Determination of Cell Operating Factor and Cell Efficiency of a 5kva Standalone Solar Photovoltaic System

Ebunilo, P. O. B., Izah, L. A.

***Abstract*— The numerous electrical energy challenges in Nigeria has made it necessary to move away from conventional methods of electrical power generation based on fossil fuels and look for a cheap, alternative, renewable source of energy such as solar energy .Solar panel (or panels) which is one of the most vital component of a photovoltaic system are imported from different manufacturers and countries and are being used locally with little or no information of their appraisal and field performance. This study determines the performance of a 5KVA standalone solar photovoltaic system by determining the cell operating factor and cell efficiency of the system. The 5KVA standalone solar photovoltaic system is made up of a 5KVA, 48V inverter; twenty (20) solar panels of 80W, 12V each; eight (8) deep cycle batteries of 150AH, 12V each; a 60A Tristar solar controller; a digital multimeter for measuring the voltage produced by the solar panels and an analog panel meter for measuring the current produced by the solar panels. The system was operated for four months, from 1st of January to 30th of April, 2014 and voltage and current readings taken for all the days from 6.00 Am in the morning to 8.00pm in the evening. From the readings, the cell operating factor and cell efficiency were calculated by using the voltage and current that correspond to the maximum power output. The average cell operating factor or fill factor for the twenty solar panels was found to be 0.49 while the average efficiency was obtained to be 9.05%. These values are however lower than the laboratory or theoretical values**

***Index Terms*—Photovoltaic system, cell operation factor.**

I. INTRODUCTION

Nigeria electricity requirements have grown tremendously and the demand has been running ahead of supply. The electrical energy problems in Nigeria ranges from inefficient and obsolete power generating plants, inadequate gas supply to the generating plants, bad maintenance culture, and sabotage of pipelines. This has led to the extensive substitution of poor public electricity supply with highly polluting self-generated power (Iwayemi, 2008). A significant solution in making electrical energy available to both the urban and rural areas of the country is to shift away from conventional methods of electrical power generation, based on fossil fuels and look for a cheap, alternative, renewable energy sources such as solar energy (Oladeji and Ladodun, 2013). Most parts of Nigeria are endowed with abundance of sunshine throughout the year and the insolation levels range between 3.5kwh/m^2/day to 7.0kwh/m^2/day with an average of 5.25kwh/m^2/day (Sambo, 2008). The insolation level varies within a small range throughout the year and is strong enough to run solar conversion devices such as solar photovoltaic systems and flat plate collectors (Babatunde, et al, 2013). However, for photovoltaic systems, solar modules or panels are needed to convert the radiant solar energy into direct current electricity (DC) which is used to charge the standby deep cycle storage batteries.

There has been influx of various types of solar panels from different countries into Nigeria as a result of the extensive usage of photovoltaic systems in the country. Some countries, as a result of technological advancement has mastered the art of producing solar cells of high quality while others has not. Consequently, the theoretical efficiency and operating factor claimed by some manufacturers may not necessarily be the practical ones because of the inefficiency of manufacturing processes and connection of solar cells into modules. It is therefore important to test the performance of these solar panels when they are in operation by determining the cell operating factor and cell efficiency (Stones, 2014). The principle of performance measurement is that if the cell operating factor and efficiency of the solar panel cannot be measured or assessed then it cannot be managed because there is no objective information to determine its value. Also, if the operating factor and efficiency of the solar panel or panels are not measured, there will be no way to know where to improve their performances. This justifies the need for the determination of cell operating factor and cell efficiency of the 5KVA standalone solar photovoltaic system. The data and information generated in this work will guide in evaluating the performance of similar systems and also help the public to be aware, advised and get value for their money when investing in solar panels or photovoltaic systems.

II. CELLS OPERATING FACTOR AND SOLAR CELLS EFFICIENCY

The cells operating factor, otherwise known as the fill factor (ff), is defined as the ratio of the maximum power output from the solar cell to the product of the Open-Circuit Voltage, V_{OC} and the Short-Circuit Current I_{SC} (Nelson, 2013).

i.e. FF = $\frac{V_{mp}I_{mp}}{V_{OC}I_{SC}} = \frac{P_{\max(output)}}{V_{OC}I_{SC}}$ -- -- -- -- -- -- 1.1

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where V_{mp} = voltage at maximum power output, I_{mp} = current at maximum power output, V_{oc} = open circuit voltage, I_{sc} = short circuit current and $P_{\max(output)}$ = power at maximum power output. Graphically, the FF is a measure of the "squareness" of the solar cell and an is also the area of the largest rectangle which will fit in the IV curve. Because FF is a measure of the "squareness" of the IV curve, a solar cell with a higher voltage has a larger possible FF curve since the "rounded" portion of the IV curve takes up less area. The maximum theoretical ff from a solar cell can be determined by differentiating the power from a solar cell with respect to voltage and finding where this is equal to zero (Preus, 2010).
The solar cell efficiency (η) is the ratio of the electrical power output of a solar cell to the incident solar energy in the form of sunlight. In order words, the energy conversion efficiency (η) of a solar cell is the percentage of the solar energy to which the cell is exposed that is converted into electrical energy (Doe, 1994). This is calculated by dividing a cell's power output in watts at its maximum power point, $P_{\max}$, by the input light or energy, E, in W/m^2 and the surface area of the solar panel, A_p, in m^2.
i.e. the efficiency of a solar panel,

$$\eta = \frac{P_{\max(output)}}{E \times A_p} \qquad \text{-- -- -- -- -- -- -- -- 1.2}$$

Where η = the efficiency of the solar panel, E = Input energy or light from the sun ($1000 w/m^2$), A_p = Total surface area of the solar panel or panels.
By convection, solar cell efficiencies (laboratory or theoretical efficiencies) are measured under standard test conditions (STC) unless stated underwise. STC specifies a temperature of 25^0C and an irradiance of $1000 W/m^2$ with an air mass of 1.5 spectrums. These conditions correspond to a clear day with sunlight incident upon a sun-facing 37^0 tilted surface with the sun at angle of 41.81^0 above the horizon (ASTM International, 2003). This represents solar noon near the spring and autumn equinoxes in the continental United States with surface of the cell aimed directly at the sun. Under these test conditions, a solar cell of 20% efficiency with a $100 cm^2$ ($0.01 m^2$) surface area would produce 2.0W.

III. Materials and Method

In this work, a 5KVA standalone solar photovoltaic system was designed, installed and operated for four months, from January to April, 2014. The 5KVA standalone solar photovoltaic system (appendix 1) is made up of a 5KVA, 48V power inverter; twenty (20) solar panels of 80W, 12V each (appendix 2); eight (8) deep cycles batteries of 150AH, 12V each; a 60A Tristar Solar Controller; a metal stand on which the twenty (20) solar panels are mounted; a digital multimeter for measuring or recording the voltage produced by the solar panels (appendix 3); an analog panel meter for measuring the current produced by the solar panels (appendix 4) and wiring systems. A block diagram of the standalone solar photovoltaic system is shown in Fig. 1.1.

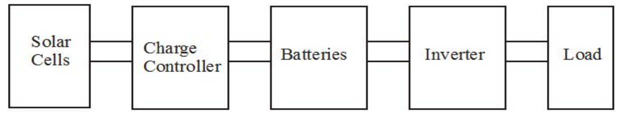

Fig.1.1: Block Diagram Showing the Connection of the Components of the Standalone Solar System

solar panels for standalone solar system are commonly installed on roof tops. However, in this work, the twenty solar panels were installed on a stand constructed with 1½ inches angle iron, 2 inches flat bar and 45mm diameter galvanized pipe. The solar panels were fixed to the top of the metal stand using washers, bolts and nuts. The panels were tilted at an angle of 7^0 facing south in an open space without obstruction of the sun rays (appendix 2). The twenty solar panels were connected together in series of 4 and then linked together in parallel as shown in Fig. 1.2. Table 1.1 is showing the electrical characteristic of each of the solar panels.

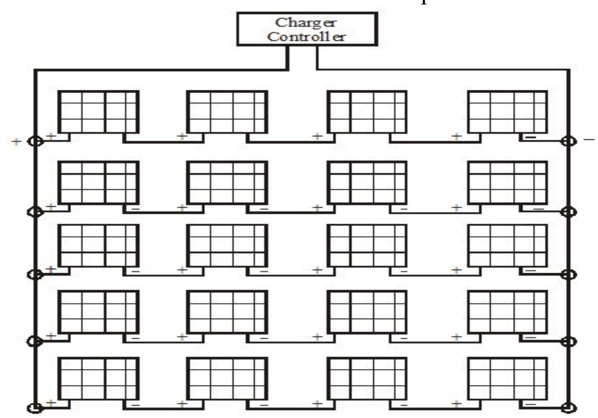

Fig. 1.2: Connection of the 20 Solar Panels

Table 1.1 Electrical characteristics of each of the solar panels [SL solar AP- PM-8o]

Weight= 7.5kg, Dimension (mm) = 935 × 670 × 35
Maximum system voltage suitable for the panel = DC 12V
Maximum series fuse rating = 600VDC
All technical data at standard test condition
AM = 1.5 E = 1000 w/m^2, TC = 25^0C
Maximum power $P_{\max}$ 80w
Open circuit voltage, V_{OC} = 21.6V
Voltage at $P_{\max}$ (V_{mp}), V_{SC} = 17.2V
Short-circuit current, I_{SC} = 5.5A
Current at $P_{\max}$ (Im p), $I_{\max}$ = 4.65A
Normal operating cell temperature = $48 \pm 2^0 C$.

The surface area, Ap of the twenty solar panels was calculated as shown in Fig. 1.3.

Total area of the 20 solar panels, Ap = ($0.648m^2 \times 10$) + ($0.626m^2 \times 10$) = $12.7445m^2$

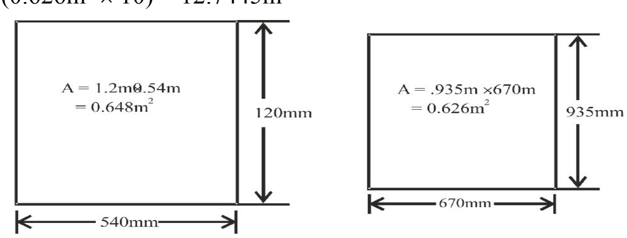

Fig. 1.3: Surface Area of the Solar Panels

The voltage produced by the solar panels was recorded with the digital multimeter everyday from 6.00AM in the morning to 8.00PM in the evening and from 1st of January to 30th of April, 2014. The corresponding current was also recorded with an analog panel meter everyday from 6.00AM in the morning to 8.00PM in the evening and from 1st of January to 30th of April, 2014. From these readings, the voltage at the maximum power output, V_{mp} and the current at the maximum power output, I_{mp} were obtained while the open circuit voltage, V_{OC} and the short circuit current, I_{SC} were calculated from table 1.1 as follows: from table 1.1, the open circuit voltage of each solar panel, V_{OC} = 21.6V while the short circuit voltage of each solar panel, V_{SC}=$17.2V$. Since there are a total of 20 panels, connected in series of 4 and 5 rows altogether,

Total $V_{OC} = 21.6V \times 4 = 86.4V$

Total $V_{SC} = V_{\max} = 17.2V \times 4 = 68..8V$

Also, from table 1.1, the short circuit current of each solar panel, $I_{SC} = 5.5A$ while the current at $P_{\max}$ of the twenty solar panels,

$I_{\max(output)} = 4.65A \times 5 = 23.25A$

Total short circuit current of the twenty solar panels,

$I_{SC(total)} = 5.5A \times 5 = 27.5A$

$P_{\max} = V_{\max} \times I_{\max(total)}$ -- -- -- -- -- 1.3

Where $P_{\max}$ = Maximum power output

$V_{\max} = V_{SC} = total$ short circuit voltage of the twenty solar panels and $I_{\max}$ = total current at $P_{\max}$ of the twenty solar panels.

$\therefore\ P_{\max} = 68.8V \times 23.25A = 1600W$ -- -- -- -- 1.4

The product of open circuit voltage (total V_{OC}) and the total short circuit current $\left(I_{SC(total)}\right)$ i.e. $V_{OC} \times I_{SC(total)}$ is 86.4V × 27.5A = 2376W -- 1.5

The above values i.e. the product of V_{OC} and I_{SC} (2376W); voltage at maximum power output, V_{mp} and current at maximum power output, I_{mp} for each day of the months were substituted into eqn 1.1 to obtain the fill factor or operating factor for that day. Also, the value of 1000W/m^2 representing input energy or light; solar panels area, Ap of 12.7445m^2; voltage at maximum power output, V_{mp} and current at maximum power output, I_{mp} for each day of the months were substituted into eqn 1.2 to obtain the cell efficiency for that day. The average of all the daily cells operating factors for any month is the cells operating factor for the twenty solar panels for that month. Similarly, the average of all the daily cells efficiency for any month gives the cells efficiency of the twenty solar panels for that month.

Results and Discussion

The results for the calculation of the solar cells operating factor (fill factor) and the cells efficiencies for the months of January, 2014 to April, 2014 are shown in tables 1.2 to table 1.5. From the tables, the solar panels operating factor for the month of January, 2014 is 0.43 while the cells efficiency is 8.08%; for the month of February, 2014, the solar panels operating factor is 0.52 while the cells efficiency is 9.4%; for the month of March, 2014, the solar panels operating factor is 0.56 while the cells efficiency is 10.4%; for the month of April, 2014, the solar panels operating factor is 0.45 while the cells efficiency is 8.4%. The cells operating factor or fill factor for the twenty solar panels was found to vary between 0.43 and 0.56 for the four months in Auchi area of Nigeria, with an average of 0.49 while the cells efficiency varies between 8.0% and 10.4% with an average of 9.05%. The above values shows that cells operating factor and cells efficiency are proportional to the power output from the solar panels and varies daily because of the earth's rotation and seasonally because of the change in the sun's declination. The values obtained for the operating factor (between 0.43 and 0.56) are satisfactory because cells operating factors varies between 0.40 to 0.70 depending on the type of semiconductor used to fabricate the cells, the physical state in which the cells are prepared, the process of extraction and purification of the raw materials, the surface preparation, dopants diffusion, anti-reflection coating, electrical contacts, connection of cells into modules, as well as insulation of the area (Sheng, 2007). Also, the values obtained for cells efficiency (between 8.0% and 10.4%) are satisfactory because at present, efficiency of commercial solar cells ranges from 5% to 20%, although in 2014, the highest laboratory efficiency of 44.7% was obtained by using multiple junction cells at high solar energy concentration in the Fraunhofer Institute of Solar Energy Systems (ISE, 2014). It should be noted that some of the factors that affect the efficiency of a solar cell are the type and area of the material (semiconductor) used to fabricate the solar cell; panel orientation; shading; temperature and accumulation of dirt on the PV module (Kotheri, et al, 2011).

Table 1.2: Solar Panels Operating Factors and Efficiencies For the Month of January 2014.

Note: Total Area of the 20 Solar Panels = 12.7445m^2; Input Energy or Light from the sun = 1000 $W/m2$;

E$\times Ac = 1000\ W/m2$ × 12.7445m^2= 12744.5W

$V_{oc} \times I_{sc}$ = 86.4v × 27.5A = 2376W

DAY	VOLTAGE AT MAXIMUM POWER OUTPUT V_{MP}	CURRENT AT MAXIMUM POWER OUTPUT I_{mp}	MAXIMUM POWER OUTPUT $P_{max}=V_{mp} \times I_{mp}$	OPERATING FACTOR $FF=\frac{P\max(output)}{Voc \times Isc}$	EFFICIENCY (%) $\eta=\frac{P\max(output}{Ex \times Ac}$
1	52	18	936	0. 39	7. 34
2	68	15	1020	0. 43	8. 00
3	54	18	972	0. 41	7. 63
4	63	17. 5	1102. 5	0. 46	8. 65
5	59	18	1062	0.45	8. 33
6	55	18	990	0. 42	7. 76
7	56	17. 5	980	0. 41	7. 69
8	54	19	1026	0. 43	8. 05
9	54. 5	17. 5	953. 75	0. 40	7. 48
10	60	18	1080	0. 45	8. 47
11	54	18	972	0. 41	7. 63
12	53	18	954	0. 40	7. 49
13	52	18	972	0. 41	7. 63
14	58	18	936	0. 39	7. 34
15	58	17	986	0. 41	7. 73
16	58	19	1102	0. 46	8. 65
17	59	18	1062	0. 45	8. 33
18	54	19	1102	0. 46	8. 65
19	58	17	918	0. 39	7. 20
20	55	18. 5	1073	0. 45	8. 42
21	58	17	935	0. 40	7. 34
22	53	18	1044	0. 44	8. 19
23	56	18	990	0. 42	7. 77
24	61	18	954	0. 40	7. 49
25	56	19	1064	0. 45	8. 35
26	61	16	976	0. 41	7.66
27	59	18	1062	0. 45	8.33
28	65	17	1105	0. 47	8. 67
29	59	16	944	0. 40	7.41
30	62	18	1116	0. 47	8.76
31	58	18	1044	0. 44	8. 19
Total				13. 23	246. 63
Solar Panels Operating factor ,For January, FF_{3aan} = 0. 43					
Cells Efficiency for January, η_{Jan} = 8. 0%					

Table 1.3: Solar Panels Operating Factors and Efficiencies for the Month of February, 2014.

Note: Total Area of the 20 panels = 12.7445m^2, Input Energy or Light from the sun = 1000W/m2; $E \times A$ =1000 $W/m2$ $\times$ 12.7445m^2 = 12775W, $V_{oc} \times I_{sc}$ = 86.4v$\times$27. 5A=2376W.

DAY	VOLTAGE AT MAXIMUM POWER OUTPUT V_{MP}	CURRENT AT MAXIMUM POWER OUTPUT I_{mp}	MAXIMUM POWER OUTPUT $P_{max}=V_{mp} \times I_{mp}$	OPERATING FACTOR $FF=\frac{P\max(output)}{Voc \times Isc}$	EFFICIENCY (%) $\eta=\frac{P\max(output}{Ex \times Ac}$
1	53	18	954	0. 40	7. 49
2	63	17	1071	0.45	8. 40
3	68. 1	18	1225. 8	0. 52	9. 62
4	68	18	1224	0. 52	9. 60
5	68. 1	19	1293. 9	0. 54	10. 15
6	68. 9	19	1309. 1	0. 55	10. 27
7	62. 8	18. 5	1161. 8	0. 49	9. 11
8	59. 2	18. 5	1095 2	0. 46	8. 59

9	59. 0	18	1062	0. 45	8. 33
10	65	18	1170	0. 49	9. 18
11	69	19	1311	0. 55	10. 29
12	65. 3	20	1306	0. 55	10. 25
13	78. 3	19	1487. 7	0. 63	11. 67
14	78.5	18	1413	0. 59	11. 09
15	68. 4	18	1231. 2	0. 52	9. 66
16	64	18	1152	0. 49	9. 04
17	58. 9	19	1119. 1	0. 47	8. 78
18	73. 2	20	1464	0. 62	11. 49
19	64. 5	18	11161	0 48	9. 11
20	68. 1	19	1293. 9	0. 54	10. 15
21	58. 5	19	111. 5	0. 46	8. 72
22	76. 0	18	1368	0. 58	10. 73
23	66. 1	18	1189. 8	0. 56	9. 34
24	65. 9	20	1318	0. 55	10. 34
25	59. 9	20	1198	0. 50	9. 40
26	75. 6	19	1436. 4	060	11. 27
27	65. 6	19	1246. 4	0. 52	9. 78
28	68. 2	19	1295. 8	0. 55	10. 17
Total				14. 57	261. 95
Solar Panels Operating Factor for February, FF_{febS} = 0. 52					
Cells Efficiency for February, η_{feb} = 9.4%					

Table 1.4: Solar Panels Operating Factors and Efficiencies for Month of March, 2014.

Note: Total Area of the 20 panels = 12.7445m^2, Input Energy or Light from the Sun = 1000 $W/m2;$ $E \times A_C$ = 1000 $W/m2;$ $\times$12.7445m^2 = 12744.5wW; $V_{oc} \times I_{sc}$=86.4v$\times$27. 5A=2376W.

DAY	VOLTAGE AT MAXIMUM POWER OUTPUT V_{mp}	CURRENT AT MAXIMUM POWER OUTPUT I_{mp}	MAXIMUM POWER OUTPUT $P_{max} = V_{mp} \times I_{mp}$	OPERATING FACTOR FF= $\frac{P\max(output)}{Voc \times Isc}$	EFFICIENCY (%) $\eta = \frac{P\max(output)}{E \times Ac}$
1	68. 5	18	1233	0. 51	9. 67
2	68. 9	18	1240. 2	0. 52	9. 63
3	65. 5	18	1179	0. 50	9. 25
4	68. 9	18	1240. 2	0. 52	9. 63
5	65. 6	18	1180. 8	0. 50	9. 27
6	68. 6	20	1372	0. 58	10. 76
7	76. 4	18	1375. 2	0. 58	10. 79
8	75. 3	18	1355. 4	0. 57	10. 64
9	69. 5	19	1320. 5	0. 56	10. 36
10	68. 3	20	1366	0. 57	10. 72
11	74. 6	18	1342. 8	0 57	10. 54
12	7. 5	19	1425	0. 60	11. 18
13	70. 2	18	1263. 6	0. 53	9. 91
14	71. 4	18	1288. 2	0. 54	10. 08
15	72. 2	19	1371. 8	0. 58	10. 76
16	68. 9	20	1378	0. 60	10. 21
17	73. 3	20	1466	0. 62	11. 50
18	72. 8	19	1383. 2	0. 58	10. 85
19	78. 3	20	1566	0. 66	12. 29
20	79. 9	20	1598	0. 67	12. 54
21	75. 1	20	1502	0. 63	11. 79
22	79. 9	19	1518. 8	0. 64	11. 91
23	60	20	1200	0. 51	9. 41

24	52. 7	19	1001.3	0. 42	7. 86
25	70. 8	20	1416	0. 60	11. 11
26	72. 5	20	1450	0. 61	11. 38
27	59. 2	16	947. 2	0. 40	7. 43
28	64. 9	19	1233. 1	0. 52	9. 68
29	72. 9	20	1458	0. 61	11. 44
30	60	19	1140	0. 48	8. 95
31	79	14	1106	0. 47	8. 68
Total				17. 25	320. 82

Solar Panels Operating Factor for March 2014, FF_{march}= 0. 56

Cell Efficiency for March 2014, η_{March} = 10. 4

Table 1.5: Solar Panels Operating Factors and Efficiencies for the Month of April, 2014.

Note: Total Area of the 20 panels = 12.7445m^2, Input Energy or Light from the Sun = 1000 $W/m2$; ; $E \times A_C$ = 1000 $W/m2$; $\times$12.7445m^2 = 12744.5W; $V_{oc} \times I_{sc}$=86.4v$\times$27. 5A=2376W.

DAY	VOLTAGE MAXIMUM POWER OUTPUT	CURRENT AT MAXIMUM POWER OUTPUT	MAXIMUM POWER OUTPUT	OPERATING FACTOR FF= $\frac{P\max(output)}{Voc \times Isc}$	EFFICIENCY (%) $\eta = \frac{P\max(output)}{E \times Ac}$
1	80. 9	20	1618	0. 68	12. 70
2	80. 2	19	1523. 8	0. 64	11. 96
3	69. 5	19	1320. 5	0. 56	10. 36
4	68. 9	20	1378	0. 60	10. 81
5	67. 8	14	949. 2	0. 40	7. 45
6	54. 8	20	1096	0. 46	8. 60
7	67	14	938	0. 39	7. 36
8	69. 3	15	1039. 5	0. 44	8. 16
9	78. 3	12	943. 2	0. 40	7. 40
10	67. 5	18	1215	0. 51	9. 53
11	69. 4	18	1249. 2	0. 53	9. 80
12	76. 8	12	883. 5	0. 39	7. 23
13	58. 9	15	986. 4	0. 37	6. 93
14	54. 8	18	1033. 5	0. 42	7. 74
15	68. 9	15	1372	0. 43	8. 11
16	68. 6	20	1132. 4	0. 58	10. 77
17	59. 6	19	392	0. 48	8. 89
18	78. 4	5	1192	0. 16	3. 08
19	59. 6	20	1132. 4	0. 50	9. 35
20	59. 6	19	1208. 4	0. 48	8. 89
21	63. 6	19	1210	0. 51	9.48
22	60. 5	20	1316. 7	0. 51	9. 49
23	69. 3	19	990. 1	0. 55	10. 33
24	58. 3	17	833. 3	0. 42	7. 78
25	64. 1	13	639	. 35	6. 54
26	63. 9	10	1206	0. 27	5. 01
27	60. 3	20	120	0. 51	9.46
28	64. 3	12	768	0. 32	6. 03
29	56. 3	9	506. 7	0. 21	3. 98
30	60. 6	18	1090. 8	0. 46	8. 56
Total				13. 53	251. 78

Solar Panels Operating Factor for April 2014, FF_{April}= 0. 45

Cell Efficiency for April 2014, η_{April} = 8. 4

CONCLUSION

The ultimate goal of this study was to develop standards by which photovoltaic modules in use can be measured. With the above in mind, the performance and reliability of a 5KVA standalone solar photovoltaic system was investigated by determining the solar cells operating factor and cells efficiency. The study revealed that the practical cell operating factor and cell efficiency are lower than the theoretical or laboratory values. One of the reasons for this, is that solar panels are usually tested under standard test conditions. The standard test conditions include irradiance of $1000w/m^2$, Air mass of 1.5 solar spectrums and cell temperature of 2.5^0C. These conditions are not always practical. Another reason is that insulation varies daily and seasonally and from one location to another as well as the fact that the practical cell operating factor and efficiency depends on the type of semiconductor used to fabricate the cells, the manufacturing techniques used, method of connection of cells into modules, etc.

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APPENDICES

Appendix 1: The 5KVA Standalone Solar Photovoltaic System

Appendix 2: The Twenty (20) Solar Panels of 80W, 12V each

Appendix 3: A Digital Multimeter for Measuring

Appendix 4: An Analog Panel the Voltage Produced by the Twenty Meter for Measuring (20) Solar Panels the Current Produced by the wenty (20) Solar Panels