Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **61**, *1*, pp. 42–47, Bucarest, 2016

SPECIFICITIES IN ANALYSIS OF ENERGY AVAILABILITY GENERATED BY PHOTOVOLTAIC SOURCES

IOAN FELEA[1], VASILE MOLDOVAN, DANIEL ALBUȚ

Key words: Photovoltaic sources, Availability, Modeling, Simulation.

Using renewable energy is developing exponentially. Reliability and availability analysis of equipment for electricity generation based on renewable energy resources have certain features due to structural and functional specificity of these facilities. This paper aims to present the specificity of availability analysis of power generation using photovoltaic sources (PVS). After showing how the subject fits into the general issue of availability analysis and into particular issues, in the second part of the paper is presented the proposed model to assess the availability of PVS structured in two levels: intrinsic and extrinsic. An appropriate case study useful for instantiating the mathematical model is exposed in the third part and in the last part conclusions are presented.

1. INTRODUCTION

With awareness of the negative effects of using fossil fuels (FF), mankind has sought solutions to increase the use of renewable energy resources (RER) whose negative environmental impact is much lower, comparing to FF. Based on the motivation for the acceleration of the use of RER and the reduction of the use of FF [1], European and national strategies have clear targets [2−4].

Harnessing wind and solar power has grown almost exponentially [5]. In Romania, between 2010 and 2014, the produced electricity from PVS increased more than 1000 times.

Structural and functional installed features of PVS involve certain specificities regarding reliability and availability analyze of these power sources (PS). This paper aims to refer to these issues. We consider that PVS with installed capacity over 5 MW – connected to national energy system (NES), dedicated to inject the generated power into the NES – should be treated in terms of availability of energy as well as any other source connected to NES, taking into account, of course, functional particularities of PVS regarding, mainly, the intermittency and variability of the energy production. Therefore, at the level of NES, PVS with installed capacity over 5 MW are considered with the intrinsic availability indicators (A) and unavailability (U), for example, within generalized Newton binomial expansion, which is used to generate the distribution of the random variable “the available power at sources”, according to the well known methodology [6−8].

2. MODELING AVAILABILITY OF THE ENERGY GENERATED BY PVS

As for any other sources, in case of PVS the availability of energy is a result of power availability (A_{PVS}^{P}) and the time dependent availability (A_{PVS}^{T}). Time dependent availability is an intrinsic characteristic and power availability has generally two components: one intrinsic component dependent of photovoltaic panels (PVP) (A_{PVS}^{PI}), and one extrinsic part, dependent of the level of solar irradiation (A_{PVS}^{PE}). Accordingly, we can write:

$$A_{PVS}^{W} = A_{PVS}^{T} \times A_{PVS}^{PI} \times A_{PVS}^{PE}. \quad (1)$$

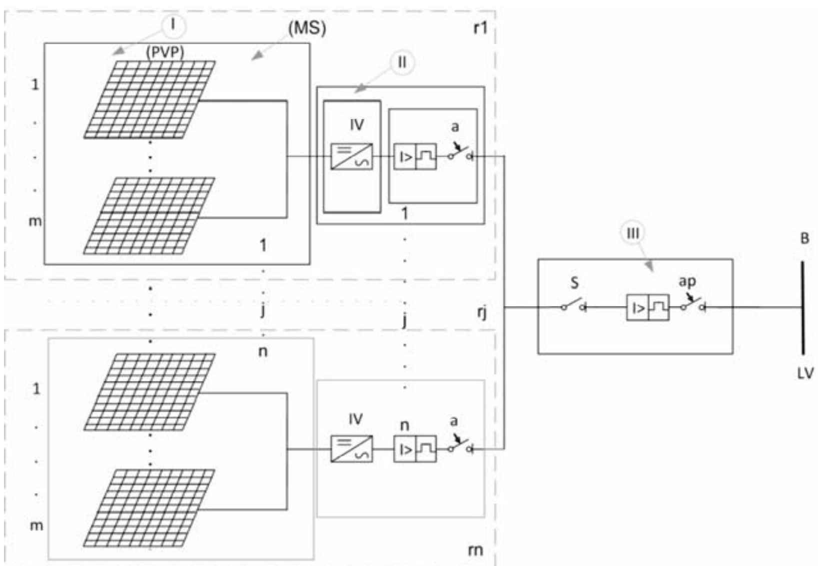


Fig. 1 – Electric scheme of an integrated PVS at consumer.

[1] University of Oradea, Department of Energy Engineering, Universitatii no.1, Oradea, 410087, Romania, E-mail: ifelea@uoradea.ro.

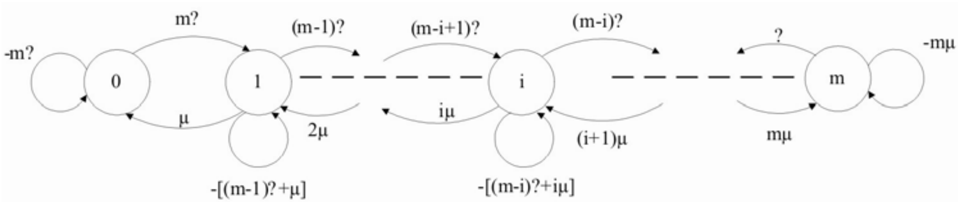


Fig. 2 – Graph of states and transitions of the source module of a branch of PVS.

In a first analysis, which is made in this paper is admitted the assumption that $A_{PVS}^{PI} = 1$, corresponding to situation when PVS has the capacity to convert maximum transmitted power (A_{PVS}^{W}) of solar radiation.

For modeling time availability of PVP we proceed from the structure of these sources. In Fig. 1 is presented the typical electric diagram of a PVS with installed capacity less than 5 MW (consumer related), which provides power on the LV (low voltage) side of the transformer substation connecting the consumer to the NES.

These types of PVS are structured typically in n branches, each containing m PVP with equally installed power. Each branch j has one inverter (IV_j) and one automatic circuit breaker (a_j), $j = \overline{1 \div n}$. Parallel linking and connection to the LV bus for the n branch is performed with usual switching equipment (S – disconnect switch, ap – automatic circuit breaker).

In this context we will first referred to the reliability modeling of PVS fundamental structure, namely PVS having scheme represented in Fig. 1, then refer to the modeling the availability of PVS.

For modeling the reliability of PVS, its structural components are delimited in categories (Fig. 1), for which the fundamental indicators of reliability (λ, μ) are supposed known or easily determined:

I – the *source* module of a branch;

II – the *conversion-regulation-switching* module of a branch;

III – the *switching* module of PVS at the transformer LV busbar.

A large part of methods of analysis developed in the specialty literature [6–10], can be applied to assess the intrinsic availability of the PVS. For an expeditiously and sufficiently precise evaluation, we propose to use the binomial method applied mainly for reliability analyzes of power sources.

In this case, the source module of a branch of PVS can be represented graphically as the graph from Fig. 2, where:

λ – failure intensity of an PVP;

μ – maintenance intensity of PVP;

m – number of PVP of a *source* module structure (MS).

State 0 is the state with the maximum structural (intrinsic) availability state, m is the minimal intrinsic availability and the other state correspond to intermediate values of the have the same value for all modules.

Based on the graph presented in Fig. 2, the method of Markov chains with continuous parameter is applicable to reliability analysis, but this approach is not justified because of the supposed simple structure of the source module which it is composed from elements (PVP) having equal values of λ and μ. The reliability indicators of PVS can be expressed as:

For the source module of one branch relative to the maximal functional level:

$$\lambda_I = \lambda_{eMS} = m\lambda_{PVP};$$
$$\mu_{eMS} = \frac{m\lambda_{PVP}}{m\dfrac{\lambda_{PVP}}{\mu_{PVP}}} = \mu_{PVP} = \mu_I. \quad (2a,2b)$$

For branch j of PVS:

$$\lambda_{rj} = \lambda_{Ij} + \lambda_{IV} + \lambda_a = \lambda_{Ij} + \lambda_{IIj};$$
$$\mu_{rj} = \frac{\lambda_{rj}}{\dfrac{\lambda_{Ij}}{\mu_{PVP}} + \dfrac{\lambda_{IV}}{\mu_{IV}} + \dfrac{\lambda_a}{\mu_a}}; \quad j = \overline{1 \div n}. \quad (3a,3b)$$

Specifications: a) if the sources are structurally identical, then λ_{Ij} has the same value for all modules; b) basic reliability indicators are of the same type, each for branch structure:

$$\lambda_{IVj} = \lambda_{IV}; \mu_{IVj} = \mu_{IV}; \lambda_{aj} = \lambda_a; \mu_{aj} = \mu_a; j = \overline{1 \div n}.$$

The PVS fundamental indicators can be expressed as:

$$\lambda_{PVS} = \sum_{j=1}^{n} \lambda_{rj} + \lambda_S + \lambda_{ap};$$
$$\mu_{PVS} = \frac{\lambda_{PVS}}{\sum\limits_{j=1}^{n} \dfrac{\lambda_{rj}}{\mu_{rj}} + \dfrac{\lambda_S}{\mu_S} + \dfrac{\lambda_{ap}}{\mu_{ap}}}, \quad (4a,4b)$$

where λ_{Ij}, μ_{Ij} – failure and maintenance intensity of the equivalent MS; rj – branch number j ;

$\lambda_{PVP}, \lambda_{rj}, \lambda_a, \lambda_{ap}, \lambda_S, \lambda_I, \lambda_{IIj}, \lambda_{III}, \lambda_{IV}$ – failure intensity of the components and the subsystems marked in the Fig. 1;

$\mu_{PVP}, \mu_{rj}, \mu_a, \mu_{ap}, \mu_S, \mu_I, \mu_{IIj}, \mu_{III}, \mu_{IV}$ – maintenance intensity of the components and the subsystems marked in the Fig.1.

Intrinsic (structural) availability of PVS is time dependent availability and can be expressed as:

$$A_{PVS}^{T} = \frac{\mu_{PVS}}{\lambda_{PVS} + \mu_{PVS}} = 1 - U_{PVS}^{T}, \quad (5)$$

where A_{PVS}^{T}, U_{PVS}^{T} are availability and unavailability of the PVS.

With reference to the model of reliability analysis of PVS, the values of probabilities for the $m + 1$ of the source module are terms obtained from Newton binomial development as:

$$\begin{cases} (p_I + q_I)^m \\ = p_I{}^m + C_m^1 p_I^{m-1} q_I + \ldots C_m^i p_I^{m-i} q_I^i + \ldots q_I^m, \quad (6) \\ p_I = \dfrac{\mu_{PVP}}{\lambda_{PVP} + \mu_{PVP}} = 1 - q_I. \quad (7) \end{cases}$$

Probabilities of each state for branch j of the PVS are derived from the development:

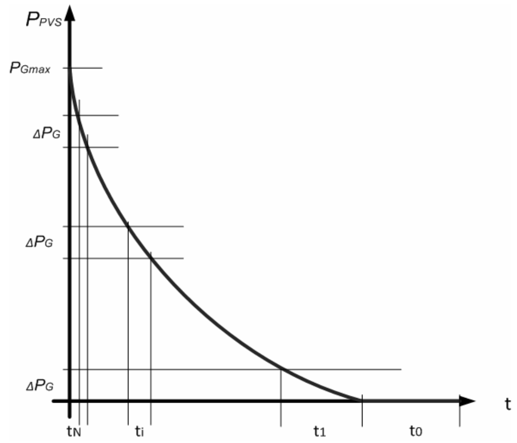


Fig. 3 – Power duration curve of a PVS.

$$\begin{aligned}&\left(p_I+q_I\right)^m\left(p_{II}+q_{II}\right)=\\&=p_{II}\sum_{i=0}^{m}C_m^i p_I^{m-i}q_I^i+q_{II}\sum_{i=0}^{m}C_m^i p_I^{m-i}q_I^i.\end{aligned}\tag{8}$$

As for the probabilities regarding the PVS states, these are obtained from the expansion of generalized Newton binomial expression:

$$\begin{cases}\left[\left(p_I+q_I\right)^m\left(p_{II}+q_{II}\right)\right]^n\left(p_{III}+q_{III}\right), & (9)\\ p_{II}=\dfrac{\mu_{II}}{\lambda_{II}+\mu_{II}}=1-q_{II}; & (10a)\\ p_{III}=\dfrac{\mu_{III}}{\lambda_{III}+\mu_{III}}=1-q_{III}. & (10b)\end{cases}$$

To evaluate the extrinsic availability of the PVS produced power (A_{PVS}^{PE}) and total availability of the PVS the power duration curve can be produced by PVS, assuming the maximum intrinsic functional level (Fig. 3).

We can divide the maximum generated power $(P_{G\max})$ in N steps of equal power (ΔP_G) corresponding to the variables of time intervals, the highest value with the time for which PVS does not generate power (t_0). The $N+1$ states of PVS, highlighting the two components of availability, are shown in Table 1, which also contains a characterization of the states.

Table 1
States of PVS and levels of the main indicators (S – success state)

State		Power produced	Unavailability level [%]	Probability
0	Stopped	0	100	$A_{PVS}^T\dfrac{t_0}{T_A}+U_{PVS}^T$
1	S (partial)	ΔP_G	$100(1-\dfrac{1}{N})$	$A_{PVS}^T\dfrac{t_1}{T_A}$
..	…	…	…	…
k	S (partial)	$k\Delta P_G$	$100(1-\dfrac{k}{N})$	$A_{PVS}^T\dfrac{t_k}{T_A}$
..	…	…	…	…
N	S (total)	$N\Delta P_G$	0	$A_{PVS}^T\dfrac{t_N}{T_A}$

As will be seen from the case study shown in the third part of this paper, the availability of power and energy of PVS is influenced mainly by the availability of solar radiation power of the PVP (A_{PVS}^{PE}), which is determined by the relation:

$$A_{PVS}^{PE}=\frac{\Delta P_G}{T_A\cdot P_{G\max}}\cdot\sum_{k=0}^{N}k\cdot t_k\ ,\tag{11}$$

where T_A is the duration of analysis; t_k is the duration of the state k.

3. CASE STUDY

The methodology described above was applied with reference to a PVS, related to consumer, with shopping center (C-COM) profile. The single line diagram regarding the power supply system shown in Fig. 4, and the characteristics of the equipment involved are shown in Table 2.

Table 2
Characteristics of the equipment involved in the power supply of C-COM

No.	Equipment	Characteristics	
1.	Power transformers (TR_1,TR_2)	S_n =1600 kVA; U_{1n} / U_{2n} = 20/0.4 kV; f_n = 50 Hz;	
2.	Automatic reactive power compensator (CAQ1, CAQ2)	Q_n =350 kvar; no. steps (T): 7; Q_{nT} =50 kvar;	
3.	Photovoltaic sources (PVS)	PVS_1	P_i = 358.8 kW; 13 inverters; 1677 photovoltaic panels
		PVS_2	P_i = 469.2 kW; 17 inverters; 2193 photovoltaic panels

Numerical inputs to perform the evaluation can be of two categories:

1) Fundamental reliability indicators of components, based on the information obtained from literature [5, 8, 11] are shown in Table 3.

2) Records of the power produced by the PVS. For example, in Figs. 5 and 6, are given two samples of recordings made on both PVS.

Table 3
Fundamental reliability indicators of components used

Indicators / Components	λ [h^{-1}]	μ [h^{-1}]
Photovoltaic panel (PVP)	7.610×10^{-6}	$1.042\ x\ 10^{-3}$
Inverter(IV)	2.283×10^{-5}	$1.042\ x\ 10^{-3}$
Branch switch (a)	2.223×10^{-5}	$3.900\ x\ 10^{-1}$
Divider (S)	3.250×10^{-12}	$1.466\ x\ 10^{-4}$
Main switch (ap)	7.500×10^{-12}	$4.149\ x\ 10^{-9}$

The results obtained are presented in Tables 4 and 5, respectively, in Figs. 7 and 8.

Based on the results described above can be determined average values of the availability, which are for PVS_1:

$A^T_{PVS1} = 0.91039$; $A^T_{PVS1} = 0.2125$; $A^T_{PVS1} = 0.19345$ and for PVS_2: $A^T_{PVS2} = 0.91739$; $A^T_{PVS2} = 0.2868$; $A^T_{PVS2} = 0.26311$. With reference to these results, we concluded that availability values are differentiated in case of the two PVS. The difference is determined essentially by the component of the extrinsic availability. The intrinsic time dependent availability values are very close in case of the two PVS.

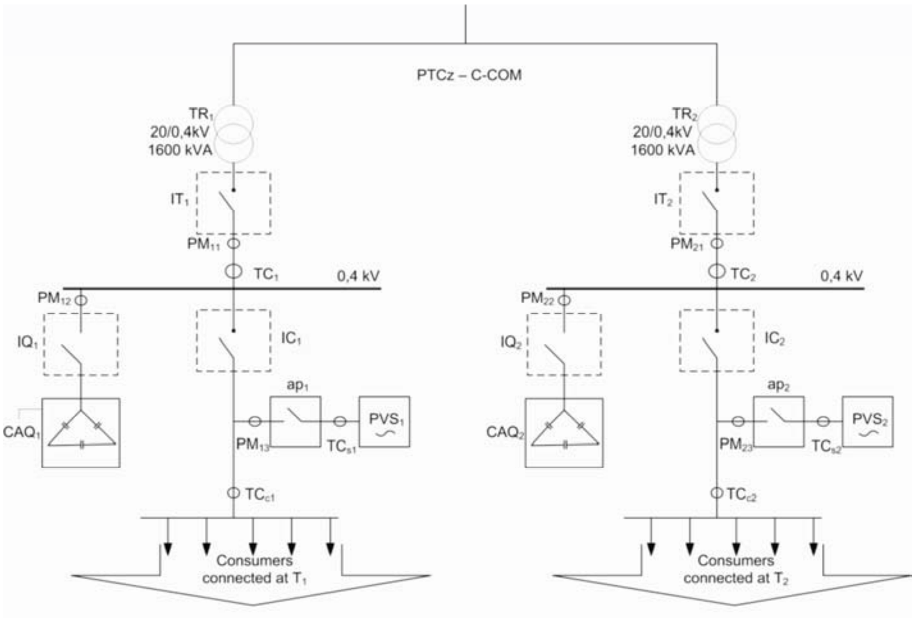


Fig. 4 – Single line diagram of power supply scheme for consumer (C-COM), PVS_1, PVS_2.

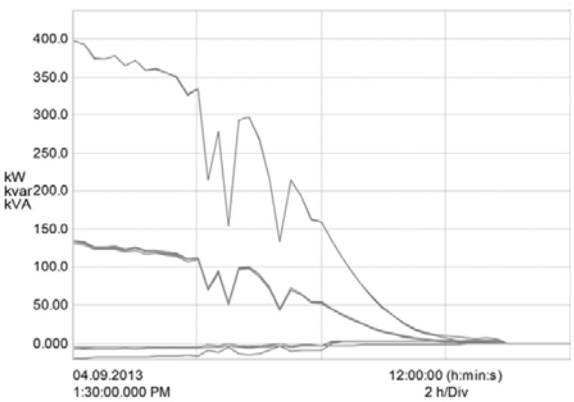


Fig. 5 – Load curves of power by PVS1.

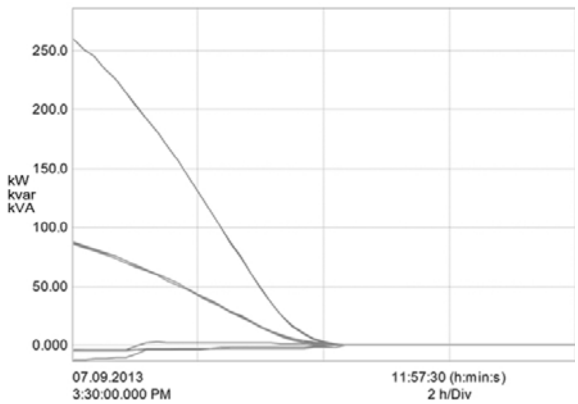


Fig. 6 – Load curves of power by PVS2.

Table 4

Characterization of intrinsic availability status for a branch of PVS_1 and PVS_2

No. (i)	Probability (p_i)	Duration ($T_i = p_i\, T_A$) [h]	Power $P_i = (m-i) \times 0.214$ [kW]
0	0.280771052	2459.554	27.606
1	0.266570827	2335.160	27.392
2	0.125570976	1100.002	27.178
3	0.039128655	342.767	26.964
4	0.009073098	79.480	26.750
5	0.001669833	14.628	26.536
6	0.000254067	2.226	26.322
7	0.000032869	0.288	26.108
8	0.000003691	0.032	25.894
9	0.000000365	0.003	25.680
10	~0.0	~0.0	25.466
…	…	…	…
i	~0.0	~0.0	…
…	…	…	…
128	~0.0	~0.0	0.2140
29	~0.0	~0.0	0.0

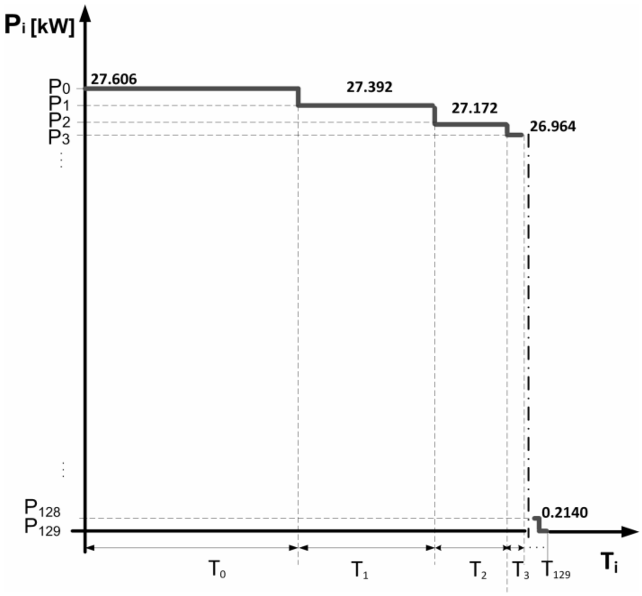
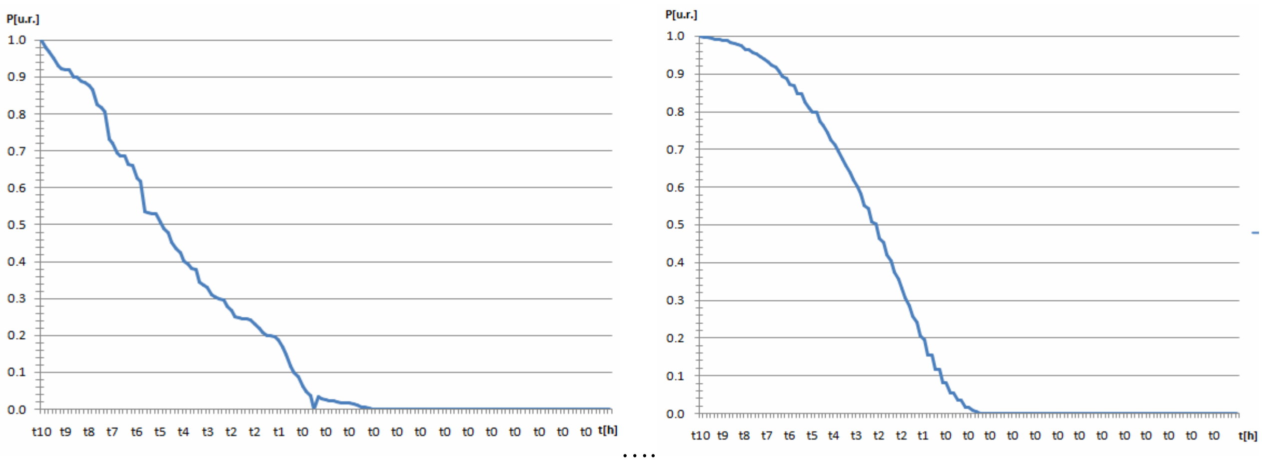


Fig. 7 – Intrinsic power-time diagram (PVS_1 and PVS_2).



a) PVS1 b) PVS2

Fig. 8 – Duration curve of power produced for maximum level of A_{PVS}^{T} .

Table 5

Cumulative states (intrinsic + extrinsic) of PVS and main levels of indicators

PVS_1					PVS_2				
State (*k*)		Produced power [kVA]	Unavai-lability [%]	Probabi-lity	State (*k*)		Produced power [kVA]	Unavai-lability [%]	Probabi-lity
0	Stopped	0.000	100	0.6781	0	Stopped	0.000	100	0.6986
1	S (partial)	40.559	90	0.0352	1	S (partial)	28.874	90	0.0232
2	S (partial)	81.117	80	0.0604	2	S (partial)	57.748	80	0.0185
3	S (partial)	121.676	70	0.0402	3	S (partial)	86.622	70	0.0185
4	S (partial)	162.235	60	0.0302	4	S (partial)	115.496	60	0.0185
5	S (partial)	202.793	50	0.0251	5	S (partial)	144.370	50	0.0278
6	S (partial)	243.352	40	0.0352	6	S (partial)	173.244	40	0.0232
7	S (partial)	283.910	30	0.0101	7	S (partial)	202.118	30	0.0325
8	S (partial)	324.469	20	0.0402	8	S (partial)	230.992	20	0.0371
9	S (partial)	365.028	10	0.0402	9	S (partial)	259.866	10	0.0974
10	S (total)	405.586	0	0.0050	10	S (total	288.740	0	0.0046

4. CONCLUSIONS

Evaluating availability of the energy sources is required for correct sizing in a power system, taking into account the availability of energy agreed between supplier and consumer. Availability analysis of photovoltaic sources involves certain characteristics, determined essentially by particularities of primary source of energy, characterized by variability and intermittency. PVS availability is treated in this paper as a result of its structural and functional specificities, highlighting the following components: the intrinsic time dependent availability, the intrinsic availability of power and the extrinsic availability of power source (solar radiation). To assess the intrinsic availability established models can be applied, as it was described in the specialized literature, mainly binomial model, based on the structural diagrams representing the PVS state graphs. To assess the extrinsic availability the power duration curve generated by PVS was used discretized into a reasonable number of steps. Availability of power and energy PVS depends essentially on the extrinsic availability of power. In Romania, the time dependent availability of PVS stands between [90–95] % and the availability of power are in the range of [15–30] % which is reflected on the availability of energy. In order to increase values of these indicators all existing solutions to maximize the produced power should be applied (proper command of inverters within the PVS structures, targeting maximum solar radiation).

Received on October 16, 2014

REFERENCES

1. *** *Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*, www.wc.wuropa.eu.
2. *** *Strategy of Sustainable Energy of EU*, http://uefiscdi.gov.ro.
3. *** *About Energy policy in the European Union*, http://www.ier.ro.
4. *** *National Strategy for Sustainable Development*, www.insse.ro/cnns.
5. *** Baza de date online – Surse de energie fotovoltaice, http://indesen.ats.com.ro.
6. R. Billinton, R. Allan, *Reliability Evaluation of Engineering Systems*, PLENUM PRE SS, New York and London, 1990.
7. V. Nitu, *Reliability of power installations* (in Romanian), Edit. Academiei, Bucharest, 1973.
8. I. Felea, *Reliability in electrical power engineering (in Romanian)*, Edit. Didactică şi Pedagogică, Bucharest, 1996.
9. Wenyanau Li, *Assessment of Power Systems Models; Methods and applications*, John Wiley and Sons, 2005.
10. C. Nemes, F. Munteanu, *A Probabilistic Model for Power Generation, Adequacy Evaluation*, Rev. Roum. Sci. – Techn. Electrotechn. et Energ., **56**, *1*, pp. 36–46, 2009.
11. *** ABB, *Power One Inverters Presentations*, www.abb.com/solarinverters.