Switched supplies with inductors

Basic principles

Basic information

- Switched supplies = supplies that works with an impulse (switched) regulation
- Stabilizer coverts non-stabilized input (DC) to stabilized output DC voltage => DC-DC Converters
- Working frequency > 20kHz (above acoustic range), usually as high as possible (> 1 MHz) **(**dimensions, mass, output signal filtration)
- High requirements on electronic switch, accumulation inductor, impulse transformer, recuperation diode (high working frequency, short switch on and off time, low barrier capacitance)
- All impulse (switched) supplies works in feedback configuration
- Thyristor cannot be used as switching device (DC circuits)

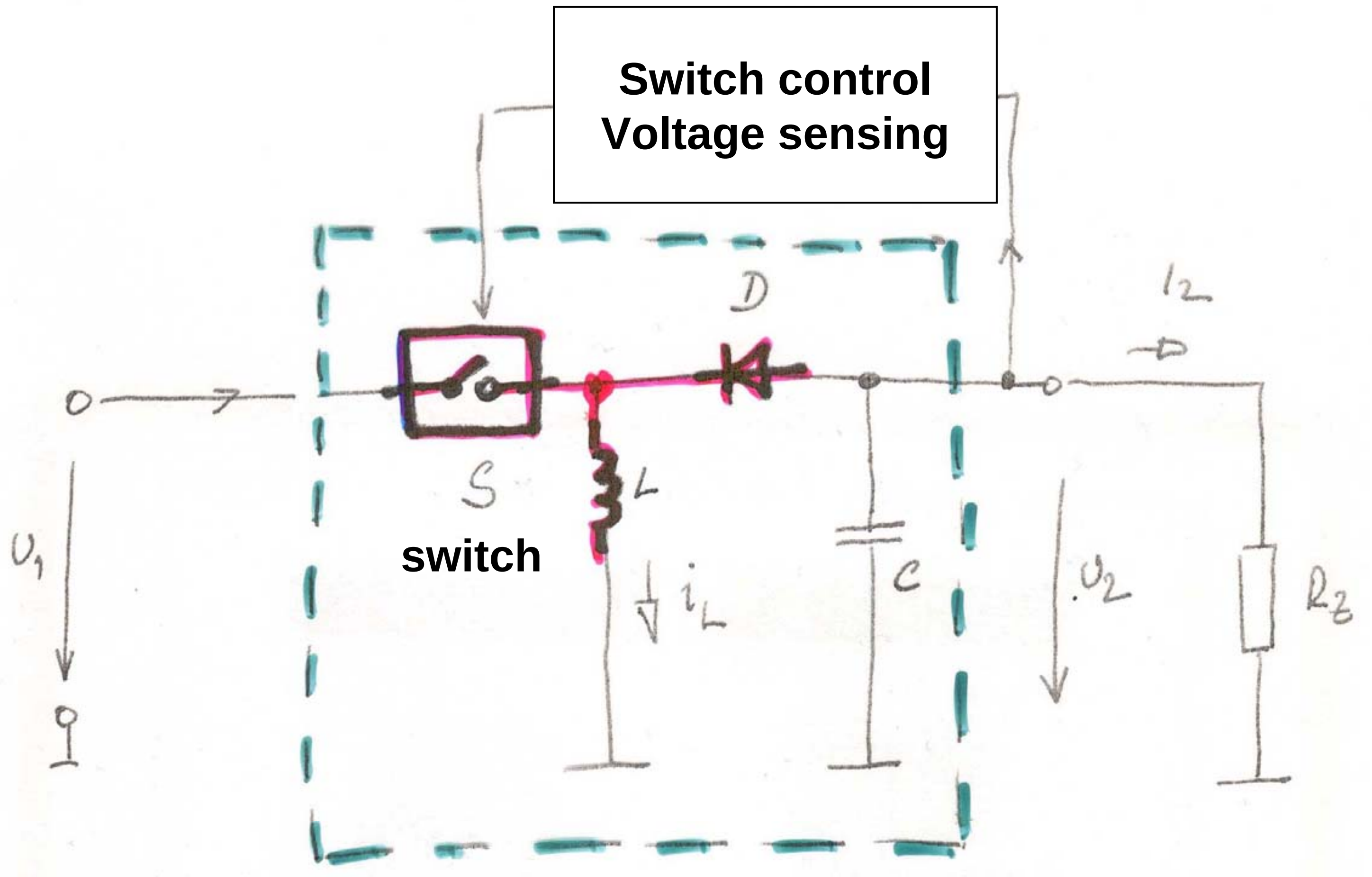
Linear vs. switched

Disadvantages: linear stabilizer: big volume and mass of the stabilizer, low efficiency

Advantages: high efficiency of regulation, low voltage devices, voltage disturbances are filtered by line transformer

Basic principles

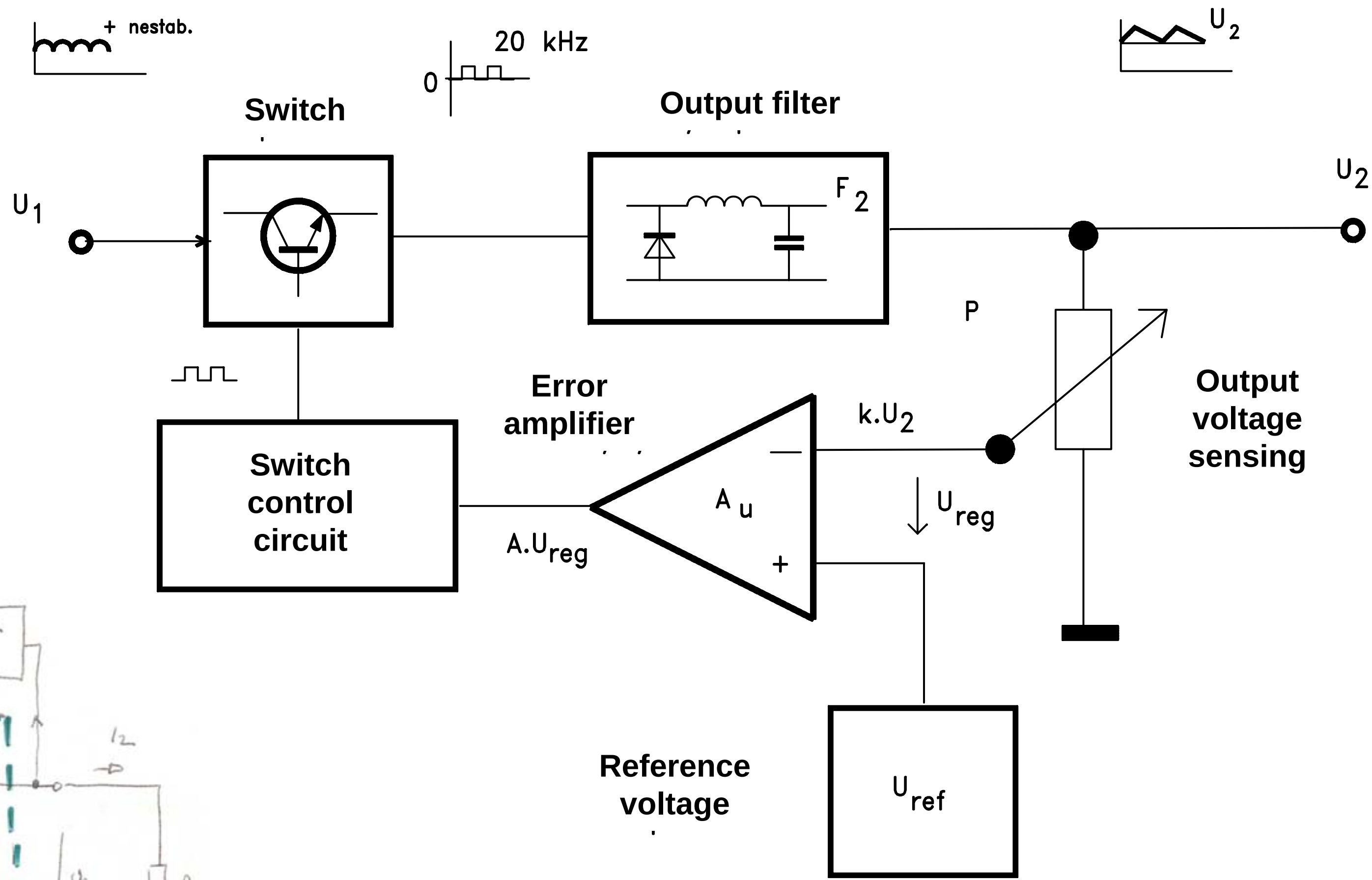
Switched supply with stabilization

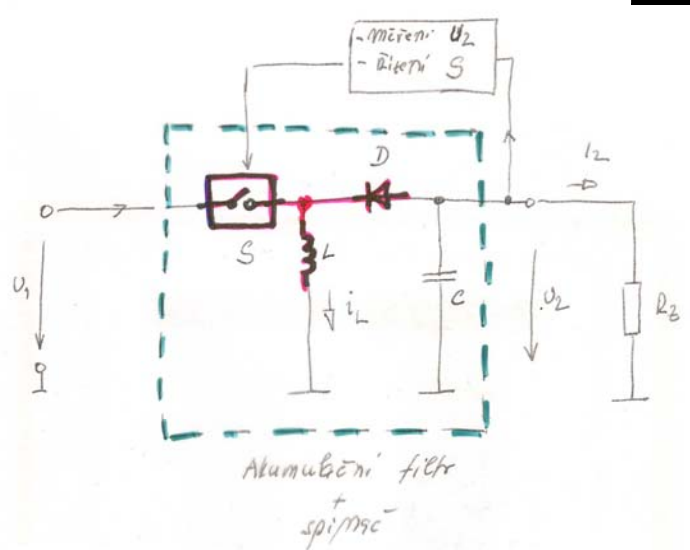


Accumulation filter

Switch

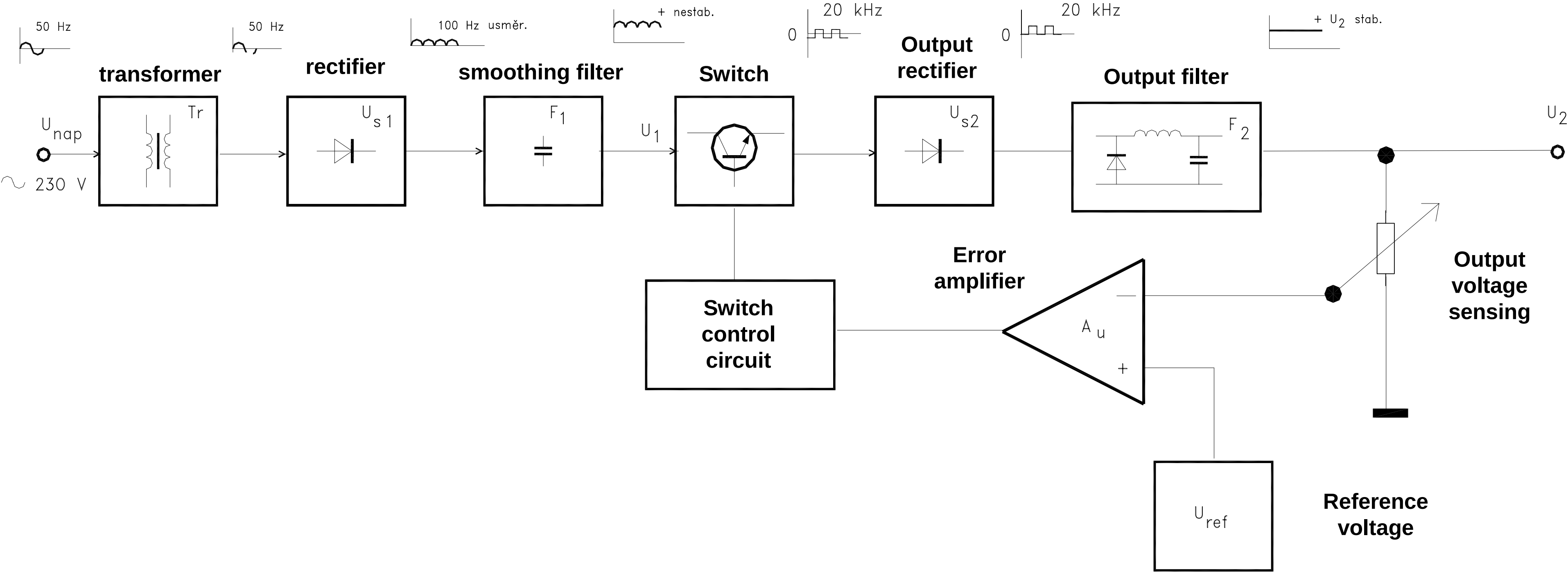
Simplified block circuit



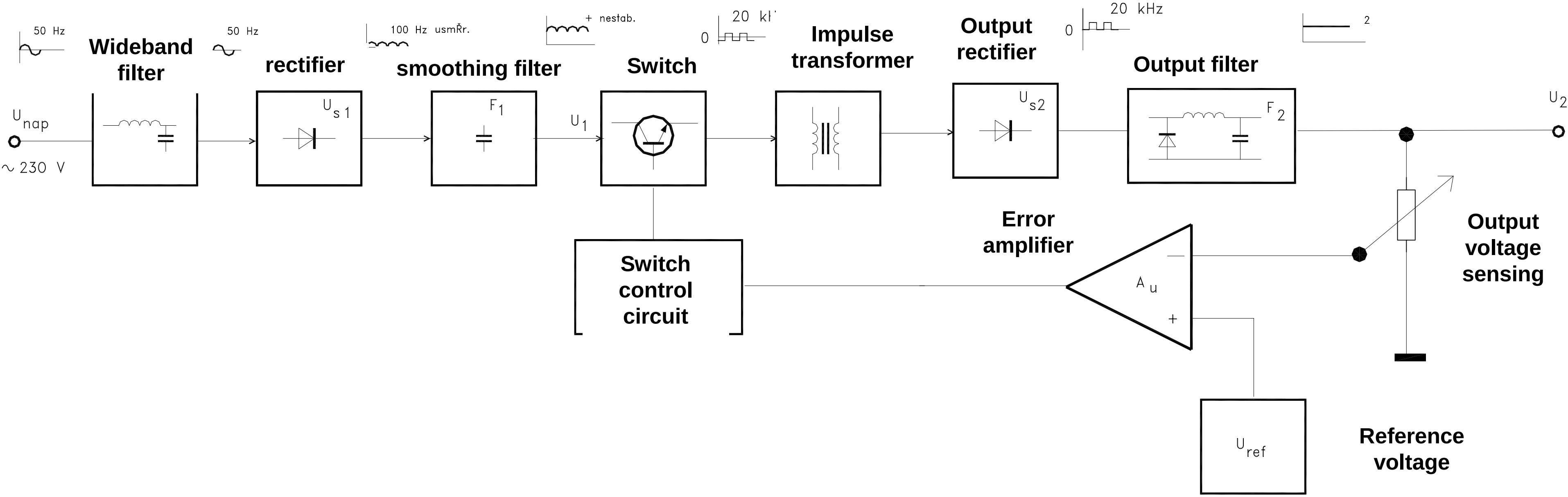


Switched supply with input transformer

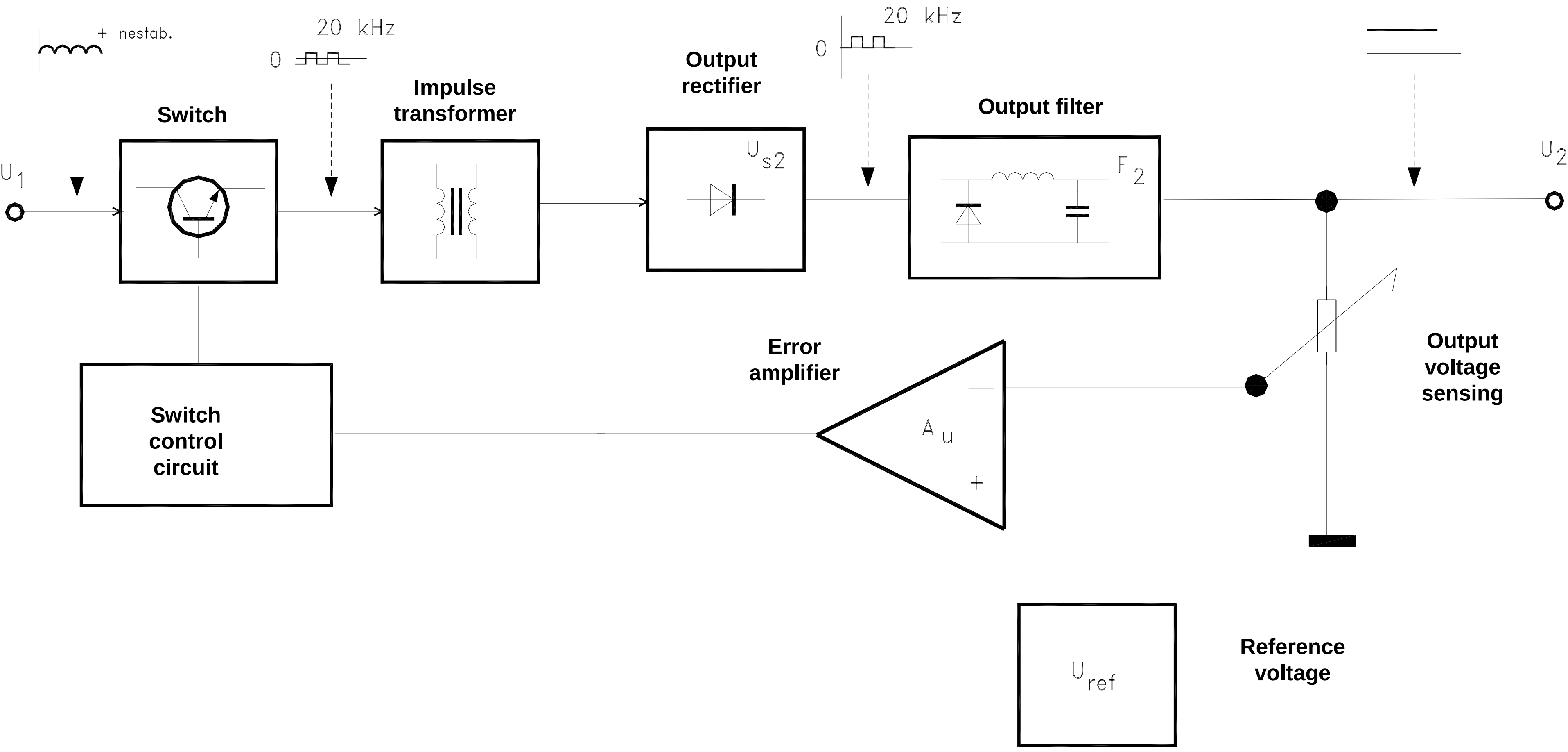
Regulated on secondary part



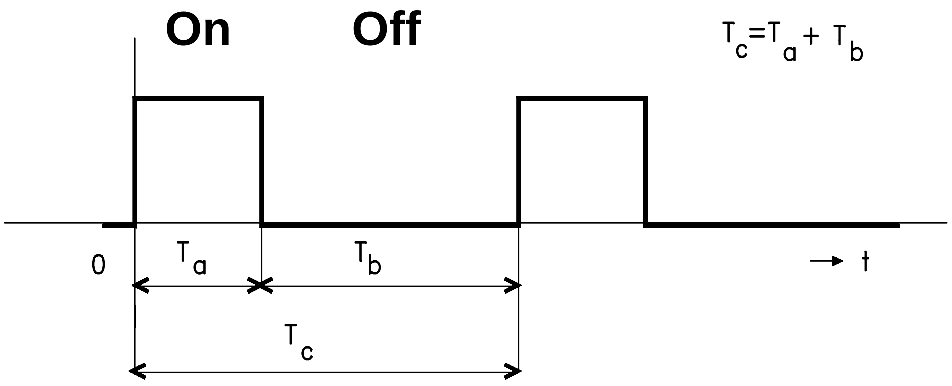
Switched supply without input transformer



DC/DC changer



Switched stabilizer controlling



$$T_c = T_a + T_b$$

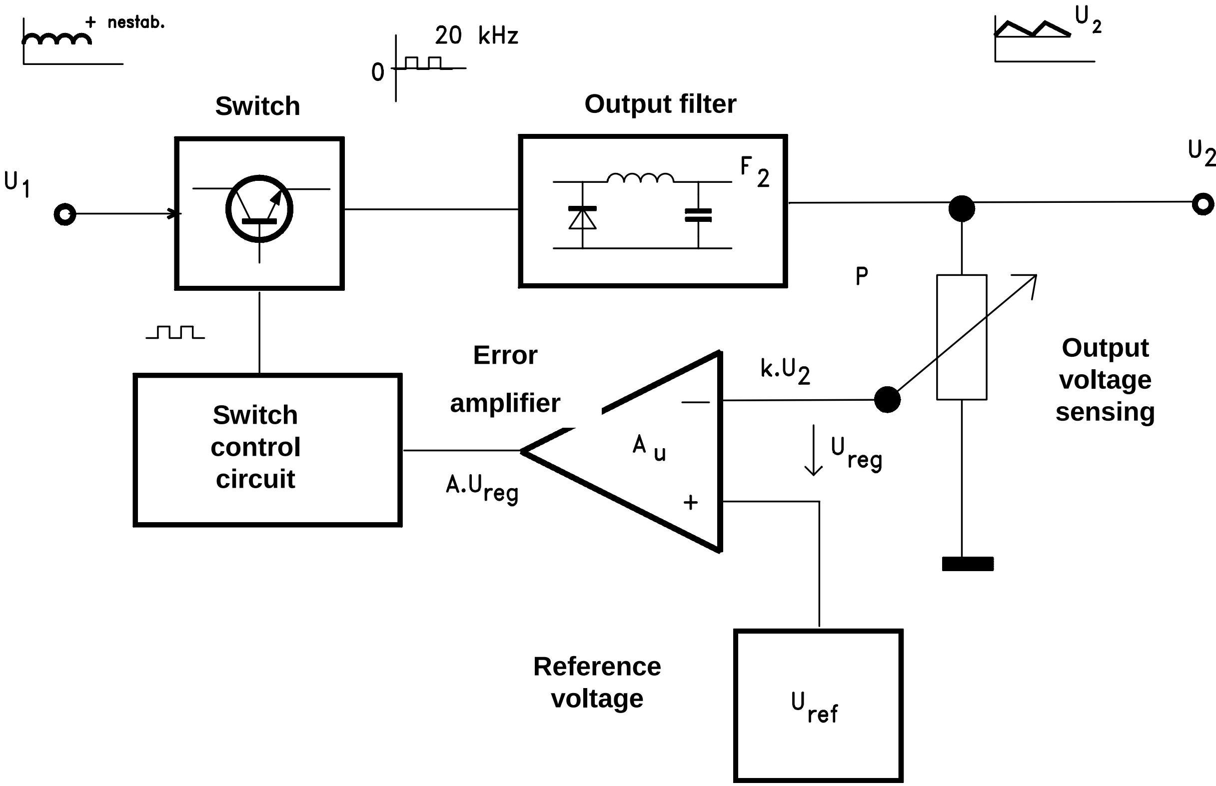
Duty cycle control

a) PFM: Ta=konst, T≠konst, Tb=g(Iz) ✡ fc=g(Iz)

b) PFM: Tb=konst, T≠konst, Ta=g(Iz) ✡ fc=g(Iz)

c) PWM: Tc=konst, Ta/Tb≠konst, Ta/Tb=g(Iz) ✡ fc=konst

Impulse (switched) stabilizer – basic operation principle



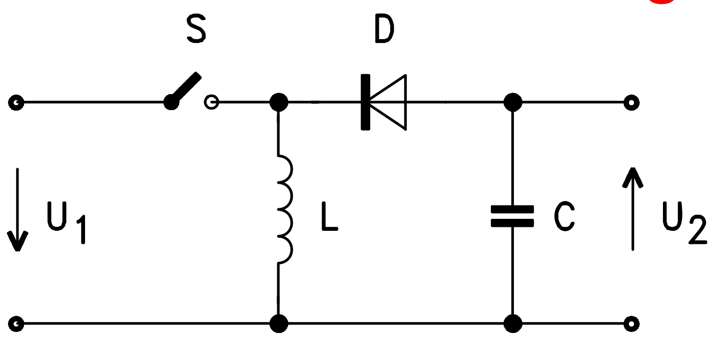
$$U_{reg} = kU_2 - U_{ref}$$

$$U_2 = \frac{1}{k} U_{ref}$$

<u>Basic problems of impulse (switched) regulation</u>

Output filter has lag character, it causes delay between corrected voltage and deviation. For good dynamic parameters is required high switching frequency

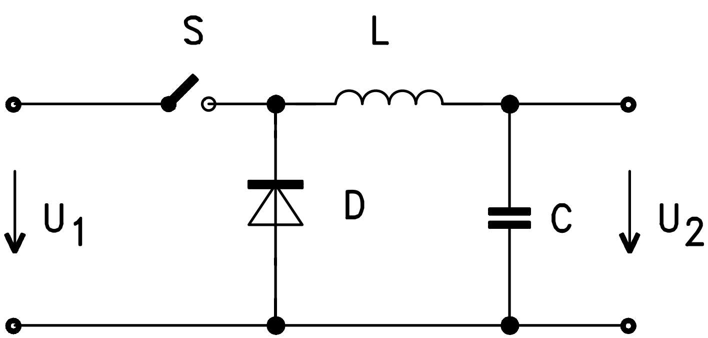
Theoretical switching-regulator circuits



a)

BUCK – BOOST

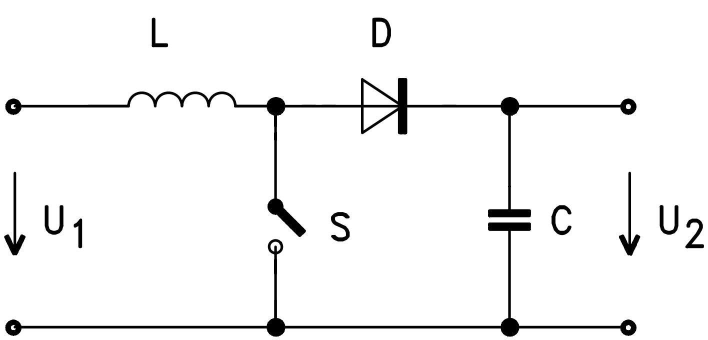
$U_2 \leq -U_1$



b)

BUCK

$U_2 \leq U_1$



c)

BOOST

$U_2 > U_1$

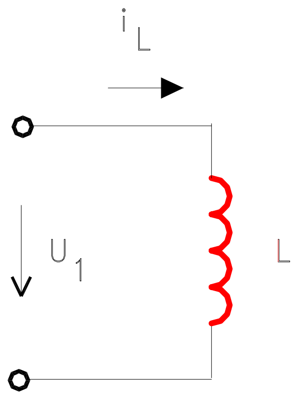
There are used three basic devices in all theoretical circuits.

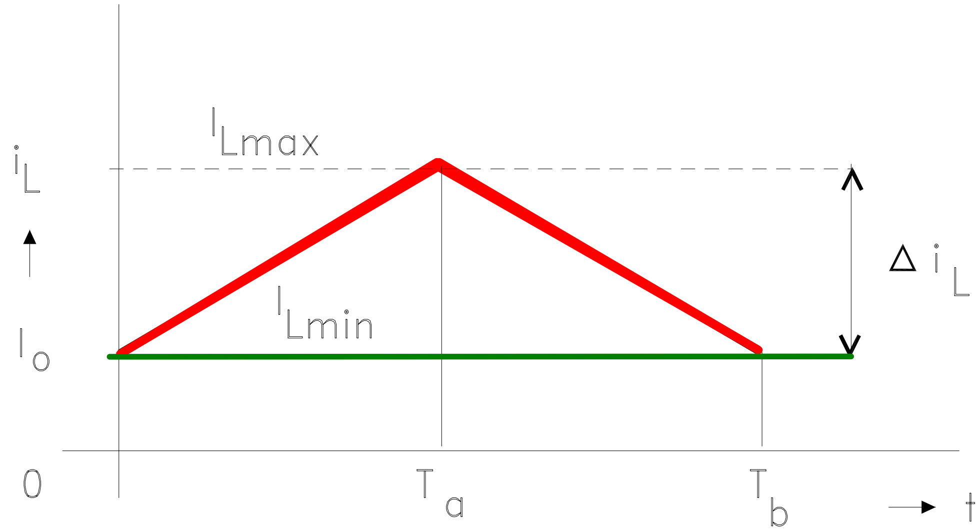
- switch
- accumulating inductor
- recuperating diode

In some cases, inductor can be changed by impulse transformer

Ta – switch ON time
Tb – switch OFF time
Tc – duty cycle

Inductor operating principle





$$u_L = L\frac{di}{dt}$$

$$di = \frac{1}{L}u_L\,dt$$

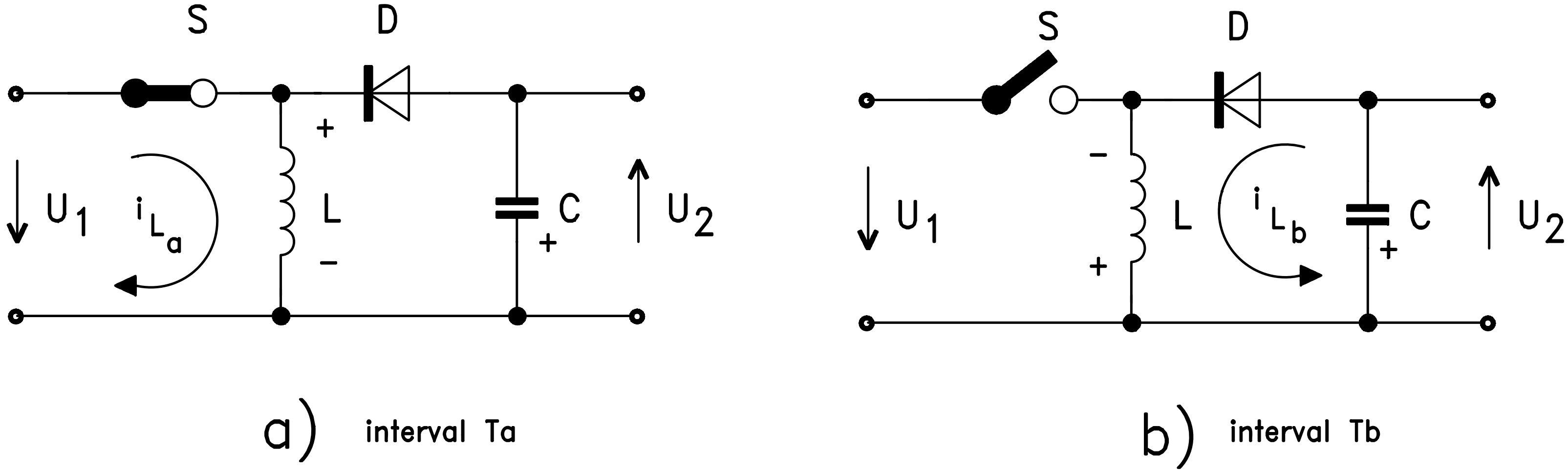
$$I_{Lmax} = \int_0^{T_a}\frac{1}{L}u_L\,dt + I_o$$

$$I_{Lmax} = \frac{1}{L}U_1T_a + I_o$$

$$\Delta i_{L_a} = I_{Lmax} - I_o$$

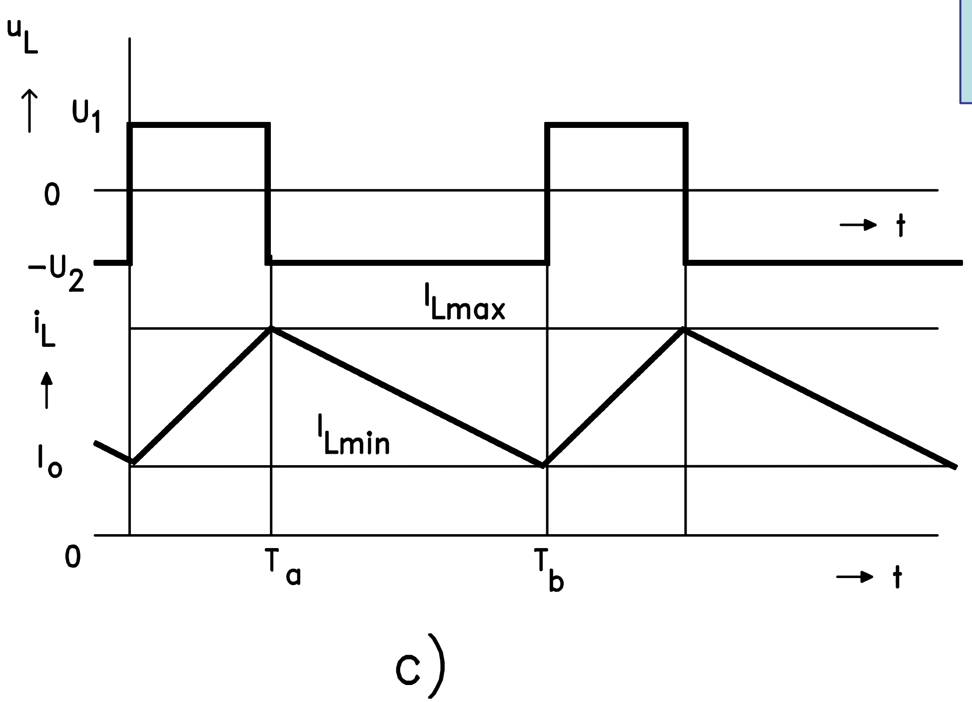
$$\Delta i_{L_a} = \frac{1}{L}U_1T_a$$

BUCK-BOOST or inverting configuration



$$U_{2\max} \leq -U_1$$

$$\Delta i_{L_a} = \frac{1}{L} U_1 T_a$$



Operating principle of BUCK-BOOST configuration

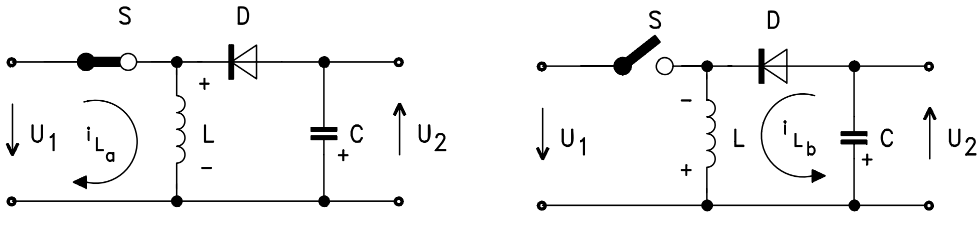
Interval Ta

Switch is ON ,L accumulates magnetic field energy. Inductor current

$$i_L = \int_0^{T_a} u_L \, dt + I_o$$

U1=konst,. For current increase at the end of Ta is:

$$\Delta i_{L_a} = \frac{U_1}{L} T_a$$



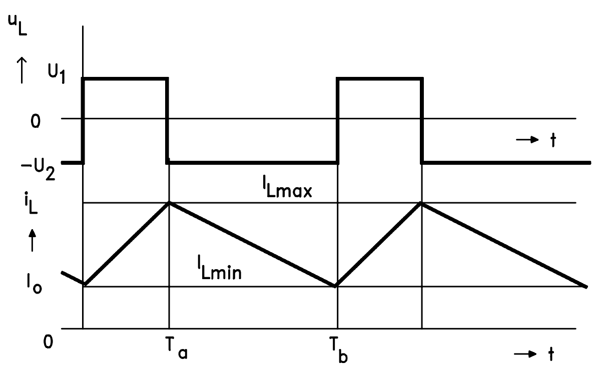
a) interval Ta b) interval Tb

Peek current at the end of Ta

$$I_{Lmax} = I_o + \Delta i_{L_a}$$

*Accumulated energy W*a at the end of Ta

$$W_a = W_o + \Delta W_a$$



c)

For energy of ideal changer in Ta and Tb

$$W_a = W_b$$

Operating principle of BUCK-BOOST configuration

Interval Tb

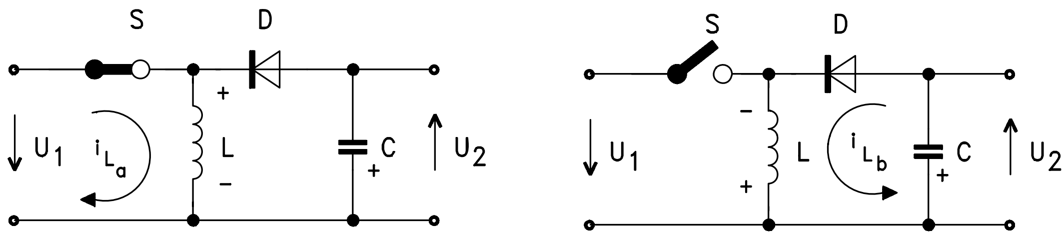
When inductor is disconnected from U1, negative voltage is induced on their pins (due to…), inductor behaves as energy supply, and current flows through Diode and capacitor. At the beginning of Tb:

$$\Delta W_a = \Delta W_b$$

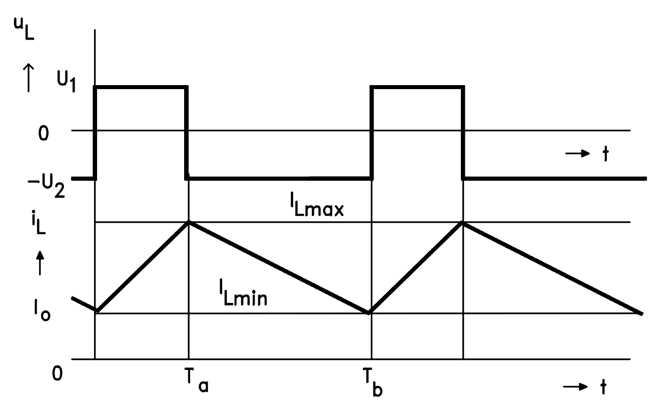
$$\Delta i_{L_a} = \Delta i_{L_b}$$

$$\Delta i_{L_a} = \frac{U_1}{L} T_a \qquad \Delta i_{L_b} = \frac{U_2}{L} T_b$$

$$\frac{U_1}{L} T_a = \frac{U_2}{L} T_b \Rightarrow U_2 = U_1 \frac{T_a}{T_b}$$



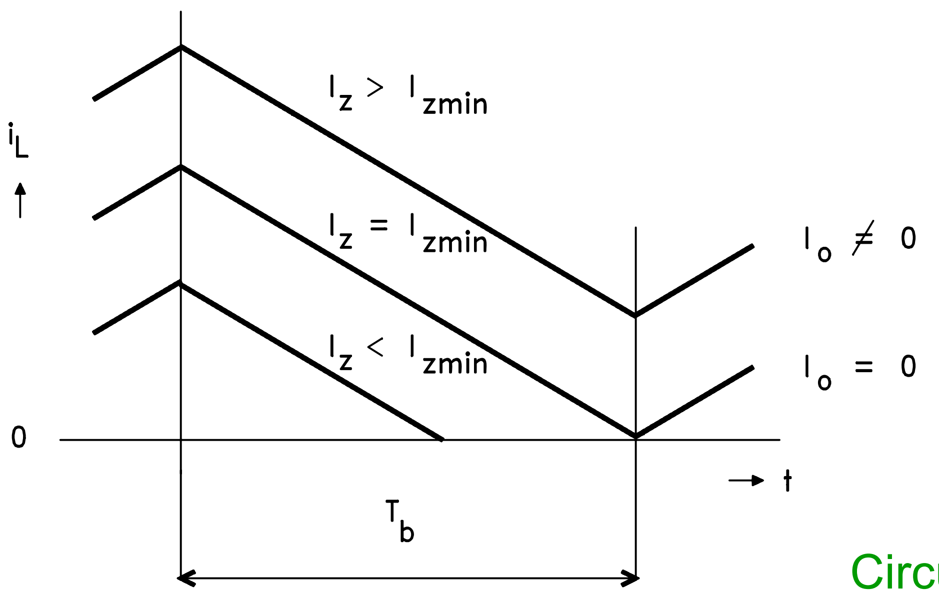
a) interval Ta b) interval Tb



c)

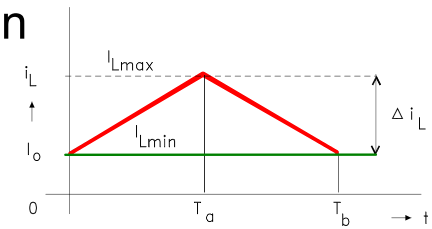
Operating principle of BUCK-BOOST configuration

Minimum and maximum allowed load current



Max load current Izmax

- Limited by magnetic saturation of impulse transformer core
- IT is not allowed to be at saturation



Min load current Izmin

$$I_o = 0$$

$$I_z < I_{zmin} \Rightarrow W_a \neq W_b$$

Circuit disadvantages

- Relatively high output ripple ΔU2, especially at low output voltages and high load currents.

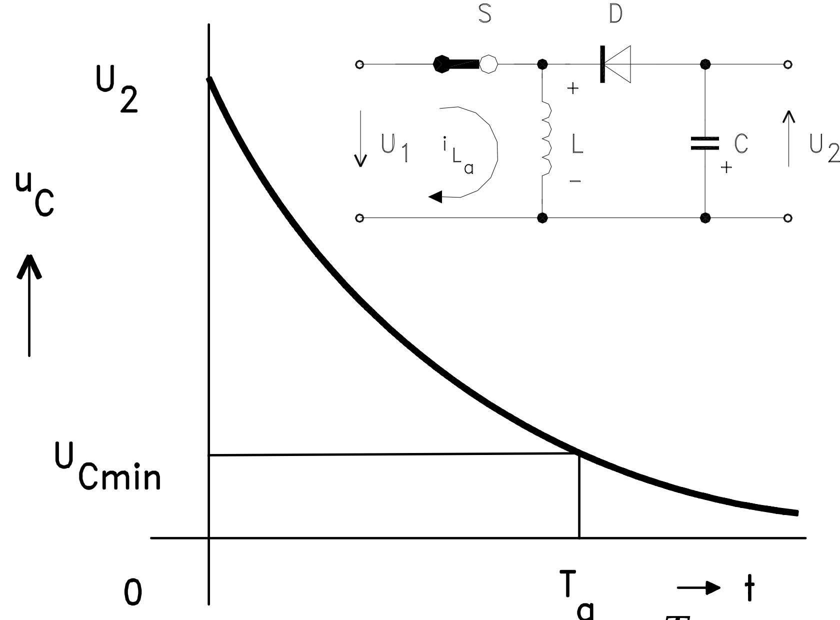
Reason:

- In Ta is load supplied just from C
- In Tb is C charged by high current impulses
- Voltage loss at diode, UAK≠0.
- Parasitic R and L of real C.

Operating principle of BUCK-BOOST configuration

Design of capacity

- according to exponential discharging in Ta of RC circuit consist of load resistor and capacitor



Voltage on capacitor when switch is switched ON (t=0)

$$U_C(0) = U_2$$

Voltage on capacitor at the end of Ta, when ripple of output voltage is ΔU2

$$U_C(T_a) = U_{Cmin}$$

$$U_{Cmin} = U_2 e^{-\frac{T_a}{R_z C}}$$

$$C = \frac{T_a}{R_z \ln \frac{U_2}{U_{Cmin}}}$$

Exponential discharging

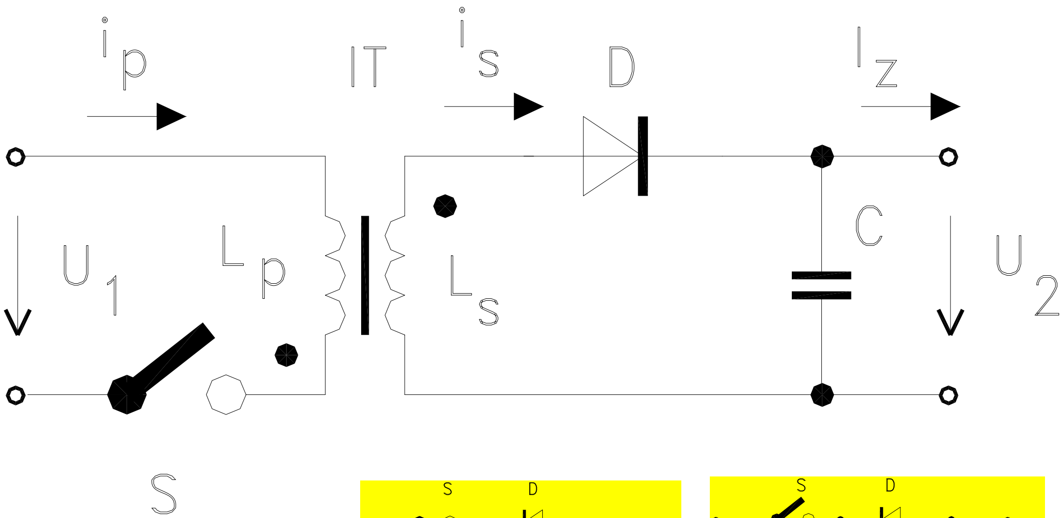
$$u_C = U_2 e^{-\frac{t}{\tau}} \qquad \tau = R_z C$$

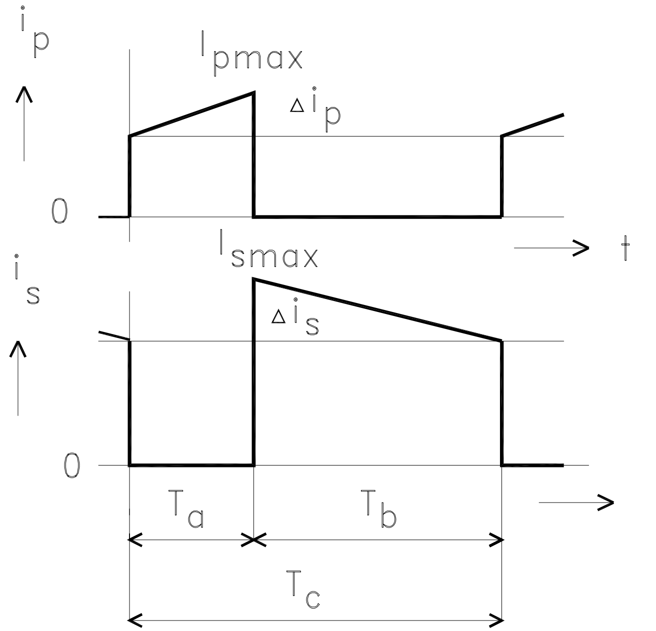
Output ripple is practically < 20%, equation can be simplified

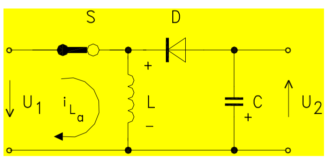
$$C \geq \frac{T_a}{R_z} \cdot \frac{U_2}{\Delta U_2} = \frac{T_a}{\Delta U_2} I_z$$

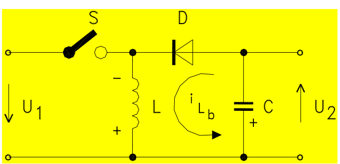
Circuit configuration with impulse transformer

Operating principle – inductor is replaced by impulse transformer









$$\Delta i_p = \frac{U_1}{L_p} T_a$$

$$\Delta i_s = \frac{U_2}{L_s} T_b$$

$$\frac{\Delta i_s}{\Delta i_p} = \frac{n_p}{n_s}$$

$$\frac{L_s}{L_p} = \left(\frac{n_s}{n_p}\right)^2$$

$$\Delta i_p = \frac{n_s}{n_p} \Delta i_s$$

$$\frac{U_1}{L_p} T_a = \frac{n_s}{n_p} \cdot \frac{U_2}{L_s} T_b$$

$$\frac{U_1}{L_p} T_a = \frac{n_s}{n_p} U_2 T_b \frac{1}{L_p} \left(\frac{n_p}{n_s}\right)^2$$

$$U_2 = \frac{n_s}{n_p} \cdot \frac{T_a}{T_b} U_1$$

Circuit configuration with impulse transformer

Design example of buck boost switching regulator with impulse transformer

a) Design of transformer secondary coil Ls

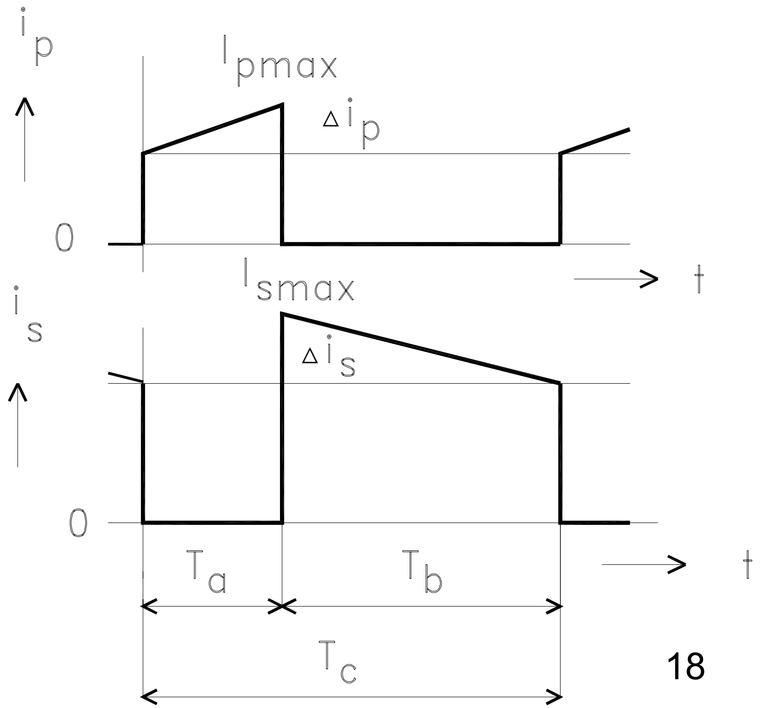
Assumption - given U2 and Izmin. Iz = Io+Δis (average value). Io=0 for Izmin.

$$I_{zmin} = \frac{\Delta i_s}{2} \cdot \frac{T_b}{T_c}$$

$$\Delta i_s = \frac{U_2}{L_s} T_b$$

$$I_{zmin} = \frac{1}{2} \cdot \frac{U_2}{L_s} \cdot T_b \cdot \frac{T_b}{T_c}$$

$$L_s = \frac{U_2}{2 I_{zmin}} \cdot \frac{T_b^{\,2}}{T_c}$$



Circuit configuration with impulse transformer

Design example of buck boost switching regulator with impulse transformer

b) Design of transformer primary

$$\frac{L_s}{L_p} = \left(\frac{n_s}{n_p}\right)^2 \longrightarrow L_p = L_s\left(\frac{n_p}{n_s}\right)^2$$

Ls from previous slide

$$L_s = \frac{U_2}{2I_{zmin}} \cdot \frac{T_b^2}{T_c}$$

Instead of square of transformer ratio

$$U_2 = \frac{n_s}{n_p} \cdot \frac{T_a}{T_b} U_1$$

$$L_p = \left(\frac{U_2}{2I_{zmin}} \cdot \frac{T_b^2}{T_c}\right) \cdot \left(\frac{U_1}{U_2} \cdot \frac{T_a}{T_b}\right)^2$$

$$L_p = \frac{U_1^2}{2U_2 I_{zmin}} \cdot \frac{T_a^2}{T_c}$$