TECHNICAL IMPLICATIONS OF MICROGENERATION INTEGRATION IN LOW VOLTAGE DISTRIBUTION GRIDS

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ABSTRACT

Since 2007 many microgeneration units have been connected to the distribution grid in Portugal.

Rules for microproducers in Portugal:

- *The entities must have a low-voltage electricity contract;*
- *The microgeneration system must be integrated in the place of consumption;*
- *The power of the microgeneration system cannot exceed 50% of the contracted power, except for electrical installations of condominiums; this rule has changed with a new Decree-Law published at the end of 2014 that allows the connection of 100% of the contracted power;*
- *The microproducers can only celebrate a sale/purchase contract with the company with whom they have a purchase contract;*
- *It is the microproducer's duty to deliver electricity according to the technical standards in order not to disrupt the normal functioning of the public low voltage distribution grid;*
- *It is the microproducer's responsibility to check the technical characteristics of the voltage wave in the connection to the grid;*
- *The access to microgeneration business can be denied if the sum of the microgeneration power exceeds the 25% limit of the installed capacity at the public transformer station (PTS).*

Portugal is one of the European countries with the highest solar radiation availability. In Portugal, there has been a great adherence to the microgeneration using photovoltaic panels, due to the tax incentives created and also the special tariffs in which the sales price of electricity is higher than the purchase price for own consumption.
According to the Europe 2020, the Portuguese goal was to achieve 31% consumption of energy produced by renewables and endogenous energy sources, a goal that was already reached and exceeded.

CURRENT SITUATION

The large scale integration of microgeneration units has caused in the distribution grids some service quality issues (Standard EN 50160).
The effect of intermittent sources, namely the variation of solar radiation, causes fluctuations in the effective value of voltage, which could compromise the quality of service.
When the load factor of an LV distribution grid is low and there's simultaneously a peak of production, the microgeneration facility injects energy into the electricity grid, increasing the voltage level, a situation mainly seen in rural grids.
The default settings for the inverters, if the DSO didn't provide any, according to Standard EN 50438, are shown in the following table:

Parameter	Maximum disconnection time	Minimum operate time	Trip value
Over-voltage – stage 1 [a]	3 s	-	230 V + 10 %
Over-voltage – stage 2	0,2 s	0,1 s	230 V + 15 %
Under-voltage	1,5 s	1,2 s	230 V – 15 %
	The stated voltages are 'true r.m.s.' or fundamental component -values.		
	[a] Over-voltage – stage 1: 10-min-value corresponding to EN 50160. The calculation of the 10 min value shall comply with the 10 min aggregation of EN 61000-4-30, class S. The function shall be based on the calculation of the square root of the arithmetic mean of the squared input values over 10 min. In deviation from EN 61000-4-30, a moving window shall be used. The calculation of a new 10-min value at least every 3 s is sufficient, which is then to be compared with the trip value. Tolerances on disconnection time are ± 10 % .		

Table 1: Default interface protection performance

The Standard EN 50438, applied to the inverters, allows a limit of 230V+15% (on stage 2 and for a maximum disconnection time of 0.2s). The upper limit of Standard EN 50160 for the root mean square voltage is 230V+10%. Despite the short disconnection time, the value 230V+15% can possibly cause problems to more sensitive equipments connected to the distribution grids.
One of the problems caused by the integration of microgeneration units in the distribution grids is the increase of the voltage levels above the regulated limits, causing:

- Disconnection of the microgeneration units;
- Economic losses to the microproducers, resultant from the not injection of the generated power in the distribution grid;
- Consequent malfunctioning of the inverters due to the continuous connection/disconnection cycles;
- Problems in the facilities connected to the distribution grids.

PROBLEMS WITH MICROGENERATION IN LV DISTRIBUTION GRIDS

The voltage regulation problems in low voltage distribution grids cannot be improved by the use of the

conventional no-load tap changer of a distribution MV/LV transformer. The tap changer merely changes the transformer turns ratio, but does not significantly change the transformer impedance.
The microgeneration in LV distribution grids can cause voltage values above the limits defined in the Standard EN 50160, mainly in rural LV distribution grids that are usually explored radially.
To demonstrate how the microgeneration can disrupt voltage values, consider the sending bus the node 1 (reference) and the bus 2 as the receiver node. The voltage buses are U_1 and U_2 modulus and argument θ_1 and θ_2, respectively.
When there is a power imbalance generated and consumed in the bus 2, there will be a power variation exchanged with the bus 1.

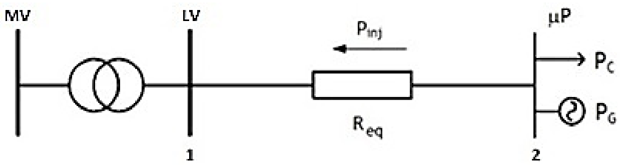


Figure 1: Simplified scheme of a MV/LV distribution grid with microgeneration injection

The apparent power injection between bus bars 2 and 1 is given by:

$$S_{21} = U_2 \cdot \bar{I}_{21} = U_2 \cdot \frac{\overline{U_2} - \overline{U_1}}{Z_{eq}}$$

$$S_{21} = \frac{U_2^2 \cdot (\cos\theta_2 + j\sin\theta_2) - U_1 \cdot U_2 \cdot (\cos\theta_1 + j\sin\theta_1)}{Z_{eq}} =$$

$$= \frac{\mathrm{U}_2^2 \cdot \cos\theta_2 - \mathrm{U}_1 \cdot \mathrm{U}_2 \cdot \cos\theta_1 + \mathrm{j}(\mathrm{U}_2^2 \cdot \sin\theta_2 - \mathrm{U}_1 \cdot \mathrm{U}_2 \cdot \sin\theta_1)}{\mathrm{R}_{eq} + \mathrm{jX}_{eq}}$$

As the LV distribution grids are predominantly resistive (R >> X), then:

$$\mathrm{S}_{21} \approx \mathrm{P}_{inj} = \frac{\mathrm{U}_2^2 \cdot \cos\theta_2 - \mathrm{U}_1 \cdot \mathrm{U}_2 \cdot \cos\theta_1}{\mathrm{R}_{eq}}$$

With the above simplified expression we can see that the voltage levels are very dependent on the injection powers in each node of the LV distribution grids.

Nowadays, to try to solve the problem load flow studies are performed and operating conditions examined to ensure that voltage tolerance ranges are not exceeded, but when the voltage values exceed the limits defined in the Standard EN 50160 many measures are adopted:

- Connection of single-phase microgeneration facilities in the phase of the distribution grid with higher power consumption;
- The change of the distribution grids configuration;
- The voltage levels adjustment by the power transformers no-load tap changers.

Even if all the above described items are accomplished, the problems can persist, mainly in rural LV distribution grids and if its microgeneration is far from the public transformer stations.

In the connection of microgeneration facilities to the distribution grids, the following operating scenarios should be taken into account:

a) **Maximum consumption and minimum production**: this scenario is the traditionally used in the planning and project of the distribution grids. It is not considered the energy production because there is no obligation to produce energy by the microproducers;

b) **Minimum consumption and maximum production**: this scenario is far different from the traditional planning methods, where can take place a reversal of energy flows in the distribution grids. The maximum production includes, for each interconnection point, the total maximum output production.

NEW APPROACHES

One of the suggestions for the future is to update the legislation to allow the usage of three-phase inverters in microgeneration facilities.

Another suggestion is to use capacitors of either switched or fixed configurations to correct the voltage range profile of a distribution system. For maximum benefit, capacitors should be located close to the load that is causing the problem.

The control of the operating voltage range can also be achieved by the use of transformers with on-load tap changers and line regulators. Applying this solution to large distribution grids with consumers far from the PTS, the usage of the line regulators is a must because of the low X/R (reactance over resistance) ratio.

Finally, a control of the reactive power can be done by the inverters when connected, for example, in a smart grid.

When there is no microgeneration connection to the distribution grid, and assuming that all consumers consume, simultaneously, active power and reactive power in each branch, there will be a voltage drop, approximated by the below expression, justified by the distribution grid characteristics:

$$\Delta U_{branch} = \frac{R_{branch} \cdot P_{\mathrm{downstream}} + X_{branch} \cdot Q_{\mathrm{downstream}}}{U}$$

Expressing in base values:

$$\Delta U_{branch,pu} =$$
$$= R_{branch,pu} \cdot P_{\mathrm{downstream,pu}} + X_{branch,pu} \cdot Q_{\mathrm{downstream,pu}}$$

In each branch there are losses. The distribution grids must be dimensioned to withstand such losses and to ensure voltage values within regulatory limits (Standard EN 50160).

After the connection of the microgeneration facility to the distribution grid, it will be subtracted the active and reactive power produced from the powers considered in the previous expressions. It can be said that generally there are three different interests for the production of reactive power by the microgeneration:

- DSO's interest is to avoid costs, reducing the dimensioning of conductors and of the upstream distribution grid, thanks to the loss reduction that those conductors have to dissipate, and also economize energy losses. It's DSO interest that the microgeneration facilities produce reactive power associated to the active power;
- Microproducers' interest is also to avoid their own costs, maximizing the active power produced capable to be generated by their equipment. It's the microproducers' interest to produce only active power;
- The consumers' interest is not to suffer any voltage quality changes, with the presence or absence of microgeneration. It's their interest that the microgeneration facilities produce reactive power associated to the active power, in such way approximately, as close as possible, to:

$$\Delta U_{branch,pu\_MicroProducer} =$$
$$= R_{branch,pu} \cdot P_{MicroProducer,\mathrm{pu}}$$
$$+ X_{branch,pu} \cdot Q_{MicroProducer,\mathrm{pu}} \approx 0$$

that is to say, there is the interest on a voltage drop resulting from the consumption of reactive power to compensate the increase of the voltage resulting from the production of active power.
This is achieved, for a microproducer facility and for the consumers located downstream of the interconnection point, if the following expression is respected:

$$Q_{MicroProducer} = P_{MicroProducer} \cdot \frac{R_{cc}}{X_{cc}}$$

the terms R_{cc} and X_{cc} are, respectively, the real and the imaginary parts of the short-circuit impedance of the distribution grid.

The production of reactive power causes a variation in the current carried. In situations where the distribution grid has a large energy consumption and where there is reactive energy compensation, the current carried over the cables is lower when compared with the situation with no compensation of reactive energy, because the requested power is only used to meet the need of active power. In scenarios where there is no such compensation the currents are greater, because there is also a need for reactive power. This means that there are more losses in the cables (higher currents) and, possibly, the dimensioning of the cables need to be increased.

There are already in the market photovoltaic inverters that allows an injection of reactive power in the distribution grids.
There is a pilot project in Portugal, in the initial phase, that allows a power factor control of the microgeneration facilities when integrated in smart grids. It's the **Sustainable Project** in which several entities are involved including the EDP Distribuição. More information about this project can be found at the following link:

- http://www.sustainableproject.eu/Home.aspx.

In the current Portuguese legislation, there's no obligation for the producers to supply reactive power.
The existing reactive power control modes according to Standard EN 50438 are:

- Q(U);
- cos φ fix;
- cos φ (P).

Fix control mode cos φ fix

The fix control mode controls the active factor cos φ of the microgenerator's output according to a setpoint set in the control of the microgenerator. This setpoint shall be given by the DSO.

Voltage related control mode Q(U)

The voltage related control mode Q(U) controls the reactive power output as a function of the voltage.
To evaluate the voltage, one of the following methods shall be used:

- the positive sequence of the symmetrical components;
- the average voltage of a three phase system;
- phase independently the voltage of every phase to determine the reactive power for every phase.

Power related control mode cos φ (P)

The power related control mode cos φ (P) controls the active factor cos φ of the microgenerator's output as a function of its active power output.

The control proposed in the **Sustainable Project** is a droop control strategy – active power / voltage droop (P-V) functionality. This functionality will be implemented at the power electronic interfaces of the microgeneration units connected to the LV grid. The control parameters of the local regulation functionality will be remotely adjusted through the DTC (Distribution Transformer Controller) in accordance to the grid operating conditions or other requirements defined by the grid operator.

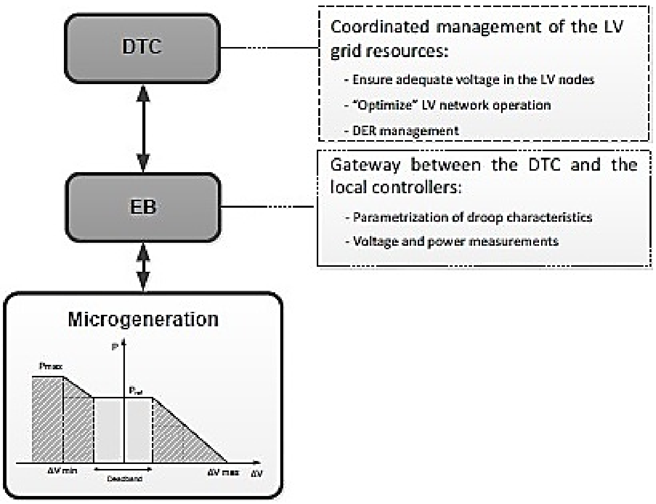


Figure 2: General overview of the LV grid control

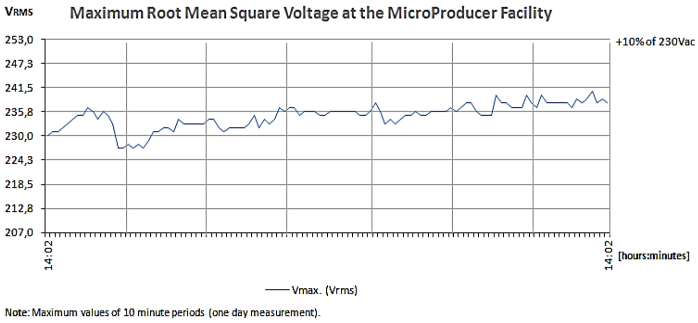
FIELD TESTS

This Paper presents two field tests. Both tests were carried out in rural distribution grids, with LXS aerial cables (aluminium twisted cable with cross-linked polyethylene insulation) and the distribution grids are explored radially.
Several measurements were taken in some distribution grids, according to Standard EN 50160.
The measurements were taken by a Fluke® power quality meter, model 1760.
In each place where the measurements were taken, the power quality meter was installed in the Public Transformer Station MV/LV and also in the microgeneration facility.

1st Field Test – Solar Microgeneration facility at 750 meters of the Public Transformer Station (before the field test, there were no records of malfunctioning in the distribution grid)

- *Field test at the microproducer facility*:

Date: 21st June
The maximum root mean square voltage at the microproducer's facility during a week was the following, as shown in the graph below.



Graph 1: Maximum RMS Voltage – MicroProducer Facility

As we can see, all the voltage levels are below the 230V+10% permitted by Standard EN 50160.

- *Field test at the public transformer station (PTS)*:

Date: 21st June
The maximum root mean square voltage values at the PTS were all below the 230V+10% permitted by Standard EN 50160.

In the Portuguese legislation, the connection of a production facility to the LV distribution grid must follow a rule which sets that it cannot exceed 4% of the minimum short-circuit apparent power at the interconnection point. To perform this calculation, the following distribution grid data was used:

S_{PTS} [kVA]	160,00
u_{sc} [%]	4,00
U_{MV} [kV]	15,00
Ssc min. Upstream [MVA]	58,51
$P_{CU\ PTS}$ [W]	2040,00
Feeder Cable Length [m]	
LXS 4×50 mm²	318,00
LXS 4×25 mm²	439,00

Table 2: Data of the distribution grid

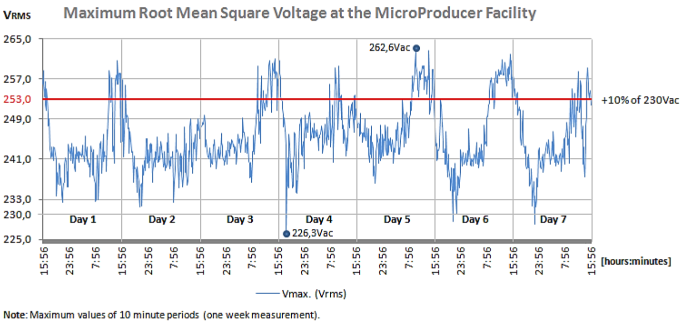
Legend: S_{PTS} – Transformer Rated Apparent Power; u_{sc} – Short-Circuit Voltage of the Transformer; U_{MV} – Rated Medium Voltage; S_{sc} min. – Upstream Short-Circuit Apparent Power; P_{CU} – Copper Losses of the Transformer.

With these values, and applying the rule presented previously in the calculation, we can conclude that the maximum power production that can be injected in the interconnection point is **2.31kVA**. As the microproducer facility power is **3.45kVA**, we conclude that the presented rule is not accomplished.
Despite the not accomplishment of the condition presented previously, the active power injected into the distribution grid didn't exceed the 2.31kVA.

2nd Field Test – Solar Microgeneration facility at 850 meters of the Public Transformer Station (before the field test, there were records of malfunctioning in the distribution grid)

- *Field test at the microproducer facility*:

Period: 13th to 20th June
The maximum root mean square voltage at the microproducer's facility during a week was the following, as shown in the graph below.



Graph 2: Maximum RMS Voltage - MicroProducer Facility

As we can see, there are many voltage values above 230V+10%, allowed by standard EN 50160.

- *Field test at the public transformer station (PTS)*:

Period: 13th to 20th June
The maximum root mean square voltage values at the PTS, recorded during a week, were all below the 230V+10% permitted by Standard EN 50160.

Applying the same rule referred in the 1st Field Test to perform this calculation, the following distribution grid data was used:

S_{PTS} [kVA]	100,00
u_{SC} [%]	4,00
U_{MV} [kV]	15,00
Ssc min. Upstream [MVA]	23,40
$P_{Cu\ PTS}$ [W]	1540,00
Feeder Cable Lenght [m]	
LXS 4×70 mm²	403,00
LXS 4×25 mm²	89,00
LXS 4×16 mm²	366,00

Table 3: Data of the distribution grid

With these values, and applying the rule presented previously in the calculation, we can conclude that the maximum power production that can be injected in the interconnection point is **1.72kVA**. As the microproducer facility power is **3.45kVA**, we conclude that the presented rule is not accomplished.

Even if the rule is accomplished it cannot be 100% guaranteed that there won't be any problems with the voltage values in the distribution grid, because if the distribution grid doesn't have any consumption it will not be capable to absorb the energy produced, the problem can persist even if the previous condition is met.

Applying the previews rule for the connection of more microgeneration facilities to the same PTS, it might not be enough to solve the problem because the S_{sc} minimum will increase each time a microproduction facility is connected to the grid, due to the contribution of the facility for S_{sc} min, and so not having any guarantee that all the energy produced will be consumed.

CONCLUSIONS

Many distribution grids are not adapted to an increase in the number of microgeneration facilities connections.

Portuguese legislation doesn't obligate the microproducers to produce reactive energy.

The production of reactive power associated to active power, with the use of capacitors or with DC/AC inverters, is one of the possible solutions to solve the problems related to microgeneration facilities connections to the distribution grids.
One of the aims of the **Sustainable Project**, in which EDP Distribuição it's a partner, is to carry out studies to solve these problems.

After the many field tests carried out by EDP Distribuição, it was found that in distribution grids with feeders with up to 200 meters, the voltage levels are imposed by the PTS. Those whose feeders' length is over 200 meters, the voltage values can be higher than the ones limited in Standard EN 50160.

EDP Distribuição and Microgeneration

EDP Distribuição sees Microgeneration as an important part of Smart Grids.

With regards to Microgeneration, EDP Distribuição is following its development and has been adapting itself to the challenges, contributing to solve the problems of microproducers.

REFERENCES

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