Grid Connected Power Converters and their Impact on Power Quality

Fábio Miguel Rodrigues de Matos Ambrósio

Abstract— Technological progress has contributed to the significant increase of electrical and electronic equipment connected to the low voltage electrical network. These devices have become increasingly sensitive and more demanding in terms of power quality, but at the same time they have contributed to a decline of power quality by the introduction of disturbances in the low voltage network. These disturbances manifest not only by the increase of the harmonic distortion of voltage and current, but also by the increase of the current that runs through the neutral conductors of the low voltage network, which could reduce the safety of the electrical installations.

The main goal of this work is to study the disturbances introduced by non-linear loads in a low voltage electrical network, as well as the improvements introduced by derating cables due to the harmonic content.

To achieve this goal, two grids representing urban and rural networks are created and some simulations are made using the software MATLAB/Simulink, in order to evaluate some indicators of power quality, including Total Harmonic Distortion of voltage and current, variations of voltage RMS values in each line, voltage unbalance and the neutral currents and voltages.

Key words: Low Voltage Electrical Network, Power Quality, Neutral Currents, Total Harmonic Distortion, Voltage Unbalance

1. INTRODUCTION

In the last decades, due to technological progress, the amount of electrical and electronic equipment connected to the low voltage electrical network, with applications to industrial and domestic level has increased considerably.

However, these devices are very sensitive and more demanding in terms of power quality (PQ), they introduce disturbances in the electrical network, not only in the power quality by increasing the total harmonic distortion of voltage and current, but also because they contribute to the increase of the neutral currents in low voltage distribution lines, which could reduce the safety of electrical installations.

Currently, the amount of non-linear loads present in electrical installations is very high. It is estimated that in many industries, as well as in some homes, the amount of nonlinear loads type exceeds 50%. In office buildings or business, may exceed 60%.

One of the factors which increase the current that runs through the neutral conductor is the generation of current harmonics by the nonlinear loads. This causes the voltage harmonic distortion (THD), which rises at a rate of 1% in every ten years, and the harmonic current that has a higher weight comparing with the remaining harmonics is the harmonic of order 5, in general low voltage electrical networks of urban areas [1].

The presence of harmonics of order multiple of three, leads to values of neutral current much higher than expected and, in many cases, higher than current phases. Normally, when the rate of harmonic distortion of current is greater than 38%, the neutral current is higher than current phases [1].

The inadequate distribution of loads by the three phases of an electrical installation may also occur, creating voltage unbalances between the phases of a line, resulting in different values of voltages and currents in each phase, which contribute to the deterioration of some equipments connected to the electrical network. So it is particularly relevant to study the unbalance between the voltages of the phases of distribution lines of a grid.

For this reason it is important to study the impact that the generation and presence of current harmonics, associated with non-linear loads have on a low-voltage electrical network, particularly in the current that goes through the phases and the neutral conductor of the lines that feeds consumers and hence the voltages of each consumer in the various connection points of a low voltage electrical network.

On the other hand it is also important to study the improvements that cable derating due to harmonic content introduces in a network with a high percentage of non-linear loads, such as the network of an urban area.

For this purpose, two low voltage electrical networks were created: one with 16 buses, to simulate the behavior of an urban network and another with 10 buses to simulate the behavior of a typical network of a rural environment. From these two networks were set up scenarios with different amounts of linear and nonlinear loads, in order to draw up conclusions on the impact they have on the lines of the network or on the power quality delivered to consumers. In the idealized scenarios, some simulations are analyzed and compared, focusing primarily on the following aspects:

- RMS values on each load;
- Current carried over the lines;
- Voltage total harmonic distortion;
- Current total harmonic distortion;
- Neutral voltage;
- Neutral current;
- Voltage unbalances.
2. POWER QUALITY

The power quality was designed to ensure that there is no degradation of the proper functioning of a device dependent on electrical power and is mainly associated to the quality and continuity of the voltage wave [2].

Among the many problems that PQ presents, the more severe is the interruption of the electricity supply, since it affects all devices connected to the distribution network. Other problems that can contribute to the damage and malfunction of the devices connected to the distribution network are [2]:

- Voltage dips;
- Transitory overloads;
- Harmonic distortion;
- Flicker;
- Voltage unbalances;
- Frequency variation;
- Supply voltage variation.

To ensure the PQ of the voltage supply of the low voltage distribution network it was created the standard EN 50160 [3], that defines and establishes a certain number of parameters that characterize the voltage available to the consumer, by a distributor of LV or MV.

2.1. Harmonic distortion

The connection of nonlinear loads to the electrical network originates currents with high harmonic content that causes distortion of the supply voltages of the network.

The Total Harmonic Distortion (THD) is used to quantify the harmonic distortion present in a network. The THD of the voltage is given by (1) [3].

\[
THD_{v} = \frac{\sqrt{\sum_{h=2}^{n} U_{h}^{2}}}{U_{1}} \cdot 100
\]

The voltage amplitude of harmonics can be evaluated by the relative amplitude of the voltage harmonics in relation to the fundamental harmonic voltage. For normal operation, 95% of the average effective values of each harmonic voltage for each period of a week, measured at intervals of 10 minutes, must not exceed the values in table 1.

<table>
<thead>
<tr>
<th>Percentage of nonlinear loads</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDF</td>
<td>1</td>
<td>0.98</td>
<td>0.97</td>
<td>0.96</td>
<td>0.95</td>
<td>0.92</td>
<td>0.91</td>
<td>0.89</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Table 2 – Typical values for cable derating

For the neutral conductor, the derating factor used is not the same as for the phases, since the neutral current is the sum of the vector current in three phases. Consequently, the harmonic derating factor for the neutral conductor is given by (3), where \( a_h \) is the content per unit of the 3\textsuperscript{rd} harmonic of neutral current [5].

\[
HDF_{N} = \frac{1}{\sqrt{1 + a_{h}^{2}}}
\]

Therefore, the maximum current that can circulate in the phases of a cable is given by (4), where \( I_N \) is the cataloged maximum current of the cable, and the maximum current that can flow in the neutral conductor of a cable is given by (5).

\[
I_{\text{max}} = K_T \times HDF \times I_N
\]

\[
I_{N_{\text{max}}} = K_T \times HDF_{N} \times I_N
\]

2.2. Voltage unbalances

When a problem occurs in one phase of a network supplied by a three-phase voltage system or there is a poor distribution of the loads in the electrical installations, a voltage unbalance is originated, which can contribute to the malfunction of some equipment connected to this network.

The Standard EN 50160 [3] defines that 95% of the average effective values of each component of reverse voltages,
measured at intervals of 10 minutes for each period of a week, should not exceed 2% of the corresponding direct component.

The expression (6) allows to calculate the voltage unbalance [6].

\[
K_u \% = \frac{1 - \sqrt{3 - 6\beta}}{1 + \sqrt{3 + 6\beta}} \times 100 \tag{6}
\]

Where,

\[
\beta = \frac{U_{AB}^2 + U_{BC}^2 + U_{CA}^2}{U_{AB}^2 + U_{AC}^2 + U_{CA}^2} \tag{7}
\]

2.3. Voltage dips

The fact that power lines have impedance originates voltage dips and thus the voltage in each point of the distribution line is not the same.

According to standard EN 50160 [3], the nominal normalized voltage is 230 V between phase and neutral conductor for tree-phase systems with 4 conductors, and 400 for three-phase systems with only 3 conductors. For normal operation of the network, 95% of the effective value, measured at intervals of 10 minutes for each period of one week, not considering the voltage interruptions should be between more or less 10% of the nominal standard.

3. LOW VOLTAGE ELECTRICAL NETWORK MODEL

This chapter describes the various components used in the development of the electrical distribution network model, simulated in this work. Special interest is given to calculate the impedance of the lines.

3.1. Transformer

The transformer plays a key role in electrical networks, since it allows changing the voltage value of a network. Thus, the link between the medium voltage and low voltage in a network is accomplished using a transformer that is connected in triangle on the side of the Medium Voltage (MV), and is connected in star with neutral solidly grounded on the side of the Low Voltage (LV). By the fact the transformer is connected in triangle on the side of the MV, there is no passage of the 3rd harmonic of this into the LV.

In this work were used two transformers: a 630 kVA of power for the urban network and a 250 kVA power to the rural network. Both transformers have a line voltage of 30 kV in the primary and 400 V in the secondary. In LV the phase voltage is 230 V. The transformer model used in this work is the T model.

In order to size the transformer is necessary to calculate the resistance and reactance of the primary, secondary and magnetizing windings of the transformer. Table 3 summarizes the parameters obtained in transformer sizing of the urban network and table 4 summarizes the parameters obtained in transformer sizing rural network.

<table>
<thead>
<tr>
<th>Transformer parameters</th>
<th>Primary</th>
<th>Magnetization</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 ) (p.u.)</td>
<td>( X_1 ) (p.u.)</td>
<td>( G_m ) (p.u.)</td>
<td>( B_s ) (p.u.)</td>
</tr>
<tr>
<td>0.007</td>
<td>0.021</td>
<td>434.78</td>
<td>34.59</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aerial lines</th>
<th>LXS 4 x 25</th>
<th>LXS 4 x 50</th>
<th>LXS 4 x 70</th>
<th>LXS 4 x 95</th>
</tr>
</thead>
<tbody>
<tr>
<td>underground lines</td>
<td>LSVAV 4 x 25</td>
<td>LSVAV 4 x 95</td>
<td>LVAV 3 x 185 x 95</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 - Characteristic parameters of the transformer of the rural network

3.2. Electrical distribution lines

The electrical distribution lines are designed to ensure the distribution of electrical power from the transformer, which performs the conversion of the voltage of the transmission network (MV) to the distribution network (LV).

The lines used in this work, presented in table 5, are made of aluminum being buried in the ground in urban areas and being aerial in rural areas.

<table>
<thead>
<tr>
<th>Cables</th>
<th>Aerial lines</th>
<th>LXS 4 x 25</th>
<th>LXS 4 x 50</th>
<th>LXS 4 x 70</th>
<th>LXS 4 x 95</th>
</tr>
</thead>
</table>

Table 5 – Cables used in the simulations

The equivalent \( \pi \) scheme is the line diagram used to represent the electrical lines. This scheme, presented in figure 1, is consisted by the series impedance and the shunt admittance.

The series impedance, present in all power lines, consists of the resistance and reactance; the shunt admittance, which is generally ignored in the calculation of the parameters of the lines, with the exception of underground lines, is formed by the capacitors [7].

![Figure 1 – Equivalent \( \pi \) scheme of the electrical lines](image)

a) Underground lines

The self inductance of a conductor of an underground cable can be calculated from the expression (8), where \( L_0 \) is the inductance due to internal flux through the conductor, \( L_1 \) is the inductance of the connection to the ground and \( L_{mutua} \) represents the mutual inductance between the conductors [8].

\[
L_s = L_1 + L_0 - L_{mutua} \ [H/km] \tag{8}
\]

The inductance due to the internal flux through the conductor, neglecting skin effect is given by (9) [8].

\[
L_1 = \frac{\mu}{2\pi} = 0.05 \text{ mH/km} \tag{9}
\]

Due to the fact that the connection to the ground is not ideal, is necessary to take into account, in the calculation of the self inductance of the conductor, the value of inductance of the connection to the ground. This corresponds to the imaginary part of expression (10), where \( R_g \) represents the ground resistance, \( \omega \) represents frequency in rad/s, corresponds to soil permeability, \( h \) is the outer radius of the
cable and r represents the radius of the equivalent circular conductor \[8\].

\[
Z_g = \frac{R_g}{d_x} + j \omega T_g = \frac{j \omega T_g}{2 \pi \log\left(\frac{2h + 2d_e}{r}\right)} \quad [\Omega/km] \quad (10)
\]

Where:

\[
d_x = \frac{\rho}{\sqrt{j \omega \mu}} \quad (11)
\]

\(\rho\): resistivity of the soil

\(\mu\): magnetic permeability of the soil

The resistivity of the soil depends mainly on the composition of the terrain. In this work it was considered that the nature of the soil is limestone, which has a resistivity of 100 \(\Omega\cdot\text{m}\) \[9\].

The value of mutual inductance between the conductors is equal to the imaginary part of expression (12), where \(a_m\) is the geometric average of the distances between conductor axes \[8\].

\[
L_{\text{mutua}} = \frac{j \mu}{2 \pi} \log\left(\frac{2h + 2d_e}{a_m}\right) \quad [H/km] \quad (12)
\]

\[
a_m = \frac{1}{2} \sqrt{\frac{r^2}{d^2}} \quad (13)
\]

\(d\): diameter of the circular equivalent conductor

\(i\): nominal thickness isolation of the conductor

Although, the conductors have a sector shaped section for the calculation of its parameters is considered an equivalent section of circular shape.

Table 6 contains the values of inductance provided by the manufacturers of underground cables used in this work, as well as the values obtained for the resistance of the conductors by the method of calculation described above.

<table>
<thead>
<tr>
<th>Cables</th>
<th>Manufacturers values [mH/km]</th>
<th>Theoretical values [mH/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSVAV 4 x 35 mm²</td>
<td>0.24</td>
<td>0.277</td>
</tr>
<tr>
<td>LSVAV 4 x 95 mm²</td>
<td>0.23</td>
<td>0.266</td>
</tr>
<tr>
<td>LVAV 3 x 185 + 95 mm²</td>
<td>0.22</td>
<td>0.259</td>
</tr>
</tbody>
</table>

Table 6 – Values of inductance

The inductance of LV conductors can be calculated by (14), where \(l_{\text{linha}}\) is the total length of the line.

\[
L_{\text{conductor}} = L_x \times l_{\text{linha}} \quad [H] \quad (14)
\]

The resistance of an electrical line represents the losses of the conductors, by Joule effect. The self resistance of a conductor of an underground cable can be calculated from the expression (15), where \(R_i\) represents the internal resistance of the conductor, \(R_g\) represents the resistance of the ground, \(R_p\) represents the resistance caused by the proximity effect and \(R_{\text{mutua}}\) represents the mutual resistance between the conductors \[8\].

\[
R_i = R_i + R_g + R_p - R_{\text{mutua}} \quad [\Omega/km] \quad (15)
\]

The internal resistance is found from the formula (16), where \(\rho\) represents the resistivity of the conductor, \(A\) represents the actual conductor area and \(a\) represents the “non-conducting area” of the conductor due to skin effect.

\[
R_i = \frac{\rho}{A - a} \quad [\Omega/km] \quad (16)
\]

Where:

\[
A = 0.884a_n \quad [\text{mm}^2] \quad (17)
\]

\(A_n\): section of the conductor

The resistance of the ground, \(R_g\), corresponds to the part of expression (10).

The skin effect and the proximity effect increase the resistance of the conductors, however we consider that this increase is negligible for conductors with a section up to 500 \(\text{mm}^2\) \[4\], that is the case of this work in which the widest section has 185 \(\text{mm}^2\). As such, the calculation of the self resistance of a conductor disregards the value of the resistance caused by the proximity effect \(R_p\), as well as the value of the “non-conducting area”, \(a\).

The value of mutual resistance between the conductors is equal to the real part of expression (18), where \(a_m\) is the geometric average of the distances between conductor axes \[8\].

\[
R_{\text{mutua}} = \frac{j \omega T_g}{2 \pi} \log\left(\frac{2h + 2d_e}{a_m}\right) \quad [H/km] \quad (18)
\]

Table 7 contains the values of resistance provided by the manufacturers of underground cables used in this work, as well as the values obtained for the resistance of the conductors by the method of calculation described above.

<table>
<thead>
<tr>
<th>Cables</th>
<th>Manufacturers values [mH/km]</th>
<th>Theoretical values [mH/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSVAV 4 x 35 mm²</td>
<td>0.868</td>
<td>0.916</td>
</tr>
<tr>
<td>LSVAV 4 x 95 mm²</td>
<td>0.32</td>
<td>0.34</td>
</tr>
<tr>
<td>LVAV 3 x 185 + 95 mm²</td>
<td>0.164</td>
<td>0.173</td>
</tr>
</tbody>
</table>

Table 7 – Values of resistance

The resistance of LV conductors can be calculated by (19), where \(l_{\text{linha}}\) is the total length of the line.

\[
R_{\text{conductor}} = R_i \times l_{\text{linha}} \quad [\Omega] \quad (19)
\]

The self capacitance of a conductor of an underground cable can be calculated from the expression (20), where \(C_g\) represents the cable capacity relatively to ground, \(C_{ch}\) represents the capacitance between adjacent conductors of the cable and \(C_d\) represents the capacitance between the conductors in the diagonal of the cable \[10\].

\[
C_s = C_g + 2C_{ch} + C_d \quad [\text{F/km}] \quad (20)
\]

The capacity of the cable relatively to the ground can be calculated by (21), where \(\varepsilon_\infty\) represents the permittivity of the vacuum, \(\varepsilon_r\) corresponds to the relative permittivity of the isolation and \(i\) represents the nominal thickness isolation of the conductor \[10\].

\[
C_g = \varepsilon_\infty \frac{b}{\varepsilon_i^2} \quad [\text{F/km}] \quad (21)
\]

In this work it was considered that the relative permittivity has a value of seven.
The capacitance between the adjacent conductors of the cable can be calculated by (22) [10].

\[ C_{zh} = \varepsilon_0 \varepsilon_r \frac{a}{2l} \text{ [F/km]} \] (22)

The capacitance between the conductors in the diagonal of the cable is calculated from (23), where \( A_g \) is the width of the air gap between the conductors and can be calculated by (24) [10].

\[ C_d = \frac{A_g}{2l} \frac{A_g}{\varepsilon_r \varepsilon_0} \text{ [F/km]} \] (23)

\[ A_g = 0.3(0.87r + 2l) \text{ [m]} \] (24)

Table 8 contains the values of capacitance provided by the manufacturers of underground cables used in this work, as well as the values obtained for the resistance of the conductors by the method of calculation described above.

<table>
<thead>
<tr>
<th>Cables</th>
<th>Manufacturers values [µF/km]</th>
<th>Theoretical values [µF/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSVAV 4 x 35 mm²</td>
<td>0.45</td>
<td>0.48</td>
</tr>
<tr>
<td>LSVAV 4 x 95 mm²</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>LSVAV 3 x 185 + 95 mm²</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 8 – Values of capacitance

The capacitance of LV conductors can be calculated by (25), where \( l_{inabh} \) is the total length of the line.

\[ C_{conductor} = \frac{C_r l_{inabh}}{2} \text{ [F]} \] (25)

b) Aerial lines

In this case we only consider series impedance, which means that we can neglect the shunt admittance to calculate the parameters of the lines. In this case, to characterize the line is only necessary to calculate the resistance and inductance of the line. Thus, the value of the self resistance of the cable can be taken of [4] and the value of the self inductance is calculated using the expression (26) [4].

\[ L_s = 0.05 + 0.2 \log \left( \frac{24a}{d} \right) \text{ [mH/km]} \] (26)

Table 9 contains the values of resistance provided by the manufacturers of aerial cables used in this work, as well as the values of inductance calculated by the expression (26).

<table>
<thead>
<tr>
<th>Cables</th>
<th>Resistance [Ω/km]</th>
<th>Inductance [mH/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LXS 4 x 25 mm²</td>
<td>1.2</td>
<td>0.246</td>
</tr>
<tr>
<td>LXS 4 x 50 mm²</td>
<td>0.641</td>
<td>0.276</td>
</tr>
<tr>
<td>LXS 4 x 70 mm²</td>
<td>0.443</td>
<td>0.273</td>
</tr>
<tr>
<td>LXS 4 x 95 mm²</td>
<td>0.32</td>
<td>0.265</td>
</tr>
</tbody>
</table>

Table 9 – Values of series impedance

3.3. Electrical loads

Low voltage networks have two types of electrical loads: linear and nonlinear. In linear loads the output current has a waveform similar to the voltage supplies them. In the other way, in nonlinear loads the output current has a different waveform of the voltage in the input of them. Some types of these loads, used in this work, will be presented below.

a) Linear loads

The linear loads are: the resistive load and the inductive load.

The resistive loads, which include incandescent lamps or heaters, have a typical power value of 1000 W. The total active power consumed by a group of this loads can be calculated by (27), where \( n_R \) is the number of resistive loads in this group.

\[ P_{RT} = n_R P_R \] (27)

The inductive loads, which include refrigerators or fluorescent lamps, have a typical power of 150 VA and a power factor of 0.57. From these values it is possible to calculate the total apparent power consumed by a group of this loads (28), where \( n_{RL} \) is the number of inductive loads in this group.

\[ S_{RT} = n_{RL} S_{RL} \] (28)

b) Nonlinear loads

The nonlinear loads are constituted by the charges that have rectifiers, such as, televisions or washing machines.

The single-phase rectifier of type I that we can found in televisions or similar equipment, have a typical active power of 200 W. The total active power consumed by a group of this loads can be calculated by (29), where \( n_{TV} \) is the number of televisions in this group.

\[ P_{RTT} = n_{TV} P_{RTT} \] (29)

In order to analyze the waveform of current drawn by this load or its supply voltage, it is necessary to scale the input filters and the output load according with the power. This scaling is done using the formulas found in [11].

In figure 2, we can see the harmonic spectrum of the current drawn by this load.

![Figure 2 – Harmonic spectrum of the current drawn single-phase rectifier type I](image)

The washing machines or similar equipment, correspond to the single-phase rectifier of type II, which have a typical active power of 2000 W, and his input filters and the output load can be found in the same way as in the single-phase rectifier of type I.

The total active power consumed by a group of this loads can be calculated by (30), where \( n_{ML} \) is the number of machines in this group.
\[ P_{ML} = n_{ML} - P_{ML} \]  

(30)

In figure 3, we can see the harmonic spectrum of the current drawn by this load.

![Figure 3 – Harmonic spectrum of the current drawn single-phase rectifier type II](image)

4. Simulations Results

This chapter presents the results of simulations, made with the software MATLAB/Simulink, for the rural and urban networks. These simulations aim to evaluate the impact that non-linear loads have on the electrical network, analyze the disturbances that contribute to the decrease of power quality delivered to consumers and to study the advantages that the cables derating introduce in power quality of an urban network, due to the large percentage of non-linear loads that constitute it.

4.1. Topology of the urban network

The urban network developed in this work is presented in figure 4.

![Figure 4 – Low voltage urban network](image)

The power consumed by each group of loads is calculated from the contracted power for each customer network. Due to the fact that each client doesn’t consume all the power contracted, is necessary to introduce a correction factor, the simultaneity factor (31), where \( n \) represents the number of clients connected to any point of the network. The power consumed by each group of loads, is given by (32), where \( \text{cor} \) corresponds to the power contracted and represents the number of customers in each group of loads.

\[ FS = 0.2 + \frac{0.8}{\sqrt{n}} \]  

(31)

\[ S_c = S_{\text{contratada}} \times FS \times N_c \]  

(32)

To study the PQ of this network and the effect that the presence of nonlinear loads has on the neutral conductor of the electrical cables, two situations were created. In scenario 1, the percentage of nonlinear loads in the network varies between 77 and 90%. In scenario 2, the percentage of nonlinear loads varies between half of these values.

In order to make the simulations more realistic, it has been introduced voltage harmonics in MV, namely, the 5th and 7th harmonic, with a total value of THD around 2%. Voltage unbalances have also been introduced, once that in a LV distribution network the distribution of loads is not equal by the three phases, what originates unbalances.

a) Scenario 1

In this scenario three simulations were made. In one of the simulations, the neutral conductor of the LVAV 3x185+95 has his normal section; in other simulation has a section with twice his size; and in the other simulation the neutral has his normal size and cable derating is not considered. The more interesting results obtained in this scenario will be presented next.

![Figure 5 – Lines currents for the scenario 1 of urban network](image)
By the analysis of figures 6 and 7, we can see that the currents increase in the phases and neutral conductors, when the section of the neutral becomes larger. We can also see that the current in the neutral conductors passes in some cases the limit value of current passing through the neutral conductor.

The neutral current in line 16 is bigger than the current in the phases.

In figure 7, we can see that the voltage THD in this scenario is very nearly of limit for the lines more far from the transformer.

b) Scenario 2

In this scenario two simulations were made varying, like in the previous scenario, the section of the neutral conductor of the LVAV 3x185+95 cable. The more interesting results obtained in this scenario will be presented next.

Analyzing figure 8, we can see that the currents in this scenario have lower values comparing with the currents of the scenario 1. Such is given to the reduction of amount of nonlinear loads.

By figure 9, we can see that the current in the neutral increases when the section of the neutral in some cables becomes bigger, having now values that are inside the limits of the maximum current that can runs through the neutral conductor. From figure 10, we can see that the THD is lower than the one of the 1st scenario.
4.2. Topology of the rural area

The rural network developed in this work is presented in figure 11.

![Figure 11 – Low voltage urban network](image)

The power consumed by each group of loads, in this network, was sized just like for the urban network. Two scenarios were also created like in the urban network. In scenario 1, the percentage of nonlinear loads in the network varies between 38 and 60%. In scenario 2, the percentage of nonlinear loads varies between half of these values.

Just like in urban area, to make simulations more close to reality, it has been introduced voltage harmonics in MV, namely, the 5th and 7th harmonic, with a total value of THD around 2%. Voltage unbalances have also been introduced, once that in a LV distribution network the distribution of loads is not equal by the three phases, what originates unbalances.

a) Scenario 1

The more interesting results obtained for the simulation made for this scenario will be presented next.

![Figure 12 – Lines currents for the scenario 1 of rural network](image)

In figure 12, are presented the lines currents for this scenario. We can see that the value of the currents is lower than the ones from urban network because in this case the amount of loads is smaller and the current carried by the cables in this case is also smaller.

From figure 13, we can see that the limit of voltage unbalance imposed by the standard EN50160 [3] is passed for the lines 2 and 3.

![Figure 13 – Voltage unbalance for the scenario 1 of rural network](image)

b) Scenario 2

This scenario corresponds to half of the loads of the previous scenario and the more interesting results will be presented next.
5. CONCLUSIONS

From the several scenarios studied in this work, it is possible to conclude that the percentage of nonlinear loads has great impact in the PQ of a low voltage distribution network. This impact can be seen not only in the current that runs through the neutral conductors of the network but also at the THD of the voltage delivered to the consumers that belong to the network.

In the first simulation of the urban network, we can see that even derating the cables in relation to the harmonic content in some lines the current in the neutral conductor is still greater than the current that should be carried by the neutral conductors of these lines, in this first scenario where the number of nonlinear loads is very big. The THD of the voltage in this scenario is also very big, standing in values near the limits imposed by the standard EN50160 [3].

In the second simulation of the urban network, we can see that when the amount of nonlinear loads is reduced, the neutral currents are now under the limit values of currents that can run through the neutral conductors without deteriorate the conductors and the voltage THD is now about a half of the values of the first situation, what brings out the great impact of the nonlinear loads in the THD of a low voltage network.

The simulations for the urban network showed that the introduction of cable derating due to harmonic content, introduce improvements in some parameters of power quality, such as: current in the neutral conductor, total harmonic distortion of voltage and voltage unbalance.

In the simulations of the rural network, the neutral currents are not a problem once the percentage of nonlinear loads is smaller than in urban areas. However, there are other situations where the limit values, imposed by the standard EN 50160[3], are exceeded.

In the first simulation, the unbalance of the voltage in some lines are now bigger than 2% and the voltage drops in some exits of the transformer are now also bigger than 10%. These values are due to the great percentage of linear loads that are present in this network and to the great resistance and length of the lines that carry the current from the transformer to consumers.

When the percentage of nonlinear loads is reduced, like in the second simulation of the rural network, the current in the lines becomes greater what increases the values of the voltage unbalances and voltage drops in the lines.

Unfortunately, are not present in this paper all the results obtained in the several simulations that were conducted in this work. However, the present results are the most relevant and the ones that can illustrate better the impact that the percentage of nonlinear loads has on the power quality of a low voltage distribution network.

REFERENCES


[9] www.qenergia.pt
