Wroclaw University of Science and Technology

Power suppliers:
- rectifiers,
- filters,
- 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

Rodzaje transformatorów sieciowych

- Rdzenie typu EI, zwijane, toroidalne
- Materiał rdzenia
  - Blachy gorąco walcowane
  - Blachy zimnowalcowane

Transformers

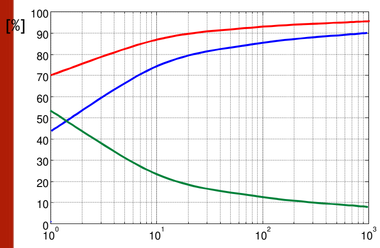
transformersr [voltage / turn]

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

Transformers - power vs. type

S[cm^2]@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”



$U_{outAV}/U_{RMS\ nominal}$

$P_{outDC}/P_{trafo.nominal}$

$I_{idel}/I_{primary\text{-}nominal}$

transformer power

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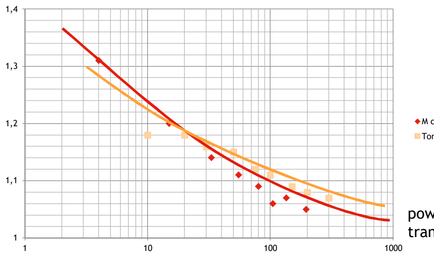
Loss vs. power of a transformer ”””experimental data”””

Loss factor



power of a transformer [W]

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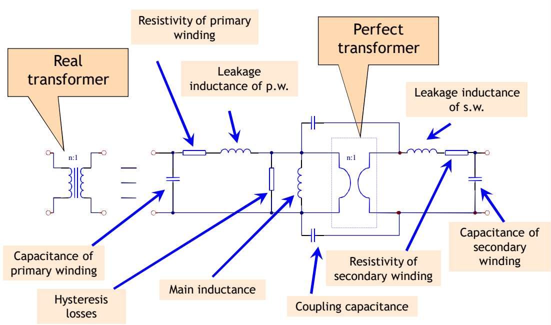
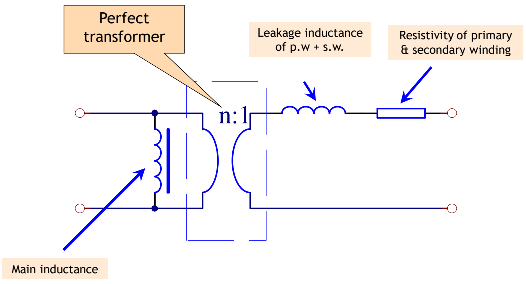
Transformer electronic model

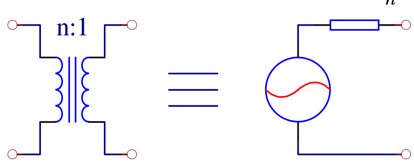


Simplified model



More simplified model

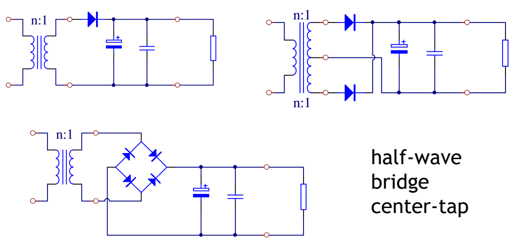
$$R_{series} = \frac{R_{primary}}{n^2} + R_{secondary}$$



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

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

power rectifiers



half-wave
bridge
center-tap

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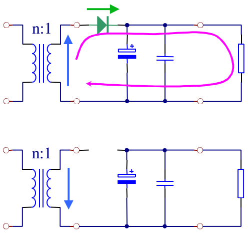
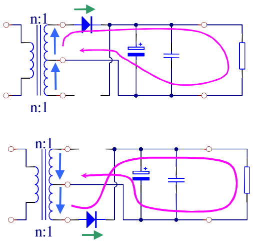
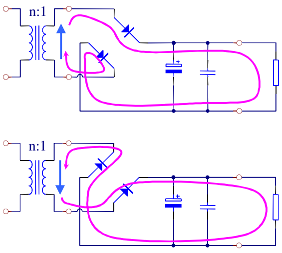
half-wave



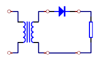
Center-tap



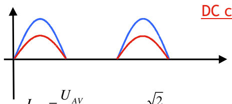
bridge



Rectifier - resistive load

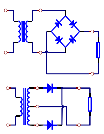


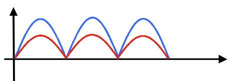
Current and voltage across resistive load

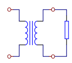


DC current is present!!!

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

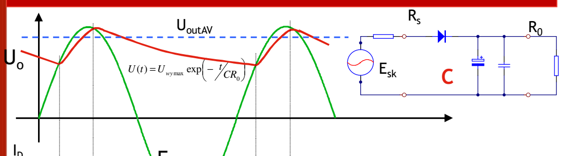


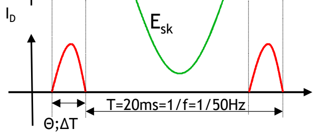




$$U_{AV} = \frac{2\sqrt{2}}{\pi} E_{AV} \quad I_{AV} = \frac{U_{AV}}{R_0} \quad U_{RMS} = E_{RMS}$$

Voltage and current for half-wave rectifier





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

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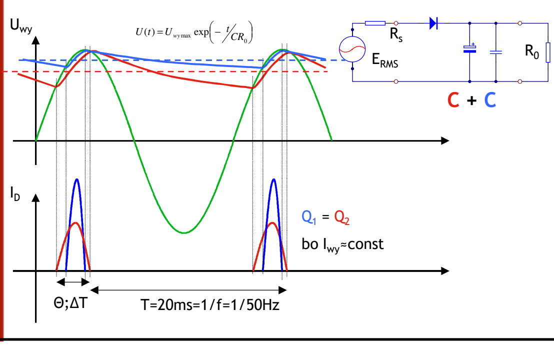
Half wave rectifier with a capacitve filter



Basic relations

Maximum idle voltage:

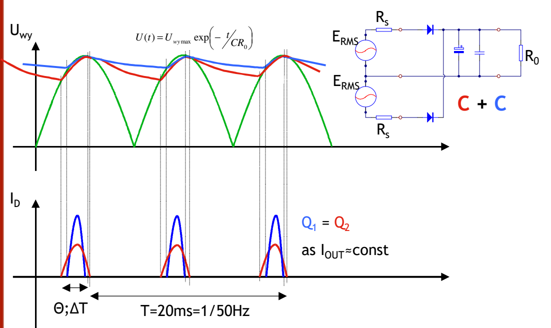
$$U_{\max} \approx \sqrt{2}E_{RMS} - U_F \approx \sqrt{2}E_{RMS}$$

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:

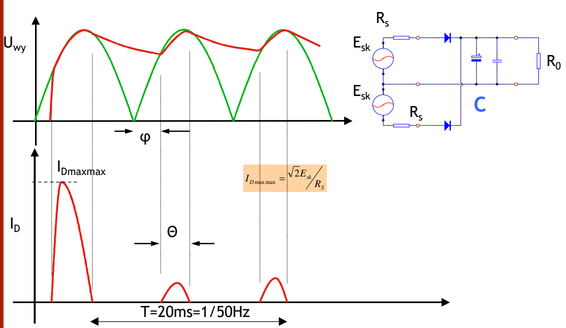
$$U_{\max} \approx \sqrt{2}E_{RMS} - 2U_F$$

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”



half-wave rectifier

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

No-load voltage	$U_{outMax} = \sqrt{2}E_{RMS} - U_F$
On-load voltage (C=∞)	$U_{outEV} = U_{outMax}\left(1 - \sqrt{\frac{R_S}{R_L}}\right)$
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=∞)	$U_{outEV} = U_{outMax}\left(1 - \sqrt{\frac{R_S}{2R_L}}\right)$
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	$I_{D\max}=U_{outAV}/\sqrt{2R_SR_L}$
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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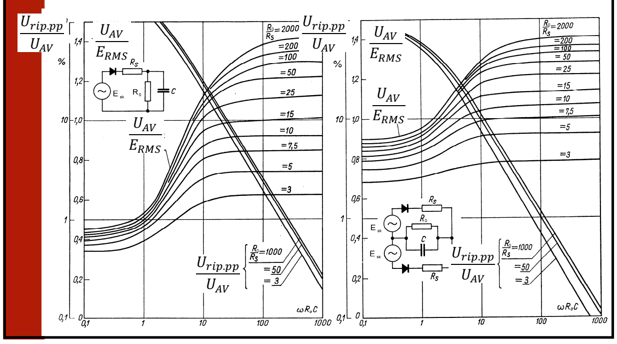
Główne parametry

- Assumed:
  - $E_{RMS}=U_{RMS}/n_{(turn\ ratio}$
  - R_S - series resistivity
  - U_F - foreward 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

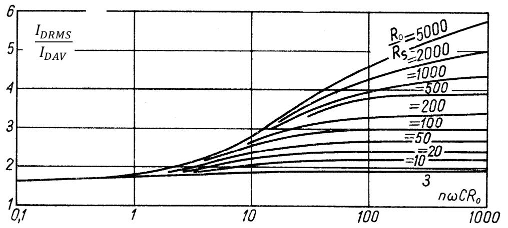
$$CF = I_{MAX} / I_{RMS}$$

Crest Factor -
For sin = 1,41= √2

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

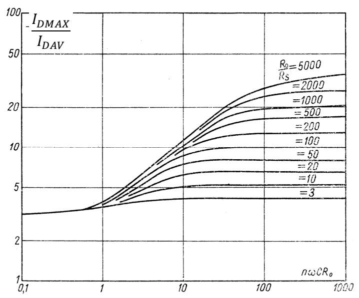
*wave*Form Factor -
For sin = 1,11=π/2√2

Form Factor



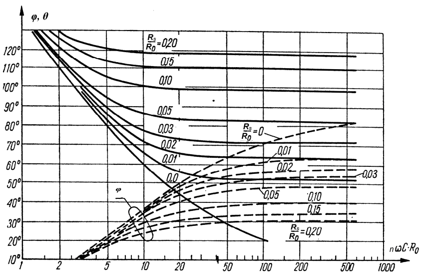
n - numbers of phases(1,2,3,6)

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



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

Flow ange Θ & start flow angle φ

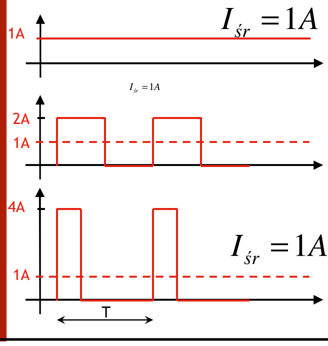


Zależności dla $\omega R_0 C >> 1$ i $R_0 >> R_s$

When C increas

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

RMS of pulse



$$I_{śr} = 1A$$

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

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

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

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

$$I_{śr} = 1A$$

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

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

Power dessipated in diode

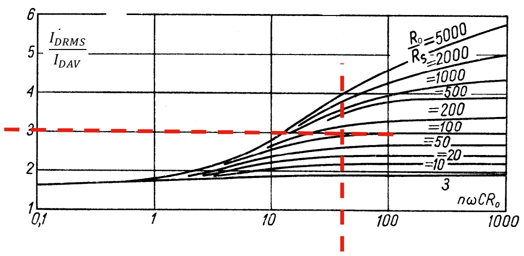
$$P_{Dreal} = \frac{1}{T}\int_0^T u_D(t) i_D(t) dt + \frac{1}{T}\int_0^T i_D^2(t) R_{D.series.} dt =$$

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

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

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

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



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

Porównanie zasilaczy

	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

Współczynnik szczytu i kształtu

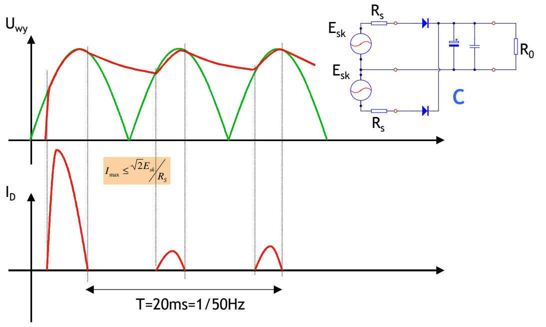
$$CF = I_{MAX} / I_{RMS}$$

Crest Factor - współczynnik szczytu
Dla sinusa = 1,41= √2

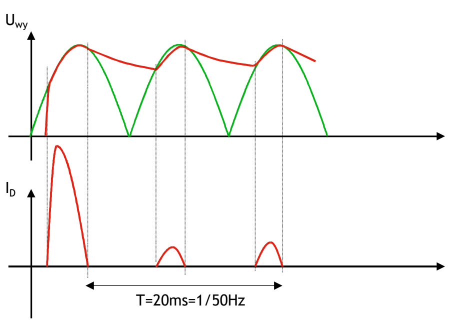
$$FF = I_{RMS} / |I|_{AV}$$

*wave*Form Factor - współczynnik kształtu
Dla sinusa = 1,11=π/2√2

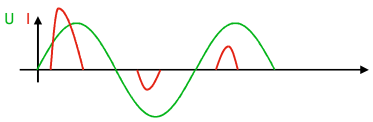
„surge current”



regulation EN61000-3-2 (IEC555)

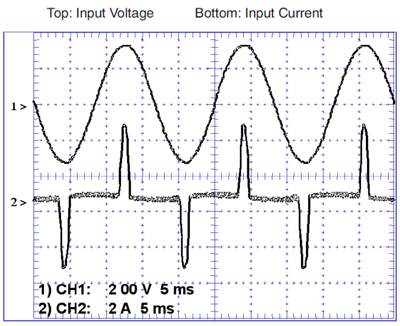


Supply current distortion - IEC555 EN 61000-3-2

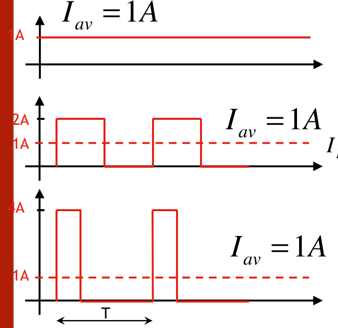


- harmonics (up to 40 harmonic)
- current fluctuations of load
- surge current ???

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



RMS vs. DC



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

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

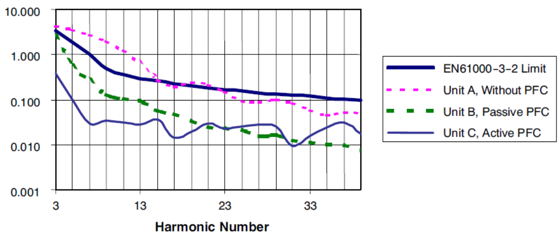
$$I_{av} = 1A \qquad I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = \sqrt{2}A$$

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

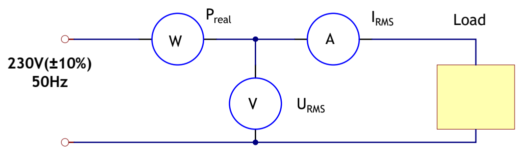
$$I_{av} = 1A \qquad I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = 2A$$

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

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



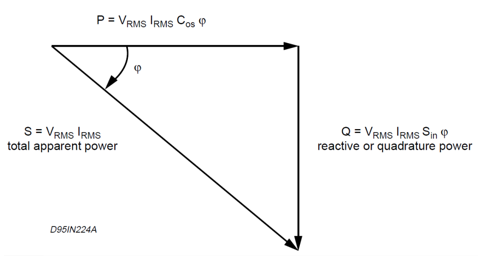
Power Factor



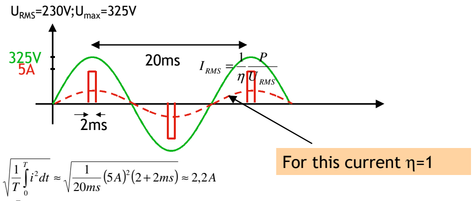
$$\eta = \frac{P_{real}}{U_{RMS} \bullet I_{RMS}} \leq 1 \quad \left[\frac{W}{VA}\right]$$

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

Power triangle (no current harmonics case)



Power Factor η=cosθ



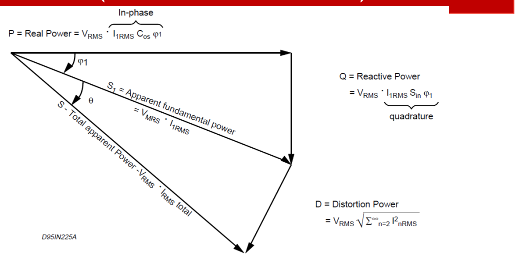
$$I_{RMS} = \frac{1}{\eta}\frac{P}{U_{RMS}}$$

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

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

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

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
θ -> 0 cos θ -> 1 = reduce harmonic content of I

THD vs. P.F. (cos φ_1 =1)

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

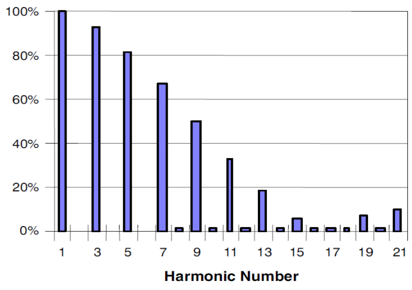
$$Kd = \frac{1}{\sqrt{(1 + \left(\frac{THD(\%)}{100}\right)^2)}}$$

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

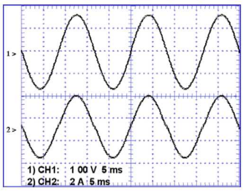
THD vs. P.F.

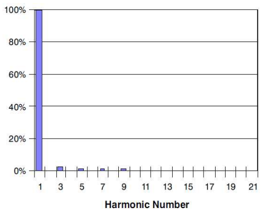
$$P.F. = \frac{\cos(\varphi_1)}{\sqrt{1 + \left(\frac{THD(\%)}{100}\right)^2}} = \cos(\theta) \cdot \cos(\varphi_1)$$

Harmonic Content of the Current Waveform

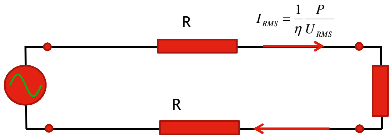


Input Characteristics of a Power Supply with Near-Perfect PFC





Why PF should be 1



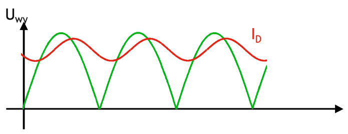
$$I_{RMS} = \frac{1}{\eta}\frac{P}{U_{RMS}}$$

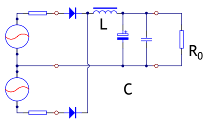
$$P = \frac{1}{T}\int_0^T u(t)i(t)dt = \eta U_{RMS} I_{RMS}$$

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

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

Filtry indukcyjno - pojemnościowe





Skutki:

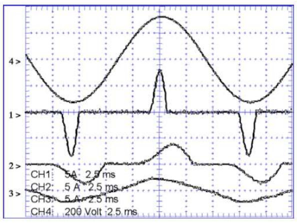
$L > L_{krytyczne} = R_0/3\omega$

- Polepszenie filtracji – zmniejszenie tętnień
- Znaczne Zmniejszenie zawartości harmonicznych
- Większy koszt
- Dławik musi być duży ze względu na jego nasycanie

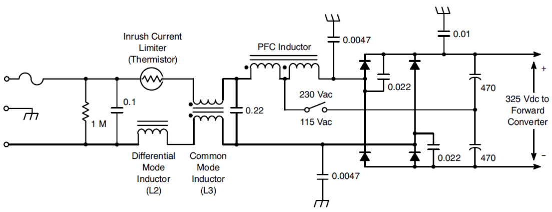
Dla $L > L_{kr}$ kąt przepływu prądu jest pełny

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

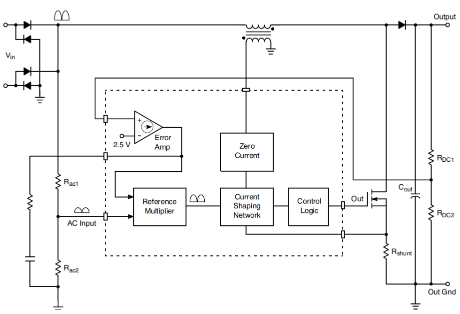
Waveforms:
1. Input current with no PFC
2. Input current with passive PFC
3. Input current with active PFC
4. Input voltage



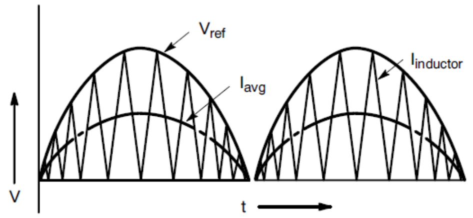
Passive PFC in a 250W PC Power Supply



Basic Schematic for a Critical Conduction Mode Converter



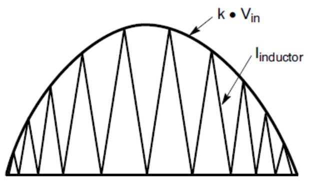
CRM Waveforms



CRM Current Envelope

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

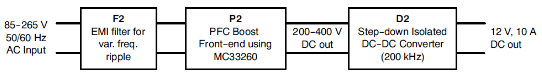
$I_{pk} = \Delta I = \frac{V_{in}(t)}{L} * t_{on}$



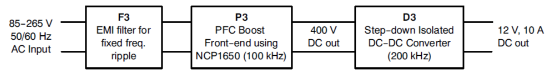
$k * V_{in}(t) = \frac{V_{in}(t)}{L} * t_{on}$

$t_{on} = k * L$

Critical Conduction Mode (CRM) PFC with Variable Output Voltage



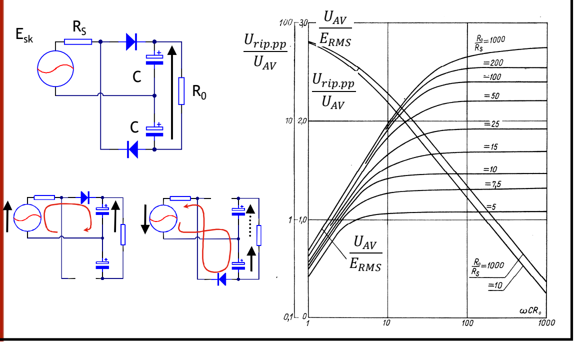
Continuos Conduction Mode PFC with Fixed Output Voltage



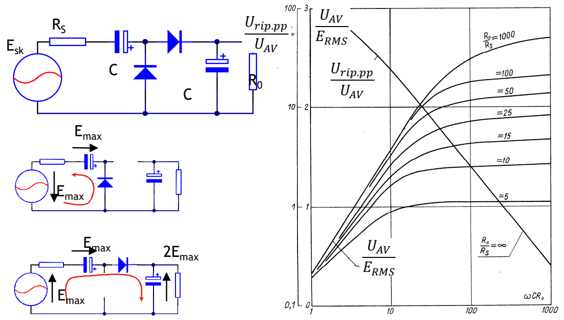
References

Advertisement materials and application notes of „ON Semiconductor”

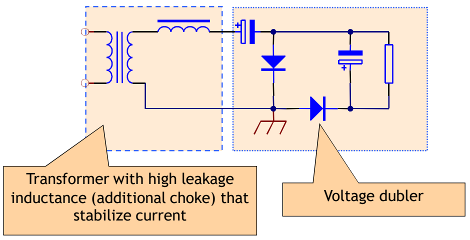
Voltage dubler (Delon)



Voltage dubler (Villarda)

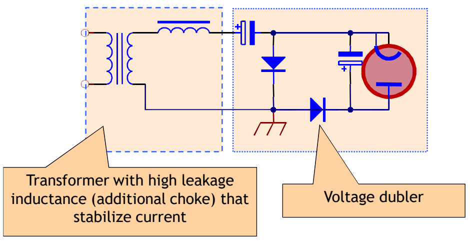


An example

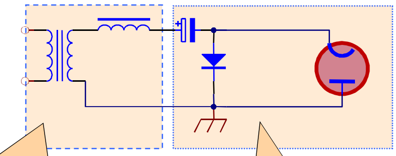


Voltage doubler!!!

En examlpe



Przykład



Transformer with high leakage inductance (additional choke) that stabilize current

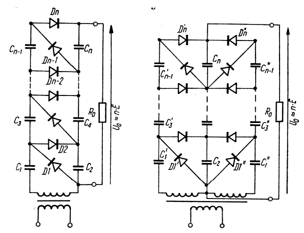
Voltage dubler

Microwave oven !!!

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)

Pytania kontrolne

- Schematy oraz zasada działania prostownika jedno-/dwupołówkowym/Gretza z filtrem pojemnościowym.
- Przebiegi napięć i prądów w prostownikach jw.
- Co to jest współczynnik mocy ?
- Co to jest napięcie tętnień i od czego zależy ?
- Uproszczony schemat zastępczy transformatora.