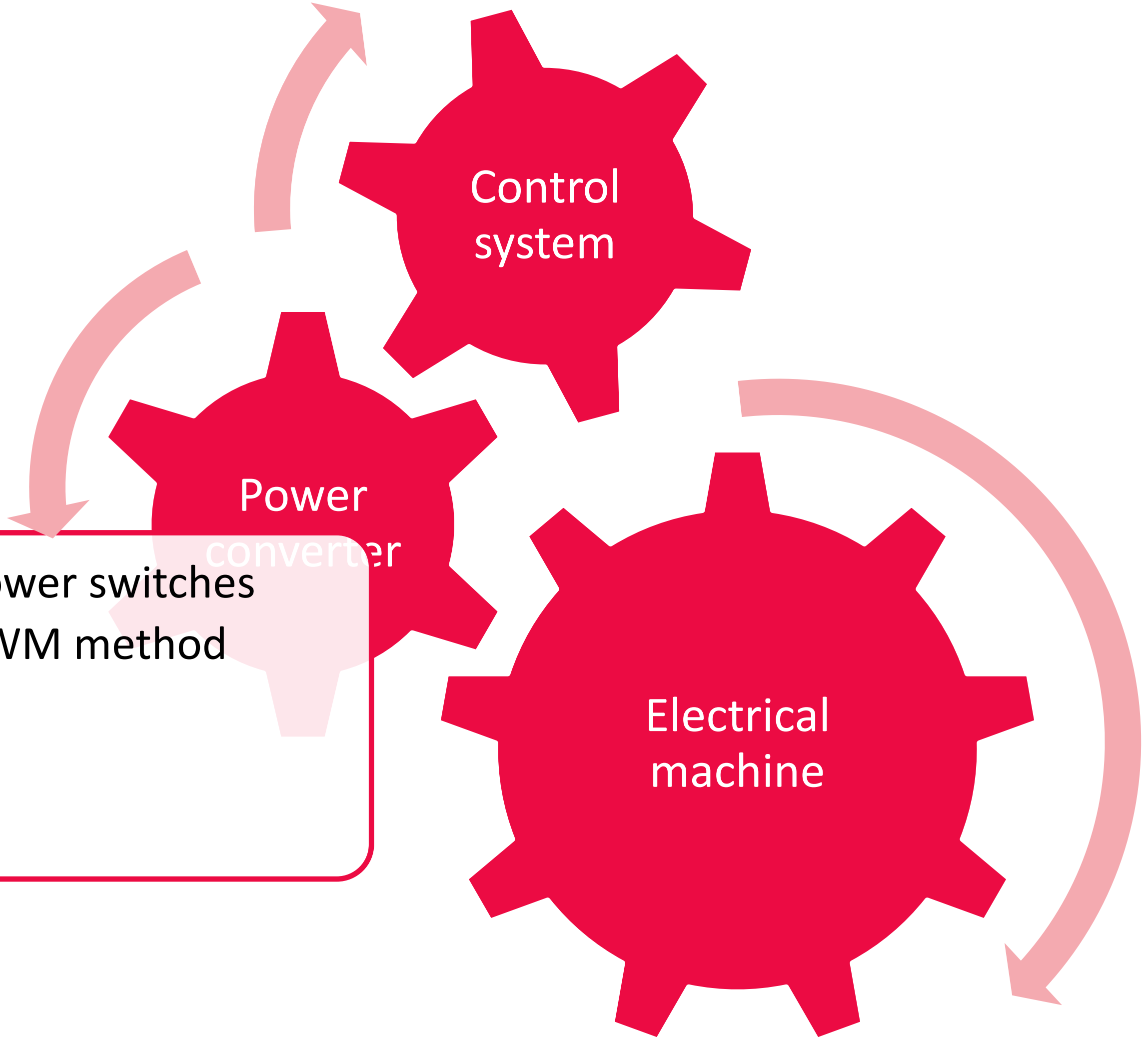
ITMO

Actuators

Lection 7
Power switches

Asc. Prof. Nikolai Poliakov
Asc. Prof. Sergei Lovlin
Asc. Prof. Dmitry Lukichev

Power switches



- Power switches
- PWM method

- DC machine
- AC Induction machine
- AC synchronous machine
  - permanent magnet synchronous machine

Power switches

Introduction

- Ideal switch
- Power switches state of art and perspectives
- Attendance and comprehension question №1

Switching losses

- Resistive load switching
- Inductive load switching issues
- Inductive load switching with reverse diode
- Attendance and comprehension question №2

Safe operation area

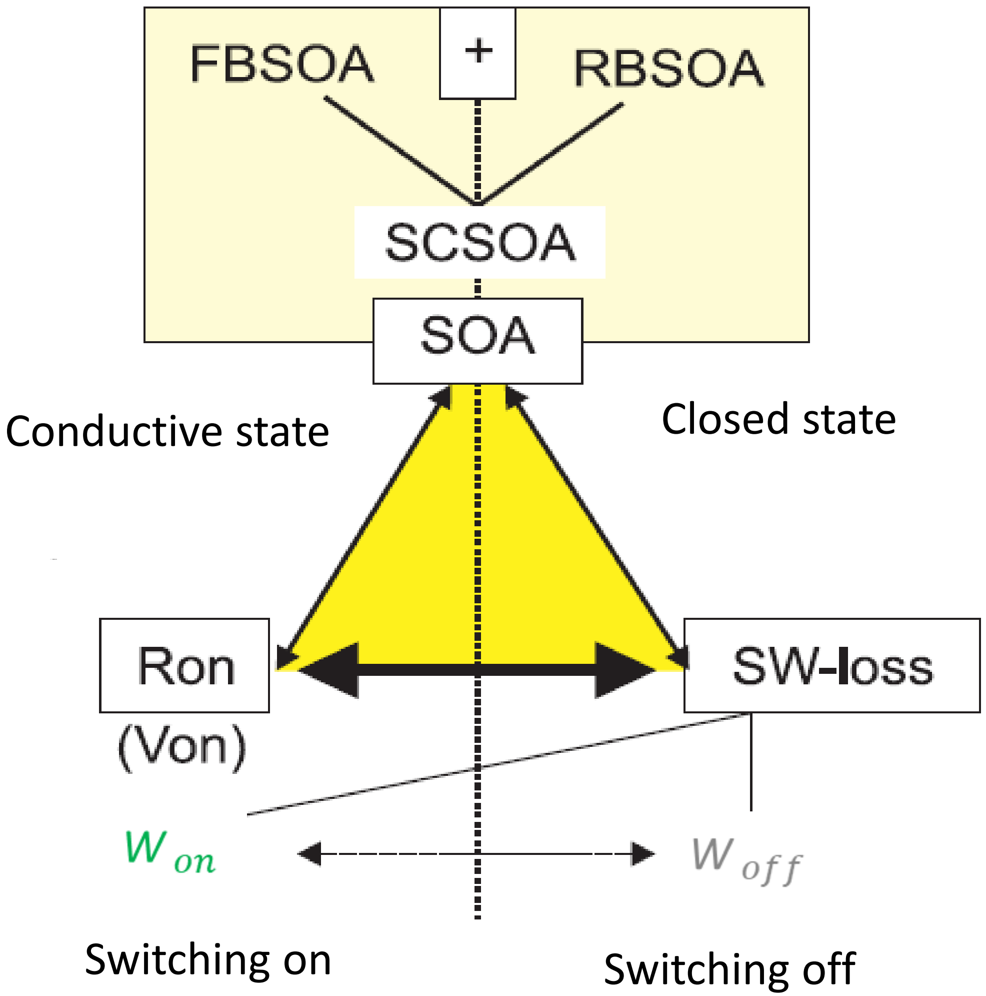
- BJT SOA
- IGBT SOA
- MOSFET SOA
- Attendance and comprehension question №3

Conclusion

- Ideal switch vs SOA

Ideal switch

- the ability to transmit an infinitely large current in the forward direction with a zero voltage drop on the device;
- the ability to exclude «dead time» to switch on;
- the ability to withstand an infinitely large reverse voltage in the locked state of the power switch with an infinitely large resistance;
- infinitely high switching frequency limit;
- Zero power required to control the power switch;
- Zero power losses when switch on;
- Zero power losses when switch off;



Classification of transistors

- Transistors
  - Bipolar Transistors (BJT)
  - Field Effect Transistors FET
  - Special type of transistors

Field-effect transistor

A **field-effect transistor** is a semiconductor device in which the amount of current flowing through a conductive channel is controlled by the field generated by the voltage at the control electrode.

Martin "John" M. Atalla

Dawon Kahng
강대원

Born	May 4, 1931[1] Keijō, Chōsen
Died	May 13, 1992 (aged 61)[2] New Brunswick, New Jersey, U.S.
Citizenship	South Korean (renounced) United States
Occupation	Electrical engineer
Known for	MOSFET (MOS transistor) PMOS and NMOS Schottky diode Nanolayer-base transistor Floating-gate MOSFET Floating-gate memory Reprogrammable ROM

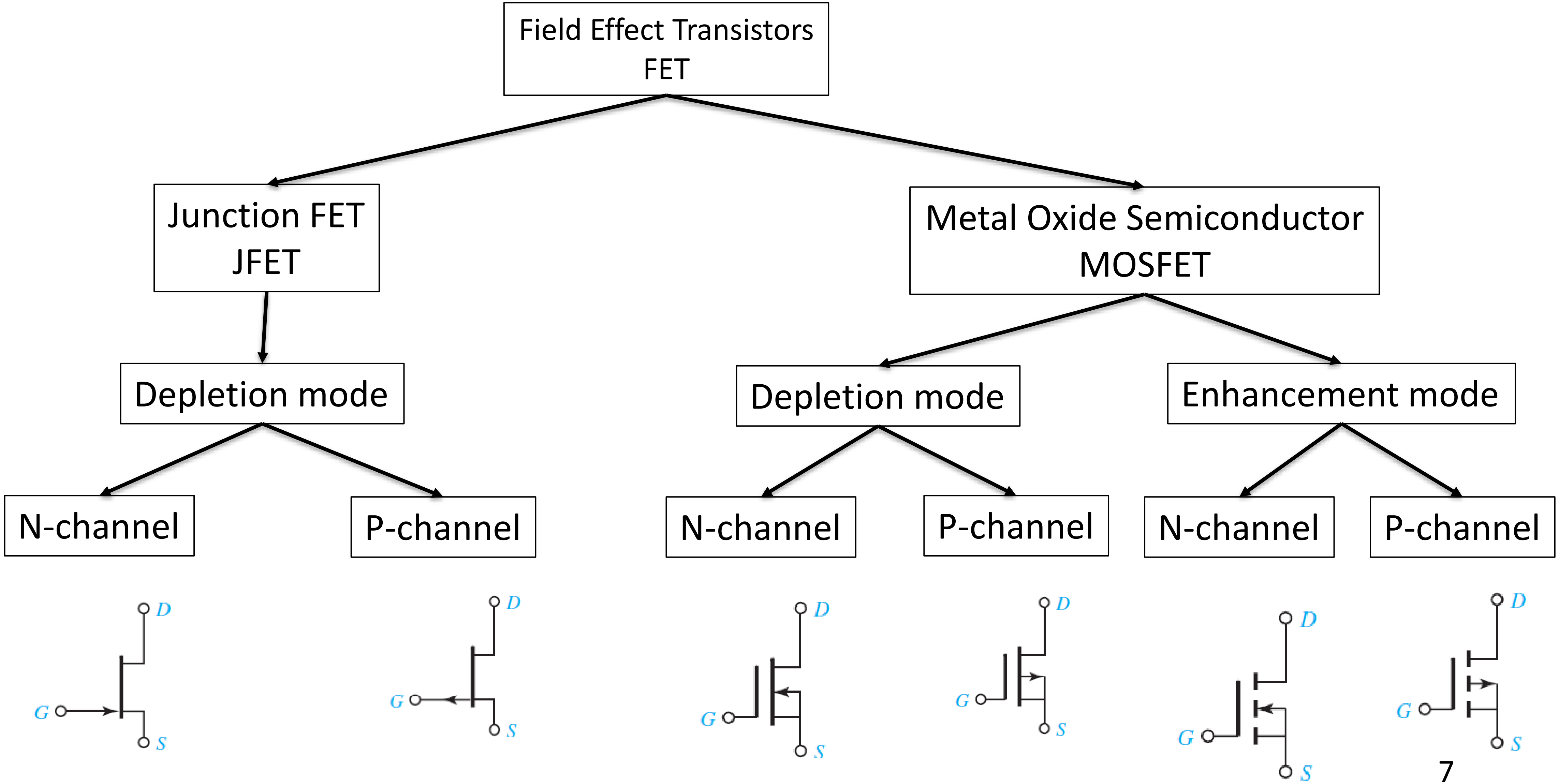
Оскар Хайль

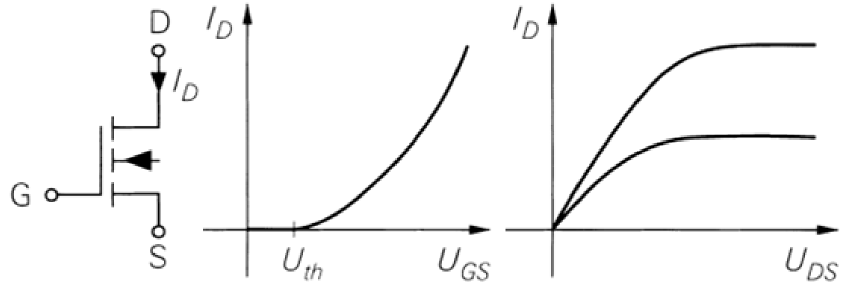
Дата рождения	20 марта 1908
Место рождения	Лангвиден, Кайзерслаутерн, Рейнланд-Пфальц
Дата смерти	15 мая 1994 (86 лет)
Место смерти	Сан-Матео, Сан-Матео, Калифорния, США
Страна	Германия
Альма-матер	Гёттингенский университет

J. E. Lilienfeld

Born	April 18, 1882 Lemberg, Galicia, Austro-Hungarian Empire
Died	August 28, 1963 (aged 81) Charlotte Amalie, Virgin Islands, U.S.
Citizenship	Austro-Hungarian (1882 – September 1919) Polish (1919–1934) American (1934–1963)
Alma mater	Friedrich-Wilhelms-Universität
Known for	Field-effect transistor Electrolytic capacitor
Scientific career	
Fields	Physicist Electrical engineer
Institutions	Leipzig University Amrad, Inc Ergon Research Laboratories
Doctoral advisor	Max Planck Emil Warburg
Other academic advisors	Jacobus Henricus van 't Hoff

Classification of transistors

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I_D
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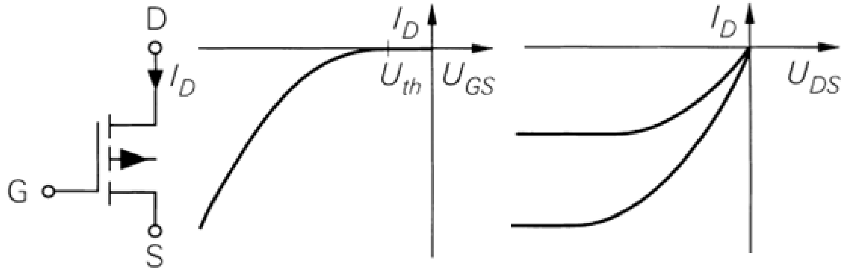
U_{GS}
I_D
U_{DS}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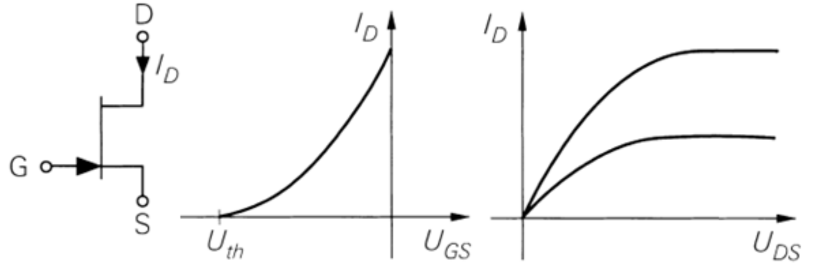
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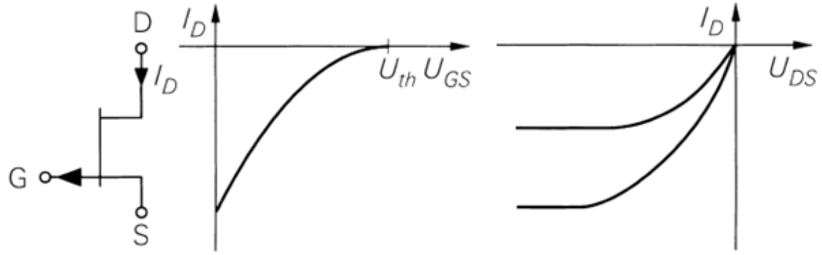
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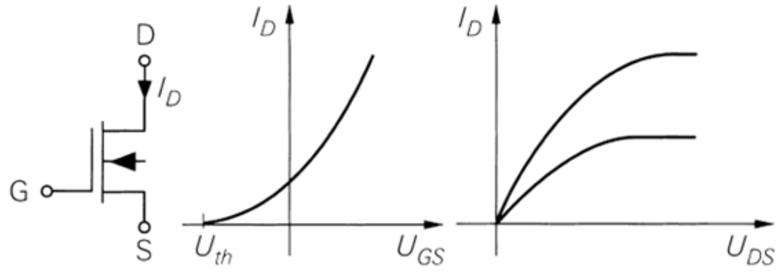
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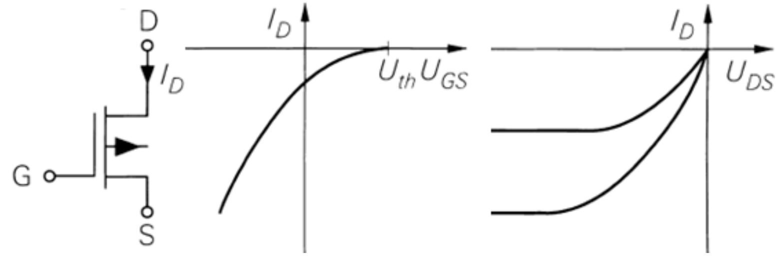
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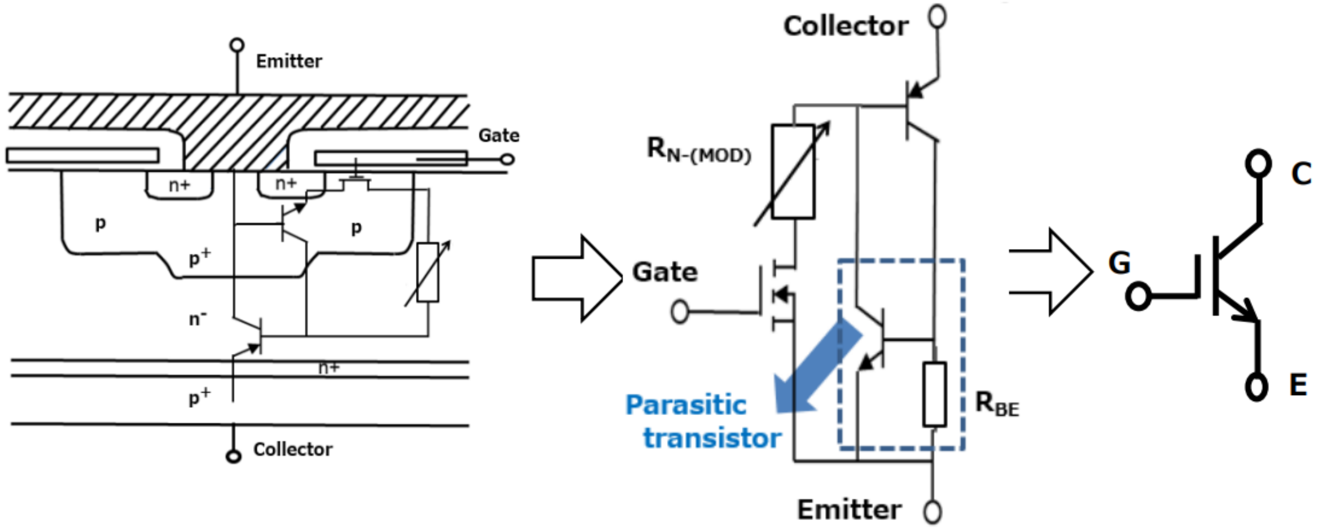
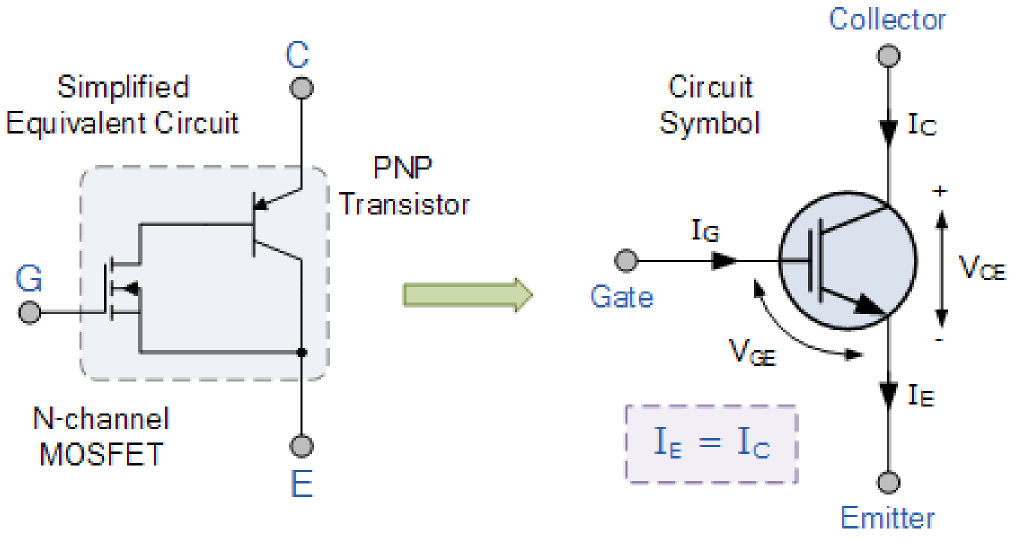
U_{GS}
I_D
U_{DS}

Comparison FET

Type FET	n-channel	p-channel
Enhancement-type MOSFET	$U_{th} > 0$ $U_{GS} > U_{th}$ $U_{DS} > 0$ $I_D > 0$	$U_{th} < 0$ $U_{GS} < U_{th}$ $U_{DS} < 0$ $I_D < 0$
Depletion-type MOSFET	$U_{th} < 0$ $U_{GS} > U_{th}$ $U_{DS} > 0$ $I_D > 0$	$U_{th} > 0$ $U_{GS} < U_{th}$ $U_{DS} < 0$ $I_D < 0$
JFET	$U_{th} < 0$ $U_{th} < U_{GS} < 0$ $U_{DS} > 0$ $I_D > 0$	$U_{th} > 0$ $0 < U_{GS} < U_{th}$ $U_{DS} < 0$ $I_D < 0$

IGBT- Insulated Gate Bipolar transistor





IGBT combines the advantages of two main types of transistors:

from MOSFET:

- ✓ high input impedance
- ✓ low control power
- ✓ voltage control

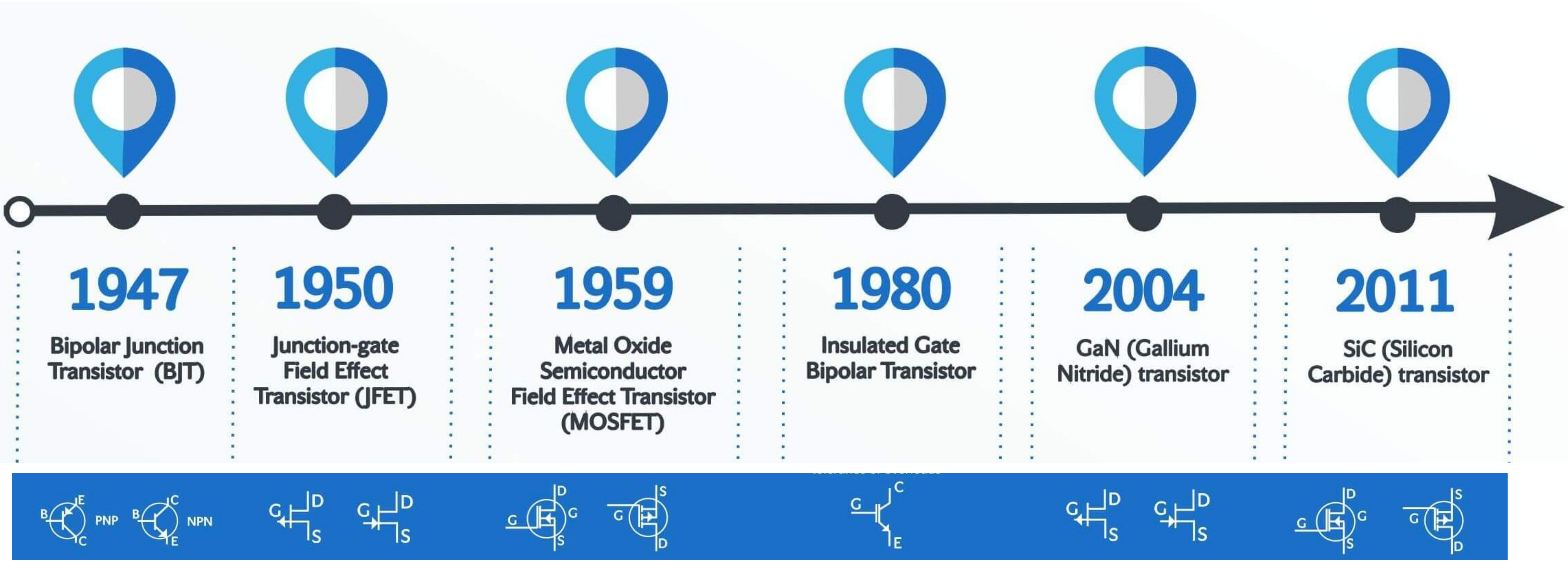
from bipolar transistors:

- ✓ low on-state residual voltages
- ✓ witching characteristics and conductivity
- ✓ low losses in the open state at high currents and high voltages;

IGBT comparison table

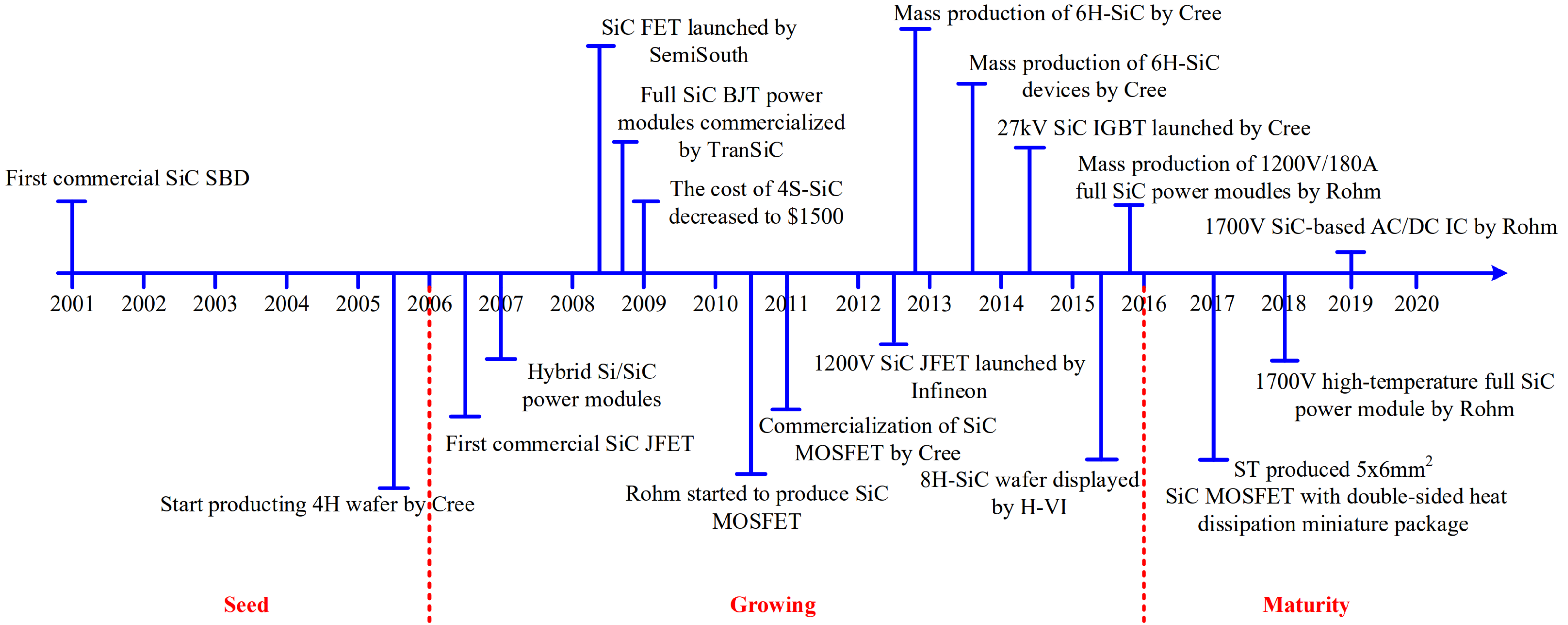
Device characteristic	Power bipolar	Power MOSFET	IGBT
Voltage rating	High <1 kV	High <1 kV	Very high >1 kV
Current rating	High <500 A	High >500 A	High >500 A
Input drive	Current ratio h_{FE} ~ 20–200	Voltage V_{GS} ~ 3–10 V	Voltage V_{GE} ~ 4–8 V
Input impedance	Low	High	High
Output impedance	Low	Medium	Low
Switching speed	Slow (µs)	Fast (ns)	Medium
Cost	Low	Medium	High

Semiconductor Power Switches



https://sparkpi.co.uk/infographic-transistor/

SiC – MOSFET



https://www.researchgate.net/publication/333867694_Silicon_Carbide_Converters_and_MEMS_Devices_for_High-temperature_Power_Electronics_A_Critical_Review

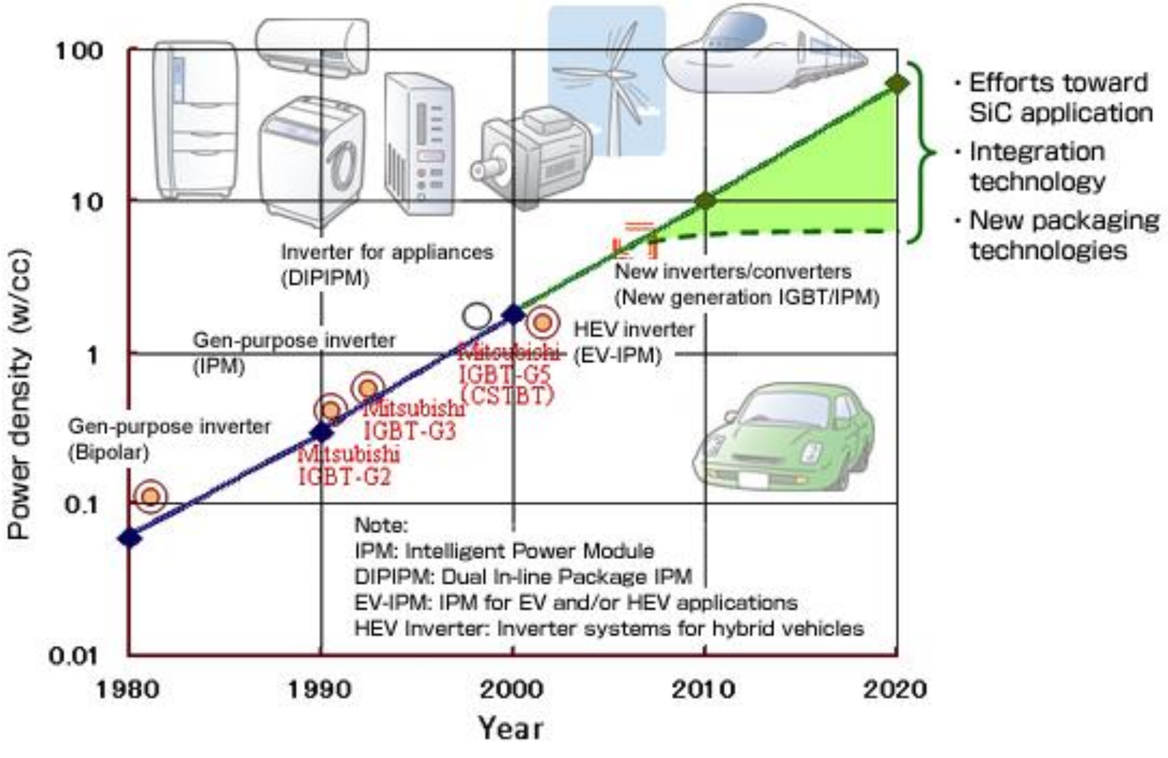
1- single-operating thyristors;

2 and

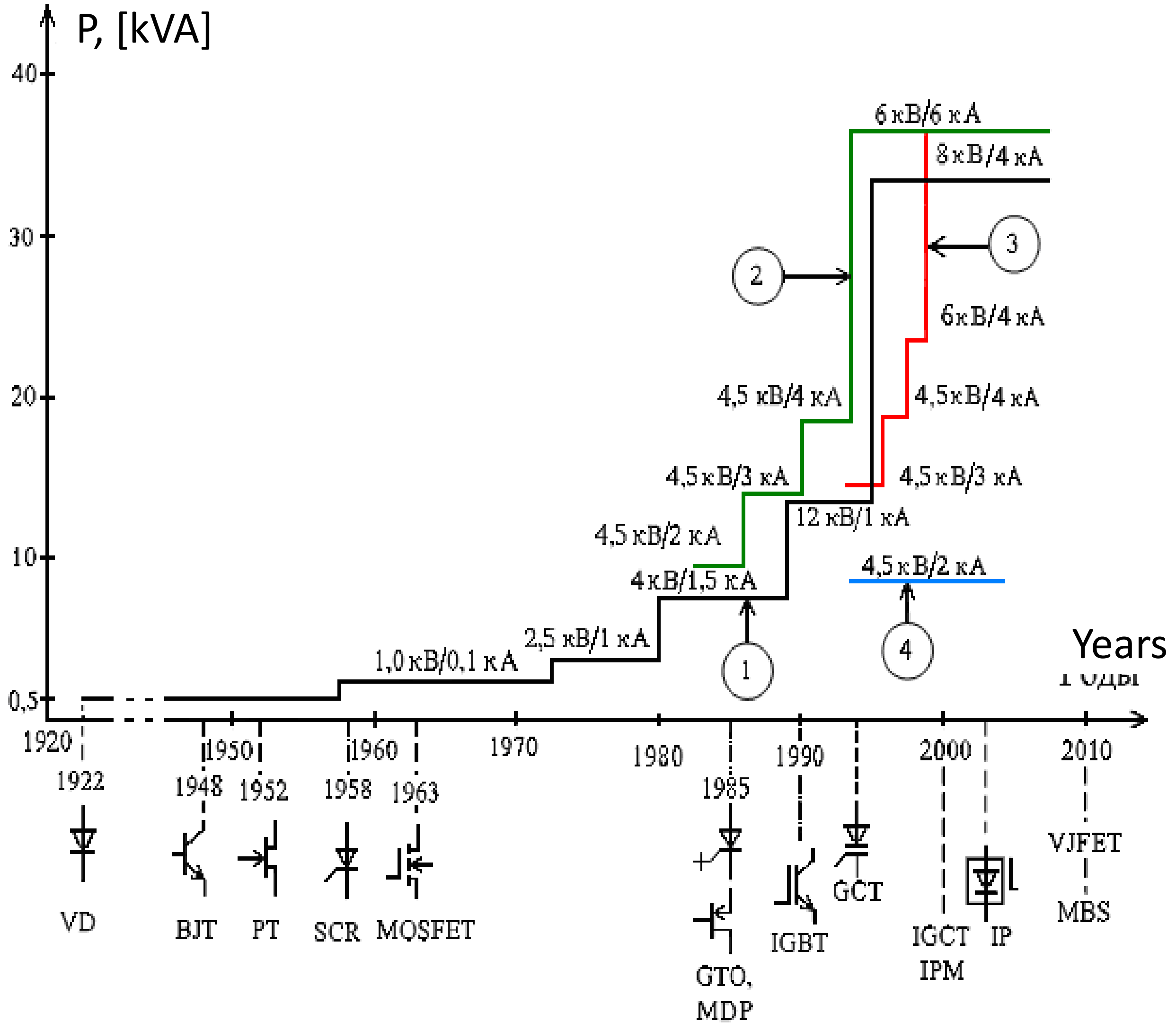
3- lockable thyristors (GTO and GCT);

4- high-voltage IGBT

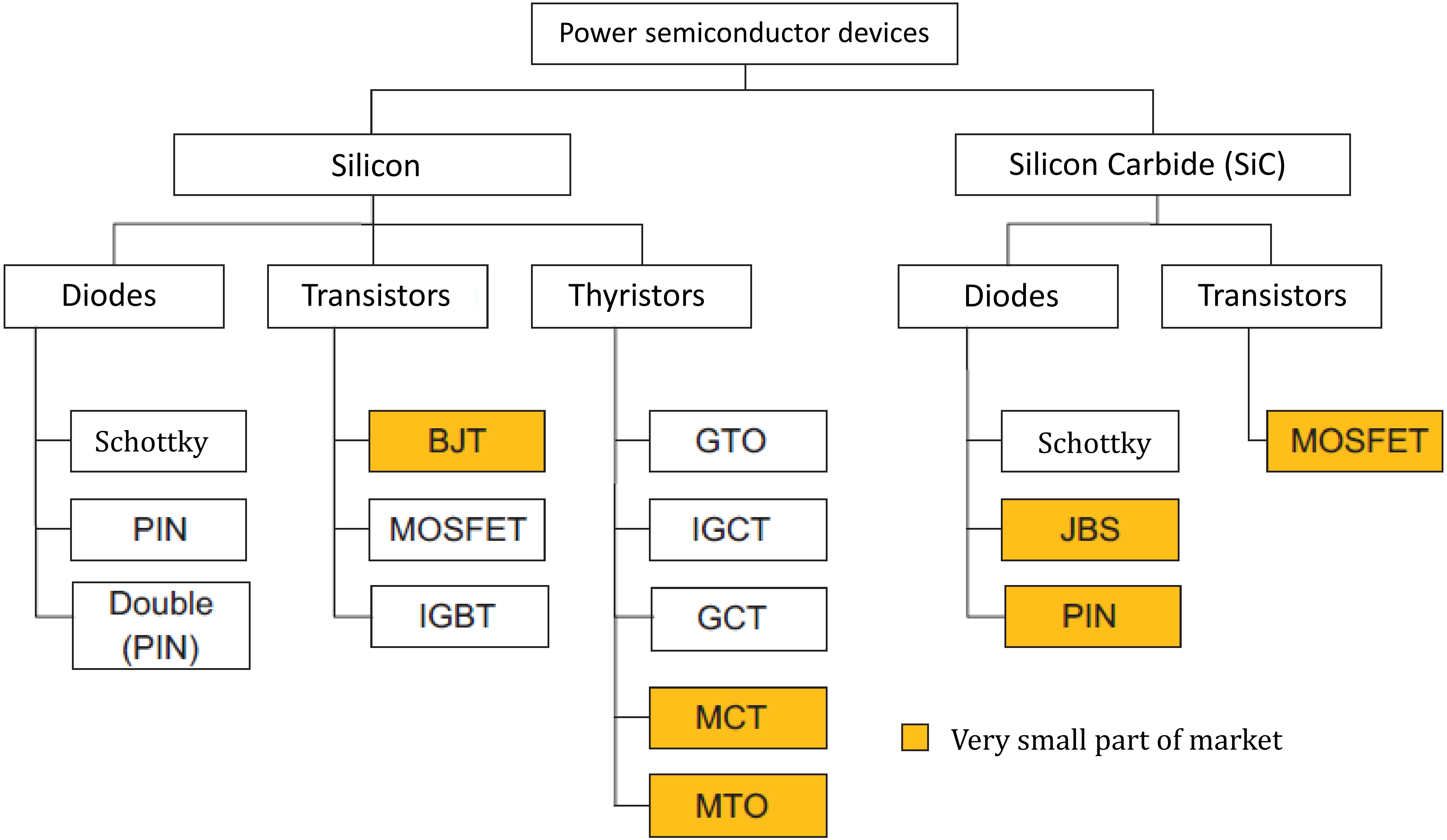
Projected growth of power density in power electronics system designs



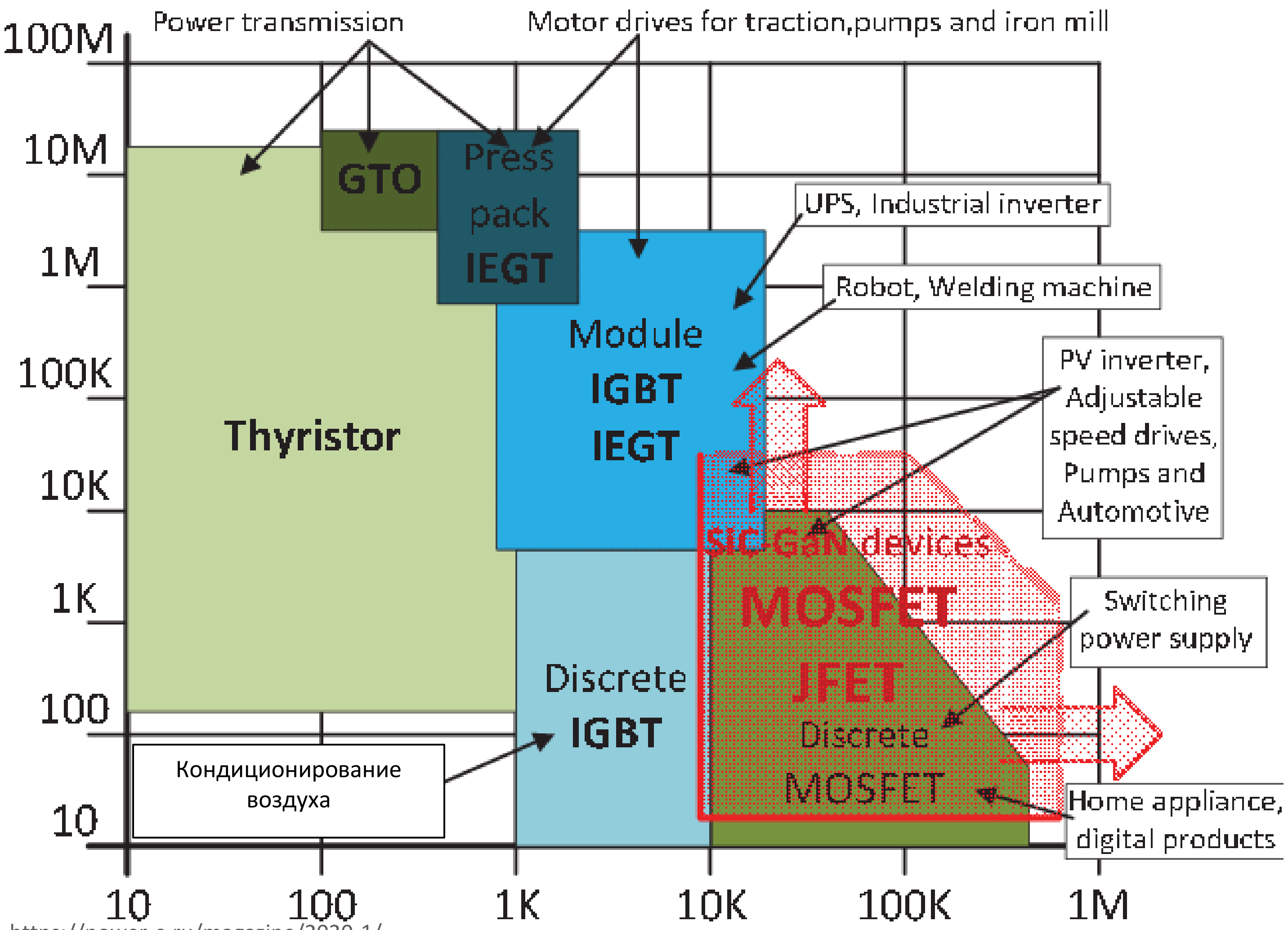
Equipment's power density = P_{out} (W) / Volume (cc)

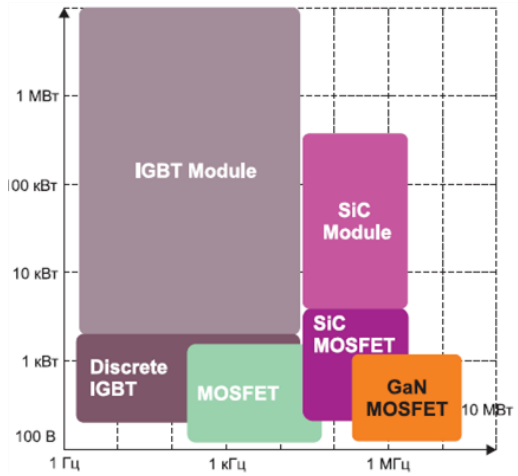


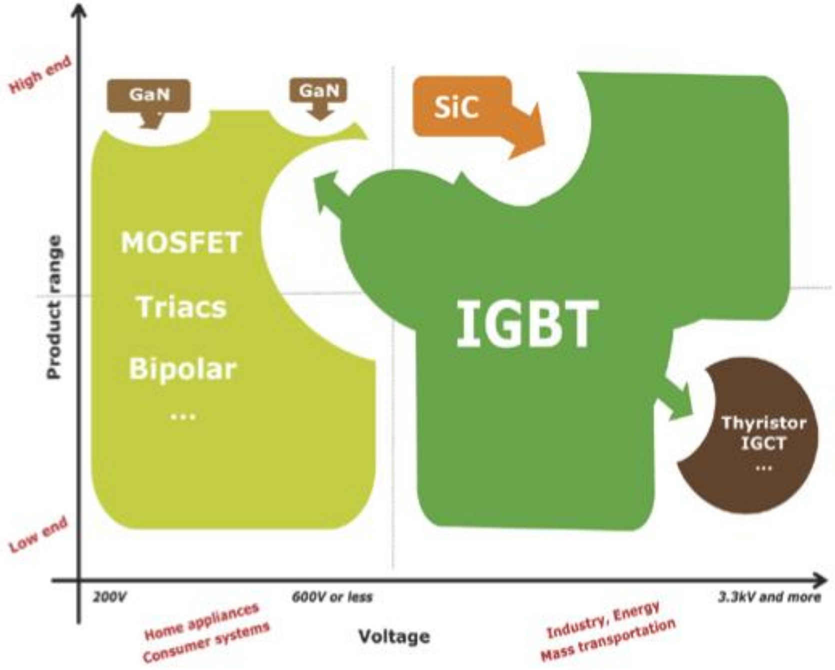
Semiconductor power switches



Applications of semiconductor switches







https://power-e.ru/magazine/2020-1/
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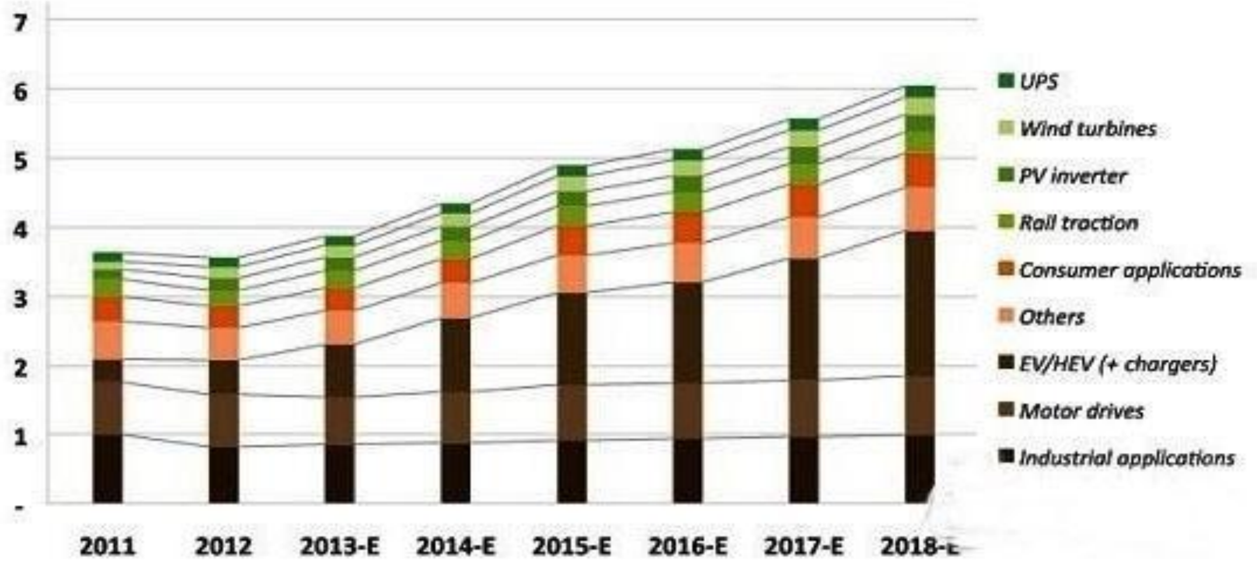
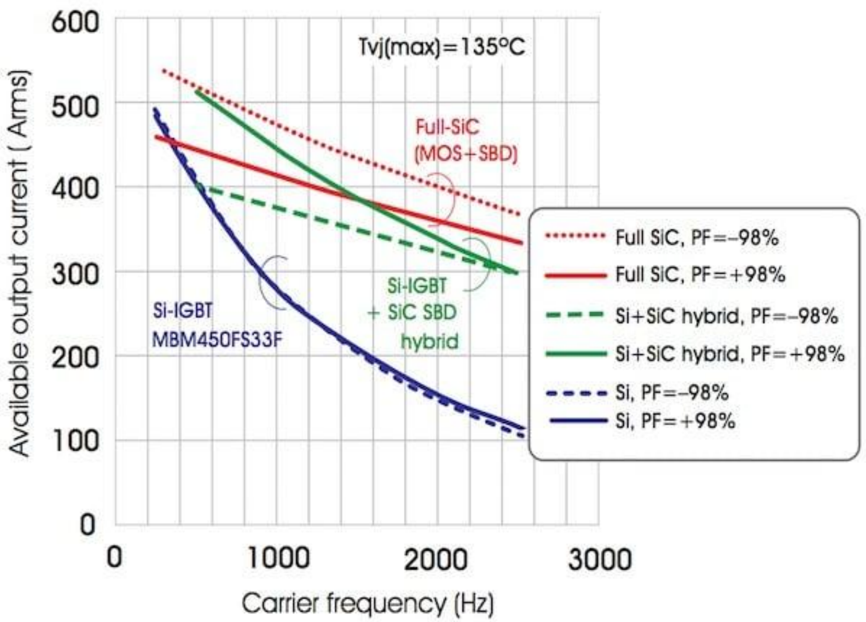
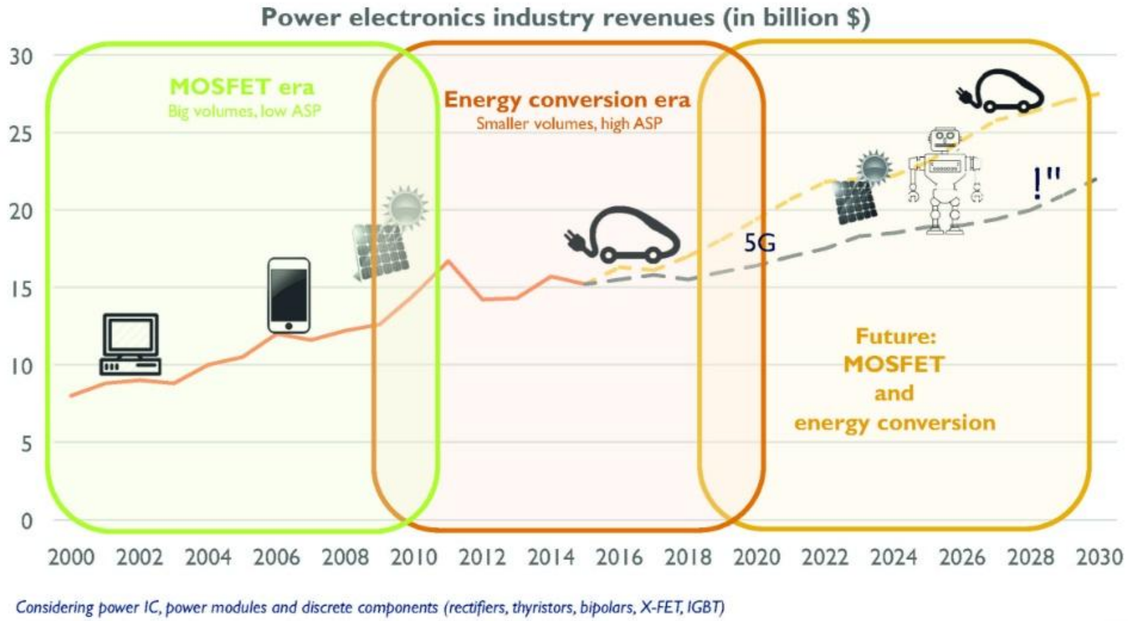
https://www.mitsubishielectric.com/semiconductors/triple_a_plus/technology/01/index.html
https://image2.slideserve.com/4168664/expanding-the-power-range-of-igbt-l.jpg
https://www.researchgate.net/publication/260316830_Real_field_mission_profile_oriented_design_of_a_SiC-based_PV-inverter_application

Applications of semiconductor switches

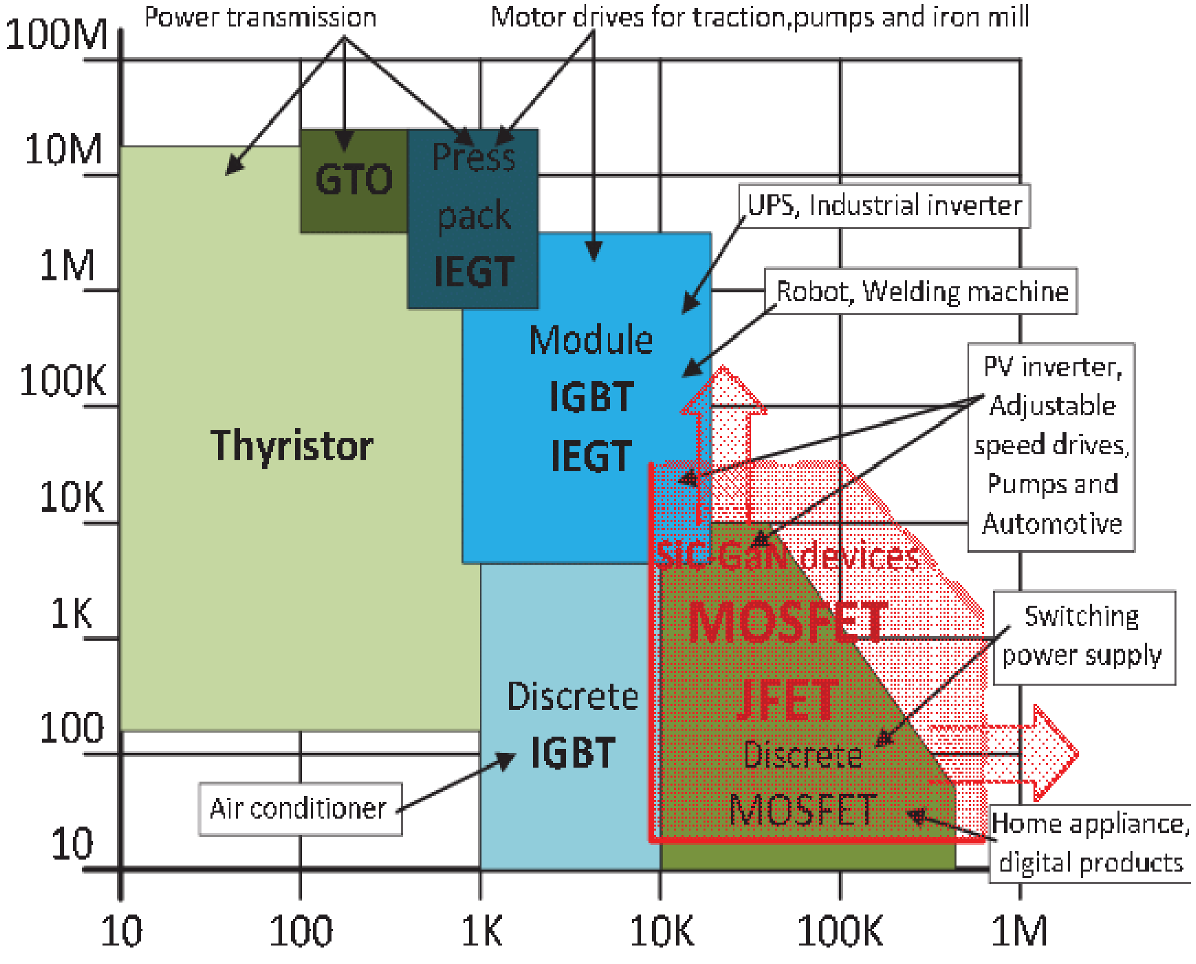


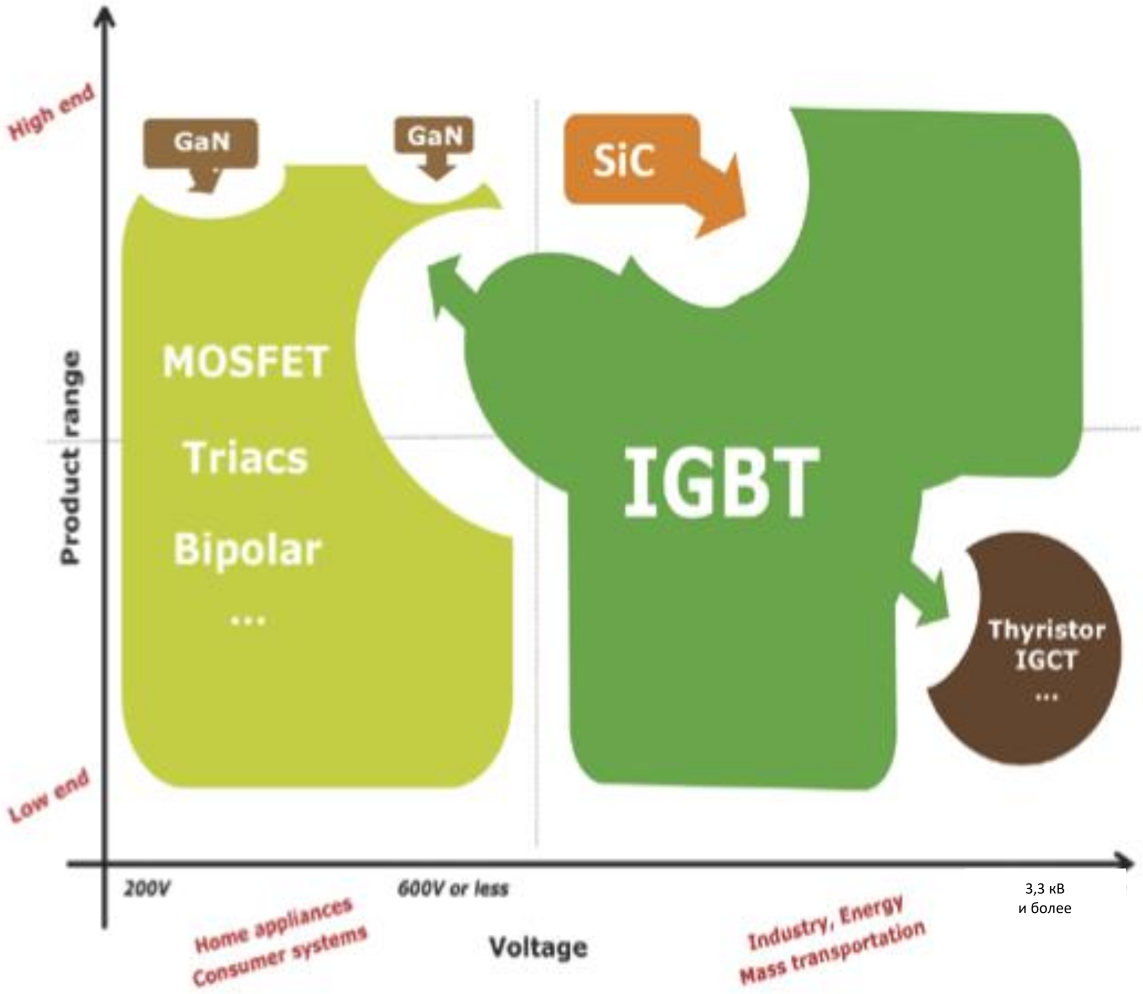




https://www.computescotland.com/silicon-carbide-anvil-semiconductor-power-devices-4830.php
http://www.welldo-weld.com/news/renewable-energy-applications-blessing-igbt-ma-1547122.html

Transistors power range and application





https://warwick.ac.uk/fac/sci/eng/research/research_lunch_seminars/20180427_pg_sic_20_min_lecture.pdf
https://www.mitsubishielectric.com/semiconductors/triple_a_plus/technology/01/index.html
https://image2.slideserve.com/4168664/expanding-the-power-range-of-igbt-l.jpg
https://www.researchgate.net/publication/260316830_Real_field_mission_profile_oriented_design_of_a_SiC-based_PV-inverter_application

Active load ideal switching

ON-transient process

$$u_S(t) = U_S\left(1 - \frac{t}{t_+}\right)$$

$$i_S(t) = I_S\left(\frac{t}{t_+}\right)$$

U_S и I_S — steady state voltage and current of the ideal switch(switch) before switching was started

$$p_{on}(t) = i_S(t) \cdot u_S(t) = U_S \cdot I_S\left(\frac{t}{t_+} - \frac{t^2}{t_+^2}\right)$$

$$W_{on}(t) = \int_0^{t_+} p_{on}(t)dt = U_S \cdot I_S\left(\frac{t_+}{6}\right)$$

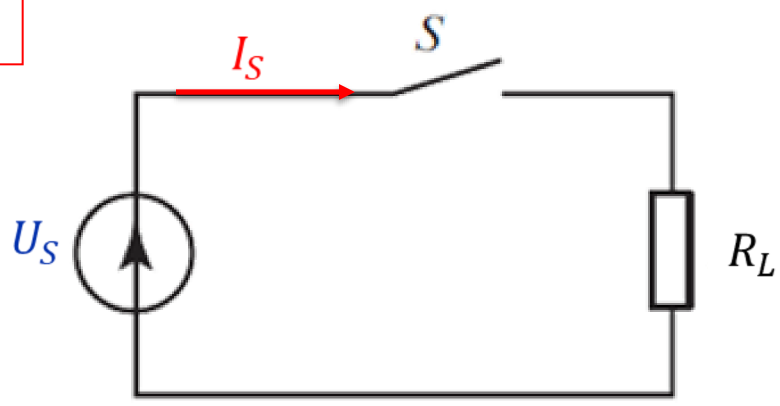
OFF-transient process

$$u_S(t) = U_S\left(\frac{t}{t_-}\right)$$

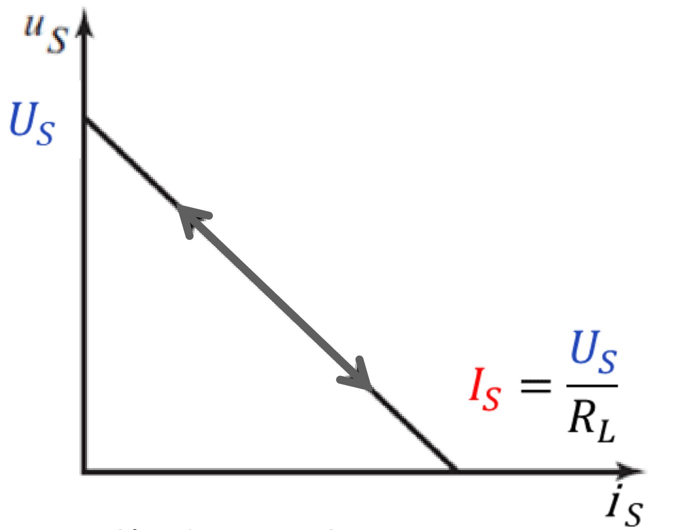
$$i_S(t) = I_S\left(1 - \frac{t}{t_-}\right)$$

$$p_{off}(t) = i_S(t) \cdot u_S(t) = U_S \cdot I_S\left(\frac{t}{t_-} - \frac{t^2}{t_-^2}\right)$$

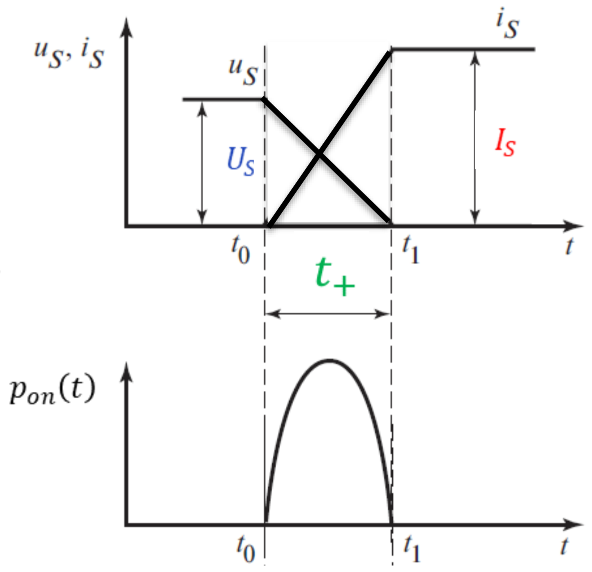
$$W_{off}(t) = \int_0^{t_-} p_{off}(t)dt = U_S \cdot I_S\left(\frac{t_-}{6}\right)$$



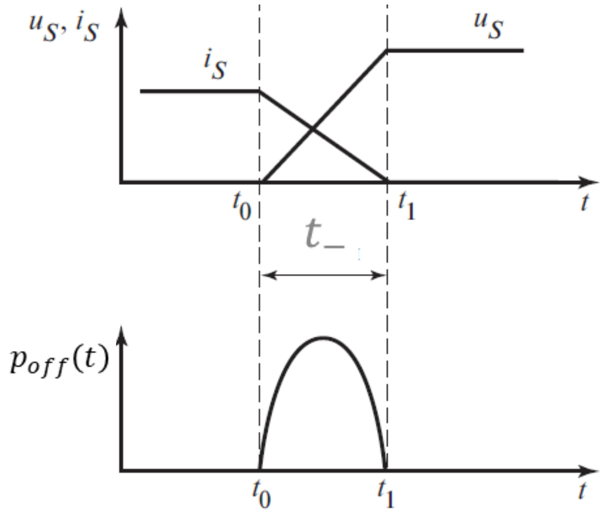
a) — ideal switching;



b) — dynamic VI-characteristic

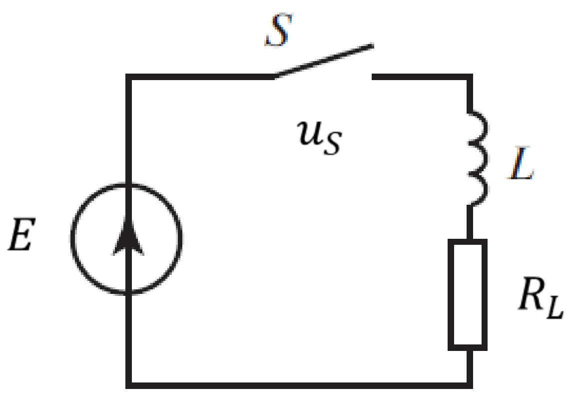


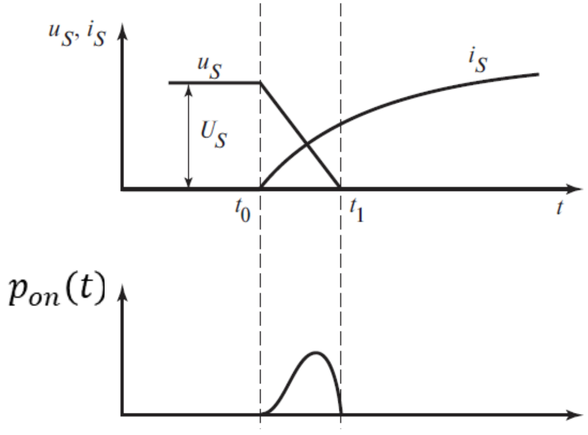
c) —i_S, u_S on transient process and p_{on};



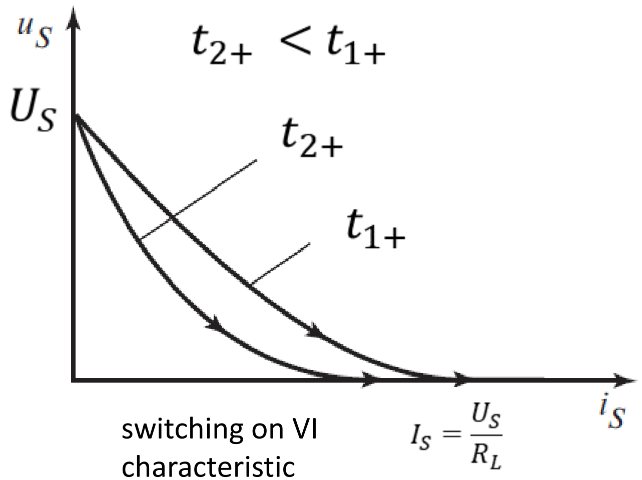
d) — i_S, u_S off transient process and p_{off}

Periodic switching. Active and inductive load

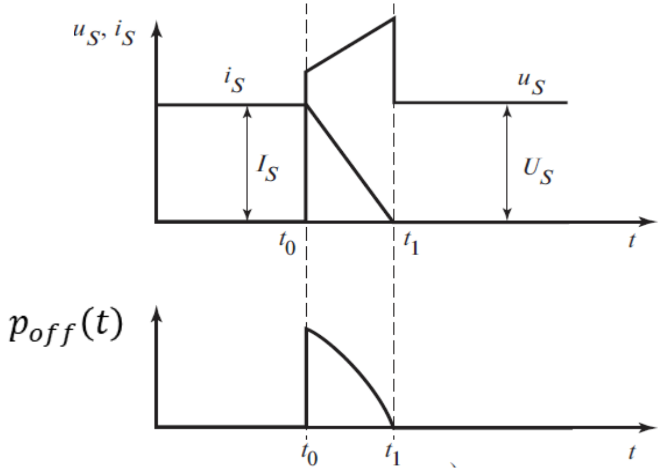




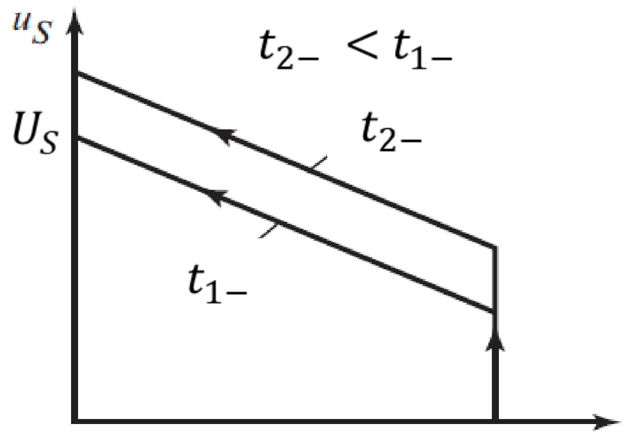
i_S, u_S, p_{on} during switching on



switching on VI characteristic

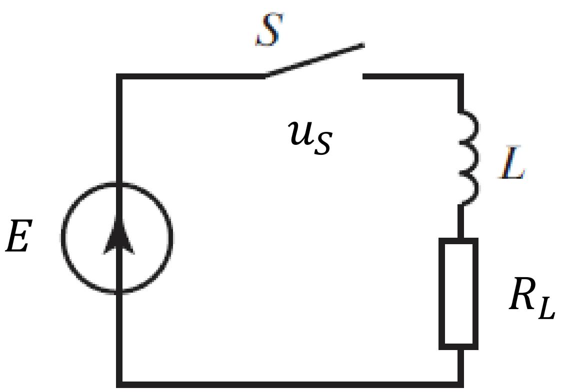


i_S, u_S, p_{off} during switching off



switching off VI characteristic

Active power loss



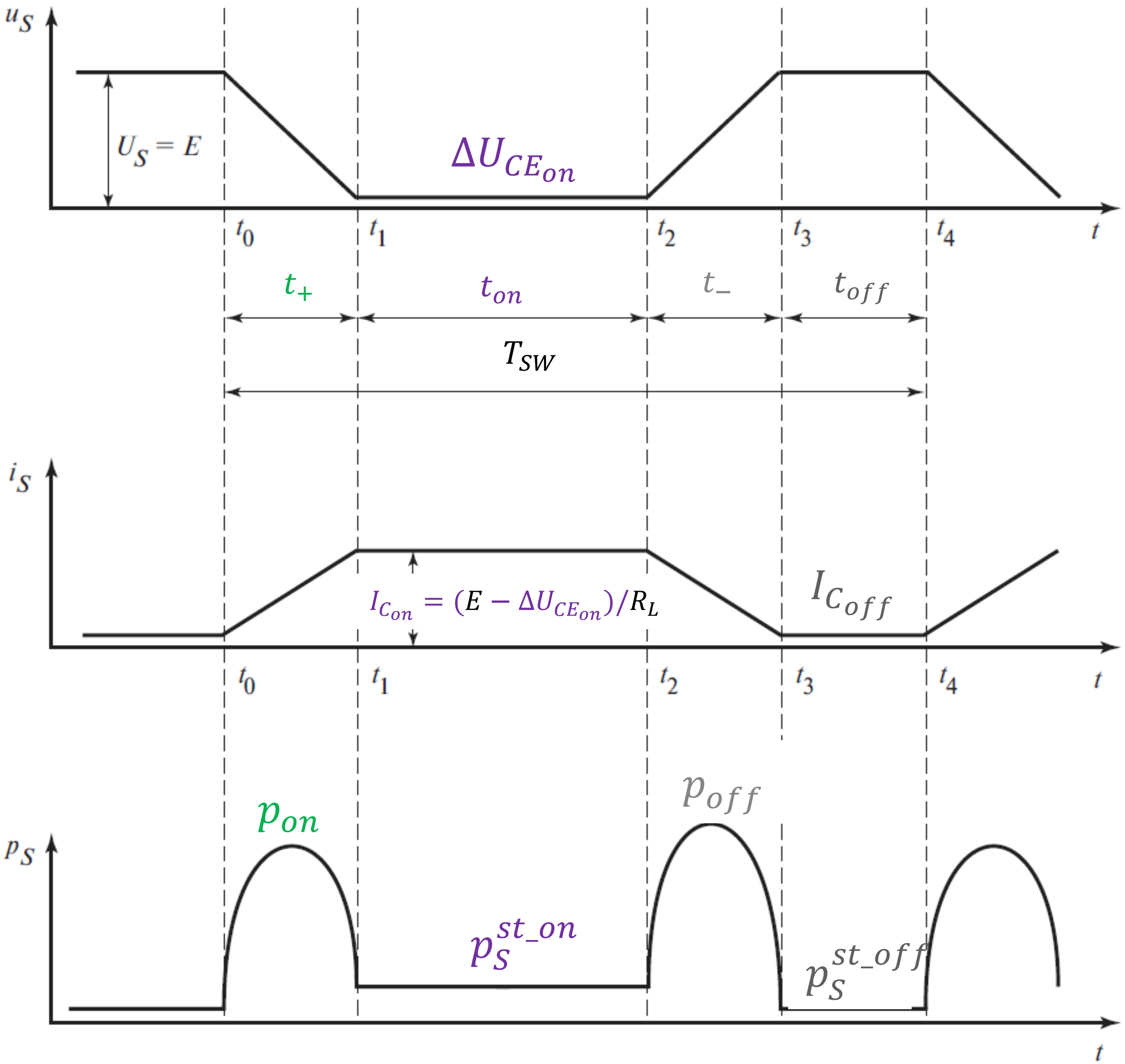
$$P_S = P_S^{st\_on} + P_S^{st\_off} + P_{on} + P_{off}$$

$$P_S^{st\_on} = \frac{1}{T_{sw}}\left[\frac{E - \Delta U_{CE_{on}}}{r_{VT} + R_L}\Delta U_{CE_{on}} \cdot t_{on}\right]$$

$$P_S^{st\_off} = \frac{1}{T_{sw}}\left[E \cdot I_{C_{off}} \cdot t_{off}\right]$$

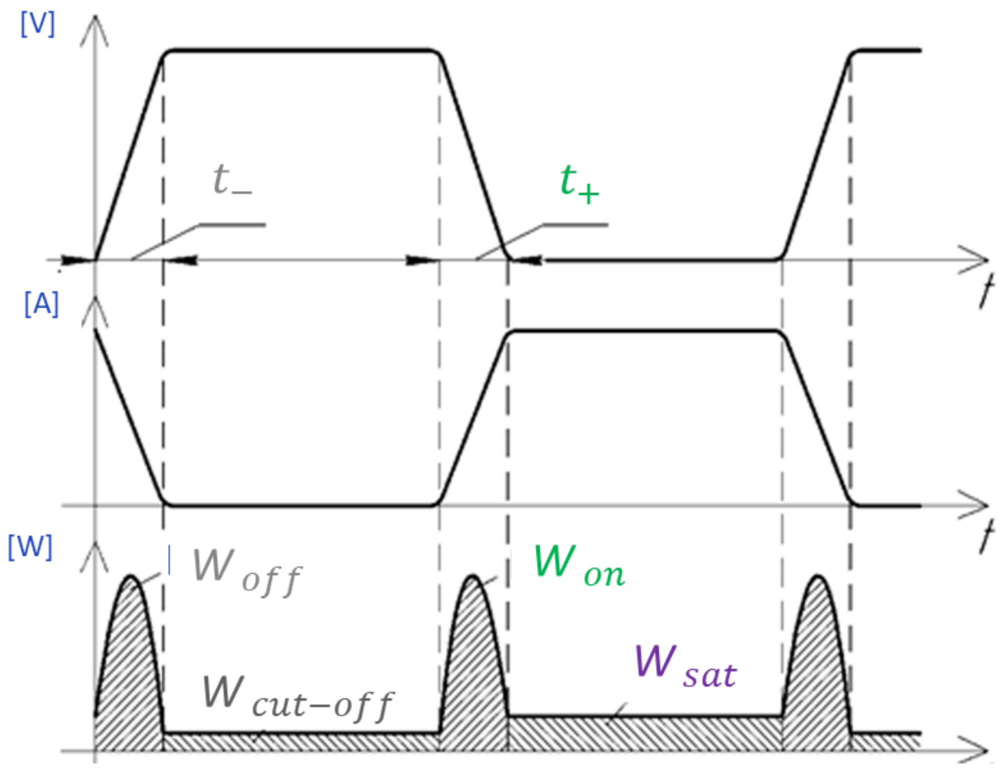
$$P_{on} = \frac{1}{T_{sw}}\left[\int_0^{t_1} i_S(t) \cdot u_s(t)dt\right]$$

$$P_{off} = \frac{1}{T_{sw}}\left[\int_{t_2}^{t_3} i_S(t) \cdot u_s(t)\,dt\right]$$

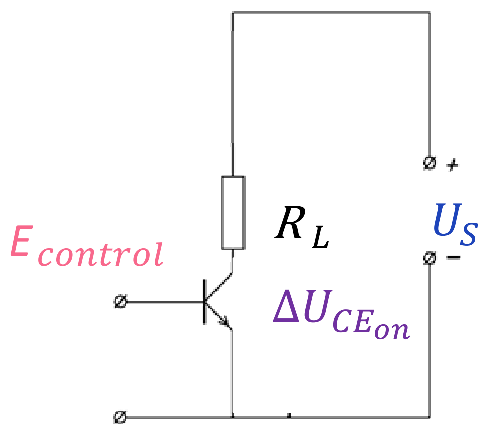


Total energy loss per cycle is the sum of the energy of switching losses (W_S) which is equal to sum of the energy of losses during the switching on (W_{on}) and switching off (W_{off}) intervals and transistor on-state W_{sat} and transistor off-state (cut-off) $W_{cut-off}$ active power losses.

$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control}$$



- $W_S = W_{on} + W_{off}$ - switching power losses
- W_{sat} - transistor on-state active power losses
- $W_{cut-off}$ - transistor off-state (cut-off) active power losses
- $W_{control}$ - (additional) control circuit (driver) power losses

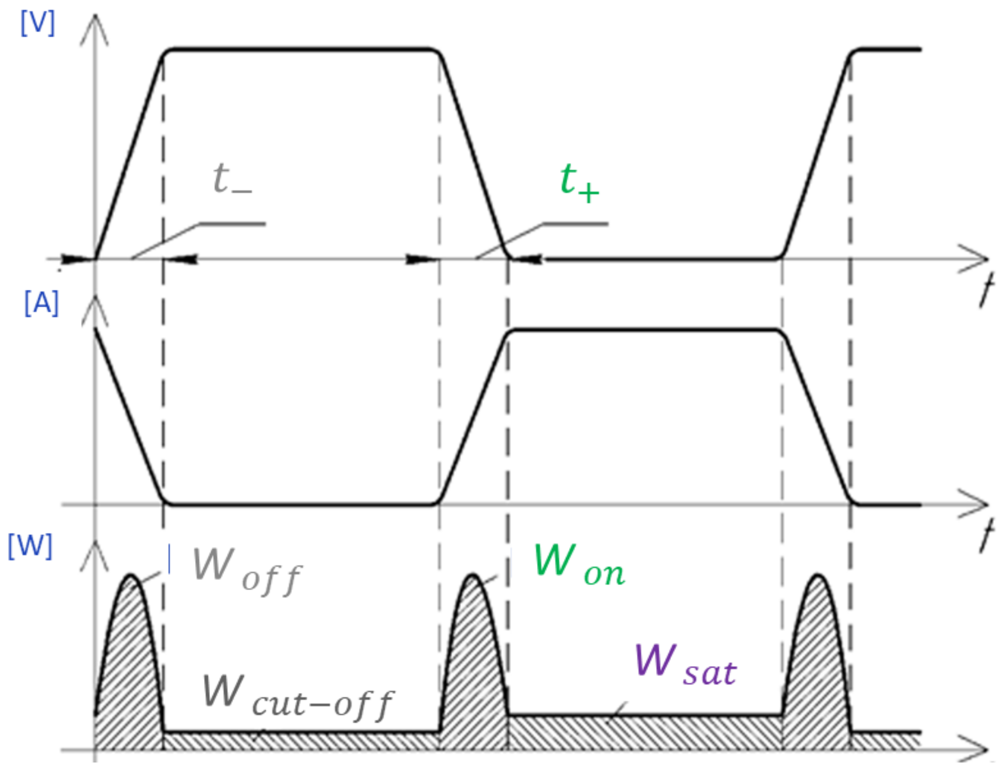


Active power loss in BJT switching active load

Total energy loss per cycle is the sum of the energy of switching losses (W_S) which is equal to sum of the energy of losses during the switching on (W_{on}) and switching off (W_{off}) intervals and transistor on-state W_{sat} and transistor off-state (cut-off) $W_{cut-off}$ active power losses.

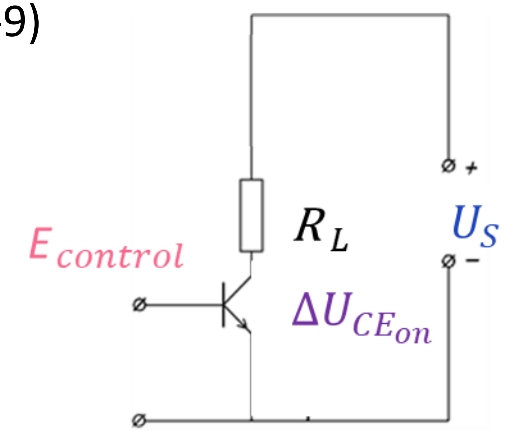
$$W_\Sigma = W_S + W_{sat} + \cancel{W_{cut-off}} + \cancel{W_{control}}$$

- $W_S = W_{on} + W_{off}$ - switching power losses
- W_{sat} - transistor on-state active power losses
- ~~$W_{cut-off}$ - transistor off-state (cut-off) active power losses~~ **(usually too small to be considered)**
- ~~$W_{control}$ - (additional) control circuit (driver) power losses~~ **(usually too small to be considered)**



$$W_S = W_{on} + W_{off} + W_{rr}$$

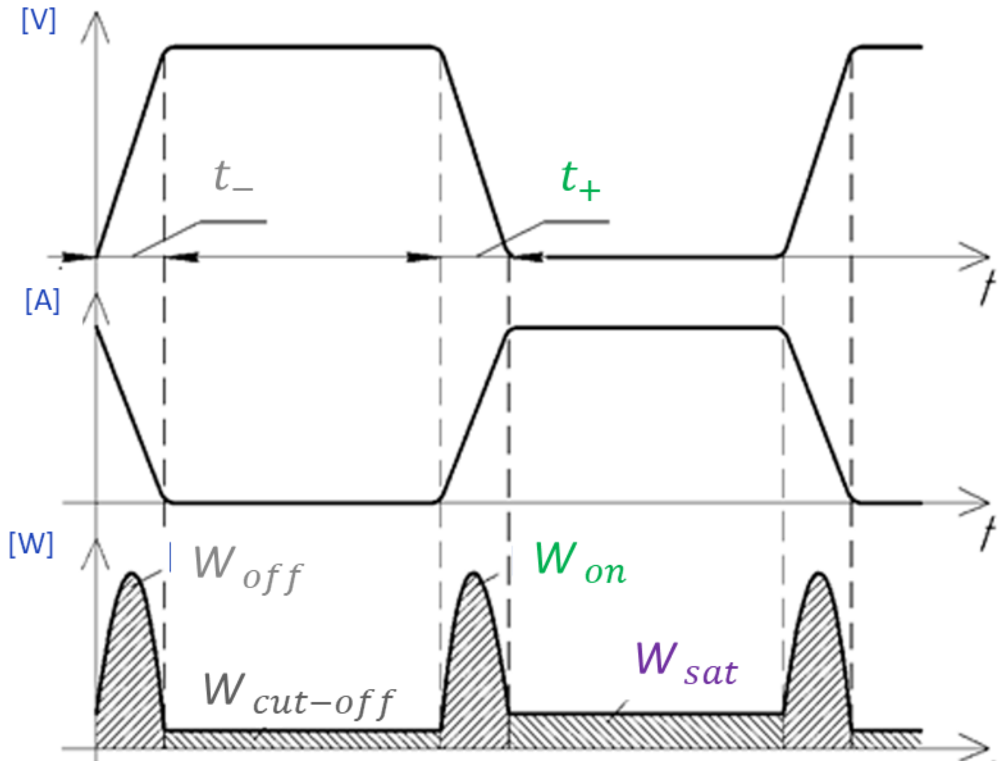
(IEC 60747-9)



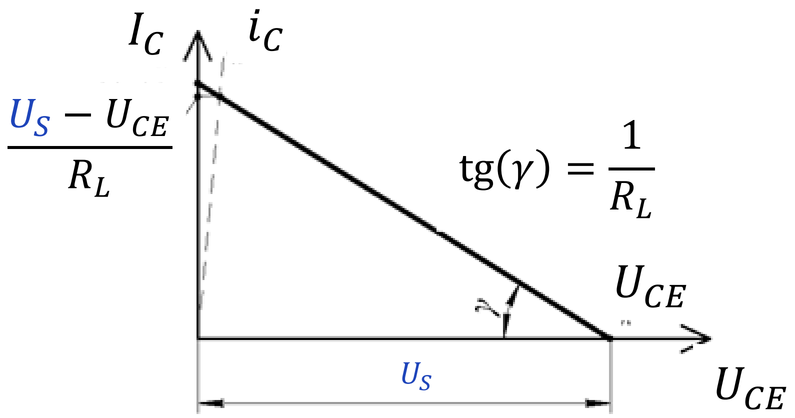
Operating point of the transistor

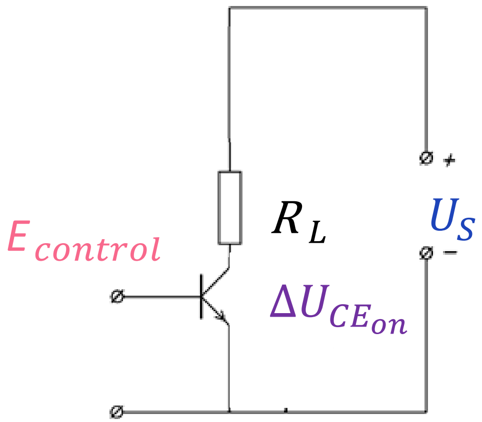
$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

- $W_S = W_{on} + W_{off}$ - switching power losses
- W_{sat} - transistor on-state active power losses
- ~~$W_{cut-off}$ - transistor off-state (cut-off) active power losses~~ (too small to be considered)
- ~~$W_{control}$ - control circuit (driver) power losses~~ (too small to be considered)

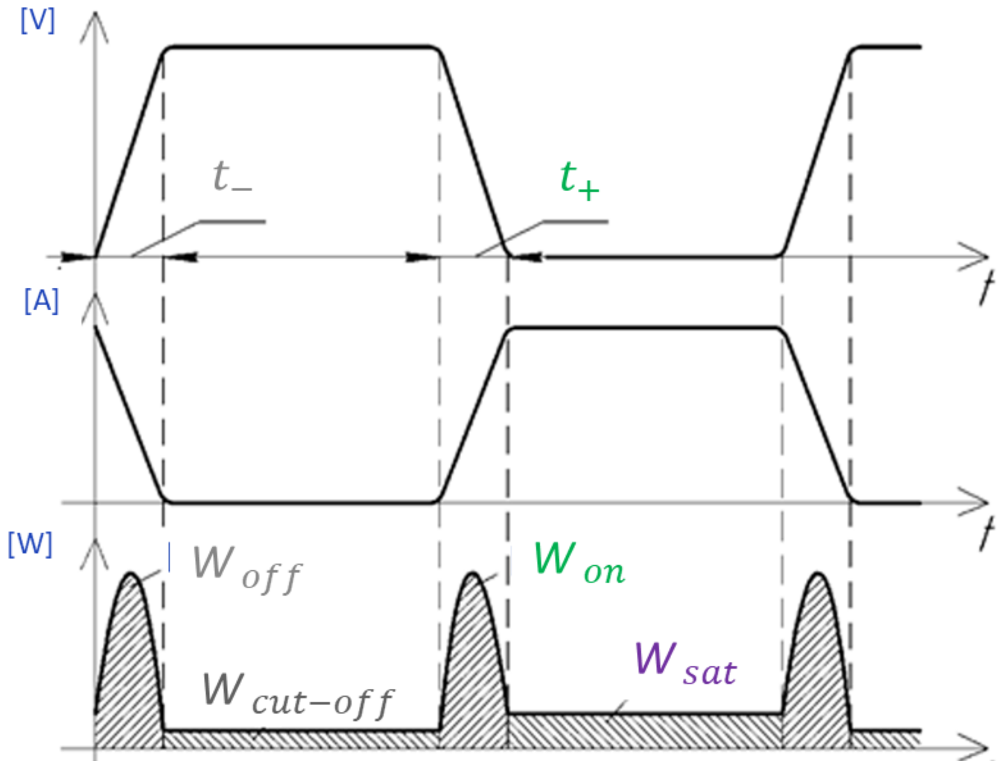


Operating point of the transistor:





$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$



- $W_S = W_{on} + W_{off}$ - switching power losses
- W_{sat} - transistor on-state active power losses
- ~~$W_{cut-off}$ - transistor off-state (cut-off) active power losses~~ (too small to be considered)
- ~~$W_{control}$ - control circuit (driver) power losses~~ (too small to be considered)

If $\frac{U_S - U_{CE}}{U_{CE}}$>>1.5, it may be considered that the voltage and current increase linearly

Operating point of the transistor

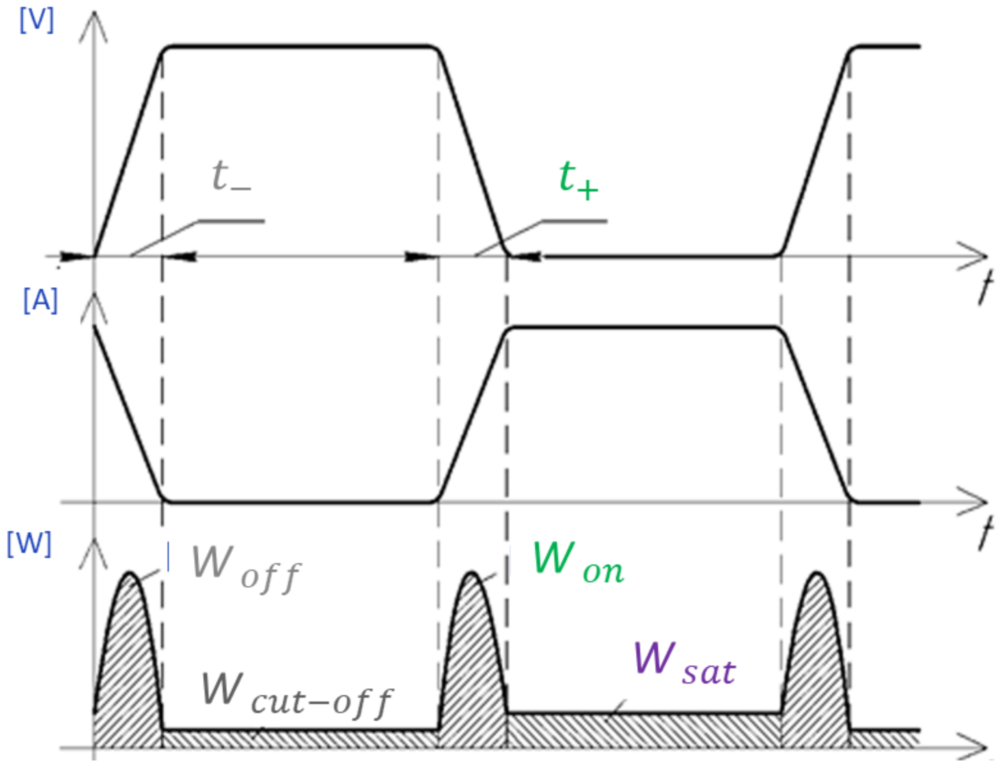
$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

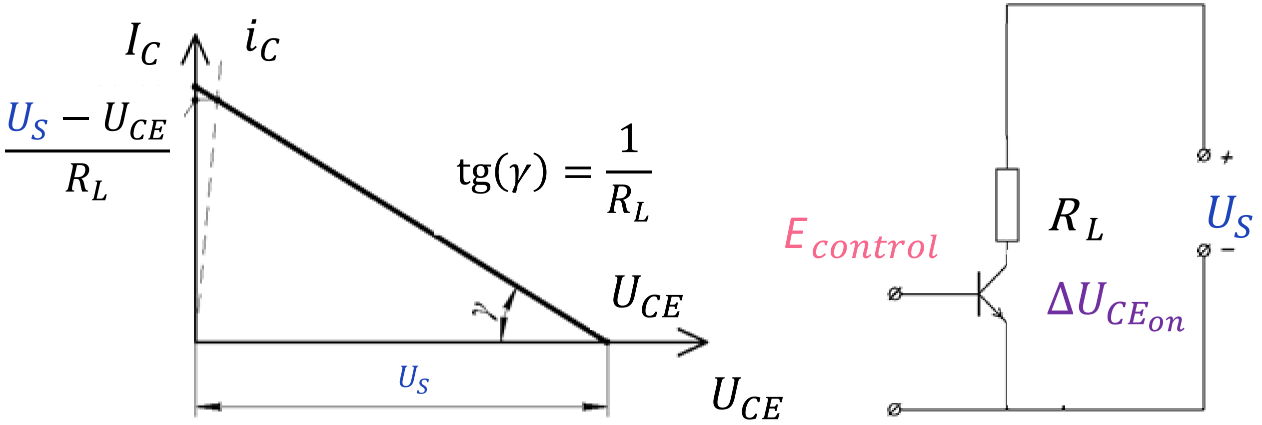
$$I_{C_{off}}(t) = I_{R_L max}\left(\frac{t}{t_+}\right)$$

$$u_{CE_{on}}(t) = U_S\left(1 - \frac{t}{t_+}\right)$$

$$I_{C_{on}}(t) = I_{R_L max}\left(1 - \frac{t}{t_-}\right)$$

$$u_{CE_{off}}(t) = U_S\left(\frac{t}{t_-}\right)$$





$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

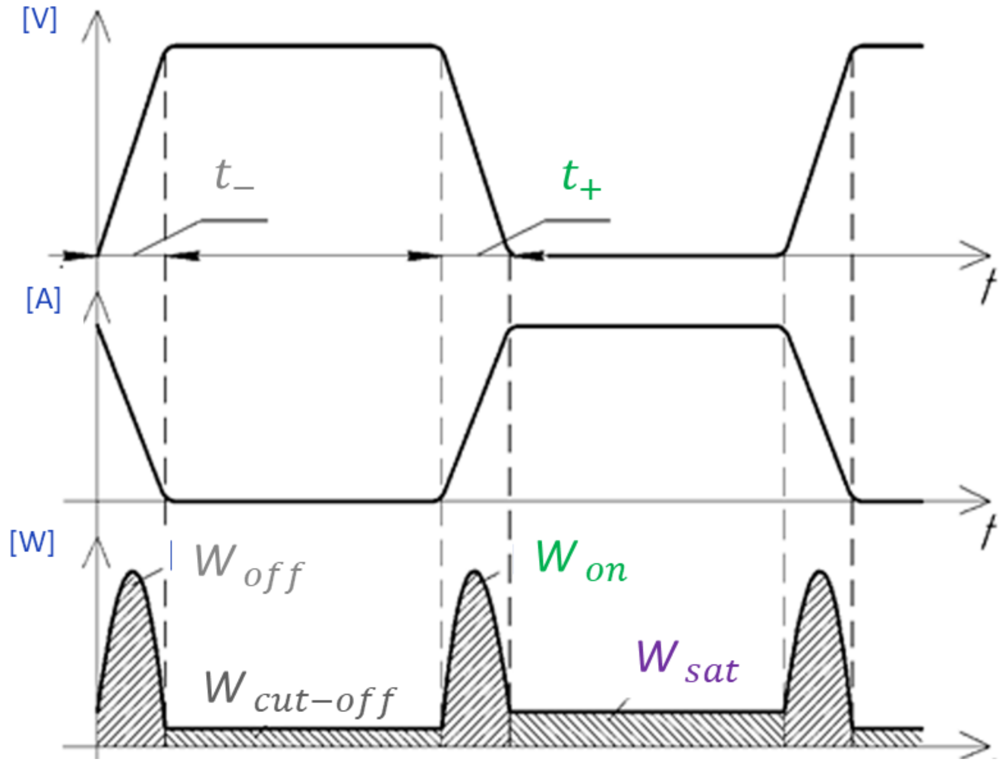
Energy losses during one switching interval

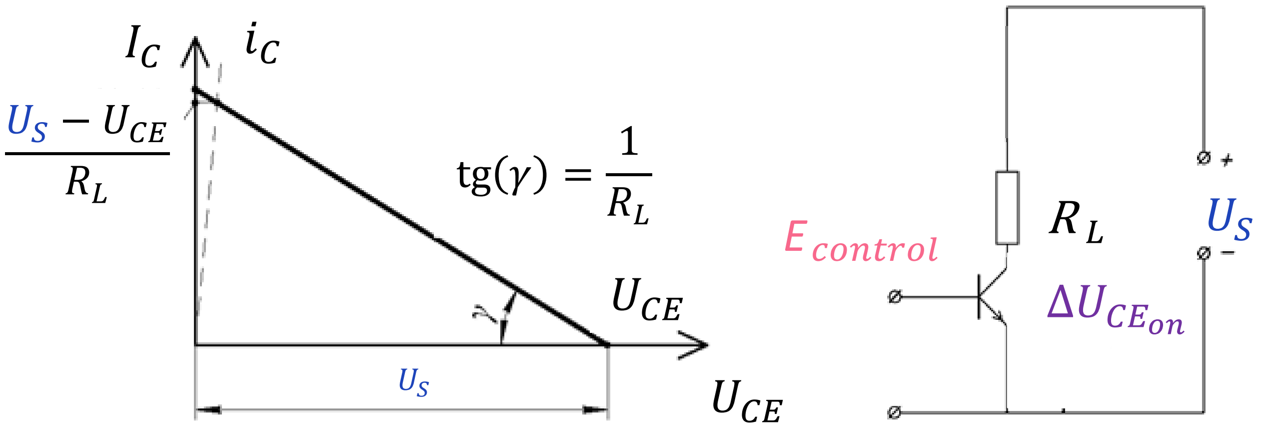
$$\Delta P = P_{sat} + P_{cut-off} + P_S = P_{sat} + P_{on} + P_{off}$$

$$W_S = P_{S_{max}} \left[\int_0^{t_+} \left(\frac{t}{t_+} - \frac{t^2}{t_+^2} \right) dt + \int_0^{t_-} \left(\frac{t}{t_-} - \frac{t^2}{t_-^2} \right) dt \right] = P_{S_{max}} \frac{(t_+ + t_-)}{6}$$

Energy losses during periodic switching:

$$W(t) = P_{S_{max}} \frac{(t_+ + t_-)}{6} f_{sw} \cdot t$$

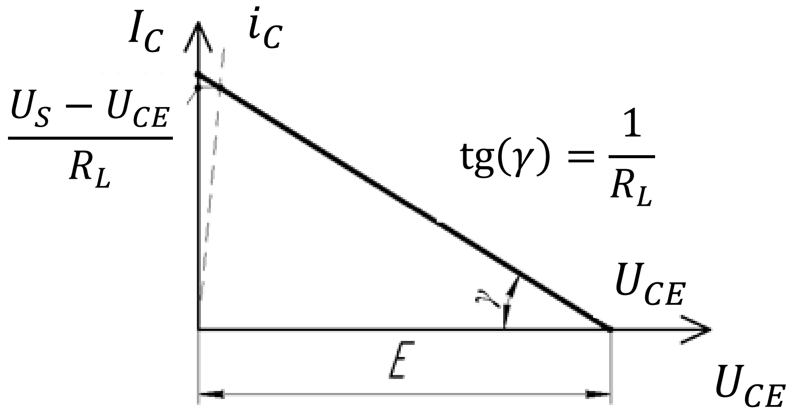




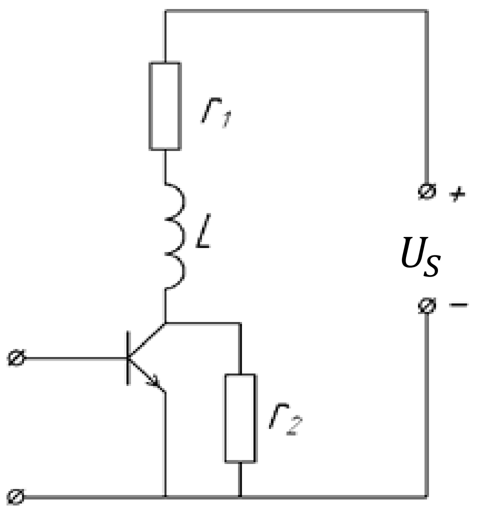
$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

The voltage applied to the BJT connecting the circuit with r_1 and r_2 resistancesand inductance L at the time of switching can be many times higher than the supply voltage

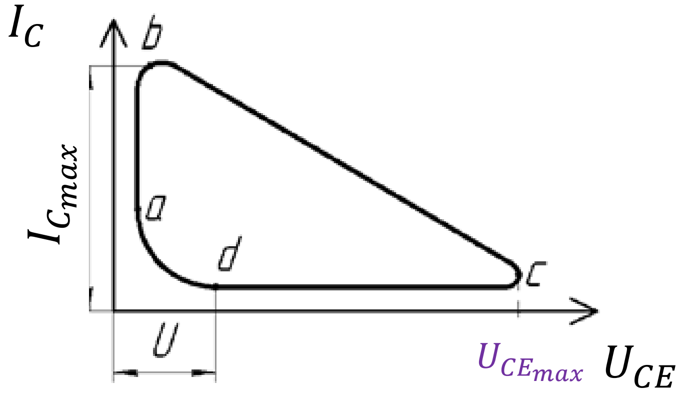
$$U_{CE} = U_s \frac{r_1}{r_2}$$



Operating point of the transistor working on resistive load



BJT working on active-inductive load

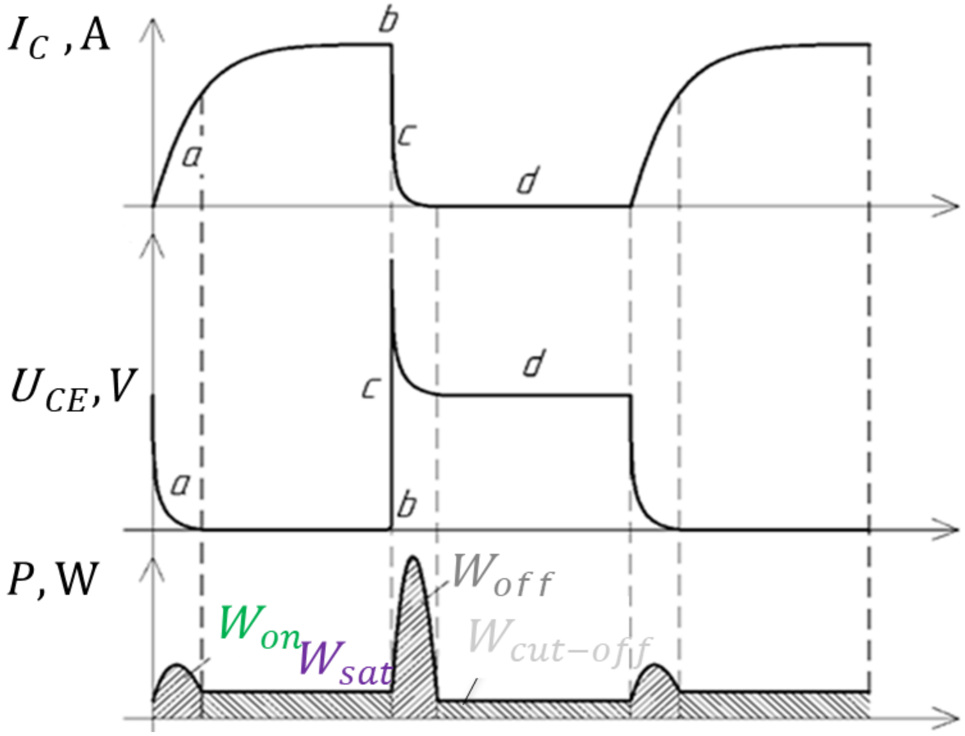


Operating trajectory of BJT working on active-inductive load

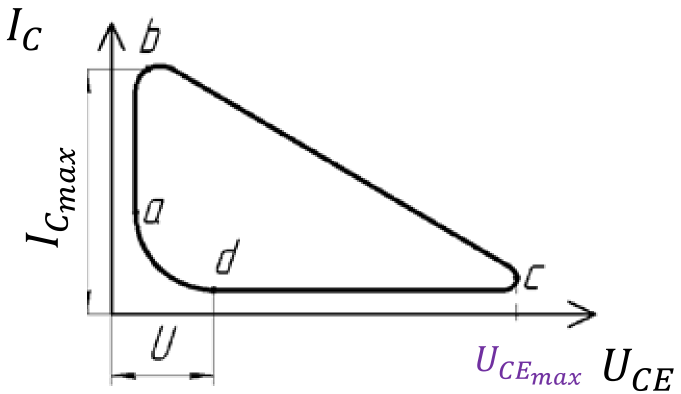
$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

$$U_{CE} = U_s \frac{r_1}{r_2}$$

Energy stored in inductance $W_L = \frac{L \cdot I_C^2}{2}$ will be released as heat in the BJT when it will be switching off



Power loss in BJT operating on an active-inductive load without reverse diode

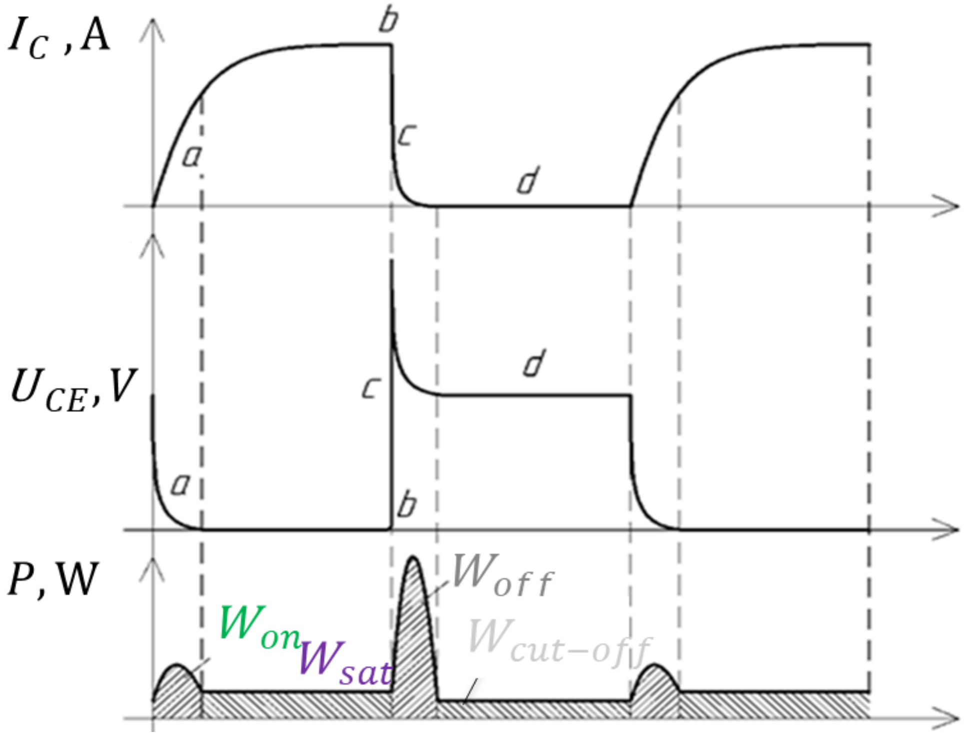


Operating trajectory of BJT working on active-inductive load

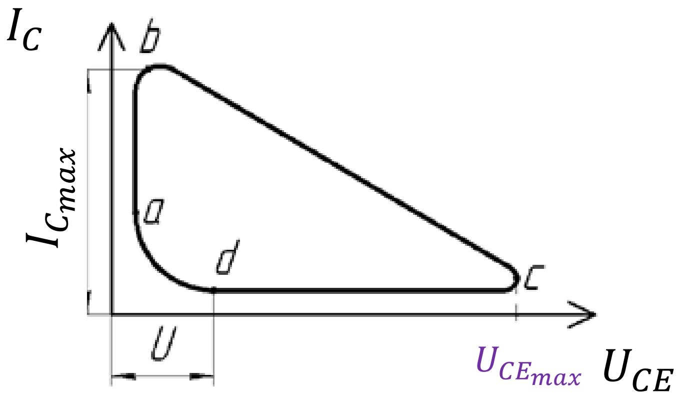
$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

Energy losses (singular switching):

$$\boxed{W_S = UI\left[\int_0^{t_+}\left(\frac{t}{t_+}\right)dt + \int_0^{t_-}\left(1-\frac{t}{t_-}\right)dt\right] = P_{S_{max}}\frac{(t_+ + t_-)}{2}}$$



Power loss in BJT operating on an active-inductive load without reverse diode

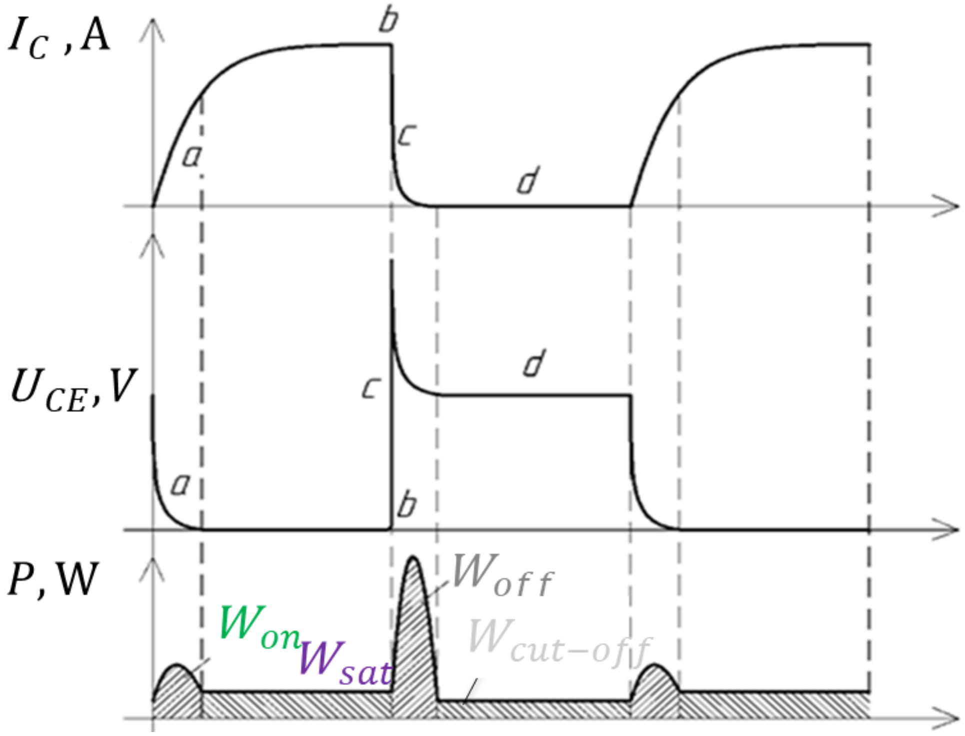


Operating trajectory of BJT working on active-inductive load

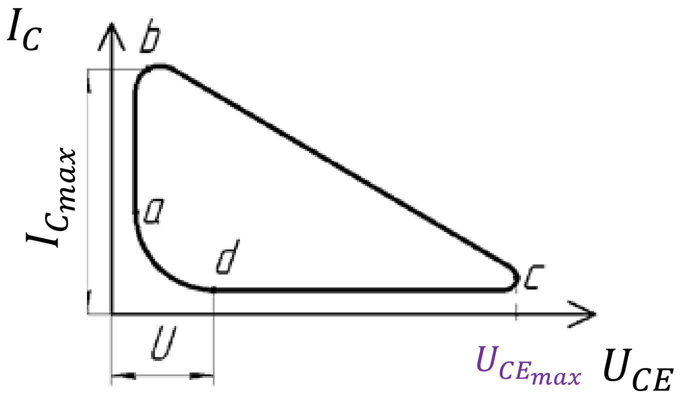
$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

Energy losses (periodic switching)

$$\boxed{W_S(t) = P_{S_{max}} \frac{(t_+ + t_-)}{2} f_{sw} \cdot t}$$



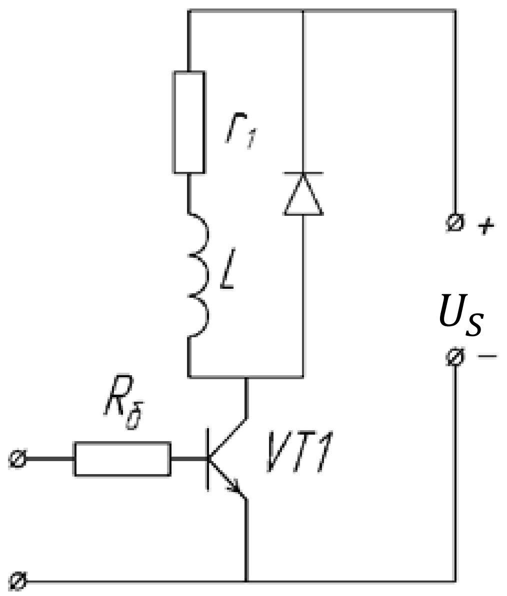
Power loss in BJT operating on an active-inductive load without reverse diode



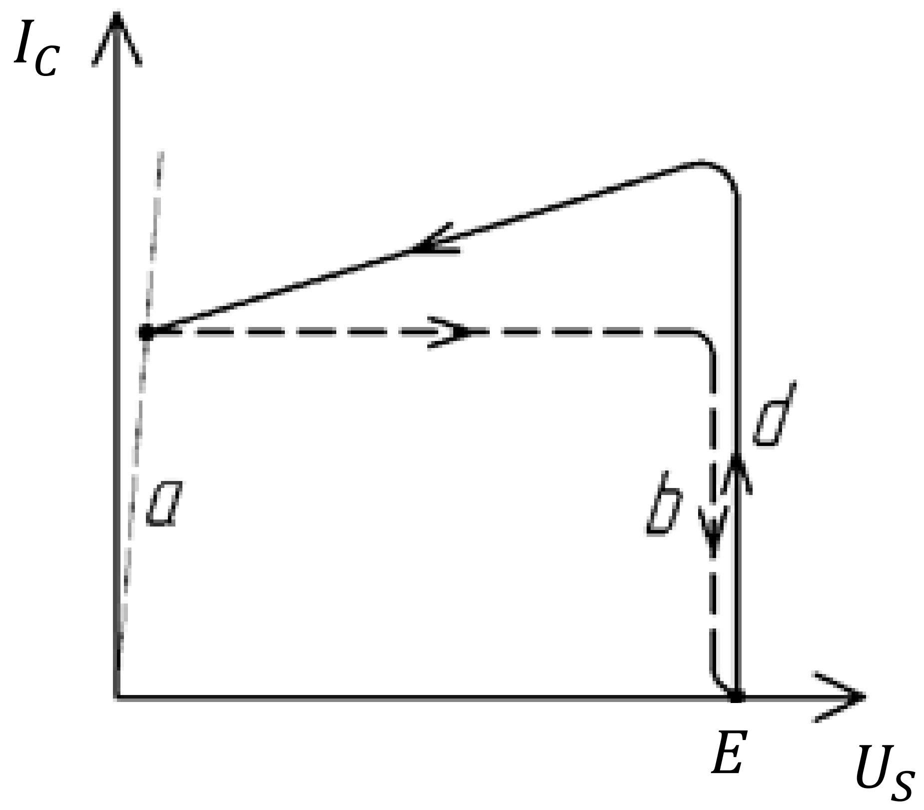
Operating trajectory of BJT working on active-inductive load

$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

Energy stored in inductance $W_L = \frac{L \cdot I_C^2}{2}$ will be released as heat in the BJT when it will be switching off



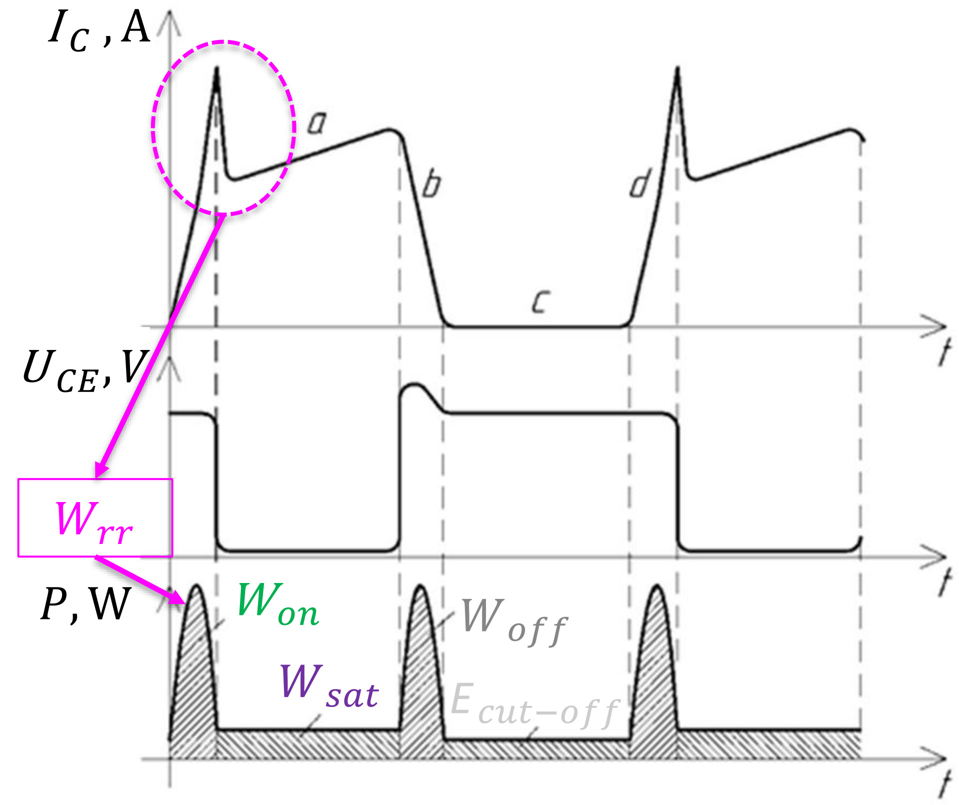
Power loss in BJT operating on an active-inductive load with reverse diode



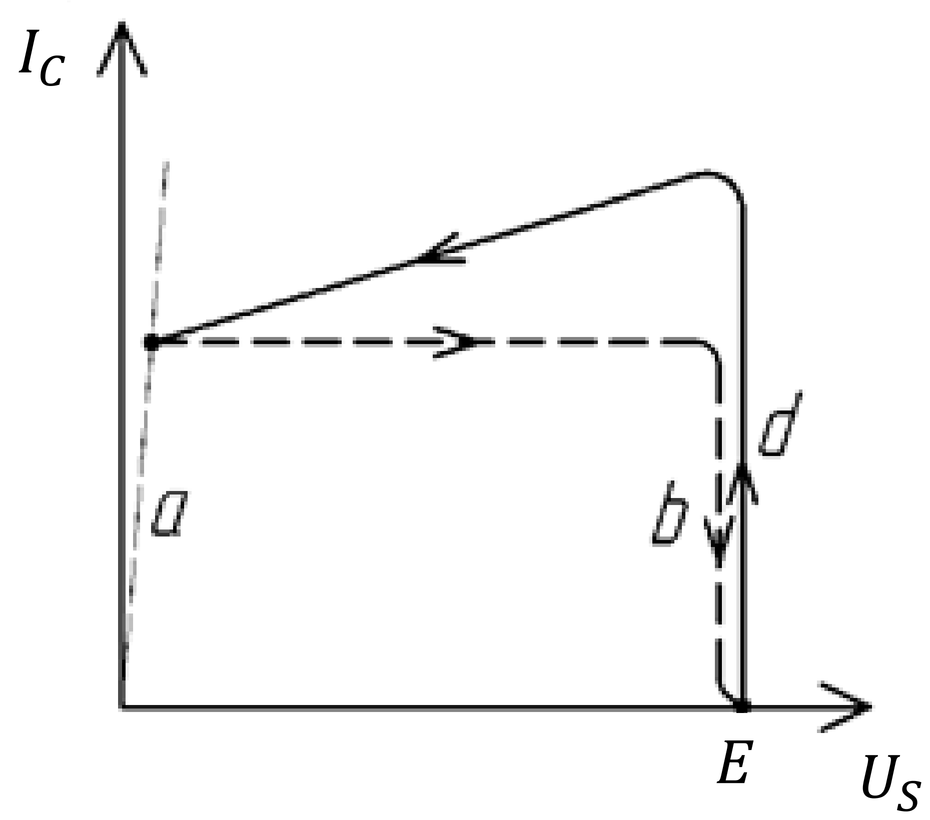
Operating trajectory of BJT working on active-inductive load with reverse diode

$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

Energy stored in inductance $W_L = \frac{L \cdot I_C^2}{2}$ will be released as heat in the BJT when it will be switching off

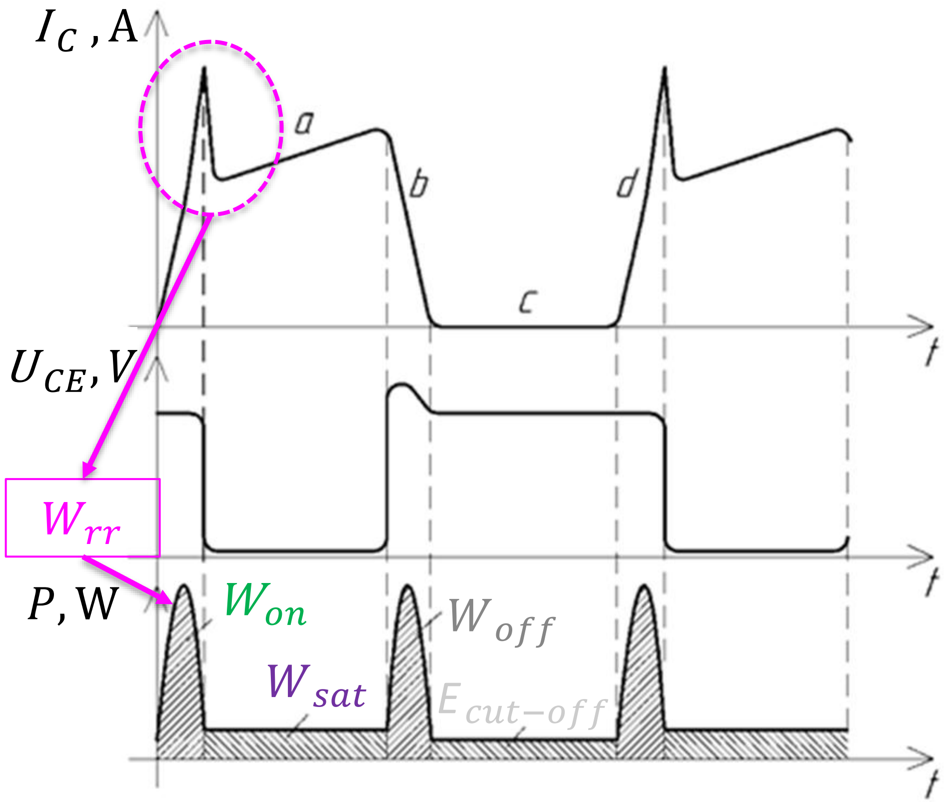


Power loss in BJT operating on an active-inductive load with reverse diode



Operating trajectory of BJT working on active-inductive load with reverse diode

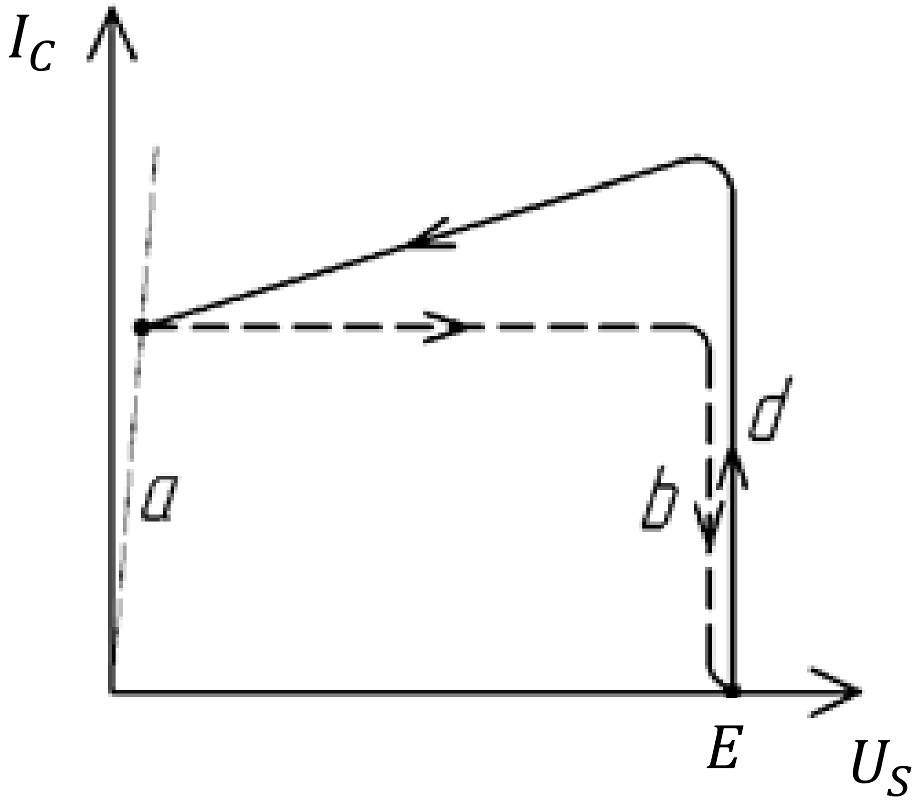
$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$



Power loss in BJT operating on an active-inductive load with reverse diode

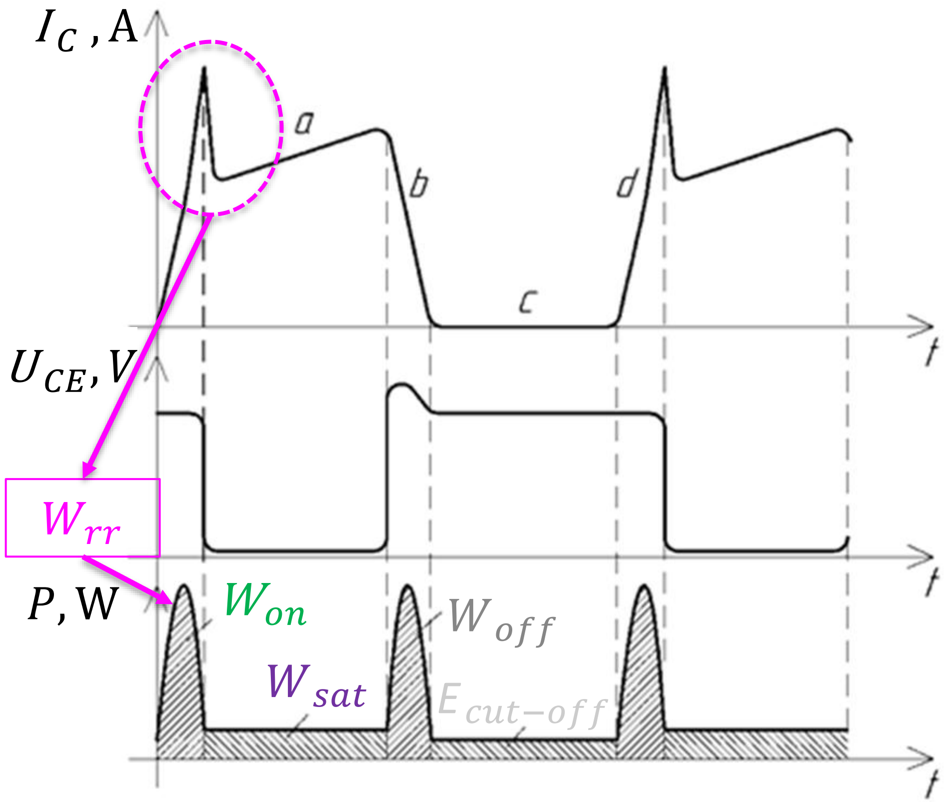
Energy losses (singular switching):

$$\boxed{W_S = UI\left[\int_0^{t_+}\left(\frac{t}{t_+}\right)dt + \int_0^{t_-}\left(1-\frac{t}{t_-}\right)dt\right] = P_{S_{max}}\frac{(t_+ + t_-)}{2}}$$



Operating trajectory of BJT working on active-inductive load with reverse diode

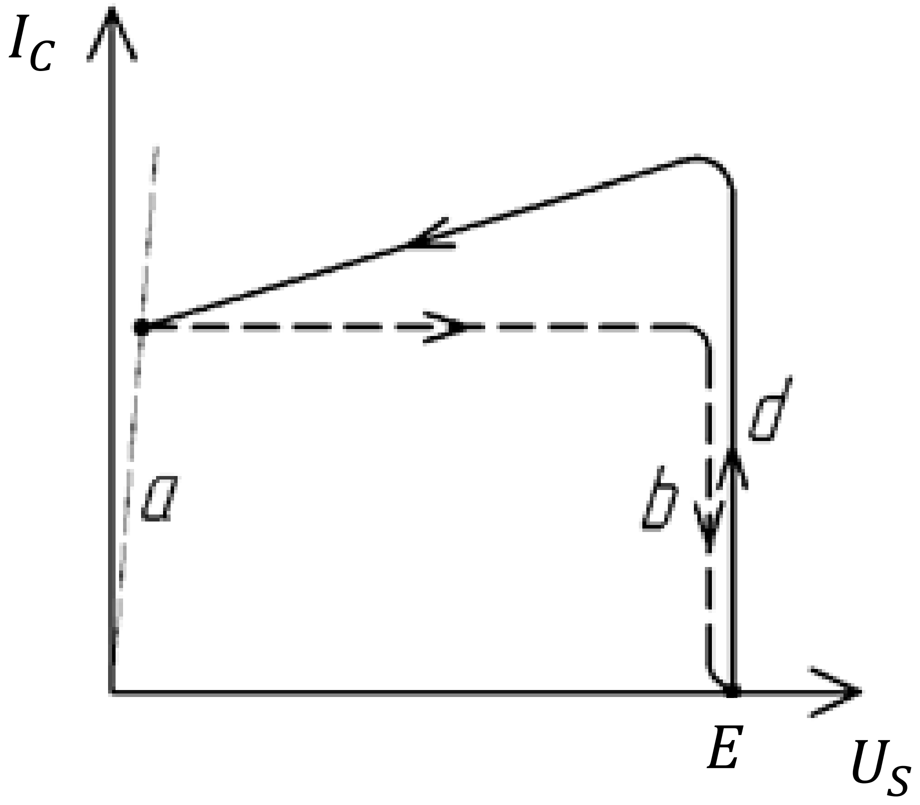
$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$



Power loss in BJT operating on an active-inductive load with reverse diode

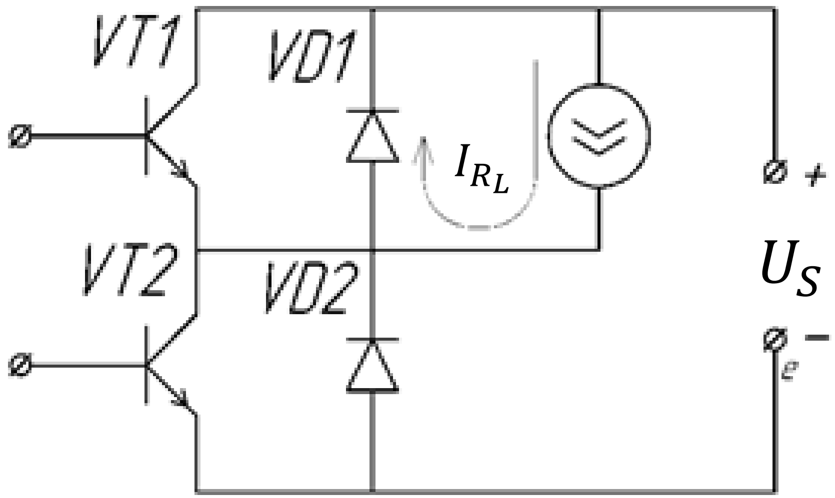
Energy losses (periodic switching)

$$\boxed{W_S(t) = \left(P_{S_{max}} \frac{(t_+ + t_-)}{2} f_{sw}\right) t}$$

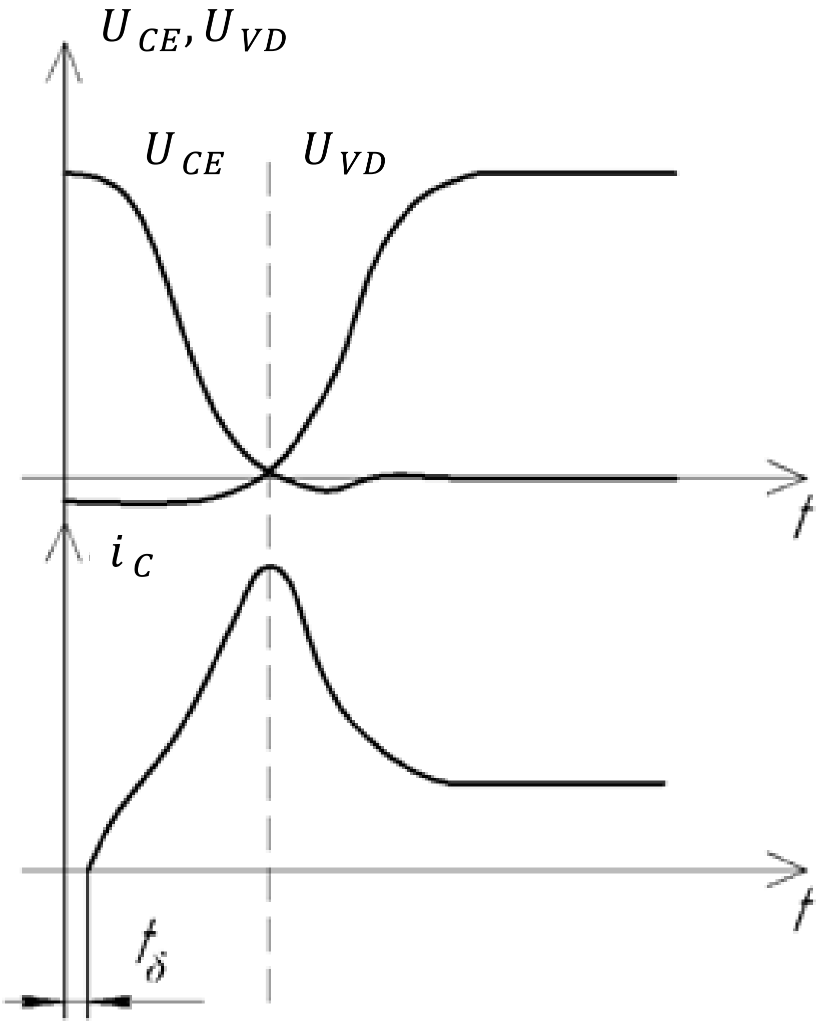


Operating trajectory of BJT working on active-inductive load with reverse diode

$$W_\Sigma = W_S + W_{sat} + W_{cut-off} + W_{control} =$$
$$= W_{off} + W_{on} + W_{rr} + W_{sat}$$

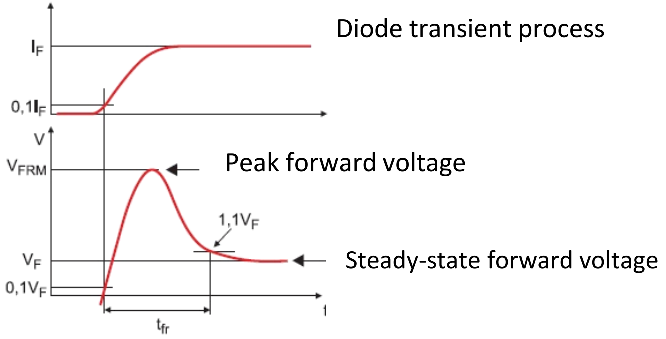


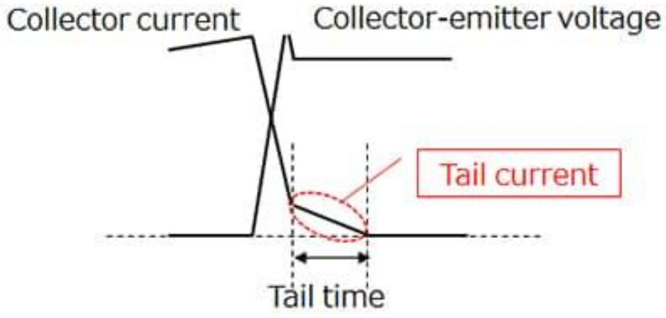
Electromagnetic processes are the most difficult if the values of the dynamic parameters of the diode and the transistor are of the same order.

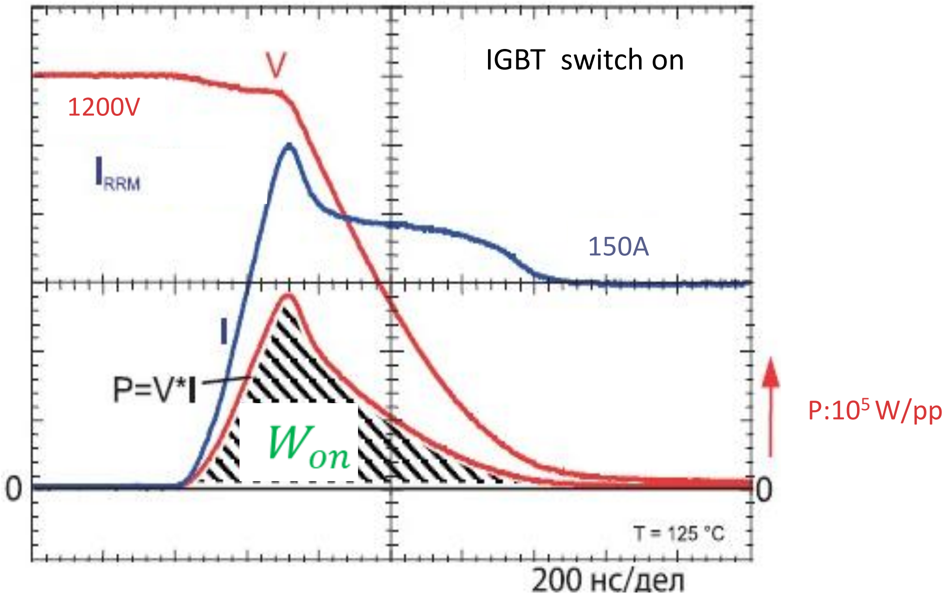


Switching processes in transistor and diode with close-value of dynamic parameters

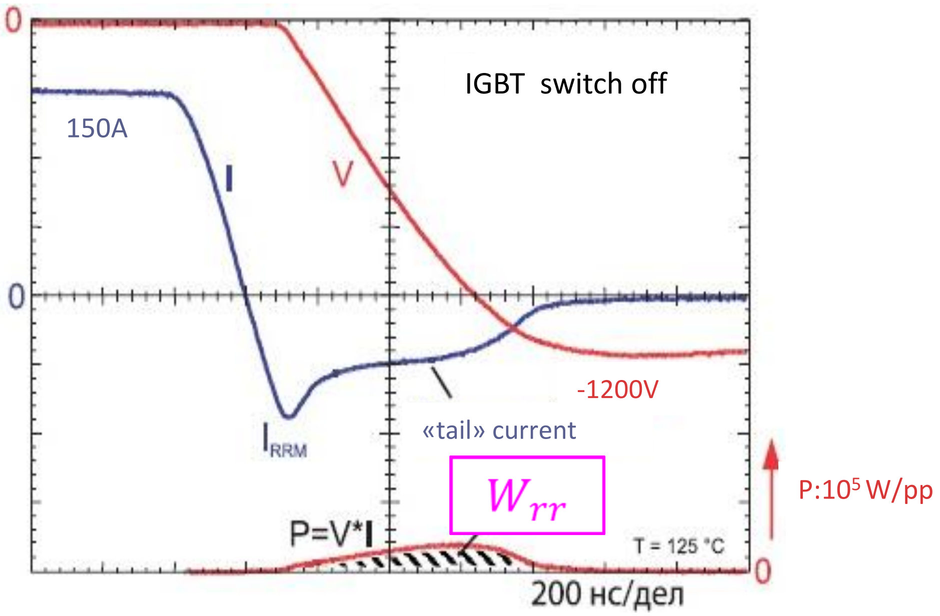
Dynamic power losses of IGBT and SiC power switches







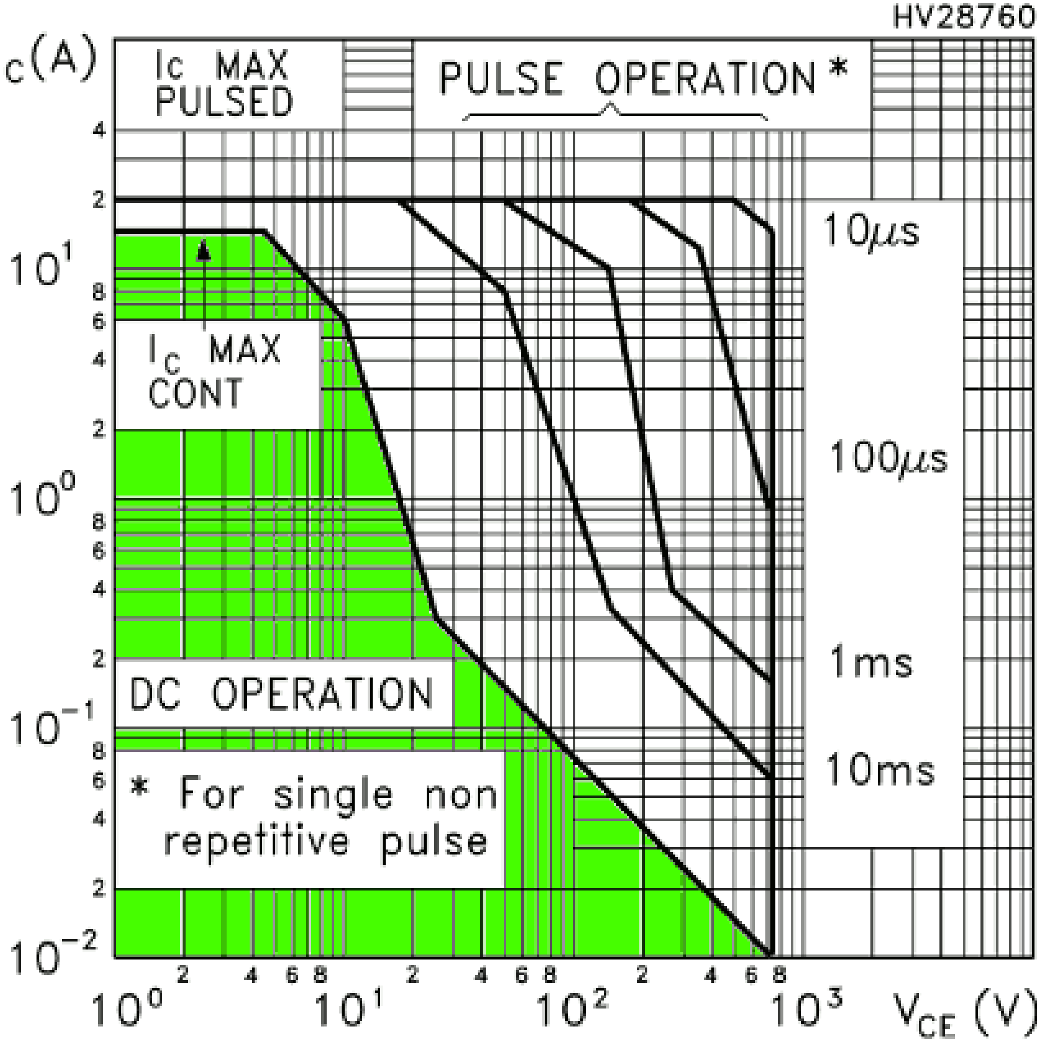
a) IGBT switch on (nominal parameters 150 A/1700 V);



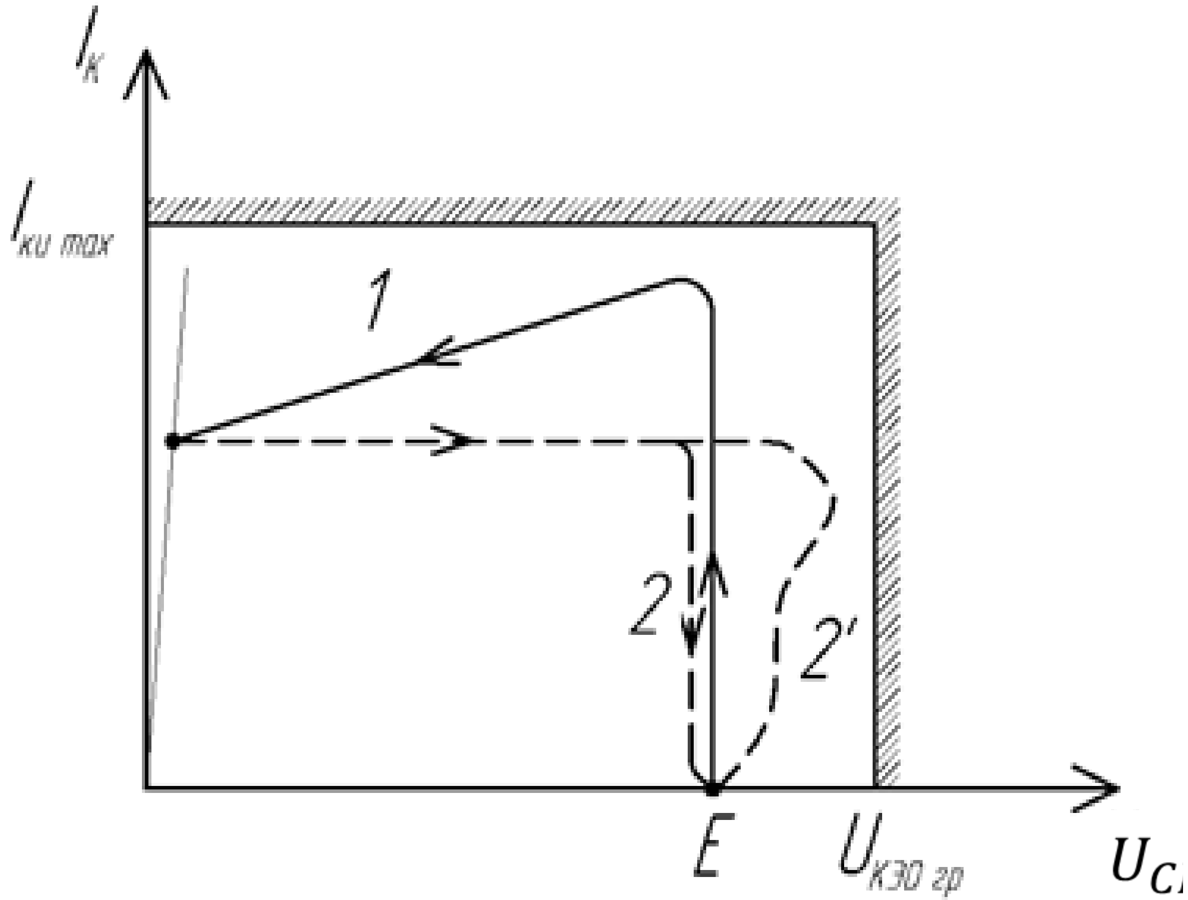
b) IGBT switch on (nominal parameters 150 A/1700 V);

https://power-e.ru/components/fakty-iz-zhizni-igbt-i-fwd-1/

Safe operation area (SOA)

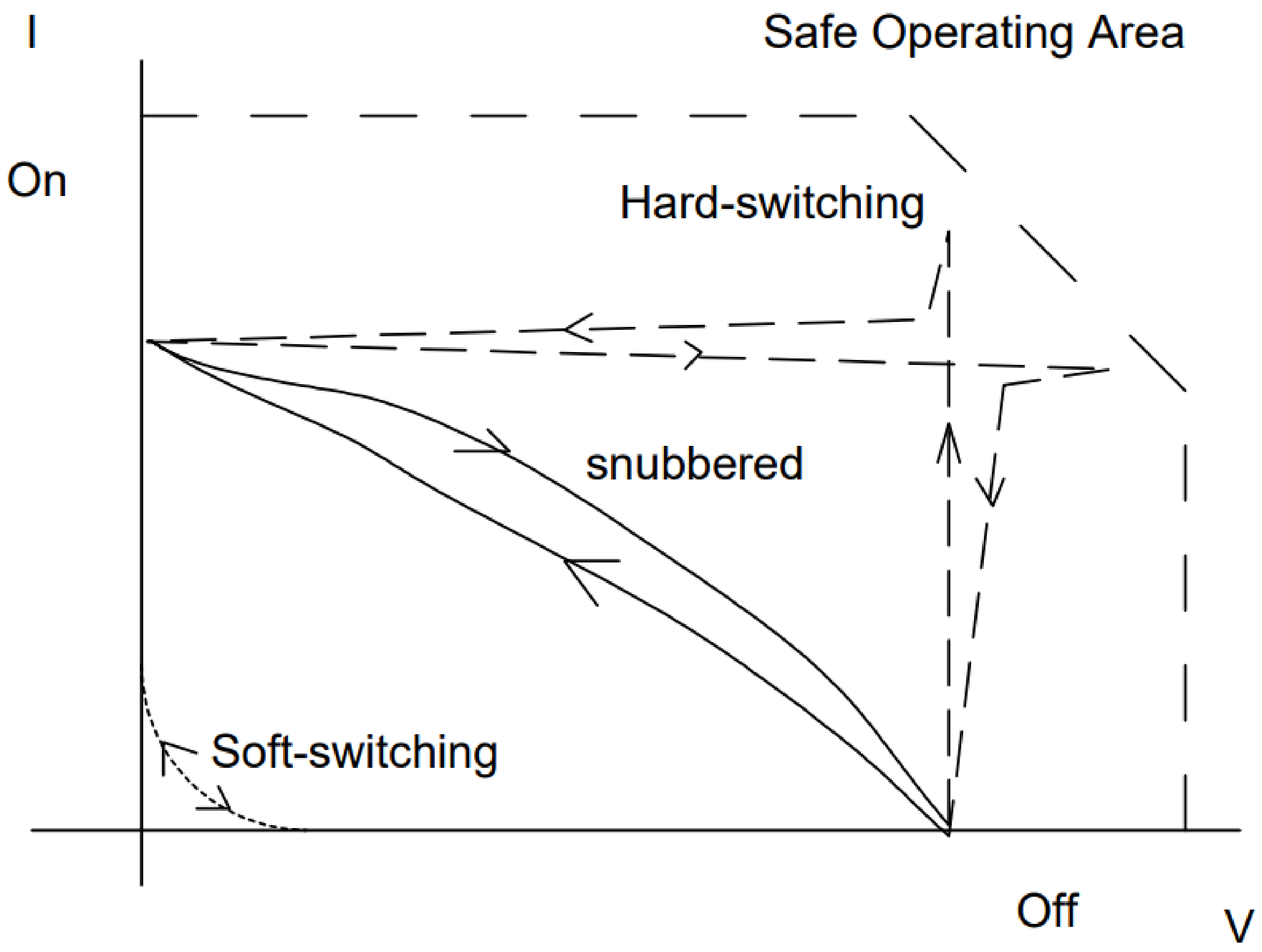


SOA

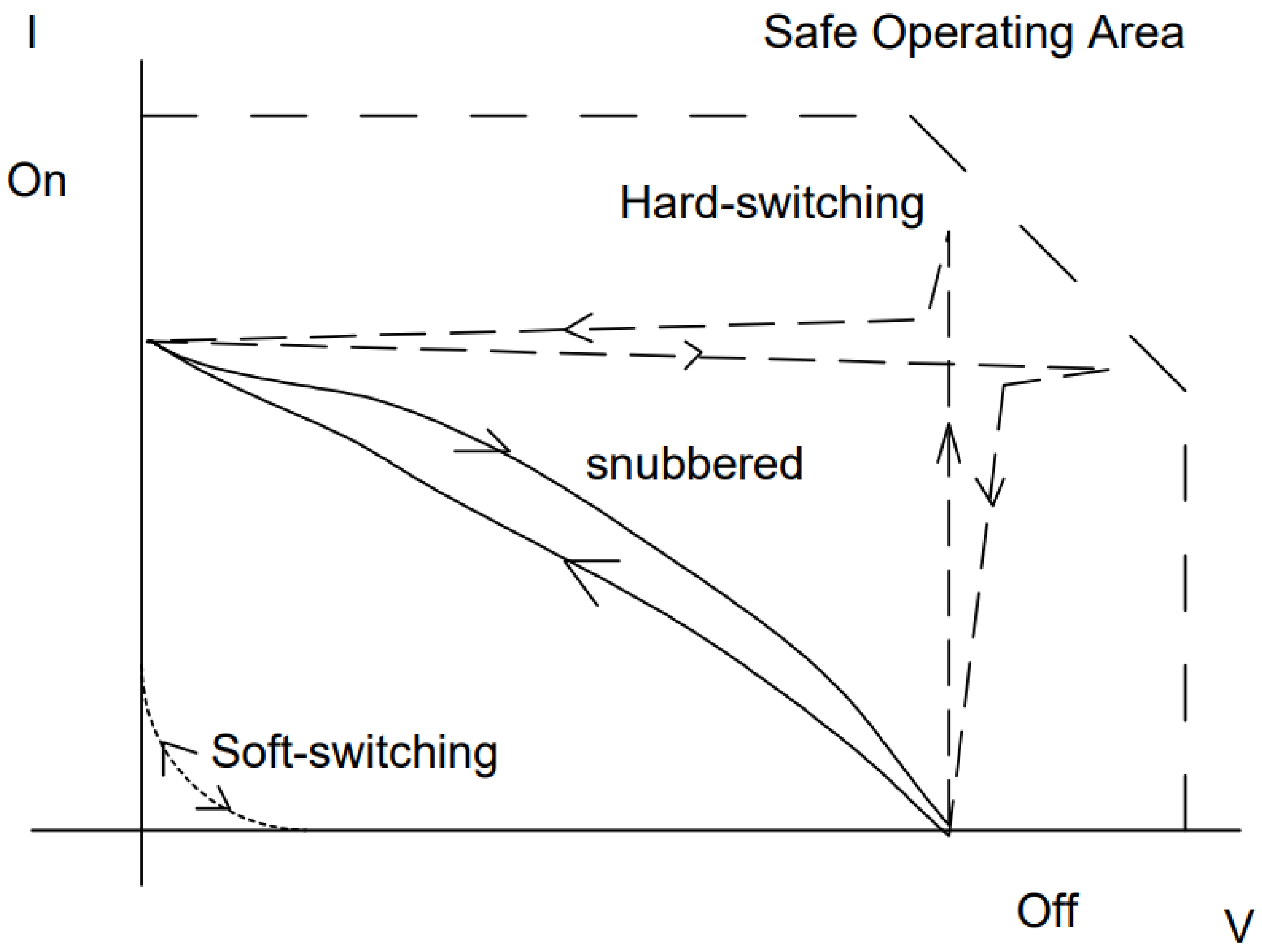


Switching trajectories of the power transistor without snubber circuits

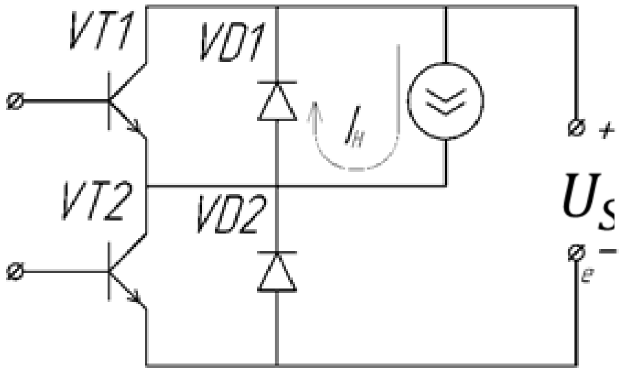
Hard and soft switching characteristics

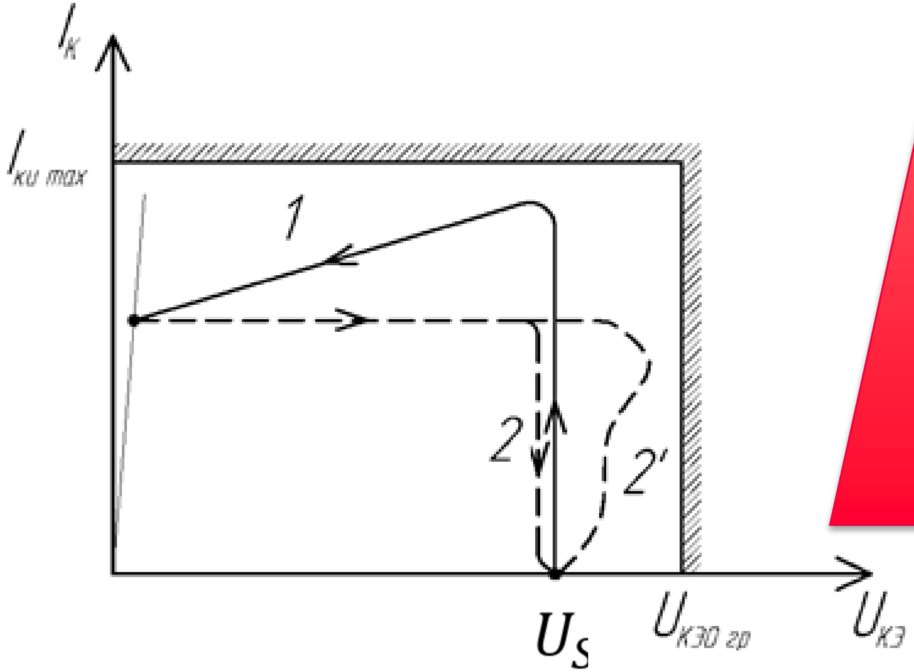


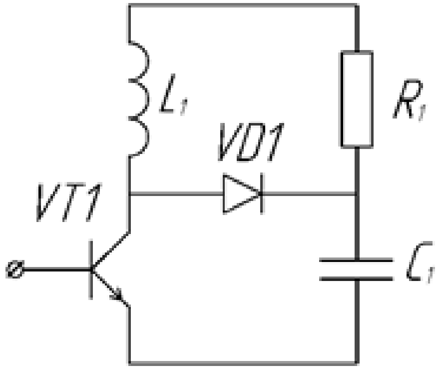
Hard and soft switching characteristics

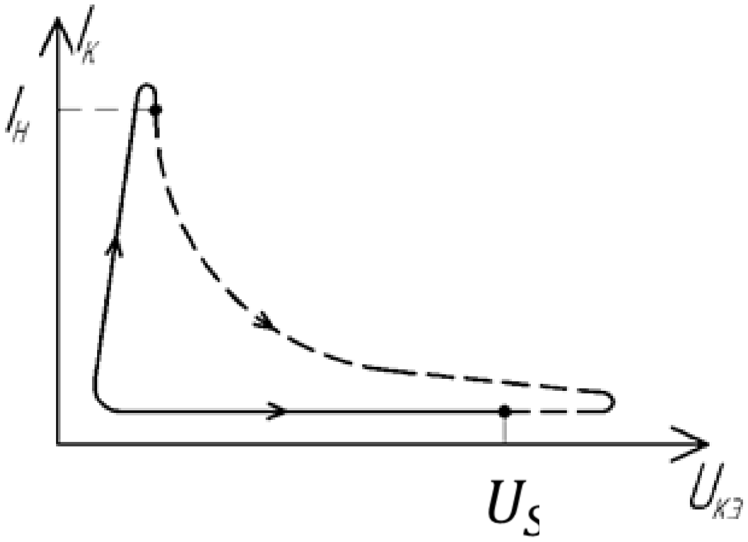


Snubber circuit transistor switching trajectory









Safe operation area (SOA)

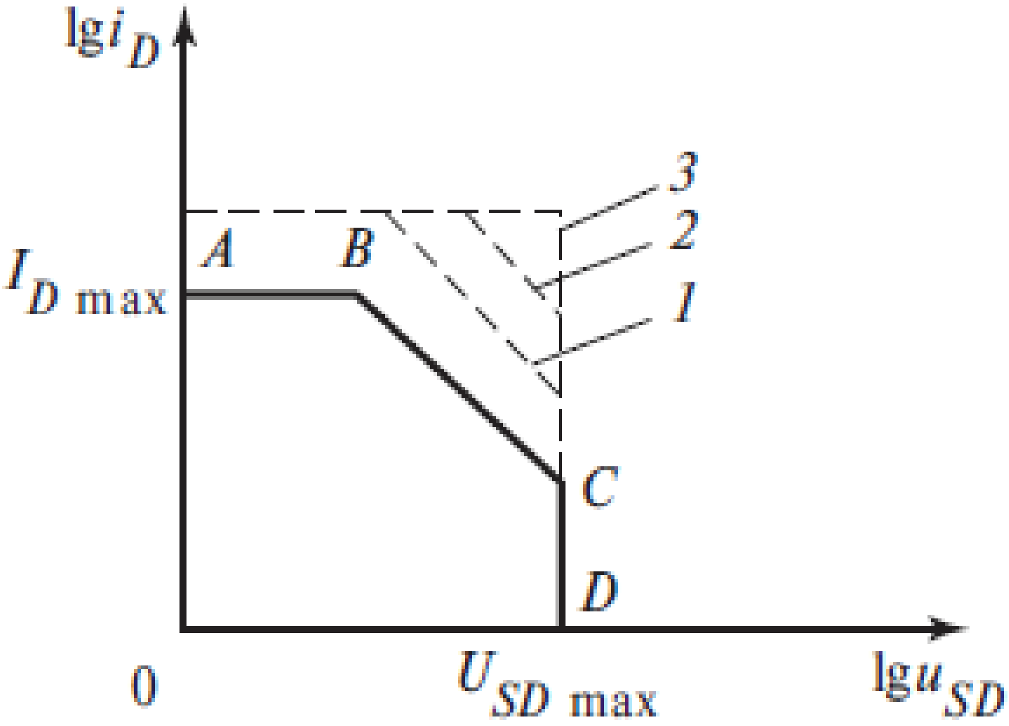
SOA is limited by:

$I_{S\,max}$, $U_{S\,max}$ и $P_{S\,max}$, :

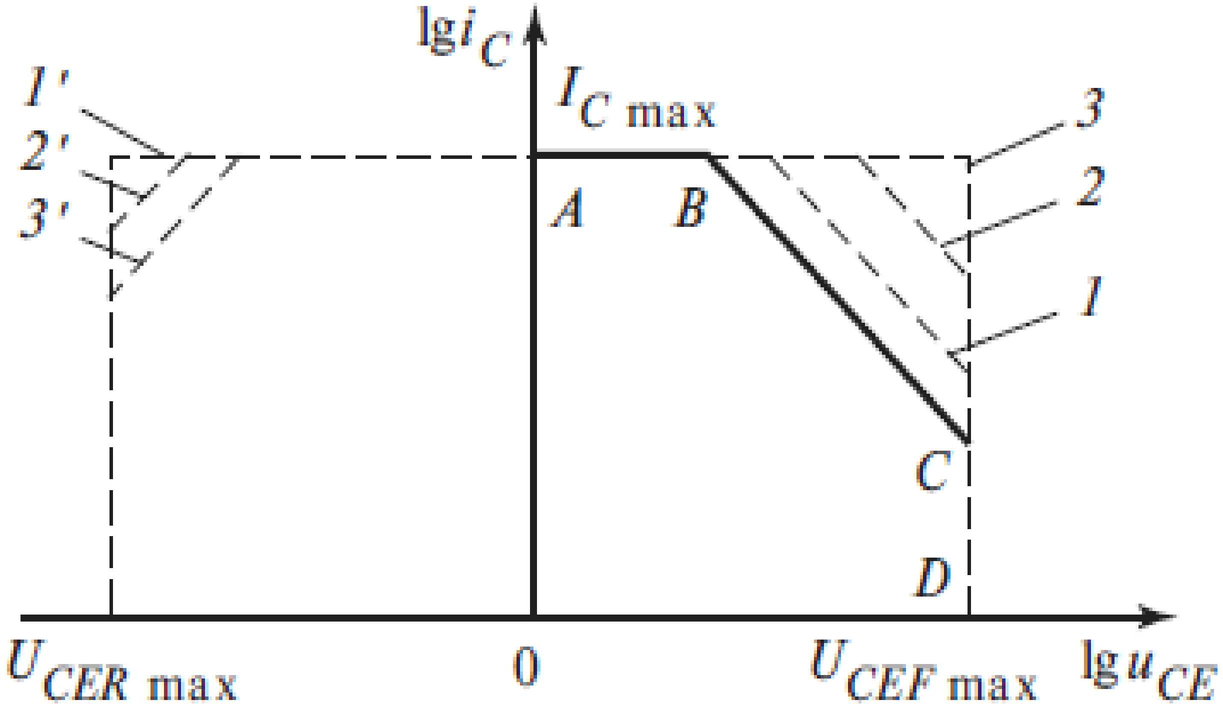
A—B — current limit value $I_{S\,max}$,

B—C — loss power limit $P_{S\,max}$

C — D— voltage limit value $U_{S\,max}$

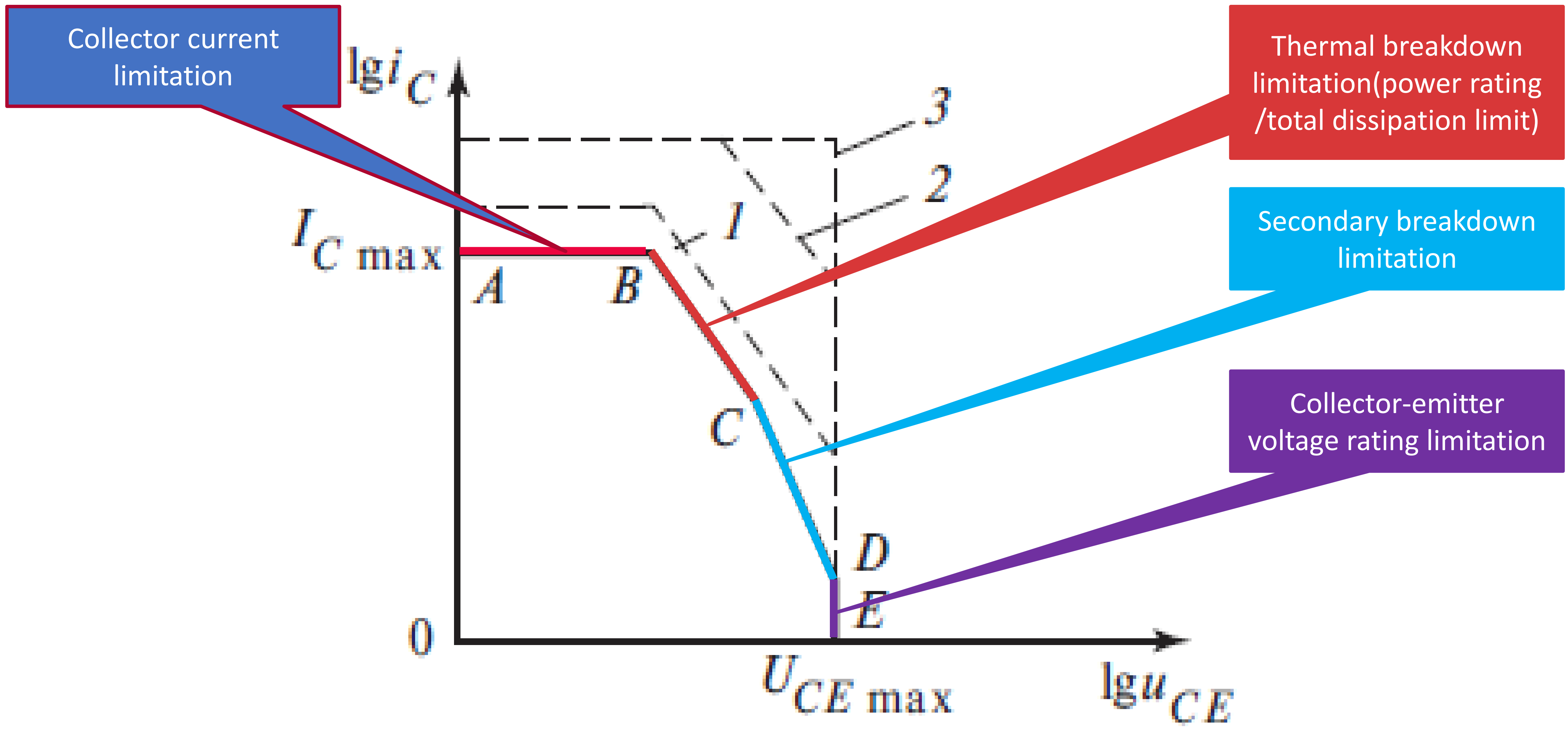


MOSFET

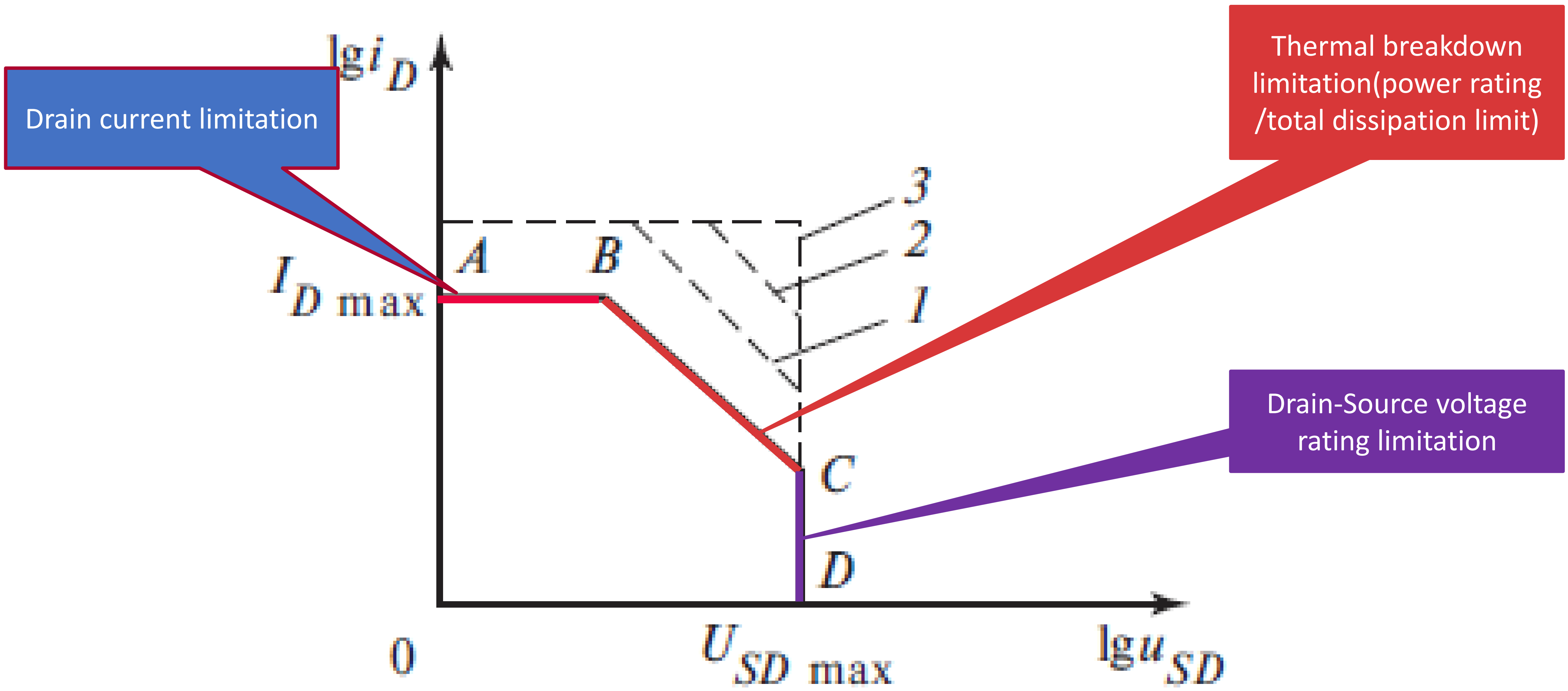


IGBT

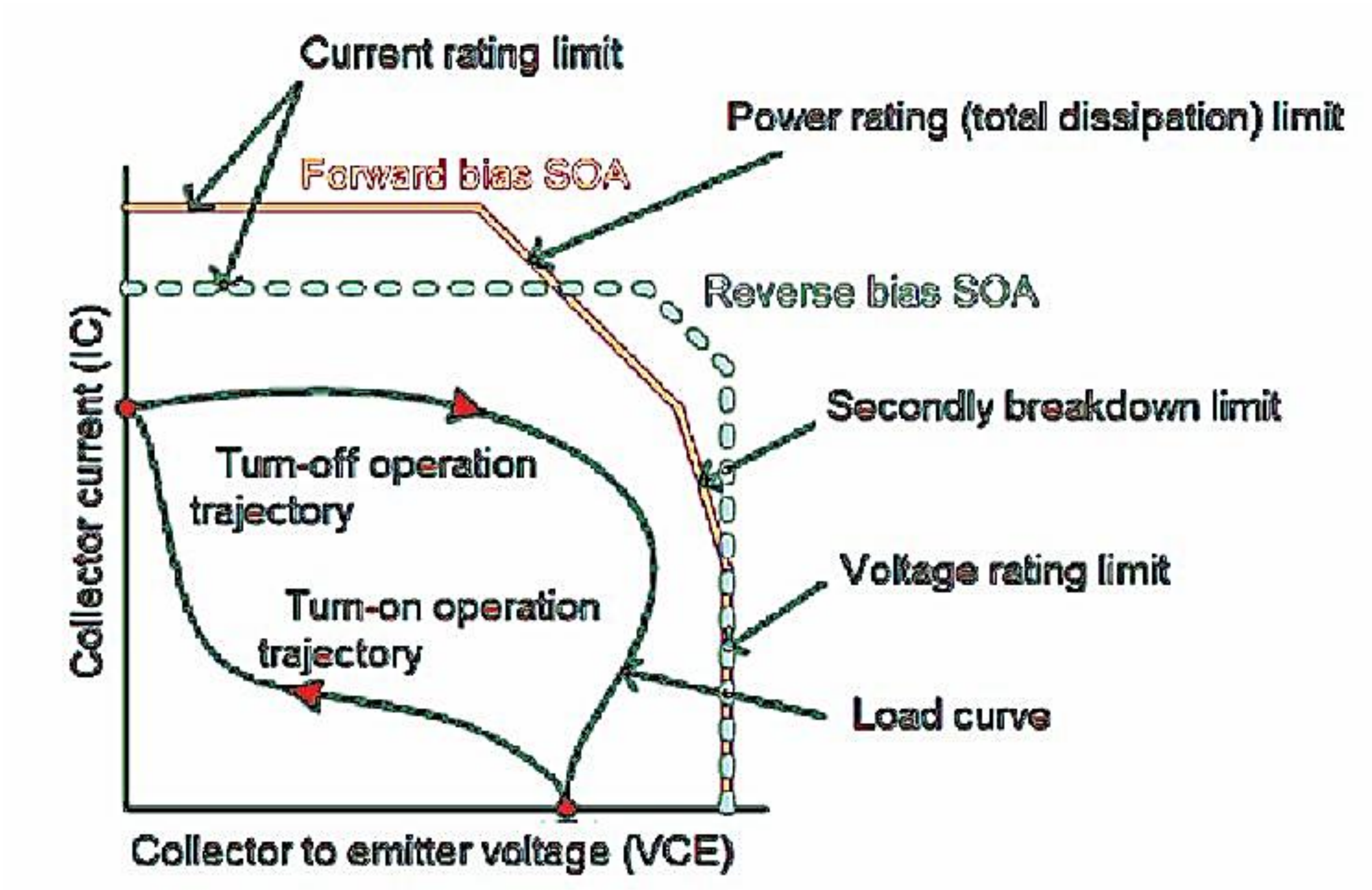
BJT safe operation area (SOA)



MOSFET safe operation area (SOA)



IGBT safe operation area (SOA)



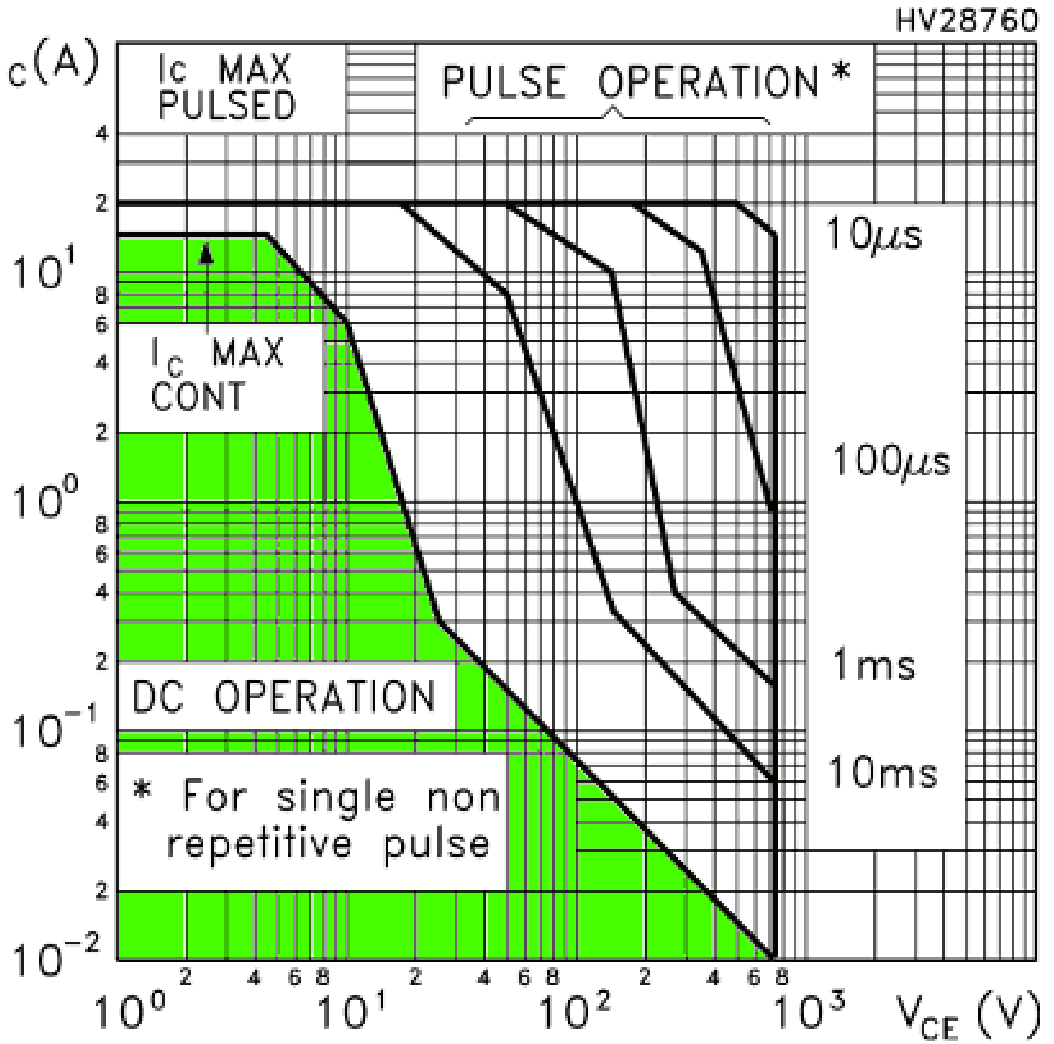
Conclusion: Ideal switch vs SOA

A Triad of compromise requirements for a power switch:

- close to zero conductivity losses, which is determined by the resistance of the R_{dson} open channel for MOSFET or the saturation voltage of V_{CEsat} for IGBT.

- high V_{CE} (V_{DS} for MOSFET)reverse bias voltage in the locked state

- close to zero W_{off} switch-off losses.



Actuators

Next Class:

Lection 8

DC drive power converters with pulse-width modulation (PWM)