COMPARATIVE REVIEW BETWEEN PROJECT SOLUTION AND REAL OPERATING CONDITIONS REGARDING THE VOLTAGE DROPS AND POWER LOSSES FOR PHOTOVOLTAIC PARK CASE FROM CHIRILEU

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Abstract - The paper is structured in five parts. In the first part is evoked the importance of distributed generation and some problems that arise during operation of these type of power plants. In the second part are presented the theoretical bases for voltage drops and power losses. In part three are presented the network connection solution for photovoltaic park and data out coming from project. In part four are presented the measurements results and their interpretation. The last part of the paper contains the main conclusion and the short-term perspectives in these issues.

Keywords: voltage drops, power losses, distributed generation, photovoltaic park, electrical energy parameters, distribution network.

1. INTRODUCTION

The reconsideration of energy policies within the E.U., around the 2000s, has led to the emergence of numerous low-power plants, which were using renewable energy.

The development of distributed generation has brought, besides its well-known benefits, a series of concerns related to the quality of electrical energy.

Distributed generation refers to producing energy in low-power plants, which commonly have implemented a 50÷100 MW power and are placed close to consumption centers. These plants provide the energy necessary for small areas and are regularly connected to the energy distribution network. [1]

The impact of distributed generation on distribution networks is highly varied, depending on types of generating installations. This study brings into discussion the photovoltaic park from Chirileu (Mureş district). The park is indirectly connected to the distribution network, using a static frequency (power) converter.

The effects produced by these plants are recognisable both at the distribution operator level and at the consumption one. In the following, we will discuss the influences of the photovoltaic park functioning on voltage drops and on power losses in the distribution network to which the park is connected.

2. VOLTAGE DROPS AND POWER LOSSES IN ELECTRICAL DISTRIBUTION NETWORKS

2.1. Voltage drops in electrical distribution networks

In order to survey voltage drops in electrical distribution networks, it's used a simplified equivalent circuit diagram (figure 1.1), in which transversal electrical parameters (conductance $G \cong 0$ and susceptance $B \cong 0$) are neglected, without causing significant errors.

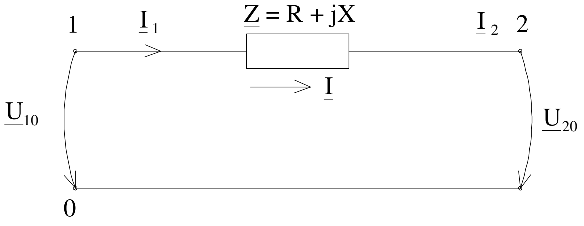

Fig 1.1 Simplified equivalent circuit diagram of an electrical distribution network

This fact is due to the voltage level in the distribution network (medium and low voltage), but also to the length of lines, raging from hundreds of meters to dozens of kilometers. As well, the nature of consumers supplied by these networks is rather inductive. Taking into account these features we can build the phasor diagram of voltage drops for an electrical distribution line (figure 1.2).[3]

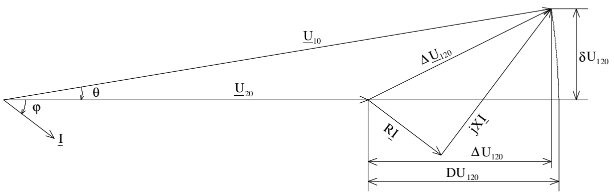

Fig. 1.2 Phasor diagram of voltage drops for an electrical distribution line

$$\underline{U}_{20} = \underline{U}_{10} - \Delta\underline{U}_{120} = \underline{U}_{10} - \underline{Z} \cdot \underline{I} \quad (1)$$

Quantities from figure 1.2. and from relation 1 have the following significations:

- $\underline{U}_{10}$ voltage between phase and earth at the beginning of the line;
- $\underline{U}_{20}$ voltage between phase and earth at the end of the line (at the consumer's terminal);
- $\underline{I}$ the current absorbed by the consumer;
- $\underline{Z} \cdot \underline{I} = \Delta\underline{U}_{120} = \Delta U_{120} + j\delta U_{120}$ phasorial voltage drop on phase;
- ΔU_{120} longitudinal voltage drop on phase;
- δU_{120} transversal voltage drop on phase;
- DU_{120} algebraical voltage drop on phase;

Based on figure 1.2. the following relations can be inferred:

$$\Delta U_{120} = R \cdot I \cdot \cos\varphi + X \cdot I \cdot \sin\varphi = R \cdot I_a + X \cdot I_r \quad (2)$$

$$\delta U_{120} = X \cdot I \cdot \cos\varphi - R \cdot I \cdot \sin\varphi = X \cdot I_a - R \cdot I_r \quad (3)$$

in which: I_a and I_r, stand for the active and reactive components of current $\underline{I}$, more specifically:

$$\underline{I} = I \cdot \cos\varphi - jI \cdot \sin\varphi = I_a - jI_r \quad (4)$$

R, X are the resistor and, respectively, the reactance of the analysed network.

$$DU_{120} = R \cdot I_a + X \cdot I_r + \frac{(X \cdot I_a - R \cdot I_r)^2}{2 \cdot U_{no}} \quad (5)$$

If the consumer is expressed through active and reactive power, P_0 and Q_0, in monophase system, relations 2, 3 and 5 become the following:

$$P_0 = U_{no} \cdot I \cdot \cos\varphi = U_{no} \cdot I_a \quad (6)$$

$$Q_0 = U_{no} \cdot I \cdot \sin\varphi = U_{no} \cdot I_r \quad (7)$$

where: $I_a = \frac{P_0}{U_{no}}$ and $I_r = \frac{Q_0}{U_{no}}$

$$\Delta U_{120} = R \cdot I_a + X \cdot I_r = \frac{R \cdot P_0 + X \cdot Q_0}{U_{no}} \quad (8)$$

$$\delta U_{120} = X \cdot I_a - R \cdot I_r = \frac{X \cdot P_0 - R \cdot Q_0}{U_{no}} \quad (9)$$

$$DU_{120} = \frac{R \cdot P_0 + X \cdot Q_0}{U_{no}} + \frac{(X \cdot P_0 - R \cdot Q_0)^2}{2U_{no}^3} \quad (10)$$

Considering the fact that in most cases the supply system is triphase, after performing the necessary calculations, the following relations would result:

$$P = \sqrt{3} \cdot U_n \cdot I \cdot \cos\varphi \quad (11)$$

$$Q = \sqrt{3} \cdot U_n \cdot I \cdot \sin\varphi \quad (12)$$

$$\Delta U_{12} = \sqrt{3} \cdot \Delta U_{120} \quad (13)$$

$$\delta U_{12} = \sqrt{3} \cdot \delta U_{120} \quad (14)$$

$$DU_{12} = \sqrt{3} \cdot DU_{120} \quad (15)$$

or:

$$\Delta U_{12} = \frac{R \cdot P + X \cdot Q}{U_n} \quad (16)$$

$$\delta U_{12} = \frac{X \cdot P - R \cdot Q}{U_n} \quad (17)$$

$$DU_{120} = \frac{R \cdot P + X \cdot Q}{U_n} + \frac{(X \cdot P - R \cdot Q)^2}{2U_n^3} \quad (18)$$

$$\Delta\underline{U}_{12} = \frac{R \cdot P + X \cdot Q}{U_n} + j\frac{X \cdot P - R \cdot Q}{U_n} \quad (19)$$

For the real case, in which the line supplies more consumers, figure 1.3., we would obtain the following relations:

$$\Delta U_{An0} = \sum_{k=1}^{n}(R_k \cdot i_{ak} + X_k \cdot i_{rk}) \quad (20)$$

$$\delta U_{An0} = \sum_{k=1}^{n}(X_k \cdot i_{ak} - R_k \cdot i_{rk}) \quad (21)$$

$$DU_{An0} = \sum_{k=1}^{n}(R_k \cdot i_{ak} + X_k \cdot i_{rk}) + \frac{\left[\sum_{k=1}^{n}(X_k \cdot i_{ak} - R_k \cdot i_{rk})\right]^2}{2U_{no}} \quad (22)$$

in which: i_{ak} and i_{rk} the active and reactive current absorbed by consumer k

R_k, X_k the sum of the resistors and, respectively, of the chukes that connect node k to the extremity of the network, A.

or:

$$\Delta U_{An} = \frac{\sum_{k=1}^{n}(R_k \cdot p_k + X_k \cdot q_k)}{U_n} = \frac{\sum_{k=1}^{n}(r_k \cdot P_k + x_k \cdot Q_k)}{U_n} \quad (23)$$

$$\delta U_{An} = \frac{\sum_{k=1}^{n}(X_k \cdot p_k - R_k \cdot q_k)}{U_n} = \frac{\sum_{k=1}^{n}(x_k \cdot P_k + r_k \cdot Q_k)}{U_n} \quad (24)$$

$$DU_{An} = \frac{\sum_{k=1}^{n}(R_k \cdot p_k + X_k \cdot q_k)}{U_n} + \frac{\sum_{k=1}^{n}(X_k \cdot p_k - R_k \cdot q_k)^2}{2U_n^3} = \frac{\sum_{k=1}^{n}(r_k \cdot P_k + x_k \cdot Q_k)}{U_n} + \frac{\sum_{k=1}^{n}(x_k \cdot P_k - r_k \cdot Q_k)^2}{2U_n^3} \quad (25)$$

where: p_k, q_k – active and reactive power absorbed by the consumer from node k;

P_k, Q_k –active and reactive power that flows on section k of the network;

U_n – nominal voltage of the line (between phases).

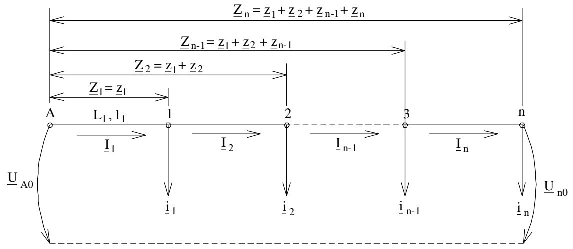

Fig. 1.3 Equivalent circuit diagram of a line which supplies more consumers

2.2. Power losses in electric distribution networks

The issue of power losses in power systems is gaining an increasing importance for system operators (transport and distribution operators), while limiting the own technological consumption (OTC).

It is known that OTC has two components: a technical and a commercial one. This study analyses the technical component of losses, given that their reducement naturally leads to the limitation of commercial losses from OTC structure, too.

a) Power losses in transformers

In order to obtain the amount of electrical energy loss it is necessary to know both the network topology and the nominal parameters of transformers.

Network topology refers to quantities which enter or exit transformers (such as currents and voltages or powers and voltages). [4]

The nominal parameters of transformers are the following:

- nominal power: S_n [kVA];
- no-load losses (iron losses) P_0 [kW];
- impedance losses (copper losses) P_{sc} [kW];
- no-load current i_0 [%];
- short-circuit voltage u_{sc} [%].

Energy losses in transformers can be divided in two categories:

- constant losses, caused by iron losses in the transformer:

$$\Delta P_f = P_0 \text{ [kW]} \quad (26)$$

$$\Delta Q_f = \frac{i_0[\%]}{100} \cdot S_n[\text{kVAr}] \ (27)$$

- variable losses of energy, due to copper losses in the transformer:

$$\Delta P_v = P_{sc} \left(\frac{S_m}{S_n}\right)^2 [\text{kW}] \ (28)$$

$$\Delta Q_v = \frac{u_{sc}[\%]}{100} \cdot \left(\frac{S_m}{S_n}\right)^2 \cdot S_n \ [\text{kVAr}] \ (29)$$

where S_m is the maximum apparent power which transits the transformer.

Total losses are obtained by summing up constant and variable losses, using relations (26) ÷ (29). [5]

$$\Delta P_T = P_0 + P_{sc} \left(\frac{S_m}{S_n}\right)^2 \ [\text{kW}] \ (30)$$

$$\Delta Q_T = \left[\frac{i_0[\%]}{100} + \frac{u_{sc}[\%]}{100} \cdot \left(\frac{S_m}{S_n}\right)^2\right] \cdot S_n \ [\text{kVAr}] \ (31)$$

b) Power losses in electrical lines

Establishing power losses in electrical lines is a more complex matter, which requires knowing the network topology as exactly as possible. In order to determine losses, it is necessary to know the following aspects:

- the type of wire (cable or overhead line - OL);
- wire section, from which results the resistance per unit of length r_0 [Ω / km] and the reactance per unit of length x_0 [Ω / km];
- the length of the wire portion having the specified section l [km];
- nominal voltage of the line U_n [kV];
- electrical powers or currents transiting the wire portion for which the calculations are performed P [kW], Q [kVAr], I [A]).

Having these data, we can determine the power losses of the line: [5]

$$\Delta P_L = \frac{P^2+Q^2}{U_n^2} \cdot R \cdot 10^{-3} = \frac{P^2}{U_n^2 \cdot \cos^2\varphi} \cdot R \cdot 10^{-3} \ [\text{kW}] \ (32)$$

$$\Delta Q_L = \frac{P^2+Q^2}{U_n^2} \cdot X \cdot 10^{-3} = \frac{P^2}{U_n^2 \cdot \cos^2\varphi} \cdot X \cdot 10^{-3} \ [\text{kVAr}] \ (33)$$

Using these elements, the total losses of the network can be determined, summing up the power losses for each network component.

3. NETWORK CONNECTION SOLUTION FOR THE PHOTOVOLTAIC PARK AND DATA OUTCOMING FROM PROJECT

The photovoltaic park brought into discussion in the present study is situated in Chirileu, Mureş district, lying on a 7,9 ha area.

The technical data of the photovoltaic park are the following:

- net injectable power in EDN: 3,2 MW;
- connection point voltage: 20 kV;
- power factor: 0,98 capacitive/ 0,96 lagging;
- annual energy provided to the system: 4262 MWh;
- usage degree of installed capacity: 15 %;
- usage time of installed capacity: 3,65 hours/day, respectively, 1332 hours/year;
- operating condition: daily maximum 12 hours/during summer, respectively daily maximum 8 hours/during winter;
- total harmonic distortion THD < 5%.

The photovoltaic plant of Chirileu is situated at 9,6 km from Ungheni 220/ 110/ 20 kV substation and at 12,7 km from Cipău Supply Point (SP Cipău) (running-off wires), SP Cipău being connected with Luduş and Târnăveni substations, through 20 kV OL.

Considering these information, a network connection solution was chosen, realized through a Connexion Substation in a precast envelope of 20 kV (CS). CS is situated inside of the photovoltaic park, at property limit, having free access from the street, connected through 20 kV underground cable (UC), in input-output system to Ungheni-Cipău OL. 20 kV UC has 460 m of length for each circuit.

The single phase diagram of system framing is shown in figure 3.1.

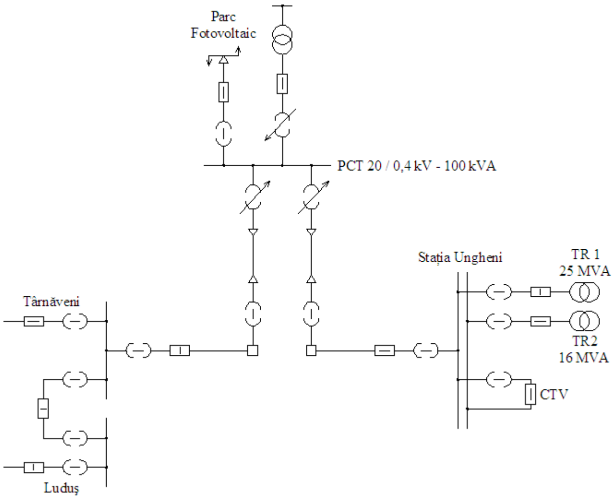

Fig. 3.1. The single phase diagram of 20 kV system framing

To the outgoing cell of producer power substation are connected, in serial assembly, as customer installation, through a 20 kV underground cable, two 20/ 0,38 kV – 1X1600kVA substations.

The simplified single phase diagram of 20/0,4 kV CS is presented in figure 3.2.

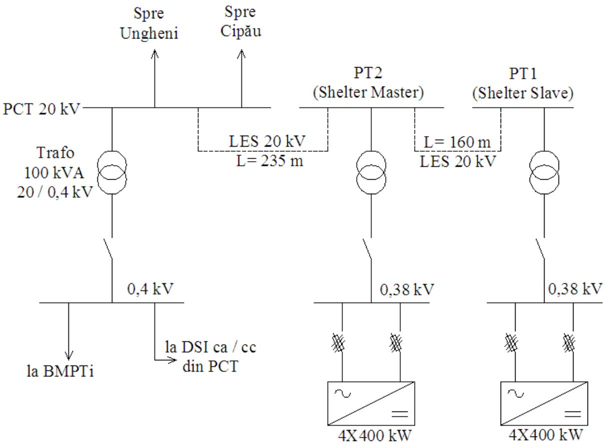

Fig. 3.2. The simplified single phase diagram of 20/0,4 kV CS

Calculation results from projecting phase for some limit-situations in photovoltaic plant working will be presented in the following. Voltage drop and power loss calculations were performed considering the next aspects:

- the network is working in normal conditions with Ungheni – Cipău 20 kV OL supplied from Ungheni Substation;
- the most disadvantaging cases of working were taken into consideration: winter night under load (4 o'clock), peak production during winter (12 o'clock), peak load in the winter evening (19 o'clock), summer night under load (4 o'clock), peak production during summer (12 o'clock), peak load in the summer evening (21 o'clock);
- voltage on 20 kV bus-bar from Ungheni Substation is of 20,6 kV.

Given that measurements were performed only in three points, the diagram will be restrained, emphasising only these points.

The topological data of simplified network are shown in table 3.1.

Using these data and based on calculations, the results presented in table 3.2. were obtained.

Table 3.1. Topological data of the network

		Without production		**With production**	
Substation / Line	Power / Length	Working conditions	Current	Working conditions	Current
	kW / m		[A]		[A]
Ungheni Substation		WNUL	49,01	WNUL	49,01
		PPW	74,45	PPW	44,3
		PLWE	79,79	PLWE	79,79
		SNUL	32,36	SNUL	32,36
		PPS	49,64	PPS	-50,89
		PLSE	60,94	PLSE	60,94
OL 70 mmp	9140 m	WNUL	31,18	WNUL	31,18
		PPW	47,38	PPW	17,22
		PLWE	50,78	PLWE	50,78
		SNUL	20,59	SNUL	20,59
		PPS	31,58	PPS	-68,94
		PLSE	38,78	PLSE	38,78
PP CS	100 kVA	WNUL	31,18	WNUL	31,18
		PPW	47,38	PPW	17,22
		PLWE	50,78	PLWE	50,78
		SNUL	20,59	SNUL	20,59
		PPS	31,58	PPS	-68,94
		PLSE	38,78	PLSE	38,78
OL 70 mmp	520 m	WNUL	24,72	WNUL	24,72
		PPW	37,55	PPW	37,55
		PLWE	40,25	PLWE	40,25
		SNUL	16,32	SNUL	16,32
		PPS	25,04	PPS	25,04
		PLSE	30,74	PLSE	30,74
OL 50 mmp	10125 m	WNUL	1,98	WNUL	1,98
		PPW	3,01	PPW	3,01
		PLWE	3,22	PLWE	3,22
		SNUL	1,31	SNUL	1,31
		PPS	2,01	PPS	2,01
		PLSE	2,46	PLSE	2,46
SS 3 Cipău	400 kVA	WNUL	1,98	WNUL	1,98
		PPW	3,01	PPW	3,01
		PLWE	3,22	PLWE	3,22
		SNUL	1,31	SNUL	1,31
		PPS	2,01	PPS	2,01
		PLSE	2,46	PLSE	2,46

Table 3.2. Projecting data

	Without production			
Substation / Line	Working conditions	Voltage drop		Power losses
		[%]	[kV]	[kW]
PP CS	WNUL	1,676	0,345	17,36
	PPW	2,546	0,524	40,07
	PLWE	2,729	0,562	46,03
	SNUL	1,107	0,228	7,57
	PPS	1,698	0,349	17,81
	PLSE	2,084	0,429	26,85
SS 3 Cipău	WNUL	2,447	0,504	21,57
	PPW	2,546	0,524	49,77
	PLWE	3,984	0,82	57,17
	SNUL	1,615	0,332	9,4
	PPS	2,478	0,51	22,12
	PLSE	3,043	0,627	33,35

	With production			
Substation / Line	Working conditions	Voltage drop		Power losses
		[%]	[kV]	[kW]
PP CS	WNUL	1,676	0,345	17,36
	PPW	1,188	0,244	9,25
	PLWE	2,729	0,562	46,03
	SNUL	1,107	0,228	7,57
	PPS	-2,829	-0,582	48,94
	PLSE	2,084	0,429	26,85
SS 3 Cipău	WNUL	2,447	0,504	21,57
	PPW	2,359	0,485	18,95
	PLWE	3,984	0,82	57,17
	SNUL	1,615	0,332	9,4
	PPS	-2,049	-0,422	53,25
	PLSE	3,043	0,627	33,35

4. PERFORMING AND INTERPRETING MEASUREMENTS

Electrical parameters measurement and monitoring was realised, as mentioned above, in three points:

- in Ungheni Substation, at the line beginning;
- in Connexion Substation of photovoltaic plant (CS Chirileu);
- at the last substation supplied by OL (SS 3 Cipău).

In order to perform measurements, we used Janitza UMG511 network analyzers. The connection scheme is presented in figure 4.1.

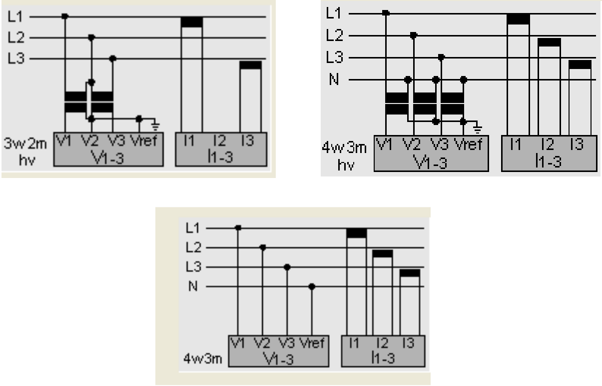

Fig. 4.1. Network analyzer connection scheme: a) in Ungheni Substation; b) in CS Chirileu; c) in SS Cipău.

The network analyzers were installed in series with energy meters, lacking the possibility of directly measuring the electrical parameters, as quantities were brought to primary values by using current or voltage ratios (for Ungheni Substation and CS Chirileu cases). For Ss Cipău, we chose to bring currents to primary values directly from the analyzer, while monitored voltage would be the secondary one and using relation (34) in order to obtain primary value.

$$U_{MTr} = U_{JTr} \cdot n_{TR} \left(1 + p \cdot \frac{v_p\%}{100}\right) \quad (34)$$

where:

- U_{MTr} real voltage inside medium voltage network;
- U_{JTr} voltage measured in the 20 / 0,4 kV power transformer secondary;
- n_{TR} 20 / 0,4 kV transformer voltage ratio (50);
- p number of contact plate on which the transformer is set;
- v_p percentage of voltage variation due to modifying a contact plate [%].

Measurements were made during a month (between 14.03.2013-14.04.2013). Because of this, situations presented in the projecting part were assimilated to some situations from the measurement period. Given the fact that measurements were performed after activation, it is impossible to realize a comparison with data obtainable without the photovoltaic park working.

Results were examined aided by GridVis program, provided by the producer of network analyzers and are synthesised in table 4.1.

Table 4.1. Measurement results

Substation	Regime	Consumption / generated power	Voltage
Ungheni	WNUL	1032,77	20,86
	PPW	419,87	20,62
	PLWE	1190,58	20,55
	SNUL	1014,75	20,34
	PPS	345,06	20,22
	PLSE	527,92	20,43
CS CHIRILEU	WNUL	0	20,61
	PPW	1400	20,55
	PLWE	0	20,25
	SNUL	0	20,09
	PPS	3200	20,57
	PLSE	360	20,18
SS 3 CIPĂU	WNUL	13,79	20,59
	PPW	22,21	20,47
	PLWE	19,28	20,21
	SNUL	14,55	20,07
	PPS	11,12	20,47
	PLSE	12,72	20,14

These data were compared to those from projecting phase and filled in table 4.2.

Table 4.2. Projecting and real working comparative results

Substation / Line	Regime	Projecting results			Measurement results		
		Voltage drop		Power losses	Voltage drop		Power losses
		[%]	[kV]	[kW]	[%]	[kV]	[kW]
PP SC	WNUL	1,676	0,345	17,36	1,198	0,25	7,61
	PPW	1,188	0,244	9,25	0,339	0,07	2,61
	PLWE	2,729	0,562	46,03	1,46	0,3	10,11
	SNUL	1,107	0,228	7,57	1,229	0,25	7,35
	PPS	-2,829	-0,582	48,94	-1,731	-0,35	48,94
	PLSE	2,084	0,429	26,85	1,224	0,25	7,49
SS 3 Cipău	WNUL	2,447	0,504	21,57	1,31	0,27	9,45
	PPW	2,359	0,485	18,95	0,73	0,15	12,31
	PLWE	3,984	0,82	57,17	1,679	0,34	12,56
	SNUL	1,615	0,332	9,4	1,344	0,27	9,12
	PPS	-2,049	-0,422	53,25	-1,215	-0,25	53,25
	PLSE	3,043	0,627	33,35	1,437	0,29	13,99

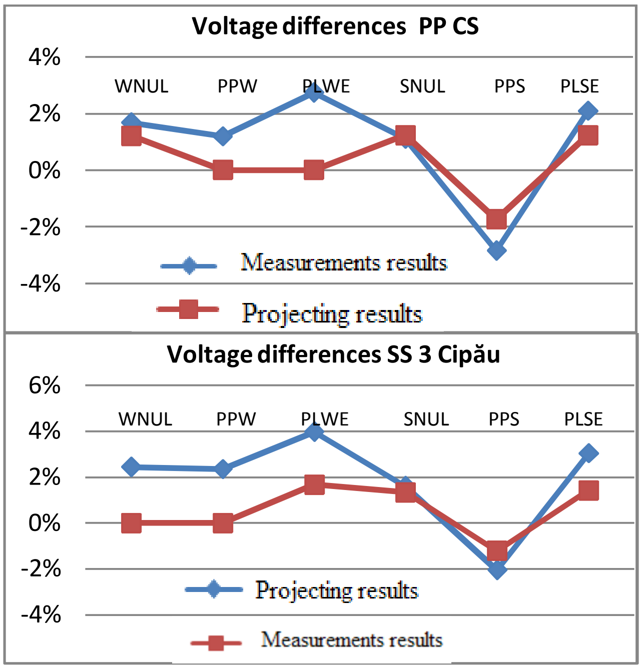

Figure 4.2. Differences between voltage in PP SC and SS 3 Cipău

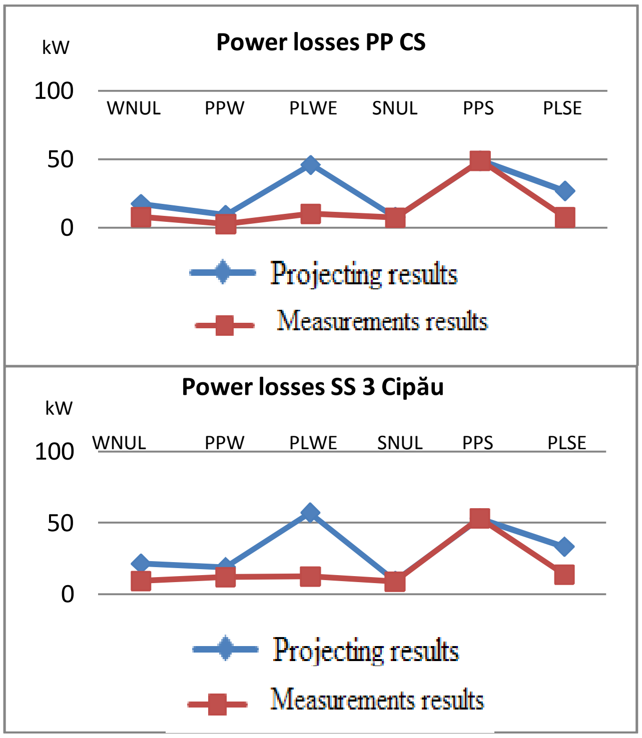

Figura 4.3. Differences between power losses in PP SC and SS 3 Cipău

5. CONCLUSIONS

Regarding real voltage drops in distribution networks, it is observable that these differ substantially from those anticipated throgh projecting, raging from -0,122% up to +2,305, in case we discuss situations in which the plant doesn't work at maximum capacity, and between – 0,838 and – 1,098, in case the plant works at full capacity (table 4.2, figure 4.2). Nevertheless the recorded voltages values do not exceed the limits (±10%).

The greatest differences are visible in the winter evening peak load (PLWE) case. These are due to the fact that measurements were performed during spring and, even though the measuring mode was assimilated to a day that would maintain the characteristics of the mentioned consumption, it was difficult to catch a likeness of the considered case. Again, differences are resulted because of improper knowledge of consumption characteristics, in the projecting case.

Concerning peak production during summer (PPS), although the day chosen for analyzing measurements closely approximates summer conditions, we can observe that voltage level on medium voltage bus-bars isn't close to the anticipated one, in none of the measurement points. This situation can amplify during summer, when, due to high temperatures, consumption would increase, naturally leading to the decrease of network voltage.

The results that are closest to measurements were registered during summer night under loads (SNUL).

Regarding power losses in the network, measurements were unable to reveal the real situation, a more complex analysis being needed, together with making up power balances for the specified line, in all considered cases.

In order to obtain power losses, logistics were used, based on table 4.2 and figure 4.3. Considering the data from measurements for power output and input in the three measurement points (the ones which could be taken into account), and using the same relations.

All things considered, it can be concluded that the main reasons which led to these errors are the following:

- improper knowledge of consumption profile for the analyzed line and the impossibility of it's precise forecasting, for the projecting part;
- the short period in which measurements were performed, and hence the necessity of assimilating some days from the monitored days to the calendar ones, in the measurement case.

Although together with the increase of the energy produced by the photovoltaic plant we can notice a normal increase of power losses on an OL, if we consider the whole distribution system, losses will lower because of reducing the distances from which the necessary power is transported.

As perspectives, our aim is to continue measurements for this OL and to make up balances for summer operating conditions, but also performing measurements for a new OL, to which a new photovoltaic plant will be connected in course of time. In this case, measurements will be made for calendar days, as well as power balances for the medium voltage OL, both before and after rendering the plant operative, having, this way, the benefit of complete and complex data for a pertinent analysis of phenomena that occur.

ABBREVIATIONS:

CS	- connexion substation
EDN	- electrical distribution network
OL	- overhead line
OTC	- own technological consumption
PLSE	- peak load in the summer evening
PLWE	- peak load in the winter evening
PPS	- peak production during summer
PPSC	- photovoltaic plant connexion substation
PPW	- peak production during winter
SNUL	- summer night under load
SP	- supply point
SS	- substation
THD	- total harmonical distortion
UC	- underground cable
WNUL	- winter night under load

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