



CHAPTER III

MODELING OF GRID-CONNECTED PHOTOVOLTAIC SYSTEM

3.1 Photovoltaic Modeling

For this research work, a model of moderate complexity was used based on [16], [17] and shown in figure 3-1. The model includes temperature dependence of the photocurrent I_{ph} and the saturation current of the diode I_0 . A series resistance R_s was included, but not a shunt resistance. A single shunt diode was used with the diode quality factor set to achieve the best curve match.

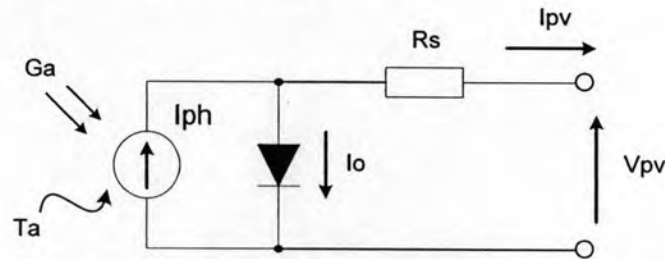


Figure 3-1 The equivalent circuit of the PV cell model

The equations which describe the I-V characteristics of the cell are as follows:

$$I_{pv} = I_{ph} - I_0 \left(e^{\frac{q(V_{pv} + I_{pv}R_s)}{nkT_a}} - 1 \right) \quad (3-1)$$

$$I_{ph} = I_{ph(T_1)} [1 + K_0(T_a - T_1)] \quad (3-2)$$

$$I_{ph(T_1)} = G_a \times (I_{sc(T_1, nom)} / G_{a(nom)}) \quad (3-3)$$

$$K_0 = (I_{sc(T_2)} - I_{sc(T_1)}) / (T_2 - T_1) \quad (3-4)$$

$$I_0 = I_{0(T_1)} \times (T_a / T_1)^{3/n} \times e^{(-qV_g / nk) \times (1/T_a - 1/T_1)} \quad (3-5)$$

$$I_{0(T_1)} = I_{sc(T_1)} / (e^{qV_{oc(T_1)} / nkT_1} - 1) \quad (3-6)$$

where q : Electron charge (Coulomb), equals $1.6 \cdot 10^{-19}$

k : Boltzmann constant (J/K), equals $1.38 \cdot 10^{-23}$

n : Diode quality factor, it takes a value between 1 and 2

T_1, T_2 : Reference temperature at T_1 and T_2 ($^{\circ}C$)

T_a : Cell operating temperature ($^{\circ}\text{C}$)

$I_{ph}(T_1)$: Photocurrent at temperature T_1 (A)

I_{ph} : Photocurrent, function of irradiation level and junction temperature (A)

G_a : Ambient irradiance (W/m^2)

$G_a(nom)$: Base value irradiance (W/m^2)

$I_{sc}(T_1, nom)$: Base value short-circuit current at temperature T_1 (A)

$I_{sc}(T_1), I_{sc}(T_2)$: Short-circuit current at temperature T_1 and T_2 (A)

K_0 : Rate of change in short-circuit current between temperature T_1 and T_2

I_0 : Reverse saturation current of diode (A)

$I_0(T_1)$: Reverse saturation current of diode at temperature T_1 (A)

I_{pv} : Cell output current (A)

R_s : Series resistance of cell (Ω)

V_{pv} : Cell output voltage (V)

The photo-current I_{ph} is directly proportional to irradiance G_a . When the cell is short-circuited, current flow in the diode is negligible. Hence the proportionality constant in equation 3-3 is set so the rated short-circuit current I_{sc} is delivered under rated irradiation. The relationship between the photo-current and temperature is linear shown in equation 3-2 and is reduced by noting the change of photo-current with the change of temperature as shown in equation 3-4. When the cell is not illuminated, the relationship between the cell's terminal voltage and current is given by the Shockley equation. When the cell is open circuited and illuminated, the photo-current flows entirely in the diode. The I-V curve is offset from the origin by the photo generated current I_{ph} shown in equation 3-1. The value of the saturation current I_0 at 25°C is calculated using the open circuit voltage and short-circuit current at this temperature shown in equation 3-6. The relationship of I_0 to temperature is more complex, but fortunately it contains no variables requiring evaluation shown in equation 3-5. The value of diode quality factor n depends on the material type of photovoltaic cell; it is between 1 and 2. In generally, the value of diode quality factor $n = 2$ for crystalline silicon and $n < 2$ for amorphous silicon PV cell. However, an estimate must be made of this unknown parameter. A value of 1.2 is suggested as typical in normal operation

of the model validation for the 80W Sharp PV module. This value may be used initially until a more accurate value is estimated later through curve fitting.

For the series resistance R_s of PV cell, it can be obtained using only manufacturer supplied data for the PV modules at standard test conditions (STC), such as open-circuit voltage V_{oc} , short-circuit current I_{sc} and maximum power P_m . The equations which are used to evaluate the value of R_s are presented as following [18], [19]:

$$V_{t, stc}^c = \frac{nkT_{c, stc}}{q} \quad (3-7)$$

$$v_{oc, stc} = \frac{V_{oc, stc}^c}{V_{t, stc}^c} \quad (3-8)$$

$$FF_0 = [v_{oc, stc} - \ln(v_{oc, stc} + 0.72)] / (v_{oc, stc} + 1) \quad (3-9)$$

$$FF = P_{m, stc}^c / (V_{oc, stc}^c \times I_{sc, stc}^c) \quad (3-10)$$

$$r_s = 1 - (FF / FF_0) \quad (3-11)$$

$$R_s^c = r_s \times (V_{oc, stc}^c / I_{sc, stc}^c) \quad (3-12)$$

where $V_{t, stc}^c$: Thermal voltage of a single cell at STC

$T_{c, stc}$: Cell temperature at STC (25 °C)

$V_{oc, stc}^c$: Open-circuit voltage of a single cell at STC

$I_{sc, stc}^c$: Short-circuit current of a single cell at STC

$P_{m, stc}^c$: Maximum power of a single cell at STC

R_s^c : Series resistance of a single cell

Since cells vary in temperature not only because ambient temperatures change, but also because irradiation on the cells changes. To help the researcher account for changes in cell performance with temperature, manufacturers often provide a normal operating cell temperature (NOCT) indicator where NOCT is cell temperature in a module when ambient is 20 °C, solar irradiation is 800 W/m², and wind speed is 1 m/s. The value of NOCT for modules currently on the market varies from about 42 to

46 °C [6]. To account for other ambient conditions, the following equation may be used [2]:

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20^{\circ}C}{800} \right) \cdot G_a \quad (3-13)$$

where T_{cell} : cell temperature ($^{\circ}C$)

T_{amb} : ambient temperature

G_a : solar irradiation (W/m^2)

Normally, cells are grouped in to “modules”, which are encapsulated with various materials to protect the cells and the electrical connectors from the environment. The manufacturers supply PV cells in modules, consisting of N_{PM} parallel branches, each with N_{SM} solar cells in series. In order to develop the PV module model, the cell output voltage V_{pv} is then multiplied by the number of the cells connected in series N_{SM} to calculate the full module voltage V^M , they all have the same voltage in each parallel branches. In the same way, the cell output current I_{pv} is then multiplied by the number of branches connected in parallel N_{PM} to obtain the full module current I^M , they all carry the same current in series each branches.

3.2 Implementation in MATLAB-SIMULINK

SIMULINK is a simulation program, which provides a graphical interface for building models as blocks diagrams. It offers to build hierarchical models, to view the system at different levels, and be able to build modular models which can be easily connected together system in order to do the simulation. From the section 3.1, the mathematic equations for PV characteristic modeling could be implemented in MATLAB-SIMULINK shown in figure 3-2 and form into block diagram in figure 3-3.

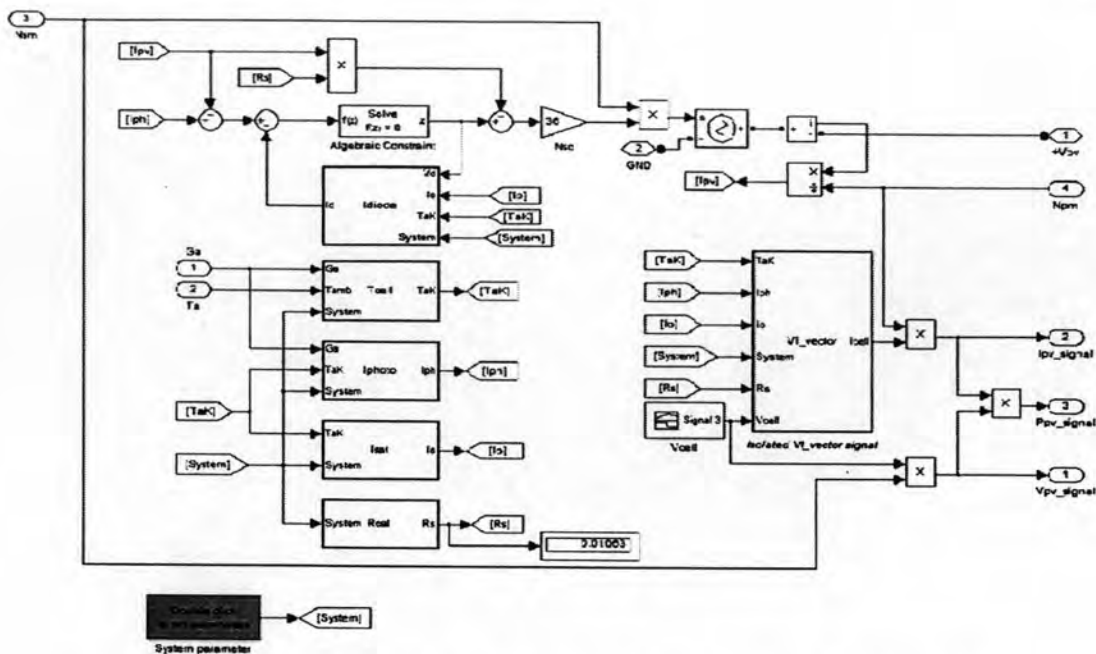


Figure 3-2 Implementation of PV characteristic modeling in SIMULINK

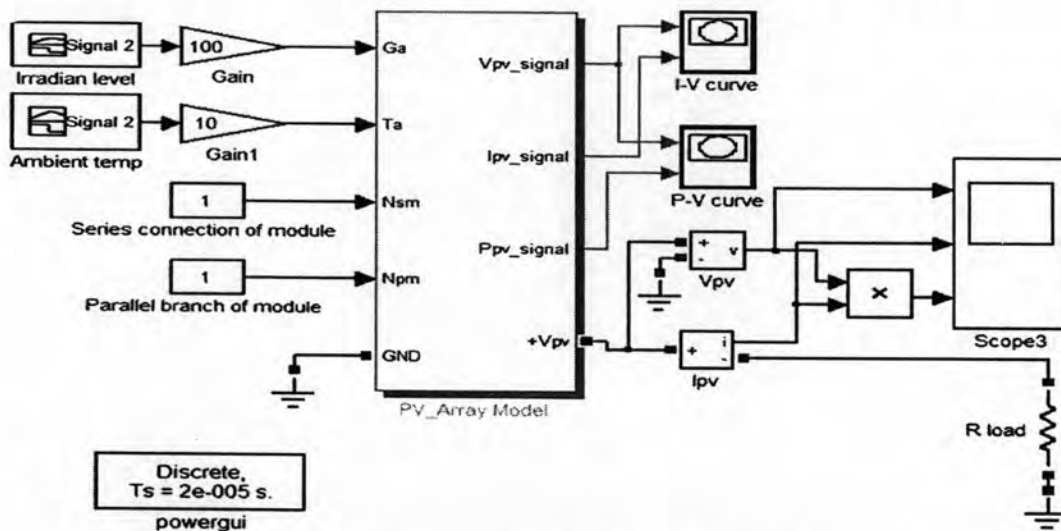


Figure 3-3 PV characteristic modeling forming in block diagram

The PV model developed in MATLAB-SIMULINK is used to simulate I-V and P-V characteristics. There are four important inputs: 1) irradiance and cell temperature, 2) the number in series and parallel of PV modules to scale up the output power, 3) voltage, and 4) current required in PV model design which contains necessary equations listed in section 3.1 to calculate the cell current I_{pv} and establish the I-V characteristic and also P-V characteristic curve by changing the terminal output cell voltage V_{pv} .

Figures 3-4 and 3-5 illustrate the example of I-V characteristic and P-V characteristic with constant ambient temperature and some various irradiances from 250-1000 W/m² of 80W Sharp PV module shown in Table 3-1. Figures 3-6 and 3.7 illustrate I-V and P-V characteristic while the irradiance is constant at 1000 W/m² and some various ambient temperatures from 0-75 °C.

TABLE 3-1 80W SHARP PV PARAMETER

Maximum Power	P_{max}	80W
Maximum Current	I_m	5.14A
Maximum Voltage	V_m	17.1V
Short Circuit Current	I_{sc}	5.16A
Open Circuit Voltage	V_{oc}	21.3V

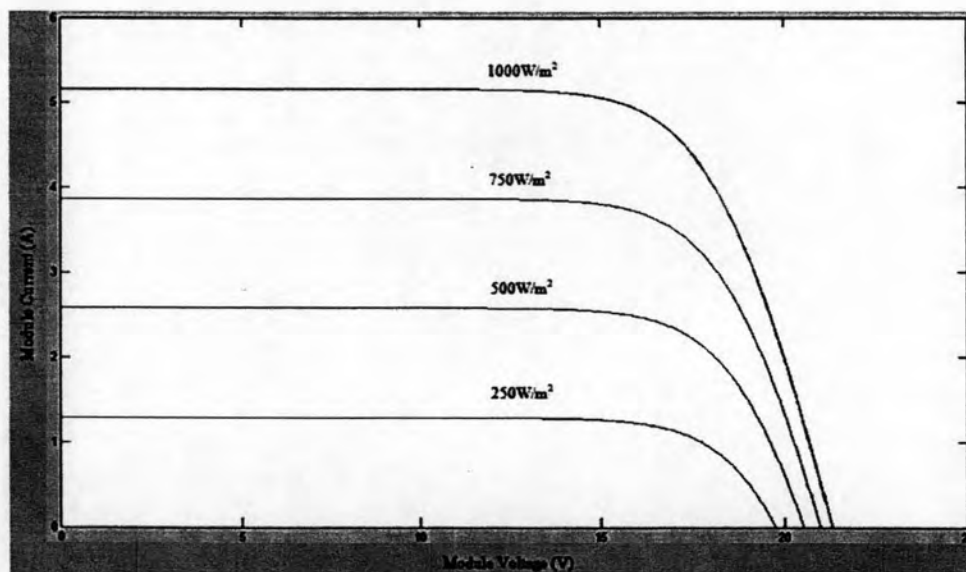


Figure 3-4 I-V characteristic with constant ambient temperature and various irradiances

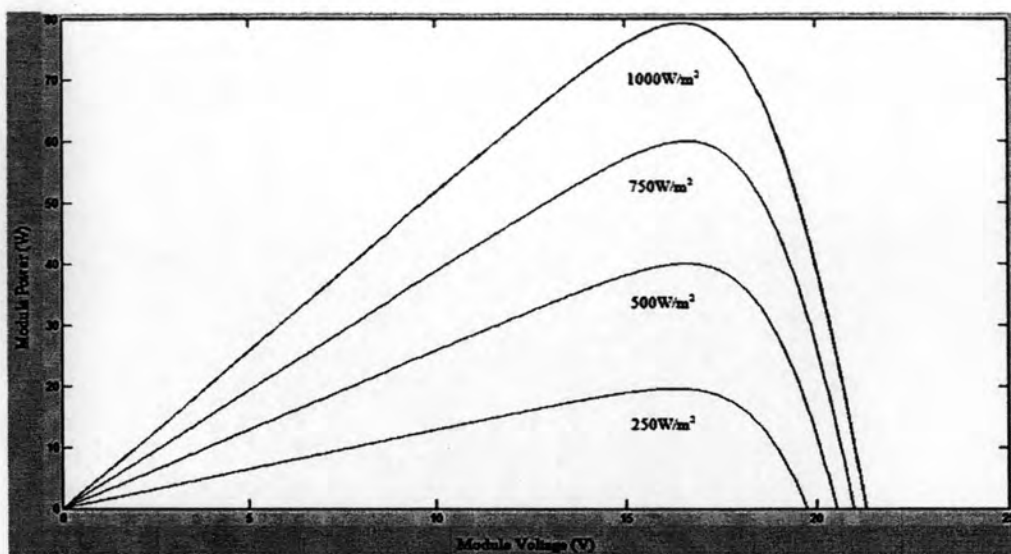


Figure 3-5 P-V characteristic with constant ambient temperature and various irradiances

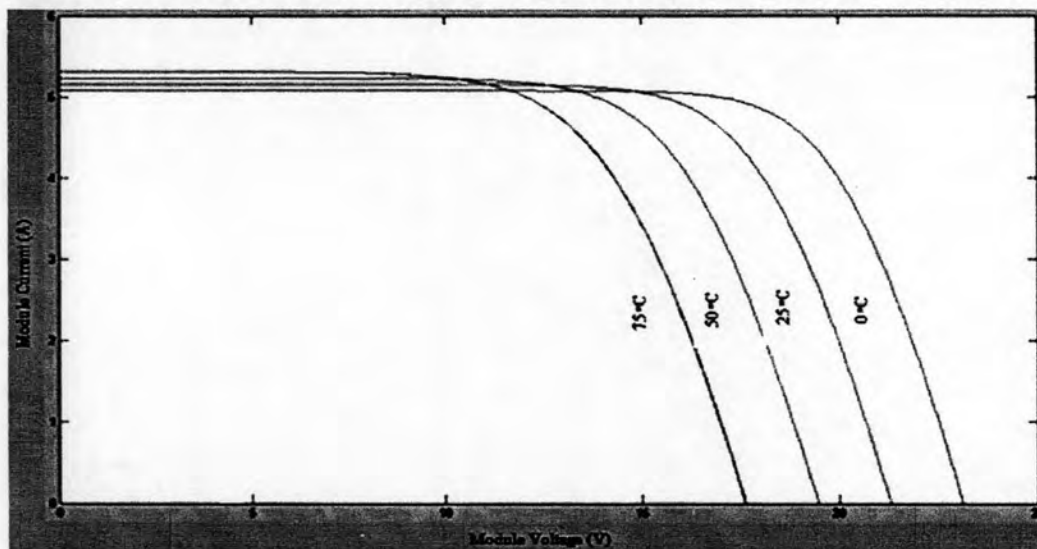


Figure 3-6 I-V characteristic with constant irradiance and various ambient temperatures

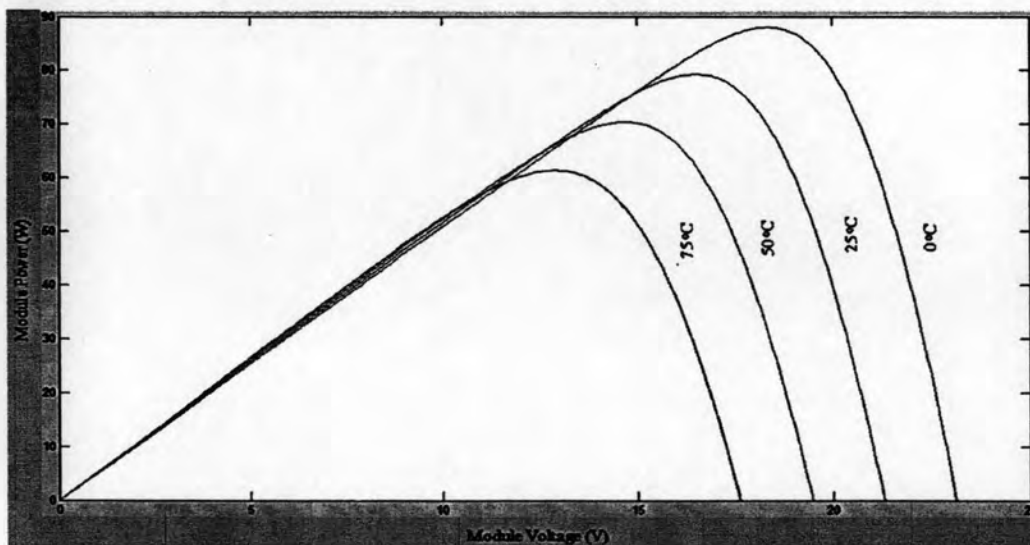


Figure 3-7 P-V characteristic with constant irradiance and various ambient temperatures

Figure 3-4 shows that the open-circuit voltage increases logarithmically with the ambient irradiation, while the short-circuit current is a linear function of the ambient irradiation. Figure 3-6 is the influence of the cell temperature on the I-V characteristic; increasing cell temperature will linearly decrease of the open-circuit voltage, the cell being thus less efficient while the short-circuit current slightly increases with cell temperature.

In order to test the PV model, some results are carried out by verifying with the actual work supported by National Science and Technology Development Agency (NSTDA) of Thailand. I-V Checker MP-140 shown in figure 3-8 and other three meters are used to measure the characteristic of Sharp PV module as shown in table 3-1. The sun irradiance, ambient temperature, and the voltage from the PV module are recorded by a pyranometer, thermometer, and voltmeter respectively.



Figure 3-8 P-V characteristic with various ambient temperatures

Table 3-2 illustrates the comparison result between the PV model simulation and those measured from the IV-Checker MP-140 at high irradiance, 1025.3 W/m^2 and temperature at $36.4 \text{ }^\circ\text{C}$, medium irradiance, 600.6 W/m^2 and temperature at $30.91 \text{ }^\circ\text{C}$,

and low irradiance, 205.1 W/m^2 and temperature at $33.80 \text{ }^\circ\text{C}$. Model results agree rather well with actual measurements. Figures 3-9, 3-10 and 3-11 are the I-V and P-V characteristic of Sharp PV module that measured from I-V Checker MP-140 and simulates in MATLAB-SIMULINK, at irradiance, 600.6 W/m^2 and temperature at $30.91 \text{ }^\circ\text{C}$ respectively.

TABLE 3-2 COMPARISON RESULT OF PV MODEL SIMULATION VIA I-V CHECKER MP-140

Irradiance	1025.3 W/m^2 and $36.04 \text{ }^\circ\text{C}$			600.6 W/m^2 and $30.91 \text{ }^\circ\text{C}$			205.1 W/m^2 and $33.8 \text{ }^\circ\text{C}$		
	Simulation	MP-140	% Error	Simulation	MP-140	% Error	Simulation	MP-140	% Error
Isc (A)	5.411	5.619	3.7	3.14	3.149	0.29	1.067	1.101	3.07
Voc (V)	18.5	19.18	3.55	18.71	19.51	4.1	17.34	17.5	0.91
Pm (W)	67.86	69.66	2.58	40.58	42.55	4.63	12.6	13.5	6.67
Ipm (A)	4.746	4.979	4.68	2.78	2.842	2.18	0.941	0.969	2.92
Vpm (A)	14.3	13.99	2.22	14.6	14.97	2.47	13.4	13.93	3.8
Fill Factor	0.6778	0.6465	4.84	0.6907	0.6925	0.26	0.681	0.7011	2.82

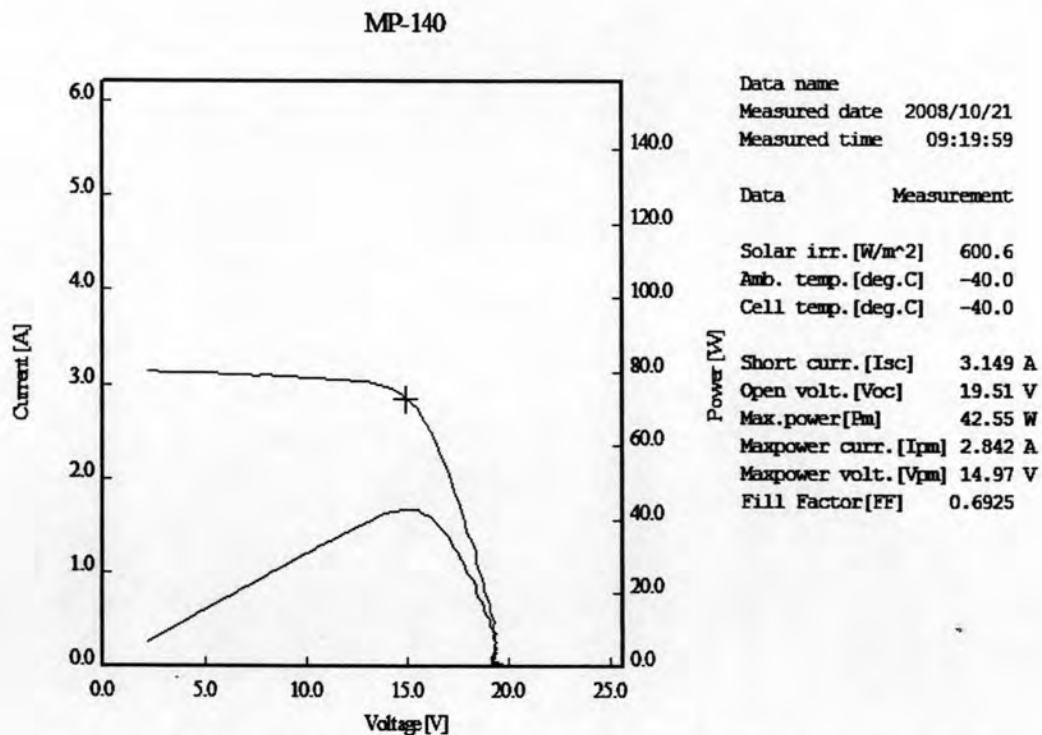


Figure 3-9 I-V and P-V characteristic with $G_a = 600.6 \text{ W/m}^2$, and $T_a = 30.91 \text{ }^\circ\text{C}$

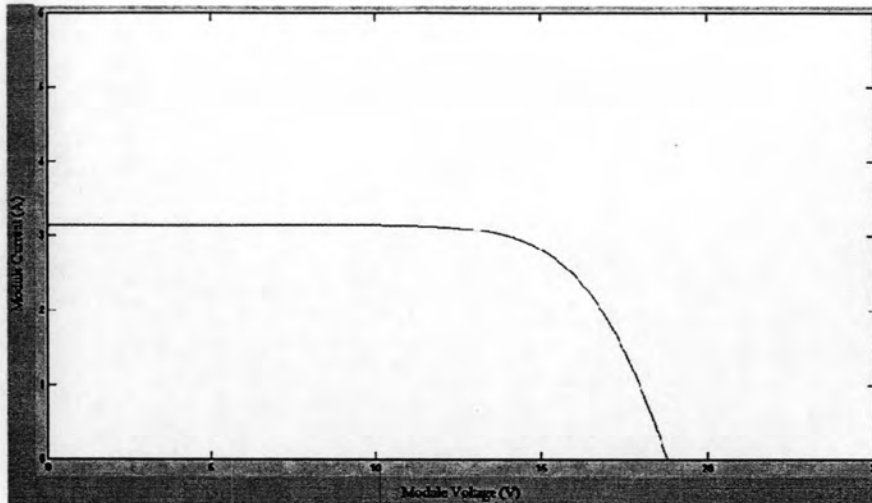


Figure 3-10 I-V characteristic with $G_a = 600.6 \text{ W/m}^2$, and $T_a = 30.91 \text{ }^\circ\text{C}$

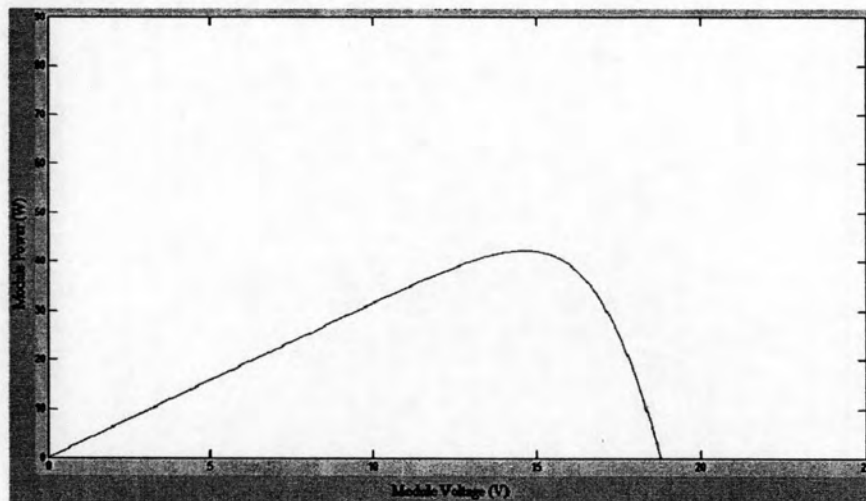


Figure 3-11 P-V characteristic with $G_a = 600.6 \text{ W/m}^2$, and $T_a = 30.91 \text{ }^\circ\text{C}$

From section 2.3.1, boost converter can be implemented in SIMULINK as shown in figure 3-12. The ideal switch is operated by the pulse signal from the P&O MPPT algorithm shown in figure 3-13.

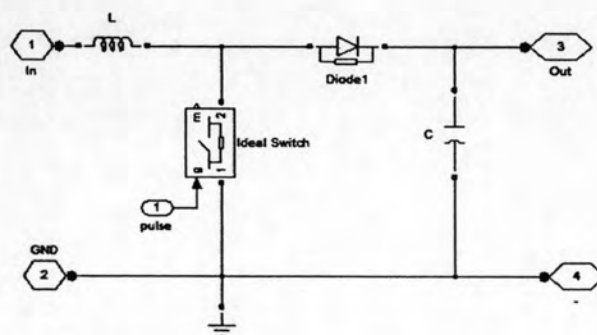


Figure 3-12 Boost converter diagram in SIMULINK

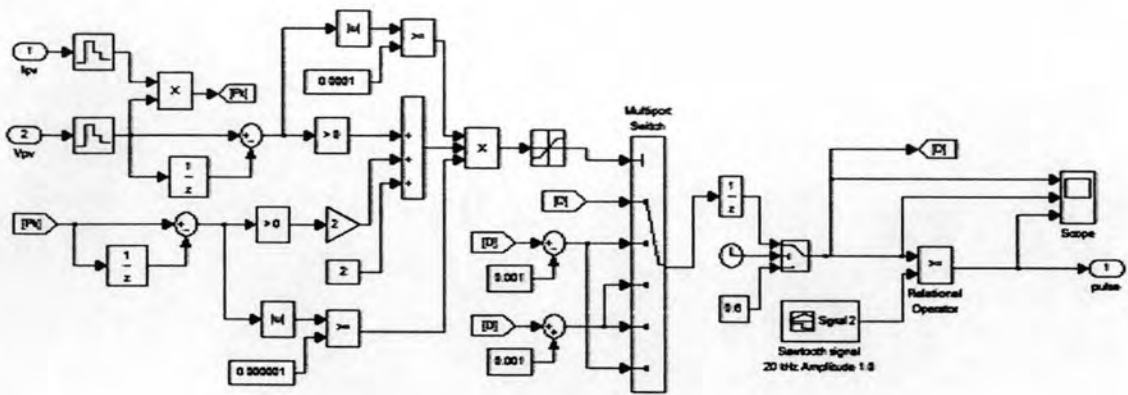


Figure 3-13 P&O MPPT algorithm in SIMULINK

From figure 3-13, the MPPT will find the operation point by tracking the power that measure from the PV module. Then, it creates the pulse signal to control the boost converter by comparing the duty cycle value with the ramp signal.

The IGBT inverter uses pulse width modulation (PWM) at a 2 kHz carrier frequency. The load voltage is regulated at 1 pu (380 V rms) by a PI voltage regulator using abc_to_dq0 and dq0_to_abc transformations shown in figure 3-14. The output of the voltage regulator is a vector containing the three modulating signals used by the PMW generator to generate the 6 IGBT pulses. The harmonics generated by the inverter around multiples of 2 kHz are filtered by the LC filter.

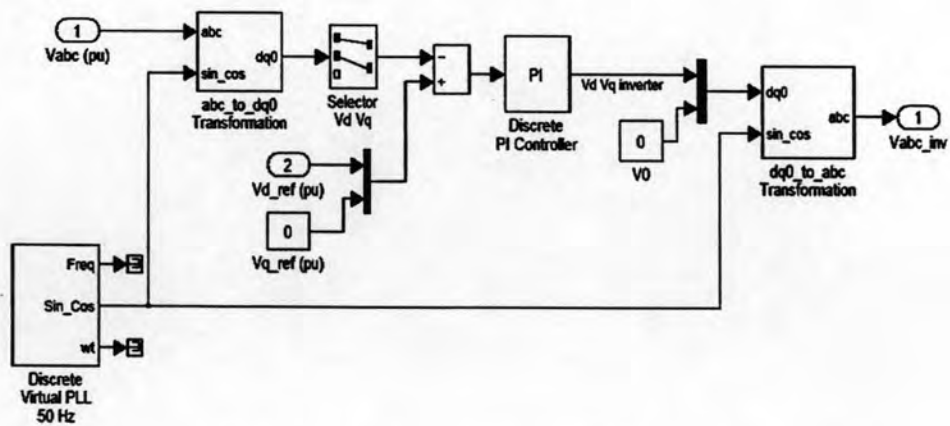


Figure 3-14 Voltage regulator in SIMULINK

The GCPV is connected to the distribution system through a step up transformer from 380 V to 22KV. Figure 3-15 [20] is a radial distribution system in Thailand containing 23 buses with 700kW load. There are some protective devices like circuit breaker at the subsystem, recloser, cut off fuse to protect the system when the fault occurs. To investigate the impact of the fault current in the presence of DG, the system is modified into 23-bus 22kV, 65MVAsc distribution system with the total load of 700kW shown in appendix B.

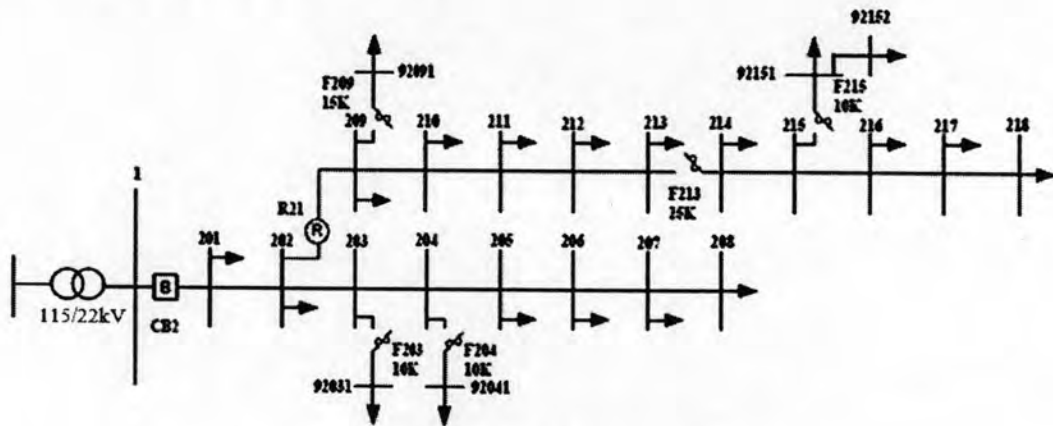


Figure 3-15 23-bus distribution system in Thailand

As the result, the GCPV model shown in figure 3-16 is implemented in MATLAB-SIMULINK, containing PV array, boost converter with maximum power point tracking, PWM inverter with voltage regulator, step up transformer, and 23 buses distribution system. The PV array could be able to form in any power ratings depend on the input number in series and parallel of the module.

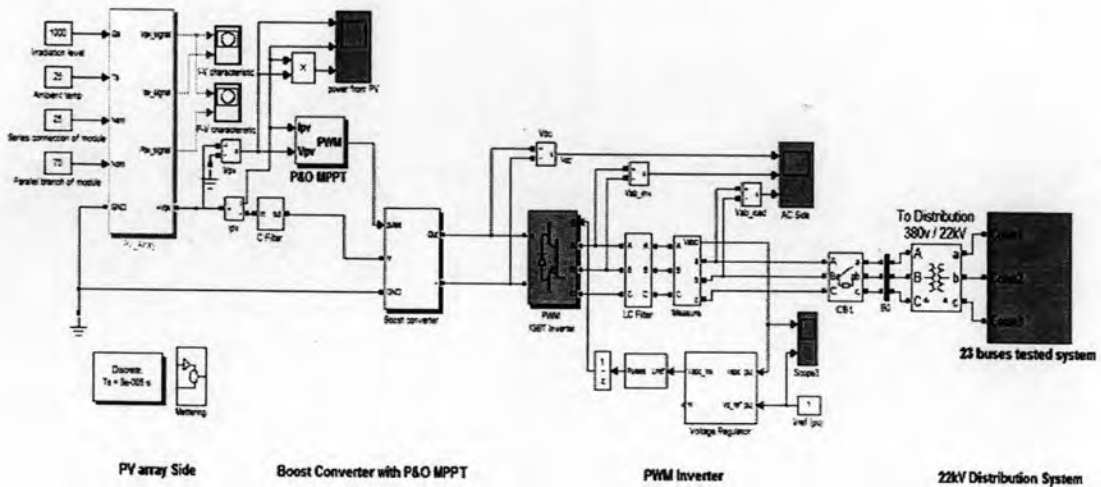


Figure 3-16 Modeling Grid-Connected PV in MATLAB-SIMULINK

To test the GCPV model and its controller, the stand alone operation is proposed with load changing. The 70kW PV array is used for simulation with the load changing from half to full load (70kW) to show the performance of the systems. The simulation time is from 0 to 0.3s where the load changes at 0.15s. Figures 3-17 and 3-18 are the voltage and current at the terminal of the PV array. Figures 3-19 and 3-20 are the voltage at 1.0 p.u or 380 V and current at the terminal of the inverter. Figure 3-21 is the comparison between the output power at PV array and inverter side when the load is changed. Figure 3.22 is the MPPT tracking curve, and figure 3.23 is the modulation index of the inverter.

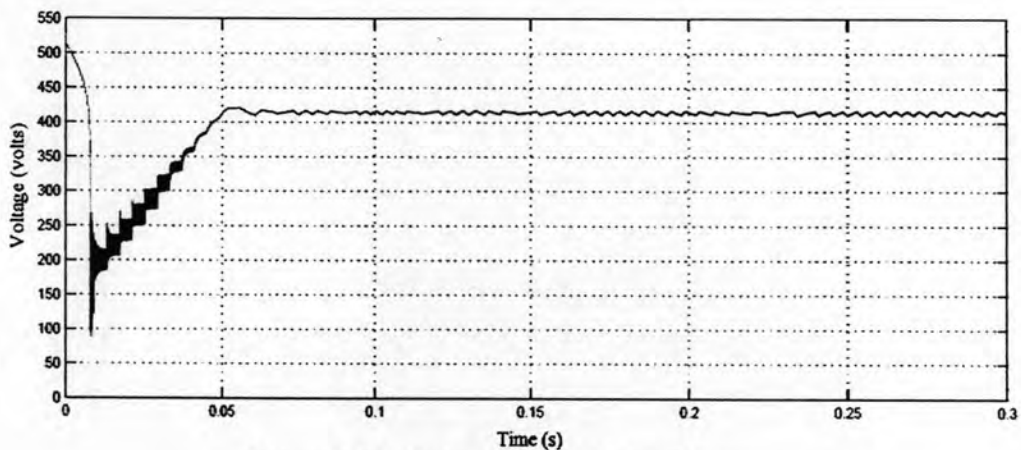


Figure 3-17 Output voltage of the PV array

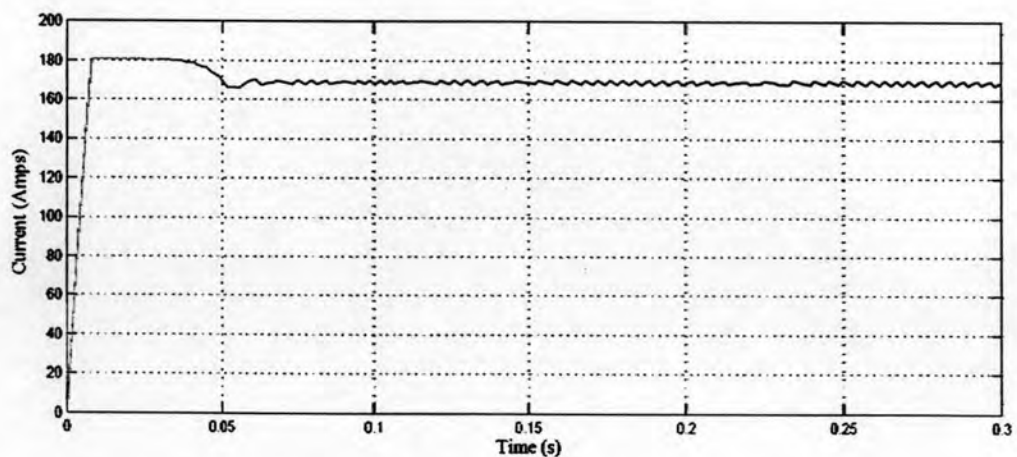


Figure 3-18 Output current of the PV array

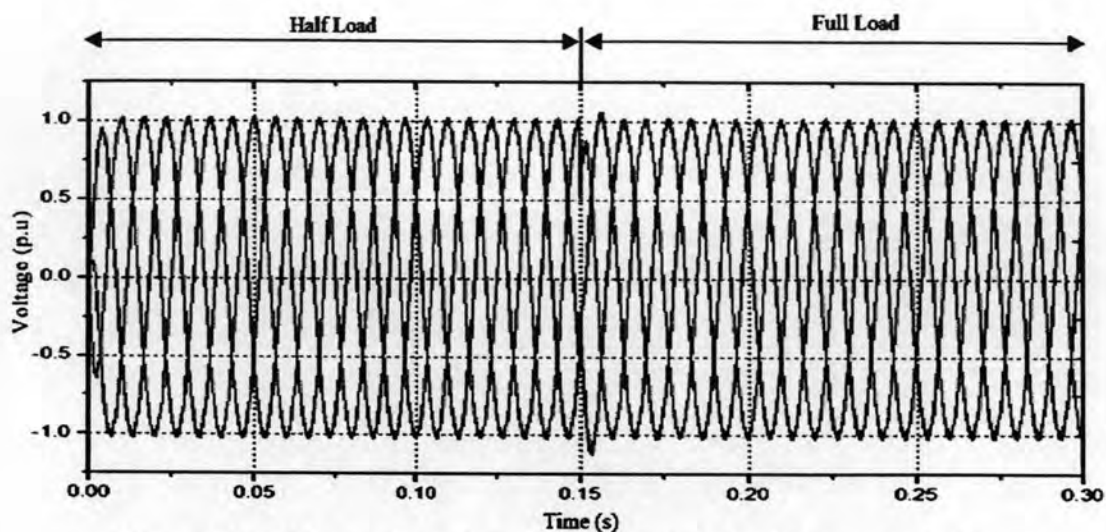


Figure 3-19 Output voltage of the inverter with the load change at $t=0.15s$

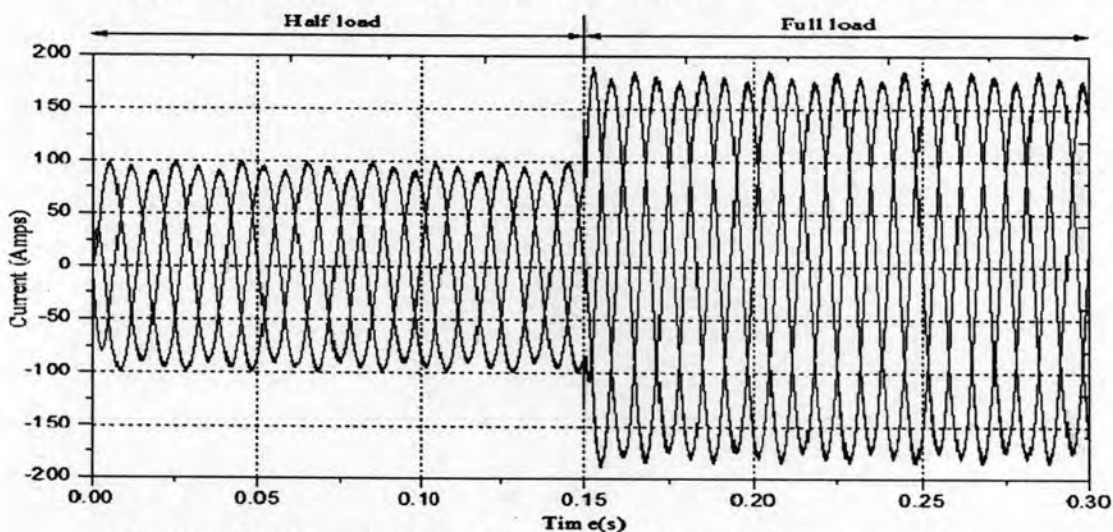


Figure 3-20 Output current of the inverter with the load change at $t=0.15s$

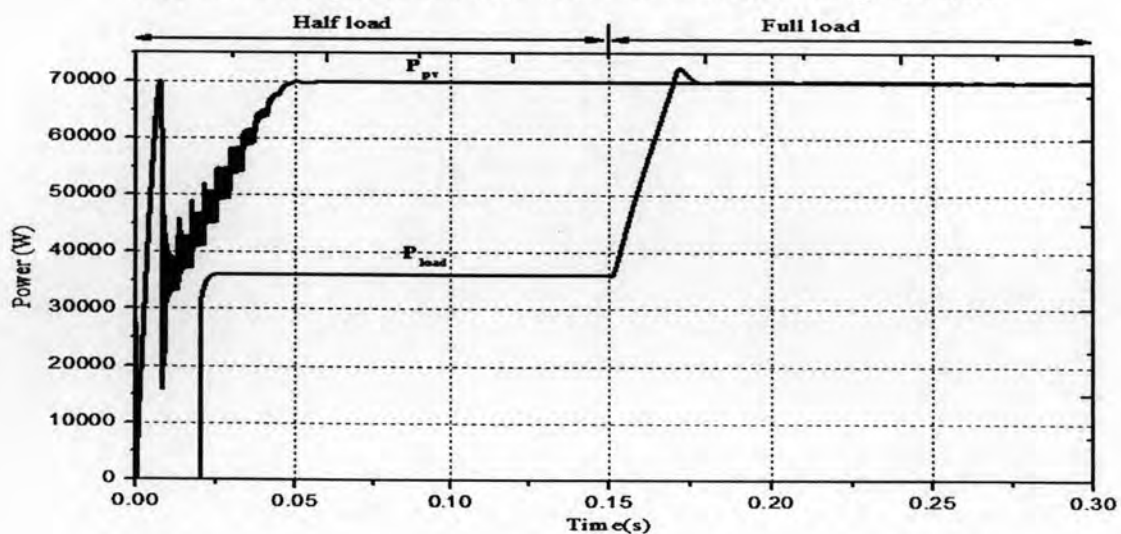


Figure 3-21 Output power of PV and inverter with the load change at $t=0.15s$

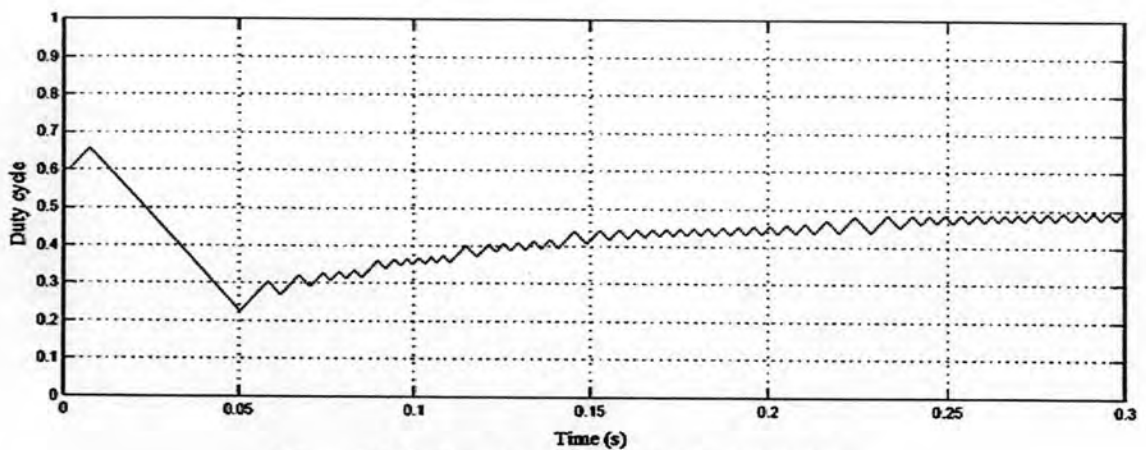


Figure 3-22 Duty cycle from MPPT controlled

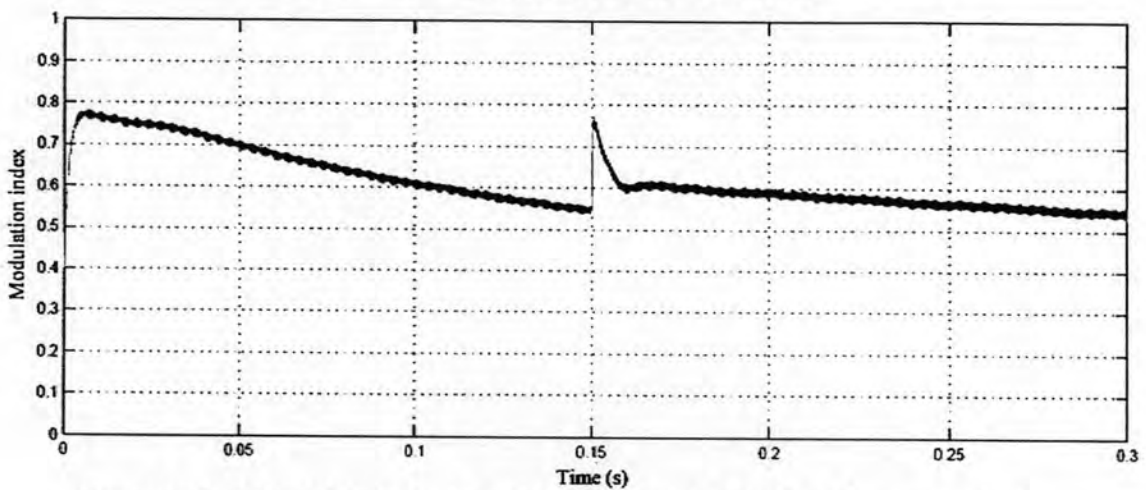


Figure 3-23 Modulation index (m_a) of the inverter with the load change at $t=0.15s$

Figures 3.19 and 3.20 illustrate how the voltage regulator works; it seems that the voltage is still 1 p.u although the load changes at 0.15s where figure 3-21 illustrates that the PV array can energize the maximum power to the system load with the help of MPPT even though the load is only half of load from 0-0.15s. Then figure 3.22 illustrates that from 0-0.05s the MPPT is tracking to find the maximum power operation point.