Single and Three Phase Rectifiers with Active Power Factor Correction for Enhanced Mains Power Quality

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Abstract

The major drawbacks of conventional diode or thyristor rectifiers are overcome by active power factor correction; this further provides additional benefits. Operating principles and features of single and three phase rectifiers with active power factor correction are explained in this paper. Calculations referring to the various power semiconductor switches in different topologies permit to derive ratings of this kind of mains rectifiers, being equipped with power semiconductor components that partially or totally integrate the circuit.

1 Introduction

Standard rectifier bridges, consisting of diodes, are rugged, simple and cheap. Their use however leads to problems of electromagnetic compatibility (EMC) due to harmonic distortion of the mains input currents, typically being shaped as peaks. The recent standardization [1] [2] specifies limits for harmonic distortion which 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 system.
As an alternative, rectifiers with active power factor correction may be used. They outperform the standard rectifiers with the following characteristics:

- The occurrence of harmonics in mains current is actively minimized.
- In operation, the intermediate circuit is charged during the whole mains period with rectified sinusoidal mains current in phase with mains voltage; this way, the maximum active power is available through a given mains fuse.
- Voltage or current of the DC link on the secondary side are controlled; thus the output is independent from mains voltage over a wide range. This helps to overcome possible problems of unstable supply voltage. Additionally, the rectifier is suitable for wide mains voltage range — there is no necessity to manually preselect the input voltage.
- 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. The general description of single phase rectifiers in section 2 can further be applied to three phase rectifiers as described in section 3.

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 1. Its operation is discussed with reference to figures 2 and 3:

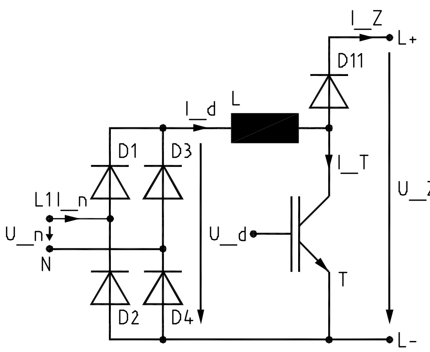

Figure 1: schematic of single phase rectifier with power factor correction

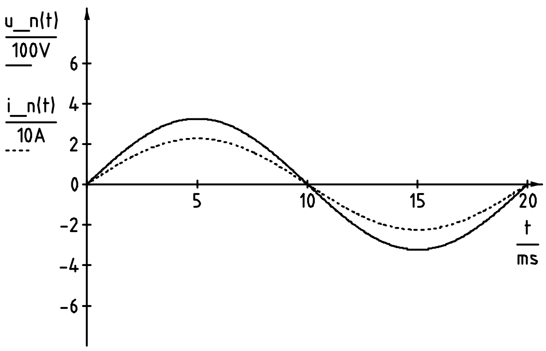

Figure 2: typical input waveforms of single phase rectifier with power factor correction ($P_n = U_n \cdot I_n = 3600W$)

Figure 2 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. At the same rectified power, the power factor corrected rectifier's mains input current has a significantly lower amplitude and RMS value compared to a standard rectifier's.

On the secondary of the diode bridge according to figure 1, the previously negative half-waves of voltage and current ideally have been folded to the first quadrant according to:

$$u_d(t) = |u_n(t)| \quad (1)$$

$$i_d(t) = |i_n(t)| \quad (2)$$

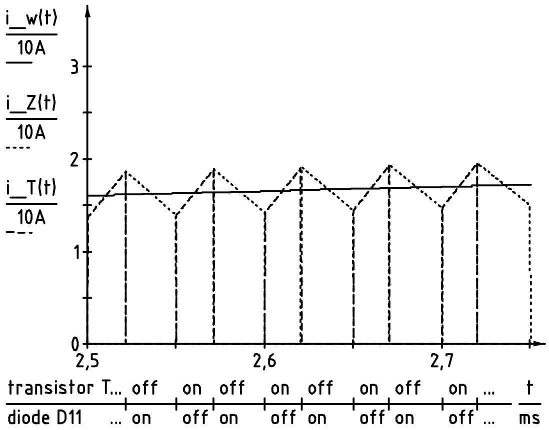

Figure 3: typical boost chopper waveforms of single phase rectifier with power factor correction ($P_n = U_n \cdot I_n = 3600W$)

Finally figure 3 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 2 and equation 2. 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 3: 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 $50kHz \leq f_T \leq 100kHz$, 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 the formers' design — see for example [3] [4] [5].

2.2 Calculation of Power Semiconductor Ratings

While the voltage ratings are determined by the operating voltage on primary and secondary side and the circuit, the current ratings depend on the power losses in operation as previously described; they may not lead to a junction temperature exceeding the maximum allowable value:
Conduction losses are caused by the forward voltage drop when the power semiconductor switch has been turned on:

$$P_C = U_{forward}(I) \cdot I \qquad (3)$$

where I is the current carried and $U_{forward}$ is the current dependant forward voltage drop.
Switching losses occur during the transients, where voltage across the switch $u(t)$ rises and current through the switch $i(t)$ falls or vice versa; assuming the switching operation to start at t_0 and to last for $t_{on/off}$ leads to:

$$E_{on/off} = \left| \int_{t_0}^{t_0+t_{on/off}} u(t) \cdot i(t) \cdot dt \right| \qquad (4)$$

Neglecting blocking and control losses, total power losses, averaged over one period of switching frequency which is assumed to be constant, are given by:

$$P_V = P_C \cdot a + f_T \cdot (E_{on} + E_{off}) \qquad (5)$$

where f_T is the switching frequency and a with $0 \leq a \leq 1$ the duty cycle — the device is turned on for $\frac{a}{f_T}$. Average power loss during one mains period thus approximately is

$$\overline{P}_V = \frac{f_n}{f_T} \cdot \sum_{i=1}^{\frac{f_T}{f_n}} P_{Vi} \qquad (6)$$

where P_{Vi} are the losses in the i-th interval of switching frequency f_T within one mains period $\frac{1}{f_n}$. Average junction temperature in steady state can then be calculated using

$$\overline{T}_J = \overline{P}_V \cdot R_{thJC} + T_C \qquad (7)$$

where T_C is a constant case temperature and R_{thJC} the thermal resistance junction to case. Junction temperature must be lower than the rated value

$$\overline{T}_J \leq T_{Jmax} \qquad (8)$$

An optimum match between the various power semiconductor switches within the rectifier topology is achieved, if their $\overline{T}_J$ is equal.

2.3 Other Requirements on Power Semiconductors

In addition to the electrical ratings as derived in section 2.2, the following aspects should be considered, choosing power semiconductor components for a power factor corrected single phase rectifier with a topology according to figure 1:

- The **rectifier diodes** D_1 to D_4 must be able to stand the inrush current peak at power on, mainly determined by mains voltage and 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. Integration further is indispensable to achieve a good operational behaviour of the chopper, particularly with respect to high frequency fast switching, requiring low parasitic inductance. Finally, packaging has a strong impact on reliability.

2.4 Examples of Integrated Power Semiconductors

Different sets of power semiconductor components to build the topology in figure 1 are listed in table 1 together with their major ratings and characteristics as explained in sections 2.2 and 2.3:

- 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 1.

- The next column names the package type. All packages are isolated. The outline of so called Isoplus i4™ is shown on the left in figure 4; this new package combines features of discrete components — it looks similar to — with features of modules — such as isolation and reliability, see [6]. Veridul module package is depicted on the right in figure 4. Eco-Pac is a similar module, however with a smaller footprint of $30,3mm \cdot 47mm$.

- 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 following columns of table 1.

- Power ratings P_n of rectifiers composed of the listed components are given in the right columns. They have been calculated according to the approach in section 2.2 for different international mains voltages U_n.

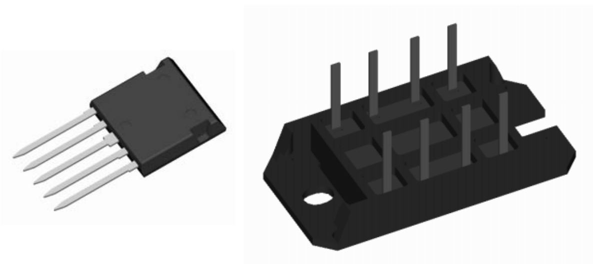

Figure 4: left: outline of Isoplus i4™ package: dimensions $\approx 20mm \cdot 21mm$; right: outline of Veridul package: dimensions $31,6mm \cdot 63mm$

3 Three Phase Power Factor Correction

There are several topologies and control methods to implement power factor correction as described in section 1 for three phase systems; a survey of techniques is given in [7].
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 1 and as explained in section 2 between each of the three mains phases 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 5; 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. It is advantageous that — due to this division of the output voltage — switches with lower blocking voltage and thus better conduction characteristics can be used.
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

Table 1: components for single phase power factor correction: type designations, features and ratings for voltage of intermediate circuit $U_Z = 400V$, switching frequency $f_T = 75kHz$, case temperature $T_C = 80°C$

type designation		features				P_n at U_n	
rectifier	chopper	package(s)	rectifier	transistor	diode	$110V$	$240V$
VUI9-06N7		Eco-Pac module	semifast	fast IGBT	ser. FRED	900W	2100W
FBO16-08N	FID35-06C	Isoplus i4™	standard	fast IGBT	ser. FRED	950W	2600W
FBO16-08N	FMD21-05QC	Isoplus i4™	standard	Q_G MOS.	ser. FRED	1400W	3100W
VUM24-05N		Veridul module	standard	MOSFET	FRED	2200W	2800W
VUM33-05N		Veridul module	standard	MOSFET	FRED	3300W	4200W

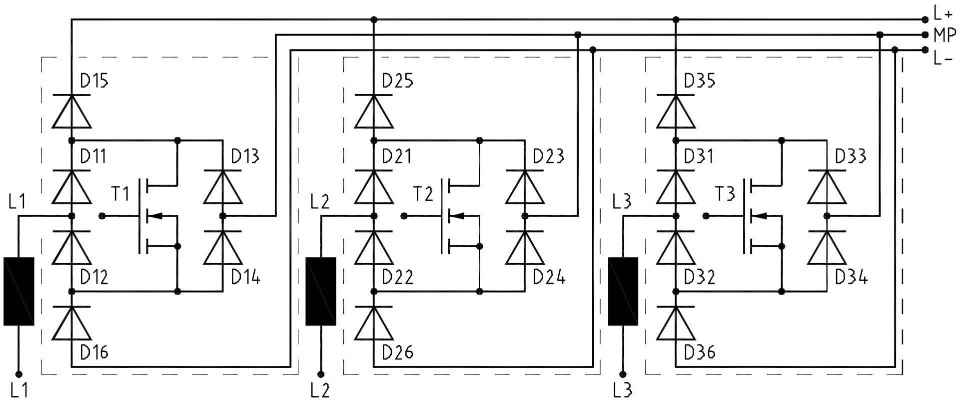

Figure 5: schematic of three phase rectifier with power factor correction — "Vienna" rectifier

factor corrected rectifier in section 2.1. Further details about operation and control of the circuit can be found in [8] [9] [10] [11].

In particular, the method explained in [8] permits the calculation of the power ratings of the "Vienna" rectifier analogous to the approach for the power factor corrected single phase rectifier as described in section 2.2. Basic ratings and characteristics of "Vienna" rectifiers built with different modules are listed in table 2. 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 1. The components in table 2 again are isolated modules, where V1-Pack has the same footprint as Veridul package — see figure 4 (right) — while V2-Pack is bigger with a footprint of $40,4mm \cdot 93mm$ according to the higher nominal power. The VUM85 module additionally provides a soft start thyristor for limiting the inrush current at power on, as already discussed in section 2.3.

Table 2: typical nominal three phase mains power P_n of "Vienna" rectifiers; conditions: mains voltage $U_{\Delta n} = 400V$, case temperature $T_C = 80°C$

type	P_n	package	options
VUM25-05	10kW	V1-Pack	
VUM85-05A	30kW	V2-Pack	soft start thyr.

3.3 Three Switch, Three Phase Unity Power Factor Rectifier with Variable Voltage DC Link

The circuit in figure 6 is again connected to three phase mains via one inductor per phase. Contrary to the "Vienna" rectifier, capacitors are located on mains side of the converter and a direct current is controlled to flow between the terminals $I+$ and $I-$ on the secondary side. It may for example be conditioned by a following boost chopper and inverted to drive a motor. The circuit again uses bidirectional switches consisting of diodes and transistors — IGBTs are depicted. Operational principle, control methods and calculation of ratings are comprehensively described in [12]. Table 3 gives ratings of a module, again comprising the power semiconductors for one phase as indicated by the dashed lines in figure 6.

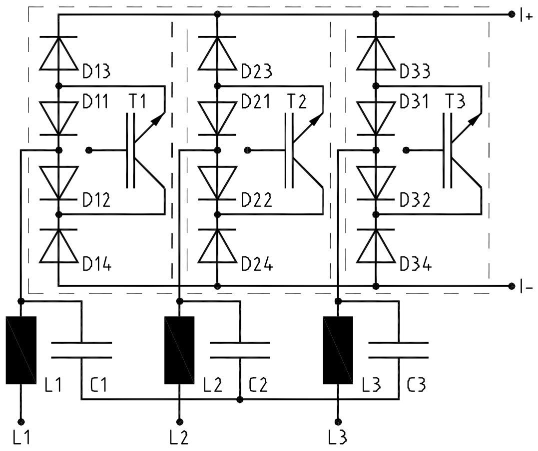

Figure 6: schematic of three switch, three phase unity power factor rectifier with variable voltage DC link

Table 3: typical nominal three phase mains power P_n of three switch, three phase unity power factor rectifier with variable voltage DC link; conditions: mains voltage $U_{\Delta n} = 400V$, switching frequency $f_T = 15kHz$, case temperature $T_C = 80°C$

type	P_n	package
VUI30-12N1	15kW	V1-Pack

3.4 Three Phase Full Bridge

Finally the self commutated three phase full bridge shown in figure 7 should be mentioned to be suitable for three phase power factor correction: Mains would be connected via inductors to the phase terminals 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 7 — compared to the rectifiers as described in sections 3.2 and 3.3; consequently driving effort is somewhat higher. In the end, the particular requirements of the actual application will decide which solution to prefer.

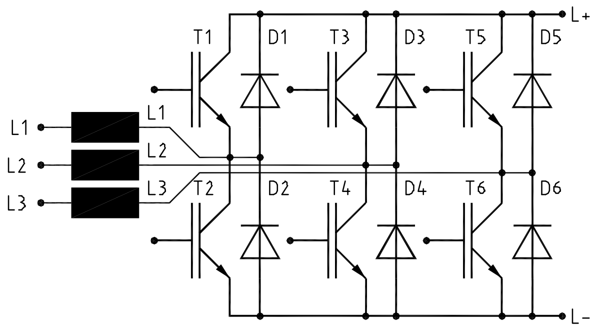

Figure 7: schematic of three phase full bridge

Anyway, this topology is frequently applied 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 suitable IGBT modules with their most important ratings.

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

type designation	U_{CEs}	I_{C80}	I_{F80}
MWI30-06A7	600V	30A	24A
MWI50-06A7	600V	50A	45A
MWI75-06A7	600V	60A	85A
MWI100-06A8	600V	88A	88A
MWI150-06A8	600V	130A	130A
MWI200-06A8	600V	165A	165A
MWI15-12A7	1200V	20A	17A
MWI25-12A7	1200V	35A	33A
MWI35-12A7	1200V	44A	33A
MWI50-12A7	1200V	60A	70A
MWI75-12A8	1200V	100A	100A
MWI100-12A8	1200V	120A	130A

4 Conclusion

Power factor correction is introduced to avoid mains disturbances caused by the increasing number of mains rectifiers, suppliing all kinds of electrical devices. The mode of operation of single phase rectifiers with active power factor correction has been described; based on its knowledge, the ratings of this kind of mains rectifiers and of power semiconductor components they are equipped with respectively have been calculated. Further, several circuits and components for three phase rectification with active power factor correction have been presented. It can be expected, that this technique which up to now is used rather seldom, will gain importance in the near future because it will be applied to innovative power supplies for sensitive loads with high power consumption, such as for telecommunication equipment or computers.

References

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