Power Factor Improvement of an AC-DC Converter via Appropriate sPWM Technique

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Abstract—The power control of a DC load can be achieved via an AC-DC converter consisting of a rectifier bridge and a switching element operating by sPWM technique. The use of such a converter causes a lot of high harmonics at the AC side, which reduce the power factor and distort the grid voltage. Using passive filter in the converter input to avoid the high harmonics consequences the power factor decrease. To improve the power factor an appropriate sPWM operation of the switching element is proposed in this paper. The system behavior is studied through simulation and experimental investigation. The power factor correction is verified.

I. INTRODUCTION

It is well known that the power control of a DC load feeding by the grid is achieved by the use of an AC-DC converter structure operating through a sPWM technique. In figure 1 one can see such a converter structure consisting of a MOSFET single phase rectifier bridge in series connected with a switching MOSFET5. In the case of an ohmic – inductive load a parallel freewheeling diode is necessary. The rectification becomes by the parasitic bridge MOSFET diodes, while the MOSFETs 1-4 enable the power inversion, if an active load is considered.

![Figure 1. An AC-DC converter structure for supplying a DC load.](image)

The sPWM operation can be succeeded by comparison of a sinusoidal voltage waveform (Uc) in phase to the grid voltage (Ug) with a high frequency triangular waveform in order to obtain a switching pulse waveform. The pulse duration inside of a half sinusoidal period is not constant and the pulse of the maximum duration is located exact at the middle of the half period, while the pulse of the minimum duration appears at the beginning of that, as it appears in figure 2a. Figure 3 shows the waveforms of the grid voltage (50Hz) and the corresponding current pulse waveforms (switching frequency 5 kHz). In case of an ohmic DC load the basic harmonic of the grid current pulse waveform (fig.3a) is in phase with the grid sinusoidal voltage waveform. If the DC load is ohmic-inductive one, then the basic current harmonic is shifted in relation to the voltage waveform Ug (fig.3b). In the case that a sinusoidal waveform Uc is leading upon the grid voltage Ug by an angle ‘a’ via comparison to the triangular waveform (fig.2b), a grid current pulse waveform is obtained of which the basic harmonic is shifted to the grid voltage. In this way the grid current basic harmonic can becomes in phase with the grid sinusoidal voltage, if we have an ohmic-inductive DC load. It means that the power factor can be corrected. In this paper an extensive investigation of the influence of the leading or lagging angle “a” to the power factor via simulation as well as experimentally has been carried out.

![Figure 2. Pulse waveforms obtained by sPWM when ‘a’=0° (2a) and ‘a’≠0° (2b).](image)

![Figure 3. Grid voltage and current in the case of ohmic load (3a) and ohmic-inductive load (3b).](image)
II. POWER FACTOR INVESTIGATION USING SIMULINK/MATLAB SIMULATION

The power factor calculation is achieved by Simulink/Matlab simulation using the appropriate models for the system which is shown in figure 1. First, the simulation has been carried out without input passive filter for two different loads: a) ohmic load and b) ohmic inductive load (several values), by a switching frequency $f_{sw}=5$ kHz. The power factor as a function of the angle ‘a’ mentioned above is depicted in the figures 4, 5 for an effective load power of $P=1200$W. Figure 14 shows the power factor in the case that a DC motor is used as a load. In figure 15 is $PF=f(\alpha)$ by $f_{sw}=10$ kHz. In figures 11 and 12 the waveforms of the ac input voltage and current are shown. The figures 6, 7, 8, 9 and 10 show the spectrum of the input current for characteristic values of the angle ‘a’. In the case of ohmic load ($R=20\Omega$) the power factor gets its maximum value ($PF_{max}=0.6548$) by ‘a’=0°, which is relatively a low value because of the great current high harmonic content. If the load has ohmic-inductive character, the maximum PF value is obtained by a negative value of angle ‘a’. This happens because the control voltage $U_{c}$ mentioned above is leading by the angle ‘a’ upon the grid voltage $U_{g}$ in order to achieve that the basic current harmonic is in phase with the grid voltage. In this point it must be remarked that the sPWM procedure, controlled by the signal $U_{c}$, leads to the correction of the power factor through the moving of the current waveform to the left in the figure 12, what can be easy shown if the figures 11 and 12. So, the waveforms of $u_{in}(t)$ and $i_{in}(t)$ get more similar to the waveform of figures 13. But, by moving of the waveform $i_{in}(t)$ increase the high harmonic content, as it can be shown in the figures 6, 7, 8, 9 and 10, which are getting through FFT analysis of the input current waveform $i_{in}(t)$ using the Origin software. It is obviously that the high harmonic content of $i_{in}(t)$, for example, by ‘a’=0° is lower than that by ‘a’=-45° (fig.7 and 10). Beginning from ‘a’=0° and gradually going on to ‘a’=-45° the harmonics of the 5th, 7th, 9th and 11th order increase.
As mentioned above, the phase angle of the basic current harmonic $\phi_1$ can be defined through the angle ‘a’.

Using the values of the calculated power factor and of the spectrum analysis the value of $\phi_1$ can be calculated as follow:

As the power factor of the basic harmonic is

$$\cos \phi_1 = \frac{PF}{\sqrt{1 + \text{THD}}}$$

where $I_1 =$ rms value of the basic current harmonic and

$$\sqrt{\sum I_i^2} - I_1^2 + I_3^2 + \ldots + I_{100}^2$$

the rms value of the high harmonics, using the known values of PF, $I_1$ and $I_n$, the values of $\cos \phi_1$ and also $\phi_1$ can be calculated. The results of such a calculation are shown in table I.

For example, for ‘a’=18°, ohmic-inductive load (R=20Ω, L=30mH), $f_{sw}=5$ kHz, $U_g=220$ V, $f_g=50$ Hz and $P=1200$W, the following values have been obtain:

$I_1=3,56$ A, $I_3=0,8918$ A, $I_5=0,16$ A, …… $I_{100}=1,112$ A, $I_{200}=0,534$ A, $I_{300}=0,2$ A, $I_{500}=0,4$ A, $PF=78,27$ %,

$$\sqrt{\sum I_i^2} - I_1^2 + I_3^2 + \ldots + I_{100}^2 = 1,622531121 A,$$

$\text{THD}=0,455767168$, $\cos \phi_1 = 0,7827 \cdot \sqrt{1 + 0,455767168^2} = 0,8574$

<table>
<thead>
<tr>
<th>Angle ‘a’</th>
<th>PF</th>
<th>$\cos \phi_1$</th>
<th>$\phi_1$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18° (lag)</td>
<td>0,7827</td>
<td>0,8574</td>
<td>30,9</td>
</tr>
<tr>
<td>9° (lag)</td>
<td>0,7928</td>
<td>0,8792</td>
<td>28,45</td>
</tr>
<tr>
<td>0°</td>
<td>0,8069</td>
<td>0,8928</td>
<td>26,77</td>
</tr>
<tr>
<td>-9° (lead)</td>
<td>0,8069</td>
<td>0,8929</td>
<td>26,76</td>
</tr>
<tr>
<td>-18° (lag)</td>
<td>0,8108</td>
<td>0,8986</td>
<td>26,02</td>
</tr>
<tr>
<td>-36° (lead)</td>
<td>0,8128</td>
<td>0,9019</td>
<td>25,59</td>
</tr>
<tr>
<td>-45° (lead)</td>
<td>0,8113</td>
<td>0,9025</td>
<td>25,51</td>
</tr>
<tr>
<td>-54° (lead)</td>
<td>0,8085</td>
<td>0,9141</td>
<td>25,92</td>
</tr>
<tr>
<td>-63° (lead)</td>
<td>0,8042</td>
<td>0,8986</td>
<td>26,02</td>
</tr>
</tbody>
</table>

In the table I one can see that using the proposed operation mode of the sPWM method, an improvement of the power factor can be achieved. We remark that by ‘a’=0° is PF=0,8009, while by ‘a’=36° is PF=0,8128, it means that an improvement of 1,48% has been succeeded. Figure 15 shows the function $\text{PF}=f(\alpha)$ by switching frequency $f_{sw}=10$ kHz and $P_{1,2}=1000W, 1600W$. In the case of this switching frequency value the results are very similar to the case of $f_{sw}=5$ kHz.

If a passive filter with appropriate L-C values ($L=100mH, C=1\mu F$) at the converter input is used, the simulation results of the system are those which are depicted in the figures 16, 17, 18, 19, 20, 21 and 22. The PF values are increased in all cases, so that an improvement of about 10% is achieved (in comparison to $\text{PF}_{max}$ in the two cases: with and without filter). The spectrum analysis show that the high order harmonics ($f_k>800$ Hz) doesn’t appear (fig.18,19 and 20). The current waveforms are different compared to those in case that no filter is used, as the figures 21 and 22 show.

Table II is obtained in similar way as table I. One can remark that by leading angle ‘a’=-54° the current basic harmonic is in phase with the grid voltage. The maximum
value of PF is at \( \alpha' = -36^\circ \), by \( f_{sw} = 5 \text{ kHz} \) and \( P = 1200 \text{ W} \).
Comparing the PF values for \( \alpha' = 0^\circ \) and \( \alpha' = -36^\circ \) one can see that an improvement of 4.47% has been succeeded.

![Figure 15](image15)

**Figure 15.** Power Factor (PF) as a function of the angle \( \alpha' \) for switching frequency 10 kHz without input filter by the output power as a parameter (simulation results).

![Figure 16](image16)

**Figure 16.** Power factor (PF) as a function of the angle \( \alpha' \) by five values of ohmic-inductive load with input filter and switching frequency 5 kHz (simulation results).

![Figure 17](image17)

**Figure 17.** Power Factor (PF) as a function of the angle \( \alpha' = 0^\circ \) for switching frequency 10 kHz with input filter by output power as a parameter (simulation results).

![Figure 18](image18)

**Figure 18.** Grid current harmonic content for angle \( \alpha' = 0^\circ \) with input filter and ohmic-inductive load (\( R = 20 \Omega, L = 10 \text{ mH} \)) (simulation results).

![Figure 19](image19)

**Figure 19.** Grid current harmonic content for angle \( \alpha' = 27^\circ \) with input filter and ohmic-inductive load (\( R = 20 \Omega, L = 10 \text{ mH} \)) (simulation results).

![Figure 20](image20)

**Figure 20.** Grid current harmonic content for angle \( \alpha' = 40.5^\circ \) with input filter and ohmic-inductive load (\( R = 20 \Omega, L = 10 \text{ mH} \)) (simulation results).

![Figure 21](image21)

**Figure 21.** Grid voltage and current waveforms for \( \alpha' = 0^\circ \) and ohmic-inductive load (\( R = 20 \Omega, L = 30 \text{ mH} \)) with input filter (simulation results).

![Figure 22](image22)

**Figure 22.** Grid voltage and current waveforms for \( \alpha' = -36^\circ \) and ohmic-inductive load (\( R = 20 \Omega, L = 30 \text{ mH} \)) with input filter (simulation results).

**TABLE II.**

<table>
<thead>
<tr>
<th>Angle ( \alpha' )</th>
<th>PF</th>
<th>( \cos \phi_1 )</th>
<th>( \phi_1 ) [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.8986</td>
<td>0.9334</td>
<td>21</td>
</tr>
<tr>
<td>-27° (lead)</td>
<td>0.9344</td>
<td>0.9853</td>
<td>9.93</td>
</tr>
<tr>
<td>-31.5° (lead)</td>
<td>0.9381</td>
<td>0.9866</td>
<td>9.39</td>
</tr>
<tr>
<td>-36° (lead)</td>
<td>0.9388</td>
<td>0.9871</td>
<td>9.21</td>
</tr>
<tr>
<td>-45° (lead)</td>
<td>0.9349</td>
<td>0.9973</td>
<td>4.21</td>
</tr>
<tr>
<td>-54° (lead)</td>
<td>0.9179</td>
<td>0.100</td>
<td>0</td>
</tr>
</tbody>
</table>

### III. EXPERIMENTAL RESULTS

A MOSFET converter has been designed and constructed in the laboratory and its operation was
controlled by a microprocessor 80C196MC. This system including an input filter \((L=3\text{mH}, C=3\mu F)\) has been used for the experimental investigation. The experimental results are depicted in the figures 23, 24, 25, 26, 27, 28 and 29.

![Figure 23](image)

Figure 23. Power factor (PF) as a function of the angle ‘a’ for ohmic-inductive load \((R=180\Omega, L=30\text{mH})\) by switching frequency 5 kHz with input filter (experimental results).

![Figure 24](image)

Figure 24. Power factor (PF) as a function of the angle ‘a’ for ohmic-inductive load \((R=180\Omega, L=30\text{mH})\) and switching frequency 2.5 kHz with input filter (experimental results).

![Figure 25](image)

Figure 25. Power factor (PF) as a function of the angle ‘a’ for ohmic-inductive load \((R=180\Omega, L=100\text{mH})\) by switching frequency 5 kHz with input filter (experimental results).

![Figure 26](image)

Figure 26. Power factor (PF) as a function of the angle ‘a’ for ohmic-inductive load \((R=180\Omega, L=100\text{mH})\) by switching frequency 10 kHz with input filter (experimental results).

![Figure 27](image)

Figure 27. Power factor (PF) as a function of the angle ‘a’ for ohmic load \(R=30\Omega\) and by switching frequency 5 kHz with input filter (experimental results).

![Figure 28](image)

Figure 28. Grid voltage and current waveforms for ‘a’=0°, ohmic load \((R=180\Omega)\) and switching frequency 10 kHz (experimental results).

![Figure 29](image)

Figure 29. Grid current waveform for ‘a’=0°, ohmic-inductive load \((R=180\Omega, L=30\text{mH})\) and switching frequency 2.5 kHz (experimental results).

In general, the differences between simulation and experimental results are small. In all cases the power factor has high values (0.85…0.99) depended on the switching frequency, the load R-L values, the output power and the L-C values of the input filter.

IV. CONCLUSIONS

The simulation and experimental results show that there is a leading angle ‘a’ by which the power factor becomes maximum. The value of this angle depends on the nature of the load, the output power, the input filter and the switching frequency. A sinusoidal signal (voltage \(U_c\)) created by microprocessor and leading upon the sinusoidal grid voltage determines the SPWM converter operation and so the appropriate value ‘a’ can be achieved. The target is to shift the grid current waveform relatively to the
grid voltage in order to be the basic current harmonic in phase with the grid voltage.

REFERENCES


