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Impact of the incorporation of photovoltaics distributed generation in electric distribution grids in Ecuador

X. Serrano-Guerrero[1], B. Marín-Toro[1], C. Ochoa-Malhaber[1] and A. Barragán-Escandón[1]

[1] Universidad Politécnica Salesiana, Grupo de Investigación en Energías (GIE)
Campus El Vecino – Calle Vieja 12 - 30 y Elia Liut, 010105 Cuenca (Ecuador)
Phone/Fax number: +5937413-5250, e-mail: **jserranog@ups.edu.ec, bmarint@est.ups.edu.ec, cochoam2@est.ups.edu.ec, ebarragan@ups.edu.ec**

Abstract. The distributed generation (DG) allows electricity production to be closer to consumers, relieving the burden on distribution grid feeders. Interest in DG has increased in recent years due to its close relationship with smart grids and the development of carbon-free generation technologies. The Ciudad del Sol feeder in the city of Machala in Ecuador is one of the feeders with the highest electricity demand. This study evaluates the incorporation of DG in several consumers connected to this feeder. Depending on the range of energy consumption of each customer, different PV systems are proposed to meet their demands. The results of the study show that the installation of PV generation systems allows considerable savings on the electricity bill. In addition, the reduction of grid demand reduces Joule effect losses and improves voltage profiles. The results suggest that the massive incorporation of correctly dimensioned PV systems does not affect the operating conditions of a distribution power grid.

Key words. Distributed generation (DG), grid connected PV systems, feeder, Ciudad del Sol, Machala.

1. Introduction

The environmental benefits of renewables, due to reduced carbon emissions, are widely known. In addition, the socioeconomic benefits are becoming increasingly evident as their deployment become more widespread [1].

Wind, solar and hydroelectric power produce little atmospheric pollution. Atmospheric pollution has become a critical problem in many developing countries. Approximately 2,9 billion people still rely on wood and charcoal for cooking and heating their homes. Cleaner options, such as biomass and solar technologies, can encourage a change in the energy model [1].

An important aspect to analyze in an electrical load feeder, is the characterization of its general load curve, as well as that of its consumers for the integral planning of a system. Alternatives of electrical demand management can be considered, where the effectiveness of each strategy can be evaluated according to its load profile [2]. For example, in [3] a method for characterizing and grouping electricity consumption patterns with the use of form factors is shown. With these patterns it is possible to understand, summarize and categorize the power consumption of consumers.

DG is becoming increasingly popular due to the multiple benefits it provides. The incorporation of renewable energy generation resources also allows the consumer's energy deficit (difference between energy demand and generated energy) to be supplied by the conventional electrical system to which it is connected [4], thus reducing or eliminating the need for energy storage in the facility [1].

It is estimated that the installation of distributed generation leads to benefits by reducing costs in transmission and distribution losses in the order of 5 to 10% of all kWh generated, and there are also avoided costs in the expansion or repowering of transmission and distribution systems, reduced costs for infrastructure maintenance, greater reliability for consumers close to distributed generation, and faster attention to demand growth due to shorter implementation times in relation to centralized generation. Among the main disadvantages of distributed generation are the lack of coordination of protection equipment, desensitization of protections, reconnection difficulties, voltage variations, overvoltages, overvoltage resonance and harmonics [5].

The benefit of distributed generation systems, can be observed in different authors, [6] use distributed systems to compensate for low voltage levels and power factor, this is important to consider, since a low power factor causes higher current consumption, causing equipment to break down and affect the conventional operation of the networks. In addition, other methods to maximize the use of distributed generation systems are studied, as seen in [7] which details the use of an optimization algorithm that minimizes the active power loss and the constraints of node voltage, branch current and permeability of the distributed generation unit.

Other studies on DG [8] show that it is not feasible to use only DG models to feed traditional distribution networks, since the energy generating sources can operate inefficiently, which will imply higher costs in energy production and problems in the operation of the equipment and the energy system. Therefore, they propose the multi-agent model that analyzes the creation of intelligent integrated energy systems with active consumers and distributed control functions, integrating centralized energy generation and distributed energy generation.

In a similar study [9], they analyze the impact of the penetration of a distribution feeder of 118 nodes and 10000 kW of installed power, which, compared to this case study, are 609 nodes and 5073,89 kW expected to be generated. It can be seen that there are more connection nodes and less generation, however, the presented study proves to be reliable since it provides 50% of the feeder demand.

Regarding voltage levels, in [10] they show that the use of PV systems in the DG increases the voltage, which can be interpreted as an improvement to the voltage profile in that feeder, they also show that there is no voltage decrease due to DG penetration, as well as overvoltages. The most significant voltage increase with 100% photovoltaic penetration goes from 11,47 kV to maximum values of 11,55 kV, while in this study the maximum value is from 7,68 kV to 7,71 kV which likewise does not represent any change to the conventional operation of the feeder.

In the present work, by means of the Cymdist software, the impact of distributed generation penetration in the "Ciudad del Sol" feeder in the city of Machala (Ecuador) is analyzed, where the changes in the power demand of the feeder can be verified, as well as the modifications in the voltage profiles and losses.

2. Methodology

A. Information of the distribution network of Ciudad del Sol feeder

The Ciudad del Sol feeder (code 07MA04T15) is located in the city of Machala, province of El Oro, Ecuador. Table I shows the maximum demands of the feeder and the load factor for the year 2020. It is evident that the month with the highest demand was February with 1888,97 kW.

Table I. - Maximum demands of the Ciudad del Sol feeder [11].

Maximum demands of the Ciudad del Sol feeder			
Substation	**Feeder**	**Maximum Demand [kW]**	**Load Factor**
S/E Machala	07MA040T15 (Ciudad del Sol)	1738,37	0,67
S/E Machala	07MA040T15 (Ciudad del Sol)	1888,97	0,65
S/E Machala	07MA040T15 (Ciudad del Sol)	1827,11	0,69
S/E Machala	07MA040T15 (Ciudad del Sol)	1724,80	0,72
S/E Machala	07MA040T15 (Ciudad del Sol)	1751,31	0,66
S/E Machala	07MA040T15 (Ciudad del Sol)	1453,16	0,64
S/E Machala	07MA040T15 (Ciudad del Sol)	1148,25	0,69
S/E Machala	07MA040T15 (Ciudad del Sol)	1226,67	0,65
S/E Machala	07MA040T15 (Ciudad del Sol)	1205,53	0,68
S/E Machala	07MA040T15 (Ciudad del Sol)	1364,20	0,63
S/E Machala	07MA040T15 (Ciudad del Sol)	1327,65	0,65
S/E Machala	07MA040T15 (Ciudad del Sol)	1513,96	0,64

Early in the morning, the feeder is observed to have a low load (up to 07:00 hours), then the demand grows, reaching its peak between 21:00 and 22:00 hours. Figure 1 shows the typical daily load curve of the feeder on an average day.

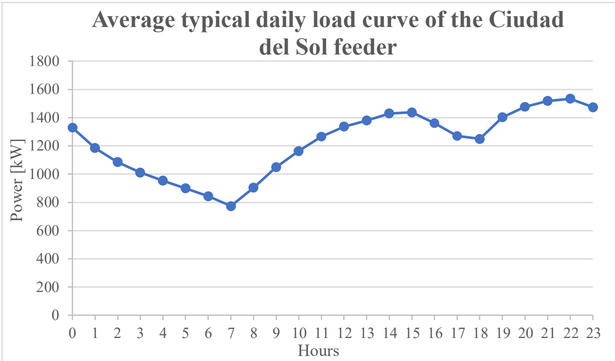

Fig. 1. Average typical daily load curve [11].

The feeder header measurements for the month of February 2020 are analysed, so Table II shows measurements of active power, reactive power, power factor, currents and hourly voltages delivered.

Table II. - Feeder Header Measurement [11].

Measurement at the head of the Ciudad del Sol feeder										
Day-Hour	**Total P [kW]**	**Total Q [kVAr]**	**Power Factor**	**Ia [A]**	**Ib [A]**	**Ic [A]**	**LL ab Voltage [V]**	**LL bc Voltage [V]**	**LL ca Voltage [V]**	**Average LL Voltage [V]**
2020-feb-01 00:00:00,000	1314,08	326,45	0,97	67,03	38,05	68,76	13744,07	13622,51	13322,20	13562,93
2020-feb-01 01:00:00,000	1156,16	314,50	0,96	58,54	32,16	62,15	13809,50	13706,25	13434,15	13649,97
2020-feb-01 02:00:00,000	1011,05	306,54	0,96	49,23	29,05	55,65	13866,29	13782,21	13543,77	13730,76
2020-feb-01 03:00:00,000	958,12	308,09	0,95	46,38	27,62	53,29	13890,89	13807,29	13587,44	13761,87
2020-feb-01 04:00:00,000	939,92	311,55	0,95	44,74	28,65	51,16	13949,93	13876,58	13661,08	13829,20
2020-feb-01 05:00:00,000	851,22	297,38	0,94	40,15	25,30	47,65	13985,80	13931,01	13719,40	13878,74
2020-feb-01 06:00:00,000	817,13	272,25	0,95	38,50	24,23	46,07	13881,07	13837,26	13625,50	13781,28
2020-feb-01 07:00:00,000	693,61	199,26	0,96	34,01	19,59	35,54	14185,43	14190,68	13988,64	14121,58
2020-feb-01 08:00:00,000	738,97	171,98	0,97	36,55	22,32	36,51	13948,08	13922,58	13726,02	13865,56
2020-feb-01 09:00:00,000	867,70	190,84	0,98	43,59	28,54	41,32	13730,04	13689,37	13496,35	13638,59
2020-feb-01 10:00:00,000	1007,98	214,73	0,98	48,30	32,45	51,80	13618,67	13576,21	13383,22	13526,03
2020-feb-01 11:00:00,000	1127,32	235,01	0,98	54,73	33,52	59,92	13613,36	13565,17	13379,76	13519,43
2020-feb-01 12:00:00,000	1212,35	242,14	0,98	58,19	34,92	66,27	13594,69	13538,05	13341,33	13491,36
2020-feb-01 13:00:00,000	1239,27	251,92	0,98	61,24	35,46	65,83	13651,47	13589,69	13372,71	13537,96
2020-feb-01 14:00:00,000	1189,83	241,78	0,98	58,05	34,78	62,82	13683,54	13621,02	13408,27	13570,94
2020-feb-01 15:00:00,000	1133,61	243,57	0,98	55,00	30,96	62,06	13749,89	13687,00	13473,96	13636,95
2020-feb-01 16:00:00,000	1103,41	248,87	0,98	54,35	30,12	59,60	13767,34	13710,26	13504,41	13660,67
2020-feb-01 17:00:00,000	1056,50	245,16	0,97	53,55	29,76	54,33	13821,14	13766,01	13556,81	13714,65
2020-feb-01 18:00:00,000	1005,76	198,29	0,98	51,24	26,71	52,47	13789,83	13770,80	13529,63	13696,75
2020-feb-01 19:00:00,000	1228,46	319,43	0,97	63,92	32,21	67,97	13632,01	13548,69	13278,32	13486,34
2020-feb-01 20:00:00,000	1332,07	321,87	0,97	69,41	36,09	71,74	13642,72	13537,04	13262,71	13480,82
2020-feb-01 21:00:00,000	1314,40	281,99	0,98	68,81	36,80	70,58	13488,15	13356,66	13090,02	13311,61
2020-feb-01 22:00:00,000	1324,79	306,17	0,97	70,16	36,13	70,18	13598,66	13486,51	13217,30	13434,15
2020-feb-01 23:00:00,000	1307,91	330,85	0,97	67,59	35,37	70,31	13733,96	13617,33	13356,31	13569,20

B. *Solar irradiation in the city of Machala*

The solar irradiation of the city of Machala in 2019 is presented in Table III, showing both the global horizontal component (GHI) and the direct normal component (DNI). The data were taken from the SOLCAST software and the solar map of Ecuador from the SCINERGY group [12].

Table III. - Contrast of daily solar irradiation of Machala city, year 2019 [12].

Month	SOLCAST		Solar map of Ecuador	
	GHI [kWh/m²]	DNI [kWh/m²]	GHI [kWh/m²]	DNI [kWh/m²]
January	4,2	2,3	4,5	2,2
February	4,1	1,8	4,4	1,8
March	4,3	2,1	4,2	2,3
April	4,6	2,8	4,2	3,2
May	3,7	1,6	4,3	2,3
June	3	1,2	3,3	2
July	3,1	1,5	3,2	2,1
August	3,1	1,7	3,5	2,5
September	4,1	2	4,1	2,7
October	3,9	1,8	4	2,5
November	3,9	1,6	4,2	2,3
December	4	1,7	4,2	2,2
Average	3,9	1,8	4	2,3

C. *Design of the modular photovoltaic system*

For the design of the photovoltaic system**,** it is necessary to collect the monthly energy consumption, the peak sun hour (PSH) and define the area to be installed, the number of solar panels and the inverter. The photovoltaic system is connected to the grid, so no charge controllers or batteries are required. In addition, having residential users with different energy demands, 4 consumption ranges and 4 types of PV systems are defined.

The daily energy demand is obtained from each user's monthly bill and is calculated with Equation 1 [13].

$$Energy\ [kWh/day] = \frac{Energy\ [kWh/month]}{30} \qquad (1)$$

The loss factor (LF) is calculated using Equation 2 [13].

$$LF = PSH \cdot Panel\ Performance \cdot Inverter\ Performance \qquad (2)$$

Where, PSH is the peak sun hour (3,6 is the average in the case of Machala) and the panel performance is given by the panel technical specifications (see Table VII), the inverter performance can be obtained with Equation 3 [13].

$$Inverter\ Performance = 1 - k_i - k_v \qquad (3)$$

Where:

- **ki:** Losses due to inverter performance.
- **0:** No inverter in the installation.
- **0,05:** Inverter performance 95%.
- **0,1:** Inverter performance 90%.
- **0,15:** Inverter performance 85%.
- **0,2:** Inverter performance < 85%.
- **kv:** Other losses not considered.
- **0,02:** If wiring and equipment losses are not taken into account.
- **0,05:** If a detailed study of losses in equipment has been carried out.

The area to install is defined by Equation 4 [13].

$$Area\ to\ Install\ [m^2] = \frac{Energy\ [kWh/day]}{LF} \qquad (4)$$

Thus, the number of panels is defined by Equation 5 [13].

$$Number\ of\ Panels = \frac{Area\ to\ Install\ [m^2]}{Area\ of\ the\ Panels\ [m^2]} \qquad (5)$$

3. Results and Discussion

The design summary of the different solar PV systems proposed is shown in Table IV. For users with energy consumption between 150 and 300 kWh/month, an array of 6 PV panels connected in series is used. For customers with consumption between 300 and 500 kWh/month, an array of 11 PV panels connected in series is determined. Customers with consumption between 500 and 760 kWh/month should use 18 PV panels connected in two strings of 9 panels in series. Finally, for customers with consumption greater than or equal to 760 kWh/month, an array of 28 panels is defined, distributed in two strings of 14 panels in series.

Table IV. - Number of panels according to the user's monthly consumption.

Monthly Energy Consumption per User [kWh/month]	Energy Consumption per Day [kWh/day]	Loss Factor	Area to Install [m²]	Solar Panel Power [W]	Area of the Solar Panels [m²]	Number of Solar Panels	Power Inverter Fronius Primo [kW]	Panels Layout
150 kWh < C < 300 kWh	5	0,5725	87,34	280	1,64	6	3	1 series of 6 panels
300 kWh < C < 500 kWh	10	0,5725	174,67	280	1,64	11	6	1 series of 11 panels
500 kWh < C < 760 kWh	16,66	0,5725	291,12	280	1,64	18	7,5	2 series of 9 panels
760 kWh < C < 2000 kWh	25,33	0,5725	442,50	280	1,64	28	6,1 - 11,7	2 series of 14 panels

A. *Simulation in CYMDIST of the Photovoltaic System at Ciudad del Sol feeder*

The entire feeder was parameterized and then loaded into the CYMDIST software. Fig. 2 shows its parameters, such as interconnections (2), nodes (609), source nodes (1) and sections (608).

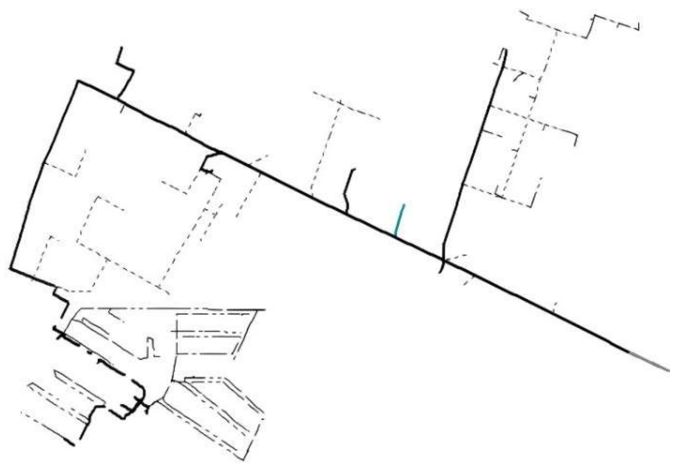

Fig. 2. Ciudad del Sol feeder.

The apparent power data of the lines and their total are configured in Table V. A, B, C are the feeder phases.

Table V. - Connected capacity [kVA] of the feeder.

A	B	C	Total
426,57	772,65	306,16	1505,38

The feeder voltage values are shown in Table VI, which are balanced.

Table VI. - Balanced voltages [kV] of the feeder.

A	B	C
13,274	13,274	13,274

The PV panel data used for the simulation of the different systems are presented in Table VII.

Table VII. - Technical data of the photovoltaic panel [14].

FV Panel Data	
Pmax	280W
Vnom	36V
Vpm	31,3V
Ipm	8,95A
Voc	38V
Isc	9,45A
Performance	0,171
Dimensions	1650mm/992mm/35mm
Area	1,64m^2

B. Integration of photovoltaic systems to the feeder

Initially, the simulation is carried out with users with a monthly demand greater than 760 kWh. Table VIII shows a customer of the feeder with a monthly consumption of 937 kWh.

Table VIII. - Monthly consumption of a customer with a demand of 937 kWh.

Connection Phase	Real Power [kW]	Reactive Power [kVAr]	Consumption [kWh]	Connected Capacity [kVA]	Customers
B	2,7	0,6	937	25	1

C. Ciudad del Sol feeder load profile

The PV generation system is expected to start operation at 05:00 and end at 17:00 hours. Table IX shows the load profile of the feeder without and with distributed photovoltaic generation, where, the section without DG shows very high demands especially at peak hours, therefore, an extra generation system is necessary to help those demands and as observed in the section with DG the distributed generation system supplies approximately 50% of the current demand of the feeder.

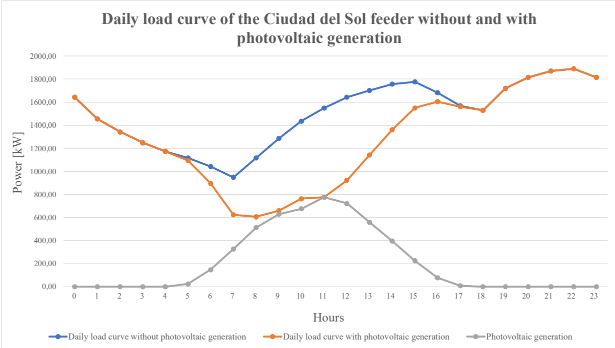

Fig. 3. Daily load curve of the Ciudad del Sol feeder without and with photovoltaic generation.

Table IX. - Feeder load profile without and with distributed generation.

Hour	Without Distributed Generation		With Distributed Generation			
	Total Load		Total Load		Generators	
	kW	FP (%)	kW	FP (%)	kW	FP (%)
0	1643,91	97,23	1643,91	97,23	0,00	0,00
1	1455,30	97,39	1455,30	97,39	0,00	0,00
2	1342,40	97,49	1342,40	97,49	0,00	0,00
3	1248,46	97,58	1248,46	97,58	0,00	0,00
4	1173,41	97,65	1173,41	97,65	0,00	0,00
5	1117,17	97,70	1093,82	97,61	23,27	100,00
6	1042,27	97,78	894,59	97,04	147,41	100,00
7	948,76	97,89	622,90	95,27	325,85	100,00
8	1117,17	97,70	605,67	92,62	512,04	100,00
9	1286,02	97,54	658,56	91,23	628,42	100,00
10	1436,47	97,40	762,49	91,36	674,97	100,00
11	1549,53	97,31	775,25	90,02	775,82	100,00
12	1643,91	97,23	923,29	91,73	721,52	100,00
13	1700,60	97,18	1141,84	94,02	558,59	100,00
14	1757,35	97,13	1360,94	95,38	395,67	100,00
15	1776,28	97,12	1550,53	96,30	224,99	100,00
16	1681,70	97,20	1603,78	96,94	77,58	100,00
17	1568,39	97,29	1560,60	97,27	7,76	100,00
18	1530,67	97,32	1530,67	97,32	0,00	0,00
19	1719,51	97,16	1719,51	97,16	0,00	0,00
20	1814,15	97,09	1814,15	97,09	0,00	0,00
21	1871,00	97,04	1871,00	97,04	0,00	0,00
22	1889,96	97,02	1889,96	97,02	0,00	0,00
23	1814,15	97,09	1814,15	97,09	0,00	0,00

D. Losses in the Ciudad del Sol feeder

The feeder has losses in the conductors, transformers and total losses, which would be the sum of both. However, the distributed generation system shows a minimum impact of about ±1%, so they do not have a representative influence on the feeder operation. Table X shows the losses of conductors, transformers and their total without and with photovoltaic distributed generation.

Table X. - Losses without and with distributed generation.

Hour	Without Distributed Generation			With Distributed Generation		
	Conductor Losses	Transformer Losses	Total Losses	Conductor Losses	Transformer Losses	Total Losses
	kW	kW	kW	kW	kW	kW
0	3,48	35,06	38,54	3,48	35,06	38,54
1	2,72	31,73	34,45	2,72	31,73	34,45
2	2,31	29,96	32,27	2,31	29,96	32,27
3	1,99	28,61	30,60	1,99	28,61	30,60
4	1,75	27,60	29,36	1,75	27,60	29,36
5	1,59	26,89	28,48	1,56	26,85	28,41
6	1,38	26,01	27,39	1,23	25,89	27,12
7	1,14	25,00	26,13	0,97	25,16	26,13
8	1,59	26,89	28,48	1,42	27,60	29,02
9	2,11	29,14	31,25	1,93	30,28	32,21
10	2,65	31,43	34,08	2,40	32,67	35,07
11	3,09	33,34	36,43	2,86	35,11	37,97
12	3,48	35,06	38,54	3,10	36,34	39,44
13	3,73	36,14	39,88	3,20	36,51	39,71
14	3,99	37,27	41,27	3,45	37,09	40,53
15	4,08	37,66	41,74	3,68	37,30	40,98
16	3,65	35,78	39,43	3,50	35,59	39,09
17	3,17	33,67	36,84	3,15	33,65	36,80
18	3,01	33,01	36,02	3,01	33,01	36,02
19	3,82	36,51	40,33	3,82	36,51	40,33
20	4,26	38,45	42,71	4,26	38,45	42,71
21	4,54	39,67	44,21	4,54	39,67	44,21
22	4,63	40,09	44,72	4,63	40,09	44,72
23	4,26	38,45	42,71	4,26	38,45	42,71

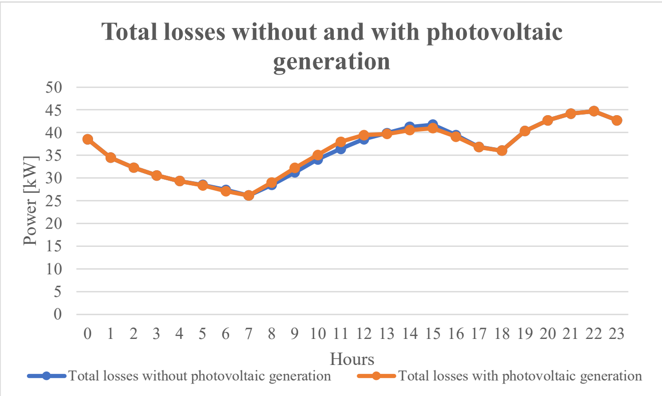

Fig. 4. Total losses of the Ciudad del Sol feeder.

E. *Voltage analysis at a given point on the Ciudad del Sol feeder*

The voltages [kV] in the different operating hours of the feeder without and with distributed photovoltaic generation are presented in Table XI. The section without DG does not show any significant variation, but in the section with DG there is a voltage increase from 07:00 to 12:00 hours, which could represent a change in the feeder operation, producing overvoltages but it is observed that from 13:00 hours it returns to the conventional operating state.

Table XI. - Voltages without and with photovoltaic distributed generation.

	Without Distributed Generation				With Distributed Generation			
Point	6671_MTA	40196_MTS	150018_MTS	169658_MTS	6671_MTA	40196_MTS	150018_MTS	169658_MTS
Hour	kV	kV	kV	kV	kV	kV	kV	kV
0	7,69	7,69	7,68	7,68	7,69	7,69	7,68	7,68
1	7,69	7,69	7,69	7,69	7,69	7,69	7,69	7,69
2	7,69	7,69	7,69	7,69	7,69	7,69	7,69	7,69
3	7,69	7,69	7,69	7,69	7,69	7,69	7,69	7,69
4	7,69	7,69	7,69	7,69	7,69	7,69	7,69	7,69
5	7,69	7,69	7,69	7,69	7,69	7,69	7,69	7,69
6	7,69	7,69	7,69	7,69	7,69	7,69	7,69	7,69
7	7,69	7,69	7,69	7,69	7,70	7,70	7,70	7,70
8	7,69	7,69	7,69	7,69	7,70	7,70	7,71	7,71
9	7,69	7,69	7,69	7,69	7,70	7,70	7,71	7,71
10	7,69	7,69	7,69	7,69	7,70	7,70	7,71	7,71
11	7,69	7,69	7,68	7,68	7,70	7,70	7,71	7,71
12	7,69	7,69	7,68	7,68	7,69	7,70	7,71	7,71
13	7,69	7,69	7,68	7,68	7,69	7,69	7,70	7,70
14	7,69	7,69	7,68	7,68	7,69	7,69	7,70	7,70
15	7,69	7,69	7,68	7,68	7,69	7,69	7,69	7,69
16	7,69	7,69	7,68	7,68	7,69	7,69	7,69	7,69
17	7,69	7,69	7,68	7,68	7,69	7,69	7,68	7,68
18	7,69	7,69	7,68	7,68	7,69	7,69	7,68	7,68
19	7,69	7,69	7,68	7,68	7,69	7,69	7,68	7,68
20	7,69	7,69	7,68	7,68	7,69	7,69	7,68	7,68
21	7,69	7,69	7,68	7,68	7,69	7,69	7,68	7,68
22	7,69	7,69	7,68	7,68	7,69	7,69	7,68	7,68
23	7,69	7,69	7,68	7,68	7,69	7,69	7,68	7,68

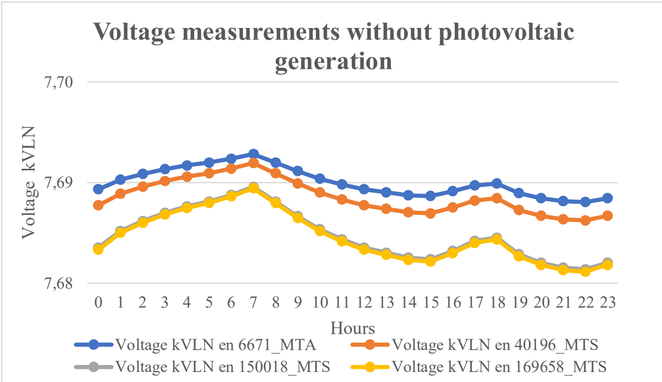

Fig. 5. Voltages without photovoltaic generation of the Ciudad del Sol feeder.

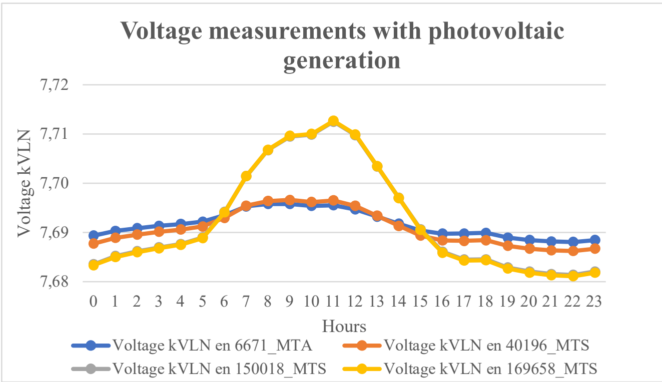

Fig. 6. Voltages with photovoltaic generation of the Ciudad del Sol feeder.

4. Conclusion

This paper has investigated the effect of four types of distributed power plants, using photovoltaic systems, on a distribution network. The data used for the feeder, load demands and transformers are real. Simulations have been performed in Cymdist software for demands between 150, 300, 500 and 760 kWh/month and the results, without and with PV distributed generation, have been analyzed.

The systems sized for distributed generation supply up to 50% of the demand of the Ciudad del Sol feeder and are therefore a viable option for consumers. System losses, in conductors and transformers, have little significant variation (around ±1%). Voltages increase between 07:00 and 12:00 hours, but after 13:00 they return to previous values.

It is important to note that the peak demand (between 20:00 and 23:00 hours) of the feeder was not affected by the incorporation of distributed photovoltaic systems, because the plants are expected to operate between 05:00 and 17:00 hours (when the sun is available). It is possible to use energy accumulators such as batteries for the night operation of the feeder, but it must be considered that the systems would have a much higher cost, which could result in consumers not incorporating these technologies.

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