{ TC "'CHAPTER 3: MOTOR AND PUMP MODEL'" \L 1 }CHAPTER THREE

MOTOR AND PUMP MODEL

One important component of a PV pumping system is the pump. In this chapter a new model of the pump has been developed. The characteristics of the motor-pump is represented by 2 functions. Those functions can be integrated into the TRNSYS Type 64.

3.1 DC Motor{ TC "3.1 DC Motor" \l 2 }

A DC pump is used in most of PV pumping systems. In this project only a DC pump is considered. A DC pump consists of a DC motor and a pump. The DC motors are classified by the type of excitation field: permanent magnet, series, shunt and separately excited motors. The circuit diagram of those four types of motors are shown in Figure 3.1 (a) through (d), respectively.

In general, the motor voltage and torque equations for all kinds of DC motors are:

$$V_m = E + I_a R \tag{3.1}$$

$$E = k_e \varnothing n \tag{3.2}$$

$$T = k_t \varnothing I_a \tag{3.3}$$

where

V_m The motor applied voltage (V){ TC "V_m The motor applied voltage (V)" \l 7 }

E The motor electromotive force, e.m.f. (V){ TC "E The motor electromotive force, e.m.f. (V)" \l 7 }

I_a The motor armature current (A){ TC "I_a The motor armature current (A)" \l 7 }

R The motor armature circuit resistance ( ){ TC "R The motor armature circuit resistance ( )" \l 7 }

$Ø$ The motor flux (Wb){ TC "$Ø$ The motor flux (Wb)" \l 7 }

n The motor shaft speed (r.p.m){ TC "n The motor shaft speed (r.p.m)" \l 7 }

T The motor electromagnetic torque (N-m){ TC "T The motor electromagnetic torque (N-m)" \l 7 }

k_e, k_t The motor voltage and torque constants, respectably.{ TC "k_t The motor voltage and torque constants, respectably." \l 7 }{ TC "k_e, .c7.k_t The motor voltage and torque constants, respectably." \l 7 }

Normally a linear dependence of the magnetic flux and the field current is assumed so that the following equations can represent these motor models.

For the permanent magnetic motor,

$$Ø = C_1 \qquad (3.4)$$

$$T = C_2 I_a \qquad (3.5)$$

For the series motor,

$$Ø = C_3 I_a \tag{3.6}$$

$$T = C_4 I_a^2 \tag{3.7}$$

$$R = R_a + R_s \tag{3.8}$$

For the shunt motor,

$$Ø = C_5 I_f \tag{3.9}$$

$$T = C_6 I_a I_f \tag{3.10}$$

$$I_m = I_a + I_f \tag{3.11}$$

$$I_f = V_m / R_{sh} \tag{3.12}$$

For the separately excited motor,

$$Ø = C_5 I_f \tag{3.13}$$

$$T = C_6 I_a I_f \tag{3.14}$$

$$I_f = V_m / R_{sh} \tag{3.15}$$

where

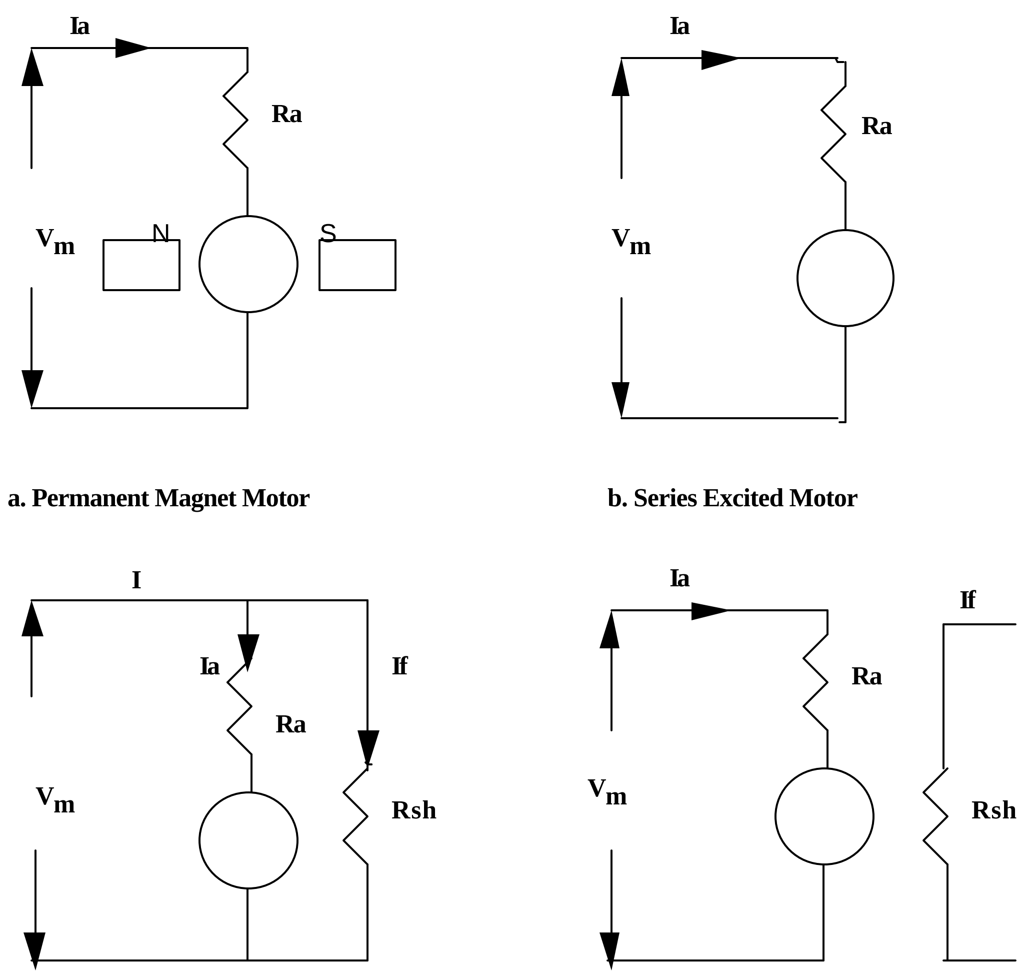
R_{sh} The filed resistance of shunt and separately excited motor( ){ TC

"R_{sh} The filed resistance of shunt and separately excited motor( )" \l 7 }

R_S The series motor field resistance ( ){ TC "R_S

The series motor field resistance ( )" \l 7 }

C_1-C_6 Motor constants



a. Permanent Magnet Motor **b. Series Excited Motor**

c. Shunt Excited Motor **d. Separately Excited Motor**

Figure 3.1 Circuit diagrams of different types of DC motors{ TC "Figure 3.1 Circuit diagrams of different types of DC motors" \l 6 }

3.1.1 The Directly Coupled Case.{ TC "3.1.1 The Directly Coupled Case." \l 3 }

By directly coupling the motor to the PV array and neglecting the motor-pump coupling losses, one may equate the motor torque to the pump torque. If the array current and voltage are equal to the motor current and voltage respectively, then the following equations will hold:

$$V_m = V_{pv} \tag{3.16}$$

$$I_m = I_{pv} \tag{3.17}$$

where

V_m and I_m are voltage and current of motor

V_{pv} and I_{pv} are voltage and current of PV array

3.1.2 The PV Pumping System with MPPT{ TC "3.1.2 The PV Pumping System with MPPT" \l 3 }

Sometimes a MPPT is used in a PV pumping system. In this case the PV array always works at its maximum power point. The motor operating voltage and current is proportional to voltage and current of the PV array in a ratio, d, as follows:

$$dV_m = V_{pv} \tag{3.18}$$

$$I_m = dI_{pv} \tag{3.19}$$

where

d is the adjustable ratio of the MPPT.

3.1.3 Brushless Permanent Magnet DC Motor{ TC "3.1.3 Brushless Permanent Magnet DC Motor" \l 3 }

Conventional DC motors use brushes sliding over the commutator attached to the rotor for commutation for electric current in the armature. Although commercially quite popular, graphite brushes can have low resistance, low friction and extremely low wear. Also they may develop high surface resistance after periods of disuse, preventing starting. Brush-type DC motors are used only for the PV application involving very low speed and standstill operations such as PV array drive, throttle valve control etc. They are not suitable for continuous high speed operation over a long period of time because of the wear and tear of the commutator and brushes, which limits the life of the motor. SolarJack developed a series of brushless permanent magnet DC motors for their pumps (SolarJack Catalog, 1995). The brushless permanent magnet DC motor has a high efficiency, a high reliability and minimum maintenance requirements. These advantages are important for the PV pumping system.

3.2 Pump{ TC "3.2 Pump" \l 2 }

The most popular pump used in a PV pumping system is the centrifugal pump. Centrifugal pumps are simple, low cost, low maintenance and are available in a wide selection of designs for a range of flow rates and heads. In this research only the centrifugal pump is considered.

The typical head profile, as shown in Figure 3.2, consists of a static component and a dynamic component. Pumps can be characterized by their head versus flow rate profile.

The friction head depends on the flow rate. The static head is defined as the height or vertical distance from the water surface to the point of free discharge or the height required to pump the water.

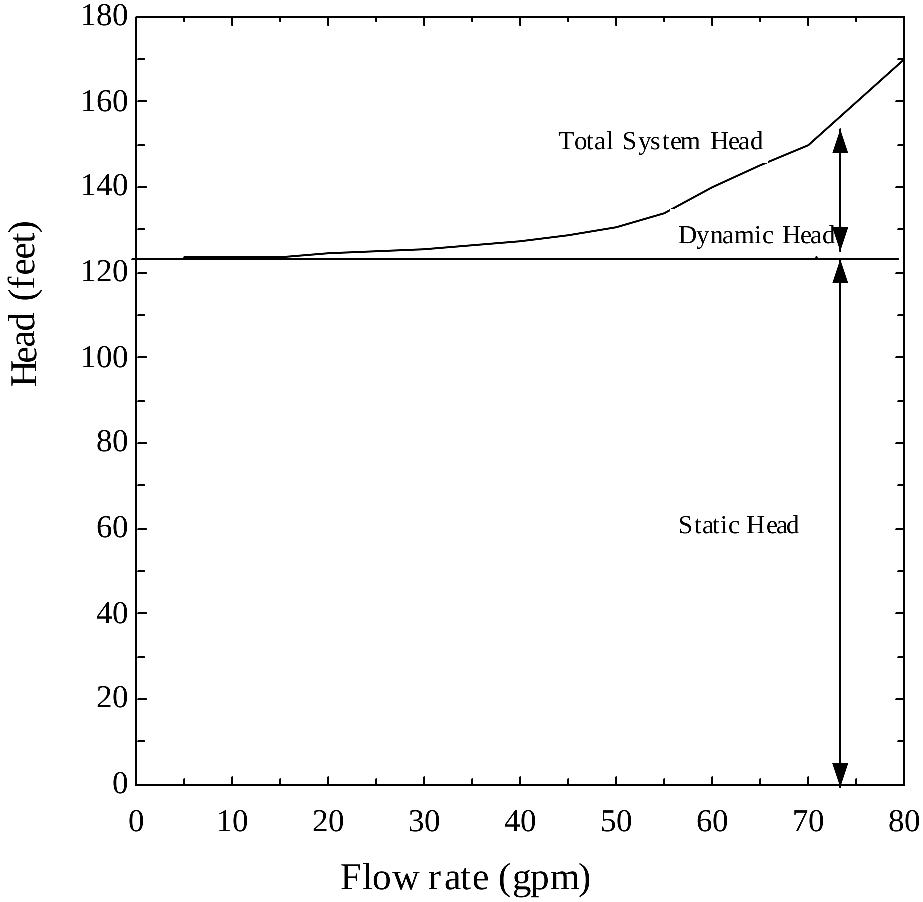


Figure 3.2 System head-flow rate profile{ TC "Figure 3.2 System head-flow rate profile" \l 6 }

For a pressurized storage system, the equivalent height of water due to the pressure contributes to the static head, while the dynamic head component is a function of flow rate and the system piping. In a PV pumping system, it is desirable to minimize the dynamic head by using large diameter pipe. Since the head is proportional to the hydraulic power and related to the electric power requirement by the efficiency of pump-motor , a lower dynamic head will reduce the required PV array size. Optimal piping designs will result in 5% to 20% dynamic head contribution to the total system head at peak-flow conditions. Therefore, for a small PV pumping system, the total head can be assumed to be total static head. We will assume that the head is constant in this project.

3.3 Previous TRNSYS Pump Type{ TC "3.3 Previous TRNSYS Pump Type" \l 2 }

Eckstein (1990) and Al-Ibrahim (1996) provided detailed information on determination of parameters for the characteristics of motors and pumps.

The model developed by Eckstein and Al-Ibrahim is a good model for a solar pumping system and briefly summarized here. The performance of pump can be predicted by using the *affinity laws* which relates speed to flow rate, head and power.

$$Q = F(n) \longrightarrow Q = Q_{ref}(n/n_{ref}) \quad (3.20)$$

$$H = F(n^2) \longrightarrow H = H_{ref}\,(n/n_{ref})^2 \quad (3.21)$$

$$P = F(n^3) \longrightarrow P = P_{ref}\,(n/n_{ref})^3 \quad (3.22)$$

where

n Speed (1/s){
TC "n Speed (1/s)" \l 7 }

n_{ref} Speed at reference condition (1/s){
TC "n_{ref} Speed at reference condition (1/s)" \l
7 }

Q Flow rate
(GPM){ TC "Q Flow rate
(GPM)" \l 7 }

Q_{ref} Flow rate at reference condition
(GPM){ TC "Q_{ref} Flow rate at reference condition
(GPM)" \l 7 }

H Head (feet){
TC "H Head (feet)"
\l 7 }

H_{ref} Head at reference condition (feet){
TC "H_{ref} Head at reference condition (feet)"
\l 7 }

P Brake horse power{ TC "P Brake horse power" \l 7 }

P_{ref} Brake horsepower at reference condition{ TC "P_{ref} Brake horsepower at reference condition" \l 7 }

The pump efficiency can be calculated as

$$\eta = a + bQ + cQ^2 + dQ^3 \tag{3.23}$$

where a, b, c, d are the coefficients at the reference condition.

The head of a pump is proportional to the square of its speed. Therefore the head under the no flow condition is related to the pump speed, under variable motor terminal voltage. Given a head profile at a reference speed, the performance of a pump can calculated for any other speed, since the affinity laws are valid for moderate change in speed.

Equations 3.20-3.23 have been used in both the motor type and the pump type to evaluate the PV pump system in the TRNSYS program. In previous models, the performance of PV pumping system is predicted by the simultaneous solution of the characteristic equations of the PV array, the motor and the pump. An iterative procedure was used to determine the system performance at each time interval. Before the simulation begins, it is necessary to use the technical data of motors and pumps. The old flow chart of TRNSYS program for the PV array, the motor and the pump is shown in Figure 3.3. This program has two problems. One is that detailed data of motor and pump is required. The other is the complex iteration required among the 3 types.

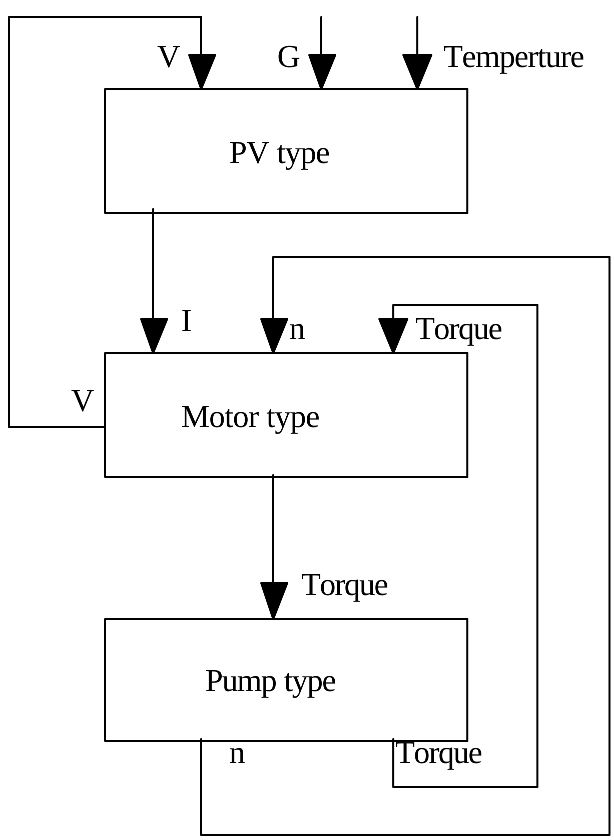


Figure 3.3 Flow chart of old PV pumping system model{ TC "Figure 3.3 Flow chart of old PV pumping system model" \l 6 }

3.4 New Motor/Pump Model { TC "3.4 New Motor/Pump Model " \l 2 }

Different combinations of motors and pumps have been investigated throughly by many researchers. Their predictions are based detail motor and pump data. However an important factor has not been considered. i.e. whether the parameters of pump and motor used in their models are available from manufacturers. At present, these parameters can not be obtained easily. The new pump model proposed here only employs the data from manufacturers' product catalog. This model can be conveniently integrated into PV type 64.

The DC motor converts the electrical energy into mechanical energy. The pump converts the mechanical energy into hydraulic energy. Therefore the characteristics of motors and pumps can be determined by current, voltage, head and flow rate. The manufacturer normally provides the head-flow-current-voltage data. For instance, SolarJack provides a comprehensive pump head versus flow rate curve of a centrifugal pump driven by a brushless permanent magnet DC motor for different operating voltages and currents as shown in Figure 3.4 and Table 3.1 (SolarJack Catalog, 1995).

Table 3.1 The measurement of performance of solar Jack SCS 18-160{ TC "Table 3.1 The measurement of performance of solar Jack SCS 18-160" \l 8 }

Head(feet)	voltage (V)	Current (A)	GPM
69	90	3.78	6.0
69	105	4.59	8.1
69	120	5.37	9.9
92	90	3.65	4.8
92	105	4.51	7.0
92	120	5.33	9.0
139	90	2.89	2.0
139	105	4.23	4.7
139	120	5.14	6.9
162	90	2.7	0
162	105	3.94	3.2
162	120	5.01	5.7

Instead of using the motor model and pump model, to represent the characteristics of the pump, the characteristics of pump and motor are represented by two functions in the new model.

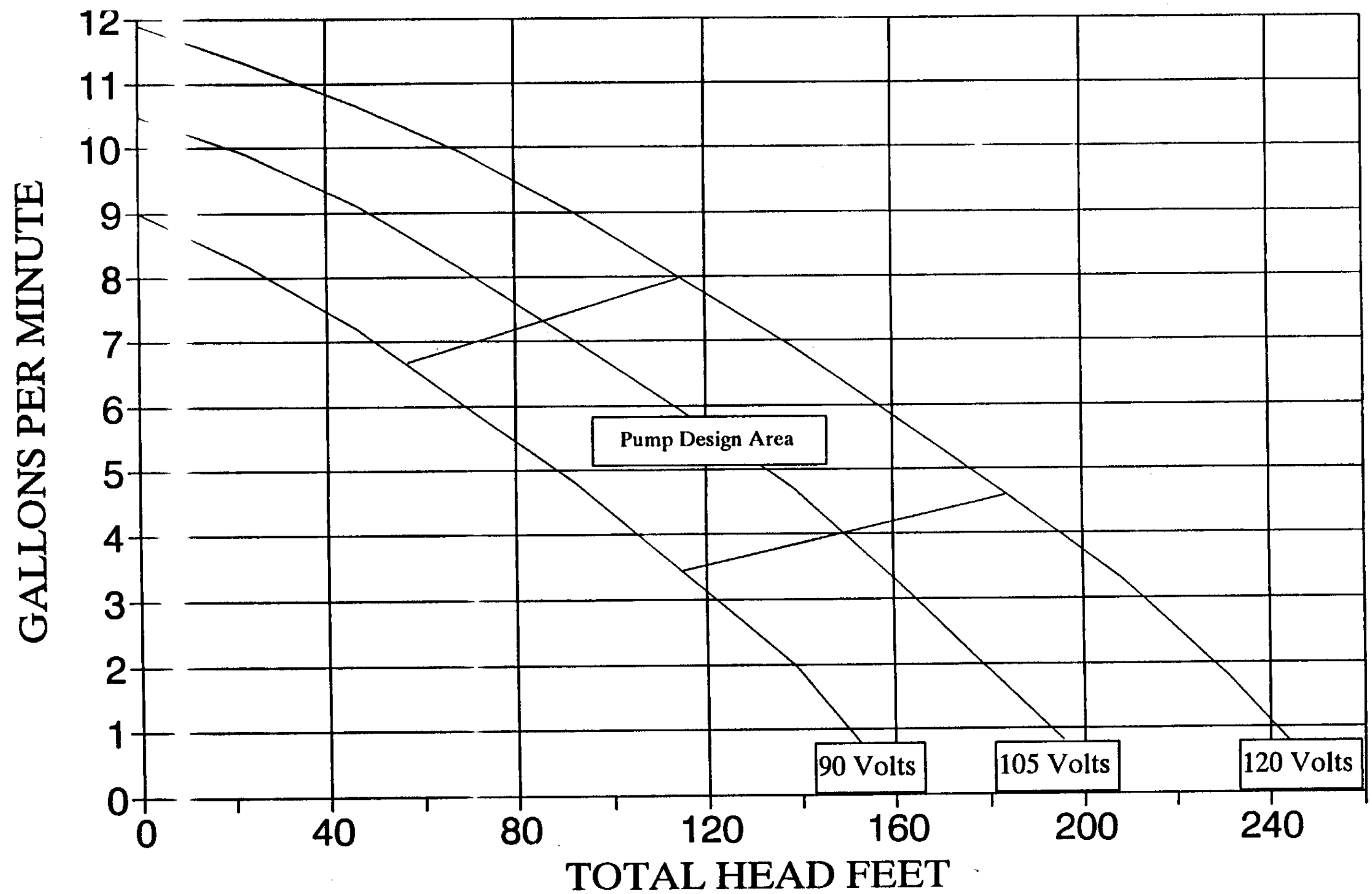

GALLONS PER MINUTE
12
11
10
9
8
7
6
5
4
3
2
1
0
0
40
80
120
160
200
240
TOTAL HEAD FEET
Pump Design Area
90 Volts
105 Volts
120 Volts

Figure 3.4 The characteristics of pump from SolarJack Inc. The type of pump is SCS18-160.{ TC "Figure 3.4 The characteristics of pump from SolarJack Inc. The type of pump is SCS18-160." \l 6 }

One is the I-V-Head function:

$$V = a_0 + a_1 I + a_2 I^2 + a3H + a4H^2 \tag{3.24}$$

where

a_0, to $a4$ are the coefficients of the function.

The I-V-H function is used to find the I-V characteristaics of the PV pumping system. The I-V curve of PV array at a certain weather condition, and the I-V-H curve of the motor-pump is solved simutoneously. See Figure 3.5.

The other motor-pump characteristaic is the GPM-V-Head function.

$$GPM = b_0 + b_1 I + b_2 Head \tag{3.25}$$

where

b_0, to b_2 are the coefficients of the function.

The coefficients of those functions can be found based on data from table 3.1 or digitized data from Figure 3.4 by using the linear regression. Using the operating point data calculated by PV model and Equation 3.24, the I-V-GPM-Head function can be used to find the flow rate of the PVPS at a fixed head. see Figure 3.5. Indeed this function relates the GPM to radiation level. Because the I-V curve of a PV array depends on the radiation level and temperature.

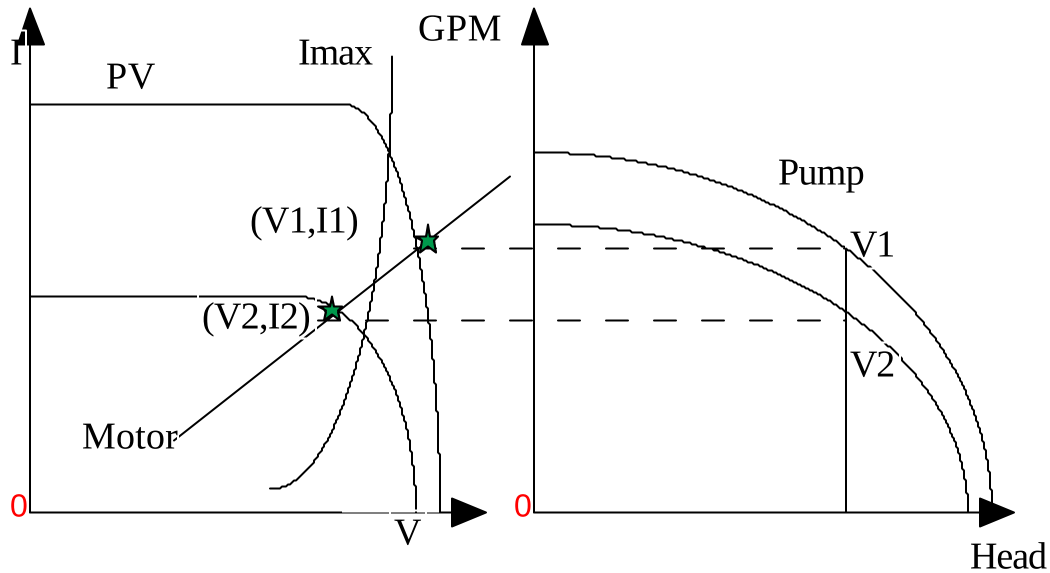


Figure 3.5 The operating point of PV pumping system{ TC "Figure 3.5 The operating point of PV pumping system" \l 6 }

3.5 Verification of New Motor/Pump Model{ TC "3.5 Verification of New Motor/Pump Model" \l 2 }

The motor-pump model was verified at different head and operation voltages. The model is powered by a data base which contains radiation and temperature data. The simulation results of the pump model were compared with SolarJack test data. The comparison of simulation by using two functions and measurement data supplied by SolarJack is shown in Figure 3.6. The pump type is SCS18-160. The results show that the two function motor-pump model is a good approximate method to simulate the characteristics of motor-pump group. The RMS difference is shown in table3.2.

Table 3.2 Statistical difference simulation and measurement of SCS18-160**{** TC "Table 3.2 Statistical difference simulation and measurement of SCS18-160" \l 8 **}**

Head	RMS(%)I-V-Head function	RMS(%)I-V-GPM-Head
23 &46 feet	0.5	0.1
92 feet	0.3	0.2
139 feet	03	0.1
162 feet	0.2	0.01

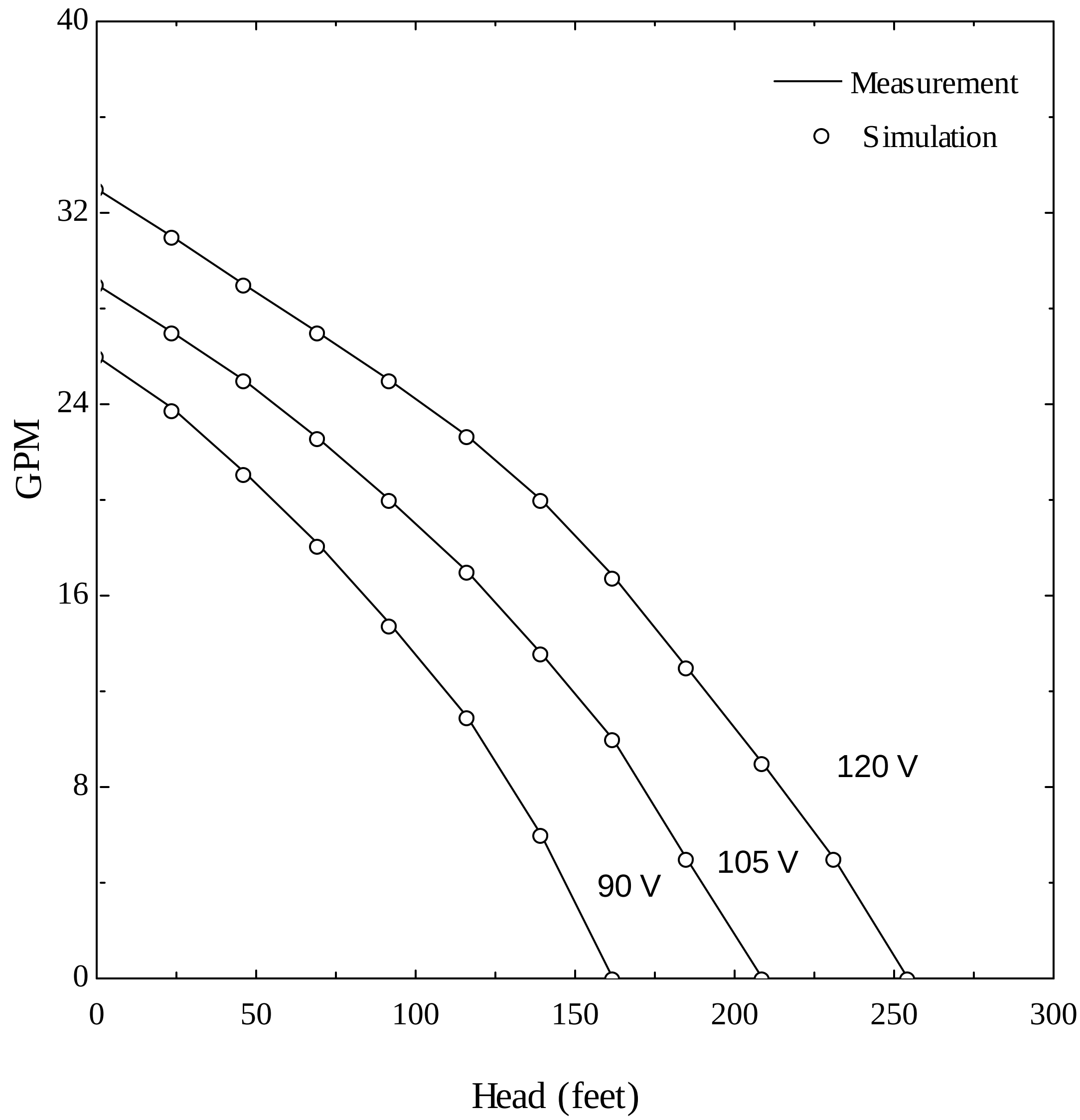


Figure 3.6 Comparison simulation and measurement of I-V-GPM-Head curve of (SolarJack Model SCS18-160) **{** TC "Figure 3.6 Comparison simulation and measurement of I-V-GPM-Head curve of (SolarJack Model SCS18-160) " \l 6 **}**

Using characteristics of the pump and PV array, the GPM and system operating points versus radiation level can be calculated as shown in Figure 3.7 and Figure 3.8.

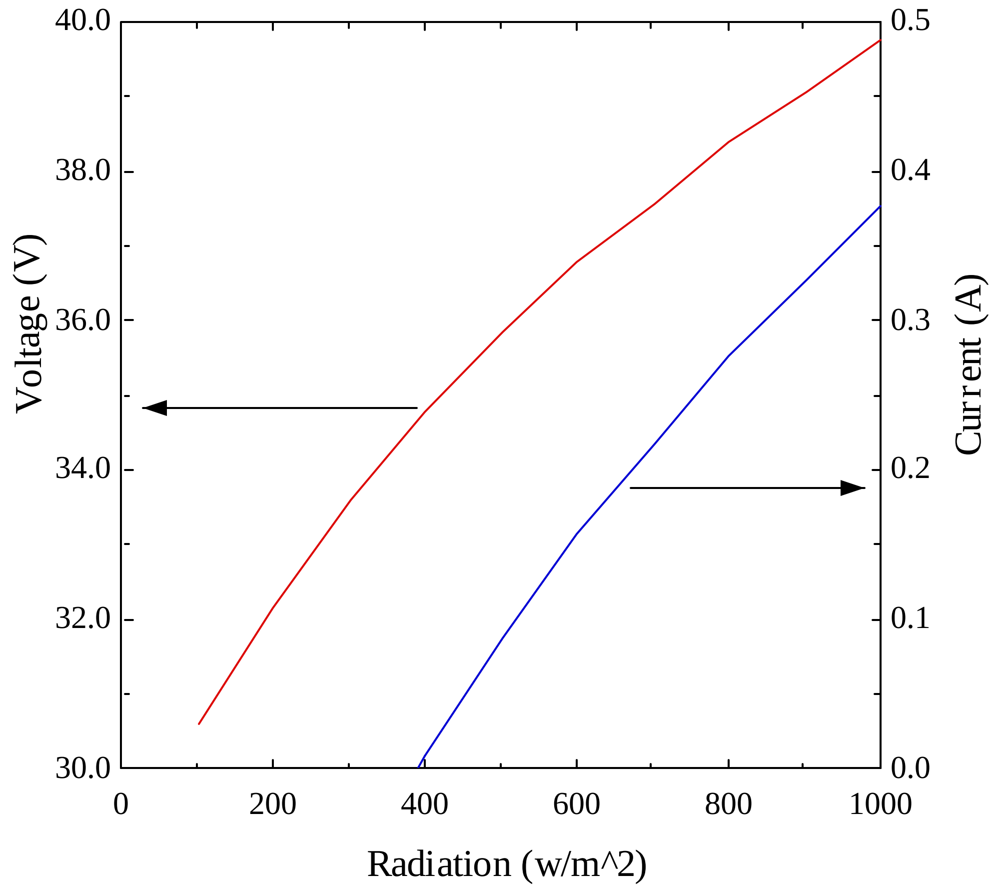


Figure 3.7 Operating point vs radiation of SCS4.5-100 at fixed head{ TC "Figure 3.7 Operating point vs radiation of SCS4.5-100 at fixed head" \l 6 }

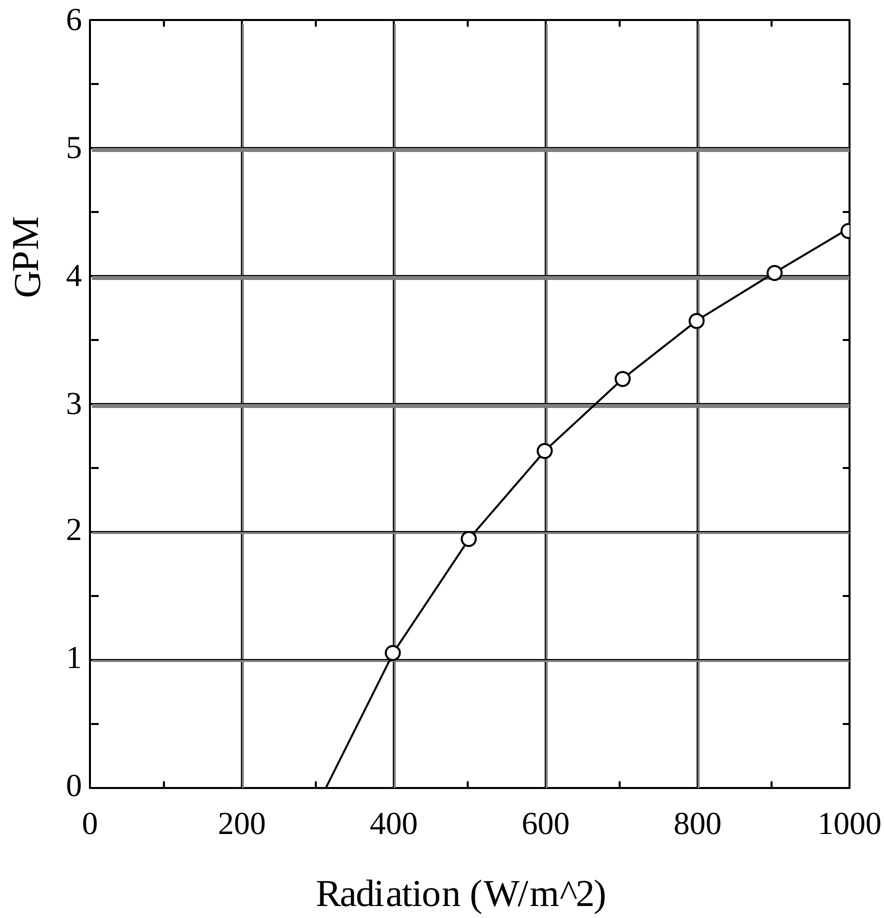


Figure 3.8 The GPM vs radiation of SCS5.7-160 at a head of 93 feet**{** TC "Figure 3.8 The GPM vs radiation of SCS5.7-160 at a head of 93 feet" \l 6 **}**

This new pump model has been used in the TRNSYS and EES programs. The flow chart of the pump model is shown in Figure 3.9. The two functions can be integrated into Type 64 which was discussed in chapter 2. The new PV pump program only has two inputs, radiation and temperature. The output can be the GPM and other parameters that user are interested in. More simulations will be discussed in the chapter 5 and chapter 6.

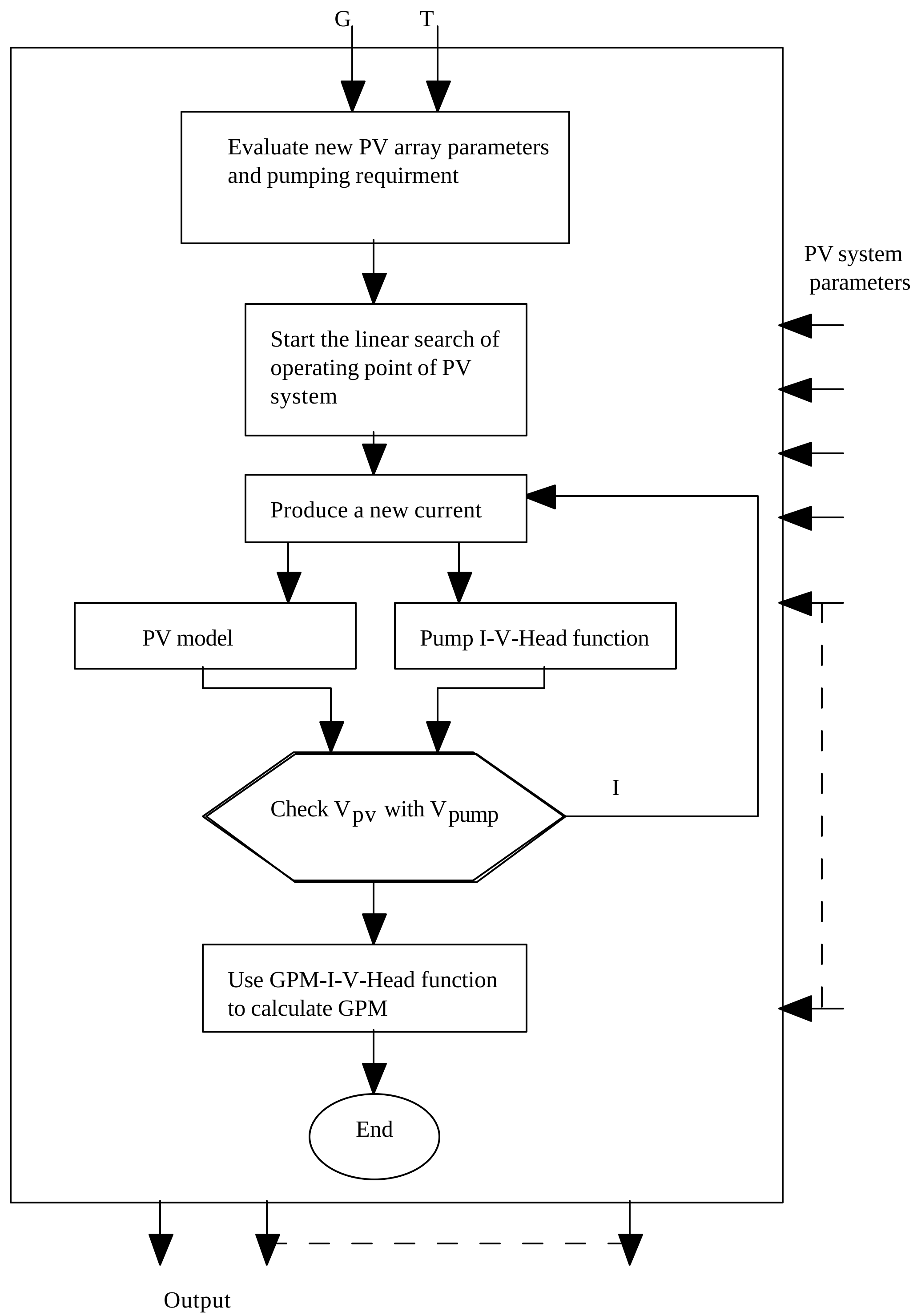


Figure 3.9 The flow chart of new TRNSYS pump model{ TC "Figure 3.9 The flow chart of new TRNSYS pump model" \l 6 }

The coefficients of these two functions for 5 pumps at different heads are found in Appendix C.