# Rectifiers with Power Factor Correction

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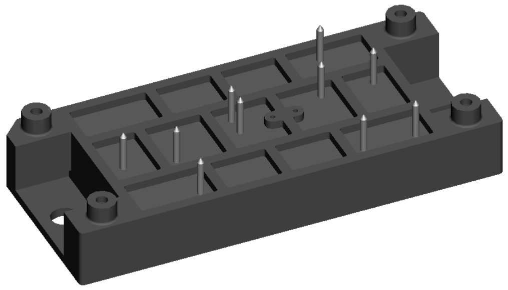

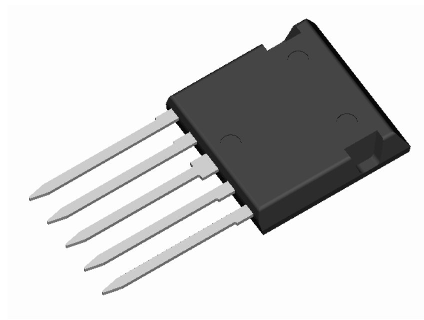

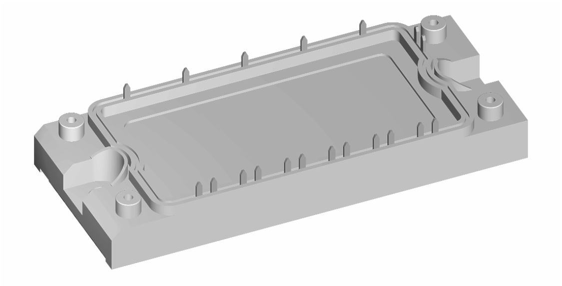

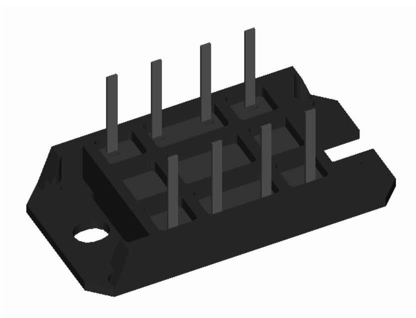

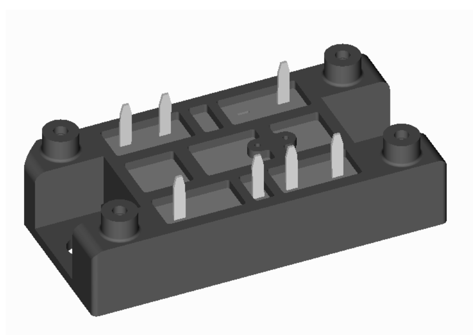

IXYS

# 1. Introduction

## 1.1 Standard Rectifiers

The topology of a standard single phase rectifier is shown in figure 1. The terminals L1 and N are connected to the grid while L+ and L- supply the intermediate circuit. Usually the DC voltage $U_Z$ in the intermediate circuit is smoothed by a capacitor. To save cost, generally no further reactive components are used; this means, that only mains inductance and additional parasitic inductances have any effect. Characteristic waveforms of this circuit are shown in figure 2.

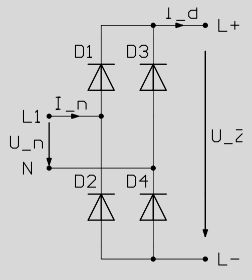


**Fig. 1:** Schematic of non controlled, single phase rectifier

This topology can be characterized as follows:

- It is simple - no control required - and rugged.
- Current flow from the grid to charge the intermediate circuit $I_d > 0$ is only possible in case the instantaneous value of the mains voltage is higher than intermediate voltage $u_n(t) > U_Z$. This leads to a short conduction period of the rectifier with the consequences that mains current $I_n$ has high peak values, high RMS values and is harmonically distorted - see figure 2.

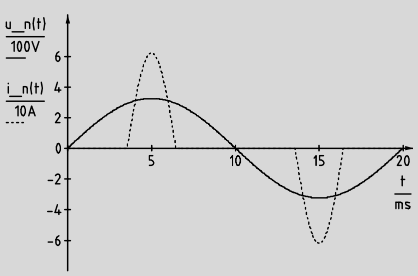


**Fig. 2** : Typical input waveforms of non controlled, single phase rectifier ($P_n$ = 3600 W)

- Further harmonic distortion of the mains current $I_n$ is caused by commutation effects of the diodes using the mains inductance as commutation inductance.
- The DC voltage $U_Z$ depends on the mains voltage $U_n$. Variations in mains voltage $U_n$ thus have to be compensated in a further stage of power section, if required.
- Turning power on leads to a high mains inrush current peak $I_n$ to charge the capacitor in intermediate circuit previously discharged.

  This may be overcome by replacing at least two of the diodes in the schematic figure 1 by thyristors, which also permits to control DC voltage. However this measure increases control complexity and its use leads to the additional generation of reactive power.

The operational behaviour of three phase rectifiers basically corresponds to these characteristics as discussed here for single phase rectifiers.
It has become obvious that the use of standard rectifier circuits leads to problems of electromagnetic compatibility (EMC) due to the harmonic distortion of the input current $I_n$. The recent standardization [1] [2] aims at their reduction. The limits specified may be met with a standard rectifier circuit, complemented by passive filter components towards mains. These however are rather large and expensive. Further, in EMC sensitive applications, such as power supplies for telecommunications or computers, the occurrence of harmonics in the rectifier, although filtered towards the grid, may disturb the operation of the whole circuit.

## 1.2 Rectifiers with Power Factor Correction

As an alternative, controlled rectifiers can be used. They can be characterized as follows:

- The occurrence of harmonics in mains current $I_n$ is actively minimized.
- In operation, the intermediate circuit is charged during the whole mains period with sinusiodal current $I_n$ in phase with the mains voltage $U_n$; this optimizes the maximum available active power through a given mains fuse.
- The voltage of DC link $U_Z$ is controlled and thus independent of mains voltage $U_n$ over a wide range.

  This helps to overcome possible problems of unstable supply voltage. Additionally, the rectifier is suitable for wide input voltage range: This means, that the device may be connected to any mains voltage $U_n$; it is not necessary to preselect the voltage range, because the controlled rectifier will keep DC voltage $U_Z$ at the required level.
- Only few and small passive components are required.

So this type of controlled rectifiers does not only help to meet the requirements of the EMC standards, but it offers significant additional benefits.
Different types of controlled rectifiers for a variety of applications are presented in the following.

# 2. Single Phase Power Factor Correction

## 2.1 Mode of Operation

The schematic of a single phase rectifier with power factor correction in boost topology is shown in figure 3. Its operation is discussed with reference to figures 4, 5 and 6:

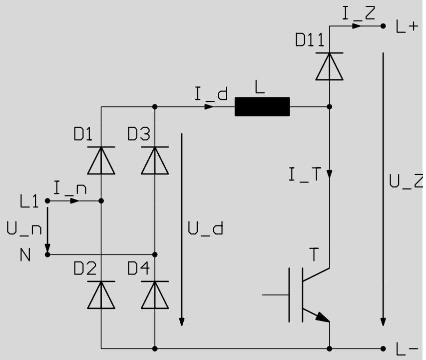


**Fig. 3:** Schematic of single phase rectifier with power factor correction

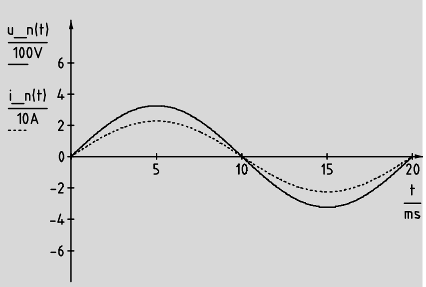


**Fig. 4:** Typical input waveforms of single phase rectifier with power factor correction ($P_n = U_n \cdot I_n$ = 3600 W)

Figure 4 depicts the waveforms of mains voltage $u_n$ (t) (solid) and mains current $i_n$ (t) (dotted). Due to the - ideally - sinusoidal shape of current $i_n$ (t), there would be no harmonic content; furthermore, the phase angle zero between mains voltage $u_n$ (t) and current $i_n$ (t) avoids the occurrence of first harmonic reactive power. Please note the significantly lower amplitude of mains input current of the rectifier with power factor correction in figure 4 compared to the standard rectifier as in figure 2; both waveforms are displayed in the same scale and for the same rectified power.

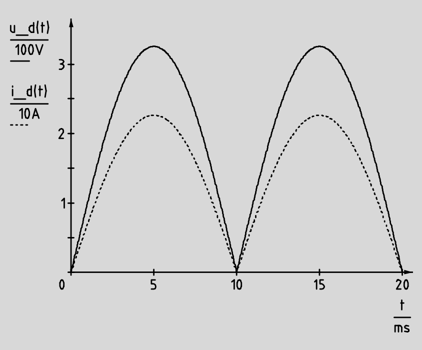


**Fig. 5:** Typical rectified waveforms of single phase rectifier with power factor correction ($P_n = U_n \bullet I_n = 3600$ W)

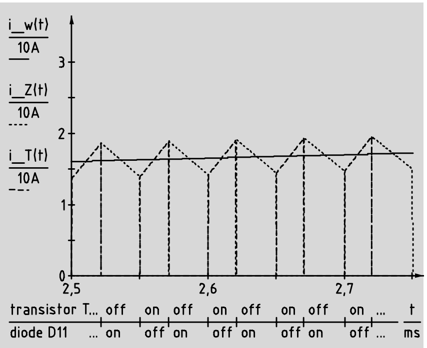


**Fig. 6:** Typical boost chopper waveforms of single phase rectifier with power factor correction ($P_n = U_n \bullet I_n = 3600$ W)

On the secondary of the rectifier bridge according to figure 3, the waveforms look as shown in figure 5: The diodes have rectified primary current and voltage as have been depicted in figure 4, thus folding the previously negative half-waves of voltage and current to the first quadrant, while their sinusoidal shape has been maintained.

Finally figure 6 depicts current waveforms taken at the chopper in a magnified time interval: The solid line represents the command variable $i_w$ (t) for the boost chopper's input current $i_d$ (t); the slightly rising slope corresponds to a section of the sinusoidal half-wave of the rectified input current $i_d$ (t) according to figure 5.
This desired waveform is approximated by the boost chopper, composing the sinusoidal half-waves of $i_d$ (t) according to $i_d (t) = i_T (t) + i_Z (t)$. The boost chopper's pulse pattern is documented below the time axis of figure 6: When the transistor T is turned on, it will carry a current $i_T$ (t) according to the broken line; current rises, because the voltage $u_d$ (t) is applied to the inductor L which will further magnetize. Having turned the transistor T off, the diode $D_{11}$ will turn on and thus cause the inductor to demagnetize by a decreasing current $i_Z$ (t) (dotted) into the intermediate circuit, with the voltage of intermediate circuit being larger than rectified mains voltage at any time $U_Z > u_d$ (t).
This way, the sum $i_d (t) = i_T (t) + i_Z (t)$ represents a waveform with an average value according to the desired sinusoidal current $i_w$ (t) and an additional triangular ripple due to boost chopper operation.

The latter's switching frequencies typically are in the range of $50\,\text{kHz} \leq f_T \leq 100\,\text{kHz}$, which minimizes size and cost of the inductor L and possible additional filter components. The control method for this kind of power factor corrected rectifiers is implemented in a variety of integrated circuits, which significantly faciliates their design - see for example [3], [4], [5], [6], [7], [8] or [9]. The following section will deal with suitable integrated power semiconductors.

## 2.2 Suitable Integrated Power Semiconductors}

### 2.2.1 General

The following aspects should be considered in choosing power semiconductor components for a power factor corrected single phase rectifier with a topology according to figure 3:

- The **rectifier diodes** $D_1$ to $D_4$ must be able to stand the inrush current peak at power on as mentioned in section 1.1, however reduced by the inductor L. Further, fast switching behaviour is advantageous to reduce the emission of disturbances during commutation at zero transition of mains current. Special mains rectifier diodes with fast switching behaviour are referred to as semifast diodes in the following.

- The **transistor in the boost chopper T** should be a fast switching device - either a high voltage MOSFET or an IGBT with optimized switching speed- to operate at the high switching frequency as mentioned in section 2.1. The use of a component with low gate charge $Q_G$ is beneficial, because it helps to minimize the required drive power.

- The **free wheeling diode of the boost chopper** $D_{11}$ must be optimized for high switching speed, particularly at turn off in switched mode operation. Fast recovery epitaxial diodes - FREDs - should be used; their performance can additionally be improved using a series connection of two diodes. If the free wheeling diode is correctly sized for operation at nominal power and high switching frequency, it generally stands the inrush current at power on as mentioned above.

- Several requirements refer to the **package**: The power circuit must be isolated from the heatsink for safety reasons; thus the package should provide an internal isolation. This, together with the integration of several power semicondcutors in the same package, leads to low mounting effort. The integration as mentioned is further indispensable to achieve a good operational behaviour of the chopper, particularly regarding high frequency fast switching.

Obviously, the whole rectifier with power factor correction should be considered as one system, the parts of which have to be matched to each other and to the application.

### 2.2.2 Component Types, their Ratings and Characteristics

In this section, several combinations of power semiconductor components constituting power factor corrected single phase rectifiers are discussed according to the approach, that the whole rectifier should be considered as one system, Consisting of several components operating together.

Different sets of power semiconductor components are listed in table 1 together with their major characteristics as explained in section 2.2.1:

- The left columns give IXYS' type designations: Either one type is mentioned, integrating all components - or two types, the first incorporating the rectifier bridge $D_1$ to $D_4$, the second the boost chopper T and $D_{11}$ according to figure 3.

- The next column names the package type. All packages are isolated. The outline of Isoplus I4-Pac is shown in figure 7; this new package combines features of discrete components - it looks similar to - with features of modules - such as isolation and reliability, see [10]. Veridul module package is depicted in figure 8. Eco-Pac is a similar module, however with a smaller footprint of 30.3 mm • 47 mm.

- Features of the chips - rectifier $D_1$ to $D_4$, boost chopper transistor T and free wheeling diode $D_{11}$ are outlined in the three columns on the right of table 1.

**Table 1:** Features of components for single phase power factor correction

| Type designation | | features | | | |
|---|---|---|---|---|---|
| **rectifier** | **chopper** | **package(s)** | **rectifier** | **transistor** | **diode** |
| **VUI9-06N7** | | Eco-Pac module | semifast | fast IGBT | series FREDs |
| **FBO16-08N** | **FID35-06C** | Isoplus I4-Pac | standard | fast IGBT | series FREDs |
| **FBO16-08N** | **FMD21-05QC** | Isoplus I4-Pac | standard | low $Q_G$ MOSFET | series FREDs |
| **VUM24-05N** | | Veridul module | standard | MOSFET | FRED |
| **VUM33-05N** | | Veridul module | standard | MOSFET | FRED |

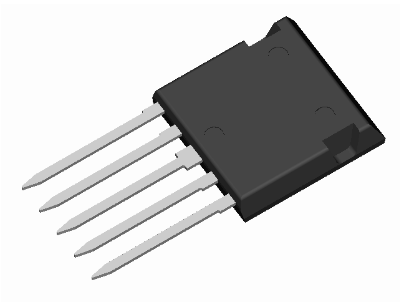

**Figure 7:** Outline of Isoplus I4-Pac package: dimensions ~ 20 mm • 21 mm

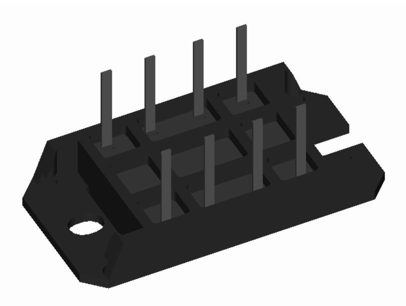

**Figure 8:** Outline of Veridul package: dimensions 31.6 mm • 63 mm

**Table 2:** Typical nominal mains power $P_n$ of components for single phase power factor correction; conditions: voltage of intermediate circuit $U_Z$ = 400 V, switching frequency $f_T$ = 75 kHz, case temperature $T_C$ = 80 °C

| Type designation | | $P_n$ | |
|---|---|---|---|
| **rectifier** | **chopper** | **at $U_n$ = 110 V** | **at $U_n$ = 240 V** |
| **VUI9-06N7** | | 900 W | 2100 W |
| **FBO16-08N** | **FID35-06C** | 950 W | 2600 W |
| **FBO16-08N** | **FMD21-05QC** | 1400 W | 3100 W |
| **VUM24-05N** | | 2200 W | 2800 W |
| **VUM33-05N** | | 3300 W | 4200 W |

According to the approach to consider the whole rectifier as one system, detailed calculations have been carried out to determine the ratings of the power factor corrected single phase rectifiers as suggested. The results are shown in table 2: Under the typical operating conditions listed in the caption, the rectifier systems can take the indicated power out of mains and transfer it - reduced by the losses - to the intermediate circuit. Two power ratings are given, covering the international mains voltage range; this way, the nominal power of a rectifier system can be determined either for a fixed input voltage or for wide input voltage range.

The calculations, leading to the results as presented in table 2, use both - the characteristic values and maximum ratings of the power semiconductor components, and the knowledge of power factor corrected rectifier's mode of operation as explained in section 2.1: At given operating conditions - such as voltage of intermediate circuit $U_Z$, switching frequency $f_T$ and case temperature $T_C$ - junction temperature of the several semiconductors $D_1$ to $D_4$, T and $D_{11}$ is calculated with the parameters mains voltage $U_n$ and current $I_n$. Maximum junction temperature of any semiconductor may not be exceeded, which determines the permitted mains voltage $U_n$ - mains current $I_n$ operating range of the rectifier system. With these limits, nominal mains power can be calculated by $P_n = U_n \bullet I_n$.

So the calculations as described have two uses: The indications of nominal power for the whole power factor controlled rectifier system permit to easily select power semiconductor components for a given rectifier rating in a variety of applications. Thus rectifier design is significantly faciliated. Further the system approach helps to match the different power semiconductors to an optimum, leading to optimized components: The most economic solution will match the ratings of the single semiconductors $D_1$ to $D_4$, T and $D_{11}$ in a way, that the $U_n \bullet I_n$ operating ranges of all parts are as congruent as possible.

## 3. Three Phase Power Factor Correction

There are several topologies and control methods to implement power factor correction as described in section 1.2 for three phase systems; a survey of techniques is given in [11].
Different types of three phase power factor corrected rectifiers with continuous mains current will be discussed in the following sections.

### 3.1 Combination of Three Single Phase Rectifiers

It is possible to connect one single phase power factor corrected rectifier as shown in figure 3 and as explained in section 2 between each of the three mains phases

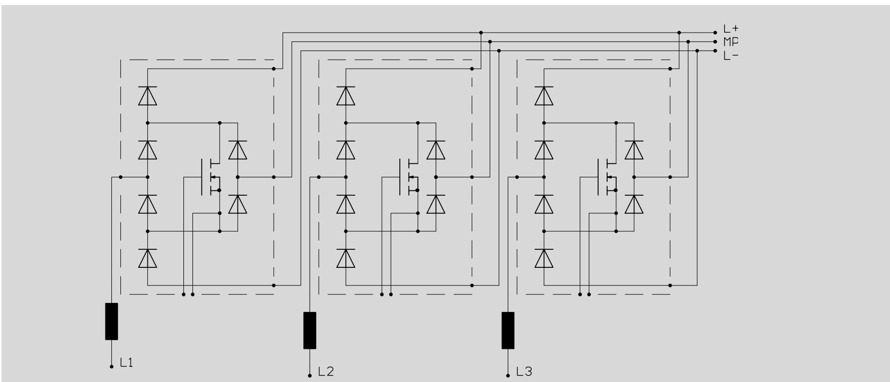


**Figure 9:** Schematic of three phase rectifier with power factor correction - "Vienna" rectifier

and the neutral conductor. However this solution is hardly used because of its drawbacks: Often no neutral conductor is available. Furthermore the rectified power is transferred to three DC links - one per phase; additional DC-DC converters with galvanic isolation would be needed to make the rectifier a single DC voltage source as commonly required.

True three phase rectifier systems as outlined in the next sections prove to be better solutions.

### 3.2 Three Phase "Vienna" Rectifier

The topology of ''Vienna'' rectifier is shown in figure 9; it can be characterized as follows:

On the mains side, there is one inductor for each phase $L_1$, $L_2$, $L_3$. There is no need for a neutral conductor. The circuit will operate with wide input voltage range.

The output of the rectifier is an intermediate circuit with controlled DC voltage between L+ and L- with center point MP.

There is one controllable switch per phase - MOSFETs are depicted. Together with the surrounding four diodes bridges, they operate as bidirectional switches: When turned on, they connect the respective mains phase to the DC center point via two diodes and the inductor, which makes the latter magnetize. When turned off, the inductor demagnetizes into the DC link via the free wheeling diodes connected to L+ or L- respectively.

It is obvious that this operational principle is similar to the one described for the single phase power factor corrected rectifier in section 2.1. Further details about operation and control of the circuit can be found in [12], [13], [14].

In particular, the method explained in [12] permits the calculation of the power ratings of the "Vienna" rectifier analogous to the approach for the power factor corrected single phase rectifier in section 2.2.2. Basic ratings and characteristics of ''Vienna'' rectifiers built with IXYS modules are listed in table 3.

**Table 3:** Typical nominal three phase mains power $P_n$ of components for three phase power factor correction; conditions: mains voltage $U_{\Delta n}$ = 400 V, case temperature $T_C$ = 80 °C

| Type designation | $P_n$ | package | options |
|---|---|---|---|
| **VUM25-05** | 10 kW | V1-Pack | |
| **VUM85-05A** | 30 kW | V2-Pack | soft start thyristor |

A ''Vienna'' rectifier will use one of the indicated modules per phase. As could be expected, its range of rectified power is higher, compared to single phase rectifiers as rated in table 2. Both components in table 3 are isolated modules, where V1-Pack has the same footprint as Veridul package - see figure 8 - while V2-Pack is bigger with a footprint of 40.4 mm • 93 mm according to the higher nominal power. The VUM85 module additionally provides a soft start thyristor to give the capability to limit the inrush current at power on, as already discussed in sections 1.1 and 2.2.1.

### 3.3 Three Phase Full Bridge

The last circuit to be presented is the self commutated three phase full bridge shown in figure 10. Mains would be connected via inductors to the phase outputs $L_1$, $L_2$, $L_3$, while L+ and L- represent the constant voltage DC link. The self commutated three phase full bridge can be used as rectifier and inverter; thus it permits bidirectional energy transfer, which is useful for applications with energy recovery. However, the circuit contains twice the amount of controllable switches - six IGBTs in figure 10 - compared to the ''Vienna'' rectifier as described in section 3.2; consequently driving effort is somewhat higher. Furthermore, semiconductors with higher blocking voltages are needed. In the end, the particular requirements of the actual application will decide which solution to prefer.

Applications of this topology are wide spread in power electronics. Many control methods are known and implemented in integrated circuits. A variety of integrated power semiconductors for a wide power range is available. Without claiming completeness, table 4 lists some module types of IXYS with their most important ratings.

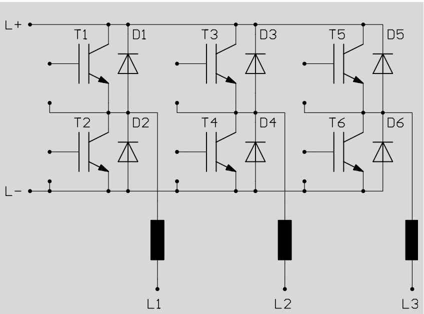

**Figure 10:** Schematic of three phase full bridge

**Table 4:** Self commutated full bridges for three phase power factor correction; breakdown voltage $U_{(Br)CEs}$ and DC ratings at case temperature $T_C$ = 80 °C of IGBTs ($I_{C80}$) and diodes ($I_{F80}$)

| Type designation | $U_{(Br)CEs}$ V | $I_{C80}$ A | $I_{F80}$ A |
|---|---|---|---|
| **MWI30-06A7** | 600 | 30 | 24 |
| **MWI50-06A7** | 600 | 50 | 45 |
| **MWI75-06A7** | 600 | 60 | 85 |
| **MWI100-06A8** | 600 | 85 | 85 |
| **MWI150-06A8** | 600 | 125 | 125 |
| **MWI200-06A8** | 600 | 165 | 170 |
| **MWI25-12A7** | 1200 | 35 | 33 |
| **MWI35-12A7** | 1200 | 44 | 33 |
| **MWI50-12A7** | 1200 | 60 | 70 |
| **MWI75-12A8** | 1200 | 100 | 100 |
| **MWI100-12A8** | 1200 | 120 | 130 |

## 4. Conclusion

Power factor correction for mains rectifiers is an upcoming issue. Operating principles of single and three phase power factor corrected rectifiers have been explained. Suitable integrated power semiconductors have been presented. Power factor corrected rectifier systems using thesecomponents have been rated as a result of detailed calculations. This paper has shown that single and three phase power factor corrected rectifiers are feasible and how they can be designed.

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