A new arrangement of AC/DC converters for high direct-current applications

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Abstract – A novel AC/DC converter designed for high-output direct currents and tight output voltage regulations is introduced. The proposed converter exhibits good efficiency and very low output voltage ripple. In order to verify the performances of the four-stage proposed converter, a 400A rated current prototype was designed and built. The prototype was properly verified by experimental tests performed in a laboratory. A subsequent FFT (Fast Fourier Transform) analysis was carried out to verify the harmonic pollution produced by the converter in the supply network.

Key-Words: - AC/DC converter, High direct-current, FFT, Electrical distribution systems.

1 Introduction
The number of applications based on power electronics is continuously increasing. As a matter of fact, static power converters are not only widely used on the end-user energy side but in electric power generation as well. An example is photovoltaic generation but also wind power generation that often use double AC/DC and DC/AC conversion in order to supply energy to the grid with constant frequency and voltage [1]. It is also well-known that a great number of motors adopt static converters to control the torque, speed and rotor position [2]. Research studies in this field are mainly directed at improving the performances of converters especially as concerns efficiency, power quality, power factor, etc. [3], [4], [5], [6], [22]. More specifically, as far as the reduction and control of the power factor are concerned, specific digital approaches, both deterministic and probabilistic, were adopted [7], [8]. On the other hand, studies were performed to evaluate costs and efficiency [9], but also conducted and radiated electromagnetic disturbances [10]. In order to reduce harmonic pollution, different methods were proposed in the specialized literature, based both on a better thyristor control [12] and on the adoption of harmonic filters [14]. Another important issue concerns the reduction of losses in high power converters [11]; in this case, a number of components were improved, among them the core of internal transformers [12]. In this paper, the attention is mainly addressed to the increase of the output current of the converter while also improving output voltage quality.

2 The proposed system
The proposed converter is schematically shown in Fig. 1.

![Fig. 1. Layout of the proposed four-stage system.](image)

In order to better understand how the system works, in the following explicit reference is made to the built prototype. The first stage of the system consists of a 6-diodes passive rectifier. The rectified voltage is applied to an inverter that in its turn is made of an ultra-fast 6-IGBT able to commute up to 100 kHz under certain operating conditions. The value of the rectified voltage was about 500 V, neglecting a ripple that can be reduced placing an active rectifier at the input terminations of the inverter. Two serially-connected capacitors, each of 2200 µF, were placed between the DC bus and frame to achieve additional voltage smoothening. The modulation technique adopted to drive the inverter was strongly characterized by the 6-phase transformer/rectifier system used. Fig. 2 shows the shape of the signals used to control the inverter.
Fig. 2. Signals used to drive the inverter.

Each inverter branch is able to conduct current for a maximum of 8.3 µs within a cycle of 25 µs (40 kHz). The phase-to-phase voltage generated downstream of the inverter is applied at the input terminations of the 6-phase transformer/rectifier block shown in Fig. 3.

![Fig. 3. Six-phase transformer/rectifier block supplying the load.](image)

The transformer reduces the voltage while increasing the current. The working principle of the sub-system shown in Fig. 3 is illustrated in Fig. 4.

![Fig. 4. Working scheme of the transformer and AC/DC rectifier.](image)

Of course, the L₁, L₂ and L₃ inductors shown in Figs. 3 and 4 were used to smoothen the load current. All the blocks shown in Fig. 1 are driven by a DSP, model dsPIC30F3011 of the Microchip family [21].

3 Harmonic analysis of the current drawn from the supply network

The procedure adopted for the current harmonic analysis is based on the FFT algorithm [15], [16], [17]. The algorithm processes current samples acquired by means of a measurement system placed between the network and the input terminations of the three-phase rectifier as shown in Fig. 5.

![Fig. 5. Currents acquired by the measurement system for the subsequent FFT analysis.](image)

For simplicity reasons, in the following the performed harmonic analysis is illustrated only for the R-phase current, since the shapes of all the currents of the three-phase system are equal and shifted of 120° from one another.

Assuming the series $i_{in}(n)\equiv i_{in}(n\Delta t)$ obtained from the $N$ coming samples of the measured $i_{in}(t)$ current, the DFT (Discrete Fourier Transform) can be expressed as:

$$I_{in}(k\Delta f) = \Delta t \sum_{n=0}^{N-1} i_{in}(n\Delta t) \cdot e^{-j2\pi kn\Delta t}$$  \hspace{1cm} (1)$$

where $\Delta f$ is the frequency sample interval (computed with the following relation: $\Delta f=1/N\Delta t$) and $\Delta t$ is the sampling time. The inverse discrete Fourier transform is:

$$i_{in}(n\Delta t) = \Delta f \sum_{k=0}^{N-1} I_{in}(k\Delta f) \cdot e^{j2\pi kn\Delta f} \cdot \Delta t.$$  \hspace{1cm} (2)$$

In order to simplify relation (1), the quantities $\Delta t$ and $\Delta f$ can be omitted obtaining the following notation:
\( I_{in}(k) = \sum_{n=0}^{N-1} I_{in}(n) e^{-j2\pi kn/N} \)  

(3)

In the same way, relation (2) can be written as:

\( i_{in}(n) = \frac{1}{N} \sum_{k=0}^{N-1} I_{in}(k) e^{j2\pi kn/N} . \)  

(4)

The computation complexity of relation (4) is \( O(N^2) \). If the \( N \) number of samples is not a prime number, it is possible to optimize the computation by properly grouping some operations depending on the factorization of \( N \). In this case, a faster algorithm can be obtained, which also causes FFT to be equivalent to a fast DFT. The maximum reduction in time computation takes place when \( N \) is a multiple of 2, i.e. \( N=2^p \). In this case, the Cooley-Tukey algorithm can be applied. The complexity of this algorithm, also known in literature as FFT-2 or “radix-2FFT”, is \( O(N \log_2 N) \) [18], [19], [20].

4 Experimental and computation results

Fig. 6 shows the wave shape of the output current coming from the six-phase AC/DC converter when a resistive load of \( R_{LOAD}=0.03 \ \Omega \) is applied. In this situation, the reference current established for feed-back control was 400A.

![Fig. 6. Wave shape of the current present downstream of the six-phase AC/DC converter.](image)

Fig. 6 shows that the AC/DC output current follows the reference value imposed by the control system, if a very small ripple factor is neglected. The wave shape of the R-phase current upstream of the non-active three-phase rectifier is shown in Fig. 7. The value of the current peak is about 36A while the T period of the current wave is 20 ms, corresponding to a frequency of 50 Hz.

![Fig. 7. Wave shape of the R-phase current drawn from the network.](image)

The results of the FFT analysis applied to the phase current of Fig. 7 are shown in Fig. 8.

![Fig. 8. Results of the FFT applied to the R-phase current drawn from the network.](image)

The amplitude of the fundamental frequency and other harmonics are reported in table I.

<table>
<thead>
<tr>
<th>Harmonic order</th>
<th>Frequency [Hz]</th>
<th>Amplitude [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50,000</td>
<td>17,2295</td>
</tr>
<tr>
<td>2</td>
<td>250,000</td>
<td>11,8556</td>
</tr>
<tr>
<td>3</td>
<td>350,000</td>
<td>8,2671</td>
</tr>
<tr>
<td>4</td>
<td>550,000</td>
<td>2,2196</td>
</tr>
<tr>
<td>5</td>
<td>650,000</td>
<td>1,4334</td>
</tr>
<tr>
<td>6</td>
<td>850,000</td>
<td>1,2213</td>
</tr>
<tr>
<td>7</td>
<td>950,000</td>
<td>0,7399</td>
</tr>
</tbody>
</table>

The results obtained give rise to the following observations. The frequency of each harmonic is greater than the previous one of 100 - 200 Hz starting and proceeding alternatively from the fundamental frequency. As concerns amplitudes, the fundamental takes up a value of \( A/2 \), where \( A \) is the peak amplitude of the wave shape of the current drawn by the converter. The second
harmonic takes up a value of $A/2$, the third harmonic $A/3$, the fourth harmonic $A/4$ and so on.

5 Conclusions
Due to the growing interest in high direct-current applications, as required for example in hydrogen production, it has become necessary to develop converters whose output direct-current is very high. In order to meet the above requirement, a new converter architecture was proposed based on an active-current wave-shaping technique. More specifically, a new four-stage AC/DC converter was developed that exhibited both high efficiency and low output voltage ripple. A rated 400A prototype was designed and tested to demonstrate the validity of the proposed converter design.

References:


