{ TC "' CHAPTER 4: MPPT MODEL'" \L 1 }CHAPTER FOUR

MPPT MODEL

4.1 Introduction{ TC "4.1 Introduction" \l 2 }

With the increased use of water pumping systems, more attention is paid to their design and optimum utilization in order to achieve the most reliable and economical operation. Normally the water pumping system consists of three devices: the PV array, the DC motor, and the pump. Each device has its own operating characteristics which are the I-V characteristics for the PV array and DC motor, and the torque-speed characteristics for the motor and pump. The DC motor drives the pump whose torque requirements vary with the speed at which it is driven. The DC motor is supplied from the PV array whose I-V characteristics depend non-linearly on the solar radiation variations and on the current drawn by the DC motor. For a PV array, there is a unique point on its I-V curve at which the power is maximum and, for optimum utilization, the equilibrium operating point of the PV array should coincide with this point. However since the maximum power point varies with radiation and temperature, it is difficult to maintain optimum matching at all radiation levels, except for a specially designed DC motor. For most DC motors and pumps, the equilibrium operating point of the system is far from the maximum power point of the PV array at most radiation levels, and thus full utilization is not achieved.

In order to improve the performance of a PV pumping system, two options are generally available to the system designer:

1) Carefully select the DC motor and the pump so that they match as close as possible to the maximum power line of the PV array.

2) Use a DC-DC converter known as a Maximum Power Point Tracker (MPPT) which can continually match the output characteristics of a PV array to the input characteristics of a DC motor. Also changing configuration of PV modules can improve the matching of the PV array and load under some of radiation levels.

Option 1 offers a compromise matching which is valid only for some solar radiation levels due to drifting of the maximum power point with radiation variations. Appelbaum (1979) investigated the starting and steady state performance of different DC motors and water pumps directly coupled to a PV array, concluding that a separately excited DC motor driving a centrifugal pump provides the best match to the PV array.

Option 2 is achieved either by discretely interchanging the series-parallel connections of solar cells in the PV array (Dunlop, 1988), which arranges the photovoltaic array in series or parallel to improve the matching between load and array; or by using controlled dc-dc converters in the step-down mode (Landsman, 1988); or in the step-up mode (Alghuwainem, 1992). By including an MPPT in a PVPS , the starting torque may increase significantly at low radiation levels resulting in desired system performance.

By matching the PV array to the motor by means of an MPPT, the motor operation can be improved. This advantage of using an MPPT can be described as follows: In PV drive systems, such as a PV pumping system, the static head may be relatively high causing the motor-pump to stay in "stand still" position until sufficient torque is developed at relatively high radiation. The typical PVPS with an MPPT is shown in Figure 4.1.

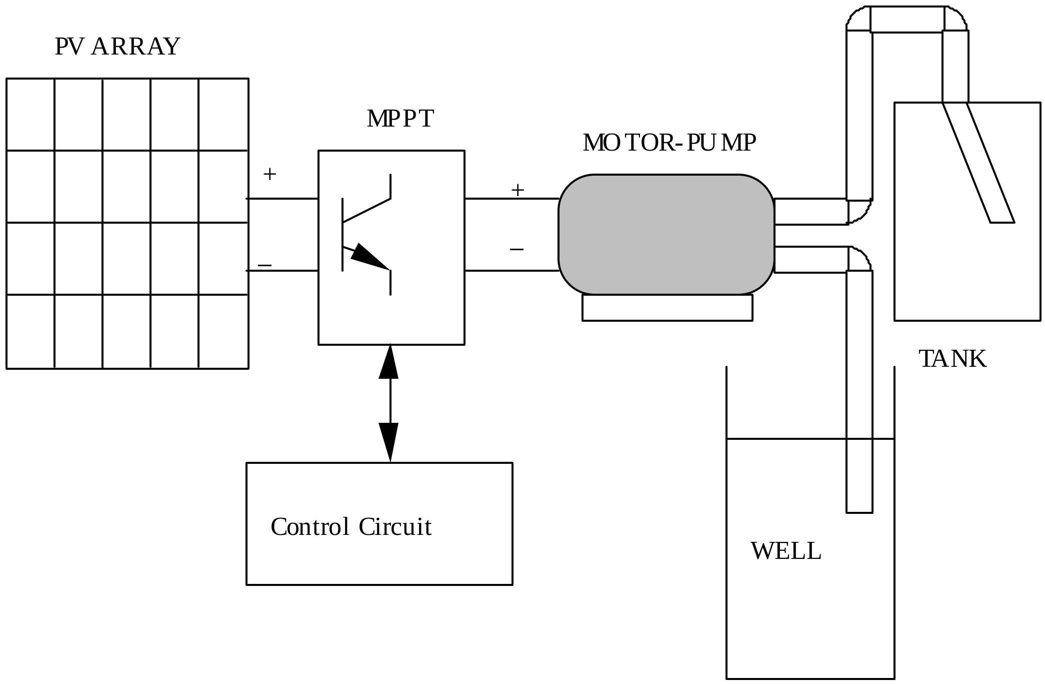

Figure 4.1 The PVPS with MPPT{ TC "Figure 4.1 The PVPS with MPPT" \l 6 }

By including an MPPT in the system, the starting torque may increase significantly at lower radiation levels resulting in desired system performance as shown in Figure 4.2. The motor-pump works at operating point (V1, I1) if there is no MPPT in the system. If the MPPT is included in the system, the operating is promoted to the operating point (V2, I2) where the voltage and current is higher than the point (V1, I1). Because the motor torque is related to the motor current, the pump may start to work earlier than the directly coupled system.

The MPPT normally consists of a power electronic circuit, (such as bulk, boost or combined circuit) controlled by a signal circuit which drives the power electronic circuit to force the PV array operating at its maximum power point. The objective of this section is to develop a general mathematical model of an MPPT for matching a motor -pump connected to a PV array. Here we assume that microprocessor is normally used to control the dc converter for optimal operation.

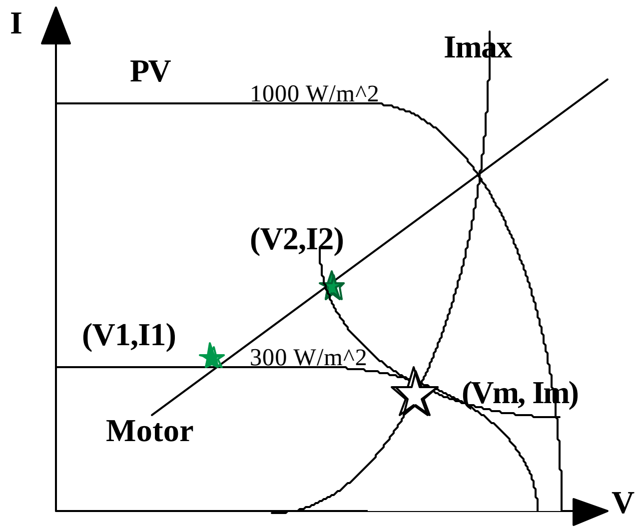

Figure 4.2 Operating point of PVPS with and without MPPT

4.2 MPPT Model{ TC "4.2 MPPT Model" \l 2 }

Most MPPTs utilize standard switch-mode power supply technologies and provide an adjustable-ratio DC to DC transformer. This provides matching between the load and the PV array. Due to this matching, the PV array is forced to deliver maximum power to the load at any time, incorporating switching transistors, diodes, capacitors and control algorithms. Three basic topologies are the Buck(step down), Boost(step up) and Buck-Boost(step-up-down) converters. Of these three converters, only the step-down and the step-up are the basic converter topologies. The Buck-boost is a combination of the two basic topologies and is more complicated. The converters will be analyzed in steady state and the switches are treated as being ideal. The losses in the inductive and the capacitive elements are neglected.

4.2.1 Step-Up (Boost) MPPT{ TC "4.2.1 Step-Up (Boost) MPPT" \l 3 }

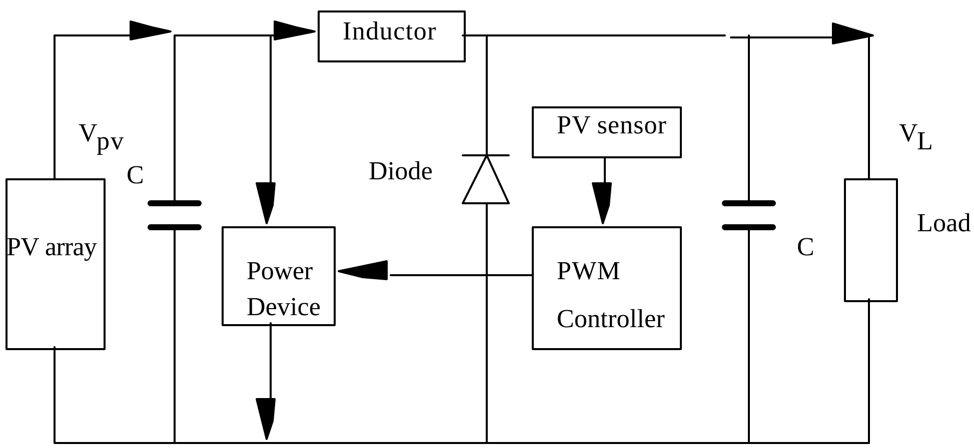

Figure 4.3 Step up mode MPPT{ TC " Figure 4.3 Step up mode MPPT" \l 6 }

Figure 4.3 shows a schematic diagram of the step-up chopper. The step-up chopper is used to drive a high voltage load from a low voltage PV array. This device works well at high radiation levels, but will not perform properly at low radiation level when the load voltage drops below that of the PV array. Power flow from the PV array to the load is controlled by means of the on/off duty cycle of the switching transistor. No extra diode D is necessary when the boost topology is used. When the power device is turned on, the diode is reverse biased and non-conducting. If current begins to flow in the inductor -power device loop, energy is stored in the inductor magnetic field. When the power device is switched off, the energy in the inductor is discharged to the output through the diode. When the power device is closed (the " on" interval) the voltage across the inductor is the supply voltage V_{pv}. During the off interval, the inductor voltage is V_{pv} minus the output voltage V_L. For steady state operation, there must be zero average voltage across the inductor. Therefore the positive volt-seconds on the inductor during the on interval must equal its negative volt-seconds when the power device is open. In general

$$V_{pv} t_{on} = (V_L - V_{pv}) t_{off} \tag{4.1}$$

and then

$$V_L = \frac{t_{on} + t_{off}}{t_{off}} V_{pv} = \frac{T}{t_{off}} V_{pv} \tag{4.2}$$

where

$$T = t_{on} + t_{off} \tag{4.3}$$

Equation 4.2 clearly indicates the step up feature of the circuit since T is greater than t_{off}. If the ratio k is defined as

$$\frac{t_{on}}{T} = k \tag{4.4}$$

then the Equation 4.2 becomes

$$V_L = \frac{1}{1-k} V_{pv} \tag{4.5}$$

From Equations 4.2 and 4.5, it is clear that the output voltage can be controlled by varying the chopper duty cycle k. A technique known as pulse width modulation (PWM) is often used to vary k. If the chopper is assumed be loss free, then the supply power (PV power) is equal to the load power or

$$V_{pv} I_{pv} = V_L I_L \tag{4.6}$$

and

$$\frac{V_{pv}}{VL} = \frac{I_L}{I_{pv}} = 1-k = d \tag{4.7}$$

which means that the chopper can be treated as a dc transformer with adjustable ratio d. The d is less than 1 in this case. A longer duty cycle would result in a higher dc current level than would result in a shorter cycle. In general, a simple and inexpensive analog circuit is used to continually set a pulse width modulated control signal to maximize the power output of the small size photovoltaic array.

4.2.2 Step-Down (Buck) MPPT{ TC "4.2.2 Step-Down (Buck) MPPT" \l 3 }

The Figure 4.4 shows a schematic diagram of the step-down chopper.

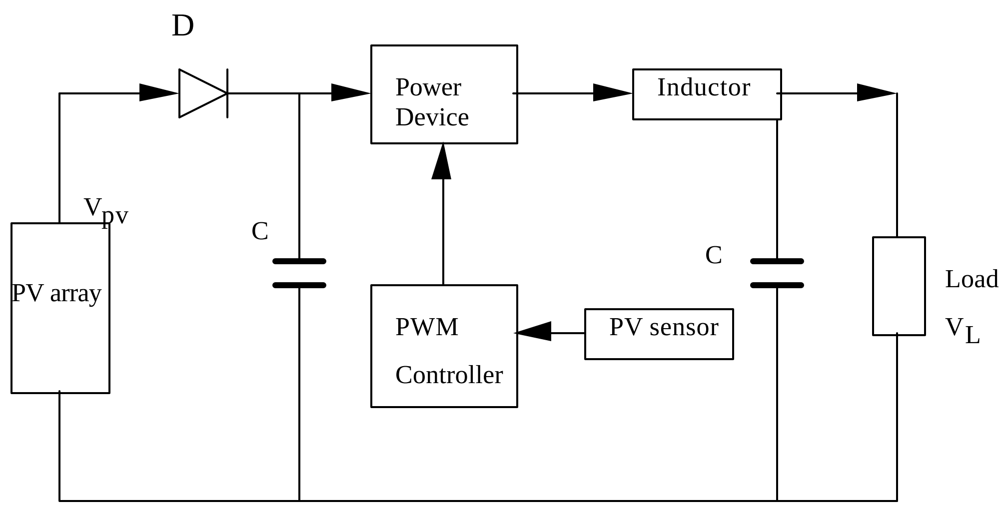

Figure 4.4 Step down mode MPPT{ TC " Figure 4.4 Step down mode MPPT" \l 6 }

The step-down chopper is used to drive a low voltage load from a high voltage PV array as shown in Figure 4.4. It is a high frequency switching converter which operates efficiently at low radiation level. For this converter the output voltage is always lower than the input PV array voltage. Power flow from the PV array to the load is controlled by means of the on/off duty cycle of the switching transistor. This topology is normally used for PV system. A blocking diode D is necessary, which has a negative effect on the total PV system efficiency.

As same way as discussed in last section, the I-V relationship of buck chopper can be found as,

$$\frac{V_L}{V_{pv}} = \frac{I_{pv}}{I_L} = d \qquad (4.8)$$

where the d is the adjustable ratio of MPPT. The value of d is less than 1.

4.2.3 Step-Up-Down MPPT{ TC "4.2.3 Step-Up-Down MPPT" \l 3 }

Some maximum power point trackers use converters which function as both step-up and step-down choppers. Theoretically it can improve the matching of PV array and load at most radiation levels except at very low radiation levels. But these converters are generally more complicated, less efficient and more expensive than that the simple buck or boost converters. The I-V relationship of the step-up-down MPPT is,

$$\frac{V_L}{V_{pv}} = \frac{I_{pv}}{I_L} = d \qquad (4.9)$$

where the d is the adjustable ratio of the MPPT. It can less than 1 or larger than 1.

4.3 The Use Criteria of The MPPT{ TC "4.3 The Use Criteria of The MPPT" \l 2 }

When using the MPPT converter, an estimated increase in energy output from the PV array of 20-30% can be expected. The energy output enhancement should be measured against the increased cost and less reliability of the MPPT converter. The added cost of the MPPT converter should be lower than the estimated savings of the system cost due to higher energy output from a given PV array. The following use criteria are applicable:

1. Where seasonal temperature and radiation vary over in a wide range, using of an MPPT may be an advantage.

2. Constant current load is the least desirable type for a PV array. Including an MPPT in such a system would result in increased performance.

3. The duty ratio of an MPPT should be limited according to the different PV pumping systems. Alghuwainem (1992) published a fixed ratio MPPT based on his experiment. They pointed out that the ratio should be in the range of 0.5 - 1 for the step-up MPPT and a simplified optimal ratio for almost all radiation levels is 0.849. Singer(1993) also gave a optimized ratio of about 0.85. Generally the ratio of short circuit current to the maximum power current of typical solar cell is about 1.2.

4. For a given PV pumping system, the type of MPPT should be determined. For a less effective system design, the benefit in using an MPPT is larger. At rated operating points, operating point of pump and the maximum power point are about equal and the efficiency is quite high. But directly driving a pump, the motor will often be operating at these low speed regarding the low efficiency range. This indicates that if the motor is supplied directly from the PV array, maximum power of PVPS can only be achieved at about 60% radiation level (Alghuwainem, 1992). At higher radiation levels the power delivered to the motor-pump is less than P_{max} by a wide margin.

To design a good PV pumping system with an MPPT, the design radiation level and the operating point of motor should be considered. Using the rated motor operating point Vm and Im close to the maximum power point of the PV array at a rated high design radiation level of 1000 w/m^2 or low design radiation level of 500 w/m^2. For the design point at low radiation level as shown in Figure 4.5, the system will work at the maximum power point of the PV array. When the radiation increases, the directly coupled system will work at (V1, I1) which is far from the maximum power point of the PV array. If a step-up MPPT is used in the system, then the motor will work at (V3, I3) which is on the contour line of the maximum power of PV array.

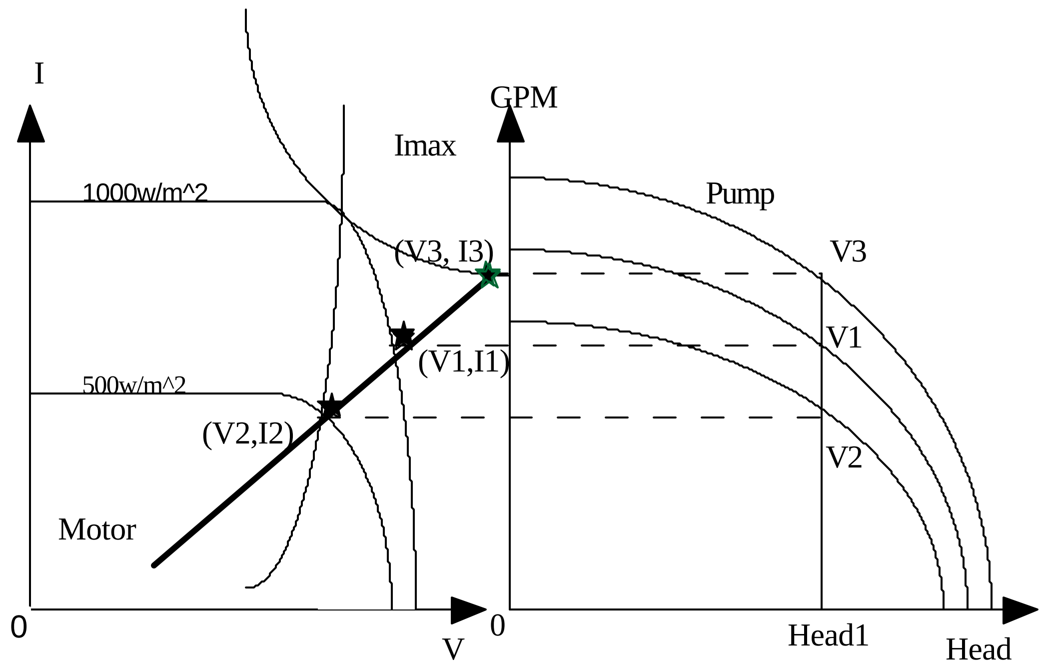

Figure 4.5 Design point at low radiation level

For the design point at high radiation level as shown in Figure 4.6, the initial best operating point is at point (V3, I3). When the radiation decreases, the system will work at point (V2, I2) if there is no MPPT in the system. If a step-down MPPT is added in the system, the motor will be forced to the point (V1, I1) where is on the contour line of the maximum power of PV array. The PV array will operate at maximum power point.

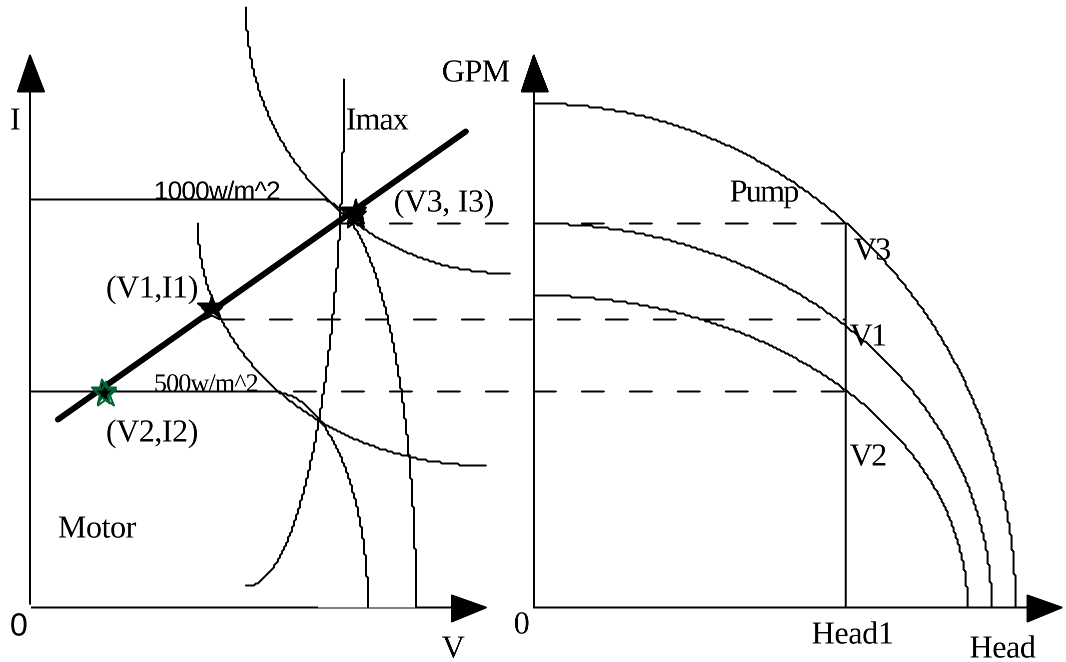

Figure 4.6 Design point at high radiation level

For the design point at middle radiation level as shown in Figure 4.7, the best initial operating point is at (V3, I3). The type of MPPT should be step-down and step-up MPPT. Whenever the radiation changes, the buck-boost MPPT always force the system works at the contour line of maximum power point of PV array, for instance, (V1, I1) and (V2, I2).

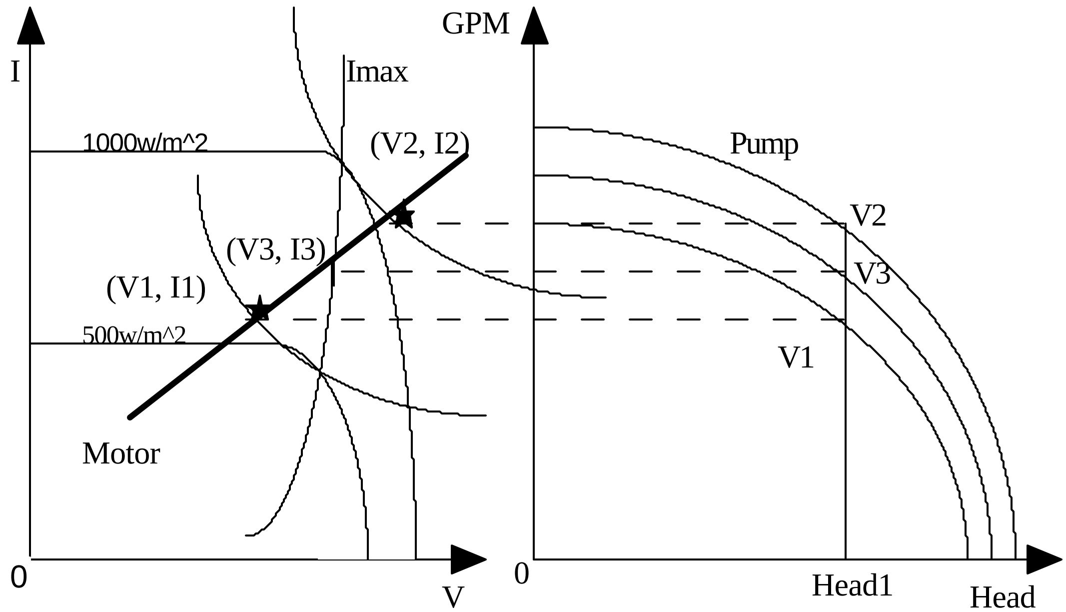

Figure 4.7 Design point at middle radiation level{ TC "Figure 4.7 Design point at middle radiation level" \l 6 }

4.4 Old MPPT Model{ TC "4.4 Old MPPT Model" \l 2 }

The MPPT model used in PV system simulation, based on a general buck-boost converter model was written as a TRNSYS type by Eckstein (1990). It is assumed that the MPPT is an ideal DC transformer then can be adjusted in any ratio. This can lead to the difficulty of finding solution of PVPS. However in practical MPPT design and application, the ratio lies in a small range (0.5-1) limited by the characteristics of the power converter. In most applications of MPPTs, only one topology is employed for cost and complicated structural reasons. Also Eckstein's model must use an iteration method to find the operating point among the MPPT and other load models. The algorithm of the iteration procedure likes the TRNSYS type 62 discussed in chapter 2. The convergence can not be achieved sometime because of this complex iteration structure.

4.5 Improved MPPT Model{ TC "4.5 Improved MPPT Model" \l 2 }

According to the characteristics of power converters, and the practical MPPTs in the PV market, an improved MPPT model was proposed. The improved MPPT model use the open loop simulation strategy as discussed in chapter 2. The model also requires the type of power converter, i.e. buck, boost or buck-boost converter. The range of adjustable ratio will depend on the different types of MPPT. The efficiency of MPPT is assumed as constant in whole range of load.

4.6 TRNSYS Type 65: PVPS with MPPT{ TC "4.6 TRNSYS Type 65: PVPS with MPPT" \l 2 }

Type 65 is based on type 64 described in chapter 2 with improved MPPT model. The information flow chart for type 65 is shown in Figure 4.8.

Parameters of type 65

1. Mode	Solar cell type	
2. $\boxed{G_{ref}}$	Reference radiation level	(w/m^2)
3. $\boxed{I_{Lref}}$	Light current at reference condition	(A)
4. $\boxed{I_{scref}}$	Short circuit current at reference condition	(A)
5. $\boxed{I_{oref}}$	Reverse saturation current at reference condition	(A)
6. $\boxed{V_{ocref}}$	Open circuit voltage at reference condition	(V)
7. $\boxed{A_{ref}}$	Thermal voltage at reference condition	(V)

8. $\boxed{R_{sref}}$ Series resistance at reference condition ( )

9. $\boxed{I_{mpref}}$ Maximum power current at reference condition current (A)

10. $\boxed{V_{mpref}}$ Maximum voltage at reference condition (V)

11. $\boxed{\mu_{Voc}}$ Temperature coefficient of cell voltage (V/C)

12. $\boxed{\mu_{Isc}}$ Temperature coefficient of cell current (A/C)

13. $\boxed{T_{cref}}$ Cell temperature at reference condition (C)

14. $\boxed{E_q}$ Band gap of silicon (eV)

15. $\boxed{N_s}$ Number of cells in series in one module

16. *N_S* Number of module in series

17. *N_P* Number of module in parallel

18.to 30 parameters of pump (or other load)

31. Type of MPPT

32. Efficiency of MPPT

33. Ratio limit of MPPT

Input of type 65

1.Radiation level (W/m^2)

2 Temperature (C)

Output of type 65

1.Operating voltage (V)

2.Operating current (A)

3.Maximum current (A)

4.Maximum voltage (V)

5.Efficiency of PV array

6.Effective factor of system

7.Water output (GPM)

8.Water shortage (Gallon)

9 Ratio of MPPT

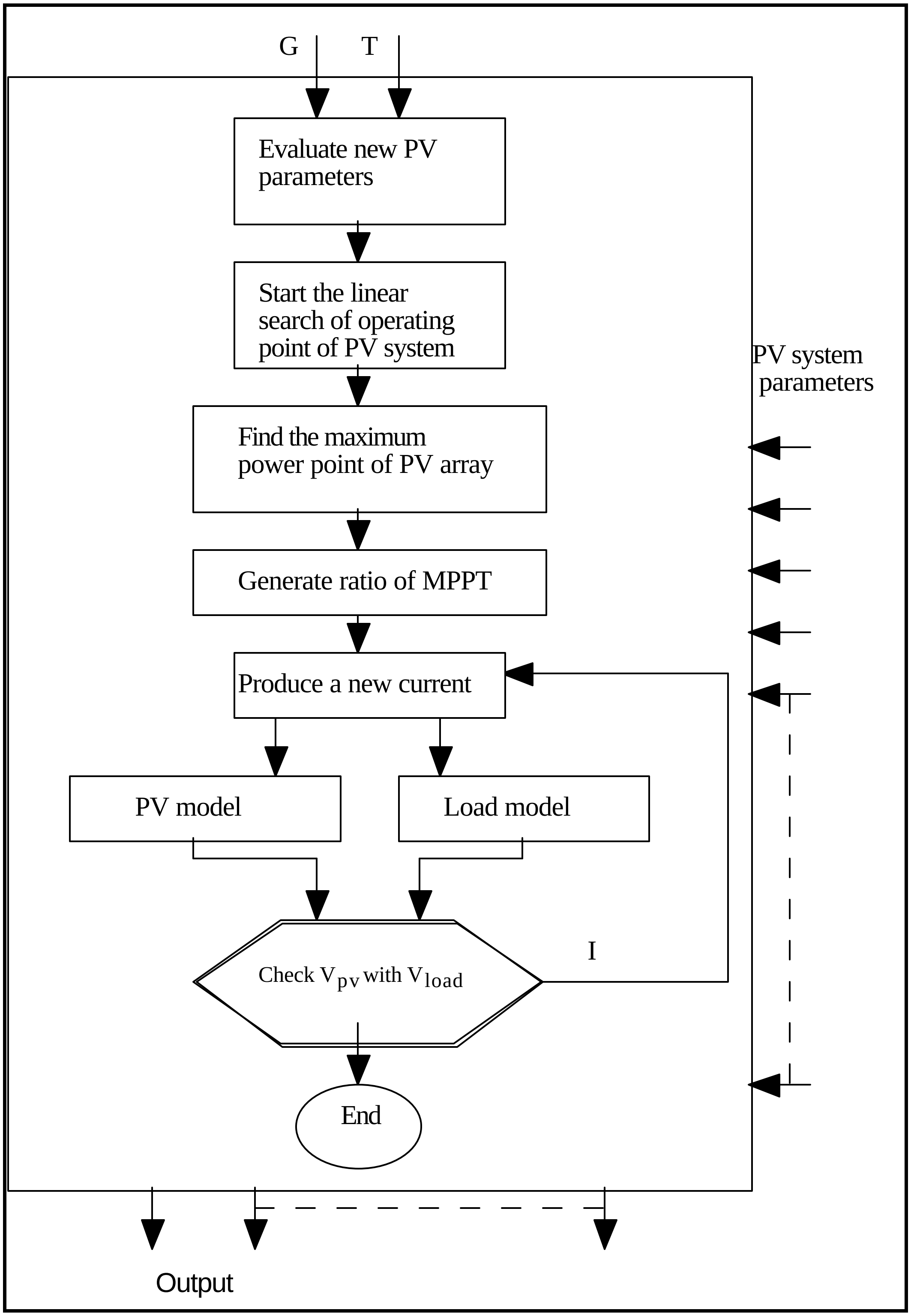

Figure 4.8 The structure of Type 65{ TC "Figure 4.8 The structure of Type 65" \l 6 }

The type 65 only uses the radiation and temperature as the inputs. This new algorithm can be used in the EES and the TRNSYS. The EES and the TRNSYS program codes are appended in Appendix A and B.

4.7 Verification of Type 65.{ TC "4.7 Verification of Type 65." \l 2 }

Validation of the MPPT model was carried out by comparing the simulation results and the measurement data of PV pumping system provided by SolarJack. The PVPS can not be always designed perfectly because the nonlinear characteristic of PV array and the motor-pump load. Under such conditions, the MPPT will improve the efficiency of a PVPS. Figure 4.9 shows an example which is a less effective design. The original PVPS is direct couple system. The operating point of system is far from the maximum points of the PV array at high radiation level. After the MPPT is used, the operating point of the PVPS is closer to maximum power point. Also the threshold of radiation level to commence water pumping is reduced to 200W/m^2 compared with old system that needs at least 300w/m^2 to start the pumping process. See Figure 4.10. The changing of adjustable ratio of the MPPT at different radiation level is shown in Figure 4.11.

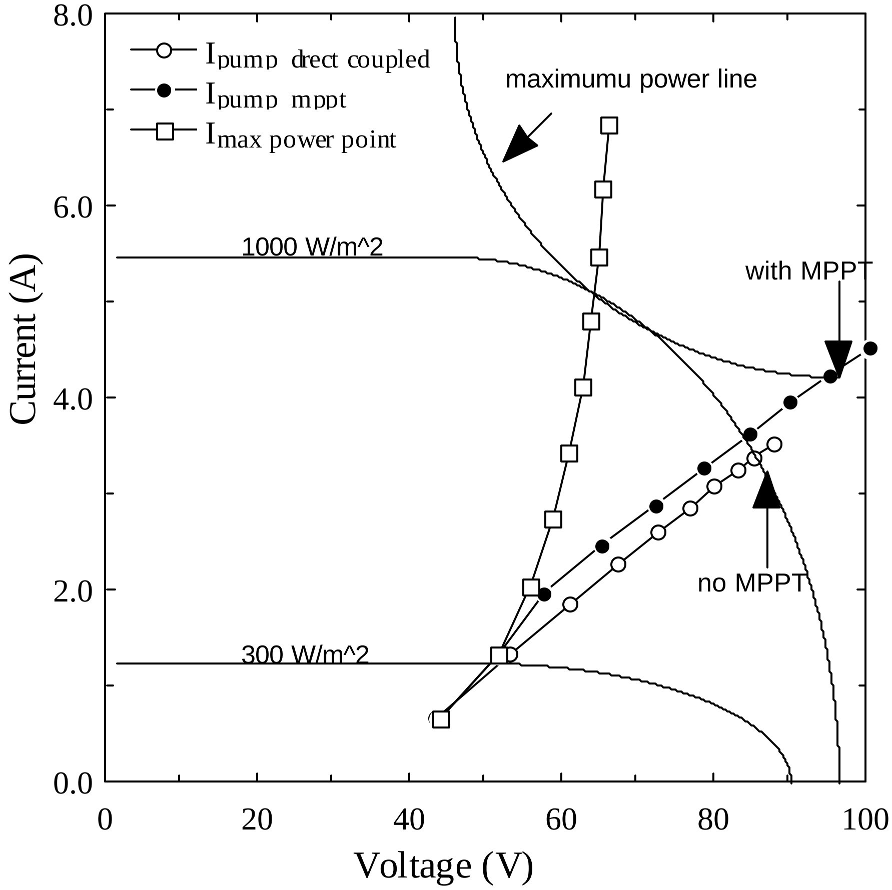

Figure 4.9 I-V curve of a directly coupled a PVPS and a PVPS with an MPPT, 5 modules in series and 3 in parallel at a head of 93 feet{ TC "Figure 4.9 I-V curve of a directly coupled a PVPS and a PVPS with an MPPT, 5 modules in series and 3 in parallel at a head of 93 feet" \l 6 }

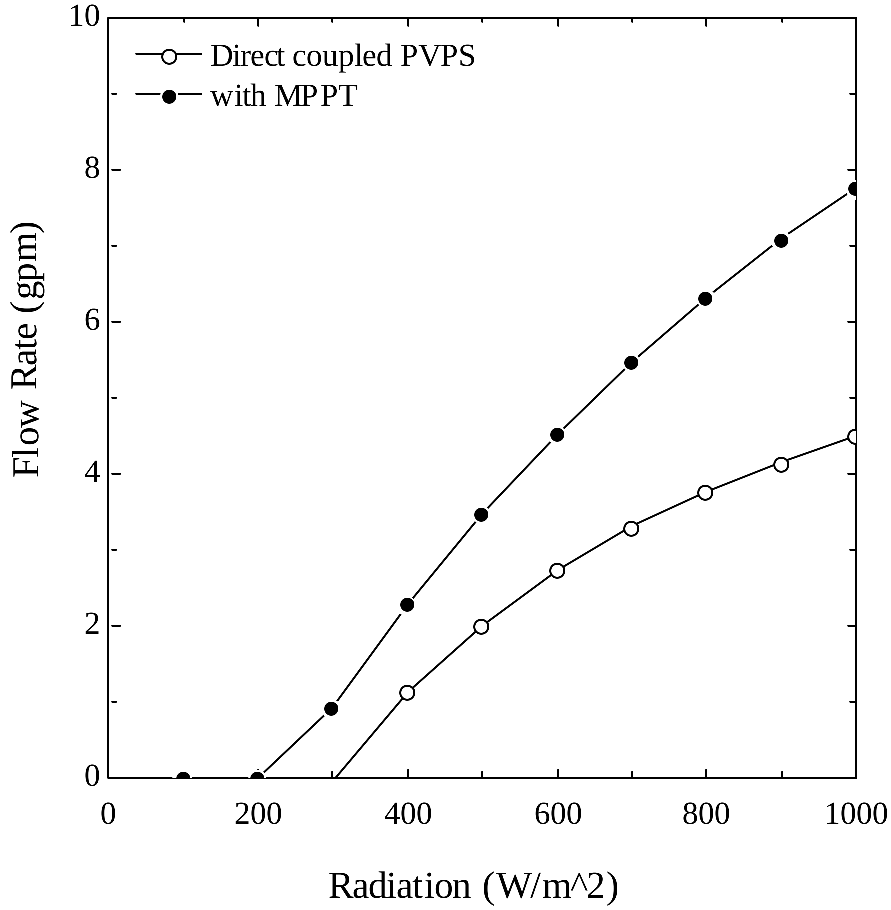

Figure 4.10 Output water from a PVPS with or without MPPT 5 modules in series and 3 in parallel at a head of 93 feet**{** TC "Figure 4.10 Output water from a PVPS with or without MPPT 5 modules in series and 3 in parallel at a head of 93 feet" \l 6 **}**

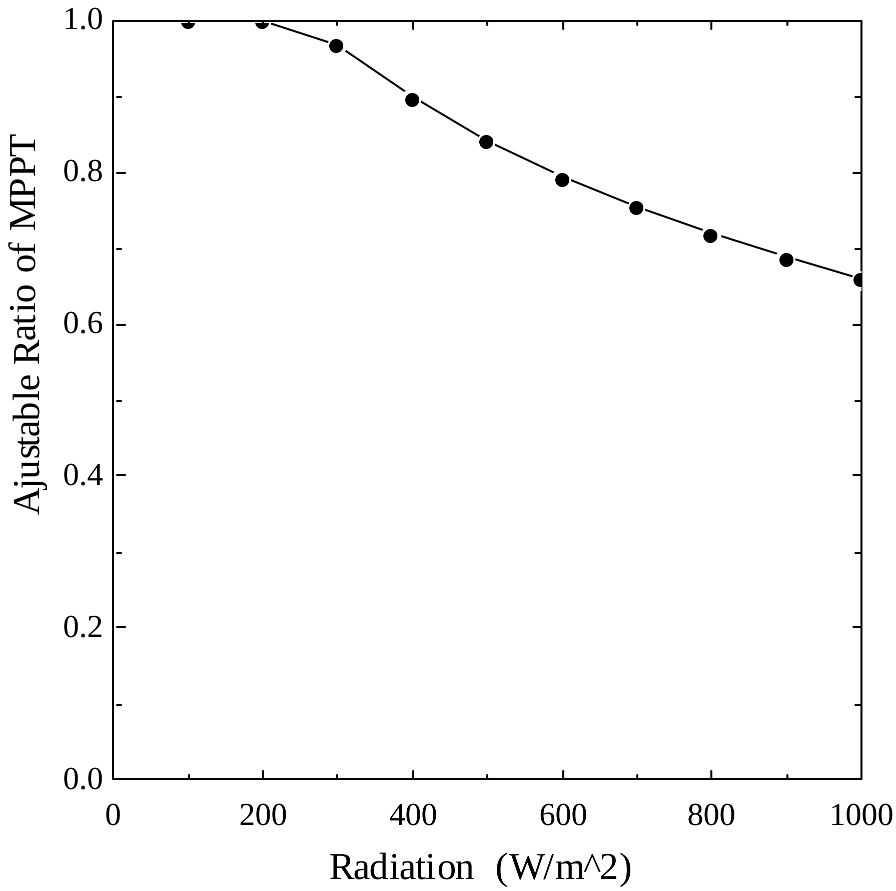

Figure 4.11 Adjustable ratio of the MPPT vs radiation.5 modules in series and 3 in parallel at a head of 93 feet{ TC "Figure 4.11 Adjustable ratio of the MPPT vs radiation.5 modules in series and 3 in parallel at a head of 93 feet" \l 6 }

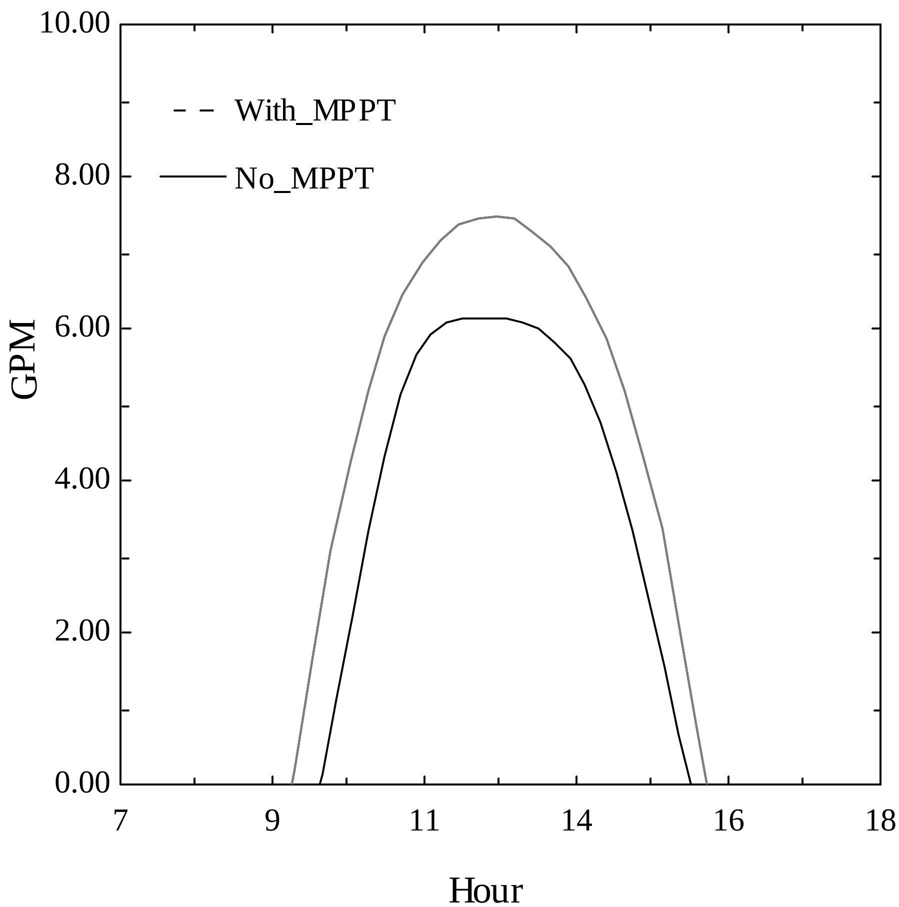

Figure 4.12 Flow rate of Pumped water using same pumping system with and without an the MPPT at Madison on Jan 15. PV modules 5 in series and 3 in parallel{ TC "Figure 4.12 Flow rate of Pumped water using same pumping system with and without an the MPPT at Madison on Jan 15. PV modules 5 in series and 3 in parallel" \l 6 }

The Figure 4.12 illustrates the impact of an MPPT on the PV pumping system. By using the MPPT, the start time of pumping is earlier than that of directly coupled system. The amount of pumped water is also increased.

But for well designed PV pumping systems, the MPPT is not important issue for the pumping system because of the tracking and the perfect matching design. The Figure 4.13 to Figure 15 show that effect of an MPPT on the PV pumping system. The amount of pumped water is increased at low radiation. But at high radiation, it is not significantly helped with the MPPT.

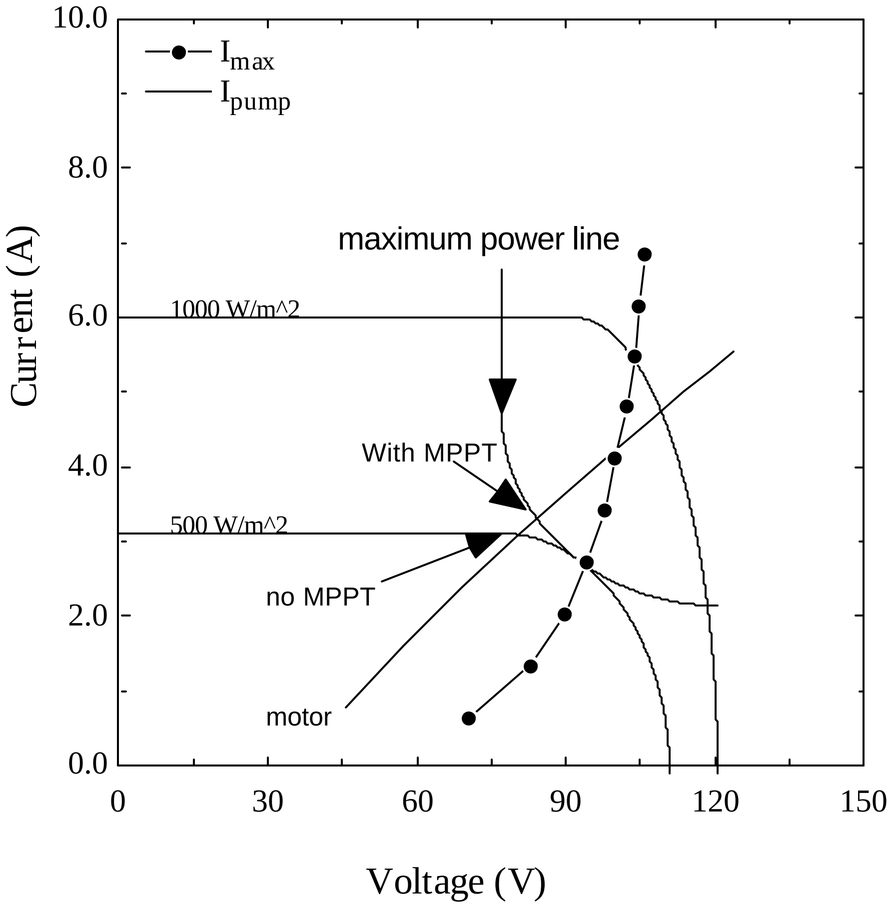

Figure 4.13 I-V curve of a PVPS with and without an MPPT, 8 modules in series and 3 in parallel at a head of 93 feet{ TC "Figure 4.13 I-V curve of a PVPS with and without an MPPT, 8 modules in series and 3 in parallel at a head of 93 feet" \l 6 }

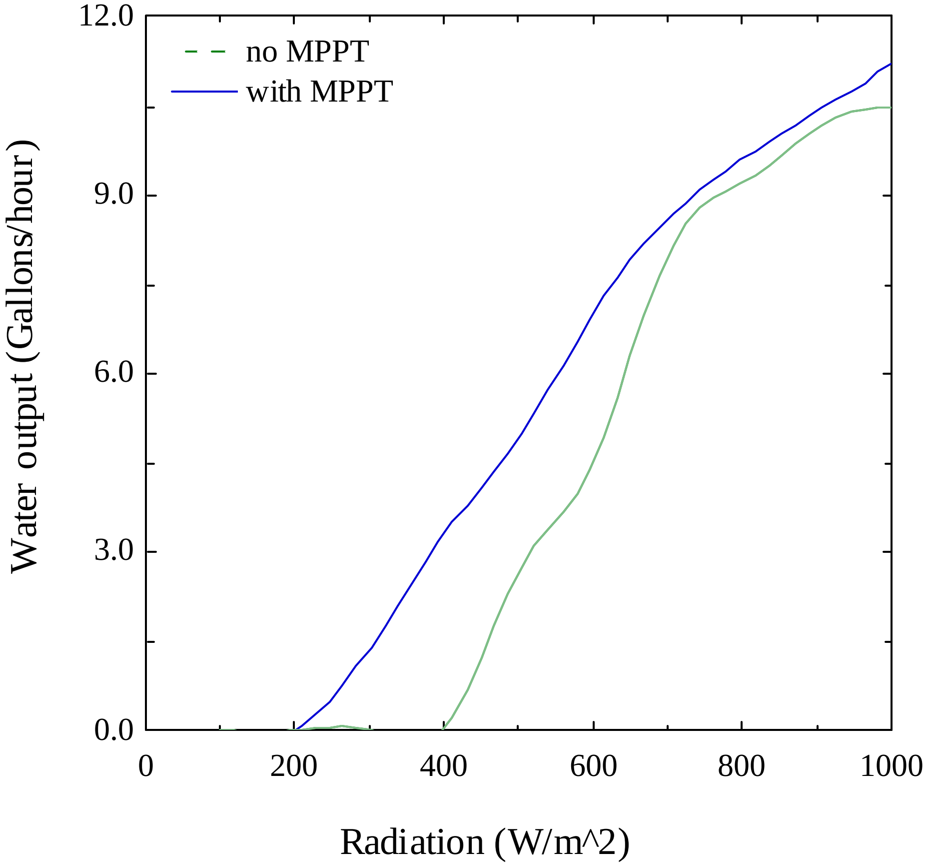

Figure 4.14 Output water from a PVPS with or without MPPT. 8 modules in series and 3 in parallel at a head of 93 feet{ TC "Figure 4.14 Output water from a PVPS with or without MPPT. 8 modules in series and 3 in parallel at a head of 93 feet" \l 6 }

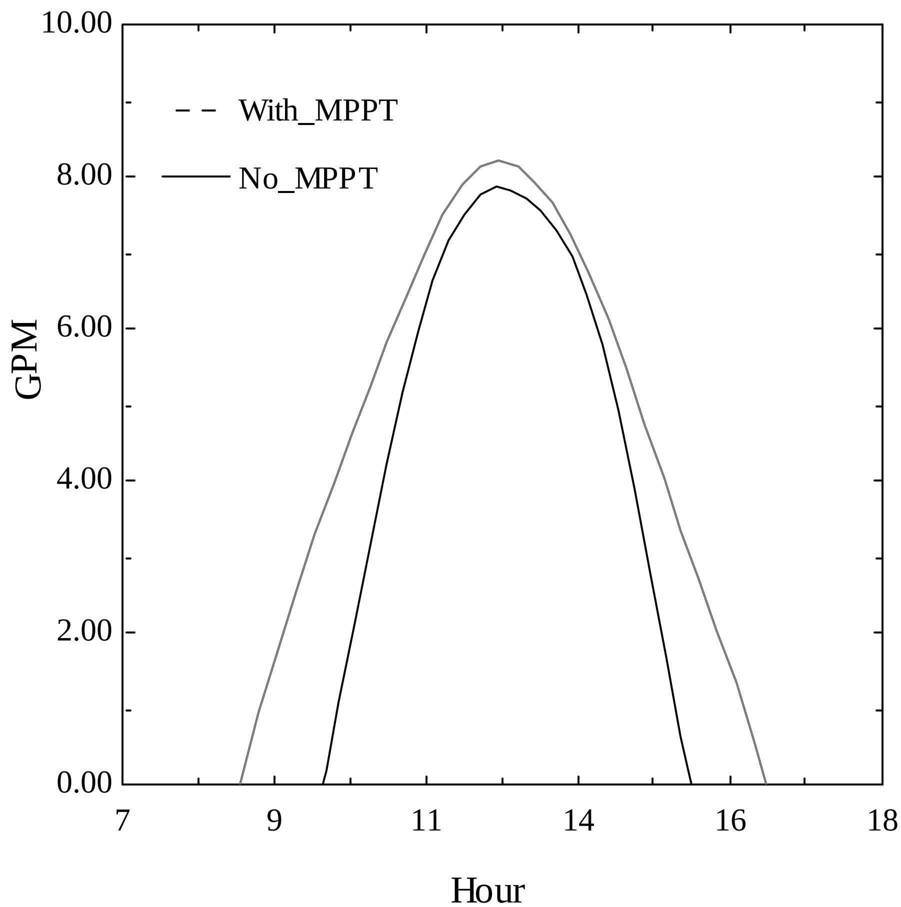

Figure 4.15 Flow rate of Pumped water using same pumping system with and without an the MPPT at Madison on Jan 15. PV modules are 8 in series and 3 in parallel. **{** TC "Figure 4.15 Flow rate of Pumped water using same pumping system with and without an the MPPT at Madison on Jan 15. PV modules are 8 in series and 3 in parallel. " \l 6 **}**

More examples regarding the MPPT used in the PVPS will be discussed in Chapter 5 and 6. The MPPT model is used the long term simulation programs.