Power suppliers:
- rectifiers,
- Power Factor
- voltage multipliers

Transformer parameters

- Power (single phase up to 3kW)
- Nominal voltage 230V +10% -10%
- Frequency 50Hz
- Transformer parameters:
  - Turn ratio (secondary voltage and current)
  - Idle current
  - Isolation breakdown voltage
  - Dimensions, weight
  - temperature

Types of transformers -most popular

- Cores: EI type (shell), wound core (strip construction) , toroidal (wound ring-shape core, strip construction)
- Core Materials
  - Silicon steel,
  - permalloy

Transformers

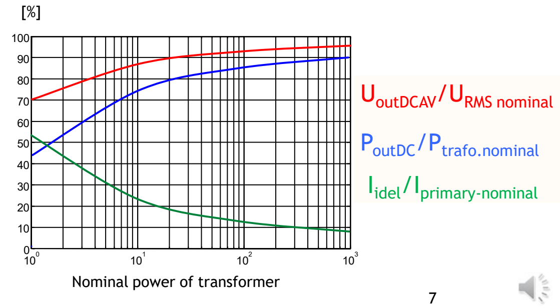
transformersr [voltage / turn]

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

Transformers - power vs. type

S[cm²]@P[W]	core	B_{max}[T]
$S \approx 1{,}25 \cdot \sqrt{P_1}$	Hot rolled steel sheet, EI core	1T
$S \approx 1{,}1 \cdot \sqrt{P_1}$	Cold rolled steel sheet EI core	1.1T
$S \approx \sqrt{P_1}$	Cold rolled steel sheet wound core	1.5T
$S \approx 0.8 \cdot \sqrt{P_1}$	Cold rolled steel sheet Toroid	1.6T

„experimental data for designers”



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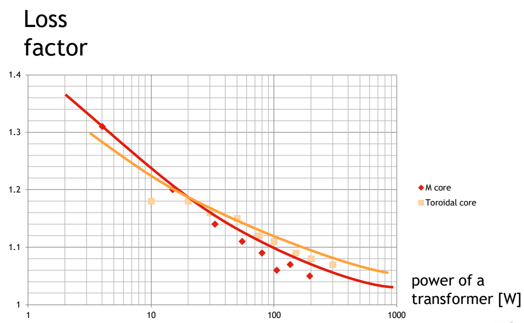
Loss vs. power of a transformer ”””experimental data”””



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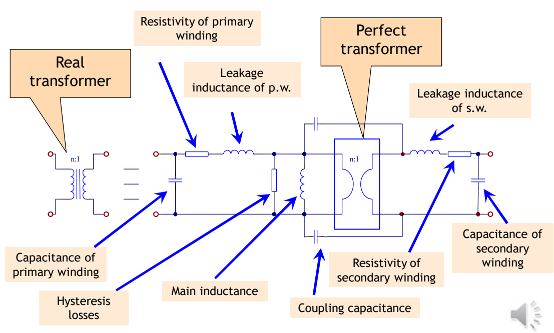
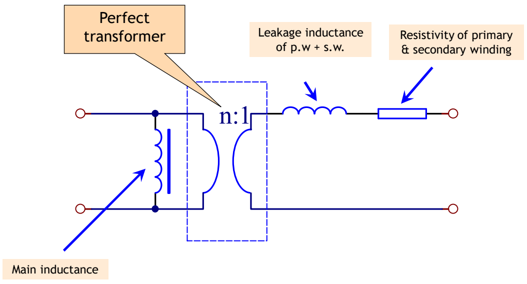
Transformer electronic model

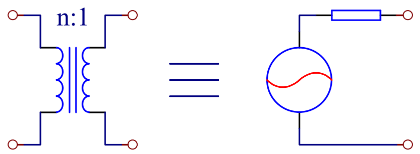


Simplified model



More simplified model

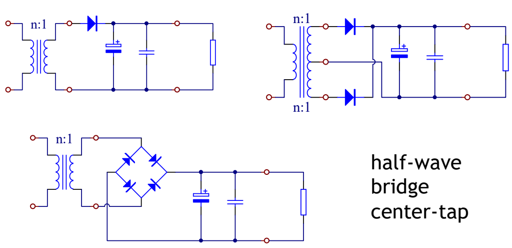
$$R_{series} = \frac{R_{primary}}{n^2} + R_{secondary}$$



$$U_{sk} = 230V \begin{cases} +10\% \\ -10\% \end{cases}$$

$$U(t) = \frac{U_{RMS}}{n} \sqrt{2} \sin(\omega t)$$

power rectifiers



half-wave
bridge
center-tap

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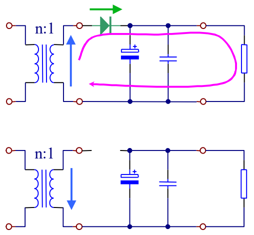
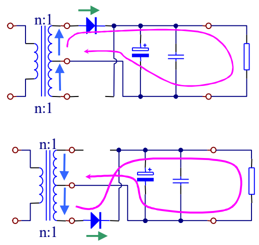
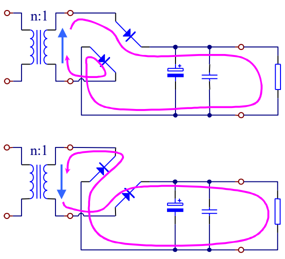
half-wave



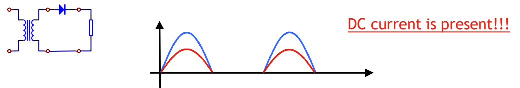
Center-tap



bridge

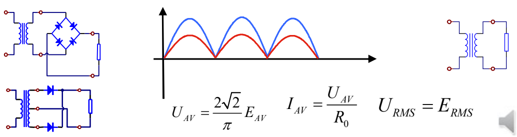


Rectifier - resistive load



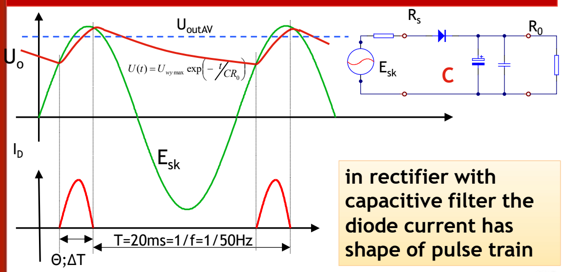
Current and voltage across resistive load

$I_{AV} = \frac{U_{AV}}{R_0}$ $U_{AV} = \frac{\sqrt{2}}{\pi} E_{RMS}$ $U_{RMS} = \frac{E_{RMS}}{2}$



$U_{AV} = \frac{2\sqrt{2}}{\pi} E_{AV}$ $I_{AV} = \frac{U_{AV}}{R_0}$ $U_{RMS} = E_{RMS}$

Voltage and current for half-wave rectifier



in rectifier with capacitive filter the diode current has shape of pulse train

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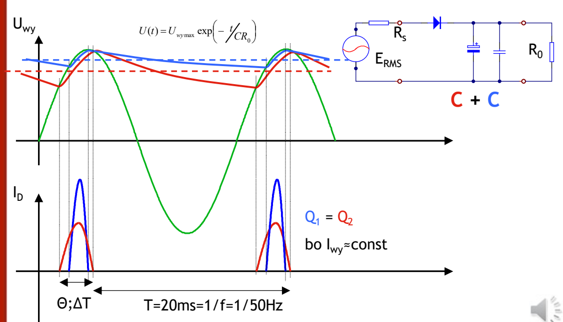
Half wave rectifier with a capacitve filter



Basic relations

Maximum idle voltage:

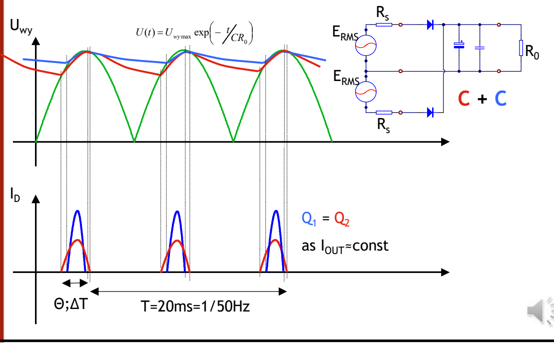
$$U_{\max} \approx \sqrt{2}E_{RMS} - U_F \approx \sqrt{2}E_{RMS}$$

ripples:

$$U_{rip.pp} \approx \frac{Q}{C} = \left(\frac{U_{\max}}{R_0}\right)\frac{T}{C} = \frac{U_{\max}}{fR_0C} \approx \frac{I_{AV}}{fC}$$

Haw to figure out this relationship!

Full wave rectifier



Basic relations

Maximum idle voltage:

$$U_{\max} \approx \sqrt{2}E_{RMS} - U_F$$

bridge:

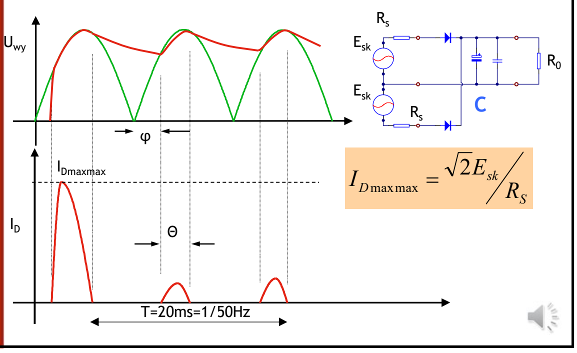
$$U_{\max} \approx \sqrt{2}E_{RMS} - 2U_F$$

ripples:

$$U_{rip.pp} \approx \frac{Q}{C} = \frac{I_{AV}\,T/2}{C} = \frac{I_{AV}}{2fC}$$

Haw to figure out this relationship!

„surge current”



$$I_{D\max\max} = \sqrt{2}E_{sk} / R_S$$

half-wave rectifier

for $U_{rpp}/U_{outAV}<10\%$

No-load voltage	$U_{outMax} = \sqrt{2}E_{RMS} - U_F$
On-load voltage (C=∞)	$U_{outAV} = U_{outMax}\left(1-\sqrt{\frac{R_S}{R_L}}\right)$
Peak revers voltage	$U_{D\max} = 2\sqrt{2}E_{sk}$
Mean diode current	$I_{Dmean} = I_{outAV}$
Repetitive diode current	$I_{D\max} = U_{outAV} / \sqrt{R_S R_L}$
Ripple voltage (peak to peak)	$U_{rpp} = \frac{I_{outAV}}{fC}\left(1-\sqrt[4]{\frac{R_S}{R_L}}\right)$
Minimum output voltage	$U_{outMin} = U_{outAV} - \frac{2}{3}U_{rpp}$

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bridge rectifier

for $U_{rpp}/U_{outAV}<10\%$

No-load voltage	$U_{outMax} = \sqrt{2}E_{RMS} - 2U_F$
On-load voltage (C=∞)	$U_{outAV} = U_{outMax}\left(1-\sqrt{\frac{R_S}{2R_L}}\right)$
Peak revers voltage	$U_{D\max} = \sqrt{2}E_{sk}$
Mean diode current	$I_{Dmean} = \frac{1}{2}I_{outAV}$
Repetitive diode current	$I_{D\max} = U_{outAV} / \sqrt{2R_S R_L}$
Pipple voltage (peak to peak)	$U_{rpp} = \frac{I_{outAV}}{2fC}\left(1-\sqrt[4]{\frac{R_S}{2R_L}}\right)$
Minimum output voltage	$U_{outMin} = U_{outAV} - \frac{2}{3}U_{rpp}$

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center-tap rectifier

for $U_{rpp}/U_{outAV}<10\%$

No-load voltage	$U_{outMax}=\sqrt{2}E_{RMS}-U_F$
On-load voltage (C=∞)	$U_{outEV}=U_{outMax}\left(1-\sqrt{\frac{R_S}{2R_L}}\right)$
Peak revers voltage	$U_{D\max}=2\sqrt{2}E_{sk}$
Mean diode current	$I_{Dmean}=\frac{1}{2}I_{outAV}$
Repetitive diode current	$I_{D\max}=U_{outAV}/\sqrt{2R_S R_L}$
Pipple voltage (peak to peak)	$U_{rpp}=\frac{I_{outAV}}{2fC}\left(1-\sqrt[4]{\frac{R_S}{2R_L}}\right)$
Minimum output voltage	$U_{outMin}=U_{outAV}-\frac{2}{3}U_{rpp}$

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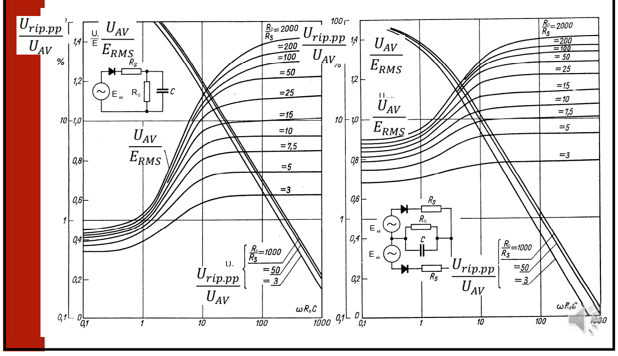
Main parameters

- Assumed:
  - $E_{RMS}=U_{RMS}/n_{(turn\ ratio}$
  - R_S - series resistivity
  - U_F - forward diode voltage
- calculated
  - U_{OUTRMS}; U_{OUTAV}; U_{OUTMAX}; U_{OUTMIN};U_{rip}
  - $I_{DAV.}$; $I_{DRMS.}$; $I_{DMAX.}$; I_{OUTAV}
  - Θ;ΔT - flow angle; conducting time
  - $k_t = U_{rip.pp}/U_{OUTAV}$- ripples coefficient
  - $\eta_u = U_{OUTAV}/E_{RMS}$ - voltage efficiency

Schade graphs

[J. Baranowski, G. Czajkowski; Układy elektroniczne. Cz. WNT 2004]
[T. Zagajewski; Układy elektroniki przemysłowej, WKŁ 1978]



Crest & Wave Form factors

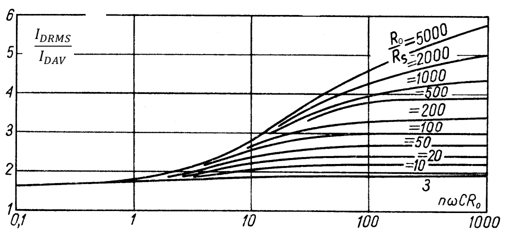
$$CF = I_{MAX} / I_{RMS}$$

Crest Factor -
For sin = 1,41= √2

$$FF = I_{RMS} / |I|_{AV}$$

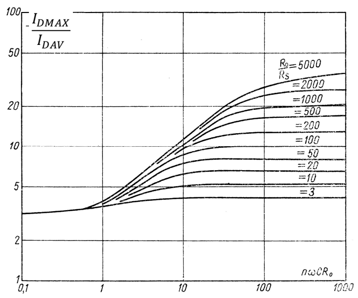
Wave Form Factor -
For sin = 1,11=π/2√2

Form Factor



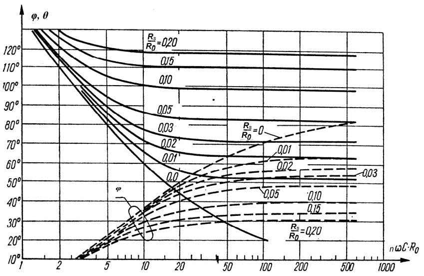
n - numbers of phases(1,2,3,6)

I_{DMAX}/I_{DAV}=CF*FF



n - liczba faz
(1,2,3,6)

Flow ange Θ & start flow angle φ

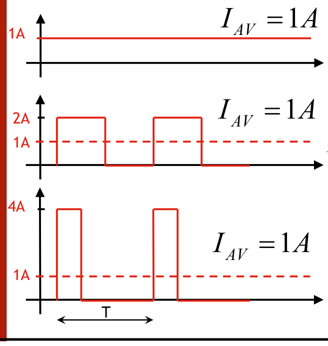


For $\omega R_0 C >> 1$ i $R_0 >> R_s$

When C increas

- Ripples fall down~$1/nfCR_0$!!!!
- Flow angle decrease (diode conducting time)
  - peak current increase
  - RMS diode & transformer currents increase (heating up)

RMS of pulse



$I_{AV} = 1A$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = 1A$$

$CF = 1; \quad FF = 1;$

$I_{AV} = 1A$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = \sqrt{2}A$$

$CF = \sqrt{2}; \quad FF = \sqrt{2};$

$I_{AV} = 1A$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = 2A$$

$CF = 2; \quad FF = 2;$

Power dessipated in diode

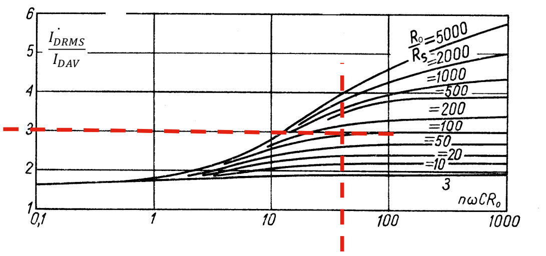
$$P_{Dreal} = \frac{1}{T}\int_0^T u_D(t) i_D(t)dt + \frac{1}{T}\int_0^T i_D^2(t) R_{D.series.} dt =$$

$$= U_D I_{DAV} \qquad + \quad \boxed{I^2_{DRMS.} R_{D.series}}$$

$$P_{Dreal} = 0.7V \bullet 1A + (3A)^2 \bullet 0.1\Omega =$$

$$= \quad 0.7W \quad + \quad 0.9W$$

Form Factor
I_{DRMS}/I_{DAV}=FF



n - liczba faz (1,2,3,6)

Rectifier comparison

	Half-wave	Center-tap	Bridge
C To reach proper U_{rip}	$C \approx \frac{U_{OUT\max}}{U_{rip.pp}} \frac{1}{fR_0}$	½(..)	½(..)
Maximum and RMS diode current)	high	meadium	meadium
Diode revers voltage	$2E_{max}$	1(..)	½(..)
Current Harmonics	All Including DC ???	odd	odd

Crest Factor & Waveform Factor

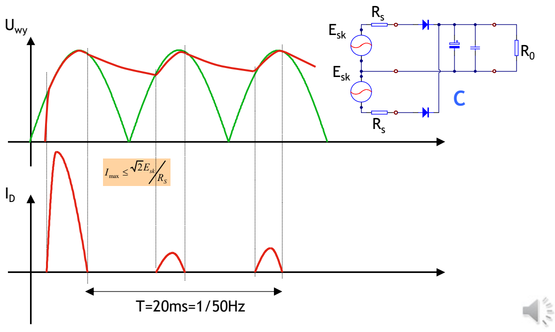
$$CF = {I_{MAX}}/{I_{RMS}}$$

Crest Factor - współczynnik szczytu
For sin wave = 1,41= √2

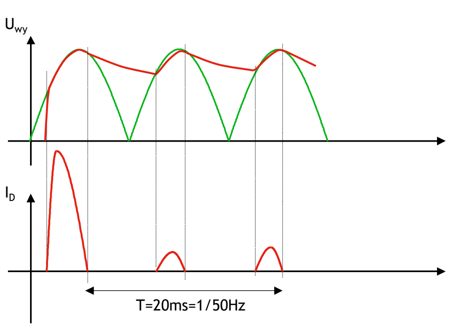
$$FF = {I_{RMS}}/{|I|_{AV}}$$

Waveform Factor - współczynnik kształtu
For sine wave = 1,11=π/2√2

„surge current”



regulation EN61000-3-2 (IEC555)



Example of parameters for a rectifier diode

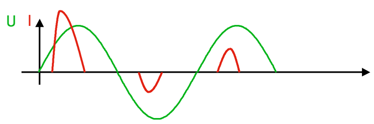
MAXIMUM RATINGS (T_A = 25 °C unless otherwise noted)

PARAMETER		SYMBOL	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	UNIT
Maximum repetitive peak reverse voltage		V_{RRM}	50	100	200	400	600	800	1000	V
Maximum RMS voltage		V_{RMS}	35	70	140	280	420	560	700	V
Maximum DC blocking voltage		V_{DC}	50	100	200	400	600	800	1000	V
Maximum average forward rectified current 0.375" (9.5 mm) lead length at T_A = 75 °C		$I_{F(AV)}$	1.0							A
Peak forward surge current 8.3 ms single half sine-wave superimposed on rated load		I_{FSM}	30							A
Non-repetitive peak forward surge current square waveform T_A = 25 °C (fig. 3)	t_p = 1 ms	I_{FSM}	45							A
	t_p = 2 ms		35							
	t_p = 5 ms		30							
Maximum full load reverse current, full cycle average 0.375" (9.5 mm) lead length T_L = 75 °C		$I_{R(AV)}$	30							µA
Rating for fusing (t < 8.3 ms)		I^2t [1]	3.7							A^2s
Operating junction and storage temperature range		T_J, T_{STG}	-50 to +150							°C

Note

[1] For device using on bridge rectifier application

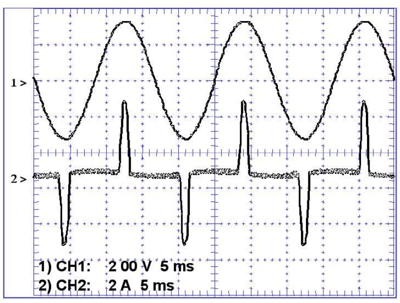
Supply current distortion - IEC555 EN 61000-3-2



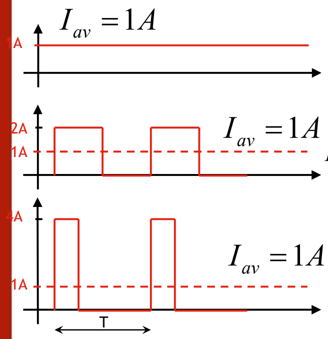
- harmonics (up to 40 harmonic)
- current fluctuations of load
- surge current ???

Input Characteristics of a Typical Switched-Mode Power Supply without PFC

Top: Input Voltage Bottom: Input Current



RMS vs. DC



$I_{av} = 1A$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = 1A$$

$CF = 1; \quad FF = 1;$

$I_{av} = 1A$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = \sqrt{2}A$$

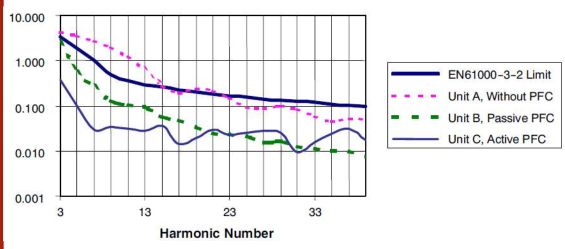
$CF = \sqrt{2}; \quad FF = \sqrt{2};$

$I_{av} = 1A$

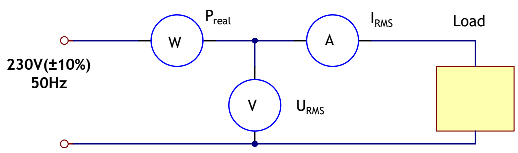
$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = 2A$$

$CF = 2; \quad FF = 2;$

Input Harmonics of Three PC Power Supplies Relative to EN61000-3-2 Limits



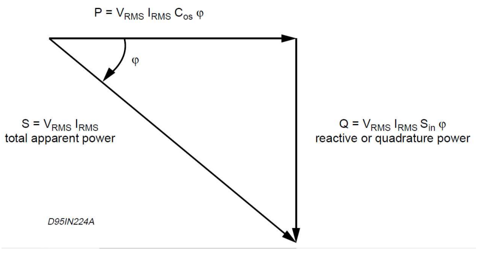
Power Factor



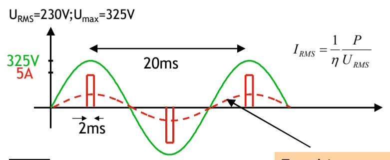
$$PF = \frac{P_{real}}{U_{RMS} \bullet I_{RMS}} \leq 1 \quad \left[\frac{W}{VA}\right]$$

P - real power [w]
Q - reactive power [Var]
S - apparent power [VA]

Power triangle
(no current harmonics case)



Power Factor η=cosθ



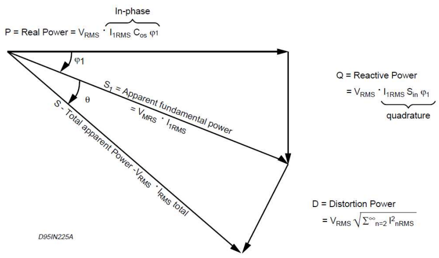
$$I_{RMS} = \frac{1}{\eta}\frac{P}{U_{RMS}}$$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2 dt} \approx \sqrt{\frac{1}{20ms}(5A)^2(2+2ms)} \approx 2{,}2A$$

$$P_{real} = \frac{1}{T}\int_0^T u(t)i(t)dt \approx 320V \bullet 5A \bullet \frac{4ms}{20ms} = 320W$$

$$\boxed{PF = \frac{P_{real}}{U_{RMS} \bullet I_{RMS}} \approx \frac{320W}{230V \bullet 2{,}2A} \approx 0{,}63 \quad \left[\frac{W}{VA}\right]}$$

Power triangle
(no current harmonics case)



Total P.F.= η = cos φ_1 cos θ

φ_1 is the "conventional" displacement angle (phase lag) between the in-phase fundamental I and V
θ is the distortion angle linked to the harmonic content of the current.

Both of reactive (Q) and distortion (D) powers produce extra RMS currents, giving extra losses so that then the mains supply network efficiency is decreased.

Improving P.F. means to improve both of factors i.e.:

φ_1 ->0 cos φ_1 -> 1 = reduce phase lag between I and U
θ -> 0 cos θ -> 1 = reduce harmonic content of I

THD vs. PF (cos φ_1 =1)

$$THD(\%) = 100 * \sqrt{\frac{1}{Kd^2} - 1}$$

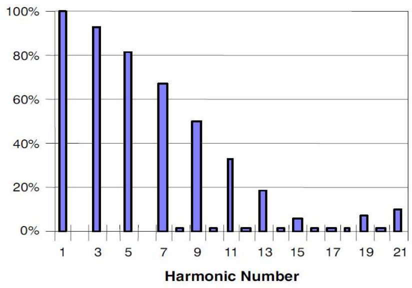
$$Kd = \frac{1}{\sqrt{(1 + \left(\frac{THD(\%)}{100}\right)^2)}}$$

$$PF = \frac{1}{\sqrt{1 + \left(\frac{THD(\%)}{100}\right)^2}}$$

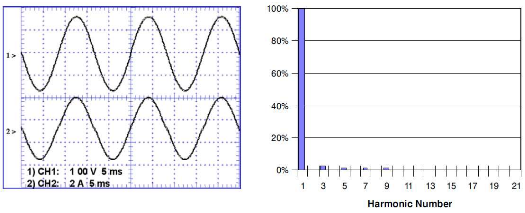
THD vs. P.F.

$$PF = \frac{\cos(\varphi_1)}{\sqrt{1+\left(\frac{THD(\%)}{100}\right)^2}} = \cos(\theta) \cdot \cos(\varphi_1)$$

Harmonic Content of the Current Waveform



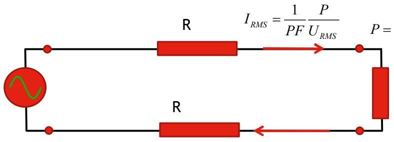
Input Characteristics of a Power Supply with Near-Perfect PFC



Why PF should be 1

$$I_{RMS} = \frac{1}{PF}\frac{P}{U_{RMS}}$$

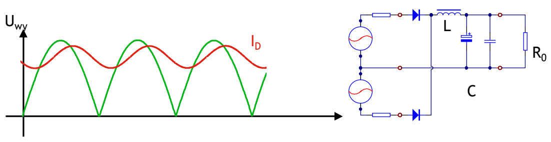
$$P = \frac{1}{T}\int_0^T u(t)i(t)dt = PF \times U_{RMS} I_{RMS}$$



$$P_{LOST} = (I_{RMS})^2 R = \left(\frac{1}{PF}\right)^2 \left(\frac{P}{U_{RMS}}\right)^2 R$$

$$\left(\frac{1}{PF}\right)^2 = \left(\frac{1}{0,63}\right)^2 = 2,52$$

LC filter



Results:

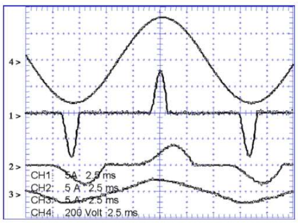
- Smaller ripples
- Smaller THD
- Higher cost
- Choke must be „big"

$L > L_{krytyczne} = R_0 / 3\omega$

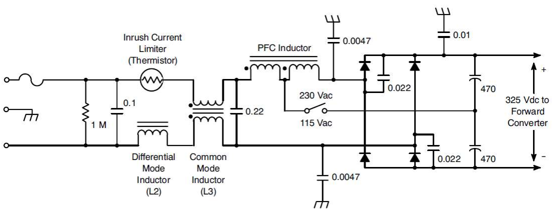
For L>L_{kr} I_L not drop to 0 (continues mode)

Input Characteristics of PC Power Supplies with Different PFC Types (None, Passive, and Active)

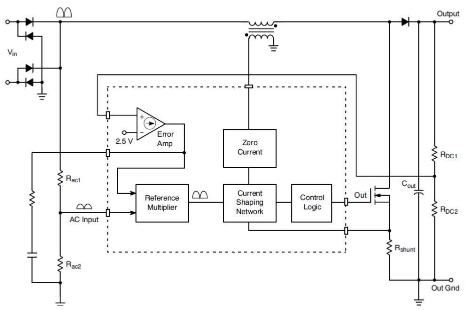
Waveforms:
1. Input current with no PFC
2. Input current with passive PFC
3. Input current with active PFC
4. Input voltage



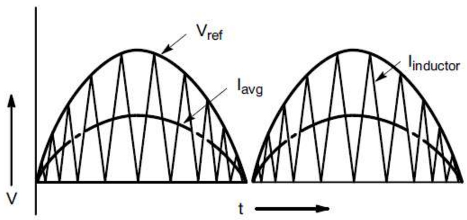
Passive PFC in a 250W PC Power Supply



Basic Schematic for a Critical Conduction Mode Converter



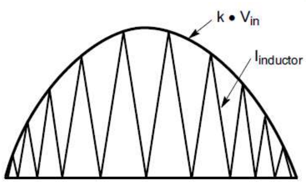
CRM Waveforms



CRM Current Envelope

$I_{pk} = k * V_{in}(t)$

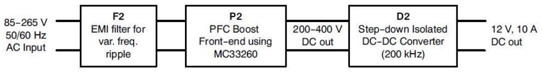
$I_{pk} = \Delta I = \frac{V_{in}(t)}{L} * t_{on}$



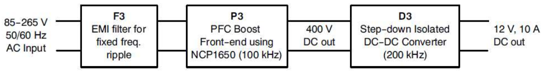
$k * V_{in}(t) = \frac{V_{in}(t)}{L} * t_{on}$

$t_{on} = k * L$

Critical Conduction Mode (CRM) PFC with Variable Output Voltage



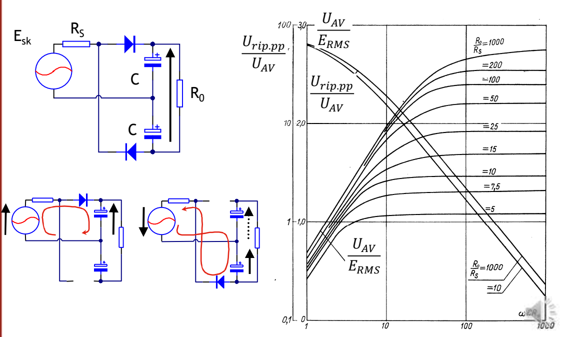
Continuos Conduction Mode PFC with Fixed Output Voltage



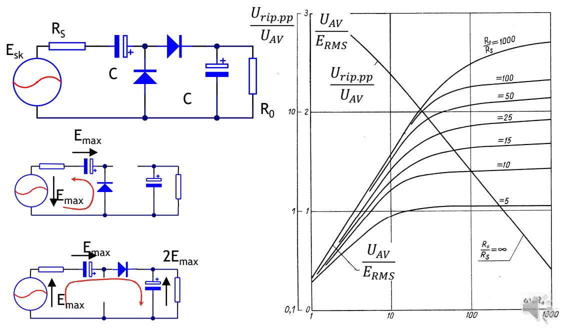
References

Advertisement materials and application notes of
„ON Semiconductor”

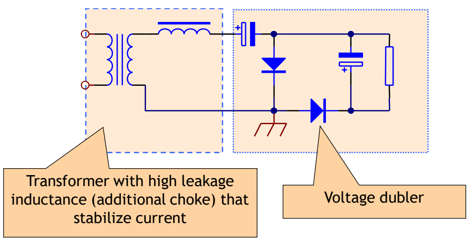
Voltage dubler (Delon)



Voltage dubler (Villarda)

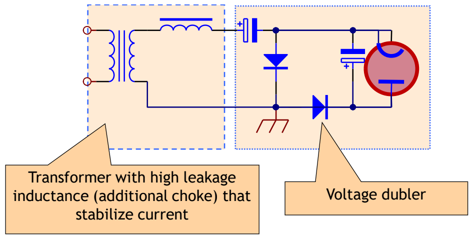


An example

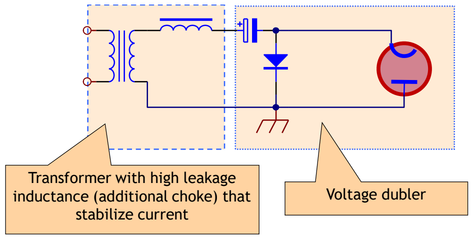


Voltage doubler!!!

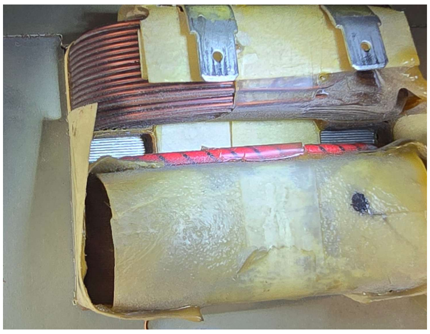
En examlpe

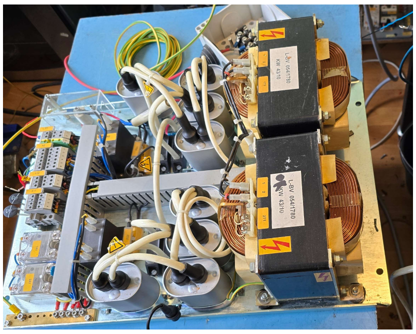


An example

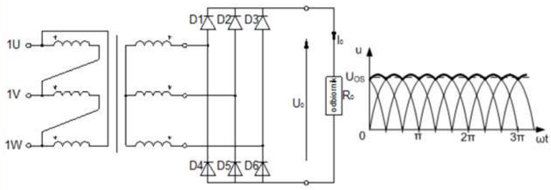


Microwave oven !!!



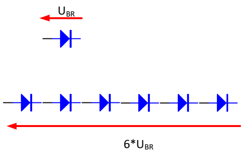


3ph rectifier

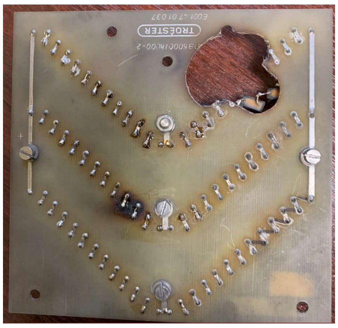


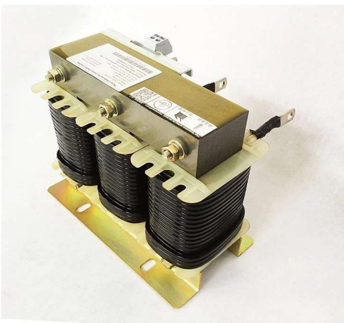
3ph rectifier - hv

- Dides must be „matched" !



3ph rectifier hv practice

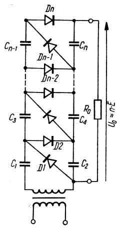


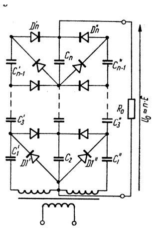


Voltage multipliers

$$C \geq \frac{2n(n+2)}{fR_0}$$

$$U_{wy.śr} = n\sqrt{2}E_{sk} - U_t$$





$$U_t \approx \frac{I_{wy.śr}}{fC}\left(\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{1}{6}n\right)$$

$$U_t \approx \frac{I_{wy.śr}}{fC}\left(\frac{1}{6}n^3 + \frac{1}{4}n^2 + \frac{1}{12}n\right)$$

summary

- Transformer (parameters, types, equivalent schematic diagram)
- Types of rectifiers
- Resistive load rectifier (voltage, current waveforms)
- Rectifier with capacitive filter (voltage, current waveforms)
- Power Factor (definition, way of correction)

Test questions

- Draw a simplified diagram of a transformer and describe its individual components.
- Draw a schematic diagram of a rectifier (half-wave, full-wave, bridge).
- Draw the voltage and current waveforms in a rectifier (3 types).
- What is the definition of power factor?
- Estimate PF using a simple example.