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Determination of Loss of Load Probability for Stand-Alone Photovoltaic Power System

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Abstract: In this paper, the loss of load probability for stand-alone photovoltaic (SAPV) power system was determined for an ICT Center with total daily energy demand of 346480 Wh/day. However, the different electrical appliances are classified into four (4) different load priority levels depending on the acceptable loss of load probability of the appliance in the data center. The ICT Center has annual averaged daily solar radiation of 4.7kWh/m^2.day and minimum (worst case) daily solar radiation of 0.574 kWh/m^2 day which occurred on 17th of June. The SAPV system is expected to satisfy with zero loss of load probability the critical load (server, switches, routers, Vsat) estimated at about 81210 Wh/day. In this wise, dynamic load shading approach can be employed to switch off certain loads based on their priority level and available solar irradiation. A cubic regression model is derived to enable the load scheduler to determine the possible LLOP for any give load level. The approach presented in this paper provides the relevant mechanism to determine at what point the dynamic load shading unit can turn off or turn on appliances in any load priority level in response to the temporal variation in solar radiation at the Data Center.

Keywords: Stand-Alone Photovoltaic, Loss of Load, Cubic Regression Model, Loss of Load Probability, Prioritized Load

1. Introduction

The use of photovoltaic (PV) cells to produce energy has increased in the last few decades and keeps growing as their manufacturing cost decreases and as the world becomes more concerned about energy use. Solar energy is abundant in nature especially in most developing countries many of which receives more than 2000 sunshine hours per year [1]. Solar energy is the most abundant permanent energy resource on earth [2, 3]. Solar stand-alone systems use photovoltaic modules to supply total electric needs [4, 5, 6, 7]. When compared to the conventional power generating technologies, the PV power system has a good number of advantages. First, PV power is environmentally friendly and non-pollutant. PV power system in most cases do not have any moving parts as such the PV cells and power system require little upkeep. These low-maintenance, cost-effective PV systems are ideal for supplying power to remote sites that are far from utility power lines. In addition, PV modules have long useful operating lives. PV system is also extremely reliable and quiet in operation. The modular nature of PV system makes is easy to construct PV power system to virtually any size based on energy requirements. Wind speed and sun intensity varies with time and location as such the amount of energy produced by solar power system and wind turbines are not constant but also exhibit spatiotemporal variations [8-10]. Carful sizing is therefore required to ensure that the energy generated by solar or wind power systems can satisfy the load demand in most cases. In this respect, storage batteries or other energy storage systems may be incorporated into the power system to store excess energy when the during high wind speed or high intensity solar radiation. The stored energy can be used to provide energy during the low energy production periods.

Furthermore, the power output from the photovoltaic cell depends on the light intensity, the cell temperature, the panel's orientation, and its size, among others [11, 12, 13, 14]. The light intensity affects primarily the amount of current produced, making it proportional, while the cell temperature controls the voltage produced. As the cell temperature increases, the current produced remains the same but the voltage is reduced, reducing the output power. All of these factors need been taken in consideration to accurately predict the energy production.

In most existing studies of solar powered systems, all the loads are considered with the same priority. No load shading is included in the occasions where the PV power output is not sufficient to carry the entire load. In that case, the entire load will lose power supply in the days where there is insufficient solar radiation for the entire load. Such situation is referred to as loss of load. The percentage of time the required power is not supplied to the total time in a year is referred to as loss of load probability (LOLP) [15, 16, 17, 18]. In this paper, prioritized load is considered. In this case, as the power generated by the PV drops due to changes in available solar radiation, some load will be switched off based on their priority level. In the worst scenario only the highest loads are left. In this paper, the LOLP for a prioritized load system is studied. The focus is the determination of the loss of load probability for each load level where load shading is employed. In this case, it is desired that the effective LOLP for each load level is satisfied.

2. Methodology

2.1. The Load Demand Profile

An ICT Center in Owerri is used for the study. The electric facilities in the ICT Center can be divided into the following categories: (i) Lighting (ii) Server and computers system (iii) Cooling (iv) Fans (inductive). Among these electrical loads are, the demand for electrical appliances, air conditionals, fans and some lighting points apply only in the day time; security lighting points are also used during the night time. The server is however in use for 24 hours of the day. The Load Demand Profile for the ICT Center is given in Table 1.

The critical loads like servers, VSAT, switches and routers have to be met 24 hour in a day. Also, solar radiation intensity varies over the day, hence there is variation in the energy output of the photovoltaic system. Consequently, the daily load has to be prioritized to meet critical load requirement in the worst scenario. The load is classified into three priority levels where the hourly load demand in a day for each priority level is given as follows;

- Hourly load demand at full load: 346480 Wh
- Hourly load demand for priority 1 load: 81210 Wh, about 23.45% of full load
- Hourly load demand for priority 2 load: 172144 Wh, about 49.68% of full load
- Hourly load demand for priority 3 load: 259600 Wh, about 74.92% of full load

Table 1. *Load estimation and daily demand of the ICT CENTER.*

ICT Center Description	Quantity	Rated Power (W)	Total Power Rated (W)	Hours/day	KWh/day
Lighting	40	30	1200	8.8	10.560
Fan	18	100	1800	8	14.400
Computer	100	200	20000	8	160.000
Servers	3	1000	3000	24	72.000
Air conditioner	9	1000	9000	8	72.000
Printer	1	240	240	8	1.920
Cisco Routers	1	50	50	24	1.200
Cisco Switches	1	50	50	24	1.200
VSAT Modem	1	50	50	24	1.200
Other	15	100	1500	8	12.000
TOTAL			36890		346.480

2.2. Solar Radiation Data for the ICT Center in Orji

Usually, the average daily solar radiation on horizontal plane in kWh/m^2/day is available at NASA website. However, the solar panels are usually tilted at optimal angle, β_{opt}. The optimal tilt angle (β_{opt}) in degree is given as:

$$\beta_{opt} = 3.7 + 0.69\ \Phi \tag{1}$$

Where Φ in degree is the latitude of the site. The transposition factor (TF) is given as [17]:

$$\frac{1}{TF} = \frac{G(\beta)}{G(\beta_{opt})} = 1 + 0.00046(\beta - \beta_{opt}) - 0.000119(\beta - \beta_{opt})^2 \tag{2}$$

Where β_{opt} is the optimal tilt angle in degree and β is any tilt angle in degree. On the horizontal plane $\beta = 0$ and $G(0)$ is the average daily solar radiation on horizontal plane in kWh/m^2/day. So, $G(\beta_{opt})$ which is the solar radiation at the optimal tilt angle of β_{opt} is given as;

$$G(\beta_{opt}) = (G(\beta))TF = \frac{G(\beta)}{1+0.00046(\beta-\beta_{opt})-0.000119(\beta-\beta_{opt})^2} \tag{3}$$

2.3. Loss of Load Probability (LLOP)

The reliability of the SAPV system is expressed in terms of the loss of load probability (LOLP). LOLP is defined as the power failure time, Tf divided by the estimated period of time T, i.e. LOLP = Tf /T. In designing the SAPV systems, it is important to know the power supply availability. 100% availability of a power supply means that the power supply is able to provide power for the entire load demand in a year without any interruptions. On the other hand, 0.0% availability of a power supply means that the power supply is not able to provide power for the entire load demand in a year at all.

One of the major objectives of this paper is to find a sizing combination that minimizes the cost while maintaining desired values of reliability of the SAPV system. Accordingly, in this paper, the LOLP values for prioritised load is determined from the daily load demand and daily power output of the SAPVsystem. The daily PV energy output for the whole year is calculated based on daily output according to the following equation [12].

$$E_{pv} = A_{pv} \, X \, G_{av} \, X \quad_{pv} \, X \quad_{bo} \tag{4}$$

$$_{bo} = \quad_{wire} \, X \quad_{inv} \tag{5}$$

where, APV is the PV-array area,

G_{av} = ESUN is the solar radiation on the PV-array,

$_{pv}$ = PV Efficiency (18.54%) or 18.54%

$_{bo}$ = Efficiency of balance of system

$_{wire}$ = wire Efficiency (95% = 0.95)

$_{inv}$ = inverter Efficiency (90% = 0.9)

The energy difference Ed is also expressed as [23]

$$E_{d(i)} = \sum_{i=1}^{i=n} \left(E_{pv(i)} - E_{L(i)} \right) \tag{6}$$

$$E_{d(i)} = \sum_{i=1}^{i=n} \left(\left[A_{pv} \, X \, G_{av(i)} \, X \quad_{pv} \, X \quad_{bo} \right] - E_{L(i)} \right) \tag{7}$$

Where, n is the number of days in a year and $E_{L(i)}$ is the load energy demand in day i (or at hour i if it is expressed as hourly load demand). Suppose the value of $E_{d(i)}$ is positive, it is affirmed that the Energy Excess (EE) state is reached and the excess energy is stored in batteries. In case Energy Deficit (ED) state is reached, for negative value of $E_{d(i)}$, it is considered that the stored energy in the batteries are utilized to provide power to the load [23].

$$\text{Energy Excess } (EE_{(i)}) = E_{d(i)} \text{ for } E_{pv(i)} \geq E_{L(i)} \tag{8}$$

$$\text{Energy Deficit } (ED_{(i)}) = E_{d(i)} \text{ for } E_{pv(i)} < E_{L(i)} \tag{9}$$

LOLP is the ratio of annual energy deficits to annual load demand, and it is given by [23]

$$LLP = \frac{\sum_{i=1}^{366} Energy\ deficit,i}{\sum_{j=1}^{366} Energy\ demand,j} \tag{10}$$

or

$$LLP = \frac{Power\ failure\ time}{Total\ period\ of\ time} \, x \, 100 \tag{11}$$

The selection of the components of the SAPV system is such that the SAPV power output at the worst scenario of solar radiation (that is, minimum($G_{av(i)}$ for the whole year) will be greater or equal to the load demand required by the priority one load. In this paper, the size of PV module that can meet the stated load demand is determined by the PV area, A_{pv} as follows;

$$\left(A_{pv} \, X \quad_{pv} \, X \quad_{bo} \right) \left(minimum(G_{av(i)}) \right) \geq E_{Lcritical(i)} \tag{12}$$

Where $E_{Lcritical(i)}$ = 81210 Wh and minimum($G_{av(i)}$) is the worst day solar radiation in a year

Hence,

$$A_{pv} \geq \frac{E_{Lcritical(i)}}{\left(\quad_{pv} \, X \quad_{bo} \right) \left(minimum(G_{av(i)}) \right)} \tag{13}$$

3. Results and Discussion

The average daily solar radiation on horizontal plane in kWh/m^2/day (Table 2) for the Data Center location is obtained from NASA website.

Table 2. *Monthly Averaged Daily Global Solar Irradiation on Horizontal Plane (kwh/m^2. mth).*

Monthly	Average Daily Solar Radiation (kWh/m²/day
Jan	5.53
Feb	5.59
Mar	5.32
Apr	5.09
May	4.72
Jun	4.31
Jul	3.85
Aug	3.77
Sep	3.94
Oct	4.27
Nov	4.84
Dec	5.29
Annual Average	4.70

Table 2 shows that there is an annual average global solar irradiation per day on horizontal plane of 4.7 kWh/m^2. day. This is equivalent to PSH of 4.7 hours per day, where

$$PSH_{month(i)} = \frac{\text{Monthly or Yearly Averaged Daily Global Solar Irradiation in } kW/m^2}{1 \, kW/m^2} \tag{14}$$

Example, for the month of January, PSH $= \frac{5.53 \, kW/m^2}{1 \, kW/m^2} =$ 5.53 Hours. Similarly, the annual averaged PSH is given as PSH $= \frac{4.7 \, kW/m^2}{1 \, kW/m^2} = 4.7$ Hours. The solar radiation on the optimally tilted plane at the Data Center with latitude of (Φ) = 5.03°, is given as $G(\beta_{opt})$ where:

$$\beta_{opt} = 3.7 + 0.69 \, x \, 5.03 = 7.1^{O}$$

$$\frac{1}{TF} = \frac{G(\beta)}{G(\beta_{opt})}$$

$$= 1 + 0.00046(\beta - \beta_{opt}) - 0.000119(\beta - \beta_{opt})^2$$

On horizontal plane $\beta = 0°$, and $G(0) = 4.7\ hours$, so

$$\frac{1}{TF} = 1 + 0.00046(-7.1) - 0.000119(-7.1)^2 = 0.99073521$$

$$TF = 1.009 \approx 1.01$$

$$G(\beta_{opt}) = TF(G(\beta)) = TF(G(0)) = 1.01(4.7) = 4.7423$$

From the solar radiation data in Table 1, PVSyst is used to generate the daily solar radiation on the optimally tilted plane. The result is plotted in figure 1 for the 365 days in a year. The minimum daily solar radiation of 0.574 kWh/ m^2 . day occurred on 17th of June (the 167th day in the year, figure 1).

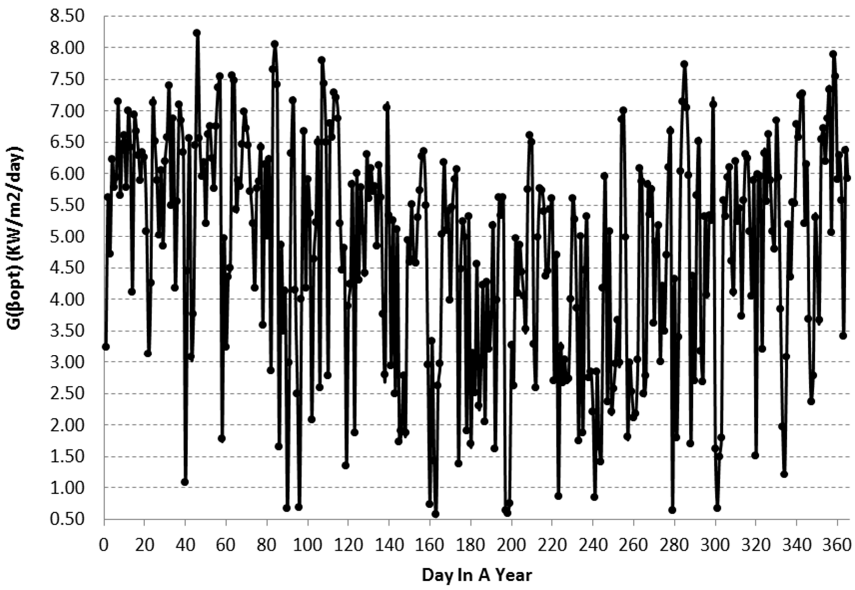

Figure 1. *The Daily Solar radiation On The Optimally tilted.*

Plane For The Data Center PV Module

For example, by using the worst case (17th of June) solar radiation of 0.574 kWh/m^2/day, that is, $\text{minimum}(G_{av(i)}) = 0.574\ kWh/m^2$ and that $\square_{pv} = 0.1854$, $\square_{wire} = 0.95$; $\square_{inv} = 0.9$ so, $\square_{bo} = \square_{wire}(\square_{inv}) = 0.95(0.9) = 0.855$. Also, $E_{Lcritical(i)} = 81210$ Wh $= 81.210$ kWh.

$$A_{pv} \geq \frac{81.210\ \text{kWh}}{0.1854(0.855)(0.574)} = 892.5\ m^2$$

So, the minimum PV area for the SAPV is $892.5\ m^2 \approx 893\ m^2$. However, is batteries that can provide more than one day of autonomy is used, the PV area can be less than the specified minimum.

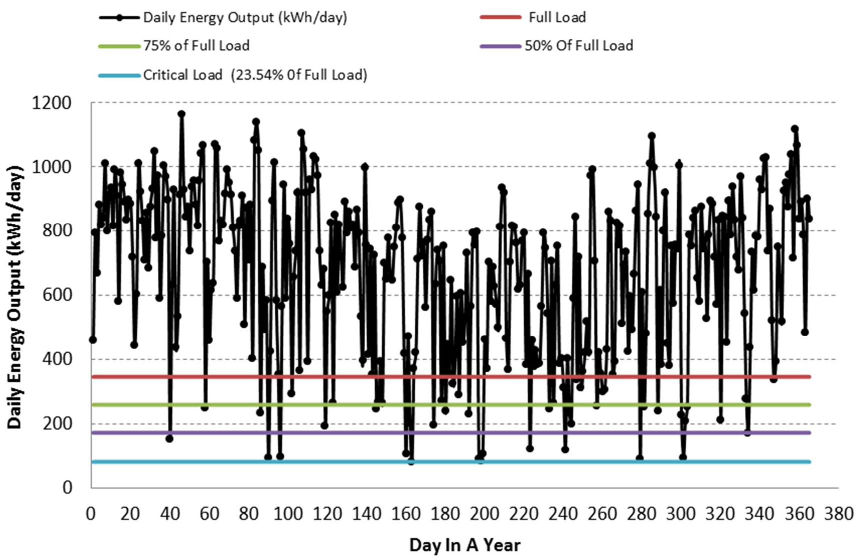

Figure 2. *The Daily Energy Output Of The SAPV.*

From figure 2, it can be seen that in many days in a year, the load demand is not satisfied for the 100%, 75% and 50% full load demand. However, the critical load which is 23.54% of full load is satisfied in all the ays in the year. Table 3 shows the loss of load probability, duration of loss of load in hours and duration of loss of load in days for the various load levels. Again, the 100% full load has 4.71% LLOP and 17.19 days of loss of load duration; the 75% full load has 2.647% LLOP and 9.66 days of loss of load duration and the 25% full load has 1.33% LLOP and 4.87 days of loss of load duration. However, the critical load which is 23.54% of full load 0% LLOP and 0 loss of load duration. Figure 3 show the graph of LLOP against the load expressed in percentage of full load, P. From the graph, the cubic polynomial model that relates P to LLOP is given as;

$$LLOP\ (\%) = 0.0000073P3 - 0.0010337P2 + 0.0954820P - 1.764753745 \quad (15)$$

Where P is the percentage of full load. Hence, load shading controller can use this cubic model to determine the LLOP for various load levels expressed as percentage of full load.

Table 3. *Loss of Load Probability, Duration of Loss Of Load in hours and Loss Of Load in days for the various load levels.*

LOAD kWh	Percentage of Full Load	LLOP%	Duration of Loss Of Load in hours	Duration of Loss Of Load in days
346.4783	100	4.710114	412.61	17.19
259.8587	75	2.646513	231.83	9.66
173.2391	50	1.333504	116.81	4.87
81.24915	23.45	0	0	0.00

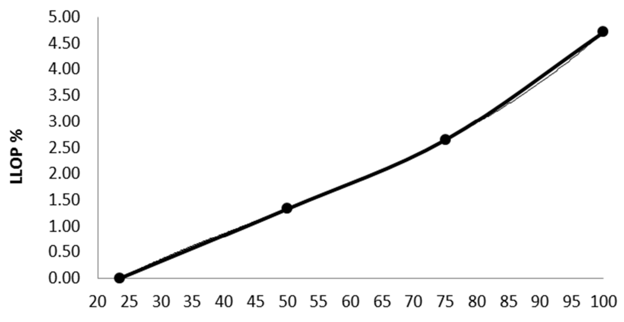

Figure 3. *Graph of LLOP Against The Load Demand Expressed In Percentage, P Of Full Load.*

4. Conclusion

In this paper, the loss of load probability for stand-alone photovoltaic (SAPV) system is determined for an ICT Center with energy demand that is classified into 4 different load priority levels. The SAPV is expected to employ dynamic load shading approach which eliminates certain loads based on their priority level and available solar irradiation. A cubic regression model for determining the loss of load probability for any give load level is derived to assist the scheduler in determining when to turn off or turn on the electrical appliance belonging to any load priority level.

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