

Non Linear I-V Curve Of PV Module: Impacts On MPPT And Parameters Estimation

B.K. Nayak¹

*School of electrical Engg.,
Kalinga Institute of
Industrial Technology,
Bhubaneswar, India*

A.Mohapatra²

*School of electrical Engg.,
Kalinga Institute of
Industrial Technology,
Bhubaneswar, India*

B.Misra³

*School of electrical Engg.,
Kalinga Institute of
Industrial Technology,
Bhubaneswar, India*

Abstract

This paper explains the various issues regarding the parameters extraction of PV module and performance improvement of MPPT tracker. The comparative analysis of parameters extraction using iterative method and trust-region-dogleg method is presented. The effect of dynamic resistance on MPPT and dc-dc converter due to non linear characteristic of PV module is presented. The criteria for choosing various type dc-dc converters are explained. The necessity of capacitor across the solar cell and its design is explained. This paper gives the basic fundamentals of PV module for researchers to extend the modelling and feedback controller design in stand-alone mode or synchronization to grid for power transfer.

1. Introduction

Clean and renewable energy sources such as photovoltaic (PV) power generation are expected to become essential for mitigating global warming. A photovoltaic cell converts sunlight to electricity. The number of cells is grouped in series and parallel to form large photovoltaic arrays in order to meet the voltage and current of the load. It is possible to use PV power in stand-alone mode or distributed generation mode (micro grid). Since PV arrays exhibit nonlinear I-V characteristic and also the characteristic is modified by changing of temperature and solar radiation, their power output mainly depends on the nature of the

connected load. Hence, direct load connections to PV systems result in poor overall efficiency. As solar panels are still expensive, minimizing the cost of their life cycle has recently become an important consideration. To achieve some of these goals, direct connected PV systems are being replaced by PV systems having an intermediate maximum power point (MPP) tracker. The power generated from a given PV module mainly depends on solar irradiance and temperature. As these quantities vary with time[1], it is necessary to develop a control logic that continuously monitors the terminal voltage and current and updates the control signal accordingly. To achieve these goals, various conventional single-stage (CSS) MPP tracking (MPPT) algorithms have been proposed and used to extract maximum power from PV arrays under different operating conditions. Connecting one PV array is not recommended due to space limitations for installation in addition to the load voltage and current demands. Normally large number of PV array known as modular connection are connected in series and parallel fashion, in order to satisfy the required voltage and current demands. Modular connection has several advantages both from a physical layout as well as a load demand point of view. These can be broadly classified into two schemes from the MPPT point of view wherein

- 1) Each modular PV system may be provided with its own MPPT controller, and
- 2) All the modular PV systems may be controlled by a single centralized MPPT controller.

A battery is required to act as extra source and load in stand-alone mode or grid connection PV module in order to mitigate the flow of power. Unlike fixed dc input voltage of dc-dc converter for regulated voltage load, the input voltage or input current of PV module is

regulated through MPPT, using dc-dc converter in such a way that the output voltage and current of the MPPT is always at maximum power point of PV module. The dc-dc converter may be buck, boost or buck-boost type depending upon PV voltage and battery voltage, used as an extra load or extra source. If the load demand is more than the maximum power production of PV panel, operated in stand-alone mode, the extra load demand is supplied by battery. In this condition the battery and PV module act as sources of the system. The extra power of PV module is used for charging of battery in reverse condition. In micro grid connection, an inverter is required for connecting to grid at the common point of coupling, where the power of PV module and battery is used to fulfil the power demand of sensitive load. During disturbances, the PV generation and corresponding loads can separate from the distribution system to isolate the microgrid's load through the static switch and thereby the PV module charges the battery without harming the transmission grid's integrity. Thus the MPPT and the dc-dc converter can provide the flow and control of power in stand-alone mode, whereas Inverter and MPPT with dc-dc converter together used to control the flow of power effectively required for plug-and- play functionally in microgrid connection. The control function of inverter includes to synchronization of voltage, frequency and phase before connecting the PV module to grid at common point of coupling.

This paper presents the various technical issues and solutions such as selection of dc-dc converter circuit, design of passive parameters in dc-dc converter and MPPT tracking problem. The aim of the paper is to provide the researcher the various problems associated with PV model used mainly in stand-alone mode, so that the researcher can enhance the research capability to improve the system dynamics. Nevertheless, the above technical issues can also be applicable in microgrid connection.

2. Modelling of PV and parameter extraction

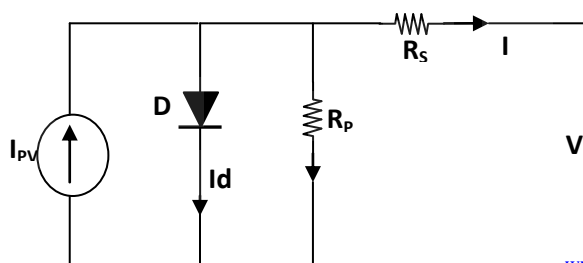


Figure 1. Equivalent circuit of a PV module using one diode

The Equivalent circuit with single diode of the photovoltaic module is shown in Fig-1. The basic equation that mathematically describes the I-V characteristic of PV array is [2]:

$$I = I_{pv} - I_0 \left[\exp \left(\frac{V + R_s I}{N_s V_{ta}} \right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (1)$$

Where I_{pv} ($I_{pv,cell} N_p$) and I_0 ($I_{0,cell} N_p$) are the photovoltaic and saturation currents of the module consist of N_s cells connected in series and N_p cells connected in parallel and $V_t = kT/q$ is the thermal voltage of the PV cell. q is the charge of electron ($1.602 \cdot 10^{-19} C$), k is the Boltzmann constant ($1.3806503 \cdot 10^{-23} J/K$), T in Kelvin (K) is the temperature of junction and a is the diode ideality constant, whose range lies between 1 to 1.5. R_s [$r_s (N_s/N_p)$] and R_p [$r_p (N_s/N_p)$] are the equivalent series resistance and equivalent parallel resistance of the module respectively, where r_s and r_p denote the series and parallel resistance of PV cell. The I-V characteristic of PV module depends on the internal passive parameters of the device (R_s , R_p) as shown in eq.-1. Not only the I-V characteristic depends on internal passive parameters but also depend on the temperature and solar insolation (irradiance) level. The change of temperature and irradiance has an effect on the PV module according to the following equations [7]:

$$I_{pv} = [I_{pv,n} + K_i (T - T_n)] \frac{G}{G_n} \quad (2)$$

$$V_{oc} = [V_{oc,n} + K_v (T - T_n)] \quad (3)$$

Here the subscript n represents the nominal condition (usually $T_n = 25^\circ C$ and $G_n = 1000 W/m^2$). K_i the short-circuit current/temperature coefficient and K_v denote the open-circuit voltage/temperature coefficients of solar cell.

As shown in equation-2 the current level of solar cell depends on temperature and irradiance level of PV module. Voltage depends on temperature directly and in turn depends on irradiance level indirectly because of current dependent. Data sheets of PV module only inform three remarkable point, that is the short circuit

point $(0, I_{sc,n})$, Maximum power point $(V_{mp,n}, I_{mp,n})$ and open circuit point $(V_{oc,n}, 0)$ under nominal operating condition (usually 25°C and $1000\text{W}/\text{m}^2$). To draw the I-V characteristic as in Fig-2, the nominal saturation current is written as [3]:

$$I_{0,n} = \frac{I_{sc,n}}{\exp\left(\frac{V_{oc,n}}{a N_s V_{t,n}}\right) - 1} \quad (4)$$

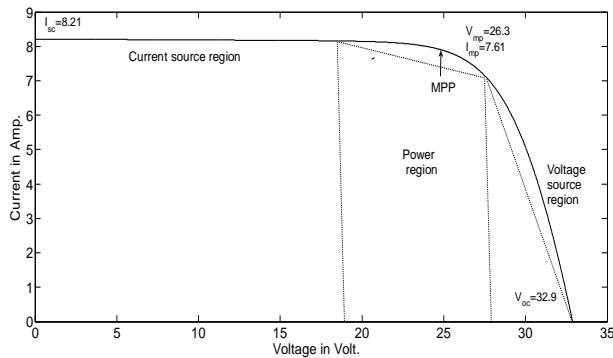


Figure 2. Characteristic I-V curve of PV module and the three remarkable points

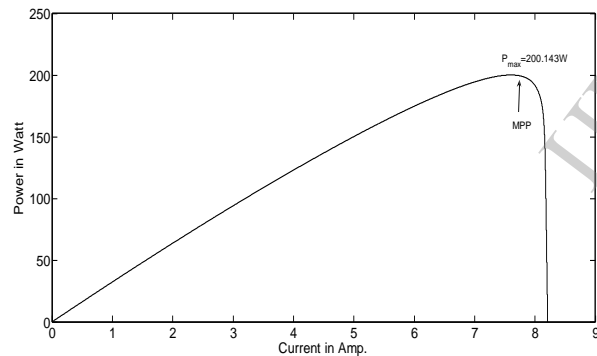


Figure 3. Characteristic P-I curve of PV module

As shown in Figure-2, the I-V characteristic is divided into three operating regions, such as voltage source region, power source region and current source region. To improve the MPP tracking of maximum power point, it is required to operate the MPP in power region and voltage region before tracking the maximum power point. The explanation of the above is explained in latter paragraph. The I-P curve is shown in Figure.3, which indicates that at one point the power of PV module is maximum. In order to examine the performance analysis and improve the dynamic performance the various parameters of PV cell must be known. By experiment in two different conditions, one at nominal condition and other at 30°C and $500\text{w}/\text{m}^2$,

the K_i and K_v are calculated. The values are found to be:

K_i	-0.1229V/K	By Expt.
K_v	0.0031 A/K	do

Table 1
Parameters of KC200G solar array at nominal 25°C , 1.5 AM, $1000\text{w}/\text{m}^2$

$I_{sc,n}$	8.21
$V_{oc,n}$	32.9
$V_{mp,n}$	26.3
$I_{mp,n}$	7.61
N_s	54

The other parameters are estimated by using different techniques given in different literatures. The equations are used as follows [3][6]:

$$I_{pv,n} = \frac{R_p + R_s}{R_p} I_{sc,n} \quad (5)$$

$$R_{p,min} = \frac{V_{mp,n}}{I_{sc,n} - I_{mp,n}} - \frac{V_{oc,n} - V_{mp,n}}{I_{mp,n}} \quad (6)$$

Rewriting equation (1) at the short circuit, open circuit and MPP points yield:

$$I_{sc,n} = I_{pv,n} - I_{0,n} \left[\exp\left(\frac{R_s I_{sc,n}}{N_s V_{t,n} a}\right) - 1 \right] - \frac{R_s I_{sc,n}}{R_p} \quad (7)$$

$$I_{pv,n} = I_{0,n} \left[\exp\left(\frac{V_{oc,n}}{N_s V_{t,n} a}\right) - 1 \right] + \frac{V_{oc,n}}{R_p} \quad (8)$$

$$I_{mp,n} = I_{pv,n} - I_{0,n} \left[\exp\left(\frac{V_{mp,n} + R_s I_{mp,n}}{N_s V_{t,n} a}\right) - 1 \right] - \frac{V_{mp,n} + R_s I_{mp,n}}{R_p} \quad (9)$$

Another three equations can be written by taking the derivative of three remarkable points[6]:

$$\left(\frac{dP}{dV}\right) \Big|_{(V = V_{mp,n})} = 0, \quad \left(\frac{dI}{dV}\right) \Big|_{(I = I_{sc,n})} = -\frac{1}{R_p}$$

and $\left(\frac{dI}{dV}\right) \Big|_{(V = V_{oc,n})} = -\frac{1}{R_s}$:

$$I_{mp,n} = V \left[\frac{I_0}{N_s a V_{t,n} \exp\left(\frac{V_{mp,n} + R_s I_{mp,n}}{N_s a V_{t,n}}\right) + \frac{1}{R_p}} \right] \quad (10)$$

$$\left[\frac{R_s I_0}{1 + N_s a V_{t,n} \exp\left(\frac{V_{mp,n} + R_s I_{mp,n}}{N_s a V_{t,n}}\right) + \frac{R_s}{R_p}} \right]$$

$$\frac{1}{R_p} = \frac{I_0}{N_s a V_{t,n}} \exp\left(\frac{R_s I_{sc,n}}{N_s V_{t,n} a}\right) + \frac{1}{R_p} \quad (11)$$

$$\frac{1}{R_s} = \frac{I_0}{N_s a V_{t,n}} \exp\left(\frac{V_{oc,n}}{N_s V_{t,n} a}\right) + \frac{1}{R_p} \quad (12)$$

The variations of I-V curve for different Rp and Rs are shown in Figures-(4, 5) and maximum power point in tabular forms in Table-2 and Table-3.

Table 2

R _s in Ohm	R _p in Ohm	V _{mp,n} in Volt	I _{mp,n} in Amp.	P _{max} in watt
0.221	415	26.3480	7.5956	200.1301
	500	26.3500	7.6051	200.3935
	800	26.3550	7.6220	200.8786

Table 3

R _p in Ohm	R _s in Ohm	V _{mp,n} in Volt	I _{mp,n} in Amp.	P _{max} in watt
415	.221	26.3480	7.5956	200.1301
	.24	26.2230	7.5904	199.0436
	.28	32.8990	7.7218	254.0396

The two parameters R_s and R_p are estimated using equation-1 and comparing the maximum power at different R_s and R_p with actual maximum power by incrementing R_s. The drawback of the method is that value of a is considered 1.3 before the iterative process starts. The other parameters (I_{pv,n}, I_{0,n}) are determined using the equations(4,5). The value of estimation is dependent upon the assumption of initial condition and also the chosen tolerance band for power. Furthermore it also depends on the increment of R_s. As shown in Figure-4, the change of value of R_p is modified the slope of current source region and also the power region, whereas the change of value of R_s is modified the slope of voltage source region and the power region. The change of power region and slope of current source region is very less with wide change of R_s as shown in table. Therefore the exact value of Rs is difficult to estimate by this method if chosen tolerance band is large. In this method the increment of Rp is not allowed because of the iterative solution may not be converged as R_s may exceed the value (greater than.28) where the slope at open circuit condition is infinity, which is confirmed by Figure-5.

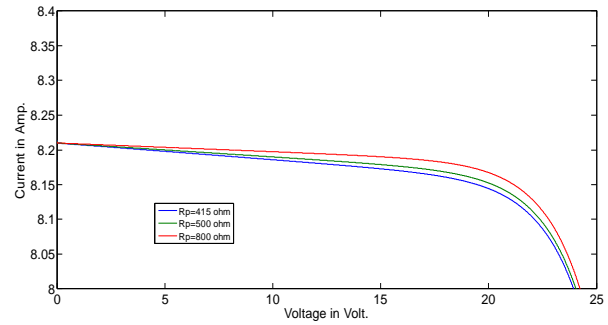


Figure 4. Partial representation of I-V curve of PV module at different values of R_p

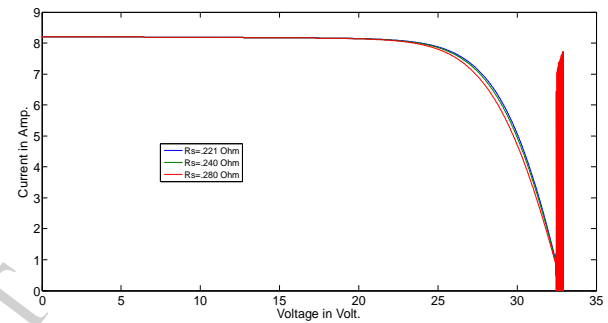


Figure 5. Characteristic of I-V curve of PV module at different values of R_s

Another method used in literature is trust-region-dogleg, which is used to solve the non-linear equations by fsolve in matlab command. The equations (7, 8, 9, 10, 11) are used. In this method the five unknown quantities are estimated. The accuracy of estimation is dependent on the initial conditions. Convergence rate depends on the initial conditions, tolerance band and the equations used in fsolve example. As for example, the estimation values are not converged, if the equation-12 is used instead of equation-11 in fsolve command. The main region is the slope at this point is more sensitive to move towards infinity. The author has verified the above two methods using the value of a=1.3 in first method. The results are shown in Table4 and Table-5.

Table 4

Tolerance=0.01	Tolerance=0.001	Remark
R _s =0.2173 Ohm	R _s =0.2246 Ohm	Estimated
R _p =370Ohm	R _p =483Ohm	do
I _{pv,n} =8.2148Ohm	I _{pv,n} =8.2138Amp.	Formula
I _{0,n} =9.8944.10 ⁻⁸ Ohm	I _{0,n} =9.8944.10 ⁻⁸ Amp.	do

Table 5

Initial	Initial values(.001,50,8,10 ⁻⁸)
---------	---

values(.001,40,8,10 ⁻⁷ ,1)	(,1)
R _s =0.260 Ohm	R _s =0.201 Ohm
R _p =462 Ohm	R _p =471 Ohm
I _{pv,n} =8.17 Amp.	I _{pv,n} =8.1637 Amp.
I _{0,n} =9.10 ⁻⁸ Amp.	I _{0,n} =9.10 ⁻⁸ Amp.
a=1.7655	a=1.7436

The exact values of unknown quantities can be found out using non linear curve fitting method. This method is based on non linear least square method using the experimental data. Hence exactness depends on the correctness of data. Detail comparative analysis of parameters estimation is explained in detail in another literature, which has submitted for publish.

3. Analysis of converter used in solar system

3.1. Selection of Proper dc-dc converter

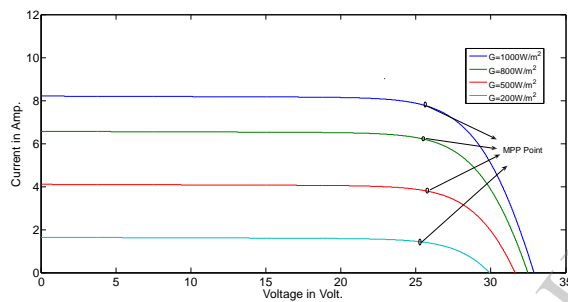


Figure 6. Simulated I-V curve of PV module influenced by different insolation levels with constant temperature of 25°C

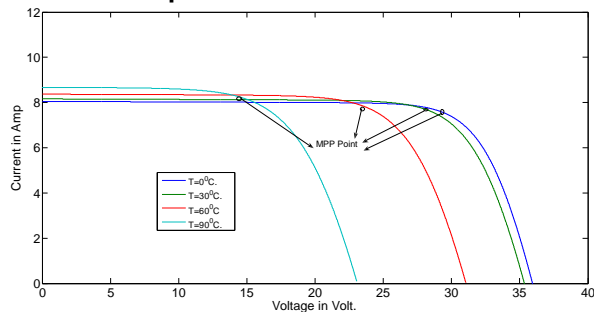


Figure 7. Simulated I-V curve of PV module influenced by different temperature levels with constant insolation of 1000W/m²

It is necessary to track the input voltage or current of PV module in such a way that power extracted from PV module is always maximum at any condition. The PV current at which maximum power occurs is highly

dependent on insolation level, but less dependent on temperature. The I-V characteristics for different insolation and temperature and are shown in Figure-6 and Figure-7. The fast dynamics of insolation is usually caused by a cover of mixed moving clouds. If the MPPT is used to track the current at the maximum power point, the MPP tracking requires fast dynamics to follow a wide operating range, depending on irradiance level which changes rapidly on weather condition. Nevertheless, the changing insolation slightly affects the voltage variation at MPP point as shown in fig. The cell temperature is the major factor for shifting the voltage at MPP point. Temperature poses slow dynamics as compared to insolation and therefore the MPPT is used to track the voltage at maximum power point. The variation of voltage is usually bounded by 70% to 80% of the open circuit voltage under any condition of temperature and insolation. This is the deciding criteria for choosing of proper dc-dc converter depending upon the battery used at output terminals of converter. The stand-alone mode of solar module using dc-dc buck converter is shown in Figure- 8. The MPPT control procedure is shown in Figure-9.

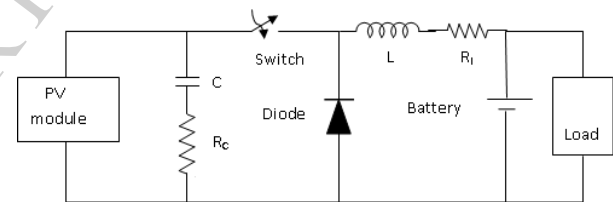


Figure 8. Circuit diagram of dc-dc buck converter in stand-alone mode

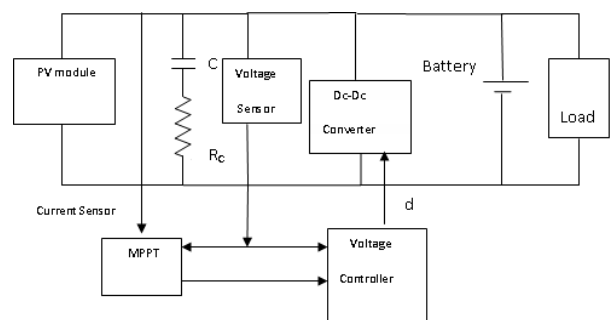


Figure 9. Block diagram for regulate of PV voltage at maximum power point through MPPT

- If the battery voltage is below the 70% of the open circuit voltage the buck converter can be used for transfer of the power.

- If the battery voltage is above the 70% of the open circuit voltage the boost converter can be used for transfer of the power.

- Buck-Boost converter is used for any range of battery voltage rating.

3.2. Capacitor requirement and determination of its value

A buck dc-dc converter has a discontinuous input current and a continuous output current. On the contrary, a boost converter has a continuous input current and a discontinuous output current. In order to flow the continuous PV current at maximum power point the capacitor must be connected in shunt to PV cell in buck dc-dc converter, so that the current will flow through the capacitor during the switch off period. Other capacitor at output may be connected for filter purpose. The value of capacitor depend upon the battery voltage ,the worst case of the PV current at MPP, open circuit voltage of PV, change of V_{mp} during switching off period and switching frequency.

Let the battery voltage is V , which is less than the 70% of the open circuit voltage and the PV current at maximum tracking point is $I_{mp,wg}$ in worst case of insolation.

$$D = \frac{V}{.7V_{oc}}$$

$$C = \frac{I_{mp,wg} (1-D)T_s}{\Delta(.7V_{oc})} \tag{13}$$

where D is the duty ratio and T_s is the switching frequency. The value of capacitor is calculated using eq-(13).

3.3.Dynamic resistance and its impact on MPP tracking[1]

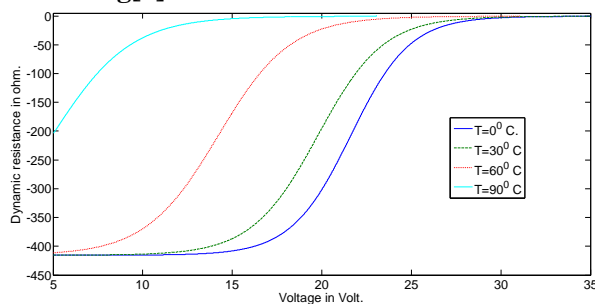


Figure 10. Dynamic resistance with change in PV voltage for different levels of module temperature

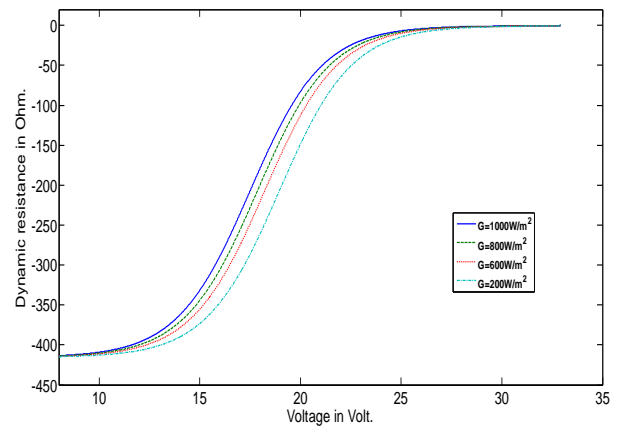


Figure 11. Dynamic resistance with change in PV voltage for different levels of module insolation

The characteristic of PV modules are nonlinear and time variant due to rapid change of insolation level. Due to nonlinearity, the ratio of the voltage across the PV module to the current through it varies with either the voltage or current. The ratio of change in voltage to change in current is known as dynamic resistance. The dynamic resistance remains constant in voltage source region due to linearity of I-V curve of PV module, whereas it remains approximately constant in power region. The wide variation of dynamic resistance in current source region makes it difficult to track the maximum power point, if the MPPT operates in current source range. The dynamic resistance of PV module is negative although the static resistance of the circuit element is defined as positive. To improve the MPP tracking and the design of feedback controller to regulate the PV voltage through dc-dc converter, it is important to understand the distribution of dynamic resistance at the MPPs regarding different temperature and insolation. Dynamic resistances with respect to PV voltage at different levels of temperature module and different insolation level are shown in Figure-10 and Figure-11 respectively. From the Figures (10, 11) it is clear that their amplitudes increase with decreasing module temperature or with decreasing insolation. The largest amplitude occurs when the insolation and temperature both are at lowest level. Unlike the control of output of dc-dc converter with fixed dc input voltage, the controller design of PV module is difficult and need more attention for achieving stability in all region of PV curve due to large variation of current and large change of dynamic resistance with the variation of insolation and temperature level.

4. Conclusion

The two methods for extraction of parameters are compared. The methods explained in this paper are not free from error. The causes of error are explained in detail. The curve fitting method is the one of the choice for exact estimation of parameters, if exact data is available by experiment. The change of the characteristic of I-V curve of PV module with change of temperature and insolation level is explained in detail. The impact of change of current due to change in insolation level in PV module is more than the change of temperature. Furthermore, the change of insolation possesses fast dynamic compared to change in temperature. For this reason, the output of MPPT must be voltage at which the PV module has maximum power. A capacitor must be connected in parallel to PV module before the dc-dc converter to transfer the power to load through battery or synchronization of the PV module to grid. The value of capacitor is calculated in worst case condition. The choice of different types of dc-dc converters depends on battery voltage is explained in detail.

5. References

- [1] W.Xiao , W.G.Dunford , P.R. Palmer, A. Capel: "Regulation of photovoltaic voltage", *IEEE Trans. Ind. Electron.*, 2007, 54, (3), pp. 1365–1374.
- [2] M.G.Villalva, J.R. Gazoli, E.F.Ruppert: "Comprehensive approach to modeling and simulation of photovoltaic arrays", *IEEE Trans. Power Electron.*, 2009, 25, (5), pp. 1198–1208.
- [3] M.G.Villalva, J.R. Gazoli, E.F.Ruppert: "Modeling and circuit-based simulation of photovoltaic arrays", *Revista Eletro`nica de Pot`ncia (SOBRAEP), Brazilian J. Power Electron.*, 2009, 14, pp. 35–45.
- [4] M.G.Villalva, T.G De Siqueira, E.Ruppert : "Voltage regulation of photovoltaic arrays: small-signal analysis and control design", *IET Power electron.*, 2010, Vol.3, Iss. 6, pp. 869–880.
- [5] Ghias Farivar, Behzad Asaei: "Photovoltaic Module Single diode Model Parameters Extraction Based on Manufacturer Datasheet Parameters" *IEEE Int. Conf. Power and energy (PECon 2010)*, Nov 29-Dec 1, 2010, Kuala Lumpur, Malaysia, pp. 929–934.
- [6] D. Sera, R. Teodorescu, and P. Rodriguez, "PV panel model based on datasheet values," in *Proc. IEEE Int. Symp. Ind. Electron. (ISIE)*, 2007, pp. 2392–2396.
- [7] Ayedh H.ALQahtani, "A Simplified and Accurate Photovoltaic Module Parameters Extraction Approach using Matlab," *IEEE 2012*, pp. 1748–1753.
- [8] B.Subidhi, R.Pradhan, "A comparative study on solar array parameter extraction methods" *Inderscience, Int.J. Renewable Energy Technology*, vol 3, No 3, 2012, pp. 295–315.
- [9] Ye Zhihao, Wu Xiaobo: "Compensation loop design of a photovoltaic system based on constant voltage MPPT". *Power and Energy Engineering Conf.*, 2009, APPEEC 2009, Asia-Pacific, 27–31 March 2009, pp. 1–4
- [10] D. Chan and J. Phang, "Analytical methods for the extraction of solar cell single- and double-diode model parameters from i-v characteristics," *Electron Devices, IEEE Transactions on*, vol. 34, no. 2, 1987, pp. 286–293.

IJERT