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The Influence of Meteorological Features on the Performance Characteristics of Solar Photovoltaic Storage System

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Abstract-

Over the years, there has been increasing interest in exploitation of renewable energy source (RES) as a result of fast depletion of fossil fuel based conventional power generation with attendant negative environmental impact. However, renewable energy sources such as solar, wind, biomass etc are not always available because of their fluctuating nature. In view of this, it has become imperative to have an efficient energy storage system (ESS) for sustained energy availability. Batteries storage often suffers early failure due to irregular charge and discharge cycle which could eventually shorten its life span. Therefore, this research focuses on investigation of the influence of meteorological parameters on battery storage in solar PV system as well as evaluating the influence of these factors on the performance characteristics of solar PV storage system. The work examines particularly the effect of varying solar temperature and irradiance on the system output charging current and overall efficiency. A modified mathematical model of a solar PV was developed to show the relationship between meteorological parameters (irradiance and temperature), and PV output short circuit current. Analysis of meteorological data obtained for determination of state of charge (SOC) of battery storage based on the six geographical areas in Nigeria revealed that, in Bornu state (North-east) the battery attained 100% (hundred percent) state of charge in 1Hr (one hour), while in Plateau state (north-central), the battery attained 60% (sixty percent) state of charge in 8hrs (eight hours), being the least in terms of charging rate. In Kaduna (North-west) region, the battery attained 88% state of charge in one hour and 96% SOC after duration of eight hours. This is quite different from Lagos (South-west), where the battery SOC in one hour was 38% and 78% SOC in eight hours. This phenomenon therefore, revealed that solar PV system implementation should be site specific and it also account for the life span of the storage and the system efficiency.

Key words: Meteorological; Storage; Irradiance; Temperature; State of charge; Solar PV

1. Introduction

The lack of regular and sustainable electrical power as obtained from the conventional source particularly in developing countries like Nigeria has continued to widen the gap between energy demand and supply to the consumers [1]. Over the years, the effectiveness and reliability of the on-grid power generation have been hampered largely by a number of identified constraints. Some of which include: unavailability of gas due to pipeline vandalism, poor gas infrastructure and uncertainty in fiscal policy and inadequate transmission infrastructure, phase sequence irregularities with it attendant effect on phase sensitive equipment to mention a few [2]. These challenges invariably result into serious socio-economic down-turn since large percentage of both economic and social activities are driven by electrical power. This gross deficiency and miss-match in energy demand and supply can be mitigated by harnessing the enormous



renewable energy source (RES) potentials across the country [3]. The penetration of RES such as: solar and wind, has continued to gain significance due to increasing difficulty in meeting the energy need of the country growing population as well the growing concern for environment pollution from fossil fuel based energy generation [4], [5], [6], [7]. However, the intermittent nature of wind and solar energy resources necessitates the need for energy storage systems (ESS) [8]. Traditionally, this function is performed by storages such as battery, super capacitor and hydrogen system (i.e Fuel cell (FC), electrolytic and hydrogen storage tanks), pump hydro, compressed air, superconducting magnetic storage thermal storage etc [9]. The ESS contributes largely to the net cost of a stand-alone hybrid renewable energy system (HRES). Research reveals that battery bank constitutes 52% of the total capital cost of stand-alone solar PV system [10]. Though there are many available storage technologies as afore mentioned, the most cost effective and mature technology on a small scale is the battery storage [11].

The solar system is found to be one of the veritable alternative sources especially for remote areas due to its direct energy conversion technology, environmental friendliness and extremely large quantity of solar irradiation virtually throughout the year. The magnitude of availability of solar energy in Nigeria makes it a veritable option for electricity generation. A vast number of rural communities in Nigeria are not connected to the national grid as a result of their location being far away from the nearest connection terminal. In such situation, solar energy can provide a more economically viable and sustainable power supply to these areas.

In Nigeria, the energy radiated from the sun is estimated to be 3.8×10^{23} KW which is equivalent to 1.052 million to of oil (mtoe) per day. This statistics shows that the quantity of solar energy that obtainable far out-ways the daily crude oil production 4000 times over [12]. Studies also reveal that the total energy requirement of the country would be met if 0.1 percent of the total solar radiation in KW/m^2 is effectively and efficiently harnessed. [13]. It is also worth noting that out of the 365 days in a year, the solar radiation is often available 75 percent with an average of 9 hours per day. The average incident annual solar energy in Nigeria is projected to be 1.804×10^{15} kWh on a geographical land area of $924 \times 10^3 \text{ km}^2$.

A photovoltaic (PV) cell converts solar energy into electrical energy. The fundamental units of a PV are solar cells which form the building blocks of a PV system. These cells are connected together to form bigger units known as modules which can also be connected together to form considerably larger unit called arrays. When the PV array is illuminated, it produces electrical power. Energy storage mechanisms which are usually series of rechargeable batteries are employed to store the energy in order to mitigate the intermittency of the solar radiation. A charge controller is often implemented to prevent negative effect of overcharge and undercharge on the battery [14]. Batteries are normally implemented in stand-alone PV system to satisfy the power mismatch between power generation and the load demand. By and large, a battery would experience regular deep cycle and inconsistent charging pattern as a result of the fluctuating output of the PV and irregular power demand of the load. This continuous operation would subject the battery to a dynamic deep cycle and shorten its life resulting in high replacement cost [15].

This research was conducted to investigate the effect of meteorological parameters differentials on battery storage in a solar PV system in the six geopolitical locations in Nigeria. The understanding of this will form the basis for making appropriate decision in terms of system components selection for optimum efficiency.

2. Methodology

In this research work, the various components of a stand-alone Solar PV system were modeled and a governing equation representing the mathematical interpolation of the components was developed and implemented in MATLAB.

2.1 Mathematical Model of a Solar Panel

The electrical circuit model of a typical photovoltaic cell represented with electrical parameters, is as shown in figure 1

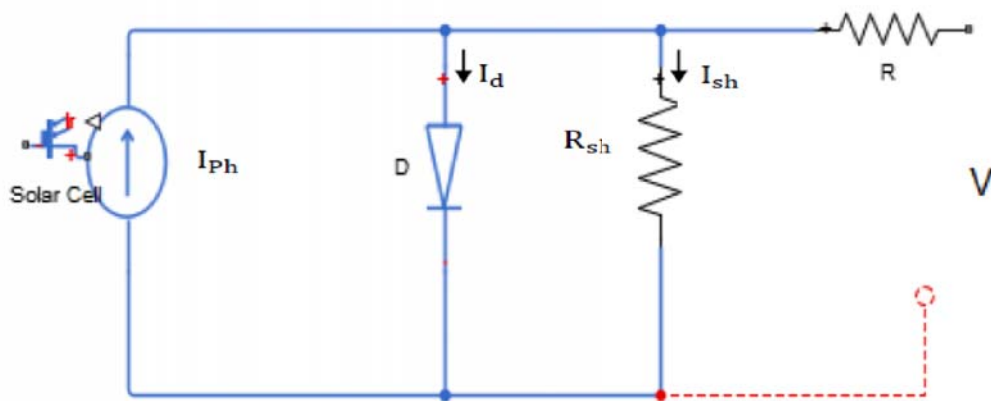


Figure 1: Circuit model of solar PV cell

A PV cell consists of a current source connected in parallel with a single diode in series with a resistance. The output current I_0 be determined from the circuit by applying Kirchhoff's law to the nodes to give:

$$I_0 = I_{ph} - I_d - I_{sh} \quad (1)$$

$$I = I_s \left[\exp\left(\frac{V}{nV_T}\right) - 1 \right] \frac{V + IR_s}{R_{sh}} \quad (2)$$

Where:

I_d is diode current

I_{sh} is shunt current

n is dependent on photovoltaic technologies

The photo current of the photovoltaic panel largely depends on the solar irradiance and the panel temperature. This is expressed as:

$$I_{ph} = [I_{sc} + K(T_c - T_{ref})] \frac{G}{G_{ref}} \quad (3)$$

Where:

I_{sc} = short circuit current of the solar cell

G_{ref} is the reference insolation given as 1000 W/m^2

K_i is the cell short circuit temperature coefficient

G is solar insolation in W/m^2

T_c is instantaneous solar cell temperature

T_{ref} solar cell reference temperature given as 25°C

Also, the cell current varies with cell temperature, and is expressed as:

$$I_s = I_{Rs} \left(\frac{T^3}{T_{ref}^3} \right) \exp - \left[\frac{qE_g}{nK} \left(\frac{1}{T_{ref}} - \frac{1}{T_c} \right) \right] \quad (4)$$

Where:

I_{Rs} is the cell reverse saturation current

E_g is the band-gap energy of the silicon cell (1.10eV)

Q is charge of electron given as 1.6×10^{-19} C

$$I_0 = [I_{sc} + K(T_c - T_{ref})] \frac{G}{G_{ref}} - I_{Rs} \left(\frac{T^3}{T_{ref}^3} \right) \exp - \left[\frac{qE_g}{nK} \left(\frac{1}{T_{ref}} - \frac{1}{T_c} \right) \right] \quad (5)$$

Equation 5 shows that factors such as solar radiation, temperature, and cloud cover are the key parameters that determine the output current of the Solar PV at any point in time. Therefore, as long as there is continuous variation in these parameters as a result of seasonal weather and climatic changes, the output current of the cell will continue to fluctuate.

2.2 Mathematical Model of the Battery

The lead acid battery was used in the study. It was represented with electrical circuit comprising of electrical parameters including the internal resistance of the battery, and a voltage source. The state of charge (SOC) of the battery and the temperature of its electrolyte give a picture of the quantity of active material present within the battery. However, for dynamic systems, characterized with non-linearity and which are fast changing, a more appropriate model that takes into account the behavior of the battery when it receives and delivers current, and the thermal phenomena taking place in it must be used. An analysis of the performance of the battery using the configuration consisting of the voltage source U_0 and the pairs of capacitors and resistors in parallel. i.e R_1C_1 and R_2C_2 was adjudged to be one of the most acceptable mathematical models in [16]. The loss resulting from the battery self-discharge is denoted by R_{ext} . Figure 2 shows the circuit model of the discharge state of the battery.

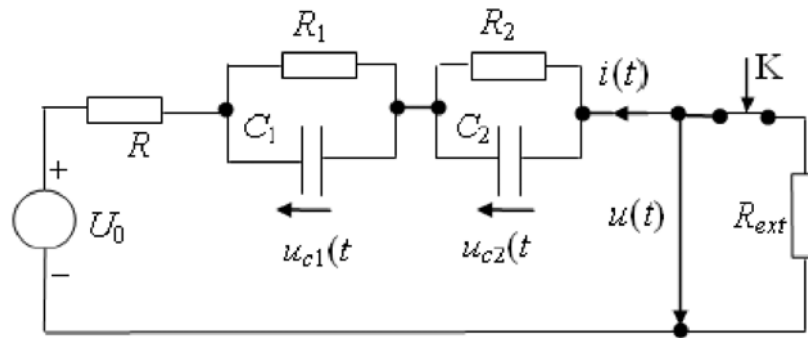


Figure 2: Circuit model of battery in discharge state

During the discharging state of the battery, when switch K is closed at $t=0$, the battery discharges through the load R_{ext} , and the voltage across the battery is given as:

$$U(t) = -i(t)R_{ext} \quad (6)$$

It also follows from Figure 2 that the current being discharged can be expressed as:

$$i(t) = \frac{U_0}{R + R_{ext} + R_1 + R_2} \left(1 + \frac{R_1}{R + R_{ext}} e^{\frac{t}{\tau_1}} + \frac{R_2}{R + R_{ext}} e^{\frac{t}{\tau_2}} \right) \quad (7)$$

Where τ_1 and τ_2 are the time constants given as:

$$\tau_1 = C_1 \frac{R_i(R + R_{ext})}{R_i + R + R_{ext}} \quad (8)$$

$$\tau_2 = C_2 \frac{R_2(R+R_{ext})}{R_2+R+R_{ext}} \quad (9)$$

Putting equation 7 into 6, the discharge voltage $U(t)$ can be obtained as:

$$U(t) = \frac{U_0 R_{ext}}{R+R_{ext}+R_1+R_2} \left(1 + \frac{R_1}{R+R_{ext}} e^{-\frac{t}{\tau_1}} + \frac{R_2}{R+R_{ext}} e^{-\frac{t}{\tau_2}} \right) \quad (10)$$

During the charging state of the battery, switch K is closed at $t=0$ and the battery charges from the power source having an output voltage denoted by U_s as shown in figure 3

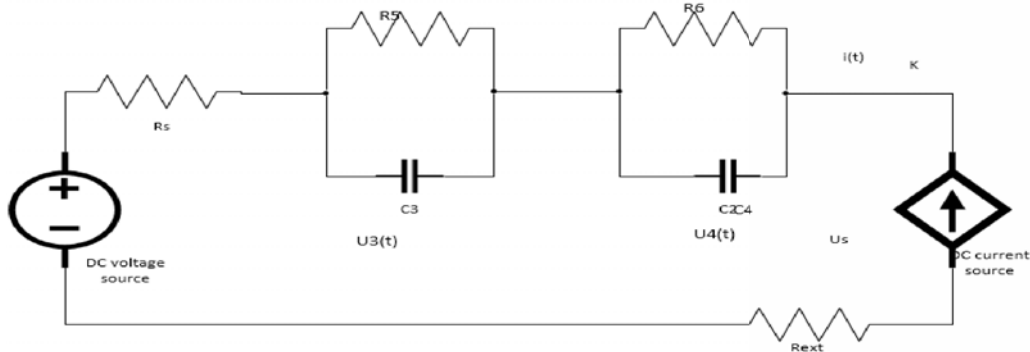


Figure 3: Circuit model of battery in charging state

From Fig 3 the voltage across the battery can be obtained as;

$$U(t) = U_s - i(t)R_{ext} \quad (11)$$

The voltages across the C_3 and C_4 are zero at $t=0$. Thus, at this point, the charging current $i(t)_{bat}$ is expressed as:

$$i(t)_{bat} = \frac{U_s - U_0}{R+R_{ext}+R_5+R_6} \left(1 + \frac{R_5}{R+R_{ext}} e^{-\frac{t}{\tau_3}} + \frac{R_6}{R+R_{ext}} e^{-\frac{t}{\tau_4}} \right) \quad (12)$$

Where τ_3 and τ_4 are the time constants

Now, since the source of supply required to charge the battery is from the solar photovoltaic panel and considering the mathematical model of the PV with particular reference equation (5), it can be inferred that the battery charging current $i(t)_{bat}$ as obtained in the model equation (12) is equal to the solar PV source output current I_0 . That is:

$$i(t)_{bat} = I_0$$

Hence;

$$i(t)_{bat} = [I_{sc} + K(T_c - T_{ref})] \frac{G}{G_{ref}} - I_{Rs} \left(\frac{T^3}{T_{ref}^3} \right) \exp - \left[\frac{qE_g}{nK} \left(\frac{1}{T_{ref}} - \frac{1}{T_c} \right) \right] \quad (13)$$

Relating the charging current to the meteorological parameters in equation (13) and substituting the values of other constants, then we have:

$$i(t) = (T_c - 25)0.001G - 8 \times 10^{-4} T^3 e^{-(0.04-T^{-1})} \quad (14)$$

Equation (14) shows the dependency of battery charging current on meteorological factors especially temperature and solar insolation.

2.3 The Meteorological Data used for the Study

The meteorological data for some selected towns representing each of the geo-political zones of Nigeria was used for the study. The data is as shown in table 1. The respective meteorological variables were substituted into the developed MATLAB codes developed for equation (14) to obtain the desired result.

Table 1: The Meteorological Data for the selected Locations in the Six Geo-Political Zones in Nigeria

Month	Plateau		Anambra		Lagos		Kaduna		Borno		Rivers	
	Temp	Irrad	Temp	Irrad	Temp	Irrad	Temp	Irrad	Temp	Irrad	Temp	Irrad
Feb-17	32	215	40	205	36	175	37	187	40	220	34	185
Mar-17	36	219	38	218	35	213	41	217	41	256	35	205
Apr-17	35	211	37	194	36	210	41	224	43	281	37	216
May17	32	202	36	185	36	192	38	242	44	290	38	205
Jun-17	31	167	32	172	34	182	36	245	42	284	34	175
Jul-17	28	153	31	161	31	158	33	215	39	255	30	162
Aug-17	27	155	30	151	31	137	31	210	37	225	32	145
Sep-17	27	203	33	159	30	132	37	209	37	205	31	151
Oct-17	29	213	38	170	32	153	35	235	38	249	30	178
Nov-17	30	217	39	175	33	136	36	241	36	265	30	150
Dec-17	31	220	38	210	34	195	35	242	34	275	32	210
Jan-18	29	241	39	207	33	201	34	230	31	241	34	215

3. Result and discussions

The result obtained for the state of charge (SOC) of the battery used from MATLAB simulation of the meteorological variables using equation (14) for each geo-political zone in Nigeria is as shown in table 2 while the associated graph is as shown in figure 4.

Table 2: Summary of meteorological parameters characteristic equations for six geographical locations in Nigeria

Geographical location	Irradiance/charging current characteristic equation	Temperature/charging current characteristic equation
Plateau state (Northcentral)	$G=0.00574e^{0.0167x}$	$T=0.0125e^{0.1416x}$
Kaduna state (North west)	$G=1.6705e^{0.0023}$	$T=0.083e^{0.0822x}$
Bornu state (North East)	$G=0.458e^{0.0073}$	$T=0.0852e^{0.0983x}$
Lagos state (South west)	$G=0.1373e^{0.0129}$	$T=0.0018e^{0.1967x}$
Anambra state (South East)	$G=0.1436e^{0.0127}$	$T=0.0149e^{0.1373x}$
Rivers state (South south)	$G=0.0895e^{0.0146}$	$T=0.0065e^{0.1801x}$

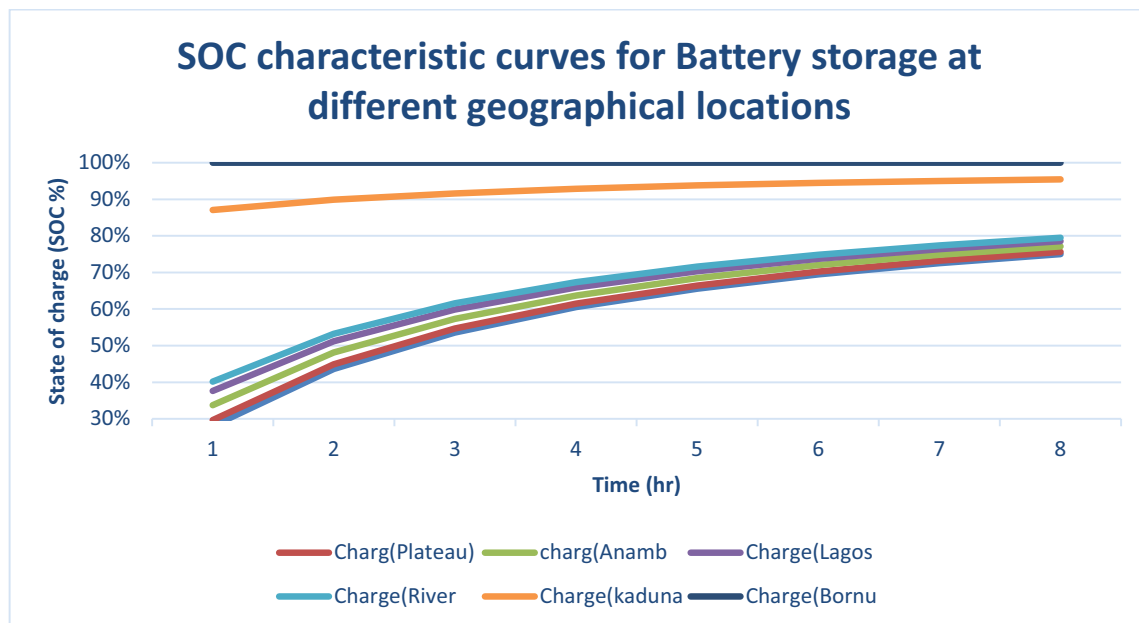


Figure 4: Battery state of charge characteristic curves for six geographical locations in Nigeria

Meteorological parameters are major factors that must be given immense consideration in relation to solar PV with storage system installation. With reference to the result obtained for six different geo-political locations in Nigeria, it can be seen that the impact of meteorological/weather parameters variation on battery storage system in a stand-alone solar PV system, vis-a vis the charging current and state of charge (SOC); determines the charging rate of the energy storage system. For instance, in north eastern region of the country, battery storage in a solar PV system will charge faster and attained 100% SOC in one hour (1Hr), which is at a faster rate than every other region. Therefore, the size and number of solar panel is expected to be lower compare to region like south-south which attained 80% SOC after 8 hours of charging at the same charging rate. In the same vein, the situation in Anambra (south east) region was such that the storage attained 35% SOC in 1hour and 76% SOC in eight hours (8hours) of constant charging. This is much different from the Kaduna (North-west) region, which attained 88% SOC in one hour (1hour) and 96% SOC in eight hours (8Hours) for the same solar PV installation configuration.

This study revealed that the impact of meteorological parameters on storage in a solar PV system cannot be under-played. The same solar PV arrangement that worked efficiently over a long period of time in the north-central may experience early failure in the south-west region due to storage failure. It is imperative at this point to emphasize that arbitrary selection of solar PV system components without given credence to geographical location meteorological conditions will have adverse effect on the overall system efficiency and the storage system in particular. Therefore, the life span of battery storages in a solar PV system will be better enhanced when the right size and number of solar panels are put in place; based on proper design and adequate consideration of weather variables as it applies to different geographical locations. In order word, the implication of this study is that; the use of a common template, as conventionally practiced and found in some literature, for the installation of solar PV with storage system

without due consideration of meteorological features in a given location, will gradually deteriorates and surely result into early failure of the system storage.

4. Conclusion

In this research, the effect of seasonal weather variation and associated key parameters such as temperature, wind speed and irradiation, on solar PV performance was investigated. Experimental data were obtained and analyzed to validate dependency of PV efficiency on weather parameters, considering six geopolitical locations in Nigeria. It can be inferred that these parameters are site specific as it reflected in the governing equation obtained from the characteristic curves (temperature/current and irradiance/current). The battery storage state of charge (SOC) can be seen to be largely depend on the output of the solar panel which is a direct function of seasonal weather variables. In view of this, in designing a solar PV system, it is imperative to look out for location based seasonal weather parameters and other prevailing conditions which is the focal point in this study. The fact also remains that, the battery storage arrangement in stand-alone solar PV system may continue to suffer inadequate charging and progressive deterioration, which could result into shortened life-span as long as there is disparity between the rate of energy stored and rate of energy discharged. Consequently, this study developed an holistic approach toward addressing this problem by considering the effect of weather variables as they pertain to different locations, in determining the charging rate for a given battery storage as well as capacity of solar panels in a stand-alone solar PV system.

5. Recommendation

Further research will consider behavior of other energy storage systems such as super-capacitor and fuel cells, under different meteorological conditions. This will helpful in determining the most efficient energy storage systems in a given meteorological zone.

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