Evaluation of Distributed Generation Impacts on Distribution Networks under Different Penetration Scenarios

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Abstract— **This paper presents a methodology and a computational tool developed for the assessment of the impacts caused by photovoltaic and wind generators, up to 100 kW, connected to the distribution networks, and aims at a real network application. The impact on the power distribution systems planning derive from the new network configuration caused by the installation of distributed generators and the demand growth. The curves associated with the distributed generators (DG) are modelled based on the average behavior of the inputs, such as irradiation and wind, and the technologies available. Their locations are defined by a DG probabilistic allocation algorithm based on attractiveness measures, as a function of economic variables. The network impacts consider prospective scenarios, and are determined by the diagnosis of network elements, by monitoring the loading of feeders and secondary networks, as well as the analysis of voltage profiles, losses, and protection effectiveness.**

Index Terms-- **Distributed power generation, Power system protection, Smart grids**

I. Introduction

The distributed generation is seen as a shift in the paradigm of energy generation in Brazil and in the world. The adoption of renewable sources of energy for small scale residential or commercial production brings not only environmental benefits, but also an opportunity to alleviate the supplying difficulties found in a developing country such as Brazil. Since 2012, the Brazilian energy regulatory agency ANEEL, in an effort to promote such alternative, has been fostering the regulatory framework to the access of small scale energy producers [1]. The normative resolution approved in the same year gave energy consumers the right to become prosumers. The same resolution categorize these prosumer in different levels, such as “micro-generator”, which has an installed power up to 100 kW and “mini-generator”, which has a minimum installed power of 101 kW up to 1MW. The resolution also creates an energy market were energy can be traded between the micro-generator and the utility, but never sold, limiting the benefits of the prosumer regarding the trade of its total energy consumption.

The present application results from a Research and Development Project supported by AES Eletropaulo, an energy distribution utility who serves 24 cities in the metropolitan area of São Paulo, the most important socioeconomic region in the country, and more than 20 million customers. Despite solving some of the suppling problems, this paradigm change can bring some undesired impacts on the distribution. Therefore, this article presents the methodology and computational tool developed for the assessment of possible impacts to the distribution network caused by the photovoltaic and wind small scale distributed generation (μDG), and aims at applying it to a real AES Eletropaulo’ distribution feeder.

The methodology developed includes many steps such as the creation of μDG evolution scenarios, electric models for the μDG, a method for probabilistic allocation of distributed generators, and the modeling of the impacts on the network planning and protection effectiveness, using power flow and short-circuit calculations. This methodology was implemented in the platform SINAPGRID, which is an electrical calculation software that can analyze real networks with a great number of bus bars and loads, and can integrate networks with different voltage levels. In the following sections each of these steps and the preliminary results will be described and presented.

II. Methodology

A comprehensive methodology was developed to achieve a reliable analysis for distributed generation impacts on distribution network of AES Eletropaulo. The main methodological steps are described as follows.

A. Distribution Feeder Data

The methodology considered a reap power distribution feeder, including its medium (13.8 kV) and low voltage networks (240/120 V, 220/127 V). Medium/low voltage distribution transformers (13.8/0,220 kV), protection devices

AES Eletropaulo sponsored the project with ANEEL R&D project resources.

and low voltage clients (represented by characteristic load curves [2]) were also modelled, in order to evaluate the impacts on such elements due to the installation of µDGs.

B. Electric model of the distributed generators and load curves

The clients in the distribution network were modelled by load curves. The load curves were calculated based on the clients typical load behavior and their monthly energy consumption. Figure 1 shows a characteristic curve for a residential client with energy consumption between 220 and 500 kWh per month.

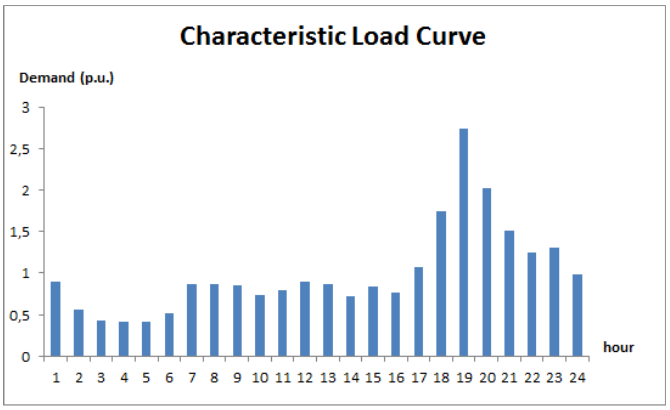

Figure 1. Client characteristic load curve

The photovoltaic generator model was designed following two steps. The first consisted on a study of the technologies that converts solar irradiation into electric energy. Thus the behavior of photovoltaic modules, inverters and maximum power point tracking (MPPT) devices were investigated. Afterwards, the availability of solar irradiation was modelled, resulting on a characteristic hourly solar irradiation curve [3]. Figure 2 illustrates an example of a modelled curve.

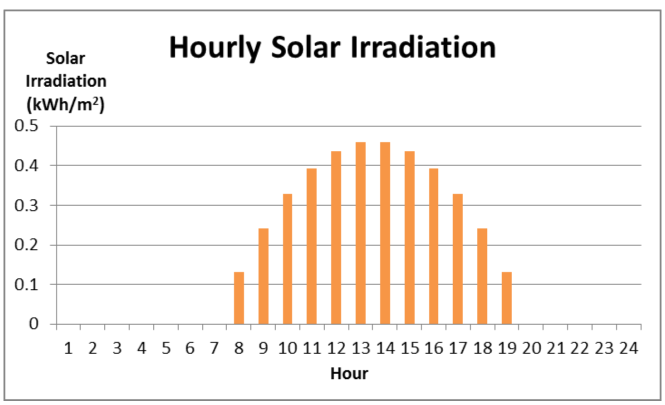

Figure 2. Characteristic hourly irradiation curve

Applying the hourly solar irradiation curve to the technologies electric models available, it was possible to create a photovoltaic generation curve, which could be used to assess the impact of the DG on the network. Figure 3. **Load curve versus photovoltaic generation** shows an example of a photovoltaic generation curve compared with the prosumer load curve.

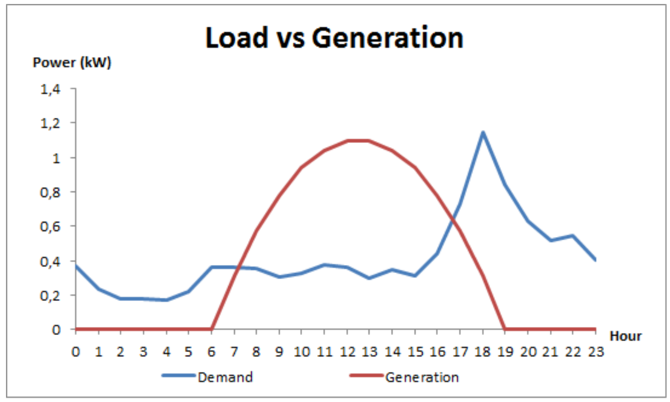

Figure 3. Load curve versus photovoltaic generation

To create the wind power generator model, the wind conversion technologies and its limitations were analyzed, such as wind turbines coefficient of power, pitch control and stall control. Three real wind turbine models were selected to compose a range of options for the possible clients. They were chosen according to clients demands. The first one was a vertical axis wind turbine with the nominal power of 3 kW, 12 meters of height and aimed small clients (0-200 kWh/month consumption). The second wind turbine was a horizontal axis wind turbine with the nominal power of 3.3kW, 20 meters of height and aimed at medium scale clients (201-600kWh/month). The last chosen turbine was 12 meters of height either, but has 20kVA of nominal power, and target large residential scale clients (601 kWh/month and up). The three models had their starting speed of 3 m/s, due to the small scale spectrum of analysis. The wind turbines characteristic curves are shown at Figure 4.

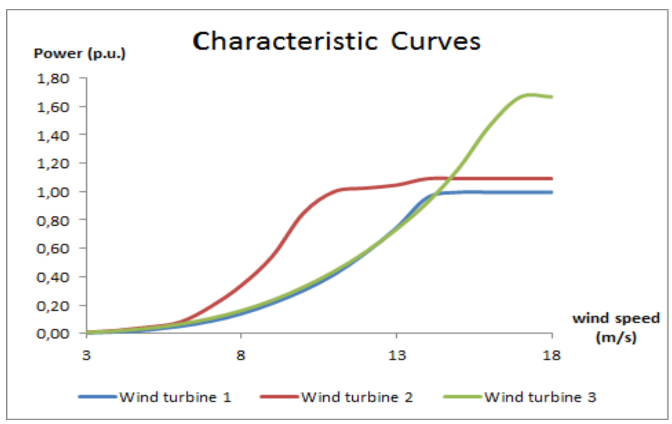

Figure 4. Wind turbine characteristic curves

Subsequently the wind availability was modelled based on wind velocity probability distribution functions, on location (urban or rural), height, altitude, etc. The wind speed distribution model utilized was the Weibull distribution and the wind speed data employed in this study was gathered from measurements made at the city of São Paulo between the years of 2007 and 2009. Figure 5 shows the hourly generation curve created for the small client turbine, based on the São Paulo data.

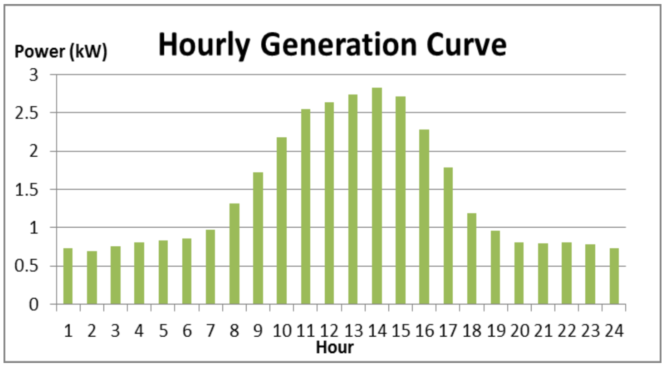

Figure 5. Characteristic hourly wind generation curve

C. *Insertion Scenarios (2014 – 2024)*

The research methodology follows the precepts of Gaston Berger, regarding the evaluation of existing alternatives and predispositions, followed by a thorough morphological analysis of penetrating technologies and subsequent evaluation of critical variables to the problem [4]. In the endeavor of modelling the distributed generation market adoption the Bass Diffusion model was used. This model is intended to represent the growth of a product category, which basically consists of four stages, which are the introductory phase of slow growth, followed by a very rapid growth stage, a maturity stage (having little or no growth) and final phase of decline (due to obsolescence or replacement) [5]. Through the morphological analysis and the penetration model, prospective scenarios could be developed. Figure 6. Methodology for scenario developmentbellow shows the method for creating scenarios.

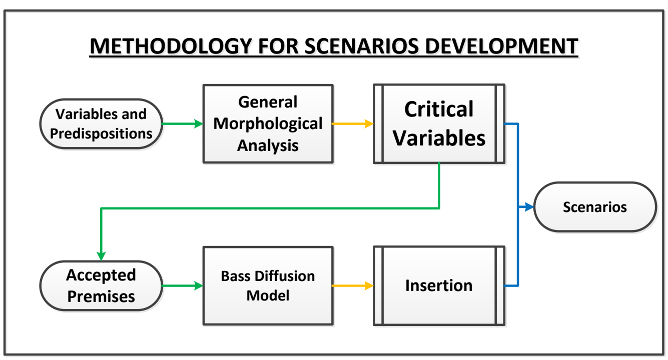

Figure 6. Methodology for scenario development

Thus, four different scenarios were created to assess the µDG role in Brazil from 2014 to 2024. A scenario should include the action of its main characters and estimate the probability of uncertain events, structured to describe the passage from a present situation to a future one in a coherent way. The great number of variables in the real world and the complexity of its interactions made working with multiple scenarios appealing. The scenarios were created considering socioeconomic and technic and economic factors. Each one of them should indicate the diffusion rate and the proportion of photovoltaic and wind generators to be installed.

The four scenarios were Green Corporation (GC), First Class Innovation (FCI), Emergent (EM) and Generation for All (GFA). They differ according to its two main variables: Information and Total Cost. The chart shown in Figure 7 was created according to the relation between the scenarios and its variables.

The creation of the scenarios considered a research on the Brazilians on renewable energy microgeneration [6]. Based on this research correlations were found between socioeconomic variables and the tendency to adopt a DG. By crossing this data with the profile of the utility clients, it was possible to determine the DG potential market for the utility distribution area. Using this information, it was possible to apply the Bass model to forecast the DG adoption rate for each scenario, resulting in the curves illustrated in Figure 7. Insertion scenarios.

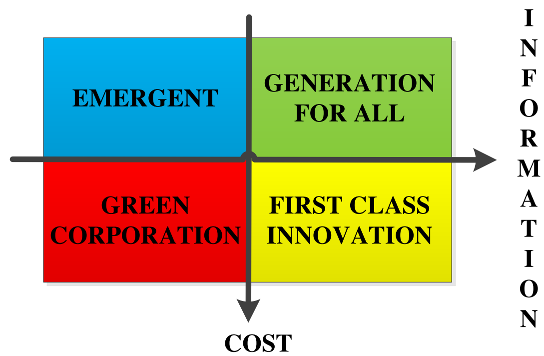

Figure 7. Insertion scenarios

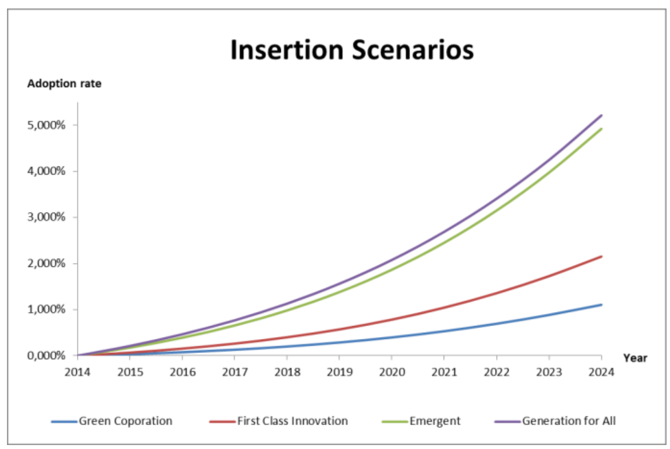

Figure 8. Diffusion rate of DG, in the utility distribution area, for the four scenarios developed

D. *DG allocation algorithm*

In order to model the assignment of the micro-generators to clients present in the distribution networks a probabilistic assumption based on the attractiveness of the DG alternative was used. Observing the distribution network clients, disparities inherent to them can be seen, either due to the type of load they represent (rural, residential, commercial, industrial, etc.) or due to their energy consumption. Therefore the tool developed should be sensitive not only to the client's economic profile, represented by its consumption, but also to financial benefits from the installation of distributed generation, which may vary for different types of clients. To that end, it was created a function capable of measuring the investment attractiveness in micro-generation through the economic feasibility calculation, for each client. The technique used for feasibility analysis was the cost of annual life cycle of the alternative. This metric was used because it is sensitive to four key variables influencing the μDG, which are the investment capacity of clients, the value of capital in time, public incentives and characteristics of each client class. The attractiveness function can be seen in equation (1).

$$Attractiveness = \frac{ALCC^{utility}}{ALCC^{DG}} \quad (1)$$

The $ALCC^{utility}$ stands for the annual life-cycle cost of having only the utility as a source, and the $ALCC^{DG}$ for the annual life-cycle cost of choosing the DG as an alternative. The ALCC equation can be seen as follows.

$$ALCC = CRF(i,n) * C_{inv} + C_{en} \quad (2)$$

The $CRF(i,n)$ is the capital recovery factor for the interest rate "i" and the annuity "n", C_{inv} is the investment cost and C_{en} is the annual cost spent in energy consumption. Considering that the consumer already has a connection with the utility, its investment cost for this alternative is null, so the annual life-cycle cost of the utility alternative is given only by the money spent in energy.

$$ALCC^{utility} = E * F * (1+T) \quad (3)$$

The "E", "F" and "I" stand for the amount of energy consumed in a year by the client, the energy fee pay by the aforementioned client and the taxes paid for the transaction, respectively. Despite using the utility as the only source, choosing to install a DG requires an investment that was modelled based on a market analysis cost projection. Its equation can be seen below.

$$C_{inv}{}^{DG} = (C_{Var} * P_{DG} + C_{Fix}) \quad (4)$$

$$C_{en}{}^{DG} = E * F * (1+T) - E_g * F_{feed-in} \quad (5)$$

The variables "C_{Var}" and "C_{Fix}" are the variable and fixed projected costs of the micro-generator. The "P_{DG}" is the DG installed capacity necessary to produce "E_g", the energy generated by the DG in a year and "$F_{feed-in}$" is the energy fee paid for the energy generated by the DG.

The attractiveness calculated for the consumers in this study considered the Brazilian background, in which there is no feed-in tariff and the most benefits come from generating all the energy that the client consumes. Nevertheless, the tool can be used for different conjunctures. The attractiveness curve generated from the analysis described above to a distribution network can be seen in Figure 9. **Attractiveness function**.

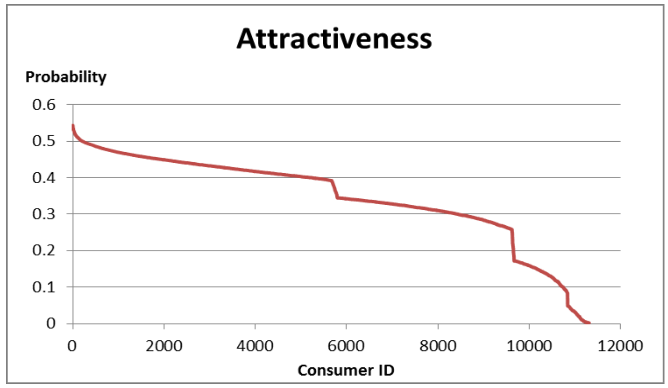

Figure 9. Attractiveness function

E. *Network impact evaluation*

A power flow calculation for each one of the 24 hours of the day was done for the evaluation of the technical impacts on the distribution network. Therefore loadings, bus-bar voltage profile, power factor and losses were calculated. The implemented simulator evaluates the technical impacts for the distribution network for a predefined insertion of small scale distributed generators, defined as the percentage of the total potential clients that could generate energy by using their DG. The evaluation is focused on a substation and the supplied circuits throughout the planning horizon, and on the scenario composed by a number of DGs.

F. *Protection impact evaluation*

The impacts on the network protections were based on the contribution of inverter based distributed generations [7]. Thus, several short-circuit calculation are done to evaluate the impacts of the DGs on the network protection devices. The impacts assessed are: ineffectiveness of the protection and lack of coordination in protection schemes, caused by the reverse power flow, considering the protection zone for every protection device.

For the first impact, several short-circuit are calculated on the limits of each protection zone, to find the minimum short-circuit current with the dispersed DGs. The value of the minimum short-circuit current was compared with the pick-up current from the protection devices. On cases where the minimum short-circuit current is under the value of the pick-up current, there is a potential problem of ineffectiveness.

For the second impact, the short-circuit current above the protection zone is calculated to find the maximum short-circuit current with the dispersed DGs. This current is compared with the device pick-up current. When this short-circuit current is higher than the pick-up current, there is a possible problem of lack of coordination. Figure 10 illustrate the lack of coordination problem.

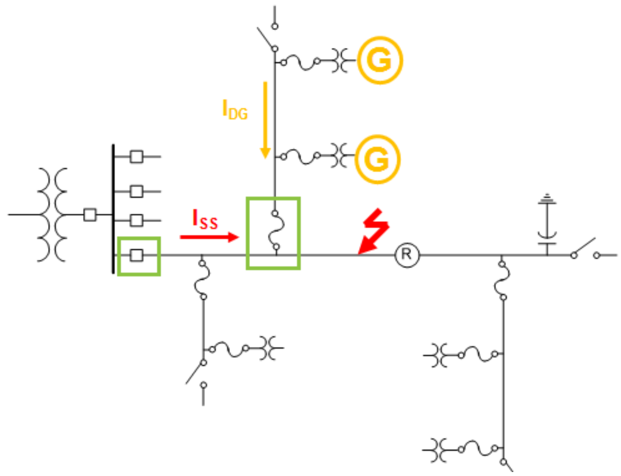

Figure 10. Impact on the coordination scheme

III. SIMULATION PLATFORM AND ANALYSIS

SinapGrid was the simulation platform used and it has a number of functions for network analysis, allowing also the inclusion and development of new modules in a transparent way. Among the main simulation platform characteristics, for the network impact analysis support under the EV presence, we can depict the following bellow:

i) Integrated modeling of all voltage levels in the distribution network (HV, MV and LV);
ii) Friendly network editor which allows the representation of all the network components (bus bars, lines, loadings, levels of demand throughout the day, capacitors banks, voltage regulators, 2 or 3 enrolment transformers, photovoltaic and wind generators, electric vehicles, EV charging, etc.) by schematic diagram means or through geo-referenced diagrams;
iii) Power flow calculation modulus, for balanced and unbalanced networks, capable to solve meshed networks through many algorithms (Gauss, Newton-Raphson);
iv) Probabilistic algorithms for the DG allocation;
v) Evaluation reports of loadings, voltage profile an voltage unbalance and energy losses following the [8] recommendations;

IV. CASE STUDY

The case study involved the inclusion of small scale distributed generators in a real feeder from AES Eletropaulo. This case study considered the developed scenarios of penetration and also a sensitivity analysis.

A. *Simulation and Analysis Framework*

The network data utilized to build the MV and LV networks was obtained from the utility's GIS system. The case study's simulation environment was the distribution feeder VGR2301 (feeder of Vargem Grande Paulista substation), which has approximately 26.589 bus bars, 9.481 clients, the demand of 10,5 MW and 154 kilometers of extension. The feeder is shown at Figure 11.

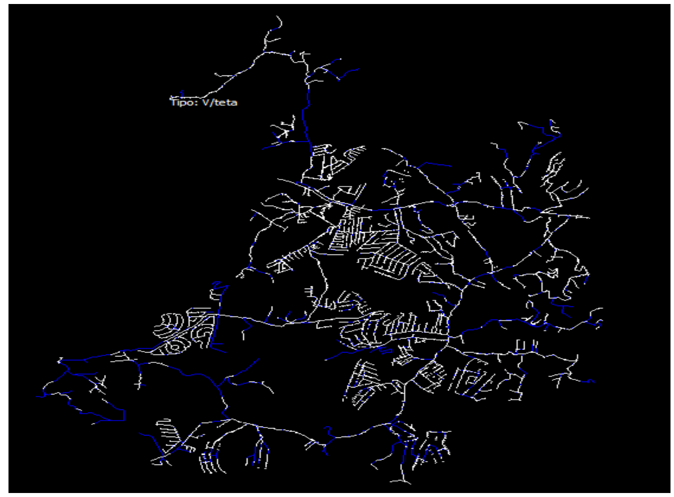

Figure 11. Pilot power distribution feeder in the study case

B. *Impact Evaluation in the Distribution Network*

The impact on the distribution network planning was evaluated according to the impact in the electric network elements, as the segments that define the topology of a distribution network and in an aggregated way at important points of the network. The aspects evaluated involve determining the network's load, power factor, voltage profile, and losses.

The first impact assessed was the number of clients' bus bars that cease to violate the voltage quality limits defined by ANEEL [9] Figure 12 shows the simulation results, for every proposed scenario at the year of 2024, being Generation for All worst DG incidence scenario, exemplifying the additional percentage of bus bars that cease to violate the voltage quality limits, when compared to the base case.

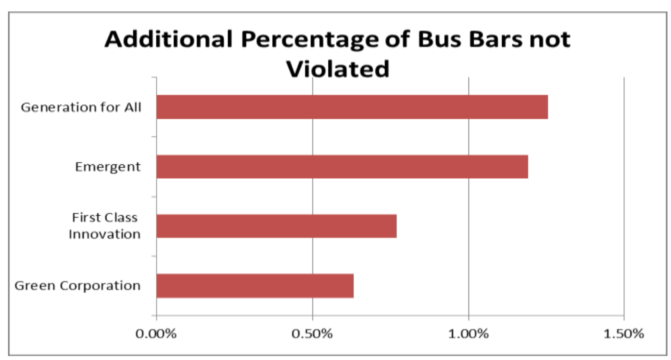

Figure 12. Additional Percentage of Bus Bars not violated

The second impact assessed shows that while the energy demand can reduce up to 5.15%, the power demand at peak hour only reduces by 0.94%. This can be seen in Figure 13.

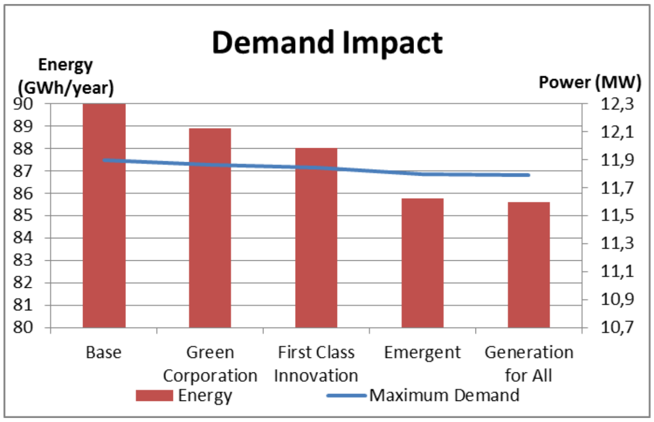

Figure 13. Energy and power demand reduction

As expected that the DG would diminish the network losses, since it causes more current to pass at the LV network and less current at the feeders. Figure 14 shows the percentage of losses in each scenario.

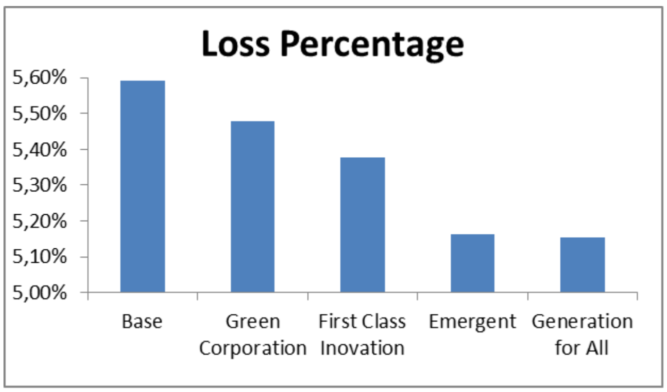

Figure 14. Loss percentage for each scenario

It was expected that the DG sources would reduce the maximum load at the network assets such as the transformers. However the reduction on the load does not coincide with the peak hour, as it can be seen in Figure 15.

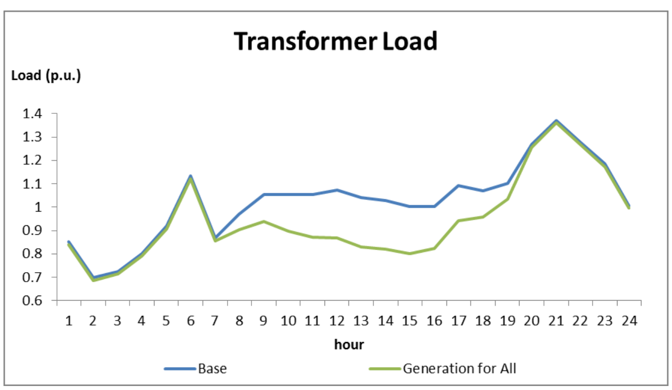

Figure 15. Daily transformer load

The impact on the network protection was assessed by a sensitivity analysis. Figure 16 shows a graph with the minimum short-circuit current and reverse short-circuit current behaviors faced with the percentage of prosumers.

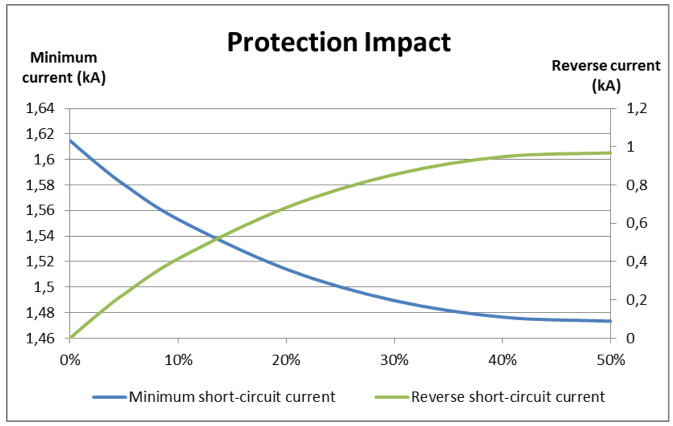

Figure 16. Short-circuit current behavior

V. Conclusion

This paper presented the developed tool and methodology for assessing the impact on distribution networks due to the inclusion of small scale distributed generators. Through simulations in real networks, it was possible to evaluate the impact on various components of the power grid: HV/MV substation transformers, MV primary networks, MV/LV transformers and LV secondary networks. Thus, issues such as load diagnoses, voltage profile, losses and also problems at protection schemes were considered. The study is strategically relevant to the distribution utilities as renewable technology tends to have a more relevant role at energy supply, and it will bring several challenges to the network planning.

Acknowledgment

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