Nigerian Journal of Technology (NIJOTECH)
Vol. 39, No. 2, April 2020, pp. **572 - 578**

Print ISSN: 0331-8443, Electronic ISSN: 2467-8821
www.nijotech.com
http://dx.doi.org/10.4314/njt.v39i1.28

DETERMINATION OF THE FAILURE MECHANISM OF STAND ALONE SOLAR STREET LIGHT

E. Anoliefo [1,]*, O. U. Oparaku[2], S. Egoigwe[3] and S. Olisa[4]
[1,2,3,4,] DEPARTMENT OF ELECTRONICS ENGINEERING, UNIVERSITY OF NIGERIA, NSUKKA, ENUGU STATE, NIGERIA
E-mail addresses: [1] *edward.anoliefo@unn.edu.ng,* [2] *ogbonna.oparaku@unn.edu.ng,*
[3] *sochima.egoigwe@unn.edu.ng,* [4] *samuel.olisa@unn.edu.ng*

ABSTRACT
Despite the acclaimed long-term benefits of solar PV systems, most stand-alone solar projects in Nigeria seem to fail within a short duration. In this work, an analysis is carried out to examine the factors that lead to such poor performance of solar projects in Nigeria. A case study of standalone solar street lights (SASSL) in Nsukka geographical region in Nigeria was explored. The field work was carried out from Dec 2016 - January 2018. Data from field indicate that in most cases, premature battery failure due to undercharging was responsible for the collapse of these stand-alone solar systems. Given that the PV module is the sole charge generator in SASSL, the energy yield of the PV modules used in the SASSLs were further investigated. Controlled experiments were carried out to determine the impact of specific environmental and installations conditions on the yield of the PV modules. The results of the experiments led to the development of a model. The weather and installation specific data were then inserted into the model and were used to determine the likely reasons for the premature failure of SASSLs. The results indicated that the within the period under review, the PV modules were capable of providing adequate energy to the battery for only 25% of the time. For another 25% of the time the energy provided were marginal while for 50% of the time the energy provided were grossly inadequate.

Keywords: *Failure, Battery, Dust, Solar, mechanism, Street light, Irradiance, PV Module.*

1. INTRODUCTION

Solar street lights, in Nigeria, seem to have very high failure rate in spite of the huge investment and expected longevity associated with them[1-2]. Thus, a question of interest to manufacturers, marketers, and users of solar PV in Nigeria concerns the primary cause of failure of the stand-alone solar systems. In an attempt to solve this problem, a case study of 125 SASSLs in Nsukka (6.8429° N, 7.3733° E) was undertaken. The field work was carried out from Dec 2016-Jan 2018. Results obtained indicate that in most cases, battery failure was responsible for the collapse of the system. Earlier works indicate that under-charging, over-charging and over-discharging are common causes of premature failure of batteries [3-5] . The field report of the present work indicate that the prevalent failure mode is associated with undercharging. Therefore, a major aim of this work is to determine whether the PV modules in the SASSLs under review were able to provide optimal charging current to the batteries. Principally, the power yield of PV module is a function of its capacity, available insolation and other environmental factors [6-8]. Accordingly, the insolation, relative humidity, temperature, dust and wind speed data of Nsukka were collated. These data were collected from the Davis weather station installed at National Centre for Energy Research and Development (NCERD), Nsukka. A model that related energy yield of PV module to available insolation, given losses due to temperature, soiling and conversion inefficiency of solar charge controllers was developed and validated. The historical data from field were then used to determine whether the PV modules in the SASSLs under review could have effectively recharged the batteries during the period under

* Corresponding author, tel: +234 806 363 0992

review. The results obtained using the model indicated that the within the period under review, the PV modules were capable of providing adequate energy to the battery for only 25% of the time. For another 25% of the time the energy provided were critical while for 50% of the time the energy provided were grossly inadequate. Given the present scenario, it is plausible to conclude that undercharging of batteries used in the installation adequately explained the failure mechanism of SASSLs in Nsukka.

2. MATERIALS AND METHODS

2.1. Description of SASSL under review

In this research, 125 Stand Alone Solar Street Lights(SASSL) installed in Nsukka (6.8429° N, 7.3733° E) were studied. Each SASSL consisted of two 80W monocrystalline PV modules mounted on top of 5m metal pole. The PV modules were used to charge 100Ah battery. The battery on each stand was enclosed in a metal container located immediately after the modules. Also found inside the container was a 20A PWM charge controller. Finally the battery on each stand was used to power a 36 watts LED bulb. Regarding the control, investigation revealed that the bulbs were programmed to come on at the onset of darkness and go off when the battery voltage goes below 10.5V. The picture of a typical stand is shown in figure 1.

2.2. Description of Test Procedure

The field work involved testing each stand to ascertain the component that failed. The PV modules were tested using I-V tracer and fluke 117 multimeter. The batteries were tested using Schumacher BT-100 100 amp Battery Load Tester. The charge controllers were tested by monitoring their ability to switch off load when the battery is below 10.5V and switch off charging when the voltage is above 14.5V. The bulbs were tested by connecting directly to a test battery. The presence of other issues like shading, soiling and improper orientation of PV modules were done by physical examination. Summary of issues discovered in the field is given in Table 1

2.3. Development of Model For Estimating PV module to Battery Power Transfer

The investigation into the possible causes of the failure of SASSL under review was undertaken after the failure of the system. Nevertheless, initial analysis of field data pointed to battery failure as the commonest cause of the system collapse. Since over charging , over discharging or under charging are the commonest causes of premature battery failure, it was necessary to determine whether the PV modules, which were the sole source of recharge for the batteries, could have over charged or undercharged the batteries.

Figure 1: Typical SASSL under review

Table 1: Summary Of Result Obtained From Field Examination Of Installed SASSLs In Nsukka

Issue	Occurrence	Possible Cause	Possible Effect
Soiling of PV modules	125	Aerosols, birds' droppings	Reduction in yield of PV module and damage to battery
Permanent shading of PV modules	13	Trees, structures	Reduction in yield of PV module and possible damage to battery
Improper orientation of PV module	96	Installation defect	Reduction in yield of PV module and possible damage to battery
Battery failure	108	Frequent overcharging, discharging or undercharging	Failure of the light to come one at night
Faulty/Burnt charge controller	15	Loose contact, lightening, or inferior material	Damage to battery
Failure of PV module	0	Physical damage, degradation	Damage to battery
Failure of bulb	0	Degradation, physical damage	Failure to come on

To do this, an effort was made to recreate the conditions under which the SASSLs operated. This was done by reference to some historical data that are known to impact on the yield of PV modules. The historical data of interest are irradiance, relative humidity, ambient temperature and wind speed within the period under review(Jan 2015-Dec 2016). The data was retrieved from Davis weather station located within the National Centre For Energy Research and Development , University of Nigeria Nsukka.

The monthly average solar radiation data was subsequently used to estimate the maximum power the PV module could have generated at the point of interest. This was done using equation 1.

$$P_m = \gamma P_{stc} \quad (1)$$

Where:

$\boldsymbol{P_m}$= estimated maximum possible power of the PV module at the given irradiance

$\boldsymbol{P_{stc}}$= The rated power of the PV module.

$\boldsymbol{\gamma = \frac{G}{G_{stc}}}$

G= The given global irradiance

$\mathbf{G_{stc}}$= The irradiance at the test condition.

Following the non linear dependence of the yield of PV module on temperature, correlations are usually used to estimate the cell operating temperature, given the ambient temperature and other environmental variables. For the purposes of this work, recourse was made to a correlation validated for Nsukka and found in [6]. The correlation is given as\

$$\boldsymbol{T_c = 0.0355H_a + 0.705RH + 1.807WS - 4.813} \quad (2)$$

Where:

Hg= insolation

Ta = ambient temperature.

RH= Relative humidity

WS= Wind speed

By finding the cell temperature at the point of interest, the departure from STC temperature is derived using the expression

$$\Delta T = T_c - T_{STC} \quad (3)$$

The temperature corrected estimated power becomes

$$P_{\Delta T} = P_m - (P_m K_p \Delta T) \quad (4)$$

Where:$\boldsymbol{K_p}$=temperature coefficient of power

For some reasons the battery in a SASSL may not be able to absorb the total possible yield of a PV module. This can be represented as source-load coefficient. It represents the percentage of the maximum possible generated power that can be consumed by the load(in this case the battery). This can be expressed as

$$\lambda = \frac{P_u}{P_g} \qquad (5)$$

Where:

P_u **=** Power that can actually be used by the load.

P_g **=** Power actually generated by the source.

In the particular case under study, the absolute maximum rating of the power generator as given in the nameplate of PV module found at the field is as follows:

Vmp =21.4V

Imp =3.74A

Voc = 25.5V

Isc= 4.23A

Assuming the following:

1. The battery has charge absorption coefficient of 1
2. The maximum current the PV module can produce is the short circuit current.
3. The maximum safe voltage the charge controller is allowed to produce is 14.5V

Hence for typical SASSL $\lambda = \frac{14.5*4.23}{21.4*3.74} =$ 0.76

The field study of the SASSL under review showed that the PV modules were not cleaned. It is , therefore necessary, to account for the losses due to soiling of the PV modules. To do this, two assumptions were made

1. Rain totally cleaned the PV module during the rainy season (march-October)
2. The rate and type of aerosol deposit on the PV modules are constant.

This led to the development of the concept of specific coefficient of dust . Specific coefficient of dust is a measure of the fidelity of the maximum power of a PV module after one month of exposure to dust in a given area. To determine the specific dust coefficient of Nsukka area, two PV modules mounted on 5m pole were exposed to dust between November 2017 and March 2018. One PV module was never cleaned while the second one was cleaned just before the short circuit current and open circuit voltages were read out. Following data from field, dust coefficient of short circuit current fitted to an exponential equation of the form:

$$\delta = exp^{-xn} \qquad (6)$$

Where

δ = the dust coefficient after n number of months without rain (Which can vary between 0 and 1)

x = rate of degradation(which can vary between 0 and 1).

n = the number of months since last rain.

The specific coefficient of dust of Nsukka was found to be

$$\delta_s = exp^{-.24n} \qquad (7)$$

Therefore, in order to estimate the average power for a given month that actually went into recharging the battery in the SASSL, equation 8 can be used.

$$P_{bat} = \lambda\delta_s P_m - (\lambda\delta_s P_m K_p \Delta T) \qquad (8)$$

It is to be noted that equation 8 assumes proper PV module orientation.

2.4. Validation of Model

To validate the model, two 80W PV modules(A and B) were used to charge a 100Ah battery via a 20A PWM charge controllers over a period of one month(November 1-November30, 2018). During the period of validation, the following precautions were taken.

1. A magnetic compass was used to ensure that the PV modules faced South.
2. The modules were cleaned daily before the commencement of reading.

The experimental set up is shown in Figure 2.

Prior to each recharge, the batteries were discharged to 10.5V using two 25W incandescent bulbs. The charge current and voltage for each module were recorded every 10 second using voltage/current data logger between 8:00hrs and 18:00hrs. The average daily and monthly power and energy were then calculated. To study the effect of temperature, the backside temperature of the modules were measured using DHT 21 temperature-humidity sensor. Module A was cooled using a film of flowing water while module B was not cooled at all. At the end of the experiment, it was clear that the power output of modules A and B were not significantly different. A simple explanation is that increase in temperature lowers the voltage . Meanwhile the rated operating voltage of the PV modules is about 21.4V while the voltage needed for optimal charge of the battery is 14.5V. This necessitated a further review of equation 8 to obtain equation 9.

$$P_{bat} = \lambda \delta_s P_m \quad (9)$$

To get a more explicit expression, the Pm term can be expanded to yield equation 10

$$P_{bat} = \lambda \gamma \delta_s P_{stc} \quad (10)$$

To validate equation 10, and weather data for Nov 2018 were used to predict the power sent into the battery. The graph of the measured and projected data is shown in Figure 3. The regression statistics gives Multiple R as 0.99 and the R square as 0.97 showing a strong correlation.

3. RESULTS AND DISCUSSIONS

The monthly average of daily insolation as measured by Davis weather station , NCERD, UNN as well as the projected energy to the battery are given in Table 2.

Figure 2: Experimental set up for validation

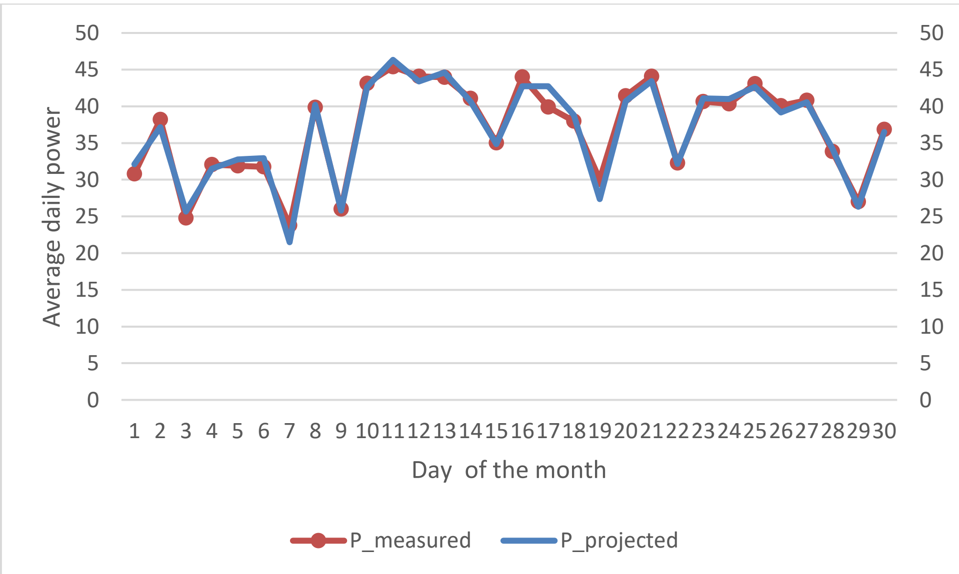

Figure 3: Comparison of measured and projected values for Nov 2018

Analysis of the data on the table shows that the peak daily energy delivered to the 100Ah batteries by 160W. Noteworthy also is the fact that thought the estimated yield from PV modules is about 500Wh, the yearly average for 2015 is 306.07Wh while that of 2016 is 311.20Wh. This is against the constant daily energy demand from the bulb in the SASSL which has been calculated to be 360Wh.

Available data shows that the PV module is able to fully meet the demand for energy from the bulb for only 25% of the time. For another 25% of the time the meeting of the energy demand was critical. In other words, the batteries are left undercharged for over 50% of the time under study. This situation has been demonstrated to be capable of causing premature failure of battery. The anode of a typical lead acid battery is made of Pb while the cathode is PbO_2. The process of charging and discharging is a redox reaction as shown in equation (11).

$$Pb + PbO_2 + 2H_2SO_4 = 2PbSO_4\, 2H_2O \qquad (11)$$

Charging involves forceful introduction of electrons into the battery. This leads to the breakdown of lead sulphate into Pb and PbO_2 with attendant increase in the concentration of H_2S0_4. On the other hand, discharging involves the production of $2PbSO_4$ and water. The above reaction will go on normally when there is full charge and discharge. Unfortunately, where there is continuous undercharge, the unconverted $2PbSO_4$ tend to solidify around the negative electrode. This causes permanent degradation called sulphation. Related to undercharging is another degrading situation called stratification. It involves $2H_2SO_4$ and H_2O. Proper charging ensures that both substances are evenly mixed. Continuous undercharging of battery often leads to an uneven mixture leading to stratification. Stratification leads to reduced capacity by limiting the reaction to specific part of the electrode. Both sulphation and stratification lead to premature battery failure.

4. CONCLUSIONS

In conclusion, it is safe to surmise that the premature failure of the SASSL in Nsukka is traceable to faulty design consequent on the designers' inability to take the environmental variables of Nsukka into consideration at the design stage. The SASSLs designed on assumption that the PV modules would deliver the rated 1600Wh whereas in the average it is able to deliver is 308Wh. This inability to take the environmentally induced derating factor into consideration is the reason for the module's inability to fully recharge the battery as well as the subsequent premature failure.

Table 2: Monthly Average Of Daily Insolation And Calculated Energy To Battery For 2015 And 2016

Month	Ave Irr	Power To Bat(W)	Energy To Bat(Wh)	Month	Ave Irr	Power To Bat(W)	Energy To Bat(Wh)
Jan 2015	234.21	13.86	138.6	Jan 2016	276.83	16.39	163.85
Feb 2015	301.92	14.06	140.	Feb 2016	315.52	14.69	146.91
Mar 2015	337.45	12.36	123.60	Mar 2016	342.86	12.56	125.57
April 2015	375.88	45.71	457.07	April 2016	408.32	49.65	496.52
May 2015	368.8	44.85	448.46	May 2016	377.51	45.91	459.05
June 2015	329.76	40.10	400.99	June 2016	352.5	42.86	428.64
July 2015	283.13	34.43	344.29	July 2016	286.21	34.80	348.03
Aug2015	283.24	34.44	344.42	Aug2016	248.9	30.27	302.66
Sept 2015	292.3	35.54	355.44	Sept 2016	278.84	33.92	339.07
Oct 2015	285.69	34.74	347.40	Oct 2016	320.47	38.97	389.69
Nov 2015	342.78	32.79	327.88	Nov 2016	320.29	30.64	306.37
Dec 2015	324.42	24.41	244.11	Dec 2016	302.97	22.80	227.97

5. REFERENCES

[1] Bolanle Omisore, "Nigeria's Solar Projects Yield Both Failure and Success," National Geographic News, Abuja, 2011.

[2] O.S Ohunakin, M.S Adaramola, O.M Oyewola, & R.O Fagbenle, . 2014, "Solar Energy applications and development in Nigeria: Drivers and barriers," *Renewable and Sustainable Energy Reviews,* vol. 32, pp. 294-301, 2014.

[3] C. Brissaud, G. Reumont , J.P. Smaha , J. Fact, "Structural and morphological study of damage in lead/acid batteries during cycling and floating tests," *Journal of Power Sources,* vol. 64, pp. 11-122, 1997.

[4] K. Brik, F. Ammar, "The fault tree analysis of lead acid batery degradation," *Journal of Electrical Energy,* vol. 4, no. 2, pp. 1-12, 2008.

[5] J.P Dunlop, B.N Farhi , "Recommendations For Maximizing battery life in Photovoltaic systems: A review of lessons learned," in *Proceedings of 2001 Solar Energy: tThe Power to Choose*, Washington DC, 2001.

[6] P. Ugwuoke, C.E. Okeke, "Perfomance of silicon PV modules in Low Latitude Regions as asessment of Polycrystalline as a Function of Temperature," *International Journal of Applied Science and technology,* vol. 2, no. 3, pp. 295-301, 2012.

[7] J.K. Kaldellis, M. Kapsali, "Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements," *Energy,* vol. 36, pp. 5154-5161, 2011.

[8] A. Lay-Ekuakille, P. Vergallo, A. Arnesano, R. Morello, C. De Capua, "Effects of environmental conditions on photovoltaic yield measurement," in *Seventh International Conference on Sensing Technologies*, Italy, 2013.

[9] A.Q. Jakhrani, A.K. Othman, A.R.H. Rigit and S.R. Samo, "Comparison of Solar Photovoltaic Module Temperature Models," *World Applied Sciences Journal ,* vol. 14, pp. 1-8, 2011.

[10] F Wakim,, "Introduction to PV power generation to Kuwait," in *Institute for scientific researchers*, Kuwait, 1981.

[11] Y. Sanusi, , "The Performance of Amorphous Silicon PV System under Harmattan Dust," *The Pacific Journal of Science and Technology,* vol. 3, no. 1, pp. 168-175, 2012.

[12] A.E Salim, "A PV Power Study of sSystem Options and Optimization," in *8th European PV solar Energy Conference*, Florence, 1988.