Unified Power Quality Conditioner based on an Indirect Matrix Converter

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Abstract—Electrical Power Systems Quality parameters as the voltage Total Harmonic Distortion (THD), power factor (PF) and root mean square (RMS) value of the voltage at the Point of Common Coupling (PCC) are main topics to be considered in an electrical installation. To address Power Quality (PQ) issues there are several solutions and in this paper a Matrix Converter (MC) based solution is proposed. The UPQC here developed guarantees the mitigation of voltage harmonics, as well as the compensation of sags and swells when supplying a sensitive load. Also, it allows the mitigation of grid current harmonics in the Point of Common Coupling (PCC). The control of the converter is performed using the Sliding Mode Control Method, associated to state-space vectors representation, allowing fast response times to disturbances in the grid.

The whole system is tested in MATLAB Simulink software, and the results obtained show that it allows the improvement of the PQ.

Index Terms — Power Quality, Unified Power Quality Conditioner, Indirect Matrix Converter, Sliding Mode Control.

I. INTRODUCTION

Electrical power systems quality has become a relevant topic in last decades, and PQ parameters as the voltage RMS value and THD are defined in international standards as EN 50160. Mainly after the 1980’s PQ is being addressed in a more sophisticated way as engineers are trying to find better solutions to improve it. Nowadays electrical systems are more complex than they were a few decades ago, so every single error or failure will have wider effects.

In the past, the term power quality was often used to quantify interruptions and for how long they lasted. However, in recent decades, other PQ parameters as RMS and THD of voltage and also PF are taking more and more relevance when Power systems are sized. Alternating Current (AC) systems are designed to operate at a certain frequency and to have a sinusoidal voltage waveform with a well-defined RMS value, bounded by certain limits. Any deviation from these limits can be considered a PQ problem that affects the normal behavior of the electrical system.

Nonlinear loads connected to the grid are the main source of current harmonics. By closing their path through the impedances of the electrical grid they distort the grid voltage.

The UPQC here developed guarantees the mitigation of voltage harmonics, as well as the simultaneous compensation of sags and swells of the electrical grid in the PCC, where a sensitive load is connected.

Until the 1970’s the majority of the loads were linear ones, mainly for lightning and heating. However, in recent decades the amount of nonlinear loads has increased due to the electronic devices used by industries and domestic consumers [1].

Probably the major concern on PQ issues is their economic impact. Some PQ issues may be responsible for the destruction of some sensitive equipment or the interruption of some industrial processes, usually resulting in high monetary losses. Therefore the industries and domestic consumers are becoming more alert to these problems.

One of the ways to mitigate PQ problems is by using Power Converters and in this paper we will try to address PQ problems taking advantage of Matrix Converters’ characteristics. In particular, the Matrix Converter here chosen was the Indirect Matrix Converter (IMC).

II. PROPOSED SYSTEM

The proposed system, Fig.1, is an interconnected set of subsystems. The main objective is to keep the RMS value of the voltage in the PCC supplied to sensitive consumers within the limits defined in the EN 50160. The goal is to mitigate the harmonic content of the voltage and also to keep the power factor as near as possible to a unitary value.

In Fig.1 we present the more relevant components of the UPQC system: three-phase grid, series transformer, AC/AC Converter (IMC), filter connecting the IMC to the grid, output capacitor to regulate the output voltage and finally the sensitive load connected to the system.

A. Series transformer

The series transformer is used to connect the IMC to the electrical grid. From Fig.2 it is possible to obtain (1):

\[ v_{\text{transf,abc}} = v_{\text{grid,abc}} - v_{\text{load,abc}} \]  

(1)

From (1) we can conclude that when a sag occurs the transformer is subjected to an electric potential difference equal to the sag’s depth. We need to design the transformer bearing this in mind and also not forgetting the whole UPQC system is developed to mitigate at most a certain deviation from the nominal voltage.
In this paper the UPQC should be able to deal with deviations of 25% in the nominal value of the voltage (2). The transformer turns ratio is considered to be unitary.

\[ v_{\text{transf, abc}} = 0.25 \ v_{\text{grid, abc}} \quad (2) \]

The goal is to keep the voltage at the load \((V_{\text{load}})\) as close as possible to the nominal value. The maximum current demanded by the load \((I_{\text{max}})\) will occur when \(P_{\text{max}}\) is demanded (3). The apparent power of the transformer can be obtained from (4).

\[ P_{\text{max}} = 3 \ V_{\text{load}} \ I_{\text{max}} \cos \varphi_1 \quad (3) \]

\[ S_{\text{transf}} = 3 \ V_{\text{transf}} \ I_{\text{max}} \quad (4) \]

### B. Power Quality

Standard EN 50160 describes the characteristics of voltage, at the point of supply to the consumer in the Low Voltage (LV), Medium Voltage (MV) and High Voltage (HV) grid. [2]

The main focus of this paper is to address the following PQ parameters in the LV grid: the voltage RMS value \((V)\) and Total Harmonic Distortion \((THD_v)\), as well as the Power Factor \((PF)\). These parameters are given by (5), (6) and (7) respectively.

\[ V = \sqrt{\sum_{n=1}^{40} V_{n}^2} \quad (5) \]

\[ THD_v = \frac{\sqrt{\sum_{n=2}^{40} V_{n}^2}}{V_1} \times 100 \quad (6) \]

\[ PF \approx \frac{1}{\sqrt{1 + THD_v^2}} \cos \varphi_1 \quad (7) \]

From (7), as \(THD_1\) is much higher than \(THD_v\), the latter’s contribution to the \(PF\) can be neglected [3] [4].

The EN 50160 considers that the supply voltage should be within 10% of the nominal value. That means that swell start threshold is equal to 110% of the nominal voltage. In the same way the sag start threshold is equal to 90%, but above or equal to 5%, of the nominal voltage.

The other important PQ quality parameter to be evaluated in this paper is the \(THD_v\). According to the standard the THD of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8%.

### III. INDIRECT MATRIX CONVERTER

To develop the system, the main characteristics of an Indirect Matrix Converter, that is functionally similar to a Conventional Matrix Converter, are presented [5].

The IMC to be used in the UPQC is represented in Fig.3.

\[ \text{Fig. 1 - UPQC system diagram} \]

\[ \text{Fig. 2 – Grid connected single phase equivalent of the proposed UPQC.} \]

\[ \text{Fig. 3 - Topology of the IMC} \]
IV. CONTROLLERS DESIGN

In this chapter the project of the controllers used to control the output current, the input PF and also the voltage at the PCC is detailed.

A. Control of the series transformer current

The series transformer current is controlled by a nonlinear process to ensure that the current \( i_{a,\beta} \) follows the reference \( i_{a,\beta \text{ ref}} \). The control objective is to guarantee: \( i_{a,\beta} = i_{a,\beta \text{ ref}} \). The control is done by analyzing the sign of the error of the current, being the current error given by

\[
e_{a,\beta} = i_{a,\beta \text{ ref}} - i_{a,\beta}.
\]

Assuming that the error value should be bounded by \( \Delta \), the controller command actions are:

- If \( e_{a,\beta} > \Delta \Rightarrow i_{a,\beta \text{ ref}} > i_{a,\beta} \uparrow \) (must increase)
- If \( e_{a,\beta} < \Delta \Rightarrow i_{a,\beta \text{ ref}} < i_{a,\beta} \downarrow \) (must decrease)
- If \( e_{a,\beta} \approx 0 \Rightarrow i_{a,\beta \text{ ref}} \approx i_{a,\beta} \leftrightarrow \) (held constant)

Then the state space vectors are chosen and the switch gate signals generated to meet these requirements [7].

B. Control of the input Power Factor in the IMC

To control the IMC input PF we will use the same approach as we did to the output currents.

By applying the Park transformation we obtain: \( v_d = \sqrt{3}V \) and \( v_q = 0 \). Thus to have the currents and voltages in phase it is necessary to guarantee \( i_q = 0 \). Due to physical limitations it is impossible to guarantee it, so assuming \( \Delta \) as the error value, the controller command actions are:

- If \( e_q > \Delta \Rightarrow i_q \text{ ref} > i_q \Rightarrow i_q \uparrow \) (must increase)
- If \( e_q < \Delta \Rightarrow i_q \text{ ref} < i_q \Rightarrow i_q \downarrow \) (must decrease)

C. Voltage at the PCC

The main objective of the UPQC is to keep the RMS voltage value at the PCC and available to the customers as near as possible to the nominal value. To obtain the necessary parameters to control that voltage we need to define clearly the currents (Fig.4) and then use the Kirchhoff laws to obtain the needed relations. After that it is useful to have a simplified current diagram as is represented in Fig.5.

To determine the Proportional-Integral (PI) \( K_p \) and \( K_i \) (9) gains the denominator of (8) is compared with the third order ITAE polynomial.

\[
\frac{v_{c,d,q}(s)}{v_{c,d,q \text{ ref}}(s)} = \frac{1}{s^3 + \frac{1}{T_d} s^2 + \frac{K_p \alpha_v}{T_d C_{\text{out}}} s + \frac{K_i \alpha_v}{T_d C_{\text{out}}}}
\]

Taking into account that the value of \( T_d \) has to be estimated because a nonlinear control method with variable switching frequency is being used, the values obtained for the controller are presented in table I. The values of capacitors \( C_{\text{out}} \) were chosen to be 0.1 mF.

<table>
<thead>
<tr>
<th>Voltage controller parameters</th>
<th>( T_d ) [s]</th>
<th>( K_i )</th>
<th>( K_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00025</td>
<td>2980</td>
<td>2.81</td>
<td></td>
</tr>
</tbody>
</table>
D. IMC input filter

The IMC is connected to the electric grid through a second order LC filter with a damping resistor (Fig. 7). This filter is used to suppress the high frequency harmonics originated by the switching process of the IMC’s semiconductors. [8]

The three phase filter is represented in Fig. 7. However, to size the filter parameters a single-phase equivalent (Fig.8) is used.

![Fig. 7 - Three-phase IMC input filter](image)

Fig. 7 - Three-phase IMC input filter

![Fig. 8 - Single-phase equivalent of the IMC input filter](image)

Fig. 8 - Single-phase equivalent of the IMC input filter

By using the equations presented in [9] we obtain the values of the filter parameters \(L_1, r_p\) and \(C_f\) whose values are presented in table II.

Table II – IMC’s input filter parameters

<table>
<thead>
<tr>
<th>Filter parameters</th>
<th>(L_1) (mH)</th>
<th>(r_p) (Ω)</th>
<th>(C_f) (μF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_1)</td>
<td>3.33</td>
<td>0.26</td>
<td>8.48</td>
</tr>
</tbody>
</table>

V. SIMULATIONS OF THE UPQC SYSTEM

The developed system is tested in MATLAB Simulink software, for different operation scenarios.

A. Load scenario and grid conditions

As it was mentioned previously nonlinear loads are increasing its presence in today’s world. In this paper we decided to consider two different situations concerning the presence of nonlinear loads. In scenario 1 we consider that 20% of the loads are nonlinear and in scenario 2 we increase that percentage to 40%.

To have a more realistic situation, we assumed that in the connection to the LV grid, the short-circuit power is \(S_{cc} = 75\) MVA and \(X/R = 0.5\). Also we consider that the grid is not supplying a perfectly sinusoidal waveform as it has 5th harmonic contribution. It is weighted 3.0% of the fundamental harmonic. So by using (6) the THD of the grid voltage at no-load is \(THD_v = 3.0\%\).

The main goal of the UPQC is to keep the voltage available at the PCC within the limits defined by EN 50160 and also with a harmonic content as low as possible. This leads us to the other simulation condition: the characteristics of the supply voltage. Here we will not consider the entire range of a sag or a swell because of physical limitations of the proposed system. Still, we will have three possible scenarios to assess the capabilities of the UPQC in restoring the voltage to normative values. These conditions are presented in table III.

Table III - Supply voltage simulation condition

<table>
<thead>
<tr>
<th>Supply voltage</th>
<th>(v_{grid})</th>
<th>(v_{nominal})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sag</td>
<td>0.75</td>
<td>1</td>
</tr>
</tbody>
</table>

In the simulations we will present always two results: with and without the UPQC. Our aim is to show how the UPQC system developed in this paper is able to improve PQ. The main results are presented in tables IV, V and VI.

With these results it is possible to see that the UPQC represents a valuable contribution to improve the PQ.

According to standard EN 50160, the rated value of the LV grid AC phase to neutral voltage is 230V. This voltage is bounded by a upper limit of +10% of this value (253 V) and a lower limit of -10% of this value (207 V). Bearing this in mind, by looking at tables IV, V and VI, it is possible to see that in the two scenarios, the UPQC is capable of restoring the voltage within those limits.
Without the UPQC the voltage applied to the load will be very similar to the supply voltage. So in case of a sag or swell it will propagate through the grid and will affect the sensitive load.

Although in nominal conditions we already have a voltage with the adequate value, even in this case the UPQC represents an advantage because as table IV shows it can provide a decrease in the \( THD_v \). These improvements made by the UPQC in harmonic distortion are also present in sag and swell conditions.

About the \( PF \) it is visible that the UPQC represents an improvement in this PQ parameter. In all the operating scenarios evaluated in this paper it was possible to guarantee a near unitary \( PF \) as its value is 0.99.

### B. Waveforms obtained for sag operating conditions

In the next figures we present some of the obtained results for a sag of 25\% depth.

Only the phase “a” of the voltage and current are shown because the supply voltages and three phase load are balanced. The waveforms were obtained for scenario 2 which is the most critical, with a higher percentage of nonlinear loads connected to the PCC.

### Table IV - Simulation results with and without UPQC in nominal conditions

<table>
<thead>
<tr>
<th>Test Scenario</th>
<th>( THD_v ) [%]</th>
<th>( THD_i ) [%]</th>
<th>RMS voltage [V]</th>
<th>RMS current [A]</th>
<th>( PF )</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPQC scenario 1</td>
<td>2.17</td>
<td>2.30</td>
<td>228.78</td>
<td>79.61</td>
<td>0.99</td>
</tr>
<tr>
<td>Without UPQC scenario 1</td>
<td>3.00</td>
<td>7.08</td>
<td>230.00</td>
<td>79.01</td>
<td>0.98</td>
</tr>
<tr>
<td>UPQC scenario 2</td>
<td>2.34</td>
<td>2.35</td>
<td>224.69</td>
<td>79.54</td>
<td>0.99</td>
</tr>
<tr>
<td>Without UPQC scenario 2</td>
<td>3.00</td>
<td>10.6</td>
<td>230.00</td>
<td>86.87</td>
<td>0.96</td>
</tr>
</tbody>
</table>

### Table V - Simulation results with and without UPQC in sag conditions

<table>
<thead>
<tr>
<th>Test Scenario</th>
<th>( THD_v ) [%]</th>
<th>( THD_i ) [%]</th>
<th>RMS voltage [V]</th>
<th>RMS current [A]</th>
<th>( PF )</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPQC scenario 1</td>
<td>2.15</td>
<td>2.25</td>
<td>219.58</td>
<td>100.11</td>
<td>0.99</td>
</tr>
<tr>
<td>Without UPQC scenario 1</td>
<td>3.00</td>
<td>7.08</td>
<td>172.50</td>
<td>59.33</td>
<td>0.98</td>
</tr>
<tr>
<td>UPQC scenario 2</td>
<td>2.21</td>
<td>2.29</td>
<td>210.89</td>
<td>100.12</td>
<td>0.99</td>
</tr>
<tr>
<td>Without UPQC scenario 2</td>
<td>3.00</td>
<td>10.59</td>
<td>172.50</td>
<td>65.19</td>
<td>0.96</td>
</tr>
</tbody>
</table>

### Table VI - Simulation results with and without UPQC in swell conditions

<table>
<thead>
<tr>
<th>Test Scenario</th>
<th>( THD_v ) [%]</th>
<th>( THD_i ) [%]</th>
<th>RMS voltage [V]</th>
<th>RMS current [A]</th>
<th>( PF )</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPQC scenario 1</td>
<td>2.21</td>
<td>2.10</td>
<td>233.71</td>
<td>65.25</td>
<td>0.99</td>
</tr>
<tr>
<td>Without UPQC scenario 1</td>
<td>3.00</td>
<td>7.07</td>
<td>287.50</td>
<td>98.74</td>
<td>0.98</td>
</tr>
<tr>
<td>UPQC scenario 2</td>
<td>2.48</td>
<td>2.19</td>
<td>230.19</td>
<td>65.24</td>
<td>0.99</td>
</tr>
<tr>
<td>Without UPQC scenario 2</td>
<td>3.00</td>
<td>10.59</td>
<td>287.50</td>
<td>108.61</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Fig. 9 - Voltage and Current Waveforms with UPQC in sag conditions with 40% of nonlinear loads

Fig. 10 - Voltage and Current Waveforms without UPQC in sag conditions with 40% of nonlinear loads

With the obtained waveforms we can see clearly what table V already expressed: without the UPQC the voltage is not within the limits defined by standard EN 50160.

Also we can see here that the \( THD_V \) is also much higher without the UPQC.

C. Waveforms obtained for swell operating conditions

In the next figures we present some of the obtained results for a swell of 25%.

Only the phase “a” of the voltage and current are shown because the supply voltages and three phase load are balanced. The waveforms were obtained for scenario 2 which is the most critical, with a higher percentage of nonlinear loads connected to the PCC.

Fig. 11 - Voltage and Current Waveforms with UPQC in swell conditions with 40% of nonlinear loads

Fig. 12 - Voltage and Current Waveforms without UPQC in swell conditions with 40% of nonlinear loads

With the obtained waveforms we can see clearly that without the UPQC the voltage is not within the limits defined by standard EN 50160 (see table VI).

Also we can see here that the \( THD_V \) is also much higher without the UPQC.

VI. CONCLUSIONS

The main aim of this work was to propose a UPQC based on an IMC.

The obtained results show that AC/AC converter based solutions can be used to improve PQ. With the proposed topology it was possible to restore the voltage applied to the sensitive load to the values bounded by standard EN 50160 while keeping lower harmonic contents.

In all the test scenarios it was possible to guarantee a nearly unitary PF in the connection to the grid.

With the results obtained we can conclude that the UPQC is a meaningful device to be implemented in an industry as it can represent a real contribution to improve PQ. Moreover it can also be a reasonable solution to domestic installations, but the costs related to its implementation could still be a substantial handicap to small consumers.

REFERENCES