DOI: 10.48011/sbse.v1i1.2307

Impacts of Distributed Generation in Electrical Grids

Maria Cecilia C. Lima * **Handerson Marques** *
Thommas Kevin Sales Flores * **Fabiano Salvadori** *
Lucas V. Hartmann * **Camila S. Gehrke** *

* *Smart Grid Group - SG2, Center for Alternative and Renewable Energies, Federal University of Paraiba, João Pessoa, PB. (e-mail: maria.lima@cear.ufpb.br; handerson.marques@cear.ufpb.br; thommas.flores@cear.ufpb.br; salvadori.fabiano@cear.ufpb.br; lucas.hartmann@cear.ufpb.br; camila@cear.ufpb.br).*

Abstract:
Unconventional energy sources such as wind, solar and biomass represents more and more an alternative in substitution of conventional energy sources. In effect, many studies still need to be done to clearly identify the impacts that the insertion of distributed generation (DG) sources represent in the power grid. In this paper, an analysis of the impact of the distributed generation (DG) insertion in the electrical grid is realized, based on impedance matrix, grid voltage and power factor (PF). Benchmarks were created to relate the sensibility in a point common coupling (PCC) to the DG insertion. Preliminary results show that sensibility does not change with the load or the PF of the DG.

Keywords: Distributed Generation; Impedance Matrix; Impacts; Insertion.

1. INTRODUCTION

Increasing electricity consumption and concern for the preservation of the environment have driven zero carbon policies, the reduction of fossil fuels for power generation and the search for alternative renewable energy sources such as wind and solar. These alternative sources contributes to the growth of grid connected distributed generation (DG), but generates some problems such as reverse energy flow, overvoltage and poor power quality Walling et al. (2008).

Several works seek the best way to analyze the impacts of DG on the electrical grid. In Cheng et al. (2016) the authors proposed to evaluate voltage fluctuation using a methodology based on real data of two distribution systems operating in California. The first step was to model the circuit using actual data from an already installed plant, but the analysis is more appropriate for operation control purposes than for impact assessment. Otherwise, in Machado et al. (2016) the impact of DG on the electrical grid was analyzed based on the economic viability analysis of consumer units to determine the penetration and location of a photovoltaic DG.

The impact of DG using real data analysis was studied by Munoz et al. (2016). The authors applied some stability indexes characterized by impedance, voltage, active and reactive power.

Based on active and reactive power and Jacobian matrix in Abri et al. (2008) a complex bus selection index prioritizing more sensitive buses was proposed. This work did not present network modeling and depends on several variables to evaluate the impact of DG. In addition, a study based on actual data analysis requires on-site measurements, increasing process costs, which can be seen as a disadvantage in implementing this technique.

The insertion sensitivity of a DG of each PCC, modeling circuits based on Kirchhoff's laws and using ideal current sources to propose indexes (sensitivity values) based on voltage and impedance, comparing the two indexes was analyzed in Lima and Gehrke (2018). The study has evaluated the influence of a DG at the PCCs voltage level based on Kirchhoff's Law and impedance matrix. The DG was considered as an ideal current source. In the study, two sensitivity indexes were implemented and compared.

This paper defines a methodology to analyze the PCC sensibility due to the insertion of a DG, setting indexes based on impedance, voltage, and also in PF, which determine the level of sensitivity, represented by the insertion of the DG at that specific point. Some scenarios are simulated considering the load and electrical grid impedance variation, using the Monte Carlo simulation method, and considering changes on the PF. Since the grid impedance is easily obtained it is used as a parameter for over-voltage evaluation and circuit analysis.

2. METHODOLOGY

2.1 Modelling and analysis of the electrical grid

To determine the voltage at a specific node, it is used Kirchhoff's Law(1).

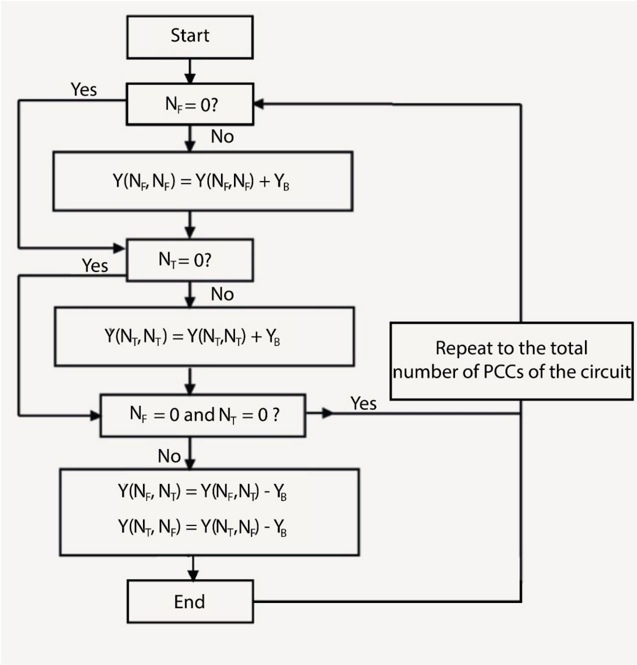


Figure 1. Flowchart of the admittance matrix of a circuit.

$$Y_{N\times N} \cdot V_{N\times 1} = I_{N\times 1} \tag{1}$$

Where: $Y_{N\times N}$ is the admittance matrix (square matrix N x N); $V_{N\times 1}$ is the voltages matrix (column matrix); $I_{N\times 1}$ the currents matrix (column matrix); and, N is the maximum number of PCCs in the circuit.

The terms of the main diagonal of the $Y_{N\times N}$ must contain the sum of all admittances directly connected to the corresponding node, and the non-diagonal terms must contain the negative sum of all directly connected admittances between the nodes. The flowchart (see Figure 1), represents the algorithm to determine the admittance matrix, where N_F is the “node from” PCC and N_T is the “node to” PCC.

Equation (2) is used to determine the influence that the DG inserted on the PCC n will have in other PCC, defined m, modifying the term Y(n,n) to Y(n,m).

$$Z_n = \frac{1}{Y(n,n)} \tag{2}$$

The current necessary in a PCC and to know the needed power to regulate the voltage level is calculated through (3):

$$I_n = \frac{V^* - V_n}{Z_n}, \tag{3}$$

Where: V^* is the reference voltage (1.0 pu); V_n is the voltage of the PCC before the insertion of the DG; Z_n is the PCC’s impedance.

Simulations were carried out with a circuit of sixteen PCCs and a voltage source of 1.0 pu, 60 Hz (Figure 2). Data were obtained in Grady et al. (1991), where PCCs 1 to 9 represent branch 1 and PCCs 10 to 16 represent branch 2. An array was created to insert the current sources data and the voltage source of 1.0 pu was replaced by a current source using Norton’s theorem, to be inserted in the currents array.

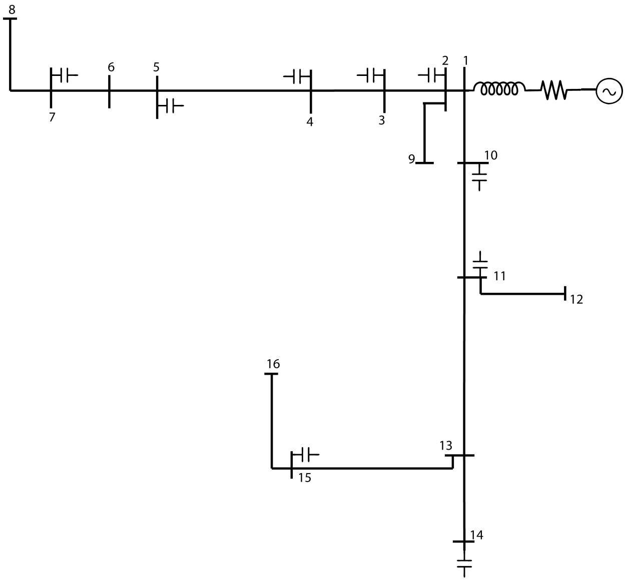


Figure 2. Circuit with 16 PCCs using PI segments.

The circuit was simulated in three scenarios: (1) without a current source; (2) with one current source (DG); and (3) with multiple current sources (DGs). The current value needed to regulate the voltage levels of the PCCs to 1.0 pu was calculated using (3). The PF of the DG was 1.0, since in the PCC, the current it’s in phase with the voltage V_n.

The voltage results when a current source is connected to PCC 8, chosen randomly, in t = 0.067s are shown in Figure 3. As expected, the voltage is 1.0 pu after the insertion of the DG. In this situation $I_8 = 0.5833\ \angle 10.35°$pu.

In the sequence, PCCs 5, 7, 11, 13 and 15 were randomly chosen to insert DGs and the current values were calculated individually for each PCC using (3). Voltage levels increased to values higher than 1.0 pu in the whole system, as shown in Figure 4 because every current source inserted increases the voltage in all the PCCs.

$$\begin{aligned} I_5 &= 0.8820\ \angle 2.5474\ ^\circ\text{pu};\\ I_7 &= 0.7265\ \angle 5.3966\ ^\circ\text{pu};\\ I_{11} &= 0.7563\ \angle 19.3276\ ^\circ\text{pu};\\ I_{13} &= 0.6050\ \angle 21.7914\ ^\circ\text{pu};\\ I_{15} &= 0.4981\ \angle 22.5585\ ^\circ\text{pu}. \end{aligned}$$

To analyze the impact of the insertion of a DG with a current higher than necessary to regulate the voltage level to 1.0 pu, the PCC 8 was chosen, and a current three times higher than the calculated was inserted (Figure 5).

2.2 Impedance sensibility index

Sensibility indexes were defined to facilitate the analysis of the DG insertion in the electrical grid and determine which points of the system are more sensitive to this insertion.

The impedance sensibility index only needs the PCCs impedance (4):

$$KZ_n = \frac{|Z_n| - |\overline{Z}|}{|\overline{Z}|} \tag{4}$$

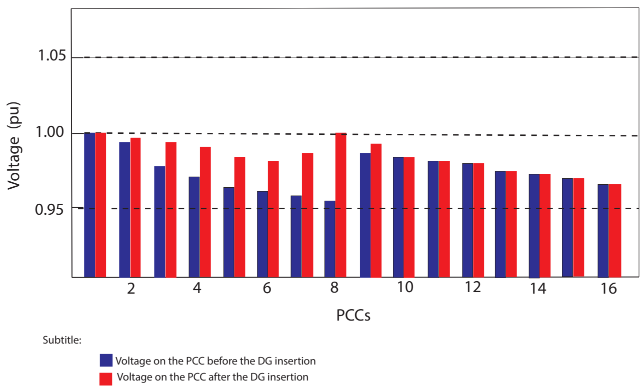


Figure 3. Voltages with DG on PCC 8.

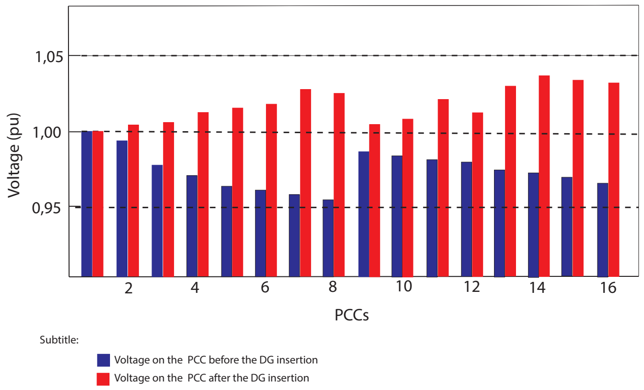


Figure 4. Voltages with DG on PCCs 5,7,11,13,15.

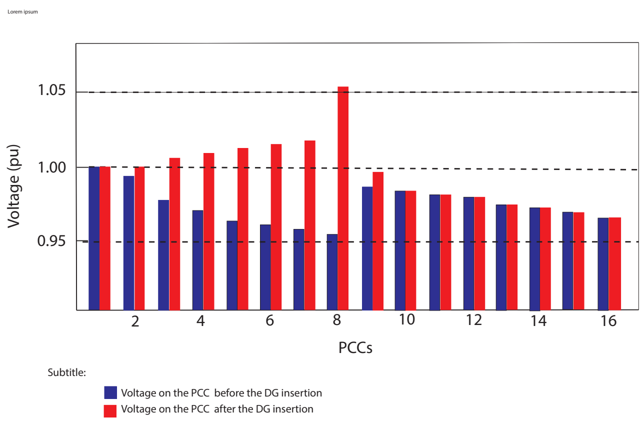


Figure 5. Voltages with DG on PCC 8 with amplitude value higher than calculated.

Where $\overline{Z}$ is the average impedance of the system, considered to calculate the impedance difference of each PCC related to all the PCCs of the system. The system impedances are obtained from the admittance matrix, so the resulting impedance in the PCC of insertion of a DG. This impedances are easily obtained, making it possible to verify the sensibility of each point and how much the insertion of a DG in a PCC affects the other PCCs.

2.3 Power Factor (PF) Analysis

The PF of the DG was changed to analyze the effects on the voltage levels of the circuit. For the analysis and to relate the voltage with the PF variation, the PF was changed to 0.85 and 0.92 (lagging and leading), and the currents were calculated to regulate the voltage level of the PCCs to 1.0 pu, using (3). A smaller circuit with 4 PCCs (Figure 6) was also considered for simulations.

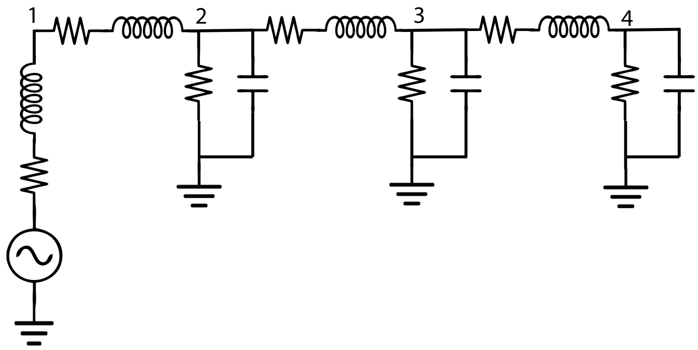


Figure 6. Circuit with 4 PCCs using PI segments.

The parameters used in the system are available in the Tables 1 and 2.

The impedance of the voltage source is R = 3,12 mΩ and L = 0,17913 mH, or Z = 0,0031 + 0,0675i.

Table 1. Circuit with 4 PACs - Parameters.

NI	NF	R (Ω)	L (mH)
1	2	1	2
2	3	1	2
3	4	1	2

Table 2. Valores de carga - Circuito com 4 PACs.

PAC	R (Ω)	C (μF)
2	200	1
3	200	1
4	200	1

A voltage sensibility index was created to analyze the influence of the DG on the PCCs of the circuits using (5).

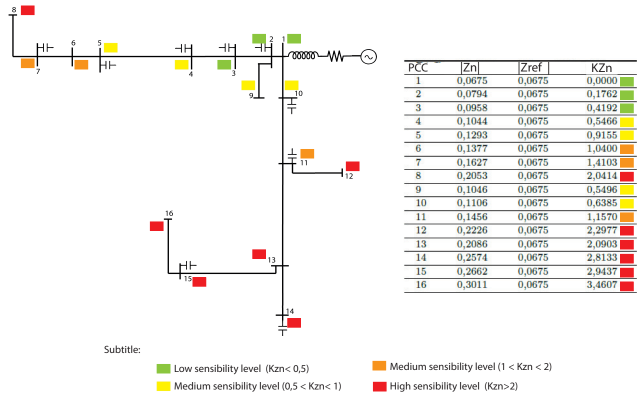
$$KV_n = \frac{\Delta V_n}{|Z_n|} \tag{5}$$

Where ΔV_n is the voltage variation on the PCC between the values obtained before and after the insertion of the DG and Z_n is the equivalent impedance of the PCC.

3. RESULTS

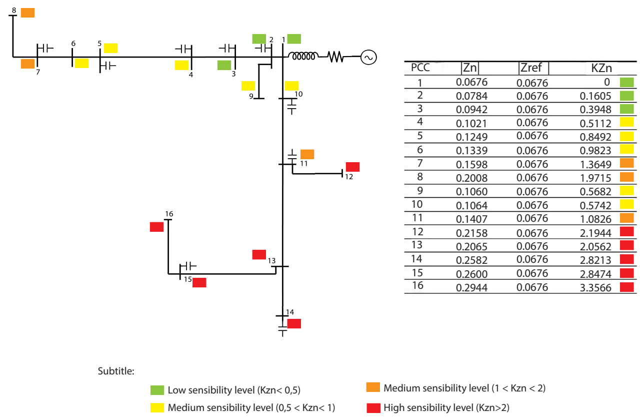
3.1 Impedance Sensibility Index

The impedance index was used based on the data obtained with the simulations. Initially, the impedance of the circuit was constant (Figure 7), then an analysis was made considering 3 cases of the impedance variation: line parameters



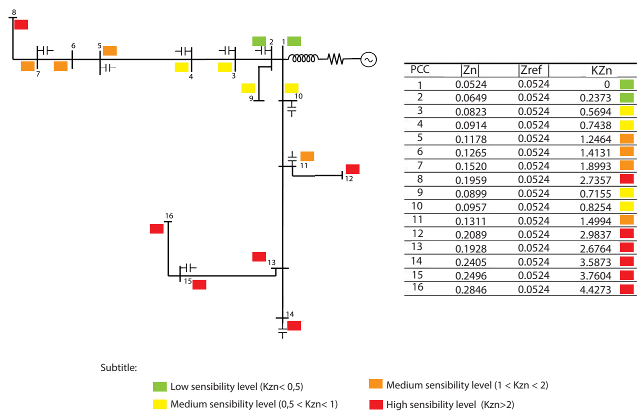
PCC	|Zn|	|Zref|	KZn
1	0,0675	0,0675	0,0000
2	0,0794	0,0675	0,1762
3	0,0958	0,0675	0,4192
4	0,1044	0,0675	0,5466
5	0,1293	0,0675	0,9155
6	0,1377	0,0675	1,0400
7	0,1627	0,0675	1,4103
8	0,2053	0,0675	2,0414
9	0,1046	0,0675	0,5496
10	0,1106	0,0675	0,6385
11	0,1456	0,0675	1,1570
12	0,2226	0,0675	2,2977
13	0,2086	0,0675	2,0903
14	0,2574	0,0675	2,8133
15	0,2662	0,0675	2,9437
16	0,3011	0,0675	3,4607

Figure 7. Constant impedance.



PCC	|Zn|	|Zref|	KZn
1	0.0676	0.0676	0
2	0.0784	0.0676	0.1605
3	0.0942	0.0676	0.3948
4	0.1021	0.0676	0.5112
5	0.1249	0.0676	0.8492
6	0.1339	0.0676	0.9823
7	0.1598	0.0676	1.3649
8	0.2008	0.0676	1.9715
9	0.1060	0.0676	0.5682
10	0.1064	0.0676	0.5742
11	0.1407	0.0676	1.0826
12	0.2158	0.0676	2.1944
13	0.2065	0.0676	2.0562
14	0.2582	0.0676	2.8213
15	0.2600	0.0676	2.8474
16	0.2944	0.0676	3.3566

Figure 8. Line impedance variation.

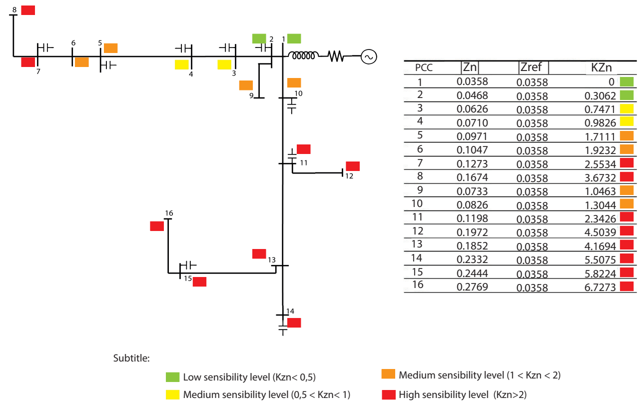


PCC	|Zn|	|Zref|	KZn
1	0.0524	0.0524	0
2	0.0649	0.0524	0.2373
3	0.0823	0.0524	0.5694
4	0.0914	0.0524	0.7438
5	0.1178	0.0524	1.2464
6	0.1265	0.0524	1.4131
7	0.1520	0.0524	1.8993
8	0.1959	0.0524	2.7357
9	0.0899	0.0524	0.7155
10	0.0957	0.0524	0.8254
11	0.1311	0.0524	1.4994
12	0.2089	0.0524	2.9837
13	0.1928	0.0524	2.6764
14	0.2405	0.0524	3.5873
15	0.2496	0.0524	3.7604
16	0.2846	0.0524	4.4273

Figure 9. Load variation.

(Figure 8), power (Figure 9), and line and load simultaneously (Figure 10). The variation of line parameters occurs mainly because of temperature variation and losses, the load changes according to the demand and the DG changes according to the solar radiation levels.

The final variation was based on *Monte Carlo* method, using random variation values to get as close as possible to real results. It can be seen that the variation of load and line parameters does not change the PCCs that are more sensitive to the insertion of DG, although the impedance influences the sensibility.



PCC	|Zn|	|Zref|	KZn
1	0.0358	0.0358	0
2	0.0468	0.0358	0.3062
3	0.0626	0.0358	0.7471
4	0.0710	0.0358	0.9826
5	0.0971	0.0358	1.7111
6	0.1047	0.0358	1.9232
7	0.1273	0.0358	2.5534
8	0.1674	0.0358	3.6732
9	0.0733	0.0358	1.0463
10	0.0826	0.0358	1.3044
11	0.1198	0.0358	2.3426
12	0.1972	0.0358	4.5039
13	0.1852	0.0358	4.1694
14	0.2332	0.0358	5.5075
15	0.2444	0.0358	5.8224
16	0.2769	0.0358	6.7273

Figure 10. Load and line variation.

Table 3. Voltage sensibility index (Kvn)

	Power Factor				
	Unit.	Leading		Lagging	
kvn	1.0	0.85	0.92	0.85	0.92
kv1	0.0002	-0.03332	-0.0227	0.02220	0.0174
kv2	0.0275	0.0290	0.0389	0.0370	0.0362
kv3	0.0226	0.0253	0.0331	0.0299	0.0293
kv4	0.0177	0.0203	0.0262	0.0233	0.0229

Table 4. Voltage sensibility index (Kvn) for Power Factor Variation with DGs in 5 PCCs.

	Power Factor				
	Unit.	Leading		Lagging	
kvn	1.0	0.85	0.92	0.85	0.92
kv5	0.3221	-0.6151	-0.2290	1.8366	1.5806
kv7	0.3605	-0.4424	-0.1141	1.6064	1.3966
kv11	0.4843	-0.1970	0.1843	2.0704	1.8535
kv13	0.5172	0.0002	0.3073	1.7712	1.6082
kv15	0.4656	0.0493	0.3019	1.4916	1.3606

3.2 Power Factor Variation

The DG current of each PCC in Figure 2 was calculated to verify the PF variation impacts on the circuit. The currents were calculated separately for 5 random PCCs (5, 7, 11, 13 and 15). Results are shown in Table 4 PCC using 3 and inserted in all PCCs at once. Results are shown in Table 3.

The same methodology was used for the circuit in Figure 2 with 5 random PCCs selected to be analysed (PCCs 5, 7, 11, 13 and 15). Results are shown in Table 4.

Table 5. PCC sensitivity according to Power Factor Variation.

Power Factor	Most sensitive PCC
1	5
0.92 leading	7
0.92 lagging	15
0.85 leading	13
0.85 lagging	15

For the small circuit when the PF is leading, the amplitude of the current inserted in the PCC is higher than when the PF is lagging. The lagging PF causes an increase in the voltage source (k1 values in columns 3 and 5), while the leading PF causes a decrease in this voltage (k1 values in columns 2 and 4). With the PF variation of the DGs, the most sensitive PCC is PCC 4, for all the cases. This analysis concludes that the change in active and reactive power inserted in the PCC by the DG does not change the PCC sensibility, even though the variation in the system's voltages are higher with the PF different than one.

When the PF = 1 the most sensitive PCC amongst the selected was #5, with the lowest voltage sensibility index. This result is consistent with the result obtained in Figures 7, 8, 9 and 10. However, with the variation of the PFs the most sensitive PCC also changes (Table 5).

Analyzing the simulations, if: (a) PF is 0.85 and 0.92 lagging, the voltage levels are higher than the limit of 1.05 pu; (b) PF is 0.85 leading, some voltage levels were lower than the limit of 0.95 pu, occurring voltage drop in a few PCCs compared to when no current source was inserted. The voltage of a few PCCs were raised, however inside the limits of 0.95 and 1.05 pu; (c) PF is 0.92 leading, some voltage levels were lower than the limit of 0.95 pu, occurring voltage drop in a few PCCs compared to when no current source was inserted, however in a few PCCs the voltage level was raised higher than the limit of 1.05 pu. The voltage levels variation, off the limits of 0.95 pu and 1.05 pu, demonstrate how harmful the PF different than recommended can affect whole circuit.

4. CONCLUSION

This paper presented a methodology for verification of the effects of DG in an electric system using current sources emulating DG. Sensibility indexes were created based on simulations results. It was verified that the connection of a DG on a PCC affects only the PCCs of the same branch, and the connection of multiple DGs not only could regulate the voltage on the PCC it was inserted but also could cause overvoltage. Besides, the equivalent impedance of a PCC influences its sensibility and the current needed to regulate the voltage level. Three cases of variation of load and line impedance were analyzed, and the PCCs of higher sensibility did not change with these variations. A power factor variation analysis was also made, changing the PF of the DG from 1.0 to 0.92 and 0.85 lagging and leading, and it showed that the sensibility also does not change with the PF changes. With the indexes presented it is possible to perform an analysis of which points of installation of a DG impact more the voltage levels of an electrical grid, without the need to run simulations. The impedance sensibility index facilitates the analysis because the only variable needed is the grid impedance, which can be easily obtained. The voltage sensibility index contributes to the analysis of the impacts of the PF variation of the DGs on the electrical network. The proposed indexes can also be used as part of optimization algorithms for location and measurement of DG impacts.

REFERENCES

Abri, R., El-Saaldany, E., and Atwa, Y. (2008). Optimal placement and sizing method to improve the voltage stability margin in a distributed system using distributed generation. *IEEE Transactions on Power Systems*, 326–334.

Cheng, D., Mather, B.A., Seguin, R., Hambrick, J., and Broadwater, R.P. (2016). Photovoltaic (pv) impact assessment for very high penetration levels. *IEEE Journal of Photovoltaics*, 295–300.

Grady, W.M., Samotyj, M.J., and Noyola, A.H. (1991). Minimizing network harmonic voltage distortion with an active power line conditioner. *IEEE Transactions on Power Delivery*, 1690–1697.

Lima, M. and Gehrke, C. (2018). Impact assessment of distributed generation based on current source and equivalent impedance (in portuguese).

Machado, I.S., Borba, B.S., and Maciel, R.S. (2016). Modeling distributed pv market and its impacts on distribution system: A brazilian case study. *IEEE Latin America Transactions*, 4520– 4526.

Munoz, F.A., Tellez, A.A., and Sanchez, J.W. (2016). Analysis of stability of tension and losses of electric power in distribution networks with distributed generation. *IEEE Latin America Transactions*, 4491– 4498.

Walling, R.A., Saint, R., Dugan, R.C., Burke, J., and Kojovic, L.A. (2008). Summary of distributed resources impact on power delivery systems. *IEEE Transactions on Power Delivery*, 1636–1644.