



A Battery Based Solution to Overvoltage Problems in Low Voltage Distribution Networks with Micro Generation

Hugo Silva¹, Rui Castro^{1,2} and M. E. Almeida^{1,2}

¹Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal

²INESC-ID, Lisbon, Portugal

rcaastro@tecnico.ulisboa.pt

Abstract: During the past years, governments throughout the world have been encouraging the installation of renewable energy systems to cope with environmental goals. In this framework, there has been a significant increase in the number of energy producers on the consumers' side, majorly due to photovoltaic and wind energy microgeneration. This has brought some concerns in voltage control on buses far away from the substation. The present paper analyses the impact of these microgeneration systems on the low voltage grid, namely in what concerns overvoltage issues. For this purpose, both stochastic models to predict solar irradiance and wind speed and a three-phase power flow algorithm to compute voltages on the buses of a test network are used. The probabilistic power flow study, carried on using Monte Carlo methods, reveals the possibility of overvoltage problems. A solution based on batteries attached to the micro generators is proposed to cope with this issue. The obtained results show the effectiveness of the solution, as a way to decrease over voltages, while preserving the producers' revenues.

Keywords: Probabilistic power flow, stochastic models, voltage control, distribution networks, micro generation.

1. Framework

Reducing the load as seen from the electrical system without compromising the welfare of the populations is one form of making the use of energy more efficient. It is now apparent that small dispersed energy production systems can help in achieving this target. This is one reason why governments are encouraging the installation of such equipment, as a mean to directly reduce the load and indirectly reduce the fossil-fuel dependency.

On the other hand, with the recent financial crisis, faith in bank applications has been damaged, and people are now looking for solid investments on their own. In order to grant an extra income, small investors have gained interest in the above mentioned low power energy systems, thus giving birth to the concept of micro generation. As so, small dispersed renewable energy systems are becoming very popular as domestic end-users generation systems. Micro generation installations use mainly solar resource as primary energy, in the so called photovoltaic (PV) micro generators. Although in a much smaller number, micro wind energy conversion systems are also being used.

In Portugal, about 100 MW of renewable micro generation capacity have been installed in the past five years, corresponding to nearly 25,000 micro producers. Of course, these figures are nothing, as compared to the 4.5 GW of large wind parks and six millions of electricity consumers, but they represent a growing trend that is much expected to increase steadily in the future. Moreover, the installed capacity of micro generation is of the same order of magnitude of the installed large photovoltaic capacity (120 MW).

The main technical underlying issue behind renewable micro generation is its impact in low voltage (LV) distribution networks. Up until a few years ago, power networks were fairly easy to analyse, as there was a standard of power flow from the large producers to the consumers, should they be in villages or in large metropolis. Nowadays, the inclusion of distributed

microgeneration is bound to raise new issues, particularly as far as the voltage profile of the network is concerned. [1–4].

Especially in rural networks, which are far from the substation transformer, the emergence of generation where there once was only consumption will most certainly contribute to a rise in the voltage level. This is because an excess of generation will substantially decrease the load seen from the point of view of the electric system, thus increasing the voltage on that bus.

Overvoltage problems are currently being tackled through power electronics. If the voltage isn't between the established limits (usually $\pm 10\%$ of the nominal value), the inverter to which the micro generation plant is connected will switch off the system from the grid, in order to preserve the power quality. These limits give rise to two important definitions: overvoltage, which is when the voltage exceeds 10% of the nominal value (1.1 pu) and undervoltage, that is based on the same concept but occurs when the voltage drops below 10% of the nominal value (0.9 pu).

Several solutions have been provided to cope with the issue of overvoltages [5–11]. They include generation shedding, power factor control through power electronics devices and transformer tap changing. From these three solutions, only power factor control did not prove to be an effective solution, due to the low inductive component of the LV cables. Transformer tap changing, while efficient, is not very cost-effective, due to the need of power transformers replacement in substations. Generation shedding is quite troublesome from the point of view of the producers, since they aren't keen of losing money.

A new solution is being proposed in this paper, one that will not only control voltage within its limits, but also that isn't frowned upon by the micro generation owners. Each generator will jointly work with a battery. If there is an overvoltage in a certain bus, the correspondent generator will be disconnected from the grid and will start charging the battery. Then, later on, when the load is higher and voltages tend to be at their lowest point, the stored energy will be returned to the network through the batteries, discharging a quarter of their stored power per hour, in order to prevent voltage spikes.

When it comes to deal with the assessment of these overvoltage issues, two main difficulties can be devised. On one hand, it is necessary to use the adequate power flow technique. The major difference between analysing this problem in a high voltage (HV) or even medium voltage (MV) distribution networks against LV ones lies with the fact that for the first set of networks, power flow is easier to compute, as the system is balanced and therefore can be assessed by an equivalent single-phase method. This is not the same for LV networks, since the loads, which are mainly of a domestic nature, can be quite unbalanced in this case. This created the need to devise a three-phase load flow, which considers each phase individually, instead of just an equivalent one [12–14]. As so, to assess overvoltage problems in LV network, the use of a three-phase unbalanced power flow algorithm is mandatory. On the other hand, the multidimensional stochastic dependence structure of the joint behaviour of the generation and load can be very complex to model. That is why the behaviour of the LV distribution network in presence of concurrent unbalanced generation and loads is a matter of great concern within the scientific community.

To address this particular issue, in this paper stochastic models are used based on real data for both solar irradiance and temperature (PV systems) and wind speed (wind systems). The latter has been well proven by Weibull's distribution, and so this model is used to represent the wind variations. Solar irradiance is far more complicated to handle, one of the reasons is because there is no sun at night. To represent this variable, a model based on the so-called clearness index is used [15–17]. This allows estimating generation more accordingly to the events throughout a year, as for there is more sun in summer than in winter.

The appropriate techniques to deal with the questions raised above were integrated in the framework of a Monte-Carlo probabilistic power flow simulation, because of the stochastic nature of the phenomena involved. As so, 96,000 simulations were performed in a test real network, for different PV and wind generation values combined with different load profiles.

The paper is organized as follows. In the next section, the models used to describe the system's components are presented – the stochastic models for solar irradiance, cell temperature and wind speed, the load model, the PV and wind generators models and the used three-phase unbalanced power-flow method. Section III contains the results obtained and a discussion about the main achievements. Finally, in the final section, some conclusions are drawn.

2. System modelling

The system to be studied is composed by PV and wind generators and by loads, interconnected through lines and transformers. A Monte-Carlo power flow simulation is to be performed, for changing power outputs of the generators and for changing loads. The power output of the PV generators depends on the irradiance and on the temperature, whereas the power output of the wind generators depends on the wind speed. As far as the load is concerned, it depends on the season of the year and on the particular hour to be simulated. In order to perform this kind of simulations, random inputs (irradiance, temperature and wind speed), following adequate probabilistic distributions, are applied to the generators and the respective power output is obtained through adequate models. Also, load variations are obtained from suitable load profiles.

The process of obtaining the random inputs is as follows: (i) to find the adequate probability density functions (pdf) based on real variables' data; (ii) to compute the cumulative distribution function (cdf) for each variable, based on (i); (iii) to generate random values of the variables, following the proper pdf.

A. Clearness index model for solar irradiance and cell temperature

During an average day, the amount of irradiance that reaches the surface of a photovoltaic module depends on the latitude and altitude of the location, and also on the climatic conditions, such as temperature and cloud cover. In fact, it is understood by the scientific community that cloudiness has a major impact when it comes to measure the difference between irradiance outside the earth's atmosphere and at its ground. This introduces the concept of clearness index.

The clearness index used in this paper is the usually referred to as hourly clearness index. As so, the data regarding the clearness index is divided into seasonal clusters, each one representing a typical 24 hours day, per each season.

The hourly clearness index (k_t) is defined as the ratio between the irradiance on a horizontal plane (G_t) and the extraterrestrial total solar irradiance (G_0) on a given day, during a certain hour:

$$k_t = \frac{G_t}{G_0} \quad (1)$$

The technique employed in this paper is to generate clearness index random values and use Eq. (1) to find the PV incident irradiance (G_t). Extraterrestrial irradiance (G_0) may be readily obtained from a well-known expression that depends on the latitude of the location in study, on the declination angle, which is the angular position of the sun at solar noon, with respect to the plane of the equator, on the day of the year, on the hour of the day and on the solar hour angle or the angular displacement of the sun.

The pdf proposed to model the clearness index is given by Eq. (2) [15]:

$$pdf(k_t) = \left[e^{\lambda k_t} - \frac{1}{k_{tu}} k_t e^{\lambda k_t} \right] \quad (2)$$

In Eq. (2), k_t is the hourly clearness index and λ can be computed using the maximum value of clearness index (k_{tu}) and the average clearness index, whose values are obtained from the horizontal plane irradiance real data set.

Integrating the pdf, one obtains the cdf as:

$$cdf(k_t) = \frac{C}{\lambda} \left[\left(\frac{\lambda k_{tu} + 1 - \lambda k_t}{\lambda k_{tu}} \right) e^{\lambda k_t} \right] - \frac{C}{\lambda} \left(1 + \frac{1}{\lambda k_{tu}} \right) \quad (3)$$

A uniform number generator draws a value between 0 and 1 for the cdf, from which k_t can be obtained.

As an example, Figure 1 shows the fitting of the data using the clearness index against its histogram, for 1 p.m., in the summer.

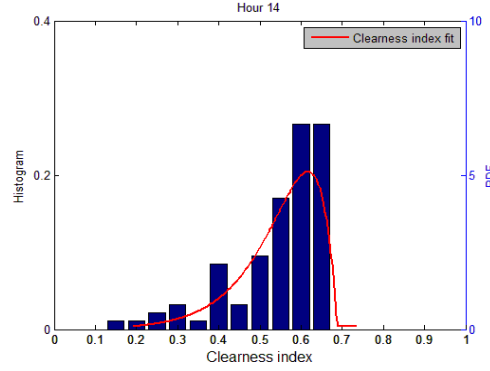


Figure 1. Clearness index distribution fitting and respective histogram, for 1 p.m. in summer

As far as the PV modules temperature (T_c) is concerned, it will be predicted from the average ambient temperature (T_a) dataset, per hour and per typical day of a season, and from the clearness index using Eq. (4) [18] (NOCT stands for Normal Operating Cell Temperature):

$$T_c = T_a + \frac{(219 + 832k_t)(NOCT - 20)}{800} \quad (4)$$

B. Weibull distribution for the wind speed

As far as the wind speed is concerned, a similar methodology is applied but with the pdf that is widely recognized as accurately describing the wind speed – the Weibull distribution, as seen in Eq. (5).

$$pdf(u) = \frac{k}{c} \left(\frac{u}{c} \right)^{k-1} \exp \left\{ - \left[\left(\frac{u}{c} \right)^k \right] \right\} \quad (5)$$

where u is the wind speed, c is a scale parameter, and k is a dimensionless shape parameter. These parameters are obtained from the real wind speed data set, using a known linearization technique and involving the Weibullcdf:

$$cdf(u) = 1 - \exp \left\{ - \left[\left(\frac{u}{c} \right)^k \right] \right\} \quad (6)$$

Once again, a uniform number generator produces a value between 0 and 1 for the cdf, from which the wind speed u can be found, following a Weibull probabilistic distribution. Figure 2 shows the good fitting that this distribution provides for the used dataset.

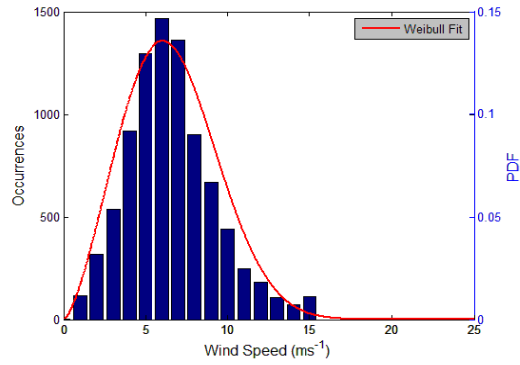


Figure 2. Weibull distribution fitting against its respective histogram

C. Photovoltaic generators

The model used for photovoltaic systems is widely known and is called the one-diode and three parameters model [19]. Figure 3 depicts the electric equivalent circuit of a PV module, as described by the above mentioned model.

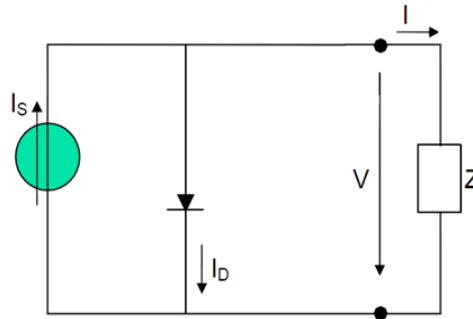


Figure 3. One-diode and three parameters electric equivalent circuit of a PV module

This model represents the PV module as a current source in parallel with a diode. The three parameters on which it depends are the short-circuit current (I_{sc}), the inverse saturation current (I_0), and the diode ideality factor (n). It uses the open circuit voltage, the short circuit current, the maximum power point voltage and the maximum power point current, as given by the manufacturer’s datasheets at Standard Test Conditions (STC), to compute the PV module power output for a given irradiance and temperature. This is done by incorporating the variation in temperature in the diode’s inverse saturation current, the variation in the solar irradiance into the short-circuit current; the ideality factor is considered as a constant. The one-diode and three parameters model is found to represent the electrical behaviour of a PV module with an adequate degree of accuracy [20].

The basic element of the PV systems configuration is a standard 240 Wp PV module, whose technical characteristics at STC are displayed in Table I.

Table 1. 240 Wp PV module technical characteristics at STC

Nominal power (Wp)	240
MPP current (A)	8.21
MPP voltage (V)	29.24
Open circuit voltage (V)	37.80
Short circuit current (A)	8.58
Module efficiency (%)	14.9
NOCT	47.3

D. Wind generators

As for wind energy converters, a standard 3 kW wind turbine was taken. Its main technical data is presented in Table II and its power–wind speed curve is depicted in Figure 4.

Table 2. 3000 W wind generator technical characteristics

Number of blades	2
Diameter (m)	4
Nominal power (W)	3000
Alternator	Permanent magnet

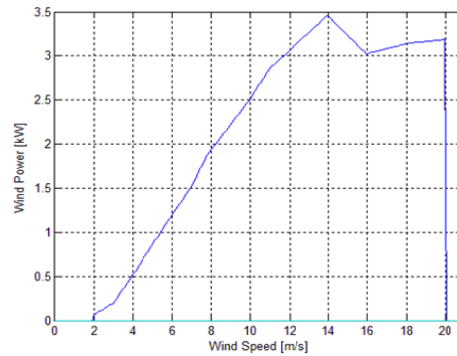


Figure 4. Power–wind speed curve of the wind generator

E. Load

The method used to model the load is based on the IEEE Reliability Test System [21], in which the load is divided into four seasons of the year, one typical day per season. This is actually quite useful, since the stochastic methods that predict solar irradiance and wind speed are also executed having in mind the same four typical days of the year.

To build the load model, three components were necessary: weekly peak load, in relation to the annual peak, daily peak load, in relation to the weekly peak and hourly peak load, in relation to the daily peak, depending on the season of the year. Every weekly load was put in a cluster in respect to each season and a seasonal average load was obtained. These four averages were then multiplied by the hourly peak load per season, forming the four curves portrayed in Figure 5 (in percentage of the nominal load).

To take the day of the week into account, a weekday factor was created, varying between 1 (Monday) and 7 (Sunday) through a random uniform variable. So, in every simulation, the load is computed according to the day of the week, hour and season being evaluated.

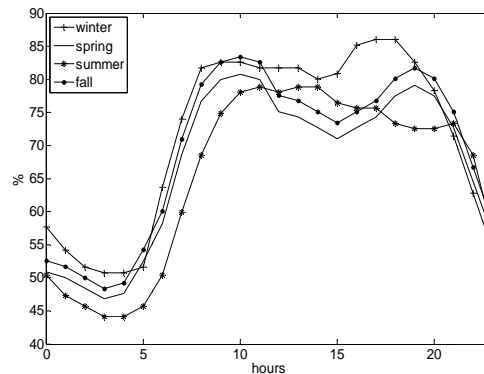


Figure 5. Load profile per season

