

COMPARATIVE STUDY ON DIFFERENT METHODS TO DETERMINE SERIES RESISTANCE OF PV MODULE

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Declaration

It is hereby declared that

1. The thesis submitted is our own original work while completing degree at Brac University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
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Abstract

In recent times, the area of the photovoltaic based system is increasing as it is a natural method of converting solar energy into electrical energy without emitting dangerous radiation using PV modules. A PV module is comprised of different parameters and series resistance is one of the most important parameters. A PV module with less R_s value indicates its efficiency, thus for designing a PV module it is essential to choose a R_s extraction method which provides least value. Considering this fact, this work is made to extract the series resistance of photovoltaic modules using different experimental and theoretical methods on fifteen different modules from three different companies and to analyze the results in a comparative approach to identify which method is better fitted. Bar chart and several error analyses have been done to give a complete overview of the work and to testify the claims.

Keywords: Series Resistance; PV Module; Comparative Study; Temperature; Irradiance

Dedication

We want to dedicate our work to our beloved parents and family whose affection, love, nurturing, inspirations and sacrifices have allowed us to become the individuals we are today.

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Firstly, we are thankful to Almighty Allah for blessing us with sound health, mind, abilities and enthusiasm to complete the thesis study.

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List of Acronyms

PV	Photovoltaic
I-V Curve	Current-Voltage Characteristic Curve
STC	Standard Test Conditions
NOCT	Nominal Operating Cell Temperature
MPP	Maximum Power Point
FF	Fill Factor
L4P	Limped Four Parameters
L5P	Limped Five Parameters
RMS	Root Mean Square
NRMSE	Normalized Root Mean Square Error
MSE	Mean Square Error

List of Symbols

a	Ideality Factor
A	Area Under the Curve
E_g	Bandgap
G	Solar Irradiance
I_{ph}	Photo-generated Current
I_o	Saturation Current
I_{SC}	Short Circuit Current
I_{mp}	Maximum Current
I_D	Diode Current
$I_{D,REF}$	Reference Diode Current
I_{pv}	PV cell generated Current
K	Boltzmann's Constant
m	Reverse Saturation Current Factor
N_s	No of cells connected in series
P_{mp}	Maximum Power
q	Electronic Charge
R_s	Series Resistance

List of Symbols (Continued)

$R_{S,STC}$	Series Resistance at Standard Test Conditions
R_{Sh}	Shunt Resistance
R_{pv}	Photovoltaic Resistance
R_p	Parallel Resistance
r_s	Normalized Series Resistance
T	Temperature
T_{cell}	Cell temperature
T_{REF}	Reference Temperature
V_i	Intrinsic Voltage
V_e	External Voltage
V_{OC}	Open Circuit Voltage
V_{mp}	Maximum Voltage
V_t	Thermal Voltage
β_{oc}	Temperature Coefficient for open circuit voltage
δ	Constant (nonlinear series resistance temperature-dependent parameter)

Chapter 1

Introduction

1.1 Introduction

Due to the increasing usage of electronic appliances in almost every work of our day-to-day life, the demand for electricity is currently at its peak. There is no doubt that the demand and consumption of electric energy will be increasing in the future. At present, the main source of energy is fossil fuels such as coal, gas, oil etc. However, usage of fossil fuel has environmental concern and there are limitations of these resources as well. An estimation is made that burning fossil fuels at the current rate will exhaust them by the year 2060 [1]. Hence, the world is moving towards utilizing renewable energy. Among the renewable energy sources, solar has huge scope due to its availability on large scale. Solar radiation on earth is estimated at around 344 Wm^{-2} [2]. In order to convert this solar energy into electricity usage of PV modules, is an essential device. Hence, analyzing the performance of PV modules is required to understand the sustainability and reliability of a module. And to analyze the performance of a module it is necessary to obtain the solar cell model parameters as accurately as possible.

1.2 Problem Statement

There are different parameters in a solar cell model including series resistance. Series resistance affects the fill factor and the efficiency of a cell or module. For better performance of a module, obtaining low series resistance is required [3]. Different methods exist to extract this parameter but it is difficult to choose which one is suitable. Hence, it is required to do comparative analysis among those extraction methods so that during the execution of performance analysis of PV module or designing a PV system one can choose the optimum method.

1.3 Objective

The purpose of this study is to review different methods of series resistance determination of PV modules and make a comparative analysis of those methods. Hence, we have selected six different methods. We have implemented those methods on fifteen different modules and it is worth mentioning that all the modules are made of Polycrystalline Silicon. So, the implementation of six different methods on fifteen Poly-Si modules and comparative assessments based on the results is the primary goal of this research.

1.4 Structure of the Thesis

This study is divided into six different chapters to obtain a good understanding of the thesis work. In Chapter 1 introduction of the work is provided along with the problem statement and objective. Chapter 2 presents the literature reviews. Chapter 3 consists of the theoretical background related to PV systems as well as the impact of series resistance on the system. Chapter 4 presents the experimental setup to obtain I-V data. This chapter also includes a brief discussion on different methods to obtain the series resistance of modules which is part of the methodology. There are two subsections in the methodology where one part includes the applied methods which have been used for R_s extraction and another part is comprised of non-applied methods, where different R_s extraction method is explained. Chapter 5 gives the presentation of all the results and comparative analysis based on those results. Finally, Chapter 6 describes the conclusion of the whole work and an insight about the future work is provided.

Chapter 2

Literature review

2.1 Literature Review

A good number of methods were mentioned by the researchers to determine model parameters including the series resistance of a PV system. A graphical method was first proposed by Swanson [4]. The method is based on two I-V curves corresponding to two irradiances as described by the authors [5]. Later many more methods are suggested to extract series resistance. These methods can be largely categorized into different types based on their approaches, namely graphical, analytical, algorithmic and compound methods.

2.1.1 Graphical Approach

One of the easiest and widely applied graphical methods is to determine series resistance from two I-V curves in response to two different irradiance levels. In the IEC-60891 standard, current and voltage equations are provided which can be utilized to calculate the I-V data for any temperature and irradiance level. But it is worth mentioning that this calculation is only possible if there an I-V data for a certain temperature and irradiance level already exists. However, to get V_{oc2} the translated I-V curve, sufficient I-V data must be collected beyond V_{oc1} . Otherwise, linear extrapolation should be utilized to obtain V_{oc2} . In this method, keeping the temperature constant, R_s is determined by varying the irradiance over a module.

Another graphical method is to determine the series resistance from the slope of the I-V curve at the open circuit point [6]. It is based on the fact that series resistance has the most impact at the slope near the open circuit point of the I-V curve [7]. A comparison of this method with commercial tracer is conducted in [8]. To find the robustness of the method they utilized additional resistance and found that this method gives less relative error compared to the

commercial tracer. However, it requires two points to determine slope and it is difficult to choose another point apart from the open circuit point. S. Benghanem and N. Alamri conducted an algorithmic search to find the suitable position of that point. The algorithm compared at which point calculated series resistance by slope method matches with their already measured series resistance utilizing measuring device and curve tracer PVPM 2540C. They concluded with the findings that the corresponding point of the half of the short circuit current is most suitable [9]. This method is advantageous since it neither requires a whole I-V curve nor a mathematical model [8]. Sera presented a modified version of the slope method where the relationship between estimated series resistance at STC condition and series resistance at any test condition is shown as well [10].

Series resistance can also be determined by comparing the series resistance affected measured I-V curve with the series resistance ignored I-V curve [11]. A review of this method can be found in [12, 13]. Araujo and Sanchez suggested an equation to determine series resistance [14], where the area under the I-V curve needs to be determined at first in order to calculate the resistance from that equation.

A graphical method is presented along with some theoretical manipulation in order to determine series resistance in [15]. There is an expression proposed to extract series resistance where slope at any particular point of the I-V curve is required to be determined at first. After plugging in the value of the slope at that point and other parameters such as ideality factor, short circuit current etc. series can be obtained.

The Dark I-V curve is utilized and compared with the one-sun I-V curve to determine series resistance in [16, 17]. However, that method ignores the effect of dark series resistance which shows the erroneous result. Hence, Dicker provided a modified equation to rectify the error [18].

2.1.2 Analytical Approach

Batzelis proposed an analytical extraction method to determine model parameters, where a set of analytical expressions along with the Lambert W function is utilized to extract series resistance [19]. Ortiz-Conde et al. introduced the Co-content function as a substitute for the Lambert W function since analytical expressions containing the Lambert W function are not suitable for numerical fitting to determine the model parameters [20]. The authors proposed a new analytical explicit expression containing the Co-content function and after determining different coefficients of that expression model parameters including series resistance are extracted.

Humada et al. presented new modeling of PV system along with parameter extraction method in [21]. In their proposed method, nine constant coefficients are utilized to determine different parameters including series resistance of the PV model. And those constant values are extracted based on the experimental values of model parameters.

A comparative study on three different methods is presented in [22]. One of them is the simplified explicit method, where the equation of series resistance is derived after conducting some approximation and simplifications of the I-V curve characteristic equation.

Bai et al. presented a compound method to extract series resistance. In that method, the piecewise curve-fitting method is utilized along with the four-parameter model to obtain the five parameters of the module [23].

2.1.3 Numerical Approach

Muhammad et al. presented a computational approach to determine model parameters and named it as approximation and correction technique. To determine series resistance, they derived an equation for series resistance and after making some approximation to that equation

an expression for the initial value of series resistance is obtained. Finally utilizing the initial value and the equation for series resistance a five-loop iteration is conducted to extract series resistance [24].

An iterative method to determine series resistance is presented in [25]. Series resistance is initially considered zero in this method. It is noticeable in the algorithm that this method quite dependent on the tolerance value and the increment of series resistance during iteration. A comparison of this method with another proposed method is shown in [26]. The authors confirmed the validity of the proposed method with their results and concluded that the accuracy of the estimation is quite dependent on the initial conditions.

A method is proposed to determine series resistance where a point near the voltage source region is selected [27]. An equation relating the corresponding current and voltage of that point is presented as well. Finally, that equation is solved numerically to extract the series resistance.

Hansen and King presented an iterative method for the extraction of series resistance. In this method they obtained the ideality factor and shunt resistance at first, then series resistance is obtained through some iterations from its expression. The presence of the Lambert-W function is noticeable in the expression of series resistance [13].

2.1.4 Advanced Approach

There are some modern techniques included in the literature regarding series resistance determination [23]. Artificial Bee Colony algorithm is utilized successfully to extract model parameters of the module in [29]. The particle swarm optimization method is applied to extract series resistance along with other parameters in [30]. Moreover, Ahhajri et al. utilized Particle swarm optimization to determine parameters by reducing the number of functions [31]. For a three-diode model, Khanna et al. also utilized the Particle Swarm Optimization algorithm in order to extract the parameters and showed the validation of their findings [32].

Chapter 3

Theoretical Background

3.1 Background

Various approaches in literature [33] have been performed to extract and determine the photovoltaic module parameters. Authors in paper [34] states that the knowledge of open-circuit voltage, short circuit current, maximum peak point voltage, and current as well as the maximum power of specific PV module can be obtained from the manufacturer's datasheet. It illustrates the values that have been taken in various indoor states only for example STC or NOCT. Aside from that, if the parameters of the PV modules are measured in different weather conditions along with different temperature and irradiance levels, the value of the parameters will vary depending on which materials have been used and what manufacturing technologies have been applied to that system. In that case, the error of the results will be increased if the parameter values from the manufacturer's datasheet are being implemented.

3.2 Single Diode Exponential Model

Every photovoltaic cell is composed of a p-n junction that can produce electrical energy immediately from its solar energy. To demonstrate the PV module, the equivalent circuit needs to be designed at first which can be illustrated using single diode or double diode models [35]. For a single diode exponential model, the equivalent circuit consists of a current source that is in parallel with a diode. Parasitic series and shunt resistance exist there as well which is shown in figure (3.1). By observing figure (3.1), a load is seen at the right side of the circuit which causes the decrement of the total reverse-biased current by increasing the potential difference in the circuit [24]. Hence, the final characteristic current of the system has been calculated by summing up the total instantaneous current of the load [24].

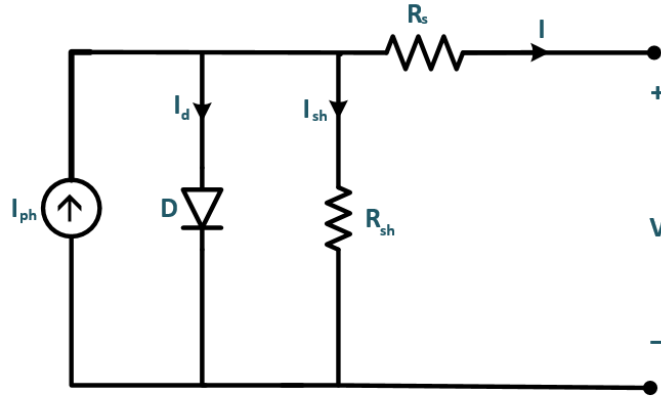


Figure 3.1: Equivalent circuit of a single diode exponential model for solar cell.

Shockley in 1950 disclosed the relation between the current and the voltage from this one-diode model by taking a single point from characteristic I-V curve and expressed the equation as follows:

$$I = I_{ph,cell} - I_{o,cell} \left[\exp \left(\frac{q \cdot V_{cell}}{AKT} \right) - 1 \right] \quad 3.1$$

This equation can be implied only for the ideal solar cell. As photovoltaic modules are the combination of multiple solar cells that are coupled in series, equation (3.1) can be modified by inserting the N_s term which denotes the number of series-connected cells. So, the equation becomes:

$$I = I_{ph} - I_o \left[\exp \left(\frac{q \cdot V}{N_s aKT} \right) - 1 \right] \quad 3.2$$

This equation is implemented for an ideal solar module and the designing of this type of module is impracticable. Thus, the equation is modified by adding a series resistance and shunt resistance for practical usage which explains the characteristic I-V curve more precisely and can be expressed as:

$$I = I_{ph} - I_o \left[\exp \left(\frac{q \cdot (V + IR_s)}{N_s aKT} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad 3.3$$

In this equation, K indicates the Boltzmann's constant, and T denotes the temperature. Correspondingly, the charge of an electron and the total number of series cells are demonstrated with q and N_s . The series and shunt resistance represent the material resistance that the photovoltaic module experiences and losses of the output power due to leakage current respectively. Moreover, from the I-V curve, it can be observed that series resistance has control over the voltage region while the effect of shunt resistance can be seen in the current region explicitly [7]. Furthermore, the photo-generated current I_{ph} and open-circuit voltage V_{oc} can be measured from the I-V characteristic curve by determining the slope in the current region and in the voltage region respectively. To measure the saturated current I_0 , the temperature sensor is used as it is a temperature-dependent parameter [37]. By measuring all these values, the calculation of the series resistance can be attained using equation (3.3).

However, to apply the single diode exponential equation, the irradiance level must be high as it fails to provide a good outcome while the irradiance becomes very low. In this case, the double diode model can be the solution which can be applied even in low illumination levels [47]. At the same time, it requires calculating some extra parameters which makes the system complicated. As a consequence, the application of the single diode model with some conditions and adjustments under different conditions is more advantageous in some cases [38-40].

3.3 Five Parameter model

Five parameter model has been designed by the University of Wisconsin-Madison which is applied on a large scale for modeling the solar cell [41]. This model helps to reduce the over prediction of maximum power point (MPP) in a substantial amount which occurs while fewer parameters are used. It incorporates both series and shunt resistance which is shown in equation (3.3). From this equation, five parameters can be extracted which are photo-generated current (I_{ph}), reverse saturation current (I_0), ideality factor (A), series resistance (R_s), and shunt

resistance (R_{sh}). These values are important for completing the relation between voltage and current. Additionally, it can be determined under certain temperature and irradiation state using three operating conditions of a PV module which are [48]:

1. **Open circuit operation:** In this condition, the output end is not connected and because of that current will be zero at the output terminal ($I=0$). Besides, terminal voltage will be equal to the open-circuit voltage ($V=V_{oc}$) that gives the highest voltage value. Hence equation (3.3) becomes [23]:

$$I_{ph} = I_o \left[\exp \left(\frac{q \cdot (V_{oc})}{N_s a K T} \right) - 1 \right] - \frac{V_{oc}}{R_{sh}} \quad 3.4$$

2. **Short circuit operation:** According to this operation, output terminals of the module are shorted which makes the terminal voltage zero ($V=0$) as no potential difference is found across the two terminals. Also, the highest amount of current is flown to the PV module which is equivalent to the short circuit current ($I=I_{sc}$). Thus, the modified form of equation (3.3) can be expressed as follows [23]:

$$I = I_{ph} - I_o \left[\exp \left(\frac{q \cdot (V + I R_s)}{N_s a K T} \right) - 1 \right] - \frac{V + I R_s}{R_{sh}} \quad 3.5$$

3. **Maximum power point operation:** In this operating condition, the values of current and voltage that we get, will be equivalent to the maximum current (I_{mp}) and the maximum voltage (V_{mp}) respectively. Besides, at the maximum power point, the derivation of power with respect to voltage gives zero $\left(\frac{dP_{mp}}{dV_{mp}} = 0 \right)$ due to the single peak characteristics of a PV module. By putting this voltage and current value to equation (3.3), the equation we get is:

$$I_{mp} = I_{ph} - I_o \left[\exp \left(\frac{q \cdot (V_{mp} + I_{mp} R_s)}{N_s a K T} \right) - 1 \right] - \frac{V_{mp} + I_{mp} R_s}{R_{sh}} \quad 3.6$$

3.4 Four parameter model

The four-parameter model is the simplified form of the five-parameter model where the shunt resistance is assumed to be infinite and inconsiderable [9, 23, 43, 49]. Despite this, it is also responsible for overestimating the output power while the irradiance is very high [44]. The equivalent circuit of this model has been displayed in figure (3.2).

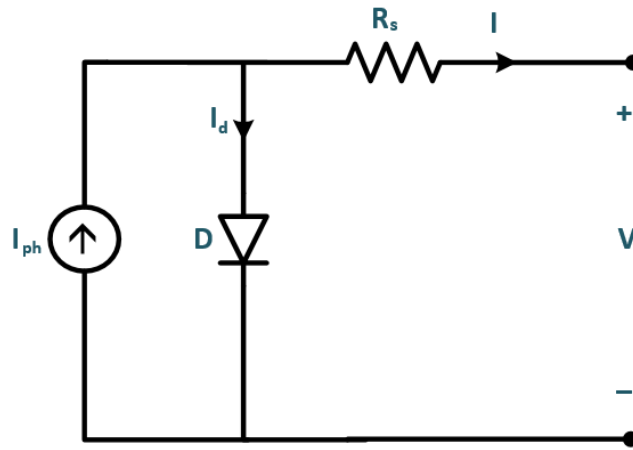


Figure 3.2: Equivalent circuit diagram of a four-parameter model.

Since the shunt resistance is neglected, the parameter extraction will be simpler and the simplified equation can be derived from equation (3.3) which is:

$$I = I_{ph} - I_o \left[\exp \left(\frac{q \cdot (V + I R_s)}{N_s a K T} \right) - 1 \right] \quad 3.7$$

The four parameters from this equation (photo-generated current (I_{ph}), ideality factor a , saturated current I_o , and series resistance R_s) can be extracted using analytical and iterative methods that have been described in the paper [35]. Between these, analytical method is more preferable for parameter extraction as it is easier to perform with high accuracy [23]. First of

all, some unknown parameters need to be determined from the I-V characteristics equation which are open-circuit voltage, short circuit current, maximum voltage, maximum current and maximum power point and for this reason, three points are taken:

1. Open circuit point: here, $V=V_{oc}$ and $I=0$. Thus, the equation becomes [22, 23]:

$$0 = I_{ph} - I_o \left[\exp \left(\frac{q \cdot V_{oc}}{N_s a K T} \right) - 1 \right] \quad 3.8$$

2. Short circuit point: At this point, $V=0$ and $I=I_{sc}$. Hence equation (7) can be expressed as follows [5,32]:

$$I_{sc} = I_{ph} - I_o \left[\exp \left(\frac{q \cdot I_{sc} \cdot R_s}{N_s a K T} \right) - 1 \right] \quad 3.9$$

3. Maximum power point: This is the point where V and I is equivalent to V_{mp} and I_{mp} respectively. Henceforth, the equation (3.7) can be stated as [22, 23]:

$$I_m = I_{ph} - I_o \left[\exp \left(\frac{q \cdot (V_{mp} + R_s)}{N_s a K T} \right) - 1 \right] \quad 3.10$$

3.5 Three Parameter Model

Three-parameter model is comprised of photo-generated current (I_{ph}), dark saturation current (I_o) and diode ideality factor (a). It is the easiest model to design where both R_s and R_{sh} values are omitted by assuming the shunt resistance to be very high while the series resistance to be quite small [50]. Similarly, the I-V characteristic curve has been explained without considering R_s and R_{sh} in the basic single diode equation. Hence the expression can be written as:

$$I = I_{ph} - I_o \left[\exp \left(\frac{q \cdot V}{N_s a K T} \right) - 1 \right] \quad 3.11$$

Here, N_s stands for the number of cells that are connected in series. If the equation is written for solar cells instead of solar modules, the N_s term will be deducted in that case. Furthermore, both the photo-generated current and the dark saturation current are temperature-dependent parameters and the value of the temperature coefficient is given by the manufacturer of PV modules [50].

3.6 Seven Parameter Model

The main concern of PV modeling is to get better output and to improve the efficiency of the solar cell or module. But practically, while measuring the parameter in outdoor conditions the temperature, as well as the irradiance level, will not be the same for the whole time. Since the effect of temperature and illumination are massive on measuring the parameters, a system has to be modeled where the series resistance will be dependent on temperature. Therefore, inserting two additional parameters along with the five-parameter model will perform better in low irradiance conditions. The equivalent circuit of the seven-parameter model is shown in figure (3.3).

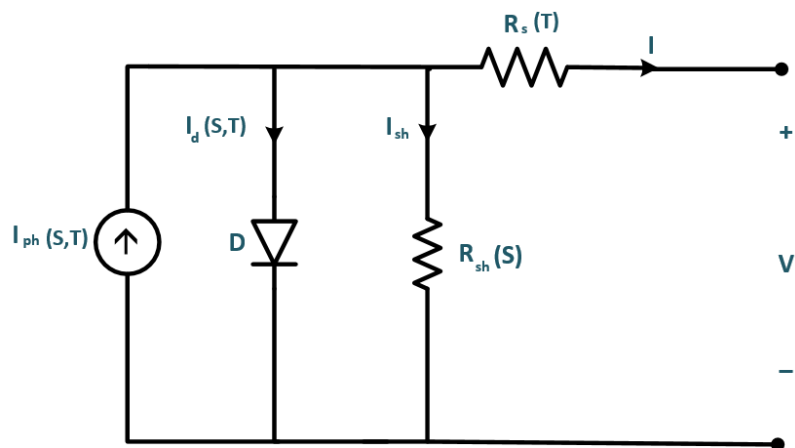


Figure 3.3: Equivalent circuit diagram of seven parameter model.

This model is the expanding version of a five-parameter model where δ is presented as a new constant which signifies nonlinear series resistance temperature-dependent parameter. The

mathematical equation can be written as [50]:

$$R_s = R_s \cdot \exp[\delta(T_{cell} - T_{REF})] \quad 3.12$$

Besides this, another parameter ‘m’ has been introduced that denotes diode reverse saturation current factor and the value of this parameter can be measured using numerical methods with the help of maximum power current and voltage at low irradiance (200W/m² and 25°c). The equation can be expressed as follows [50]:

$$I_D = I_{D,REF} \left(\frac{S_{REF}}{S}\right)^m \left(\frac{T}{T_{REF}}\right)^3 \exp\left(\frac{qE_g}{K} \left[\frac{1}{T_{REF}} - \frac{1}{T}\right]\right) \quad 3.13$$

Like five parameter model, seven parameter model gives the same information of the PV module along with two new parameters.

3.7 Double Diode Exponential Model

The photovoltaic module experiences some losses caused by the recombination process in the surface part as well as nearby the junction space area while recombining the carrier. To reduce these losses, solar modules need to be designed with two exponential diode junctions [45, 46] which is shown in figure (3.4).

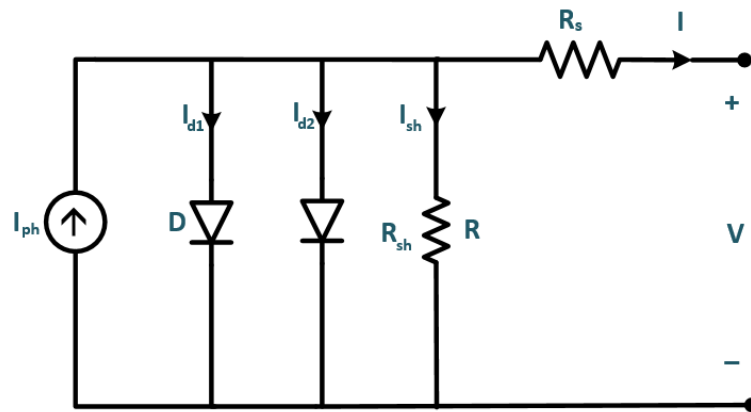


Figure 3.4: Equivalent circuit of a double diode exponential model for solar cell.

Mathematical equation of this circuit can be expressed as:

$$I = I_{ph} - I_{o1} \left[\exp \left(\frac{q(V + IR_s)}{a_1 \cdot K \cdot T} \right) - 1 \right] - I_{o2} \left[\exp \left(\frac{q(V + IR_s)}{a_2 \cdot K \cdot T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad 3.14$$

In this equation, photo-generated current I_{ph} , saturation current I_{o1} of diode 1, saturated current I_{o2} of diode 2, R_s and R_{sh} are presented by taking specific temperature and irradiance. These parameters can be derived from the I-V characteristics curve (figure 3.5) using the value of open-circuit voltage V_{oc} , short circuit current I_{sc} , maximum current I_{mp} , maximum voltage V_{mp} , R_{s0} and R_{sh} as well [35].

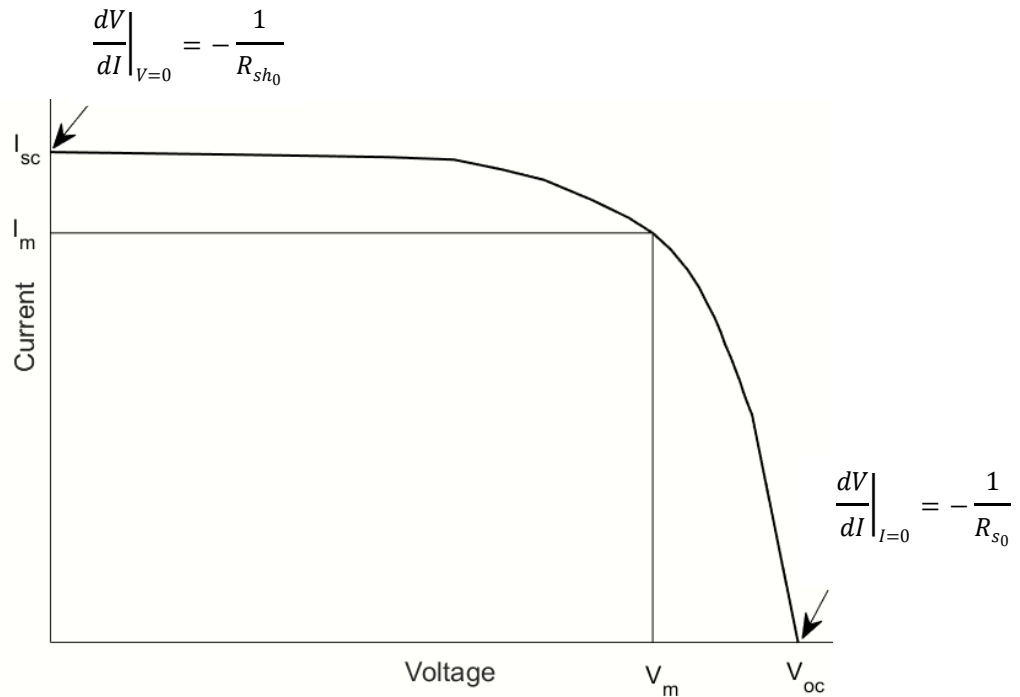


Figure 3.5: Input parameters from I-V characteristics curve.

By assuming $I_{ph} = I_{sc}$ the diode1 and diode 2 saturated current will be [9]:

$$I_{o1} = \frac{1}{2} \cdot \frac{I_{ph}}{\left(\exp \left(-\frac{q \cdot V_{oc}}{K \cdot T} \right) - 1 \right)} \quad 3.15$$

$$I_{o2} = \frac{1}{2} \cdot \frac{I_{ph}}{\left(\exp\left(\frac{q \cdot V_{oc}}{2KT}\right) - 1\right)} \quad 3.16$$

R_s optimization can be done as well by deriving an equation of double diode [9] which is as follows:

$$R_s = \left[\frac{dv}{dI} \Big|_{v = V_{oc}} + \frac{1}{X1v + X2v + \frac{1}{R_{sh}}} \right] \quad 3.17$$

Where,

$$X1v = -\frac{q \cdot I_{o1}}{KT} \cdot \exp\left(-\frac{q \cdot V_{oc}}{KT}\right) \quad 3.18$$

And

$$X2v = -\frac{q \cdot I_{o2}}{aKT} \cdot \exp\left(-\frac{q \cdot V_{oc}}{aKT}\right) \quad 3.19$$

The simplification of equation (3.17) can be made by estimating $\frac{1}{R_{sh}} \ll (X1v + X2v)$ [9]:

$$R_s = -\left[\frac{dv}{dI} \Big|_{v = V_{oc}} + \frac{1}{X1v + X2v} \right] \quad 3.20$$

In addition to that, if we take equation (3.14) at short circuit point where $V=0$ and $I=I_{sc}$, we could get short circuit current and the equation will be as follows:

$$I_{sc} = I_{ph} - I_{o1} \left[\exp\left(\frac{q \cdot I_{sc} \cdot R_s}{a_1 \cdot K \cdot T}\right) - 1 \right] - I_{o2} \left[\exp\left(\frac{q \cdot I_{sc} \cdot R_s}{a_2 \cdot K \cdot T}\right) - 1 \right] - \frac{I_{sc} \cdot R_s}{R_{sh}} \quad 3.21$$

Also, the equation for the open circuit point ($V=V_{oc}$ and $I=0$) can be expressed as:

$$I_{ph} = I_{o1} \left[\exp\left(\frac{q \cdot V_{oc}}{a_1 \cdot K \cdot T}\right) - 1 \right] + I_{o2} \left[\exp\left(\frac{q \cdot V_{oc}}{a_2 \cdot K \cdot T}\right) - 1 \right] + \frac{V_{oc}}{R_{sh}} \quad 3.22$$

3.8 Effect of the Series Resistance on the Fill Factor

The reduction of the fill factor happens due to the parasitic series and shunt resistance which are found more or less in every practical solar module. This happens due to the use of semiconductor materials in solar modules which contains bulk amount of resistance. Likewise, the design of the photovoltaic system needs to have an interconnection that connects the metal contact with the semiconductor. For interconnection and transportation of the carrier to the diffused layer, some amount of series resistance is produced. Moreover, in practical diodes, the junctions have some non-ideal factors with impurities which is responsible for shunt resistance. It occurs specifically in the adjoining part of the junction end and cell corner. Hence, the presence of both series and shunt resistance reduces the fill factor which causes efficiency and output power dropping as well. The maximum power of the solar cell can be derived from:

$$P'_m = P_{mp} - I_{mp}^2 R_s \quad 3.23$$

Here, P'_m indicates maximum power for a nonzero value of R_s and from this equation, the maximum power will be shifted by a multiplicative term of maximum current value and nonzero R_s value. If the second term of the right side of equation (3.23) is divided by V_{mp} , then the equation that we get can be expressed as:

$$P'_m = P_{mp} \left(1 - \frac{I_{mp}}{V_{mp}} R_s \right) \quad 3.24$$

From equation (3.24), an assumption can be made which is:

$$\frac{I_{mp}}{V_{mp}} \approx \frac{I_{sc}}{V_{oc}} \quad 3.25$$

So, equation (3.24) changes into:

$$P'_m = P_{mp} \left(1 - \frac{I_{sc}}{V_{oc}} R_s \right) \quad 3.26$$

Here, $\frac{I_{sc}}{V_{oc}} R_s$ is the normalized series resistance value which can be expressed by r_s and for normalization factor calculation, open circuit voltage is divided by the short circuit current.

Thus equation (3.26) turns out to be:

$$P'_m = P_{mp} (1 - r_s) \quad 3.27$$

Correspondingly, equation (3.27) can be converted into the fill factor equation later:

$$\begin{aligned} FF &= \frac{P'_m}{V_{oc} \cdot I_{sc}} \\ &= \frac{P_{mp}(1 - r_s)}{V_{oc} \cdot I_{sc}} \\ &= FF_o (1 - r_s) \end{aligned} \quad 3.28$$

The above-mentioned equation connects FF_o (which is found by considering zero series resistance) with FF (which is calculated by putting a nonzero series resistance value). Additionally, from this equation, the independent nature of open circuit voltage (V_{oc}) and short circuit current (I_{sc}) are observed in accordance with the series resistance value.

Chapter 4

Experimental Setup and Methodology

4.1 Experimental Setup

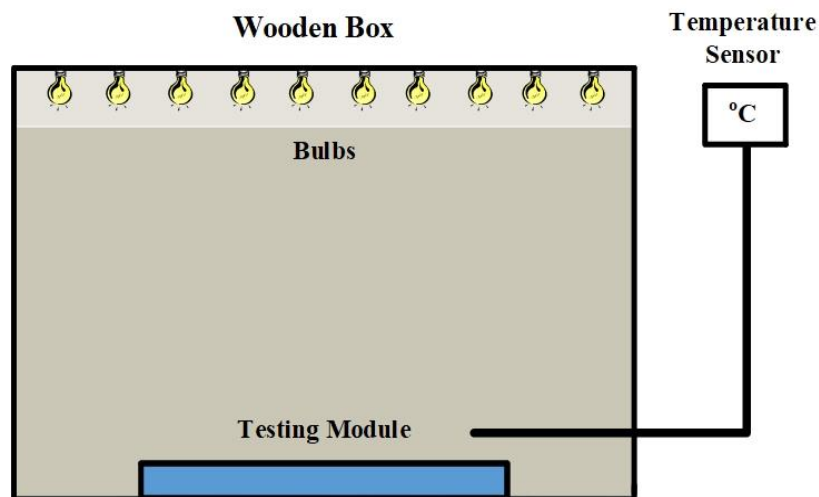


Figure 4.1: Block diagram for experimental setup to measure I-V data of the modules.

As per Figure 4.1, ten incandescent light bulbs of 200 watts each fitted inside a wooden box, have been used to perform the I-V measurement test. The temperature sensor that has been used in this testing, is DS18B20 which helped us to measure the panel surface temperature. Here, all five methods will be requiring STC, a temperature of 25° C, which is maintained with the help of a room air conditioner.

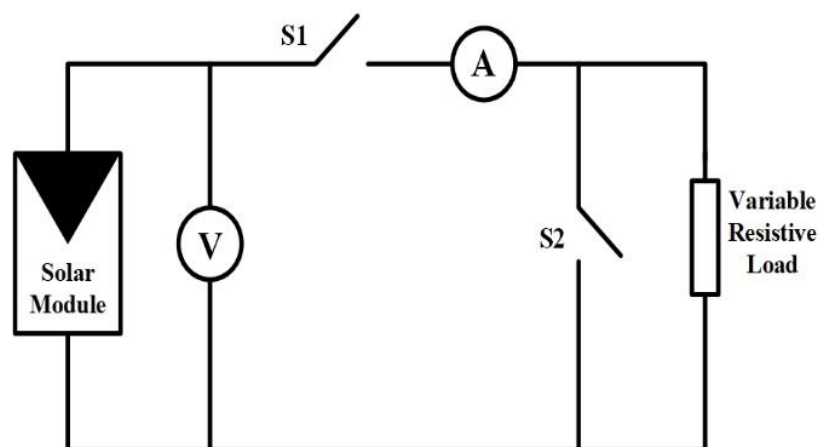


Figure 4.2: Circuit diagram representation for I-V data measurement of the modules.

A 100-ohm rheostat is used as the load as shown in Figure 4.2 which represents the circuit diagram of the experimental setup. Moreover, switch 1 is kept open in order to measure the open-circuit voltage. On the other hand, both switches are kept close to measure the short-circuit current.

4.2 Methodology

In this study, we have worked with six methods but during our research we have found twelve different methods to extract series resistance.

4.2.1 Applied Methods

Method 01

In literature, numerous methods are present for extracting the parameters of the PV module. According to the point of view of the Authors [8], all these methods seem complex having 4 to 5 parameters. Thus, they presented a modified three-parameter single diode exponential model which is not only simple but also effective. They chose to modify a four-parameter single diode exponential model where the shunt resistance is not considered for having a small value. The equation used for simplification is given below:

$$v = V_t \ln \left(\frac{I_{ph} + I_0 - i}{I_0} \right) - iR_s \quad 4.1$$

This equation is simplified by neglecting the dark saturation current I_0 , as it provides a small insignificant value. Another modification is made considering $I_{ph} \approx I_{SC}$ because the existing difference between photo-generated current and short circuit current is negligible. Thus, the three-parameter model equation took this form:

$$v = V_t \ln \left(\frac{I_{SC} - i}{I_0} \right) - iR_s \quad 4.2$$

Based on the above simplification an equation system is provided for determining panel parameters R_S , V_t , and I_O , which is mentioned below:

$$\begin{cases} V_{OC} = V_t \ln\left(\frac{I_{SC}}{I_O}\right) \\ V_{mp} = V_t \ln\left(\frac{I_{SC}-I_{mp}}{I_O}\right) - I_{mp}R_S \\ \frac{V_{mp}}{I_{mp}} = \frac{V_t}{I_{SC}-I_{mp}} + R_S \end{cases} \quad 4.3$$

R_S can be extracted using the following equation which was determined by solving the equation system (4.3):

$$R_S = \frac{V_t \ln\left(\frac{I_{SC}-I_{mp}}{I_{SC}}\right) + V_{OC} - V_{mp}}{I_{mp}} \quad 4.4$$

$$\text{Where } V_t = \frac{N_s a k T}{q}$$

It is mentioned that, for implementing this equation, data-sheet measurements are used.

Method 02

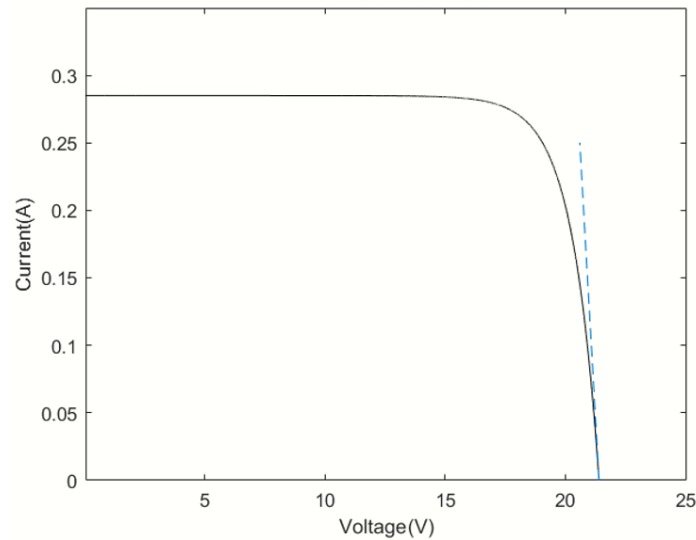


Figure 4.3: Slope of the I–V curve in the vicinity of the open-circuit voltage.

The most straightforward method for extracting the series resistance would be the slope method. As per [10], the highest forward bias for the junction is at the open-circuit voltage

which is the operating point where the slope of the I–V curve is the closest to be determined solely by the series resistance. Therefore, the nearer point to the open-circuit voltage we choose to determine the slope, the better results it gives us. Author [10] also stated one more advantage that this method does not require the entire I-V curve, only a small portion in the vicinity of open-circuit voltage. Being nearer to the open-circuit voltage helps to reduce the effects of other factors such as irradiation changes during the measurement, or distortions of the characteristic caused by partial shadows. Henceforth, by measuring the slope of a module’s I-V curve in the vicinity of the open-circuit voltage, series resistance can be estimated as shown in the following equation:

$$R_S = - \left. \frac{dV}{dI} \right|_{V \approx V_{oc}} \quad 4.5$$

Here, dV denotes voltage difference, and dI refers to current difference. We have chosen different voltage values in such a way so that the voltage difference for all the modules remains constant (0.15) which will help us to compare more accurately between different modules.

Method 03

In this method, the series resistance is determined by utilizing the measured I-V curve and the simulated I-V curve. For the simulated curve, shunt resistance is considered very high while keeping the series resistance at zero value. The measured I-V curve is obtained from the measured I-V data for each module. Figure 4.4 shows the measured curve and the simulated curve together.

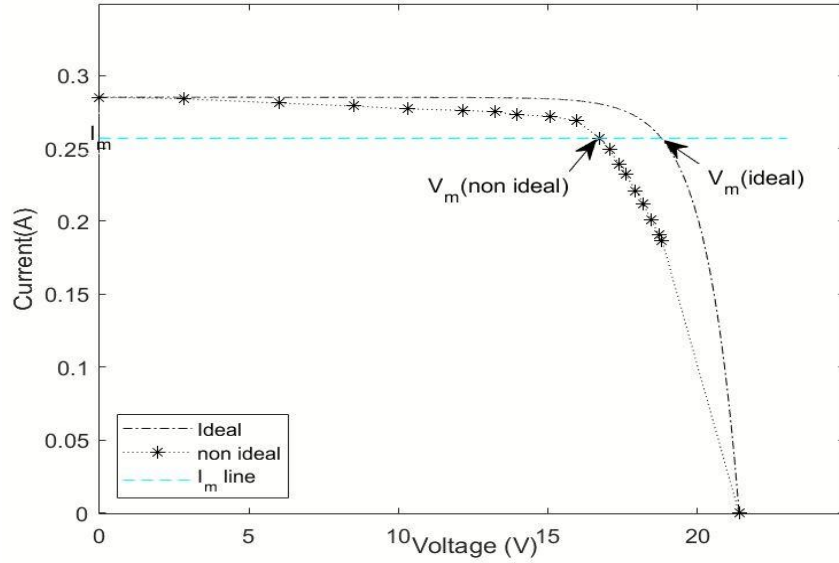


Figure 4.4: Measured vs. simulated I-V curve.

While comparing both curves it can be observed that at the maximum current level corresponding maximum voltage is different. Hence, this voltage difference is actually the loss due to the series resistance in the measured I-V curve. Thus, by applying Ohm's law the series resistance of the module can be obtained very simply (4.6):

$$R_s = \frac{\Delta V}{I_{mp}} \quad 4.6$$

In Eq. 4.6 $\Delta V = V_2 - V_1$, where V_2 represents the maximum voltage of the simulated I-V curve and V_1 represents the maximum voltage of the measured curve, while maximum current is denoted by I_{mp} .

While utilizing this method, based on our measured data I-V curve is plotted. And another series resistance-free I-V curve is also simulated from the I-V curve characteristic equation where shunt conductance is considered very high. After plotting both curves corresponding voltages of the I_{mp} line are obtained through some coding in MATLAB. Finally, utilizing (4.6) the value series resistance is extracted.

Method 04

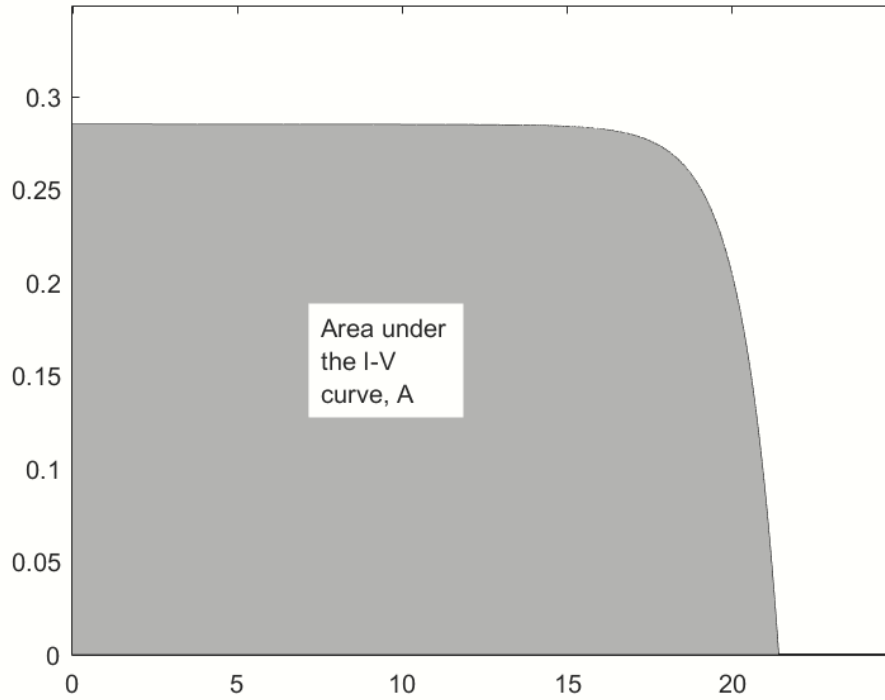


Figure 4.5: I-V curve characteristics of a PV module.

A very simple method of determining series resistance is described for which the I-V curve needs to be plotted for each module at first. Then series resistance is to be determined for cell from the following equation [16]:

$$R_{s,cell} = 2 \left[\frac{V_{oc}}{I_{sc}} - \frac{A}{I_{sc}^2} - a \frac{KT}{q} \frac{1}{I_{sc}} \right] \quad 4.7$$

For the module, the above equation needs to be modified by including a number of series cells connected with each module. Hence, for the module the modified series resistance is given below:

$$R_{s,module} = 2 \left[\frac{V_{oc}}{I_{sc}} - \frac{A}{I_{sc}^2} - N_s a \frac{KT}{q} \frac{1}{I_{sc}} \right] \quad 4.8$$

Here, the number of series cells for each module is denoted by N_s , while A represents the area under the module's I-V curve (Figure 4.5). Hence, the area under the curve:

$$A = \int_0^{I_{sc}} V(I) dI \quad 4.9$$

After determining the area under the curve, the value must be plugged in (4.8) along with other parameter values to obtain the series resistance of the modules.

Method 05

Authors in [26] discussed that, rather than using equations to determine parameters, another approach can be made where one of the parameters is adjusted based on the existing values to match a known condition such as the maximum power point. The current and voltage value for this point is known from the datasheet, thus the series resistance can be adjusted per MPP. It is mentioned that Moballegh and Jiang in their paper [28], considered the initial value of series resistance as zero. Then they slowly increased the R_s value to the point where they finally got an error value between the measured and maximum power point value which was acceptable. Authors [48] clarified that the obtained values are only valid for STC conditions and this method abides by the three operative conditions of the PV module which are open circuit, short circuit, and maximum power point condition. The equation between the current and voltage at the terminals of the PV cell is represented by:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{V+IR_s}{N_s V_t}\right) - 1 \right] - \frac{V+IR_s}{R_{sh}} \quad 4.10$$

And the equation presented for R_s is given below:

$$R_s = \frac{V_{OC} - V_{mp} + N_s V_t \ln \left[\frac{N_s V_t R_{sh} I_{mp} - N_s V_t V_{mp} + N_s V_t I_{mp} R_s}{(V_{mp} I_{SC} R_{sh} + V_{mp} I_{SC} R_s - V_{mp} V_{OC} + I_{mp} R_s V_{OC} - I_{mp} R_s I_{SC} R_s - I_{mp} R_s R_{sh} I_{SC})} \right]}{I_{mp}} \quad 4.11$$

As mentioned before, R_s is considered zero initially so that the value can be adjusted with maximum power point. For this reason, equation (4.11) then simplifies and becomes:

$$R_s = \frac{V_{OC} - V_{mp} + N_s V_t \ln \left[\frac{N_s V_t R_{sh} I_{mp} - N_s V_t V_{mp}}{V_{mp} I_{sc} R_{sh} - V_{mp} V_{OC}} \right]}{I_{mp}} \quad 4.12$$

The value of V_t is:

$$V_t = \frac{aKT}{q}$$

Method 06

The authors proposed [23] a method of determining series resistance for the five-parameter model, where series resistance for the four-parameter model has a crucial role. Series resistance for the four-parameter model is given by the following equation:

$$R_{s4} = \frac{a_4 \ln \left(1 - \frac{I_{mp}}{I_{ph4}} \right) - V_{mp} + V_{oc}}{I_{mp}} \quad 4.13$$

Here, the modified ideality factor for the four-parameter model is denoted by a_4 , whereas I_{ph4} represents photo-generated current of the four-parameter model. For a four-parameter model, the short-circuit current is approximately equal to the photo-generated current due to the existence of series resistance. Hence, the following relationship is used to determine photo-current:

$$I_{ph4} \approx I_{sc} \quad 4.14$$

However, a_4 can be obtained from the following expression:

$$a_4 = \frac{(2V_{mp} - V_{oc})}{\frac{I_{sc}}{I_{sc} - I_{mp}} + \ln \left(1 - \frac{I_{mp}}{I_{sc}} \right)} \quad 4.15$$

IV-curve can be divided into three different sections, namely low voltage, mid voltage and high voltage as shown in Figure 4.6 Two points can be selected from the low voltage section and high voltage section each in order to calculate the slope.

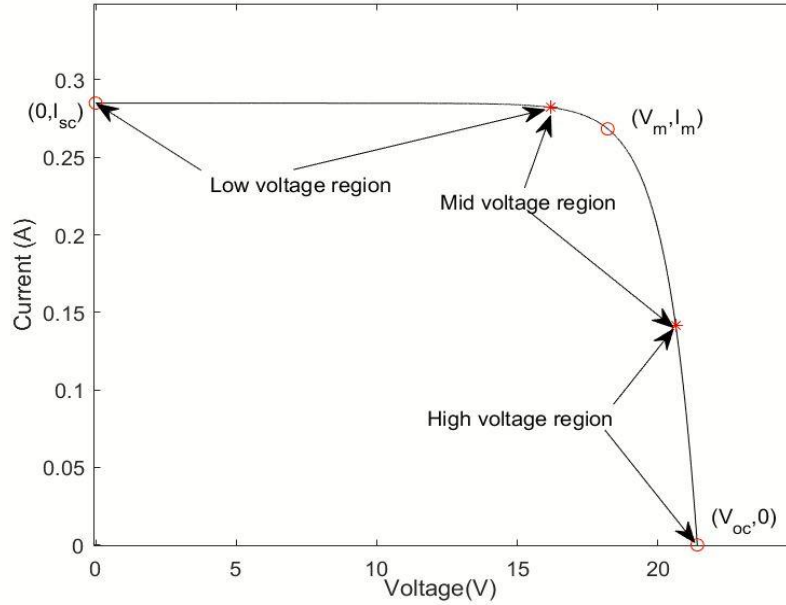


Figure 4.6: Three different sections in the I-V curve of a PV module.

Hence, from the low voltage section, $(0, I_{sc})$ and $(V(0.5*(I_{sc}+I_{mp})), 0.5*(I_{sc}+I_{mp}))$ are chosen, while from the high voltage section, $(V_{oc}, 0)$ and $(V(0.5*I_{mp}), 0.5*I_{mp})$ points are chosen. So, the slopes can be calculated from the following expressions:

$$\left. \frac{dV}{dI} \right|_{V=0} = \frac{a_4 \ln \left(\frac{0.5 * (I_{sc} - I_{mp})}{I_{o4}} + 1 \right) - 0.5 * (I_{sc} + I_{mp}) R_{s4}}{0.5 * (I_{sc} - I_{mp})} \quad 4.16$$

$$\left. \frac{dV}{dI} \right|_{I=0} = \frac{a_4 \ln \left(\frac{I_{sc} - 0.5 * I_{mp}}{I_{o4}} + 1 \right) - 0.5 * I_{mp} R_{s4} - V_{oc}}{0.5 * I_{mp}} \quad 4.17$$

Series resistance for five parameter model can be extracted from the following expression:

$$R_s = \frac{V_{mp} \left(\left. \frac{dV}{dI} \right|_{I=0} - \left. \frac{dV}{dI} \right|_{V=0} \right) \left[\left. \frac{dV}{dI} \right|_{V=0} (I_{sc} - I_{mp}) + V_{mp} \right] - \left. \frac{dV}{dI} \right|_{I=0} \left(\left. \frac{dV}{dI} \right|_{V=0} I_{mp} + V_{mp} \right) \left(\left. \frac{dV}{dI} \right|_{V=0} I_{sc} + V_{oc} \right)}{I_{mp} \left(\left. \frac{dV}{dI} \right|_{I=0} - \left. \frac{dV}{dI} \right|_{V=0} \right) - \left[\left. \frac{dV}{dI} \right|_{V=0} (I_{sc} - I_{mp}) + V_{mp} \right] + \left(\left. \frac{dV}{dI} \right|_{V=0} I_{mp} + V_{mp} \right) \left(\left. \frac{dV}{dI} \right|_{V=0} I_{sc} + V_{oc} \right)} \quad 4.18$$

After calculating all the necessary values from (4.13-4.17) and plugging in the values at (4.18) series resistance of each module for the five-parameter model is obtained.

4.2.1 Non-applied Methods

Method 07

Authors in paper [34] presented an approach for estimating PV module parameters using the experimental measurements based on the nonlinear least-square fitting algorithm method and an excel spreadsheet was developed to determine the initial values of parameters which helped to find the optimal values using excel solver. An implementation on 295W polycrystalline TRINA TSM-295 PC14 PV module using single diode models (L4P, L5P) is presented.

For the L5P model the used main equation is discussed in [42, 52]:

$$I_{pv} = I_{ph} - I_o \left[\exp^{\left[\frac{q(V_{pv} + R_s I_{pv})}{aKT_c} \right]} - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad 4.19$$

To determine R_s , firstly the STC value was calculated according to the equation provided by the authors in [36]:

$$R_{s,STC} = n_o \times \frac{V_t}{I_2 - I_1} \times \log \left(\frac{I_{ph} - I_2}{I_{ph} - I_1} \right) - \frac{V_2 - V_1}{I_2 - I_1} \quad 4.20$$

Then this $R_{s,STC}$ value was used to calculate R_s according to [23,36,42,54]:

$$R_s = R_{s,STC} \frac{T_c}{T_{STC}} \left[1 - \beta_{oc} \ln \left(\frac{G}{G_{STC}} \right) \right] \quad 4.21$$

Here, $\beta_{oc}=0.217$ which is the temperature coefficient.

For the L4P model the main equation is discussed in [46], where R_{sh} is neglected:

$$I_{pv} = I_{ph} - I_o \left[\exp^{\left[\frac{(V_{pv} + R_s I_{pv})}{a} \right]} - 1 \right] \quad 4.22$$

Here, $a = n \times V_t$ and the value is considered in between 1-1.5 according to [51].

STC and actual value of R_s was found accordingly using equations mentioned in [52]:

$$R_{S,STC} = \frac{a_{STC} \times \ln \left[1 - \left(\frac{I_{mp,STC}}{I_{ph,STC}} \right) \right] - V_{mp,STC} + V_{oc,STC}}{I_{mp,STC}} \quad 4.23$$

$$R_s = R_{S,STC} \quad 4.24$$

Standard error analysis like RMS and NRMES are used to check accuracy by [34] where they used equations from [53,55] accordingly:

$$RMS(\%) = \frac{\left[\frac{1}{n} \sum_{i=1}^n (I_{i,measured} - I_{i,model})^2 \right]^{\frac{1}{2}}}{\sum_{i=1}^n I_{i,measured}} \times 100 \quad 4.25$$

$$NRMSE = \frac{\left[\frac{1}{n} \sum_{i=1}^n (I_{i,measured} - I_{i,model})^2 \right]^{\frac{1}{2}}}{\frac{1}{n} \sum_{i=1}^n I_{i,measured}} \quad 4.26$$

Simulation results were compared with the in-field outdoor results for concluding that the approached method which proposed fitting, gives out an excellent close result per the experimental one while using the L4P model [34].

Method 08

Authors in paper [57] presented a method to estimate R_s where they used only one I-V curve under illumination and the second I-V curve was simulated using the effective solar cell equation method.

The following equation follows the effective solar cell characteristic:

$$I = I_{ph} - I_o \left(e^{\frac{V+IR_{pv}}{V_t}} - 1 \right) \quad 4.27$$

The explicit version of the equation:

$$V = V_t \ln \left(\frac{I_{ph} - I + I_o}{I_o} \right) - IR_{pv} \quad 4.28$$

Two IV curves of different irradiance but of the same spectrum and at the same temperature are necessary according to IEC 60891 [56] was mentioned by the Authors [57].

Firstly, two working points V_1 and V_2 are obtained using equation (4.28), from which the series resistance is calculated. Equations are given below:

$$V_1 = V(I_{SC1} - \Delta I, R_{pv1}, V_{T1}, I_{o1}, I_{ph1}) \quad 4.29$$

$$V_2 = V(I_{SC2} - \Delta I, R_{pv2}, V_{T2}, I_{o2}, I_{ph2}) \quad 4.30$$

The equation for R_s is as follow:

$$R_s = \frac{V_2 - V_1}{I_{SC1} - I_{SC2}} \quad 4.31$$

The second I-V curve can be obtained by covering the cell or module with an insect screen but this cannot be applied for larger PV generators.

Hence, the Authors [57] said that the first characteristic can be measured under open-air conditions with natural sunlight as the actual spectrum during the measurement is not relevant for the calculation of R_s . From this curve, four parameters are determined I_{sc1} , V_{oc1} , I_{pmax1} , V_{pmax1} Which are then used for obtaining the simulated second I-V curve. The following Equations are used:

$$FF = \frac{I_{pmax1} \cdot V_{pmax1}}{I_{SC1} \cdot V_{OC1}} \quad 4.32$$

$$f_i = \begin{cases} FF & \text{if } FF \geq 0.7 \\ 2.2 \cdot 10^{-9} \cdot e^{28 \cdot FF} & \text{otherwise} \end{cases} \quad 4.33$$

$$f_v = 1 \rightarrow \text{no change in Voltage} \quad 4.34$$

FF is considered the same for both curves, Hence:

$$I_{SC2} = f_i \cdot I_{SC1}$$

$$V_{OC2} = V_{OC1}$$

$$I_{pmax2} = f_i \cdot I_{pmax1}$$

$$V_{pmax2} = V_{pmax1}$$

Because of the above simplification R_s can be calculated only using one I-V curve.

Method 09

The authors of the paper [28] proposed a method for modeling photovoltaic arrays where they adjusted the curve with three points (open circuit, maximum power, short circuit) to determine the parameters of the non-linear I-V. For practical array, they used equation (4.35).

$$I = I_{pv} - I_o \left[\exp\left(\frac{V+R_s I}{V_t a}\right) - 1 \right] - \frac{V+R_s I}{R_p} \quad 4.35$$

Here R_s is the equivalent series resistance and R_p is the equivalent parallel resistance of the array. They used an iterative process where they increased the R_s value slowly starting from 0. The authors suggested that there is only a pair of R_s and R_p adjusted values which ensures $P_{max,m} = P_{max,e} = V_{mp} \times I_{mp}$.

Where, $P_{max,m}$ is the maximum power of the model, and $P_{max,e}$ is the maximum power from the datasheet.

R_s can be determined by solving the equation mentioned below:

$$P_{max,m} = V_{mp} \left\{ I_{pv} - I_o \left[\exp\left(\frac{q}{KT} \frac{V_{mp} + R_s I_{mp}}{a N_s}\right) - 1 \right] - \frac{V_{mp} + R_s I_{mp}}{R_p} \right\} = P_{max,e} \quad 4.36$$

For every value of R_s , there exist a value of R_p which can be determined using equation (4.36).

$$R_p = \frac{V_{mp}(V_{mp} + I_{mp} R_s)}{\left\{ V_{mp} I_{pv} - V_{mp} I_o \exp\left[\frac{(V_{mp} + I_{mp} R_s) q}{N_s a K T}\right] + V_{mp} I_o - P_{max,e} \right\}} \quad 4.37$$

Method 10

In [3] the authors proposed a new method that concerns directly to the usual IV measurement system (dark IV) giving IV data. Here, the current is taken from the IV curve and then R_s is measured by putting the value in some equations. To approach this method in cell IV curve, two diode model and equation have been used:

$$I = I_{s1}[\exp(\alpha_1(V - IR_s)) - 1] + I_{s2}[\exp(\alpha_2(V - IR_s)) - 1] + \frac{V - IR_s}{R_{sh}} \quad 4.38$$

Here, $\alpha_i = \frac{q}{akT}$;

As the main concern of this paper is to extract the series resistance, so this equation has been divided into two parts where the higher part effect R_s and the equation for this part can be written as:

$$I = I_{s1}[\exp(\alpha_1(V - IR_s)) - 1] \quad 4.39$$

If $I \gg I_{s1}$; equation (4.39) will be expressed as follows:

$$I = I_{s1}[\exp(\alpha_1(V - IR_s))] \quad 4.40$$

By taking ln it can be simplified as:

$$\ln I = \ln I_{s1} + \alpha_1(V - IR_s) \quad 4.41$$

After that the authors took one point (V_0, I_0) from the dark IV curve and tried to put this point to the equation (4.42) which can be stated by the following equation:

$$\ln I - \ln I_0 = \alpha_1(V - IR_s) - \alpha_1(V_0 - I_0R_s) \quad 4.42$$

From this equation (4.42), final relation can be expressed as:

$$\frac{\ln \frac{I}{I_0}}{I - I_0} = -\alpha_1 R_s + \alpha_1 \frac{V - V_0}{I - I_0} \quad 4.43$$

By assuming,

$$X = \frac{V-V_0}{I-I_0}$$

And $Y = \frac{\ln \frac{I}{I_0}}{I-I_0}$

The authors established a straight line:

$$Y = \alpha_1(-R_s + X) \quad 4.44$$

The linear regression of this equation provides R_s and α_1 , V is independent here and there is no restriction about voltage step which is the main advantage of this approach. They considered a I_i-V_i data set where they varied I from 1 to N and put the value of I to X and Y . Here to mention that, to extract proper value of R_s , I_0 must be taken from the higher part of the dark IV curve. In this way they iterated the process and extracted the most appropriate value of R_s .

Method 11

Authors in [3] divided the two diode equation into two parts and used the first part of the equation for estimating R_s :

$$I = I_{s1} [e^{\alpha_1(V-IR_s)} - 1] \quad 4.45$$

They took the differentiation of equation (4.45) and obtained equation (4.46) where R_s has been separated from the exponential term:

$$\frac{dV}{dI} = \frac{1}{\alpha_1(I+I_{s1})} + R_s \quad 4.46$$

$$\frac{dV}{dI} = \frac{1}{\alpha_1 I} + R_s \quad 4.47$$

If $I \gg I_s$ condition is applied in equation (4.46), the relation between $\frac{dV}{dI}$ and $\frac{1}{I}$ can be stated by equation (4.47) and from the plotting of this relation R_s can be extracted easily [3].

Method 12

In [22] four parameter model and equation have been used in solar module which is:

$$I = I_{ph} - I_o \left[\exp \left(q \frac{(V + IR_s)}{N_s aKT} \right) - 1 \right] \quad 4.48$$

According to the author, these parameters can be determined from the IV characteristics by using reference irradiance ($E=1000\text{W/m}^2$) and reference temperature ($T=25^\circ\text{C}$). Here, the author takes some point to determine the unknown parameter.

$$I_{sc} = I_{ph} - I_o \left[\exp \left(q \frac{I_{sc}R_s}{N_s aKT} \right) - 1 \right] \quad 4.49$$

$$0 = I_{ph} - I_o \left[\exp \left(q \frac{(V_{oc})}{N_s aKT} \right) - 1 \right] \quad 4.50$$

$$I_{mp} = I_{ph} - I_o \left[\exp \left(q \frac{(V_{mp} + I_{mp}R_s)}{N_s aKT} \right) - 1 \right] \quad 4.51$$

By taking $(0, I_{sc})$ they get equation (4.49) and by inputting $(V_{oc}, 0)$ to equation (4.48) they develop equation (4.50) and equation (4.51) has come from using (V_{mp}, I_{mp}) .

The first approximation that the authors made for the simplified explicit method is $I_{ph}=I_{sc}$.

Using this approximation, the modified equations of (4.49), (4.50), (4.51) can be written as:

$$I_{ph} = I_{sc} \quad 4.52$$

$$0 = I_{ph} - I_o \left[\exp \left(q \frac{(V_{oc})}{N_s aKT} \right) \right] \quad 4.53$$

$$I_{mp} = I_{ph} - I_o \left[\exp \left(q \frac{(V_{mp} + I_{mp}R_s)}{N_s aKT} \right) \right] \quad 4.54$$

In this paper the I_o equation has been written from equation (4.53) by putting $I_{ph}=I_{sc}$.

$$I_o = I_{sc} \exp \left(-q \frac{V_{oc}}{N_s aKT} \right) \quad 4.55$$

After that, the equation of R_s is construed from equation (4.54) by inputting the I_o equation and $I_L=I_{sc}$ approximation which is as follows:

$$R_s = \frac{\frac{N_s a K T}{q} \ln\left(1 - \frac{I_{mp}}{I_{sc}}\right) V_{oc} - V_{mp}}{I_{mp}} \quad 4.56$$

Chapter 5

Result and Analysis

5.1 Result and Analysis

This chapter is dedicated to explain and analyze extracted R_s parameter values which are found using different methods and solidifying our claims through several error analysis processes. Throughout the methodology several R_s extraction methods are explained, from there six methods are selected and have been used to extract series resistance based on our data. Among these six methods, four methods are experimental and two are theoretical. For providing variation and better clarity, 15 different modules from 3 manufacturers are used for implementing these methods. Several basic parameters are involved for R_s extraction. All those parameters are displayed in tabular form and are separated by the manufacturing company.

Table 5.1: Parameters used for extracting R_s Genetic modules

Genetic					
	Module 3	Module 4	Module 5	Module 6	Module 12
V_{oc}	20.81	21.17	21.2	18.81	21.52
I_{sc}	0.302	0.312	0.303	0.299	0.297
V_{mp}	16.52	16.95	16.74	15.01	14.44
I_{mp}	0.268	0.284	0.275	0.277	0.286
R_{sh}	1.0003e3	961.5385	1.0837e3	961.5719	4.70806
P_{mp}	4.4274	4.8138	4.6035	4.1577	4.70806
I_o	2.482e-9	1.858e-9	1.757e-9	1.471e-8	1.2932e-9

Table 5.2: Parameters used for extracting R_s Greenland modules

Greenland					
	Module 1	Module 11	Module 13	Module 14	Module 15
V_{oc}	21.45	21.35	21.43	21.56	21.44
I_{sc}	0.307	0.301	0.3	0.319	0.307
V_{mp}	17.18	18.1	16.66	18.86	17.55
I_{mp}	0.285	0.252	0.284	0.234	0.279
R_{sh}	1.0883e10	413.3289	1.0868e10	378.7500	1.0258e10
P_{mp}	4.8963	4.5612	4.7314	4.4132	4.8965
I_o	1.4232e-9	1.5259e-9	1.4158e-9	1.3402e-9	1.4359e-9

Table 5.3: Parameters used for extracting R_s Solar modules

Solar					
	Module 1	Module 11	Module 13	Module 14	Module 15
V_{oc}	18.8	18.55	19.35	19.43	18.73
I_{sc}	0.337	0.352	0.386	0.366	0.388
V_{mp}	16.25	16.36	15.07	16.67	15.09
I_{mp}	0.265	0.246	0.352	0.282	0.324
R_{sh}	161	14.6591	723.9287	145.5814	620.5412
P_{mp}	4.3063	4.0246	5.3046	4.7009	4.8892
I_o	1.6724e-8	1.6724e-8	1.1711e-8	1.0338e-8	2.0499e-8

Table 5.4: Constant valued Parameters

Parameters	Values
N_s	36
a	1.2
K	$1.38 \cdot 10^{-23} \text{m}^2 \text{kgs}^{-2} \text{K}^{-1}$
q	$1.60 \cdot 10^{-19} \text{C}$
T	300K

5.2 Extracted R_s Values and Bar-chart Implementation

It is needless to mention that, analyzing the extracted R_s data is essential to build a solid claim. Bar-chart implementation is an effective way to analyze how each method is performing for a certain module. It enhances our visual understanding as we can differentiate between each method only by looking at the graphical figures.

Table 5.5: Extracted R_s values - Genetic Module

Module List	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6
M-3	6.9615	10.2646	6.8754	3.6464	4.3694	5.8043
M-4	5.4367	9.2386	5.3444	3.3634	3.8808	6.2213
M-5	6.6055	13.7968	8.0111	5.0828	4.9183	8.5158
M-6	3.262	8.3616	3.1592	2.1922	3.0219	6.8921
M-12	5.1032	9.1000	5.0082	2.9106	2.9106	4.3848

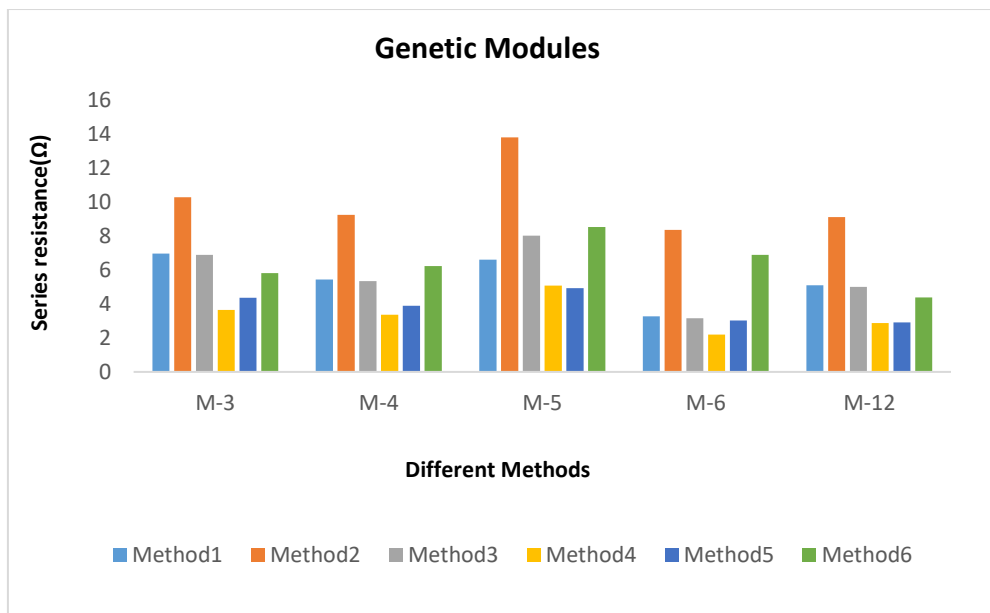


Figure 5.1: Bar-Chart Representation of Genetic Modules.

Analysing Figure 5.1, the order of preference for methods can be deciphered. Moreover, the overview displays that the R_s value of each method for M-6 is less than that of other modules.

Hence, M-6 is a better-fitted module for all the applied methods. Further inspecting the graph, it can be noticed that the series resistance values for Method 1 and Method 3 are somewhat close. Also, interestingly enough Method 4 provided the best R_s value for each tested module. However, Method 2 can be considered as the least preferred method, since it provides high values for all modules. The theoretical methods (4 & 5) display a good range of R_s values. Although these two methods have higher values than Method 4, they have lower values than Method 2.

Table 5.6: Extracted R_s values - Greenland Module

Module List	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6
M-1	4.1767	8.65	4.6114	2.4284	4.0678	7.4773
M-11	4.9009	8.9796	4.8272	5.9574	0.1841	3.9073
M-13	5.3393	10	5.214	3.5626	6.0512	11.1364
M-14	5.2694	9.0547	5.2505	8.0177	3.5599	22.5117
M-15	4.4156	8.7065	4.3217	3.3503	2.6155	4.4067

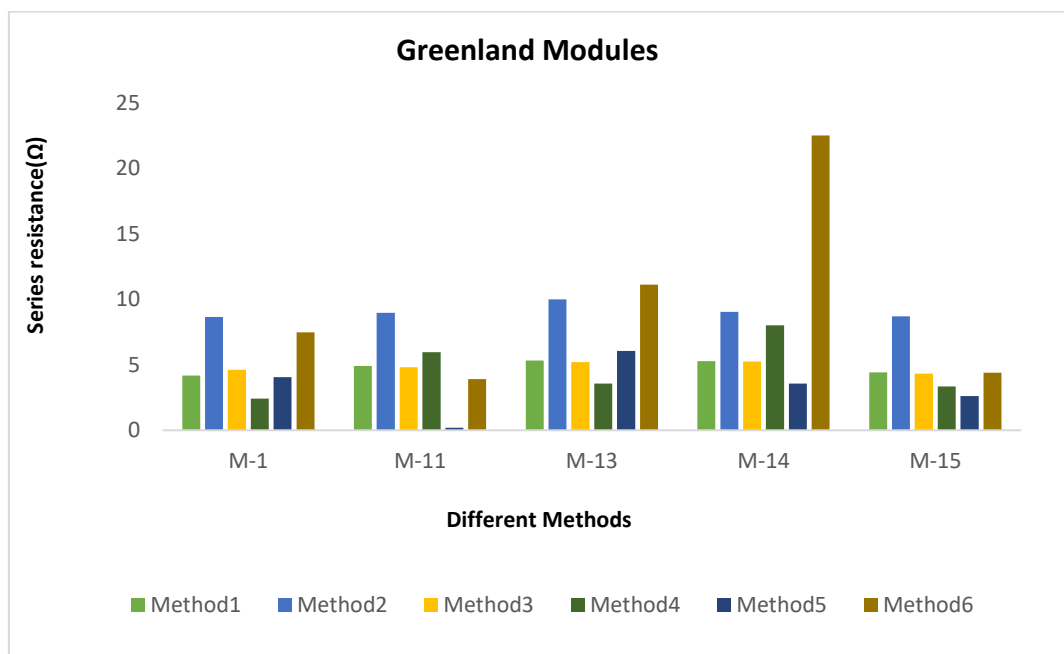


Figure 5.2: Bar-Chart Representation of Greenland Modules.

Greenland modules provided variation in their extracted series resistance values. Table 5.6 and Figure 5.2. both testify that among all these five modules, M-15 values are lowest ranging from 2.6155Ω to 8.7065Ω . Consistency is found regarding Method 1 and Method 3, for both methods R_s value ranged between 4Ω to 5.5Ω . It can be seen that, depending on the lowest series resistance value, for M-1 and M-13 Method 4 is more suited and for M-11, M-14 and M-15 Method 5 is a better choice. Method 2 displays a higher R_s value among the graphical methods. But if the theoretical methods are included then it is evident that in the case of M-13 and M-14 Method 6 has a very high series resistance value.

Table 5.7: Extracted R_s values - Solar Module

Module List	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6
M-2	3.1578	6.9101	3.1023	6.6067	2.8428	9.0094
M-7	3.4869	6.6619	3.4415	11.1368	3.4487	26.3781
M-8	4.498	6.6839	4.4286	2.1484	3.683	6.3243
M-9	3.9939	6.3388	3.9448	6.8818	2.1596	9.3336
M-10	5.0606	6.8189	5.0082	2.5106	1.6932	1.1189

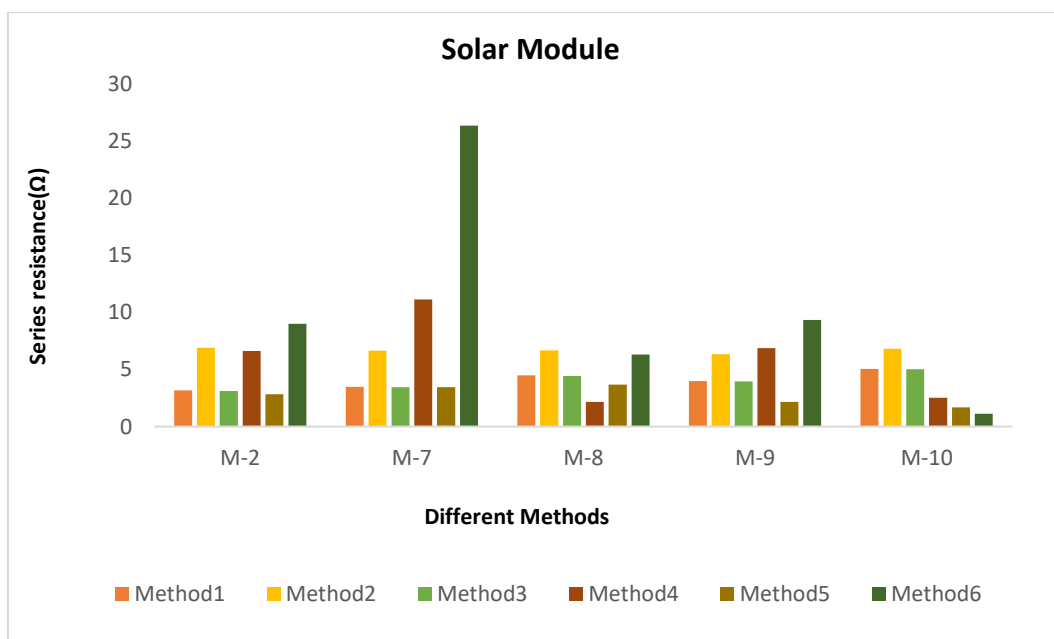


Figure 5.3: Bar-Chart Representation of Solar Modules.

The test conducted on Solar modules provided a more suited range for R_s values than genetic and Greenland modules. An amusing fact can be seen in Figure 5.3. regarding the values of Method 2 for each module, it ranges between 6.3Ω to 6.91Ω . Whereas, Method 2 displayed a high and variety in the range of values in genetic and Greenland modules. Method 5 has the lowest ranging series resistance values. A similar range of R_s value is found for Method 1 and Method 3. Method 4 has a moderate range of series resistance value, except for M-7 it gives a high value. However, Method 6 covers the highest range which is between 1.1Ω to 26.37Ω .

5.3 Relative Error Analysis

Conduction of error analysis is very much essential for an in-depth understanding of a work. It provides the audience with different approaches to evaluate the work which enables them to observe the pros and cons of a certain work. In this section, several approaches to error analysis are discussed and demonstrated. Relative error and mean square error (MSE) have been conducted on the extracted R_s values to solidify the claims about which method can provide a better series resistance value. A difference analysis has also been conducted to get an overview of the difference existing between the methods for all modules. What makes a relative error analysis interesting is that there is no hard and fast rule regarding the results or a standard value by which the analysis is compared. The result is based on the individual set of work that is being evaluated. From the determined data, a set that provides the least error value is considered a more suited set. Hence, it is a very flexible approach to find validation. The equation used to find the relative error is as below:

$$Relative\ Error(\%) = \left| \frac{(R_{measured} - R_{model})}{R_{measured}} \right| \times 100 \quad 5.1$$

This equation has been used for two different approaches.

5.3.1 Approach 1 - Theoretical Standard Method

This approach is based on a theoretical standard method. Method 5 & Method 6 are two theoretical methods, whereas Method 1-Method 4 are graphical. In this analysis, we have taken the least valued theoretical method as the standard method, and based on this we have calculated relative error for each graphical method. Conducting this analysis has helped us to understand for each used module which method performs well and is most preferred. Table (5.8-5.10) contains the relative error values of the modules from all the manufacturing companies. From Table 5.5 it is evident that among Method 5 and Method 6, the prior method has the least value. Hence, in the case of Table 5.8 the result is extracted by keeping Method 5 as the model. Error value for Method 4 is the lowest in the case of every module except M-6. Thus, it can be stated that Method 4 performs better if a genetic module is used. The relative error values for Method 1 and Method 3 are very close and in the case of M-6, both these methods perform better than Method 4. It can also be stated that Method 2 performs poorly, compared to other ones, as it has the highest error value. While determining the relative error for the Greenland module, it was seen that Method 5 provided the least value between the theoretical methods for each module (Table 5.6). Keeping Method 5 as a model method it is found that in the case of M-1, M-13, and M-14, the performance provided by Method 1 and Method 3 are better and also share a close-range value among themselves (Table 5.9). Moreover, an interesting fact is observed that for M-11 every method is giving very high value compared to other modules. Error-values of Method 4 is high for most modules, except M-15. On an overall basis, Method 4 can be said to be the least preferred method for Greenland modules. Although Method 2 values are high the range can be considered as moderate. Table 5.7 brings it to our attention that for the first four modules Method 5 has the least value but for M-10, Method 6 has the least value. Since our approach is to keep the least valued theoretical method as the model method, we have kept Method 5 as the model for the first four modules

and Method 6 as the model for M-10. Table 5.10 showcases a similar pattern to what we observed regarding the methods of the Greenland module, which is Method 1 and Method 3 has the least error for each module except the one. But in this case of the Solar module, for the last module, our model method was different from the other four modules. Thus, it might be the reason for the observed exception. Method 2 displays a moderate range of error for every module but for M-10 the error is higher than other methods. When Method 4 is observed, it can be seen that for most modules it provided a high value, however for M-10 it had the lowest error value. With this analysis, we can come to the term that method performance differs for modules from different manufacturers; in fact, as it is discussed over this section, even for the modules of the same manufacturer the method can perform differently. Hence, this thorough analysis comes to the rescue if someone decides to apply these methods to these modules. Figure 5.4 displays the graphical representation of Table (5.8-5.10). The analyzed conclusion can be visually confirmed by this figure.

Table 5.8: Relative Error-values - Genetic Module

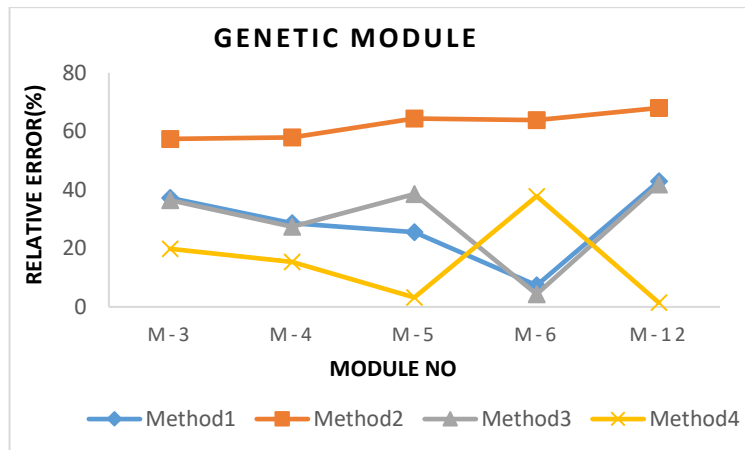
Relative Error	M-3	M-4	M-5	M-6	M-12
Method1	37.2348	28.6185	25.5424	7.3605	42.9652
Method2	57.4323	57.9936	64.3519	63.8598	68.0154
Method3	36.4488	27.3857	38.6064	4.346	41.8833
Method4	19.8278	15.3832	3.2364	37.8478	1.4323

Table 5.9: Relative Error-values - Greenland Module

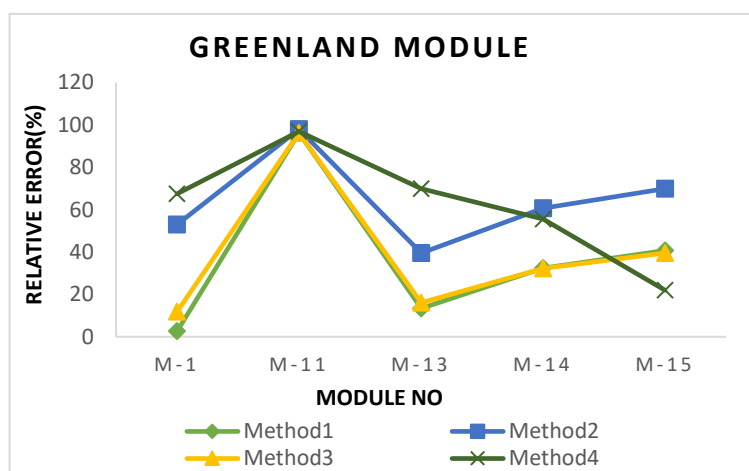
Relative Error	M-1	M-11	M-13	M-14	M-15
Method1	2.6073	96.2435	13.3332	32.442	40.7668
Method2	52.9734	97.9498	39.488	60.6845	69.9592
Method3	11.7882	96.1862	16.0568	32.1988	39.4798
Method4	67.5095	96.9097	69.8535	55.5995	21.9324

Table 5.10: Relative Error values - Solar Module

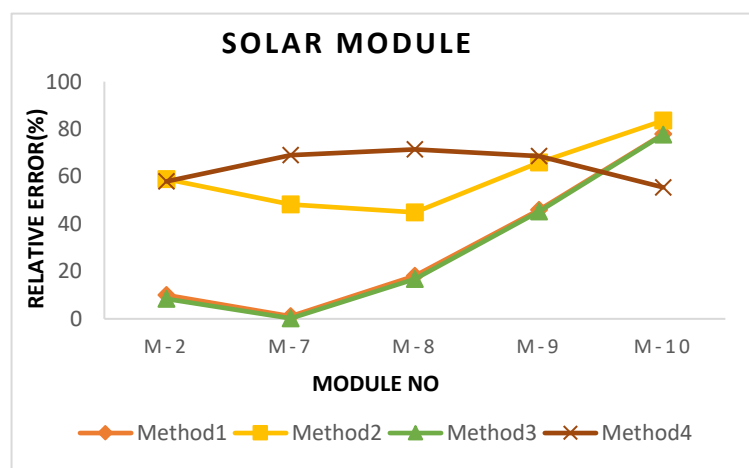
Relative Error	M-2	M-7	M-8	M-9	M-10
Method1	9.9753	1.0955	18.1192	45.9275	77.89
Method2	58.8602	48.2325	44.8974	65.9305	83.5912
Method3	8.3648	0.2092	16.836	45.2545	77.6586
Method4	57.971	69.0333	71.4299	68.6187	55.433



Relative Error values of Genetic Modules.



Relative Error values of Greenland Modules.



Relative Error values of Solar Modules.

Figure 5.4: Graphical Representation of Relative Error Analysis Based on Standard Theoretical Method.

5.3.2 Approach 2 - Standard Module Analysis

This analysis is based on a standard module. Five modules from each company have been used in our analysis. Hence, for each company, the least valued module has been considered as the model module. Then the relative error analysis has been executed using equation (5.1). This analysis is a different approach to find the conclusion about the most preferred method for each module. Moreover, in the previous approach, the theoretical methods were used as model methods, hence we could not analyze the error range for those two methods. However, in this analysis, we will be observing how the theoretical methods perform along with the graphical ones. M-6, M-15, and M-10 have been considered as the model modules because as per Table 5.5-Table 5.7 these displayed the lowest series resistance values for genetic, Greenland, and solar modules accordingly. From Table 5.11 it can be seen that the error values of Method 2 are comparatively lower than other methods. Method 4 is displaying errors more than Method 2 but fairly less than Method 1 and Method 3, hence it is maintaining a moderate range of error. Method 1 and Method 3 on the other hand are providing high error values. If the two theoretical methods are considered, then it can be noticed that Method 6 values have less relative error and Method 5 more error but an exception is seen regarding M-12. For this module Method, 5 has the lowest error value not only among theoretical methods but also compared to graphical methods. Likewise, Method 6 displayed the highest error value for M-12 among all applied methods. Evidently from Greenland modules, it can be stated that Method 2 is the least error valued method. Method 1 and Method 3 are also displaying a range of error values that can be considered as moderate. The error range is high for Method 4. Between the two theoretical methods, Method 5 has lower error values, thus this is a better performing method than Method 6. Moreover, Table 5.12 solidifies the fact that error values of Method 6 are higher than all other applied methods. Observing Table 5.13 we can come to this conclusion that in the case of solar modules Method 2 is the least error valued method. Similar to the Greenland module,

Method 1 and Method 3 display a moderate range of relative error which is preferable over Method 4, since it has very high error values. Method 5 is again proved to be the better theoretical method than Method 6. Moreover, it is clear that for modules from every company Method 6 is the least suited as the error range is extremely high. Figure 5.5 contains the graphical form of Table (5.11-5.13).

These two approaches provided us with data to evaluate the work from two different directions. Amusingly, from both approaches, we found that Method 1 and Method 3 always provide a similar range of relative error. However, in comparison with theoretical methods as standard, these two methods are more preferred because of providing less error. But in the standard module analysis, these methods provided fairly high error for both genetic and solar modules. Although the error was very less in Greenland modules. Another interesting aspect is that Method 2 is considered the least preferred method when compared to the theoretical ones for all three manufacturing companies. On the other hand, for approach two Method 2 provided the least error value for almost every module, making it the most preferred method. Thus, we can say that both approaches have their purposes and both can be used according to the need of one's work.

Table 5.11: Relative Error-values using Standard Module Analysis - Genetic Module

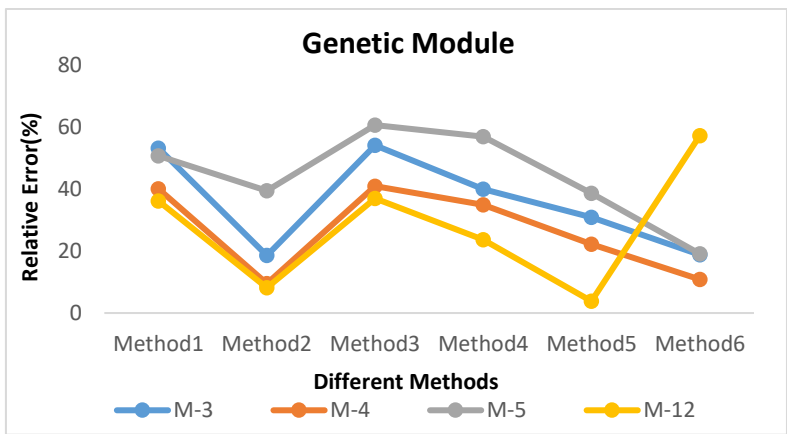
Relative Error	M-3	M-4	M-5	M-12
Method1	53.1423	40.0004	50.6169	36.0793
Method2	18.5394	9.4928	39.3946	8.1143
Method3	54.0507	40.8877	60.5647	36.9195
Method4	39.8804	34.8219	56.8702	23.6034
Method5	30.8395	22.132	38.5580	3.824
Method6	18.7413	10.7823	19.0669	57.1816

Table 5.12: Relative Error-values using Standard Module Analysis - Greenland Module

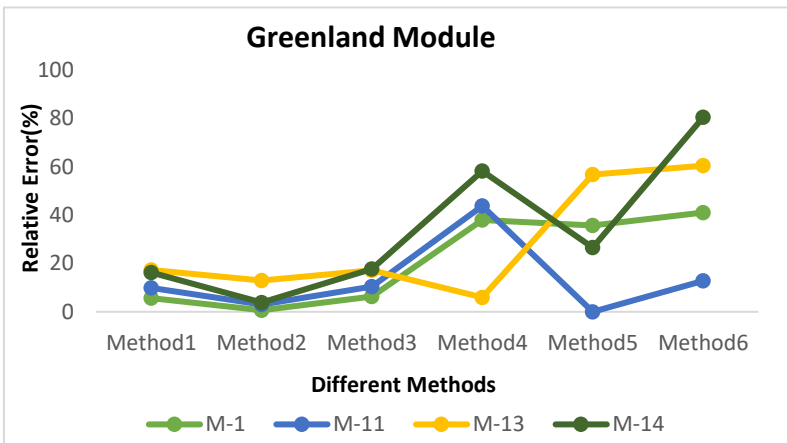
Relative Error	M-1	M-11	M-13	M-14
Method1	5.7198	9.9023	17.3	16.203
Method2	0.6532	3.0413	12.935	3.8455
Method3	6.2823	10.4719	17.1135	17.6897
Method4	37.9633	43.7624	5.9591	58.2137
Method5	35.7023	1.3207*10 ³	56.7772	26.5288
Method6	41.0656	12.7812	60.4298	80.4248

Table 5.13: Relative Error-values using Standard Module Analysis - Solar Module

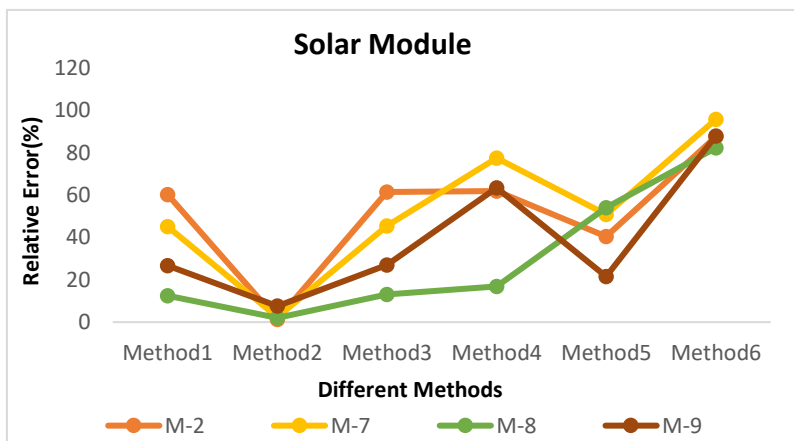
Relative Error	M-2	M-7	M-8	M-9
Method1	60.2571	45.1318	12.5078	26.7082
Method2	1.3198	2.3567	2.0198	7.574
Method3	61.4351	45.5238	13.0877	26.957
Method4	61.9992	77.4567	16.8591	63.5183
Method5	40.439	50.9032	54.0266	21.5966
Method6	87.5807	95.7582	82.3079	88.0121



Relative Error values of Genetic Modules.



Relative Error values of Greenland Modules.



Relative Error values of Solar Modules.

Figure 5.5: Graphical Representation of Relative Error Analysis based on Standard Module.

5.4 Mean Squared Error (MSE) Analysis

MSE is a frequently used error estimation process that helps to determine the accuracy of applied methods. It is a good way of solidifying one's claims. MSE value is always positive since the estimated errors are squared and then summed. An MSE value is considered to be good if it is closer to zero. Hence, the method which will provide a closer MSE value to zero can be considered as a more suited method than the rest. Regression analysis can be used to find MSE. In this case, a set of data needs to be considered where there are two types of variables. One type of the variable must be independent and the other must be the dependent variable. The dependent variable will change based on the independent variable and will provide a set of data using a regression line equation which is considered as the estimated data. From the actual dependent set, the estimated data set will be subtracted and the subtracted data set is known as the error. These error values are then squared and summed. The reason for squaring is to avoid any negative value and to have a smoother result. The sum is then divided by the number of samples used in the data set.

In our case, we have used this process of regression analysis to find the MSE of each method more accurately. For the independent variable set, we have considered the method which has the least R_s value for each module. Rest methods have been considered as the dependent variable sets. We have determined the MSE separately for all three manufactures and provided an order of preference while choosing a method according to the analysis result. At a time, we have taken one method which was considered as a dependent variable set and determined the estimated set of dependent variables. Then from the set of actual dependent variables, the estimated set was subtracted for finding the error set. The error set was then squared and summed. Lastly, the summed value was divided by 5; as the number of data samples in a set of variables is 5.

5.4.1 MSE Analysis on Genetic Modules

As per Table 5.5 module values of Method 4 are taken as the independent set of variables, as Method 4 has the lowest value than other Methods. The dependent set of variables are taken per method one at a time. For each method, we found out the MSE value. Then, a comparison has been made between all the found MSE values and a conclusion is conducted about the order of preference of methods in the case of the used genetic manufacturer.

The data table calculation, regression equation, and determined MSE per method are demonstrated below:

i. Independent set of Variables X-Method 4 & Dependent set of Variables Y-Method 1

Table 5.14: Regression Analysis and MSE Calculation for Method 1

Method4- X	Method1- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE1
3.6464	6.9615	5.7131	1.2484	1.5585		
3.3634	5.4367	5.3988	0.0379	1.4364*10 ⁻³		
5.0828	6.6055	7.3081	-0.7026	0.4936	2.8168	0.5634
2.1922	3.262	4.0983	-0.8363	0.6994		
2.8695	5.1032	4.8504	0.2528	0.0639		

Regression line equation used for estimating Y':

$$Y' = 1.6641709212019 + 1.1103947927919x$$

$$MSE1 = \frac{2.8168}{5} = 0.5634$$

ii. Independent set of Variables X-Method 4 & Dependent set of Variables Y-Method 2

Table 5.15: Regression Analysis and MSE Calculation for Method 2

Method4- X	Method2- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE2
3.6464	10.2646	10.5674	-0.3028	0.0916		
3.3634	9.2386	10.0224	-0.7838	0.6144		
5.0828	13.7968	13.3336	0.4632	0.2145	1.2749	0.2549
2.1922	8.3616	7.7669	0.5947	0.3536		
2.8695	9.1	9.0713	0.0287	8.2369*10 ⁻⁴		

Regression line equation used for estimating Y':

$$Y' = 3.5451800859397 + 1.9257970054331x$$

$$MSE2 = \frac{1.2749}{5} = 0.2549$$

iii. Independent set of Variables X-Method 4 & Dependent set of Variables Y-Method 3

Table 5.16: Regression Analysis and MSE Calculation for Method 3

Method4- X	Method3- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE3
3.6464	6.8754	6.0349	0.8405	0.7064		
3.3634	5.3444	5.5684	-0.224	0.0502		
5.0828	8.0111	8.4026	-0.3915	0.1533	1.2035	0.2407
2.1922	3.1592	3.6379	-0.4787	0.2292		
2.8695	5.0082	4.7544	0.2538	0.0644		

Regression line equation used for estimating Y':

$$Y' = 0.024451362169226 + 1.6483355886952x$$

$$MSE3 = \frac{1.2035}{5} = 0.2407$$

iv. Independent set of Variables X-Method 4 & Dependent set of Variables Y-Method 5

Table 5.17: Regression Analysis and MSE Calculation for Method 5

Method4- X	Method5- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE5
3.6464	4.3694	3.9798	0.3896	0.1512		
3.3634	3.8808	3.7703	0.1105	0.0122		
5.0828	4.9183	5.0434	-0.1251	0.0156	0.437	0.0874
2.1922	3.0219	2.9031	0.1188	0.0141		
2.8695	2.9106	3.4045	-0.4939	0.2439		

Regression line equation used for estimating Y':

$$Y' = 1.2798650614748 + 0.7404367821844x$$

$$MSE5 = \frac{0.437}{5} = 0.0874$$

v. Independent set of Variables X-Method 4 & Dependent set of Variables Y-Method 6

Table 5.18: Regression Analysis and MSE Calculation for Method 6

Method4- X	Method6- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE6
3.6464	5.8043	6.5453	-0.741	0.5491		
3.3634	6.2213	6.3068	-0.0855	7.3103*10 ⁻³		
5.0828	8.5158	7.7555	0.7603	0.5781	5.874	1.1748
2.1922	6.8921	5.3199	1.5722	2.4718		
2.8695	4.3848	5.8907	-1.5059	2.2677		

Regression line equation used for estimating Y':

$$Y' = 3.4729081327626 + 0.84257354343734x$$

$$MSE6 = \frac{5.874}{5} = 1.1748$$

Table 5.19: Determined MSE Values - Genetic Module

Method	Method1	Method2	Method3	Method5	Method6
MSE	0.5634	0.2549	0.2407	0.0874	1.1748

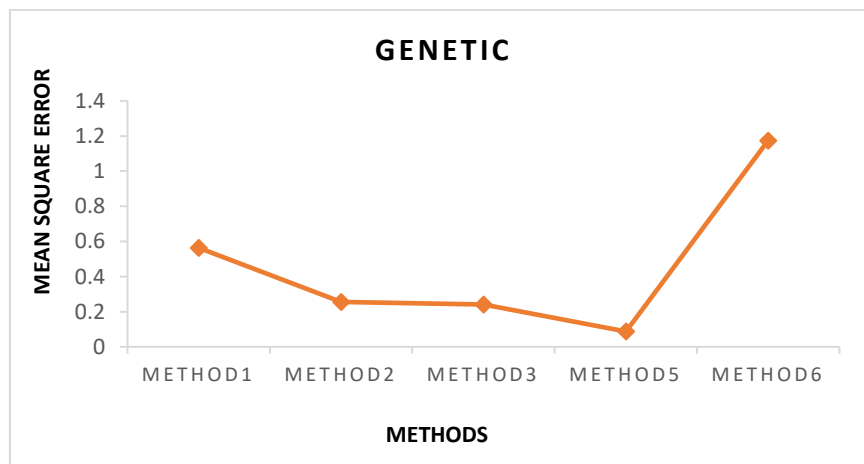


Figure 5.6: Graphical Representation of MSE for each Method.

The order of preferences while choosing methods based on MSE are as below:

Method5>Method3>Method2>Method1>Method6

Since Method 5 has the least MSE value which is closest to 0, it should get the first preference if the choice is available. For Method 6 the MSE value is highest, so it should be least preferred. Method 1 - Method 3 also provided a very close value to 0. Thus, these three methods are also very preferable.

5.4.2 MSE Analysis on Greenland Modules

Method 5 is taken as the independent set of variables, as Method 5 displays the lowest value compared to other methods (Table 5.6). Rest 4 methods are considered as the dependent variable set. The same process as section 5.4.1 is followed for determining MSE and providing an order of preference for the Greenland modules. All the data are as follows:

i. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 1

Table 5.20: Regression Analysis and MSE Calculation for Method 1

Method5- X	Method1- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE1
4.0678	4.1767	4.8655	-0.6888	0.4744		
0.1841	4.9009	4.6384	0.2625	0.0689		
6.0512	5.3393	4.9815	0.3578	0.128	0.9925	0.1985
3.5599	5.2694	4.8358	0.4336	0.188		
2.6155	4.4156	4.7806	-0.365	0.1332		

Regression line equation used for estimating Y':

$$Y' = 4.6276328572407 + 0.058484432065821x$$

$$MSE1 = \frac{0.9925}{5} = 0.1985$$

ii. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 2

Table 5.21: Regression Analysis and MSE Calculation for Method 2

Method5- X	Method2- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE2
4.0678	8.65	9.1941	-0.5441	0.296		
0.1841	8.9796	8.611	0.3686	0.1358		
6.0512	10	9.4918	0.5082	0.2583	0.7667	0.15334
3.5599	9.0547	9.1178	-0.0631	3.9816*10^-3		
2.6155	8.7065	8.976	-0.2695	0.0726		

Regression line equation used for estimating Y':

$$Y' = 8.5833904203917 + 0.15012579409784x$$

$$MSE2 = \frac{0.7667}{5} = 0.15334$$

iii. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 3

Table 5.22: Regression Analysis and MSE Calculation for Method 3

Method5- X	Method3- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE3
4.0678	4.6114	4.9018	-0.2904	0.0843		
0.1841	4.8272	4.6158	0.2114	0.0447		
6.0512	5.214	5.0478	0.1662	0.0276	0.5294	0.10588
3.5599	5.2505	4.8644	0.3861	0.149		
2.6155	4.3217	4.7948	-0.4731	0.2238		

Regression line equation used for estimating Y':

$$Y' = 4.6023263720721 + 0.073621272545416x$$

$$MSE3 = \frac{0.5294}{5} = 0.10588$$

iv. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 4

Table 5.23: Regression Analysis and MSE Calculation for Method 4

Method5- X	Method4- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE4
4.0678	2.4284	4.3693	-1.9409	3.767		
0.1841	5.9574	5.8478	0.1096	0.012		
6.0512	3.5626	3.6143	-0.0517	2.6728*10 ⁻³	18.1894	3.63788
3.5599	8.0177	4.5627	3.455	11.937		
2.6155	3.3503	4.9222	-1.5719	2.4708		

Regression line equation used for estimating Y':

$$Y' = 5.9179063189443 - 0.38068583880338x$$

$$MSE4 = \frac{18.1894}{5} = 3.63788$$

v. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 4

Table 5.24: Regression Analysis and MSE Calculation for Method 6

Method5- X	Method6- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE6
4.0678	7.4773	11.0312	-3.5539	12.6302		
0.1841	3.9073	5.2802	-1.3729	1.8848		
6.0512	11.1364	13.9682	-2.8318	8.019	192.4309	38.4862
3.5599	22.5117	10.2691	12.2426	149.8812		
2.6155	4.4067	8.8806	-4.4739	20.0157		

Regression line equation used for estimating Y':

$$Y' = 5.0076166661457 + 1.4807972005505x$$

$$MSE_6 = \frac{192.4309}{5} = 38.4862$$

Table 5.25: Determined MSE Values - Greenland Module

Method	Method1	Method2	Method3	Method4	Method6
MSE	0.1985	0.15334	0.10588	3.63788	38.4862

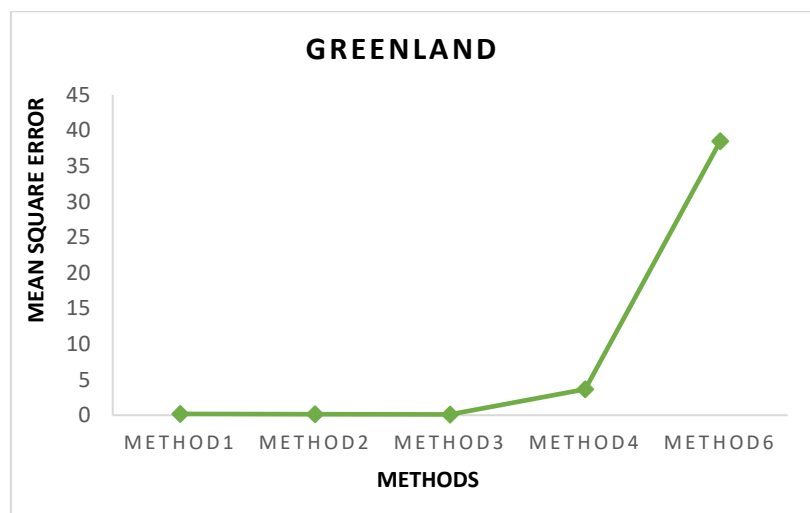


Figure 5.7: Graphical Representation of MSE for each Method.

The order of preferences while choosing methods based on MSE are as below:

Method3>Method2>Method1>Method4>Method6

Figure 5.7 demonstrates that the method which has the closest value to 0 is Method 3, so has a high preference and Method 6 has an extremely high value which is not preferable at all. As for Method 1 and Method 2, both provide very close values to 0. It makes them better suited than Method 6. Method 4 has a higher value than Method 3 but less value than Method 6, also the value is not very high than 0. Thus, if no other better-suited method is available, Method 4 can give a good performance.

5.4.3 MSE Analysis on Solar Modules

Regarding the solar module, it is visible from Table 5.7 that Method 5 has the least series resistance value. For this reason, Method 5 has been considered as the independent variable set and other methods are considered as the dependent variable set. MSE determination is done using the same process as section 5.3.1 and section 5.3.2.

Essential data tables and equations are given below:

i. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 1

Table 5.26: Regression Analysis and MSE Calculation for Method 1

Method5- X	Method1- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE1
2.8428	3.1578	4.0096	-0.8518	0.7256		
3.4487	3.4869	3.7758	-0.2889	0.0835		
3.683	4.498	3.6854	0.8126	0.6603	2.6184	0.5237
2.1596	3.9939	4.2732	-0.2793	0.78		
1.6932	5.0606	4.4531	0.6075	0.369		

Regression line equation used for estimating Y':

$$Y' = 5.1062833974061 - 0.38577430062488x$$

$$MSE1 = \frac{2.6184}{5} = 0.5237$$

ii. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 2

Table 5.27: Regression Analysis and MSE Calculation for Method 2

Method5- X	Method2- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE2
2.8428	6.9101	6.6845	0.2256	0.0509		
3.4487	6.6619	6.6988	-0.0369	1.3616*10 ⁻³		
3.683	6.6839	6.7043	-0.0204	4.1616*10 ⁻⁴	0.1873	0.0375
2.1596	6.3388	6.6684	-0.3296	0.1086		
1.6932	6.8189	6.6574	0.1615	0.026		

Regression line equation used for estimating Y':

$$Y' = 6.6174872305079 + 0.02358839740663x$$

$$MSE2 = \frac{0.1873}{5} = 0.0375$$

iii. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 3

Table 5.28: Regression Analysis and MSE Calculation for Method 3

Method5- X	Method3- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE3
2.8428	3.1023	3.9548	-0.8525	0.7267		
3.4487	3.4415	3.7184	-0.2769	0.0767		
3.683	4.4286	3.6268	0.8018	0.6428	1.8882	0.3776
2.1596	3.9448	4.2216	-0.2768	0.0766		
1.6932	5.0082	4.4037	0.6045	0.3654		

Regression line equation used for estimating Y':

$$Y' = 5.0646735765079 - 0.39038480994406x$$

$$MSE3 = \frac{1.8882}{5} = 0.3776$$

iv. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 4

Table 5.29: Regression Analysis and MSE Calculation for Method 4

Method5- X	Method4- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE4
2.8428	6.6067	5.9451	0.6616	0.4377		
3.4487	11.1368	6.6362	4.5006	20.2554		
3.683	2.1484	6.9035	-4.7551	22.6109	50.7564	10.1513
2.1596	6.8818	5.1657	1.7161	2.9449		
1.6932	2.5106	4.6337	-2.1231	4.5075		

Regression line equation used for estimating Y':

$$Y' = 2.7022869758442 + 1.1407046293043x$$

$$MSE4 = \frac{50.7564}{5} = 10.1513$$

v. Independent set of Variables X-Method 5 & Dependent set of Variables Y-Method 6

Table 5.30: Regression Analysis and MSE Calculation for Method 6

Method5- X	Method6- Y	Estimated Y'	Error (Y-Y')	Error Squared	Sum of Squared Errors	MSE6
2.8428	9.0094	10.9154	-1.906	3.6328		
3.4487	26.3781	14.6961	11.682	136.4691		
3.683	6.3243	16.158	-9.8337	96.7016	250.874	50.1748
2.1596	9.3336	6.6525	2.6811	7.1883		
1.6932	1.1189	3.7423	-2.6234	6.8822		

Regression line equation used for estimating Y':

$$Y' = 6.2396750154083x - 6.8227116681111$$

$$MSE6 = \frac{250.874}{5} = 50.1748$$

Table 5.31: Determined MSE Values - Solar Module

Method	Method1	Method2	Method3	Method4	Method6
MSE	0.5237	0.0375	0.3776	10.1513	50.1748

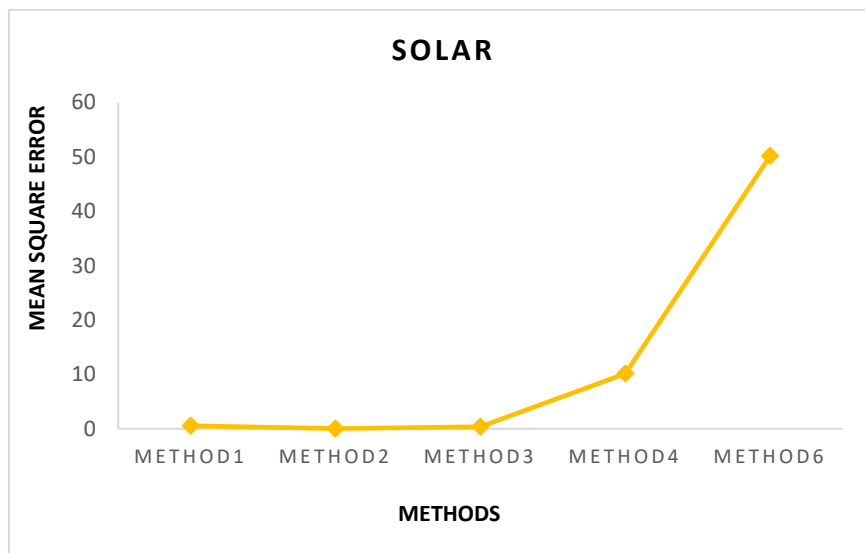


Figure 5.8: Graphical Representation of MSE for each Method.

The order of preferences while choosing methods based on MSE are as below:

Method2>Method3>Method1>Method4>Method6

The method that provides closet value to 0 is Method 2(Figure 5.8). Thus, for solar modules, it should be the most preferred method. Besides, the values provided by Method 1 and Method 3 are also closer to 0. MSE for Method 4 and Method 6 is extremely high. If other choices are available, these methods should be avoided regarding the solar module.

5.5 Relative Difference Analysis

This analysis is conducted so that the overall performance of each method on all the tested modules can be compared. Similar to approach 2, here we have taken a module as a model to find the relative difference. The difference is that for approach 2 we analyzed modules from three different manufacturers separately but now among all the 15 tested modules we chose a module that gave the least and most suited value of series resistance. M-2 is considered as the model module for its low and preferable R_s value for all applied methods. After selecting the model module, other modules for each method have been analyzed using equation (5.1). However, in this case, we are not finding which method is providing the least error. Rather, from this analysis, we are comparing the difference between each method to understand how much the results vary for the error analysis. A table containing values of 14 modules will be very large and clustered, hence it has been divided into two parts for a better presentation. Table 5.32(a-b) demonstrates the fact that the difference between Method 2 and the rest of the methods is very high. On the other hand, the difference between Method 1 and Method 3 is quite low, thus any of these two methods can be used as alternates depending on which one is preferred by the user. A range of relative differences prevails between Method 4 and the rest of the methods as well. Also, from Table 5.5-Table 5.7 it can be noticed that Method 2 does have a high value of series resistance for most modules and is least preferred. The relative difference between the two theoretical methods and graphical Method 1, Method 2, and Method 3 are comparatively low, whereas the difference with Method 4 is extremely high. The more the difference, the less it is possible for two methods to be each other's alternate; This also solidifies the fact that if the difference between the two methods is very high, we need to consider a lot of aspects for choosing the best-suited method.

Table 5.32(a): Relative Difference of all tested Modules

Relative Difference	M-1	M-3	M-4	M-5	M-6	M-7	M-8
Method1	24.3949	54.6391	41.917	52.1944	3.1944	9.4382	29.7955
Method2	20.1145	32.6803	25.204	49.9152	17.3591	3.7257	3.3843
Method3	32.7254	54.8783	41.9523	61.275	1.8011	9.8562	29.9485
Method4	172.0598	81.1842	96.4292	29.9815	201.3730	40.6769	207.5172
Method5	30.1146	34.9384	26.7471	42.1995	5.9267	17.5689	22.8129
Method6	20.49	55.2194	44.8154	5.7963	30.7207	65.8452	42.4569

Table 5.32(b): Relative Difference of all tested Modules

Relative Difference	M-9	M-10	M-11	M-12	M-13	M-14	M-15
Method1	20.9344	37.6003	35.5669	38.1212	40.8574	40.0229	28.4854
Method2	9.0127	1.3375	23.0467	24.0648	30.899	23.6849	20.6329
Method3	21.3572	38.0556	35.7329	38.0556	40.5006	40.9142	28.2157
Method4	3.9975	163.1522	10.899	130.2387	85.446	17.5986	97.1973
Method5	31.6355	67.8951	1.4442e ³	2.3294	53.0209	20.1438	8.6905
Method6	3.4735	705.2015	130.5787	105.4689	19.0995	59.9790	104.4478

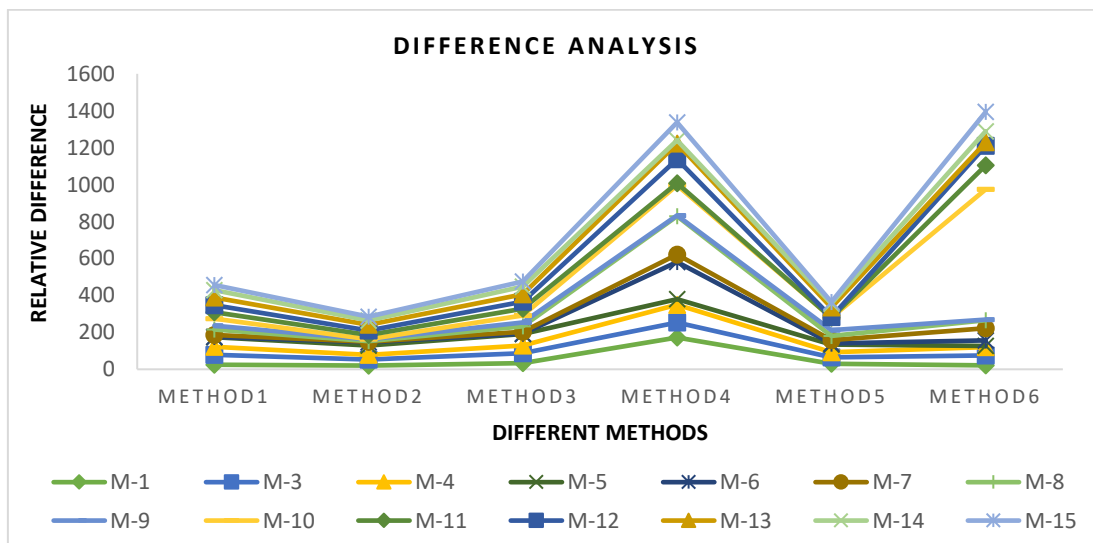


Figure 5.9: Graphical Representation of Relative Difference Analysis.

Chapter 6

Conclusion and Future work

6.1 Conclusions

The principal objective of this thesis is to study and compare different series resistance extraction methods from the literature. Among the thirteen methods found from the literature, we have applied six methods to analyze. The foregoing study on extracting the series resistance of the PV modules by applying six different methods enlightens the difference among the outputs of those methods. In order to extract different module parameters, indoor I-V measurement test was performed. The aforementioned MSE analysis suggests that method 2, 3 and 5 show more consistency and less error than other three. Among the other three method, method 6 shows the least consistency as well as unreasonably high error. Although method 4 displays the most preferred R_s value for genetic modules, in case of other two it displays the opposite. However, from bar chart analysis, method 1 and 3 provide similar range of series resistance values and the range is within 7Ω which is suited R_s value for all the solar modules. We are hoping to come up with a more optimized method which will predict R_s in all dynamic conditions regardless of change in parameter values.

6.2 Future Works

In this research, though thirteen methods were discussed, we have only applied six of them. In the future, we intend to analyze all of the methods that we found in our research. We are hoping to apply all those methods to a bigger number of modules and expecting significant improvement while predicting the series resistance of the modules. Apart from this, we are planning to add two more comparison techniques, so that it can provide much better accuracy.

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