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Modeling and Simulation of Solar Photovoltiac Module using Matlab-Simulink

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Abstract- **Escalating energy demands, greenhouse gases, climate changes and evisvration of fossil fuel are major issues in front of all over the world. The one of optimum solution to these problems is the acceptance and deployment to renewable energies resources. Among all the existing renewable energy sources, solar energy has momentum due to its many features. Usage of solar energy can play a significant role in economic development and improvement in quality of life. The objective of present investigation is to discuss mathematical modelling and design simulation models of photovoltaic modules under given environment physical conditions. System parameters of photovoltaic module such as $I_{SC,}$ short circuit current, V_{OC}, open circuit voltage, P_M maximum output power, and their corresponding current and voltage investigated under environment factors.**

***Keywords* —*Solar Silicon Cells (SSC), Mathematical Modelling Photo Voltaic Module, Circuit model of Module, Simulation Modeling, Characterization of PV module*.**

I. Introduction

The Photovoltaic cells are solid state electronic device which convert photo energy into electrical energy [1-3]. The principle of PV cells is photovoltaic effect. The photovoltaic effect is generating electrons due to bombarding of photons. Energy of the photon larger than forbidden gap energy of semiconductor material can generate electrons. The photovoltaic effect is physical or chemical effect. The PV cell efficiency is ratio of input power due to incidence of photons and electric energy that is generated by the cell. The current and power of PV cell or module are function of solar irradiance and temperature.

The PV systems can be installed anywhere, since solar energy is feasible almost in all locations of world. The solar energy is most promising form of the renewable energy which is increasing continuously due to advancement in technology and awareness among peoples. Solar photovoltaic has a long life, low maintenance cost, easy to install, no noise, simple to operate.

In present investigation, the current and power characteristics of PV module are analyzed by using the modeling and simulation of the PV module. The characteristics depend on environmental factors solar irradiation and temperature. Simulation models are developed on the graphical user interface Simulink environment. Moreover, other system parameters of photovoltaic module such as $I_{SC,}$ short circuit current, V_{OC}, open circuit voltage, P_M maximum output power, and their corresponding current and voltage investigated under environment factors.

The present investigation is employed to achieve following objectives:

- To provide an account on mathematical modeling of photovoltaic cell and module.
- To explain electrical equivalent of PV cell and module
- To implement of the details modeling and simulation of PV cell and module on matlab in graphical environment Simulink the integrated development environment (IDE).
- To develop general simulink model, can be used for all photovoltaic module available in market, to obtain current voltage and power voltage characteristics curves.
- To study effect of series resistance R_s loss resistance, and shunt resistance $R_{p,}$ leakage source of current in cell and, module.
- To explore the fill factor and its effect on other parameters of photovoltaic module.

To understand the functioning photovoltaic cell and module, the modeling and electrical circuits equivalent are necessary to develop the simulation models. Mathematical modeling of photovoltaic module is presented in the forthcoming section. The mathematical equations are employed to obtain the output current and power of photovoltaic module.

II. Mathematical Modeling and Electrical Equivalent of Photovoltaic Cell and Module

In present section, different equivalent circuits and mathematical modeling of PV module has been presented.

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Ideal circuit model photovoltaic cell

The electrical circuit model of ideal photovoltaic cell is depicted in fig.1.

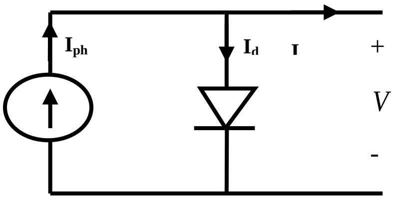

Fig.1 Ideal Model of Photovoltaic Cell

The ideal photovoltaic cell model has zero series resistance and shunt resistance infinity. This equivalent circuit consist the photo current as current source and anti parallel diode. The output load current of ideal photovoltaic cell is obtained by using KCL and is given in eq. (1).

$$I = I_{ph} - I_d \tag{1}$$

I : Output load current (A)

I_{ph} : Current known as photo current and it is due to solar irradiations (A)

I_d : Diode current (A)

Diode current is obtained by diode equation and given by eq. (2).

$$I_d = I_0\left[\exp\left(\frac{V}{AN_sV_T}\right)-1\right] \tag{2}$$

V : Load Voltage (V)

A: Ideality constant factor, which depends on the photovoltaic cell technology and different ideality factor for different technology [2].

V_T : known as thermal voltage.

$$V_T = \frac{kT_c}{q} \tag{3}$$

Electron charge, $q = 1.602\times10^{-19}$ (C)

Boltzmann's constant, $k = 1.381\times10^{-23}$ (J/K)

Reverse saturation current, I_0 (A)

Tc: Operating temperature (K)

Thermal Voltage: V_{Tc}=26 mV, at $300\,^0K$ for Silicon cell

If V_T is multiplied with N_s and A , then

$$a = \frac{Ns.A.k.Tc}{q} = Ns.AV_T \tag{4}$$

a: modified ideality constant factor

Circuit Model of photovoltaic Cell with Series Resistance R_s

In practical implication, it is not possible to prevail over the effect of the series resistance R_s that is internal loss in cell and parallel resistance R_p. Efficiency of photovoltaic cell is affected by series and shunt resistance. Circuit model of practical photovoltaic cell with R_s is depicted in fig.2.

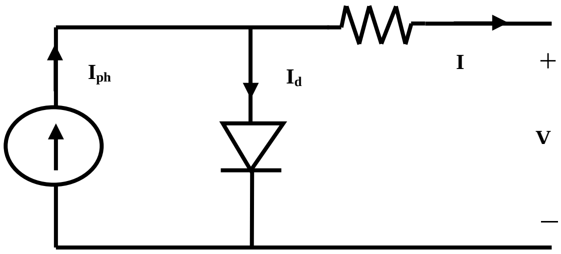

Fig.2 Equivalent Circuit Model of Photovotaic Cell with Rs

If, R_s into consideration, and diode current is affected, as given by eq. (5),

$$I_d = I_0\left[\exp\left(\frac{V+IR_s}{AN_sV_T}\right)-1\right] \tag{5}$$

The photovoltaic cell circuit model with Rs depicted in fig.2 is known as simplified form and widely used by the simulators.

Practical Circuit Model with R_s and R_p

In fig.3, equivalent circuit model of photovoltaic cell with series resistance R_S and parallel resistance R_p is shown. It is widely used model of photovoltaic cell. The output current is obtained by using the Kirchhoff's current law, as given by eq. (6).

$$I = I_{ph} - I_d - I_p \tag{6}$$

By substitution of eq. (5) in eq. (6)

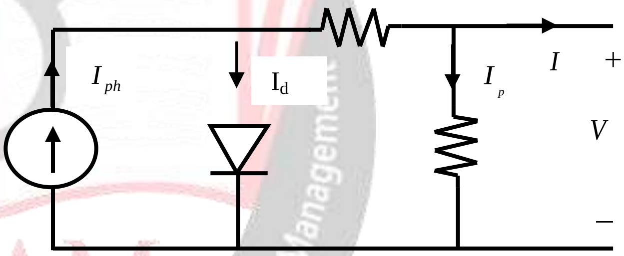

Fig.3 Circuit Model of Photovoltaic Cell with Rs and Rp

Output current of photovoltaic module based on Fig. 3, is obtained by using eq. (7)

$$I = I_{ph} - I_0\left[\exp\left(\frac{V+I.R_s}{AN_sV_T}\right)-1\right]-\frac{V+R_s.I}{R_p} \tag{7}$$

It is one of the complex tasks to obtain the solution of eq. (7), it is a transcendental equation.

Double Diode Circuit Model

In fig.4, double diode circuit model is depicted. This circuit model of photovoltaic cell has photocurrent parallel combination of two diode, series resistance and shunt resistance.

In this case load output current, I is given by eq. (8)

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$$I = Iph - I_0\left(\exp\left(\frac{V+I.Rs}{A.Ns.V_T}\right)-1\right) - I_0\left(\exp\left(\frac{V+I.Rs}{A.Ns.V}\right)-1\right) - \frac{V+I.Rs}{Rp} \tag{8}$$

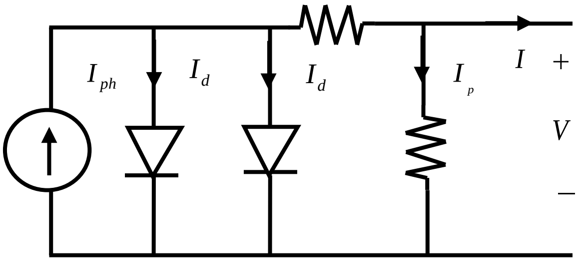

Fig.4 Double Diode Circuit Model

III. DETERMINATION OF PARAMETERS

The system parameter of PV module varies depending on the chosen model and assumption adopted by searcher. For instances, in five parameters model includes I_{ph}, I_0, R_s, R_p, and A and or four parameters are I_{ph}, I_0, R_s, and $A.N_s$. In present study, the four parameters that have been evaluated are I_{ph}, I_0 R_s and R_p.

A. Determination of Photo current

In fig.1, the output current is determined by using Kirchhoff's current law at STC (Solar radiations $G_{ref} = 1000W/m^2$ and $T = 298\,^0K$). The relation of output current I and photo current I_{ph} is represented in eq. (9).

$$I = I_{ph,ref} - I_{0ref}\left[\exp\left(\frac{V}{a_{ref}}\right)-1\right] \tag{9}$$

Now, on short circuit of fig. 1 the eq. (9) becomes.

$$I_{sc,ref} = I_{ph,ref} \tag{10}$$

This eq. (10) is valid only in case of ideal PV cell, otherwise

$$I_{sc,ref} \approx I_{ph,ref} \tag{11}$$

The photo current is depends upon the solar irradiance and temperature, and its mathematical relation is represented in eq. (12).

$$I_{ph} = \frac{G}{G_{ref}}\left[I_{ph,ref} - k_i(T - T_{ref})\right] \tag{12}$$

G: Solar irradiations (W/m^2)

G_{ref} : 1000 W/m^2

$I_{ph,\,ref} = I_{sc,\,ref}$

$I_{sc,\,ref}$ is known as short circuit current at STC (A)

T : Operating temperature of cell (K)

T_{ref} : Reference temperature (298 K)

ki : Coefficient of short circuit current (A/K)

B. Determination of Saturation Current I_0

The last term of the relationship (9) can be eliminated by considering large shunt resistance. Due to this reason, by using equation (9) at the three most significant coordinate points of characteristics at standard test condition (STC); the open circuit voltage ($V = V_{oc,ref}$, $I = 0$), and the short circuit current ($V = 0$, $I = I_{sc,\,ref}$), and the voltage ($V_{mp,ref}$), and current ($I_{mp,\,ref}$) at maximum power ($P_{mp,\,ref}$), the subsequent equation can be expressed as:

$$I_{sc,ref} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{I_{sc,ref}.R_s}{a_{ref}}\right)-1\right] \tag{13}$$

$$0 = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{Voc}{a_{ref}}\right)-1\right] \tag{14}$$

$$I_{pm,ref} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V_{pm,ref} + I_{pm,ref}.Rs}{a_{ref}}\right)-1\right] \tag{15}$$

If the exponential part of eq. (15) is larger than -1, in such point -1 can be eliminated. According to eq. (12) and by substituting $I_{ph,\,ref}$ in eq. (15);

$$0 \approx I_{sc,ref} - I_{0,ref}\left[\exp\left(\frac{V_{oc,ref}}{a_{ref}}\right)\right] \tag{16}$$

$$I_{0,ref} = I_{sc,ref}\left[\exp\left(\frac{-V_{oc,ref}}{a}\right)\right] \tag{17}$$

Let I_0 is reverse saturation current and it is defined by

$$I_0 = DT^3\, e^{\frac{-qE_g}{A.k}} \tag{18}$$

D : Diode diffusion factor

E_g : Forbidden gap energy, (1.12 eV for Si)

In processing of elimination of the diode diffusion factor D, eq. (18) is computed twice, at T_c, $T_{c,\,ref}$. Then the ratio of two equations is written in next expression:

$$I_0 = I_{0,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left[\left(\frac{qE_g}{A.k}\right)\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \tag{19}$$

$$I_0 = I_{sc,ref}\exp\left(\frac{-Voc,ref}{a}\right)\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left[\left(\frac{qE_g}{A.k}\right)\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \tag{20}$$

Eq. (20) presents I_0 some parameters are provided by the manufacturer as ($V_{oc,ref}$, $T_{c,ref}$), other to relate the technology of PV cell, as (A, E_g) and other some constants. But a and T_c are dependents of actual temperature. That is why, I_0 has to be determined at real time.

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C. Determination of Series Resistance R_s and Shunt Resistance R_p

In order to make the proposed model more credible, R_s and R_p are chosen so that the simulated max power P_{mp} is equal to the experimental one $P_{max,\,ex}$ at STC conditions.

$$I_{mp,ref} = P_{mp,ref}/V_{mp,ref} = P_{mp,ex}/V_{mp,ref} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V_{mp,ref} + I_{mp,ref}.Rs}{a}\right) - 1\right] \quad (21)$$

$$R_p = \frac{V_{mp,ref} + I_{mp,ref}.Rs}{I_{sc,ref} - I_{sc,ref}\left\{\exp\left[\frac{V_{mp,ref} + I_{mp,ref}.Rs - V_{oc,ref}}{a}\right]\right\} + Isc,ref\left\{\exp\left[\frac{-V_{oc,ref}}{a}\right]\right\} - \frac{P_{max,ex}}{V_{mp,ref}}} \quad (22)$$

D. Design Process of Iteration

The experimental value especially, P_{mp} is compared with $P_{mp,\,ref}$ to propose the values of the series resistance R_s and Shunt resistance R_p. The design process of iteration to compute the pair of series resistance and shunt resistance at $P_{mp,\,ref}$ is depicted in Fig.5.

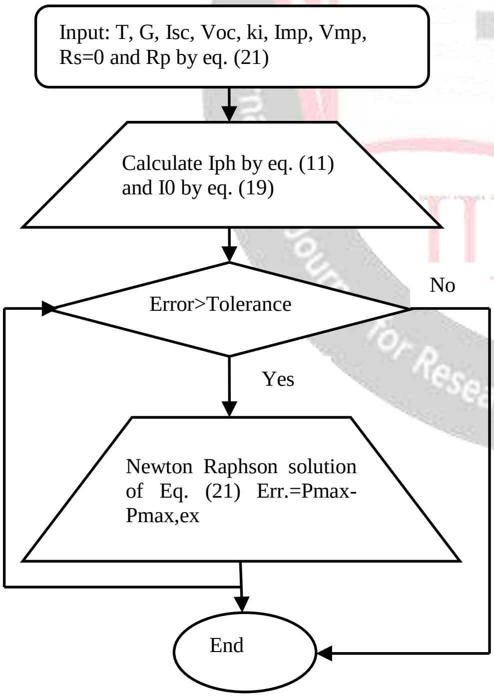

Fig.1: Iteration Flow Chart (Belia et. Al.)

In subsequent section, the simulation models based on the electrical equivalent of the PV module and the equations are developed. The simulation models are developed in Simulink, graphical user interface environment in Matlab. These models are used for the purpose of analysis $I(V)$ and $P(V)$ characteristics of PV module.

IV. SIMULATION MODELS OF PV MODULE

A. Simulink Model of Photo Current (I_{ph})

Simulink Model of photo current eq. (12) is developed in Simulink. The Detailed implementation of Iph in Simulink environment, with its subsystem and effect of environmental factor solar irradiations G and temperature T is depicted in Fig. 6

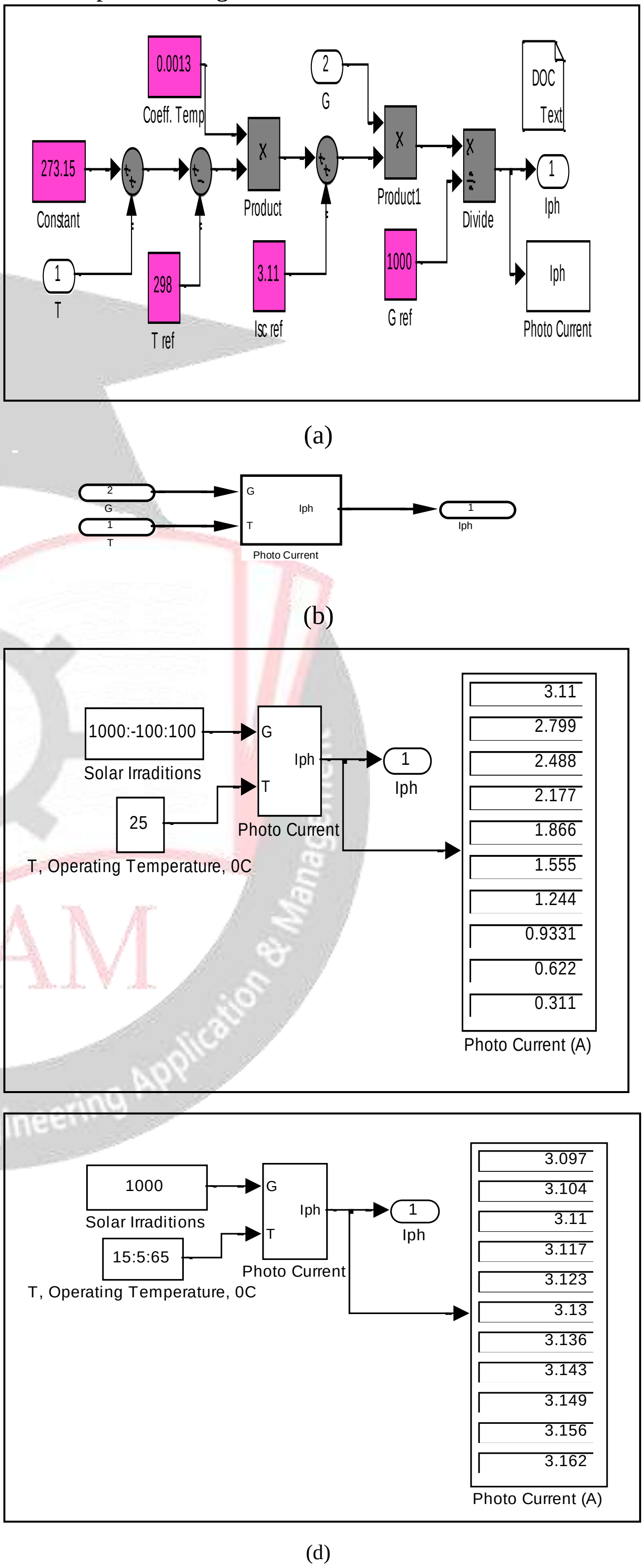

Fig.5 Photo Current (a) Detailed Simulink Model (b) Subsystem of Iph (c) Effect of Solar Irradiance on Iph, Keeping T Constant (d) Effect of Temperature on Iph, with Solar Irradiations constant

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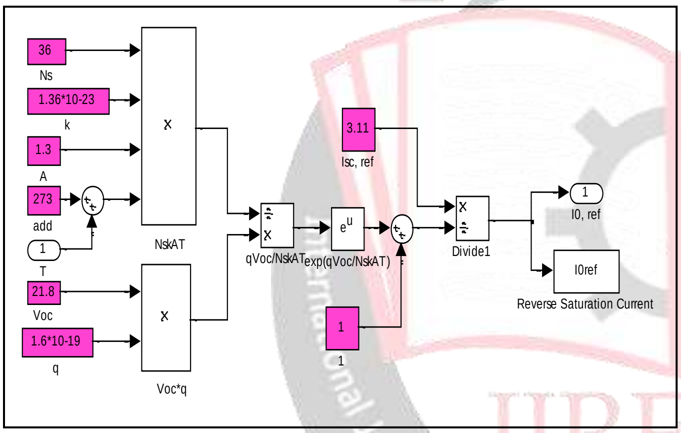
System parameters required to determine the photo current is taken from Table 2 PWX 500 PV Module (49 W) [2].

TABLE I. PWX 500 PV MODULE (49 W)

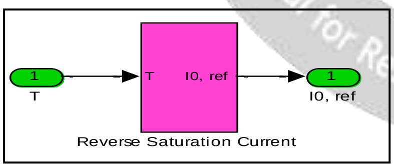
Parameters	Symbols	Values
Maximum Power	P_{mp}(W)	49
Maximum Current at P_{mp}	I_{mp}(A)	2.88
Maximum Voltage at P_{mp}	V_{mp}(V)	17
Short Circuit Module Current at STC	I_{sc}(A)	3.11
Open Circuit Voltage of Module at STC	V_{oc}(V)	21.8
Series Resistance	Rs (Ohm)	0.55
-	Noct ^{0}C	45
Coeff. Temp. of short circuit current	ki(A/^{0}K)	1.3*10-3
-	Kd (^{0}K)	-72.5*10-3

B. *Reverse Saturation Current ($I_{0,ref}$)*

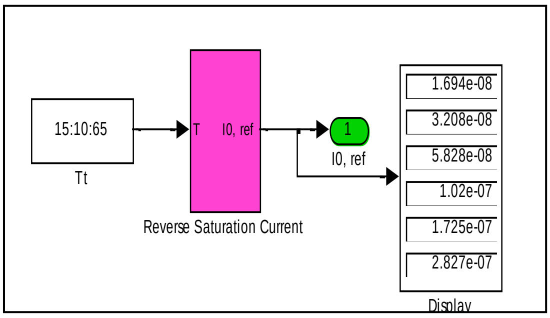
In Fig.7 reverse saturation current, eq. (17) is implemented using Simulink model. In this the simulation model also computes the $I_{0,ref}$ as function of temperature.



(a) Detailed Simulink Model I0, ref



(b) Subsystem Representation of I0,ref of PV Module

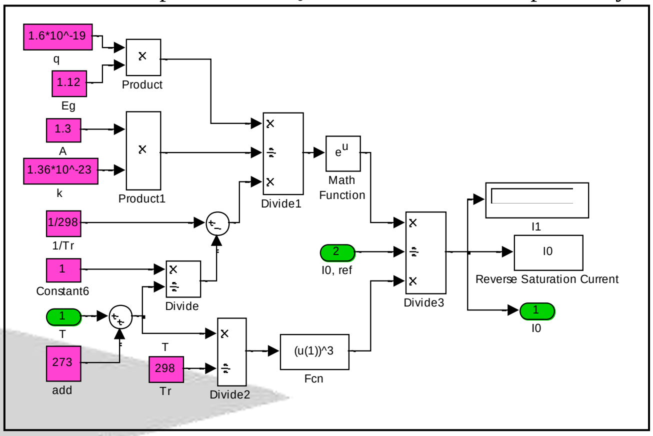


(c) Effect of Temperature on I0, ref

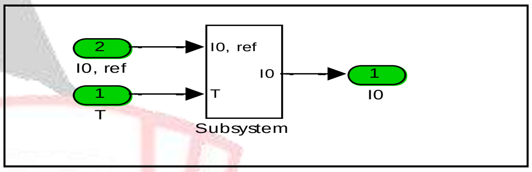
Fig.7 Detailed Simulink Model Implementation of Saturation Current ($I_{0,\,ref}$)

C. *Saturation Current (I_0)*

Eq. (19) represents I_0, and same is investigated by using the simulation model developed in Simulink environment. The simulation model is depicted in Fig. 8. The subpart of the Fig 8 (a), (b), and (c) represent the detailed, subsystem, account of temperature on I_0 Simulink models respectively.



(a) Detailed Simulink Model of I_0



(b) Subsystem Simulink Model of I_0

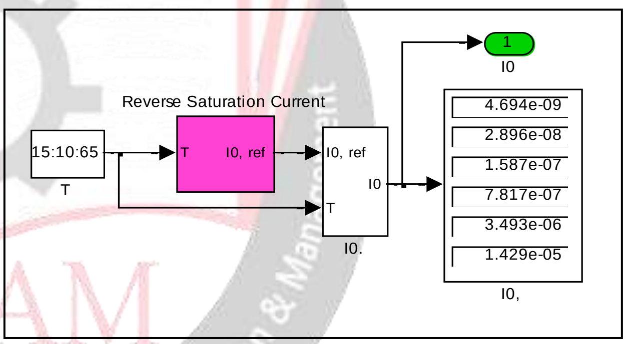
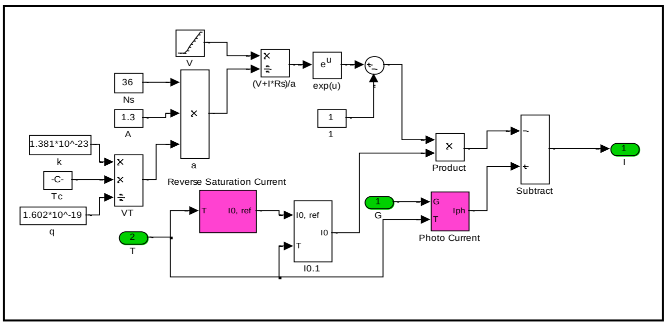


Fig. 8: Detailed Simulink Model Implementation of I_0

D. *Output Current of Ideal PV Module (I)*

Output current given by Eq. (7) is developed as simulation model depicted in Fig.9. The output current characteristics w.r.t voltage can be investigated for $I\ (V)$ dependency on G and T using this Simulink model of ideal PV module. In present model R_s and R_p is considered as zero, lossless PV module is realized.



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(a) Detailed Simulink Model of Ideal PV Module

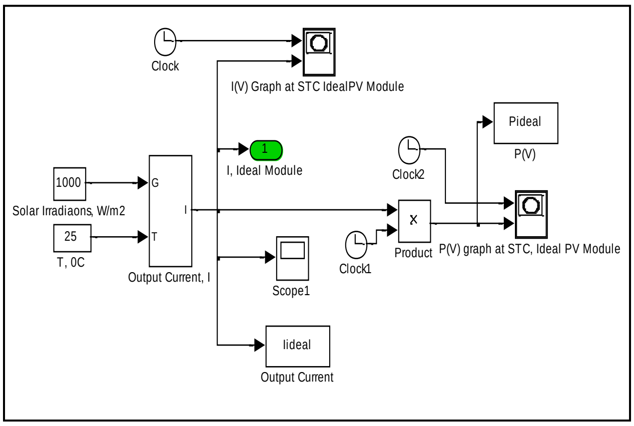
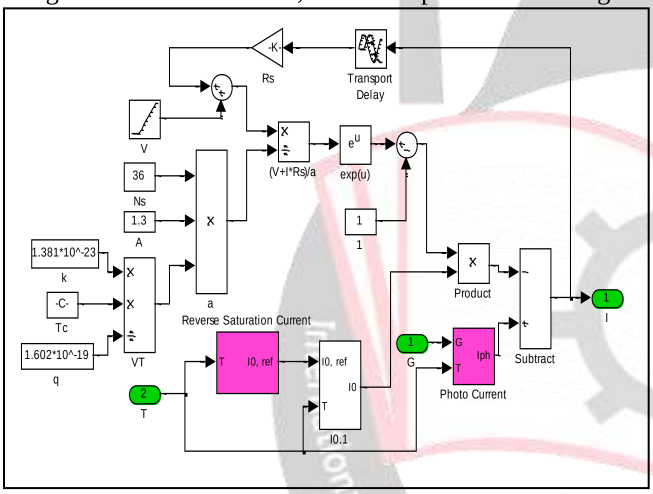


Fig.9 Ideal_PV_Module.mdl

E. Output Current of Practical PV Module (R_s=0.55 Ohm)

The output current of PV module at Rs=Ohm is determined using Simulink model, is depicted in fig.10



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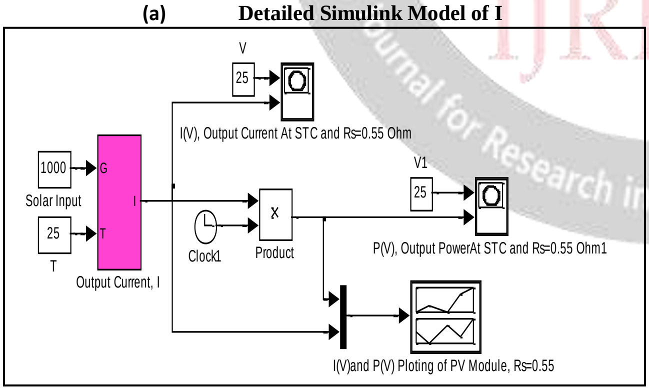
(a) Detailed Simulink Model of I



(b) Subsystem Implementation of I Based on Eq. (7)

Fig.10 Detailed Simulation Implementation of I using eq. (7), Rs=0.55

F. Computation of shunt Resistance R_p

The shunt resistance Rp is calculated using eq. (22), implementation is presented in Fig 11.

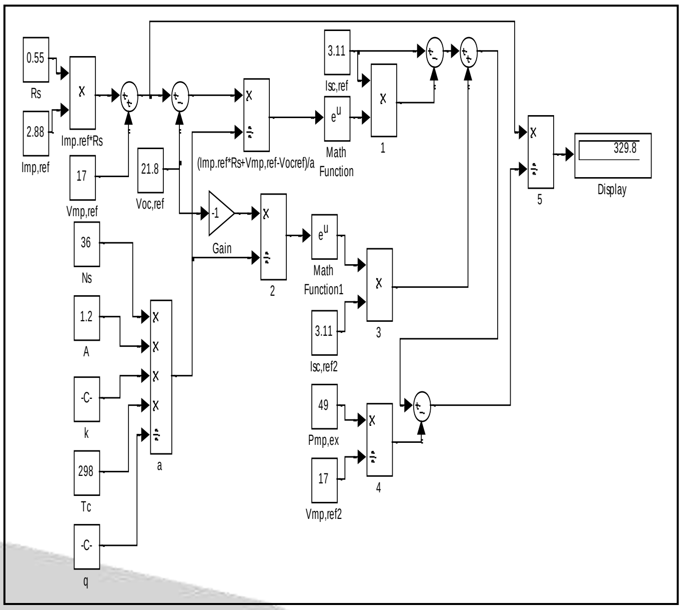
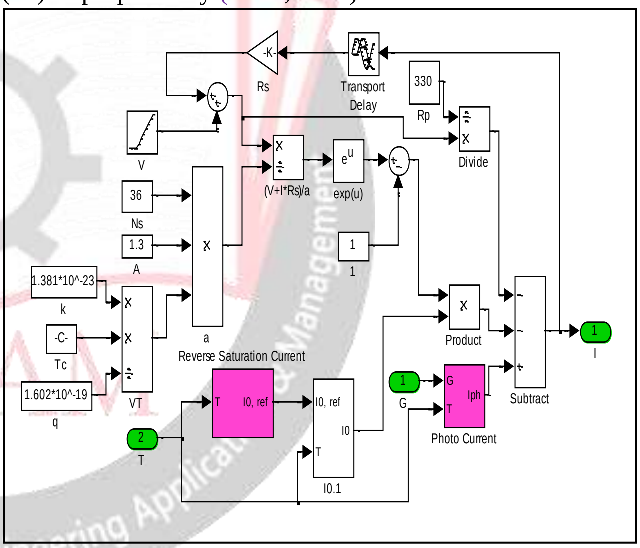


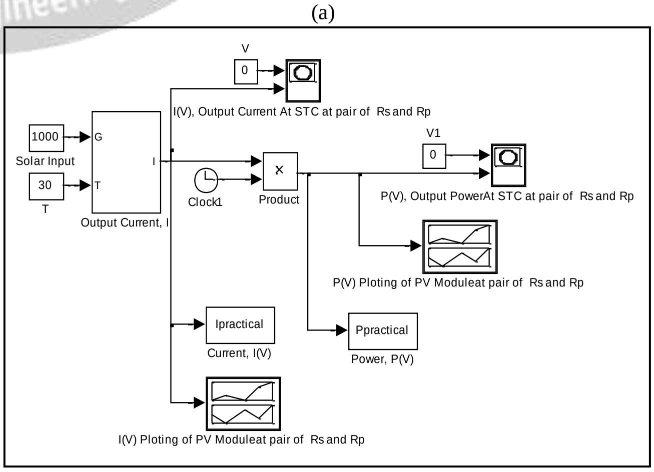
Fig.11 Calculation shunt resistance Rp

E. Simulated Output Current of Practical PV Module (Inclusion of Series and Shunt Resistance)

The eq. (7) is implemented using simulink model depicted in Fig. 12, to compute the output current of PV module. The shunt resistance of the PV module is calculated by using eq. (22) as proposed by (Belia, et. al).



(a)



(b)

Fig.12 Implementation of Rs and Rp to calculate Output Current of Module

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Output Results of simulation models of PV module PV are exemplify in forthcoming section. In this section the simulation result of different electrical equivalent models of PV module is described and compared with the data given by manufacturer related to the PV characteristics.

F. GUI Model

The graphical user interface model of output current of PV cell is depicted in Fig. 13

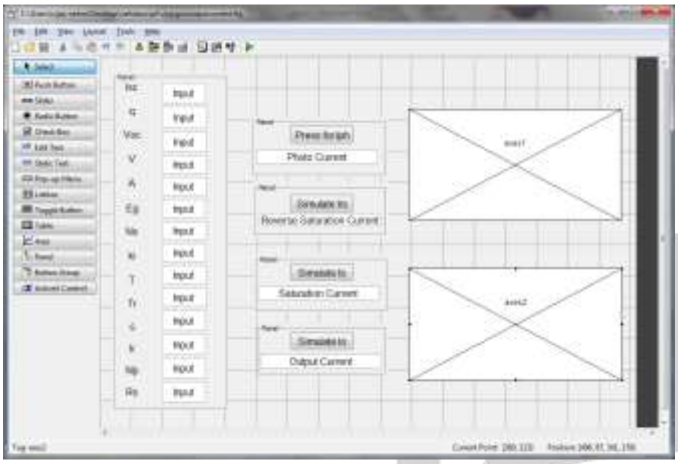


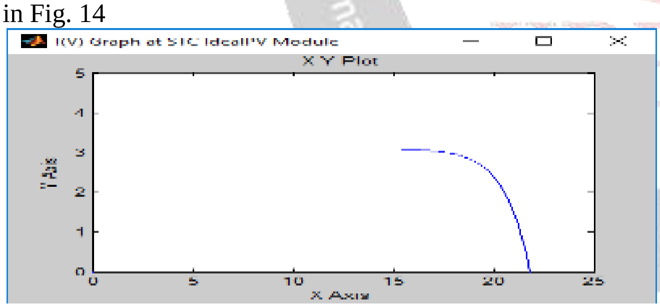
Fig.13 Graphical User Interface Simulation Model of Photovoltaic Module

V. RESULTS OF SIMULINK MODELS OF PV MODULE

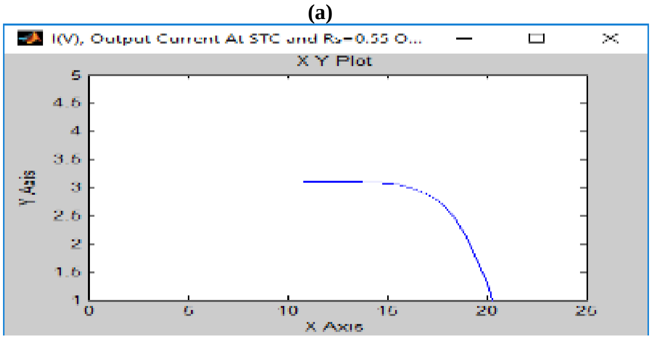
In preceding section different simulink models of PV module have designed and in present section their simulation result is represented.

A. Characterization of Ideal Photovoltaic Module

On running of Ideal_PV_Module.mdl Fig 9, the simulated I-V and P-V curves of ideal photovoltaic module are shown in Fig. 14



(a)



(b)

Fig.14 Current Characteristics Ideal PV Module

B. Characterizations of Practical PV Module

The simulation output of the Practical_PV_Mod_Series_Res.mdl is current and power characteristics. These characteristics are developed by using eq. (7), the non linear behavior between current and voltage, and power versus voltage are depicted in Fig.15

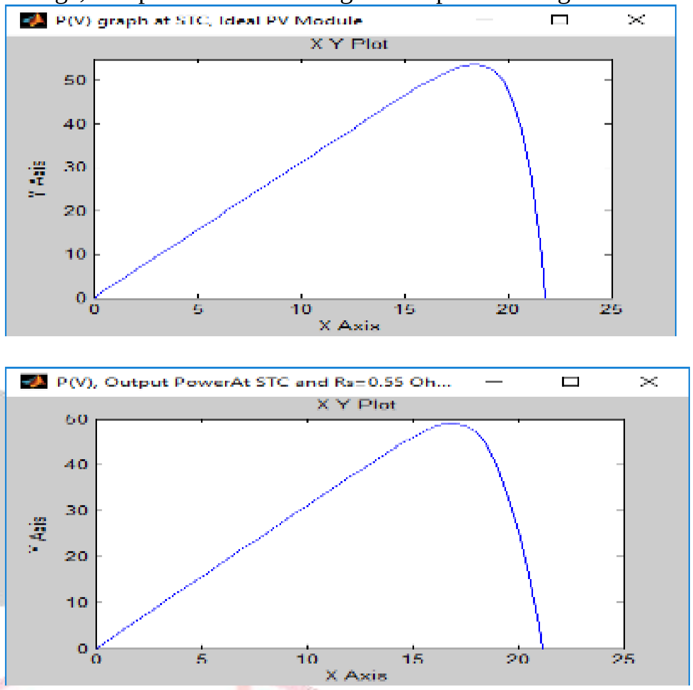
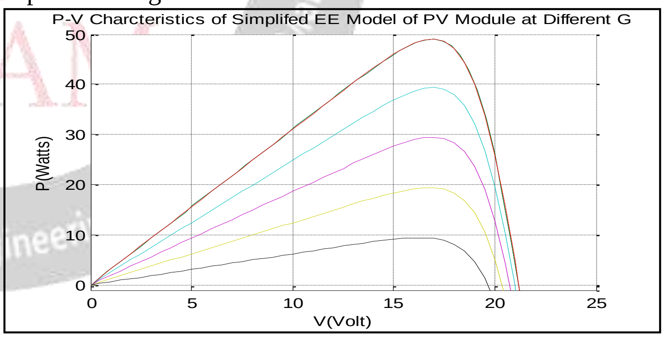


Fig.15 I(V) Plotting of Practical PV Module, Simulation

It is remarkable fact, that both of the characteristics I-V and P-V of photovoltaic module are nonlinear. As indicated in preceding discussion, iteration approach is used to get maximum power point, depicted in Fig. 15

B. Effect of Solar Irradiations

The output power and voltage develop a non linear relations and the effect on the curve between V and P clearly depicted in Fig. 16



(a)

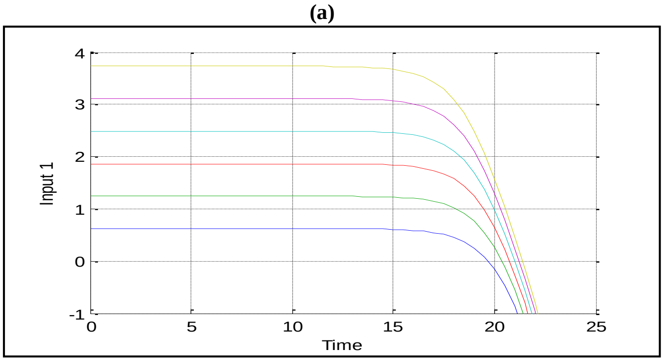


Fig.16 I-V and P-V Characteristics of PV Module Under Solar Irradiances Variation

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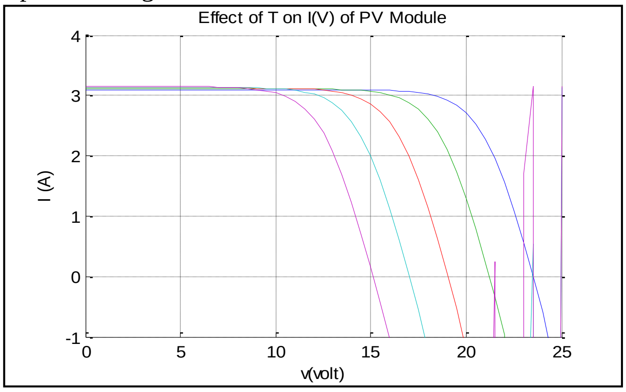
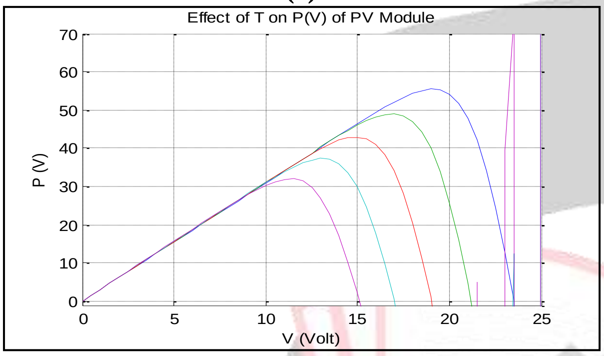
C. *Effect of operating temperature*

The output power and voltage develop a non linear relations and the effect on the curve of operating temperature is depicted in Fig. 17



(a)



(b)

Fig.17 Simulated I-V and P-V of Electrical Equivalent Simplified Circuit Model of PV Model
I (V) of PV Module Under Influence of Temperature
P-V characterization of PV Module Based on Temperature

TABLE II. PARAMETRES OF PV MODULE AT T=15 :5:55 ^{O}C

T in ^{0}C	Pmp (W)	Imp (A)	Vmp (V)	Isc (A)	Voc (V)	FF=Pmp/ IscVoc
15	55.4598	2.9189	19.00	3.0970	23.5	0.7620
25	**49.0016**	**2.8824**	**17.00**	**3.110**	**21.5**	**0.7328**
35	42.9650	2.8643	15.00	3.1230	19.5	0.7055
45	37.3244	2.8711	13	3.1360	17.5	0.6801
55	32.0195	2.7843	11.5	3.1490	15.5	0.6560

D. *Effect of Rs on Characteristics of Module at STC*

It is obvious from graphical representation of P (V) depicted in Fig.18 in account of Rs; Pmp decrease with increase in Rs,

Moreover Voc also decrease with increase in Rs series resistance of photovoltaic module

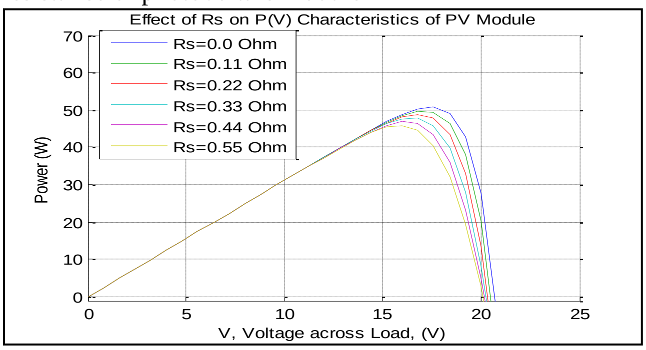


Fig.18 : P-V Characterization of PV Module with Rs Variation at STC

The simulated result, for ideal PV module, Pmp is larger than given value, and at Rs (0.55), the result is almost same.

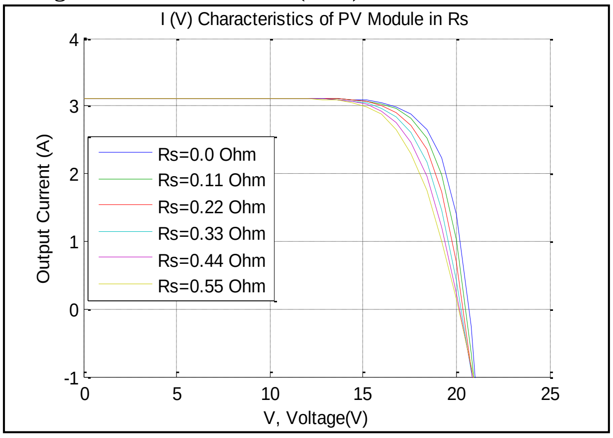


Fig.19 : I (V) of PV Module with Rs

Noticeable fact from the graphical representation of I (V) in account of series resistance Rs is depicted in Fig. 19, and short circuit current, Isc is least effected by rise in series resistance.

VI. CONCLUSION

The observation of the Table 3, simulation output Pmp(W), Imp(A), Vmp(V), Isc(A), and Voc(V) of the electrical equivalent simplified PV module and PWX 500 (49 W) PV Module almost matched.

TABLE III. PARAMETRES OF IDEAL PV MODULE AT STC, SIMULATION MODEL(RS=0.55 AND RP=330 OHM), AND PWX 500 AT STC

Parameters (Unit)	**Simulation Values Ideal PV**	**Simulation Values(Rs=0.55)**	**PWX 500 at STC of PV Module**
Pmp(W)	53.8356	48.9922	49
Imp(A)	2.9258	2.9162	2.88
Vmp(V)	18.4	16.8	17
Isc(A)	3.11	3.11	3.11
Voc(V)	22.02	21.60	21.8

The output power continuously decreases with decrease in solar irradiances. The effect of G on parameters of photovoltaic modules from the simulation results, shown in Table-4; it is take in from the Table-4, Pmp(W), Imp(A), and Isc(A) greatly affected parameters of PV module due G and all these parameters increase with increase in G. Vmp(V) and Voc(A) are least affected parameters.

TABLE IV. **SYSTEM PARAMETERS UNDER EFFECT OF SOLAR IRRADIATIONS OF PV MODULE**

G (W/m^2)	**P_{mp}(W)**	**I_{mp}(A)**	**V_{mp}(V)**	**I_{sc}(A)**	**V_{oc}(A)**	**FF=P_{mp}/ $I_{sc}V_{oc}$**
200	9.43920	0.5721	16.5	0.662	19.55	0.7293
400	19.4557	1.1445	17.0	1.244	20.50	0.7629
600	29.4876	1.7346	17.0	1.866	21.00	0.7525
800	39.3520	2.3148	17.0	2.488	21.00	0.7532
1000	**49.0016**	**2.8824**	**17.0**	**3.110**	**21.5**	**0.7328**
1200	58.3789	3.4341	17.0	3.732	21.5	0.7276

Most considerable environmental factor is temperature which effect the operation of photovoltaic module, effect of temperature is concluded by using the simulation models; shown in Table 4

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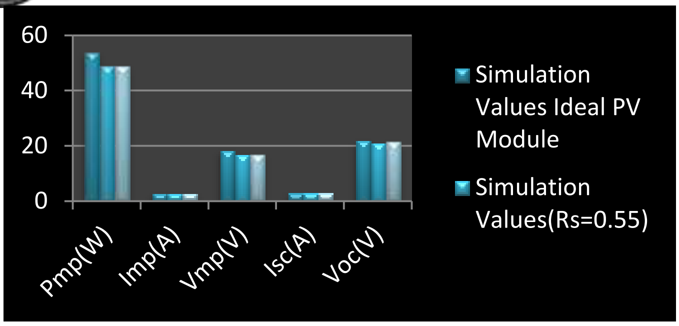

Fig.20 : Comparision of System Parameters between Simulation Output and Manufactorer Listing

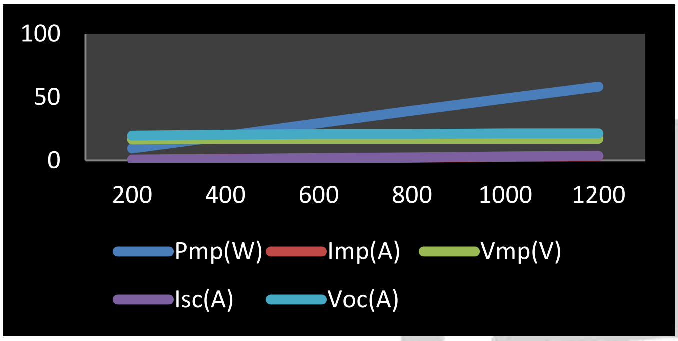

Fig.21 System Parameters (Solar Irradiations, G) [y-axis=Syste Parameters, x-axis=Solar Irradiations]

Fill Factor: Fill factor of PV module is defined in eq. (22)

$$FF = \frac{P_{mp}}{I_{sc}V_{oc}} = \frac{\eta A_c G}{I_{sc}V_{oc}} \qquad (22)$$

$$\eta = \frac{FF.I_{sc}.V_{oc}}{A_c.G} \qquad (23)$$

The variation of fill factor due to solar irradiations is depicted in Table 4 and Fig.22. Moreover, changing in fill factor due to temperature is illustrated in Fig. 23

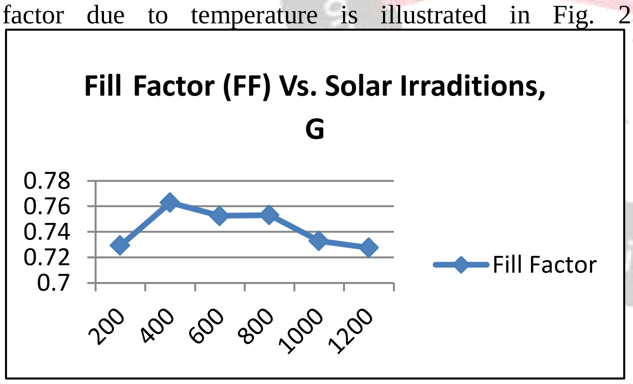

Fig.22 : Variation of Fill Factor due to Solar Irraditions G

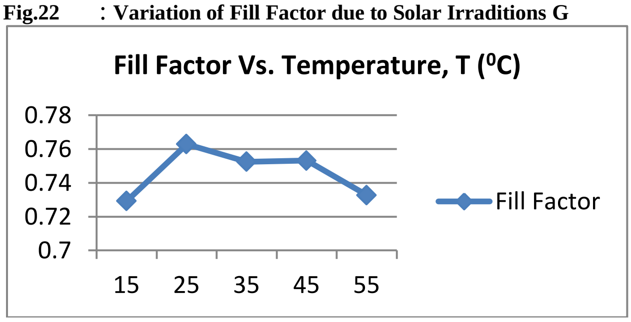

Fig.23 Variation of Fill Factor due to Temperature T (^{0}C)

The fill factor continuously decreases with increase in temperature. The graphical representation of system parameters by taking in account of temperature is depicted in Fig. 24 and Fig. 25.

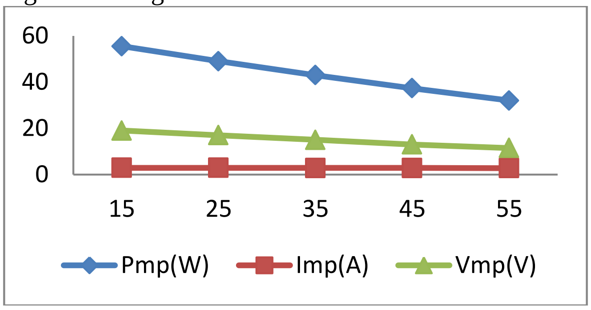

Fig.24 : System Parameters (Temp. Consequence)

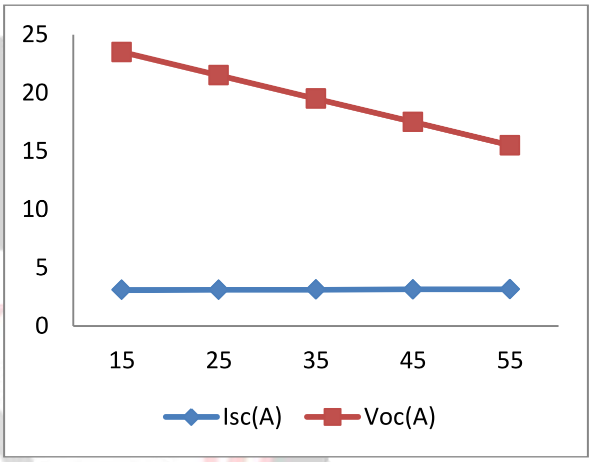

Fig.25 : System Parameters (Temp. Consequence)

In nutshell, decreases in fill factor result output downsize the efficiency of PV module as per eq. (23). The fill factor depends on the shunt resistance and series resistance. Eventually, growth in shunt resistance and series resistance is cause of decline in the fill factor.

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