Harmonics and Unbalances Generated by Microgeneration Systems

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Abstract - The use of micro-generation as a way to meet the challenges of environmental and energetic sustainability has consequences on the quality of power.

The main goal of this MSc thesis is to analyze the impact of single phase and three phase microgeneration on the voltage waveform of a low voltage (LV) network. A model of an urban low voltage underground network is built in Matlab/Simulink environment, including the model of: medium / low voltage transformer, electrical cables, loads, microgenerators and their current controllers.

The impact of single phase and three phase microgeneration in the quality of voltage waveform is evaluated simulating the proposed network for different scenarios. Power quality parameters as voltage variations, Total Harmonic Distortion (THD) and Voltage Unbalance Factor (VUF) are evaluated. Simulation results are obtained for different distributions of non linear loads, load power and microgeneration power.

Keywords: Microgeneration, Power Quality Low Voltage Network, Total Harmonic Distortion, Voltage Unbalance Factor (VUF).

I. INTRODUCTION

The use of renewable natural resources for electricity generation has been widespread in recent years. New technologies have emerged and others have evolved allowing greater exploitation of these resources. With the Kyoto treaty, the commitment of most countries worldwide is to reduce the emission of greenhouse gases by making a more rational use of existing energy resources, and for greater investment in energy forms considered clean. Wind farms, small hydro plants, photovoltaic and biomass power stations are some of the existing solutions in Portugal, which represent an increasing share of clean energy produced in the country. At a time when the use of renewable energy is growing consensus, the concept of microgeneration arises. Investment in, small-scale electricity production and selling it to the grid is at present being subjected to economic incentives by the government, in order to promote microgeneration in Portugal.

The Decree-Law 363/2007 of 2 November [1] has established the legal framework of microgeneration in Portugal. According to existing legislation is possible to who has a contract to purchase electricity, selling energy to the electricity grid. However the installed power in microgeneration cannot exceed 50% of the contracted power, with a limit of 5.75kW to facilities not integrated into condominiums. The document sets out conditions of access and limits to microgeneration (recommended maximum of 25% of the power adapter) and also planned a system of subsidized prices for the sale of electricity. Wind and solar microgeneration systems are the ones with better conditions for a higher yield in Portugal (mainly solar), and this fact is the country's geographical location.

The photovoltaic microgeneration is the utilization of solar radiation through the photovoltaic effect. Cells on the panels are composed of semiconductor materials that allow the conversion of energy associated with solar radiation into electrical energy.

Regarding the wind microgeneration, it uses small wind turbines to transform the kinetic energy of wind into electricity. Microgeneration systems may or may not be connected to the LV network. As part of the isolated systems, the microgenerators must have equipment of energy storage - batteries. Systems connected to the grid use voltage inverters to inject a sinusoidal current in phase with the voltage. To date there are already registered in Portugal a few thousand micro-producers of electricity [2]. Given the growing interest in this new form of energy production, it is expected that this number continues to grow.

II. LV NETWORK

The model grid of low voltage was built in Power Systems Toolbox of Matlab / Simulink. The network includes models of the transformer MV / LV, cables used and the more representative loads of the LV network.

A. MV/LV Transformer

The operation of the electricity MV (medium voltage) is carried out in three levels of voltage: 10kV, 15kV and 30kV. In urban network (underground grid) transformers commonly used in connecting the MV network and the LV network have powers of 630kVA, 400kVA and 250kVA. These transformers are connected in a delta (MV)/star (LV) system with neutral grounded in LV.

In this work was considered a 630kVA transformer
with a voltage level in the primary winding of 30kV and 400V in the secondary (phase-to-phase voltages). The model of the transformer used in the network is the T model that is represented in Fig. 1.

From the values cataloged [12] for tests on open and short-circuit the parameters \( R_a, R'_b, X_p, X'_p, G_m \) and \( B_m \) were calculated [11].

B. Electrical Cables

In LV urban networks are commonly used underground cables, whose length from the transformer to the farther customer, does not exceed, usually, 500m. Generally, in Portugal are used insulated low-voltage cables with three different sections: 185mm², 95mm² and 35mm². The cables have aluminum conductor core, and PVC insulation (cables LVA1 and LSVAV). From the \( \pi \) model of a transmission line [4] a cable model is built (modified \( \pi \) model). This model considers the three phases and neutral conductor of the cable.

The resistance, inductance and capacity are calculated from the values cataloged by the manufacturers [3] and their length.

C. Linear Loads

The low-voltage networks are predominantly single-phase loads, which can be linear or nonlinear. In the model constructed, the linear loads are considered to be of purely resistive or inductive nature.

The network model is intended to represent groups of consumers, distributed by various outlets of the transformer. Thus, for each resistive load type a typical power \( (P_R = 1000W) \) is assumed. This value is then affected by the amount of devices with resistive behavior that are connected to the network at any given moment (e.g. incandescent bulbs or heaters). To make the network more representative of reality inductive loads were designed. In Fig. 3 the waveforms of voltage and current of a refrigerator are recorded. Whereas an inductive load has \( S_L = 150 VA \) and power factor 0.56 the waveforms in Fig. 4 were obtained.

D. Non-Linear (NL) Loads

The single-phase rectifiers presented in this work are not commanded full-wave rectifiers (rectifiers with diodes) - Fig 5. Two types of rectifiers were scaled differing in power.

The equivalent resistance of the rectifier output is determined based on the power of the device, according to where \( v_{out} \) is the average value of output voltage and power is \( P_{TV} \) equivalent of an entire set of \( n \) devices that are connected to the network.

\[
R_0 = \frac{v_{out}^2}{P_{TV}} \tag{1}
\]

The rectifier has an input filter \( L_{IN} \) filtering the current [5]. It is considered that the \( L_{IN} \) is 3% of the load(2).

\[
L_{IN} = \frac{0.03 R_0}{2\pi f} \tag{2}
\]
The condenser is sized to limit the ripple of the output voltage.

\[ C_o = \frac{V_{out} \Delta t}{R_o \Delta v_o} \tag{3} \]

Where \( \Delta v_o = 10 \text{ms} \). [5]

The type 1 rectifier is intended to represent a TV. It is considered that the power of each TV is 200W. The voltage and current waveforms measured in a TV and type 1 rectifier are shown in Fig. 6 and Fig. 7.

The type 2 rectifier is intended to represent a washing machine. It is considered that the power of each machine is 2000W. The voltage and current waveforms measured in a washing machine and the type 2 rectifier are shown in Fig. 8 and Fig. 9.

The output voltage of the inverter is given by (3).

\[ V_o(t) = \gamma U_{DC}(t) \tag{3} \]

where

\[ \gamma = \begin{cases} -1, & \text{if } S1 \text{ ON and } S4 \text{ ON} \\ 0, & \text{if } S1 \text{ ON and } S3 \text{ ON} \\ 1, & \text{if } S2 \text{ ON and } S3 \text{ ON} \end{cases} \tag{4} \]

and \( U_{DC} \) is the DC input voltage.

The connection to the network is made through a filter (\( L_o \)) that will reduce the ripple of the current injected into the network [5].

\[ L_o = \frac{U_{DC}}{4\Delta i_o f_c} \tag{5} \]

\( U_{DC} \) is the DC input voltage of the inverter, \( A_i_o \) is the current ripple injected into the network and \( f_c \) the
switching frequency. Resistance $R_L$ represents the internal resistance of $I_{ref}$. The equivalent resistance ($R_{eq}$) at the converter terminals represents the impedance of the network seen from the inverter terminals. To ensure the proper functioning of the inverter, the DC voltage should be higher than the amplitude of the grid voltage. It is assumed that $U_{DC}$ is 400V.

To represent a microgenerator, the inverter must inject a current in the network that is proportional to the power generated by solar radiation received by a set of photovoltaic panels, or wind covering a microturbine. Reference currents were calculated based on the microgeneration units power - $I_{ref} = 12.75A$. Only the magnitude of reference current can be manipulated, and the phase is obtained from the supply voltage. The block diagram that illustrates the current control is shown in Fig. 11.

![Fig. 11 – Block diagram of the current control](image)

It is intended that the current to inject into the network follow the reference, which will be established based on the maximum power that can be extracted from the sun or wind. In order to ensure that the error between the current and its reference value tends to be zero is necessary to scale a power compensator, $C(s)$.

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

(6)

Where $T_p$ e $T_z$ are:

$$T_p = \frac{2K_{p}k_{1}T_{d}}{L_{L}+R_{L}}$$

(7)

$$T_z = \frac{L_{o}}{R_{L}+R_{R}}$$

(8)

Where $K_{p}$ is the gain of the association modulator + converter, $k_{1}$ is the close loop gain and $T_{d}$ is the system response delay.

In Fig. 12 is shown the voltage and current of the inverter output.

![Fig. 12 – Grid voltage and injected current into the grid by a single-phase inverter](image)

In Fig. 13 is represented the harmonic specter and THD of the current injected into the network by a single-phase inverter. The THD current of the inverter doesn’t reach the limit (3%) indicated by the manufacturers [7].

![Fig. 13 – Injected current harmonic specter – single-phase inverter](image)

It was also scaled a three-phase inverter - Fig. 14.

![Fig. 14 - Three-phase inverter model](image)

Because there are two components of the currents, two current controllers $C_{d}(s)$ and $C_{q}(s)$ must exist. The design principles of the controllers are the same used in the single-phase inverter. The block diagram of the controlled system is represented in Fig. 15.

![Fig. 15 – Decoupled block diagram of the current controllers](image)

When connected to the grid, inverters must be synchronized with it, which means that the angular position of the network should be calculated. In Fig. 16 is represented the block diagram of the synchronizer used [8].

![Fig. 16 – Block diagram of the grid synchronizer](image)

The current injected by the inverters on the network are represented in Fig. 17.
It can be seen in Fig. 18 that the distortion in the current three-phase inverter is lower than in the single-phase inverter and the manufacturer limit [7].

IV. SIMULATIONS AND RESULTS

The simulations of the electricity of the LV network were performed using the software Matlab / Simulink. The objective of the network simulations is to evaluate the impact of microgeneration on the quality of the waveform.

A. Parameters analyzed

The parameters that measure the quality of the waveform evaluated are: variation in supply voltage, Voltage Unbalance Factor (VUF), power factor and Total Harmonic Distortion (THD). These parameters have limits defined by the standard NP EN 50160 [14] - Tab. 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage Variation</td>
<td>10% of Nominal Voltage</td>
</tr>
<tr>
<td>Voltage Unbalance Factor (VUF)</td>
<td>2%</td>
</tr>
<tr>
<td>Voltage Total Harmonic Distortion (THDV)</td>
<td>8%</td>
</tr>
</tbody>
</table>

THD is calculated using (9).

\[
THD_v = \sqrt{\sum_{n=2}^{\infty} V_n(BMS)^2 / V_1(BMS)^2} \tag{9}
\]

The constant \(\beta\) is given by (11) and depends on the RMS phase-to-phase voltage \(U_{AB}, U_{BC}, U_{CA}\).

\[
\beta = \frac{u_{AB}^4 + u_{BC}^4 + u_{CA}^4}{(u_{AB}^2 + u_{BC}^2 + u_{CA}^2)} \tag{11}
\]

The power factor is defined by:

\[
FP = \frac{\cos \phi_1}{\sqrt{1 + THD_v^2}} \tag{12}
\]

B. Network Topology

The proposed network is an underground low voltage network, so it is more common in urban centers. The nominal voltage is 230V/400V. In this model it is considered a generator of medium voltage (30kV) with short circuit impedance which aims to represent the network of medium voltage. The MV/LV transformer has 630kVA and the wiring diagram is delta / star with grounded neutral. The transformer has six outputs connected directly to sections of cable sections 95mm2 and 185mm2.

Load groups were set up to represent a set of customers. In each output of the transformer are several groups of loads connected by sections of cable with different lengths, all of which have the neutral grounded. The maximum length between the transformer and the most distant group of loads is 100 meters.
The value indicating the maximum \( S_N \) of 13 groups of charges is given by (13), where \( S_i \) represents the power associated with each group of loads.

\[
S_N = \sum_{i=1}^{13} S_i
\]  
(13)

The power for each group of loads \( S_i \), is calculated as the sum of products of power contracted by factor of simultaneity and the number of customers associated with each step.

\[
S_i = \sum S_{\text{Contratada}} \times FS \times n^\text{costumers}
\]  
(14)

Where,
- \( S_{\text{Contratada}} \) is the power contracted by customers: 3.45kVA; 6.9kVA e 20.7kVA.
- \( FS \) is the factor of simultaneity associated with the number of customers every step of contracted power. [10]
- \( n^\text{costumers} \) associated with each of the power contracted.

As the power consumption at each time by all consumers connected to the network can vary, as well as the percentage of non-linear loads, scenarios have been set up where these two factors vary.

Variation of power consumption,
- 20% of \( S_N \)
- 80% of \( S_N \).

Variation in load distribution,
- 50% of non-linear loads.
- 70% of non-linear loads.

C. Results

The simulations for the scenario without microgeneration revealed variations in supply voltage below the value required by the standard. Power factors in this scenario are all above 0.8.

For the scenario with 10% of microgeneration the variations on supply voltage are reduced in both scenarios load (20% SN 80% SN). However there is a greater voltage drop in a setting of the network power edge. The power factor of the network with 80% \( S_N \) is above 0.8. For 20% SN situation power factor has some low values and, in some cases negative - Fig. 20. This is due to the fact that in the groups were the microgenerators are installed, the current is more distorted (high current THD values) inversely influencing the value of power factor. In some cases the values are negative, which corresponds to a reversal in the power flow, that is, the microgenerator providing active power to the network.

![Fig. 19 – LV network scheme](image)

![Fig. 20 – Power factor of the LV grid with 10% of microgeneration units, 70% of non-linear loads with 20%\( S_N \) load](image)

![Fig. 21 - Power factor of the LV grid with 25% of microgeneration units, 70% of non-linear loads with 20%\( S_N \) load](image)

For the scenario with 25% of microgeneration with three-phase units, the voltage variation and power factor behavior are identical to the scenario with single-phase units.
Comparisons of the THD voltage in the scenarios with and without microgeneration with 50% of non-linear loads are represented in Fig. 22 and Fig. 23.

![Fig. 22](image)

Fig. 22 – Comparison of the voltage THD in one phase of the LV grid with 50% of non-linear loads with 20% S₀ load for the different scenarios.

With 70% of non-linear loads the THD results obtained are in Fig. 24 and Fig. 25.

![Fig. 23](image)

Fig. 23 – Comparison of the voltage THD in one phase of the LV grid with 50% of non-linear loads with 80% S₀ load for the different scenarios.

![Fig. 24](image)

Fig. 24 – Comparison of the voltage THD in one phase of the LV grid with 70% of non-linear loads with 20% S₀ load for the different scenarios.

![Fig. 25](image)

Fig. 25 – Comparison of the voltage THD in one phase of the LV grid with 70% of non-linear loads with 80% S₀ load for the different scenarios.

The values of VUF remained well below the values imposed by the standard in all simulations. In Fig. 26 and Fig. 27 is represented the comparison of VUF to the network with 70% of non-linear loads.

![Fig. 26](image)

Fig. 26 – Comparison of VUF of the LV grid with 70% of non-linear loads and 20% S₀ load for the different scenarios.

![Fig. 27](image)

Fig. 27 – Comparison of VUF of the LV grid with 70% of non-linear loads and 80% S₀ load for the different scenarios.

V. CONCLUSIONS

To study the impact caused by the introduction of microgeneration in the voltage waveform, a LV network was built. The model included: a source of medium voltage, a transformer MV / LV; cables; linear and nonlinear loads; microgeneration units and power quality meters. The simulations were made for various scenarios of loading and microgeneration levels.

The variation of voltage and VUF never exceed the limits imposed by the standard NP EN 50160. In all scenarios it was found that the increase of nonlinear loads on the network is a factor undermining the quality of the waveform.

When the microgeneration totals 10% of the transformer power, the values of THD go very close to those obtained in the scenarios without microgeneration.

With the increase in microgeneration for 25% of the transformer power, it was found that the values of THD increased. However, they remained below the limit (8%) imposed by the standard. For this microgeneration scenario, the network presented differing behavior, in the 20%SN situation THD increases were higher than those registered at the 80% situation.

When you combine single-phase inverters with three-phase there is a reduction in THD for the equivalent scenario with only single-phase microgeneration.

In general, the values of power factor measured in microgeneration scenarios decreased for scenarios
without microgeneration, becoming, in some cases, negative. This is due to the reversal of the power flow carried over the network.

The simulations performed to the scaled low-voltage grid make it possible to conclude that the influence of non-linear loads is important in the quality of the waveform. The existence of microgeneration leads to an increase in rms voltage, the VUF and the THD. However, despite the increase in values of these parameters, the limits defined by the standard NP EN 50160 have never been exceeded. The power factor was the parameter that showed worse performance with the introduction of microgeneration.

VI. REFERENCES


