A Granular Monte Carlo Based Methodology to Estimate PV Generation Impacts on the Utility Long-Term Energy Planning

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***Abstract*—With the publication of resolution #482/2012 by the Brazilian Electricity Regulatory Agency (ANEEL), the penetration of small-scale photovoltaic (PV) generators has started to increase rapidly in Brazil. This trend will reduce the total energy consumed by customers from the utility. Therefore, traditional techniques used by distribution utilities for long-term energy planning (1 to 5-year horizon) must be updated to include PV generation impact. In response, this paper proposes a Monte Carlo based methodology for the long-term energy planning of distribution utilities, taking into account the probabilistic aspects of PV penetration growth. However, if simulations are conducted with high resolutions (e.g. 1-minute resolution) the time required to run all simulations may be excessive. To overcome this issue, an analysis of the data granularity impact on results precision is presented. It is observed that 1 "average day", described using 1-hour data resolution, is sufficient to provide a good and quick estimate of the PV generation impact on long-term energy planning.**

***Index Terms*—Long-term technical impact, Monte Carlo simulation, Photovoltaic generation.**

I. Introduction

According to the European Photovoltaic Industry Association (EPIA), the total installed photovoltaic (PV) generation capacity has exceeded 130 GW by the end of 2013, continuing an exponential growing trend observed in the past years [1]. In Brazil, besides the outstanding solar radiation levels throughout the territory [2], the installed PV capacity started to grow only from 2012, due to the publication of resolution #482/2012 by the National Electricity Regulatory Agency [3]. As a result, installed PV capacity has increased from negligible to 15 MW by the end of 2014 [4], raising utilities concern over the potential technical impacts of this trend on grid operation.

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Among the main concerns is the PV generation impact on utility long-term energy planning. In Brazil, distribution utilities have to buy the energy that will be supplied to customers on government-regulated auctions, which are performed based on five-year-ahead market. Therefore, utilities have methodologies to estimate the energy that must be supplied to the network considering the same horizon. However, the increasing PV penetration will unavoidably influence the energy consumed by customers and the network losses. Such impacts may invalidate the traditional methodologies employed to predict the long-term behavior of a network energy demand.

In response to such issue, this paper proposes a Monte Carlo based methodology to estimate the long-term impact of PV generation on the utility energy planning. The Monte Carlo method provides approximate solutions to problems by performing statistical analyses [5]. The proposed approach includes probabilistic models for the uncertainties involved in PV connections such as PV location and PV rating power. The probabilistic aspects of load behavior are also considered in the studies by using realistic load profiles provided by a low-voltage simulator [6]. Once these uncertainties are included, a more realistic estimation of PV impact on the customer consumption and network losses can be obtained and more sound decisions can be taken.

Since the main application of the proposed methodology is to estimate long-term energy impacts of PV generation, a massive number of power flow simulations is required. For instance, if load and generation information are available with 1-minute resolution, 525,600 power flow simulations must be run for one Monte Carlo scenario of 1-year study. To overcome this issue and avoid excessive computational effort, this paper presents an analysis of data granularity (data resolution) impact on the results precision. As will be shown later, such analysis is performed by evaluating the errors that appear if lower data resolutions and an "average day" are

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considered when running the proposed Monte Carlo simulation approach. In [7], a data granularity analysis has shown that hourly resolution underestimates PV generation impacts on voltage level. However, the current work shows that, for long-term energy planning, the advantages of hourly resolution can overcome the disadvantages.

This paper is organized as follows. Section II describes the proposed Monte Carlo based methodology to estimate the PV generation impact on long-term energy planning. An assessment of data granularity impact on results precision is presented in Section III. Finally, Section IV outlines the main conclusions of this work.

II. Probabilistic Methodology for the Assessment of PV Impacts on Long-Term Energy Planning

Since many characteristics of a widespread PV connection are random, a probabilistic assessment must be adopted to determine its impacts. In this paper, a Monte Carlo based methodology is proposed. The basic idea of a Monte Carlo technique consists in simulating hundreds or thousands of deterministic scenarios where the random variables are sampled, based on probabilistic models, to assume a specific value for each simulation scenario. Deterministic tools such as sequential power flow are used to simulate each scenario. The results can be condensed using different sorts of indices according to the type of analysis that is performed. For the data granularity analysis performed in the following section, the use of results average is adequate.

The proposed Monte Carlo simulation methodology and the techniques used to model the problem variables will be presented in this section. Figure 1 shows the flowchart of the proposed algorithm.

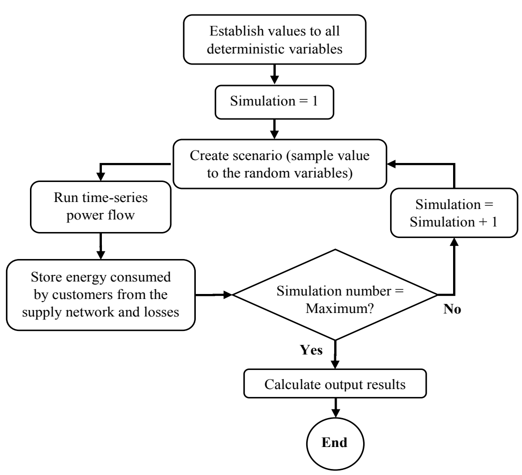

Figure 1. Flowchart of the Monte Carlo based algorithm

Initially, values are assigned to all deterministic variables of the problem. These deterministic variables are:

- Grid characteristics (length, lines impedances, etc.): This information is usually known by the respective utility. In this paper, real data from a Brazilian distribution utility is used;
- Load profile: Realistic load profiles provided by a low voltage simulator proposed in [6] are used. This simulator models the probabilistic behavior of individual home appliances, including characteristics such as switch-on/off times of each appliance and number of occupants in the house. One different 24-hour load profile has been generated for each customer. On multi-day simulations, the same 24-hour behavior is assigned to all days;
- PV penetration level: this is the ratio between total installed PV power and total customer load (only active peak power). It imposes how much PV power must be installed on the grid to perform the analyses. In this paper, different PV penetration levels are analyzed in the studies (from 0% up to 100%, with steps of 25%);
- Solar irradiance profile: The National Renewable Energy Laboratory (NREL [8]) has real data for solar irradiance, which are used to create a normalized profile for the PV arrays. The same profile is applied to all PV arrays since a single LV network is considered in the studies.

Then, a specific value is assigned to the random variables, based on the respective probabilistic model, in order to create one simulation scenario. The considered random variables are PV location and PV power rating.

Each scenario is created as follows. One customer (bus and phase/phases) is randomly selected to have a PV array, taking into account that all customers have the same probability of owning a PV array. Then, the PV power rating for the chosen customer is randomly selected between 0.25 and 5 kWp (typical low voltage PV power rating in Brazil [9]) using a uniform probability density function. This process continues until the total PV power reaches the penetration level determined at the beginning. If the number of customers is not sufficient to achieve the desired PV penetration level, the power of all PV plants is normalized to achieve this objective. PVs are phase-to-neutral connected for single-phase customers and phase-to-phase connected for multi-phase customers, although the algorithm is valid for any connection type.

Once the scenario is created, the time-series power flow can be conducted. The results are the total power consumed in the network and power losses for each instant of the simulated period. With such information, the consumed energy and energy losses can be calculated using (1) through trapezoidal method, where *P* is the consumed power.

$$E = \int_{t_0}^{t_f} P(t)dt \tag{1}$$

Hundreds of scenarios are simulated until results convergence is achieved. During tests, 200 scenarios were found sufficient. Then, the last step is to calculate the average of these 200 results. Studies are conducted using the OpenDSS interfaced with MatLab.

III. Data Granularity Analyses

In this section, data granularity analyses are carried out to evaluate how much data can be reduced in order to improve computational performance, without compromising the result quality. The impact of data resolution is assessed by determining errors introduced by lower resolutions. 1-minute is the maximum resolution considered.

Analyses for 1-day and 1-year horizon are shown. One shall notice that a maximum 1-year horizon is considered, instead of a 5-year complete study. This is because distribution utilities must conduct demand projection analyses annually and correct the initial 5-year forecast, if necessary, in the course of time.

A. Study Network

The study LV network is illustrated in Figure 2. This is a real network from a Brazilian distribution utility, and its main characteristics are described as follows:

- Three-phase four-wire LV network;
- 32 residential customers;
- 75 kVA service transformer;
- Total line length of approximately 800 meters;
- Peak loading level is approximately 95% of transformer rated power;
- Load profiles are provided by the low voltage simulator [6].

Each PV generator included on the network has power rating sampled based on the probabilistic model described in Section II, and is modeled by a normalized solar irradiance profile extracted from NREL database. PV penetration level is considered in the range varying from 0% to 100%, with steps of 25%.

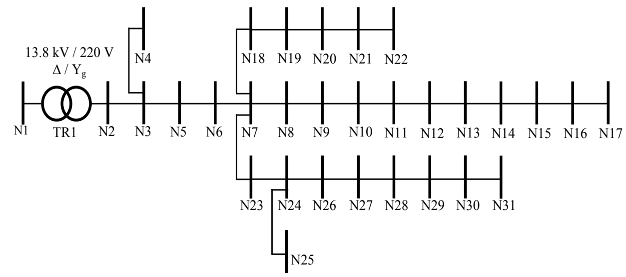

Figure 2. Test network schematic.

B. 1-Day Horizon

In this first study, the PV impact is analyzed considering four data resolutions (5, 15, 30 and 60 minutes) and results are compared with 1-minute resolution (base case), over a period of 24 hours.

In this paper, the relative error between the resolution under analysis and the base case (1-minute resolution) is presented to quantify disadvantages (loss of precision) of lower resolutions. The error for a given *"x-min"* resolution is calculated using (2), where E_{base} is the energy consumed by the network during the study period for the base case and $E_{x\text{-}min}$ is the energy consumed by the network during the study period for the *"x-min"* resolution. Figure 3 illustrates the relative error obtained for the energy supplied to the network in 1 day if 5-minute or lower resolutions are considered.

$$\text{Relative Error}_{\text{x-min}}\,[\%] = 100 \times \frac{E_{base}[kWh] - E_{x-\min}[kWh]}{E_{base}[kWh]} \tag{2}$$

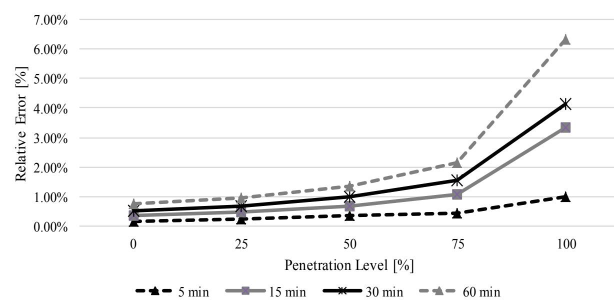

Figure 3. Relative error of energy supplied considering 1-day horizon.

The error increases for lower data resolutions and higher PV penetration levels. Nevertheless, even with 1-hour resolution and 100% penetration level, the error still remains below 7%, which indicates an acceptable approximation. Furthermore, for PV penetrations lower than 75% the error is limited to 2%. The positive value indicates that energy estimated considering 1-minute resolution is higher than energy estimated by other resolutions, that is, the energy is underestimated if lower resolutions are used.

Figure 4 illustrates the deviation of technical losses with respect to the base case. Since losses are typically calculated as a percentage of the total supplied energy, this deviation index is simply the difference between losses percentage for the base case ($Loss_{base}$) and losses percentage for another given *"x-min"* resolution ($Loss_{x\text{-}min}$), as shown in (3).

$$\text{Deviation}\,[\%] = \left(Loss_{base}[\%] - Loss_{x-\min}[\%]\right) \tag{3}$$

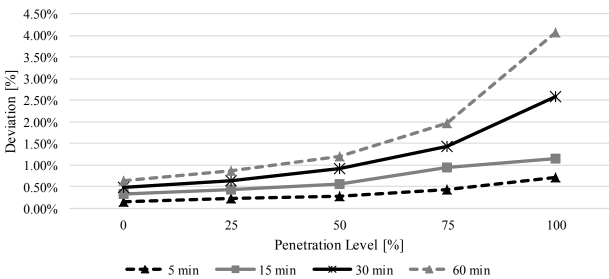

Figure 4. Deviation of technical losses for 1-day horizon.

The deviation errors follow the same pattern observed in the total energy results, also showing that the errors of PV penetrations lower than 75% are acceptable (deviation < 2%).

Such use of lower data resolutions significantly reduces the required computational time. This can be visualized in Table 1, which shows the number of power flows performed for each scenario of the Monte Carlo simulation. For 60-minute resolution the number of power flows is reduced from 1440 (1-minute resolution) to 24. Therefore, there is a good potential for practical application of lower resolution studies, since utilities are interested in achieving a compromise between computational time and results precision.

TABLE 1. TOTAL NUMBER OF POWER FLOWS PERFORMED IN EACH SCENARIO OF THE MONTE CARLO SIMULATION WITH 1-DAY HORIZON.

Data Resolution [min]	Number of power flows performed for each scenario
1 (base case)	1440
5	288
15	96
30	48
60	24

C. 1-Year Horizon

Although studies presented in Section III.B offer the impression that lower resolution simulations lead to reasonable results, they consider only 1-day horizon. The following study evaluates the impact of data granularity reduction in 1-year energy planning. In this study, the base case (detailed study) consists in a Monte Carlo simulation performed with 1-minute resolution for 1-year horizon. Thus, 525,600 power flows must be calculated for each Monte Carlo scenario (200 scenarios are generated for the entire process). In this base case (detailed study), real solar irradiance profiles measured by NREL during 1 year are used and, therefore, different types of days (such as clear, overcast and partially cloudy), different seasons and cloud movements are taken into account. The 24-hour load profile of a given customer is considered the same for every day during the year.

On the other hand, the simplified cases can be described as follows. For each Monte Carlo scenario, only an "average day" is simulated; that is, only one 24-hour simulation is performed (for each data resolution) and the energy results are multiplied by 365 to obtain 1-year results. In this "average day", load level and solar irradiance at a particular instant are the arithmetic mean of all values at this particular instant throughout the year. For example, Figure 5 illustrates the calculation process of an "average day" out of 30 solar irradiance profiles (i.e., out of 1-month).

If this "average day" approach leads to acceptable errors with respect to the base case results (detailed study), the computational time demanded for a long-term energy planning will be reduced significantly.

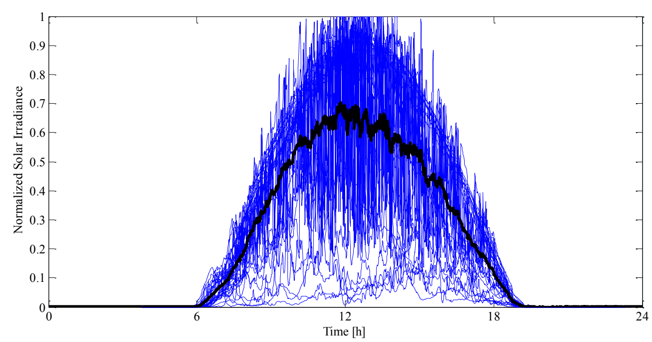

Figure 5. Graphic illustration of average day process. Normalized solar irradiance for thirty days are drawn in blue and the respective "average day" in black.

After performing the 1-year simulations, Figure 6 illustrates the relative error (with respect to the base case) of total energy consumption. The "average day" approach and different data resolutions are considered in these simulations. Figure 7 presents the results for technical losses.

The errors are lower than 1% for 1-minute "average day" study and lower than 2.5% for the lowest studied resolution (60-minute "average day"). Such small errors indicate that the proposed Monte Carlo technique can be applied using low resolution data, if long-term horizons are considered. This is because the fluctuations on load and generation throughout the year are likely to cancel each other, leading to a reasonably smooth final shape (i.e., low-resolution profiles become sufficient to describe the overall system behavior).

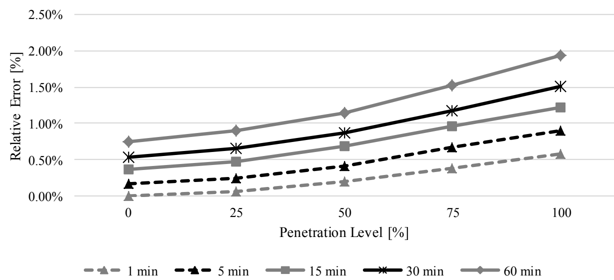

Figure 6. Relative error of energy supplied for 1-year horizon (case 1).

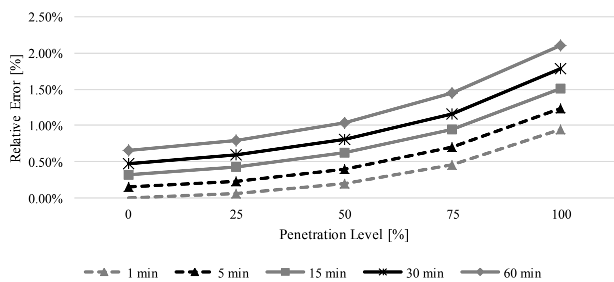

Figure 7. Deviation of technical losses for 1-year horizon (case 1).

D. *Further Tests*

To further verify the applicability of the proposed method, previously performed tests have been repeated on a different LV network, whose main characteristics are: three-phase four-wire low voltage network, 23 residential customers, 45 kVA service transformer and peak loading level is approximately 100% of transformer rated power. Figure 8 and Figure 9 show the error obtained for total energy supplied and total losses on this new studied LV network.

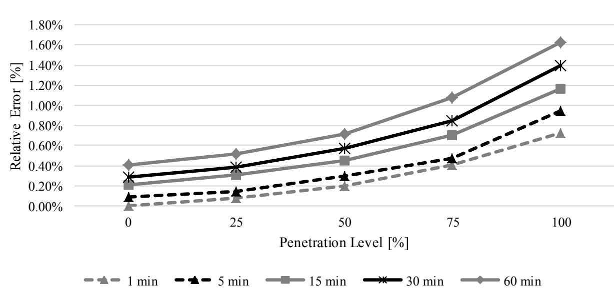

Figure 8. Relative error of energy supplied for 1-year horizon (case 2).

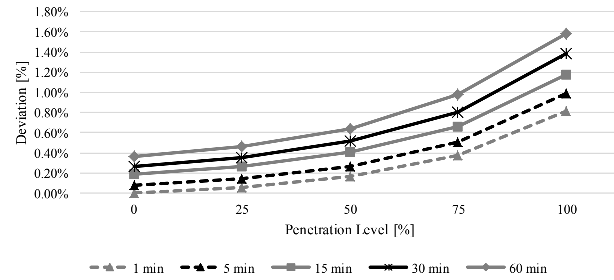

Figure 9. Deviation of technical losses for 1-year horizon (case 2).

Both cases indicate errors below 2.0%, which confirms the findings obtained previously, in Section III.C. Therefore, the proposed Monte Carlo simulation method, combined with the "average day" approach (with 1-hour data resolution) can, in fact, be used for long-term energy planning of distribution networks with PV generation. This will reduce the number of required simulations by more than 99%, since only 24 power flow simulations (1 "average day" with 1-hour resolution) are required, while a detailed study (base case) requires 525,600 simulations (1 year with 1-minute resolution) for each generated Monte Carlo scenario.

IV. CONCLUSIONS

This paper has presented an effective method to assess the impact of PV generators on the utility long-term energy planning. The method uses Monte Carlo simulations to consider the probabilistic factors involved in a widespread small-scale PV connection scenario, such as PV location and PV power rating. As long-term analyses may require an excessive number of simulations, data granularity analyses have also been performed to determine whether lower data resolutions could be used with acceptable errors. Results have shown that 1 "average day" with 1-hour resolution can be used to estimate energy consumption and technical losses of a LV network considering a long-term horizon (1-year). The results are less than 2.5% different from the true results (base case). If this "average day" approach is adopted, significant time can be saved on utilities energy planning studies.

This is part of an ongoing research. Future steps include using solar irradiance profiles measured in Brazil and analyzing other MV/LV networks. Analyses will be carried out to verify whether the conclusions presented here may be extended to any LV network and also to the high-voltage/medium-voltage substation scale.

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