Compensation of Overvoltages caused by Microgeneration Systems on Low-Voltage Grids

Filipa Bernardes, Instituto Superior Técnico, UTL.

Abstract - The use of microgeneration as a way to meet the current challenges of environmental and energetic sustainability can have consequences on the Power Quality. Therefore, this paper deals with the analysis of low-voltage grids in which photovoltaic microgenerators with switched converters have been introduced, studying and mitigating the impact that these systems can cause on the quality of the voltage waveform and, in particular, disturbing the line rms value.

In this context, the introduction of microgeneration systems in the low-voltage networks can cause an increase of rms voltage values, which is more pronounced as the network load is smaller. Exceeding the maximum voltage defined in the standard NP EN 50160, there are conditions for a permanent overvoltage and microgenerators turn off automatically. This leads to an inefficient use of existing microgeneration system.

In order to solve this problem, it is presented a possible solution that involves updating the already existing control algorithm in the microgenerator, adding overvoltage control functionality by allowing it to continue its normal function by injecting a slightly lower active power instead of shutting down.

For this it is also necessary to build a suitable model of the real microgenerator, associated to the photovoltaic panels, and update the existing current and voltage control algorithms.

Based on the detailed representation of the various circuit elements of a rural low-voltage network, namely the models of MV/LV transformer, electrical cables and loads, several simulations are carried out, which cover different scenarios of power consumption and the presence of microgeneration systems, allowing to evaluate the level of voltage in study. The proposed microgenerator control system update was validated by simulations.

Index Terms - Microgeneration, Low-Voltage Grids, Power Quality, Overvoltage, Photovoltaic Inverter, Power Electronics Control.

I. INTRODUCTION

The use of fossil fuels leads to environmental degradation. New renewable energy sources with almost no negative impact on the environment were explored as a way to improve environment. The use of renewable energy has emerged, whose concept is based mainly on free and unlimited access to renewable sources, generating a so called "clean" energy. In this context, a new legislation was approved (Decree-Law nº118-A/2010) [1] which allows LV electrical power consumers to be also electricity producers through the installation of microgeneration systems. Most common examples of microgeneration systems is the production of electricity using photovoltaic panels (solar energy).

The Microgeneration systems are composed by electronic equipment in nonlinear operation and, therefore, they may contribute to the degradation of Power Quality (PQ). Recently, on a LV rural network, where the power station (PS) is considerably away from facilities use, it was observed that microgeneration systems can affect quite significantly the RMS voltage at the installation site [2].

In periods of no load electrical consumption, which typically correspond to periods where microgenerators are in their maximum power production, these systems impose a local overvoltage which exceeds the permitted in NP EN 50160:2001 and makes the microgenerator to shut down [3]. This leads to an inefficient operation of the microgeneration systems because energy production is compromised and is usually below what was anticipated when the project and consumer investment was made.

The purpose of this work is to develop a solution for this issue which might be installed in the microgenerator, just updating its control software (local solution).

II. LV NETWORK MODEL

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

A. MV/LV Transformer

The 250kVA transformer used in the simulations is ΔYN connected, where the secondary neutral is connected to the ground. It is fed by a 30kV voltage on MV side and in LV the line/phase voltage is 400V / 230V. Its parameters are obtained calculating both the magnetization and the primary and secondary windings reactance and resistance, based on the transformer manufacturer open-circuit and short-circuit tests. For this level of power transformer there are usually 3 outputs per phase (3 buses) on the secondary side.
B. Electrical Cables

The power distribution in LV rural networks is typically done through overhead lines using cables of LXS model (bundled conductors), wherein the conductive material is aluminum. The cables are made of 4 conductors with a section of 50mm² each and its characteristics fulfill the standard DMA-C33-209 [4].

C. Typical Electrical Loads

The linear three-phase loads used in this work are intended to represent groups of residences at various points of the network. The electrical scheme used is the RL parallel type in order to reduce the model complexity, taking also in account most of the home equipments. Thus, it is necessary to define the active and reactive power consumed by each load based on the number of residences, in the contracted power and on stipulated power factor (PF). In addition, it is considered another factor, the simultaneity coefficient (cof), which allows a more realist distribution of power consumed and therefore the LV network is not oversized. The division of power loads for the different phases is not equitable in order to account for the imbalances of a real network.

III. MICROGENERATOR MODEL

A solar microgeneration consists of a set of photovoltaic (PV) panels, a system of electronic power conversion and a control system. The photovoltaic system is constituted by photovoltaic cells connected in series and / or parallel with protective devices. The conversion system power electronics may include a converter for maximum power tracking (MPPT) and an inverter that allows connection to the electrical network. The control system has the function of ensuring the proper functioning and interaction of these elements.

A. Photovoltaic Panel

The main aspects of the photovoltaic effect are the solar radiation and the p-n junction of semiconductors material, being represented in the equivalent electrical circuit by a current source Is and a diode with voltage V, Vf and a factor m, respectively. The equivalent circuit used in this study corresponds to the single-diode five-parameters model (Fig.1) [5].

Analyzing Fig.1 the output current of a photovoltaic cell is

\[ I = I_l - I_o \left( e^{\frac{V + R_s}{Rsh}} - 1 \right) - \frac{V + R_s I}{Rsh}, \]

The model parameters \( I_l, I_o, m, R_s \) and \( R_{sh} \) are determined for the standard test conditions (STC), i.e., for a working temperature \( \theta = 25°C \) and incident radiation \( G = 1000 \text{ W/m}^2 \), using the expressions (2), (3) and also the equation system (4) where \( I_{cc} \) is the short circuit current and \( V_{oc} \) is the open circuit voltage of the PV cell.

![Fig.1 – Electrical equivalent circuit of single-diode five-parameter model](image)

The expressions (2) and (3) are obtained from (1) taking into account the short circuit and open circuit operating points. Also, the system of equations (4) includes the condition of maximum power point.

\[ I_l = \left( I_o + \frac{V - R_s I}{R_{sh}} \right) \left( e^{\frac{V}{R_s I}} - 1 \right) \]

\[ I_o = I_l \left( e^{\frac{V}{m R_f}} - 1 \right) - \frac{V}{R_{sh}} \]

\[ I_{MP} = \frac{V_{oc}}{R_{sh}} \]

\[ \frac{dP}{dV} = \left( 1 + \frac{dI}{dV} \right) \left( V + R_s I \right) - \frac{dI}{dV} = I_{MP} + \left( I_o - I_{cc} \right) \left( \frac{dV}{dI} \right) \left( V + R_s \frac{dV}{dI} \right) - \frac{dV}{dI} = 0 \]

Assuming that all cells are identical and work in the same operating conditions, all of the model approach taken for a photovoltaic cell can be applied to an expanded system like the PV panel.

The values provided by manufacturer catalog of the PV panel implemented (Shell Ultra 175) are shown on Table 1.

![Table 1 - Features of Shell Ultra 175 PV module provided by the manufacturer](image)

The Fig.2 represents the I-V and P-V characteristics curves of implemented PV module for STC conditions where the marked point corresponds to the maximum power point characterized by \( P_{MP}, V_{MP}, I_{MP} \) variables.

---

2
The MPPT system is an algorithm that, for each pair of
irradiance-temperature values, determines the values
of voltage and current corresponding to the maximum power
point, which is characterized by a null \( \frac{dP}{dV} \). In particular,
the voltage of maximum power point is calculated by the
expression (5), obtained through manipulation of (4) [5].

\[
V_{MP}^r = I_{MP}^r \frac{(R_{sh}V_{cc}^r - V_{ca}^r + R_3I_{s}^r) e}{mV_f^r R_{sh}} + \frac{1}{R_{sh}} \cdot \frac{1}{1 + \frac{R_3(R_{sh}V_{cc}^r - V_{ca}^r + R_3I_{s}^r) e}{mV_f^r R_{sh}} + \frac{R_3}{R_{sh}}} \quad (5)
\]

In this work, the PV panel represents an association of 20
PV modules in series, giving a total of nearly 3500W of
installed power and a maximum power voltage of 708V.

B. Single Phase Inverter

The switched converter used is a full bridge single-phase
voltage inverter which is responsible for definition of the
current waveform injected into the LV network, composed
of 4 MOSFETs with an anti-parallel diode (Fig.3).

The semiconductor driving is done by three level pulse
width modulation (PWM) with a switching frequency

\[ f_{PWM} = 10 \text{ kHz}. \]

Considering continuous conduction, the output voltage inverter’s \( v_{PWM} \) is given by [6]

\[ v_{PWM} = \gamma V_C, \quad (6) \]

where \( \gamma \) is a ternary variable that quantifies the three
voltage levels, given by (7).

\[
\gamma = \begin{cases} 
1, & \text{iff } S1\& S4 \text{ ON } \\
0, & \text{iff } S1\& S3 \text{ or } S2\& S4 \text{ ON } \\
-1, & \text{iff } S2\& S3 \text{ ON }
\end{cases} \quad (7)
\]

The capacitor on the input of the inverter \( C_{\mu C} \) is sized to
withstand voltage \( V_C = V_{MP}^r \) so as to maintain it nearly
constant, assuming a maximum of \( \Delta V_C = 0.5\% \) ripple, and is
calculated by (8) where \( I_{\mu C} \) is the output current of PV
panels and \( \omega \) is the network angular frequency.

\[ C_{\mu C} = \frac{I_{\mu C}}{\omega \Delta V_C} \quad (8) \]

The connection of the inverter to the network is done through a filter consisting of an inductance in series \( L_f \) and
a capacitance in parallel \( C_f \) whose values are determined
based on the expressions for the buck converter, shown on
(9) and (10) [6] where \( \Delta i_{\text{max}} \) is the maximum ripple of the
output current \( i_0 \).

\[ L_f = \frac{V_C}{4 \Delta i_{\text{max}} f_{PWM}} \quad (9) \]

\[ C_f = \frac{V_C}{32 \Delta V_C L_f f_{PWM}} \quad (10) \]

C. Nonlinear Current Control

One approach to control the output filter current is using the
sliding mode control (Fig.4), since it is a robust and easy to
implement controller [6][7]. The current error \( e \) is given by
the difference between the reference current \( i_{\text{ref}} \) and the
inverter output current \( i_0 \) (11), which is determined by the
equation (12).

\[ \frac{di_0}{dt} = \frac{\gamma V_C}{L_f} - \frac{V_{\text{ref}}}{L_f} \quad (11) \]

\[ e = i_{\text{ref}} - i_0, \quad -\epsilon < e < \epsilon \quad (12) \]

The stability condition that guarantees the convergence of the
system to the reference value is given by

\[ e \frac{de}{dt} < 0. \quad (13) \]

Therefore, according to (11), (12) and (13), there are three
possible situations:

- If \( e > \epsilon \) \( \Rightarrow i_{\text{ref}} > i_0 \Rightarrow i_0 \uparrow \Rightarrow \frac{di_0}{dt} > 0 \Rightarrow \gamma = 1 \)
- If \( e < -\epsilon \Rightarrow i_{\text{ref}} < i_0 \Rightarrow i_0 \downarrow \Rightarrow \frac{di_0}{dt} < 0 \Rightarrow \gamma = -1 \)
- If \( -\epsilon < e < \epsilon \Rightarrow i_{\text{ref}} \equiv i_0 \Rightarrow \frac{di_0}{dt} = 0 \Rightarrow \gamma = 0 \)
Fig. 4 – Hysteretic control scheme of the three levels of current $i_0$

Fig. 5 shows that the inverter output current tracks the reference current when a sliding mode strategy is used.

D. Linear Voltage Control

In order to control the DC input voltage of the inverter, a linear voltage controller with internal current control is employed, ensuring that the capacitor voltage follows a reference value defined by the maximum power operating point of the PV panel. The transfer function of the linearized control current is given by (14) where $G$ is inverter gain and $T_d$ is delay time of the inverter. Fig. 6 shows the block diagram of voltage control representing the linearized system of Fig. 3.

$$
\frac{i_0}{i_{0\text{ref}}}(s) = \frac{G}{1 + sT_d} 
$$

Fig. 6 – Block diagram of the voltage control at the inverter input

The compensator $C_v(s)$ (15) is of Proportional-Integral (PI) type, ensuring a zero static error with acceptable rising times.

$$
C_v(s) = \frac{T_x s + 1}{T_p s} = K_p + \frac{k_i}{s} 
$$

The global closed-loop transfer function of the system in Fig. 6 is given by

$$
V_c(s) = \frac{T_p s (1 + s T_d) \mu G (s) - G (T_x s + 1) V_{ref}(s)}{s^3 C \mu G T_p T_d + s^2 C \mu G T_p - s \alpha G T_x G - \alpha G} 
$$

PI compensator parameters can be determined by applying the criteria $b_k^2 = a b_{k-1} b_{k+1}$ to the denominator polynomial of the transfer function (16), which has to ensure Routh-Hurwitz stability, with $a = 2$ (Symmetrical Optimum). Thus, the proportional and integral gains, $K_p$ and $k_i$, are determined by (17) and (18), respectively [5].

$$
K_p = \frac{T_x}{T_p} = -\frac{C \mu G}{2 \alpha G T_d}
$$

$$
k_i = \frac{1}{T_p} = -\frac{C \mu G}{8 \alpha G T_d^2}
$$

Fig. 7 – Controlled capacitor voltage on the DC side of the inverter

The proposed controller is simulated and the steady state response is illustrated in Fig. 7, where it is visible a small oscillating of the capacitor DC voltage around its average value. Nevertheless, the amount of power supplied by the PV system remains almost constant.

IV. SIMULATION OF THE TEST NETWORK

The test network represented in Fig. 8 takes into account the information shown in Tables 2 and 3 and also in the legislation [1] concerning the installation of microgeneration systems. This network has 3 buses, in which Bus 1 has 5 line sections and a total length of 500m between the PS and the end of line.

In Bus 1, the microgeneration groups $\mu G2$ and $\mu G4$ each consist of 3 microgeneration units of 3450W, distributed one per phase. On the equivalent bus of Buses 2&3, two microgeneration groups are connected, $\mu G1$ and $\mu G3$, each one with 2 microgenerators per phase. Finally, at the end of the line there is a single microgeneration system, $\mu G5$. 
The network of Fig.8 is simulated for five different scenarios, with and without microgeneration, considering two situations: the high load situation with a load factor of 65% and the low load situation with a load factor of 15%. Figs.9 to 13 shows the profile of the rms voltages values along the line of the Bus 1 for each scenario. On scenarios 1 (Without \( \mu G \), High load) and 2 (Without \( \mu G \), Low load), the profile of the rms voltage values decreases along the line which is the expected progress (Fig.9) (Fig.10). On the contrary, scenario 3 (\( \mu G \) of Branch 1, Low load) presents an increase of the rms voltage value, especially on R phase, because of the presence of Bus 1 microgeneration systems (Fig.11). However, in all of these cases the rms voltage values complies with the stipulations of the standard NP EN 50160 [3].
by acting on the operating point of PV system that is usually the point of maximum power, guaranteed by the MPPT algorithm.

Looking at the shape of the typical I-V characteristics of a PV panel (Fig.2), it follows that any variation in voltage or current around the MPPT point leads to a decrease of the power supplied by the panel. This paper chooses to consider possible variations in the voltage output of the panels, either increasing it or decreasing it, because this voltage is already being tracked by the existing algorithm. Therefore, the upgraded controller will have an additional outer loop, based on the value of the AC network voltage.

Fig.14 represents an equivalent circuit for Bus 1 of the LV network in steady state where $V_{PT}$ is the output voltage of PS, $V_r$ is the voltage at the end of the line, $R_{lin}$ is the line resistance and $i_L$ is the line current [8]. Based on this model, the expression (19) can be written where rms voltage values in opposite buses and the line resistance are related.

The equation (19) can be written in the form (20) considering the relation between the injected power and the produced power by PV panels $P = \eta P_{\mu G} = \eta V_C I_{\mu G}$, where $\eta$ is the efficiency of the converter.

$$P_{\mu G} = \frac{V_r^2 - V_{PT} V_r \cos \theta}{\eta R_{lin}}$$  \hspace{1cm} (19)

Differentiating the expression (20) in order to $V_C$, and neglecting the terms $dV_{PT}/dV_C$ and $d\cos \theta/dV_C$ for being relatively small, the expression (21) is obtained.

$$\frac{dP_{\mu G}}{dV_C} = \frac{1}{\eta R_{lin}} \left( 2V_r - V_{PT} \cos \theta \frac{dV_r}{dV_C} - V_r \cos \theta \frac{dV_{PT}}{dV_C} - V_r \frac{d\cos \theta}{dV_C} \right)$$

$$= \frac{1}{\eta R_{lin}} \left( 2V_r - V_{PT} \cos \theta \frac{dV_r}{dV_C} \right)$$ \hspace{1cm} (21)

Analyzing the shape of the P-V characteristic (Fig.2), it is found that the power derivative $dP_{\mu G}/dV_C$ is positive for voltage values lower than the maximum output voltage, and negative for higher voltage values as shown in (22). Thus,
the sign of the derivative of the power injected in order to maximum power voltage influences directly the sign of supply voltage.

\[
\frac{dP_{\mu G}}{dV_c} \begin{cases} > 0 & \text{for } V < V_{MPPT} \\ < 0 & \text{for } V > V_{MPPT} \end{cases} \tag{22}
\]

The expression (23) demonstrates the relationship between the supply voltage and the output voltage of the PV panels, \(V_c\), considering a regime of small perturbations of the system model in Fig.14. The system can be viewed as a positive or negative gain \(K_{\nu r}\) (24) in accordance with the area that the PV system intended to work, when considering sufficiently slow dynamics in respect to the period of the supply voltage.

\[
\Delta V_r \approx \frac{\eta R_{\text{lin}}}{(2V_r - V_{PT} \cos \theta)} \frac{dP_{\mu G}}{dV_c} \Delta V_c \tag{23}
\]

\[
K_{\nu r} \approx \frac{\Delta V_r}{\Delta V_c} = \frac{\eta R_{\text{lin}}}{(2V_r - V_{PT} \cos \theta)} \frac{dP_{\mu G}}{dV_c} \tag{24}
\]

Fig.15 illustrates a block diagram representing the voltage control system using an integral controller to improve the permanent regulation. Then closed loop transfer function is given by (25) in which the time constant depends on gains \(k_i\) and \(K_{\nu r}\) (26).

\[
\frac{V_{r ref}(s)}{V_{ref}(s)} = \frac{k_i s K_{\nu r}}{1 + k_i s K_{\nu r}} = \frac{k_i K_{\nu r}}{s + k_i K_{\nu r}} = \frac{1}{1 + sT_{d v}} \tag{25}
\]

\[
T_{d v} = \frac{1}{k_i K_{\nu r}} \tag{26}
\]

On scaling the integral gain is assumed for simplicity \(\eta = 1\) and \(cos \theta = 1\) (the line is nearly resistive), and it is determined by the values of the network, defined by \(V_{PT} = 240\text{V}, V_r = 250\text{V}\) and \(R_{\text{lin}} = 0.8\Omega\), and on a stipulated value of time constant. In fact, the system is not a pure gain, but a system with nonlinear dynamics of higher order, that is here neglected. Thus, a reasonable value of \(T_{d v}\) has to be chosen, so that the neglected dynamics is not excited. A time constant response of \(T_{d v} = 2s\) is selected, resulting in a gain value of \(k_i = 32.5\).

The block diagram of the global controller is presented on Fig.16. The inclusion of a limiter block is due to the fact that the control signal \(\Delta V_{c ref}\) affects the value of the variable \(V_c\) only when the error between the supply voltage and its reference is negative. Furthermore, the signal connection between the overvoltage detection system and the existing control loop can be positive or negative, directly influenced by the signal of derived of the power generated by the panels, as shown in (21).

Figs.17 and 18 represent the time behaviour of the output variables of the PV system of the test network, with positive feedback signal, where it is visible that stability of operation (steady state) is achieved within \(1s < t < 3s\). At time \(t = 3s\), rms voltage value at the terminals of the microgenerator increases, activating the integral controller and consequently the voltage and power output decrease, as was expected according with the theoretical analysis.

Figs.19 and 20 represent the time behavior of the output variables of the PV system assembled on the test network, with negative feedback signal. In this case the PV panel output voltage increases, contrary to the previous case, but the value of the power supplied is also reduced. This confirms the possibility of designing a controller that allows acting on the operating point of the PV panels moving them to the left or right of point MPPT in order to reduce the injected power, as predicted based on theoretical approach.
Since it is not feasible that the DC voltage increases to values in the order of 800V, as evidenced by the simulation with negative feedback, because this order of values approach the limit of semiconductor voltage, and lead to a malfunction or even destruction of these equipments. That said, the option is to set the positive signal in the upgrade of the control algorithm.

VI. OVERVOLTAGE MITIGATION RESULTS

Once designed and sized the upgraded microgenerator overvoltage mitigation system is integrated into the network described earlier in order to check its behaviour when the network withstood an overvoltage. In particular, it is simulated the scenario 5 in which there was an overvoltage at the end of the line.

- **Scenario 5**: All μG, Low load, upgraded μG5

The results for this scenario are similar to the scenario 5 presented above, except for the rms voltage value (252.9V) at the end of the line that is now below the limit set by the NP EN 50160 (Fig.21). Thus, it can be concluded that the new control is able to mitigate the overvoltage at the end of the line allowing the continuous operation of the microgenerator.

It is also important to test whether the new control disturbs the functioning of microgenerator when not in an overvoltage situation. Accordingly, a new scenario is taken, Scenario 6, which includes the conditions of scenario 5 plus an increased AC load on the previous bus of the line end.
Scenario 6: Scenario 5 with increased load

Thus, it is concluded that the new control works as intended in all scenarios studied.

VII. Conclusions

The existence of an overvoltage at the end of a rural network due to the presence of a microgenerator was mitigated through a local solution, upgrading the control system microgenerator to slightly reduce the injected active power, just enough to avoid entering the permanent overvoltage limit.

The upgrade developed for the microgenerator is an additional regulation loop of the AC voltage at input of microgenerator based on an integral controller, which keeps the value of the supply voltage on a reference value set by reducing the DC voltage of the inverter DC bus microgenerator, offsetting the PV panel from the maximum power point.

The test network was simulated for different scenarios, varying the power consumption of loads and the presence of several microgeneration groups. The test results showed that some scenarios give a voltage value well above the rated value. This occurs to low load type scenario with all the allowed microgeneration systems operating near its point of maximum power.

However, when the new control system is included on the test network, the results obtained by simulation of the same scenario showed that the rms voltage value decreases, reaching a value slightly below the limit value of the overvoltage, confirming the proper operation of the implemented system according to the designed from theoretical assumptions.

With this solution, it is concluded that it is possible to keep the microgenerator operating in low load periods wherever it is installed at the expense of a slight decrease in power production, about -6% relative to the maximum installed power in microgenerator, rather than to shut down the inverter and produce nothing.

In practice, this solution is easy to deploy because it only involves modifying the microgenerator control software, upgrading code that translates the new implemented functionalities.

VIII. References


