STATISTICAL ANALYSIS AND STRUCTURE OPTIMIZATION OF LARGE PHOTOVOLTAIC MODULE

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Abstract – There has been an increasing interest in powering electronic systems using solar energy. Designers are seeking for techniques to manufacture solar panels using low cost material in a massive scale. This will likely lead to wide process variation and hence unreliable performance. This paper considers the impact of the process variations on the output power of large Photovoltaic (PV) module by modeling each PV cell as a current source whose short circuit current is a normal random variable. The probability distribution of the overall output power of an *N*x*M* PV module is analytically derived. The proposed statistical analysis technique will enable the designer to predict the maximum output power of a PV module for a given confidence level. This analysis also reveals that, when the size and the manufacturing technology are given, the efficiency of a PV module is determined by its topology. The proposed power prediction model can be applied to find the optimal structure of the PV module that maximizes the energy harvesting rate at the given confidence level.

I. Introduction

Solar energy in one form or another is the source of nearly all energy on the earth. Photovoltaic (PV) is a simple and elegant method of harnessing the sun's energy. PV devices (solar cells) are unique in that they directly convert the incident solar radiation directly into electricity, with no noise, pollution or moving parts, making them robust, reliable and long lasting. Solar cells are connected in series to increase the voltage output and are connected in parallel to increase the current output. PV module consists of individual solar cells electrically connected in series and parallel to increase the power output. Modules, in turn, can be combined and connected to form PV arrays of different sizes and power output. Fig 1 shows a solar module with two solar cells in series (N= 2) and two cells in parallel (M=2).

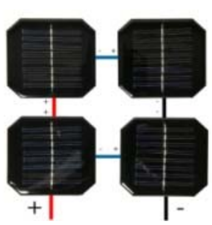


Fig 1: Solar cell Series Parallel Combination

Over the past decades, different solar cell fabrication techniques, such as screen printing [1], buried contact [2], rear contact [3], thin film technology [4] etc., have been proposed. And different materials, such as silicon, gallium arsenide, polymers, organic materials etc., are used for the manufacturing of the solar cell. As the solar energy harvesting system becomes more and more widely used, designers are seeking for techniques to manufacture solar panels using low cost material on a massive scale. However, this will likely lead to wide process variation and hence unreliable performance. In order to design a large-scale PV module with reliable performance and predictive yield, there is an urgent need to study the performance of solar panel under wide process variations. Process variation has already become a major design concern in the VLSI industry. Statistical models for performance prediction [5][6]and leakage estimation [7][8] have been investigated. Unlike leakage power, the output power of a PV module is not a simple addition of the output power of each PV cell when they are working independently. Therefore, new models must be proposed.

When the PV cells are no longer identical, the structure of the PV module, which refers to how the PV cells are connected, will have significant influence on the module efficiency. For example, the short circuit current of a set of series connected PV cells is bounded by their minimum current while the open circuit voltage of a set of parallel connected PV cells is bounded by their minimum voltage. It is also important to study the impact of the structure of the PV module on the energy efficiency under wide process variations.

The contribution of the paper is twofold. First, we propose a statistical model that derives the probability distribution of the PV module output power under wide process variations. The proposed model can be used to predict the output power at given confidence level or be used to predict yield of the PV module for the given output power constraint. Secondly, we apply the proposed prediction model to find the optimal structure of the PV module. The objective of the design optimization problem is to maximize the output power of the PV module at given confidence level or to maximize the probability that the output power of a PV module exceeds the given threshold while the constraint is the area of the PV module. The dual problem of this formulation is to minimize the area of the PV module while meeting the given output power constraint. The first problem is equivalent to optimizing the yield of the PV module at the given cost constraint while the second problem is equivalent to minimizing the cost of the PV module at the given performance constraint.

Here we need to point out that the intensity of solar radiation obviously has the first order impact on the efficiency of the PV module. However, in this paper, we target at improving solar panel efficiency from the designer’s point of view. We assume that the input solar radiation is uniform across the entire PV module. Research work has been proposed to adjust the angle of the solar panel to receive the maximum sunlight [9].Those application time technologies are complementary to the proposed design optimization techniques.

Many of the existing research works aim at increasing the PV module efficiency by making it work at maximum power point using hardware and software techniques[10][11][12].Others focus on improving the fabrication technologies[13][14]. To the best of our knowledge, this paper is the first that considers the relation between the process variations and the energy efficiency of a PV module. It is also the first one that shows the impact of the structure of a PV module on its efficiency.

The remainder of the paper is organized as follows. A background on characteristics of solar cells is discussed in Section II. Section III describes the parameter estimation of Parallel, Series and Series Parallel solar cells. How to analytically optimize the power and proposed model of the harvester is presented in Section IV and finally Section V concludes the paper.

II. Background

The I-V characteristic of a solar cell follows superposition principle [15]. The superposition principle states that the current in an illuminated device subjected to a forward bias voltage is the sum of the short circuit photocurrent and the current flowing at bias V in the dark. Based on the superposition principle, a solar cell can be modeled by its equivalent circuit given in Fig 2 and the output current of a solar cell is calculated as:

$$I = I_{ph} - I_d$$

Where I_d is the diode current and I_{ph} is the light generated current [16].

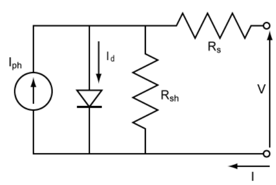


Fig 2: Solar cell equivalent circuit

The diode current I_d is calculated as the following

$$I_d = I_O \left[e^{\frac{V_a}{V_t}} - 1 \right] \quad (1)$$

Where I_O is the saturation current of the diode, V_t is the thermal voltage in Volts and V_a is the applied voltage in Volts [16]. The light generated current I_{ph} is determined by the light intensity, the area and the dimensions of the PN junction. It is calculated as:

$$I_{ph} = A\,\mathrm{q}(L_h G + L_e G)$$

Where L_h is the diffusion length of holes on N side of PN junction. L_e is the diffusion length of electrons on P side of PN junction. G is the generation rate and q is the charge of electron in coulombs and A is the area of the solar cell.

This expression only includes the ideal diode current of the diode, thereby ignoring recombination in the depletion region. The short circuit current I_{SC} is the current at zero voltage and ideally, this is equal to the light generated current, i.e. $I_{SC} = -I_{ph}$.

By setting the net current equal to zero in (1), we can obtain the open circuit voltage (V_{OC}) of a solar cell

$$V_{OC} = V_t \ \ln\left[\frac{I_{ph}}{I_O} + 1\right] \quad (2)$$

V_{OC} is the maximum voltage available from a solar cell and is the amount of forward bias on the solar cell junction due to the light generated current.

Practical solar cells will have series (R_s) and shunt resistances (R_{sh}). R_s is caused by the resistance encountered by the movement of current through the emitter and base of the solar cell and R_{sh} occurs because of the material defects in the solar cell.

Combining resistive and recombination loss the total current I is given by [17]

$$I = I_{ph} - I_O \left[e^{\left(\frac{V_a + I\mathrm{R_s}}{V_t}\right)} - 1 \right] - \left(\frac{V_a + I\,\mathrm{R_s}}{\mathrm{R_{sh}}}\right)$$

III. Parameter Estimation

From the previous analysis we know that the light generated current is determined by the dimension of the PN junction and the doping technology. Hence, it is subjected to process variation. Here we assume that, due to the lumped effect of these variations, the short circuit current (i.e. I_{ph}) of a solar cell is i.i.d (independent and identically distributed) and it follows normal distribution. As the result, the PV cells on the same PV module are different.

For a PV module made of different PV cells, the energy harvesting efficiency is determined by the connections between the PV cells. For determining the parameters, first we will find the distribution of the short circuit current I_{SC}. Then from I_{SC} we will find the distribution of the open circuit voltage V_{OC}. Distribution of Power is obtained based on the distribution of I_{SC} and V_{OC}. Let ρ denote the covariance between I_{SC} and V_{OC}.

$$\rho = \mu\,(I_{SC}\,V_{OC}) - \mu\,(I_{SC})\ \mu\,(V_{OC})$$

The mean (μ_p) and the variance (σ_p^2) of the Power can be calculated as the following [18]

$$\mu_P = \mu_I \mu_V + \rho \quad (3)$$

$$\sigma_P{}^2 = \mu_I{}^2 \sigma_V{}^2 + \mu_V{}^2 \sigma_I{}^2 + 2\mu_I \mu_V \rho - \rho^2 + \mu_P + 2\mu_V \mu((I_{SC} - \mu_I)^2 V_{OC}) + 2\mu_I \mu((V_{OC} - \mu_V)^2 I_{SC}) \quad (4)$$

Where μ_I and σ_I^2 are the mean and variance of I_{SC} respectively and μ_V and σ_V^2 are the mean and variance of V_{OC} respectively.

Next, we will present a statistical analysis model that predicts the output power of PV modules that have a set of series and parallel connected PV cells.

A. Output power of parallel connected PV cells

We first consider a set of M PV cells that are connected in parallel. Let $X_1, X_2 \ldots\ldots\ldots X_M$ denote the short circuit currents of these M cells. They are independent and identically distributed random variables and they follow a Normal distribution N (μ, σ^2). The overall short circuit current ($I_{SC\ parallel}$) of the M PV cells is the sum of the I_{SC} of each PV cell, and hence it follows a normal distribution with mean $\mu_{I-parallel} = M\mu$ and variance $\sigma_{I-parallel}^2 = M\sigma^2$.

The following lemma states that the open circuit voltage and the short circuit current of the parallel connected PV cells still satisfy equation (2).

Lemma 1: The open circuit voltage ($V_{OC\text{-}parallel}$) and the short circuit current ($I_{SC\text{-}parallel}$) of M parallel connected PV cells has the following relation: $V_{OC-parallel} = V_t ln\left[\frac{I_{SC-parallel}}{M*I_O} + 1\right]$.

Proof: According to Kirchhoff's current law incoming current is equal to outgoing current. $I_{SC-parallel}$ is the sum of short circuit currents of M parallel connected solar cells $I_{SC-parallel} = \sum_{i=0}^{M} I_{ph_i}$ and I_O is the saturation current of a single diode. The net output diode current of M parallel connected solar cells in open circuit $I_D = MI_d$ and $I_{SC-parallel} = I_D$ and substituting this in (2) will give the V_{OC} of parallel connected solar cells.

Based on the lemma, we can have the following theorem regarding to the open circuit voltage $V_{OC\text{-}parallel}$ of the parallel connected PV cells.

Theorem 1: The open circuit voltage $V_{OC\text{-}parallel}$ follows normal distribution $V_{OC-parallel} \sim \mathrm{N}\left(V_t ln\left(\frac{\mu}{I_O}\right), \frac{\sigma^2 V_t^2}{\mu^2}\right)$. We use $\mu_{V-parallel}$ and $\sigma^2_{V-parallel}$ to denote the mean and variance of the distribution.

Proof: Since short circuit currents follows a N(μ, σ^2) distribution then from [19] ln of a distribution is assumed to be same as that distribution and since V_t is a constant according to the relation if $X \sim \mathrm{N}(\mu, \sigma^2)$ then aX will follow N(aμ, (aσ)^2) distribution where a is a constant. i.e. $V_{OC-parallel}$ follows a normal distribution. It can be proved that the mean of $ln\ X$ is $ln\ \mu$ where μ is the mean of the distribution of X and variance of $ln\ X$ is $\frac{\text{Variance } X}{\mu^2}$ [19]. Since V_t and Io are constants, mean of $V_{OC-parallel}$ is $V_t ln\left(\frac{\mu}{I_O}\right)$ and variance is $\frac{\sigma^2 V_t^2}{\mu^2}$.

In this paper, we are interested in the output power of the PV module when it is working at the maximum power point (MPP). It is known that the output current at the MPP is typically between 71%-78% of the short circuit current for Si solar cells and voltage at the MPP is typically between 78%-92% of the open circuit voltage of the PV module [11]. Therefore in this paper, our goal is to estimate and optimization the product of I_{SC} and V_{OC}.

$Power_{\text{-}parallel} = I_{SC\text{-}parallel}\, V_{OC\text{-}parallel}$

It can be proved that the $Power_{\text{-}parallel}$ also follows a normal distribution

Theorem 2: According to Gaussian product theorem, the product of two Gaussian functions is again a Gaussian function.

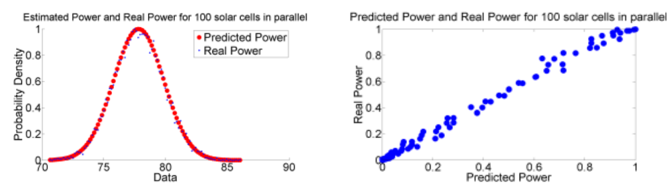
If $I_{SC\text{-}parallel} \sim \mathrm{N}(\mu_{I-parallel}, \sigma^2_{I-parallel})$ and $V_{OC\text{-}parallel} \sim \mathrm{N}(\mu_{V-parallel}, \sigma^2_{V-parallel})$ and $\rho_{\text{-parallel}}$ indicates the covariance between the $V_{OC\text{-}parallel}$ and $I_{SC\text{-}parallel}$ then mean of $Power_{\text{-}parallel}$ can be obtained from (3) and variance of $Power_{\text{-}parallel}$ can be obtained from (4).

We have tested the estimation model for M = 10, 50 and 100 PV cells. In the experiment, we assume that the short circuit current follows a Normal distribution with mean=3A and standard deviation=0.5. We use two parameters *SSE* and *R-Square* to represent the estimation error and the correlation between the estimated distribution and sampled distribution of the $V_{OC\text{-}parallel}$ and $Power_{\text{-}parallel}$. The sum of squares due to error (*SSE*) measures the total deviation of the response values from the fit. *SSE* is calculated as: $\sum_{i=1}^{n}(y_i - f_i)^2$ where y_i denotes the observed data and f_i denotes the predicted data and n is the number of data points. *R-Square* is the square of the correlation between the response values and the predicted response values. *R-Square*=$1 - \frac{\sum_{i=1}^{n}(y_i - f_i)^2}{\sum_{i=1}^{n}(y_i - y_{avg})^2}$ where y_{avg} denotes the mean of the observed data. An estimation model should have a small *SSE* value and *R-square* close to 1. We can see that the model has small estimation error with *SSE* =0.0792 and good correlation. Table 1 shows the *SSE* and *R-Square* values for $V_{OC\text{-}parallel}$ and $Power_{\text{-}parallel}$ from short circuit current $I_{SC\text{-}parallel}$ where M=No. of cells in Parallel.

Table 1: *SSE* and *R-Square* values for Parallel connected PV cells

M	$V_{OC\text{-}parallel}$		$Power_{\text{-}parallel}$	
	SSE	*R-Square*	*SSE*	*R-Square*
10	0.259	0.976	0.079	0.993
50	0.188	0.983	0.127	0.989
100	0.201	0.981	0.079	0.993

Fig 3(a) gives the comparison between the estimated pdf and the sampled pdf of the output power while Fig 3(b) shows the correlation between these two. As we can see that the model represents the actual power distribution highly accurately.



(a) (b)

Fig 3: Estimation of parallel PV module output power (a) estimated pdf Vs sampled pdf (b) correlation between the model and the sampled distribution

B. Output power of series connected PV cells

In this section, we consider a PV module that consists of a set of N PV cells that are connected in series. Again, let X_i denote the short circuit current of the i th cell. The short circuit current of the PV module is bounded by the minimum current of N cells in series, i.e. $Isc_{\text{-}series} = I_{sc(min)} = Min_{1\leq i\leq N}(X_i)$.

According to [20], the distribution of the minimum of a set of i.i.d random variables can be approximated by a Weibull distribution.

In this paper, we modeled the minimum short circuit current $I_{sc(min)}$ using two parameter Weibull distribution, whose pdf is given by the following equation:

$$f(X;\alpha,\beta) = \begin{cases} \frac{\beta (X)^{\beta-1} exp^{-\left(\frac{X}{\alpha}\right)^{\beta}}}{\alpha^{\beta}}, & X \geq 0 \\ 0, & X \leq 0 \end{cases}$$

The scale parameter α and shape parameter β are estimated using maximum likelihood estimation based on a set of sampled minimum. From Table 2 we can see that the *SSE* value is close to 0 and *R-Square* value is close to 1.This means that the Weibull distribution has a good correlation with the distribution of sampled minimum.

Once parameters are estimated for the $I_{SC\text{-}series}$, its mean and variance are obtained from equation (5) and (6).

$$\mu = \left(\alpha\Gamma\left(1+\frac{1}{\beta}\right)\right) \quad (5)$$

$$\sigma^2 = \left(\alpha^2\Gamma\left(1+\frac{2}{\beta}\right)-\mu\right) \quad (6)$$

Similar to the parallel connected PV modules, the open circuit voltage of a set of PV cells connected in series can also be calculated from its short circuit current using equation (2).

It is not difficult to prove that the linear scale aX of a Weibull variable X is also a Weibull variable. Its mean and variance equal to $a\mu$ and $a^2\sigma^2$, where μ and σ are the mean and variance of X. We could not find any existing work that gives the distribution of lnX, when X follows Weibull distribution. We observed that the logarithm of a skew normal distribution has a similar shape, therefore, it is our hypothesis that the logarithmic of a Weibull distribution can be approximated as a Weibull distribution. Its mean and variance are $ln\mu$ and $\frac{\sigma^2}{\mu^2}$.

Based on the above analysis, it is not difficult to see that the open circuit voltage $V_{OC\text{-}series}$ can be approximated by a Weibull distribution, with mean $NV_t\,ln\left(\frac{\mu}{Io}\right)$ and variance $\frac{\sigma^2 N^2 V_t^2}{\mu^2}$. Once we know the mean and variance by solving (5) and (6) we can estimate scale parameter α and the shape parameter β.We also use Weibull distribution to approximate the power, which is the product of $I_{SC\text{-}series}$ and $V_{OC\text{-}series}$.

$Power_{\text{-}series} = I_{SC\text{-}series}\, V_{OC\text{-}series}$

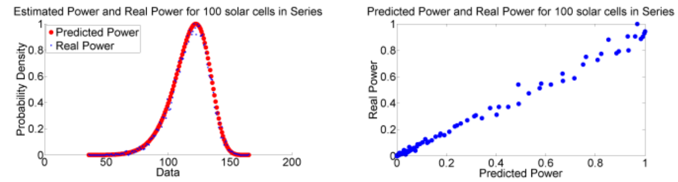
If $I_{SC\text{-}series}$ ~ Weibull (mean $\mu_{I-series}$, Variance $\sigma^2_{I-series}$) and $V_{OC\text{-}series}$ ~ Weibull (mean $\mu_{V-series}$, Variance $\sigma^2_{V-series}$) $\rho_{\text{-}series}$ indicates the covariance between the $V_{OC\text{-}series}$ and $I_{SC\text{-}series}$ then mean of $Power_{\text{-}series}$ can be obtained from (3) and variance of $Power_{\text{-}series}$ can be obtained from (4).Once we know the mean and variance by solving (5) and (6) we can estimate scale parameter α and the shape parameter β.

In the experiment, we assume that short circuit current follows a Normal distribution with mean =3A and standard deviation = 0.5. We use two parameters, *SSE* and *R-Square*, to represent the estimation error and the correlation between the estimated distribution and sampled distribution of the $V_{OC\text{-}series}$ and $Power_{\text{-}series}$. We have tested the estimation model for N = 10, 50 and 100 PV cells. Each PV cell has the same property as the experiment in the parallel connection case. Again, we can see from Table 2 that the model gives small estimation error and good correlation.

Table 2: *SSE* and *R-Square* values for Series connected PV cells

N	$V_{OC\text{-}series}$		$Power_{\text{-}series}$	
	SSE	*R-Square*	*SSE*	*R-Square*
10	0.188	0.987	0.071	0.992
50	0.198	0.985	0.240	0.971
100	0.111	0.991	0.291	0.981

Fig 4(a) gives the comparison between the estimated pdf and the sampled pdf of the output power while Fig 4(b) shows the correlation between these two. As we can see that the model represents the actual power distribution highly accurately.



(a) (b)

Fig 4: Estimation of series PV module output power (a) estimated pdf Vs sampled pdf (b) correlation between the model and the sampled distribution

C. Output power of Series Parallel connected PV cells

Here we consider a PV module with series-parallel connected PV cells. We assume that the PV module consists of M groups of parallel connected sub modules and each sub module consists of N series connected PV cells. We call each sub module a *branch*.

Total current of such PV module can be calculated as $I_{sc-series\,parallel} = \sum_{i=1}^{M} I_{SC-branch-i}$. It is known that $I_{SC\text{-}branch\text{-}i}$ follows Weibull distribution and the sum of a set of Weibull variables can be approximated to follow a Weibull distribution. Therefore, $I_{sc-series\,parallel}$ is also a Weibull variable.

Once parameters are estimated for the $I_{SC\text{-}series\ parallel}$, its mean μ_T and variance $\sigma^2{}_T$ are obtained from equation (5) and (6).

Similar to the series connected PV modules, the open circuit voltage of a set of PV cells connected in series parallel can also be calculated from its short circuit current using equation (2).

Based on the analysis from series PV modules, it is not difficult to see that the open circuit voltage $V_{OC\text{-}series\ parallel}$ can be approximated by a Weibull distribution with mean $NV_t\,ln\left(\frac{\mu_T}{MIo}\right)$ and variance $\frac{\sigma^2 N^2 V_t^2}{\mu_T{}^2}$.

$Power_{\text{-}series\ parallel} = I_{SC\text{-}series\ parallel}\, V_{OC\text{-}series\ parallel}$

It has been proved using curve fitting that the $Power_{\text{-}series\ parallel}$ also follows a Weibull distribution.

If $I_{SC\text{-}series\ parallel}$~ Weibull (mean $\mu_{I\text{-}series\ parallel}$, and variance $\sigma^2{}_{I\text{-}series\ parallel}$) and $V_{OC\text{-}series\ parallel}$ ~ Weibull (mean $\mu_{V\text{-}series\ parallel}$ and variance $\sigma^2{}_{V\text{-}series\ parallel}$) $\rho_{\text{-}series\ parallel}$ indicates the covariance between the $V_{OC\text{-}series\ parallel}$ and $I_{SC\text{-}series\ parallel}$ then mean of $Power_{\text{-}series\ parallel}$ can be obtained from (3) and variance of $Power_{\text{-}series\ parallel}$ can be obtained from (4).Once we know the mean and variance by solving (5) and (6) we can estimate scale parameter α and the shape parameter β.

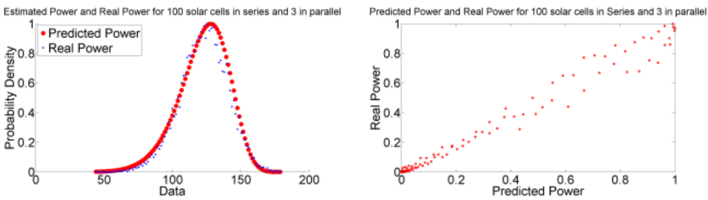
In the experiment, we assume that short circuit current follows a Normal distribution with mean=2A and standard deviation= 0.5. We use two parameters, *SSE* and *R-Square*, to represent the estimation error and the correlation between the estimated distribution and sampled distribution of the $V_{OC\text{-}series\ parallel}$ and $Power_{\text{-}series\ parallel}$. We have tested the estimation model for different combinations of M and N .Each PV cell has the same property as the experiment in the series connection case.

Table 3 shows the *SSE* and *R-Square* values for $V_{OC\text{-}series\ parallel}$ and $Power_{\text{-}series\ parallel}$ from $I_{SC\text{-}series\ Parallel}$ where M=No. of cells in parallel and N=No. of cells in series.

Table 3: *SSE* and *R-Square* values for Series Parallel connected PV Cells

NxM	$V_{OC\text{-series parallel}}$		$Power_{\text{-series parallel}}$	
	SSE	*R-Square*	*SSE*	*R-Square*
10x3	0.168	0.984	0.257	0.978
10x10	0.235	0.992	0.274	0.986
100x20	0.273	0.988	0.147	0.974

Fig 5(a) gives the comparison between the estimated pdf and the sampled pdf of the output power while Fig 5(b) shows the correlation between these two. As we can see that the model represents the actual power distribution highly accurately.



(a) (b)

Fig 5: Estimation of series parallel PV module output power (a) estimated pdf Vs sampled pdf (b) correlation between the model and the sampled distribution

IV. Power Optimization

For a given area constraint i.e. a combination of N x M < K where N=No. of cells in series and M=No. of cells in parallel and K is the given area, we find the probability of power > a under process variation by $1 - F(X > a)$ where $F(X)$ is the CDF of two parameter Weibull distribution as power of a series parallel combination follows Weibull distribution.

$$(1 - F(X > a) = e^{-\left(\frac{a}{\alpha}\right)^{\beta}}$$

Where α is the scale parameter which is a $f(M, N)$ and β is the shape parameter a $f(M, N)$ and a is the power.

In this section, we provide some guidelines to increase the harvester efficiency and to optimize the design of the PV module. The proposed architecture of the harvester is shown in Fig 6. We focused on the DC–DC input and output stage increasing the conversion efficiency.

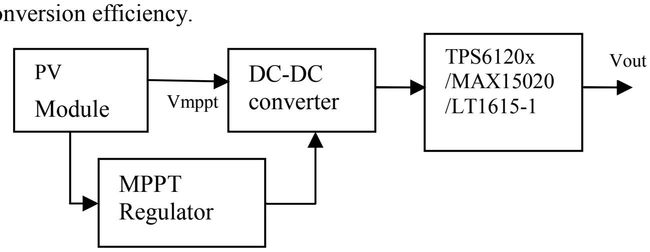


Fig 6: Harvester Architecture

The PV module is connected to DC-DC converter and MPPT (Maximum Power Point Tracking) regulator which together will fix the PV module at the MPP (Maximum Power Point). There are several methods and algorithms to analyze and find the MPP [11].Among the simplest methods for MPPT is Fractional Open-Circuit Voltage and is definitely the most used and cost-effective in medium and small-scale PV systems. This method exploits the nearly linear proportional relationship between the operating voltage at MPPT (Vmppt) of a PV module and the open circuit voltage (Voc) [21].The MPPT can be achieved using conventional DC-DC boost converter with passive components [22].The second DC-DC converter is used to buck or boost the output voltage. We can use high efficiency DC-DC converter ICs for this purpose. Depending on the input voltage for the DC-DC converter TI Boost Converter TPS6120x (0.3-5.5V)[23] or LT1615 or LT1615-1(1-6V) [24] or MAX15020(7.5-40V)[25] can be used for this purpose. The converters provide an extremely low 0.5-V start-up capability in any load condition, and can operate with around 90% efficiency. Efficiency Vs Input voltage curves for TPS6120x ICs are shown in Fig 7. Efficiency Vs Output current for MAX15020 is shown in Fig 8 and Efficiency Vs Output current for LT1615-1 is shown in Fig 9.

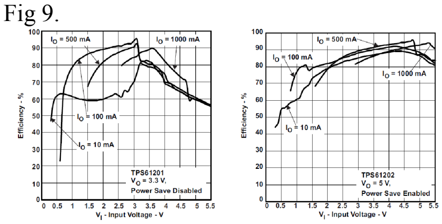


Fig 7: Efficiency Vs Input Voltage TPS6120x

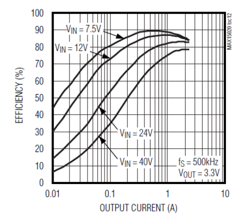


Fig 8: Efficiency Vs Output current for MAX15020

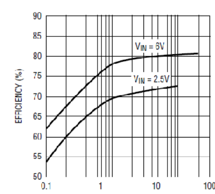


Fig 9: Efficiency Vs Output current for LT1615-1

Probability of Harvester output power>3W with 90% confidence level under process variation for different configurations from a PV module with area (MxN) ≤ 5 using TPS61201 IC is shown in Table 4 Where M=No. of cells in Parallel and N=No. of cells in series.

Table 4 : Probability of harvester output for different MxN≤ 5

M x *N*	Probability
1x4	0.30
1x5	0.87
2x2	0.55
4x1	0.84
5x1	0.99

Probability of Harvester output power>10W with 90% confidence level under process variation for different configurations from a PV module with area (MxN) ≤ 10 using LT1615-1 IC is shown in Table 5 Where M=No. of cells in Parallel and N=No. of cells in series.

Table 5: Probability of harvester output for different Mx$N \leq 10$

M xN	Probability	M xN	Probability	M xN	Probability	M xN	Probability
1x7	0.69	1x8	0.97	1x9	0.98	1x10	0.99
2x5	0.93	3x3	0.86	4x2	0.57	5x2	0.99
7x1	0.14	8x1	0.90	9x1	0.98	10x1	0.99

Using our proposed model we can get maximum power from PV module using minimum area and can deliver power to the output source with maximum efficiency.

V. Summary and Conclusion

In this paper, we have proposed an efficient method for estimating the power of the solar array due to process variations. We presented a general method for statistical analysis. The correlation coefficient is considered for the estimation of power but it is a very small as there is log relationship and no linear relationship between the short circuit current and the open circuit voltage. The mean open circuit voltage of the PV module is used for calculating the efficiency of the DC-DC converter as the variance is a very small value. Since efficiency is a function of input voltage and output current, the configuration of the PV module determines the efficiency of the harvester.

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