Voltage Regulation in Low Voltage Networks aided by Micro-producers

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Abstract— This paper presents the study and development of a decentralized solution to mitigate the impact that the growing integration of microgeneration systems causes in Low Voltage distribution networks. The integration of dispersed generation systems using renewable energy sources has several advantages. However, the existence of these systems in the electrical network, especially when located at a considerable distance from the transformer substations, entails a set of problems that compromise the regular operation of the microproduction systems and the electric network where they deliver power. One of these problems is associated with the quality of the voltage’s waveform, where a variation of its RMS voltage value, exceeding the maximum value defined in the standard NP EN 50160, can lead to permanent overvoltages in the network. In order to solve this problem, a decentralized regulation is proposed, based on a local closed-loop controller for reactive power, which allows, in most cases, to adjust the voltage profiles on the network for values within the established limits, by modifying the existing control algorithm in the microgenerator. A network model was developed that includes a representation of the Medium Voltage (MV) / Low Voltage (LV) transformer, Low Voltage distribution lines, electrical loads and microgenerators. The network model simulation using Matlab/Simulink software allowed the analysis of different network operating conditions, studying its voltage level profiles, currents and power flow on the network to evaluate the performance of the proposed solution, which regulates the voltage in the Low Voltage network.

Index Terms— Low Voltage Networks, Microgeneration, Permanent Overvoltage, Electric Power Quality, Reactive Power, Voltage Regulation.

I. INTRODUCTION

The liberalization of the electric sector and the growth of decentralized production may affect consumers due to an increase of the network’s RMS voltage value above the limits defined by the applicable norms, with network operators as well as the micro-producers aware of the concerns raised by such anomalies. Therefore, it is critical to implement monitoring and control systems that make it possible to detect, evaluate and correct such disturbances in the Electric Power System. The increase of the RMS voltage value is a consequence of the increasing number of microgenerators connected throughout the low voltage networks, especially when connected at a considerable distance from the transformer substation. For example, in the case of a rural network, where the distance between the center of consumption and the transformer substation can be significant, the RMS voltage values at the microgenerator’s installation location, can increase considerably, mainly during off-peak hours, when the change of direction of the power flow occurs, since at that time the consumption is greatly reduced and the microgenerator supplies its peak power to the network. So, sometimes it results in an overvoltage at the microgenerator connection to the network, or nearby locations where the maximum allowed voltage is exceeded, which results in the trigger of the maximum voltage protections. According to standard NP EN 50160 [3], the value of the supply voltage must be within a -15% to + 10% range of its RMS value of 230V. Thus, permanent overvoltage is defined as a disturbance occurring at a given point in the network where the RMS voltage value is greater than 253V for longer than one minute. The microgenerators are provided with a maximum voltage protection, which switch off when the overvoltage occurs, interrupting the injection of energy to the network. During approximately 10 minutes the microgenerator will then remain shut down, and when this situation occurs, the micro-producer is harmed because he stops selling power to the grid. When a reconnection of the system occurs, as the operating point is sometimes the same, the microgenerator shuts down again, which results in an inefficient functioning of the equipment, since it decreases the producer’s income, thus increasing the amortization time of the amounts invested in the microproduction system. Hence, issues related with the voltage profiles in the electrical networks are the most problematic in terms of the Quality of Electric Energy (QEE), and, therefore, improving the voltage profiles throughout network is the basis of this work.

Hence, this work presents a solution to the overvoltage problem associated with the integration of microgeneration systems placed in a power distribution network. The goal is to modify the microcontrollers (software update) of the microgenerators, so that the reference voltage value remains below 253V, which is the maximum permitted value, according to NP EN 50160 [3]. Thus, maximizing the energy sold to the grid.

To achieve the proposed solution, the following objectives are defined:

- Simulation of a low voltage distribution network with rural characteristics, including the determination of the representative model of the network components: medium to low voltage transformer, overhead distribution lines and typical electric loads for residential areas.
- Microgenerator model simulation and analysis of the network’s voltage profiles evolution due to the integration of microgenerators, considering both high load situation and low load situation scenarios.
- Implementation of a solution based on the phase shift of the current injected by the microgenerators, relative to the voltage at its terminals in order to get voltage profiles to respect the legally established values by absorbing reactive power from the network.
- Demonstration of the performance of the solution, using a linear control system of the RMS voltage value at the connection point to regulate the phase shift to be applied to the output current of the microgenerators.
Obtain and demonstrate other possible solutions, such as a slight reduction of the installed microgenerators power, in order to reduce the RMS voltage values at the connection points of microgenerators.

II. LOW VOLTAGE NETWORK MODEL

The model of the low voltage network was built using Matlab/Simulink software. The grid includes models of the MV/LV transformer, low voltage overhead distribution lines and electrical loads.

The structure of the simulated network is represented in Fig. 1, showing on the low voltage the 3 electrical feeders, in which feeder 1 has 5 line sections and feeders 2 and 3 (feeders represented by an equivalent system) have 2 line sections, and also the location of microgeneration systems installed along the 3 feeders. The total length of feeder 1 is 500m, which is an acceptable distance for a typical rural network because they shall not exceed 700-1000m of maximum distance between the transformer substation and the client [4]. The configuration of the network is based on an existing network [5], which was built in accordance with the legislation of Decree-Law 363/2007 [6], where the power of microgeneration connected to power substation was limited to 25% of the nominal power of the respective transformer, and the injected power was also limited to 50% of the contracted power for each electrical installation. Knowing that today’s residences mostly have a contracted power of 6.9kVA, it’s possible to install in the network up to 18 microgeneration systems of 3.45kW each.

The microgeneration groups are each composed of three microgeneration systems, one per phase. The microgeneration group 2 is the only composed of 6 microgeneration systems, i.e., at each phase of this group is provided twice the power.

The connection of the medium voltage to the low voltage is performed by a three-phase power transformer, with appropriate characteristics to the desired power and network voltage level of Medium Voltage / Low Voltage network.

In the Portuguese power grid, the exploitation of MV, is performed in three levels of RMS voltage between phases: 10kV, 15kV and 30kV. In LV the network may have transformation powers that can be 630kVA, 400kVA or 250kVA, being the RMS level of the secondary voltage of transformer 400V / 230V.

In this work, the transformer is connected in delta in MV and star in LV with neutral solidly grounded. It was considered an apparent power transformer of 250kVA with a voltage level of the primary side of 30kV.

Since most of these transformers allow to adjust the output voltage within ± 5% of its value in order to compensate for losses in distribution lines, it was applied 420V (line-to-line voltage) to the secondary side of the transformer.

The transformer used in the simulation, showed in Fig. 2 comprises three output phases (R, S, T) and a neutral (N) (three-phase transformation system with neutral ground).

![Fig. 2 – Model of MV network and the MV/LV transformer.](image)

The model of the transformer used in the network is the T model [7] that is represented in Fig. 3, it has been used for sizing the transformer model parameters based on the values of the parameters in the catalog available from Merlin Gerin [8].

![Fig. 3 – T model of the transformer.](image)

B. Distribution power lines model

As overhead distribution lines are the typical solution in rural distribution networks, this is what was decided to adopt for this work. The distribution lines were dimensioned according to the technical standard solutions of EDP [9]. Taking into account the maximum operating current flowing through the cables, and network line length values, it was selected the cable, LXS 4x50 (50mm2 section) in a configuration of 4 conductors (3 phase conductors and neutral).

The three-phase radial network topology is constituted exclusively by overhead cables isolated on bundle of type LXS. In the context of simulation, neglecting the shunt admittances, the low voltage network lines can be modeled by fixed parameters of passive elements (resistance and inductive reactance), so it was adopted the RL series model shown in Fig. 4.

![Fig. 4 – a) Representative block of a LV line; b) Model of the phases and neutral of a power line.](image)

C. Electrical loads model

For the model of linear loads connected to the buses of the low voltage network, and given the limitations of computer calculation speed, several houses were considered in a single point of consumption represented as an equivalent three-phase load.
The linear loads are frequently resistive and inductive, and for this reason, in this work are represented by the three-phase loads RL type connected in star (with accessible neutral) and whose model implemented in the simulation of loads is presented in Fig. 5.

![Fig. 5 – Model of electric loads.](image)

To define the active and reactive power consumed by each load it was necessary first to define the number of residences, based in the contracted power, the power that transits in each feeder, the load factor, and the simultaneity coefficient which allows more realistic distribution of power consumed. In addiction it is considered a stipulated power factor $\cos(\phi)$ or $P_F$. Table 1 shows the load characteristics for the three feeders of the rural network.

<table>
<thead>
<tr>
<th>Loads</th>
<th>Feeder 1</th>
<th>Feeder 2</th>
<th>Feeder 3</th>
<th>Feeder 4</th>
<th>Feeder 5</th>
<th>Feeder 6 or 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presence of microgeneration</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Contracted Power (kVA)</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
</tr>
<tr>
<td>No. residences</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>Coefficient of Simultaneity</td>
<td>0.5266</td>
<td>0.5266</td>
<td>0.5578</td>
<td>0.6619</td>
<td>0.6619</td>
<td>0.3540</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.8</td>
<td>0.8</td>
<td>0.75</td>
<td>0.8</td>
<td>0.75</td>
<td>0.8</td>
</tr>
<tr>
<td>$S_c$ (kVA)</td>
<td>21,801</td>
<td>21,801</td>
<td>19,243</td>
<td>13,701</td>
<td>13,701</td>
<td>58,993</td>
</tr>
<tr>
<td>$P_c$ (kW)</td>
<td>17,441</td>
<td>17,441</td>
<td>14,432</td>
<td>10,961</td>
<td>10,267</td>
<td>47,195</td>
</tr>
<tr>
<td>$Q_c$ (kVar)</td>
<td>13,081</td>
<td>13,081</td>
<td>12,728</td>
<td>8,2206</td>
<td>9,0623</td>
<td>35,396</td>
</tr>
</tbody>
</table>

In order to account the unbalances of a real network it was made a distribution of power loads for the R, S, T phases, as shown in Table 2.

<table>
<thead>
<tr>
<th>Phases</th>
<th>Loads of feeder 1</th>
<th>Loads of feeders 2 and 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>35%</td>
<td>30%</td>
</tr>
<tr>
<td>S</td>
<td>30%</td>
<td>35%</td>
</tr>
<tr>
<td>T</td>
<td>35%</td>
<td>35%</td>
</tr>
</tbody>
</table>

### D. Microgenerator model

The microgenerator model is simplified and consists in using a source of alternating current to represent the behavior of the voltage inverter used in microgeneration, which is controlled to provide a certain current. The current supplied by the current source, represented by $I(t)$ is determined based on the active power $P$ that is to be injected in the network, and the voltage value $V_{MG}(t)$ obtained in microgenerator terminals.

The modeling microgenerator it is established by relations (1) and (2), considering as reference the phase voltage $V_{MG}(t)$.

$$V_{MG}(t) = \sqrt{2} V_{MGef} \sin(\omega t) \iff \sin(\omega t) = \frac{V_{MG}(t)}{\sqrt{2} V_{MGef}}$$ (1)

$$I(t) = \sqrt{2} I_{ef} \sin(\omega t) \iff I(t) = \sqrt{2} I_{ef} \frac{V_{MG}(t)}{\sqrt{2} V_{MGef}} = \frac{I_{ef} V_{MG}(t)}{V_{MGef}}$$ (2)

The active power injected into the network is represented by the following expression:

$$P = V_{MGef} I_{ef} \cos(\phi)$$ (3)

Of this expression (3) is obtained the RMS current value (4).

$$I_{ef} = \frac{P}{V_{MGef} \cos(\phi)}$$ (4)

The alternating current as a function of the active power, and the voltage at the microgenerator’s terminals (5) is obtained using the expression (2) and replacing the RMS current value present in (4)

$$I(t) = \frac{P}{V_{MGef} \cos(\phi)} \cdot V_{MG}(t) = \frac{P}{V_{MGef} \cos(\phi)} \cdot V_{MG}(t)$$ (5)

The microgenerator simplified model scheme is represented in Fig. 6. The transfer block present in the output of the voltmeter is composed of a time constant $T_{d} = 100\mu s$ that filters the signal of the network voltage. The following transfer block before the current source has a time constant $T_d = 100\mu s$ that reduces the distortion of the current that is injected into the network. Subsequently, this model will change when a current phase shift (relative to the voltage $V_{MG}(t)$) is induced.

![Fig. 6 – Structure of simplified model microgenerator.](image)

### III. SIMULATION OF NETWORK MODEL

The network of Fig. 1 is simulated for seven different scenarios, being chosen for this paper the three most relevant, which are scenarios 1, 2 and 7. The scenarios are simulated with and without microgeneration, considering two situations: the high load consumption situation with a load factor of 70% and the low load consumption situation with a load factor of 2%.

In Fig. 7 is presented the first simulated scenario (without microgeneration and with a high load) and in Fig. 8 is shown the second scenario (without microgeneration and with a low load). The RMS voltages profiles decrease, as expected, in both cases along the feeder 1. On the contrary, the scenario 7 (Fig. 9) when all microgenerators are operating at rated power on the network and we have a low load situation there is an increase in the RMS voltage value along the feeder 1 and exist a permanent voltage at the end of the line. Moreover, the RMS voltage value is 253,4V, not complying with the standard NP EN 50160 [3]. The Table 3 shows the values of neutral voltage and currents measures between the neutral of the line and the ground for the scenario 7.
Table 3 – Neutral voltages and currents measured in all bus of the feeder 1(Scenario 7).

<table>
<thead>
<tr>
<th>Bus</th>
<th>(V_{ef}(V)) - Neutral</th>
<th>(I_{ef}(A)) - Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0030</td>
<td>0.0659</td>
</tr>
<tr>
<td>2</td>
<td>0.0120</td>
<td>0.1555</td>
</tr>
<tr>
<td>3</td>
<td>0.0191</td>
<td>0.1257</td>
</tr>
<tr>
<td>4</td>
<td>0.0235</td>
<td>0.0627</td>
</tr>
<tr>
<td>5</td>
<td>0.0269</td>
<td>0.0579</td>
</tr>
</tbody>
</table>

IV. MITIGATION OF OVERVOLTAGES

A. Operation principle of the overvoltages reduction system

The microproduction systems inject in the network a current in phase with the voltage of the connection point. The method implemented in this work, in order to mitigate the overvoltage regimes, is based on a current phase shift of the microgenerator which is injected into the network, originating a reactive power which promotes a small lowering of voltage, enough to bring the voltage to the threshold range of the standard, so that the relay overvoltage protection does not act. Considering the system feeder 1 in a situation of low load and assuming its permanent operation, it is possible to design the model in Fig. 10, which contains two voltages, the reference voltage \(V_R\) and the microgenerator terminals voltage to be controlled \(V_{MG}\), and a line resistance \(R_{eq}\), and a line inductive reactance \(X_{eq}\).

![Simplified model of feeder 1.](image)

Given the previous model, the variation of voltage or voltage drop which occurs on the line can be written by the following equation (according to [7]):

\[
\Delta V \approx V_{MG} - V_R = I_{MG}(R_{eq} + jX_{eq})
\]  

(6)

As the microgenerator output current is given by (7) \((\phi_{MG} > 0)\), the expression (6) can be written as (8), knowing that \(\frac{Q}{P} = \tan \phi_{MG}\).

\[
I_{MG} = \frac{P}{V_{MG}} e^{j\phi_{MG}} = \frac{P}{V_{MG}} + j \frac{Q}{V_{MG}}
\]  

(7)

\[
\Delta V = V_{MG} - V_R = \frac{P}{V_{MG}} \left(1 - \frac{X_{eq}}{R_{eq}} \tan \phi_{MG}\right)^{1/2} + \frac{\left(\tan \phi_{MG} + \frac{X_{eq}}{R_{eq}}\right)^{1/2}}{1 - \frac{X_{eq}}{R_{eq}} \tan \phi_{MG}}
\]  

(8)

Neglecting the square root contribution in equation (8), since this term is approximately 1 for the values of \(\phi_{MG}\) of interest, is obtained:

\[
\Delta V \approx \frac{R_{eq} P}{V_{MG}} \left(1 - \frac{X_{eq}}{R_{eq}} \frac{Q}{P}\right) = \frac{R_{eq}}{V_{MG}} \left(1 - \frac{X_{eq}}{R_{eq}} \tan \phi_{MG}\right)
\]  

(9)

For the voltage variation \(\Delta V\) be zero must be injected a reactive power:
\[ Q \approx \frac{P_{eq}}{X_{eq}} \]  

Making \( V_{MG} = V_{R} + \Delta V \), substituting in (9) and solving the resulting equation is obtained:

\[ \Delta V = -\frac{V_{R}}{2} + \frac{V_{R}^2}{4 + P_{eq} R_{eq}} \left( 1 - \frac{X_{eq}}{R_{eq}} \tan \phi_{MG} \right) \]  

Being \( R_{eq} > X_{eq} \) in the LV networks, given (9) and (10) it can easily be conclude that the compensation process can only mitigate small voltage variations, i.e. reducing from 250,817V to 242V imply a reactive power out of specification the microgenerator. Assuming \( P = 3450W \), \( V_{R}=242 \), \( R_{eq}=0.641\Omega \) and \( R_{eq}/X_{eq}=6.41 \) is obtained for \( \phi_{MG}=0 \) a voltage variation of \( \Delta V=8.817V \) and for \( \phi_{MG}=60^\circ \) a variation of \( \Delta V=6.495V \), achieving a decrease of 2.322V relative to the case where \( Q=0 \).

**B. Voltage drop with phase shift of the output current of microgenerator.**

The evolution of the AC voltage input to the microgenerator is described by the following equation:

\[ V_{MG}(t) = \sqrt{2} V_{MG_{ef}} \sin(\omega t) \]  

The evolution of the injected alternating current network, in case of unit power factor is described by the following equation:

\[ I(t) = \sqrt{2} I_{ef} \sin(\omega t) \]  

Intending to apply a phase shift to the current equation:

\[ I(t) = \sqrt{2} I_{ef} \sin(\omega t + \phi_{MG}) \]  

Where \( \phi_{MG} \) is the phase angle to be applied.

Through trigonometric relationships it is known that:

\[ \sin(\omega t + \phi_{MG}) = \sin \omega t \cos \phi_{MG} + \cos \omega t \sin \phi_{MG} \]  

In terms of simulation, as it is intended to apply a \( \phi_{MG} \), it is necessary to obtain the components \( \sin \omega t \) and \( \cos \omega t \) of expression (15). Manipulating the equation of the alternating voltage microgenerator (12) it can be obtained its sinusoidal component in pu values:

\[ \sin(\omega t) = \frac{V_{MG}(t)}{\sqrt{2} V_{MG_{ef}}} \]  

The component \( \cos \omega t \) is obtained knowing that:

\[ \cos(\omega t) = -\omega \int \sin(\omega t) \, dt \]  

The Fig. 12 shows how the phase shift has been applied in the simulation.

**Fig. 12 – Implementation of the phase difference in the simulation.**

Thus, the current injected into the grid by the microgenerator now has the following expression:

\[ I(t) = \sqrt{2} \frac{P}{V_{MG_{ef}}} \cos(\phi_{MG}) \sin(\omega t + \phi_{MG}) \]  

The Fig. 13 shows the relationship between voltage-reactive power allusively to a microproduction system. The analysis of the figure shows that when the reactive power increases as a consequence of the network’s reactive power absorption due to the injected current phase shift, the voltage of the connection point of the microgenerator decreases.

**Fig. 13 – Characteristic voltage-reactive power of power systems (Source [7]).**

Analyzing Fig. 14 it is possible to conclude that the active power of microgenerator number 5 has a negative sign due to the active power that it injects in the network. Moreover, its reactive power grows which is a consequence of the absorption of reactive power coming from the network.

**Fig. 14 – Active power (kW) and reactive power (kVar) as a function of phase shift of the microgenerator output current.**
C. Regulation using the reactive power in passive elements

To illustrate that the method proposed for the phase shift corresponds to a reactive power, it was tested in an equivalent network with a microgenerator of unity power factor, the placement of a coil in parallel with the current source microgenerator (Fig. 15).

From the equation (19) and by comparing the effect of the presence of the coil in the microproduction system with a phase shift of 45° without the presence of the coil, the method used for simulation of a phase shift in the current is equivalent to placing a reactive element parallel to the microgenerator.

\[
L = \left(\frac{V_{MG_{\phi=45}}}{{\omega Q_L}}\right)^2 \quad (H)
\]

Where:

\( V_{MG} \) – RMS voltage value in microgenerator for a phase shift of 45°.

\( Q_L \) – Inductive reactive power the coil.

\( \omega \) – Angular frequency network.

D. Regulator operating in reactive power to reduce overvoltages

The control system has the function to adjust the angle of phase shift of the microgenerator output current in relation to the supply voltage at the connection point. Its operation is based on the comparison of the RMS voltage read to microgenerator terminals with a reference value less than 253V. If the error of comparing, presents a negative value it means that the microgenerator voltage is higher than the value stipulated in the reference and so there is an overvoltage. In this case using a value \( \phi_{MG} \) proportional to the integral of the error, the microgenerator voltage at the connection point is set to the reference value. If it is established that the error is positive should be kept operating point of microgenerator, i.e., there is no action of this regulator (which saturates in \( \phi_{MG} = 0 \)) should be kept the injection state of the maximum power available microgeneration.

From (8) can be obtained:

\[
V_{MG} - V_R = \frac{P R_{eq}}{V_{MG}} \left(1 - \frac{X_{eq}}{R_{eq} \tan \phi_{MG}}\right) \Rightarrow
\]

\[
\Rightarrow V_{MG} \approx \frac{V_R}{2} + \frac{\sqrt{V_R^2 + P R_{eq}}}{{\omega R_{eq}}^2} \left(1 - \frac{X_{eq}}{R_{eq} \tan \phi_{MG}}\right)
\]

Taking the derivative of \( V_{MG} \) in order to the phase angle \( \phi_{MG} \), we obtained the expression (21), which allows to proceed the calculation of the incremental gain of the microproduction system.

\[
K_{i} \approx \frac{dV_{MG}}{d\phi_{MG}} \approx \frac{1}{2} \left(\frac{-P X_{eq}}{X_{eq}}\right)^2 \left(1 - \frac{X_{eq}}{R_{eq} \tan \phi_{MG}}\right)
\]

The value of this incremental gain is negative in the interval \(-3.395 < K_i < -0.0894\) for the values of interest \( \phi_{MG} \), i.e., \(0 < \phi_{MG} < 60°\).

Assuming one delay \( T_d \) on inverter modulator, the Fig. 16 illustrates the block diagram that represents the input voltage control system of microgenerators, i.e. voltage \( V_{MG} \). It adopts as a reference value for this voltage the value \( V_{MGref} = 252V \). On this closed-loop control is used an integral controller, which allows adjust the value of the phase shift to be applied to the system, whose transfer function is given by equation (25).

\[
\frac{V_{MG}}{V_{MGref}} = \frac{K_i}{1 + K_i s T_d} = \frac{K_i K_d}{s^2 T_d + s + K_i K_d} = \frac{K_i K_d}{T_d}\left(\frac{1}{s^2 + \frac{s}{T_d} + \frac{K_i K_d}{T_d}}\right)
\]

Comparing the equation (22) with the canonical form of a 2nd order system \( \frac{w_n^2}{s^2 + 2\xi T_d s + \omega_0^2} \), we obtain:

\[
2\xi w_n = \frac{1}{\omega_0 T_d} \Rightarrow w_n = \frac{1}{2\xi T_d}
\]

\[
w_n^2 = \frac{K_i K_d}{T_d} \Rightarrow \frac{1}{4\xi^2 T_d^2} = \frac{K_i K_d}{T_d} \Rightarrow \xi = \frac{1}{\sqrt{4\xi^2 T_d^2}}
\]

Adopting a damping factor \( \xi = \frac{\sqrt{\pi}}{2} \) and a time constant \( T_d \approx 92.39\text{ms} \) with \( K_i \approx -5.412 \), obtain a quick response in the system. Thus the integral controller gain can be calculated by expression (25):

\[
K_i = \frac{1}{4 \times \left(\frac{\sqrt{\pi}}{2}\right)^2 \times (-5.412) \times 0.09239} \approx -1
\]

E. Regulator behavior verification by phase difference of the current in a balanced microgeneration system

Once sized and implemented into the network the upgraded microgenerator overvoltage system, proceeds to check its behavior when the network presents an overvoltage, particularly being tested and simulated for scenario 7.

In Fig. 17 presents the results under the action of the regulator, for scenario 7. In this case the RMS voltage value, at the end of the line, converged to the reference value 252V. Thus, it can be concludes that the control is able to mitigate the overvoltage. The voltage value at the end of feeder 1 stays in the threshold range set by the NP EN 50160 and allowing the continuous operation of the microgenerator. On Table 4 is show the values in degrees of the phase shifting that occurred in the output currents of the microgeneration group 5. The Fig. 18 represents the temporal evolution of voltages and currents in all three phases belonging to the inputs of the micro group 5 at the end of this feeder. Analyzing the figure it can be observed the phase shift between the output currents and voltages of the microgenerators in the connection point.
In this section it is presented and analyzed the results of the simulation of the regulator in microgenerators in the low voltage network in a situation of low load, for two scenarios characterized by a power unbalance in micro injection group 5.

**Scenario 1:** LV network, with unbalance in the power injected by the S phase of the micro group 5.

In this scenario, without the presence of regulators, the S phase of the micro group 5 is disconnected from the network, causing an unbalance between the three phases of this group. In Fig. 19 one can verify that the profiles of the RMS voltage values in the phases R and T of the groups MG4 and MG5 are in an overvoltage situation, worse than the previous scenarios.

In Table 6 it is observed that the voltages and neutral currents have a significant increase in its RMS value, which is justified by the unbalance created in the network. The neutral current different of zero implicate a higher neutral voltages and therefore impact with the phase-neutral voltages.

**Table 6 – Neutral voltages and currents measured in all bus of the feeder 1.**

<table>
<thead>
<tr>
<th>Bus</th>
<th>( V_{df} ) (V) - Neutral</th>
<th>( I_{df} ) (A) - Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,6142</td>
<td>13,5250</td>
</tr>
<tr>
<td>2</td>
<td>1,4087</td>
<td>13,6070</td>
</tr>
<tr>
<td>3</td>
<td>2,3028</td>
<td>13,7824</td>
</tr>
<tr>
<td>4</td>
<td>3,2822</td>
<td>13,7245</td>
</tr>
<tr>
<td>5</td>
<td>4,4567</td>
<td>13,9261</td>
</tr>
</tbody>
</table>

In Fig. 20 are shown the results obtained for the voltage profiles along the feeder 1, by actuation of the inserted regulators in all micro groups of the LV network, in the situation previously described of an unbalance in the S phase of the micro group 5. In this figure, there is an unexpected situation, i.e. by regulating the microgenerators in the network, the S phase has a significant increase in its RMS voltage value, while the other two phases has a decrease in their RMS voltage value, not converging to the reference value stipulated by the regulators.

In Table 7 shows the values of the voltages and neutral currents, measures the five buses in feeder 1. Although they are lower RMS values (because of the presence of the micro group controller 5) than the initials (see Table 6), remains very high values which contribute to instability in the network.

**Table 7 – Neutral voltages and currents measured in all bus of the feeder 1.**

<table>
<thead>
<tr>
<th>Bus</th>
<th>( V_{df} ) (V) - Neutral</th>
<th>( I_{df} ) (A) - Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,0022</td>
<td>0,0473</td>
</tr>
<tr>
<td>2</td>
<td>0,0036</td>
<td>0,0637</td>
</tr>
<tr>
<td>3</td>
<td>0,0024</td>
<td>0,0501</td>
</tr>
<tr>
<td>4</td>
<td>0,0015</td>
<td>0,0394</td>
</tr>
<tr>
<td>5</td>
<td>0,0057</td>
<td>0,0706</td>
</tr>
</tbody>
</table>
Fig. 20 – Variation of the RMS voltage values along the feeder 1 (with regulation).

Table 7 – Neutral voltages and currents measured in all bus of the feeder 1.

<table>
<thead>
<tr>
<th>Bus</th>
<th>$V_{ef}$ (V) - Neutral</th>
<th>$I_{ef}$ (A) - Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,5271</td>
<td>11,5864</td>
</tr>
<tr>
<td>2</td>
<td>1,2002</td>
<td>11,5065</td>
</tr>
<tr>
<td>3</td>
<td>1,9226</td>
<td>11,1173</td>
</tr>
<tr>
<td>4</td>
<td>2,7197</td>
<td>11,1510</td>
</tr>
<tr>
<td>5</td>
<td>3,6281</td>
<td>10,7558</td>
</tr>
</tbody>
</table>

Scenario 2: LV network with power unbalance injected by the phases S and T of the micro group 5.

In this scenario, without the presence of regulators, the S and T phases of the micro group 5 are disconnected from the network. In Fig. 21 it can be seen that the profile of the RMS voltage on phase R in the MG4 and MG5 groups are in a overvoltage. In Table 8 are shown the values of the voltages and neutral currents, measures the five buses in feeder 1.

![Fig. 21 – Variation of the RMS voltage values along the feeder 1 (without regulation).](image)

Table 8 – Neutral voltages and currents measured in all bus of the feeder 1.

<table>
<thead>
<tr>
<th>Bus</th>
<th>$V_{ef}$ (V) - Neutral</th>
<th>$I_{ef}$ (A) - Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,5952</td>
<td>13,1062</td>
</tr>
<tr>
<td>2</td>
<td>1,3656</td>
<td>13,1940</td>
</tr>
<tr>
<td>3</td>
<td>2,2271</td>
<td>13,2805</td>
</tr>
<tr>
<td>4</td>
<td>3,1752</td>
<td>13,2860</td>
</tr>
<tr>
<td>5</td>
<td>4,3066</td>
<td>13,4145</td>
</tr>
</tbody>
</table>

Fig. 22 illustrates the results concerning the profiles of the voltage along of feeder 1 by actuation of the inserted regulators in all micro groups of the LV network, on the situation described above, characterized by an unbalance in the S phase and group T micro 5. In this figure is again seen a situation unexpected and shortly desired, that is, to introduce the regulation of microgenerators, T phase has a significant increase in its RMS voltage value, while the other two phases has a decrease in their RMS voltage values does not converge to the reference value established by the regulators. Table 9 shows the values of the voltages and neutral currents, measures the five buses of feeder 1. In contrast to scenario 1 with regulation, the RMS voltage values and currents neutral in this scenario are even higher than the initial (see Table 8), which contribute to instability in the network, making impossible the adjustment of the tension profiles.

![Fig. 22 – Variation of the RMS voltage values along the feeder 1 (with regulation).](image)

Table 9 – Neutral voltages and currents measured in all bus of the feeder 1.

<table>
<thead>
<tr>
<th>Bus</th>
<th>$V_{ef}$ (V) - Neutral</th>
<th>$I_{ef}$ (A) - Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,8834</td>
<td>19,4401</td>
</tr>
<tr>
<td>2</td>
<td>2,0232</td>
<td>19,5097</td>
</tr>
<tr>
<td>3</td>
<td>3,2734</td>
<td>19,2624</td>
</tr>
<tr>
<td>4</td>
<td>4,6449</td>
<td>19,2079</td>
</tr>
<tr>
<td>5</td>
<td>6,6878</td>
<td>24,5420</td>
</tr>
</tbody>
</table>

Since the values of voltages and neutral currents are very high, at network unbalance the regulators for both scenarios described above have an inefficient operation and therefore the approach to the existing overvoltage problem by the regulation of the phase shift of the current, is not feasible because of the possibility of at least one of the phases presents an overvoltage disturbance or very close in achieves this regime, not respecting this way, the NP EN 50160 and holding a malfunction of microgenerators.

In order to overcome this problem, one solution would be the implementation of three-phase microproduction systems, in what is considered in three phases of microgenerator’s, a uniform...
distribution of power that is injected into the network, so as to reduce the unbalances between the links of phases and neutral. Another solution is to reduce the active power as proposed below.

G. Linear power reduction of microgenerators

In the following simulations, the power variation is characterized by the successive decrease of 10% of its maximum initial value of 3.45kW up to half value.

In Fig. 23 is shown the variation of the RMS voltage in the three phases of the micro group 5 in function of the power injected into the network by the three microgenerators group 5. This figure was obtained in a balance network (corresponding to scenario 7 of Section III). For analysis of the figure is observed the decrease of the RMS voltage values in the three phases of the group 5, and from a reduction of roughly 10% of initial power no longer verifying the overvoltage regimes.

![Fig. 23 – Linear power reduction in the three phases of the micro group 5.](image)

A network unbalance as the example given for scenario 1 of Section IV (without regulation), the R and T phases of micro groups 4 and 5 shown a overvoltage regime. So, in this scenario proceeds to the gradual reduction of active power in those four microproduction systems. Fig. 24 shown the variation of RMS voltage in the R and T phases of the micro groups 4 and 5 as a function of the power injected into the network by these phases. For analysis of the figure is evidenced in both micro groups a decrease of the RMS voltage value in both R and T phases and that from a decrease within 20% to 30% of initial power, no longer verifying the overvoltage regimes.

![Fig. 24 – Linear reduction of power in phases R and T of micro groups 4 and 5.](image)

In the network unbalance, as the example given for scenario 2 of Section IV (without regulation), the phase R of micro groups 4 and 5 presents a voltage to the terminals of the respective microgenerators. So, in this scenario proceeds to the gradual reduction of active power in both of these microproduction systems.

The Fig. 25 shown the variation of RMS voltage in phase R of the micro groups 4 and 5 in function of the power injected into the network by these phases.

From the analysis of the figure it is evidenced in both micro groups a decrease of the RMS voltage value of the phase R, and that from a decrease between 30% to 40% of initial power, no longer verifying the overvoltages regime.

![Fig. 25 – Linear power reduction in the phase R of micro groups 4 and 5.](image)

The purpose of the linear power reduction of microgenerators is to reduce the voltage on the microproduction system terminals. The results presented above show that the goal is fulfilled.

V. CONCLUSIONS

This work aims to contribute to the evaluation and resolution of problems in the quality of electricity, particularly in inconveniences related to overvoltages occurrence in networks with high integration of microgeneration. Thus, one of the main objectives of this study was to analyze the variation of voltage profiles in a network of rural Lower voltage where various groups of microgeneration are connected.

With the implementation of the model of the network and the microgeneration model in Matlab/Simulink, it was possible to evaluate the behavior of the voltage, current and active and reactive
power, for different scenarios, changing the load factor of the transformer and the number of microgeneration groups. The simulation results have shown that at the endpoint of the network (whose distance from the transformer substation is 500m), to a low load scenario where the client consumption is low and where there is a maximum power injection in the network, is the situation in which effectively occurs permanent overvoltage’s, since the variation in the voltage profiles tends to be lower.

The presence of an overvoltage at the end of the network was mitigated using the microgenerators phase shift of the output current in relation to its supply voltage. Thus, through an updating of the models of the microgenerators, the phase shift applied to the current injected by microgeneration allows that some reactive power is absorbed from the network, conducting to a reduction in the RMS voltage value at the connection point of microgenerators. The value of the phase shift in the current, by direct action of the controller in the microgeneration system, reduces the voltage on the network to the desired reference value. The implementation of the proposed solution allows concluding, that it is possible to maintain a continuous operation of microgenerators in low load periods to any microproduction system installation point on the network at the cost of an increase value of the injected current and absorbing reactive power from that network. The studied and implemented current phase shift method was also proved by placing a coil in parallel with the current source of each microgenerator. Other microgenerator grid connection conditions have been tested, either changing the phases connected to the network of the microgeneration group 5, or by applying a slight decrease in active power output, relative to the peak power installed in microgenerators groups 4 and 5. For the first case, it was found that due to the presence of high neutral voltages and neutral currents, there would be a huge unbalance in the network and, therefore, the control it’s no longer possible in this situation, since at least one phase tends to increase relative to the other two. In the second case, the simulation results have shown that the RMS voltages values decrease, remaining below the threshold featuring an overvoltage, thus ensuring the correct functioning operation of microgeneration systems.

REFERENCES