# Rectifiers for Power–Factor–Correction (PFC)

## Historical background: Why PFC is important for all future electronic equipment

Since the beginning of 1998 the new european standard EN 61000–3–2 should have come into force. It says that every power–supply with an input power of more than 75 W has to be equipped with so–called power±factor correction. It has been delayed to January 1st 2001, still it is not sure that it will become effective. When this happens it is then not allowed to bring power–supplies into the market that are not equipped with PFC or the user has to provide an additional electronic ballast with PFC.

## Technical background: What are the effects of non–PFC–equipped circuits

Non±PFC power supplies use a capacitive input filter, as shown in Figure 1, when powered from AC power line. This results in rectification of the AC line, which in turn causes peak currents at the crest of the AC voltage, as shown in Figure 2. These peak currents lead to excessive voltage drops in the wiring and imbalance problems in the three–phase power delivery system. This means that the full energy potential of the AC line is not utilized.

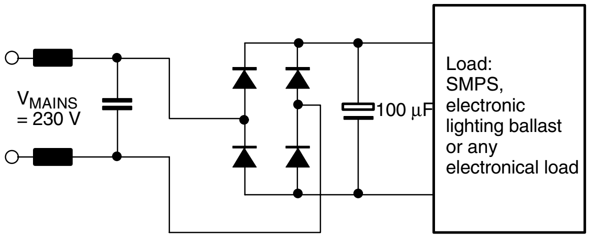

Figure 1. Standard bridge rectification of line voltage

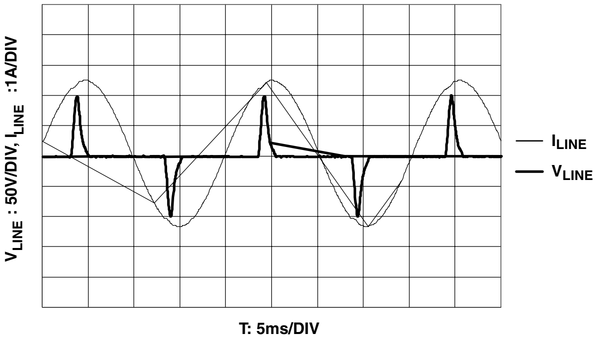

Figure 2. 20 W Resistive load powered by a circuit like Fig.1

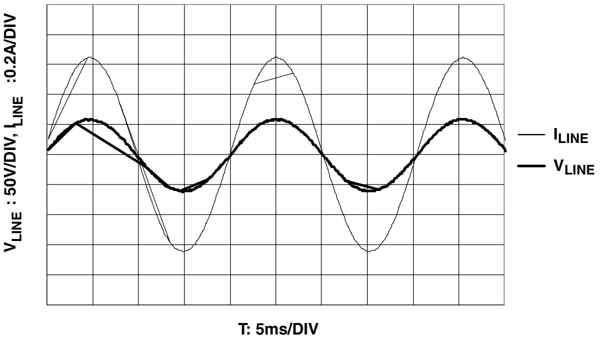

Figure 3. Same load like Fig. 2, but unity powerfactor

**P**ower **F**actor **C**orrection (PFC) can be defined as the reduction of the harmonic content. By making the current waveform look as sinusoidal as possible, as shown in Figure 3, the power drawn by the power supply from the line is then maximized to real power. Assuming that the voltage is almost sinusoidal, power factor depends first of all on the current waveform. Thus real power can be defined as:

$$P \quad V_{RMS}\ \mathrm{x}\ I_1\ \mathrm{x}\ \sin(\ \ {}_1t)$$

$$S \quad \overline{P^2 \qquad Q^2}$$

$$S \quad V_{RMS}\ \mathrm{x}\ \overline{I_1{}^2\ \mathrm{x}\ \sin(\ \ {}_1t)^2 \qquad I_2{}^2\ \mathrm{x}\ \sin(\ \ {}_2t)^2 \qquad \ldots I_n{}^2\ \mathrm{x}\ \sin(\ \ {}_nt)^2}$$

That means that real power only is carried by the fundamental harmonic, all the higher harmonics are carrying only reactive power. Eliminating the higher harmonics means increasing power factor to unity.

The defination of power factor is:

$$\text{Power factor} \quad \frac{\text{Real Power}}{\text{Apparent Power}}$$

For the circuit in Figure 1 the power factor is typically about 40 to 50%.

For example (related to figures 1 & 2):

The following measurements can be done with the circuit in Figure 1:

| | | | | | |
|---|---|---|---|---|---|
| C | = | 100 µF | R | = | 680 Ω |
| $I_{TRMS}$ | = | 495 mA | P | = | 20 W |
| S | = | 43 VA | Q | = | 38 var |
| Power factor | = | 0.464 | | | |

With the same resistor directly connected to the line terminals or using power factor correction the following results can be achieved:

| | | | | | |
|---|---|---|---|---|---|
| $I_{TRMS}$ | = | 172 mA | P | = | 20 W |
| S | = | 20 W | Q | = | 0 |
| Power factor | = | 1 | | | |

This simple example gives a good impression what happens if all electronic equipment is powered without PFC. Obviously we see in this example the same real power, but big differences in RMS current.

# Description of Standard EN 60000–3–2

It is expected that the above standard will be effective by January 1 2001. The standard has 2 parts that are for the manufacturer of electronic devices important :

Classification of electrical loads
Limitation of line current harmonics depending on the effective class of the load

## Classification of electrical loads

This standard will be effective for all electrical loads supplied by the low voltage power line with line input currents up to 16 Amps.

In general all 3–phase line–loads and all loads that can not be classified to be class B, C or D loads are class A loads.

All portable electrical tools are class B loads.

All lighting devices or lighting regulators are class C loads.

All electrical loads with a power consumption below 600 W and line input current waveform that for a half period of the line voltage is 95% or more inside the hatched area of the diagram shown in Figure 5.

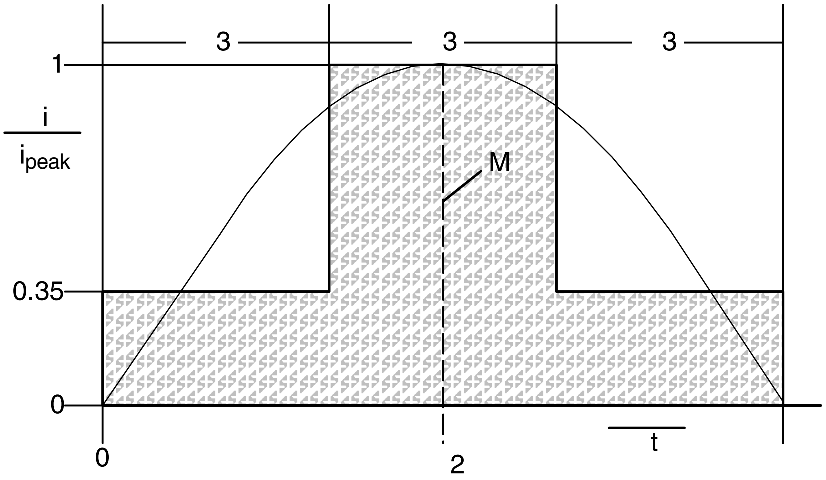

Figure 4. Defination criterium for Class D load

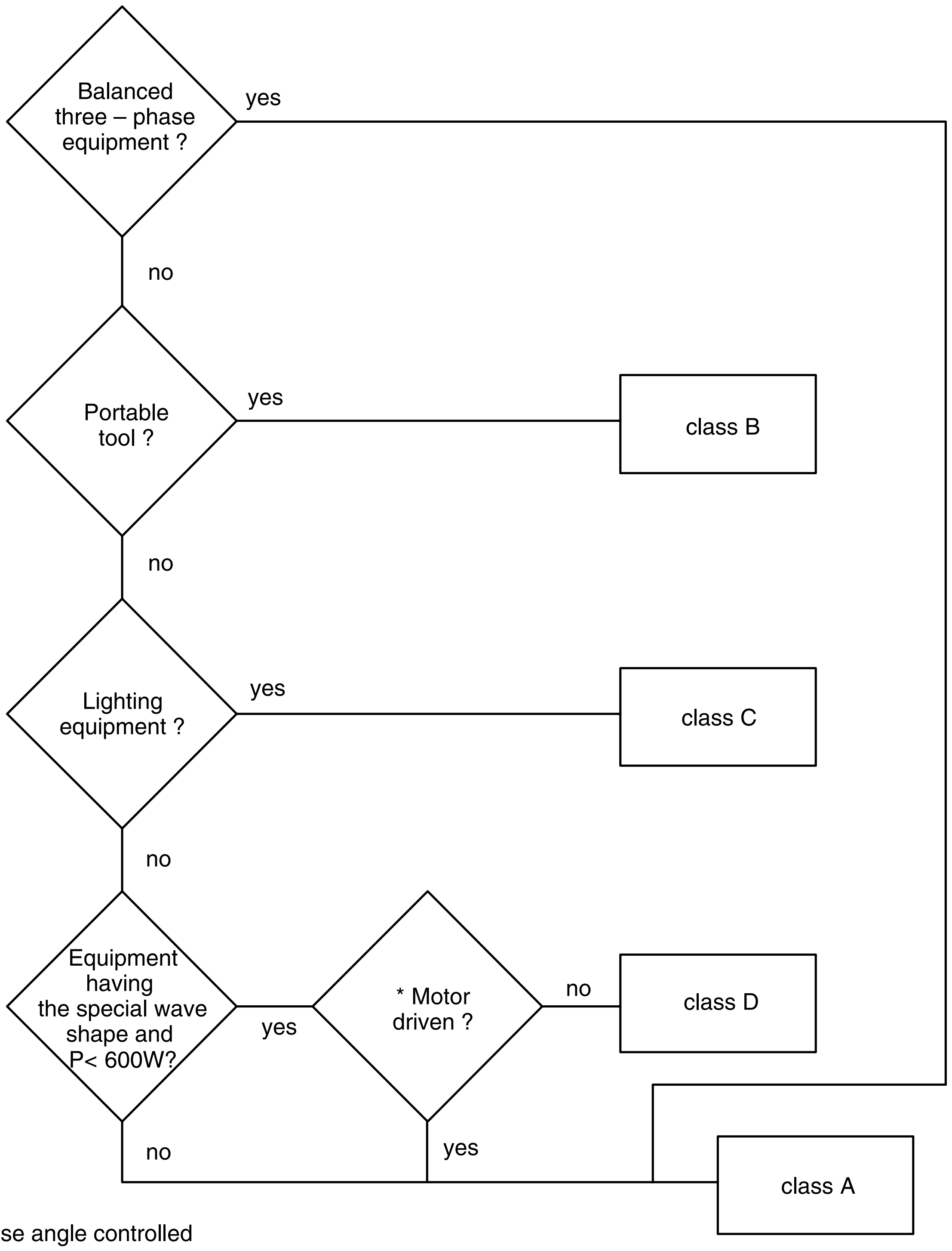

Figure 5. Flow chart for the classification of equipment

# Class related limitations of harmonics

Table 1. Limits of class A odd harmonics

| # of harmonic [n] | RMS current limit [A] |
|---|---|
| 3 | 2.3 |
| 5 | 1.14 |
| 7 | 0.77 |
| 9 | 0.40 |
| 11 | 0.33 |
| 13 | 0.21 |
| 15 < < 39 | 0.15 x 15/n |

Table 2. Limits of class A: even harmonics

| # of harmonic [n] | RMS current limit [A] |
|---|---|
| 2 | 1.08 |
| 4 | 0.43 |
| 6 | 0.30 |
| 8 < n < 40 | 0.23 x 8/n |

Electrical loads in class B show 1.5 times higher limit currents compared to class A limits

Table 3. Limits of class C

| # of harmonic [n] | RMS current limit [% of the fundamtal harmonic] |
|---|---|
| 2 | 2 |
| 3 | 30 x $\lambda$ 3) |
| 5 | 10 |
| 7 | 7 |
| 9 | 5 |
| 11 < n < 39 | 3 |

3) $\lambda$ = Powerfactor of the circuit

Because usually the third harmonic has the highest amplitude using the power factor as a factor for the limit becomes of greater importance. Smaller power factor means tougher limit and vice versa.

Table 4. Limits for class D harmonics

| # of harmonic [n] | RMS current limit per Watt [mA / W] | RMS current limit [A] |
|---|---|---|
| 3 | 3.4 | 2.3 |
| 5 | 1.9 | 1.14 |
| 7 | 1.0 | 0.77 |
| 9 | 0.5 | 0.40 |
| n > 13 | 3.85/n | 0.15 x 15/n |

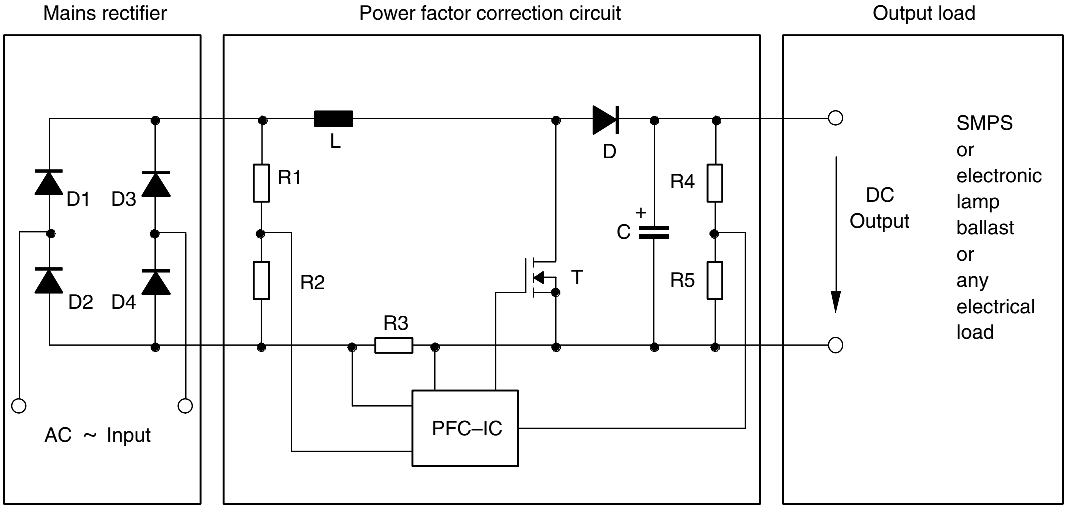

Figure 6. Typical boost converter topology for active PFC

Because it is the most cost saving solution the continuous current mode boost converter as shown in figure 6 is today the most used topology for active power factor correction.

The bridge rectifier BR1 converts the AC input current into DC current. The MOSFET T is used as an electronic switch, and is cycled “on” and “off” driven by the PFC–IC. While the MOSFET is “on” the inductor current through L increases. While the MOSFET is “off”, the inductor delivers current to the capacitor C through the forward biased output rectifier diode D. The inductor current does not fall to zero during the entire switching cycle, because this operation is called “continuous current mode”. This mode is suitable for almost all load current variations. If a constant load current is expected the so–called “discontinuous current mode”, where currents falls at the end of each cycle to zero, should be preferred. The MOSFET anyway is pulse–width–modulated so that the input impedance of the circuit appears purely resistive, and the ratio of peak to average current is kept low.

The most cost–effective way of reducing losses in the circuit is by choosing a suitable diode D for the application. Diodes for use in PFC circuits typically have higher forward voltages than conventional fast epitaxial diodes, but much shorter (faster) reverse recovery times.

# How a standard PFC circuit works

Figure 6 shows the typical topology of a PFC prestage that is built of a standard boost converter driven by a control IC. It is important that at the output of the Rectifier BR1 there will be no ”large” smoothing capacitor with several µF connected, because that would eliminate all efforts of the PFC circuit, although it would operate sufficiently. The input voltage of the PFC is a rectified DC voltage pulsed with double line frequency. The shown switch is usually implemented by an IGBT or Power–MOS transistor.

**Operation principle :**

The instantaneous value of the current through the boost inductor has to be adapted as well as possible to the instantaneous value of the line voltage through suitable pulse–width modulation of the transistor switch T. The actual inductor current can be won by the voltage drop at R3. The input voltage can be found at the voltage divider R1, R2. The current amplitude will be regulated on the value of the output voltage, R4, R5.

To be able to control the current through the boost inductor, the output voltage of the PFC has to be higher at every moment of operation than the crest of the line input voltage. For 230 V mains the DC output should be about 400 V. A large capacitor at the ouput does not affect the power factor, but is good for smoothing the DC voltage.

An additional advantage of PFC circuit is the regulated DC voltage that gives the opportunity of having a following SMPS to be wide range operated (e.g. 110 V to 230 V input voltage).

# Advantages of circuits with PFC

The use of PFC allows the manufacturer of electrical load to use smaller, more cost–effective mains rectifiers because of smaller RMS current with PFC.

Offers a stable regulated output voltage which is the input voltage for the following electrical load. Indeed the PFC makes it a system based wide–range power supply itself.

The following electrical load (SMPS, Electronic ballast unit or other electrical load) can be much simpler, which is also a cost saving factor.

VISHAY Semiconductor recommends the use of their ultra–fast rectifier series of PFC rectifier.

Table 5. Recommended reverse voltages for most used line voltage levels

| $V_{LINE}$ RMS [V] | $V_{RRM}$ [V] |
|---|---|
| 110 | 400 |
| 120 | 400 |
| 230 | 600 |
| 277 | 600 |

Preferred types for the mains rectifier and the boost rectifier are listed in Tables 6 and 7

## Mains Rectifiers (4 devices each)

Table 6. Selection Guide for the mains rectifiers

| Input Power | Mains Voltage | | |
|---|---|---|---|
| | 120 V | 230 V | 277 V |
| ≤ 75 W | BYG10G, S1G, MB4S(1) | BYG10K<br>BYT41K<br>S1K<br>GP10K<br>DF08M(1), W086(1) | BYG10M<br>S1M<br>DF10M(1), W106(1) |
| ≤ 100 W | BYT41G, GP10G<br>BYT51G, GP15G<br>BYW53, GP20G | | |
| ≤ 150 W | BYW83<br>GP30G<br>GBU4G(1), GBL04(1) | | |
| ≤ 200 W | | BYT51K, GP15K<br>BYW55, GP30K | BYT41M<br>GP10M, DF1(1) |
| ≤ 250 W | GP30G<br>GBU4G(1), GBL04(1) | BYW85<br>GP30K<br>GBU4K(1), GBL08(1) | BYT51M, GP15M<br>BYW56, GP30M |
| ≤ 400 W | P600G<br>BI540(1) | | BYW86, GP30M |

Conditions: $T_{amb}$ = 40 °C
Leaded Rectifiers PCB mounted, SMD Rectifiers mounted on standard PCB

**Because of large variations in the applications the table above shows a rough selection only. The appropriate Rectifier must be selected depending on the application! For wide range power supplies the lowest mains voltage will result in the highest forward losses of the Rectifier. For these applications the selection of the reverse voltage must be at the highest voltage, the power selection at the lowest.**

**Note: (1) Full-wave single phase bridge rectifiers**

# Boost – Rectifiers

Table 7. Selection Guide for the boost rectifiers

| Input Power | Mains Voltage | | |
|---|---|---|---|
| | 120 V | 230 V | 277 V |
| ≤ 75 W | BYG20G, UG1G<br>BYT43G, EGP10G<br>BYV26B, UF4004 | BYG20J<br>US1J | BYG20J, UG1J<br>BYT43J, UF4006<br>BYV26C |
| ≤ 100 W | BYV27–600, SUF15G<br>SF4004, UF4004<br>*2* BYG22D, 2* ES1D*<br>*2* BYT44D, US1G* | | |
| ≤ 150 W | BYV28–600, MUR460<br>*2* BYV27–200*<br>*2* UG2D* | BYT43J<br>BYV26C, SUF15J<br>SF4005, UF4005<br>*3* BYG22D, 3* ES1D* | |
| ≤ 200 W | BYW178, MUR460<br>SF5404, UF5404<br>*2* BYV98–200, UG4D* | SUF15J<br>3* BYT44D<br>3* UG2D | SF4005, UF4005<br>*3* BYG22D*<br>*3* ES1D* |
| ≤ 250 W | 2* BYV28–200, UG4D | BYV27–600, SUF15J | 3* BYT44D<br>3* UG1D, SUF15J |
| ≤ 300 W | BYT85–600<br>UG8GT | SF5406, UF5406<br>*3* BYV98–200* | BYV27–600, SUF15J<br>3* UG2D |
| ≤ 350 W | | BYV28–600, SUF15J<br>BYW178<br>*2* BYV27–200, 2* UG2D* | SF5406, UF5406 |
| ≤ 400 W | | SUF30J<br>3* BYV28–200<br>3* UG4D | BYV28–600, SUF30J<br>BYW178<br>*3* BYV27–200, 3* UG2D* |
| ≤ 500 W | | | 3* BYV98–200, 3* UG4D |
| ≤ 600 W | BYT08P–600A, UG8JT<br>BYT108–400, UG10GT<br>BYT86–600 | BYT85–600<br>UG8JT | 3* BYV28–200, UG4D (3*) |
| ≤ 1000 W | | | BYT85–600, UG8JT |

Conditions: $T_{amb}$ = 40 °C,
Leaded Rectifiers PCB mounted, SMD Rectifiers mounted on standard PCB,
TO220 Rectifiers mounted on a heat sink with a total $R_{thJA}$ 3.5 K/W

***Because of large variations in the switching conditions (frequency....) the table above shows a rough selection only, the data are calculated with ≈25% switching losses. The appropriate Rectifier with the right characteristics (especially switching characteristic/reverse recovery time $t_{rr}$ ) must be selected depending on the application! Depending on these requirements the series connection of 2 or 3 Rectifiers (e.g. 3*BYG22D, UG4D, ES1D) can be the better solution.***