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Steady State Analysis of a Medium/Low Voltage Distribution Grid Behavior with PV System Penetration

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Abstract. This paper aims to present a preliminary study of the behavior of a distribution network with the penetration of grid-connected photovoltaic (PV) system. The work used measurements and data from an area of Palmas, the capital of Tocantins state, Brazil, which is attended by the power utility CELTINS. Three cases were analyzed here: (1) at a given daytime with the original distribution system, (2) at the same time with part of the distribution grid supplied by grid-connected PV systems, and (3) at a given nighttime. All the simulations were performed with PSAT software.

Key words

Distributed generation (DG), grid-connected photovoltaic (PV) system, PV penetration, PSAT, renewable energy.

1. Introduction

Distributed generation (DG), also called dispersed or embedded generation is a new approach in the electricity industry and, as the analysis of the relevant literature has shown, there is no generally accepted definition for the technical term [1]. In Brazil it is generally used to describe the generation of electricity close to consumer, regardless of capacity, technology and energy source [2]. DG takes advantage over centralized generation due to reductions of transmission and distribution losses and investments, thus improving electricity supply service [3]. DG allows greater diversification of technologies that make up the energy matrix, which leads to a more rational use of the primary sources available to produce electricity. The main DG technologies that use renewable source are: small hydroelectric plants, thermoelectric plants fueled by biomass, wind generators and photovoltaic systems [3].
Currently, large hydropower plants are responsible for 78.4% of all electricity produced in Brazil [4], but such plants are too far from major consuming centers. However, in the last decade, as has occurred in developed countries [5], there was a trend for increased distributed generation of electricity in the country due to the following causes: [6]:

- strong upward trend in electricity tariffs;
- restructuring of the Brazilian electric sector, new rules established by the Brazilian Electrical Energy Agency (ANEEL), legalization of the sale of electricity to the market for independent producers and self-producers;
- increasing availability of natural gas for generation, because of increase in supply, both domestic or foreign, the pipeline construction and the development of electricity distribution networks;
- awareness of environmental problems, promoting solutions to reduce the environmental impacts of the generation, among them, those that allow a better energy use from fossil or renewable fuels;
- technological improvements that make competitive the use of new processes and new sources of power generation in comparison to classical generation.

ANEEL approved in April 2012 rules intended to reduce barriers to the installation of small DG, including micro generation, up to 100 kW of power, and mini generation, from 100 kW to 1 MW. The objective was to facilitate the generation of electricity by consumers. The new rule creates the Energy Compensation System that allows consumers to install small generators and exchange energy with the local power utility. It is only valid for generators that use subsidized sources of energy such as hydro, solar, biomass, wind and qualified cogeneration. For this scheme, the generating unit installed in a residence (farm, etc.) will produce a certain amount of energy that, if not consumed, will be injected into the distribution system of the electricity company. Then, the power utility will use such energy as credit to discount in the consumption of subsequent months [4].

Thus, to enable consumers to become energy producers, one of the currently viable alternatives is the installation of grid-connected PV systems. However, there is not yet an exact idea of the impact of this kind of installation on the main grid. Based on this, this paper performs a evaluation of the behavior of certain part of the CELTINS's distribution network for the penetration of this type of generation. For this study, actual distribution system measurements are used and computer simulations are conducted using PSAT software.

2. Characteristics of Distribution System

For this work it was considered the block 1106 South, located in Palmas city, Tocantins, Brazil. It has approximately 700 consumers connected to the system, mostly residential ones (Fig. 1).

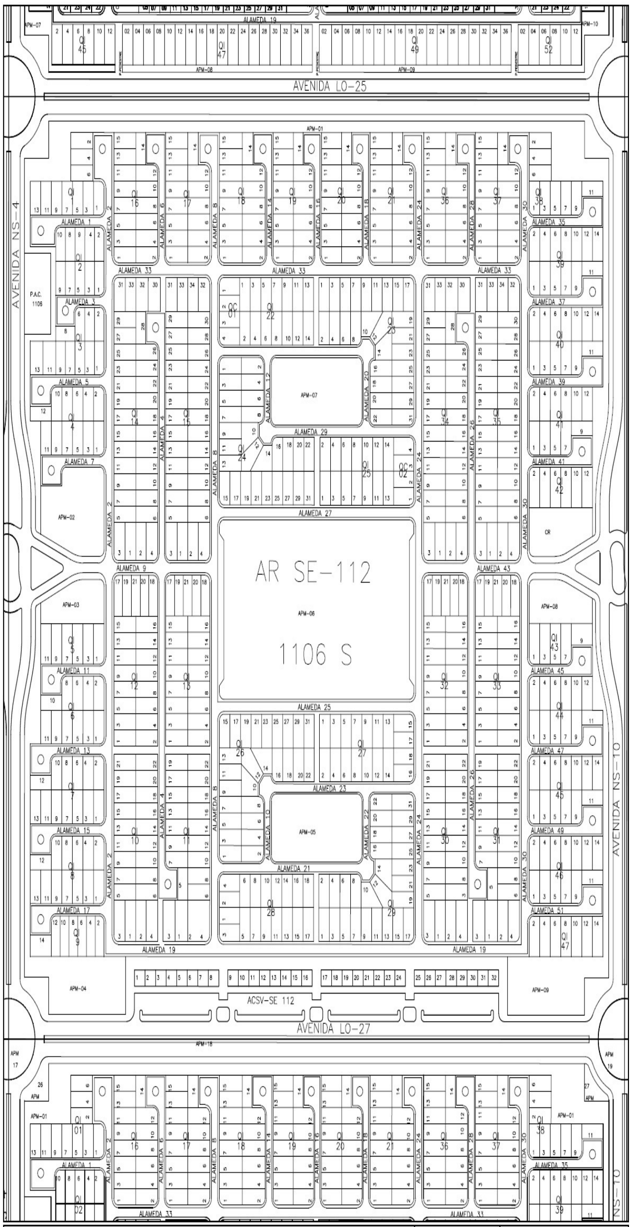

Fig. 1. Map of block 1106 South in the Palmas city [7].

The feeder from the substation number 2, called Palmas III, is responsible to provide electricity to all the CELTINS consumers installed in this block (Fig. 2).

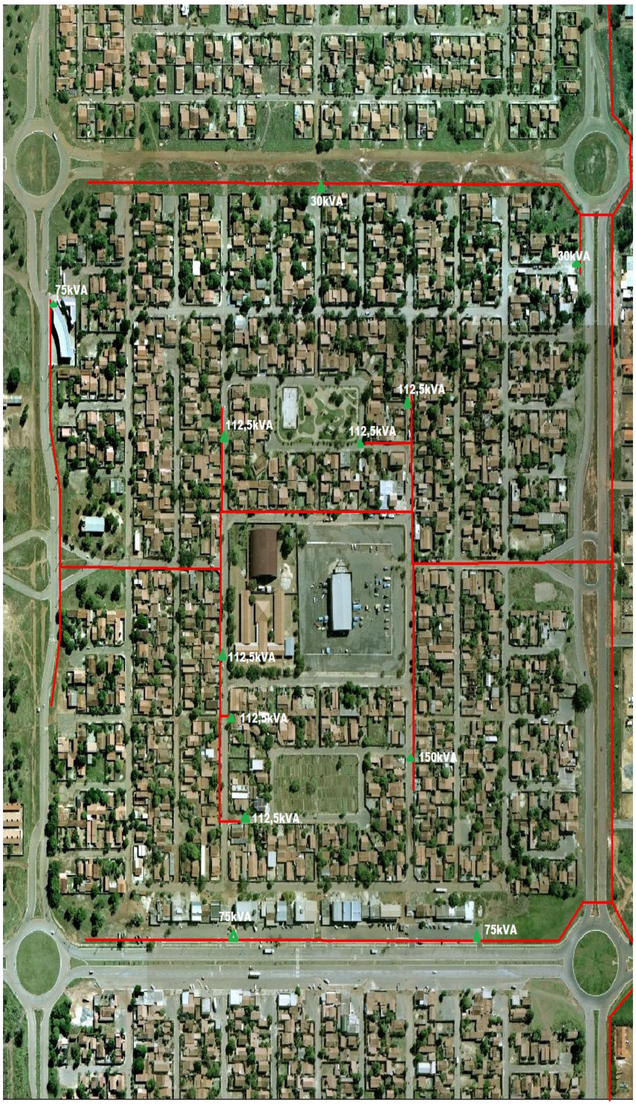

Fig. 2. Aerial photo [7], adapted by CELTINS, with the route network energy of block 1106 South.

This study also considered the following information extracted from software Eletricalc and the EU Viewer Elucid Solutions S/A (owned by CELTINS): transformer, load and branch data, input and output powers and voltages of the block distribution system, according to Tables I, II, III, IV and V.

Notes:

(a) The values given in the column "Max Power (kVA)" of Tables II and III are the maximum powers of the whole set of consumer units (CUs) connected to a given transformer at the time of study.

(b) Table V presents information (models and lengths of the cables) provided by CELTINS. With the aid of the available data in [8] the resistances and reactances could be calculated.

TABLE I
Transformer Data (CELTINS)

Bus	Bus	Power (kVA)	Voltage ratio (kV)	Resistance (pu)	Reactance (pu)
4	5	75	13.8/0.38	0.0160	0.0311
6	7	30	13.8/0.38	0.0190	0.0294
9	10	112.5	13.8/0.38	0.0147	0.0318
11	12	112.5	13.8/0.38	0.0147	0.0318
13	14	112.5	13.8/0.38	0.0147	0.0318
15	16	112.5	13.8/0.38	0.0147	0.0318
19	20	112.5	13.8/0.38	0.0147	0.0318
21	22	112.5	13.8/0.38	0.0147	0.0318
24	25	30	13.8/0.38	0.0190	0.0294
28	29	150	13.8/0.38	0.0137	0.0322
31	32	75	13.8/0.38	0.0160	0.0311
33	34	75	13.8/0.38	0.0160	0.0311
38	39	112.5	13.8/0.38	0.0147	0.0318

TABLE II
Loads connected to transformers at 2:45 pm in October 3, 2012

Bus	Voltage (kV)	Number of consumers connected to the bus (*)	Max Power (kVA)
5	0.38	13 R,C	8.52
10	0.38	280 R	15.75
12	0.38	1 P	50.23
14	0.38	251 R	15.25
16	0.38	122 R	18.55
20	0.38	171 R	11.28
22	0.38	309 R	15.43
29	0.38	265 R	19.61
32	0.38	4 C	15.17
34	0.38	11 C	24.98
39	0.38	1 I	8.34

(*) R, C, P, I stand for Residential, Commercial, Public, Industrial CU, respectively.

TABLE III
Loads connected to transformers at 9:45 pm in October 3, 2012

Bus	Voltage (kV)	Number of consumers connected to the bus (*)	Max. Power (kVA)
5	0.38	13 R,C	55.53
10	0.38	280 R	72.00
12	0.38	1 P	61.55
14	0.38	251 R	81.29
16	0.38	122 R	71.86
20	0.38	171 R	55.48
22	0.38	309 R	85.90
29	0.38	265 R	85.67
32	0.38	4 C	9.17
34	0.38	11 C	14.99
39	0.38	1 I	4.34

(*) R, C, P, I stand for Residential, Commercial, Public, Industrial CU, respectively.

TABLE IV
Active and reactive powers, and voltages (CELTINS)

Bus 37 – system input busbar		
	2:45 pm	**9:45 pm**
P (kW)	2683.95	2311.71
Q (kVAr)	1598.16	1412.61
V (kV)	13.62	14.08
Bus 1 – system output busbar (for other blocks)		
P (kW)	2292.26	1701.48
Q (kVAr)	1374.58	966.26
V (kV)	13.58	14.03

TABLE V
Branch Data (CELTINS)

Cable model AWG/ MCM	From Bus	To Bus	Length (km)	Resistance (pu)	Reactance (pu)
2	2	3	0.201	0.010166	0.003610
2/0	2	4	0.237	0.005962	0.003926
2/0	6	23	0.319	0.008025	0.005285
2	23	24	0.075	0.003793	0.001347
2	3	8	0.046	0.002327	0.000826
2	8	9	0.063	0.003186	0.001131
2	17	8	0.237	0.011987	0.004256
2	3	11	0.078	0.003945	0.001401
2	11	13	0.064	0.003237	0.001149
2	13	15	0.16	0.008092	0.002873
2/0	30	31	0.158	0.003975	0.002618
2/0	31	33	0.285	0.007170	0.004722
2/0	37	30	0.05	0.001258	0.000828
2	37	38	0.044	0.002225	0.000790
2/0	30	26	0.175	0.004403	0.002899
2	26	27	0.246	0.012442	0.004418
2	27	28	0.134	0.006777	0.002406
2	27	17	0.096	0.004855	0.001724
2	17	18	0.085	0.004299	0.001526
2	18	19	0.122	0.006170	0.002191
2	18	21	0.055	0.002782	0.000988
2/0	26	1	0.175	0.004403	0.002899
2/0	23	1	0.05	0.001258	0.000828

The power values of PV Panels were defined by the authors in Table VI in order to perform the simulations of Case 2 shown in Section IV (Case Studies).

TABLE VI
PV generation (defined by the authors)

Bus	Power of PV Panels (kW)
5	10.30
7	0
10	18.20
12	15.00
14	16.90
16	7.80
20	11.70
22	19.50
25	0
29	16.90
32	4.00
34	11.00
39	0

3. Modeling of Distribution System

Based on system data, shown in Tables I, II, III, IV and V, it was performed a complete modeling of the medium/low voltage distribution system using the software PSAT (see Fig. 3).

The simulations were configured with the parameters shown in Tables I, II, IV, V and VI for the day 03/10/12 at 2:45 pm, excluding and including DG, and with load data from Table III (at 9:45 pm) without the presence of DG.

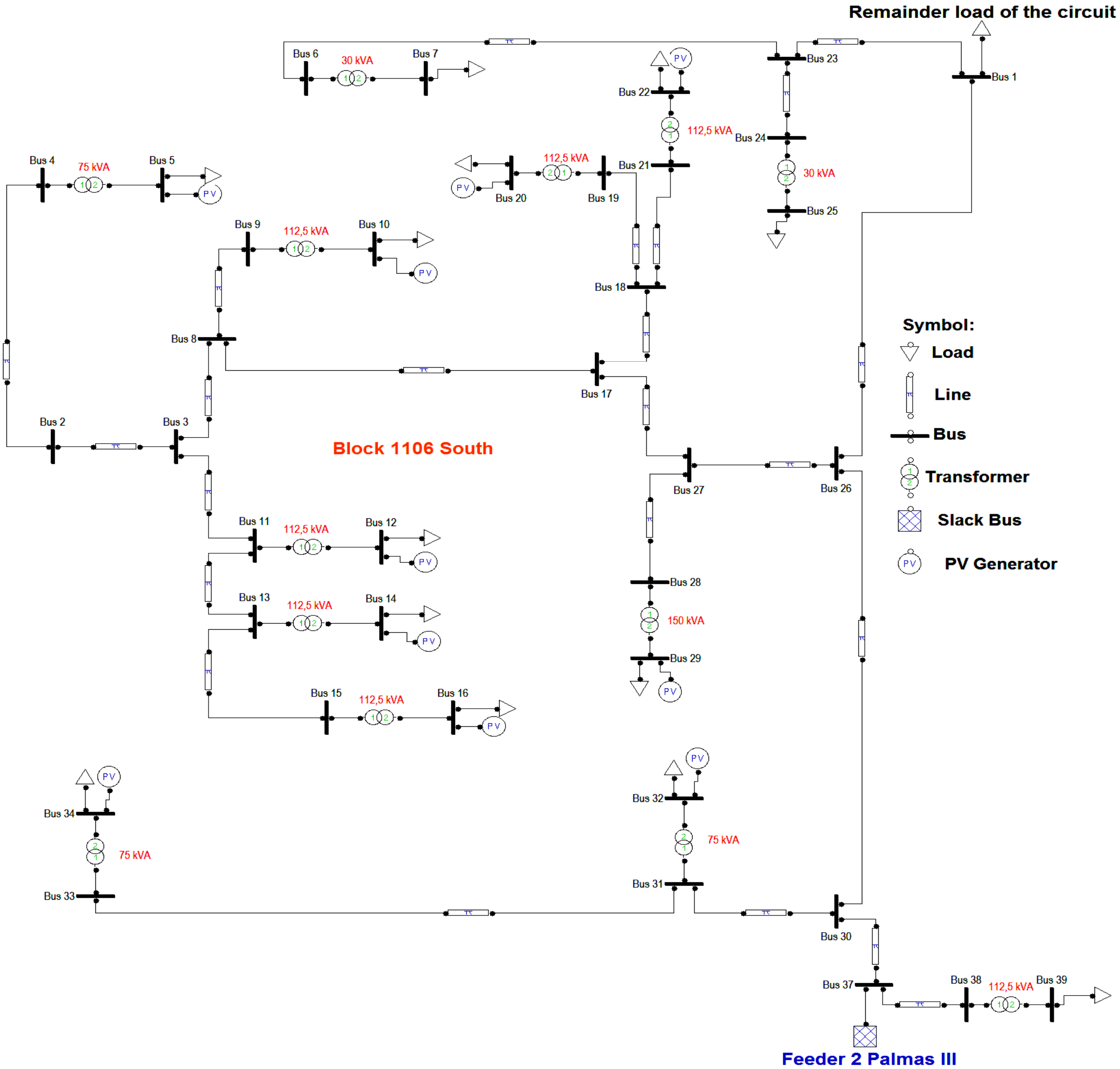

Fig. 3. Network model created with PSAT

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4. Case Studies

The case studies were performed with PSAT software using the information provided by the electrical company for day 03/10/2012 at 2:45 pm and 9:45 pm.

A. Case 1

The above date was chosen for this work because it was when there was the register of the highest consumption of daylight energy during that year (without the PV system) according to the power utility. For this first study, the aim was to verify if load flow results (voltages and powers) were in agreement with the information received from CELTINS and similar to the real system at time 2:45 pm. A file with these data was generated by PSAT using the function Power Flow.

In Table II, the last column described as “Max Power (kVA)” presented the total power of the consumer units at a given time (2:45 pm).

B. Case 2

A model based on assumptions and characteristics of the work presented by Albuquerque in 2012 [9] was used to analyze the operation of PV systems. Taking into account the same electrical configuration of Case 1, PV systems were then inserted according to column “Power of PV Panels (kW)”, as shown in Table VI, adopting the following criteria:

(a) for residential (R) CUs: 5% of all CU connected to the transformer with PV panel power equal to 1.3 kW, occupying approximately 12 m^2 of each residence roof. These data were collected from a tool called Solar

Simulator, developed by a partnership between the Brazilian company called Institute Ideal and a German Cooperation formed by *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) *GmbH* and *Kreditanstalt für Wiederaufbau* (KfW) [10][11].
(b) for commercial (C) CUs: values which are compatible with the needs of the installations.
(c) for public (P) CUs:
Then, with the above assumptions, the PSAT Power Flow was executed and a new data file was generated.

C. Case 3

This case considered the greatest consumption during the nighttime which occurred at 9:45 pm. Thus, a new simulation was performed now using the data in Table III without PV systems.

5. Analysis of Results

Table VII shows the active, reactive and apparent powers, as well as the power factor provided by the electrical company through the feeder number 2 for all cases. Comparing case 1 with case 2, it can be observed reductions in the powers and considerably improvements in power factors (PF) due the presence of PV systems. This reinforces the need for the PV system to also perform the compensation of reactive. Albuquerque showed and proved the viability this compensation [12].
Notice that the power consumption (without PV systems) during the day or nighttime are quite the same because the distribution system studied has a large presence of air conditioners. This fact is normally observed in that tropical region which presents high temperatures along the whole year.

TABLE VII
Power provided by feeder number 2 of Palmas III

Feeder no. 2 Palmas III	Daytime without PV system (Case 1)	Daytime with PV system (Case 2)	Nighttime (Case 3)
P [MW]	2.4896	2.3605	2.2688
Q [MVar]	1.4536	0.9040	1.2014
S [MVA]	2.8829	2.5277	2.5673
FP	0.8636	0.9339	0.8837

Fig. 4 and 5 show, respectively, that the active and reactive power flows in several branches of the distribution system decrease because of PV systems connected to the grid.
It can be seen from Fig. 6 that all transformer secondary windings, where PV systems are connected, the voltages have stabilized at 380V ensuring a constant voltage level to supply the loads. This shows the improvement of power quality as a result of PV penetration.
Values of primary voltages also result in a small increase due to these conditions. This shows the improvement in the voltage regulation in transformer of the electrical system studied.

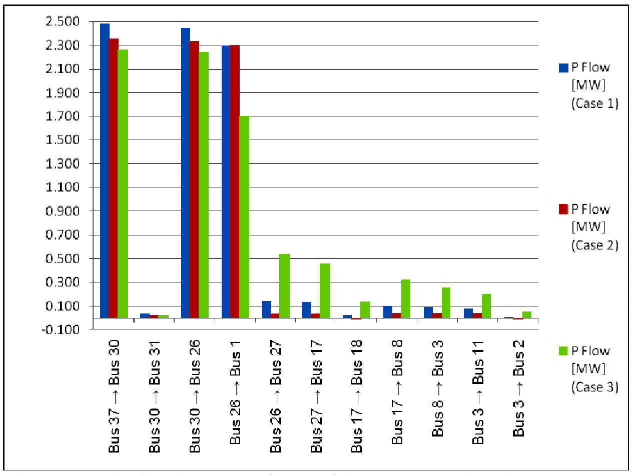

Fig. 4. Graph of active power flows of the system analyzed.

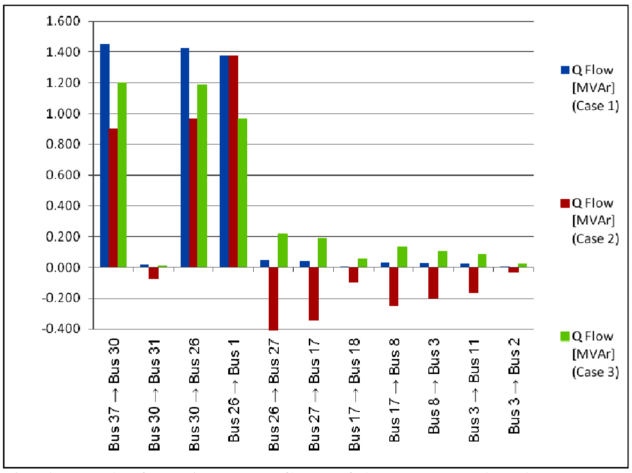

Fig. 5. Graph of reactive power flows of the system analyzed.

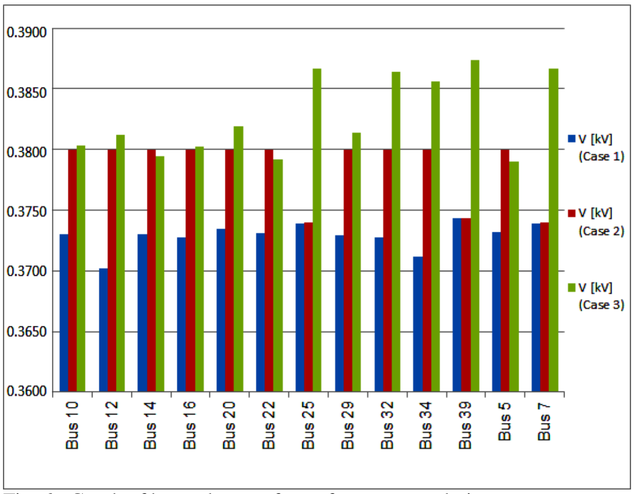

Fig. 6. Graph of bus voltages of transformer secondaries.

6. Conclusion

This study analyzed the results of simulations of a real power system, installed in Palmas-TO, at block 1106 South. The simulation considered the insertion of PV systems to a number of customers connected to some transformers.
It was possible to observe a reduction in the energy delivered by the electrical company and an increase in

power factor of the system with the penetration of PV systems in this block. It is important to note that the block has power consumptions during the whole day (24 hours), however, the analysis considered only highest consumption moments.

It is noteworthy that, from the moment that the PV systems become more popular, there may be a greater number of homes, businesses and public facilities with this kind of DG system, allowing the use of this source of clean and renewable energy which is abundant not only in this city but also throughout Brazil.

Thus, PV systems allow users to achieve a significant reduction in power consumption and can compensate their bills by the power equivalent produced, respecting the normative resolution Nº 482 of ANEEL [4]. The effect is beneficial for the power distribution network due to the decrease in transformer and cable loadings, with a consequent reduction of electrical losses and power factor increase [13]. And it may be a new source of income and employment for the population [14].

In order to sensibly improve the analysis of the results, new investigations will be performed for the PV system penetration, covering a whole day (twenty four hours period).

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