Wroclaw University of Science and Technology

Basic blocks of converters

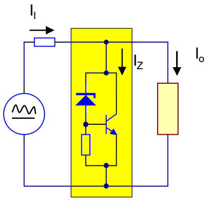
Jerzy Witkowski

References

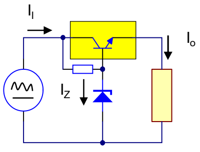
1. Marcelo Godoy Simões and Tiago Davi Curi Busarello , Power Electronic Converters and Systems, 2nd Edition Volume 1 (source of illustrations)

Serial & parallel controller

$$I_I = I_Z + I_O$$
$$P_{loses} = I_Z U_O + I_I \left(E - U_O\right)$$



$$I_I \approx I_O$$
$$P_{loses} = I_I \left(E - U_O\right)$$

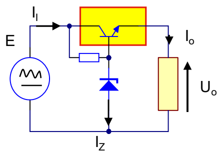


Smaller dissipation power

Better efficiency

Linear vs. Pulse (switching) controller

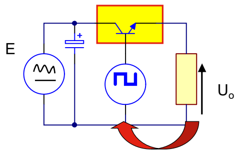
$\boxed{P_{strat} \approx (E - U_O) I_O}$



Smaller dissipation power

Better efficiency

$\boxed{P_{strat} \approx U_{sat} I_{\max}}$

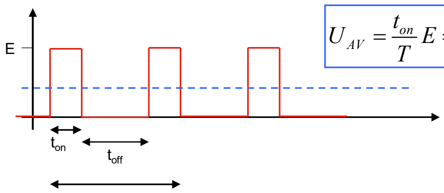


$$U_O = U_{AV} = \frac{t_{on}}{t_{on} + t_{off}} E$$

Even smaller dissipation power

Even better efficiency

The average value of the impulse waveform



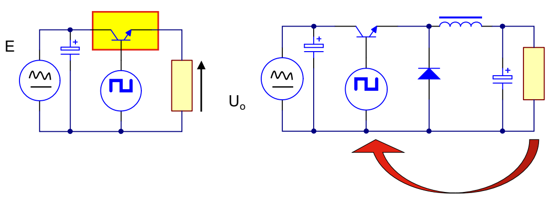
$$\boxed{U_{AV} = \frac{t_{on}}{T} E = \gamma E}$$

$T = t_{off} + t_{on}$

T – period

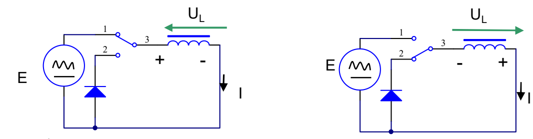
$\gamma = t_{on}/T$ – duty factor

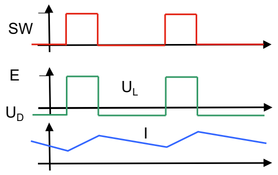
Step down converter



$$U_O = U_{AV} = \frac{t_{on}}{t_{on} + t_{off}} E = \gamma E$$

Choke

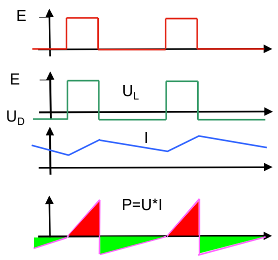




$$U(t) = L\frac{di(t)}{dt} \approx L\frac{\Delta i}{\Delta t}$$

$$i(t) - i(t_0) = \frac{U}{L}(t - t_0)$$

Choke



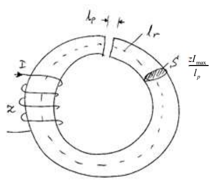
$$U(t) = L\frac{di(t)}{dt} \approx L\frac{\Delta i}{\Delta t}$$

$$i(t) - i(t_0) = \frac{U}{L}(t - t_0)$$

High inductance-
Small voltage-
Small current slope

Power stored = power transferred to output

Choke - some parameters



B_{max}=0.05…0.1…0.2..0.3 [T] for ferrites
and frequencies 200…20..10[kHz]..2[MHz]

when $\mu_w \frac{l_p}{l_r} >> 1$

$$\frac{BSz}{I} = L = \mu_0 \mu_w \frac{z^2 S}{l_r\left(1 + \mu_w \frac{l_p}{l_r}\right)} = A_L z^2 \approx \mu_0 \frac{z^2 S}{l_p}$$

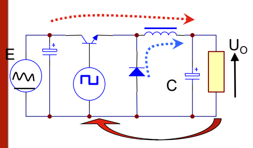
For sine waveforms:

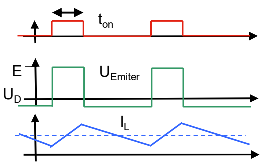
$$\frac{U_{max}}{z} = 2\pi f B_{max} S = \frac{\sqrt{2} U_{skut}}{z}$$

For square wave:

$$\frac{U_{max}}{z} = \frac{1}{\gamma} f B_{max} S = \frac{1}{t_{on}} B_{max} S$$

Step down (buck) converter





$$U_0 = \gamma E = \frac{t_{on}}{T} E$$

$$I_{L\max} \approx 2 I_{O\max}$$

$$L_{\min} \geq \frac{E - U_0}{I_{L\max}} t_{on}$$

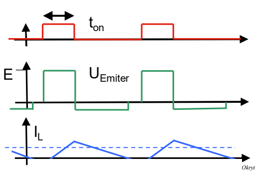
$$C > \frac{I_{O\max} T}{4 U_{Orip}}$$

U_O – output voltage,
E – input voltage,
t_{on}, t_{off}, T – turn on, off, period
I_{Lpeak} – peak current of choke and switch
L_{min} – minimum inductance
U_{Oripp} – ripple output voltage

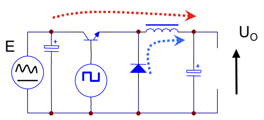
simplified way of deriving equastion of the output voltage of the step-down converter

chalk board or separate video

Step down converter (discontinues mode)

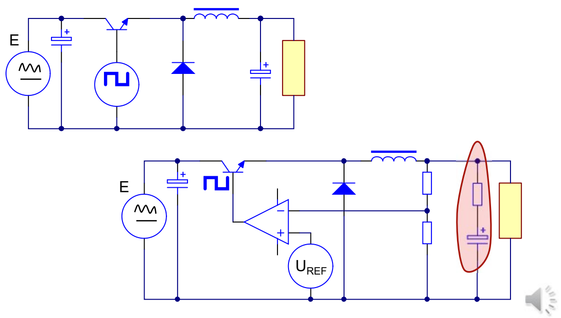


$$_{Okryt} = \frac{ET}{2L}(1-\gamma)\gamma$$

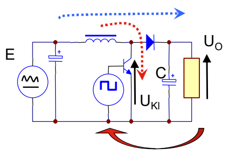


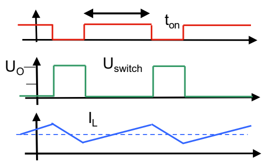
Output voltage can reach the value E !!!

self-excited step-down controller



Step up (boost) converter





$$U_0 = \frac{1}{1-\gamma}E$$

$$I_{Lszczyt} \approx 2I_{O\max}\left(1+\frac{t_{on}}{t_{off}}\right)$$

$$L_{\min} \geq \frac{E}{I_{Lszczyt}}t_{on}$$

$$C > \frac{I_{O\max}T}{U_{Otetnień}}$$

U_O – output voltage,

E – input voltage,

t_{on},t_{off},T – turn on, off, period

I_{Lpeak} – peak current of choke and switch

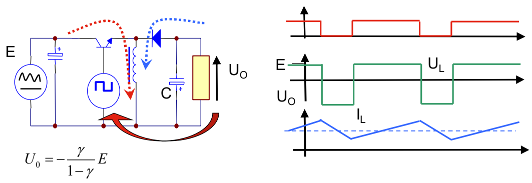
L_{min} – minimum inductance

U_{Oripp} – ripple output voltage

simplified way of deriving equastion of the output voltage of the step-up converter

chalk board or separate video

Inverter (buck-boost)



$$U_0 = -\frac{\gamma}{1-\gamma}E$$

$$I_{Lszczyt} \approx 2I_{O\max}\left(\frac{1}{1-\gamma}\right)$$

$$L_{\min} \geq \frac{E}{I_{Lszczyt}}t_{on}$$

$$C > \frac{I_{O\max}T}{U_{Otetnień}}$$

U_O – output voltage,

E – input voltage,

t_{on},$t_{off,}$T – turn on, off, period

I_{Lpeak} – peak current of choke and switch

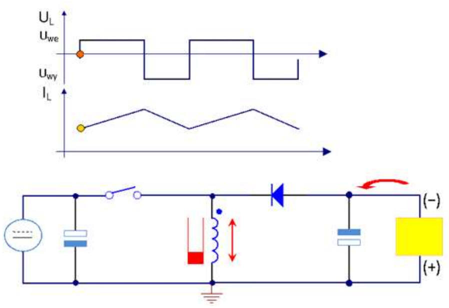
L_{min} – minimum inductance

U_{Oripp} – ripple output voltage

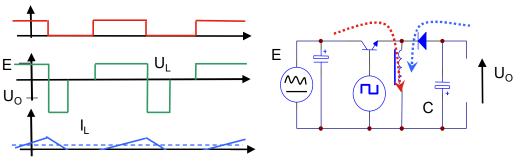
simplified way of deriving equastion of the output voltage of the inverter

chalk board or separate video

Inverter



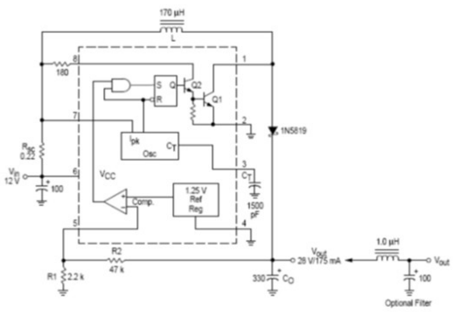
Inverter (discontinues mode)



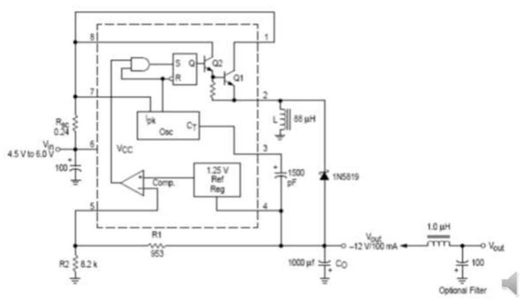
$$I_O < I_{Okryt} = \frac{E\gamma}{2L}(1-\gamma)T$$

Output voltage can ????∞ !!!

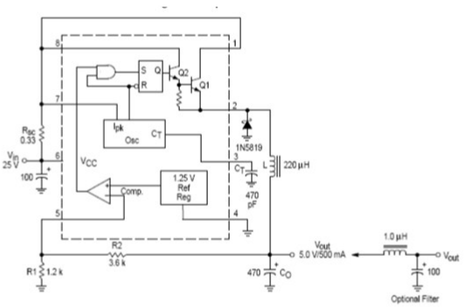
Step up MC34063



Inverting MC34063



Step down MC34063



MC34063 data sheet expressions

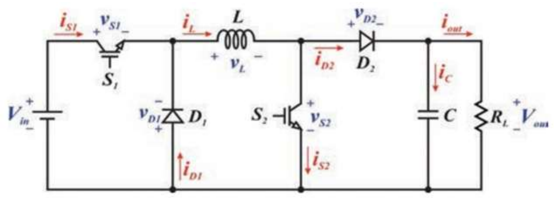
Calculation	Step–Up	Step–Down	Voltage–Inverting
t_{on}/t_{off}	$\frac{V_{out} + V_F - V_{in(min)}}{V_{in(min)} - V_{sat}}$	$\frac{V_{out} + V_F}{V_{in(min)} - V_{sat} - V_{out}}$	$\frac{\lvert V_{out}\rvert + V_F}{V_{in} - V_{sat}}$
$(t_{on} + t_{off})$	$\frac{1}{f}$	$\frac{1}{f}$	$\frac{1}{f}$
t_{off}	$\frac{t_{on} + t_{off}}{\frac{t_{on}}{t_{off}} + 1}$	$\frac{t_{on} + t_{off}}{\frac{t_{on}}{t_{off}} + 1}$	$\frac{t_{on} + t_{off}}{\frac{t_{on}}{t_{off}} + 1}$
t_{on}	$(t_{on} + t_{off}) - t_{off}$	$(t_{on} + t_{off}) - t_{off}$	$(t_{on} + t_{off}) - t_{off}$
C_T	$4.0 \times 10^{-5}\, t_{on}$	$4.0 \times 10^{-5}\, t_{on}$	$4.0 \times 10^{-5}\, t_{on}$
$I_{pk(switch)}$	$2I_{out(max)}\left(\frac{t_{on}}{t_{off}} + 1\right)$	$2I_{out(max)}$	$2I_{out(max)}\left(\frac{t_{on}}{t_{off}} + 1\right)$
R_{SC}	$0.3/I_{pk(switch)}$	$0.3/I_{pk(switch)}$	$0.3/I_{pk(switch)}$
$L_{(min)}$	$\left(\frac{(V_{in(min)} - V_{sat})}{I_{pk(switch)}}\right) t_{on(max)}$	$\left(\frac{(V_{in(min)} - V_{sat} - V_{out})}{I_{pk(switch)}}\right) t_{on(max)}$	$\left(\frac{(V_{in(min)} - V_{sat})}{I_{pk(switch)}}\right) t_{on(max)}$
C_O	$9\,\frac{I_{out} t_{on}}{V_{ripple(pp)}}$	$\frac{I_{pk(switch)}(t_{on} + t_{off})}{8V_{ripple(pp)}}$	$9\,\frac{I_{out} t_{on}}{V_{ripple(pp)}}$

V_{sat} = Saturation voltage of the output switch.
V_F = Forward voltage drop of the output rectifier.

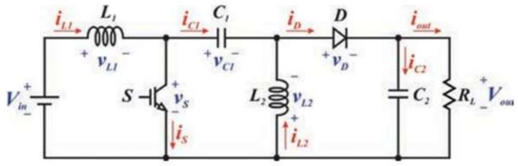
The following power supply characteristics must be chosen:

V_{in} – Nominal input voltage.
V_{out} – Desired output voltage, $\lvert V_{out}\rvert = 1.25\left(1 + \frac{R2}{R1}\right)$
I_{out} – Desired output current.
f_{min} – Minimum desired output switching frequency at the selected values of V_{in} and I_O.
$V_{ripple(pp)}$ – Desired peak–to–peak output ripple voltage. In practice, the calculated capacitor value will need to be increased due to its equivalent series resistance and board layout. The ripple voltage should be kept to a low value since it will directly affect the line and load regulation.

Buck & Boost

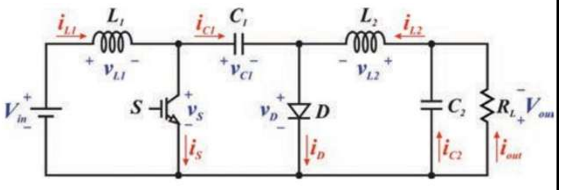


SEPIC
Single-ended Primary-Inductor Converter)



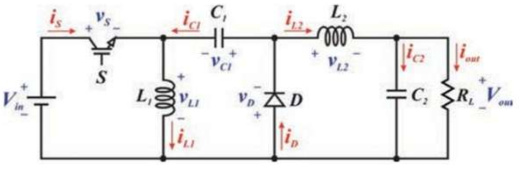
$$V_{out} = V_{in}\frac{\gamma}{1-\gamma}$$

Čuk



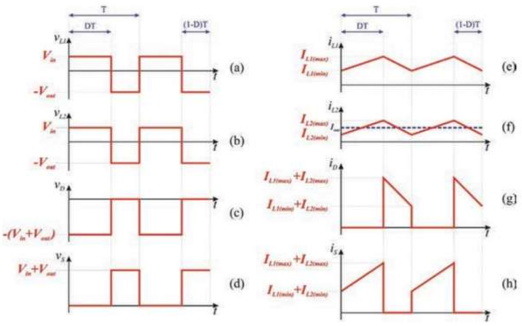
$$V_{out} = -V_{in}\frac{\gamma}{1-\gamma}$$

Zeta

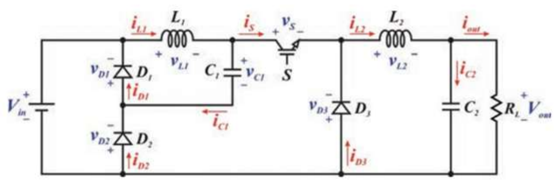


$$V_{out} = -V_{in}\frac{\gamma}{1-\gamma}$$

SEPIC

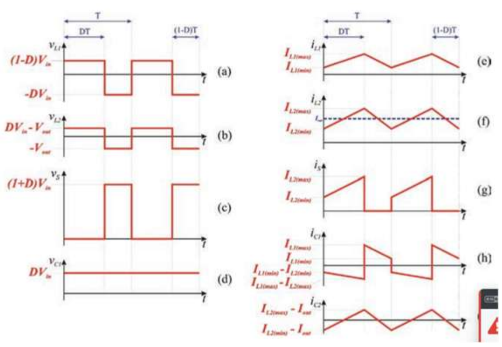


Quadratic Buck converter

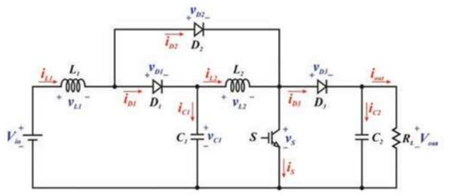


$$V_{out} = V_{in}\gamma^2$$

Quadratic Buck converter

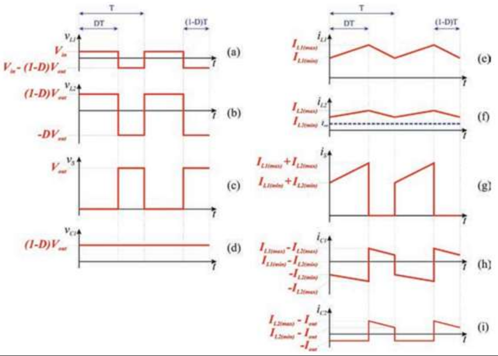


Quadratic Boost

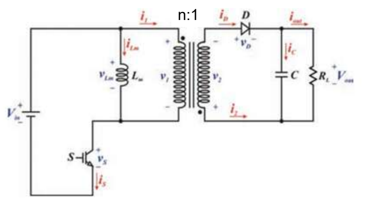


$$V_{out} = V_{in}\frac{1}{(1-\gamma)^2}$$

Quadratic Boost

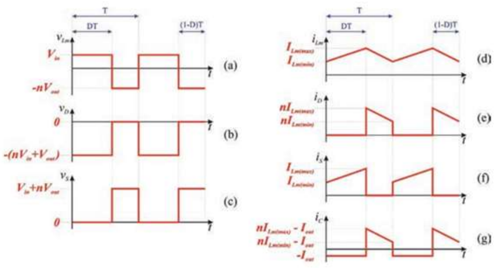


Flyback converter

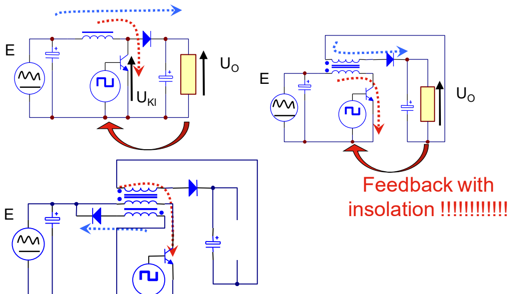


$$V_{out} = V_{in}\frac{1}{n(1-\gamma)}$$

Flyback converter

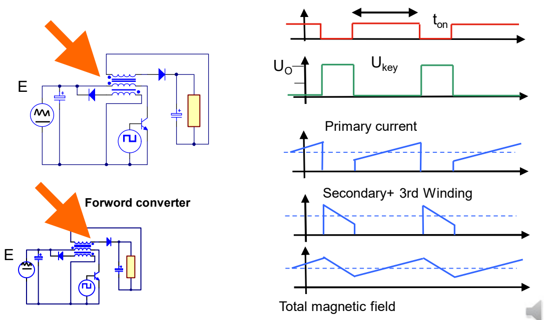


Choke converter (flyback)

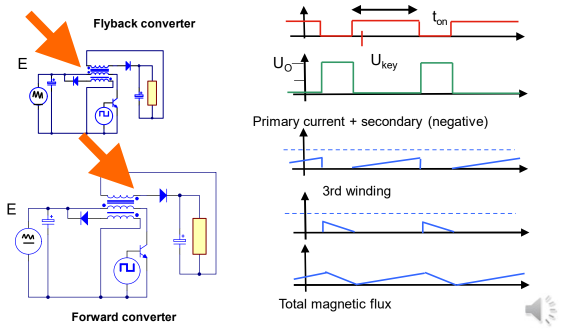


3rd winding allows release the energy in the choke when there is no load

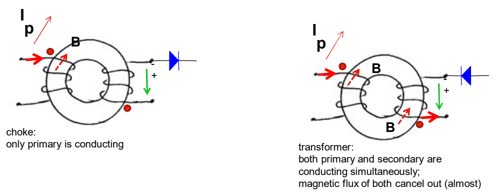
Flyback vs. Forword converter



forward converter



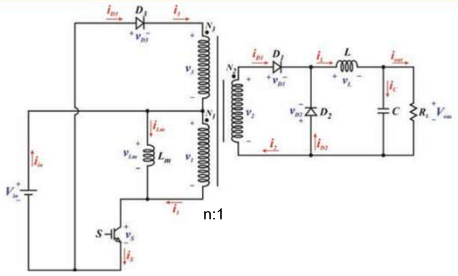
Choke vs. transformer



Foreword converter

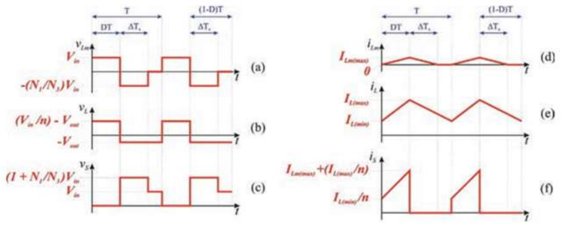
- In foreword converters:
- Energy is „transformed” (is not stored in magnetic field)
- Magnetization current is small
- Instead of choke a smaller transformer is used
- In symmetrical (push-pull, half-bridge, full-bridge, foreword converters average magnetization current is zero !

Forward converter

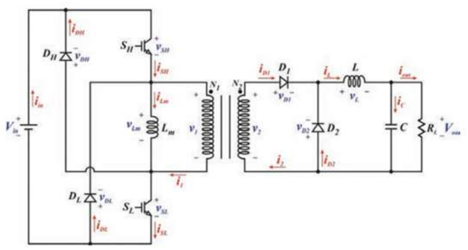


$$V_{out} = V_{in}\,\frac{\gamma}{n}$$

Forward converter

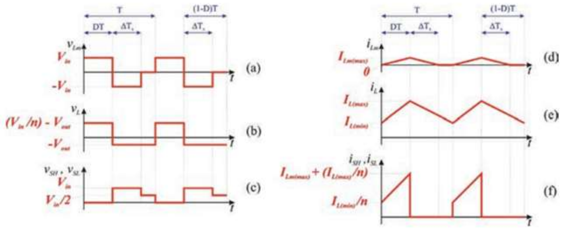


Two swich forward converter

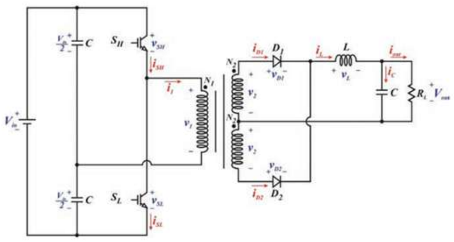


$$V_{out} = V_{in}\,\frac{\gamma}{n};\qquad \gamma < 0.5$$

Two swich forward converter

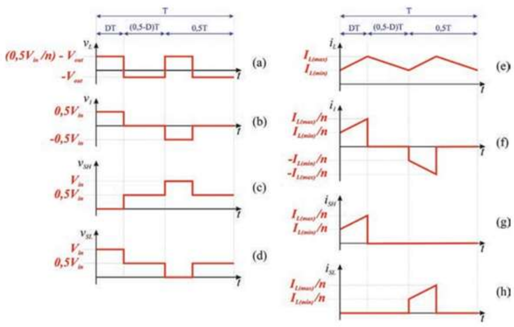


half-bridge converter

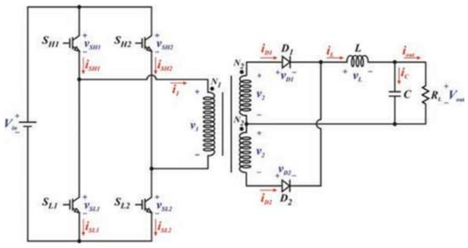


$$V_{out} = V_{in}\,\frac{\gamma}{n};\qquad \gamma < 0.5$$

half-bridge converter

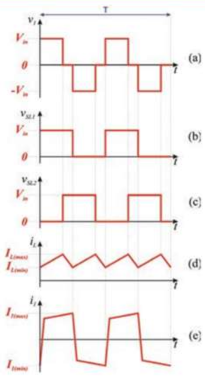


Full-bridge converter

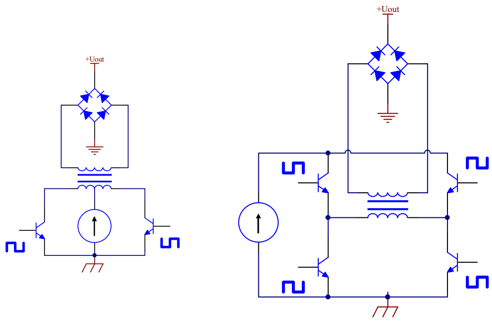


$$V_{out} = V_{in}\,2\frac{\gamma}{n}; \qquad \gamma < 0.5$$

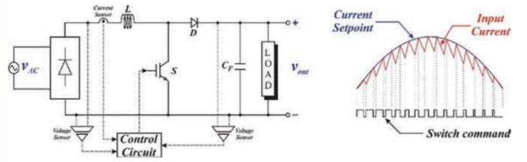
Full-bridge converter (phase controll)



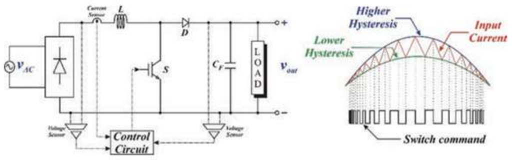
High power converters (foreword)



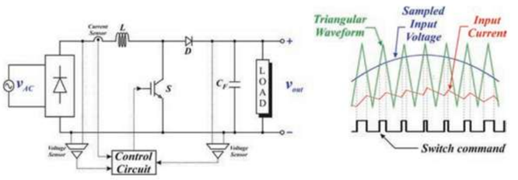
PFC - peak current modulation



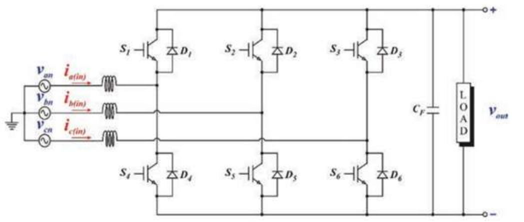
PFC - histeresis modulation



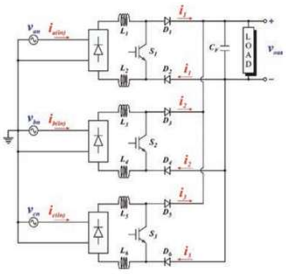
PFC - sinusoidal PWM



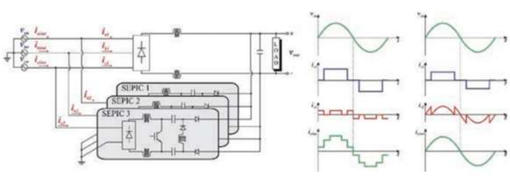
3p PFC



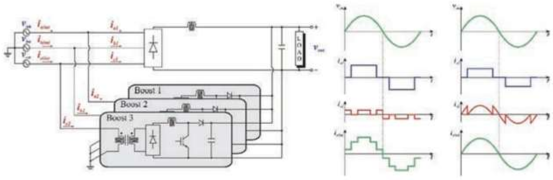
Clasic 3p PFC



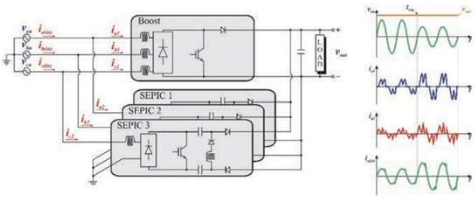
Hybrid PFC with SEPIC



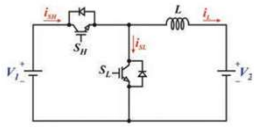
Hybrid PFC wth BOOST



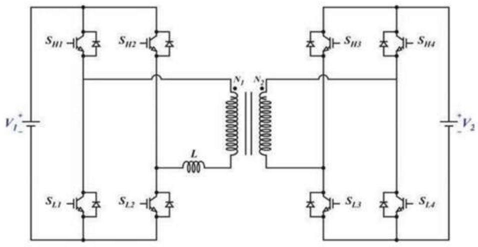
Hybrid PFC with BOOST+SEPIC



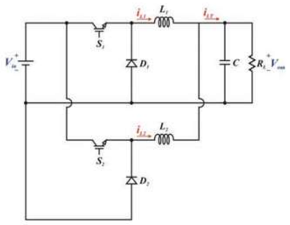
Bidirectional converters buck / boost



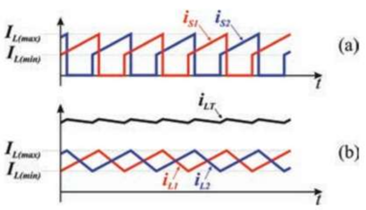
Bidirectional converters



Interleaving



Interleaving



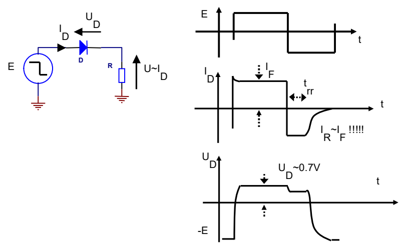
Converters - problems to overcome

High frequency (10-200kHz-2MHz) and short switching times (10-200ns):

- fast diodes and transistors
- distortions - noises
- voltage spikes
- parasitic capacitances (resonances)
- skin effect

Additional reference:
I. Pressman, Switching Power Supply Design 3/e, Mcgraw-Hill Education Ltd.

Dymamic model of diode recovery time t_{rr}



Same diode comparison „oscilloscope show”

Symbol	U_{RRM} [V]	I_R [uA]	U_F @ I_F [V]	[A]	U_{FM} @ I_{FSM} [V]	[A]	t_{rr} [ns]	C[pF]@ U_{RRM}	zastosowanie
1N4002	100	50	0.9	1	2.3	25	3500	15	Dioda prostownicza 1A
1N4007	1000	50	0.9	1	2.3	25	5000	15	Dioda prostownicza 1A – 1000V
BA159	1000	5	1.3	1	1.8	20	500	12/4V	Szybka prostownicza
1N4148	75	25n	1	0.1		4A/1us	4	0.8	Szybka przełączana
1N5819	40	1m	0.4	1	1.2	25	?	40	Prostownicza Shottky
BAT 43	30	100	0.3	0.002	1	0.2	5	5	Shottky (zw. moc)
DSEP12-12A	1200	100	2.7	15		90	40	?	Szybka, wysokonapięciowa, mocy;schottky
SDT06S60 Silicon-carbide	600	200	1.7	6		21.5	00	15	Szybka, wysokonapięciowa, mocy;

Sam diode parameters cont.

Symbol	U_F @ I_F [V]	[A]	U_F[V] @ I_F=1mA	t_{rr} [ns]	IR [μA]
1N4002 (prostownicza 100V)	0.9	1	0.5	3500	50
1N4007 (prostownicza 1kV)	0.9	1	0.5	5000	50
BA159 (szybka 1kV)	1.3	1	0.47	500	5
1N4148 (przełączająca)	1	0.1	0.55	4	25nA
1N5819 (Shottky 1A)	0.4	1	0.2	?	1000
BAT43 (Shottky 0.2A)	0.3	0.2	0.25	5	100
DSEP12-12A (Shottky power; trr=40ns)	2.7	15	0.7	40	200
DT06S60 (SiC zero trr)	1.7	6	0.4	000 !!	100
LED IR			0.9		
LED R G Y O			1.3 ÷ 1.6		
LED Blue & White			3.6		

Summary

Advantages:

- High efficiency
- Small dimensions

Drawbacks:

- Worse line and load regulation
- Interferences
- More expensive

Capacitive converters (charge pump) - for self studies (n.ICL7660)

Test problems

- Sketch a simplified model of a converter and derive the formula for the output voltage for: – a step-down converter (buck) – a step-up converter (boost) – an inverter (buck-boost).
- List the advantages and disadvantages of DC-DC converters.