Aspects of Reliability Implementation of Photovoltaic Systems

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Abstract ***– The high-cost energy provided by operating centralized power plants and their related infrastructures, immerse researchers to find other means of fulfilling energy requirements. Solar photovoltaic (PV) technology is an appropriate and cost-effective source of electricity for many applications, bringing basic services and facilities in an environmentally friendly manner. Photovoltaic systems involve an interdisciplinary approach in ranging fields, namely reliability, motor drives, controls, inverters, switched mode converters, battery chargers etc.***

With this as the area of interest, focus of paper is in the reliability of switched mode power converters area, which supports advancement and dissemination of the PV application technology domain. The PV applications involve a switched mode power converter that drives a physical system that is either a mechanical system or an electro-mechanical system.

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Keywords: *Solar Photovoltaic (PV) Technology, Uncertain system, Converters, optimal approach.*

I. INTRODUCTION

Utility restructuring, technology evolution, environmental policies and increasing electric demand are stimuli for deploying new distributed generation (DG), the modular electric generation or storage located near the point of use. The dilemma that researchers have to face is to maintain a system which only to keep lamps burning, but to keep them in working for billions of people to meet needs, while protecting the environment. The solution is not a choice between tradition and innovation but reconciliation between them. Renewable energies were used to enlarge the advantages of inexhaustible resources, little pollution, a insignificant contribution to changes climate.

Photovoltaic converters translate directly solar energy into electricity through optical excitement p-n junctions. Although the first effective photovoltaic converter has been developed on the mid-20th century, the conversion of solar energy is very topical because it is clean energy. The first applications of it were referred to the space missions.
Foreseeable future use today may include production of electricity needed to power domestic consumption between 1-4kW, the converters of the order of 0.1 mW as electrical sources for artificial organs implanted in the human body.
The main advantages of photovoltaic converters are:
- Maximum energy efficiency 14-25% now;
- Unlimited duration of operation;
- Constructive simplicity;
- Specify the weight W product reduced.

The disadvantages include:
- Need for energy storage for periods of low solar activity;
- Degradation due to radiation of certain frequencies.

II. PHENOMENOLOGY OF PHOTOVOLTAIC EFFECT

Load encircled in a p-type semiconductor is negative ion of boron and in an n-type semiconductor is positive phosphorus ion are fixed in the network. Free loads (uncircled) are electrons in the material n and gaps in material p.
Free electrons diffuse in left as the gaps distribute in the right. This occurs until the potential V that is formed is able to stop further diffusion of tasks. Thus was created a macroscopic magnetic field in the junction without an external electric field. The macroscopic potential V can not even provide a direct current from an external load. Internal potential V increases with increasing doping of the two parties, until the forbidden band width, e.g. According to the trend towards the position of energy minimum electrons tend to move to the right and left pre gaps, so only the minority carriers are sensitive to this phenomenon. By bombing junction with a photon, $h\nu$, whose energy

exceeds the forbidden band, it will be absorbed, and as a result.

During the formation of electron-pair gap and separation of duties should avoid their recombination. In other words, the life time of the minority holder should be large enough to prevent recombination. By separating the tasks are created due to the action of a photonic electric field, $E_{photons}$, opus created by the internal diffusion $E_{diffusion}$, corresponding internal potential V. As the two fields come to cancel each other to carry traffic attenuates reach in the final to the idle the junction. Elementary photovoltaic converter based on silicon irradiated by the sunlight has the following characteristics V_{OC} = 0.58 V (voltage V_{OC}-voltage in no load regime) = 45mA ISC (ISC-current at maximum power). Short circuit current is higher as the number of electrons and holes created by photons is higher, i.e, in the case of solar photovoltaic converter, while the optimum tension photovoltaic converter which is obtain a maximum cutting power increases with forbidden band width. It is easy to predict that there is an optimum voltage at which the photovoltaic converter to obtain maximum cutting power.

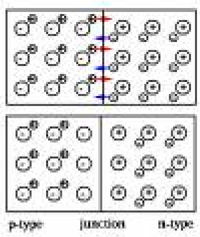

Figure 1: The photon effect

To identify and evaluate the important elements which are responsible for the life cycle economic performance of PV systems by investigating economic data for all key components of PV systems and by gathering information about real life costs of maintenance of PV systems. Balancing the investments, the capital costs against the electrical and economical output of the PV system during its life cycle will enhance the knowledge of true life cycle economic performance of PV systems.

III. QUANTUM ANALYSIS OF THE PHOTOVOLTAIC EFFECT

If we note with *f* the number of pairs of electron-gaps created by solar radiation per cm^3 *second, then increasing of electron density and the usable gaps in converter is expressed according to equation:

$$\Delta_n = f \cdot \tau_n^*,\ \Delta_p = f \cdot \tau_p^* \qquad (1)$$

where τ_n^* and τ_p^* represent the effective life time of the minority holder.

Therefore changing electric conductivity $\Delta\sigma$ is formalized as stated in equations (2):

$$\Delta\sigma = e(\Delta_n \cdot \mu_n + \Delta_p \cdot \mu_p) = ef(\tau_n^*\mu_n + \tau_p^*\mu_p) \qquad (2)$$

The current I_s produced by irradiation with photons has the following representation:

$$I_s = e \cdot F^/ \cdot \tau^* / T_r \qquad (3)$$

where $F^{'}$ is the number of electron-gaps pairs created per second by absorbed photons, τ^* is the effective life of the holders, and T_r is the time of electron transition between the two sides of the junction:

$$T_r = L/(\mu E) \qquad (4)$$

where μ is drift and E is the electrical applied time. But how V=LE, it will result that:

$$Tr = L^2/(\mu V) \qquad (5)$$

A photon can create more than one electron - gap pair and the apparent growth G, is:

$$G = \tau^* / T_r \qquad (6)$$

Irradiation of the junction with photon has a similar effect by applying a direct voltage *u* on the junction. If I_p is the current of the electrons in the conduction band thermic excited in the *p* region and I_n is the current of the electrons in the region *n*. For u = 0, equilibrium equation may be written as:

$$I_n = I_p e^{(eU/kT)} \qquad (7)$$

Electrons in the *n* region are favored to go to the left in region *p* by *u* potential while in the p electrons are not influenced by the potential *u*.

If we consider and current produced by photons, then the total current through the junction I is:

$$I = I_\phi - I_n + I_p = I_\phi - I_p(e^{(eU/kT)} - 1) \qquad (8)$$

Maximum voltage occurs in no-load regime (I = 0), u_0, and concludes equation 8

$$u_0 = \frac{KT}{e}\ln\left(\frac{J_s}{J_0} + 1\right) \qquad (9)$$

Specific power, P [W/cm^2] is:

$$P = J \cdot V = \left(J_s - J_0\left(e^{eV/KT} - 1\right)\right) \cdot V \qquad (10)$$

Maximum specific power in relation to the voltage V is obtained from the condition:

$$\frac{\partial P}{\partial V} = 0 \qquad (11)$$

and has the expression:

$$P_{\max} = \frac{(eV_{mp}/KT)V_{mp}J_s}{1 + eV_{mp}/KT}\left(1 + \frac{J_0}{J_s}\right) \qquad (12)$$

where: V_{mp} is the voltage which maximize the specific power calculated iteratively from ec.11.

If we note the number of photons (N_f) of the solar spectrum per cm^2, energy average E_{mediu}, then maximum efficiency of the converter may be written as:

$$\eta_{\max} = \frac{(eV_{mp}/KT)V_{mp}J_s}{(1 + eV_{mp}/KT)N_f \cdot E_{mediu}} \qquad (13)$$

admitting that $J_s >> 5J_0$.

It should be noted that the number of photons in the solar spectrum whose energy is higher than the prohibited bandwidth E, decreases with the increase of E_g while V_{mp} voltage and increase with J_s/J_0 E_g

IV. RELIABILITY OF PHOTOVOLTAIC CONVERTERS

In general, due to low voltage and power, photovoltaic cells are connected in panels in order to obtain the power required by consumers. Failure of cells will lead to the deterioration of the system. The main causes of the defect of a photovoltaic cell are:

- Contact inadequately leading to disconnection of the cell;
- Increasing series resistance due to damage to cell contacts or terminals;
- Contact melting and the production of a short circuit on the junction;
- Due to radiation damage.

By linking a series-parallel cell failure in one cell does not function out of the whole converter.

Effect of electron radiation and high energy protons on photovoltaic converters is of great interest because they have discovered the radiation belts around Earth. Improving resistance to radiation is achieved by:

- Reducing the life of the holder by increasing their mobility.
- Recent research has demonstrated outstanding qualities of self cells p / n lithium dosage at the junction p / n.
- Adding a roof protecting the sapphire of 0.25 g per cm2 ensure protection against electrons with energies below 1MeV.

The reliability of PV modules and systems is critical to the commercial success of Photovoltaic. Financial payback requires PV systems to reliably produce the promised electricity over the warranted time period.

Sunlight is ubiquitous and the worldwide potential for solar photovoltaic systems is indeed very high. Two factors determine lifetime of PV: reliability, which refers to premature failure of the product, and durability, which attends to slow degradation that eventually decreases production to unacceptable levels. Cost effectiveness, energy payback balance and public acceptance of photovoltaic energy strongly rely on the reliability and the long lifetime of modules. However, in order for PV technology to achieve the growth needed to establish itself as one of the key renewable energy technologies, certain technological difficulties, both at the component level and at system level must be overcame. These challenges, in turn, form the opportunities for research and further development in this technology. Besides policy and economic issues, the issues that drive a renewable energy source can be classified into:

1) Environmental impact including safety and health and 2) Performance including safety and health aspects related to performance.

For a renewable energy source, the issues of importance related to environmental impact are energy pay back time (EPBT), greenhouse gases (GHG material availability can possibly occur in the case of thin-film technologies involving scarce) emission, emission of pollutants and resource availability. In general, material availability is not expected to be a major constraint in the development of PV technologies [1]. This is particularly true for silicon based technologies. The emission of pollutants in the manufacturing process of PV technology is minimal and is mainly due to the use of energy during manufacture [2]. The life cycle GHG emissions from PV installations are also significantly lower than from a few of the major options, for e.g., fossil fuel combined with carbon capture and sequestration. Though the GHG emissions due to PV technologies are somewhat higher than those due to two nuclear power and wind power, this may be expected to be lower and can be comparable to that achieved by current wind energy technologies in future.

The Energy Pay Back Times (EPBT) of a renewable energy system is the time needed in years for the energy invested in manufacturing and installing the system to be recovered. The estimates of EPBT differ significantly based on the technological assumptions made and the installation locations considered.

For Si PV technologies, the pay back period is currently between 1.6 years and 2.2 years when the irradiation level is 1700 kWh/m2/year and increases to between 2.7 years and 3.6 years if the insulation is only 1000 kWh/m2/year [2]. In future, when Si PV cells are made directly from solar grade silicon instead of waste electronic grade silicon, the energy requirements will be even lower. For thin film technologies, since less material is used, the EPBT values are low, even as low as 1 year.

It is also found that life-cycle studies of PV inverters are not easily available with low values of EPBT being attributed generally to inverter sub-systems. In view of the limited life times of typical PV inverters, further study of the EPBT of PV inverters is called for. Also, as PV penetration becomes deeper, energy storage will become more and more necessary in grid-tied systems. The EPBTs of such systems with large energy storage will be significantly higher and must be investigated.

Modules in the field are subjected to static and dynamic mechanical loads, thermal cycling, radiation exposure, ambient humidity, hail impact, dirt accumulation, partial shading and so on. Common failure modes [124, 141] are related to the action of weather agents in combination with deficiencies in fabrication.

The various aspects of concern with regard to performance can be divided into as being related to cell/module technologies or BOS (balance of system) technologies. The most commonly used cell technologies have so far been wafer based single crystalline silicon (s- Si) or multicrystalline silicon (m-Si) technologies or ribbon based silicon technologies. If photovoltaic systems are to deliver energy at low enough prices to compete in the wholesale electricity and energy markets, then the technology should be capable of high efficiency and be nontoxic, based on abundant materials and also durable [3]. Thin-film technologies use less material and are more suited to module production. Since crystalline Si, PV cells use thicker materials and are inherently more expensive, the performance efficiencies of thin film technologies need to be improved in order for PV technology to become competitive.

For PV systems to perform well, both the cell technologies and BOS component technologies are equally important. Ref. [4] provides a good review of the overall status of the reliability of both PV modules and balance of system components.

The output of a PV array is DC and this poses special problems to be addressed both in terms of design and installation. System safety is particularly important in residential roof-top PV ms with high DC system voltages. Thus, as PV systems become more common, there is a need for the development and strict enforcement of design, installation and maintenance standards. With age, the installation can deteriorate can become potentially hazardous.

The short circuit current in a PV system is low and varies with insulation. Also, the system will generally include another source (battery or the grid) capable of high fault current. These factors complicate the task of PV system protection. Being a DC power system, potential for sustained and dangerous arcing exists in a PV array even at comparatively low voltages. It is imperative that this issue is addressed through reliable and inexpensive arc detection scheme [6] or by other means. While the average life duration of PV modules have reached 20 years and more, the inverters are typically guaranteed for only 5 years; they are generally considered to be the weak link undermining a PV system's long term reliability. According to [7], the mean time to first failure (MTFF) for an inverter is estimated to be five years and there is a need to develop the next generation inverter with an MTFF of at least ten years. Ref. [7] also discusses the issues to be addressed and the approaches to be taken for improving the reliability of the inverter. This includes standardization and modularization of inverters, efficient inverter technologies, advanced packaging and interconnection technologies and mature manufacturing practices and testing methods. Reliability of electrolytic capacitors is a critical area requiring technological improvement. Several well-known problems arise when several PV generators simultaneously feed energy in to the system [8], particularly during periods of high solar insulation.

These include issues such as

1) introduction of unwanted harmonics and EMI noise in to the power system,
2) voltage rise due to lack of reactive power support;
3) overloading of system resources;
4) difficulty in fault current protection
5) personnel safety considerations which require that adequate 'anti-islanding' measures be incorporated into PV inverter systems.

Besides the above, a major issue is the intermittent nature of the PV (as well as wind) energy source and its consequent effect on power system reliability. The problem is somewhat mitigated in the case of PV systems, due to the period of solar energy availability coinciding generally with the periods of increased electricity demand. However, problems will still arise if PV penetration increases significantly, which will require that the flexibility of the utility run power system be increased significantly [9]. Before large-scale introduction of such systems, environment issues including material resource availability and energy payback periods and end-of life disposal of such systems must be fully investigated besides energy turn-around efficiencies and cost.

In reliability theory, one way to improve the performance of a system is to use the redundancy method. There are two main such methods:

1. Hot duplication method: in this case, it is assumed that some of the system components are duplicated in parallel;
2. Cold duplication method: in this case, it is assumed that some of the system components are duplicated in parallel via a perfect switch. Unfortunately, for many different reasons, such as space limitation, high cost, etc, it is not always possible to improve a system by duplicating some or all of its.

CASE STUDY

We assume that the time between failures can be modelled as a form of the two-parameter Weibull distributed random variable, with probability density function *f(t)* and cumulative distribution function *F(t)* defined as follows [4],[5]:

$$f(t) = \frac{\beta}{\eta^{\beta}} t^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{14}$$

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{15}$$

The scale parameter η, (63.21% of the values fall below this parameter) is directly proportional to the mean time between failures (MTBF) index, while the shape parameter β, which determines distribution shape, provides more information about the nature of the failure mode. β values lower than 1 indicate the so-called infant-mortality period when the system is more likely to fail early on and becomes more reliable as time passes. If β≈1, failures occur independently of time and the system is in the useful life period. Finally β values higher than 1 indicate so-called wear-out failures, indicative of the more frequent failures occurring toward the end of the projected lifetime of the system.

The Weibull, one of the most versatile distributions is commonly used in reliability engineering, partially due to its flexibility and ability to represent those three distinct periods in the life of a complex system just by changing the shape parameter β. An alternate description of the failure distribution can be made using the failure rate function λ(t), which shows the relationship between the age of the system and its failure frequency, i.e. represents the probability of failure at time t given that the system has not failed before t. In the case of the Weibull distribution, the parameter β dictates the shape of the failure rate function, making it a decreasing function, when β<1, constant for β=1 and increasing for β>1, as shown in figure 2 [4].

$$\lambda(t) = \frac{f(t)}{1-F(t)} = \frac{\beta}{\beta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{15}$$

We assume that the behavior of PV systems can be characterized using the so-called reliability bathtub curve, as shown in Figure 1, i.e. the initial decreasing failure rate period (infant-mortality) is followed by a relatively long constant failure rate period (useful life),while the probability of failures sharply increases toward the end of the system's design life (wear-out period). The bathtub curve represented in Fig. 2 is obtained as a superposition of three failure modes, with shape parameter (β), lower, equal and respectively higher than 1. Over the life of a complex system, three distinct failure rate phases may become apparent. The first phase or period is referred to as the infant mortality period, which is shown as the decreasing failure rate on the left segment of Fig 2. The second phase is the random or constant cause failure period, which is the period of time encircling the flat portion of the curve, where the failure rate remains constant. The last phase is the wear-out period, which is shown on the right side of Fig. 2 as an increasing failure rate. The wear-out phase is more predominant in mechanical systems than in electronic system.

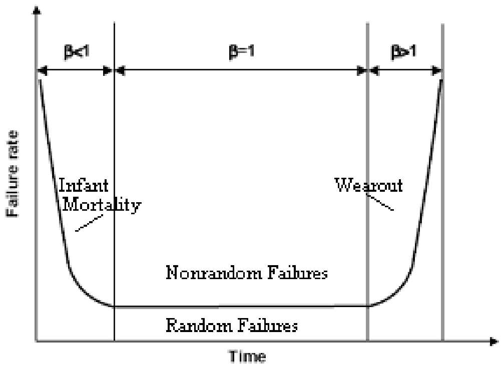

Figure 2: The Bathtub curve for a dynamic system

The system under inspection may have several failure modes, i.e. there may be several independent failure mechanisms in all three periods. If these failure mechanisms can be identified, a separate analysis may be used for each mode, and the performance prediction is obtained as a superposition of the effects of all failure modes. However, we assume that the system's performance can be modelled using only three failure modes. A failure mode decomposition can be used if the cause each failure is known; in the absence of the information about the exact cause of each particular failure, the decomposition of the system's failure data into separate failure modes may be greatly complicated. Closed-form solutions for individual failure mode parameters are in general intractable, except for several special cases. In the case of only two competing failure modes, several methods are available for estimating the parameters for each of the competing failure modes. Assuming that the underlying distribution for both failure modes is Weibull, the shape and scale parameters can be obtained using the procedure presented in [10]; however the estimates are valid only when for each mode k, its shape parameter β_k is higher than 1, or when the times to failure corresponding to mode *k* are not small compared to the total sample size. The procedure can be used to obtain the parameters for both modes if at least two known-cause failures for each failure mode are known.

Unfortunately, these assumptions may not always be guaranteed. The most likely scenario would be that only the times between typical system (Fig.3) failures would be known, and that the cause of each individual failure has not been recorded.

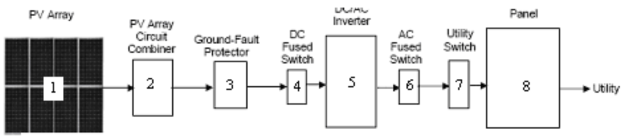

Fig. 3 Typical photovoltaic system

Given the complexity of the CNE to determine the reliability of indicators commonly used in the predictive study should be treat successive level subsystems, and then corroborating the results from the system. For the structuring the subsystems are taking into account the complexity of the system, depth of proposed analysis and specific functions. The first step in analyzing the reliability is representing the system by an equivalent reliability block diagram (RBD) for the first level of detail to study the estimated reliability.

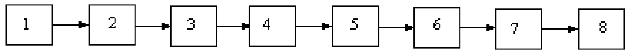

Fig. 4. Reliability Block Diagram for a photovoltaic system

This scenario which shows failures of a system with three failure modes; failures corresponding to each of the three modes and their cumulative effect are shown. If the resulting system level failures are used to extract Weibull distribution parameters, assuming that all failures are due to only one failure mode, significant errors may be introduced.

For the purpose of reliability-based prediction of a PV system's energy output throughout its life, only the distribution parameters that govern the constant failure period (when β≈1) are of interest. We assume that the early failures will become less frequent in the future as the PV inverter technology matures, and that the wear-out failures will be engineered to occur only after the design life of t After the parameters for the useful-life period are obtained, slightly modified procedure can be utilized to continuously monitoring the system's reliability characteristics, and possibly discover the appearance of a wear-out failure mode. Weibull distribution parameters are calculated using only the data in the interval [t-T_a, t] where t represents the present time and T_a represents the length of the window that guarantees correct determination of the useful life Weibull parameters, as explained previously. If no wear-out failures exist, the estimates obtained using the data in $[t-T_a, t]$ and $[t-T_a, t+\Delta t]$ (and $[t-T_a+\Delta t, t+\Delta t]$) should be the same. The existence of another failure mode is detected as a deviation from the constant line in the graphs. The length of the interval used for wear-out detection should not be larger than Ta, the length that was determined to be large enough for accurate detection of the useful-life period parameters. This period was determined to be 5 years. We could use all data from T_1 until the present time, but this might decrease the ability to detect the wear-out failure mode since too many data points from the useful-life period would have been used for parameter estimation, and more wear out failures would be needed before the new failure mode is detected. The system have been monitored for several more years, and the third, wear-out, mode with parameters $\eta_3=0.6$ and $\beta 3=4$ has been introduced at $T_2=15$ years.

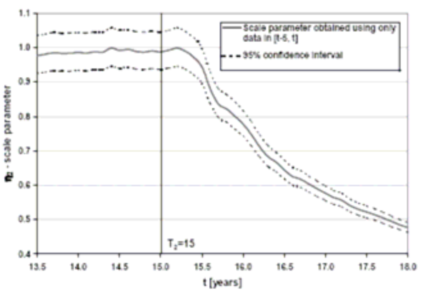

Fig. 5: The estimate of Weibull scale parameter η_2 for failure mode of PV showing the detection of the wear-out failure mechanism

For the analyzed PV system it were calculated the empiric reliabilities which were compared with the reliabilities obtained using the analytical method. Therefore, they were taken into account the next parts of the PV system: the PV array (1) , the PV array circuit combiner (2), the ground fault protector (3), the DC fuse switch (4), AC/DC invertor (5), the AC fuse switch (6), the utility switch (7), the main service pannel (8). It must to be mentioned that the AC/DC invertor (5) and the main service pannel (8) were considered separately because there were many cases when just one of them was damaged. In Fig. 6 is represented the reliability of the PV system.

TABLE 1. The Weibull parameters values.

PV system	Weibull parameters		Correlation coefficient
	β	η	
PV arrray	1.0783	1.0323	0.9632
PV arrray circuit combiner	1.0642	1.0215	0.9752
Ground fault protector	1.0564	1.0367	0.9748
DC fuse switch	1.0647	1.0204	0.9468
AC/DC invertor	1.0539	1.0194	0.9735
AC fuse switch	1.0745	1.0245	0.9784
Utility switch	1.0578	1.0576	0.9687
Main service pannel	1.0739	1.0781	0.9877

It was represented by points the empiric reliability and it was plotting the analytical curve based on the parameters values which were determined using the regression analysis. The parameter values and the correlation coefficients for each case are presented in Table 1. Thus, it can be remarked for each situation the high values of the correlation coefficient.

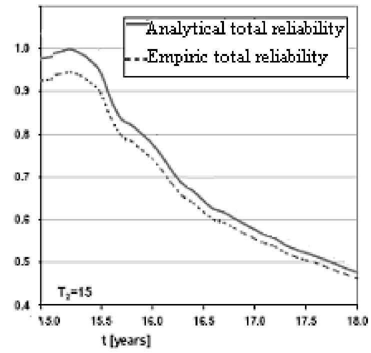

Fig. 6 The total reliability of the PV system: 1-empiric total reliability; 2 – analytical total reliability.

From Fig. 6 it can be observed that after approximately 15.5 years of working of the PV system the total reliability decrease very much.

V. CONCLUSIONS

The necessity of filtering initial, infant mortality, failures, estimating, useful-life, distribution parameters, and detecting the end of the useful-life period of PV systems is emphasized in the paper. Infant mortality failures are generally the result of manufacturing errors that are not caught in inspection prior to burn-in or placing in service. Failures resulting from time/stress dependent errors may occur in this period. Random Failures and wear-out failures are generally a factor of design.

No distinct break off from infant mortality to random to wear-out failure has been established. Random failures can occur anywhere in the three periods, as can infant mortality failures. A failure caused by a cold solder joint may occur well into the service life, but this is really an infant mortality type failure. Wear-out of mechanical parts also begins the moment the product is put into service.

The probability distributions occurring most often during the infant mortality period are Weibull, gamma, and decreasing exponential. Probability distributions of value in the constant failure rate period are exponential and Weibull. During the wear-out period, the curves generally follow the normal or Weibull distributions.

Photovoltaic (PV) energy system, the system is usually assumed to work without interruptions over its entire life. PV energy systems are fairly reliable, but as any complex system, they may fail. In PV systems, the inverter is responsible for the majority of failures, and most inverter failures are blamed on the aluminum electrolytic capacitors typically used in the dc bus. Product reliability and durability and environmental and aesthetical friendliness are as important as cost for the growth of PV industry and this also influences technology.

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