Mansoura Engineering Journal (MEJ) Vol. 12, No. 1. June 1987 E. 13

" RELIABILITY AND ECONOMICS OF PVPS - UG AGGREGATION : ESTIMATION AND ANALYSIS ."

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ملخصة :-

ان مشكلات ربط منظومة الخلايا الشمسيه (الفوتوفولطيه) بشبكه كهربيه مازال البعض منها فى حاجه الى مزيد من البحث والتحليل وبحل هذه القضايا يصبح هذا الربط هو التطبيق المامول للانتاج المباشر للطاقه الكهربيه من الطاقه الشمسيه باستخدام الخلايا المذكوره ·

وتمثل اعتمادية واقتصادية المجموعه اكبر المشكلات الملحه والبارزه التى تحد من تنفيذ وتعميم هذا الربط ·

وقد تم اقتراح طريقة فى هذا البحث تستخدم الحاسب الالي فى تقدير وتحليل درجة اعتمادية عناصر كل منظومه بالاضافه الى اعتمادية منظومه الخلايا الشمسيه بقدرات مختلفه ، والشبكه الكهربيه قبل وبعد ربطهما معا · ولتحقيق هذا الهدف اخذت معدلات مختلفه مستقاة من الواقع لانهيار كل عنصر من هذه العناصر بالاضافة الى احتمالات مختلفه للاشعاع الشمسى للموقع المقترح للدراسه وكذلك الاخذ فى الاعتبار مكونات الشبكه الكهربيه من خطوط نقل واجهزة فصل وتحويل ·

ABSTRACT

Still there are unanswered questions related to the problem of integrating PVPS with UG. This interconnection becomes the most promising future application for photovoltaic (PV) energy production if these questions are researched deeply and answered .

The most significant questions are those related to the photovaltaic - Utility grid power system aggregation (PVPS - UG) reliability as well as its economics. This paper presents a computer-aided approach by the aid of which the reliability of components , PVPS, and PVPS-UG aggregation is estimated and analyzed for practical failure rates of each component as well as alternative probabilities of insolation. On other hand , the impact of the reliability of UG Subsystems : transmission, switching and transformation with various ratings of hypothetical PVPS is demonstrated .

In addition, the economics of this integration are evaluated for the present and hopeful PV array prices. Complete numerical application with an argument is introduced for a PVPS , hypothetically sited at kafr - EL - Sheikh region, EGYPT .

I INTRODUCTION

The developing countries of the world, especially the ones that are resource-poor and population - rich, are confronted with a multitude of complex problems involving population growth, economics, energy, and development. Unfortunately, all these problems are closely interrelated and they have been seriously aggravated by the strong fluctuations in the oil prices of the past and present time [1] . With the continuous rises in oil prices and capital costs of conventional power plants in the last several years, increased for development of electric supplies utilizing renewable energy resources. Photovoltaic (PV) generation represents one of the method that converting directly the sunlight into electricity and is applicable to most geographical regions.

The early stage of photovoltaic power systems (PVPS) applications had been concentrated on the residential ones with secondary emphasis on intermediate load applications. Integrating such systems into electric utility grid is a new concept and has received an increasing interest. Thus, the key issue in utility-interactive PVPS is that they put electricity back into the utility system. Since the utility is ultimately responsible for the power system, request for interconnecting such systems raises several technical and economic questions and operational concerns safety, power quality, reliability, power system protection and metering. Thereby, intensive efforts should be carried out and continued to tackle such issues .

This paper deals with the effect of such interconnection on the reliability and economics of the PVPS - UG aggregation. Computer programs are prepared to estimate the PVPS capacity factor, components, PVPS and PVPS - UG aggregation reliability and the energy cost figure .

The impact of insolation reliability, PVPS ratings and the components failure rates is found and analyzed, The cost/reliability tradeoff is also investigated to determine the sensitivity of the energy cost figure to any incremental change in the reliability of PVPS and PVPS - UG aggregation.

II PVPS -UG INTERCONNECTION RELATED ISSUES

The injection of a bulk amount of power into the utility grid from dispersed generation (DG) is a new concept. It becomes a hopeful goal in view of the possibility of mass - producing and improving the technology of the fabrication and performance of its heart device and components. Photovoltaics has endured as the leading high technology solar option that promises to supplement the world's declining long term stocks of fossil - fuels for generating electricity. From the UG perspective, there are many requirements and issues related to PVPS must be achieved and analyzed .

A complete listing and description of all the issues relating to DG was reported by Jet. Propulsion Laboratories [2 , 3]. Voltage regulation with the reactive compensation, harmonic distortion, power conditioner power factors, reliability of PVPS - UG aggregation and finally the economics of this integration constitute the principle interconnecting issues .

This paper will emphasize on the latter two issues to demonstrate firstly the compatibility and competency of PVPS to the conventional systems despite of its uncertainty. Secondly it is aimed at exploring the economics of such expensive systems in view of the present cells price and the expected mide - application if a step cost reduction will be achieved in the near future .

III CAPACITY EACTOR

The block diagram of PVPS - UG aggregation taken for this research is shown in Fig. 1. For the PVPS peak ratings, its design parameters are determined using an especially prepared computer program. It enables also the assessment of the PVPS and PVPS - UG capacity factors. Hourly irridiance data are taken [4] . The used module characteristics are summarized in Table (1). It is assumed to instal this PVPS at Kafr-El-Sheakh site, EGYPT of a latitude; 31.07°N and longitude; 30.57°E. It is intened to interconnect this system with the h.V. transmission system fed by TALKHA Power Station. It has a total installed generation power of 327.5 MW. Table (1) also illustrates the design parameters for the prementioned PVPS ratings of 5, 10 and 15 MW.

The capacity factor varies with the time of year. Thereby, the hourly, monthly and annual capacity factors are calculated. It is defined as :

$$CF_{PV}(hr) = \frac{P_{PV}(hr),\ MW}{PVPS\ rating\ ,\ MW}$$

$$CF_{UG}(hr) = \frac{P_{PV}(hr),\ MW}{hourly\ UG\ load\ demand,\ Mw}$$

Where:

CF_{PV} (hr) is the hourly capacity factor of PVPS as a ratio of its rating.

CF_{UG} (hr) is the hourly capacity factor of PVPS related to the corresponding hourly UG load demand.

P_{PV} (hr) is the hourly output of PVPS.

Shown in Fig. 2.a. are these hourly capacity factors for summer and winter seasons with a PVPS rating, of 10 MW. It is noticeable that the highest CF_{PV} occurs at 1 o'clock instant in June while in December, it happens at 11 o'clock, at the morning. Also, the peak load demand during these seasons occurs at these instants. Fig.2.b. illustrates the monthly capacity factor for the same rating. It can be seen that during June and September, the respective capacity factors have the highest value. This means that the peak PV output matches with the peak demand for our case study.

The annual CF_{PV} has been found for the PVPS considered which has a ratio of 53.425% for its ratings. If it is compared with that obtained for the system prementioned in Ref. [7] and installed at California site, USA of 1.0 MW peak rating, having

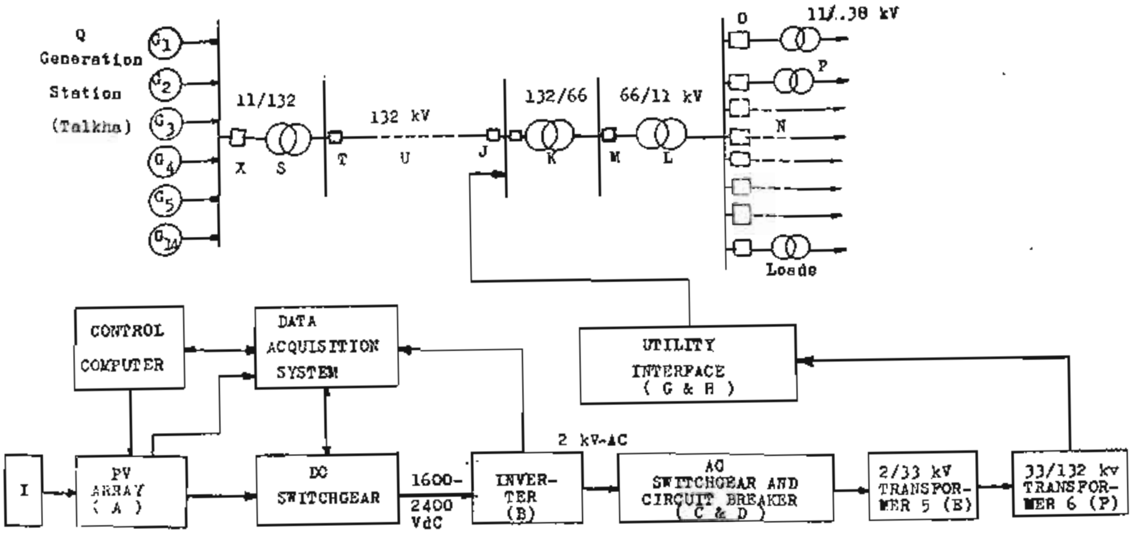


Fig.1. The Block Diagram of PVPS ~ UG .

Table (1) Design Parameters of PV Array of Flat Plate Type For Different Peak Ratings .

Cells : Dendritic web, Silicon. NOCT : 44°C
Module size : 1.32 m x 1.32 m. Module construction :
Extruded Al Fram, EVA Pottant, 0.32 cm full-tempered glass, 0.13 mm craneglass, mylar backing.
Module Aperture : 1.486 m^2. Bypass diode : 1 per module
Module performance at 1000 W/m^2, AM 1.5, 28°C Cell :
η_c = .142 , η_m = o.122 , V_{oc} = 24.5 V_{dc} , I_{sc} = 9.52 A,
V_{mp} = 19.91 V_{dc} , I_{mp} = 8.98 A P_{mp} = 178.8 We
Inverter used : 4.95 KW solid-state, static, self-commutated Using Pulse-width-Modulated Switching, η_{IN} = 96.5% at Full load, Input voltage = 1600 V_{dc} to 2400 V_{dc}, at 5 MW,
Total Harmonic Distortion = 5% rms on the output current Waveform [5] .

PV Array Peak Rating (MW) / Design parameters	5 MW	10 MW	15 MW
Total land Area, m^2	88209	176418	264627
Land (Array), m^2	70568	141136	211701
No. of Modules	40500	81000	121500
No. of Panels	2250	4500	6750
No. of parallel strings	405	810	1215
String Rating, kW	17.8	17.8	17.8
No. of Modules/String	100	100	100
Nominal dc bus voltage	± 980.6 (to ground)	± 980.6 (to ground)	± 980.6 (to ground)
dc Power Collection efficiency	0.981	0.981	0.981
Estimated annual energy production	40 GWh	80 GWh	120 GWh

CF_{PV} of 24.9%, then one can conclude that is possible to install such systems in EGYPT because of its attractiveness and superiority from the utility perspective.

IV RELIABILITY ESTIMATION

It is intended, here, to find the PVPS - UG aggregation reliability and how it is affected. Thus, an approach has been followed which is an accurate execution of the known methodology applied for a large system composed of series - parallel components. A comparative study is also carried out to explain the change that may be happened in the UG reliability on introducing the PVPS output.

Thereby, the reliability block diagram should be designed for the whole system incorporating all its components . Fig.3. reveals this diagram from which the UG reliability (R_{UG}) before interconnecting PVPS can , then , be found by ,

$$R_{UG} = R_1 \cdot R_2$$

Where $R_1 = R_Q \cdot R_X \cdot R_S \cdot R_T \cdot R_U$

$R_2 = R_J \cdot R_K \cdot R_L \cdot R_M \cdot R_N \cdot R_O \cdot R_P$

The reliability function is taken, here, to follow an exponential (Poisson) law given as [8]

$$R(t) = e^{-t/MTBF} = e^{-\lambda \cdot t}$$

where $R(t)$ = reliability of the item for a given period of time, t

t = Calendar time in units of hours, days, months, etc., as applicable.

MTBF = Mean time between failure for the item.

λ = item failure rate. in failures per unit of time; = 1 / MTBF .

Now, on injecting the expected PVPS output into the utility grid, the reliability of the conbination will be defined by the following expression :

$$R_{UGPV} = [\,1-(1 - R_1)\,(1 - R_{PV})\,] \cdot R_2$$

where

$$R_{PV} = R_I \cdot R_A \cdot R_B \cdot R_C \cdot R_D \cdot R_E \cdot R_F \cdot R_G \cdot R_H$$

$$R_I = \text{Prob.}\ (\ I \geqq I_{min}\ )$$

$$R_A(t) = \sum_{X=0}^{r} \frac{e^{-m.\lambda_m.t.n}\ (m.\lambda_m t\ .n)^X}{X\,!}$$

where

m = number of modules in one string

λ_m = module failure rate

n = number of strings in the array

r = number of allowable string failures.

Table (2) summarizes the results illustrating the components, utility, photovoltaic system and PVPS - UG aggregation reliability For different component failure rates and a peak rating of PV of 5 MW of a penetration level of 1.52% .Insolation reliability of 0.9 is taken in this case. The influence of other insolation probabilities on R_{PVUG} is explained in Fig.4. The results , clearly ,

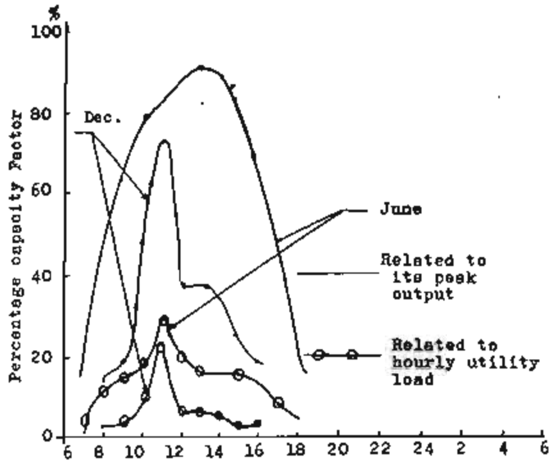


Fig. 2.a. Hourly Capacity Factor of PVPS Related its Peak and hourly utility load.

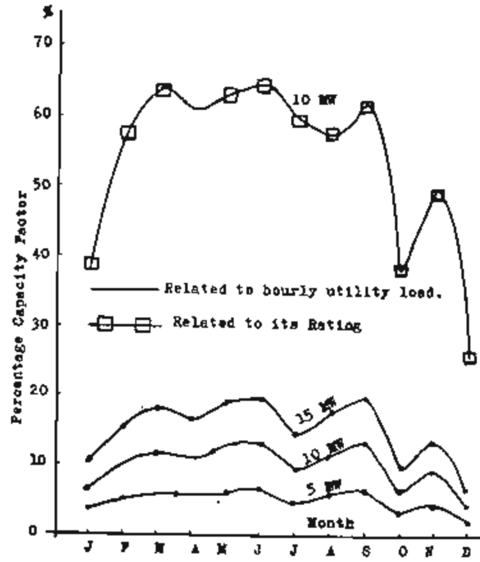


Fig. 2.b. Monthly Capacity Factor of PVPS .

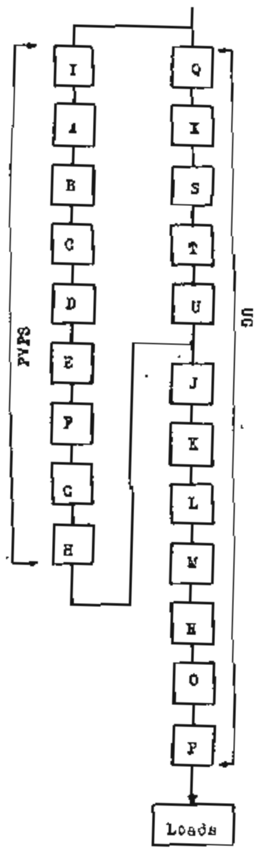
Table (2) Components , PVPS, UG and PVPS - UG Aggregation,

Reliability For Different Failure Rates,

(5 MW. R_I = 0.9).

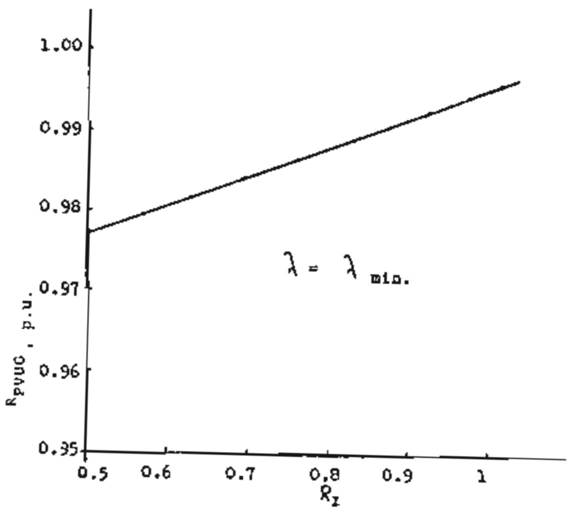
Component	Component Reliability		
	$\lambda_{min.}$ / 10^6 hrs	λ_{av} / 10^6 hrs	$\lambda_{max.}$ / 10^6 hrs
R_A	.99667 (.1)+	.81931 (.5)++	.51232 (.9)+++
R_B	.99497 (7)	.98570 (20)	.93053 (100)
R_C	.99928 (1)	.98570 (20)	.86588 (200)
R_D	.99928 (1)	.99784 (3)	.99283 (5)
R_E	.99964 (.5)	.99928 (1)	.99641 (5)
R_F	.99964 (.5)	.99928 (1)	.99641 (5)
R_G	.99928 (1)	.98570 (20)	.86589 (200)
R_H	.99986 (.2)	.99641 (5)	.99283 (10)
R_J	.99990 (.15)	.99960 (.5)	.99860 (2)
R_K	.99960 (.8)	.99930 (1)	.99640 (10)
R_L	.99942 (.15)	.99928 (1.1)	.99283 (6)
R_M	.99928 (1)	.99784 (20)	.99283 (200)
R_N	.99942 (.15)	.99928 (1.1)	.99283 (6)
R_O	.99928 (1)	.99784 (3)	.99283 (5)
R_P	.99928 (1)	.99856 (2)	.99283 (10)
R_Q	.96464 (50)	.93053 (100)	.74976 (400)
R_R	.99928 (1)	.99784 (3)	.99283 (5)
R_S	.99964 (.5)	.99928 (1)	.99641 (5)
R_T	.99928 (1)	.99784 (3)	.99283 (5)
R_U	.99964 (.5)	.99928 (1)	.99641 (5)
R_{PV}	.88980	.701138	.31482
R_{UG}	.95893	.91756	.70423
R_{PVUG}	.99212	.96958	.78469

( )+, ( )++ & ( )+++ The figures between brackets illustrate respectively the min., average and max. failure rate of each component.



I : Insolation
A : PV Array
B : Inverter
C : Switchgear
D : Circuit Breaker
E : Transformer 5
F : Transformer 6
G : Power Switch
H : Utility Interface
J : Circuit Breaker and Protective Equipment
K : Transformer 2
L : Transformer 3
M : Circuit Breaker
N : Feeder
O : Circuit Breaker
P : Transformer 4
Q : Generator
X : Circuit Breaker
S : Transformer 1
T : Circuit Breaker
U : Transmission Line

Fig.3. System Reliability Block Diagram .



Fi4. The Effect of Insolation Reliability on the Reliability of PVPS - UG Aggregetion.

display the improvement of UG - reliability that is obtained on interconnecting the hypothetical PVPS installed at the egyptian site under study. These results are predictable for similar sites which offers a strong recommendation of constructing such systems at EGYPT from the reliability point of view .

On other hand, the reliability figures of the aggregation has been derived at various levels of PV penetration. Three levels are taken for investigation. They correspond to peak ratings of 5 , 10 and 15 MW. Table (3) tabulates the results for these penetration levels with various component failure rates.

Thus, it can be concluded that the addition of more PV units enhances, but slightly, the PVPS - UG reliability in the order of 0.4%. This is an attractive result which means that in spite of the additional uncertainties obtained on adding more PV systems, the reliability of the aggregation has't been decreased and , have practically constant figure .

Now, what is the position if a forced outage of certain number of parallel strings has been expected ? With the aim of keeping the reliability of aggregation to have the original level, it is substarlal to add an equal number of these string compensating the expected shortage in PV output. Also, one can expect that the addition of more strings may enhance the reliability. This question can be answered by assuming alternative number of strings and estimating the new reliability levels. Table (4) explains the results which have been drawn in fig. 5 . The behavior of the PVPS -UG reliability and its incremental change on increasing the PV parallel strings is depicted. The addition of more than 10 PV - parallel strings has't increase the aggregation reliability level. This is the most economic one required to improve the PVPS - UG reliability. This results in an important conclusion which states that the addition of more parallel strings doesn't affect or improve the basic reliability

V ECONOMIC ANALYSIS

The primary objectives of this section are confined in :

(1) Making an economic comparison on feeding part of the load demand either by the PVPS or by the conventional system. This part is varied and determined by the PVPS ratings. Several cells and power conditioner prices are introduced involving the present and expected figures till 2000's year. The results are summarized in Table (5) which display competitive figures with those of the conventional one even the 1986's prices being taken. With the hopeful prices, the PV energy cost figures are less than that on using the conventional - burning system. The savings in the kWh cost figure on displacing conventional system range between 42% and 94% with C_S = \$ 2/W_P , C_P = \$ 0.2/W and C_S = \$ 0.2/W_P, C_P=\$0.01/W , respectively. Thereby, it is recommended today to start with the integration of PVPS with the egyptian UG because of its appropriateness economically as the time proceeds.

(2) Making a cost/reliability tradeoff analysis. Table (6) tabulates the elements of this analysis. The PVPS reliability can be improved considerably but with a slight increase of the kWh cost figure. For example, this reliability can be increased from 0.7011388 to 0.8409536 i.e. by an amount

Table (3) Reliability of PVPS - UG Aggregation With PVPS Peak Ratings (R_I = 0.9).

λ / PVPS Rating / R	$\lambda_{min.}$			$\lambda_{av.}$			$\lambda_{max.}$		
	5 MW	10 MW	15 MW	5 MW	10 MW	.5 MW	5 MW	10 MW	15 MW
R_A	.99667	.99965	.99999	.81931	.82917	.86530	.51232	.52496	.61024
R_{PV}	.88980	.89246	.891615	.70114	.70958	.82607	.31482	.34455	.37499
R_{UG}	.95893	.95893	.95893	.91756	,91756	.91756	.70423	.70424	.70424
R_{PVUG}	.99212	.99222	.99618	.96958	.97021	.97885	.78469	.78873	.80007

Table (4) Additional PVPS Parallel Strings necessitated to improve PVPS - UG Aggregetion Reliability, (At $\lambda_{av.}$, R_I = 0.9).

No. of Strings / Item	405* (0)	409 (4)**	413 (8)**	415 (10)**	417 (12)**
R_A	.8193138	.9826936	.9999742	.99999987	.999999999
R_{PV}	.7011388	.8409536	.9057416	.905764967	.905764968
R_{PVUG}	.9695793	.9799530	.9810508	.9826521	.98298715

* Base Strings's number

** Additional Strings; 409 - 405 = (4).

Table (5) Economic Results of PVPS and Conventional Fuel - burning system (CFBS).

Taking : Engineering, Installation and Management cost = 0.14 of total first cost. (PVPS)
discount Rate = 0.1 (PVPS & CFBS)
O & M = 0.02 (PVPS), .05 (CFBS) of the Total First Cost needed per year.
C_f = $ .5651/MBTU (CFBS) & 0.0 (PVPS)
k = 0.742 (CFBS), 0.333 (PVPS), $_{CFBS}$ = 0.95,
Total life cycle = 30 years (PVPS & CFBS).
Land area cost = $ .5/m^2 (PVPS & CFBS).[5,6,8] .

System	year	C_S $/$W_p$	C_P $ / W	Energy cost figure $ / kWh		
				5 MW	10 MW	15 MW
PVPS	1986	3.5	.50	.2387	.2387	.2387
	1988	2.0	.20	.1329	.1329	.1329
	1990	1.0	.05	.0645	.0645	.0645
	2000	0.2	.01	.0132	.0132	.0132
CFBS	Capital cost $ 625/kW		-	0.22914	.22914	.22914

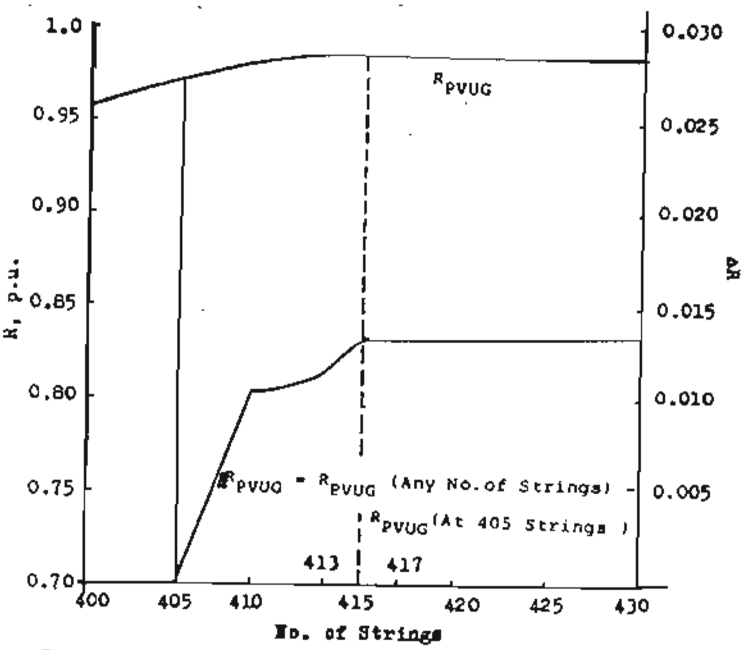


Fig.5. Effect of no. of Strings on the Reliability of PVPS - UG with $\lambda = \lambda_{av}$.

Table (6) Changes of kWh cost Figure with PVPS - UG Reliability For Present and hopeful cells and Power conditioner Prices. (At 5 MW and λ_{av}).

year	C_s \$ / W_p	C_p \$/W_p	Energy Cost Figure \$ / kWh		
			R_{PV} = .7011388	.8409536	.9057416
			R_{PVUG} = .9695793	.9799530	.9810508
1986	3.5	.50	.2387	.2408	.2430
1988	2.0	.20	.1329	.1342	.1354
1990	1.0	.05	.0645	.0652	.0660
2000	.20	.01	.0132	.0133	.0135

of 0.1398148 p.u. or 13.98% by increasing the kWh cost with an amount of \$ 0.0021. While the PVPS - UG aggregation reliability has been enhanced by 1% with the same cost increase. This conclusion represents another phase of many advantages of the PVPS. Of course any improvement achieved for PVPS reliability results in respective increase in the PVPS - UG aggregation reliability .

Direct mathematical relationships are developed giving the PV energy cost figure for any imposed PVPS reliability. The Coefficients of these models depend naturally on the cells and power conditioner prices. Therefore, the following equations are deduced having the form of :

(a) With C_S = \$ 3.5/W_P and C_P = \$ 0.5/w

$$C_{PV} = 0.01041\ R^2_{PV} - 0.00103\ R_{PV} + 0.23431$$

(b) For C_S = \$ 2 / W_P and C_P = \$ 0.2/W

$$C_{PV} = 0.0065\ R_{PV} - 0.0005\ R_{PV} + 0.1305$$

(c) If C_S = \$ 0.2 /W and C_P = \$ 0.01/W

$$C_{PV} = 0.0006\ R^2_{PV} - 0.00005\ R_{PV} + 0.01296$$

CONCLUSION

Out of this paper, the following conclusions can be drawn regarding the issues of interconnecting PVPS with a utility grid:

(1) With an egyptian site located at the North of EGYPT, high hourly capacity factors of PVPS are attained either as a ratio of its rating or referred to the corresponding hourly UG Load demand. It reaches, in this case, ratio of 53.425 % on the annual base. This figure is superior than that obtained for a PVPS of a rating of 1 MW installed at California having a ratio of 24.9% only [7].

(2) A linear behavior, of a positive slope is noticeable, expressing the change of the PV-UG aggregation reliability and the insolation probability.

(3) The PVPS-UG aggregation has a higher reliability level than that of the UG alone by a discriminative difference in the range of 4-8% dependent on the failure rates of the components constituting the whole aggregation as demonstrated in Table(2)

(4) The addition of more PV units enhances, but slightly, the PVPS-UG aggregation reliability in the order of 0.4%. Thus, in spite of the increasing the uncertainities on adding more PVPS the aggregation reliability has't been decreased and have, practically, constant figure.

(5) For the problem solved throughout this paper, the addition of more than 10 PV-parallel strings has't increase the aggregation reliability. Thus, this number represents the most economic one required to improve the PVPS-UG reliability.

(6) The PV energy cost figure has been estimated for some alternatives of cells and power conditioner prices. They are compared with that of the energy produced by the conventional systems which demonstrate the superiority of PVPS over the other in 1988's year .

GLOSSARY OF TERMS AND UNITS

PV	Photovoltaic
PVPS	Photovoltaic Power System

PVPS-UG	Photovoltaic power system - Utility Grid Aggregation.
CFBS	Conventional Fuel - Burning Systems
R	Reliability level, p.u.
λ	Failure Rate, $/10^6$ hrs.
λmin	Minimum Failure Rate, $/10^6$ hrs.
$\lambda av.$	Average Failure Rate, $/10^6$ hrs.
λmax	Maximum Failure Rate, $/10^6$ hrs.
ηc	Solar Cells efficiency, %
ηm	Module efficiency, %
NOCT	Normal Operating Cell Temperature, °C.
C_S	Solar cells Array Price. $ $/W_p$
C_P	Inverter Price. $ $/W_p$.
C_{PV}	Photovoltaic Energy Cost figure, $ /kwh.

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