UTILITY INTERFACE ISSUES OF POWER ELECTRONIC CONVERTERS

III. INTRODUCTION TO IEC 1000-3-2 HARMONIC STANDARDS

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OUTLINE

- Definitions
- Basics of power factor correction
- Basics of single-phase PFC topologies
- Review of harmonic standards IEC 1000-3-2

POWER FACTOR DEFINITION

Input voltage and current are periodic waveforms with period $\mathbf{T_i}$.

Power factor **PF**:

$$PF \equiv \frac{P}{V_{i,rms} \cdot I_{i,rms}}$$

where $\mathbf{P}$ is the average power:

$$P = \frac{1}{T_i} \cdot \int_{T_i} v_i \, i_i \, dt$$

and $\mathbf{V_{i,rms}}$ and $\mathbf{I_{i,rms}}$ are :

$$V_{i,\,rms} \equiv \sqrt{\frac{1}{T_i} \int_{T_i} v_i^2 \, dt} \qquad I_{i,\,rms} \equiv \sqrt{\frac{1}{T_i} \int_{T_i} i_i^2 \, dt}$$

POWER FACTOR DEFINITION

Being voltage and current periodic waveforms we can write in Fourier series:

$$v_i = V_0 + \sum_{k=1}^{\infty} \sqrt{2} V_k \sin(k\omega_i + \phi_k)$$

$$i_i = I_0 + \sum_{k=1}^{\infty} \sqrt{2} I_k \sin(k\omega_i + \gamma_k)$$

V_0 , I_0 = average values

V_k , I_k = RMS values of harmonics

The average power is:

$$P = V_0 I_0 + \sum_{1}^{\infty} V_k I_k \cos(\phi_k - \gamma_k)$$

CONSEQUENCE:

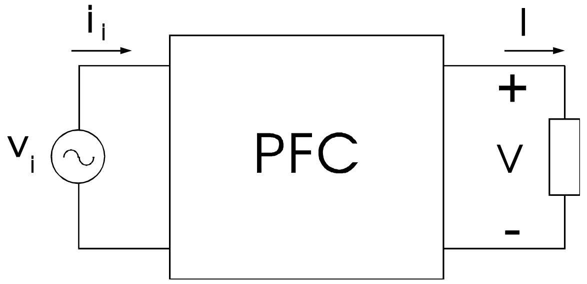
Current harmonic terms contributes to active power only in the presence of voltage harmonic terms of the same frequency.

POWER FACTOR DEFINITION

$$0 \leq \mathbf{PF} \leq 1$$

PF = 1 only if current and voltage are proportional

Power Factor Correction



An ideal Power Factor Corrector (PFC) takes from the supply a current which is proportional to the supply voltage

$$R_{em} = \frac{v_i}{i_i}$$ **emulated resistance**

POWER FACTOR DEFINITION

PARTICULAR CASE: SINUSOIDAL INPUT VOLTAGE

$$\mathrm{PF} = \frac{V_1 I_1 \cos(\phi_1)}{V_1 \cdot I_{i,rms}} = \frac{I_1}{I_{i,rms}} \cdot \cos(\phi_1)$$

$\mathrm{D.F.} = \dfrac{I_l}{I_{i,rms}}$ = DISTORTION FACTOR

$\cos(\phi_1)$ = DISPLACEMENT FACTOR

$$\mathrm{D.F.} = \frac{1}{\sqrt{1 + (\mathrm{THD})^2}}, \qquad \mathrm{THD} = \frac{\sqrt{I_{i,rms}^2 - I_1^2}}{I_1}$$

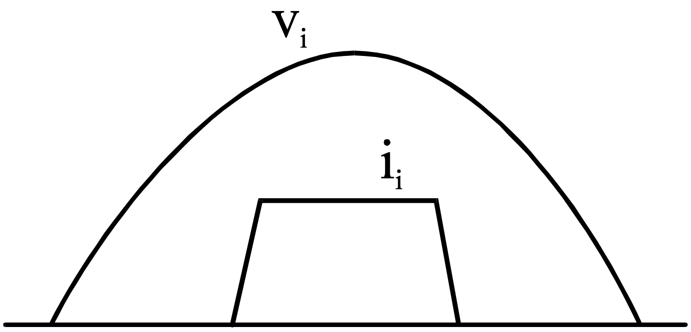
(THD = Total Harmonic Distortion)

POWER FACTOR REQUIREMENTS

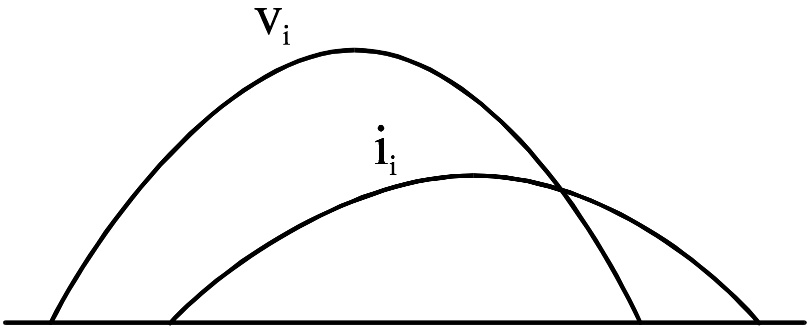
PF = 1 implies:

- zero displacement between voltage and current fundamental component ($\phi_1 = 0$)
- zero current harmonic content

EXAMPLES:



$\cos(\phi_1) = 0$, D.F. $\neq 0$



$\cos(\phi_1) \neq 0$, D.F. $= 0$

In both cases PF<1

BASICS OF ACTIVE POWER FACTOR CORRECTION

POWER FACTOR CORRECTION TECHNIQUES

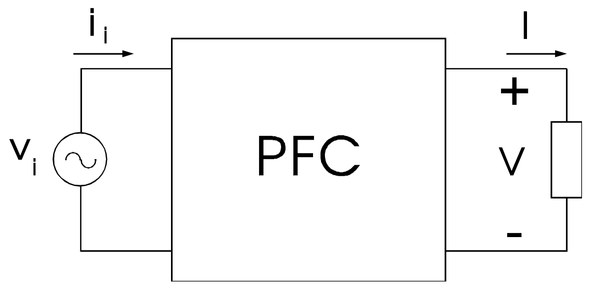
PASSIVE METHODS: LC filters

- power factor not very high
- bulky components
- high reliability
- suitable for very small or high power levels

ACTIVE METHODS: high-frequency converters

- high power factor (approaching unity)
- possibility to introduce a high-frequency insulating transformer
- layout dependent high-frequency harmonics generation (EMI problems)
- suitable for small and medium power levels

ACTIVE POWER FACTOR CORRECTION



DEFINITION:

Power Factor Corrector (PFC):
AC/DC converter with sinusoidal current absorption
(Current Proportional To Supply Voltage)

$$v_i = V_i \, \mathrm{sen}(\vartheta)$$

$$i_i = I_i \, \mathrm{sen}(\vartheta), \vartheta = \omega_i t$$

The converter behaves like an equivalent resistance R_{em} given by:

$$R_{em} = \frac{V_i}{I_i}$$

ACTIVE POWER FACTOR CORRECTION: BASIC CONSIDERATIONS

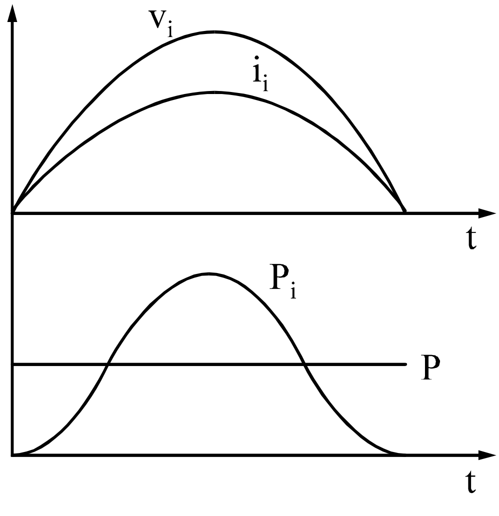
Input power:

$$p_i(\vartheta) = v_i(\vartheta) \cdot i_i(\vartheta) = 2 \cdot V_{i,rms} I_{i,rms} \sin^2(\vartheta) =$$
$$= V_{i,rms} I_{i,rms} (1 - \cos(2\vartheta))$$

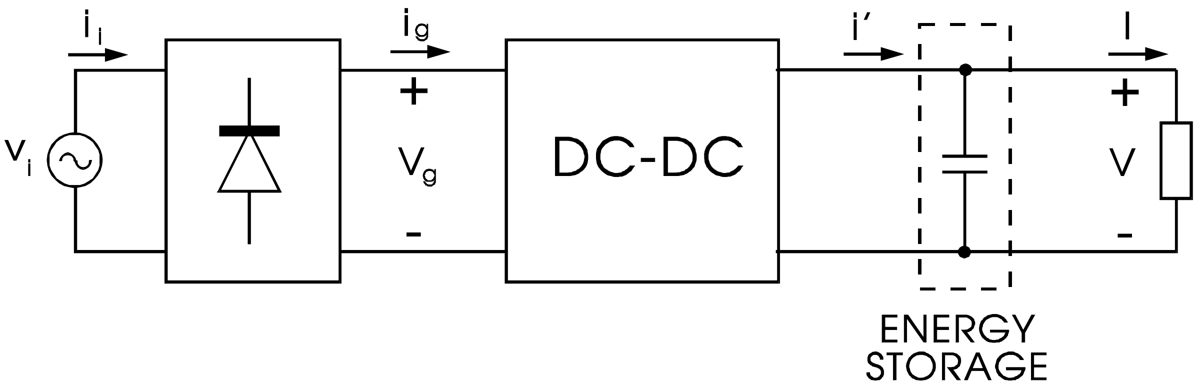
Considering unity efficiency:

$$V_{i,rms} \cdot I_{i,rms} = P = V \cdot I$$

P = output power



PFC WITH CAPACITIVE FILTER



ASSUMPTIONS:

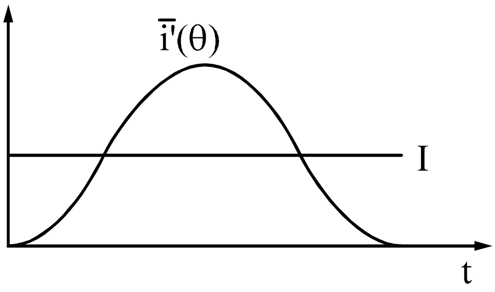
- constant output voltage
- unity efficiency
- no low-frequency pulsating energy stored in the dc/dc stage

$$\Rightarrow \quad p_i(\vartheta) = V \cdot \bar{i}'(\vartheta)$$

PFC WITH CAPACITIVE FILTER

$$\bar{i}'(\vartheta) = \frac{p_i(\vartheta)}{V} = 2I\sin^2(\vartheta)$$

$\bar{i}'(\vartheta)$ = average value of $i'(\vartheta)$ in a switching period



Voltage conversion ratio M':

$$M'(\vartheta) = \frac{V}{v_g(\vartheta)} = \frac{\bar{i}_g(\vartheta)}{\bar{i}'(\vartheta)}$$

Load seen by the dc/dc stage:

$$R'(\vartheta) = \frac{V}{\bar{i}'(\vartheta)} = M'(\vartheta)^2 \cdot \frac{v_g(\vartheta)}{\bar{i}_g(\vartheta)} = M'(\vartheta)^2 \cdot R_{em}$$

PFC WITH CAPACITIVE FILTER

$$R'(\vartheta) = \frac{R}{2 \cdot \sin^2(\vartheta)}$$

$$M'(\vartheta) = \frac{M}{|\sin(\vartheta)|}, M = \frac{V}{V_g}$$

For a PFC we have:

$$\frac{R'(\vartheta)}{M'^2(\vartheta)} = R_{em}$$

a dc/dc converter when used as rectifier operates as a PFC with constant control if : $M'(\vartheta) \propto \sqrt{R'(\vartheta)}$

PFC WITH CAPACITIVE FILTER

OUTPUT FILTER DESIGN

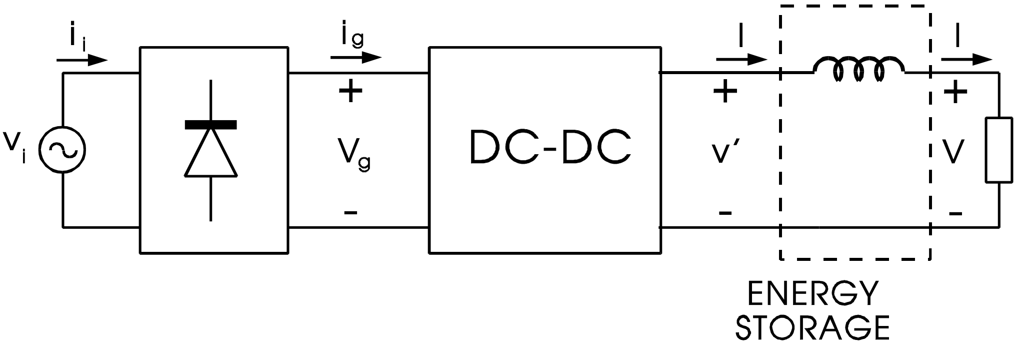
Output filter capacitor current:

$$i_c(\vartheta) = \bar{i}'(\vartheta) - I = -I \cdot \cos(2\vartheta)$$

If ΔV is the desired peak-to-peak output voltage ripple, then:

$$C \geq \frac{I}{\omega_i \, \Delta V}$$

PFC WITH INDUCTIVE FILTER



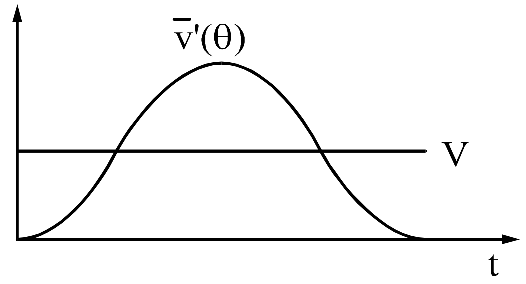
ASSUMPTIONS:

- constant output current
- unity efficiency
- no low-frequency pulsating energy stored in the dc/dc stage

$$\overline{v}'(\vartheta) = \frac{p_i(\vartheta)}{I} = 2V\sin^2(\vartheta)$$

$\overline{v}'(\vartheta)$ = average value of $v'(\vartheta)$ in a switching period

PFC WITH INDUCTIVE FILTER



Voltage conversion ratio M’:

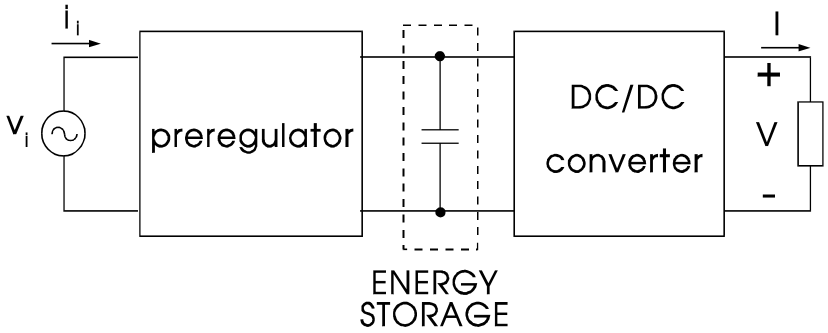
$$M'(\vartheta) = \frac{\bar{v}'(\vartheta)}{v_g(\vartheta)} = \frac{\bar{i}_g(\vartheta)}{I} = 2M\left|\sin(\vartheta)\right|$$

Load seen by the dc/dc stage:

$$R'(\vartheta) = \frac{\bar{v}'(\vartheta)}{I} = 2R\sin^2(\vartheta)$$

POWER FACTOR CORRECTORS: STANDARD CONFIGURATION

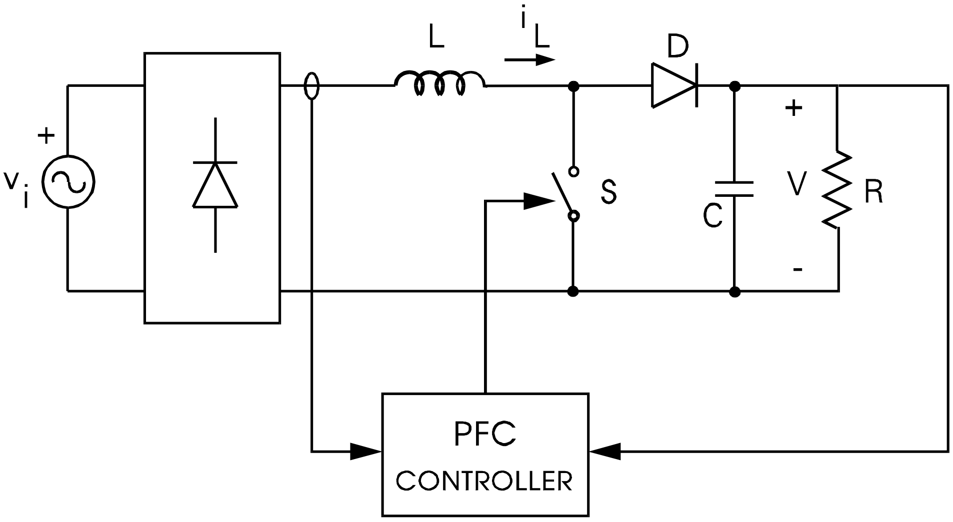
TWO STAGE PFC: CASCADE CONNECTION



PREREGULATORS: AC/DC converters with high power factor and poor output voltage regulation

LOW EFFICIENCY: THE SAME POWER IS PROCESSED TWICE

BASIC PREREGULATORS: BOOST TOPOLOGY



CHARACTERISTICS:

- ❑ Inherent input filter (low input current harmonic content)
- ❑ Simple topology
- ❑ high power factor
- ❑ Output voltage greater than peak input voltage
- ❑ no start-up or short circuit protection
- ❑ no high-frequency insulation

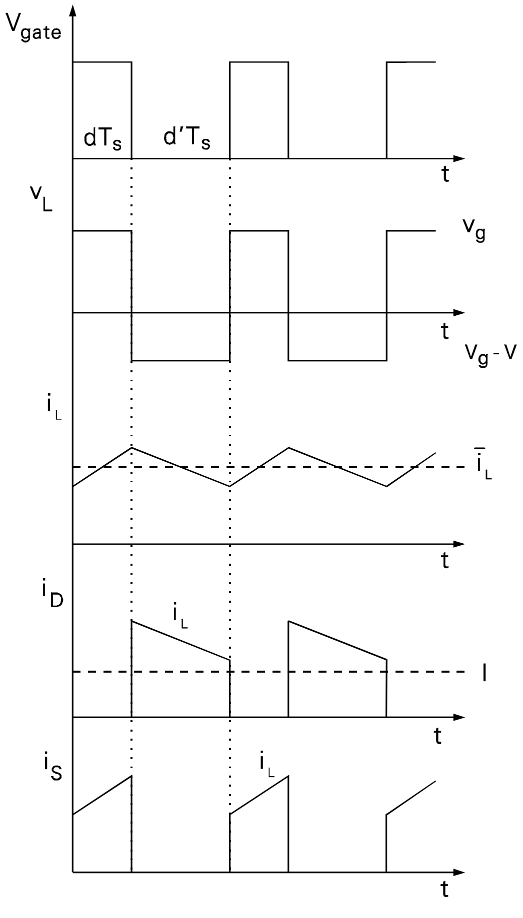
BASIC PREREGULATORS: BOOST TOPOLOGY

CCM OPERATION

Assumption:

switching frequency much greater than line frequency (quasi-stationary approach).

Main waveforms in a switching period



BASIC PREREGULATORS: BOOST TOPOLOGY

OPERATION AS DC/DC CONVERTER

Voltage conversion ratio : $$M = \frac{1}{1-d}$$

d = duty-cycle

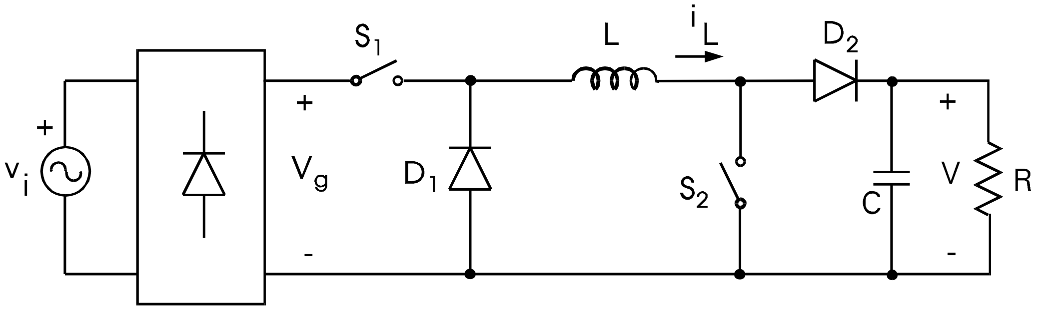
OPERATION AS AC/DC CONVERTER

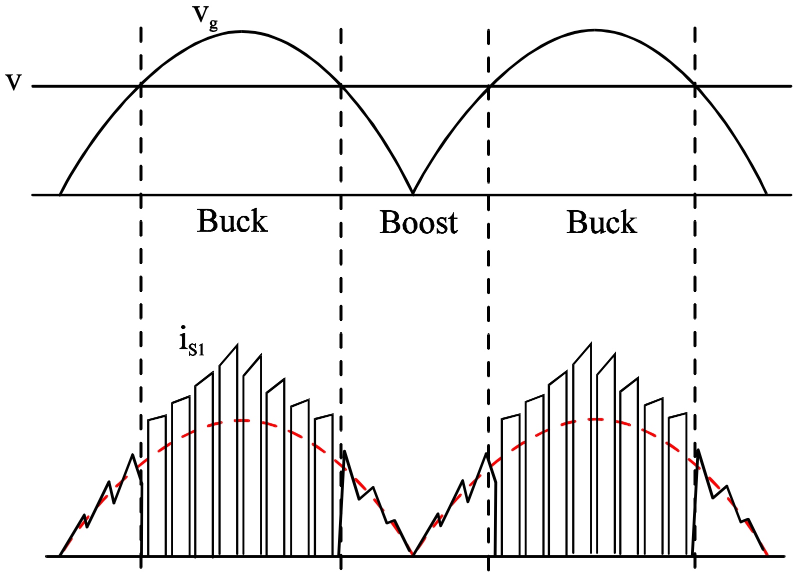
In order to draw a sinusoidal current the duty-cycle must be modulated during the line period:

$$d(\vartheta) = 1 - \frac{V_g \left|\sin(\vartheta)\right|}{V}$$

(This is an approximation because CCM operation cannot be maintained during the whole line period)

BASIC PREREGULATORS: BUCK + BOOST TOPOLOGY

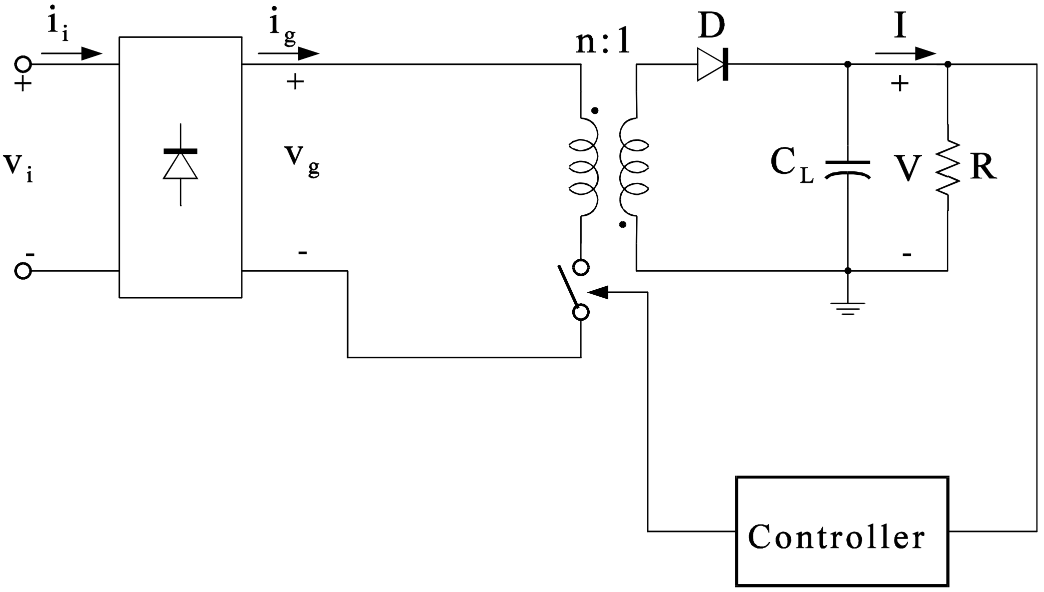




CHARACTERISTICS:

- ❑ S_1 and D_1 provide start-up and short circuit protection
- ❑ buck-mode operation for v_g higher than output voltage and boost mode-operation for v_g lower than output voltage
- ❑ high conduction losses (four semiconductors in series)

BASIC PREREGULATORS: FLYBACK TOPOLOGY



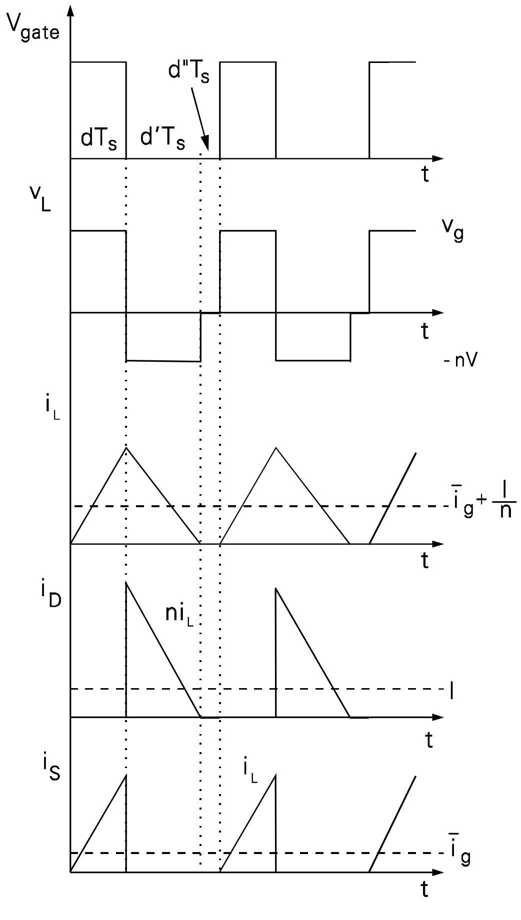
CHARACTERISTICS:

- ❑ Simple topology
- ❑ high power factor with constant duty-cycle in Discontinuous Conduction Mode (DCM) operation
- ❑ inherent start-up and short circuit protection
- ❑ high-frequency insulation transformer
- ❑ high input current harmonic content

BASIC PREREGULATORS: FLYBACK TOPOLOGY

DCM OPERATION

Main waveforms in a switching period



BASIC PREREGULATORS: FLYBACK TOPOLOGY

DCM OPERATION

OPERATION AS DC/DC CONVERTER

Voltage conversion ratio : $M = \frac{d}{\sqrt{k}}, \qquad k = \frac{2L}{RT_s}$

d = duty-cycle

L = transformer magnetizing inductance (primary side)

R = load resistance

T_s = switching period

$M \propto \sqrt{R}$ $\Rightarrow$ automatic PFC when used as rectifier

OPERATION AS AC/DC CONVERTER

Average input current:

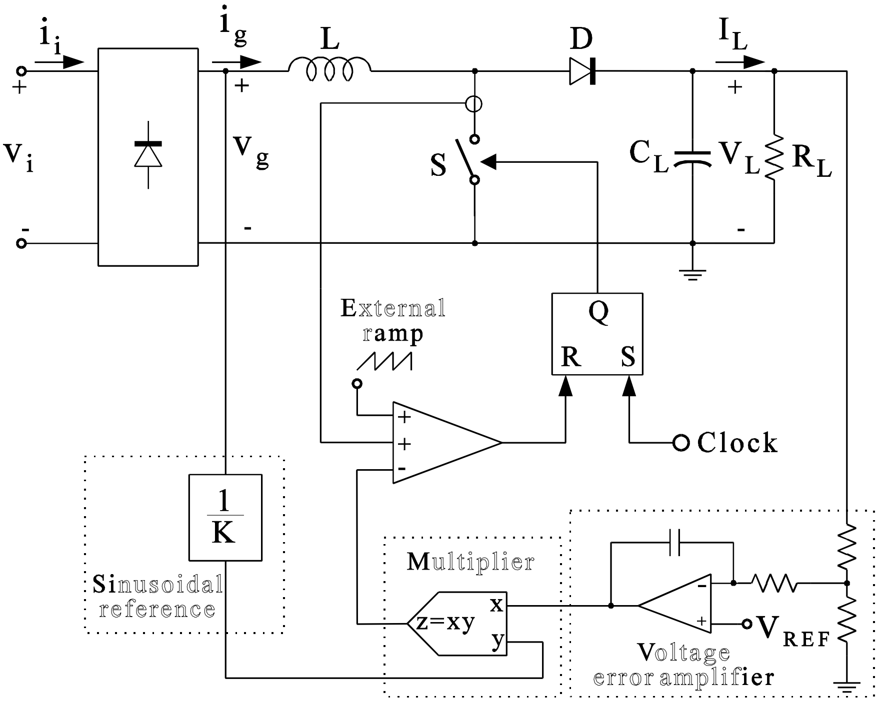
$$\bar{i}_g(\vartheta) = \frac{v_g(\vartheta)}{L} \cdot d^2 T_s$$

At constant duty-cycle and switching frequency the input current is sinusoidal

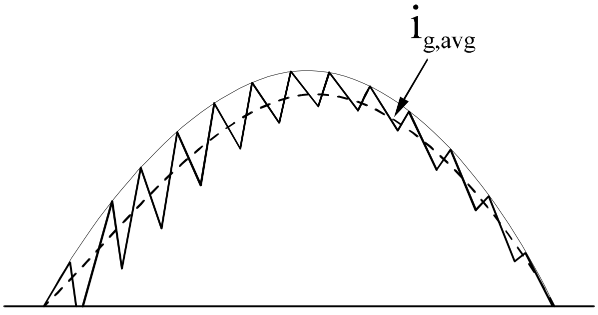
CONTROL TECHNIQUES FOR SINGLE-PHASE PFC’S AND COMMERCIAL CONTROL IC’S

BOOST PREREGULATOR

PEAK CURRENT CONTROL



Input current waveform



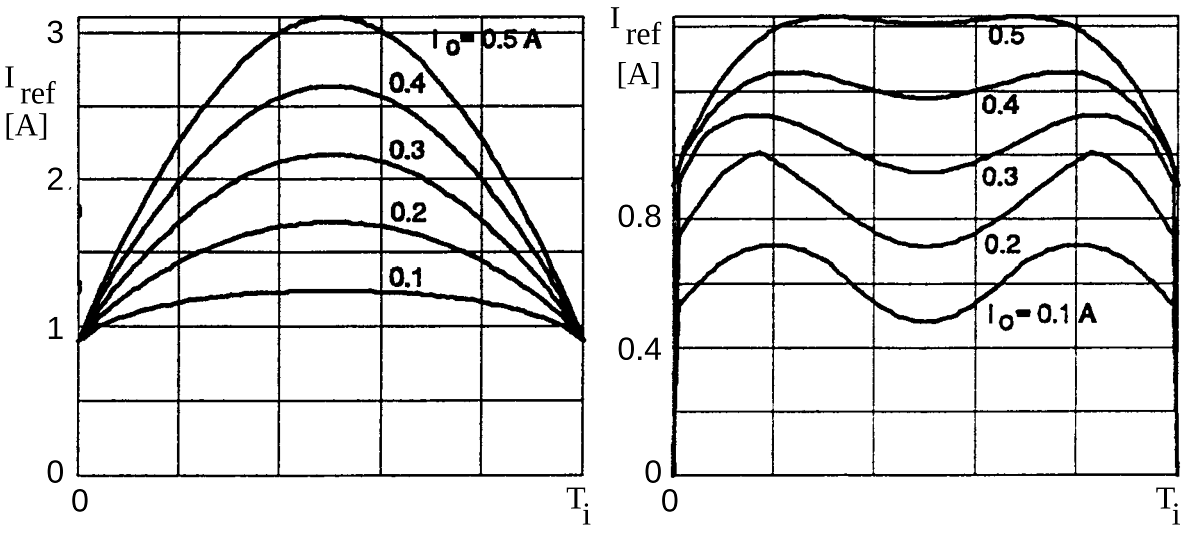
PEAK CURRENT CONTROL

CHARACTERISTICS:

- CONSTANT SWITCHING FREQUENCY
- CONTINUOUS CONDUCTION MODE (CCM) OPERATION
  - low device current stresses
  - low RMS current
  - small EMI filter
- POSSIBILITY TO SENSE ONLY SWITCH CURRENT
  - efficiency improvement
  - possibility to implement a pulse-by-pulse current limit
- SUBHARMONIC OSCILLATIONS (for duty-cycle > 50%)
- LINE CURRENT DISTORTION (increases at high line voltages, light load and high amplitude of compensating ramp)
- COMMUTATION NOISE SENSITIVITY
- REVERSE RECOVERY OF FREEWHEELING DIODE (increased commutation losses and EMI)

PEAK CURRENT CONTROL

IDEAL REFERENCE CURRENT WAVEFORMS



V_i=115V_{rms}

V_i=230V_{rms}

DISTORTION REDUCTION TECHNIQUES

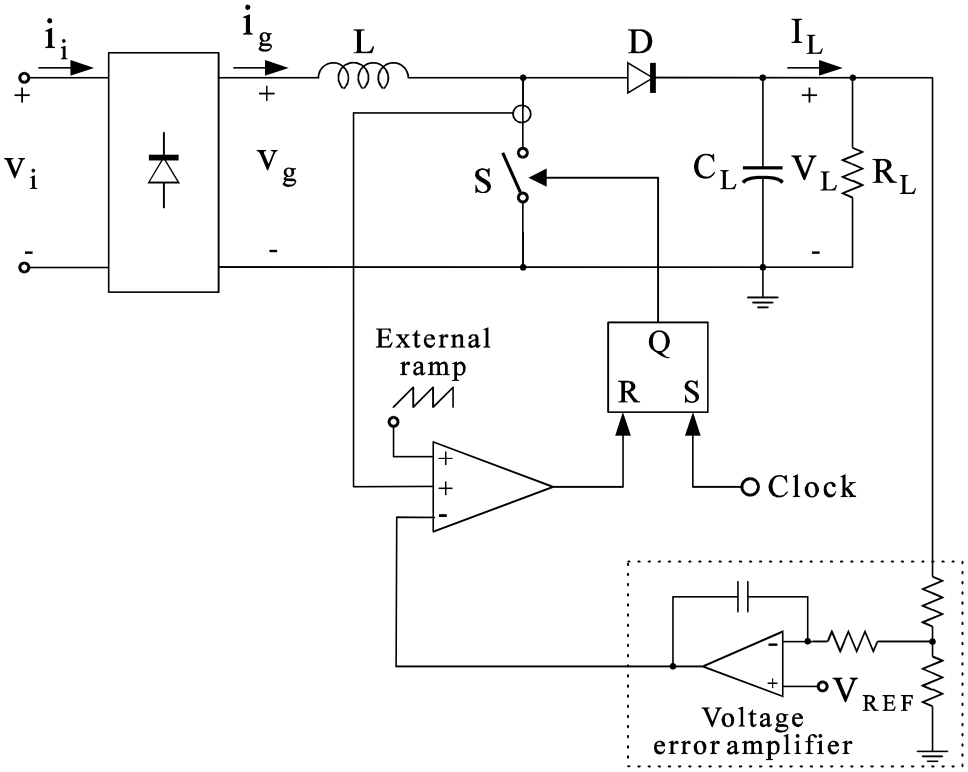
o ADDING A DC OFFSET TO CURRENT REFERENCE

(function of both line voltage and load current)

o PROGRAMMED DISTORTION CURRENT REFERENCE

- line dependent DC offset
- constant offset plus soft clamp

CURRENT CLAMPING CONTROL

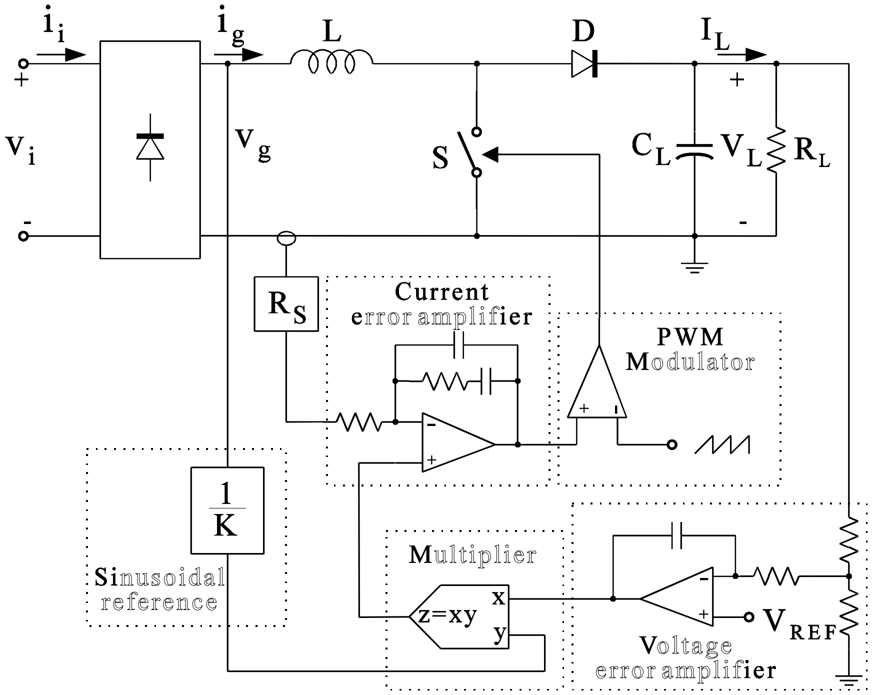


CHARACTERISTICS:

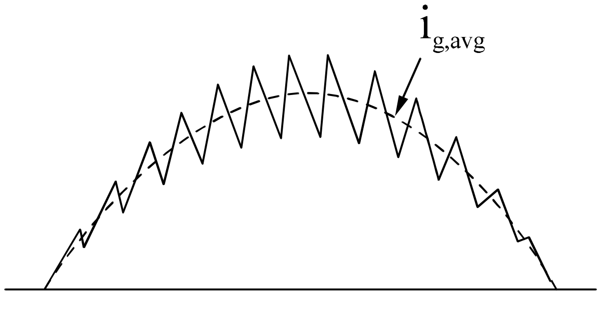
- VERY SIMPLE CONTROL STRUCTURE
- LINE CURRENT DISTORTION BELOW 10% FOR LIMITED LOAD AND LINE RANGE
- UNIVERSAL INPUT VOLTAGE OPERATION CANNOT BE EASILY ACCOMPLISHED

BOOST PREREGULATOR

AVERAGE CURRENT CONTROL



Input current waveform



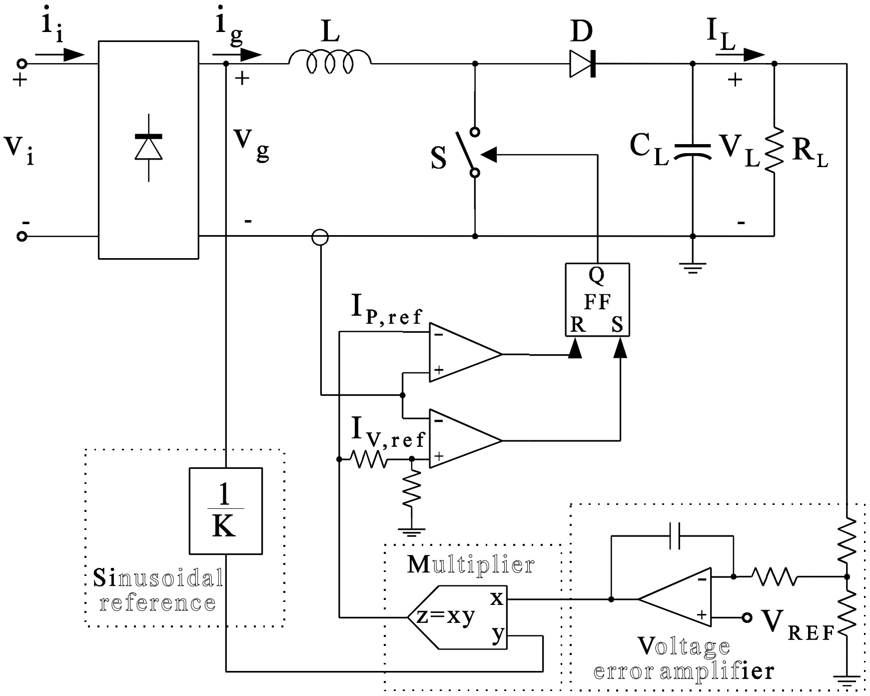
AVERAGE CURRENT CONTROL

CHARACTERISTICS:

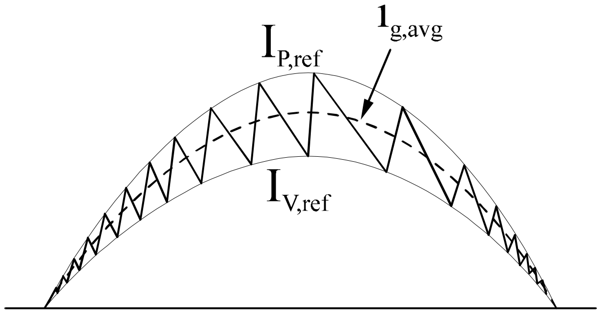
- CONSTANT SWITCHING FREQUENCY
- CONTINUOUS CONDUCTION MODE (CCM) OPERATION
  - low device current stresses
  - low RMS current
  - small EMI filter
- COMPLEX CONTROL SCHEME
  - need of inductor current sensing
  - need of a multiplier
- COMMUTATION NOISE IMMUNITY
- REVERSE RECOVERY OF FREEWHEELING DIODE (increased commutation losses and EMI)
- SEVERAL CONTROL IC's AVAILABLE

BOOST PREREGULATOR

HYSTERETIC CURRENT CONTROL



Input current waveform



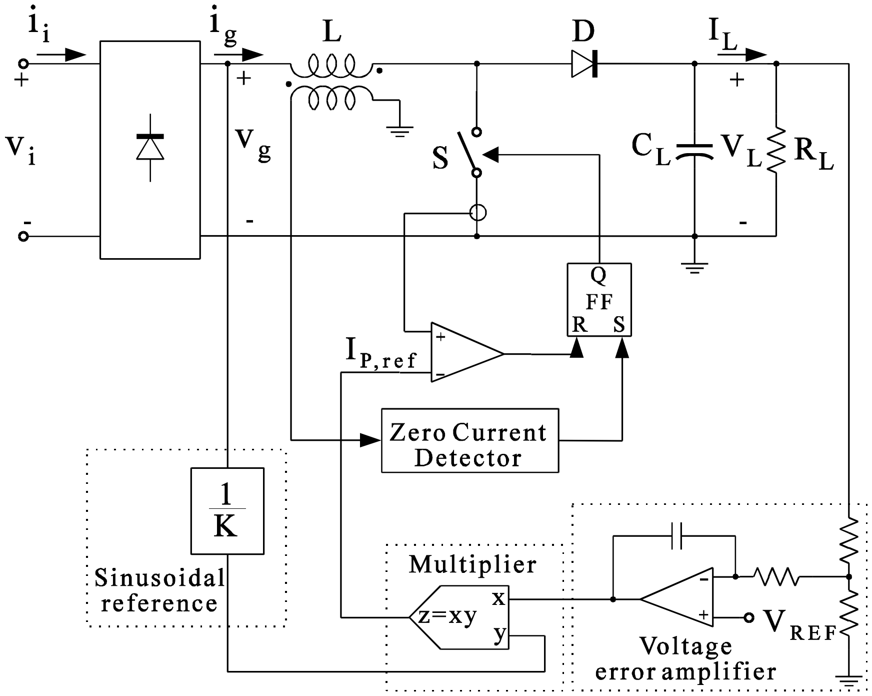
HYSTERETIC CURRENT CONTROL

CHARACTERISTICS:

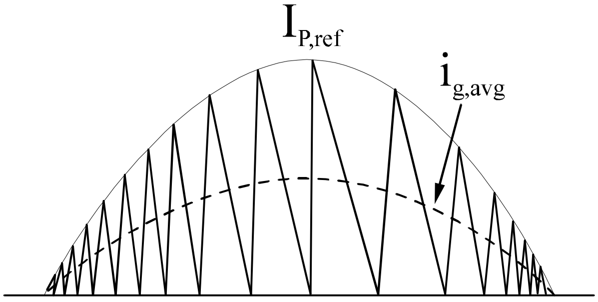
- WIDE SWITCHING FREQUENCY VARIATION
- CONTINUOUS CONDUCTION MODE (CCM) OPERATION
  - low device current stresses
  - low RMS current
  - small EMI filter
- COMPLEX CONTROL SCHEME
  - need of inductor current sensing
  - need of a multiplier
- COMMUTATION NOISE SENSITIVITY
- REVERSE RECOVERY OF FREEWHEELING DIODE (increased commutation losses and EMI)
- SMALL INPUT CURRENT DISTORTION NEAR ZERO CROSSING OF LINE VOLTAGE TO AVOID TOO HIGH SWITCHING FREQUENCY

BOOST PREREGULATOR

BORDERLINE CONTROL
(Operation at the boundary between DCM and CCM)



Input current waveform



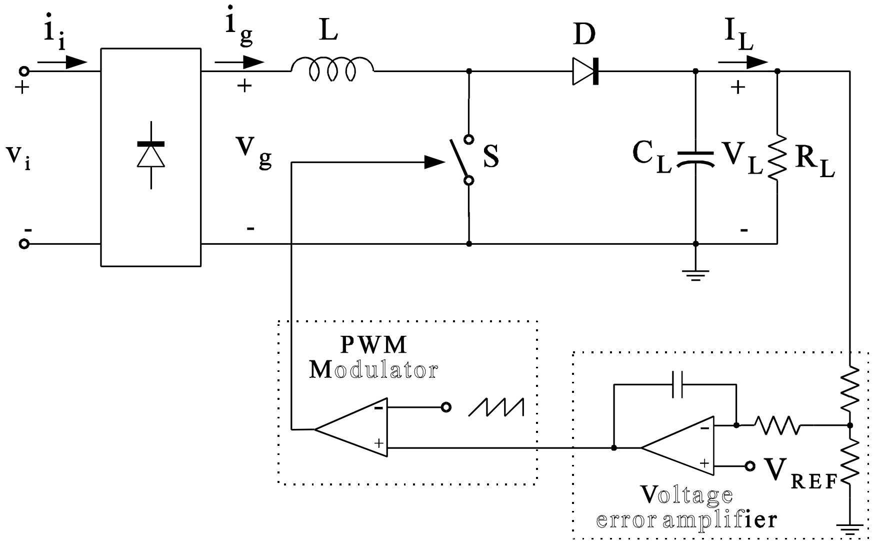
BORDERLINE CONTROL

CHARACTERISTICS:

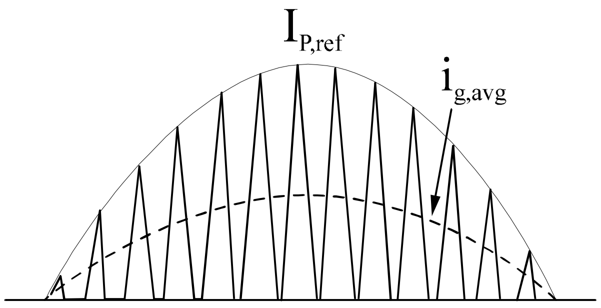
- AUTOMATIC PFC (CONSTANT SWITCH ON TIME)
- VARIABLE SWITCHING FREQUENCY (function of load current and instantaneous line voltage)
- DISCONTINUOUS CONDUCTION MODE (DCM) OPERATION
  - high device current stresses
  - high RMS current
  - large EMI filter
  - reduced switch turn on losses and increased turn off losses
- SIMPLE CONTROL SCHEME
  - no need of multiplier (however some IC's use it)
  - need of sensing the instant of inductor current zeroing
- ELIMINATION OF RECOVERY PROBLEM OF FREEWHEELING DIODE

BOOST PREREGULATOR

DISCONTINUOUS CURRENT PWM CONTROL



Input current waveform



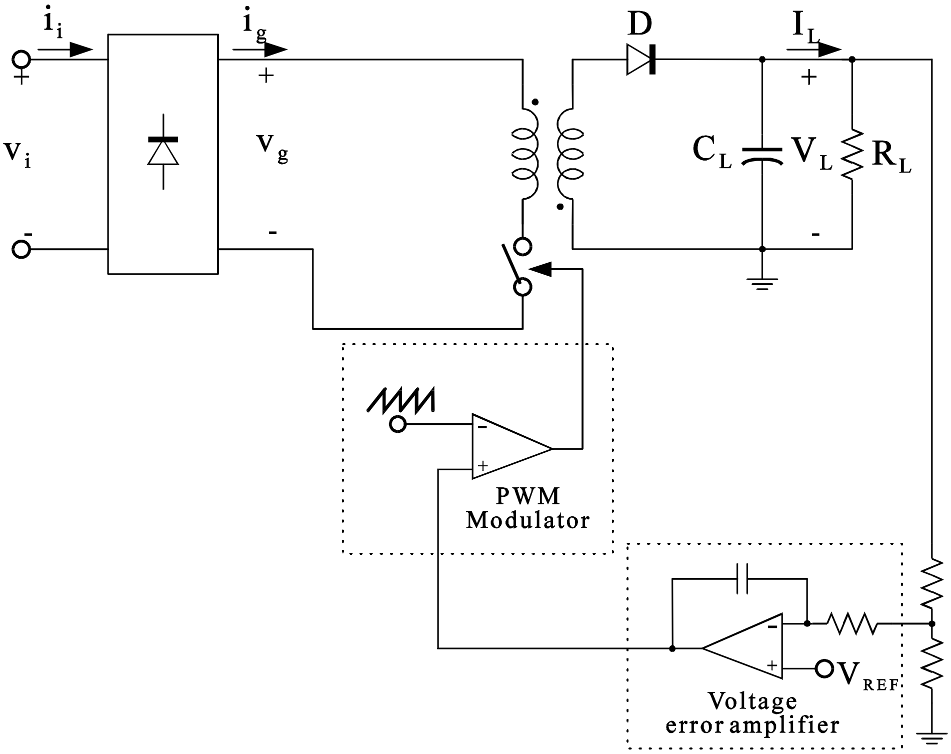
DISCONTINUOUS CURRENT PWM CONTROL

CHARACTERISTICS:

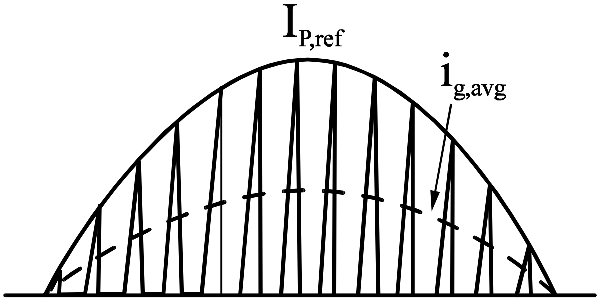
- CONSTANT SWITCHING FREQUENCY
- DISCONTINUOUS CONDUCTION MODE (DCM) OPERATION
    - high device current stresses
    - high RMS current
    - large EMI filter
    - reduced switch turn on losses and increased turn off losses
- NO NEED OF CURRENT SENSING
- SIMPLE PWM CONTROL
- INPUT CURRENT DISTORTION (WITH BOOST CONVERTER)
    - distortion reduction by subtracting a fraction of rectified line voltage from the error voltage or by modulating the clock frequency with rectified line voltage
- ELIMINATION OF RECOVERY PROBLEM OF FREEWHEELING DIODE

FLYBACK PREREGULATOR

DCM OPERATION



Input current waveform



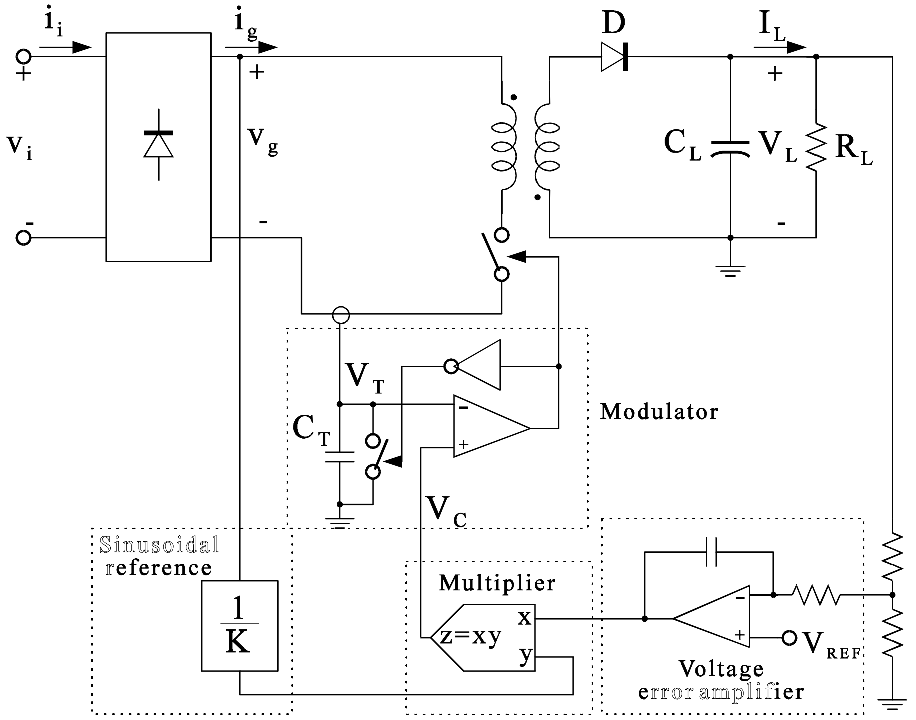
DCM OPERATION

CHARACTERISTICS:

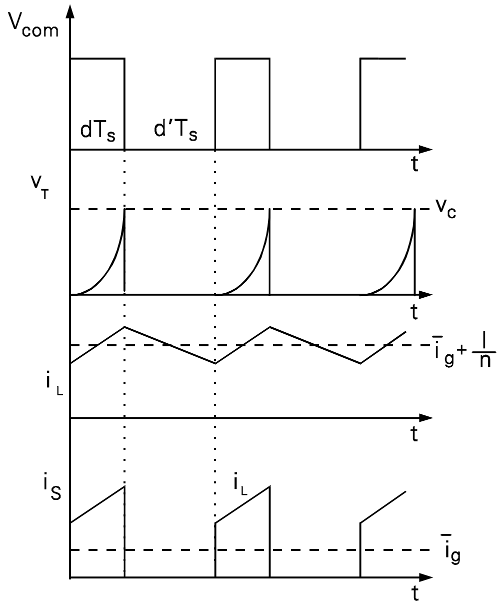
- AUTOMATIC PFC (CONSTANT SWITCH ON TIME)
- CONSTANT SWITCHING FREQUENCY
- DCM OPERATION
  - high device current stresses
  - high RMS current
  - large EMI filter
  - reduced switch turn on losses and increased turn off losses
- NO NEED OF CURRENT SENSING
- SIMPLE PWM CONTROL
- ELIMINATION OF RECOVERY PROBLEM OF FREEWHEELING DIODE

FLYBACK PREREGULATOR

CCM OPERATION - CHARGE CONTROL



Main waveforms



CCM OPERATION - CHARGE CONTROL

CHARACTERISTICS:

- CONSTANT SWITCHING FREQUENCY
- CONTINUOUS CONDUCTION MODE (CCM) OPERATION
  - low device current stresses
  - low RMS current
  - small EMI filter
- SUBHARMONIC OSCILLATIONS (for duty-cycle > 50%)
- COMPLEX CONTROL SCHEME
  - need of inductor current sensing
  - need of a multiplier
- COMMUTATION NOISE IMMUNITY
- REVERSE RECOVERY OF FREEWHEELING DIODE (increased commutation losses and EMI)

CONTROL IC'S

Constant frequency peak current control	ML4812 (Micro Linear) TK84812 (Toko)
Constant frequency average current control	UC1854/A/B family (Unitrode) UC1855 (Unitrode) TK3854A (Toko) ML4821 (Micro Linear) TDA4815, TDA4819 (Siemens) TA8310 (Toshiba) L4981A/B (SGS-Thomson) LT1248, LT1249 (Linear Tech.)
Hysteretic control	CS3810 (Cherry Semic.)
Borderline control	TDA4814, TDA4816, TDA4817, TDA4818 (Siemens) SG3561 (Silicon General) UC1852 (Unitrode) MC33261, MC33262(Motorola) L6560 (SGS-Thomson)
Two stage PFC with average-current control	UC1891/2/3/4 family (Unitrode) ML4824, ML4826 (Micro Linear) TK65030 (Toko)
Two stage PFC with peak-current control	ML4819 (Micro Linear) TK84819 (Toko)
Buck-boost constant frequency automatic control	ML4813 (Micro Linear)

EXPERIMENTAL RESULTS

BOOST PREREGULATOR WITH AVERAGE CURRENT CONTROL

Converter parameters

Input voltage: .... V_g = 220 V_{rms}

Output voltage:.. V_o = 380 V

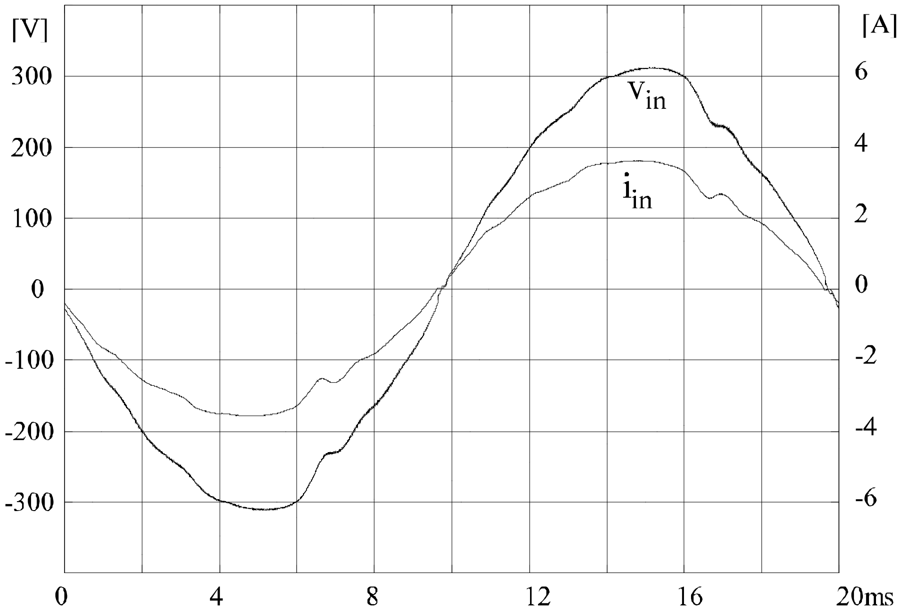
Output power: .... P_o = 550 W

Switching frequency:.. f_s = 70 kHz

Input inductance:.. L = 500 μH

Output Capacitance: ....C_o = 470 μF

Input voltage and current waveforms



Voltage THD = 3.2%, Current THD = 4.2%

P.F. = 0.998

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STANDARD

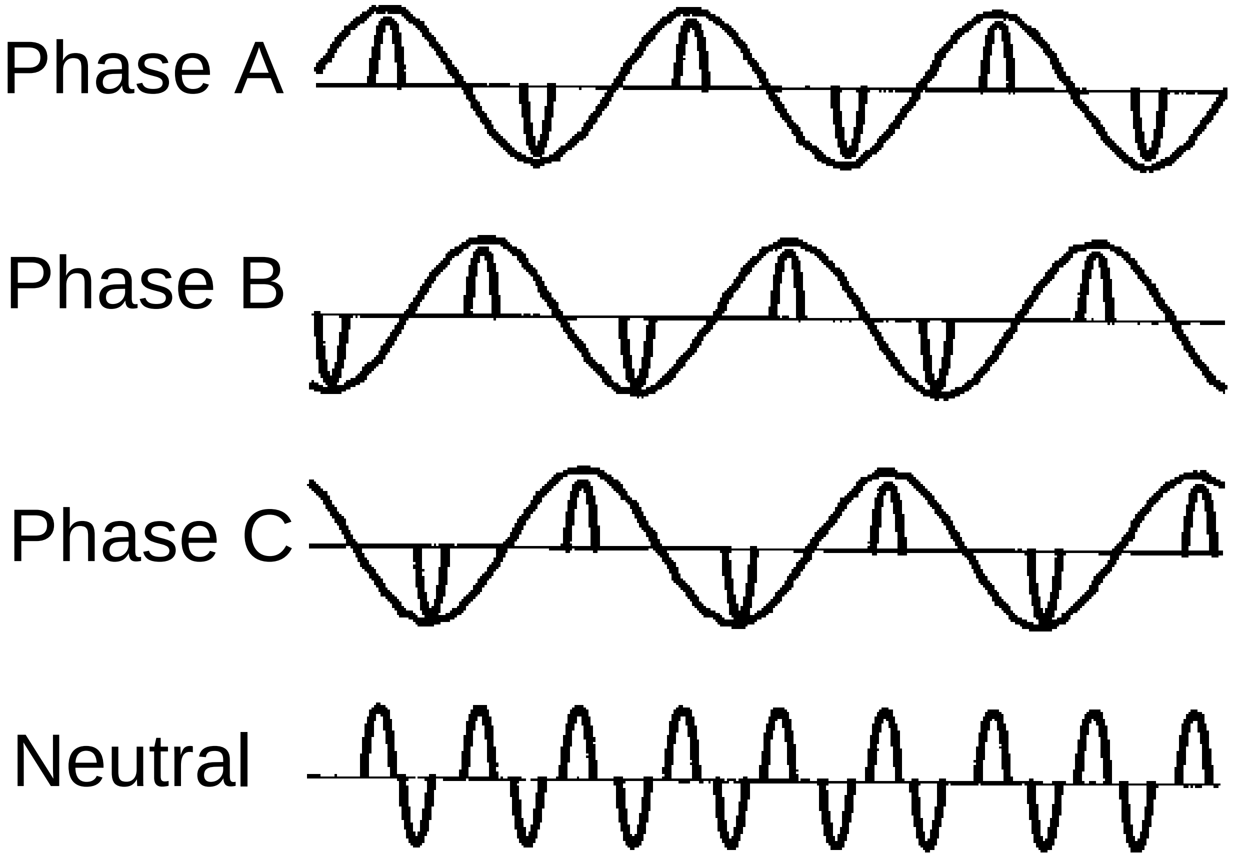
IEC 1000-3-2

WHY LINE HARMONICS REDUCTION?

- Main reasons:
    - agency regulations
    - market expectations or specifications
- Auxiliary reasons:
    - increased power factor
    - reduced current in neutral wire
    - wide input voltage range
    - increased hold-up time
    - regulated source voltage for isolated dc/dc converter
    - reduced ac UPS capacity

⇒ increased available power

CURRENTS IN PHASE
AND
NEUTRAL CONDUCTORS



COMPARISON OF CURRENT AND VOLTAGE DISTORTION EFFECTS ON POWER SYSTEMS

Current distortion I_{load}

Intermittent effects

- Improper operation of protection relays and circuit breakers;
- Amplified voltage distortion due to resonance

Steady-state effects

- Increased losses in series components of power transmission, distribution, and building wiring;
- Decreased accuracy of measuring instruments and metering;
- Voltage distortion directly proportional to I_{load}/I_{SC}

COMPARISON OF CURRENT AND VOLTAGE DISTORTION EFFECTS ON POWER SYSTEMS

Voltage distortion V_{source}

Intermittent effects

- Improper operation of protection relays and circuit breakers;
- Disruption of harmonic sensitive loads

Steady-state effects

- Increased losses in parallel connected capacitors, transformers, and motors;
- Decreased accuracy of measuring instruments and metering;

IEC 1000-3-2

- IEC Publication 1000-3-2: Limitation of harmonics in low-voltage supply systems for equipment with rated current less than 16A
- Standard limits harmonic currents caused by individual equipment
- Four categories of equipment
- Absolute and/or relative limits; relative limits are based on input power
- Assumption: line voltage has negligible distortion
- Standard has taken effect in 1996; revisions are expected

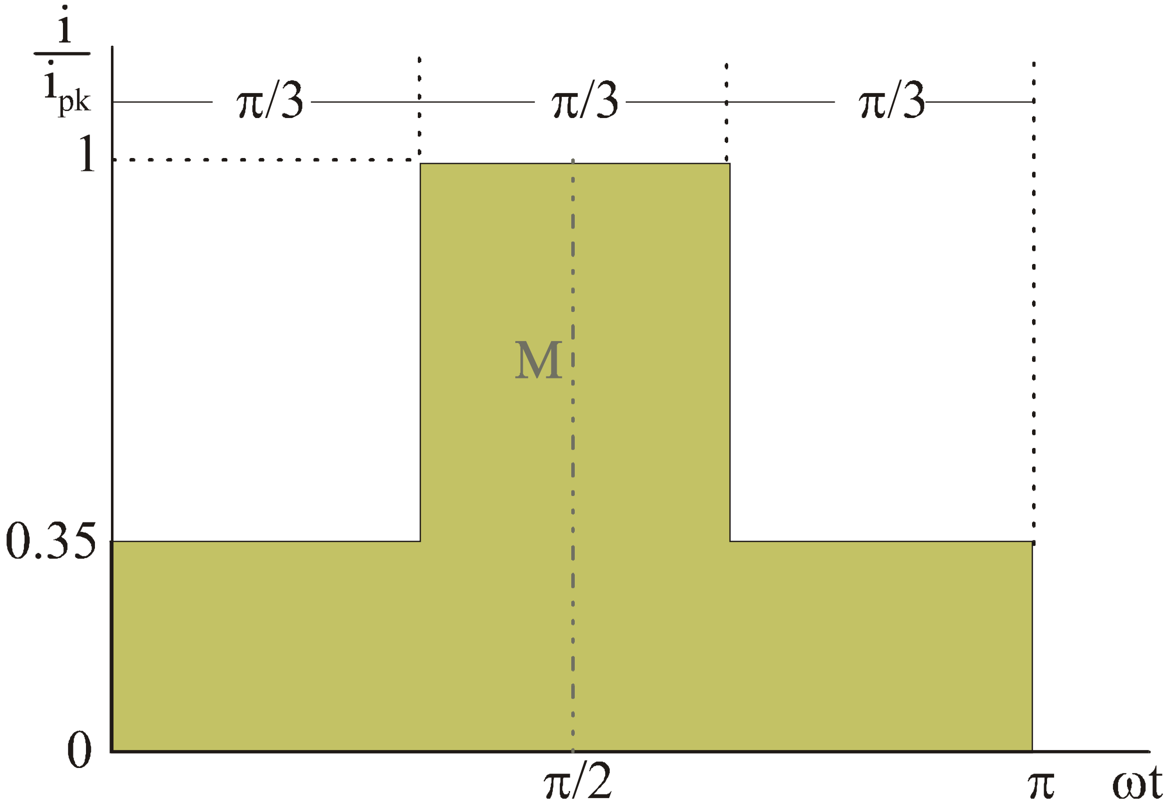
CLASSIFICATION OF EQUIPMENT

IEC 1000-3-2

- ***Class A***: balanced 3-phase equipment and all other equipment, except those in one of the following classes
- ***Class B***: portable tools
- ***Class C***: lighting equipment including dimming devices with active input power above 25 W
- ***Class D***: equipment having an input current with a “special wave shape” as defined in Fig.1 [of the document] and a fundamental active input power between 75 and 600 W; lower power limit will be reduced to 50 W in four years after the introduction (1996) if it is found that the mains distortion is not sufficiently controlled. Whatever the wave shape of their input current, Class B, Class C, and provisionally motor-driven equipment are not considered as Class D equipment
- Standard is applicable to equipment connected to public low-voltage distribution systems with input current up to 16 A/phase

SPECIAL WAVE SHAPE

IEC 1000-3-2



- Class D equipment: each half cycle of input current is within the envelope for at least 95% of the time

HARMONIC LIMITS

Class A and Class B

Harmonic order n	Class A max permissible harmonic current A	Class B max permissible harmonic current A
Odd		
3	2.30	3.45
5	1.14	1.71
7	0.77	1.155
9	0.40	0.60
11	0.33	0.495
13	0.21	0.315
15 <=n<= 39	2.25/n	3.375/n
Even		
2	1.08	1.62
4	0.43	0.645
6	0.30	0.45
		2.76/n

HARMONIC LIMITS

Class C > 25

Harmonic order n	Maximum value expressed as a percentage of the fundamental input current of the luminaries
2	2
3	30 λ^*
5	10
7	7
9	5
11<= n<=39	3

$^*\lambda$ is the power factor

HARMONIC LIMITS

Class D

Maximum permissible harmonic

Harmonic order n	75W<P<600W mA/W	P>600W A
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.22
13	0.296	0.21
15 <= n <= 39	3.85/n	2.25/n

No limits apply for equipment below 75 W input

COMMENTS

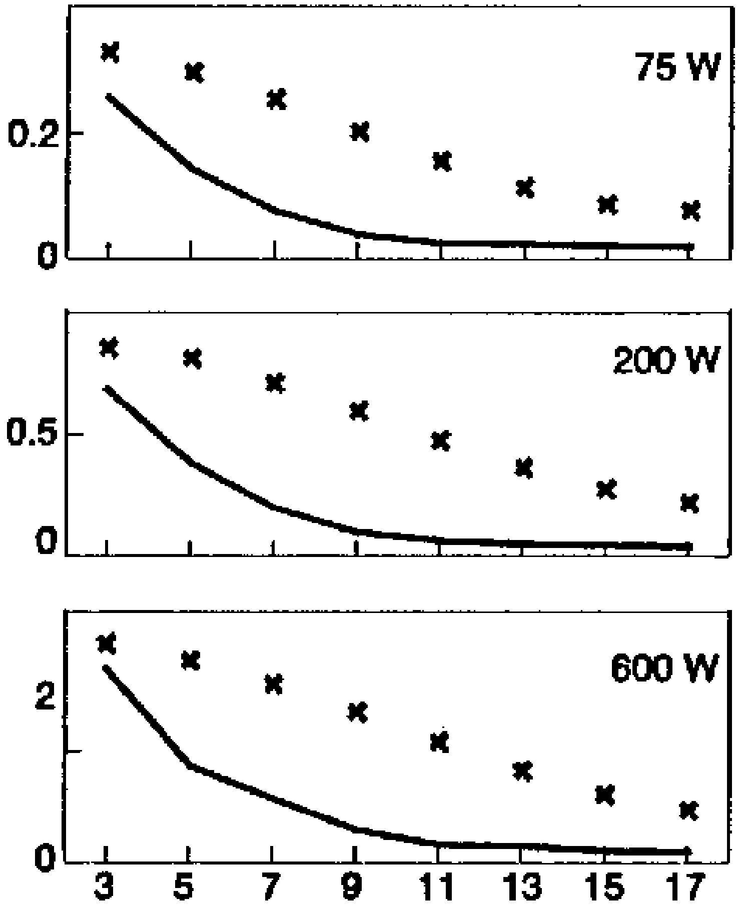
- High crest-factor waveforms are penalized (Class D), in order to reduce peak-clipping effect. If line-voltage distortion will not improve in the future, lower power limit will be reduced to 50 W from 75 W
- Even harmonics are penalized in order to reduce asymmetry
- Below 600 W: Class A is preferred to Class D. Consider changing the input current waveform
- Requirements for lamps above 25 W are severe, below 25 W there is presently no limit

<u>Note 1</u>: in the future, limits will be needed for lamps below 25 W, too. (Compact fluorescent lamps with up to 23 W input power have excessive distortion.)
<u>Note 2</u>: 30 to 40% of the total utility load is lighting, with lamp power above 25 W

RECTIFIER HARMONIC CURRENTS AND CLASS D LIMITS

230 V, 50 Hz, 10%

Harmonic current [A]



Harmonic number [n]

Rectified
harmonic
currents
x x x

Class D limit
———

TOTAL HARMONIC DISTORTION AND POWER FACTORS IN SINGLE-PHASE RECTIFIERS

	75 W	200 W	600 W
THD	172%	182%	182%
$PF_{\cos\phi}$	0.953	0.953	0.959
PF	0.479	0.459	0.462
$THD_{\text{Class D}}$	94%	94%	105%

IMPACT OF IEC 1000-3-2

- Equipment-level compliance; cost is directly borne by the end user
- Cost increase: US$ 0.1/W to US$ 0.3/W; size increase: 10 to 30%
- High-quality (i.e. low harmonic) rectification is required. Passive solutions are quiet and reliable but are too heavy and bulky for most applications; also they might not satisfy future revisions of the standard. Active solutions generate much EMI, are less reliable, and significantly increase the cost
- Low-cost solutions must be developed:
  - ⇒ optimized passive and slow-switching active solutions
  - ⇒ simplified power-circuit topologies and control methods
  - ⇒ inexpensive filters for filtering the excess differential-mode EMI
  - ⇒ better semiconductor devices in order to eliminate snubbers