Development of a Matlab-Simulink Based Hybrid Model for Photovoltaic (Pv) Modules to Investigate Partial Shading Effect

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Abstract- Power generated by a photovoltaic (PV) module depends upon its materials, manufacturing methods, operational conditions as well as the different environmental factors. The performance of PV modules under different operational conditions must be determined before installation. This can be achieved either through testing using hardware simulators, or by development of prediction models which are low cost, robust and accurate. This paper details the development of hybrid single and double diode Rp models for multi-crystalline silicon PV modules in SimscapeTM Simulink. The hybrid model is a combination of mathematical equations and circuit modelling, providing a fast and efficient means of analysing the PV module. The model allows to alteration of irradiance and surface temperature of an individual cell within a module, making it possible to analyse the partial shading effect on a cell level. A case study is also presented in which a single string is shaded with two irradiance levels. This shading reduces the maximum power generated by 8.07% for single cell shading to 10.94% for full string shading as compared to no shading condition. Thus, percent drop in power for a single cell shading is more significant than for the remaining 9 cells in string. Therefore, the least shaded cell controls the output power of the module.

Index Terms- Hybrid PV Model, PV Module Modelling, Partial Shading, Simulink SimscapeTM, MATLAB

I. INTRODUCTION

The use of Photovoltaic (PV) technology for utilizing the abundantly available solar energy has increased rapidly in the last two decades. International Environmental Agency (IEA) in its report "Renewables 2019" forecasted the solar PV to surpass 1.1TW [1] . However, the installed PV capacity has already surpassed 1.1TW in 2022 with an addition of over 230GW in the mentioned year [2], [3]. The increasing utilization of PV technology has urged the researchers all over the world to carryout extensive research for enhancing its performance and durability. Since the output power from PV modules varies with the vibrant irradiance and temperature [4], maximization of the output power from solar PV modules under different conditions is one of the active areas of research currently. Generally, solar simulators are used to measure the performance of PV modules under varying conditions. These simulators replicate environmental conditions and provide controlled environment for large durations, making repeatable testing of solar modules possible under the desired test conditions. Efficiency and current-voltage (IV) characteristics of the PV module are the most widely quoted performance parameters. Such simulations are also performed virtually through the development of mathematical and circuit models. Software based simulations provide a low cost and faster alternative to hardware testing but need development of robust and reliable PV models. The ever increasing demands of energy, and connectivity of solar PVs with grid is compelling manufacturers to produce better quality PV modules [5]. This requires shortening of the design time, which is only possible through realistic simulation model which can incorporate both environmental and electrical effects.

PV module modelling can be classified into two major categories: mathematical modelling approach and physical components circuit modelling [6], [7]. Mathematical modelling is applied using complicated set of implicit non-homogenous equations while circuit modelling employs electronic components instead of equations and has got lower computational cost. However, circuit modelling is unable to integrate dynamically fluctuating environmental conditions such as irradiance and temperature [8]. This has compelled the research community to develop hybrid models, incorporating the benefits of both the mathematical and circuit models. Single diode and double diode Rp models are the most widely used PV module circuit models, and have been able to predict the performance of PV module accurately [9]. There are five unknown parameters in single diode model namely series resistance (Rs), parallel resistance (Rp), photocurrent (Ipv), diode ideality factor (a), and dark saturation current (Io) which increase to seven for the double diode model with the addition of a second diode ideality factor (a2), and a second diode dark saturation current (I2) (Fig. 1). These parameters are evaluated using data provided by the manufacturer at standard test conditions (STC: 1000 W/m^2 and 25°C). However, all these parameters vary with change in environmental conditions and cell material type [10]. Hence, the values are generally updated for conditions other than STC.

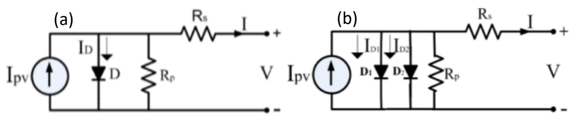

Fig. 1. (a) Single and (b) double diode Rp models

Gauging the performance of PV modules becomes more complex, when different areas of a panel are exposed to different irradiance levels i.e. non-uniform irradiance, commonly referred to as partial shading. Partial shading causes electrical mismatches between different sections of the electrical circuit, which leads to significant efficiency losses as well as localized heating [11]. The unshaded cells start operating towards the open circuit voltage causing the shaded cell to operate in reverse bias to achieve the intended current [12], dissipating electrical power [13]. To overcome the effects of partial shading bypass diodes are connected in parallel to cells connected in series. These reverse electrical characteristics of solar PVs cannot be investigated using simple equation modelling mentioned above. However, electric circuit modelling which allows interfacing the model with other electronic components can be used to study the partial shading effects [14]. Since the IV curves of solar PV cell shows large variations while working in reverse bias conditions, electric circuit models will help study the effects on output power of solar modules under partial shading conditions. Thus, there is a need to develop modelling methodologies capable of predicting partial shading behaviour by incorporating reverse biasing [15].

Different configurations are applied in order to achieve higher power from PV modules under partial shading condition, which include series-parallel (SP), Bridged Linked (BL), Honey-Comb (H-C) and Total Cross tied (TCT) [16]. Tubniyom et al. conducted solar PV module based (3x3 PV modules) simulations to study the effect of partial shading, in which various degrees of shading have been analysed on three different array configurations [17]. They concluded that the power output cannot be increased more than 5% by reconfiguring the solar PV arrays if the shading is equal or greater than 50% of the total area. Quaschning and Hanitsch incorporates numerical simulation for generating the solar PV characteristics curves for 36 cells mono crystalline module with two bypass diodes [18]. They considered the effect of only one cell shading (75%, 50%, 25%) and verifies the results, both in simulations as well as experimentally. Furthermore, their simple simulation output curves were obtained for partial shading when bypass diodes were connected at various string sizes. Silvestre and Chouder uses Simulink modelling for the study of partial shading, a PV module with 36 cells in series are considered where only one cell is assumed to be at varying rates of shadows [19]. The output behaviour of shadowed solar cell is obtained by subtracting the IV characteristic curve of the module with one cell shaded from the IV curve without shading. They conducted the simulations with the assumption that the photo-generated current is proportional to the rate of shading. Besides, they also concluded that the Rs has significant effect on the output power at shading conditions. Although work has been done in the area of partial shading modelling but most of this work is focused on shading different modules but shading of individual cells within a module has not been touched upon. This research work reports a hybrid modelling approach (mathematical equation modelling combined with the circuit modelling) for predicting the reverse electrical characteristics of PV modules. The model developed in this work enables the users to apply shading of the individual cells and analyse its effect on the module's performance.

II. MODELLING METHODOLOGY

In this work, a hybrid modelling technique was used in which the mathematical equation-based modelling was combined with the circuit modelling using Simscape™ module in MATLAB Simulink®. Single and double diode Rp models were developed and the results for both the models were compared with the data of 260W 60 cell multi-crystalline 'The Honey' Module of TrinaSolar. This work was divided into three parts as given in the figure 2.

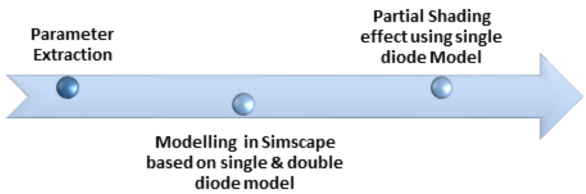

Fig. 2. Stepwise methodology used in this research

The unknown parameters for the diode models were first evaluated and incorporated in Simscape™ and then validated with the data of the TrinaSolar PV module. Simscape™ has the capability of modelling the dynamic system in such a way that it converts the output of mathematical modelling to a physical signal which can be used as an input signal to an electronic based model [20]. Thus, it is easy and less time consuming to study the partial shading effect of PV modules by developing a hybrid model using Simscape™. The details of the three steps used are given below.

A. Parameters Extraction for SimscapeTM PV Cell Models

The approach used in this work for determining the unknown parameters for the Simscape™ PV Cell Models was similar as that presented in the literature, both for the single diode Rp model [21] as well as for the double diode Rp model [22]. For both the models, a combined analytical and numerical approach was used to extract the unknown parameters. Analytical technique is the faster but without any assumptions and approximations it is difficult to determine the unknown parameters with high accuracy, as the PV module is highly non-linear multi-variable system [8]. On the other hand, numerical computation techniques possess high computational cost [22], [23] but provide a way to approximate the unknown parameters. Thus, combining both the approaches allows to utilize their benefits for the comparatively easy determination of parameters. In previous studies, the manufacturer provided data at STC was used for determining the unknown parameters [21], [22]. In our model, the manufacturer provided data at STC was first updated at specified conditions, that is, at specific irradiance and temperature and then the unknown parameters were determined. The manufacturer provided data act as boundary values for I-V curve at STC. The boundary conditions used in this study are given in table 1.

Table 1. Boundary conditions used for PV modelling

S. No.	Boundary Condition	Values
1	Short Circuit Point	$V=0$, $I=I_{SC}$
2	Open Circuit Point	$V=V_{OC}$, $I=0$
3	Maximum Power Point (MPPT)	$V=V_M$, $I=I_M$, $P_{max}=I_M * V_M$

Moreover, the literature suggests that the sum of ideality factors for double diode should be 3 for multi-crystalline and thin film solar cell, and 4 for amorphous solar PV cells [24] while certain researchers have assumed the values of diode ideality factors. In our case for double diode model the summation of ideality factors was taken to be 3.8 for multi-crystalline TrinaSolar module. A summary of the derived equations and the proposed algorithm is given in table 3 and figure 4 respectively. All the equations are derived considering the following assumption:

$$1+\frac{Rs}{Rp}\approx 1 \tag{1}$$

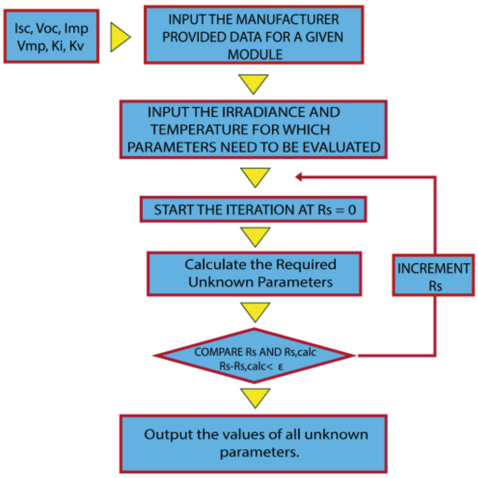

Fig. 3. Algorithm Used for Modelling in this research

B. Modelling of Solar Cell in Simscape™

The parameters extracted in the previous step were incorporated in the models developed in Simscape™ and was validated with the data of 260W – 60 cell multi-crystalline 'The Honey' Module of Trina Solar manufacturer, the data is presented in table 2. The manufacturer provided voltage data was divided by the number of cells (Ns=60) to get MPPT voltage and open circuit voltage for individual cell of the module. The different unknown parameters were then extracted for a single PV cell at standard temperature and different solar irradiance levels. Both the models were validated with the manufacturer provided data for various irradiance levels at standard temperature. The I-V and P-V characteristics curve comparison of both the models with the manufacturer data is shown in figure 4 and 5 respectively.

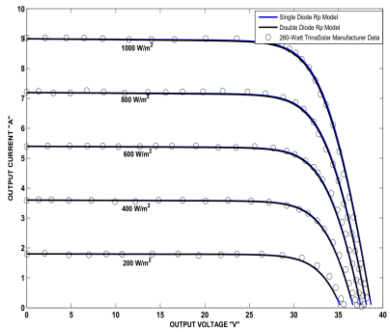

Fig. 4. Comparison of IV Characteristics of both the models with Manufacturer data

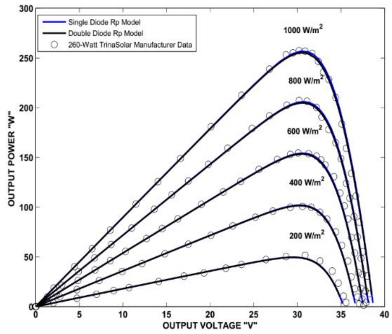

Fig. 5. Comparison of IV Characteristics of both the models with Manufacturer data

It can be seen from figure 4 and 5 that the data from the manufacturer is updated at different irradiance levels, thus we have the data points of the IV characteristic curve at other than STC. The comparison shows that both the models very closely match with the manufacturer provided data considering the assumed diode ideality factors. The two models not only match at STC but at other irradiance levels too. Thus, single diode Rp model can be conveniently used for further modelling, which will save the computational time provided the double diode model has more equations in it.

Table 2. 260-Watt TrinaSolar Manufacturer Data at STC

Parameters	Values	Units
Peak Power	260	Watts
Maximum Power Voltage (Vm)	30.60	Volts
Maximum Power Current (Im)	8.50	Amperes
Open Circuit Voltage (Voc)	38.20	Volts
Short circuit current (Isc)	9.00	Amperes
Temperature Coefficient of Voc (Kv)	-0.32%	Volts/°C
Temperature Coefficient of Isc (Ki)	0.05%	Amperes/°C
Number of cells (Ns)	60.00	-

C. Solar PV Module Modelling in Simscape™

Simscape™ enables its users to quickly create physical models within Simulink® environment. Physical single components are connected as they are combined together in real life. These single components along with their connections can be fused with classical block modelling that were used in MATLAB earlier. Simulink to PS block in Simscape™ converts Simulink block signal to physical signal.

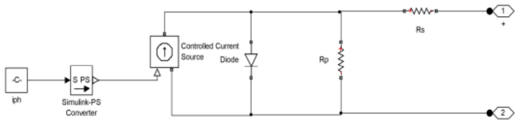

Fig. 6. Single Diode Rp Model in Simscape™

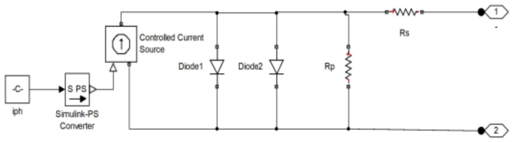

Fig. 7. Double Diode Rp Model in Simscape™

Table 3. Equations for parameter extraction for both single and double diode Rp model

S. No.	Equation for Single Diode Model	Equation for Double Diode Model	Description
1	$I = I_{pv} - I_s\left(e^{\left(\frac{V+IR_s}{aV_T}\right)} - 1\right) - \left(\frac{V+IR_s}{R_p}\right)$	$I = I_{pv} - I_{s1}\left(e^{\left(\frac{V+IR_s}{a_1V_{T1}}\right)} - 1\right) - I_{s2}\left(e^{\left(\frac{V+IR_s}{a_2V_{T2}}\right)} - 1\right) - \frac{V+R_SI}{R_P}$	PV cell output current derived using Kirchoff's Current Law: $I = I_{pv} - I_D - I_{RP} - I_{RS}$ (For single Diode) $I = I_{pv} - I_{D1} - I_{D2} - I_{RP} - I_{RS}$ (For Double Diode)
2	$I_{pv} = I_s\left(e^{\left(\frac{V_{OC}}{aV_t}\right)} - 1\right) + \left(\frac{V_{OC}}{R_p}\right)$	$I_{pv} = I_{s1}\left(e^{\left(\frac{V_{OC}}{a_1V_{T1}}\right)} - 1\right) + I_{s2}\left(e^{\left(\frac{V_{OC}}{a_2V_{T2}}\right)} - 1\right) + \frac{V_{OC}}{R_P}$	Equation 4 is evaluated at the first boundary condition which is the open circuit condition, where: *I=0 & V=*V_{OC}
3	$I_S = \frac{V_{OC}(I_{SC} - I_M) - V_MI_{SC}}{V_{OC}(X_M - X_S) - V_M(X_{OC} - X_S)}$	$I_{S1} = \frac{V_{OC}(I_{SC} - I_M) - V_MI_{SC}}{V_{OC}(X_{M1} + KX_{M2}) - V_M(X_{OC1} + KX_{OC2})}$ $I_{S45} = KI_{S1}, \quad K = \frac{T^{\frac{2}{5}}}{3.77}$	These equations were obtained by applying the other two boundary conditions to Eq. 5 and by solving the equations obtained. The following simplification has been done in order to make the code execution easy and to make equations readable. $X_{OC} = e^{\left(\frac{V_{OC}}{aV_T}\right)} \quad X_{OC1,2} = e^{\left(\frac{V_{OC}}{a_{1,2}V_{T1,2}}\right)}$ $X_M = e^{\left(\frac{V_M+I_MR_S}{aV_T}\right)} \quad X_{M1,2} = e^{\left(\frac{V_M+I_MR_S}{a_{1,2}V_{T1,2}}\right)}$ $X_s = e^{\left(\frac{I_{SC}R_s}{aV_T}\right)} \quad X_{s1,2} = e^{\left(\frac{I_{SC}R_s}{a_{1,2}V_{T1,2}}\right)}$ X_M and X_S are both functions of R_S only. Using this equation, I_S can be calculated in each iteration.
4	$R_p = \frac{V_{OC}(X_M - X_S) - V_M(X_{OC} - X_S)}{I_{SC}(X_M - X_{OC}) - I_M(X_{OC} - X_S)}$	$R_p = \frac{V_M + R_SI_M}{I_{PV} - I_M - I_{S1}(X_{M1} - 1) - I_{S2}(X_{M2} - 1)}$	This equation represents R_P, which is function of R_S and is evaluated in every iteration.
5	$R_{S_{calc}} = \frac{V_M}{I_M} - \left(\frac{6}{\frac{I_SX_M}{\alpha V_T} + \frac{7}{R_p}}\right)$	$R_{S,CALC} = \frac{V_M}{I_M} - \frac{1}{\frac{I_{S1}X_{M1}}{a_1V_T} + \frac{I_{S1}X_{M1}}{a_1V_T} + \frac{1}{R_P}}$	This equation is obtained by differentiating power w.r.t voltage at maximum power point values, where the slope of the curve is zero. $\frac{dP}{dV} = \left(\frac{dI}{dV}\right)V + I = 0$

The values of the parameters extracted were incorporated in Simscape™ and single cell models were produced, as shown in figure 6 and 7. To simulate complete TrinaSolar PV module, the individual cell models were connected in a series, whereas every ten cells were connected with a reverse bias bypass diode in parallel. These ten cells connected in parallel with the bypass diodes were named as string. Overall there were six strings; hence require six bypass diodes. To investigate the effects of different patterns of partial shading two terminologies were considered, string and row. String is the number of series cells connected in parallel with the bypass diode in reverse bias. Whereas, row means single cell of each string. If a module is considered as a 2-D matrix, then string is the column of the matrix and row is the rows of that matrix. In our PV module, there are 10 rows and 6 strings (columns), as can be seen in figure 8.

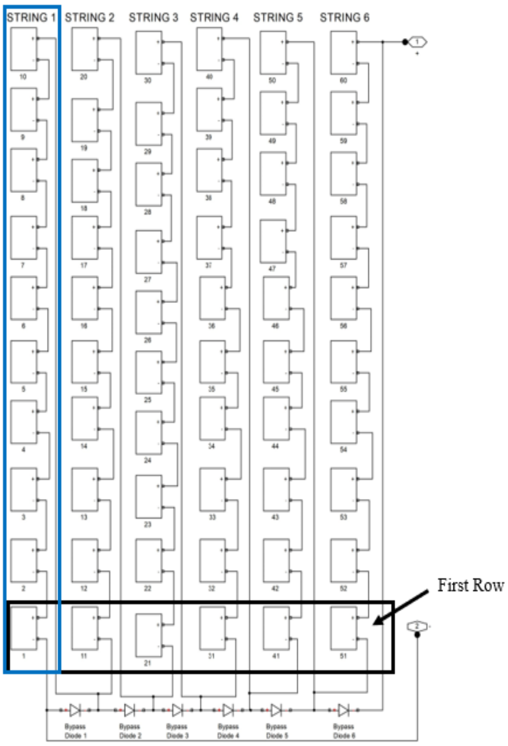

Fig. 8. Complete Module (10 X 6 Cell Orientation) in Simscape™

The simulation results were obtained through a variable load resister, and current and voltage values across the variable load were recorded. The ramp function was given as input to the variable resister. The data recording circuit were merged into a block, named as data logger. Complete Solar PV module with data logger is shown in figure 9.

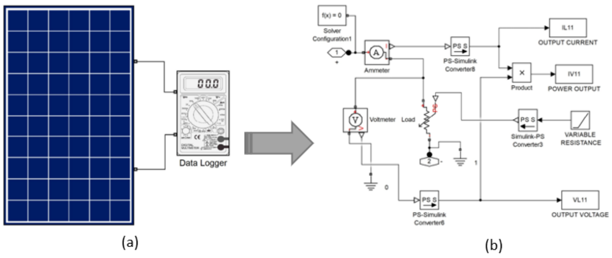

Fig. 9. (a) Full module block connected with data logger, (b) Detailed circuit of data logger

D.Solar PV Module under Non-Uniform Shading

Non-Uniform or Partial shading is the presence of various irradiance level on the surface of solar PV modules. Our model enables us to variate the solar irradiance and surface temperature of individual cell within a module. This capability enables us to study the effect of different patterns of non-uniform/partial shading using a flexible arrangement shown in figure 10. This flexible arrangement is required because at different irradiance level the parameters of single diode change which need to be updated for specific partial shading condition. The faded cells are disconnected cells with irradiance levels other than 1000 W/m^2. To investigate different partial shading conditions these faded cells are connected in the desired pattern and simulations are carried out. In this research, the shading effects were investigated at standard temperature i.e. 25^{0}C only. Moreover, the bypass diode forward voltage was also kept constant at 0.3V. A case study of single string shading using our developed model is presented here.

Fig. 10. Simscape™ arrangement for the simulation of non-uniform shading

III. CASE STUDY: SINGLE STRING SHADING WITH TWO IRRADIANCE LEVELS

Here a single string with two irradiance levels has been considered i.e. 800 W/m^2 (Shading) and 1000 W/m^2 (Full irradiance, No shading). All cells within the same string were one by one shaded with 800 W/m^2 irradiance level. For the said condition, the operating characteristics curves were working between the full irradiance level 1000 W/m^2 (no shading, red curve) and 800 W/m^2 (green curve) as visible in figure 11. This is because, initially at lower load resistance less output power is required and large current flows hence, less voltage is required. So, at lower loads 5 unshaded strings (Strings with 1000 W/m^2 level) are sufficient to provide the required power. As long as the five unshaded strings are capable of meeting the demand of output voltage, the bypass diode is active and the shaded string is bypassed. Five unshaded strings can give maximum output voltage of 31.83 V which is the difference of module Voc and shaded string voltage and this point is the minima in PV curve. As the load increases further, the required output voltage exceeds the output voltage of five unshaded strings; the bypass diodes reverse biases to provide the extra voltage needed as shown in figure 12.

In other words, the bypass diode will be forward biased until the required output voltage is less than the maximum voltage capacity of the unshaded strings and it will be reverse biased as the output voltage exceeds it. As the bypass diode is reverse biased the shaded string is connected to the unshaded strings, causing the module to produce less current, and thus the output current is then controlled by the shaded strings. The MPPT varies from 236.27W (single cell shaded) to 228.87W (Full string shaded) corresponding to a percent decrease of 8.07% to 10.94% compared to no shading. The percent decrease in MPPT for one cell shading is significant as compared to the percent decrease in MPPT for remaining 9 cell shading within a string. This concludes that one cell shading in a string results in major MPPT loss. The number of peaks in the characteristics PV curve equals to the number of different irradiance levels that are present on the module for the said case.

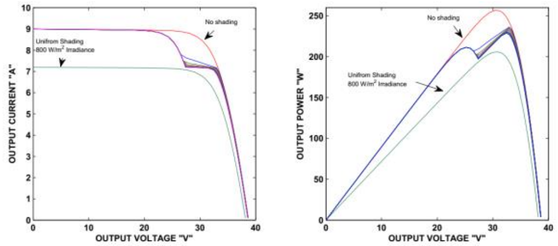

Fig. 11. IV and PV characteristics considering Various number of Shaded cells (from 1 to 10) within a Single string (Irradiance Level 800 W/m^2)

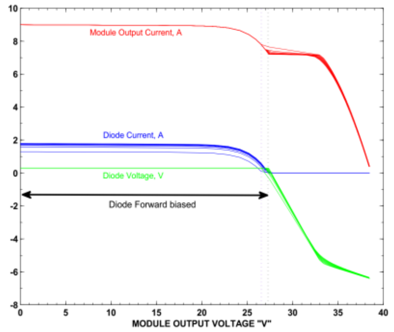

Fig. 12. Diode current and voltage Vs Module Output Voltage of the PV Module

A comparison of using a bypass diode in such condition was also performed and figure 13 & 14 show the comparison of IV curves with and without bypass diodes. In the absence of bypass diodes under partial shading condition the whole module is underperforming. The cells with lower irradiance levels are the weakest link. As all the cells are in series these cells are forcing other unshaded cells to produce lessor current in order to obey Kirchhoff nodal principal (Current going in to a node must be equal to current going out). On the other hand, when the bypass diode is present, the shaded cells are bypassed, and hence larger currents are produced at same output voltage. The power loss at lower output voltages is significant which is up till the minima in PV curve in case of bypass diode. As a result, one peak in the PV curve is lost and the output current falls significantly until the minima. As the current output of unshaded cells matches the output current of the shaded cells the IV and PV curve starts following the IV and PV curves obtained from the simulation considering the bypass diodes. After minima IV and PV characteristics curve remain the same.

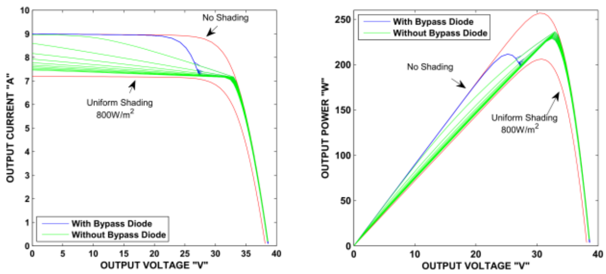

Fig. 13. IV curve with and without bypass diodes

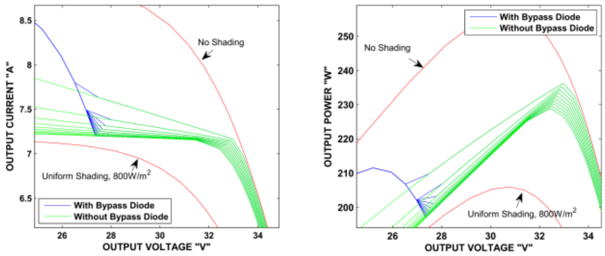

Fig. 14. Zoomed view of Figure 12

IV. Conclusion

A Simulink based hybrid model for mutli-crystalline silicon PV module was developed for studying the partial shading effect. This model has the ability to analyse the partial shading effect for PV modules on a cell level. The hybrid model consists of a combination of mathematical equations based technique coupled with the electronic circuit based methodology in Simscape™ Simulink. Initially, two Rp models; a single diode and a double diode model, were developed and the results were compared with the manufacturer provided data. The results suggest that the single diode model is as effective as the double diode model, thus using it saves the computational cost. Finally, the single diode model was used for partial shading analysis and a PV module with six bypass diodes was designed in Simscape™ Simulink. Every bypass diode was connected with a string of ten cells within a module. A single string was shaded and the output power was varied between 236.27W (single cell shaded) to 228.87W (Full string shaded), which corresponds to a power drop of 8.07% to 10.94% respectively compared to no shading. Thus, the developed model can be an efficient way of analysing the PV modules for different operational conditions.

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