Appendix A

A.1 Model Description of ACPPVC-50

A photovoltaic system is basically a large p-n junction i.e. its current shunting behaviour can be approximated with a diode. Therefore the PV element acts as a photo generator along with a diode in parallel. In addition, a resistor (called series resistance i.e. R_s) is added into series to account for the ohmic losses in the PV. Another resistor (called shunt resistance i.e. R_{sh}) can be added in order to measure the voltage drop across the PV. The equivalent circuit of a single PV generator is shown in figure A.1.1.

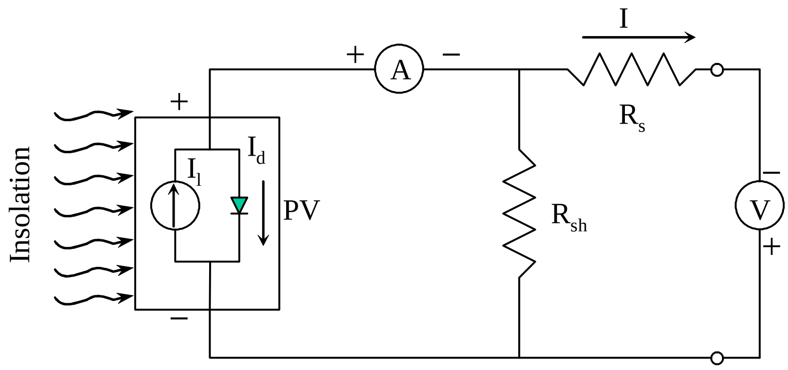

Figure A.1.1 Circuit diagram for determining I-V characteristics of a photovoltaic system.

The basic current voltage relationship of figure A.1.1 can be expressed as;

$$I = I_L - I_0\left\{\exp\left[\frac{q(V+IR_s)}{AkT_{ct}}\right]-1\right\}-\frac{V+IR_s}{R_{sh}} \tag{A.1}$$

where a shunt resistance has been introduced in parallel to the diode resistance.

Differentiating equation (A.1) with respect to voltage

$$\frac{dI}{dV} = -I_0\frac{q}{AkT_{ct}}\left(1+\frac{dI}{dV}R_s\right)\left\{\exp\left[\frac{q(V+IR_s)}{AkT_{ct}}\right]\right\}-\left(\frac{1+\frac{dI}{dV}R_s}{R_{sh}}\right) \tag{A.2}$$

The simulated parameters are defined as shown in figure A.1.2.

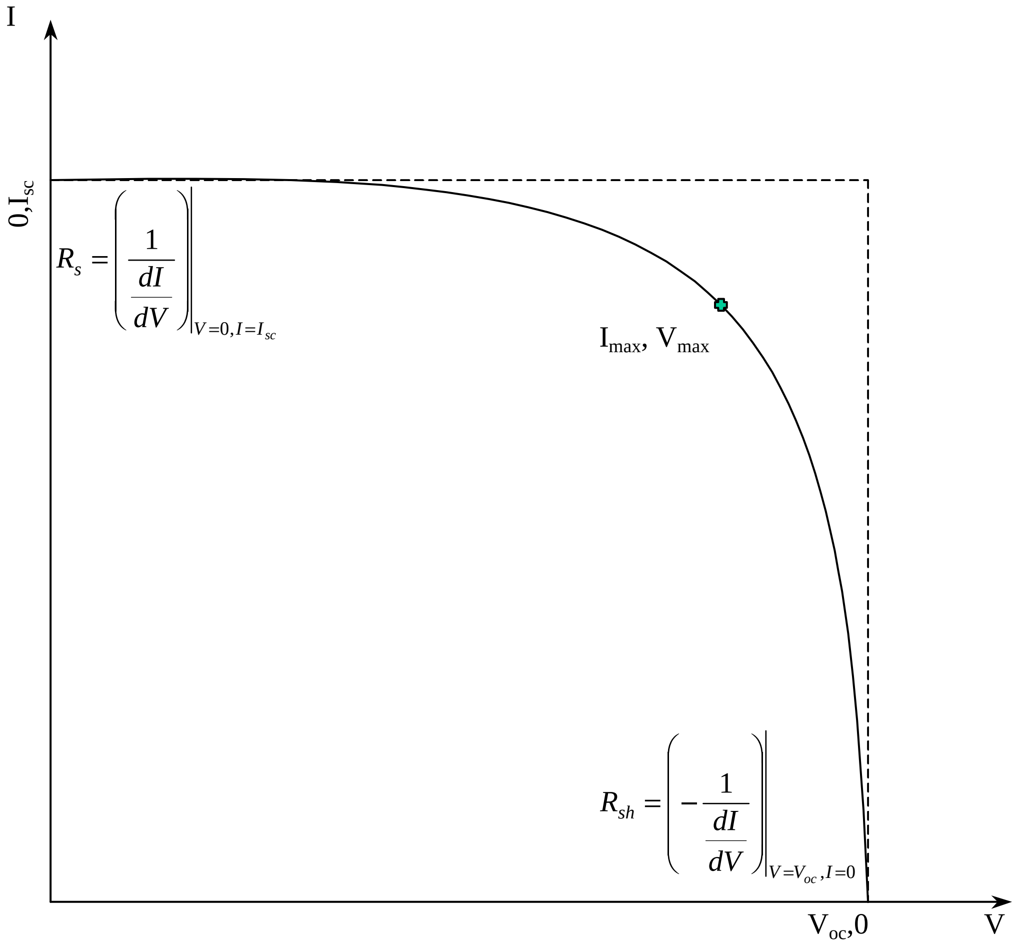

Figure A.1.2 I-V curve for the electrical simulation of a photovoltaic system.

Setting V=0 and $I=I_{sc,ref}$ the above equation becomes

$$\left.\frac{dI}{dV}\right|_{V=0} = -I_0 \frac{q}{AkT_{ct}}\left(1+\left.\frac{dI}{dV}\right|_{V=0} R_s\right)\left\{\exp\left[\frac{q\left(I_{sc,ref}R_s\right)}{AkT_{ct}}\right]\right\} - \left(\frac{1+\left.\frac{dI}{dV}\right|_{V=0} R_s}{R_{sh}}\right) \tag{A.1.3}$$

simplifying the above equations and replacing m by $\left.\frac{dI}{dV}\right|_{V=0}$

$$m = -I_0 \frac{q}{AkT_{ct}}\left(1+mR_s\right)\left\{\exp\left[\frac{q\left(I_{sc,ref}R_s\right)}{AkT_{ct}}\right]\right\} - \left(\frac{1+mR_s}{R_{sh}}\right) \qquad i.e. \tag{A.1.4}$$

$$R_{sh} = \frac{-\left(1+mR_s\right)}{m + I_0 \frac{q}{AkT_{ct}}\left(1+mR_s\right)\exp\left[\frac{q}{AkT_{ct}}\left(I_{sc,ref}R_s\right)\right]} \tag{A.1.5}$$

The shunt resistance can be approximated as (Rauchenbach, 1980)

$$R_{sh} \approx \frac{-1}{\left(\frac{dI}{dV}\right)_{V=0}} \tag{A.1.6}$$

Applying the open circuit voltage (i.e. I_{sc}=0), short circuit current (i.e. V_{oc}=0) and maximum power point conditions equation (A.1.1) becomes

$$0 = I_{L,ref} - I_0\left\{\exp\left[\frac{q}{AkT_{ct,ref}}V_{oc,ref}\right]-1\right\} - \frac{V_{oc,ref}}{R_{sh}} \tag{A.1.7}$$

$$I_{sc,ref} = I_{L,ref} - I_0\left\{\exp\left[\frac{q}{AkT_{ct,ref}}I_{sc,ref}R_s\right]-1\right\} - \frac{I_{sc,ref}R_s}{R_{sh}} \tag{A.1.8}$$

$$I_{mp,ref} = I_{L,ref} - I_0\left\{\exp\left[\frac{q}{AkT_{ct,ref}}\left(V_{mp,ref}+I_{mp,ref}R_s\right)\right]-1\right\} - \frac{\left(V_{mp,ref}+I_{mp,ref}R_s\right)}{R_{sh}} \tag{A.1.9}$$

at maximum power point the maximum power becomes

$$P = IV \equiv I_{L,ref}V - I_0V\left\{\exp\left[\frac{q}{AkT_{ct,ref}}\left(V+IR_s\right)\right]-1\right\} - V\frac{\left(V+IR_s\right)}{R_{sh}} \tag{A.1.10}$$

At maximum power point the following condition can be implemented into the equation (A.1.10)

- $$\left(\frac{dP}{dV}\right)_{V_{\max}=V_{\max,ref}} = 0 \tag{A.1.11}$$
- $$\left(\frac{d^2P}{dV^2}\right)_{V_{\max}=V_{\max,ref}} \prec 0 \tag{A.1.12}$$

Applying equation (A.1.11)) into equation (A.1.9) becomes

$$\left.\frac{dP}{dV}\right|_{V=V_{\max}} = \left(I + V\frac{dI}{dV}\right) \equiv 0 \quad i.e.\ \left.\frac{dI}{dV}\right|_{V=V_{\max}} = -\frac{I_{\max}}{V_{\max}} \tag{A.1.13}$$

Simplying equation (A.1.2), the coefficient of $\frac{dI}{dV}$ becomes

$$\frac{dI}{dV}\left(1+\frac{R_s}{R_{sh}}+I_0\frac{q}{AkT_{ct}}R_s\exp\left[\frac{q\left(V+IR_s\right)}{AkT_{ct}}\right]\right) = -\left(1+I_0\frac{q}{AkT_{ct}}\exp\left[\frac{q\left(V+IR_s\right)}{AkT_{ct}}\right]\right) \tag{A.1.14}$$

i.e.

$$\frac{dI}{dV} = -\frac{\left(1+I_0\frac{q}{AkT_{ct}}\exp\left[\frac{q\left(V+IR_s\right)}{AkT_{ct}}\right]\right)}{\left(1+\frac{R_s}{R_{sh}}+I_0\frac{q}{AkT_{ct}}R_s\exp\left[\frac{q\left(V+IR_s\right)}{AkT_{ct}}\right]\right)} \tag{A.1.15}$$

therefore from equation (A.1.12) and (A.1.13) the maximum power point equation becomes

$$\frac{I_{\max,ref}}{V_{\max,ref}} = \frac{\left(1+I_0\frac{q}{AkT_{ct,ref}}\exp\left[\frac{q\left(V_{\max,ref}+I_{\max,ref}R_s\right)}{AkT_{ct,ref}}\right]\right)}{\left(1+\frac{R_s}{R_{sh}}+I_0\frac{q}{AkT_{ct,ref}}R_s\exp\left[\frac{q\left(V_{\max,ref}+I_{\max,ref}R_s\right)}{AkT_{ct,ref}}\right]\right)} \tag{A.1.16}$$

therefore final four equation for solving I-V equation are

$$0 = I_{L,ref} - I_0\left\{\exp\left[\frac{q}{AkT_{ct,ref}}V_{oc,ref}\right]-1\right\}-\frac{V_{oc,ref}}{R_{sh}} \tag{A.1.17}$$

$$I_{sc,ref} = I_{L,ref} - I_0\left\{\exp\left[\frac{q}{AkT_{ct,ref}}I_{sc,ref}R_s\right]-1\right\}-\frac{I_{sc,ref}R_s}{R_{sh}} \tag{A.1.18}$$

$$I_{mp,ref} = I_{L,ref} - I_0\left\{\exp\left[\frac{q}{AkT_{ct,ref}}\left(V_{mp,ref}+I_{mp,ref}R_s\right)\right]-1\right\}-\frac{\left(V_{mp,ref}+I_{mp,ref}R_s\right)}{R_{sh}} \tag{A.1.19}$$

$$\frac{I_{\max,ref}}{V_{\max,ref}} = \frac{\left(1+I_0\dfrac{q}{AkT_{ct,ref}}\exp\left[\dfrac{q\left(V_{\max,ref}+I_{\max,ref}R_s\right)}{AkT_{ct,ref}}\right]\right)}{\left(1+\dfrac{R_s}{R_{sh}}+I_0\dfrac{q}{AkT_{ct,ref}}R_s\exp\left[\dfrac{q\left(V_{\max,ref}+I_{\max,ref}R_s\right)}{AkT_{ct,ref}}\right]\right)} \tag{A.1.20}$$

A.2 Numerical Solution of the Model

The set of non-linear equations in the PV model were solved using the Newton-Raphson method. Initial R_s value was considered as 0.1Ω and R_{sh} was considered as 100Ω, the subsequent parameters were calculated by using the equation below

$$\left(I_{\max},V_{\max},A\right)_{new} = \left(I_{\max},V_{\max},A\right)_{old} - \frac{F\left(I_{\max},V_{\max},A\right)_{old}}{F'\left(I_{\max},V_{\max},A\right)_{old}} \tag{A.2.1}$$

A new set of values $\left(I_{\max},V_{\max},A\right)_{new}$ were calculated from the established value of R_s and R_{sh}, the new values of R_s and R_{sh} were calculated from:

$$\left(R_s,R_{sh}\right)_{new} = \left(R_s,R_{sh}\right)_{old} - \frac{F\left(R_s,R_{sh}\right)_{old}}{F'\left(R_s,R_{sh}\right)_{old}} \tag{A.2.2}$$

The equations (A.2.1) and (A.2.2) were solved iteratively until a converged solution was achieved.