Research and Control of Photovoltaic Inverter Response to Voltage Rise in Weak Low-voltage Networks

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Abstract – The penetration of small roof-top photovoltaic (PV) installations at domestic low voltage (LV) residential sites has been growing in the last decade. High penetrations have led to voltage rise above the legal limit of 253V in weak networks. Several solutions have been implemented to mitigate the voltage rise problems such as the disconnection of the PV inverter from the grid, which among other inconveniences, decreases the micro-producer profit. In this paper we analyze the response of PV inverters to voltage rise under realistic situations to then propose an automatic control solution to voltage rise mitigation that can be implemented economically. Such solution is implemented in a prototype and tested under different situations to validate its effectiveness and its compliance with the international quality of service standards, namely those for maximum harmonic distortion.

Keywords – Local voltage control, Photovoltaic inverter, weak low-voltage networks, Micro-generation penetration, Voltage rise mitigation.

I. INTRODUCTION

During the last decades, distributed generation has become an important means of production of electricity. Lower prices of technology and high tariffs for electricity sale have made PV micro-generation an interesting investment for small domestic producers, being the non-centralized production more than 50% of the total PV installed production worldwide nowadays [1]. However, the penetration of distributed generation in low-voltage networks has brought a serious problem to these. LV networks have to follow strict rules in what concerns to some parameters of its voltage, namely the maximum RMS voltage and total harmonic distortion allowed, 253Vrms and 8%, respectively [2]. With the penetration of high levels of micro-generation in weak LV networks, the voltage rise above the legal limit is a common occurrence. Becoming necessary to prevent and mitigate this occurrence, the objective of this paper is to study the response of PV inverters to the rise of voltage in LV networks and to evaluate the different control approaches, choosing the best one and implementing it in a prototype.

II. DESCRIPTION OF THE PROBLEM

LV networks can be represented by a generator (transformer station) connected to loads (consumers) through a series of impedances (power lines) as it can be schematized in fig. 1.

![Fig. 1 – Simplified Representation of a LV network](image)

The network power lines can be represented by a resistance, (since $\frac{V}{I} \gg 1$) consumer loads are unknown and variable throughout the day and through the time of the year and transformer stations have a nominal voltage of 230Vrms but a narrow range of operation, with a maximum deviation of 10%. This means that voltage in a network cannot exceed 253Vrms or fall under 207Vrms. Yet, maintaining network voltage between these values is not an easy task. Because LV lines aren’t perfect conductors, voltage drops appear at the ends of each section of cable. These voltage drops are proportional to the current requested by consumers to the grid, leading to a decreasing available voltage at each point of the network as we go further from the transformer station. The transformer must be then adjusted so the voltage in the first consumer is lower than 253Vrms and the voltage in the last consumer is higher than 207Vrms. This would be easy if the network didn’t experience changes, but, throughout the day there are periods with extreme consumption, peak hours, and periods with a great lack of consumption, off-peak hours. In an extreme situation, presented in fig. 2, in which a transformer is set to 253Vrms but experiences a period on which there is no consumption, the voltage through the network will be approximately equal throughout all the line. If a micro-producer placed at the end of the network wanted to deliver its maximum power (which represents a current of 16A) into the network, which can be 1km long and may have 1Ω/km in the worst case scenario [3], a voltage drop of 32V (16A x 2Ω) would appear, meaning that the voltage in the micro-generation point would rise to 285V and the inverter would disconnect. Even
though this is a worst-case scenario, the disconnection of PV inverters due to voltage rise, especially in the summer, is a real paradigm.

\[ V_i = 253 \sin(\omega t) \]

**Fig. 2 – Representation of the worst-case scenario for voltage rise**

The existence of weak LV networks, in majority, is mostly due to the high fluctuation of consumption in certain areas where micro-generation penetration is high. The fact that most of the times the peak of micro-production overlaps with the off-peak hours of consumption causes serious voltage oscillations. Moreover, many of the LV networks were dimensioned at a time when micro-generation wasn’t a common reality and several have experienced expansions that have exceeded the ones initially planned. Although this situation is envisaged by a law that forbids PV micro-generation installation to be greater than 25% of the transformer station installed capacity, this number has been revealed as a rough solution. We suggest micro-generation to be taken into consideration when planning the maximum assessment of PV generation in old LV networks with simultaneity coefficients closer to 1, since when one producer is able to generate energy, all the others in the same network will also be. As the reinforcement and systematic adjustment of LV networks are expensive and inconvenient, especially in isolated situations, a control method must be applied. The On/Off control approach, which most current inverters apply, is not only prejudicial to the producer’s income but may also cause a cascade disconnection of all other PV inverters in the same network. Two other controls, global and local control are alternatives to the previous one. As global control is heavy in terms of variables which need to be acquired throughout the LV network, it is necessary to establish an expensive telecommunications network to communicate from the dispersed points to the central. Along with the fact that global control is the approach that needs the biggest reduction of active power in order to be effective, the consequent choice is to implement the local control, a cheaper control that can be installed only in the locations where it is needed.

**III. PROPOSED SOLUTION**

The proposed approach intends to introduce a partial consumption of energy, only in sufficient quantity to keep the voltage below the maximum legal limit. This way, the generator will always be producing and delivering energy into the network, although less than its full available power for that instant, but always a better solution than a total disconnection.

The circuit is projected to permanently monitor the RMS network voltage in the point of injection and when it exceeds the threshold voltage, a control block will generate a triggering voltage that will be used as control voltage for a thyristor triggering integrated circuit, an Infineon / Siemens TCA 785, that sends a pulse triggering signal, \( \epsilon \), to a TRIAC, two anti-parallel thyristors that precede a dissipation high power resistor. All of this electronics are projected so the control voltage and the triggering angle result in a new network voltage wave, consisting of two sinusoidal waves with different amplitudes, after and before \( \epsilon \), so the final RMS value for the voltage in the network is less than the maximum permitted by law.

The electronics behind the solution can be separated in 7 blocks, as fig. 3 shows, each with different functions: The PV Generator (1), the LV network (2), the triggering circuit (3), the RMS-DC conversion (4), the proportional control (5), the triggering signal processing (6) and the partial energy consumption (7).

**Fig. 3 – Block diagram of the electronics for the proposed solution**

The first and second blocks are only the inputs/outputs of the solution, and their implications have been briefly explained in chapter II. Besides that information, it’s from the network that we are going to acquire the signal to be controlled, although that voltage has to be lowered by a transformer to an acceptable level to the electronics. It’s also from the network voltage that we are going to feed the +15.0-15V DC power source to supply the electronics.

The 3rd block is mainly composed by an integrated circuit, a TCA 785, that from a network synchronism signal (\( V_s \)) and a control voltage (\( V_{ii} \)), generates two triggering signals for a TRIAC, spaced from each other by 180º. Since this control voltage will be compared with a ramp signal that will be generated internally (starting from each zero of the network voltage), the higher the control voltage, the later the triggering signal will appear, as. Fig. 4 exemplifies.

**Fig. 4 – Main input, internal signals and outputs of the TCA 785 IC**
The triggering time is given by eq. 1, where \( R_9 \) and \( C_{10} \) are an external resistor and an external capacitor and \( V_{\text{REF}} \) equals 3,1V and \( K \) is approximately 1,2.

\[
I_{TR} = \frac{V_{11} \times R_9 \times C_{10}}{V_{\text{REF}} \times K} \quad (1)
\]

To obtain the triggering angle, we just need to convert it to degrees, as eq. 2 demonstrates.

\[
\theta_{TR} = \frac{I_{TR} \times 360}{0,02} = V_{11} \times 12,8572^\circ \quad (2)
\]

The 4th block is constituted by an RMS-DC converter. This IC is able to receive a sine wave (or a similar signal) and convert it to its equivalent RMS value, which is a DC equivalent. At the end of this block, a RC filter is installed to stabilize the output signal.

At this stage, it is important to state the relation of conversion between the real magnitude of the RMS voltage in the network and its equivalent at an electronics level, as eq. 3 states.

\[
V_{o-\text{electr}} \simeq 3,7064 \times 10^{-3} \times V_{1-\text{net}} \quad (4)
\]

The fifth block is the one responsible for the automatic control of the solution. It is composed by a proportional controller with 3 different sectors, as fig. 5 exemplifies.

The equation that defines this stage, thus, the control voltage is defined by (6).

\[
V_{11} = 14 - (-1753,127 + 7,013V_{1-\text{net}})(V) \quad (6)
\]

Next on the path of the electronic signal, specifically at the output of the triggering signal from the 3rd block, we find the triggering signal processing. Since TRIACs need a special kind of gate/triggering signal, we must assure that the signal obtained from the TCA 785 IC is adequate to the triggering, otherwise, the TRIAC won’t fire. The sixth block, responsible for this, and represented in fig. 6, is composed by a NPN transistor, with the function of attenuating the value of the voltage to an admissible value for the TRIAC-This block is also composed by a pulse transformer, in order to provide galvanic insulation for the triggering signal from the rest of the electronics. The insertion of a couple of diodes ensures the only possible path for the signal at the secondary of the transformer and the flyback path for the current, in the primary.

The last block of the solution is the power dissipation block. It’s constituted by a TRIAC (two anti-parallel thyristors) preceding a high power resistor, where the partial energy dissipation will be performed. Each existent thyristor on the TRIAC is a semiconductor device that only allows current to flow in a certain direction, if the voltage at its
terminals is positive and if the gate/triggering signal has been received. Placed in anti-parallel, as in a TRIAC, we can control the two cycles of a sinusoidal wave. Besides the TRIAC and the dissipation resistor, a snubber circuit is also used, with the objective of suppressing high voltage transients that could undesirably trigger the thyristor. The specifications of the chosen resistor will determine the maximum power that the device can dissipate, having been chosen the value of 18Ω and 3.6kW in order to dissipate the maximum power that the PV inverter in study can produce.

IV. THEORETICAL ANALYSIS OF THE PROPOSED SOLUTION

After the device goes into operation, the waveform of the network sine wave is modified. Instead of a single amplitude throughout the entire period of the wave, we will have two different amplitudes per cycle, one before the triggering angle, ε, and other after the triggering angle. The objective of this solution is to achieve a waveform RMS value lower than the threshold, having the original waveform reduced in amplitude from the triggering angle on, so the RMS value of the aggregate of the two sine waves with different amplitudes equals the threshold. Fig. 7 exemplifies one possible waveform after implementing the solution.

![Fig. 7 – Characteristic waveform of the voltage in the point of operation of the solution, after it has gone into operation](image)

Two regions of operation can be identified. From 0 to ε degrees, the TRIAC hasn’t been triggered and the circuit remains the same, with the inverter injecting all the current to the network. From ε to 180 degrees, a new circuit is in operation, with a parallel dissipation resistor, making the RMS value in the aggregate equal to the threshold. In the negative cycle, the analogy is the same, but with negative values for the voltage. Fig. 8 represents the two equivalent circuits per cycle.

From the two regions, equations that define the variable to be controlled, $V_{fv}$ - the voltage in the point of micro-generation - can be obtained.

For the first region of operation, we compute:

$$V_{fv1} = V_r + R_r I_{fv} \tag{7}$$

For the second region of operation, we have a system of equations:

$$\begin{align*}
-V_{fv2} + 1.73 + R_d (I_2 - I_1) &= 0 \\
V_r + R_d (I_1 - I_2) - 1.73 + R_r I_1 &= 0 \\
I_1 + I_2 &= I_{fv} \tag{8}
\end{align*}$$

Solving the system of equations in (8), we achieve eq. 9:

$$V_{fv2} = R_d \left( I_{fv} - 2 \left( \frac{V_r - 1.73}{R_r} \right) \right) + 1.73 \tag{9}$$

The new waveform for the voltage in the micro-generation location is given by (in one period):

$$V_{fv} = \begin{cases} 
V_{fv1} \sqrt{2} \sin(wt); & 0 < t \leq \frac{\varepsilon}{18000} \\
V_{fv2} \sqrt{2} \sin(wt); & 0.01 \geq t > \frac{\varepsilon}{18000} \\
V_{fv1} \sqrt{2} \sin(wt); & 0.01 < t \leq \frac{\varepsilon + 180}{18000} \\
V_{fv2} \sqrt{2} \sin(wt); & \frac{\varepsilon + 180}{18000} \geq t > 1 
\end{cases} \tag{10}$$

Having described the resulting waveform, it is necessary to obtain the equations that define the operation of the solution and assure that its THD and voltage are under the maximum legal limits.

One of the most important equations we must obtain is the expression for the RMS voltage for this signal in particular. Since RMS value is given by (11), if we replace the variable with its expression, composed by four sub-expressions, equal two by two but in different periods, we end up with the final expression for the RMS voltage applied to our case, (12).
Where,

\( \text{coef}_\varepsilon = \varepsilon - (\sin(\varepsilon) \cos(\varepsilon)) \)  

And

\( \text{coef}_\pi = (\pi - \sin(\pi) \cos(\pi)) = \pi \)

With equation (12) achieved, we can now calculate the most important equations that define the theoretical response of the solution, \( \varepsilon(I_{fo}) \), \( V_r (I_{fo}) \), worst-case THD and \( V_{r-after}(\varepsilon) \).

We may easily calculate the required triggering angle for the correct operation of the solution, \( \varepsilon(I_{fo}) \), by ratiocinating the following: The final RMS voltage of the solution will always be 250V (between 250 and 252, to be more accurate, but we can neglect this at this point). With this value, and having the equation (12) that defines this RMS voltage, we can make the inverse calculations so we can find what will be the value for our two new unknowns. If \( \left( \frac{1}{2} V_{fo}^2 \text{coef}_\varepsilon \right) = x_1 \) and \( \left( \frac{1}{2} V_{fo}^2 \text{coef}_\pi - \frac{1}{2} V_{fo}^2 \text{coef}_\varepsilon \right) = x_2 \), we have:

\[
\sqrt{\frac{1}{T} \left[ 2(x_1 + x_2) \right]} = 250 \iff x_1 + x_2 = \frac{250^2 \times T}{2} = 196349,54
\]

Having only one equation and two unknowns, more equations are needed. We can easily reach the system of equations in (16).

\[
\begin{cases}
    x_1 + x_2 = 196349,54 \\
    x_1 = \frac{1}{2} V_{fo}^2 \text{coef}_\varepsilon \\
    x_2 = \frac{1}{2} V_{fo}^2 \text{coef}_\pi - \frac{1}{2} V_{fo}^2 \text{coef}_\varepsilon \\
    V_{fo} = (V_r + R_d I_{fo}) \sqrt{2} \\
    V_{fo2} = \left[ R_d (I_{fo} - 2 \left( \frac{\text{v}_{fo}}{V_{fo}} \right) \frac{1,73}{2} \frac{R_d}{2} \frac{R_d}{2} \right] + 1,73 \right) \times \sqrt{2}
\end{cases}
\]

The fourth and fifth equation values are obtained by direct substitution of variables. Given that and that \( \text{coef}_\pi \) is always equal to \( \pi \), we can easily manage the three first equations so we can obtain the value of \( \text{coef}_\varepsilon \). To obtain the actual value of \( \varepsilon \), and since \( \text{coef}_\pi \) is a complex non-linear function, an iterative method for solving it must be applied. The most adequate one should be Newton’s Method. We just need to expand the function (17) and get its derivative (18). The Newton method is applied as in (19), given an initial iterate different than \( \pi \) or \( \frac{\pi}{2} \).

\[
f(\varepsilon) = 2\text{coef}_\varepsilon - 2\varepsilon + \sin(2\varepsilon) \]

\[
f'(\varepsilon) = -2 + 2 \cos(2\varepsilon)
\]

\[
x_{n+1} = x_n - \frac{\left( f(x_n) \right)}{f'(x_n)}
\]

In order to calculate \( V_r (I_{fo}) \), that will be needed to compute the maximum THD, we will only need to manipulate the system in (16) in order to the new unknown, \( V_r \). Starting by solving the fourth equation in order to \( V_r \) and making some simplifications assuming new unknowns for aggregations of values, the equation we look for is given by (20).

\[
V_r (I_{fo}) = V_{fo2} (I_{fo}) f + g(I_{fo})
\]

Where,

\[
g = \left( -\frac{a d f_{re}}{2} + a f_{re} + ac - \frac{e d}{2} \right)
\]

\[
a = R_d, c = \frac{1,73}{R_d}, d = 2 + \frac{e}{R_d} d, e = 1,73
\]

With this relation obtained, we may now compute the worst-case THD, that will occur when the gap between the amplitudes of the two components of the voltage signal are greater. Since the new voltage signal is a compound signal of two sine waves, one before and one after the triggering angle, we can easily infer that the biggest gap will be at 90 degrees, as fig. 9 shows.

![Fig. 9 – Localization of the biggest gap between two sine waves](image-url)

Besides this fact, we must also understand what will be the worst-case scenario conditions that create a larger gap. We must thus conjugate the 90º triggering angle with the maximum possible injected power by the PV inverter. Although we know very well the maximum limit for the RMS voltage, knowing the peak voltage for each cycle of operation is not a direct observation. Having the final RMS voltage and the maximum current injected by the PV inverter, the time to use eq. 20 comes and we then obtain all the unknowns for the worst-case scenario: \( V_r = 232,06V, I_{fo} = 16 A, V_{fo1} = 264,06V_{rms}, V_{fo2} = 235,10V_{rms} R_r = 22, R_d = 180I \) and \( e = 90º \).

Since THD is given by (23) and the worst-case scenario voltage by (24), we must now find the Fourier Series coefficients for the first harmonic of the voltage, so that we can compute THD.

\[
\text{THD}(%) = \sqrt{\frac{X_{rms}^2 - X_1_{rms}^2}{X_1_{rms}^2}} \times 100
\]
The Fourier Series is given by (25) and its coefficients are calculated by (26) and (27).

\[ f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left( a_n \cos(\omega_0 kt) + b_n \sin(\omega_0 kt) \right) \]  

(25)

\[ a_n = \frac{2}{T} \int_{0}^{T} f(t) \cos(\omega_0 kt) \, dt \]  

(26)

\[ b_n = \frac{2}{T} \int_{0}^{T} f(t) \sin(\omega_0 kt) \, dt \]  

(27)

After heavy calculations, that we skip on this paper, we get \( a_1 = 13.03 \) and \( b_1 = 352.96 \). Converting the cosine coefficient to a sine, we must get an aggregate amplitude coefficient for the first harmonic, given by (28).

\[ C_n = \sqrt{a_n^2 + b_n^2} = \sqrt{9.21^2 + 249.58^2} = 249.75 \]  

(28)

Finally, one can compute the maximum THD for our solution (29), observing this way that the maximum THD, 4.48% is under the maximum permitted by law, 8%, being practically half its value.

\[ \text{THD(\%)} = \frac{\sqrt{250^2 - 249.75^2}}{249.75} \times 100 = 4.48\% \]  

(29)

At last, it is also important to predict the real and final RMS value of the network voltage, after the solution is in operation, since we have been neglecting its small margin of operation between 250 and 252V. This is an easy task, since we just need to calculate the triggering angle for the current being injected at the time, using \( \epsilon(I_{FE}) \) and substitute this value in eq. (2) (and where \( V_{11} \) must also be substituted by eq. 6).

The final equation is given by:

\[ V_{r-after} = -\frac{\epsilon}{90.16754} + 252(V) \]  

(30)

V. SIMULATION OF THE SOLUTION

In order to test the proposed solution, a simulator was used. The chosen one was Proteus™ from Labcenter Electronics®, since it integrated representations of the real components used in the solution, such as the TCA 785 and AD736. We must call the attention to the fact that component values and results of simulations will not be exactly equal to the real projected prototype, computed in chapter IV, due to non-idealities of the real circuits and to the lack of possibility of a gradual increase of energy injection as it happens in reality, with PV inverters starting injecting gradually from zero to nominal. With the test conditions of \( V_r = 230V \), \( I_{FE} = 16A \), \( R_d = 18\Omega \) and \( R_r = 2\Omega \), the following results were obtained:

Fig. 10 shows the internal triggering ramp of the TCA 785 (yellow), the control voltage \( V_{11} \) (pink), a representation of the network voltage (blue) and the current through the dissipation resistor (green). Visualizing these results we perceive that the solution is working as expected, partially dissipating energy in the resistor and presenting a waveform of the network voltage at the point of injection modified with the expected step at the triggering angle. We can visually confirm that the triggering angle is the expected, since the theoretical calculations (17), (18) and (19), give us a value of 96º and the actual triggering angle is around (95-97º) (as 3.3-3.4ms equate those angles)

Analyzing fig. 11, we can also verify that the numerical value for the voltage is the expected by eq. 30.

Having these positive results, we may now proceed to the real implementation of the solution by means of a prototype.

VI. PROTOTYPE CONSTRUCTION AND LABORATORIAL ENVIRONMENT

After projecting the circuit theoretically, we must select the appropriate components and assemble them in a printed circuit board (PCB) and in a device container. The selection of the required components led to a prototype cost of 275€. This value is going to be much lower when producing massively, making it expectable to cost less than 200€, a very economical value. A PCB (Fig. 12 and 13) had to be designed and a single layer board was the option.
In order to test the prototype, a laboratorial environment that simulated the network conditions had to be prepared. Since a PV panel wasn’t available at the laboratory it had to be simulated with a DC voltage, rectified from the network. The PV inverted in study was the SMA SB3300 and two tests have been performed. One on which an auto-transformer plus a transformer simulated the LV network in different conditions and other where we represented the network simply with resistors. A schematic of the laboratorial environment is represented in fig. 14.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Test conditions</th>
<th>( V_r ) (V) before</th>
<th>( V_r ) (V) after</th>
<th>THD (%) after</th>
<th>( I_fv ) (A)</th>
<th>( \phi )°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>( V_r = 230V, ) ( I_{fv} = 4A )</td>
<td>230</td>
<td>245.8</td>
<td>1.8</td>
<td>3.8-4.3</td>
<td>-</td>
</tr>
<tr>
<td>1.2</td>
<td>( V_r = 240V, ) ( I_{fv} = 4A )</td>
<td>240</td>
<td>249.7</td>
<td>6.8</td>
<td>3.7-4.3</td>
<td>135</td>
</tr>
<tr>
<td>1.3</td>
<td>( V_r = 250V, ) ( I_{fv} = 4A )</td>
<td>248.3</td>
<td>250.2</td>
<td>8.9</td>
<td>3.7-4.2</td>
<td>108</td>
</tr>
<tr>
<td>1.4</td>
<td>( V_r = 230V, ) ( I_{fv} = 8A )</td>
<td>230</td>
<td>249.7</td>
<td>5.6</td>
<td>7.7-8.3</td>
<td>135</td>
</tr>
<tr>
<td>1.5</td>
<td>( V_r = 240V, ) ( I_{fv} = 8A )</td>
<td>240</td>
<td>250.2</td>
<td>9.7</td>
<td>8-8.6</td>
<td>99</td>
</tr>
<tr>
<td>1.6</td>
<td>( V_r = 250V, ) ( I_{fv} = 8A )</td>
<td>248.3</td>
<td>250.5</td>
<td>11.5</td>
<td>7.8-8.5</td>
<td>81</td>
</tr>
<tr>
<td>1.7</td>
<td>( V_r = 230V, ) ( I_{fv} = 15A )</td>
<td>230</td>
<td>250.3</td>
<td>10.5</td>
<td>14.1</td>
<td>90</td>
</tr>
<tr>
<td>1.8</td>
<td>( V_r = 240V, ) ( I_{fv} = 15A )</td>
<td>240</td>
<td>250.4</td>
<td>10.7</td>
<td>14.18</td>
<td>63</td>
</tr>
<tr>
<td>1.9</td>
<td>( V_r = 250V, ) ( I_{fv} = 15A )</td>
<td>248.3</td>
<td>251.3</td>
<td>6.5</td>
<td>14.11</td>
<td>36</td>
</tr>
</tbody>
</table>

\( ^1 \) The angle was obtained through visual analysis
In the second test, the transformers were substituted by simple resistors, to modulate the network as seen in chapter II. In order to produce a higher voltage drop, to get wider results, since we couldn’t change the network voltage in this case, $4\Omega$ were used to simulate the LV network. Due to this situation, the test subject was only to obtain the prototype response at the most important triggering angles: 135, 90, and 45°. Again, the threshold of 250V was the preset. Results for this test are shown in table 2.

**Table 2 – Results for the second test (resistors)**

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Test conditions</th>
<th>$V_r$ (V) before</th>
<th>$V_r$ (V) after</th>
<th>THD (%) after</th>
<th>$I_v$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>$\varepsilon = -$</td>
<td>230.8</td>
<td>246.3</td>
<td>2.4</td>
<td>2.7 – 3.5</td>
</tr>
<tr>
<td>2.2</td>
<td>$\varepsilon = 126^\circ$</td>
<td>230.8</td>
<td>249.7</td>
<td>4.8</td>
<td>6.6 – 7</td>
</tr>
<tr>
<td>2.3</td>
<td>$\varepsilon = 90^\circ$</td>
<td>230.8</td>
<td>250.9</td>
<td>4.9</td>
<td>11.6 – 12</td>
</tr>
<tr>
<td>2.4</td>
<td>$\varepsilon = 63^\circ$</td>
<td>230.8</td>
<td>250.6</td>
<td>5.2</td>
<td>14.7</td>
</tr>
</tbody>
</table>

In the second test, the transformers were substituted by simple resistors, to modulate the network as seen in chapter II. In order to produce a higher voltage drop, to get wider results, since we couldn’t change the network voltage in this case, $4\Omega$ were used to simulate the LV network. Due to this situation, the test subject was only to obtain the prototype response at the most important triggering angles: 135, 90, and 45°. Again, the threshold of 250V was the preset. Results for this test are shown in table 2.

**VIII. ANALYSIS OF THE RESULTS**

A global analysis of the results verifies the operational conformity of the solution and the prototype. We can verify that in all the tests, as the threshold was reached, the solution started dissipating energy partially, only in sufficient quantity to keep network voltage under the legal limit. In respect to the THD, the first test has reached values above the 8% limit. This was due to inductance effects that are not present in a LV network. This test was, then, important to reach higher values of triggering angles, being possible to reach a 10° angle.

The second test, closer to a real situation, needs a more careful analysis. The maximum THD achieved was 5.2%, under the 8% limit, but above the theoretical expected value by 15%. In both tests, it was around the 90° triggering angle that the higher values of THD were obtained, as expected. Detailed results showed that the major harmonics were the 3rd and 5th ones, easy to filter.

Using an auxiliary calculus sheet, reliability of the results in relation to the theoretical equations was verified. To the second set of tests, with $R_d = 20\Omega$ and $R_r = 4\Omega$, the results are shown in tables 3 and 4.
Table 3 – Triggering angle error between the prototype test and the theoretical equation

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Triggering angle (experimental)</th>
<th>Triggering angle (theoretical)</th>
<th>Triggering angle error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>ε = -</td>
<td>Doesn’t fire</td>
<td>0</td>
</tr>
<tr>
<td>2.2</td>
<td>ε = 126°</td>
<td>118°</td>
<td>7</td>
</tr>
<tr>
<td>2.3</td>
<td>ε = 90°</td>
<td>80°</td>
<td>13</td>
</tr>
<tr>
<td>2.4</td>
<td>ε = 63°</td>
<td>64°</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4 – Final voltage error between the prototype test and the theoretical equation

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Triggering angle (experimental)</th>
<th>Vr (V) after (experimental)</th>
<th>Vr (V) after (theoretical)</th>
<th>Voltage Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>ε = 126°</td>
<td>249.7</td>
<td>250.6</td>
<td>0.36</td>
</tr>
<tr>
<td>2.3</td>
<td>ε = 90°</td>
<td>250.9</td>
<td>251.0</td>
<td>0.04</td>
</tr>
<tr>
<td>2.4</td>
<td>ε = 63°</td>
<td>250.6</td>
<td>251.3</td>
<td>0.28</td>
</tr>
</tbody>
</table>

With the results from table 3 and 5 we can prove that besides the conformity with the proposed objectives, the prototype responds in a very consistent way in relation to the theoretical equations which define it and under which it was projected. With errors below 13% for the triggering angle and 0.36% for the final network voltage, the correct operation of the prototype is assured. A final exhaustive test of 35 minutes showed the solution operating consistently within the specified threshold of 250V and with oscillations smaller than 0.3V and 0.55A throughout all the time.

IX. TECHNICAL SPECIFICATIONS OF THE PROTOTYPE

![OVsolver](image)

**Fig. 19 – Final assembly of the prototype, OVsolver**

Table 5 – Prototype specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum threshold operating voltage</td>
<td>Vr,max</td>
<td>250 - recommended (adjustable between 0 and 293)</td>
<td>Vrms</td>
</tr>
<tr>
<td>Maximum admissible current^2</td>
<td>I_fVmax</td>
<td>16</td>
<td>A</td>
</tr>
<tr>
<td>Maximum admissible power^2</td>
<td>P_max</td>
<td>3600</td>
<td>W</td>
</tr>
<tr>
<td>Maximum voltage total harmonic distortion</td>
<td>THDv, max</td>
<td>4.5</td>
<td>%</td>
</tr>
<tr>
<td>Internal power consumption</td>
<td>P_int</td>
<td>&lt;0.5</td>
<td>W</td>
</tr>
</tbody>
</table>

X. CONCLUSIONS

The objective of this paper was to study the implications of micro-generation to the LV networks stability, the response of PV inverters, alternative control approaches and select one of the approached to implement in a prototype that could efficiently and economically mitigate the voltage rises.

With regards to the implications of PV micro-generation penetration into LV networks, the problem resides on the fact that for any injection of power in the grid, the voltage must rise in that same point. Weak LV networks and fluctuations on the consumption throughout the day make voltage rises easier to occur.

The majority of the PV inverters, nowadays, perform a simple control ON/OFF approach, which is too drastic and leads to extended periods of non-production, with reduction of income.

Two general control approaches can be used: global and local control. Since the global control needs a larger quantity of measurements, and, consequently, an expensive telecommunications’ network in order to transmit these measurements to a central, and being a solution that needs a higher reduction of active power, local control was the choice, as it is simpler, cheaper, easier to be applied and it can be applied only in the locations where it is effectively necessary.

The proposed solution has proven to be an efficient, economical and practical solution for the voltage control, being one of its advantages the fact that it only dissipates the part of the energy that would make the voltage go higher than the legal limit. With this solution, the micro-producer maintains its production throughout all the time, even if in smaller quantity, but instead of being completely disconnected, as the studied PV inverter proceeds.

The prototype has got the particularity of being able to be easily adjusted according to variable conditions of different networks and can be easily modified to dissipate more

^2 With dissipation resistor of 18Ω
power by a simple installation of a greater dissipation resistor.

Referring to the technical aspects of the solution, it is operating entirely within the law, with a worst-case scenario THD of 4.48% theoretical and 5.2% practical.

Economical, versatile, easy to install and within the legal operational parameters, this solution pretends to be an ideal alternative to mitigate voltage rises in LV networks, instead of the inconvenient adjustments of voltage in the transformer stations or the expensive network reinforcements.

**APPENDIX**

LV – Low-Voltage
PCB – Printed Circuit Board
PV - Photovoltaic
RMS – Root Mean Square
TRIAC – Triode for Alternating Current
THD – Total Harmonic Distortion

$\varepsilon_{\text{tr}}$ - Triggering angle
$a_n$ - Fourier series cosine coefficient for $n^{th}$ harmonic
$b_n$ - Fourier series sine coefficient for $n^{th}$ harmonic
$c_n$ - Fourier series absolute coefficient for $n^{th}$ harmonic
$C_{\text{10}}$ - External TCA 785 capacitor
$I_1$ - Network current
$I_2$ - Dissipation resistor current
$I_{PV}$ - PV inverter current
$I_i$ - Input network current
$K$ - Internal TCA 785 constant (1,2)
$R_0$ - External TCA 785 resistor
$R_d$ - Dissipation resistor
$R_l$ - Network line resistance
$R_n$ - Network neutral resistance
$R_r$ - Network total resistance
$\tau_{\text{tr}}$ - Triggering time
$V_{11}$ - TCA 785 control voltage
$V_{PV}$ - PV inverter voltage
$V_{f1}$ - PV inverter 1$^{st}$ cycle voltage
$V_{f2}$ - PV inverter 2$^{nd}$ cycle voltage
$V_{\text{rms}}$ - RMS PV inverter voltage
$V_i, V_{i-\text{net}}$ - Input network voltage
$V_{\text{electr}}$ - Electronics equivalent level of network voltage
$V_e$ - Network voltage
$V_{\text{after}}$ - Network voltage after prototype has entered in operation
$V_{\text{REF}}$ - Internal TCA 785 reference voltage (3.1V)

**REFERENCES**


