Abstract - The main aim of this work is to evaluate the impact of microgeneration on the quality of a low voltage distribution network. To achieve this goal, a model of a low voltage network has been developed using the Matlab/Simulink PowerSystem toolbox. This model presents: medium voltage generation, a medium/low voltage transformer, several load types, and single phase and three phase microgenerators models.

In the low voltage network each one of these components is designed using values from catalogues and measurements obtained for different load types.

Using the developed model, several load scenarios are studied: with and without microgeneration, considering the medium voltage most significant harmonic (5th harmonic) and assuming that the transformer output voltage is equal to its nominal value or is 5% above the nominal value.

The simulations carried out with the developed model allow the evaluation of microgeneration impact on a low voltage grid, especially on the Total Harmonic Distortion (THD), Power Factor and Unbalanced Factor.

Keywords: Power Quality, Microgeneration, Low Voltage Network, Electric Loads Models, Total Harmonic Distortion.

I. INTRODUCTION

In recent years, the new reality of the energy sector and the economic and environmental pressures have led to the need for new forms of energy production through use of small generators next to the loads using renewable energy sources. This type of energy production is called distributed generation or micro generation. In most cases it makes use of so-called renewable energy and is the responsibility of independent operators or even consumers. They are usually referred to as renewable energy, energy sources that can be considered inexhaustible or whose potential energy can be renewed. Are included in this area: wind power, geothermal, solar, wave energy, tidal energy and biomass utilization.

As most common examples of micro generation systems is the production of electricity at low voltage using photovoltaic panels (solar energy) and wind turbines (wind energy).

However, the generation of energy using small-scale equipment, including solar panels, micro turbines or other technology, will have its impact on the electrical network. The study of the impact of microgeneration on the energy quality of a low voltage network can minimize the disturbances and costs associated with this type of energy production.

The non-linear loads use power electronic converters (generally non controllable diodes rectifiers) and represent much of the residential, commercial and industrial equipment. As domestic and commercial loads it can be found in most household appliances (TVs, DVD players / recorders, washing machines, microwave), computers, printers, phone chargers and UPS. In the industrial equipment they are present in most variable speed and electrical drives.

These loads cause energy pollution and are also more sensitive to the energy quality. In recent years, improving the quality of electricity has become essential to ensure the productivity, competitiveness and sustainability of the vast majority of economic activities, especially the most advanced technology.

Among the many disorders that may exist on a power grid, it will be given particular emphasis to the harmonic distortion, since the injection of harmonic currents in the electrical network results on harmonic voltages that causes many problems in the electrical charges.

Microgeneration equipment does not produce perfect sinusoidal waveforms and therefore they will disturb the power quality of a low voltage network, injecting harmonic current in the network.

II. LV POWER GRID MODEL

With the aim to monitorising the disturbances that microgeneration introduce on a low-voltage network, it was developed an equivalent model of a LV network using Simulink.

The building process of the network model can be compared to the development project of a lab test for a LV network. Each individual load was tested and the final model of the LV network was obtained from the association of models such as: a MV/LV transformer; distribution lines; and several loads previously sized.

A. Medium Voltage

There was considered a block of generation in the medium voltage. The generator parameters are represented in table I.
TABLE I
Medium Voltage Generator Parameters

<table>
<thead>
<tr>
<th>VRMS_MV (KV)</th>
<th>f (Hz)</th>
<th>P_n (KVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>50</td>
<td>250</td>
</tr>
</tbody>
</table>

Due to the type of transformer used, there isn’t considered the presence of the third harmonic. The fifth harmonic is considered in the medium voltage and it was represented by a voltage generator connected in series, with each electric phase. Each generator provides a maximum voltage equal to 2% of the medium voltage (≈ 163.3 Volt) at a frequency of 250 Hz.

B. Transformer MV/LV

The low and medium voltage connection is performed by a transformer (250 KVA) connected in delta-star with neutral grounded.

To obtain the transformer parameters it is necessary to calculate the resistance and chokes on the spreading of primary, secondary and magnetizing windings.

From data obtained on manufacturers catalog it was possible to measure the transformer MV/LV.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>Transformer MV/LV parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (KVA)</td>
<td>250</td>
</tr>
<tr>
<td>Voltage MV (KV)</td>
<td>10</td>
</tr>
<tr>
<td>Voltage LV (V)</td>
<td>400</td>
</tr>
<tr>
<td>Open circuit test</td>
<td></td>
</tr>
<tr>
<td>Open circuit voltage V_o (p.u.)</td>
<td>1</td>
</tr>
<tr>
<td>Power loss in open circuit P_o (p.u.)</td>
<td>0.00</td>
</tr>
<tr>
<td>Magnetizing current I_m (p.u.)</td>
<td>0.02</td>
</tr>
<tr>
<td>Short-circuit test</td>
<td></td>
</tr>
<tr>
<td>Current I_s (p.u.)</td>
<td>1</td>
</tr>
<tr>
<td>Short-circuit voltage V_c (p.u.)</td>
<td>0.40</td>
</tr>
<tr>
<td>Power loss with load P_c (p.u.)</td>
<td>0.01</td>
</tr>
</tbody>
</table>

From the open circuit test it is possible to obtain the magnetization resistance and inductance and from the short-circuit test it is possible to obtain the resistance and inductance of primary and secondary windings.

C. Distribution Network

On this work there was considered an aerial network because this is the one used in a rural setting. For economic and technical reasons the cables selected are the LXS. The sections considered in the simulation are: 50mm2 and 70mm2.

From data obtained on manufacturers catalog it was possible to size the LV network cables. The parameters that characterize the power lines are the longitudinal impedance and the transversal admittance. However, for the LXS cables, it is only considered the longitudinal resistance and reactance.

The behavior of an aerial cable depends on the linear characteristics of each conductor: resistance and inductance. The resistance value R_cabo [Ω / km] was given by technical guide Solidal [Solidal Conductores Eléctricos, 2007]. The inductance value L_cabo [H / km] is calculated in two different ways. At first, it is used the expression (1) present in [Solidal Electrical Conductors, 2007].

\[
L_{\text{cabo}_{\text{Solidal}}} = 0.05 + 0.2 \cdot \log\left(\frac{2 \cdot a_m}{d}\right) \cdot 10^{-3} \quad (1)
\]

The second way to calculate the induction coefficient for each phase is by expression (2) present in [Sucena Paiva, 2007].

\[
L_{\text{cabo}_{\text{SucenaPaiva}}} = 2 \cdot 10^{-4} \cdot \ln\left(\frac{D}{r_c}\right) \quad (2)
\]

Given the similarity between the values calculated by the two expressions (1) and (2) the values obtained by the expression (1) present in [Electrical Conductors, 2007] are the ones taken in consideration.

D.1 Resistive Linear Loads

Resistive linear loads represent for example incandescent lighting, some electric ovens or heaters.

Using the measurements made with an energy quality analyzer from Fluke in different load types, it was possible to design them.

What distinguishes the various resistive loads that may exist in a low-voltage network it’s their power. Thus, smaller loads such as incandescent lamps are defined with a power of 100 W, while for electric ovens and heaters is defined a power of 1000 W.

D.2 Inductive Linear Loads

Inductive linear loads can represent for example, refrigerators.

The RL load was designed with data measured in a refrigerator, with an energy quality analyzer from Fluke. Those measurements are present on table III

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>RL load parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_RL (VA)</td>
<td>P_RL (W)</td>
</tr>
<tr>
<td>150</td>
<td>90</td>
</tr>
</tbody>
</table>
and obtained the values of resistance R, which simulates the equivalent power load [Fernando Silva, 2006] and the capacity C of the filtering capacitor.

The calculation of R depends on the average value of the rectifier output voltage \( V_{out} \) and the load power P (for example, the TV).

\[
R = \frac{V_{out}^2}{P} \quad (3)
\]

When the diodes are reverse-biased, the load current is supplied exclusively by the capacitor.

\[
C = \frac{V_{out} \cdot \Delta t}{R \cdot \Delta V} \quad (4)
\]

The rectifier coil input smoothes the current applied to the network and it is calculated as a percentage of the load [Fernando Silva, 2006]. In the case of television, the calculation of \( L_{TV} \) (5) is usually considered to be 3% of the load.

\[
L_{TV} = \frac{0.03R}{2\pi f} \quad (5)
\]

For the washing machine, to calculate \( L_{ML} \) (6), usually considers 10% of the load.

\[
L_{ML} = \frac{0.1R}{2\pi f} \quad (6)
\]

E.2 Non–Linear Three Phase Rectifier

It was considered a three-phase rectifier, not controlled (with diodes) and in complete wave. The three-phase rectifiers represent higher power loads such as an equipment of a small industry.

The expressions used to design the three-phase rectifier are the same used in the single-phase rectifier [Fernando Silva, 2006].

To calculate the inductances of the three-phase rectifier it was considered 3% of the load (5).

F.1 Single Phase Inverter

Voltage inverters were used to represent the microgenerator circuits. In this study were considered two different types of inverters: a single phase inverter and a three phase inverter. The first one is designed for low power applications and the second one for higher power applications.

In the simulation of the single-phase inverter was used the pulse width modulation command (PWM) of three levels.

The \( L_{inv1F} \) (7) is the connecting coil between the inverter and the network. It depends on the inverter voltage input, on the semiconductor switching period, which is considered close to 10kHZ, on the inverter topology (full bridge) and the type of control chosen (three-level PWM) [Fernando Silva, 2006]. This coil limits the flicker \( \Delta i_L \), which should not exceed 10% of the maximum current that the microgenerator can inject into the network.

\[
L_{inv1F} = \frac{U_{DC} \cdot T_C}{4 \cdot \Delta i_L} \quad (7)
\]

The simulated inverter is controlled in current in order to obtain an output power equal to a microgenerator. The block diagram of the current control is shown in Fig 1, where \( I_{ref} \) is the reference current and \( I_{fuse} \) the current injected into the network by the inverter. Both are multiplied by a gain \( K_I \) and the difference between them is applied to the compensator \( C(s) \). The group converter plus modulator has the modulating \( u_f \) as an input and \( V_o \) is the output voltage of the inverter. \( V_{fuse} \) is the supply voltage which is considered as a disturbance.

\[
G(s) = \frac{K_D}{1 + sT_d} \quad (8)
\]

\( K_D \) (9) is given by the ratio between the supply voltage \( U_{DC} \) [V] of the inverter and the modulating maximum amplitude \( U_{Cmax} \) [V] [Fernando Silva, 2006].

\[
K_D = \frac{U_{DC}}{U_{Cmax}} \quad (9)
\]

Usually, it is considered that the average delay \( T_d \) (10) is equal to half of the switching period \( T_c \) [ms] [Fernando Silva, 2006].

\[
T_d = \frac{T_c}{2} \quad (10)
\]

The compensator \( C(s) \) (11) is a Proportional-Integral (PI) type, ensuring a 2nd order dynamic in
closed chain. It ensures a zero static error with acceptable rising times [Fernando Silva, 2006].

\[ C(s) = \frac{1 + sT_z}{sT_p} \]  

(11)

To design parameters \( T_p \) and \( T_z \), it is considered that the zero of the compensator cancels the pole of lower frequency [Fernando Silva, 2006] introduced by the filter network connection. The zero is determined by (11) and (12), where L represents the coil of the filter and R is the parasitic resistance of that coil.

\[ T_z = L / R_{invAF} \]  

(12)

\( T_p \) is calculated by (13), where \( K_i \) is the gain of the current, \( K_D \) and \( T_d \) are the gain and time delay of the group modulator plus converter.

\[ T_p = \frac{2K_DK_iT_d}{R_{invAF}} \]  

(13)

The synchronization of the single-phase inverter with the simulated network is achieved by manipulation of the reference current. The result is a current waveform with the shape of the voltage waveform but with the amplitude of the current reference (Fig 2).

\[ \begin{align*}
  \frac{di_d}{dt} &= \frac{v_d}{L_d} - \frac{R_D^2i_d}{L_d} \\
  \frac{di_q}{dt} &= \frac{v_q}{L_q} - \frac{R_D^2i_q}{L_q} \\
  \frac{di_R}{dt} &= \frac{v_R}{L_R} - \frac{R_D^2i_R}{L_R} \\
  \frac{di_S}{dt} &= \frac{v_S}{L_S} - \frac{R_D^2i_S}{L_S} \\
  \frac{di_T}{dt} &= \frac{v_T}{L_T} - \frac{R_D^2i_T}{L_T}
\end{align*} \]  

(14)

Using the transformation of Park on (14) is possible to obtain the three-phase inverter state model in dq coordinates (15).

\[ \begin{align*}
  \frac{di_d}{dt} &= -\frac{R}{L}i_d + \frac{1}{L}H_d \\
  \frac{di_q}{dt} &= -\frac{R}{L}i_q + \frac{1}{L}H_q
\end{align*} \]  

(15)

The command diode and \( H_d \) result from the current \( i_d \) and \( i_q \) controllers.

For the three-phase inverter was considered the two levels pulse width modulation command.

The three phase inverter also needs a connecting coil between the inverter and the network. The coil value (16) is calculated assuming that the maximum current variation \( \Delta i_L \) is 10% of the maximum current injected into the network, multiplied by the switching period, the inverter voltage input and a factor that depends on the topology of the inverter (full bridge) and the type of control chosen (two-level PWM) [Fernando Silva, 2006].

\[ L_{invAF} = \frac{U_{DC} \cdot T_C}{6 \cdot \Delta i_L} \]  

(16)

The block diagram of the controller of the linearized current injected by the three-phase inverter into the network is shown in Fig (3) [S. Ferreira Pinto and J. Fernando Silva, 2006] where Iodref and Iodref represent the references currents injected into the network in dq components, and Iod and Iodq represent the current injected into the network and Vod and Vodq represent the dq components of the inverter voltage output.

\[ \begin{align*}
  \text{FIGURE 2 – Synchronization of the inverter with the network} \\
  \text{FIGURE 3 – Current control block diagram}
\end{align*} \]

The design of the three phase compensator is similar to the process used in the single phase inverter and from the expressions (11) (12) and (13) is possible to obtain the parameters \( T_p \) and \( T_z \).

From equations (9) and (10) result the gain of \( K_D \) and delay \( T_d \) of the inverter. It is considered \( T_d \) equal to half of the switching period, and \( K_D \) is as a unity gain due to correcting the disturbance \( wL \) [Fernando Silva, 2006] [S. Ferreira Pinto and J. Fernando Silva, 2006].

For the three-phase inverter the reference currents are also synchronized with the network voltages. To do this synchronization is necessary to determine the angular position of the network voltages. In this work
was used the vector synchronization method [Bruno Costa, 2007] which is represented by the block diagram in Fig (4).

\[ \begin{align*}
V_A & = V \cos(\theta) \\
V_B & = V \sin(\theta)
\end{align*} \]

\[ |V| = \sqrt{V_A^2 + V_B^2} \]

\[ \frac{V_A}{|V|} \]

\[ \frac{V_B}{|V|} \sin(\theta) \]

\[ V_A \]

\[ V_B \]

\[ V_T \]

\[ V_{\alpha} \]

\[ V_{\beta} \]

\[ RST/\alpha\beta \]

\[ VR \]

\[ FPBx \]

\[ FPBx \]

\[ \cos(\theta) \]

\[ \theta \]

\[ \text{FIGURE 4 – Synchronization of the inverter with the network} \]

In the synchronization process it is necessary to calculate the network voltages in \( \alpha \beta \) coordinates using the Concordia transformation. This transformation turn a three-phase system, in RST coordinates, into a two phase equivalent system in \( \alpha \beta \) coordinates.

On the voltages calculated in \( \alpha \beta \) coordinates is applied a low-pass filter to eliminate the noise in the signal acquisition. After calculating the amplitude of the voltage vector, it is possible to calculate the value of the cosine and sine of the angle of this voltage vector. This angle is then used in the Park’s transformation for the state model system ensuring that inverter currents are inject into the network in phase with the network voltages.

III. RESULTS

The simulated LV network model was based on the characteristics of the Portuguese electrical network and in data present on a low voltage air network. The electric network typically used in a rural setting has got an arborescent development with progressive reduction of sections and is connected to customers in several sections. Normally, the maximum length between the PT and the client does not exceed 1000 meters.

From data present on a low-voltage network is known its topological structure, the typical PT parameters, the hired power of each client and the type and length of cables used in distribution.

In the network model there was not considered the individual consumer, but groups of consumers. This consideration implies higher power for each group of energy consumers and therefore the cable length was adjusted to the level of power loads.

In figure (5) is shown the simulated LV network.

\[ \text{FIGURE 5 – Simulated LV network diagram} \]

In the created scenarios is considered a balanced system, referring to the distribution of loads for each phase. It was also considered the relationship between the linear loads and nonlinear loads assuming that normally, the percentage of non-linear loads on a rural type network does not exceed 50%.

It should be noted that in all simulated scenarios, it was considered the 5th harmonic present on the medium voltage.

In the simulations with microgeneration, are created two scenarios called "Microgeração 1" and "Microgeração 2" that differ in the amount of connected microgeneration into the network and how they are distributed for each phase.

In the first scenario "Microgeração 1" (Fig 6) there are seven microgenerators connected to the simulated LV network which represent 10% of the PT nominal power output (24.15 kVA).

\[ \text{FIGURE 6 – Simulated LV network with "Microgeração 1"} \]

The second scenario is called "Microgeração 2" (Fig 7) and there are sixteen microgenerators (fifteen
A. Scenario 1 – PT with low load

In the first scenario the PT is at 20% of the nominal power output (20% PT) and 50% of the connected loads are nonlinear.

From the simulations results it’s possible to see that the voltage waveforms are consistent with reality - almost sinusoidal waveforms with rms value (around 230 V), despite a slight imbalance between phases. This imbalance is consistent with the load distribution of this scenario, which are not perfectly balanced in all three phases. The current waveforms have a high distortion that results from the high percentage of the considered nonlinear loads.

In all measurements the voltage drop values are consistent with a real scenario and always below the standard value (10%) imposed by NP50160 [Norma Portuguesa EN 50160, 1995].

B. Scenario 2 – PT with high load

The second scenario corresponds to a load power peak in the network. The PT is at 80% of the nominal power (80% PT) and 50% of loads are nonlinear.

From the simulations results it’s possible to see that the voltage and current waveforms are consistent with reality.

In all measurements the voltage drop values are consistent with a real scenario and always below the standard value (10%) imposed by NP50160 [Norma
Considering that in a real network scenario the power factor measurement is around 0.9, the simulation results are acceptable for this characteristic.

Figures 11, 12 and 13 shows three graphics that compare \( \text{THD}_U \) values for each group of consumers in the different phases (RST) for each microgeneration scenario.

In the two scenarios with microgeneration the measured values are generally slightly higher than the scenario without microgeneration.

Despite the higher values of \( \text{THD}_U \) measured in scenarios with microgeneration, never occur values above the 8% required by NP50160 [Portuguese Standard EN 50160, 1995].

IV. CONCLUSIONS

In this work was developed a model of a low-voltage network in Matlab-Simulink, which allowed to characterize disturbances associated with the connection of microgeneration equipment to the LV network. Based on this model, it was possible to quantify total harmonic distortion voltage rate (THD) of the LV network.

The \( \text{THD}_U \) values for simulations with PT voltage 5% above the nominal value are very similar to results at nominal value. These values are slightly higher but consistent with the measured values in a real network.

In this work was developed a model of a low-voltage network in Matlab-Simulink, which allowed to characterize disturbances associated with the connection of microgeneration equipment to the LV network. Based on this model, it was possible to quantify total harmonic distortion voltage rate (THD) of the LV network.

The low-voltage grid model was constructed considering a Medium Voltage (MV) generator, a MV/LV transformer, distribution lines (twisted air cables), various types of loads (linear and nonlinear) and mono-phase and three phase microgeneration. Among the modeled loads are: pure resistive loads, inductive loads, single-phase rectifiers and three-phase rectifiers. The microgeneration was represented as voltage inverters controlled in current.

In constructing the LV network model, each component was designed, using the values of manufacturer catalogs of cables and transformers as well as measurements taken on some loads (house appliances) with a power quality analyzer (Fluke). Thus, it was obtained a LV network model consistent with reality.

Based on this model were studied two load scenarios, with and without microgeneration, considering the most significant harmonic present on medium voltage (5th harmonic), and assuming that the output voltage of the transformer is equal to the nominal voltage or is 5% above this value.

In the first load scenario, it was considered the network on a low load state and the second, on a high load period. In both scenarios the percentage of nonlinear loads is about 50% and it was attempted to obtain a balanced load distribution (not ideal) for the three phases (RST).

In the simulations, were monitored over the network: the waveforms, the power factors, the voltage drops, and the harmonic distortion rates. All these characteristics showed the typical values of a
The results confirmed a plausible model for a low-voltage grid.

- The voltage waveform monitored at the transformer output shows a sinusoidal shape with around 230 V of rms value.
- The voltage drops along the line are below 10% Un defined in by NP50160 [Norma Portuguesa EN 50160, 1995].
- The values obtained for the power factor are close to 0.9 measured on the network.
- It appears that the values of THD voltage vary with the type, amount and distribution of loads and never exceed the 8% defined in the NP50160 [Norma Portuguesa EN 50160, 1995].

The microgeneration was added to the final model of the LV network. From the new model was obtained new results for the THD and these were compared with the previous (no microgeneration).

For the simulated network, it was found that the microgeneration has always a negative impact on the harmonic distortion rate. In general, the values of THD increased with the microgeneration, but never approached the limit of 8% [Norma Portuguesa EN 50160, 1995].

It was found interesting differences between the two analyzed scenarios. In the peak scenario, the increase on TDH values was negligible but on the low load scenario the THD increase was higher.

As expected, the simulations with the voltage 5% above the nominal value, it was obtained slightly higher THD values. In these simulations, the impact of microgeneration was very similar to the tests at nominal voltage.

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