UNIDIRECTIONAL THREE PHASE HIGH POWER FACTOR HYBRID
RECTIFIER

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Abstract – Power factor corrected rectifiers are new
tendency in development of power supplies. This paper
presents a brief review of some high power rectifiers
structures and provides an assessment of each analyzed
technology. As contribution, a novel hybrid high power
rectifier topology is proposed and analyzed. An active
unidirectional three phase rectifier is associated in
parallel with a three-phase 6-pulse diode bridge. The
main objective is to achieve a unity power factor high
power converter, so that 50% of the total power are
processed by the diode bridge and the other ones 50% for
the active rectifier. The mathematical analysis and
simulation results for a 26kW converter are presented.

Keywords – Hybrid Rectifier, High power Factor, Load
Sharing,

I. INTRODUCTION

The industrial rectifiers have its origin in the USA. In the
late 1890s Peter Cooper-Hewitt, an American electrical
engineer, invented an arc lamp working with mercury vapor
and observed the unidirectional behavior of current flow
through this device. In 1902 Hewitt designed a reasonable
working mercury arc rectifier and received as well a German
patent. Before this, the use of rectifiers in industrial
applications was made with the electromechanical contact
converters (an AC motor coupled with a DC generator).

The mercury converter technology remained until the late
1950s, when, in 1948, the diode and the bipolar transistor
were developed by the Bell Telephone Labs. In 1960,
the first diode rectifier above 100kA was placed to the market,
and, ten years later, the first thyristor plant of this rating was
operational.

Rectifier units of more than 150kA and industrial plants
with process currents above 350kA are often today. The
future in the aluminum industry goes toward 500kA [1].

The use of a semiconductor element mainly depends on its
capability to dissipate the semiconductor losses. This way, to
medium and high power converters forced-cooled heat sinks
is frequently used.

However, to obtain low THD in high power converters
can be a complex job. Some technological limitations restrict
the use of certain topologies in pre-established power
levels. The latest advances in high-power semiconductor
devices have introduced newer solutions for high power
conversion systems, however, the degree of acceptance of
each technology vary in according with various industry and
applications.

A. Diode Rectifiers

Diode rectifiers are the simplest of all rectifier topologies.
Robustness and low cost are main attractive characteristics
that allow these structures to be applied in high power
applications. In the other hand, the low power factor and high
harmonic distortion of the input currents are the factors that
make the rectifier to be seldom applied in industrial
applications. A power factor improvement can be achieved
by inserting a high value of inductance to filter the output
current, as showed in Fig. 1. The maximum theoretical power
factor obtained is 0,95 and a 31% of total harmonic distortion
of input currents. However, the standards requirements can
not be contemplated with this structure.

Fig. 1. Six pulse diode bridge rectifier

The concerns regarding restrictions in the harmonic
content generated by the power converters, above all the
framing in the standards IEEE 519 and IEC 61000 3-4, it has
been objective of many recently studies. To compensate the
harmonic distortion generated by the standards diode
rectifiers, passive linear filters or power factor correction
structures can be employed. In multipulse rectifiers special
winding connections are used in transformers and, for this
reason, they become, as the linear filters, heavy and bulky,
however are extremely robust.

In Fig. 2 a 12 and 18 pulse high power rectifiers are
depicted. For the twelve pulse rectifier, the total harmonic
distortion is approximately 14%, while for the eighteen pulse
structure, the obtained THD is of approximately 9% [1, 10].

A significant reduction in the final weight and volume can
be achieved replacing the transformers by autotransformers
with delta-differential connections, however, for the 12 pulse
structure 6 secondary windings and 4 interphase reactors are
necessary. For the 18 pulse, 12 secondary and 6 interphase
reactors. The disadvantage is that the insulation will be lost,
but, in the other hand, the power processed by the
autotransformer is only 20% of the rated power [2,10].
Other interesting ideas to obtain the reduction of these structures can be obtained in [3] and [4].

![Diagram](image1.png)

Fig. 2. 12 pulse (a) and 18 pulse (b) high power rectifiers.

**B. Thyristor Rectifiers**

The thyristor rectifiers present the same robustness of the diode rectifiers. The complexity and the costs are a little increased due to gate drive circuit. The harmonic distortion of input currents is worst if compared with diode rectifiers but the output voltage regulation is possible with this structures. Due to the simplicity, reliability and efficiency, the thyristor rectifier has been, until today, the most commonly used rectifier configuration for high power applications [1].

**C. Active Rectifiers**

Active rectification techniques are the most promising rectifier technology from a power quality viewpoint. A unity power factor and a very low harmonic distortion can be achieved. The topology illustrated in Fig. 3 is an example of an active high power factor rectifier. The most important characteristics of this structure are the unidirectional power flow and a low number of active switches.

The commonly high power factor PWM rectifier topologies are Boost type. The Buck is little spread topologies because they present low frequency input inductors and need bulky input filters.

![Diagram](image2.png)

Fig. 3. Unidirectional Three Phase High Power Rectifier.

The use of active rectifier is standard in low and medium power drive applications. However, these topologies are current not available for high power rectifier applications, partly due to unavailable of suitable cost-effective power electronic devices. In applications where the weigh and volume are decisive factors, active power factor correction structures are employed, but, the complexity and the cost obtained are significantly increased.

This way, to obtain a rectifier capable to gather the robustness, lightness, simplicity and the low cost of passive rectifiers with the efficient reduction of the harmonic content obtained with the PWM rectifiers becomes a quite interesting challenge and with great possibility of practical application.

A new hybrid rectifier, based on the connection of two converters in parallel operation, composed by the association of the previously presented rectifiers with the capacity to assemble the characteristics before mentioned is the aim of this paper.

**II. THE PROPOSED HYBRID RECTIFIER**

Hybrid rectifier denotes the series and/or parallel connection of a line-commutated (in this case, the six pulse diode bridge) and a self-commuted converter (PWM rectifier) [5], [6]. It can not be classified as an active filter due to the fact that the active rectifier, in this case, process active power while the active filters have the characteristic of process only reactive power and compensate the harmonic content.

The proposed hybrid rectifier is presented in Fig. 4.

![Diagram](image3.png)

Fig. 4. Proposed Hybrid Rectifier.

To perform the mathematical analysis the input voltages are supposed perfectly sinusoidal and expressed by (1):  

\[
\begin{align*}
V_1(t) &= V_p \cdot \sin(\omega \cdot t) \\
V_2(t) &= V_p \cdot \sin(\omega \cdot t - 120^\circ) \\
V_3(t) &= V_p \cdot \sin(\omega \cdot t + 120^\circ)
\end{align*}
\]

(1)

It is known that the diode bridge output voltage is dependent of the input voltages rms value [7] according to the expression (2). This way, the output voltage of the Hybrid rectifier is also dependent of the mains voltage.

\[
V_o = \frac{3 \cdot \sqrt{3}}{\pi} V_p
\]

(2)
In normal operation, the output voltage of the boost type PFC structures must be higher than to the line peak voltage to achieve high power factor. But, if the voltage produced by the rectifier PWM goes larger than the limit imposed by the expression (2), the diode bridge blocks and the whole power begin to be supplied by the active structure. To solve this incompatibility an autotransformer can be used to reduce the PWM rectifier input voltages, as can be observed in Fig. 4. The autotransformer leakage inductances are added to the input inductors of the PWM rectifier. This way, the input inductors are reduced or can be suppressed, just depending on the autotransformer leakage inductances.

To achieve unity power factor, the mains currents must be sinusoidal. However, they are composed by two parts; the first one originated by the active rectifier and the other by the passive structure. This statement allows establishing the expression (3):

\[
\begin{align*}
\mathbf{i}_1(t) &= \mathbf{i}_{1a}(t) + \mathbf{i}_{1p}(t) = I_p \cdot \sin(\omega t - 120') \\
\mathbf{i}_2(t) &= \mathbf{i}_{2a}(t) + \mathbf{i}_{2p}(t) = I_p \cdot \sin(\omega t - 240') \\
\mathbf{i}_3(t) &= \mathbf{i}_{3a}(t) + \mathbf{i}_{3p}(t) = I_p \cdot \sin(\omega t + 120')
\end{align*}
\]

Where:
- \( \mathbf{i}_1(t), \mathbf{i}_2(t), \mathbf{i}_3(t) \) - Line input currents.
- \( \mathbf{i}_{1a}(t), \mathbf{i}_{2a}(t), \mathbf{i}_{3a}(t) \) - Active rectifier input currents.
- \( \mathbf{i}_{1p}(t), \mathbf{i}_{2p}(t), \mathbf{i}_{3p}(t) \) - Passive rectifier input currents.
- \( I_p \) - Peak value of line input currents.

Considering the input currents perfectly sinusoidal:

\[
I_p = \frac{2 V_L - I_L}{3 V_p} = \frac{2 P_o}{3 \sqrt{3}}
\]

In normal operation the diode bridge currents can not be controlled [7]. Their amplitudes are imposed by the load. However, the PWM rectifier allows that the currents to follow a predetermined reference signal [8]. So, substituting (4) in (3):

\[
\begin{align*}
\mathbf{i}_{1a}(t) &= \frac{2}{3} \frac{P_o}{V_p} \cdot \sin(\omega t - \phi) - \mathbf{i}_{1p}(t) \\
\mathbf{i}_{2a}(t) &= \frac{2}{3} \frac{P_o}{V_p} \cdot \sin(\omega t - 120') - \mathbf{i}_{2p}(t) \\
\mathbf{i}_{3a}(t) &= \frac{2}{3} \frac{P_o}{V_p} \cdot \sin(\omega t + 120') - \mathbf{i}_{3p}(t)
\end{align*}
\]

To simplify the analysis, the filter inductor current used in six pulse diode bridge is considered sufficiently large that the output current can be considered constant as can be observed in Fig. 5.

So, the filter inductor current \( i_1(t) \) can be expressed in function of passive rectifier output power \( P_{op} \) and the input voltage:

\[
i_1(t) = I_L = \frac{P_{op}}{V_p} \cdot \frac{\pi}{3 \cdot \sqrt{3}}
\]

Substituting (6) in (5) and analyzing the waveform of Fig. 4:

\[
i_{1a}(t) = \begin{cases} \frac{2}{3} \frac{P_o}{V_p} \cdot \sin(\omega t), & \text{if } 30' \leq \omega t \leq 150' \\ \frac{2}{3} \frac{P_o}{V_p} \cdot \sin(\omega t - 120'), & \text{if } 150' \leq \omega t \leq 180' \end{cases}
\]

Due to unidirectional characteristic of the PWM rectifier, the instantaneous power only can assume positive or zero values. Analyzing (7), the solution that satisfies this condition is presented in (8):

\[
P_{op} \leq \frac{\sqrt{3}}{\pi} \cdot P_o = 0.552 \cdot P_o
\]

So, the active power rectifier operation limit is:

\[
P_{op} \leq (1 - 0.552) \cdot P_o = 0.448 \cdot P_o
\]

The expression (8) is very important to define the load sharing between the two converters. If this relation is not satisfied, the input currents will be distorted as depicted in Fig. 6. The shaded areas denote the intervals where the relation is not satisfied.

III. CONTROL STRATEGY

The control loop scheme is presented in Fig. 7. The currents on the mains must be sensed and compared with their respective sinusoidal references. These references signals should be synchronized with the mains voltages. A good practical way to obtain these signals is through

\[
\begin{align*}
\mathbf{i}_1(t) &= \mathbf{i}_{1a}(t) + \mathbf{i}_{1p}(t) = I_p \cdot \sin(\omega t) \\
\mathbf{i}_2(t) &= \mathbf{i}_{2a}(t) + \mathbf{i}_{2p}(t) = I_p \cdot \sin(\omega t - 120') \\
\mathbf{i}_3(t) &= \mathbf{i}_{3a}(t) + \mathbf{i}_{3p}(t) = I_p \cdot \sin(\omega t + 120')
\end{align*}
\]
synchronization transformers. The error signals produced by these comparisons are applied in respective compensators and the PWM modulators generate the gate signals.

\[ V(t)_1, V(t)_2, V(t)_3 \]
\[ i(t)_1, i(t)_2, i(t)_3 \]
\[ i(t)_1^p, i(t)_2^p, i(t)_3^p \]
\[ i(t)_1^a, i(t)_2^a, i(t)_3^a \]

\[ \text{PWM Current Control Loop} \]
\[ \text{Gate M1, Gate M2, Gate M3} \]
\[ M1, M2, M3 \]
\[ \text{AUTOTRANSFORMER} \]
\[ Lp, L1, L2, L3 \]
\[ \text{Current compensator} \]
\[ \text{RC1, CC1, RC2, CC2} \]
\[ +, - \]
\[ \text{Sum, Mult, Sum, Mult, Sum, Mult} \]
\[ Rf, Cf \]
\[ \text{Low pass Filter} \]
\[ k1, k2 \]
\[ k0 \]

**IV. SIMULATION RESULTS**

The specifications used in simulation are presented in Table I.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_p )</td>
<td>Peak of line voltage</td>
<td>311V</td>
</tr>
<tr>
<td>( V_{in} )</td>
<td>Input voltage rms value</td>
<td>220V</td>
</tr>
<tr>
<td>( V_o )</td>
<td>Output voltage</td>
<td>514V</td>
</tr>
<tr>
<td>( P_r )</td>
<td>Rectifier rated load power</td>
<td>26kW</td>
</tr>
<tr>
<td>( r_t )</td>
<td>Autotransformer turns ratio</td>
<td>1.5:1</td>
</tr>
<tr>
<td>( L_p )</td>
<td>Passive rectifier filter Inductor</td>
<td>5mH</td>
</tr>
<tr>
<td>( L_1, L_2, L_3 )</td>
<td>active rectifier Input Inductors</td>
<td>350( \mu )H</td>
</tr>
<tr>
<td>( C_o )</td>
<td>Output Capacitor</td>
<td>1500( \mu )F</td>
</tr>
<tr>
<td>( f_s )</td>
<td>Switching frequency</td>
<td>30kHz</td>
</tr>
</tbody>
</table>

**A. Operation with \( k_1, k_2 \) ratio = 0.55**

In Fig. 8 the mains currents and the input current on phase 1 of passive and active rectifiers are depicted. As expected, the mains currents present a sinusoidal shape. It must be observed that the power processed by passive and active rectifiers (proportional to the amplitudes of the passive and the active currents) correspond to about 50% of the total input power.

Some peaks can be observed in line current presented in Fig. 8. This is due to the impossibility of imposing a high current derivative on active rectifier. If the line impedances were contemplated in simulation, the passive rectifier input currents would present slow derivatives and, consequently, the peaks would be minimized.
The total harmonic distortion observed in input currents is about 3.18%. In Fig. 9 the harmonic amplitudes and the limits imposed by the IEEE 61000-3-4 are depicted. As can be observed, the harmonics 7, 11, 13, 17 and 19 are not in accordance with IEEE 61000-3-4, however, a better result can be achieved if the line impedances are contemplated in simulation.

![Fig. 9. Harmonic amplitudes](image)

To verify the dynamic response of the system, a load variation was performed and presented in Fig. 10. Between 0 and 20ms the converter operates with 50% of the rated power. After this interval the converter operates with the rated power until 50ms, when the load current is 50% again. In 80ms the converter operates with full load again.

![Fig. 10. Load step response.](image)

The current compensator output, the sinusoidal references and the control signals, can be observed in Fig. 12.

![Fig. 12. Control signals](image)

**B. Operation with $k_1, k_2$ ratio = 0.45**

As previously mentioned, values far from 0.552 for the ratio established by $k_1$ and $k_2$ will result in input current distortion.

In Fig. 13 the distortion generated by a 0.45 ratio can be observed.

![Fig. 13 – Simulation results to $k_1, k_2$ ratio = 0.45.](image)

The power stage and the control circuit used in simulation are presented in Fig. 14 and Fig. 15. It should be observed that only the phase 1 control circuit is presented. However, the phase 2 and 3 uses the same circuit, just the references should be changed.

![Fig. 14, 15. Control circuits.](image)
The fact that the passive rectifier is responsible to about 50% of the output power allows using the active structure and improves the robustness, reliability, costs and providing a high efficiency to the power converter.

An autotransformer is required; however, the input inductors of the active rectifier are reduced or can be suppressed, just depending of the autotransformer leakage inductances.

The simulation results show that the approach can compensate up to 3.2% making this structure interesting and with great possibility of practical application in high power AC to DC conversion.

REFERENCES


