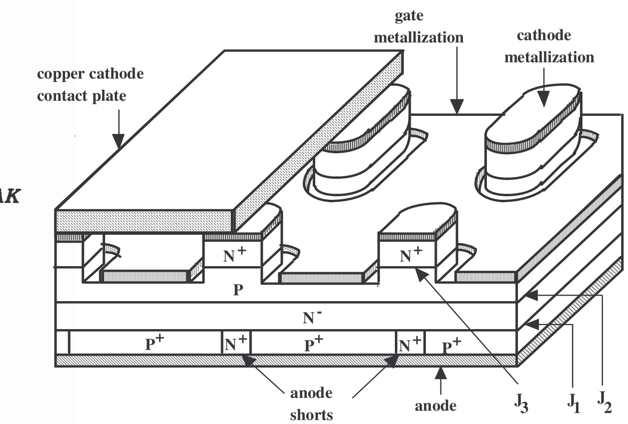
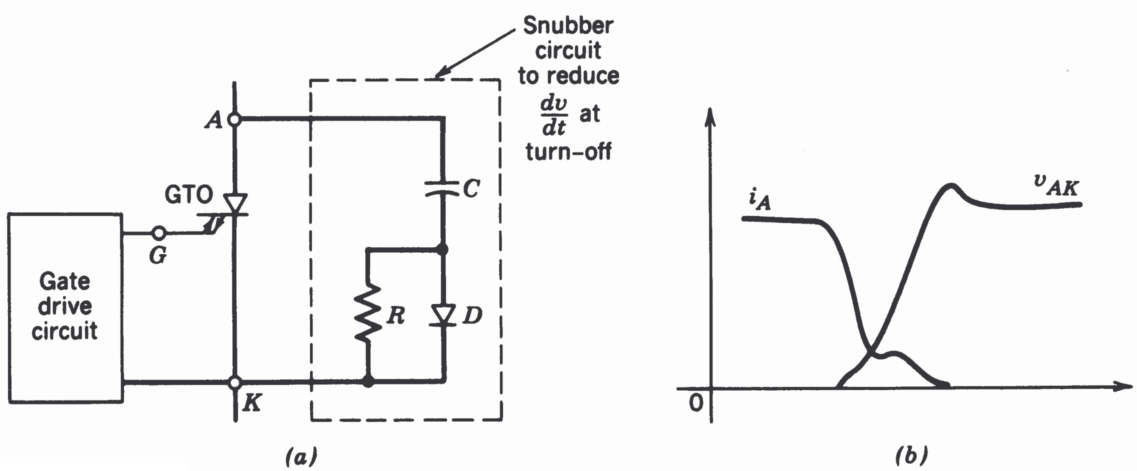
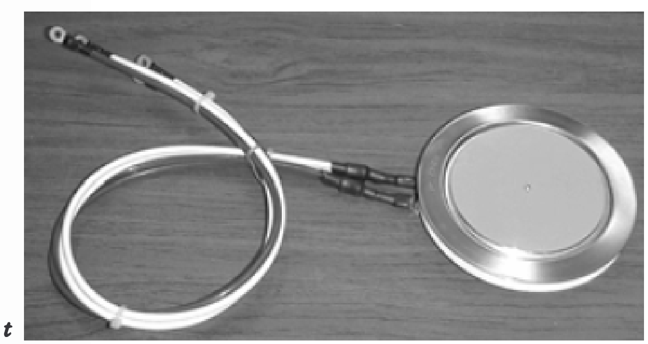


Figure 2-10 A GTO: (*a*) symbol, (*b*) *i–v* characteristics, (*c*) idealized characteristics.

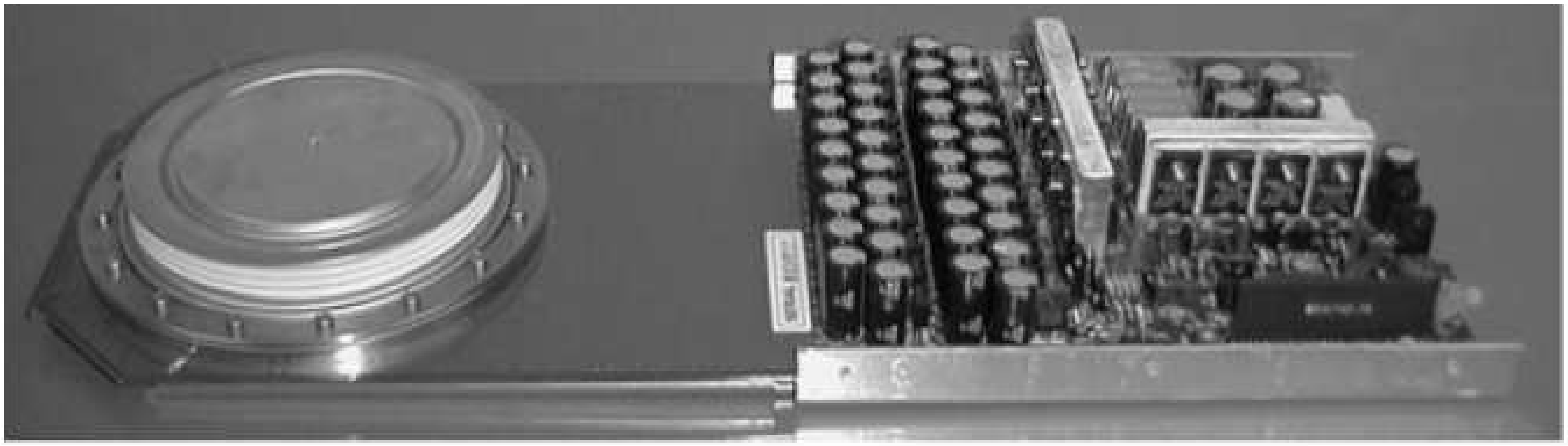




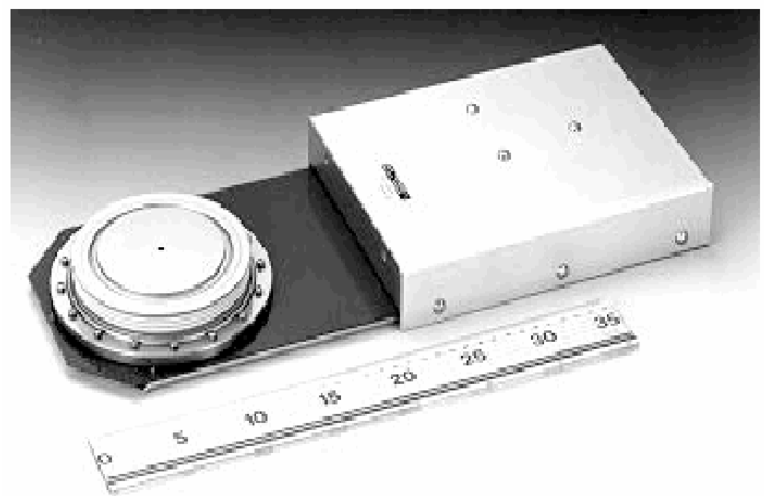
Gate turn-off transient characteristics: (*a*) snubber circuit, (*b*) GTO turn-off characteristic.



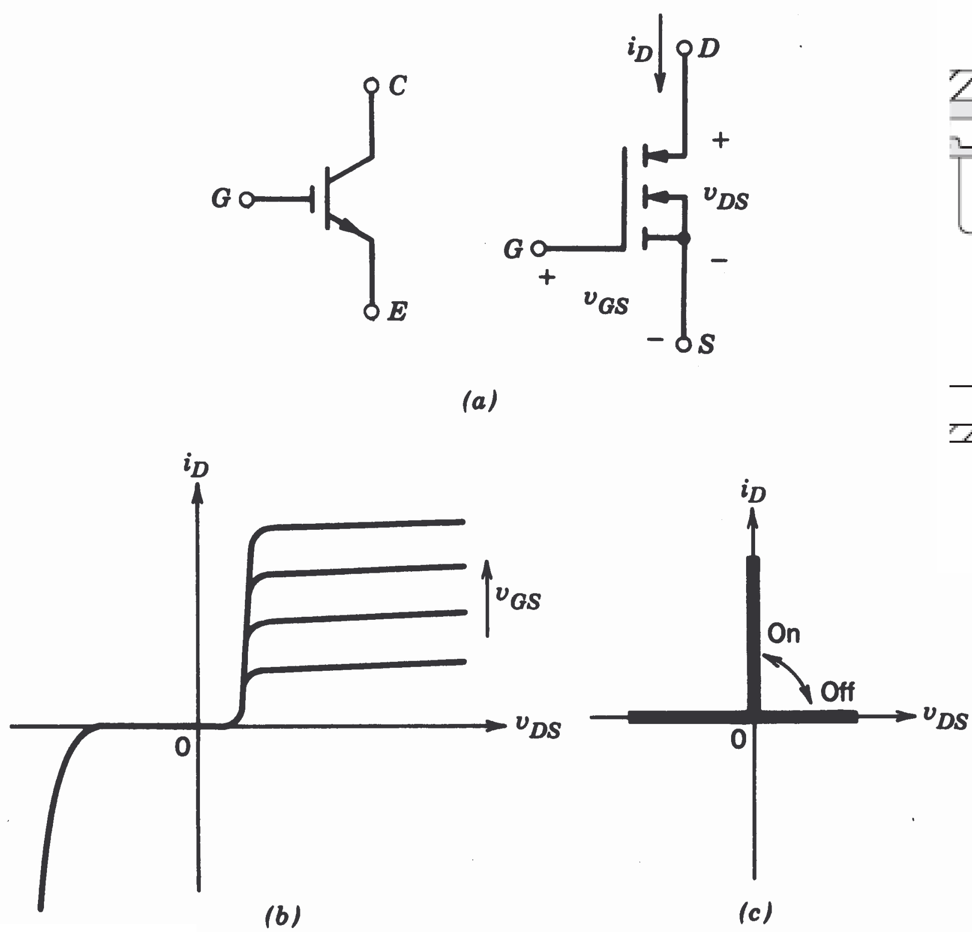
Conversores DC-DC ACCIONAMENTOS ELECTROMECÂNICOS



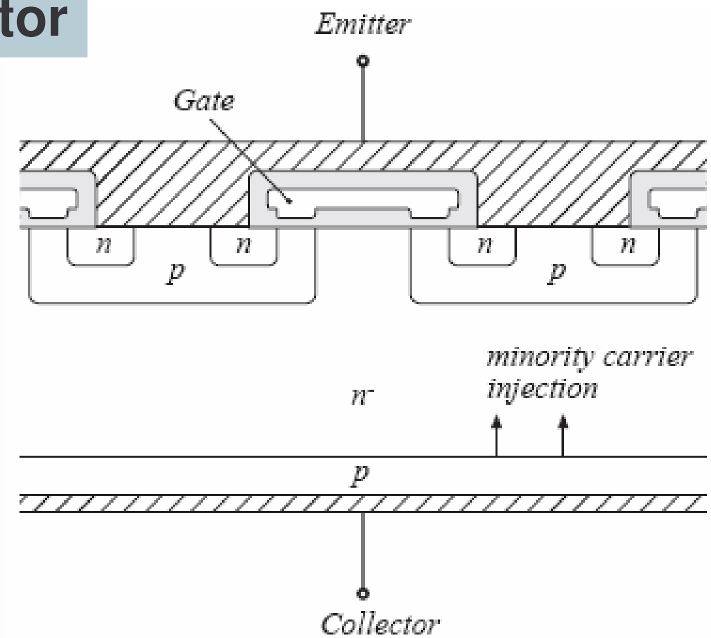
Mitsubishi 4kA / 4.5 kV GCT

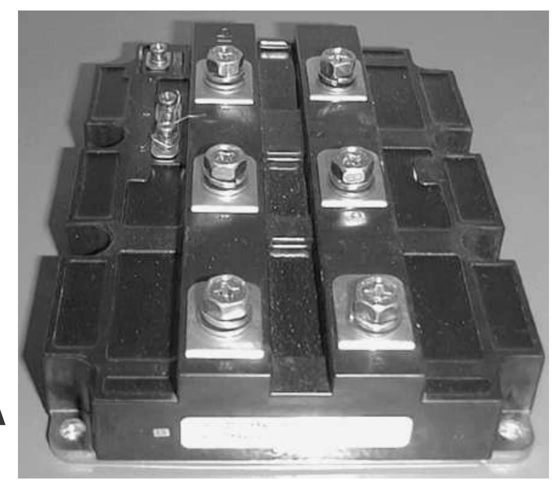


IGBT – Isolated Gate Bipolar Transistor

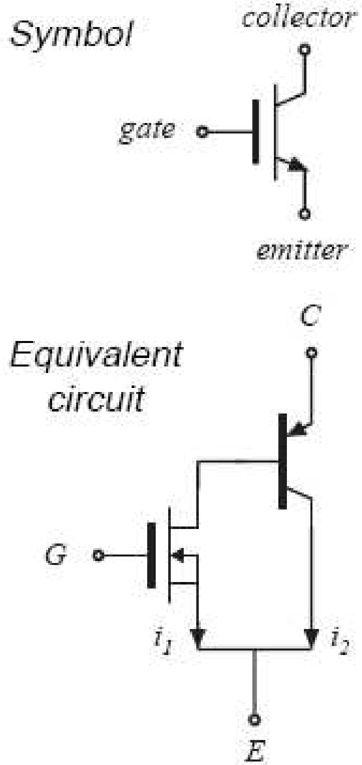


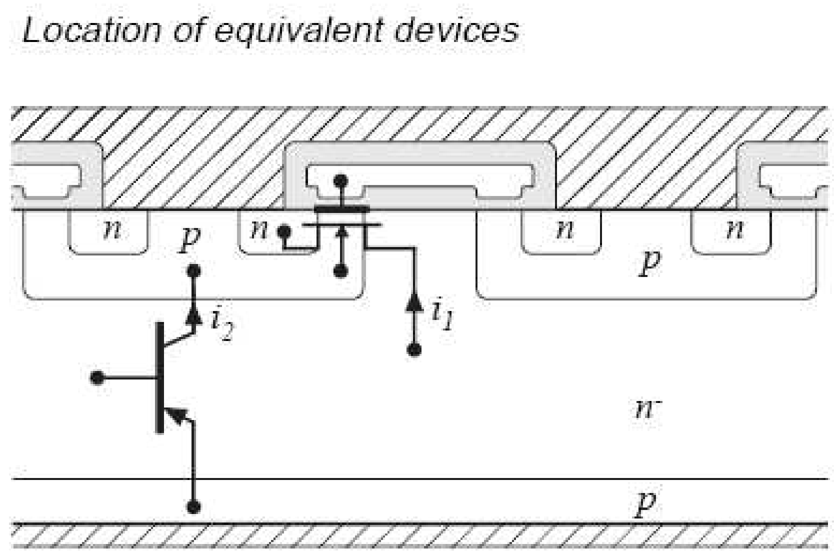
An IGBT: (*a*) symbol, (*b*) *i–v* characteristics, (*c*) idealized characteristics.





IGBT 1200A 3300V



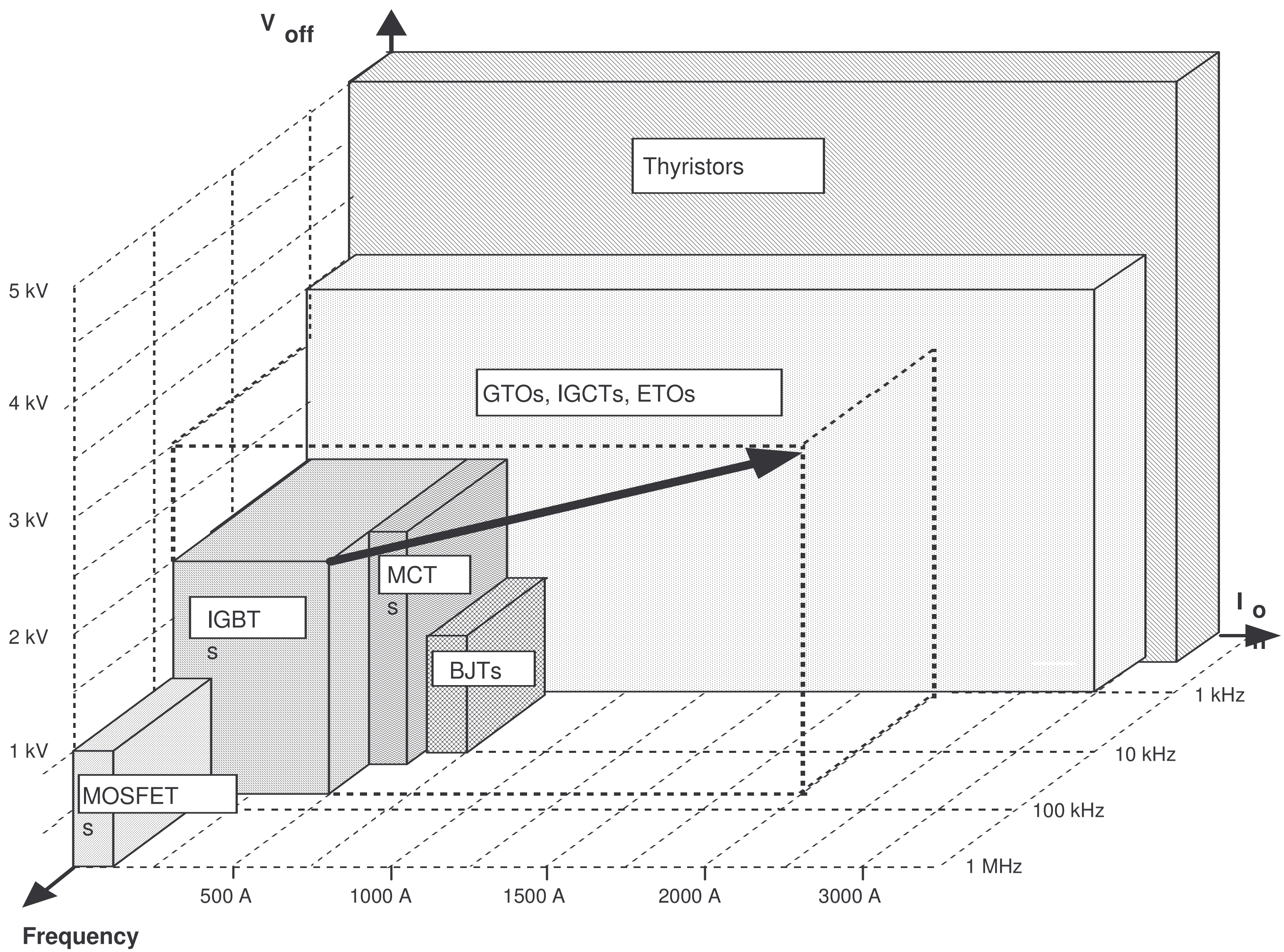


Part number	Rated max voltage	Rated avg current	V_F (typical)	t_f (typical)
Single-chip devices				
HGTG32N60E2	600V	32A	2.4V	0.62µs
HGTG30N120D2	1200V	30A	3.2A	0.58µs
Multiple-chip power modules				
CM400HA-12E	600V	400A	2.7V	0.3µs
CM300HA-24E	1200V	300A	2.7V	0.3µs

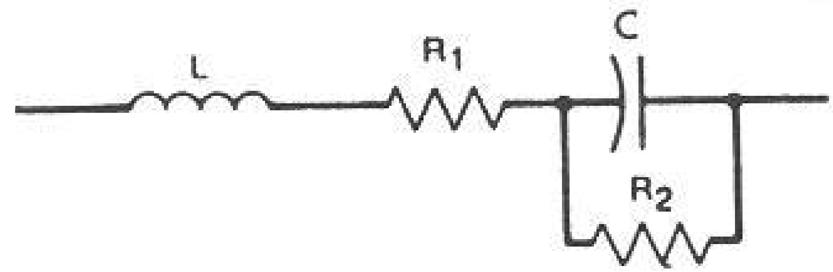
Relative Properties of Controllable Switches

Device	*Power Capability*	*Switching Speed*
BJT/MD	Medium	Medium
MOSFET	Low	Fast
GTO	High	Slow
IGBT	Medium	Medium
~~MCT~~	~~Medium~~	~~Medium~~

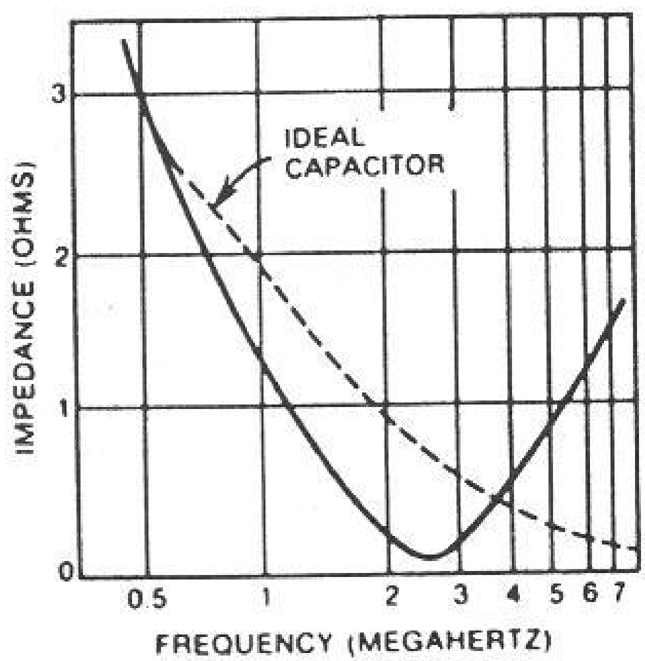
Conversores DC-DC ACCIONAMENTOS ELECTROMECÂNICOS



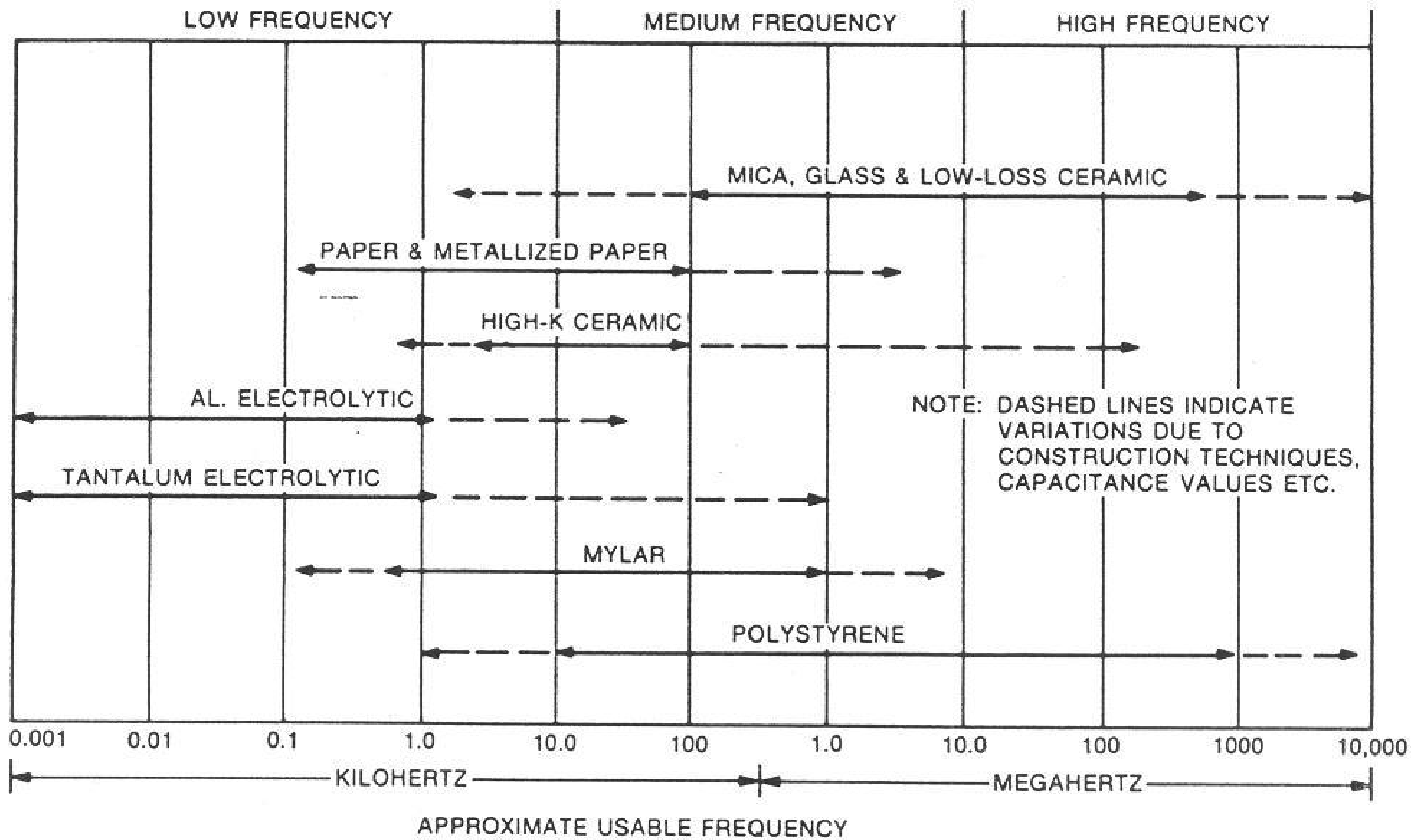
Condensadores



Equivalent circuit for a capacitor.

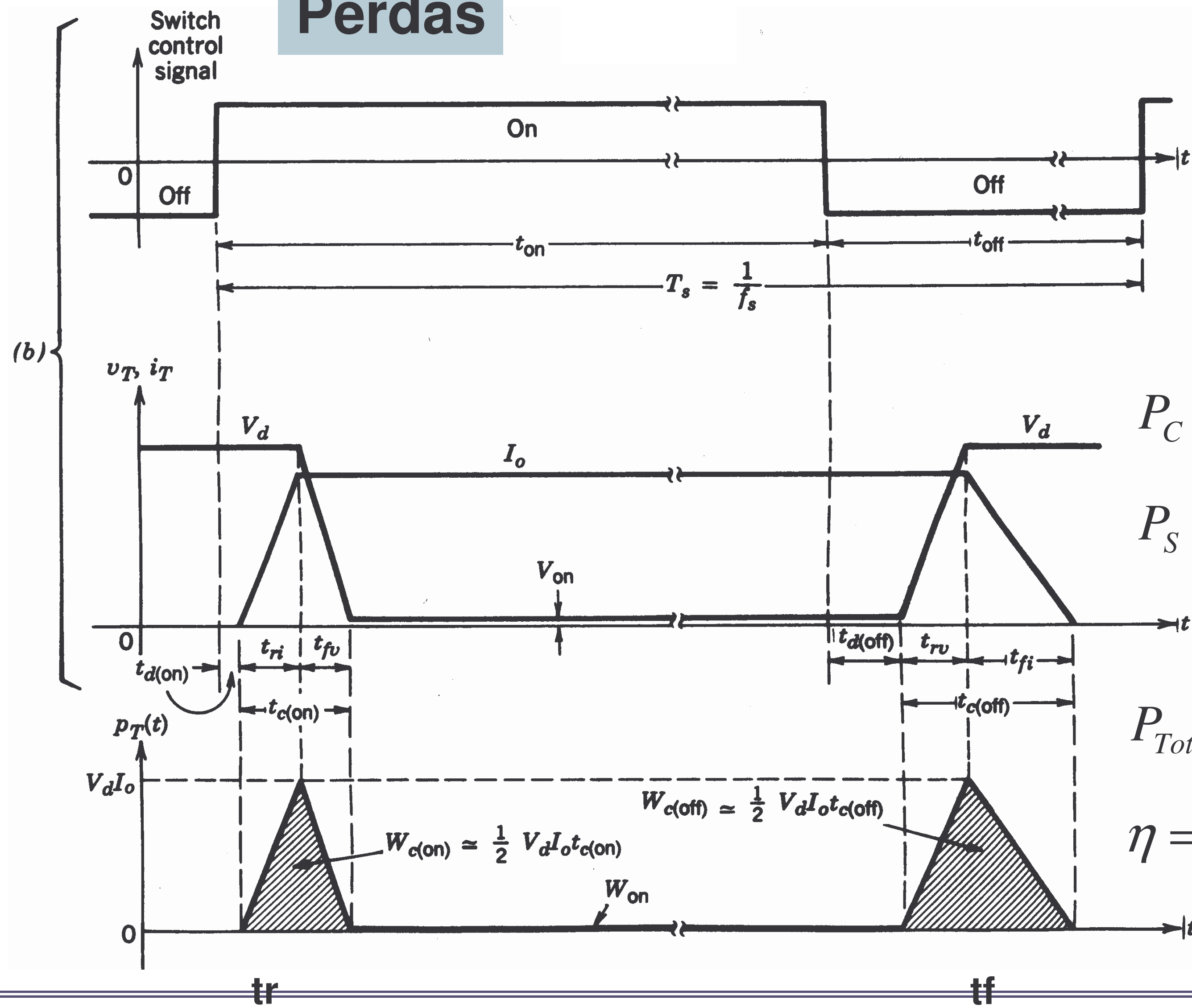


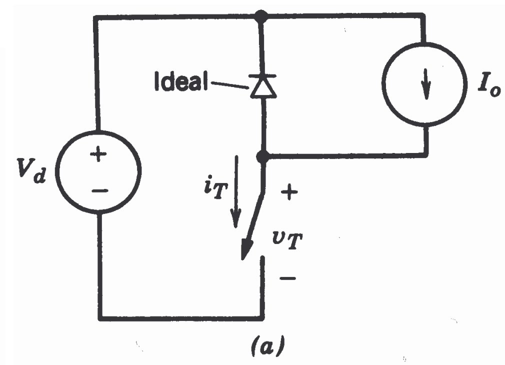
Effect of frequency on the impedance of a 0.1 μF paper capacitor.



Approximate usable frequency ranges for various types of capacitors.

Perdas





Perdas condução

$$P_C = V_{ON} I_O D = R_{on} I_o^2 D$$

$$P_S = \frac{F_S}{2} V_d I_O \left(t_r + t_f\right)$$

Perdas comutação

$$P_{Totais} = P_C + P_S$$

$$\eta = \frac{P_O}{P_I} = \frac{1}{1 + \frac{P_{Totais}}{P_O}} \times 100\%$$

Fim