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Contributing Factors and their Effects on Reliability Analysis of Solar Energy System

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Abstract—*This paper includes the different factors to be included to find reliability. The generalized reliability definitions are studied. The solar power unit model is taken into consideration to calculate reliability. An SPU includes a photovoltaic panel, power converter, control and sensing. Possible faults in each component of the unit are surveyed. PV panel faults include possible installation faults, environmental effects and material degradation. Result shows the value of failure rate of every component, from which it is clear that the failure rate of PV panel is significant to consider while calculating reliability. The SPU model is flexible and can be used for various operating conditions, panel design and electrical ratings.*

Keywords: *Reliability, solar power unit (SPU), Military Handbook (217F), photovoltaic reliability.*

1. INTRODUCTION

Reliability is an important issue in renewable energy generation systems. The global surface temperature increased because of global warming. The problems with energy supply and use are related not only to global warming, but also air pollution, air pollution, acid precipitation, ozone depletion, forest destruction, and radioactive substance emissions. To avoid such effects, some potential solutions have evolved including energy conservation through improved energy efficiency, a reduction in fossil fuel use and an increase in environmentally friendly energy supplies. Among a variety of the renewable energy sources, photovoltaic (PV) sources have no supply limitations and are predicted to become the biggest contributors to electricity generation among all renewable energy candidates by 2040 [1]. Solar energy generation system is used now-a-days for stand alone as well as grid connected systems. Solar panels are being costly; the reliability of the panel must be high for economic and quality power generation. Solar power system mainly consists of dc-dc converter, dc-link capacitor and inverter. Inverter is an essential component of renewable energy generation which processes the obtained output power and is the recent matter of investigation for few researchers from the Reliability point of view. [2]

The solar power unit reliability can be calculated by calculating the failure rate of every component.

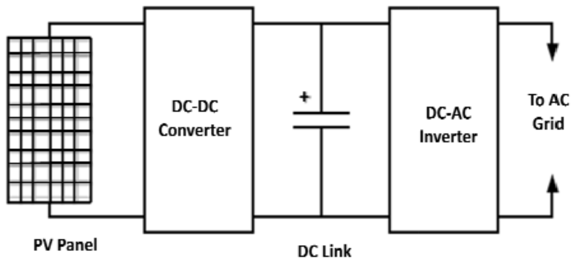

Fig. 1: Solar power system.

Recently, dc–dc converters with high voltage gain have become usually required in many industrial applications such as the front-end stage for clean-energy sources, the dc back-up energy system for uninterruptible power supply, high intensity discharge lamps for automobile headlamps, and tele-communication industry applications. Military Handbook 217F is to be used for the calculation of failure rate of every component.

2. RELIABILITY PREDICTION

Definition of Reliability

Reliability (for non-repairable items) can be defined as the probability that an item will perform a defined function without failure under stated conditions for a stated period of time [3]. Reliability predictions are one of the most common forms of reliability analysis. Reliability predictions predict the failure rate of components and overall system reliability. These predictions are used to evaluate design feasibility, compare design alternatives, identify potential failure areas, trade-off system design factors, and track reliability improvement. The general expression for reliability is given by (1), where λ denotes the instantaneous failure rate.

$$R(t) = \exp\left[-\int_0^t \lambda(x)dx\right] \tag{1}$$

Mean Time to Failure (MTTF)

MTTF is a basic measure of reliability for non-repairable systems. It is the mean time expected until the first failure of a piece of equipment. MTTF is a statistical value and is intended to be the mean over a long period of time and with a large number of units. For constant failure rate systems, MTTF is the inverse of the failure rate λ .The general expression for MTTF is given by (2).

$$E(t) = MTTF = \int_0^\infty xf(x)dx = \int_0^\infty R(x)dx \quad (2)$$

When the failure rate is constant with time, the times to failure are exponentially distributed. This leads to $\lambda(t)$.

$$MTTF = \int_0^\infty R(x)dx = \int_0^\infty \exp(-\lambda x)dx = \frac{1}{\lambda} \quad (3)$$

Mean Time between Failures (MTBF)

MTBF is a basic measure of reliability for repairable items. MTBF can be described as the time passed before a component, assembly, or system fails, under the condition of a constant failure rate. Another way of stating MTBF is the expected value of time between two consecutive failures, for repairable systems [4]. It is a commonly used variable in reliability and maintainability analyses. MTBF can be calculated as the inverse of the failure rate, λ for constant failure rate systems. For example, for a component with a failure rate of 2 in (failures per million hours), the MTBF would be the inverse of that failure rate, λ .The general expression for MTBF is given by (4).

$$MTBF = \int_0^\infty R(x)dx = \int_0^\infty \exp(-\lambda x)dx = \frac{1}{\lambda} \quad (4)$$

Mean Time to Recovery (MTTR)

MTTR is a factor expressing the mean active corrective maintenance time required to restore an item to an expected performance level. This includes for example, troubleshooting, dismantling, replacement, restoration, functional testing, but shall not include waiting times for resources.

3. MILITARY HANDBOOK (MIL-HDBK-217F)

Introduction and Applicability

Military Handbook 217F was developed in 1962 by the U.S. Department of Defense. The last edition of this handbook has been released in 1995.The purpose of this handbook is to establish and maintain consistent and uniform methods for estimating inherent reliability of military electronic equipments and systems. It also establishes a common basis for comparing and evaluating reliability predictions of related or competitive designs. The handbook is intended to be used as a tool to increase the reliability of the equipment being designed. There are two different methods for the calculation of reliability explained in detailed below.

Parts Count Method

Parts Count method is the failure rate prediction method at reference conditions. The failure rate for equipment under reference conditions is given by (5).

$$\lambda_{s,i} = \sum_{i=1}^{n} (\lambda_{ref}) \quad (5)$$

Where, λ_{ref} is the failure rate under reference conditions; n is the number of components.

The reference conditions adopted are typical for the majority of applications of components in the equipment. Reference conditions include statements about operating phase, failure criterion, operation mode (e.g. Continuous, intermittent), climatic and mechanical stresses, and electrical stresses.

Part Stress Method

Parts stress method is the Failure rate prediction at operating conditions. Components in equipment may not always operate under the reference conditions. In such cases, the real operational conditions will result in failure rates different from those given for reference conditions.

Therefore, models for stress factors, by which failure rates under reference conditions can be converted to values applying for operating conditions (actual ambient temperature and actual electrical stress on the components), and vice versa, may be required. The failure rate for equipment under operating conditions is calculated as follows given by (6).

$$\lambda = \sum_{i=1}^{n} (\lambda_{ref} \times \pi_u \times \pi_I \times \pi_T)_i \quad (6)$$

4. SOLAR POWER UNIT

Components of SPU

Solar power unit (SPU) mainly consists of three components: (1) solar panel, (2) Power converter and (3) Sensing component. The PV panel is a series parallel interconnection of PV cells and is the main power source. The power converter sets the maximum power point of the panel as desired by the controller that uses maximum power point tracking (MPPT) [5]. PV panel current and voltage sensing is achieved with simple sensing resistors or other devices, such as hall-effect current sensors. The SPU uses a dc-dc converter per panel, also called a micro-converter, with a dc output. Recent technologies show a push towards micro-inverters that are mounted on the PV panel and provide an ac output rather than dc.

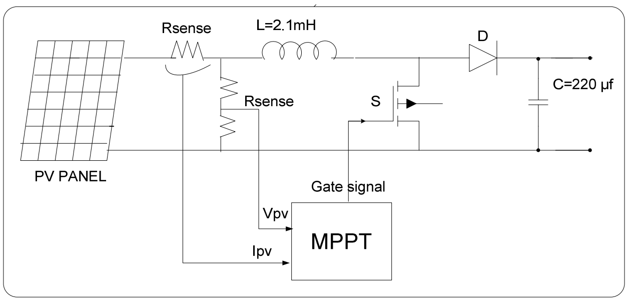

Fig. 2: Solar power unit

Faults in PV Panel

There are several faults in the panel, though PV panels are assumed significantly more reliable. PV panel reliability reduces significantly due to the occurrence of following types of faults. PV reliability depends heavily on PV material and temperature, humidity and radiation of the environment. Mono crystalline, crystalline and poly crystalline silicon PV panels which makes up over 90 % of the market degrade at a reasonably small rate. Amorphous silicon and copper indium de-selenide (CIS) PV panels show significantly higher degradation rates. Generally shading effect in PV panel degrades its performance [6]. Common faults are shown in Table 1. [7],[8],[9]

Localized heating within a PV panel called a hot spot is another fault that reduces reliability. When a cell in a standard panel configuration becomes negatively biased and dissipates power as heat rather than producing electrical power, Hot spot heating occurs. This occurs when the current produced by the cell is lower than the string current which results partial shading, cell damage, connection failure or uneven degradation. To limit the reverse biased voltage across the PV panel and limit hot spot heating bypass diodes are often used [10].

A component based approach can also be used to estimate the PV panel reliability. A closest component to a cell [11] is a photo-diode. A solar panel can be modeled as a series parallel combination of photo-diodes where the equivalent failure rate is that of a 6 x 12 matrix of photo-diodes.

Table 1: Faults in PV panel and its electrical impact

Fault	Electrical effect
Interconnect, contact insulation failure	Arcing or open circuit
Corrosion of Wire, terminals, and cell metal (including hail impact, moisture, and de-lamination)	Open circuit if severe, or reduced PPV
Severely cracked, fractured, mismatched cell	Cell back-biasing (reduced ISC) and/or overheating (Reduced VOC)
UV weathering	Material degradation (reduced PPV)
Optical surface soiling	Temporary reduction of PPV and ISC

Other faults and physical effects on failure rates

With one converter, control and sensing per PV panel, SPUs can be aggregated in series parallel combinations to form larger arrays. Most of these faults are outlined in [12]. These faults occur in semiconductors, electrolytic capacitors and other components as summarized in table 2.

Table 2: Faults occur in components used in SPU

Components	Faults
MOSFET(S)	Open circuit (OC) Short circuit (SC)
Diode (*D*)	OC SC
Capacitor (*C*)	Degradation: *C* drops by 25% OC SC
Inductor (*L*)	Multiple-winding short: *L* drops by 90%
PV panel	*VOC* drop by 50% *ISC* drop by 50% *VOC* and *ISC* drop by 25%
Connector	OC
Physical faults	Connector OC, *VOC* and *ISC* drop

Failure Rates

Failure rates vary with varying operating conditions and ratings. Table 3 summarizes the failure rates denoted by λ with appropriate subscript for each component and the subscript *b* denoting the component base failure rate. The values of affecting factors are denoted by π with appropriate subscript [13][14].

Table 3: Failure rate model for different components

Components	Failure Rate Model
Capacitor (*C*)	$\lambda_C = \lambda_{C,b}\,\pi_T\,\pi_C\,\pi_S\,\pi_{SR}\,\pi_Q\,\pi_E$
Inductor (*L*)	$\lambda_L = \lambda_{L,b}\,\pi_T\pi_Q\,\pi_E$
MOSFET (S)	$\lambda_S = \lambda_{S,b}\,\pi_T\pi_A\,\pi_Q\,\pi_E$
Diode (*D*)	$\lambda_D = \lambda_{D,b}\,\pi_T\,\pi_{CC}\,\pi_S\,\pi_Q\,\pi_E$
R_{sense}	$\lambda_R = \lambda_{R,b}\,\pi_T\,\pi_P\,\pi_S\,\pi_Q\,\pi_E$
Connector	$\lambda_{CN} = \lambda_{CN,b}\,\pi_T\pi_K\,\pi_Q\,\pi_E$
One PV cell	$\lambda_P = \lambda_{P,b}\,\pi_T\,\pi_Q\,\pi_E$

5. SPU'S RELIABILITY MODEL

Table 4 provides base failure rate for selected type of components used in SPU. These base failure rates vary according to the type of component and other π- factors vary according to operating conditions, ambient and junction temperature as shown in Table 5.

Table 4: Base failure rate for components of SPU

Components	Value (Failure/hour x 10^{-6})
Capacitor (*C*)	$\lambda_{C,b}$=0.00012
Inductor (*L*)	$\lambda_{L,b}$=0.00003
MOSFET (S)	$\lambda_{S,b}$=0.012

Diode (D)	$\lambda_{D,b}$=0.025
R_{sense} λ_R	$\lambda_{R,b}$=0.0037
R_{sense} (voltage)	$\lambda_{R,b}$=0.0017
Connector	$\lambda_{CN,b}$=0.007
One PV cell	$\lambda_{P,b}$=0.04

Table 5: Different application factors for failure rate

Factor	Value
π_T Ambient temperature = 20°C, junction temperature = 40°C	*C*, 0.79 *L*, 0.93 *S*, 1.4 *D*, *1.6* *Rsense*(current), 0.95 *Rsense* (voltage), 0.88 Connector, 1.3 PV cell, 1.6
π_E	Benign environment 1
π_Q, Quality	*C*, *L*, *Rsense* (current), *Rsense*(voltage), 3 *S*, *D*, PV cell, 5.5 Connector, 2
π_S, Stresses (voltage or power)	*C*, 1.4 D, 0.19 *Rsense*(current), 0.79 *Rsense*(voltage), 0.66
π_C, Capacitance	3.4
π_{SR}, Series resistance	3.3
π_A, Application, 250Wmax	8
π_{CC}, Contact construction	1
π_K, Mating factor	1
π_P, Power rating	0.4

6. RELIABILITY CURVE OF SPU

Figure 3 shows the reliability curve of SPU model as designed above. The failure rates are calculated by using Military Handbook 217F. The failure rates vary according to variation in the operating environment. There are different types of environments considered in Handbook given by Table VI [12].

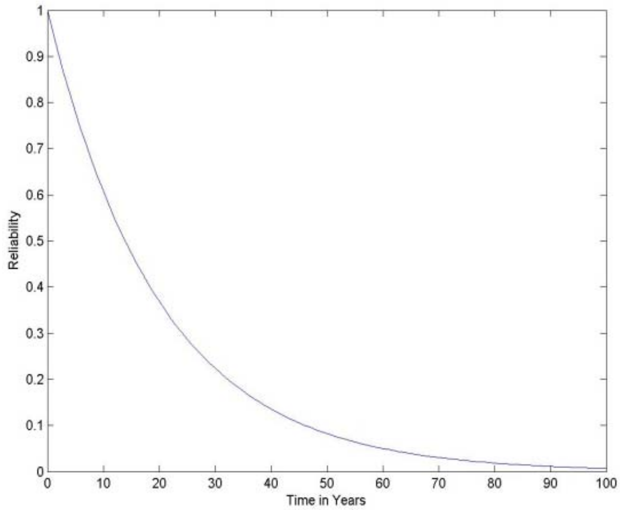

Fig. 3: Reliability Curve

Calculated Failure Rates:
lambda_d = 0.0418
lambda_S = 0.7392
lambda_C = 0.0045
lambda_L = 8.3700e-005
lambda_P = 2.1120
MTBF = 3.4246e+005

Table 6: Different Types of Operating Environments

Environment	Symbol	Environment	Symbol
Ground benign	GB	Ground fixed	GF
Airborne uninhabited (cargo)	AUC	Airborne uninhabited (fighter)	AUF
Ground mobile	GM	Missile launch	ML
Naval sheltered	NS	Space flight	SF
Naval unsheltered	NU	Missile flight	MF
Airborne inhabited (cargo)	AIC	Airborne rotary winged	ARW
Airborne inhabited (fighter)	AIF	Cannon launch	CL

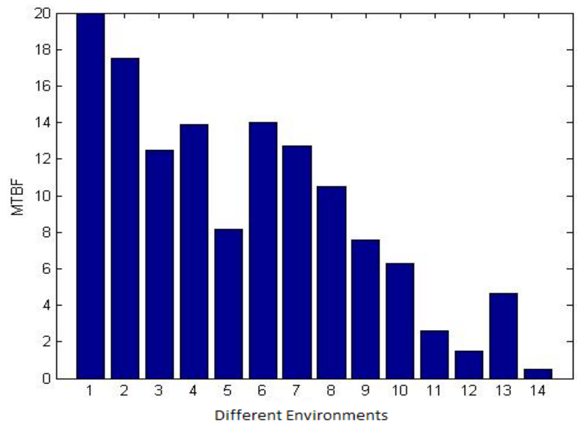

Fig. 4: MTBF for different environments

7. CONCLUSION

This paper shows the calculation of overall Reliability of solar power unit. It is clear that the PV panel reliability is an important factor of the system. The MTBF variation with different operating environments is significant and is shown in Fig. 4. Benign, ground and air borne environments maintain a reasonable MTBF while harsher operating environments greatly reduces the reliability.

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