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Proportional Hazards Modeling of Environmental Impacts on Reliability of Photovoltaic Modules

E. Suresh Kumar, Bijan Sarkar

Abstract— The effect of operational environment on the reliability performance of solar photovoltaic module can be analysed . The first step is to identify which factors have the most significant influence on the reliability performance of photovoltaic modules and systems and how large is the effect. The available information about the operating conditions of the PV modules can be uniformly formulated based on two alternatives , good/desired (+1) and bad/undesired (-1) conditions. With respect to reliability, the available method PHM (Proportional Hazards Model) can be used for predicting the effect of environment on the system reliability. The reliability characteristics of PV modules can be influenced by environmental conditions such as temperature , snow, wind etc and these influences therefore need to be seriously considered in the prediction of reliability in the design phase. The conventional reliability equation deals with over a time interval and is a measure of the probability for failure-free operation during the given interval, i.e., it is a measure of success for a failure free operation. It is often expressed as $R(t) = exp(-t/MTBF) = exp(-\lambda t)$, where MTBF is the Mean Time Between Failure and λ is the failure rate, which is the reciprocal of MTBF. In this paper an attempt is made to modify the time equation of reliability with incorporating environmental impacts like temperature, wind and snow.

Index Terms—Mean Time Between Failures, Failure rate, Weibull distribution, Proportional Hazards Model, Time to failure (TTF) Ttime between failures (TBF).

I. INTRODUCTION

There are a number of factors affecting PV module performance, viz, the nonlinear dependence of conversion efficiency on module temperature (which in turn depends on air temperature, the type of mounting and wind) and irradiance levels, typically declining for low irradiances and for high temperatures, Changes of reflectivity when irradiance hits the module at an angle that differs from perpendicular usually termed angle-of-incidence effect (AOI) considering different type of modules surfaces, angle and type of dirtiness, Changes of efficiency of PV modules due to the variable spectrum of the sunlight, which in turn depends on sun height and meteorological conditions, usually termed spectral effects, For thin film modules, changes in conversion efficiency due to its previous state, the history of the module (usually termed light-soaking and thermal annealing effects), Changes of modules performance with long-term exposure to outdoor conditions (normally degrades), which in turn affects the overall lifetime energy output (ageing effects), Intermittent occasional variables such as shading, pollution, snow, mismatch, etc. The above list is not exhaustive. The strength of these effects varies between PV technologies and even between modules using the same class of PV material. At the PV system level there are other factors determining PV power production: (1). Losses in cables and interconnections. (2). Efficiency of inverters, transformers and other power electronics. (3). PV system downtime due to component failures or maintenance.

But several other issues should be considered for failure free operation of the system in the site even though the modules and the balance of system components have high reliability and life time. The following are the factors which should be considered for long term reliability of the overall system in the field.

1. Sun shine hours at the site. 2. Lightning and thunder at the site. 3. Earthquake at the site. 4. Wind and wind direction at the site. 5. Corrosion at the site. 6. Strategic importance of the site. 7.Power availability and demand mismatch. 8. Shades at the site.9. Alternate power availability at the site. 10. Transportation access to the site. 11. Albedo effect at the site. 12. Icing and snow at the site. 13. Dust at the site. 14. Land availability. 15. Staebler- Wronski effect. 16.Heat island effect at the site.

A PV module will be typically rated at 25ºC under 1 KW/m^2. However , when operating in the field, they typically works under a lot of environmental stresses like varying module temperature, ambient temperature, long term degradation, spectral issues, irradiance , wind speed, wind direction, air gap between modules, dust, rainfall, corrosion, water vapour intrusion, delamination of encapsulant materials, Thermal expansion, ultraviolet radiation, humidity, mechanical load, salt mist, partial shading, heat island impact, global climate change, summer-winter climate change, Staebler- Wronski effect, Clearness of sky, urban heat island (UHI) effect, ageing and component derating. Further, the PV performance depends on material technology, production and manufacturing process.

Literature survey shows that experimental, analytical and simulation studies of PV system is the measurement of performance of the system with varying irradiance for different technologies. Also the study reveals the variation in performance of the system under STC and real field. Real field implies that the location chosen by the analyst. But the same performance may not be available from the system when the geographical area is changing. In India itself, the climate and the weather is totally different for different parts, like Leh

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(The temperature can range from −28°C in winter to 33 °C) in summer, Bikaner (In summer, temperatures exceed 50 °C and during the winter it dips to freezing point), Chennai (18°C to 45°C), Mumbai (The temperatures in average about 30 °C in summer and 18 °C in winter). This will be totally different even for other cities in the Asian countries. The performance entirely varies for Europe, American and African Countries.

A model developed based on such field data may not be useful for a design engineer and reliability analyst to design and assess the performance of a PV system for some other climatic conditions in a different location. Performance variation due to some parameters were addressed in this paper. No model so far developed with addressing all these parameters and a global model. Being an emerging filed for the future, a lot of study , experiment and modeling required to improve the efficiency and reliability as well to support design engineers with maximum possible data for improved design.

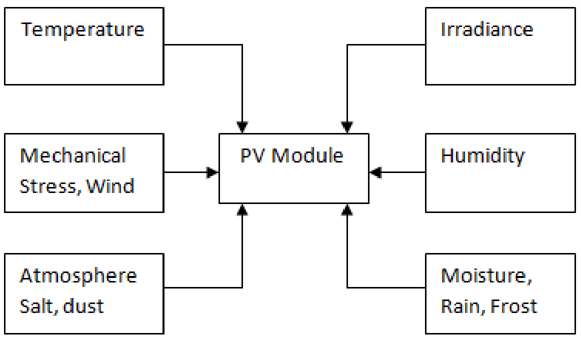

Figure 1: Various environmental stresses on PV module

Table I lists the observed field failures as a percentage of the total number of failures observed from 1994 through 2005 at BP Solar and Solarex [1].

TABLE I - Types of Field Failures Observed

Sl. No.	Types of Failures	% of Total Failures
1	Corrosion	45.3
2	Cell or Interconnect Break	40.7
3	Output Lead Problem	3.9
4	Junction Box Problem	3.6
5	Delamination	3.4
6	Overheated Wires, Diodes, Terminal Strip	1.5
7	Mechanical Damage	1.4
8	Defective Bypass Diodes	0.2

Since that time the statistics have changed somewhat with fewer returns due to corrosion, delamination and interconnect breakage as the materials utilized and automated processing have reduced these types of failures. A larger fraction of returns now involve workmanship issues. These types of problems can be harder to solve as they do not tend to show up in the accelerated stress tests nor in design qualification tests of prototypes. The best approaches to eliminating workmanship issues are to design for manufacturability and to build in redundancy. In other words make the process steps easy to perform and build in safety margins such as using both mechanical and solder connection where there is the potential for a single point failure.

II. ENVIRONMENTAL IMPACTS

Collision theory supposes that the rate of reaction depends on the rate collision of particles that are reacting. The rate of reaction directly depends on the rate constant k which can be expressed as $k=A*\exp^{(-E_a/R*T)}$, known as the Arrhenius equation [2], where, A is a constant, E_a is the activation energy, R is the universal gas constant, and T is the temperature (in kelvin).

A. *Temperature Impacts*

TABLE III - Accelerated Life Testing Data Of Same Set Of Pv Modules At Two Different Temperatures.

Accelerated Life Testing Data		
i	**Failure time (h) at 373ºK**	**Failure time (h) at 393ºK**
1	18816	14112
2	26880	20160
3	32760	24696
4	37968	28560
5	42840	32088
6	47712	35784
7	52752	39648
8	58464	43848
9	65352	49056
10	76272	57288

Table II the simulated failure times at 100°C (373°K) and 120°C (393°K).

The lifetime follows a Weibull distribution [3] with $ß = 2.6$, $\eta_{373K} = 52006$ h and $\eta_{393K} = 39151$h. This permits obtaining the two parameters of the Arrhenius model. The slope and intercept of the line suggest an activation energy E_a

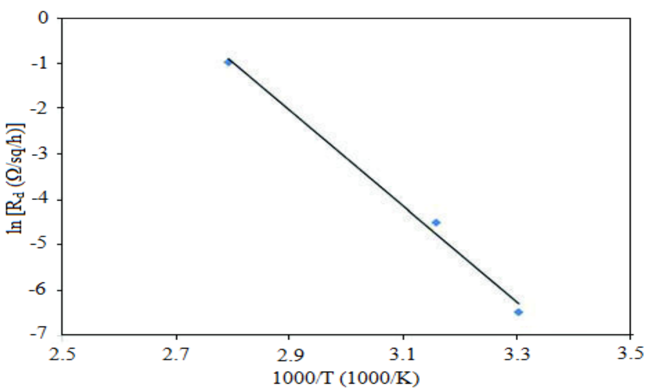

Figure 2 : Linear model for high stress and use stress for life

of 0.91eV and pre-exponential factor (A) of 2.341012. The Arrhenius values are only valid at the lower temperatures where degradation occurs at a constant rate throughout the temperature exposure at 85% RH. These values are chosen to accelerate the degradation because a PV module has a high temperature operating limit of 90°C and a high temperature destruct limit of 120°C.

B. *Wind and Wind Direction*

The common praxis is to install photovoltaic plants on existing large flat roofs. In most cases it is not allowed to fix the modules by screwing at the roof plane.

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The only way to fix the modules is by activating sufficient friction between the module support frame and the roof surface and this requires additional ballast weight on the module frame structure. Consequently the additional weight on the roof can be too large and the photovoltaic plant cannot be installed. The required ballast depends on the lift force caused by the wind. Therefore it is of eminent interest to know the real lift force on the modules and further to minimize the lift force, if possible. A similar problem exists at photovoltaic plants mounted on the ground (free field plants).
The economic purpose is here in the foreground. If the supporting system is too strong, the plant may be safe against wind action but it is too expensive. Therefore the real wind load must be known.

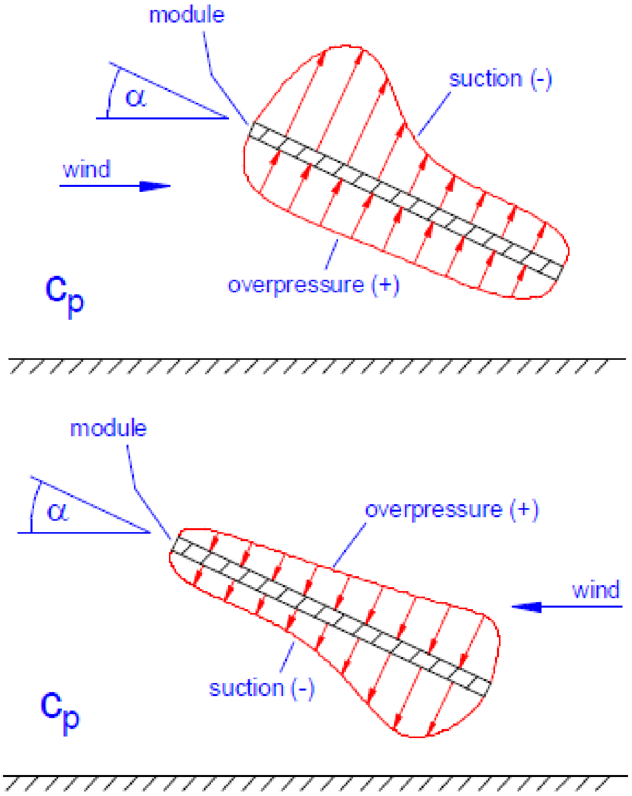

Figure 3 : Pressure distribution at the module for wind directions from north and south.

Numerous parameters influence the wind load. (1).Angle of the module to the horizontal plane. (2).Distance of the module rows to each other.(3).Distance to the building walls.(4).Position of the module in the module field.(5).Gaps between the modules respectively gap to the ground or roof surface. (6).Closed or open side of the module rows. (7).Wind safe deflector at the north side of the module. (8). Supporting system. (9). Free zones inside of the module field. (10).Height of the building. (11). Arrangement parallel or diagonal to the building walls. (12). Roof with or without a parapet. (13). Shape of the building roof corner (round or sharp). (14). Geometry of the module field arrangement. (15). Slope of the ground at free field plants. (16). Wind direction.

The wind pressure at the module is not homogeneously distributed [4]. The distribution is similar to the pressure distribution at an airfoil respectively at a flat plate. The suction at the front side is larger than on the rear side. Figure 3 presents the real pressure distribution and the simplification for practical application for the suction case (north wind) and for the positive pressure case (south wind). This distribution causes an overturning moment to the supporting structure.

C. Icing and Snow at the Site

Snow and ice can accumulate on a PV array in a number of physical forms [5]: (1) Dry snow deposition; (2) Wet snow accretion; (3) Rime, which occurs when super cooled water droplets impinge on a structure and freeze before forming a continuous liquid layer; (4) Glaze, which occurs when rain or super cooled water droplets impinge on a structure and freeze after forming a continuous liquid layer; (5) Hoarfrost, which occurs when super cooled or supersaturated water vapour encounters a nucleating surface and forms crystals.
Snow, rime, glaze, and hoarfrost are very unpredictable, both from year to year and from site to site. Whether they are a problem at a particular PV site depends on many site-specific factors that cannot be deduced from commonly available meteorological data. Simple models for the accumulation of rime and snow are presented in this report, mainly to identify for the reader the principal factors affecting the rate of accumulation. Qualitative information on snow and ice accumulation is available, on the other hand, from experts in the field of atmospheric icing of structures and from PV installers and users, eighteen of whom were contacted for this report.

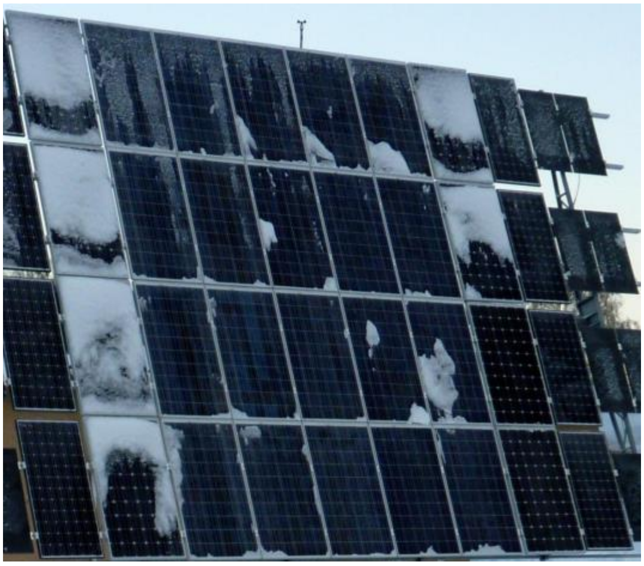

Figure 4 : Snow and icing on PV array.

Even so, several PV installers pointed out that it is difficult to know whether snow or ice accumulation is a problem at remote PV systems, since oversized battery banks power the load even when the panels fail for an extended period of time.

III. PROPORTIONAL HAZARDS MODEL

The effect of operational environment on the reliability performance of solar photovoltaic modules can be analysed. The first step is to identify which factors have the most significant influence on reliability of PV modules and numerically quantify how large is the effect. For this purpose, the available information about the operating conditions of PV

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TABLE III
Numerical Classification Of Environmental Influence Factors On Reliability Of Pv Modules.

Influence Factors		Assigned Values	
		-1	+1
Maintenance staff skill	M	Unskilled staff	Expert staff
Protection condition	P	Improper electrical protection	Proper electrical protection
Climatic condition	C	Abnormal weather	Normal weather
PV Module Quality	Q	Bad quality	Good quality

modules can be uniformly formulated based on two alternative, good/desired (+1) and bad/undesired (-1) conditions. The influence factors that have a significant effect on the life length of the PV module are identified as follows in table III.

Proportional hazards models are a class of survival models in statistics [6]. Survival models relate the time that passes before some event occurs to one or more covariates that may be associated with that quantity. In a proportional hazards model, the unique effect of a unit increase in a covariate is multiplicative with respect to the hazard rate. Random effects models provide a powerful tool in a wide variety of statistical applications, where the data have a natural clustered structure. In the survival context, a natural extension of the proportional hazards model to clustered survival data is to incorporate the random effects in the log relative risk $\lambda_{ij}(t)=\lambda 0(t)\exp(\beta z_{ij} + w_{ij}b_i)$, where $\lambda ij(t)$ is the hazard function of the j_{th} observation for the ith cluster (i=1. . . n, j=1. . . n_i), b_i is the random effect from the i_{th} cluster, and z_{ij} ,w_{ij} are the covariate vectors for the fixed and random effects. Model reflects the fact that some of the regression parameters in the proportional hazards model are cluster-dependent and that they may be treated as random.

The PHM is widely used in reliability engineering field in order to estimate the effects of different covariates influencing the time to failure (TTF) or time between failures (TBF) of a system [7]. Reliability characteristics of PV modules, which are always installed outdoor, can be influenced by environmental conditions such as temperature , wind speed , snow, long term degradation, spectral issues, irradiance , air gap between modules, dust, rainfall, corrosion, water vapour intrusion, delamination of encapsulant materials, Thermal expansion, ultraviolet radiation, humidity, mechanical load, salt mist, partial shading, heat island impact, global climate change, summer-winter climate change, Staebler- Wronski effect, Clearness of sky, urban heat island (UHI) effect, ageing and component derating etc and these influences can accounted with PHM for prediction of reliability in the design phase. The PHM is the best statistical method to estimate the reliability and failure rate of system under the influence of operating environmental conditions. In PHM, the hazard function for an influential factor is a product of the baseline hazard function and an exponential term incorporating the effect of a number of explanatory variables.

The general form of PHM is, $h(t,z) = h_0(t)\varphi(z\alpha)$, where $h(t,z)$ = resultant hazard, $h_0(t)$ = baseline hazard, and $\varphi(z\alpha)$ = the influence function. The influence factors should be identified and quantified by numeric variables, called covariates. These variables may be constant or may vary over time. A more precise and accurate reliability analysis must consider not only the characteristics of the components used, but the external operating conditions also. The baseline hazard rate is assumed to be identical and equal to the hazard rate when the covariates have no influence on the failure pattern. The covariate can influence the hazard rate so that the observed hazard rate is either greater or smaller. Under bad operating conditions, poor and incomplete maintenance or incorrect spare parts, the observed hazard rate is greater.

In case of new improved component, under good operating conditions and with reliable components, the observed hazard rate is smaller than the baseline hazard rate. According to the PHM, the actual failure rate and the reliability function of the PV module, considering the environment can be presented as follows [8].

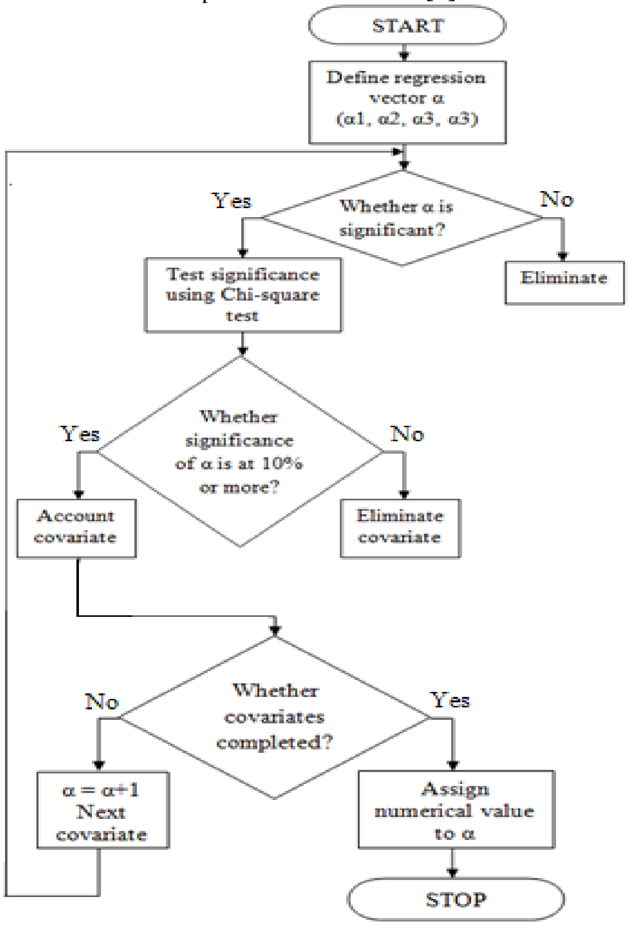

Figure 5 : Significant covariate estimation algorithm.

The failure rate $\lambda(t, z) = \lambda_0(t)\exp(\alpha_1 M + \alpha_2 P + \alpha_3 C + \alpha_4 Q)$ – Equation 1

and reliability function, $R(t, z) = R_0(t)^{\exp(\alpha 1M + \alpha 2P + \alpha 3C + \alpha 4Q)}$ – Equation 2

where $\alpha = (\alpha 1,\alpha 2,\alpha 3,\alpha 4)$ is the regression vector. In the estimation process, a step-down procedure (backward procedure) can be used. This is because of the fact that the estimation of the effect of a covariate in the PHM may be biased if a significant influential covariate has not been considered in the model. Thus covariates found to have no significant value were eliminated in subsequent calculations. The corresponding estimates of α were obtained and tested for their significance on the basis of chi-square test [9].

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In PHM, the functional form of φ (z, α) is assumed to be known. It may be in the exponential form exp (zα), the logistic form, log (1+exp (zα)), the linear form, (1+ (zα)) and the inverse linear form 1/ (1+ (zα)). Exponential form is widely used because of its simplicity [10].

$$h(t, z) = h_0(t)\exp(z\alpha) = h_0(t)\exp\left(\sum_{j=1}^{q} Z_j\alpha_j\right) \quad \text{- Equation 3}$$

Where Zj, j = 1,2, - - - q are the covariates associated with the system, and αj, j = 1,2, - - - q are the unknown parameters of the model, defining the effects of each of the q covariates. The multiplicative factor, exp (zα) is termed as the relative risk of failure due to the presence of the covarite Z. The related reliability function is given by,

$$R(t, z) = R_0(t)^{\exp\left(\sum_{j=1}^{q} Z_j\alpha_j\right)} \quad \text{- Equation 4}$$

$$R_0(t) = \exp\left[-\int_0^t \lambda_0(x)\,dx\right] = \operatorname{Exp}\left[H_0(t)\right] \quad \text{- Equation 5}$$

$R_0(t)$ = The baseline reliability function , dependent only on time and $H_0(t)$ = Cumulative baseline hazard rate.

$h(t, z) = h_0(t)\exp(Z_1\alpha_1 + Z_2\alpha_2 + Z_3\alpha_3 + Z_4\alpha_4 + \ldots\ldots\ldots\ldots + Z_n\alpha_n)$.

– Equation 6.

TABLE IV
Sample Time Between Failures Data

TBF Hours	Censored	M	P	C	Q
31840	1	1	1	1	1
22345	0	-1	1	-1	-1
26730	1	1	-1	-1	-1
26935	1	1	-1	-1	1
30750	1	-1	1	1	-1
25140	0	1	-1	-1	-1
25930	1	1	1	-1	-1
31830	1	1	-1	1	1
33240	0	1	1	1	1
32230	1	-1	1	1	1
32740	1	-1	1	1	1
30140	1	-1	-1	1	1
27250	1	1	-1	-1	1
25230	0	-1	-1	-1	1
26240	1	1	1	1	-1

Data courtesy : X. Gao et al [11]

In this modeling, three environmental impacts are considered for simplicity. Hence Z_1 can be assigned the covariate wind and α_1 is the corresponding unknown parameter. Similarly, Z_2 can be assigned the covariate snow and α_2 is the corresponding unknown parameter and Z_3 can be assigned the covariate temperature and α_3 is the corresponding unknown parameter. Now the equation 6 can be rewritten as,

$h(t, z) = h_0(t)\exp(Z_{wind}\,\alpha_{wind} + Z_{snow}\alpha_{snow} + Z_{Temperature}\,\alpha_{Temperature})$. - Equation 7

IV. PARAMETER ESTIMATION WITH SAMPLE DATA

The sample time between failures (TBF) data from X. Gao et al is assumed in this analysis as shown in table III. The censored value 1 represents the failure of PV modules and 0 represents that the failure due to some other unknown factor , the module is working , but no output. The influence factors M, P, C and Q can assign -1 and +1 values as shown in table II. The significant covariates can be estimated using the significant covariate estimation algorithm as shown in the flow chart in figure 5.

TABLE IV
Parameter Values In The Regression Vector

Algorithm Step No.	Influence Factor	Covariate Parameter
1	M C P Q	0.05 -0.55 -1.00 -1.19
2	C P Q	-0.57 -1.02 -1.18
3	P Q	-1.40 -1.01

Now consider the equations 1, 2 and 6.The M,P,C and Q can be assigned -1 as per table II. The failure rate $\lambda(t, z) = \lambda_0(t)\exp(\alpha_1 M + \alpha_2 P + \alpha_3 C + \alpha_4 Q)$, the reliability function, $R(t, z) = R_0(t)^{\exp(\alpha 1M + \alpha 2P + \alpha 3C + \alpha 4Q)}$ and $h(t, z) = h_0(t)\exp(Z_1\alpha_1 + Z_2\alpha_2 + Z_3\alpha_3 + Z_4\alpha_4 + \ldots\ldots\ldots\ldots + Z_n\alpha_n)$. $\lambda(t, z) = \lambda_0(t)\exp(\alpha_1 M = \lambda_0(t)\exp(0.05 \text{ x } -1) = 0.95\,\lambda_0(t)$. Similarly, $R(t, z) = R_0(t)^{\exp(\alpha 1M)} = R_0(t)^{\exp(0.05 \text{ x } -1)} = R_0(t)^{0.95}$ and $h(t, z) = h_0(t)\exp(M\alpha_1) = h_0(t)\exp(-0.05) = 0.95\,h_0(t)$. The analysis reveals that the maintenance staff skill won't affect the performance of the PV module or system. The is negligible change in failure rate, hazard rate and reliability performance.

Consider the electrical protection condition (P) and the PV Module Quality (Q) whose covariate parameters are -1.40 and -1.01 respectively. Now substitute the parameters in equations 1, 2 and 6. $\lambda(t, z) = \lambda_0(t)\exp(\alpha_1 P = \lambda_0(t)\exp(-1.40 \text{ x } -1) = 4\lambda_0(t)$. Similarly, $R(t, z) = R_0(t)^{\exp(\alpha 1P)} = R_0(t)^{\exp(-1.40 \text{ x } -1)} = R_0(t)^{4}$ and $h(t, z) = h_0(t)\exp(P\alpha_1) = h_0(t)\exp(-1.40 \text{ x } -1) = 4\,h_0(t)$. $\lambda(t, z) = \lambda_0(t)\exp(\alpha_1 Q = \lambda_0(t)\exp(-1.01\text{x } -1) = 2.7\lambda_0(t)$. Similarly, $R(t, z) = R_0(t)^{\exp(\alpha 1Q)} = R_0(t)^{\exp(-1.01 \text{ x } -1)} = R_0(t)^{2..7}$ and $h(t, z) = h_0(t)\exp(Q\alpha_1) = h_0(t)\exp(-1.01\text{x } -1) = 2.7\,h_0(t)$.

V. INTERPRETATION OF THE ANALYSIS AND CONCLUSION

The calculations shows that the two covariates P and Q were significant at the 10% level. The analysis reveals that the electrical protection and the quality of PV modules and hence the quality of production are the major factors need to be controlled or improved to avoid the failure of PV modules or to improve the reliability. During the design stage and the production stage, this information is very useful for improvement of reliability. Similarly the impact of other environmental parameters can be assessed using practical field failure data or using accelerated test data.

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