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Mathematical Modeling for Reliability Assessment of 250-5000 Watts Pulse Width Modulation Power Inverter in Nigeria

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ABSTRACT: *A power inverter, or inverter, is an electrical power converter that changes direct current (DC) to alternating current (AC) the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. The paper presents mathematical modeling for assessing reliability of PWM power inverter in Nigeria. The part stress method was used to predict the reliability of the system. Data on the failure of PWM Inverter in Sokoto were used as a case study, with special consideration given to factors like environmental impact, quality of power supply, service personnel, human factors (over and under usage). A comparative assessment was made on the reliability and reliability indices of the power inverter when operated within Sokoto environment and when operated within the environment for which it was designed (china). The result shows that lower reliability level is associated with the use of PWM power inverter in Sokoto state of Nigeria, as compared with the country for which it was designed.*

Keywords: *Failure rate. Inverter, Modeling, PWM, Reliability*

I. INTRODUCTION

250-5000 watts PWM DC/AC 220V power inverter is as electrical device which is designed to coverts direct current DC to alternating current AC with the use of a transformer, switching and control circuits [13][14]. The reliability of this system, which has an original environment for which it was designed for, becomes necessary to determine the degree to which it could be relied upon in the applied environment –Sokoto state Nigeria [1][2][6][7].

1.1 Reliability

Reliability in engineering can generally be defined as the characteristic of an item expressed as the probability that it will perform a required function understated conditions for a stated period of time [4]. Reliability predictions are an important tool for making design trade-off decisions and estimating future system reliability [8][11]. This requires the understanding of probability and statistical concepts and has, therefore, been found to be a very important tool in forecasting the patter of failure for systems and hence the reliability assessment of the system at hand [10].

1.2 Part stress method

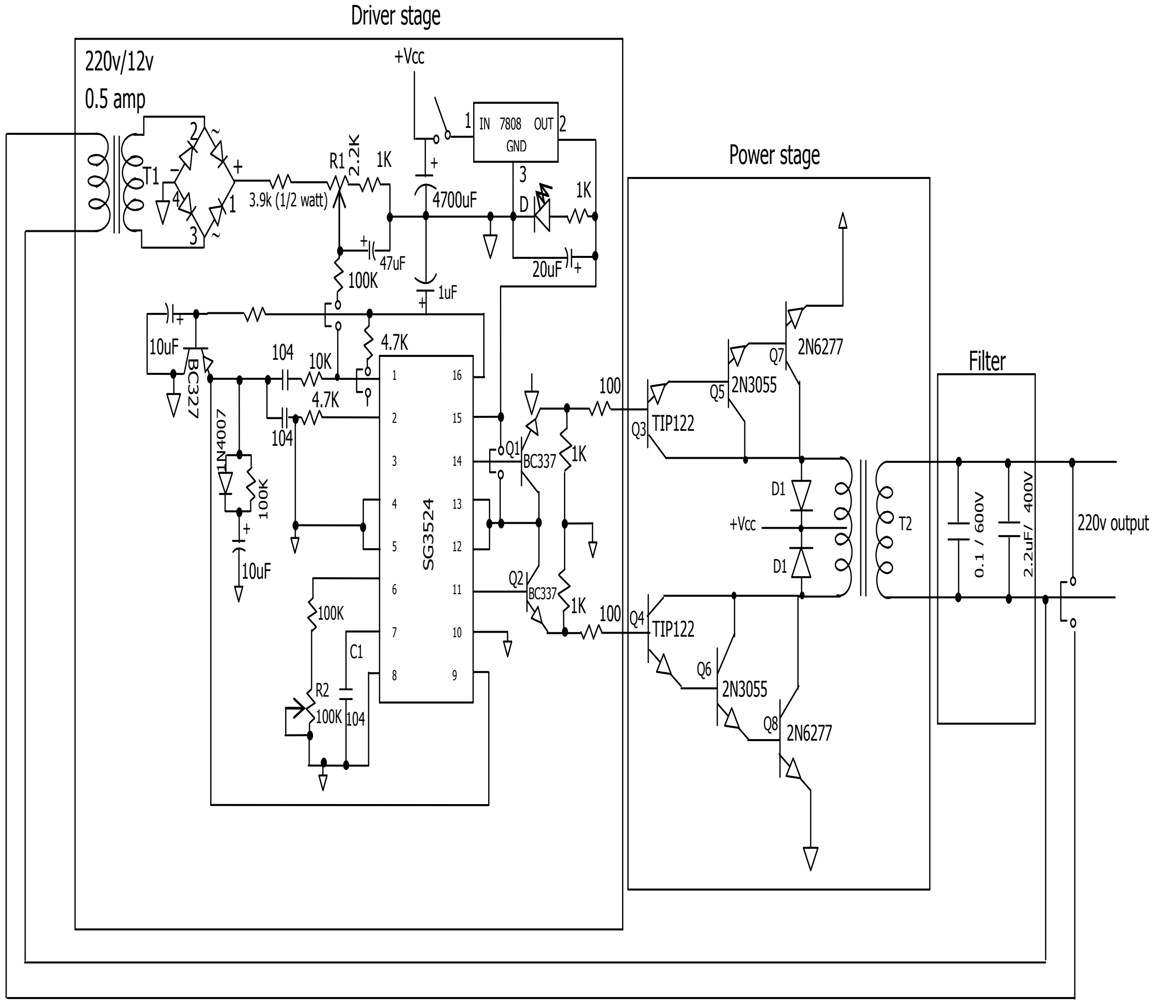
This is one of two methods used in assessing the reliability of electronic equipment. In the part stress method, the effects of the various stresses on the actual hardware are put into consideration, with the environmental factor and the quality of the utility. The parts count method (the other method) of assessing the reliability of system is based on the number of different parts, quality level and application environment. The aim in both cases is to determine the failure for a given system operating in a specific environment [9].
However, the part stress method is better method for mathematical assessing the reliability of the existing system, based on the possibility of considering various stress peculiar to the equipment in a specific area of application [4] and as such cold be relied upon to asses the reliability of the PWM power inverter.

1.3 The PWM power inverter system

Pulse-width modulation (PWM) is a commonly used technique for controlling power to inertial electrical devices made practical by modern power switches. Power inverter is an electrical device that converts direct current DC to attempting current AC with the use of a transformer, switching and control circuits. These are two general types of power inverter: true sine wave or modified-sine wave (square wave). True sine wave inverter produce power that is either identical or sometimes slightly better to power from the public utility power grid system [13].

Modified sine wave and square wave inverters are the most common types of power inverters on the market. Modified sine wave produces a power wave that is sufficient for most devices. The power wave is not exactly the same as electricity from the power grid. It has a wave form that appears as a choppy square off wave when viewed through an oscilloscope [14].

The schematic circuit design is for a 250 watt output to increase the power of the circuit you have to add more of the Q7 and Q8 transistor in parallel, each pair you add will increase your power by 250 watts.
If you increase the power transistors you have to enlarge the T2 transformer to match the new needs. The circuit transformer is rated 25 amps to handle 220V.



Dc voltage and transformer “t_2” winding recommendation:
Power Supply Winding

750W 12VDC p: 24V “12 – 0 – 12” / S: 220V
1500W 24VDC p: 48V “24 – 0 – 24” / S: 220V
2250W 36VDC p: 72V “36 – 0 – 36” / S: 220V
3000W 48VDC p: 96V “48 – 0 – 48” / S: 220V
3750W 60VDC p: 120V “60 – 0 – 60” / S: 220V
4500W 72VDC p: 144V “72 – 0 – 72” / S: 220V
5250W 84VDC p: 168V “84 – 0 – 84” / S: 220V

The transformer should be “centre tapped” at the primary side.

- R_1 is to set the PWM to 220V
- R_2 is to set the frequency to 50 or 60Hz
- Wiring should be thick enough to handle the huge amps drain from the batteries.

- A cooling fan will be needed to reduce heat off the heat sinks and transformer, when you power up the circuit the fan will start this will give you a simple way to know that 220V is present and everything is ok.
- Two circuit breakers are recommended instead of fusses, one on the DC side and one on the AC side, depending on your design example; for a 24VDC (1500 watts design) put a 6 Amps breaker on the DC side and a 6 Amp on the AC side. For every 1 Amp of 220AC you will be raining like 8 to 10 Amps from the 12V battery, make your calculations.
- The two heat sinks should be big enough to cool the transistors, they are separate and should not touch each other.
- Be caution when building this circuit it involves high voltage which is lethal.

1.4 Nigeria

There are three infrastructural indices of development. These are adequate, reliable and always available energy supply, communication and transportation system. Any society that has got these thee indices is generally characterized as developed society. Such societies includes USA, UK, Russia, Canada, France, Italy, Germany and Japan – popularly called G_8. Countries which have not attained the three perfect indices above are generally termed developing countries. Example of such are Nigeria, Malaysia and so on.
Nigeria is mainly considered or at best, assemblers or product designed by developing nations. They inhabit lands with tropical climates in Africa, Asia and Latin America [5]. The electrical power and hence, have fluctuating voltages. Some of the region are periodically subjected to every dry dust (harmattan) which is capable of introducing a high electric field strength of above 4000V/m and sometimes metallic objects moving in this environment accumulate an average of 1000v/m charge [5].

II. MATERIALS AND METHODS

It is convenient to specify the reliability of electronic equipment by some probability parameters, which give indication of the failure rate of such system or equipment and does not depend on the operating time [12]. By using such parameters, it is also possible to compare the performance between different systems with different periods. Two of such parameters that are commonly used are the mean time between failure (MTBF) and mean time to failure (MTTF) [12].

2.1 Mean Time between Failures (MTBF)

Reliability is quantified as MTBF (Mean Time between Failures) for repairable system. Avoiding failure in a critical data centre is always a top priority; as such a correct understanding of MTBF is important. Therefore systems users are usually concerned with the length of time that a system will run without failure. This is a measure of the reliability of such a system [4][12]. The MTBF can be obtained by running a system for a predetermined length of time under specified conditions. Hence for the failure rate λ (the number of failure per unit time) MTBF is given as [4]:

$$MTTF = \frac{\sum_{t=1}^{n}(t_i - t_0)}{N}$$

i.e. $$MTTF = \frac{(t_1 - t_0) + (t_2 - t_0) + \cdots + (t_n - t_0)}{N}$$

where t_0 = starting (reference time)
$(t_1 - t_0)$ = period to 1st failure
$(t_2 - t_0)$ = period to 2nd failure
$(t_n - t_0)$ = period to nth failure
N = total number of failure components.

Consider the case in which a fixed number N_0 of identical components are tested.
Let N_s = number surving up to time t.
N_f = number failed up to time t.
$N_0 = N_s + N_f$ = total number in operation at t=0
∴ Reliability at any time t becomes

$$R(t) = \frac{N_s}{N_0} \tag{1}$$

The failure rate λ(t) is normally defined by the mathematical relation

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{1}{N_s} \times \frac{\Delta N_f}{\Delta t}$$

$$\lambda = \frac{1}{N_s} \times \frac{dN_f}{dt} \qquad (2)$$

where N_s = number of serving items after a life test

ΔN_f = number of failure item during the time interval, Δt.

Consider the case in which a fixed number N_0 of identical components are tested,

Let N_s = number surving up to time t

N_f = number failed up to time t

$N_0 = N_s + N_f$ = total number in operation at t=0

$\therefore$ Reliability at anytime t becomes

$$R(t) = \frac{N_s}{N_0}$$

and failure rate (for constant failure rate)

$$\lambda = \frac{1}{N_f} \times \frac{dN_f}{dt} \qquad \text{from Equation (2)}$$

$$\lambda = \frac{1}{N_0 - N_s} \times \frac{dN_f}{dt}$$

or $$\int \lambda dt = \int \frac{1}{N_0 - N_s} dN_f$$

introducing the limits

$$\int_0^t \lambda dt = \int_0^{N_f} \frac{1}{N_0 - N_s} dN_f$$

$$\lambda t = -\left[\log_e\left(N_o - N_f\right) - \log_e\left(N_o - 0\right)\right]$$

$$-\lambda t = \log_e\left(\frac{N_0 - N_f}{N_0}\right)$$

Thus $$e^{-\lambda t} = 1 - \frac{N_f}{N_0} \qquad (3)$$

But from Equation (1)

$$R(t) = \frac{N_s}{N_o} = \frac{N_0 - N_s}{N_0} = \left(1 - \frac{N_s}{N_0}\right) \qquad (4)$$

Comparing equations (3) and (4), we have

$$R(t) = e^{-\lambda t} \qquad (5)$$

The general expression for MTBF, m is (Epsma 2005, Oroge 1991, Susan, 2010)

$$m = \int_0^{\infty} R(t) dt \qquad (6)$$

For the case when λ is constant from equation (5)

$R = e^{-\lambda t}$ so equation (6) becomes

$$m = \int_0^\infty R(t)dt$$

$$= -\left[\frac{1}{\lambda}e^{-\lambda t}\right]_0^\infty$$

$$= -\frac{1}{\lambda}\left[e^\infty - e^0\right]$$

$$m = \frac{1}{\lambda} \qquad (7)$$

If failure are due to chance and if the failure rate λ is constant, then

$$\lambda = \frac{1}{MTBF} \quad \text{for repairable items}$$

$$\lambda = \frac{1}{MTTF} \quad \text{for non-repairable items}$$

2.2 Equipment Availability

Mathematically, the utilization factor μ can be express as [4]:

$$\mu = \frac{t_{op}}{t_m + t_{id} + t_{op}} \qquad (8)$$

As seen in equation (8), if the idle time is equal to zero, (i.e. $t_{id} = 0$) and the maintenance time become as small as possible, then utilization factor will approach its maximum value and can now be called availability of a unit or system. Mathematically, this can be expressed as

$$\frac{t_{op}}{t_{m(\min)} + t_{op}} \qquad (9)$$

Where t_{op} = the mean time before failure and $t_{m(min)}$ = the mean time to failure

$$\therefore \quad A = \frac{MTBF}{MTBF + MTTF} \qquad (10)$$

2.3 Mean time to failure (MTTF)

The mean time to failure is a term which applies to non-repairable items (such as resistors, capacitors, electric bulbs and so on, which are disposed off as soon as they fail [12]. MTTF is the average time an item may be expected to function before failure. This MTTF can be obtained by stressing a large number of components under known conditions for a period of time and noting the number of failures [4][5]

2.4 Equipment Failure Profile

Over the years, complex equipment and components have been found to follow a familiar pattern of failure, which has been well documented. Failure rates have been calculated for equal time intervals from installation to replacement. When the failures rates is plotted against a time scale spanning the equipment life time, the resulting graph, popularly known as "bathtub is obtained as shown in figure 2.1 [2][4].

It exhibits three district periods or zones, the infant mortality period, the constant failure rates period and the wear out period.

Infant mortality period

This is the running-in period. During this period, the failure rate has been found to be high, due to other design or manufacturing errors, misuse. It however, falls off rapidly with operation. Failures in this period can be avoided during product development through the use of stimulated tests, or by vigorous stressing during commissioning tests.

Constant Failure Rate Period

This period follows the running-in period. During this period, the failure rate is lowest and is a function of the basic design. Failure results either through accidents or poor operation or maintenance. In this phase, the mean time to failure (MTTF) is the reciprocal of the (constant) failure rate.

Wear Out Period

This period manifests towards the tail end of the equipment component life. During this period, failure is due to old age, various components are worn-out, metals become embrittled, and insulation dries out and so on. Failure rates can only be reduced by preventive replacement of these components.
Generally in some systems, one or two of the phase (usually the ecouly failure and wear our failures) could be more reduced or effectively absent. Therefore, estimates for parameters that affect equipment failure profile of the constituent components, especially the length of the constant failure rate period and associated failure rates are essential ingredients for predicting the reliability.

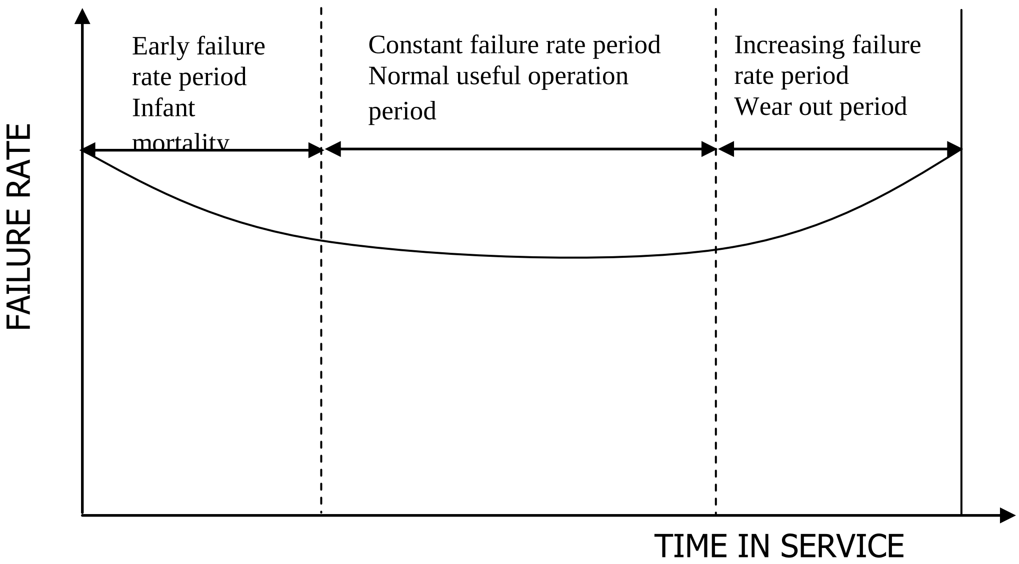


Fig.2. 1. Equipment failure profile – Bathtub-curve

2.5 RELIABILITY ASSESSMENT OF ELECTRONIC EQUIPMENT

The general expression for the parts stress method of mathematically assessing reliability is given as [8][10][15]

$$\lambda_i = n\lambda_B \pi_E \pi_A \pi_Q \pi_N \quad (11)$$

Where

λ_i = the failure rate i^{th} part

λ_B = The basic failure rate obtained from derated data for each generic part against normalized stress and temperature factors.

π_E = Account for the environmental factors other than temperature

π_A = Account for secondary stresses (e.g. vibration, shock, e.t.c.)

π_Q = Account for the degree of manufacturing control

π_N = Account for any additional factor that has not been taken care of above.

n = Number of particular component.

For the scope of this work, the above equation (11) for the part stress method was reduced to the expression of:

$$\lambda_i = n\lambda_B TK \quad (12)$$

Where

λ_i = The failure of the i^{th} part

n = number of particular component

λ_B = Base failure rate obtained from the derated data for each generic part against normalized stress and temperature factor.

T = Room temperature of the environment

K = Voltage stress ratio

Voltage stress (K) = $\frac{Measurd \ \ voltage}{Rate \ \ voltage}$

The failure rate of the regions under consideration, Sokoto-Nigeria and China are summed up to calculate the inherent system reliability. These failures are constant and as best described by the exponential distribution law for useful operation region.

RELIABILITY ASSESSMENT OF 250-5000 WATTS PWM DC/AC POWR INVERTER

The design criteria presented above will be used to assess 250-5000 watts PWM DC/AC power inverter in Sokoto-Nigeria and in the country for which it was designed for (China). Hence, we shall have designed failure rate, as it will be applicable to the system operating in the environment for which it was designed and a relative failure rate as it will be applicable to the system operating in the Sokoto state Nigerian environment [5]. The conclusion arrived at will be used assess the reliability of the PWM power inverter. The components of the 250 to 5000 watts PWM power inverter with the generic failure rate, which has been taken care of the environmental factors and the application stress factor and the results of the failure rates are shown in **Table 3.**

Table 1: failure rates of the pwm dc/ac power inverter

Circuit Ref	Component description	Qty (n)	TD (^{0}C)	TN (^{0}C)	Voltage stress ratio K	λ_{BD} (x10^{-6}/hr)	λ_{BN} (x10^{-6}/hr)	λ_{eff}^D = (nKTλ_{BD})	λ_{eff} (nTKλ_{BN})
T_1	Transformer	1	25	27	0.1167	0.011	0.019	0.0320925	0.0598671
D_1	General purpose diode (germanium)	1	25	27	0.006	0.0032	0.102	0.00048	0.016524
D_2	-do-	1	25	27	0.03875	0.0032	0.102	0.0031	0.1067175
D_3	-do-	1	25	27	0.1755	0.0032	0.102	0.01404	0.483327
D_4	-do-	1	25	27	0.0125	0.0032	0.102	0.001	0.034425
R_1	-do-	1	25	27	0.8	0.0219	0.105	0.438	2.268
R_2	-do-	1	25	27	2.0	0.0219	0.105	1.095	5.67
R_3	-do-	1	25	27	0.05	0.0219	0.105	0.027375	0.14175
R_4	-do-	1	25	27	1.90	0.0219	0.105	1.04025	5.3865
C_1	Ceramic capacitor	1	25	27	0.0625	0.033	0.141	0.0515625	0.2379375
C_2	-do-	1	25	27	0.045	0.033	0.141	0.037125	0.171315
C_3	-do-	1	25	27	0.0512	0.033	0.141	0.04224	0.1949184
IC_1	IN 7808	1	25	27	0.125	0.007	0.91	0.021875	3.07125
R_5	Film resistor	1	25	27	6.10	0.105	0.0219	16.0125	3.60693
D_5	LED	1	25	27	0.0025	0.102	0.0032	0.006375	0.000216
C_4	Electrolytic capacitor	1	25	27	0.563	0.033	0.171	0.464475	2.599371
C_5	-do-	1	25	27	0.0085	0.033	0.171	0.0070125	0.0392445
Q_2	Transistor	1	25	27	0.0975	0.0144	0.860	0.0351	2.26395
R_6	Film resistor	1	25	27	0.0340	0.0008	0.011	0.00068	0.010098
D_6	Diode	1	25	27	0.0052	0.0066	0.51	0.000858	0.071604
D_7	-do-	1	25	27	0.0066	0.0066	0.51	0.001089	0.090882
C_6	Electrolytic capacitor	1	25	27	0.5148	0.0047	0.025	0.060489	0.34749
C_7	Electrolytic capacitor	1	25	27	0.7613	0.0047	0.025	0.08945275	0.5138775
C_8	Film capacitor	1	25	27	0.1145	0.0008	0.011	0.00229	0.0340065
R_8	Film resistor	1	25	27	0.0110	0.0008	0.011	0.00022	0.003267
Circuit Ref	Component description	Qty (n)	TD (^{0}C)	TN (^{0}C)	Voltage stress ratio K	λ_{BD} (x10^{-6}/hr)	λ_{BN} (x10^{-6}/hr)	λ_{eff}^D = (nKTλ_{BD})	λ_{eff} (nTKλ_{BN})
R_9	Film resistor	1	25	27	0.0340	0.0008	0.011	0.00068	0.010098
R_{10}	Film resistor	1	25	27	0.0348	0.0008	0.011	0.000696	0.0103356
IC_2	SG3524	1	25	27	0.03875	0.011	0.15	0.1065625	1.569375
R_{11}	Film resistor	1	25	27	0.528	0.0008	0.011	0.01056	0.156816
R_{12}	Variable resistor	1	25	27	0.5097	0.086	1.3	1.095855	17.89047
C_9	Electrolytic capacitor	1	25	27	0.5148	0.0047	0.025	0.060489	0.34749
Q_2	Power transistor	1	25	27	3.3	0.0085	0.078	0.70125	6.9498
Q_3	-do-	1	25	27	3.34	0.0085	0.078	0.70975	7.03404
Q_4	-do-	1	25	27	2.77	0.0085	0.078	0.588625	5.83362
Q_5	-do-	1	25	27	8.35	0.0085	0.078	1.774375	17.5851
Q_6	-do-	1	25	27	11.80	0.0085	0.078	2.5075	24.8508
Q_7	-do-	1	25	27	2.74	0.0085	0.078	0.58225	5.77044
Q_8	-do-	1	25	27	1.76	0.0085	0.078	0.374	3.70656
Q_9	-do-	1	25	27	2.13	0.0085	0.078	0.452625	4.48578
D_7	Diode	1	25	27	0.0036	0.0066	0.51	0.000594	0.049572
D_8	-do-	1	25	27	0.0018	0.0066	0.51	0.000297	0.024786
T_2	High power x4mer	1	25	27	0.1043	0.003	0.047	0.0078225	0.1323567
C_{10}	Polyester film capacity	1	25	27	0.22	0.0008	0.011	0.0044	0.06534
C_{11}	-do-	1	25	27	0.1167	0.0008	0.011	0.002334	0.0346599
D_9 - D_{12}	Bridge rectifier	1	25	27	0.0192	0.0066	0.51	0.003168	0.264384
	TOTAL							28.46851425	124.099455

Where

λ_{BN} = Base failure rate of the inverter in Sokoto-Nigeria
λ_{BD} = Base failure rate of the inverter in designed environment (China)
$T^{oc}(D)$ = Average room temperature of the designed environment (China)
$T^{oc}(N)$ = Average room temperature of Sokoto-Nigeria
K = Voltage stress ratio
$\lambda_{eff}D$ = Effective base failure rate for designed environment (China)
$\lambda_{eff}N$ = Effective base failure rate for the applied environment (Sokoto-Nigeria)

Reliability can be assessed from the failure rates obtained from table 3 for China and the applied environment (Sokoto-Nigeria).

Table 3: Reliability result

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
China	**0.779284**	**0.607283**	**0.473246**	**0.368793**	**0.2873943**
Nigeria	**0.337190**	**0.1136968**	**0.0383374**	**0.012927**	**0.0043588**

Table 4: Percentage of reliability

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
China	**77.9284%**	**60.7283%**	**47.3246%**	**36.8793%**	**28.73943%**
Nigeria	**33.7190%**	**11.36968%**	**3.83374%**	**1.2927%**	**0.43588%**

Example, for one year, = 365 days x 24 hours = 8760hrs

$R = e^{-(28.4685E-06 \times 8760)} = 0.779284$

The reliability result taken over five years for the two environments were plotted against time

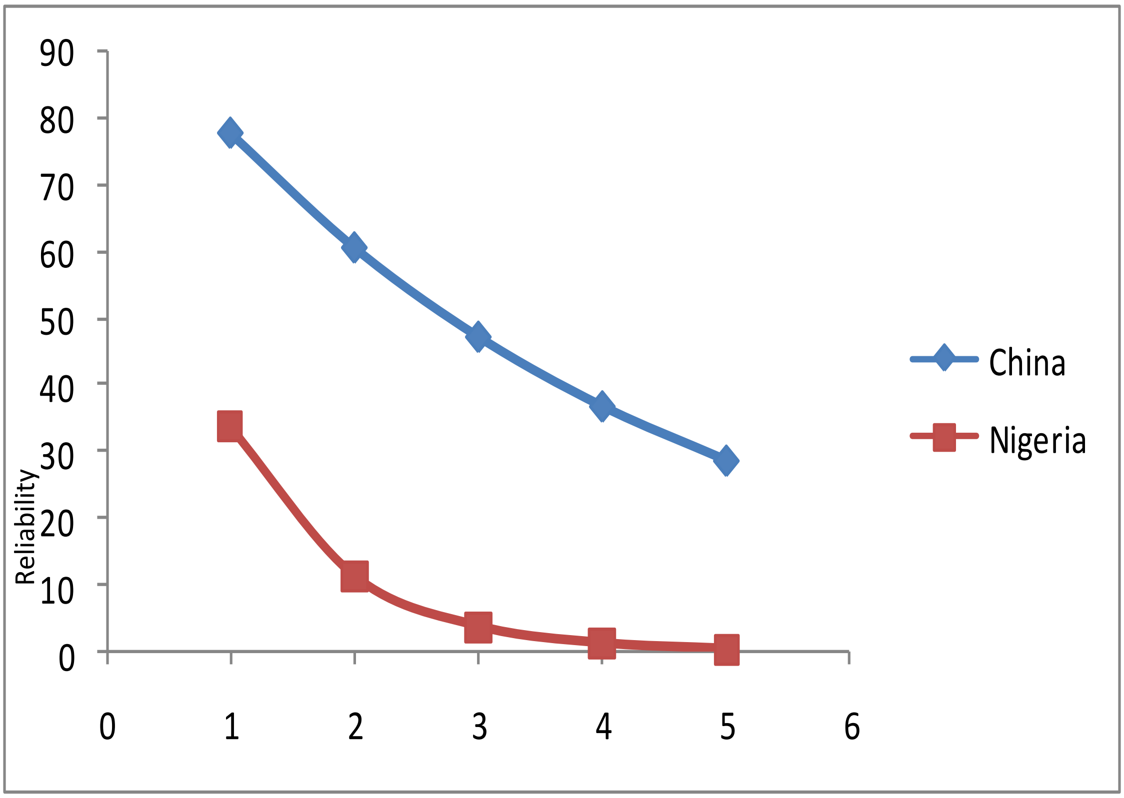


Fig.2.2: Graph of reliability Vs year

Year

III. DISCUSSION OF RESULT

From fig.2.2, we can appreciate and compare the reliability of the country for which the system was designed for and that of Sokoto-Nigeria. And from it we see that the power inverter under consideration has a relatively higher reliability in the designed country (China) than the applied environment (Sokoto-Nigeria).

The exponentially decaying reliability function graph above shows that the system has a higher failure rate in Nigeria, due to factors, which are associated with the environment like voltage fluctuation, surge frequency, high relative humidity, among others. The ratio of the failure rate of Sokoto-Nigeria to China is approximately 4:1.

Comparatively, the rate of failure of the power inverter in the designed country is much less than the Nigerian case. From the failure rate of the system obtained for the two environments, we obtain the mean time to failure (MTTF) of the system as follows

$$MTTF = \frac{1}{\lambda_{eff} D}$$

$MTTF_{China}$ = 4.0099 yrs.

$MTTF_{sokoto}$ = 0.92 yrs.

The mean time the system is expected to function before failure (MTTF) in Sokoto-Nigeria is 0.9 years as against 4.0 years for the designed country. The rate is about four times higher than the Sokoto-Nigerian case.

IV. CONCLUSION AND RECOMMENDAITONS

The comparative results for the system at hand, taken over five years between the country for which the system was designed for and that of Nigeria, showed that lower reliability is associated with the use of the system in Nigeria than the designed country (China).

The following steps are recommended for the reliability of the power inverter to be higher in Nigeria:

a. Provision of a parallel configuration in the design so as to reduce the rate of failure of the components in the system.

b. The design of power inverter that will consider the environmental as well as stress factor in Nigeria.

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