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

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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 paperanalyses 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 systemsare 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

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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 ± 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:

$$k_t = \frac{G_t}{G_0} \tag{1}$$

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]:

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

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:

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

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.

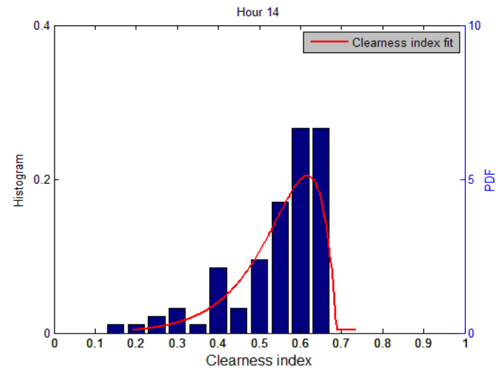

Figure 1. Clearness index distribution fitting and respective histogram, for 1 p.m. in summer

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):

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

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).

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

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:

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

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.

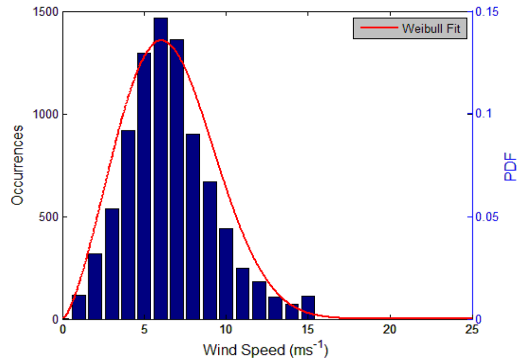

Figure 2. Weibull distribution fitting against its respective histogram

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.

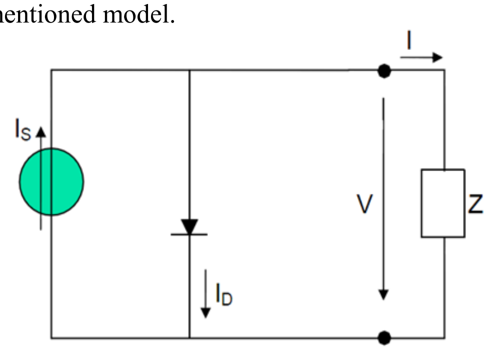

Figure 3. One-diode and three parameters electric equivalent circuit of a PV module

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 ( ), the inverse saturation current ( ), and the diode ideality factor( ). 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

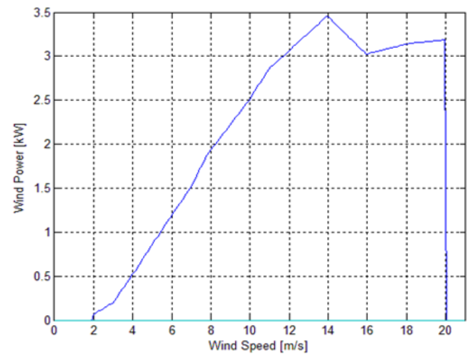

Figure 4. Power–wind speed curve of the wind generator

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.

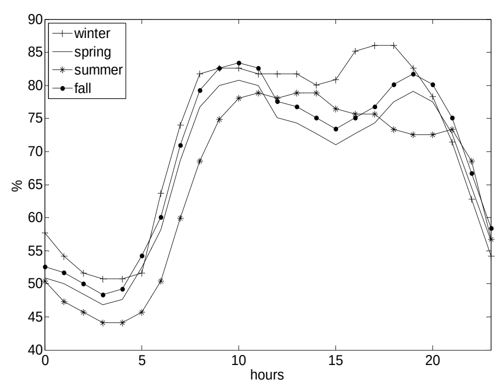

Figure 5. Load profile per season

F. Three-phase power flow

To be able to analyse power flow on LV distribution networks, special methodologies are required. In this kind of networks, the load as seen from the power transformer is quite unbalanced, because sometimes domestic appliances are run at different times in different phases or there can even be several monophasic consumers on one phase and very few on another one, due to the daily behaviour of common people. As a consequence, a solution for this problem called three-phase power flow was developed, in which the behaviour for a single phase cannot apply as it did for HV and MV and each phase needs to be handled individually.

The used three-phase power flow algorithm is based on the superposition method, and there are three main steps [10–11].First, all bus voltages are set equal to the stipulated voltage on the feeder bus and branch currents can be calculated, starting from the farthest bus and ending in the substation transformer. The contributions of each load/generator are added one at a time to calculate branch current. The return conductor current is also obtained in order to determine the neutral voltage.The second step consists in determining the new bus voltages using the branch currents from the first step, as well as the neutral voltage. The calculations in this step start from the source to the end buses. In this step, the computed bus voltage corresponds to the phase–neutral voltage.The final step is to compare the voltages against their previous iterations. If the difference is above an established error margin, steps one to three have to be repeated until convergence is achieved.

If generation is included in the network, the process will be similar. The inclusion of generators will subtract their injected power from the load in the bus to which they are connected.

3. Simulations Results

A. Simulation conditions

In order to perform a probabilistic power flow assessment, the stochastic values are taken per hour, during different days, each day representing a different season of the year. This means that if every hour is simulated once, there will be a total of 96 simulations. Since the objective is to use a Monte Carlo method, each hour needs to be computed a reasonably large number of times, in this case, one thousand, resulting in a total of 96,000 simulations.

To obtain the values for the generators power output for a particular hour, the simulation startswith a value of solar irradiance (or wind speed, in case it is a wind generator) that is drawn from the stochastic model that describes it. After obtaining these variables, the power output of the generatorsis computed according to the photovoltaic or wind generator model.In what concerns the load, it is a percentage of the maximum load as shown in Figure5, according to the day of the week, which is selected through a random number.

This procedure will be repeated 1000 times per hour with different load and generation values according to the stochastic methods and the load model, during four different seasons, translating in the 96,000 simulations referred to above. In each simulation, a power flow is executed and the number of times the voltage at any bus exceeds the upper or the lower bound is evaluated.

B. Test network

The test network used is based on a real LV distribution network in the southern part of Portugal and is depicted in Figure 6.

Table 3. Load characterization of the test network

Contracted power (kVA)	1.15	2.3	3.45	5.75	6.9	Total
Nº clients	11	1	52	1	40	105
Total contracted power (kVA)	12.65	2.3	179.4	5.75	276	476.1

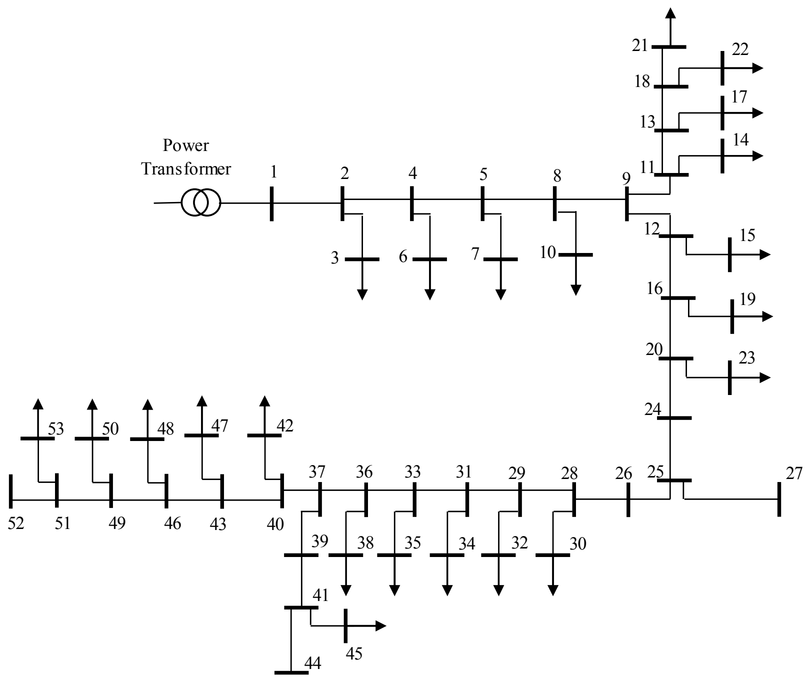

Figure 6. Diagram of the test network

This network contains 54 buses and 105 single-phase clients. The clients are distributed by several levels of contracted power, as it is shown in TableIII.

In what concerns the micro generation, every client is considered to have a PV module or a wind generator attached to him, with a maximum power that is half the maximum (contracted) power load per client, as to respect the Portuguese micro generation legislation. In each simulation, the clients are distributed randomly across the three phases of the bus to which they are connected. This means that every hour will have a different configuration of both generation and load.

In Portugal, 98% of the micro generation plants are PV based and only 2% are wind generators. As to respect the same proportion, 2 clients have wind generators attached.

C. Base-case

Given the simulation conditions presented in subsection A, a Monte-Carlo simulation was performed in the test network described in subsection B. It is commonly accepted that normal operating conditions correspond to a voltage profile between 0.9 (lower bound) and 1.1 pu (upper bound). As so, a transgression is defined as a violation of one of these voltage limits in, at least, one bus. Table IV presents the Monte-Carlo results achieved in the base-case.

Table 4. Number of transgression in the Monte-Carlo simulation of the test network

Total simulations	**Total transgressions**	**Upper Bound**	**Lower Bound**	**Both**
96,000	3008	3007	1	0
100%	3.13%	3.13%	≈0%	0 %

Table 4 reports that in 3007 out of 96,000 power flow simulations, a voltage value above 1.1 pu was identified in at least one bus. Therefore, one can conclude that over voltages are likely to happen, in at least one bus, with a probability of about 3%,and no undervoltages are expected in the studied network.

Due to the characteristics of solar irradiance that inputs the PV modules, these overvoltagesare expected to occur more often in the spring and summer as can be observed in Figure 7.

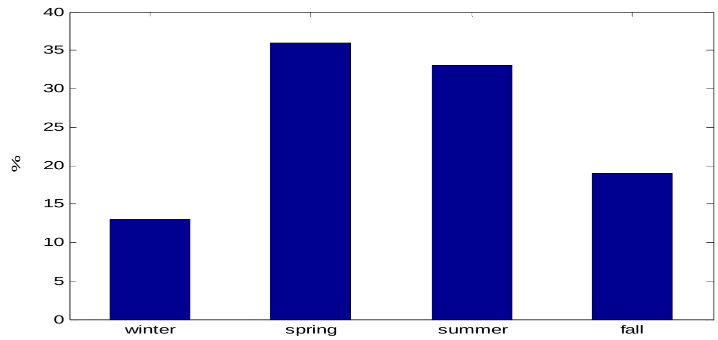

Figure 7. Distribution of the over voltages by the season of the year

It is known that during spring, temperatures are lower than in summer and that irradiance tends to peak more often in the reverse way. This leads to a sort of equilibrium between both seasons regarding PV systems power output, because higher temperatures will decrease the peak voltage and lower irradiance will decrease the peak current, which means that in both situations the peak power will be similar.

D. Battery systems

As mentioned before, several solutions have been provided to cope with the issue of overvoltages in LV distribution networks with dispersed micro generation. One of the most obvious is to adjust the inverters, which interface renewable energy generators with the power grid and can regulate the power factor, in order to absorb reactive power from the grid. By doing so, the voltage in the buses where this procedure is applied should notice a decrease in the voltage. However, this measure has proven to be not effective, due to the significant resistive nature of low voltage lines [11].

It was also suggested the replacement of actual MV/LV transformers with automatic tap changing transformers that can be automatically controlled to reduce the nominal voltage in the transformer (reference bus), in case of overvoltage or increase it for undervoltages. Although this method is effective, it is quite expensive for the MV/LV range.

The most used solution is micro generation shedding, in which a generator is disconnected from the grid in case there is an overvoltage in its bus or any surrounding bus. However, generation shedding is quite troublesome from the point of view of the producers, as no one enjoys investing in systems that have to be turned off, due to voltage issues which people think that are not related to them.

This introduces a solution based on the use of batteries. Batteries are now the state of the art in what concerns electric vehicles and could also be used to face such issues, but the usage of batteries is a sensible question. They have been applied in electric vehicles, but the truth is that they were too expensive a decade ago. However, with recent breakthroughs in power electronics and in the manufacturing of the batteries themselves, it is expected that their price will decrease significantly in the next years. As so, for arelatively small extra investment, a battery could be installed along with a photovoltaic module or a wind energy converter.

Still, one needs to assess the true interest of having such systems aid in voltage control, and therefore this situation was simulated in the scope of the present paper. Whenever the voltage is above the stipulated operational limit, the generator would disconnect from the grid in a procedure similar to generation shedding, but, this time, it will redirect its power output into charging the battery. This would be done on the bus that registers the highest overvoltage, if there are generators in it. The proposed algorithm will then move to neighbour buses that have generators and execute the same procedure until voltage comes within commonly acceptable values or there are no more generators to disconnect. Later on, during higher load periods (from 8 p.m. until 11 p.m.), this energy willbe softlyreturned to the network along a four hour period to prevent voltage spikes. In practical terms, this can easily be done using current control on the batteries, to limit their power output per hour, setting that, in each hour, only a fourth of the stored energy in the battery would be returned to the grid. It is worth to mention that the battery has the same capacity as the renewable generator to which it is attached.

The process of charging a battery can last for more than one hour. Whenever the same generator is disconnected from the grid due to an overvoltage event, it will charge the attached battery until its storing capacity is fully reached. Moreover, when the battery is fully charged, the generator is disconnected from the grid and no more charging is allowed.

Monte Carlo methods in this situation have to beslightly altered. The network configuration must be kept from one hour to the next, otherwise, a generator in a given phase in a given bus that had to be disconnected may not be on the same phase, since the network load placement was randomly attributed up to this point. So a full day will have to be simulated using the same network, but still using stochastic methods to predict solar irradiance and wind speed. 4000 days will be simulated (1000 per season), each with 24 hours, translating into 96,000 simulations as done before.

A similar simulation to the one referred to in subsection C was then performed in order to assess the voltage transgressions in the attached batteries case. Table V presents the results achieved in the overall simulation outlined above.

Table 5. Number of transgressions in the Monte-Carlo simulation of the test network,with batteries attached to the renewable generators

Total simulations	Total transgressions	Upper Bound	Lower Bound	Both
96,000	37	0	37	0
100%	0.39%	0%	0.39%	0%

In this situation, no overvoltages were found. This means that the generators were successfully disconnected from the grid and charged the batteries instead, which in turn were able to discharge their stored power again onto the network, without causing any voltage spikes. However, some undervoltages may occur (with a very low probability) because the disconnection of generation from the grid will lead to a voltage drop in the concerned buses.
This control strategy accomplishes a twofold objective: (i) from the Distribution System Operator point of view, the overvoltage events were eliminated; (ii) from the micro generation producers' standpoint it is far more beneficial, since they will not lose the money that would be lost otherwise with simple generation shedding procedures.

4. Conclusions

In the present paper, the overvoltage issue in low voltage distribution networks with micro generation was addressed. Due to the stochastic nature of both solar and wind resources, a Monte-Carlo technique was undertaken.

In this context, a solar irradiance and cell temperature stochastic model based on the clearness index was used. As far as the wind speed was concerned, a Weibull distribution was the tool at hand. Also, appropriate load and renewable generators power output models were applied.

In order to compute the phase voltages in the network buses, a three-phase power flow algorithm based on the superposition method was introduced.

The proposed overall model was applied to a test network based on a real low voltage distribution network. It was found that, due to the combination of high renewable generation with low load, voltages above the normal operational limit (1.1 pu) are likely to occur, however with a low probability of about 3%. Nevertheless, some countermeasures have to be taken.

A solution to this problem based on batteries was presented. Should an overvoltage occurs, related generators are disconnected from the grid and charge an attached battery instead. At night, during higher load periods, the stored energy is smoothly returned back to the grid, thus improving the generation profile and preventing under voltages to occur. This solution proved to be effective, since all over voltages were eliminated in the test network. Furthermore, power was returned to the grid, when it is more needed, in the peak load hours.

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