MODELING OF A PHOTOVOLTAIC POWERED REFRIGERATION SYSTEM

by

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ABSTRACT

Photovoltaic powered refrigerators are a new technology for storing vaccine in remote areas of developing countries. These systems consists of a d.c. vapor compression refrigerator with freezer, a controller, a battery to store and supply energy and a photovoltaic (PV) generator which supplies the refrigerator, and charges the battery with excess energy. The advantage of this system compared to the common fuel systems is that it does not require an outside fuel supply. When properly designed it guaranties the safe storage of vaccine.

All PV systems have high initial costs. A design that minimizes initial costs and always meets the load will waste the least energy. In order to determine the suitability of a specific design, it is necessary to simulate the system performance over a time scale on the order of one year. It is not possible to estimate performance at a single "design condition" and guarantee proper long-term operation. TRNSYS was used to simulate the system performance. Component models are available for the PV array, the battery, the refrigerator case, the charge controller and the motor-cooling system combination. Except for this last model, the component models are typical TRNSYS models based upon first principles. The combined motor-cooling system model is a curve fit from calculations of the performance of a typical refrigeration cycle with evaporator, condenser, expansion valve and compressor being driven by a brushless d.c. motor. This curve fit model is much faster than trying to solve all of the

cycle equations at each integration time step and yields nearly identical results. The purpose of the controller is to protect the battery from overcharge and deep discharge.

TRNSYS can do annual simulations on an hourly, or shorter, time basis. The weather data for estimating the annual performance of the PV system were TMY (typical meteorological year) data for Miami. The effect of slopes of 0, 20, 25, 40 and 60° for a PV array consisting of two and three parallel modules were studied. The result was that a PV array consisting of three parallel modules was necessary to meet the load and that a slope of 20° gave the most efficient output. Then PV systems with battery sizes of 25, 50, 100 and 250 Ah were studied. The battery sizes of 25 and 50 Ah were to small to supply the load during a period of bad weather, whereas the systems with rated battery capacities of 100 and 250 Ah met the load over the whole year. The final system consisted of a PV array of three parallel modules sloped at 20° and a battery with a rated capacity of 100 Ah.

ACKNOWLEDGMENT

In March 1991 I applied for a scholarship at the German Academic Exchange Service (DAAD) to study abroad. After many months of waiting I finally got a positive response. At that time many thoughts went through my head. One of them was if I really want to leave my decent job and friends to study in the US. But this was a chance one does not get very often in life and I left Germany. Even if there was a lot of frustration during my first semester I figured soon that it was the right decision to leave the country in which I grew up to study in the Solar Energy Lab in Madison.

My advisors in the Lab were Bill and Sandy. Both of you gave me some headaches by pointing out aspects of my work I did not even think about. Thanks to you, I learned a lot. And then there were the two TRNSYS masters Jeff and Alex. I know that I bothered you with tons of questions and took away a lot of your time. Didn't I make you sick sometimes? Especially you Alex heard often: "Hey, TRNSYS does not run." Of course most of the time it was me who made the error. I appreciate your help a lot.

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I also would like to thank you Patricia, Shashi, Despo and Gina for being such good friends. I always felt very comfortable at your place. Lise, even if your country won the European Championships in Soccer against us, Andreas and I won the Water Battle Championships against Denmark. And you Elmar, your height and our friendship turned out to be directly proportional. And you are pretty tall. Then there is you Rainer, our Nahanni trip was fantastic. I will never forget your face when we thought there was a bear in front of our tent. During the whole time my parents and my sister always sent me unexpected care packages with good chocolate and kept me informed about things at home. You did a good job.

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The German Academic Exchange Service (DAAD) made this trip possible for me. I think we all can be glad about the existence of this or other organizations who finance students to study abroad and therefore let you get in contact with other cultures totally different to ones own.

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NOMENCLATURE

Roman Symbols

A	- area	[m2]
A	- static frictional loss coefficient	[N-m]
A_c	- air changes per minute	
A_{ref}	- refrigerator area	[m^2]
B	- dynamic frictional loss coefficient	[N-m-sec]
CAP	- refrigeration capacity	[kW], [Btu/hr]
COP	- coefficient of performance	
C_p	- cells-modules in parallel	
cp_{air}	-specific heat of air	[kJ/kg-K]
cp_{ice}	-specific heat of ice	[kJ/kg-K]
C_s	- cells-modules in series	
cp_{wat}	-specific heat of wat	[kJ/kg-K]
E_a	- electromagnetic force	[V]
E_c	- constant open circuit voltage of the battery when charging	[V]
E_d	- constant open circuit voltage of the battery when discharging	[V]
E_D	- battery constant	[V]
F	- fractional state of charge of the battery	
G_c	- current capacity on charge	

G_d	- current capacity on discharge	
G_T	- solar insolation	[W/m^2]
h	- enthalpy	[kJ/kg-K]
h	- heat transfer coefficient	[W/m^2-K]
I	- PV current	[A]
I_{bat}	- battery current	[A]
I_{cell}	- current through a battery cell	[A]
I_d	- diode current	[A]
I_{di}	- curve fitting parameter	
I_l	- light current	[A]
I_{mp}	- current at maximum power	[V]
I_o	- diode reverse current	[A]
I_{sc}	- short circuit current	[A]
I_{sh}	- current through the shunt resistance	[A]
I_t	- current	[A]
k	- conductivity	[W/m-K]
K_b	- back EMF constant	[V-sec/rad]
K_{di}	- curve fitting parameter	
Kt	- torque constant	[N-m/A]
l	- thickness	[m]
L	- inductivity	[H]
m	- ratio of clearance volume over displacement volume	
M_{AF}	- mutual inductance	[Vsec/A]
m_c	- cell type parameter	
m_d	- cell type parameter	

m_{ice}	- mass ice	[kg]
M_p	- # of PV modules in parallel	
M_s	- # of PV modules in series	
m_{wat}	- mass water	[kg]
n	- polytropic exponent	
N	- speed	[1/sec]
N_s	- # of cells in series times # modules in series	
P	- pressure	[kPa]
P_{in}	- input power	[watts]
P_{loss}	- loss of energy for the battery	[watts]
P_o	- output power	[watts]
Q	- actual capacity of a battery cell	[Ah]
Q_d	- capacity parameter on discharge	[Ah]
Q_m	- rated capacity of battery	[Ah]
Q_{rej}	- rejected energy	[kJ], [Btu]
Q_{lat}	- latent heat	[W]
Q_{load}	- total heat of the load	[W]
Q_{sen}	- sensible heat	[W
R	- resistance	[ohms]
RPM	- revolutions per minute	[1/min]
R_s	- series resistance	[ohms]
R_c	- internal resistance at full charge when charging battery	[ohms]
R_d	- internal resistance at full charge when discharging battery	[ohms]
R_D	- battery constant	[ohms]
R_{sh}	- shunt resistance	[ohms]

t	- time	[sec]
T	- temperature	[C], [F]
T	- d.c. motor torque	[Nm]
T_a	- ambient temperature	[C]
T_c	- cell temperature	[C]
t_{do}	- daily opening time	[min]
T_{fr}	- freezer temperature	[C]
T_{loss}	- rotational losses	[Nm]
T_o	- output torque	[Nm]
T_{ref}	- refrigerator temperature	[C]
T_{rm}	- room temperature	[C]
UA_{con}	- overall heat transfer coefficient area product, condenser	[W/K]
UA_{ev}	- overall heat transfer coefficient area product, evaporator	[W/K]
U_L	- heat transfer loss coefficient	[W/m^2-K]
V	- volume	[m^3]
V	- voltage	[V]
V_{bat}	- battery voltage	[V]
V_c	- maximum charge voltage for the battery	[V]
V_{cell}	- voltage of a battery cell	[V]
V_d	- maximum discharge voltage for the battery	[V]
V_{di}	- voltage drop over diode	[V]
V_{displ}	- displacement volume	[m^3]
V_{mp}	- voltage at maximum power	[V]
V_{oc}	- open circuit voltage	[V]
V_{ref}	- refrigerator volume	[m^3]

V_t	- terminal voltage	[V]
v	- specific volume	[m^3/kg]
W_{pol}	- polytropic work	[
w	- mass flow rate	[kg/sec], [lbs/hr]

Greek symbols

η	- efficiency	
η_c	- efficiency of PV a cell	
η_{mot}	- motor efficiency	
η_{vol}	- volumetric efficiency	
ρ	- density	[kg/m^3]
ω	- angular velocity	[1/sec]
γ	- curve fitting parameter	
ε	– bandgap energy	[eV]
$\mu_{V,oc}$	- temperature coefficient for open circuit voltage	[V/K]
$\mu_{I,sc}$	- temperature coefficient for short circuit current	[A/K]
τ	- transmittance	
α	- absorptance	
ϕ	- magnetic flux	[Wb]

Chapter 1

INTRODUCTION

In the year 1839 Becquerel discovered the photovoltaic (PV) effect in electrolytic cells. 34 years later Willoughby Smith discovered the photoconductivity in selenium which led to the first PV cell described by Fritts in 1883. It took 58 more years of development to prepare the first single - crystal silicon PV device at Bell Telephone Laboratories. In the same year a silicon cell conversion efficiency of 6 % was achieved. Within two years private industry started producing PV cells. An improvement of the fabrication processes and the understanding of the theory of the device led to an efficiency of 14 % in terrestrial sunlight by 1958. From that point on until the mid seventies photovoltaic energy became interesting for space power systems which built the biggest market for the PV industry.

In the last 15 years the situation has been changed dramatically. An increase of the energy demand, the fact that fossil energy is finite, the impact of burned fossil fuels on the environment and the storage problem of nuclear waste increased the effort towards better production technologies and higher conversion efficiencies. These efforts led to an efficiency of 22.8 % for a single crystal silicon cell under laboratory conditions in the year 1988. Also the price drop was tremendous. 20 years ago 1 peak watt was $ 1000, today the price is between $ 5 and $ 10 per peak watt. This price drop makes PV systems economical, especially in remote areas.

1.1 Objectives

The origin of this thesis is the Central American Health Clinic Project, initiated in 1986 by the US Department of Energy (DoE) and the Organization of American States (OAS). The main purpose of this project is to improve health care in the rural areas in Central America by storing vaccine in PV powered refrigerators. Testing of PV powered vaccine refrigerators was started in 1987 at the Florida Solar Energy Center (FSEC) [1] to observe, document, and evaluate the performance of these systems.

An important field in PV technology is system design. Because the efficiency of commercial PV cells is only between 10 and 15 % and the energy supplied from the PV array depends on the incident solar radiation, the components should be well matched to each other to operate the system at an optimal level.

The components of the stand alone system described in this thesis are a PV array, a controller, a battery, a brushless d.c. motor and a vapor compression refrigerator. Figure 1.1 shows the system configuration.

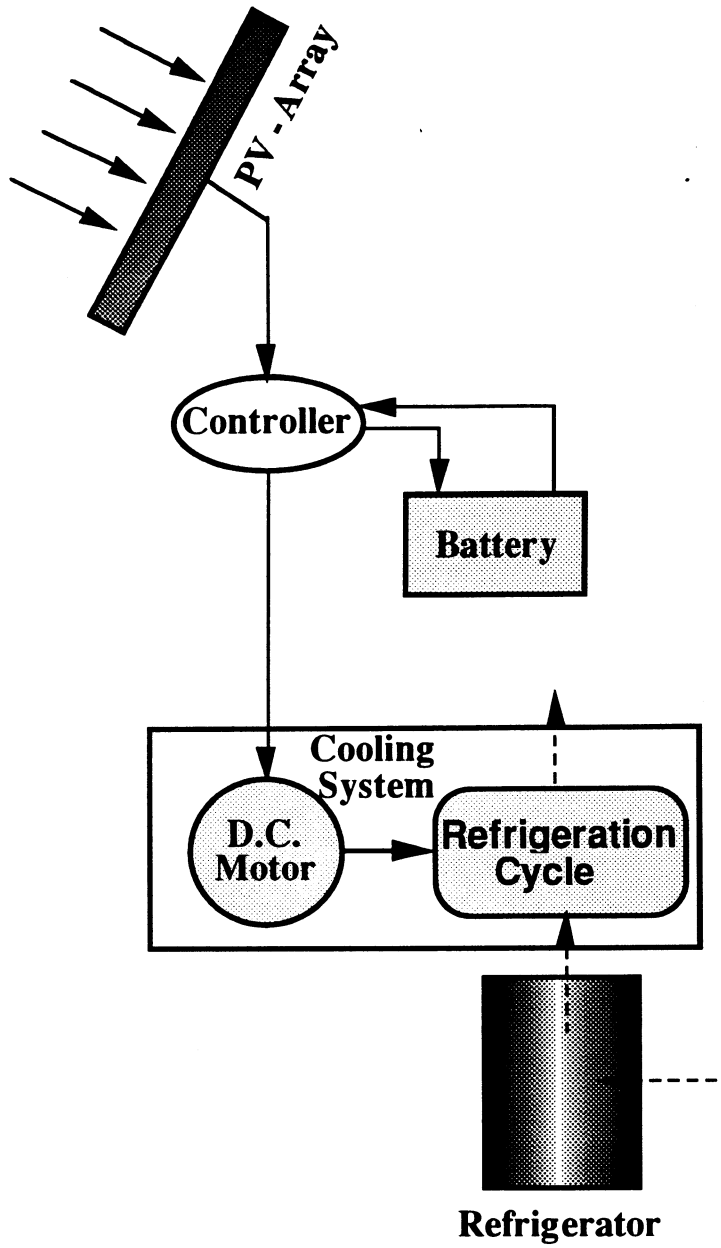

Figure 1.1: System configuration for a PV powered refrigerator

The task of this research is to develop computer models for the components of the stand alone refrigerator system, and to optimize the size of the PV array and battery such that the refrigerator load is always met while minimizing initial costs. The computer models are developed with the *Engineering Equation Solver* (EES) [2] and analyze the behavior of each component under steady state operating conditions. Then FORTRAN models are written to be used in the *Transient System Simulation Program* (TRNSYS) to predict and analyze the performance of the PV system and to improve system design.

The thesis is organized in the following way: Chapter two to five describe the PV array, the battery and controller, the brushless d.c. motor and the refrigeration cycle. Chapter six analyses the cooling system consisting of d.c. motor and refrigeration cycle, and shows the steady state operating conditions of the PV system. Chapter seven is about the information flow of the TRNSYS components and Chapter eight describes the simulation. Chapter nine presents conclusions and recommendations for future work.

1.2 Applied programs

1.2.1 EES

EES [2] is an acronym for Engineering Equation Solver. The program was written at the University of Wisconsin - Madison and is an equation solving program that provides many built-in mathematical and thermophysical property functions. For example, the steam tables are implemented such that any thermodynamic property can be obtained from a built-in function call in terms of any two other properties. Because of its large data bank of thermodynamic and transport properties EES is an easy and ideal tool for solving problems in thermodynamics, fluid mechanics, and heat transfer.

EES is a flexible tool for solving large systems of equations. The program solves systems of non-linear equations by a Newton-like algorithm. This equation solver includes optimization algorithms, and parametric tables to quickly determine the behavior of a model by varying different parameters after each run.

1.2.2 TRNSYS

TRNSYS [3] stands for Transient System Simulation Program and was developed at the University of Wisconsin-Madison. It has a modular structure and contains individual subroutines, called TYPES. The subroutines are mathematical models of a real physical devices. By interconnecting different subroutines a variety of systems can be constructed. The construction of such a system is called TRNSYS deck and has all the information necessary to run a simulation.

To make the program flexible each subroutine seems like a black box to the environment. The interface of a subroutine consists of inputs, outputs and parameters. While the inputs and outputs may be time dependent, the parameters are fixed values throughout the simulation. The TRNSYS deck interconnects the outputs of a subroutine with an input of another subroutine and determines the data flow of the calculations.

Most of the simulations are driven by meteorological data. For a PV system the necessary data are the solar radiation and the ambient temperature. For many locations data are available on an hourly basis for a typical meteorological year (TMY). If these data are not available TRNSYS provides a tool to generate hourly weather data for a single year given a number of average monthly values for the desired location.

For any timestep TRNSYS will solve all the equations defining the system via successive substitution. The starting time, the length of the simulation and the timestep are specified by the user and can easily be changed. The reader will become more familiar with the possibilities of this program while reading Chapter 7 and 8.

Chapter 2

PHOTOVOLTAIC (PV) ARRAYS

Photovoltaic cells are semiconductor devices that convert part of the incident solar radiation into electrical energy. Several connected PV cells form a PV module, connected modules form a PV array. The necessary size of the array for a particular load depends primarily on the meteorological conditions. A PV array delivers energy depending on the incident solar radiation. Because of the transient behavior of the meteorological condition the selection of the individual components is important in order to produce energy at the lowest costs. When operating such a PV system, usually a second energy source is necessary as a backup. To size a PV system, the current-voltage (I-V) characteristic of each component has to be known. This chapter describes a mathematical model for a PV module. The information on which this model is based can be found in references [4] and [5].

2.1 Electrical circuit for a PV generator

Figure 2.1 shows the equivalent electrical circuit for a PV generator.

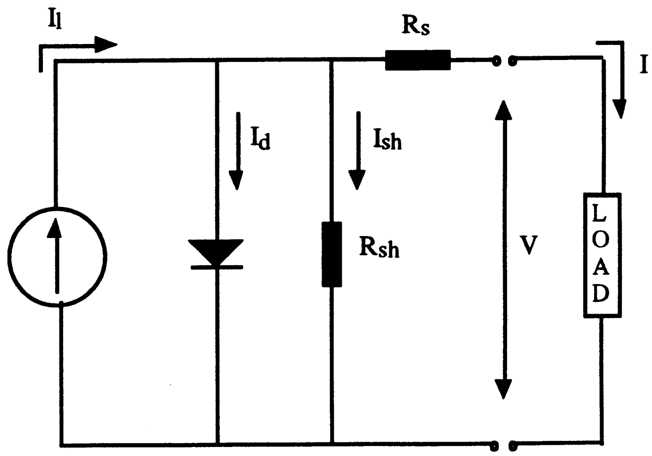

Figure 2.1: Equivalent electrical circuit for a PV generator

The light current , I_l, is generated from the PV array and is proportional to the incident radiation. The diode describes the semiconductor behavior of the PV cells. The current through the diode, I_d, is the loss current through the junction of the cell. The shunt resistance , R_{sh}, accounts for leakage losses at the outer edges of the cell and is usually very large, and often neglected. In this model, R_{sh} is assumed to be infinite. The series resistance, R_s, accounts for the resistances at the connections between cell and contact grid.

2.2 Governing equations and I-V characteristic of the PV module

Using Kirchhoff's law, the load current, I, can be calculated with equation [2.1].

$$I = I_l - I_d - I_{sh} \qquad [2.1]$$

where

I_l is the light current,

I_d is the current through the diode,

I_{sh} is the current through the shunt resistance.

Replacing I_d and I_{sh} with their characteristics, equation [2.1] can be rewritten as shown in equation [2.2].

$$I = I_l - I_o \{exp(\frac{V + I R_s}{\gamma}) - 1\} - \frac{V + I R_s}{R_{sh}} \qquad [2.2]$$

where

I_o is the diode reverse saturation current

V is the output voltage,

R_s is the series resistance,

γ is a curve fitting parameter,

R_{sh} is the shunt resistance.

Equation [2.2] is valid for a fixed solar radiation, ambient and cell temperature. The influence of the cell temperature is discussed later in this chapter.

To solve equation [2.2] for the current as a function of the voltage the five parameters I_l, I_o, R_s, γ and R_{sh} are needed. The current-voltage (I-V) and the power-voltage (P-V) characteristics of the PV module are illustrated in Figure 2.2 for a typical set of the five parameters.

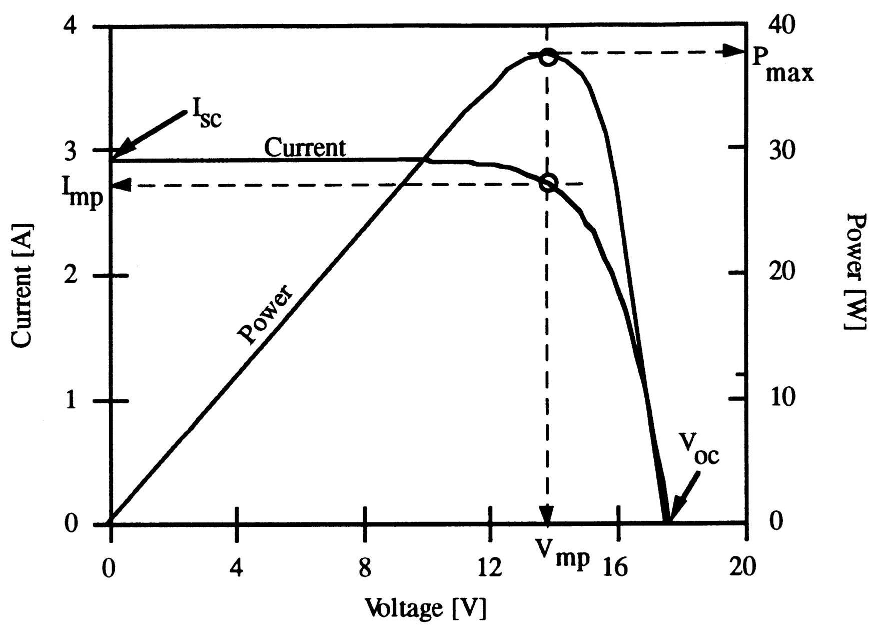

Figure 2.2: I-V and P-V characteristics for a PV module

If the voltage is zero, short circuit conditions exist. The current at this point is called short circuit current, I_{sc}. If the load resistance is infinite, the current is zero, the voltage is at its maximum. This voltage is called open circuit voltage, V_{oc}. The second curve in Figure 2.2 shows the behavior of the power with respect to the voltage. The point where the power reaches its maximum is called the maximum power point. The voltage at this point is written as V_{mp}, the current as I_{mp}.

The manufacturer of PV modules usually provides measured values of V_{oc}, I_{sc}, V_{mp} and I_{mp} at reference conditions. The reference conditions usually are at an incident solar radiation of 1000 W/m^2 and an ambient temperature of 25 C. With these measured values, the four parameters I_l, I_o, γ and R_s can be evaluated. R_{sh} is assumed to be infinite. At short circuit conditions, the diode current, I_d is very small and can be neglected. It follows that the light current, I_l is equal to the short circuit current, I_{sc}.

$$I_l = I_{sc} \qquad [2.3]$$

Under open circuit conditions, the load current, I, is zero. The light current is equal to the current through the diode. With equation [2.4] the diode reverse saturation current, I_o, is evaluated.

$$I_o = I_l \, exp(- \frac{V_{oc}}{\gamma}) \qquad [2.4]$$

The 1 in Equation 2.2 is neglected because it is small compared to the exponential term. The maximum power conditions and Equations [2.3] and [2.4] are substituted into equation [2.2] and the series resistance is evaluated.

$$R_s = \frac{\gamma \, ln \, (1- \frac{I_{mp}}{I_{sc}}) - V_{mp} + V_{oc}}{I_{mp}} \qquad [2.5]$$

Equations [2.4] and [2.5] can only be solved when the curve fitting parameter γ is known. The manufacturers do not provide a value for γ at reference conditions, but in addition to the four numbers mentioned before, they provide the cell temperature at reference conditions and the temperature coefficients for the short circuit current, $\mu_{I,sc}$, and the open circuit voltage, $\mu_{V,oc}$. These coefficients describe the temperature behavior of the module shown in Figure 2.3.

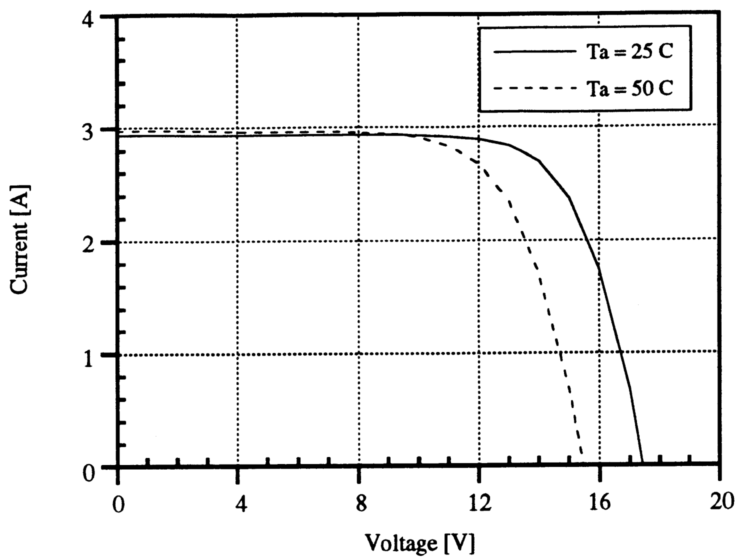

Figure 2.3: I-V characteristics of a PV module for different ambient temperatures

With this additional information Townsend [6] derived the following equation for calculating the curve fitting parameter under reference conditions (γ_{ref}).

$$\gamma_{ref} = \frac{\mu_{V,oc} T_{c,ref} - V_{oc,ref} + \varepsilon N_s}{\frac{\mu_{I,sc} T_{c,ref}}{I_{l,ref}} - 3} \qquad [2.6]$$

where

ε is the bandgap energy (1.12 eV for silicon),

N_s is the number of cells in series times the number of modules in series.

With equation [2.6] Townsend showed that the following equations are valid for most PV modules.

$$\frac{\gamma}{\gamma_{ref}} = \frac{T_c}{T_{c,ref}} \qquad [2.7]$$

$$I_l = \frac{G_T}{G_{T,ref}} [I_{l,ref} + \mu_{I,sc} (T_c - T_{c,ref})] \qquad [2.8]$$

$$\frac{I_o}{I_{o,ref}} = (\frac{T_c}{T_{c,ref}})^3 \; exp \; [\frac{\varepsilon N_s}{\gamma_{ref}} (1 - \frac{T_{c,ref}}{T_c})] \qquad [2.9]$$

With these equations, the I-V curves for different radiation levels can be obtained. Figure 2.4 shows the characteristic for different insolation levels.

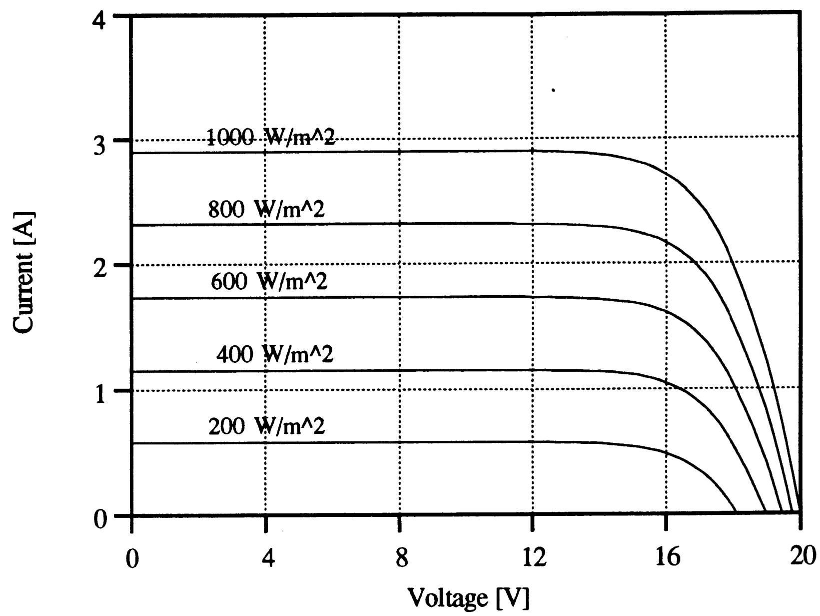

Figure 2.4: I-V curves for a PV generator at different radiation levels

The cell temperature used to develop Figure 2.4 is constant.

The following section describes the effect of connecting PV modules in parallel and series.

2.3 Modules connected in series and parallel

PV cells are connected in series and parallel in a PV module. A PV module is characterized by its peak power (i.e., its maximum electrical power at a solar intensity of 1000 W/m^2). This power is increased if several modules are connected in parallel and series to form a PV array. Depending if the modules are connected in series or parallel, either the voltage or the current is increased. Figure 2.5 shows curves for differently connected PV arrays.

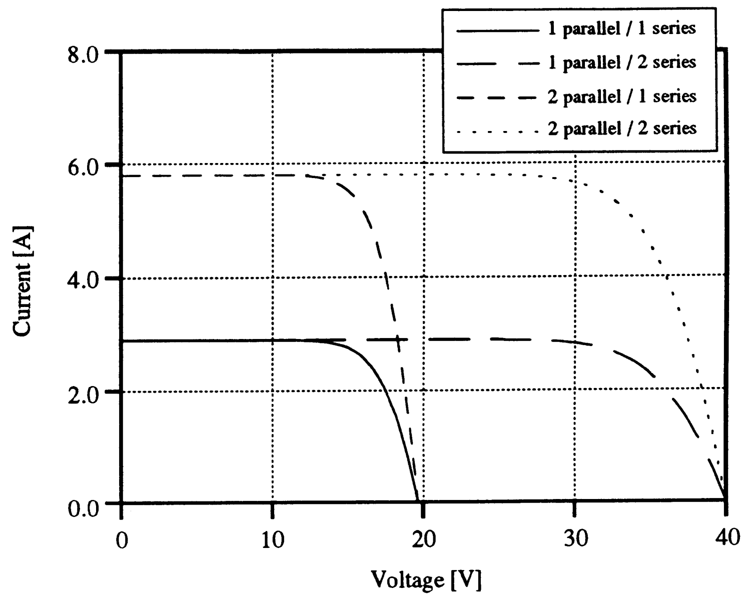

Figure 2.5: I-V characteristics for differently connected PV arrays

To describe the IV characteristics of an array the following parameters are scaled.

$$I_{l,tot} = M_p\, I_l \qquad [2.10]$$

$$I_{o,tot} = M_p\, I_o \qquad [2.11]$$

$$\gamma_{tot} = M_s\, \gamma \qquad [2.12]$$

$$R_{s,tot} = \frac{M_s}{M_p} R_s \qquad [2.13]$$

where

M_p is the number of modules in parallel,

M_s is the number of modules in series.

The outputs of interest are:

$$I_{tot} = M_p I \qquad [2.14]$$

$$V_{tot} = M V \qquad [2.15]$$

Using these equations assumes modules to be identical. In practice this is not the case. The production tolerances are between $\pm$ 5 - 10 %.

2.4 Influence of the cell temperature

The solar energy that is absorbed by the module is converted into thermal energy and electrical energy. The electrical behavior of the PV module was described in the previous sections. Here the influence of the cell temperature on the I-V characteristic is analyzed. To determine the cell temperature of a PV module, an energy balance is made.

$$\tau\, \alpha\, G_T = \eta_c\, G_T + U_L\, (T_c - T_a) \qquad [2.16]$$

where

τ is the transmittance of the cover,

α is the absorption coefficient,

G_T is the incident solar radiation,

η_c is the efficiency of the module,

U_L is the loss coefficient of the module,

T_a is the ambient temperature.

The ratio $\tau\alpha/U_L$ is assumed to be constant. To determine this ratio the nominal operating cell temperature (NOCT) is measured. The NOCT conditions are an incident solar radiation of 800 W/m^2, a wind speed of 1 m/s and an ambient temperature of 20 C. The measurement is made under no load conditions. In this case the efficiency, η_c, is zero, whichleads to Equation [2.17] for the ratio $\tau\alpha/U_L$. Once $\tau\alpha/U_L$ is known, Equation [2.18] can be applied to calculate the cell temperature at other operating conditions.

$$\frac{\tau\alpha}{U_L} = \frac{(T_{c,NOCT} - T_{a,NOCT})}{G_{T,NOCT}} \qquad [2.17]$$

$$T_c = T_a + (G_T \frac{\tau\alpha}{U_L})\,(1 - \frac{\eta_c}{\tau\alpha}) \qquad [2.18]$$

To show the influence of the cell temperature, the calculations used to create Figure 2.4 are redone with a cell temperature that depends on the ambient conditions. Figure 2.5

shows the IV characteristics for an ambient temperature of 25 C and $\tau\alpha/U_L$ equal to 0.0325 K-m^2/W.

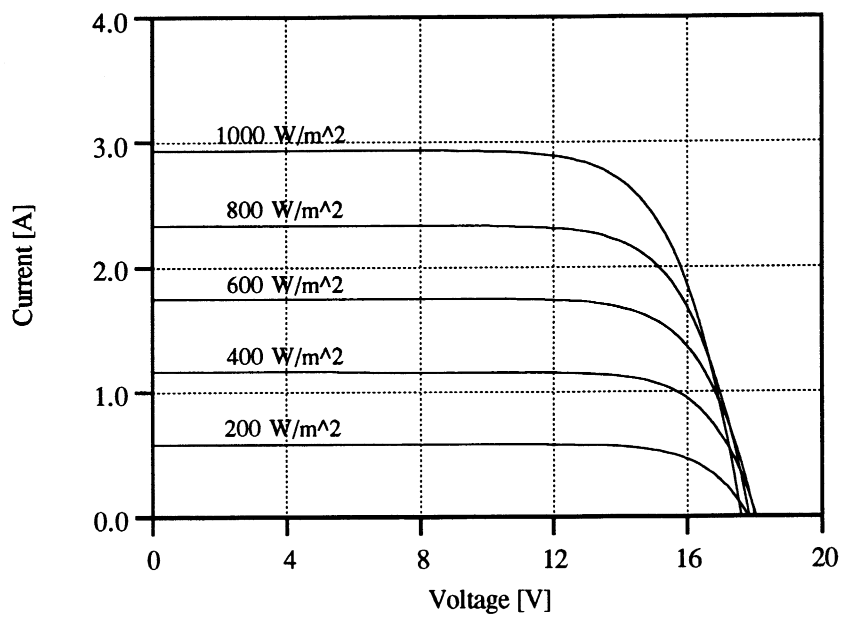

Figure 2.6: I-V curves for a PV generator at different radiation levels with a variable cell temperature

Figure 2.6 shows the effect of the cell temperature at voltages close to the open circuit voltage. In comparison to the behavior with a constant cell temperature as shown in Figure 2.4, the open circuit voltage decreases with an increase of the incident solar radiation.

The behavior of the cell temperature as a function of the incident solar radiation is illustrated in Figure 2.7.

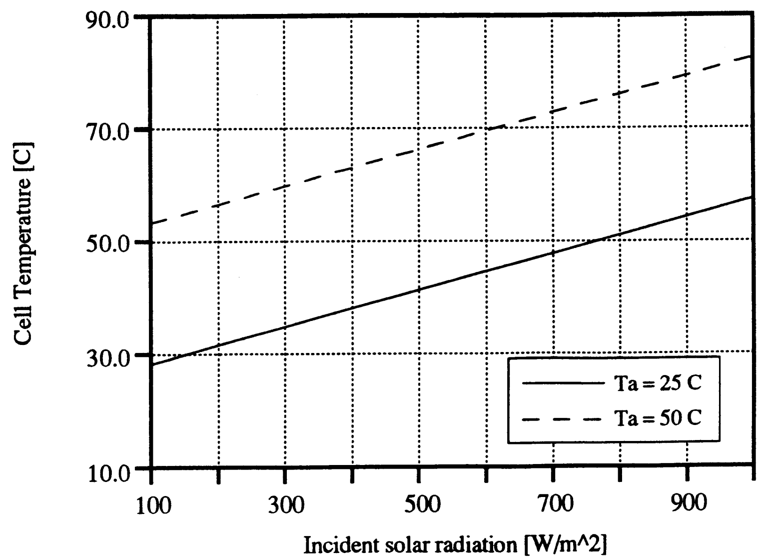

Figure 2.7: Cell temperature as a function of the incident solar radiation

Figure 2.7 shows that the cell temperature increases linearly with the incident solar radiation and the ambient temperature.

The cell temperature as a function of the voltage at two different radiation levels is shown in Figure 2.8.

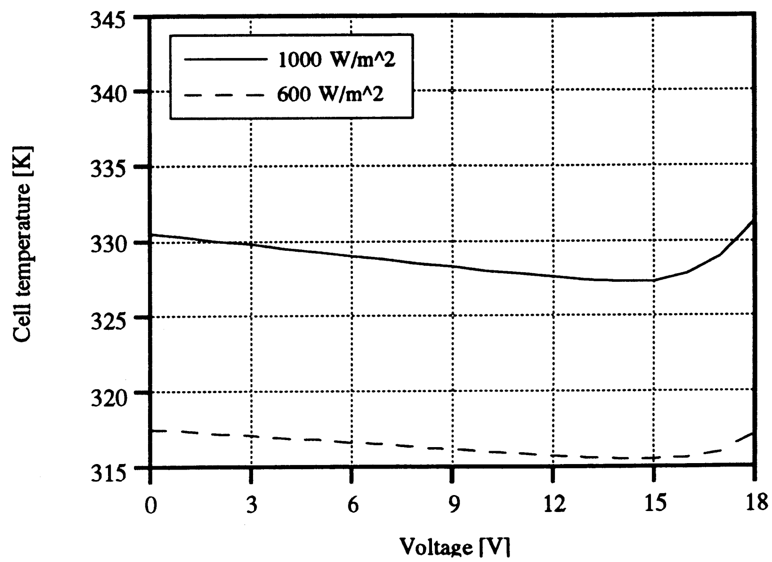

Figure 2.8: Cell temperature as a function of the voltage

The cell temperature for 1000 W/m^2 decreases between 0 and 13 V. If the voltage is greater than 13 V, the cell temperature increases.

Equation [2.18] shows that the cell temperature is a function of the cell efficiency. Figure 2.9 shows the efficiency of the PV module as a function voltage at an ambient temperature of 25 C.

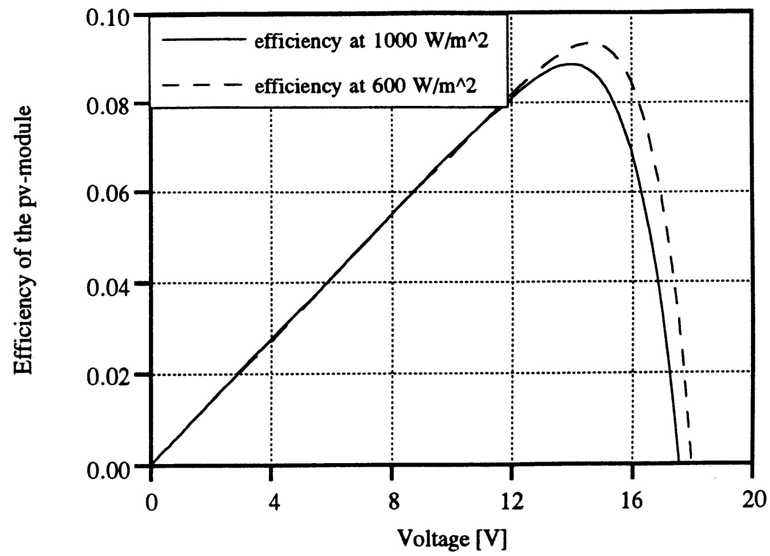

Figure 2.9: PV module efficiency as a function of the voltage

Rearranging equation [2.18] to equation [2.19] shows more clearly that the cell temperature is always equal to or larger than the ambient temperature.

$$T_c = T_a + (\tau\alpha - \eta_c)\,\frac{G_T}{U_L} \qquad [2.19]$$

The value of $\tau\alpha$ is usually not exactly known. Reference [5] uses an estimate of 0.9. The efficiency η_c of the cell is between 0.08 and 0.1 for operating voltages around 12 V (Figure 2.9). This means ($\tau\alpha$-η_c) is always a positive number. The minimal cell temperature therefore exists when the incident solar radiation (G_T) is zero.

Chapter 3

BATTERY STORAGE

The following description of the lead acid battery is based on the models developed by Shepherd [8] and Zimmermann and Peterson [9]. The model provides a relationship between voltage, current and the state of charge (SOC) of the battery. The model does not consider thermal effects and battery aging, i.e. the number of charging - discharging cycles the battery has undergone. Also, self discharge is neglected. Figure 3.1 shows the equivalent circuit for a lead acid battery cell.

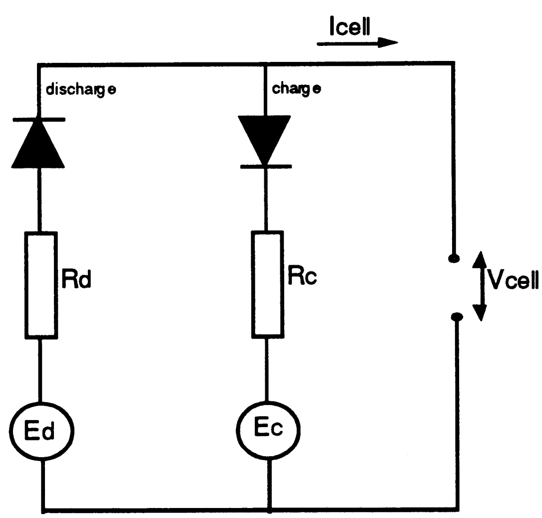

Figure 3.1: Electrical circuit for a lead acid battery cell

The left path represents discharge, the right one charge. Shepherd [8] introduces E_c and E_d as extrapolated constant open circuit voltages for charge and discharge, and R_c

R_d are the internal resistances for charge and discharge as a function fractional state of charge, F. The diodes introduced by Peterson and Zimmermann [9], take into account the behavior at low current.

3.1 Governing equations

Equation [3.1] expresses the open circuit voltage as a function of E_c and E_d .

$$V_{oc} = \frac{E_c + E_d}{2} \qquad [3.1]$$

where

E_c, E_d are the constant open circuit voltages.

The voltage drop over the diodes , V_{di}, is shown in equation [3.2].

$$V_{di} = \frac{1}{K_{di}} \, ln \, (\frac{|I_{cell}|}{I_{di}} + 1) \qquad [3.2]$$

where

K_{di}, I_{di} are curve fitting parameters,

I_{cell} is the cell current.

The cell voltage, V_{cell}, as a function of the cell current , I_{cell},, is described by Equation [3.3] and [3.4]. Equation [3.3] is used when the battery is charged, equation [3.4] when the battery is discharged.

$$V_{cell} = V_{oc} - V_{di} - G_d (1 - F) + I_{cell} R_d (1 + \frac{m_d (1 - F)}{\frac{Q_d}{Q_m} - (1 - F)}) \quad [3.3]$$

$$V_{cell} = V_{oc} + V_{di} - G_c (1 - F) + I_{cell} R_c (1 + \frac{m_c (1 - F)}{\frac{Q_c}{Q_m} - (1 - F)}) \quad [3.4]$$

where

Q_c, Q_d are capacity parameters on charge, discharge,

Q_m is the rated capacity of the cell,

m_c, m_d are cell type parameters which determine the shape of the I-V-capacity characteristics,

R_c, R_d are the internal resistances at full charge when charging and discharging,

G_c, G_d are the small valued coefficients of F for charge, discharge,

F is the fractional state of charge.

The expression $G_{c,d}$ (1 - F) is a curve fitting term introduced by Shepherd [8].

The fractional state of charge can be expressed as the ratio of the state of charge, Q, over the rated capacity.

$$F = \frac{Q}{Q_m} \qquad [3.5]$$

where

Q is the actual capacity of the cell.

The total internal resistance of the battery cell, R, is expressed as a function of the internal resistances of charge, discharge (c,d) and the fractional state of charge of the battery. Its behavior is expressed in equation [3.6].

$$R = R_{c,d}\,(1 + \frac{m_{c,d}\,(1 - F)}{\frac{Q_{c,d}}{Q_m} - (1 - F)}) \qquad [3.6]$$

When the battery is fully charged $(F=1)$, the total internal resistance (R) is equal to the resistance of charge, discharge ($R_{c,d}$).

Figure 3.2 illustrates the I-V characteristics of a battery cell for different levels charge.

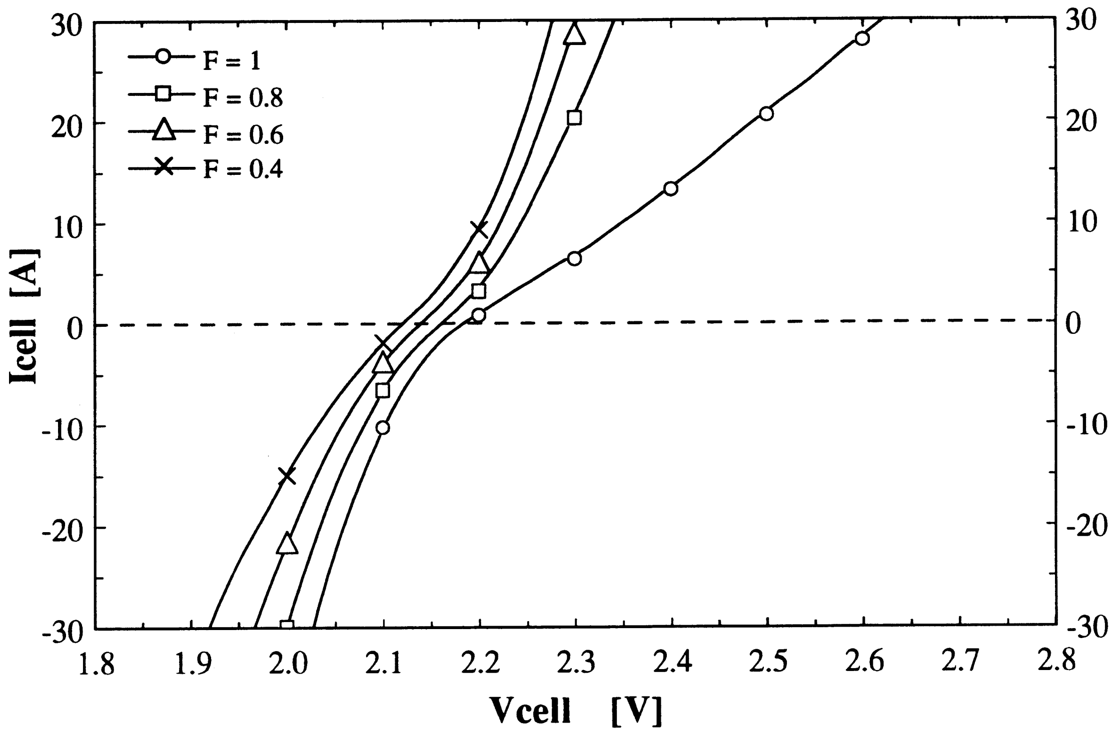

Figure 3.2: I-V characteristics for a single cell lead acid battery at different levels of charge

At low currents the I-V characteristics of the battery cell shows a exponential behavior of the cell current with respect to the voltage, caused by the diodes. The current changes almost linearly when the its absolute value increases.

The change in the state of charge (Q) is determined on discharge by equation [3.7] and on charge by equation [3.8]

$$\frac{dQ}{dt} = I_{cell} \tag{3.7}$$

$$\frac{dQ}{dt} = I_{cell}\,\eta \qquad [3.8]$$

where

η is the charging efficiency of the battery.

As can be seen in Figure 3.2, the current for discharge is negative, the current for charge is positive. The charging efficiency is assumed to be constant and takes into account that some charging energy is wasted in producing gas. The energy losses are described by equation [3.9].

$$P_{loss} = (1 - \eta)\,P \qquad [3.9]$$

where

P is the input energy.

Until now, the behavior of a single cell was described. Equation [3.10] and [3.11] show the current - voltage relationship between a single cell and a battery made of many cells.

$$I_{bat} = C_p\,I_{cell} \qquad [3.10]$$

$$V_{bat} = C_s\,I_{cell} \qquad [3.11]$$

where

C_p is the number of cells in parallel,

C_s is the number of cells in series.

If the battery is overcharged, hydrogen and oxygen gases are generated and released, which decreases the charging efficiency (η). When discharging the battery to its deep discharge level the voltage drops rapidly. The exhaustion of the cell is then reached. If the battery is discharged further, permanent damage may result. A charge controller, which is described in the following section, limits the charge and discharge voltage (V_c and V_d). The limiting equations are [3.12] and [3.13].

$$V_c = const. \qquad [3.12]$$

$$V_d = E_D - /I_{cell}/\, R_D \qquad [3.13]$$

where

E_D, R_D are constants.

The maximum charging voltage, V_c, is a constant, whereas the minimum discharging voltage, V_d, is a function of the cell current.

3.2 Charge controllers

A charge control is needed when using a battery for energy storage in PV systems. The battery must be protected from overcharge and from deep discharge or damage to the battery may result. A series controller and a parallel controller have been modeled and will be compared in this chapter.

The state of charge of the battery depends on many factors and it is difficult to directly measure. The state of charge is usually obtained by sensing the battery terminal voltage.

3.2.1 Series type charge controller

The system configuration of a PV system with battery storage and the series controller is shown in Figure 3.3.

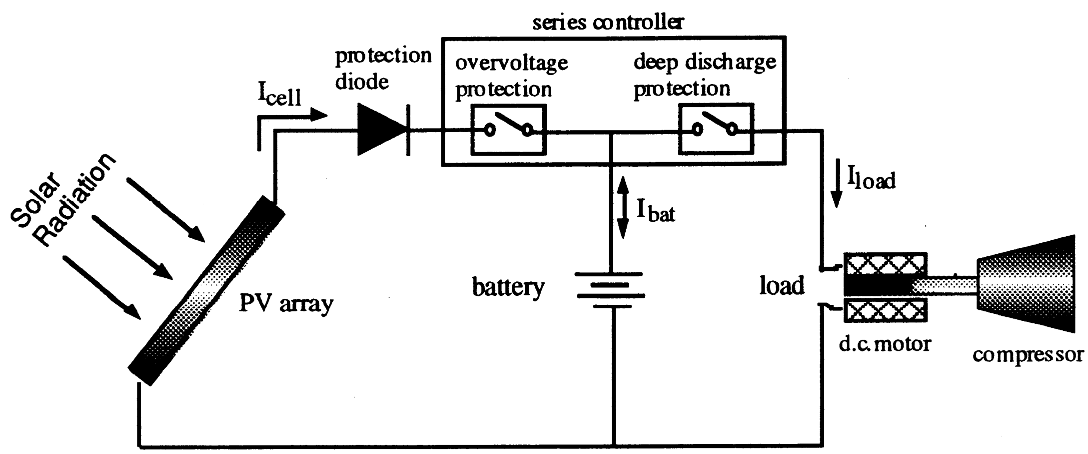

Figure 3.3: PV system configuration including a series controller

The main parts of the controller are the overvoltage and the deep discharge protection. When either the maximum state of charge or the maximum charge voltage is reached, the overvoltage relay disconnects the PV array from the system and the load is supplied from the battery. When the state of charge reaches its minimum or the minimum discharge voltage is reached, the load is disconnected from the system and the PV array charges the battery. With this control strategy the battery state of charge is kept within an appropriate range.

3.2.2 Parallel type charge controller

The system configuration of the PV system with the parallel type charge controller is shown in Figure 3.4.

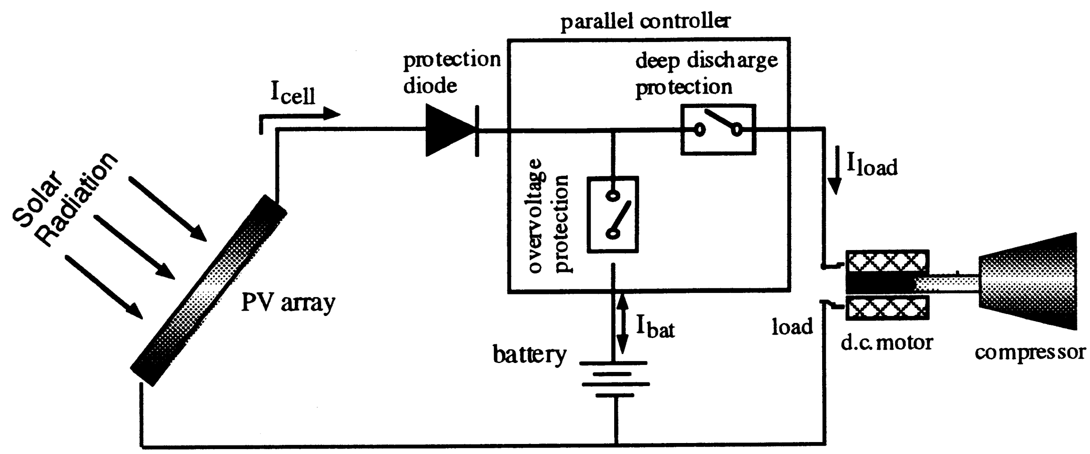

Figure 3.4: PV system configuration including a parallel controller

The parallel controller consists of the overcharge and the deep discharge protection. When enough energy is provided from the PV array, and the battery reaches its maximum state of charge, the relay for the overcharge protection opens. The battery can not be charged any more. Assuming no self discharge, the state of charge stays constant. In comparison to the series controller the load is supplied from the PV array, when possible. If the state of charge is at its minimum and the PV current can not meet the load, the relay for the deep discharge protection opens and the load is disconnected from the system. The PV array charges the battery. If the PV current can meet the load again, the deep discharge relay closes and the load is reconnected. The battery is charged if the PV current is in excess of that needed to supply the load.

Chapter 4

BRUSHLESS DIRECT CURRENT (D.C.) MOTOR

Since brushless direct current (d.c.) motors are permanent magnet motors and have the same characteristics as brush commutated d.c. motors, they can be used in the same applications. Eckstein [4], Kosow [10] and Toro [11] give an overview of d.c. motors. The equations of Magnetic Technology Company [12] provide the fundamentals of the model of the brushless d.c. motor considered in this chapter. The power flow of a d.c. motor is shown in Figure 4.1:

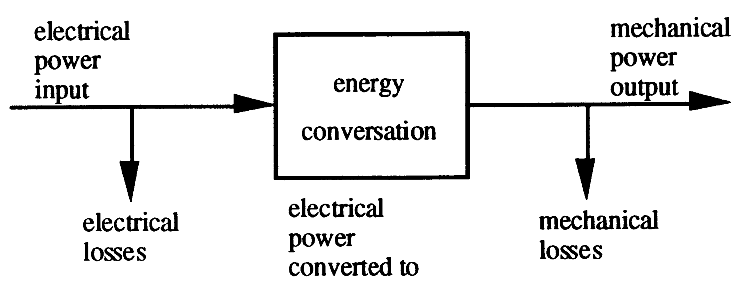

Figure 4.1: Power flow diagram of a brushless d.c. motor

The emphasis of this chapter is on developing a model which can be combined with the load, in our case the refrigeration system introduced in the following chapter. Here a brushless d.c. motor is used to run the compressor. This motor system consists of four basic sub - assemblies, which are also shown in Figure 4.2:

1. A stator wound with electromagnetic coils.
2. A rotor consisting of a soft iron core and permanent magnet poles.
3. A rotor position sensor assembly which contains enough sensing devices to define the rotor position.
4. Communication logic and switching electronics which convert the rotor position information to the excitation for the stator phases.

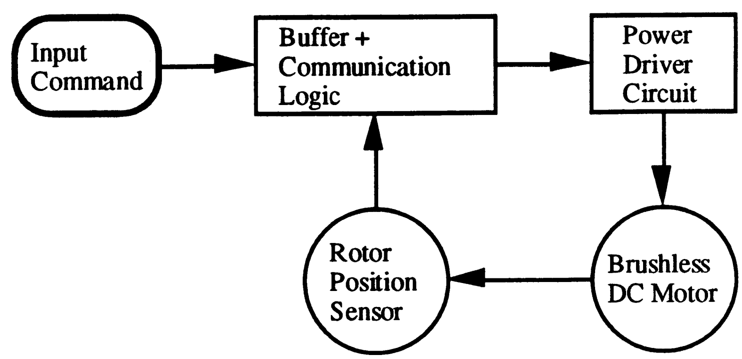

Figure 4.2: Functional block diagram of a brushless d.c. motor system

4.1 Losses

Kosow [10] divides the motor losses into three classes, the electrical losses, the rotational losses and the stray load losses. The stray load losses consist of

1. iron losses due to flux distortion
2. skin effect losses in armature or stator conductors
3. iron losses in structural parts of machines

and are assessed at 1% of the output for motors above 200 hp and considered to be negligible below this power rating. The analysis of losses reveals that certain losses are directly related to the load and some are independent of it. A breakdown of the three classes is listed in Table 4.1.

A: Electrical Losses	
Description for losses	Effects of load
- winding and resistant losses ($I^2 R$)	- increase with the load
B: Rotational Losses	
Description for losses	Effects of load
1. Mechanical losses	
- friction losses ($T_{loss} = A + B\ \omega$)	- constant at constant speed
2. Core (or iron) losses	
- hysteresis loss ($P_h = K_h\ B_x\ f\ V$)	- constant at constant speed and field flux
- eddy current losses ($P_c = K_1\ B^2\ f^2\ t^2\ V$)	- constant at constant speed and field flux
C: Stray Load Losses	
negligible for motors below 200 hp	

Table 4.1: Distribution of the losses for d.c. motors

4.2 Governing equations for the brushless d.c. motor

The brushless d.c. motor, when properly commutated, will exhibit the same characteristics as a brush commutated permanent magnet d.c. motor. The electrical model is shown in Figure 4.3:

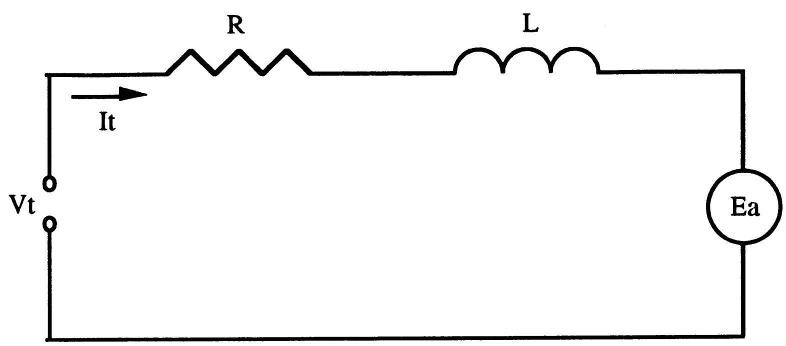

Figure 4.3: Equivalent electrical circuit of a brushless d.c. motor

The terminal voltage, V_t, is expressed by:

$$V_t = R\,I_t + L\frac{dI_t}{dt} + E_a \qquad [4.1]$$

where

E_a is the electromagnetic force (EMF),

R is the winding resistance,

L is the inductance,

I_t is the motor current.

Equation [4.1] is used for dynamic behavior of the system. For slowly changing or steady processes, as assumed here, Equation [4.2] can be used. The electrical and mechanical time constants, which are given by the manufacturer, limit the usage of equation [4.2]. When the time scale of change in voltage or torque is smaller than the electrical or the mechanical time constant, equation [4.1] must be used instead of equation [4.2].

$$V_t = R\, I_t + E_a \qquad [4.2]$$

The term $R\ I_t$ describes the voltage over the resistant R. This voltage times the current describes the electrical losses, $I_t^2\ R$, shown in Table 4.1.
The electromagnetic force, E_a, can be expressed as:

$$E_a = K_b\ \omega \qquad [4.3]$$

where

K_b is the back EMF constant,

ω is the angular velocity.

The electromagnetic torque equation is given by:

$$T = K_t\ I_t \qquad [4.4]$$

and

$$T = T_{loss} + T_o \qquad [4.5]$$

where

K_t is the torque constant,

T_{loss} describes the rotational losses ,

T_o is the output torque.

The rotational losses are shown in Table 4.1 and described in equation [4.6]:

$$T_{loss} = A + B\ \omega \qquad [4.6]$$

where

A is the static friction coefficient,

B is the dynamic friction coefficient.

The efficiency, η, of the motor is given by the ratio of output power, P_o, to the input power, P_{in}:

$$\eta = \frac{P_o}{P_{in}} \qquad [4.7]$$

where the following relationships can be found:

$$P_o = T_o\ \omega \qquad [4.8]$$

and

$$P_{in} = V_t I_t \qquad [4.9]$$

4.3 Characteristics of the brushless d.c. motor

By fixing the voltage and varying the output torque, the related speed and input voltage can be determined. Figure 4.4 shows the characteristics of brushless d.c. motor. The motor data are taken from reference [11] and are listed in Appendix A. For a constant voltage, the speed and the input current are linear functions of the torque. The maximum torque is obtained at starting conditions (RPM=0).

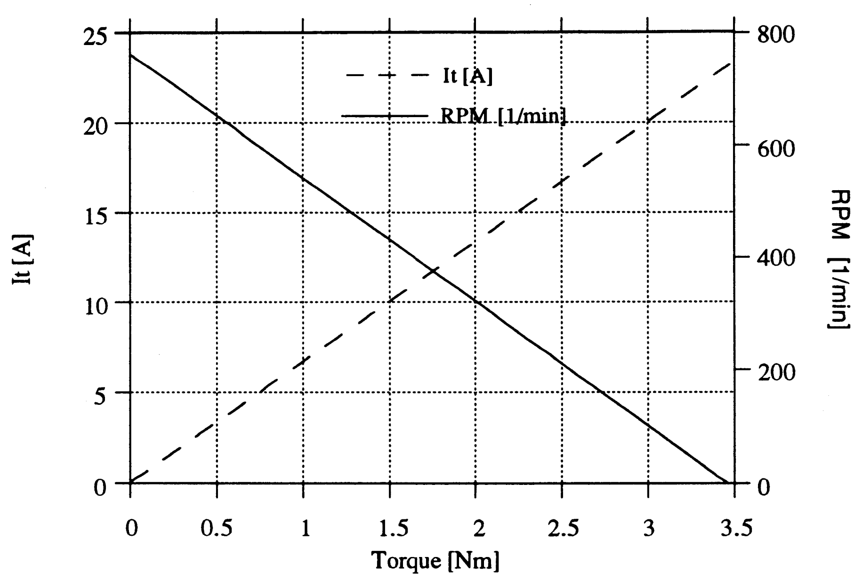

Figure 4.4: Speed-torque and current-torque characteristic for a brushless d.c. motor

Because the brushless d.c. motor is a permanent magnet motor, the magnetic flux is constant during all conditions. This leads to the linear behavior shown in Figure 4.4.

4.4 Efficiency of the brushless d.c. motor

In a PV system the terminal voltage of the motor depends on the current ambient conditions and the state of charge of the battery. Therefore, the efficiency as a function of the terminal voltage is of interest and is illustrated in Figure 4.5.

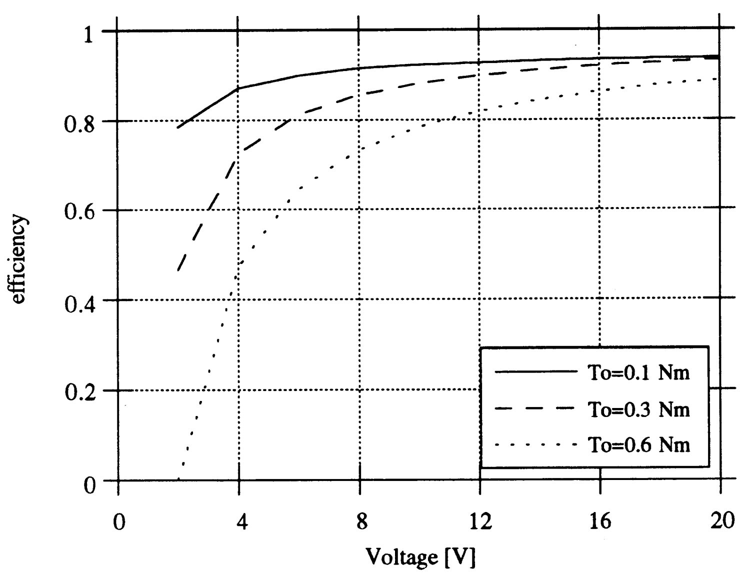

Figure 4.5: Motor efficiency versus voltage for different torques

The motor used was the type EYQM No. A3000-500 from Barber Colman Company [13]. The motor specific data are listed in Appendix A.

The efficiency varies with the load. Figure 4.6 shows the relationship between efficiency and torque for the motor No. A3000-500 . The input voltage is 12 V.

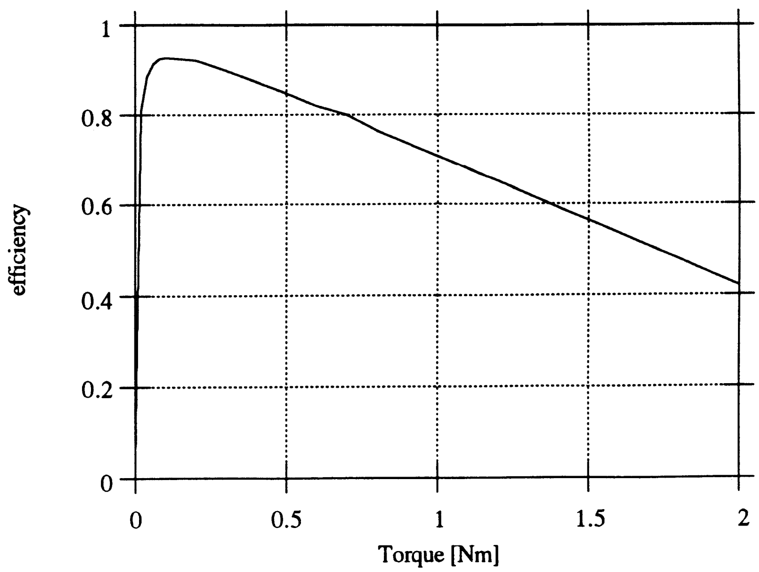

Figure 4.6: Motor efficiency versus torque

Figure 4.6 shows, that the maximum efficiency for this motor can be achieved for a load of around 0.1 Nm.

4.5 Comparison study with the series d.c. motor

Figure 4.7 shows the electrical circuit of the series d.c. motor. One can see the similarity to the brushless motor.

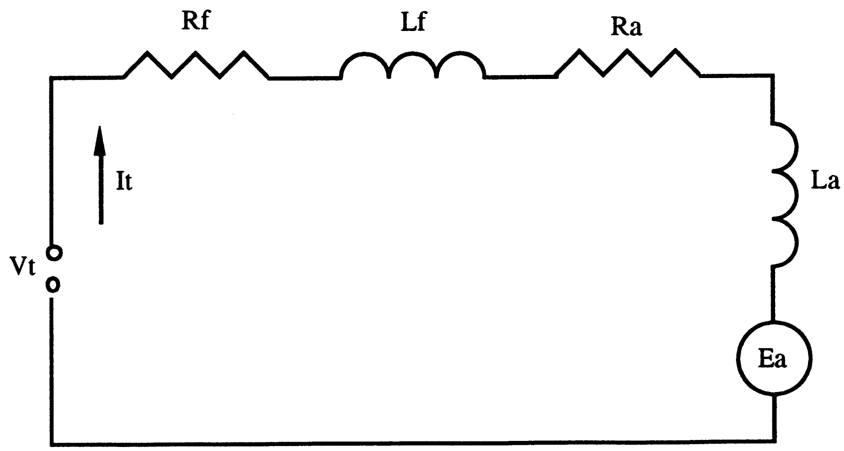

Figure 4.7: Equivalent electrical circuit for a series motor

4.6 Governing equations for the series d.c. motor

When adding field and armature resistances ($R = R_f + R_a$) and field and armature inductivities ($L = L_f + L_a$), the electrical circuit for the brushless d.c. motor and the series motor are the same. Except for the electromagnetic force, E_a, and the torque, T, the governing equations are alike.

The electromagnetic force and the torque are expressed with the following equations:

$$E_a = K_b \, \phi \, \omega \qquad [4.10]$$

$$T = K_t \, \phi \, I_t \qquad [4.11]$$

where

ϕ is the magnetic flux with it's unit [V-sec = Wb].

To compare the EMF and the torque equation of the brushless d.c. motor and the series motor, one can compare the units of the two motor constants K_b and K_t. For the brushless permanent magnet motor the unit for K_b is [V-sec/rad] and for K_t [N-m/A]. For the series motor the unit for K_b is [1/rad] and for K_t [N-m/A-V-sec].

Because of the permanent magnets in the brushless d.c. motor, the magnetic flux is a constant for all current conditions. In contrast to the permanent magnet motor, the magnetic flux of the series motor will vary with the terminal current. Magnetic flux and current are related through a proportional factor, the constant k_f.

$$\phi = k_f I_t \qquad [4.12]$$

Substituting [4.12] into equation [4.11], the torque can be expressed by

$$T = K_t \ k_f \ I_t^2 = M_{AF} \, I_t^2 \qquad [4.13]$$

where K_t and k_f are lumped together into the constant M_{AF}, called the mutual inductance.

4.7 Characteristics of the series d.c. motor

Equations [4.10] through [4.13] lead to the characteristics illustrated in Figure 4.8.

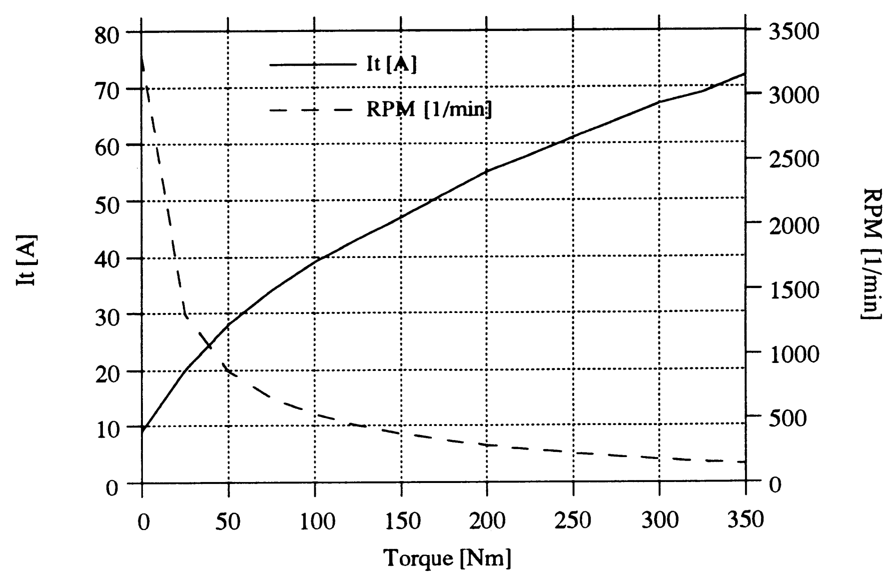

Figure 4.8: Speed-torque and current-torque characteristic for a series motor

The current and speed behavior of the permanent magnet motor in Figure 4.4 are quite different from those of the series d.c. motor due to the influence of the changing magnetic flux.

However, in the PV powered refrigerators the compressor is driven by a permanent magnet brushless d.c. motor and therefore no more comparison studies were made.

Chapter 5

REFRIGERATION SYSTEM

Chapter 5 describes the commonly used mechanical vapor compression refrigeration cycle and its components. The result is a steady-state model, which is based on the fundamental equations described by Threlkeld [14] and Chlumsky [15]. The typical components are illustrated in Figure 5.1. The pressure enthalpy diagram is shown in Figure 5.2.

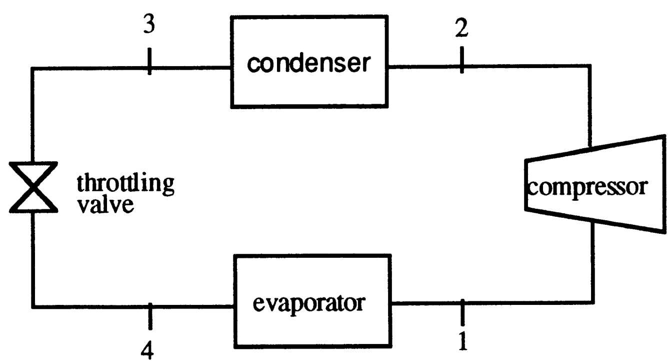

Figure 5.1: Refrigeration cycle

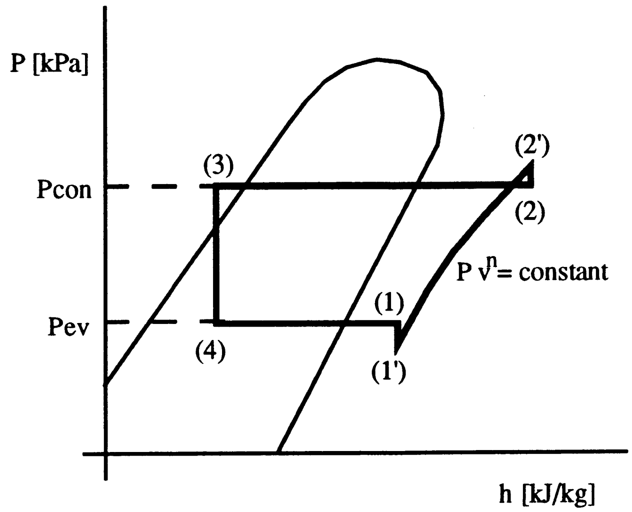

Figure 5.2: Pressure - enthalpy diagram

The superheated refrigerant at State 1 is at low pressure and temperature. State 1' results because of the pressure drop in the inlet compressor valve. A polytropic compression process and a pressure drop in the outlet compressor valve leads to States 2' and 2, respectively. The superheated vapor is at relatively high pressure and temperature. It enters the condenser, where it is desuperheated and then condensed at constant pressure. At State 3 the liquid refrigerant is subcooled and at high pressure and medium temperature. The refrigerant expands through the throttling valve and then flows through the evaporator where it picks up the refrigeration load.

5.1 Governing equations

Evaporator

The heat transfer rate into the evaporator is called the refrigeration capacity. An energy balance defines the capacity as the refrigerant flow rate times the enthalpy difference across the evaporator. It is also expressed as the overall heat transfer coefficient area product times the temperature difference between refrigerant, and freezer.

$$CAP = w\,(h_1 - h_4) \qquad [5.1]$$

$$CAP = UA_{ev}\,(T_{fr} - T_{ev})\ ^{*} \qquad [5.2]$$

where

CAP is the capacity,

w is the mass flow rate,

h_1 and h_4 are the enthalpies at State 1 and 4,

UA_{ev} is the overall heat transfer coefficient area product,

T_{fr} and T_{ev} are the temperatures for freezer and the refrigerant in the evaporator.

Compressor

Threlkeld [14] describes the compressor with a volumetric efficiency, η_{vol} . η_{vol} is defined as the mass of vapor actually pumped divided by the mass of vapor which the compressor could pump if it handled a volume of vapor equal to its piston displacement and if no thermodynamic state change occurred during the intake stroke. A compression cycle for a reciprocating compressor is illustrated in Figure 5.3.

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* The equation is not exactly correst because the evaporator temperature increases from the state of saturated vapor to state 1.

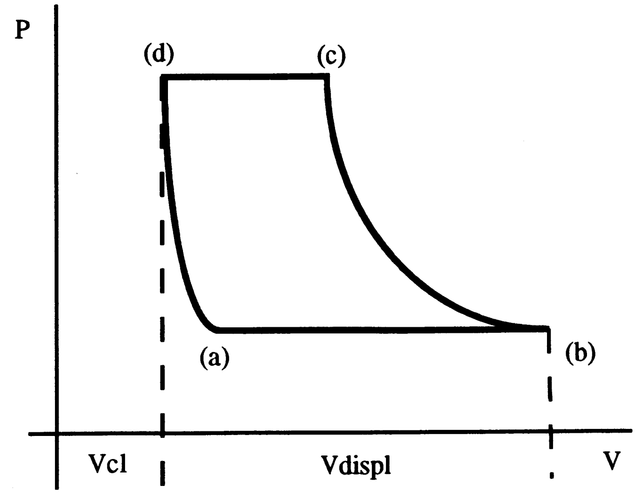

Figure 5.3: Compression cycle for a reciprocating compressor

$$\eta_{vol} = \frac{(V_b - V_a)\ v_1}{(V_b - V_d)\ v_1'} \qquad [5.3]$$

where

V_a is the volume after expansion of the rest gas in the cylinder,

V_b is the maximum volume and

V_d is the clearance volume,

v_1 is the specific volume at State 1,

v'_1 is the specific volume at State 1'.

The polytropic work as a function of the ratio of the clearance volume over the displacement volume, m, and the pressure ratio of the condenser pressure over the evaporator pressure is introduced by Threlkeld [14] and shown in Equation [5.4].

$$\eta_{vol} = [1 + m - m \left(\frac{P'_{con}}{P'_{ev}}\right)^{\frac{1}{n}}] \frac{v_1}{v'_1} \quad [5.4]$$

where

m is the ratio of the clearance volume over the displacement volume V_{displ},

n is the polytropic exponent,

P'_{ev} is the input pressure inside the compressor,

P'_{con} the output pressure inside the compressor.

The mass flow rate w can be estimated with

$$w = \rho_1 V_{displ} N \eta_{vol} \quad [5.5]$$

where

ρ_1 is the density of State 1,

N is the compressor speed in 1/sec.

Threlkeld [14] defines the polytropic work as the work to compress the refrigerant from State 1' to State 2'. It is defined with the following equation:

$$W_{pol} = P'_{ev} \; v'_1 \frac{n}{(n-1)} [\left(\frac{P'_{con}}{P'_{ev}}\right)^{\frac{(n-1)}{n}} - 1] \quad [5.6]$$

Condenser

The rate at which heat is rejected from the condenser to the ambient is the product of the mass flow rate and the enthalpy difference across the condenser. It can also be rewritten as the overall heat transfer coefficient area product times the temperature difference between the condenser temperature and the room temperature, T_{rm}.

$$Q_{rej} = w\,(h_2 - h_3) \qquad [5.7]$$

$$Q_{rej} = UA_{con}\,(T_{con} - T_{rm}) \qquad [5.8]$$

where

Q_{rej} is the rejected energy,

h_2, h_3 are the enthalpies at State 2 and 3,

UA_{con} is the overall heat transfer coefficient area product of the condenser

T_{con}, T_{rm} are the temperatures for condenser and room.

The temperature difference between condenser and room temperature in equation [5.8] is an approximation. The first reason is that UA_{con} is not a constant. It varies with changing condenser temperatures. The second reason is that the refrigerant leaves the compressor at State 2 with a temperature higher than the condenser temperature. This is to be neglected because the released energy between output of the compressor and reaching the condenser temperature at the state of saturated vapor is much smaller then the energy that is released during the phase change. To increase the accuracy, an additional UA for the vapor region (between State 2 and the state of saturated vapor) would have to be added.

Throttling valve

From State 3 to 4 the liquid flows through the throttling valve, where it undergoes an adiabatic expansion. An energy balance indicates that the enthalpies before and after the valve are the same.

$$h_3 = h_4 \qquad [5.10]$$

5.2 Accuracy of the compressor model

The first goal is to develop a model which agrees with data given from a compressor manufacturer.

The catalog of the compressor manufacturer COPELAND provides data for capacity, mass flow rate and power as a function of the evaporator and the condenser temperature. The rotation also was given with 1750 1/min. R22 was the refrigerant. The power provided in the catalog is the input for the direct current (d.c.) motor, which is directly coupled to the compressor. The data used were from the COPELAND compressor CRD4-0200-PFV. The specific compressor data are listed in Appendix A .

5.2.1 Influence of the volume ratio *m* and the polytropic exponent *n*

Before comparing the model with the given data the influence of the clearance volume to displacement volume ratio, m, and the polytropic exponent, n, need to be evaluated. With the governing equations (Equations [5.1] - [5.6]) and the data for evaporator and condenser temperature, capacity, mass flow rate and power, the values for m and n

were evaluated. This calculation was made for several operating conditions. Then several average *m-n* combinations, consisting of three to five operating points were calculated. Table 5.1 is an example of an average *m-n* combinations.

data comb.	T_{ev} [F]	T_{con} [F]	CAP [Btu/hr]	w [lbs/hr]	power [kW]	m	n
1	10	80	14600	183	1.38	0.086	1.143
2	20	90	18200	233	1.59	0.091	1.1
3	30	100	22000	289	1.82	0.095	1.062
4	40	110	26000	351	2.06	0.097	1.020
5	50	120	30300	422	2.31	0.101	0.982
avg						0.094	1.061

Table 5.1: Calculation of an average *m-n* combination with given values for evaporator temperature, condenser temperature, capacity, mass flow rate and power.

The calculated *m-n* combination out of the Table 5.1 was m=0.094 and n=1.061. The next step was to look at the influence of different average *m-n* combinations. Three of the calculated combinations were used to determine the capacity, *CAP*. Figure 5.4 illustrates the result. No matter what combination was used, the calculated capacity of the model stayed almost the same. The differences were negligible.

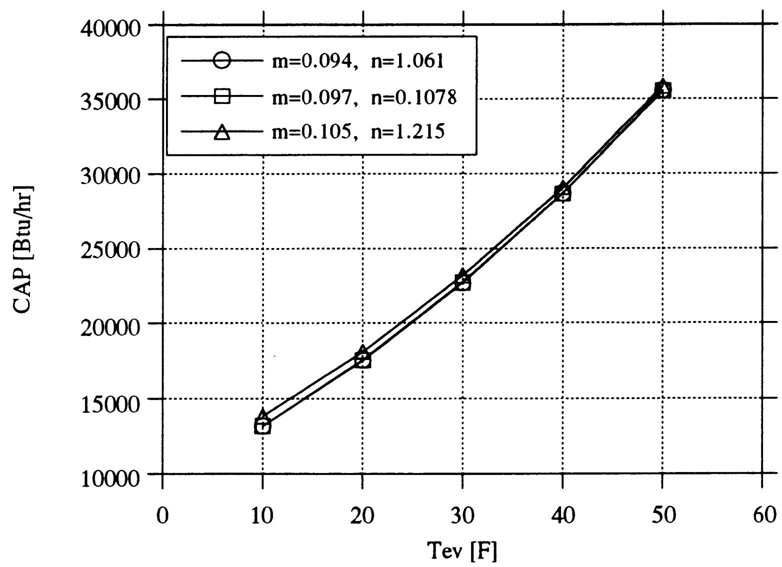

Figure 5.4: Comparison of the CAP various average *m-n* combinations

5.2.2 Comparison of the model to manufacturer data

Out of the average *m-n* combinations shown in Figure 5.4, the combination m=0.094 and n=1.061 was used for the comparison studies. Of particular interest is how well the model agrees with the data for capacity, *CAP*, and the coefficient of performance, *COP*. Because data for the *COP* were not directly available they had to be evaluated otherwise. Given *CAP* and the power input of the d.c. motor, P_{in}, and assuming a motor efficiency the *COP* can be calculated with the following equation:

$$COP_{data} = \frac{3.413\ CAP_{data}\ \eta_{mot}}{P_{in}} \qquad [5.11]$$

where

η_{mot} is the motor efficiency.

Because P_{in} was given in kW, whereas the *CAP* was provided in Btu/hr, the conversion factor 3.413 Btu/hr-kW had to be used.

Depending on the speed of the motor, the efficiency can vary in between 50 to 95 %. Because no data were provided for the d.c. motor an average efficiency of 70 % was assumed. This value was held constant. An efficiency study of the brushless d.c. motor is shown in Chapter 4.4.

The EES program REFRIGERATION MODEL (Appendix B) calculates the CAP and the COP and compares these values with the provided data. Figure 5.5 illustrates the CAP-comparison as a function of the evaporator temperature for different condenser temperatures,. Figure 5.6 shows the COP-comparison of both temperatures.

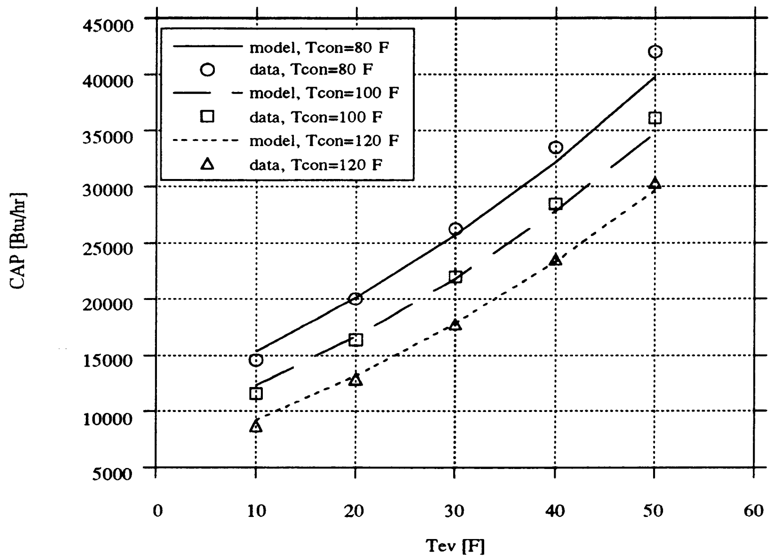

Figure 5.5: CAP as a function of the evaporator temperature

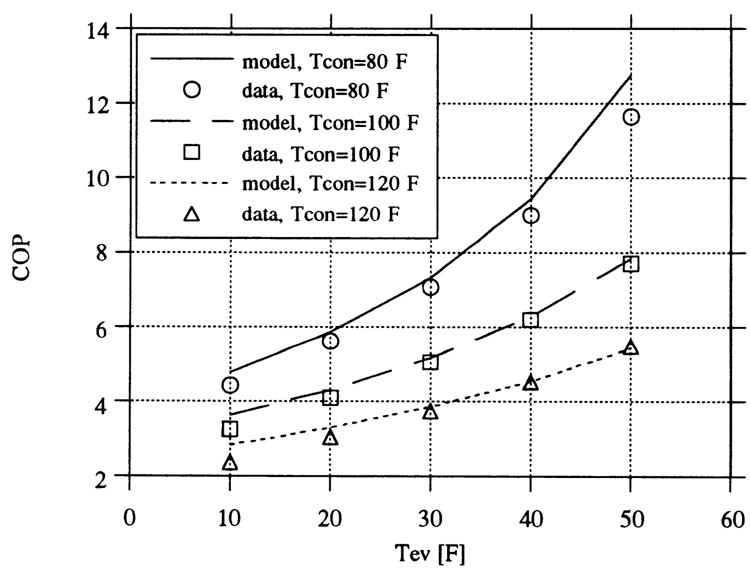

Figure 5.6: COP as a function of the evaporator temperature

Looking at these figures, the model seems to fit the data well, even with the assumption of a constant motor efficiency. The model underpredicts the CAP data for high evaporator and low condenser temperatures.

For an evaporator temperature of 50 F and a condenser temperature of 80 F, the model overpredicts the calculated COP data of the compressor with around 6 %. The error could be the result of the assumption of a fixed motor efficiency.

5.3 Refrigeration model

The model described in the Sections 5.1 and 5.2 has been further developed for the use in a combined system, including PV array, battery, d.c. motor and refrigeration cycle.

In contrast to the model described in chapter 5.2, the compressor speed is not fixed, it is a function of the room and freezer temperature. The overall heat transfer coefficient area products for the evaporator and condenser, UA_{ev} and UA_{con}, are required. The determination of these parameters is described in the following section.

5.3.1 Determining the UA values of the condenser and evaporator

The size of the refrigerators considered to determine the UA values is listed below:

- volume, V_{ref}, between 0.084 and 0.133 m^3
- area, A_{ref}, between 2.5 and 3.2 m^2
- thickness of the walls, l, between 0.06 and 1.14 m

A reasonable condenser area for this size is A_{con} between 0.2 and 0.4 m^2. Table 1.1 of reference [16] indicates that the heat transfer coefficient, *h*, for free convection ranges from 2 to 25 W/m^2-K, leading to UA values between 0.4 and 10 W/K. For further calculations the value was fixed at 10 W/K. The largest value was chosen to achieve the highest *COP*.

Figures 5.7 and 5.8 illustrate the *CAP* and *COP* as a function of the evaporator and condenser UA.

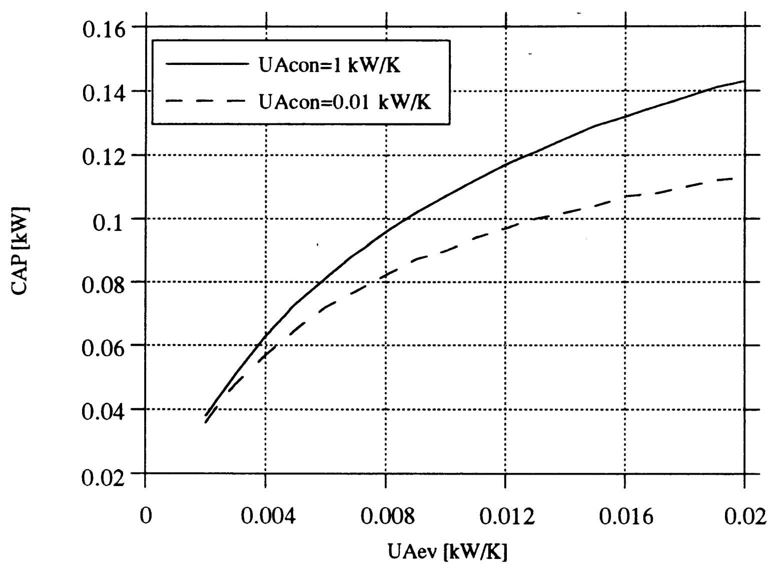

Figure 5.7: CAP as a function of the $UA_{evaporator}$ and $UA_{condenser}$

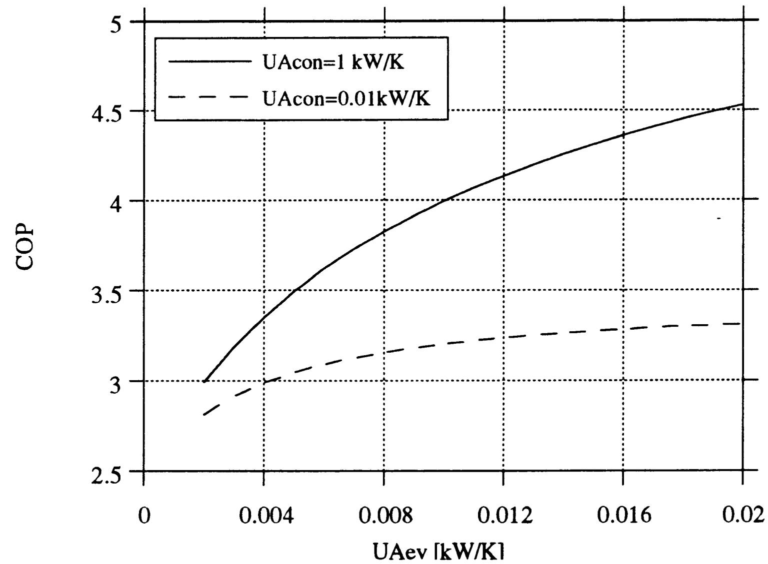

Figure 5.8: COP as a function of the $UA_{evaporator}$ and $UA_{condenser}$

A compromise had to be made in determining the UA value of the evaporator. Choosing a large value, at e.g. 20 W/K we also obtain a large coefficient of performance. On the other hand, a large UA_{ev} means the equipment is physically large and expensive.

With a small UA_{ev} (e.g. 4 W/K), an increase of the capacity because of varying conditions causes a drop of the evaporator pressure and an increase of the compressor work. As can be seen in Figure 5.8, and as expected the COP decreases with a decrease in the UA value of the evaporator.

Reference [1] shows an average refrigerator load of 50 W. A UA_{ev} value of 10 W/K with a refrigeration capacity of around 100 W seems to be a reasonable value for further calculations.

Reference [17] analyzed the COP versus UA_{ev} and UA_{con} fractions for different external heat capacitance rate ratios. The result is that for equal UA values for evaporator and condenser the maximum COP is reached. The values for UA_{ev} and UA_{con} chosen in this chapter satisfy the results in reference [17].

5.3.2 Influence of room and freezer temperature on the capacity

With the further evaluated model the relationship CAP and COP versus room and freezer temperature was analyzed. Figure 5.9 and 5.10 illustrate the dependency of CAP and COP on room and freezer temperatures.

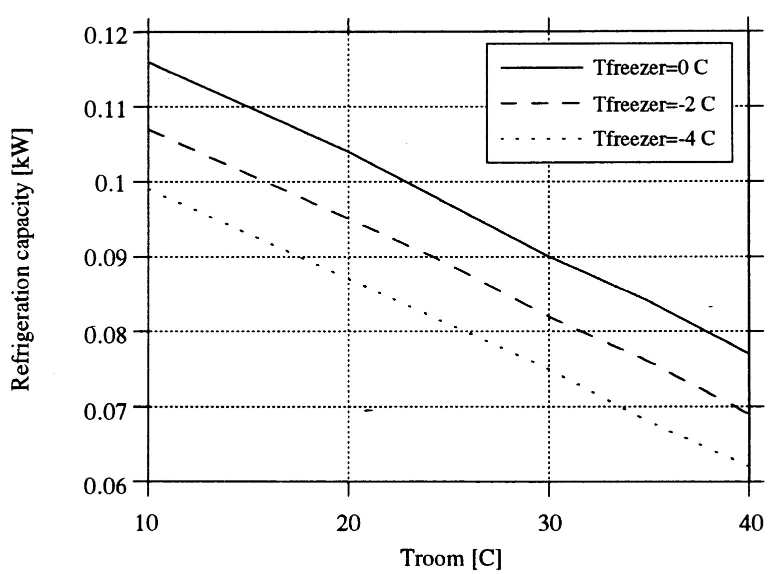

Figure 5.9: CAP versus room temperature for different freezer temperatures

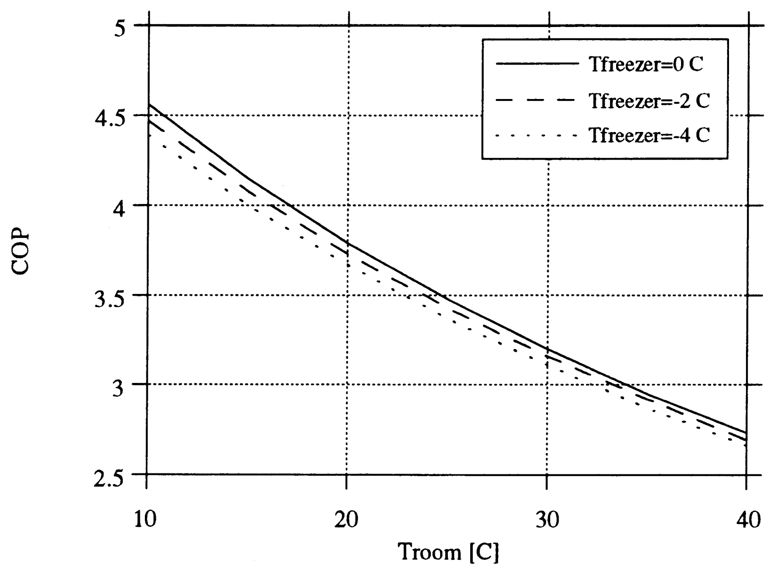

Figure 5.10: COP versus room temperature for different freezer temperatures

To study the influence of the room and freezer temperature on the *CAP* and the *COP* the compressor speed was fixed to 1000 1/min and the output torque was fixed to 0.3 Nm. The capacity and the coefficient of performance decrease with an increase of the room temperature.

For a constant room temperature the *CAP* and the *COP* increase with an increase of the freezer temperature.

5.4 Refrigerator Load

The refrigeration cycle removes the energy gains of the refrigerator. Energy is gained by conduction through the refrigerator walls, ice making, water cooling and door opening. To determine the energy gains it is assumed that the refrigerator temperature is constant at 5 C and the ice is cooled down to -10 C. The energy gains by conduction through the refrigerator walls is given by:

$$\dot{Q}_1 = \frac{k}{L} A_{ref} (T_{rm} - T_{ref}) \quad [5.12]$$

where

k is the conductivity of the refrigerator walls,

L is the thickness of the walls,

A_{ref} is the area of refrigerator,

T_{rm} is the room temperature,

T_{ref} is the refrigerator temperature.

To determine the energy needed to make ice, it is assumed that the ice originally is at room temperature, T_{rm} , and is cooled down to the ice temperature, T_{ice}. Another assumption is that the total amount of ice is made within 24 hours. The sensible heat to cool the water from room temperature to 0° ($Q_{sen,w}$) is:

$$\dot{Q}_{sen,w} = m_{ice}\, cp_{wat}\, T_{rm} \quad [5.13]$$

The latent heat ice - water (Q_{lat}) is:

$$\dot{Q}_{lat} = m_{ice}\, 273\, (cp_{wat} - cp_{ice}) \quad [5.14]$$

The sensible heat to cool the ice to its final temperature ($Q_{sen,i}$) is:

$$\dot{Q}_{sen,i} = m_{ice}\, cp_{ice}\, T_{ice} \qquad [5.15]$$

The total energy needed to make ice is the sum of $Q_{sen,w}$, Q_{lat} and $Q_{sen,i}$ which is given by Equation [5.16].

$$\dot{Q}_2 = \frac{m_{ice}\,(cp_{wat}\, T_{rm} - cp_{ice}\, T_{ice})}{86400} \qquad [5.16]$$

where

m_{ice} is the mass of the ice,

cp_{wat} is the specific heat of water at 20 C,

cp_{ice} is the specific heat of ice at 0 C,

T_{ice} is the final ice temperature.

To determine the energy to cool water it is assumed that the water originally is at room temperature and reaches the temperature of the refrigerator within 5 hours. Equation [5.17] shows the energy needed to cool the water.

$$\dot{Q}_3 = \frac{m_{wat}\, cp_{wat}\,(T_{rm} - T_{ref})}{18000} \qquad [5.17]$$

where

m_{wat} is the mass of the water.

When opening the door, the air in the refrigerator is exchanged. The air in the refrigerator is displaced by the outside air with room temperature. The temperature of the mass in the refrigerator increases depending on its specific heat and the time the door is open. To simulate the increase of the internal energy of the mass in the refrigerator the parameter Ac (air changes per minute) is introduced. Reference [1] assumes that the value of Ac is the product of the inside area of the refrigerator times a number depending on the position of the door. For a top door the number is 5, for a front door it is 15. Equation [5.18] describes the energy gained by door openings during one day.

$$\dot{Q}_4 = \frac{V_{ref}\, cp_{air}\, (T_{rm} - T_{ref})\, A_c\, t_{do}}{86400} \qquad [5.18]$$

where

V_{ref} is the volume of the refrigerator,

cp_{air} is the specific heat of air,

A_c are the air changes per minute,

t_{do} is the assumed daily opening time of the refrigerator.

The total energy which has to be removed from the refrigerator to keep the temperature at 5 C while making ice and cooling water is shown in equation [5.19].

$$\dot{Q}_{load} = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_4 \qquad [5.19]$$

The next chapter analyses the cooling system and determines the operating point of the PV system consisting of PV array, battery, refrigeration cycle and brushless d.c. motor.

Chapter 6

SYSTEM ANALYSIS

In the previous chapters the system specific components were described. In this chapter the operating conditions of the cooling system and the PV system are studied. The analysis was made with the engineering equation solver [2]. The programs for the components and the PV system are listed in Appendix B.

6.1 Cooling system characteristic

The cooling cycle consists of a brushless d.c. motor driving a refrigeration cycle compressor. These components were described in the two previous chapters. Figure 6.1 shows the connection between refrigeration cycle and the brushless d.c. motor.

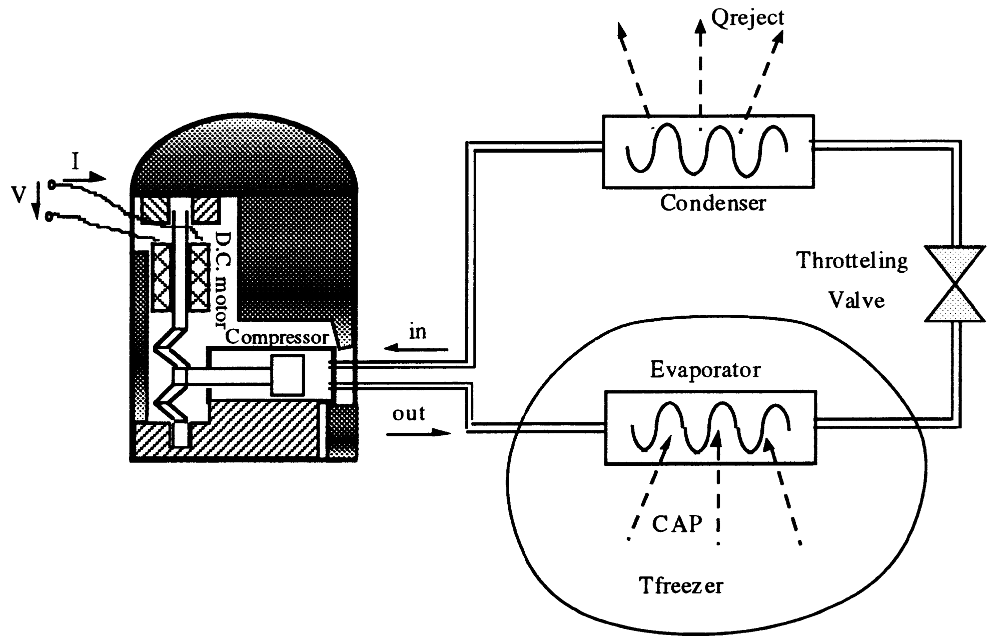

Figure 6.1: Connection between compressor and d.c. motor

As can be seen in Figure 6.1, the rotation of the d.c. motor is converted into the translational movement of the compressor piston. The motor and the compressor are directly coupled. The output power, P_o, of the motor, which is described by Equation [6.1] is equal to the product of polytropic work of the compressor and the mass flow rate of the refrigerant. The mass flow rate, w, presented in equation [6.2], is a function of the compressor speed.

$$P_o = \frac{\pi RPM\, T_o}{30} = w\, W_{pol} \qquad [6.1]$$

$$w = \frac{\rho\, V_{displ}\, RPM\, \eta_{vol}}{60} \qquad [6.2]$$

where

RPM is the revolutions per minute,

T_o is the output torque,

ρ is the density of the refrigerant,

V_{displ} is the displacement volume,

η_{vol} is the volumetric efficiency,

W_{pol} is the polytropic work.

The *COP* of the refrigeration cycle can be described as follows:

$$COP = \frac{CAP}{P_o} \qquad [6.3]$$

The following sections of this chapter describe the characteristic of the cooling cycle with respect to the operating conditions. The operating conditions are the room temperature, freezer temperature and voltage.

6.1.1 Voltage - speed characteristic

To prevent operation of a compressor beyond its maximum allowable speed, the revolutions per minute (*RPM*) as a function of voltage (*V*) room temperature (T_{rm}) and freezer temperature (T_{fr}) must be calculated. The calculated speed is compared to the maximum speed allowed by the manufacturer.

The EES program Compressor-Motor, which can be found in Appendix B calculates the *RPM's* for the combined refrigeration cycle - d.c. motor with respect to the voltage. Figure 6.2 illustrates the behavior for different room and freezer temperatures.

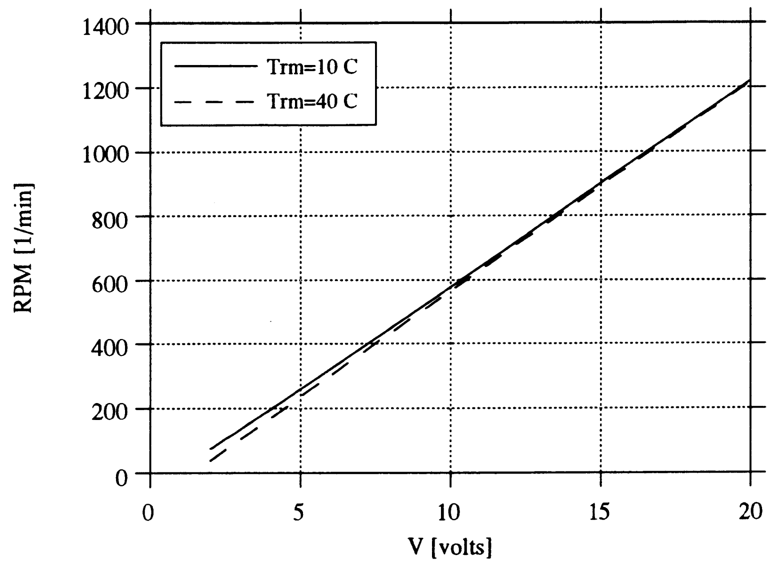

Figure 6.2: Behavior of the speed as a function of voltage and room temperature

Assuming a range for the room temperature between 10 and 40 C, and between -4 and 0 C for the freezer temperature, the characteristics with the extreme values (lowest and highest room temperature) were compared. Figure 6.2 illustrates that the speed - voltage behavior is almost independent of the room and freezer temperature. The influence of the freezer temperature was so small that it did not show up in the results.

6.1.2 Voltage - torque, current characteristic

The voltage supplied to the motor is not constant in the application described in this thesis. Figure 6.3 shows the torque as a function of the voltage for different room and freezer temperatures.

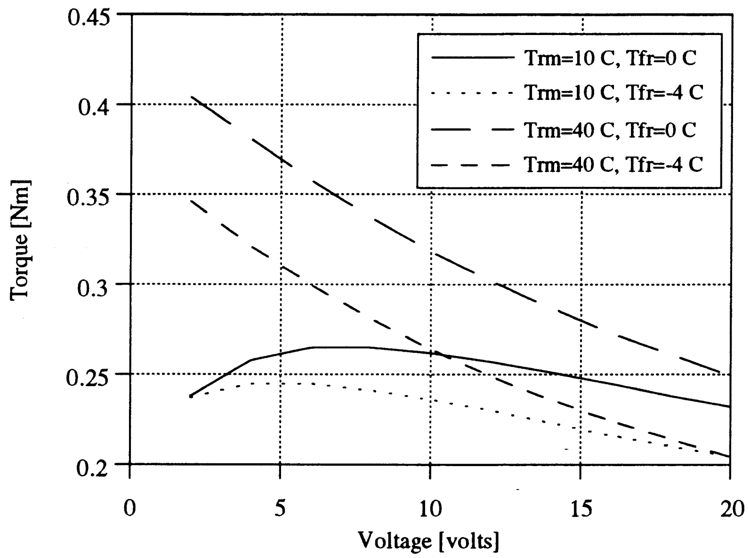

Figure 6.3: Behavior of the torque as a function of the voltage, room and freezer temperature

For high room temperatures the torque decreases with an increasing voltage. For low temperatures the torque increases until it reaches its maximum and then behaves as described for high room temperatures.

Equation [4.4] shows that the current is proportional to the torque. The proportionality factor is K_t, the torque constant. The proportionality results in the same behavior for the current with respect to voltage, room and freezer temperature as for the torque and is illustrated in Figure 6.4. For a fixed voltage and room temperature the current decreases with a decrease in the freezer temperature. The reason for this apparently anomalous behavior is discussed in detail in Section 6.1.4

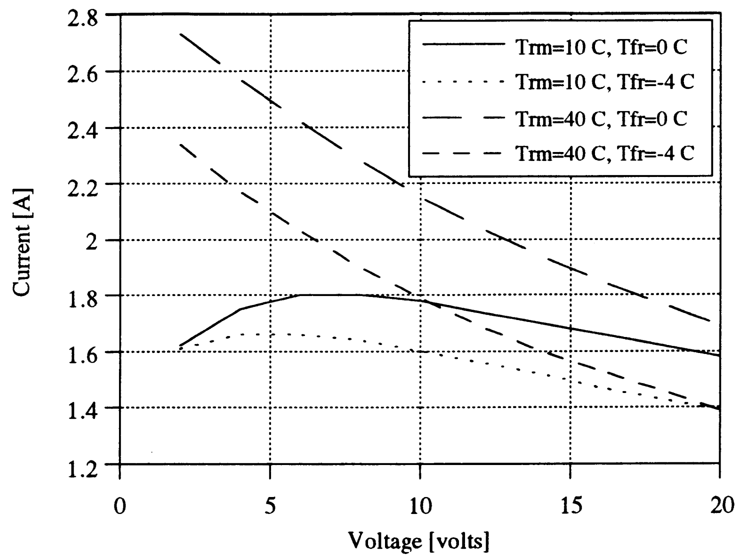

Figure 6.4: Behavior of the current as a function of the voltage, room and freezer temperature

6.1.3 Voltage - CAP, COP characteristic

The refrigeration capacity and coefficient of performance are illustrated as a function of the voltage for different environmental conditions in the Figures 6.5 and 6.6.

As can be seen in Figure 6.5, the capacity increases with increasing voltage and freezer temperature, whereas the room temperature has the opposite effect on the capacity. Figure 6.6 shows that the COP decreases with increasing voltage and room temperature, whereas the COP increases when the freezer temperature increases.

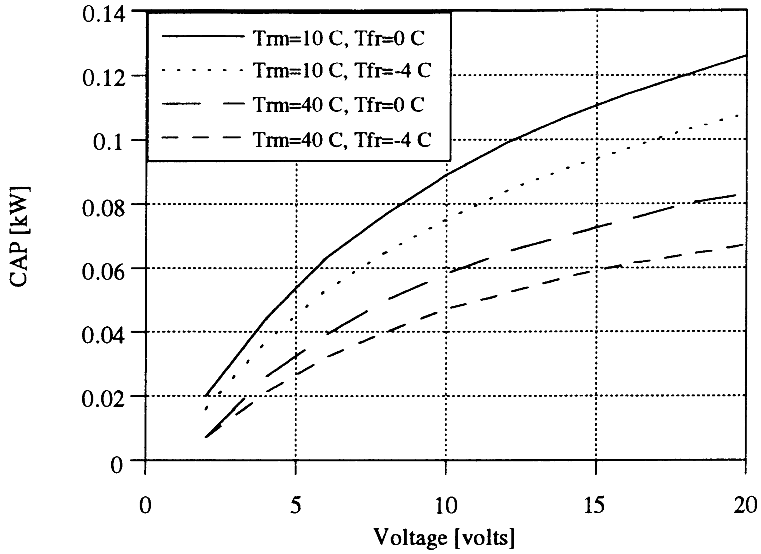

Figure 6.5: Behavior of the CAP as a function of the voltage, room and freezer temperature

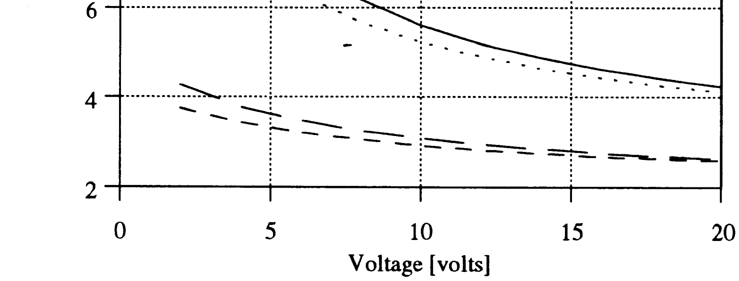

Figure 6.6: Behavior of the COP as a function of the voltage, room and freezer temperature

6.1.4 Average input power versus the freezer temperature

The compressor input power depends on the room and freezer temperature, and the voltage. Figure 6.7 illustrates the behavior of the compressor input power versus the freezer temperature at a voltage of 13 V. For purposes of the following discussion the UA values of the evaporator and the condenser are infinite, resulting in a condenser temperature equal to the room temperature and an evaporator temperature equal to the freezer temperature.

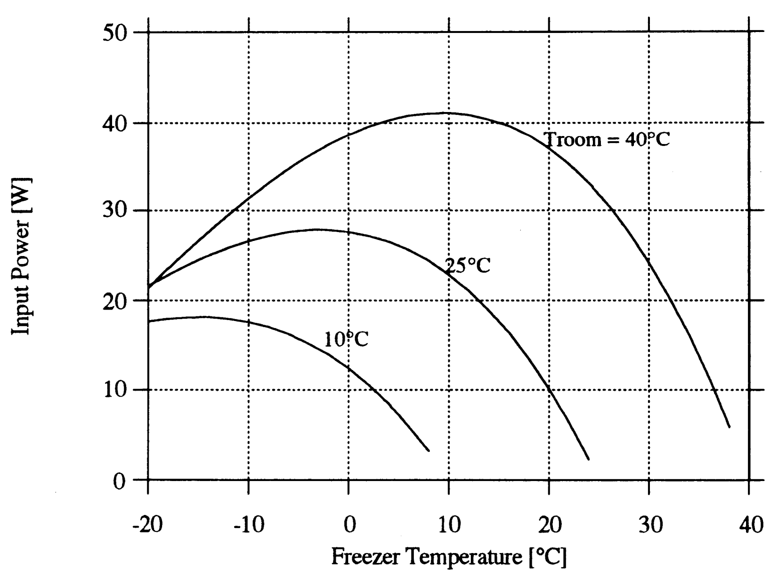

Figure 6.7: Compressor input power versus the freezer temperature for the room temperatures of 10, 25 and 40° C. The evaporator and condenser UA values are infinite, the motor voltage is 13 V and the motor losses are zero.

Figure 6.7 shows that the compressor input power increases with increasing freezer temperature, reaching a maximum and then decreases. When increasing the freezer temperature, the evaporator pressure and the density at the inlet of the compressor increases. Equation [5.5] shows that a density increase results in an increase in the mass flow rate. The polytropic work (Equation [5.6]) decreases proportionally to the ratio of the condenser and evaporator pressure. The input power to the compressor is the product of the polytropic work and the mass flow rate and thus can either increase or decrease with increasing freezer temperatures. This apparently anomalous behavior in which the power decreases as the freezer temperature decreases is a result of the fact that Figure 6.7 does not consider the fact that the refrigeration cycle actually turns on and off to meet the average load. As the freezer temperature decreases the refrigeration cycle runs longer, resulting in an increase in average power.

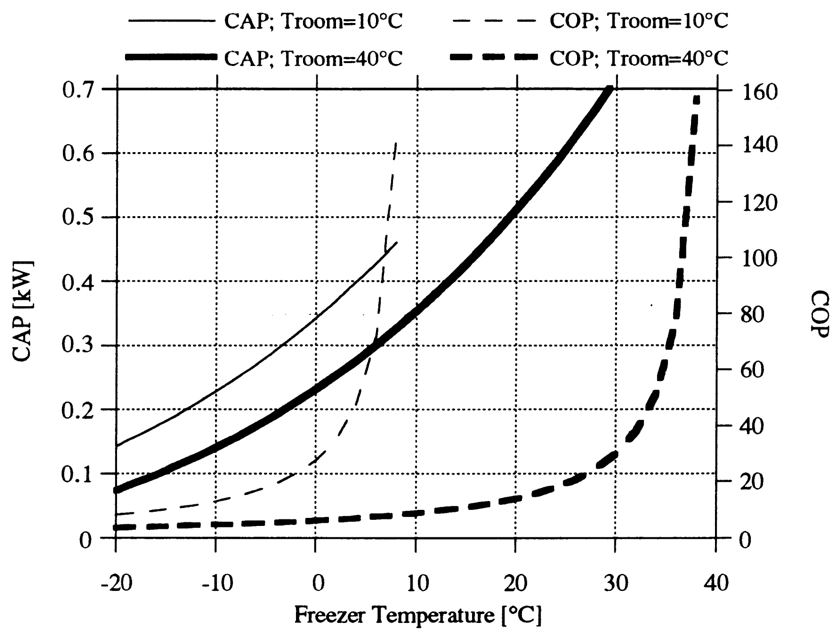

Figure 6.8: CAP and COP versus the freezer temperature for the room temperatures of 10 and 40° C. The evaporator and condenser UA values are infinite, the motor voltage is 13 V and the motor losses are zero.

Figure 6.8 shows that the refrigeration capacity and the COP decrease with decreasing freezer temperature and therefore the maximum load that can be met also decreases but will exceed the actual freezer load). Thus there are two effects that result in the cycle on time increasing as the freezer temperature decreases: the load is increasing and the refrigeration capacity is decreasing.

Figure 6.9 shows the average power needed to meet load (which is a function of the difference in temperatures between the room and the freezer) as a function of the freezer temperature. As expected the average input power increases when the freezer temperature decreases. Figure 6.9 is obtained as the product of the fractional on-time times the motor input power at the existing conditions, where the fractional on-time is the ratio of the existing load to the refrigeration capacity.

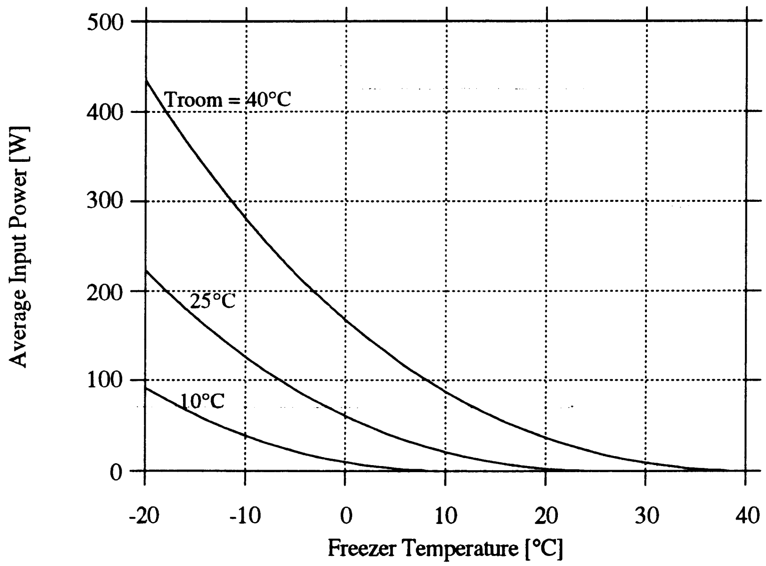

Figure 6.9 Average input power versus freezer temperature for room temperatures of 10, 25 and 40° C. The evaporator and condenser UA values are infinite, the motor voltage is 13 V and the motor losses are zero.

Figure 6.10 shows the average input power including the motor inefficiencies, versus the freezer temperature for three different input voltages. Since the motor efficiency increases with voltage, as shown in Figure 4.5, the average input power decreases with increasing voltage.

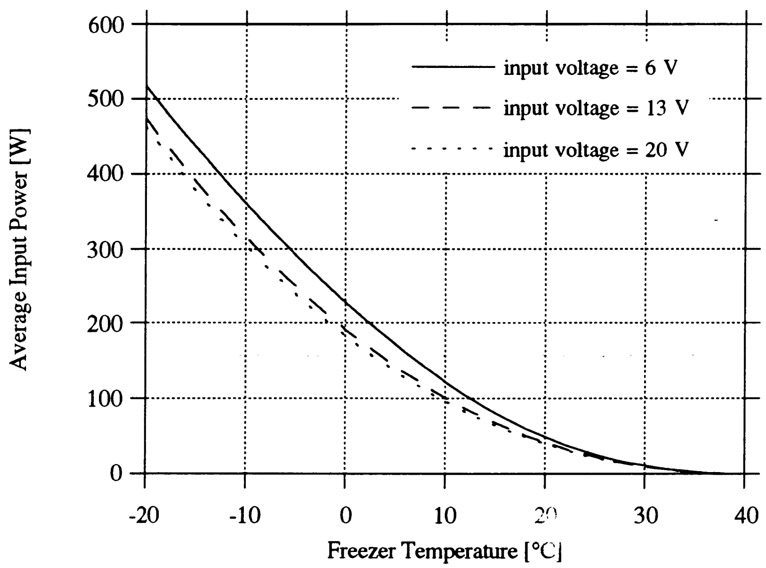

Figure 6.10 Average input power versus freezer temperature for input voltages of 6, 13 and 20V including motor losses. The evaporator and condenser UA values are infinite.

The UA values for the condenser and the evaporator for Figures 6.7 to 6.10 are infinite. Figure 6.11 illustrates the influence of finite UA values for evaporator and condenser and shows that as the UA values increase less power is needed to run the compressor.

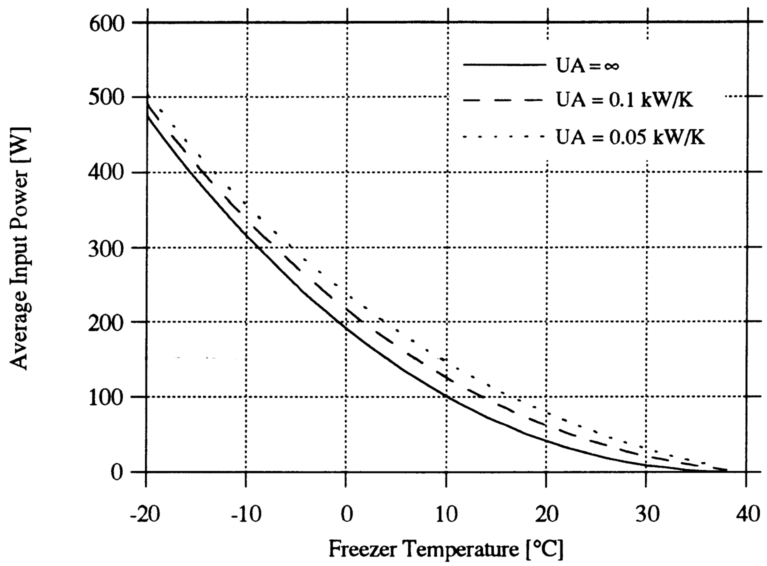

Figure 6.11 Average input power versus freezer temperature for an input voltages of 13 V including motor losses for three UA values for evaporator and condenser.

6.2 PV system analysis

Each PV array has a unique maximum power line, the locus of points of maximum power for different radiation levels. To operate a system along this line, electronic equipment called maximum power point trackers are used. These devices cause the PV array to operate at its highest efficiency. The disadvantage of the maximum power point trackers is its costs and the decrease of reliability of the system. In addition, if the system is properly designed, it can operate close to the maximum power point line. In the case described in this thesis maximum power point trackers are not used.

6.2.1 Direct coupled system

A system consisting of PV array and load is called direct coupled system. Figure 6.12 shows this configuration.

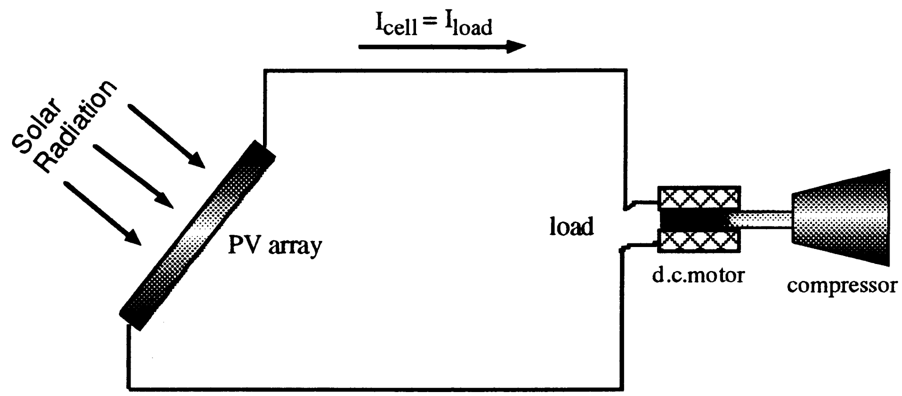

Figure 6.12: Direct coupled system configuration

The system operating point is the current-voltage intersection between the characteristics of the PV array and the cooling system. Figure 6.13 shows the current-voltage characteristics of the direct coupled system and the points of maximum power.

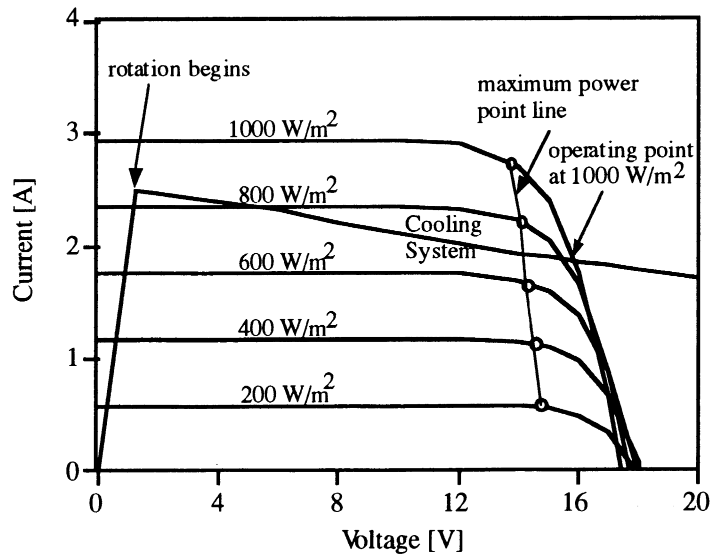

Figure 6.13: Characteristics of a direct coupled PV system

For a solar radiation of 1000 W/m^2, for example, the operating voltage is 16 V and the current 1.7 A. The power provided from the system is 27.2 W. In comparison, the maximum power for 1000 W/m^2 would be at around 38 W. This operating point results in a refrigeration capacity of 81 W and a speed of 960 1/min. The speed and capacity versus voltage is illustrated in Figure 6.14

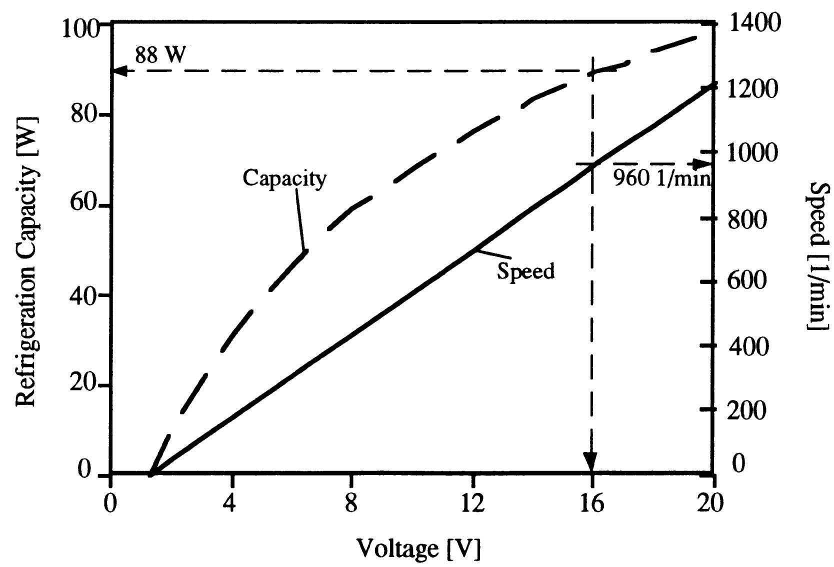

Figure 6.14: Capacity and speed versus voltage

The configuration of a direct coupled system causes problems during the time of low solar radiation. For the particular system shown in Figure 6.13 the cooling system would not operate for a solar insolation less than 620 W/m^2. To operate the refrigeration cycle also at hours of low incident radiation, a second energy source is necessary. The following chapter describes the system including the battery storage.

6.2.2 PV system including battery storage

Figure 6.15 illustrated a PV system including a parallel connected battery.

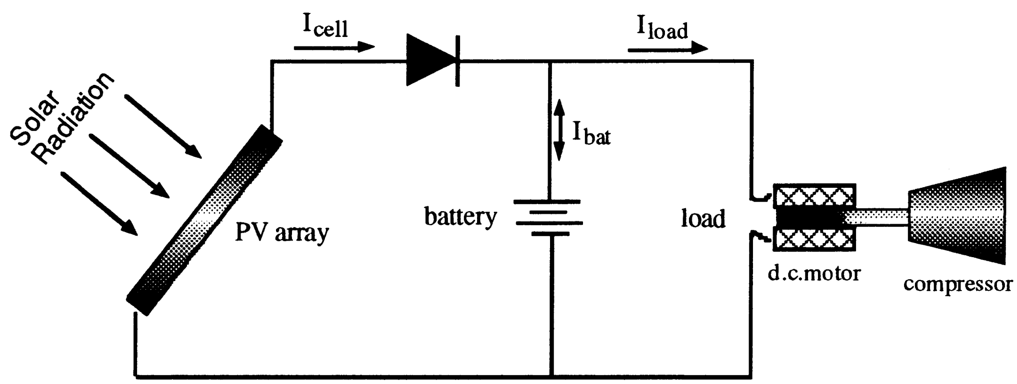

Figure 6.15: PV system including battery storage

The operating voltage of such a system depends on the I-V characteristic of all components, that is the PV array, the battery and the load. Since all the components are connected in parallel, their voltage must be the same. The voltage drop over the diode is neglected. Kirchhoff's law states that the incoming current at each node is equal to the outgoing current. The operating voltage depends on the incoming insolation, the state of charge of the battery, and the load. The battery current can be either negative or positive. If the cell current is large enough the PV array operates the load. The excess energy charges the battery, its current flow is then defined as positive. If the current is too small, the current which is needed to supply the load can be drawn from the battery. The current flow from the battery would then be negative. Figure 6.16 and 6.17 illustrate the operating conditions for the PV system.

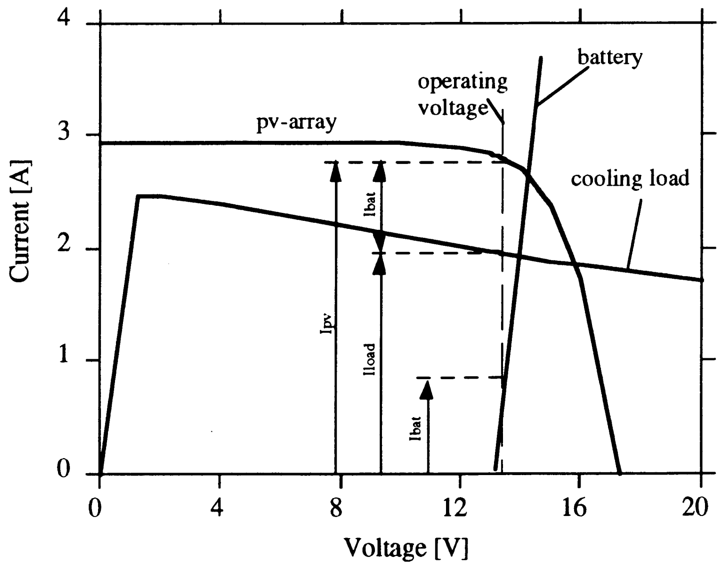

Figure 6.16: Operating conditions fora PV system including PV array, battery and refrigeration load for an incident solar radiation of 1000 W/m^2

For the case that the PV array can supply the load, represented in Figure 6.16, the operating voltage is given at the voltage where the sum of the battery current and load current is equal to the PV current. The slope of the battery characteristics is positive. The excess current charges the battery.

The situation illustrated in Figure 6.17 shows the discharge of the battery. The PV array is not able to meet the load. Therefore the battery has to supply energy.

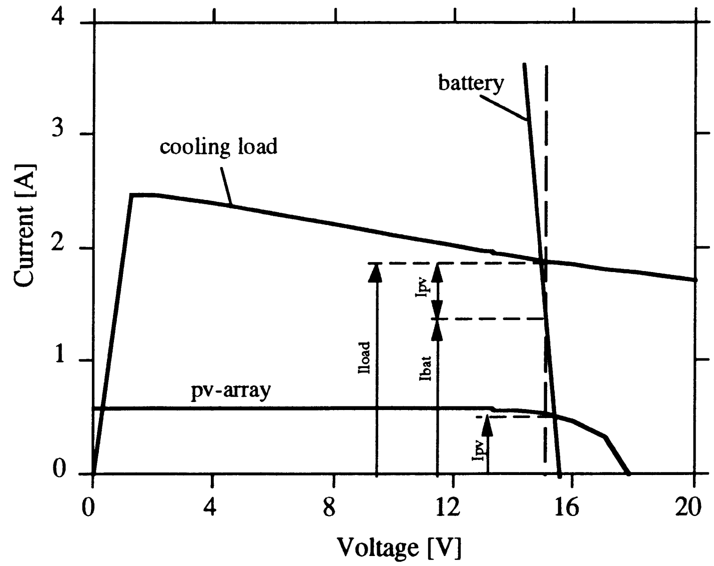

Figure 6.17: Operating conditions for a PV system including PV array, battery and refrigeration load for an incident solar radiation of 200 W/m^2

The discharge characteristic of the battery is apparent in that the slope of the curve is negative. In this case the operating voltage is the voltage where the sum of the battery current and the PV current equals the load current.

As can be seen in Figures 6.16 and 6.17, the range of the operating voltage is limited by the battery voltage. The upper limit of the operating range is determined when the battery is fully charged and operates at its maximum voltage, the lower limit when the battery is fully discharged and operates at its minimum voltage.

The operating point of the battery varies with the SOC and the charge and discharge current. The maximum power line depends on the ambient temperature and the solar radiation. Therefore the operating condition can generally not match the point of maximum power, but it can be close. To achieve a high utilization of the PV array, the system must be designed properly.

Chapter 7

TRNSYS MODELS

The simulation program TRNSYS [3] requires models for each component of the PV system. The simulation results are described in Chapter 8. This chapter describes the TRNSYS TYPES for the PV array, the battery storage, the series and the parallel controller, the cooling system and the refrigerator load. All the TYPES are listed in Appendix C.

7.1 TRNSYS component for the PV array

The TRNSYS routine for the PV array already existed as TYPE 62 and was updated to the new version of TRNSYS. The information flow diagram is illustrated in Figure 7.1.

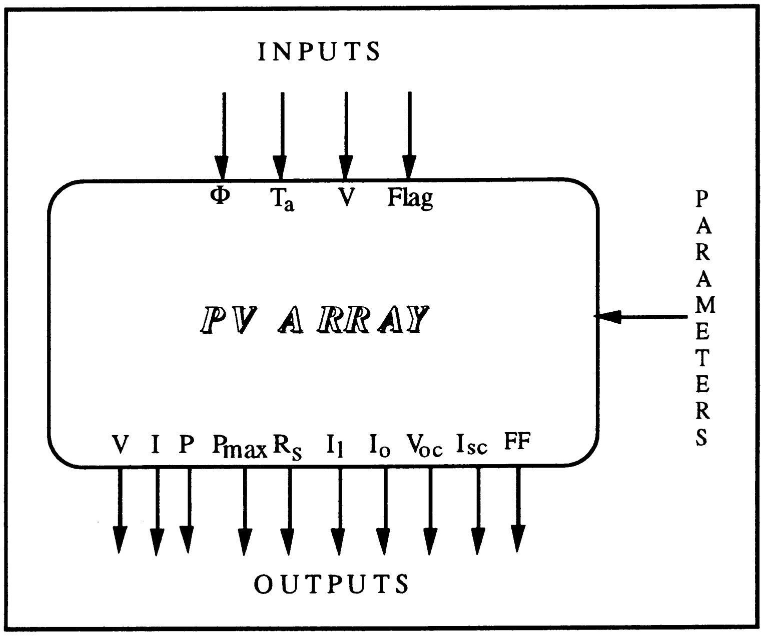

Figure 7.1: Information flow diagram for the PV array

INPUTS:

ϕ	incident solar radiation
Ta	ambient temperature
V	voltage
Flag	switches the convergence promotion on - off

OUTPUTS:

V	voltage
I	current
P	output power
P_{max}	maximum output power
R_s	series resistance
I_l	light current

I_o	reverse saturation current
V_{oc}	open circuit voltage
I_{sc}	short circuit current
FF	fill factor

PARAMETERS:

$I_{sc,ref}$	short circuit current at reference conditions
$V_{oc,ref}$	open circuit voltage at reference conditions
$T_{c,ref}$	cell temperature at reference conditions
ϕ_{ref}	incident solar radiation at reference conditions
$V_{mp,ref}$	voltage at maximum power at reference conditions
$I_{mp,ref}$	current at maximum power at reference conditions
$\mu_{I,sc}$	temperature coefficient for short circuit current
$\mu_{V,oc}$	temperature coefficient for open circuit voltage
NCS	number of cells in series
NS	number of modules in series
NP	number of modules in parallel
$T_{c,NOCT}$	cell temperature at NOCT conditions
$T_{a,NOCT}$	NOCT ambient temperature
ϕ_{NOCT}	NOCT incident solar radiation
AREA	module area
$\tau\alpha$	transmittance - absorptance product
ε	bandgap energy
R_s	series resistance

7.2 TRNSYS component for the lead acid battery

The TRNSYS routine for the lead acid battery already existed as TYPE 74 and was adjusted to the new version of TRNSYS. The information flow diagram is illustrated in Figure 7.2.

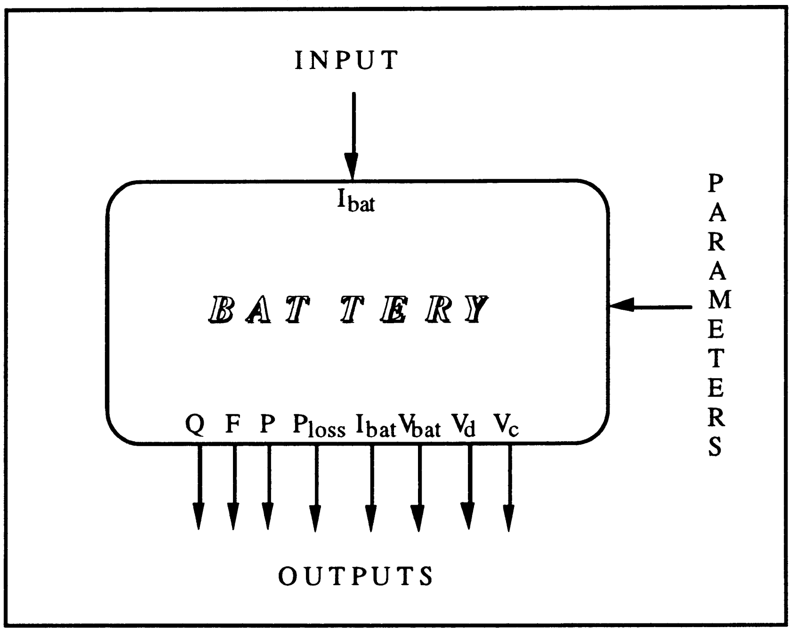

Figure 7.2: Information flow diagram for the lead acid battery component

INPUT:

I_{bat}	battery current

OUTPUTS:

Q	state of charge
F	fractional state of charge
P	power

P_{loss}	power losses
I_{bat}	battery current
V_{bat}	battery voltage
V_d	cutoff voltage on discharge
V_c	cutoff voltage on charge

PARAMETERS:

Q_M	rated capacity
C_p	cells in parallel
C_s	cells in series
η	charging efficiency
V_c	cutoff voltage on charge
V_{contr}	specification of the cutoff voltage on discharge
$I_{c,tol}$	parameter for iterative calculations
E_c	extrapolated open circuit voltage on charge
E_d	extrapolated open circuit voltage on discharge
G_c	small valued coefficient of F
G_d	small valued coefficient of F
M_c	cell type parameter which determine the shape of the I-V characteristics
M_d	cell type parameter which determine the shape of the I-V characteristics
E_D	battery constant
R_D	battery constant
I_{di}	curve fitting parameter

K_{di}	curve fitting parameter
Q_c	capacity parameter on charge
Q_d	capacity parameter on discharge
R_c	internal resistance on charge
R_d	internal resistance on discharge

7.3 TRNSYS component for the series controller

The basic TRNSYS routine for the series controller already existed as TYPE 59. It was updated to the new version of TRNSYS and modified to include additional needs for the simulation. The information flow diagram is illustrated in Figure 7.3.

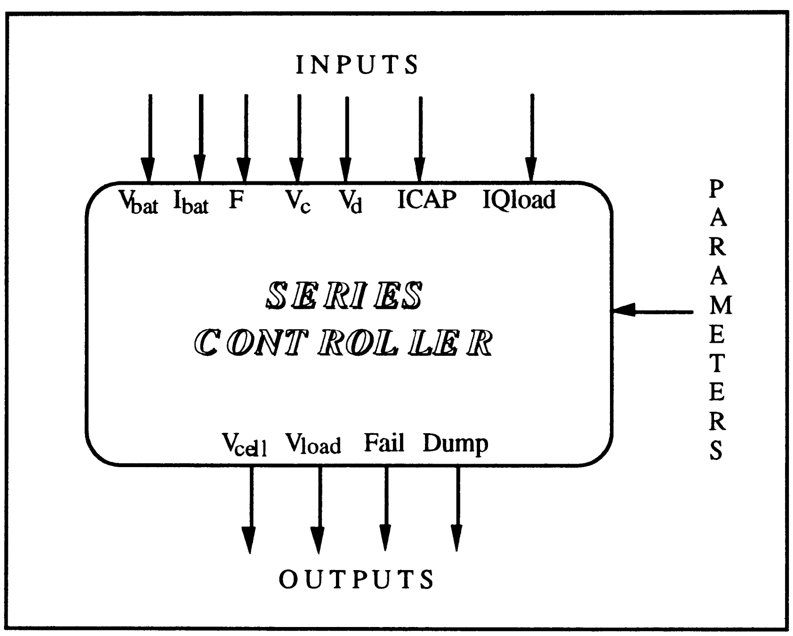

Figure 7.3: Information flow diagram for the series controller

INPUTS:

V_{bat}	battery voltage
I_{bat}	battery current
F	fractional state of charge of the battery
V_c	battery cutoff voltage on charge
V_d	battery cutoff voltage on discharge
ICAP	cooling energy from the refrigeration cycle
IQload	refrigerator load

OUTPUTS:

V_{cell}	voltage for the PV array
V_{load}	voltage for the load
Fail	current indicator
Dump	indicator if energy from the PV array must be dumped

PARAMETERS:

F_d	fractional SOC discharge limit
F_c	fractional SOC charge limit
F_{da}	fractional state of charge above which the battery can be discharged
F_{ca}	fractional state of charge below which the battery can be charged
V_{da}	voltage above which the battery can be discharged
V_{ca}	voltage below which the battery can be charged
$I_{b,max}$	maximum battery charge current
$I_{b,min}$	maximum battery discharge current

V_{diode} diode voltage drop

TOL value related to the heat gains of the refrigerator to raise from the lower to the upper thermostat limit

The inputs V_{bat} , I_{bat} and F are connected to the related battery outputs and supply the controller with the actual voltage, current and state of charge of the battery. V_c, V_d and the parameters F_c and F_d limit the voltage and the SOC for charge and discharge. The parameters V_{ca}, V_{da}, F_{ca} and F_{da} describe the hysterisis to prevent an oscillation of the system. The parameters $I_{b,max}$ and $I_{b,min}$ do not have an influence on the behavior of the system. When the current is greater than $I_{b,max}$ or smaller than $I_{b,min}$, the output "Fail" is set to 1 or 2. Inside this range "Fail" remains zero. V_{diode} is the voltage drop over the diode and depends on the voltage diode material. For a silicon diode it is set to 0.7 V.

In a real PV powered refrigeration system, the thermostat set points cause the compressor to turn on and off. If the refrigerator temperature reaches the upper thermostat level, the cooling system is switched on and the temperature decreases until the lower thermostat level is reached. At that point the cooling system is switched off.

In the simulation, the parameter *TOL* and the inputs *ICAP* and *IQload* cause the cooling system to operate or not. *TOL* in [Wh] describes the energy that is necessary to overcome the temperature difference in the refrigerator, given by the lower to the upper thermostat setting. *ICAP* describes the energy that is removed from the refrigerator through the evaporator of the refrigeration cycle. *IQload* describes the heat gains of the refrigerator through walls, ice making, door opening and water cooling. If the removed energy minus the heat gains is greater than *TOL* , the cooling system is disconnected from the PV system. If the removed energy is smaller than the heat gains the cooling system is reconnected. For a state in between, the old status remains and the cooling system would operate. If the low temperature is reached, the cooling system is disconnected and the temperature in the refrigerator increases.

If the maximum state of charge or charge voltage is reached and the energy difference is greater than *TOL,* the PV array can neither supply the load nor charge the battery and its energy is then dumped. This energy is identified with the output "Dump".

To determine the difference in the internal energy of the refrigerator between 2 C and 8 C the lumped capacitance method was used. Equation [7.1] shows the basic differential equation, neglecting the convection thermal resistance at the inside and outside of the refrigerator.

$$\frac{k}{L} A_{ref} (T_{rm} - T_{ref}) = m\, cp \frac{dT_{ref}}{dt} \qquad [7.1]$$

$$mcp = \rho_{air} V_{ref} cp_{air} + m_{wat}\, cp_{wat} + m_{ice}\, cp_{ice} \qquad [7.2]$$

where

k is the conductivity of the refrigerator walls,

L is the thickness of the refrigerator walls,

m_{wat} is the mass of water to be cooled,

m_{ice} is the mass of ice to be made,

cp_{wat} is the specific heat of water,

cp_{ice} is the specific heat of ice,

cp_{air} is the specific heat of the air,

A_{ref} is the area of the refrigerator,

V_{ref} is the volume of the refrigerator,

ρ_{air} is the density of air,

T_{rm} is the room temperature,

T_{ref} is the refrigerator temperature.

Introducing the temperature difference Θ

$$\theta = T_{rm} - T_{ref} \qquad [7.3]$$

and recognizing that $(d\Theta/dt) = (dT_{ref}/dt)$, it follows that after integrating from the initial conditions for which the time $t = 0$ and $\Theta_i = T_{ref,i} - T_{rm}$, we then obtain

$$\frac{L\, m\, cp}{k\, A_{ref}}\, ln \frac{\theta_i}{\theta} = t \qquad [7.4]$$

The values of the variables for determining the time the refrigerator temperature needs to increase from 2 C to 8 C are listed below.

k=0.025 W/m-K	L=0.06m	m_{wat}=2kg
m_{ice}=3kg	cp_{wat}=4190J/kg-K	cp_{ice}=2110J/kg-K
cp_{air}=1006J/kg-K	A_{ref}=2.595m^2	V_{ref}=0.127m^3
ρ_{air}=1.18kg/m^3	T_{rm}=30 C	

The result is a time of 3314 seconds. The refrigerator load under these conditions varies between 30 W and 70 W depending on the room temperature. The energy range is between 27 Wh and 64 Wh. For the simulation 50 Wh is the value for the parameter *TOL*.

7.4 TRNSYS component for the parallel controller

The TRNSYS routine for the parallel controller is TYPE 66. The information flow diagram for the parallel controller is shown in Figure 7.4.

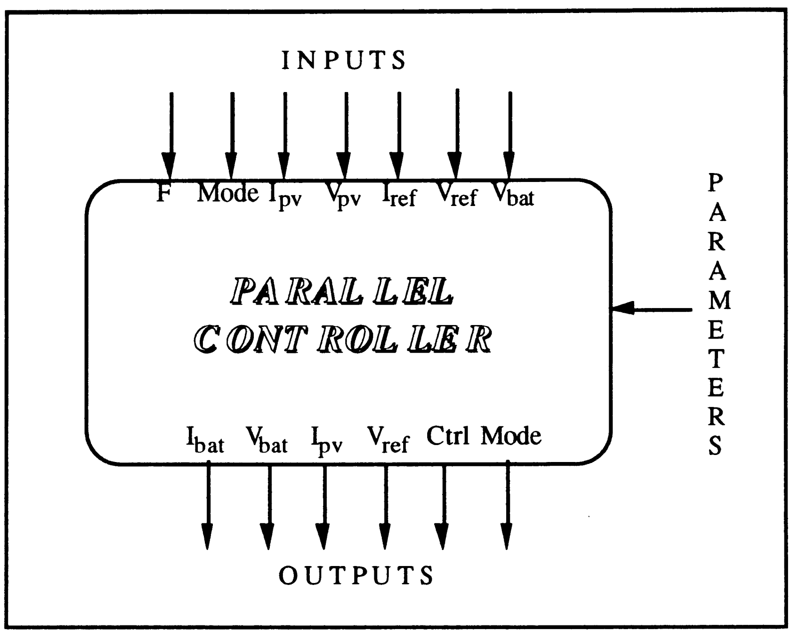

Figure 7.4: Information flow diagram for the parallel controller

INPUTS:

F	fractional state of charge
Mode	current state
Ipv	current from PV array
Vpv	voltage from PV array

Iref	current from cooling system
Vref	voltage from cooling system
Vbat	battery voltage

OUTPUTS:

Ibat	battery current
Vbat	battery voltage
Ipv	PV current
Vref	voltage for cooling system
Ctrl	indicator
Mode	current state

PARAMETERS:

S_{max}	maximum fractional state of charge of the battery
S_{min}	minimum fractional state of charge of the battery
$Delta_{SOC}$	state of charge hysterisis
I_{max}	maximum current to drive the load

The inputs F and V_{bat} are directly connected to the battery, I_{pv}, V_{pv} to the PV array and I_{ref}, V_{ref} to the refrigeration cycle with the d.c. motor.

In the real equipment the relay state (on or off) of the last measurement can be stored and used to determine their state for the current state of charge of the battery.

In the TRNSYS simulation the input *Mode* describes the old relay state and the output *Mode* the current state. If the input *Mode* is equal to zero, the battery was on discharge, what means that further discharge is not allowed. An input *Mode* of one describes normal operating conditions for the previous calculation. Normal operating conditions means that the battery can be charged and discharged. If the input *Mode* is equal to two, overcharge condition are present, which means that charging the battery is not allowed. The parallel controller routine checks the current state of charge and adjusts the output *Mode*. If the battery was on discharge (input *Mode* = 0), the SOC must be greater than the sum of S_{min} plus $Delta_{SOC}$ to allow discharging again, which would then cause the output *Mode* to be one. If the battery operated under normal conditions (input *Mode* = 1), the state of charge is compared to the limits S_{min} and S_{max}. If the deep discharge or the overcharge level is reached *Mode* is set to either zero or two. The third case (input *Mode* = 2) indicates that the overcharge condition existed at the last calculation. If the current state of charge is smaller than the difference of S_{max} minus $Delta_{SOC}$, the battery can be operated under normal conditions and the Mode is set to one.

7.5 TRNSYS component for the cooling system

The TRNSYS routine for the cooling system is TYPE 73. TYPE 73 consists of curve fits of the results achieved with the EES program Cooling system in Appendix B.

7.5.1 Curve fit procedure

With the EES-program Compressor-Motor the current, the capacity and the coefficient of performance are calculated for 252 operation points. The voltage range was from 0 - 20 V, the room temperature from 10 to 40 C and the freezer temperature from -4 to 0 C. The curve fit procedure yields with the current as a function of each of the three inputs.

For each combination of freezer temperature and room temperature the calculated values of the current with respect to the voltage are fit by a polynomial of n-the order.

$$I = a_0 + a_1 V + a_2 V^2 + \ldots + a_n V^n \qquad [7.5]$$

As an example, Figure 7.5 shows two curve fits for different temperature combinations.

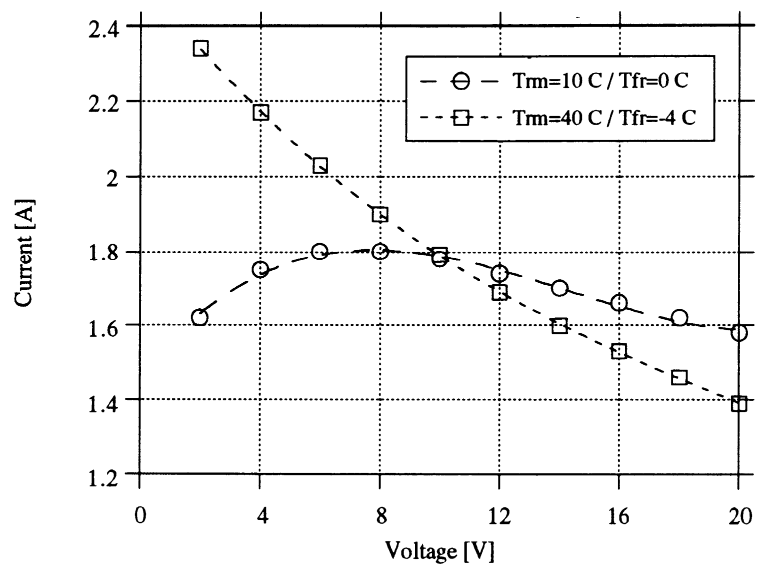

Figure 7.5: Curve fit of the current for two different room and freezer temperatures

The dotted lines are the fitted curves through the given points (squares, circles). Each of the coefficients a_0 - a_n with n equal to or less than the number of given operating points is a function of the room and the freezer temperature. For each freezer temperature the coefficients can be expressed by a polynomial of m-th order with respect to the room temperature.

$$a_0 = b_{00} + b_{10}\, T_{rm} + b_{20}\, T_{rm}^2 + \dots + b_{m0}\, T_{rm}^m \qquad [7.6]$$
$$a_1 = b_{01} + b_{11}\, T_{rm} + b_{21}\, T_{rm}^2 + \dots + b_{m1}\, T_{rm}^m$$
$$\vdots$$
$$\vdots$$
$$a_n = b_{0n} + b_{1n}\, T_{rm} + b_{2n}\, T_{rm}^2 + \dots + b_{mn}\, T_{rm}^m$$

Figure 7.6 shows the curve fit for the coefficient a_0 with respect to the room temperature for several freezer temperatures.

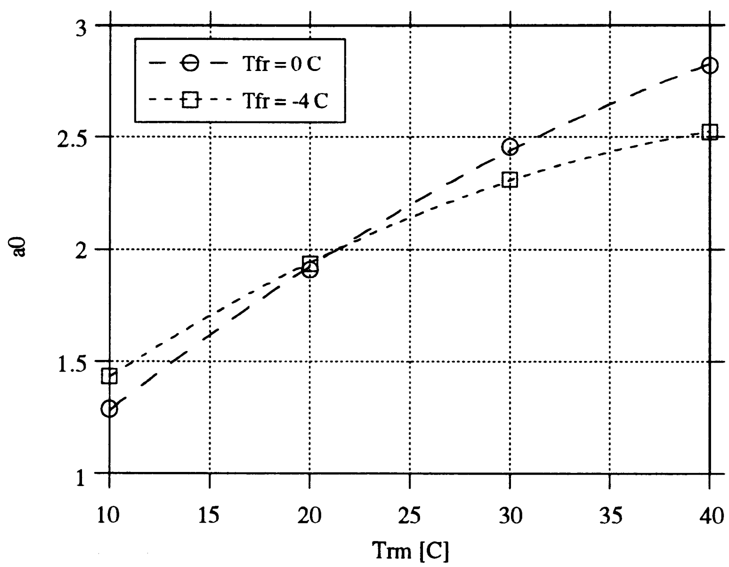

Figure 7.6: Curve fit for a_0 for different freezer temperatures

Each of the coefficients b_{00} - b_{mn} is a function of the freezer temperature. For each freezer temperature the coefficient can be expressed by a polynomial of k-th order.

$$b_{00} = c_{000} + c_{100}\, T_{fr} + c_{200}\, T_{fr}^2 + \ldots + c_{k00}\, T_{fr}^k \qquad [7.7]$$
$$b_{10} = c_{010} + c_{110}\, T_{fr} + c_{210}\, T_{fr}^2 + \ldots + c_{k10}\, T_{fr}^k$$
$$\vdots$$
$$b_{mn} = c_{0mn} + c_{1mn}\, T_{fr} + c_{2mn}\, T_{fr}^2 + \ldots + c_{kmn}\, T_{fr}^k$$

Figure 7.7 shows the curve fit for the coefficient b_{00} with respect to the freezer temperature. The numbers for b_{00} are evaluated at the first step for different freezer but constant room temperatures.

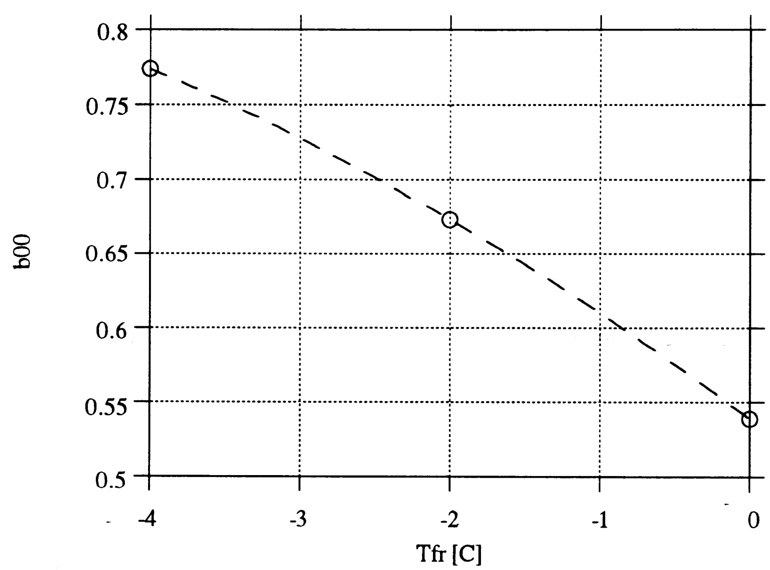

Figure 7.7: Curve fit for b_{00} as a function of the freezer temperature

This results in the final equation to calculate the current.

$$\begin{aligned} I = \; & c_{000} + c_{100}\,T_{fr} + c_{200}\,T_{fr}^2 + \ldots + c_{k00}\,T_{fr}^k + \\ & [c_{010} + c_{110}\,T_{fr} + c_{210}\,T_{fr}^2 + \ldots + c_{k10}\,T_{fr}^k]\,T_{rm} + \ldots + \\ & [c_{0m0} + c_{1m0}\,T_{fr} + c_{2m0}\,T_{fr}^2 + \ldots + c_{km0}\,T_{fr}^k]\,T_{rm}^m + \ldots + \\ & \{c_{001} + c_{101}\,T_{fr} + c_{201}\,T_{fr}^2 + \ldots + c_{k01}\,T_{fr}^k + \\ & [c_{011} + c_{111}\,T_{fr} + c_{211}\,T_{fr}^2 + \ldots + c_{k11}\,T_{fr}^k]\,T_{rm} + \ldots + \\ & [c_{0m1} + c_{1m1}\,T_{fr} + c_{2m1}\,T_{fr}^2 + \ldots + c_{km1}\,T_{fr}^k]\,T_{rm}^m\}\,V + \ldots + \\ & \{c_{00n} + c_{10n}\,T_{fr} + c_{20n}\,T_{fr}^2 + \ldots + c_{k0n}\,T_{fr}^k + \\ & [c_{01n} + c_{11n}\,T_{fr} + c_{21n}\,T_{fr}^2 + \ldots + c_{k1n}\,T_{fr}^k]\,T_{rm} + \ldots + \\ & [c_{0mn} + c_{1mn}\,T_{fr} + c_{2mn}\,T_{fr}^2 + \ldots + c_{kmn}\,T_{fr}^k]\,T_{rm}^m\}\,V^n \end{aligned} \qquad [7.8]$$

The coefficients c_{000} to c_{kmn} are listed in the TRNSYS TYPE 73 in Appendix C. The accuracy of this curve fit is illustrated in the next figure with 20 data points.

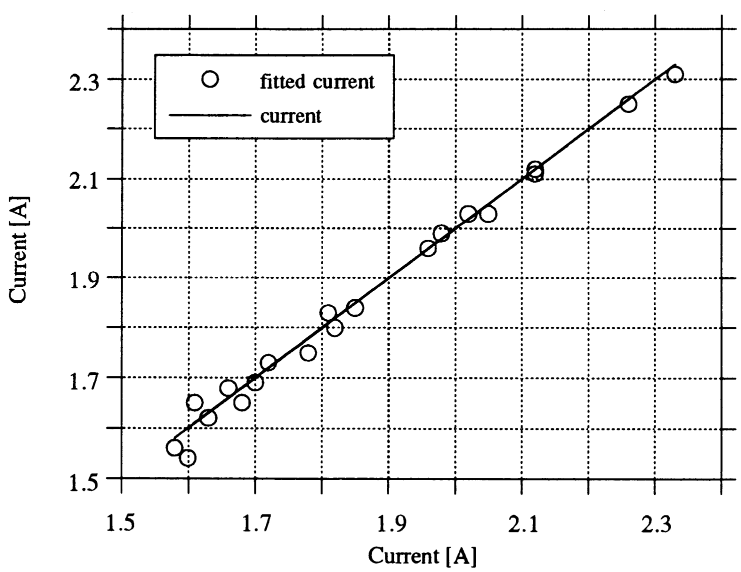

Figure 7.8: Accuracy of the curve fit current

The maximum deviation to the numbers calculated with the EES-model is 3.75 %.

The same procedure was tried with the capacity, but in comparison to the current, the assumed polynomial did not fit the data well. Therefore a curve fit with the coefficient of performance was made as described for the current. Equation [7.9] gives the COP as a function of the voltage, room and freezer temperature.

$$\begin{aligned} COP = \; & d_{000} + d_{100}\, T_{fr} + d_{200}\, T_{fr}^2 + \dots + d_{k00}\, T_{fr}^k + \\ & [d_{010} + d_{110}\, T_{fr} + d_{210}\, T_{fr}^2 + \dots + d_{k10}\, T_{fr}^k]\, T_{rm} + \dots + \\ & [d_{0m0} + d_{1m0}\, T_{fr} + d_{2m0}\, T_{fr}^2 + \dots + d_{km0}\, T_{fr}^k]\, T_{rm}^m + \dots + \\ & \{d_{001} + d_{101}\, T_{fr} + d_{201}\, T_{fr}^2 + \dots + d_{k01}\, T_{fr}^k + \\ & [d_{011} + d_{111}\, T_{fr} + d_{211}\, T_{fr}^2 + \dots + d_{k11}\, T_{fr}^k]\, T_{rm} + \dots + \\ & [d_{0m1} + d_{1m1}\, T_{fr} + d_{2m1}\, T_{fr}^2 + \dots + d_{km1}\, T_{fr}^k]\, T_{rm}^m\}\, V + \dots + \\ & \{d_{00n} + d_{10n}\, T_{fr} + d_{20n}\, T_{fr}^2 + \dots + d_{k0n}\, T_{fr}^k + \\ & [d_{01n} + d_{11n}\, T_{fr} + d_{21n}\, T_{fr}^2 + \dots + d_{k1n}\, T_{fr}^k]\, T_{rm} + \dots + \\ & [d_{0mn} + d_{1mn}\, T_{fr} + d_{2mn}\, T_{fr}^2 + \dots + d_{kmn}\, T_{fr}^k]\, T_{rm}^m\}\, V^n \end{aligned} \qquad [7.9]$$

The accuracy of the curve fit is shown in Figure 7.9 for 20 data points.

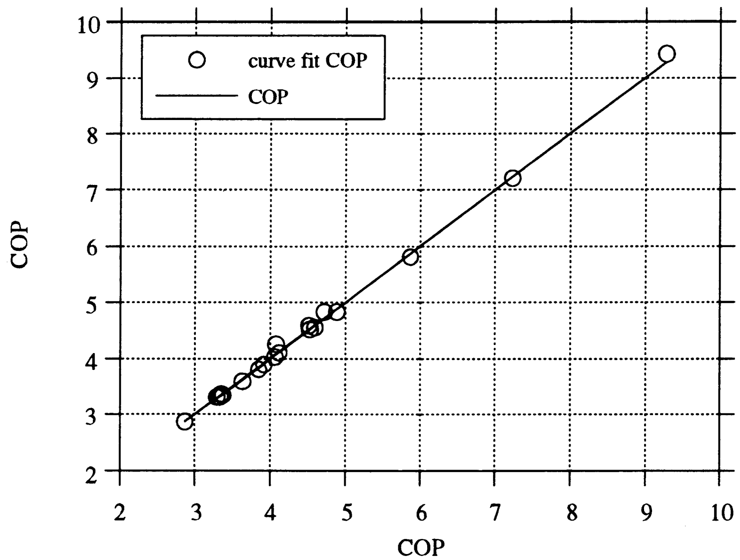

Figure 7.9: Accuracy of the curve fit COP

The maximum deviation to the numbers calculated with the EES-model is 4.4 %. With the COP known the capacity can be calculated from:

$$CAP = \frac{COP}{V\,I\,\eta_{mot}} \qquad [7.10]$$

where

η_{mot} is the efficiency of the motor.

The efficiency of the motor varies with changing conditions. Figure 7.10 and 7.11 illustrate the curve fit for the capacity with varying motor efficiency (Figure 7.10) and with a constant efficiency of 90% (Figure 7.11) for 20 data points.

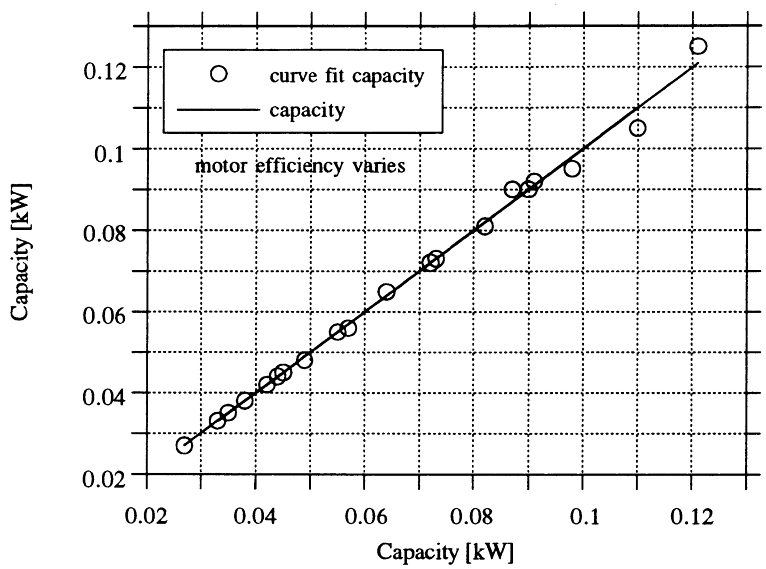

Figure 7.10: Accuracy of the curve fit CAP with a varying motor efficiency

The maximum deviation to the numbers calculated with the EES-model is 4.5 %.

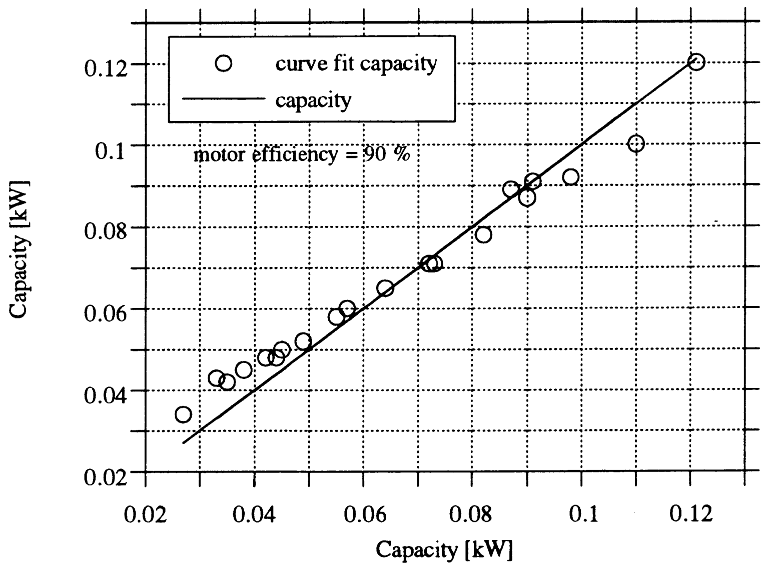

Figure 7.11: Accuracy of the curve fit CAP with a motor efficiency of 90 %

Figure 6.6 shows that the capacity range for an operating voltage of 12 V is between 50 and 90 watts which leads to a maximum deviation to the numbers calculated with the EES model of 5 %. For lower refrigeration capacities the motor efficiency is too small, for higher capacities the efficiency is too high.

7.5.2 TRNSYS flow diagram for the cooling system

The information flow diagram for the refrigeration cycle - d.c. motor component is illustrated in Figure 7.12.

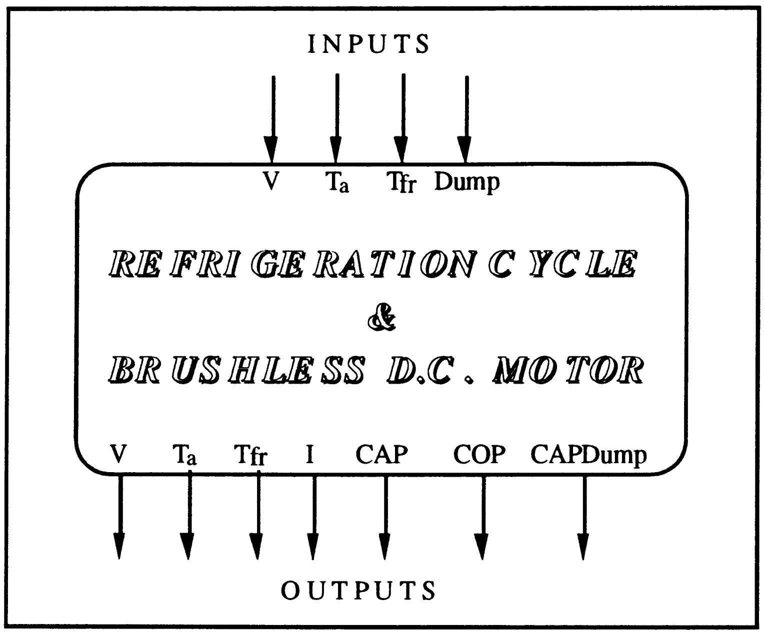

Figure 7.12: Information flow diagram for the refrigeration cycle - d.c. motor component

INPUTS:

V	voltage
T_a	ambient temperature
T_{fr}	freezer temperature
Dump	dumped energy indicator

OUTPUTS:

V	voltage
T_a	ambient temperature
T_{fr}	freezer temperature
I	current
CAP	refrigeration capacity
COP	coefficient of performance
CAP_{Dump}	dumped refrigeration capacity

The input variable *Dump* is set from the controller when the battery is at its maximum state of charge and no energy is needed to cool the refrigerator. The output CAP_{Dump} is the wasted cooling power.

7.6 TRNSYS component for the refrigerator load

The information flow diagram for the refrigerator load is illustrated in Figure 7.13.

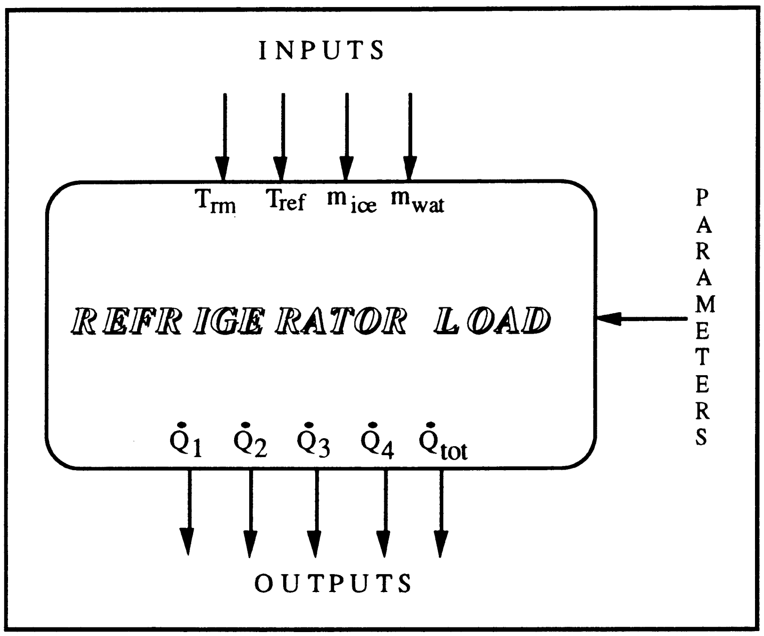

Figure 7.13: Information flow diagram for the refrigerator load

INPUTS:

T_{rm}	room temperature
T_{ref}	freezer temperature
m_{ice}	mass ice to be made
m_{wat}	mass of water to be cooled

OUTPUTS:

Q_1	heat gains through conduction
Q_2	ice making capacity
Q_3	door opening capacity
Q_4	water cooling capacity
Q_{tot}	total capacity

PARAMETERS:

k	conductivity of the refrigerator walls
L	thickness of the refrigerator walls
cp_{wat}	specific heat of water
cp_{ice}	specific heat of ice
A_{ref}	area of the refrigerator
T_{ice}	temperature for the ice
V_{ref}	volume of the refrigerator
cp_{air}	specific heat of air
ρ_{air}	density of air
A_c	number of air changes per minute
t_{do}	time the door is open per day

7.7 TRNSYS component for the integration and resetting procedure

The TRNSYS routine for the integration and resetting procedure is called TYPE 71. The information flow diagram is shown in Figure 7.14.

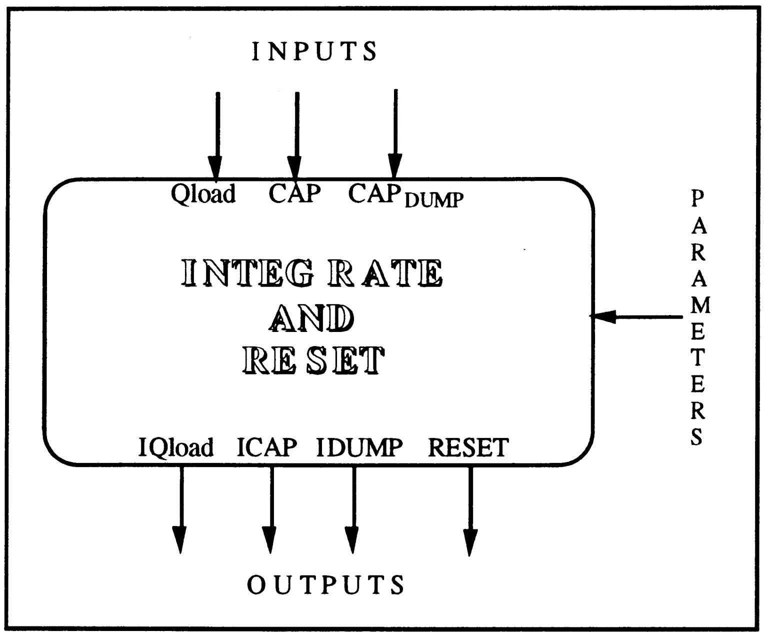

Figure 7.14: Information flow diagram for the integration and reset procedure

INPUTS:

Qload	refrigeration load
CAP	cooling capacity
CAP_{Dump}	dumped refrigeration capacity

OUTPUTS:

IQload	refrigerator energy
ICAP	cooling energy
IDump	dumped cooling energy
Reset	reset time check

PARAMETERS:

TOL	value related to the heat gains of the refrigerator to raise from the lower to the upper thermostat limit

In TYPE 71 the refrigeration, cooling and the dumped energy is calculated. The output energies are to determine the on - off cycles of the cooling system (Section 7.3).
To determine whether the refrigerator load can be met during a bad weather period, the cooling and the refrigerator energy are reset each day. If the difference between the cooling system and the refrigerator load is within the specified tolerance, given by the parameter TOL, its value is the reset value for the cooling energy, if not the cooling energy is reset to zero. The reset value for the refrigerator load is zero.

Chapter 8

SIMULATION AND OPTIMIZATION

The purpose of the PV refrigeration system is to store vaccine in remote places, particularly in developing countries. To safely store the vaccine, the system must meet the load at the worst ambient conditions in its location. A simulation study was done to optimize the size of the system components. A comparison of the series and parallel controller was made and the behavior of the PV system for different slopes of the array and various battery sizes was studied. The simulations used TMY (typical meteorological year) weather data for Miami. The TRNSYS decks SContr.dck and PContr.dck for the controller simulation and Simul.dck for the sizing simulations are listed in Appendix D. Figure 8.1 illustrates the PV system consisting of PV array, battery, charge controller, cooling system and a refrigerator.

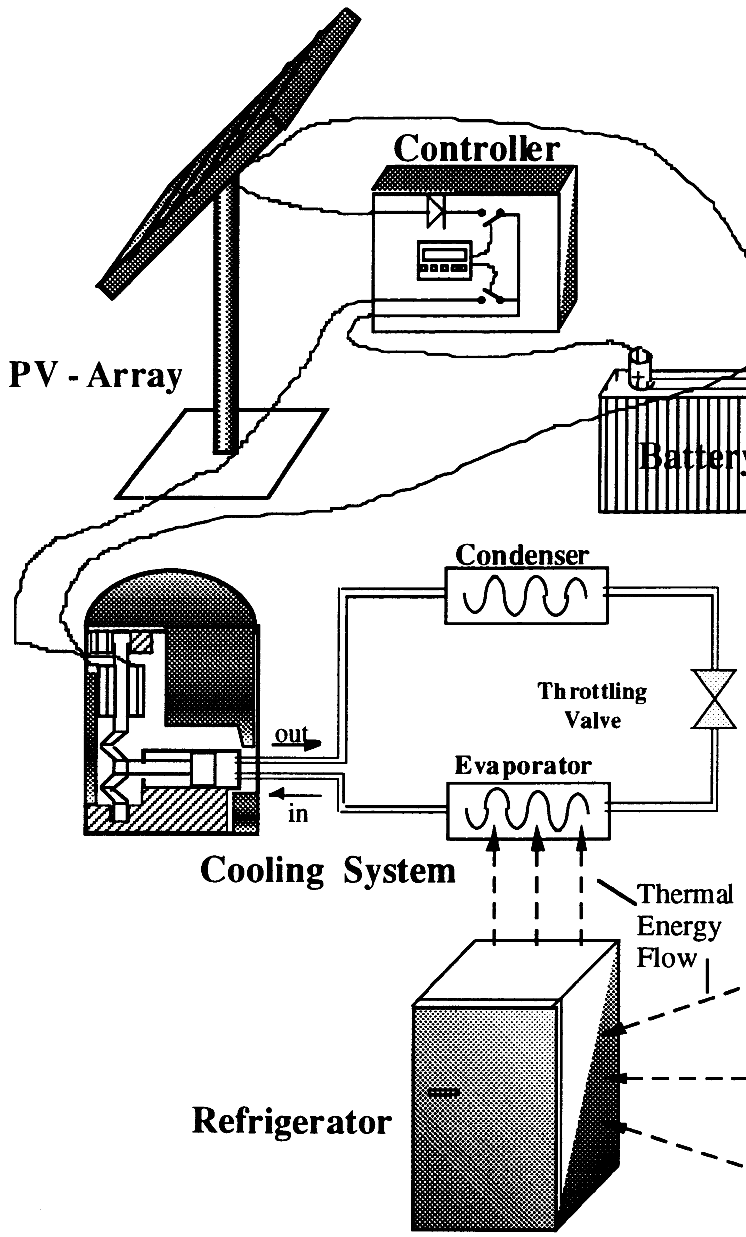

Figure 8.1: PV system

8.1 Charge controller comparison

The controller protects the battery from being overcharged or undercharged. This section compares the performance of a series and parallel controller. The TRNSYS simulation program for the series controller is SContr.dck and PContr.dck for the parallel controller. The information flow diagrams for SContr.dck and PContr.dck are illustrated in Figures 8.2 and 8.3.

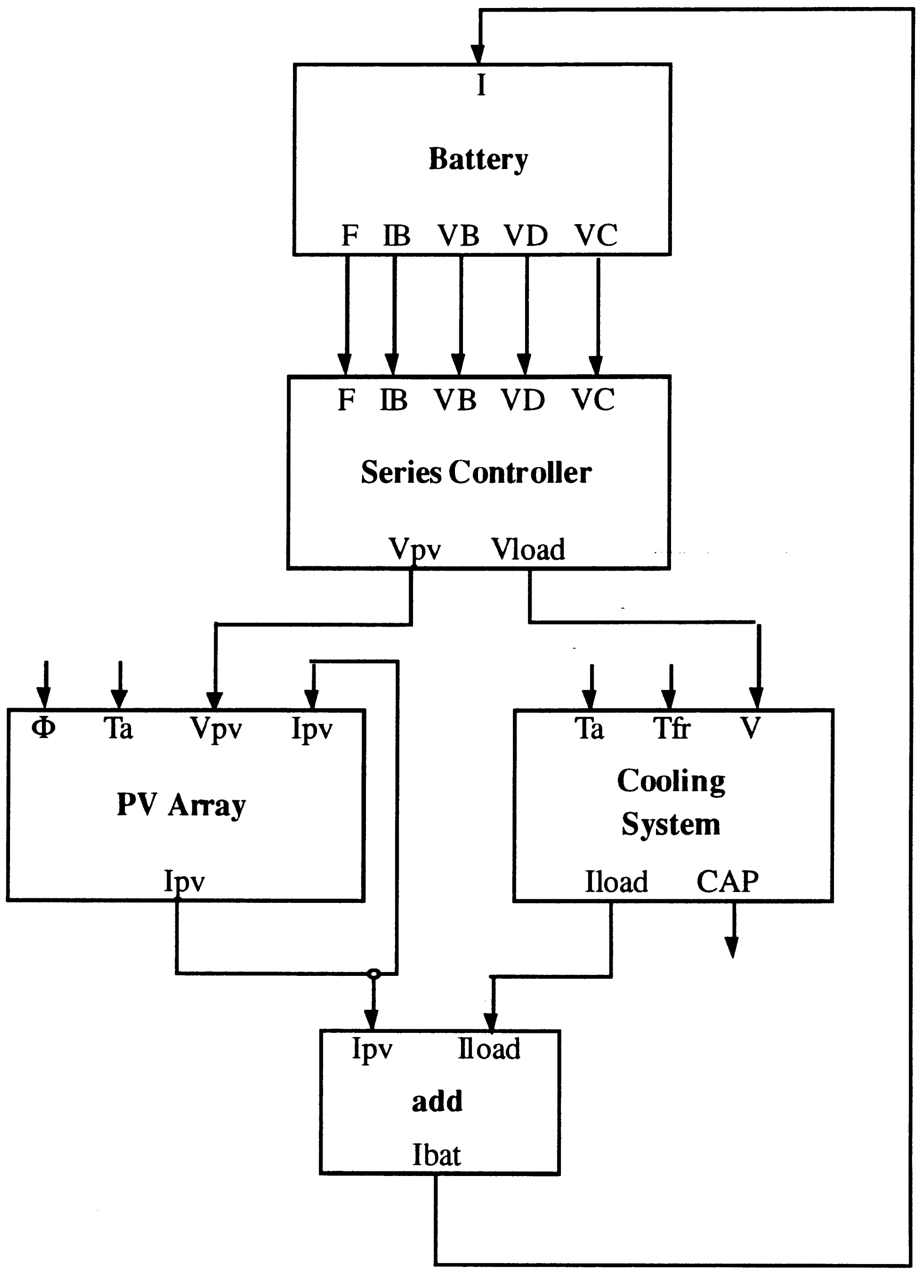

Figure 8.2: Information flow diagram for simulation with the series controller

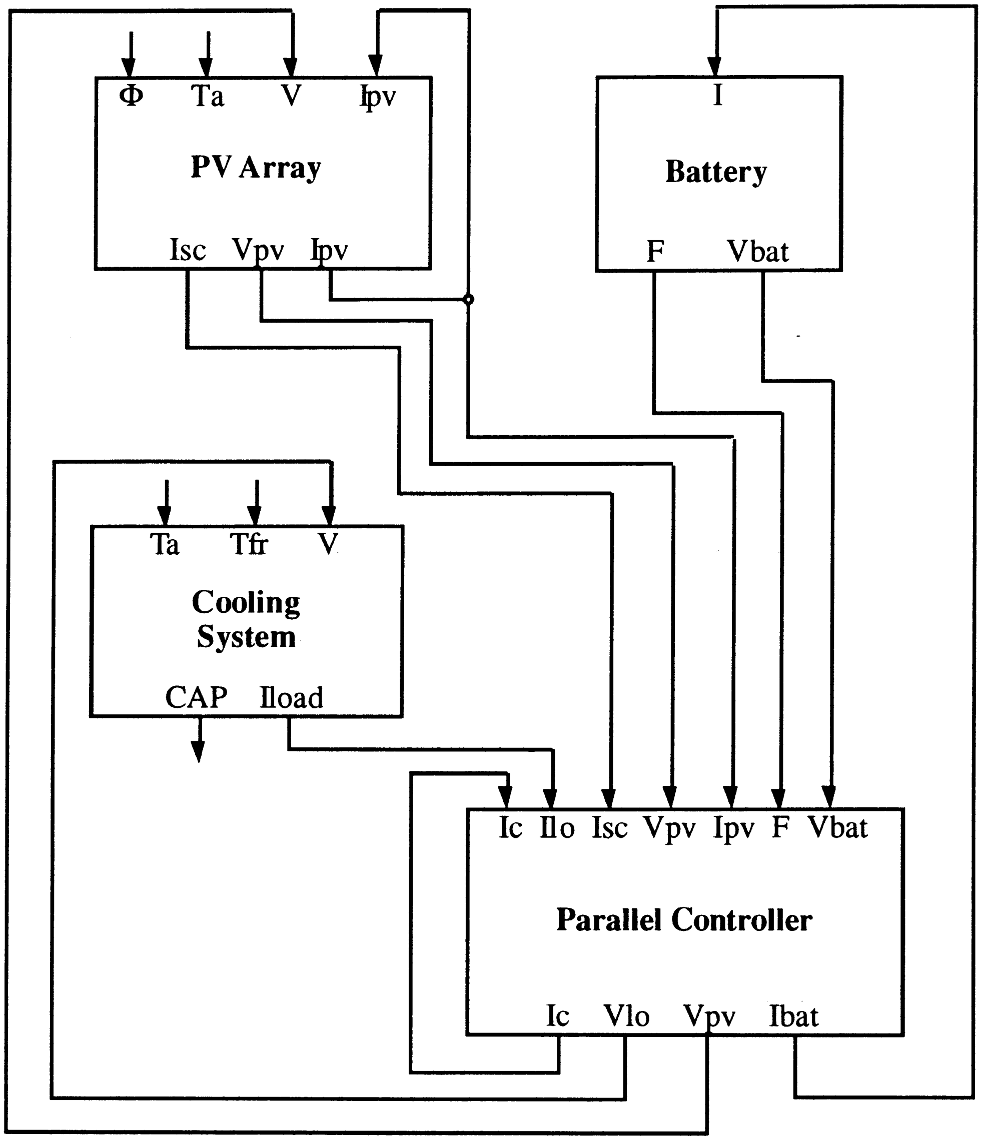

Figure 8.3: Information flow diagram for simulation with the parallel controller

The number of PV modules in series was one, the number of parallel modules was three. All the parameters of the PV module, the battery and the cooling system are listed in Appendix A.

The behavior of the PV system currents for the series and the parallel controller are shown in Figures 8.4 and 8.5.

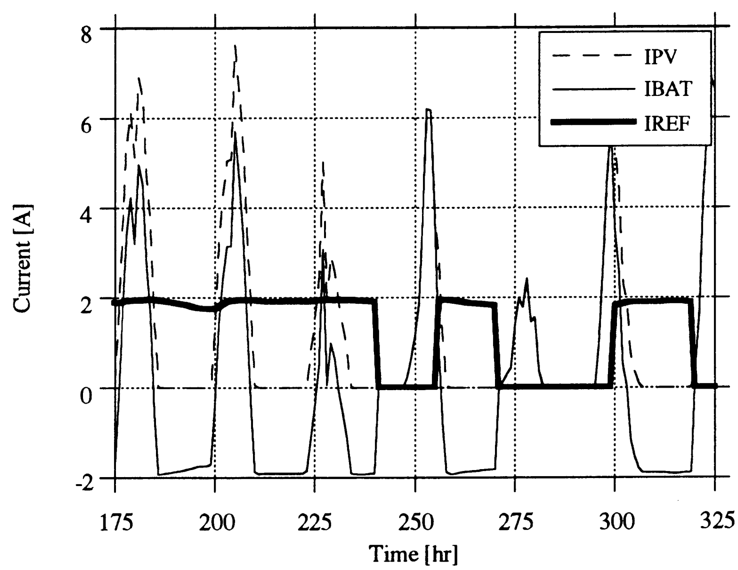

Figure 8.4: Current versus time for the series controller for the second week in January in Miami. IPV is the current from the PV array, IBAT the battery current and IREF the current for the cooling system.

For the first three days, the PV array and the battery are able to supply the energy for the refrigeration cycle. At hour 240 of the year the state of charge reaches its minimum of 35 %. To protect the battery from deep discharge the cooling system is disconnected from the PV system and the battery is charged until the fractional state of charge of the battery reaches 45 %. If the state of charge is greater than 45 %, the controller reconnects the load.

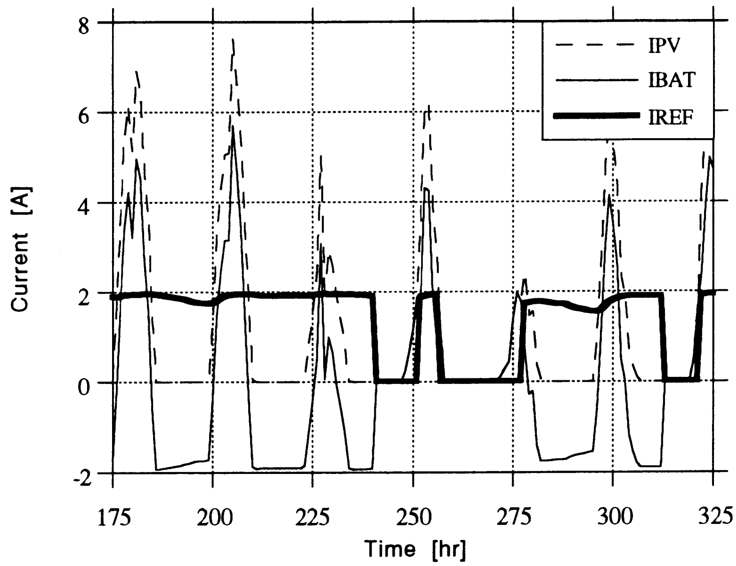

Figure 8.5: Current versus time for the parallel controller for the second week in January in Miami. IPV is the current from the PV array, IBAT the battery current and IREF the current for the cooling system.

Figure 8.5 shows the current versus the time plot for the parallel controller. As in Figure 8.4, the load can be met by the PV array and the battery at the first three days. Then the load is disconnected from the system. Unlike the simulation with the series controller, the load is reconnected as soon as the PV current is greater than the current required by the cooling system. With the excess energy the battery is charged. Because the required state of charge level to redischarge the battery was not reached, the cooling system is disconnected again when the PV current drops under the current required from the cooling system. The first cut off period for the series controller was longer but the battery was charged with a larger current of the PV array, which then supplied the cooling system. The second connected period for the series controller is longer than for the parallel controller.

To compare the cooling capacity that is produced with both systems, an annual simulation was made for the Miami climate. In the simulation the cooling cycles were only turned off when the minimum state of charge was reached. Figure 8.6 illustrates the monthly load what can be removed with both controllers.

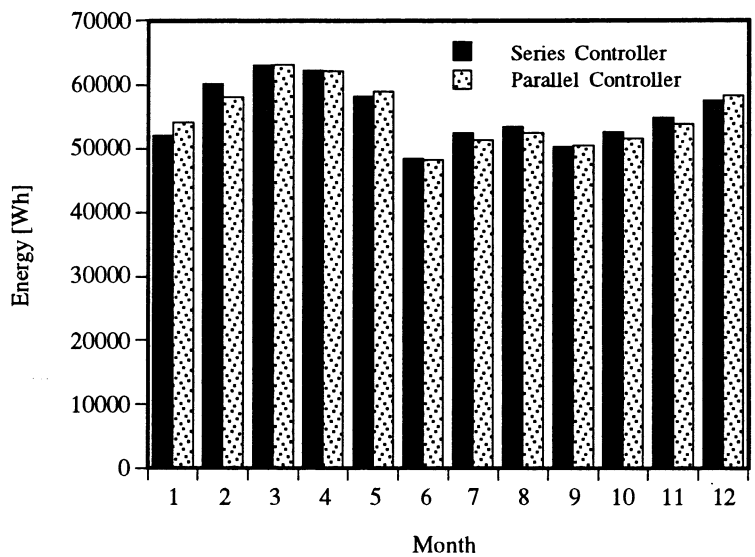

Figure 8.6: Comparison of the monthly energy supply from the systems with series and parallel controller

The cooling capacity, shown in Figure 8.6, for both control strategies is nearly the same. Interesting is the energy drop in the summer months for both controllers, which can be explained by the ambient conditions in Miami. Figure 8.7 illustrates the monthly average incident solar radiation on a tilted surface of 25° and the monthly average ambient temperature for Miami.

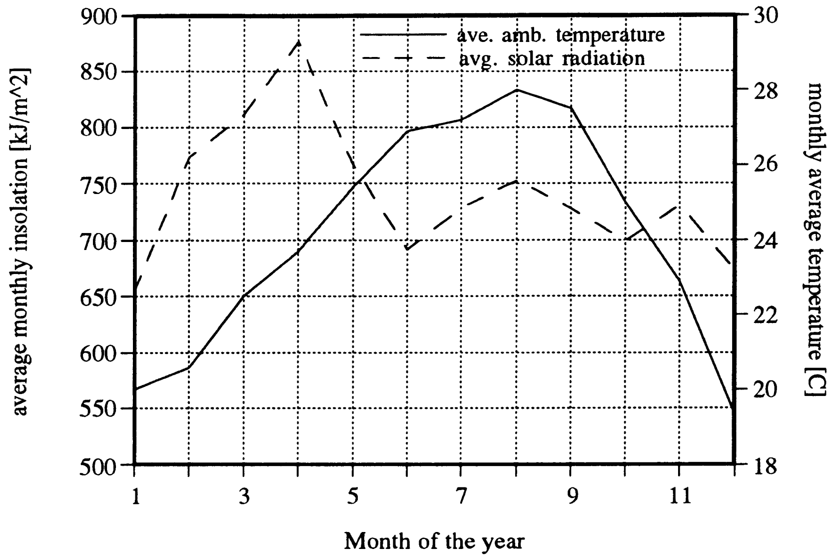

Figure 8.7: Average monthly insolation and ambient temperature for a one year time period

The maximum average solar insolation is in April and the highest ambient temperature is in August. As described in Chapter 5, the refrigeration capacity is a function of the room temperature. Assuming the room temperature to be the ambient temperature (no air conditioning available in developing countries) the capacity of the refrigeration cycle drops with an increase of the ambient temperature. The total annual cooling energy for the series controller is 667 kWh and for the parallel controller 661 kWh. For the sizing simulations in the following sections the series controller was used.

8.2 PV system performance

The performance of the PV system depends on the size of its components and on the slope of the PV array. The goal of this section is to optimize the output energy of the PV array by varying its slope and to determine the minimum size of the battery for a given cooling system and refrigerator. Figure 8.8 shows the information flow diagram for the simulation in order to size the PV system.

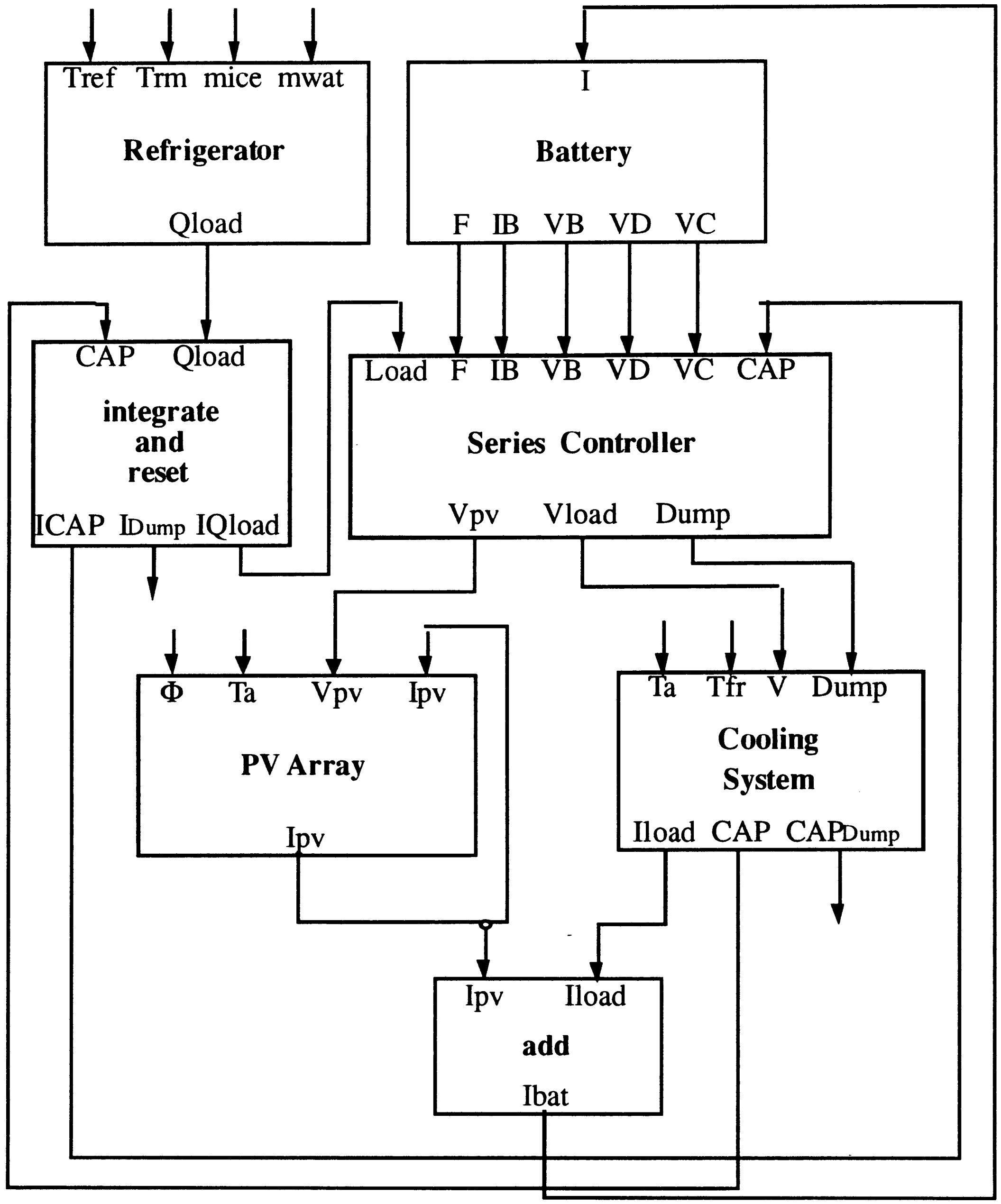

Figure 8.8: Information flow diagram for the sizing simulation

In the real refrigerator the compressor is disconnected when the refrigerator temperature drops below the lower thermostat setpoint and reconnected when the refrigerator temperature reaches the upper thermostat setpoint.

In the TRNSYS simulation the refrigeration capacity and the heat gains of the refrigerator are integrated over one day and then reset. With the integration time chosen it can be seen if the load can be met every day. In the terminology used the energy what can be removed from the cooling cycle is called cooling capacity and the energy gains of the refrigerator is called refrigerator load. After each timestep the cooling capacity and the refrigerator load are compared and a decision is made to turn the cooling cycle on or off. The cooling system is turned off when its cooling capacity exceeds the refrigerator load plus the energy (50 Wh) to cool the refrigerator from the upper thermostat setpoint to the lower setpoint (the calculation to receive the value of 50 Wh is shown in Section 7.3). When the cooling system is disconnected no more energy can be removed from the refrigeration cycle and the temperature in the refrigerator increases. The value for the cooling capacity remains the same. If the refrigerator load exceeds the cooling capacity, the upper thermostat level is reached and the cooling system is reconnected.

8.2.1 Influence of the slope and the number of PV modules

Simulations were made for slopes of the PV array between 0 and 60°. Figures 8.9 and 8.10 illustrate the system performance for a PV array of two modules in parallel.

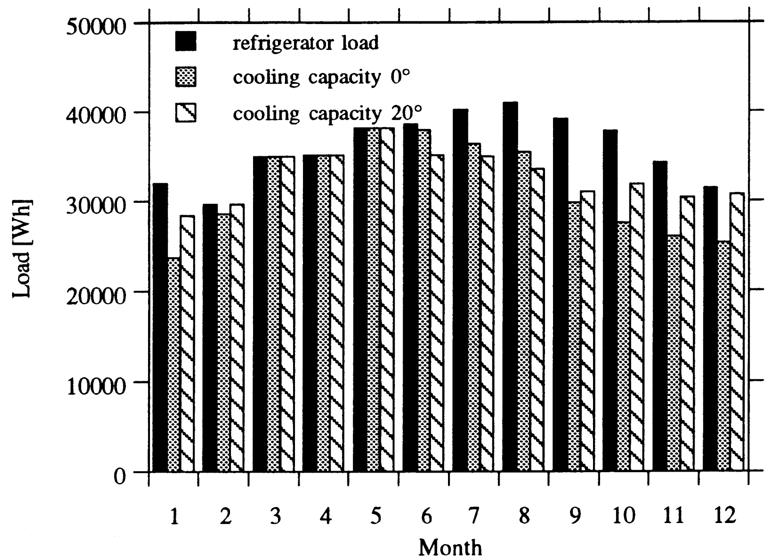

Figure 8.9: Refrigerator load and cooling capacity versus time for PV array slopes of 0° and 20°

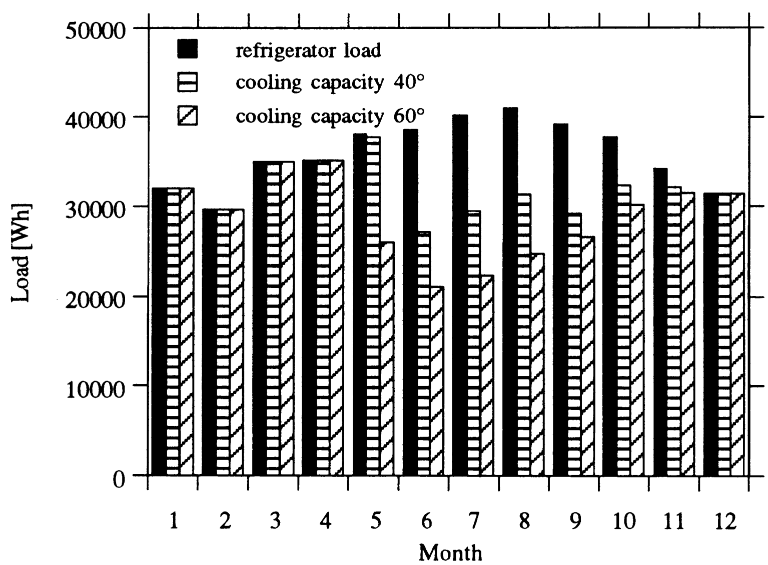

Figure 8.10: Refrigerator load and cooling capacity versus time for PV array slopes of 40° and 60°

The values for the refrigerator load and the cooling capacity were calculated for each month. Figure 8.9 and 8.10 show that no matter how the PV array is tilted, the refrigerator load is not met for some months of the year.

Increasing the number of parallel panels to three leads to the performance shown in Figures 8.11 to 8.13.

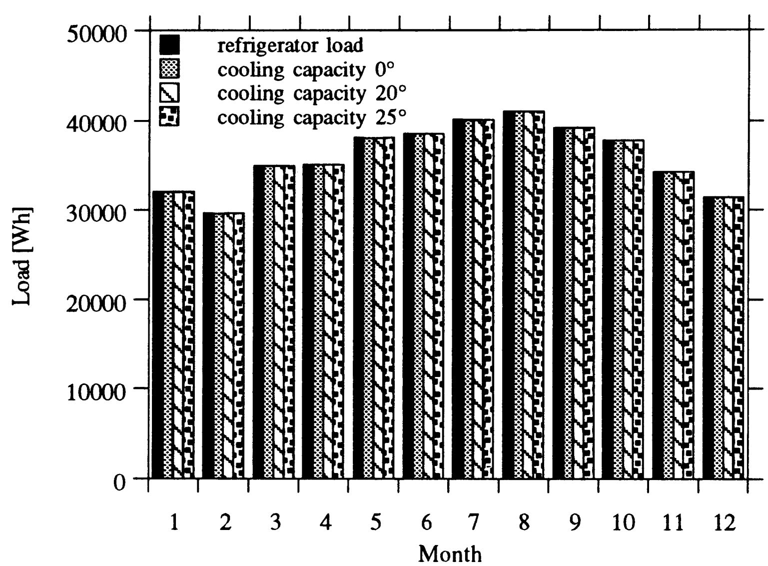

Figure 8.11: Refrigerator load and cooling capacity versus time for PV array slopes of 0°, 20° and 25°

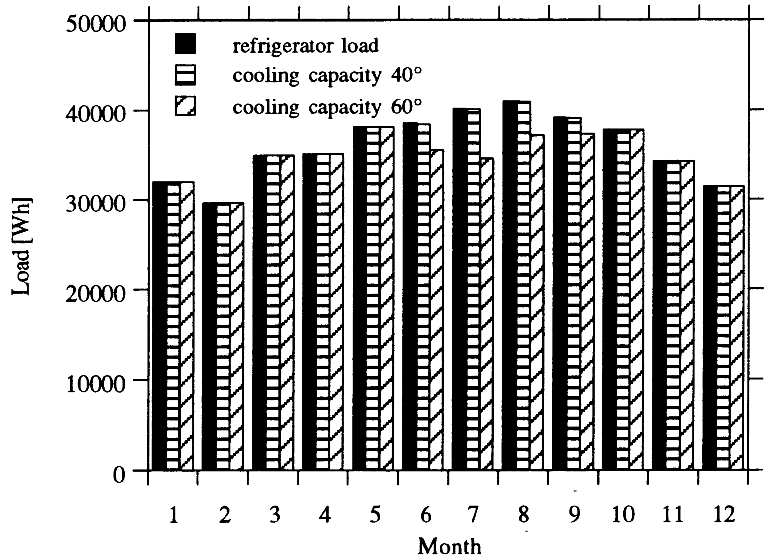

Figure 8.12: Refrigerator load and cooling capacity versus time for PV array slopes of 40° and 60°

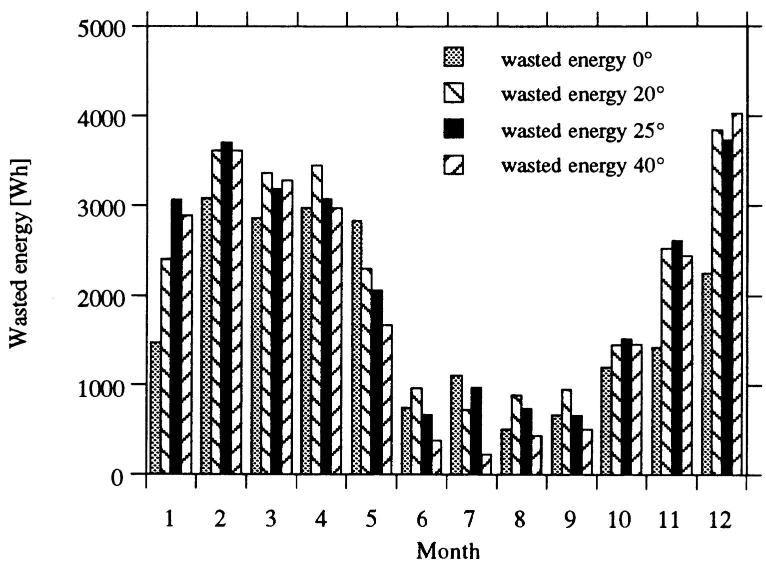

Figure 8.13: Wasted energy versus time for PV array slopes between 0° and 40°

The refrigerator load is met by all slopes except 60°. To still meet the refrigerator load every month, theoretically the area of the PV array could be reduced until the wasted energy for the worst month (the worst month depends on the slope of the PV array) is zero. The worst month is the one where the wasted energy is closest to zero. For a slope of 20°, the month would be August, for 40° it would be June. Comparing the wasted energies for the different slopes the design slope will be the one with the largest wasted energy for the worst month. For the PV system located in Miami the slope would be 20°.

8.2.2 Sizing of the battery

For the previous simulations the rated capacity of the battery was 250 Ah. Assuming that the refrigerator load is 50 W and the voltage 12 V the battery can supply the refrigerator with energy for 60 hours from being fully charged to fully discharged. The performance of the PV system is compared for rated battery capacities (Qm) of 25 Ah, 50 Ah, 100 Ah and 250 Ah. The rated capacity of 25 Ah could supply the refrigerator with energy for 6 hours, 50 Ah for 12 hours and 100 Ah for 24 hours. Figures 8.14 and 8.15 illustrate the performance of the PV system for the 4 batteries.

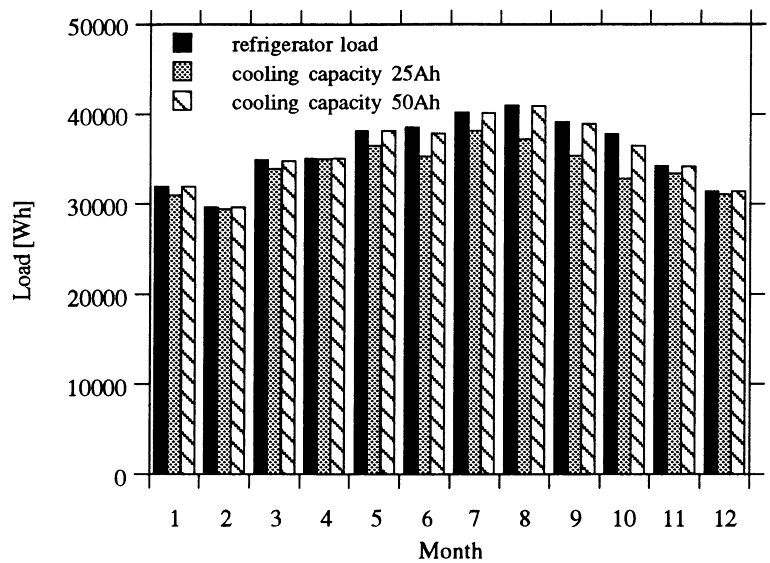

Figure 8.14: Refrigerator load and cooling capacity versus time for rated battery capacities of 25 and 50 Ah

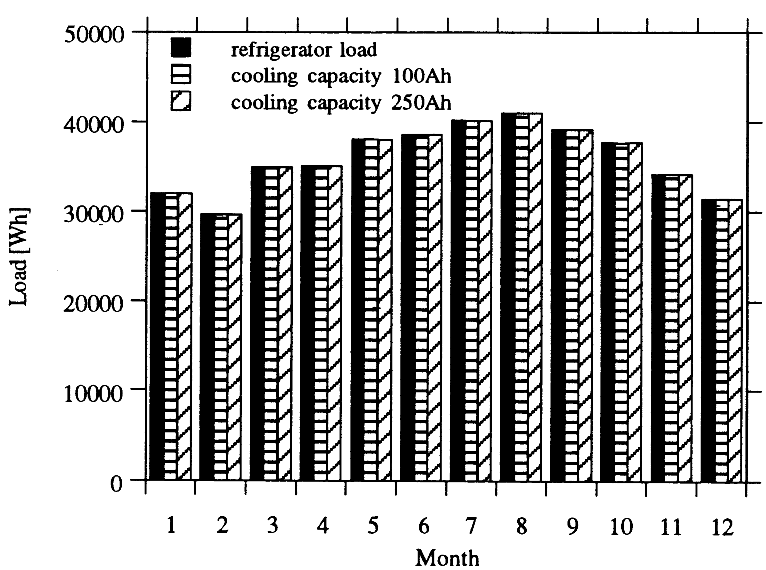

Figure 8.15: Refrigerator load, cooling capacity versus time for rated battery capacities of 100 and 250Ah

Figure 8.14 shows that the PV system with the rated battery capacities of 25 Ah and 50 Ah are not able to meet the refrigerator load every month of the year, whereas the PV systems with the rated capacities of 100 and 250 Ah, shown in Figure 8.15, do.

The PV array of 3 modules in parallel and a battery size of 100 Ah is a proper size to make certain that the refrigerator temperature stays in the range of 2 to 8 C.

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The objective of this research is twofold; to develop computer models for the components of a PV powered refrigeration system, and to optimize the size of the PV array and battery such that the refrigerator load is always met while minimizing initial costs. The PV systems consists of a d.c. vapor compression refrigerator with freezer, a controller, a battery to store and supply energy and a photovoltaic generator which supplies the refrigerator, and charges the battery with excess energy. To protect the battery from overcharge and deep discharge a controller was used. Annual simulations were run to size the system components using TRNSYS. With the exception of the combined motor-cooling system, the developed component models are typical TRNSYS models based upon first principles. The combined motor-cooling system is a curve fit from calculations of the performance of a typical vapor compression refrigeration cycle with evaporator, condenser, expansion valve and compressor being driven by a brushless d.c. motor. The curve fit model is more efficient than solving the cycle equations at each timestep, yielding nearly identical results.

The comparison between the series and parallel controller revealed a better performance for the PV system using the series controller.

For each location the simulation must be made to find the best system combination. For a given refrigerator and cooling system placed in Miami, the necessary number of PV modules was three in parallel, combined with a battery with a rated capacity of 100 Ah.

Recommendations

As mentioned above, the basic models of the PV refrigeration system have been developed. Since TRNSYS facilitates the implementation of user written components, users can expand the developed models to any load model or include other components. This opportunity gives users a chance to compare different kinds of storage systems such as cold storage instead of battery storage or a combined cold-battery storage.

As mentioned earlier, the combined motor-cooling system component uses a curve fit from calculations made with EES. To vary the size of the cooling system, the EES calculations and the curve fit have to be redone. Because the curve fit procedure is time intensive, a TRNSYS model based on first principles for the refrigeration system would be desirable.

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Appendix A

LIST OF DATA

This Appendix contains the data for the component analyses performed in Chapters 2 to 6.

Data for the PV Module

The data describe a PV module from the company KYOCERA.

$I_{sc,ref} = 2.9$ A	$V_{oc,ref} = 20$ V	$T_{c,ref} = 301$ K
$\phi_{ref} = 1000$ W/m2	$V_{MP,ref} = 16.5$ V	$I_{MP,ref} = 2.67$ A
$\mu_{I,sc} = 0.001325$ A/K	$\mu_{V,oc} = -0.0775$ V/K	$T_{c,NOCT} = 319$ K
$T_{a,NOCT} = 293$ K	$\varepsilon_g = 1.12$ eV	area = 0.427 m2

Data for the lead acid battery

The data are from TRNSYS [2].

$E_c = 2.25$ V	$E_d = 2.1$ V	$G_c = 0.08$
$G_d = 0.08$	$M_c = 0.864$	$M_d = 1$
$E_{const,d} = 1.8$ V	$R_{const,d} = 2.4E\text{-}3\ \Omega$	$\eta = 0.95$
$I_{di} = 2.5$ A	$K_{di} = 29.3$	

$Q_c = -0.0035\ Q_M$	$Q_d = Q_M/0.85$
$R_c = 3/Q_M$	$R_d = 0.5/Q_M$

Data for the brushless d.c. motor

The data are from the motor type EYQM No. A3000-500 from the company Barber Colman.

$K_b = 0.04$ V/rad-sec	$K_t = 0.04$ Nm/A	$R = 4.52\ \Omega$
$F_{stat} = 4.38E\text{-}3$ Nm	$F_{dyn} = 2.54E\text{-}6$ Nm-sec	

Comparison data for the refrigeration cycle

The actual data to compare the model of the refrigeration cycle are taken from the company Copeland for the compressor CRD4-0200-PFV.

Capacity in Btu/hr

Condensing Temperature in deg F	Evaporator Temperature in deg F				
	10	20	30	40	50
80	14600	20000	26200	33500	42000
90	13100	18200	24100	31000	39000
100	11600	16400	22000	28500	36100
110	10100	14600	19900	26000	33200
120	8700	12900	17800	23500	30300

Power in watts

Condensing Temperature in deg F	Evaporator Temperature in deg F				
	10	20	30	40	50
80	1380	1490	1550	1560	1510
90	1440	1590	1700	1750	1750
100	1490	1670	1820	1920	1960
110	1510	1730	1920	2060	2180
120	1530	1770	1990	2170	2370

Mass flow rat in lbs/hr

Condensing Temperature in deg F	Evaporator Temperature in deg F				
	10	20	30	40	50
80	183	246	319	403	500
90	170	233	305	387	482
100	156	219	289	370	463
110	142	203	272	351	443
120	128	187	254	331	422

Appendix B

EES CODE

This Appendix contains the EES code for the components and the programs for the cooling system analysis and the PV-system analysis.

EES model for the PV module (File: PV model)

This program models a solar module with data from the company Kyocera. The theory is from "Solar Engineering of Thermal Processes", Duffie, Beckman.

{Variable description:
a = curve fitting parameter
Ac [m^2] = area solar generator
aref = curve fitting parameter at reference conditions
e=1.12 [eV] bandgap energy for silicon
eta = conversion efficiency
etamp = maximum conversion efficiency
etampref = maximum conversion efficiency at reference conditions
GT [W/m^2] = incident solar radiation
GTNOCT [W/m^2] = solar insolation at NOCT conditions
GTref [W/m^2] = solar insolation at reference conditions
I [A] = current
ID [A] = diode current
IL [A] = light current

ILref [A] = light current at reference conditions
Imp [A] = current at max. power
Io [A] = diode reverse current
Ioref [A] = diode reverse current at reference conditions
Isc [A] = short circuit current at reference conditions
muIsc [A/K] = temperature coeffitient of the short circuit current
muVoc [V/K] = temperature coeffitient of the open circuit voltage
Ns=36 = # of cells in series times # of moduls in series
P [watts] = output power
Rs [ohms] = series resistance
Ta [K] = ambient temperature
TaNOCT [K] = ambient temperature at NOCT conditions
taualpha = transmittance-absorptance product
TcNOCT [K] = cell temperature at NOCT conditions
Tcref [K] = cell temperature at reference conditions
UL= overall loss coefficient
V [V] = terminal voltage
Vmp [V] = voltage at max. power
Voc [V] = open circuit voltage at reference conditions}

{reference conditions}
Tcref=25+273
GTref=1000

{nominal operating cell temperature conditions}
TaNOCT=20+273
TcNOCT=319
GTNOCT=800

{known from supplier; the numbers are for reference conditions}
Isc=2.9
Voc=20

```
Imp=2.67
Vmp=16.5
muIsc=1.325e-3
muVoc=-0.0775

{other fixed parameters}
taualpha=0.9
Ac=0.427
e=1.12
Ns=36

{variables}
V=12
GT=1000
Ta=25+273

{calculation of IV-curve}
I=IL-ID
ID=Io*(exp((V+I*Rs)/a)-1)
P=I*V

{calculations of numbers at reference conditions}
ILref=Isc
Ioref=ILref*exp(-Voc/aref)
Rs=(aref*ln(1-Imp/ILref)-Vmp+Voc)/Imp
aref=(muVoc*Tcref-Voc+e*Ns)/(muIsc*Tcref/ILref-3)

{calculation of numbers at any cell temperatur}
a/aref=Tc/Tcref
IL=GT/GTref*(ILref+muIsc*(Tc-Tcref))
Io/Ioref=(Tc/Tcref)^3*exp(e*Ns/aref*(1-Tcref/Tc))

{efficiency}
```

•

```
eta=I*V/(Ac*GT)
etampref=Imp*Vmp/(Ac*GTref)
etamp=etampref+mump*(Tc-Tcref)
mump=etampref*muVoc/Vmp

{cell temperature; assume taualpha/UL=taualphaUL=constant}
taualphaUL=(TcNOCT-TaNOCT)/GTNOCT
Tc=Ta+GT*taualphaUL*(1-eta/taualpha)
```

EES model for the lead acid battery (File: Battery model)

This program describes the behavior of a lead acid battery. The theoretical background is from Sheperd, Zimmermann and Peterson and was described by Eckstein. The numbers are from the MS thesis of Eckstein.

{Variable description:
Cp = # of cells in parallel
Cs = # of cells in series
Ed [V], Rd [ohms] = constants to calculate the voltage limit on discharge
eff = charging efficiency
Esd, Esc [V] = extrapolated open circuit voltages
F = fractional state of charge
Gd, Gc = small valued coefficients of F for charge, discharge
H = depth of discharge
Ibat [A] = battery current
Icell [A] = cell current
Idi, Kdi = curve fitting parameters
md, mc = cell type parameters which determine the shape of the IV-capacity characteristics
Qc [Ah] = capacity on charge
Qd [Ah] = capacity on discharge

```
Qm [Ah] = rated capacity of the battery
Rsc [ohms] = resistance on charge
Rsd [ohms] = resistance on discharge
Vbat [V] = battery voltage
Vc [V] = voltage limit on charge
Vd [V] = voltage limit on dischrage
Vdi [V] = diode voltage
Vocbat [V] = open circuit voltage of the battery}

{Battery Voltage}
FUNCTION BAT_VOLT(Vocbat,Vdi,Gd,Gc,H,Ibat,Rsd,Rsc,md,mc,Qd,Qc,Qm)
IF Ibat<0 THEN goto 10
   V=Vocbat+Vdi-Gc*H+Ibat*Rsc*(1+mc*H/(Qc/Qm-H))
goto 20
10: V=Vocbat-Vdi-Gd*H+Ibat*Rsd*(1+md*H/(Qd/Qm-H))
20: BAT_VOLT=V
END

{variables}
Cp=1
Cs=6
Gd=0.08
Gc=0.08
md=1
mc=0.864
Idi=2.5
Kdi=29.3
Esd=2.1
Esc=2.25
Qm=250
Vc=2.3
eff=0.95
Ed=1.8
```

```
Rd=2.4e-3
F=1

{equations}
Vocbat=(Esc+Esd)/2
Vdi=1/Kdi*ln(abs(Icell)/Idi+1)
Rsc=3/Qm
Rsd=0.5/Qm
Qc=-0.035*Qm
Qd=Qm/0.85
F=Q/Qm
H=1-F
Vd=Ed-abs(Icell)*Rd
Vcell=BAT_VOLT(Vocbat,Vdi,Gd,Gc,H,Icell,Rsd,Rsc,md,mc,Qd,Qc,Qm)
Vbat=Cs*Vcell
Ibat=Cp*Icell
```

EES model for the brushless d.c. motor (File: Motor model)

This program is based on the fundamental equations for a brushless d.c. motor with a permanent magnet. The equations were found in the book of the company Magnetic Technology, Canoga Park, Ca, "Direct Drive - Engineering Handbook". The given numbers are from Barber Colman Company, Type EYQM No. A3000-500.

```
{Variable description:
Ea [V] = electromagnetic force
eff = motor efficiency
Fdyn [Nms] = dynamic friction constant
Fstat [Nm] = static friction constant
It [A] = terminal current
Kb [V/rad-sec] = back EMF constant
```

Kt [Nm/A] = torque constant
omega [1/sec] = angular velocity
Pin [watts] = input power
Po [watts] = output power
R [ohms] = resistance
RPM [1/min] = revolutions per minute
Tm [Nm] = motor torque
Tloss [Nm] = torque for rotational losses
To [Nm] = output torque
Vt [V] = teminal voltage

```
{variables}
R=4.52          {ohms; resistance}
Kb=0.04         {V/rad/sec; back EMF constant}
Kt=0.04         {Nm/A; torque sensitivity}
Fstat=4.38E-3   {Nm; static friction constant}
Fdyn=2.54E-6    {Nms; dynamic friction constant}


{steatdy state equations}
Vt=12
Vt=It*R+Ea
Ea=Kb*omega
Tm=Kt*It
Tm=Tloss+To
To= 0.1
Tloss=Fstat+Fdyn*omega
eff=Po/Pin
Po=To*omega
Pin=Vt*It
omega=2*pi*RPM/60
```

EES model for the refrigeration cycle (File: Refrigeration model)

This program compares results of the refrigeration model with data from the Copeland reciprocating compressor CRD4-0200-PFV. Input parameters are the evaporator and condenser temperature, and data for the input power and the refrigeration capacity of the Copeland compressor. The refrigerant is R22.

{Variable description:
CAP [Btu/hrs] = refrigeration capacity
COP = coefficient of performance
dPev [psia] = pressure difference at inlet valve of the compressor
dPcon [psia] = pressure difference at outlet valve of the compressor
etavol = volumetric efficiency
h1 = enthalpy at state 1
h2 = enthalpy at state 2
h2' = enthalpy at state 2'
h3 = enthalpy at state 3
h4 = enthalpy at state 4
m = ratio of the clearance volume over the displacement volume
n = polytropic exponent
Ndot [1/hr] = revolutions per hour
rho1 = density at state 1
RPM [1/min] = revolutions per minute
Tcon [F] = condenser temperature
Tev [F] = evaporator temperature
Tsh [F] = superheat
Tsc [F] = subcooling
T1 [F] = temperature at state 1
T2 [F] = temperature at state 2
T3 [F] = temperature at state 3
Vdispl [ft^3] = displacement volume

```
v1 = specific volume at state 1
v1' = specific volume at state 1'
v2 = specific volume at state 1
wdot [kg/sec] = mass flow rate
x = quality}

{variables}
Tsh=20
Tsc=15
T1=Tev+Tsh
T3=Tcon-Tsc
Ndot=RPM*60
dPev=10
dPcon=1

{variables}
Vdispl=3.2e-3
RPM=1750
m=0.126
n=1.146

{calculate the volumetric efficiency}
etavol=(1+m-m*((Pcon'/Pev')^(1/n)))*volratio
Pev'=Pev-dPev
Pcon'=Pcon+dPcon
v1'=Volume(R22,h=h1,P=Pev')
volratio=v1/v1'

{State 1}
h1=Enthalpy(R22,T=T1,P=Pev)
v1=Volume(R22,T=T1,P=Pev)
Pev=Pressure(R22,T=Tev,x=1)
s1=Entropy(R22,T=T1,P=Pev)
```

```
{evaporator}
wdot=rho1*Vdispl*Ndot*etavol
rho1=1/v1

{state 2s}
s2s=s1
h2s=Enthalpy(R22,s=s2s,P=Pcon)

{isentropic efficiency}
effisen=(h2s-h1)/(h2-h1)

{state 2}
v2=v1*(Pev/Pcon)^(1/n)
T2=Temperature(R22,v=v2,P=Pcon)
h2=Enthalpy(R22,P=Pcon,T=T2)

{State 3}
Pcon=Pressure(R22,x=1,T=Tcon)
h3=Enthalpy(R22,T=T3,P=Pcon)

{State 4}
h4=h3

{calculate refrigeration capacity and the rejected power}
CAP=wdot*(h1-h4)

{calculate capacity error}
CAPerror=CAP-CAPdat

{calculate COP}
powerdat=Wpower*3.413*0.7        {Btu/hr;  value from katalog, motor efficiency =
70%}
```

COPdat=CAPdat/powerdat

power=wdot*Wpol {Btu/hr; not including the motor efficiency}
COP=CAP/power

{calculate the polytropic work}
Wpol=(Pev'*v1'*n/(n-1)*((Pcon'/Pev')^((n-1)/n)-1))*144/778

{calculate work error}
enthdiff=h2-h1
errorwork=enthdiff-Wpol

{calculate the isentropic efficiency out of datas}
COPdat=(h1-h4)/(h2s-h1)*effisendat

EES model for determining the UA values (File: UA value model)

This model determines the behavior of the capacity and the coefficient of performance as a function of the evaporator UA value. With this information the evaporator UA-values can be chosen.

{Variable description:
CAP [kW] = refrigeration capacity
COP = coefficient of performance
dPev [kPa] = pressure difference at inlet valve of the compressor
dPcon [kPa] = pressure difference at outlet valve of the compressor
etavol = volumetric efficiency
h1 = enthalpy at state 1
h2 = enthalpy at state 2
h3 = enthalpy at state 3

h4 = enthalpy at state 4
m = ratio of the clearance volume over the displacement volume
n = polytropic exponent
power [Nm/sec] = input power
Qcon [kW] = rejected energy
RPM [1/min] = revolutions per minute
RPS [1/sec] = revolutions per second
Trm [C] = room temperature
Tev [C] = evaporator temperature
Tfr [C] = freezer temperature
Tcon [C] = condenser temperature
T2 [C] = temperature at state 2
UAev [kW/K] = overall heat transfer coefficient area product for the evaporator
UAcon [kW/K] = overall heat transfer coefficient area product for the condenser
Vdispl [m^3] = displacement volume
v1 = specific volume at state 1
v1' = specific volume at state 1'
wdot [kg/sec] = mass flow rate
x = quality
rho = density

```
{variables}
Trm=30
Tfr=0
Vdispl=1e-5
m=0.094
n=1.061
dPev=70
dPcon=7
RPM=1000

{equations}
RPM=60*RPS
```

```
UAcon=0.01

{calculate the volumetric efficiency}
etavol=(1+m-m*(Pcon'/Pev')^(1/n))*volratio
Pcon'=Pcon+dPcon
Pev'=Pev-dPev
volratio=v1/v1'
v1'=Volume(R12,h=h1,P=Pev')

{calculate refrigeration capacity}
CAP=wdot*(h1-h4)
CAP=UAev*(Tfr-Tev)

{State 1}
h1=Enthalpy(R12,T=Tev,x=1)
v1=Volume(R12,T=Tev,x=1)
Pev=Pressure(R12,T=Tev,x=1)

{evaporator}
wdot=rho1*Vdispl*RPS*etavol
rho1=1/v1

{State 2}
v2'=v1'*(Pev'/Pcon')^(1/n)
h2'=Enthalpy(R12,P=Pcon',v=v2')
h2=h2'
T2=Temperature(R12,h=h2,P=Pcon)

{heat transfer condenser}
Qcon=(h2-h3)*wdot
Qcon=UAcon*(Tcon-Trm)

{State 3}
```

```
Pcon=Pressure(R12,x=0,T=Tcon)
h3=Enthalpy(R12,x=0,P=Pcon)

{State 4}
h4=h3

{calculate COP}
COP=CAP/power

{calculate the polytropic work}
Wpol=(Pev'*v1'*n/(n-1)*((Pcon'/Pev')^((n-1)/n)-1))

{calculate power}
power=wdot*Wpol
```

EES model for the cooling system (File: Cooling system model)

This program determines the capacity, the current and the coefficient of performance as a function of the room temperature, freezer temperature and the input voltage. The variables are already explained in the models for the d.c. motor and the refrigeration cycle and therefore not listed again.

```
{Part for the refrigeration cycle}

{Refrigerant = R12}
{Trm=30}
{Tfr=0}
Vdispl=1e-5        {m^3}
m=0.094            {clearance volume/displacement volume}
```

```
n=1.061          {polytropic exponent}
dPev=70           {kPa, assumed value}
dPcon=7           {kPa, assumed value}

RPM=60*RPS

UAev=0.01
UAcon=0.01

{calculate the volumetric efficiency}
etavol=(1+m-m*(Pcon'/Pev')^(1/n))*volratio
Pcon'=Pcon+dPcon
Pev'=Pev-dPev
volratio=v1/v1'
v1'=Volume(R12,h=h1,P=Pev')

{calculate refrigeration capacity}
CAP=wdot*(h1-h4)
CAP=UAev*(Tfr-Tev)

{State 1}
h1=Enthalpy(R12,T=Tev,x=1)
v1=Volume(R12,T=Tev,x=1)
Pev=Pressure(R12,T=Tev,x=1)

{evaporator}
wdot=rho1*Vdispl*RPS*etavol
rho1=1/v1

{State 2}
v2'=v1'*(Pev'/Pcon')^(1/n)
h2'=Enthalpy(R12,P=Pcon',v=v2')
h2=h2'
```

```
T2=Temperature(R12,h=h2,P=Pcon)

{heat transfer condenser}
Qcon=(h2-h3)*wdot
Qcon=UAcon*(Tcon-Trm)

{State 3}
Pcon=Pressure(R12,x=0,T=Tcon)
h3=Enthalpy(R12,x=0,P=Pcon)

{State 4}
h4=h3

{calculate COP}
COP=CAP*1000/(To*omega)

{calculate the polytropic work}
Wpol=(Pev'*v1'*n/(n-1)*((Pcon'/Pev')^((n-1)/n)-1))
To*omega=wdot*Wpol*1000

{Part for the brushless d.c. motor}

{Vt=15 }          {V; terminal voltage}
R=0.52            {ohms; resistance}
Kb=0.15           {V/rad/sec; back EMF constant}
Kt=0.15       {Nm/A; torque sensitivity}
Fstat=4.38E-3   {Nm; static friction constant}
Fdyn=2.54E-6    {Nms; dynamic friction constant}

{steatdy state equations}
Vt=It*R+Ea
Ea=Kb*omega
```

```
Tm=Kt*It
Tm=Tloss+To

Tloss=Fstat+Fdyn*omega
Po=To*omega

Pin=Vt*It
omega=2*pi*RPM/60
```

EES model for the PV-system (File: PV-system model)

With this program a steady state analysis to determine the operating conditions of the PV-system consisting of PV array, battery and cooling system can be made. The variables used are described in the EES models listed before.

```
{Battery Voltage}
FUNCTION BAT_VOLT(Vocbat,Vdi,Gd,Gc,H,Icell,Rsd,Rsc,md,mc,Qd,Qc,Qm)
IF Icell<0 THEN goto 10
   V=Vocbat+Vdi-Gc*H+Icell*Rsc*(1+mc*H/(Qc/Qm-H))
 goto 20
10: V=Vocbat-Vdi-Gd*H+Icell*Rsd*(1+md*H/(Qd/Qm-H))
20: BAT_VOLT=V
END


{Part for the PV array}

{reference conditions}
Tcref=25+273          {K}
```

```
GTref=1000            {W/m^2}

{nominal operating cell temperature conditions}
TaNOCT=20+273         {K}
TcNOCT=319            {K}
GTNOCT=800            {W/m^2}

{known from supplier; the numbers are for reference conditions}
Isc=2.9               {A; short circuit current}
Voc=20                {V; open circuit voltage}
Imp=2.67              {A; current at max. power}
Vmp=16.5              {V; voltage at max. power}
muIsc=1.325e-3        {A/K; temperature coeffitient of the short circuit current}
muVoc=-0.0775         {V/K; temperature coeffitient of the open circuit voltage}

{other fixed parameters}
taualpha=0.9          {tau=transmittance of glass / alpha=fraction of radiation incident
on surface of the cells that is absorbed}
Ac=0.427              {m^2; area solar generator}
e=1.12                {eV for silicon; material bandgap energy}
Ns=36                 {# of cells in series times # of moduls in series}

{variables}
{GT=1000 }            {W/m^2; incident solar radiation}
Ta=25+273             {K;  ambient temperature}

{calculation of IV-curve}
I=IL-ID    {-Ish; the shunt current is assumed to be negligable}
ID=Io*(exp((V+I*Rs)/a)-1)

P=I*V

{calculations of numbers at reference conditions}
```

```
ILref=Isc
Ioref/exp(-Voc/aref)=ILref

Rs=(aref*ln(1-Imp/ILref)-Vmp+Voc)/Imp
aref=(muVoc*Tcref-Voc+e*Ns)/(muIsc*Tcref/ILref-3)

{calculation of numbers at any cell temperatur}
a/aref=Tc/Tcref
IL=GT/GTref*(ILref+muIsc*(Tc-Tcref))

Io/Ioref=(Tc/Tcref)^3*exp(e*Ns/aref*(1-Tcref/Tc))

{efficiency}
eta=I*V/(Ac*GT)
etampref=Imp*Vmp/(Ac*GTref)

etamp=etampref+mump*(Tc-Tcref)
mump=etampref*muVoc/Vmp

{cell temperature; assume taualpha/UL=taualphaUL=constant}
taualphaUL=(TcNOCT-TaNOCT)/GTNOCT
Tc=Ta+GT*taualphaUL*(1-eta/taualpha)


{Part of the refrigeration cycle}

{Refrigerant = R12}
Trm=30
Tfr=0
Vdispl=1e-5     {m^3}
m=0.094         {clearance volume/displacement volume}
n=1.061         {polytropic exponent}
dPev=70         {kPa, assumed value}
```

```
dPcon=7                {kPa, assumed value}

RPM=60*RPS

UAev=0.01
UAcon=0.01

{calculate the volumetric efficiency}
etavol=(1+m-m*(Pcon'/Pev')^(1/n))*volratio
Pcon'=Pcon+dPcon
Pev'=Pev-dPev
volratio=v1/v1'
v1'=Volume(R12,h=h1,P=Pev')

{calculate refrigeration capacity}
CAP=wdot*(h1-h4)
CAP=UAev*(Tfr-Tev)

{State 1}
h1=Enthalpy(R12,T=Tev,x=1)
v1=Volume(R12,T=Tev,x=1)
Pev=Pressure(R12,T=Tev,x=1)

{evaporator}
wdot=rho1*Vdispl*RPS*etavol
rho1=1/v1

{State 2}
v2'=v1'*(Pev'/Pcon')^(1/n)
h2'=Enthalpy(R12,P=Pcon',v=v2')
h2=h2'
T2=Temperature(R12,h=h2,P=Pcon)
```

```
{heat transfer condenser}
Qcon=(h2-h3)*wdot
Qcon=UAcon*(Tcon-Trm)

{State 3}
Pcon=Pressure(R12,x=0,T=Tcon)
h3=Enthalpy(R12,x=0,P=Pcon)

{State 4}
h4=h3

{calculate COP}
COP=CAP*1000/(To*omega)

{calculate the polytropic work}
Wpol=(Pev'*v1'*n/(n-1)*((Pcon'/Pev')^((n-1)/n)-1))
To*omega=wdot*Wpol*1000


{Part of the brushless d.c. motor}

R=0.52          {ohms; resistance}
Kb=0.15         {V/rad/sec; back EMF constant}
Kt=0.15     {Nm/A; torque sensitivity}
Fstat=4.38E-3   {Nm; static friction constant}
Fdyn=2.54E-6    {Nms; dynamic friction constant}

{steatdy state equations}
Vt=It*R+Ea
Ea=Kb*omega

Tm=Kt*It
Tm=Tloss+To
```

Tloss=Fstat+Fdyn*omega
{eff=Po/Pin}

Po=To*omega
Pin=Vt*It

omega=2*pi*RPM/60
V=Vt

{Part of the lead acid battery}

{variables}
Cp=1 {# cells parallel}
Cs=6 {# cells in series}
Gd=0.08 {Coefficient of (1-F) in V formulas}
Gc=0.08 {Coefficient of (1-F) in V formulas}
md=1 {Cell type parameter which determines the shape of the I-V-Q characteristic}
mc=0.864 {Cell type parameter which determines the shape of the I-V-Q characteristic}
Idi=2.5
Kdi=29.3
Esd=2.1 {Extrapolated open circuit voltage}
Esc=2.25 {Extrapolated open circuit voltage}
Qm=250 {Rated capacity of cell}
Vc=2.3
eff=0.95
Ed=1.8
Rd=2.4e-3
F=1

```
{equations}
x=0
Vocbat=(Esc+Esd)/2
Vdi=1/Kdi*ln(abs(Icell)/Idi+1)
Rsc=3/Qm
Rsd=0.5/Qm
Qc=-0.035*Qm
Qd=Qm/0.85
F=Q/Qm
H=1-F
Vd=Ed-abs(Icell)*Rd
Vcell=BAT_VOLT(Vocbat,Vdi,Gd,Gc,H,Icell,Rsd,Rsc,md,mc,Qd,Qc,Qm)
Vbat=Cs*Vcell
Ibat=Cp*Icell
Vbat=Vt
```

Appendix C

TRNSYS TYPES

This Appendix contains the TRNSYS TYPES for the components to simulate the PV-system

TRNSYS TYPE for the PV array (File: TYPE 62)

```
C**************************************************************
      SUBROUTINE TYPE62(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICONTROL,*)
C
C     THIS IS VERSION FOR TRNSYS 14, MODIFIED BY A.FIKSEL.
C     IT IS THE SAME AS OLD ONE, I JUST DELETED ALL
C     CONVERGENCE PROMOTIONS
C     8/20/93
C     Version from: 11/16/89
C--------------------------------------------------------------
C     This subroutine represents a four parameter model of
C     a Photovoltaic array. It is capable to predict the
C     complete current-voltage characteristic over the entire
C     operating voltage range of a flat-plate, non-sunconcen-
C     trated collector. While a series resistance is taken
C     into account, a shunt resistance is assumed to be infinite
C     and thus neglected in the model.
C     A routine is implemented which determines the voltage and
C     current at maximum power point.
C     The operating current is found for a given voltage,
C     irradiance and ambient temperature as input.
```

```
C      An option is provided to evaluate the series resistance with
C      the bisection method, if not given as input.
C      To overcome convergence problems which appear when simul-
C      ating direct coupled systems, a bisection method type of
C      convergence promotion is included. It is turned off, if
C      input FLAG is equal zero.
C*************************************************************

C*************************************************************
C**** Definition of the variables:

C**** TRNSYS specific variables:
C    XIN == input array
C    OUT == output array
C    PAR == parameters
C    TIME == simulation time
C    T,DTDT == not used in this component
C    S == storage array
C    NSTORE == dimension of S
C    IAV == pointer within S
C    ISTORE == index
C    INFO == array to use TRNSYS internal information

C**** component specific variables:
C    A == completion factor
C    AREA == collector area [m^2]
C    CURRENT == function called current
C    DUMMY == auxiliary variable for convergence promotion
C    EFFREF == reference max. power efficiency
C    EG == bandgap energy [eV]
C    FF == fill factor
C    FIRST == auxiliary variable; allows that at first timestep
C                 with solar radiation, V = VMP, otherwise the first
```

```
C              guess for V is V from the previous timestep
C   FLAG == switch: if FLAG=1 then convergence promotion is on
C              if FLAG=0 then convergence promotion is off
C   GAM == curve fit factor
C   I == current [amps]
C   IL == light current [A]
C   ILR == reference light current [A]
C   IMP == current at max. power [A]
C   IMR == reference current at max. power [A]
C   IO == reverse saturation current [A]
C   IOR == dito at reference [A]
C   ISC == short circuit current [A]
C   ISCR == dito at reference [A]
C   MEMO == memorizer if convergence promotion is on or off
C   MISC == temperature coefficient: short circuit current [A/K]
C   MVOC == temperature coefficient: open circuit voltage [V/K]
C   N == pointer to a relative adress in program
C   NP == number of modules in parallel
C   NS == number of modules in series
C   P == power [W]
C   PMAX == power [W]
C   Q_BZ == electron charge/Boltzmann constant [C*K/J]
C   TA == ambient temperature [Kelvin (K)]
C   TANOCT == ambient temperature at NOCT [K]
C   TAU_AL == transmittance-absorptance product
C   TC == cell temperature [K]
C   TCR == reference cell temperature [K]
C   TCNOCT == cell temperature at NOCT [K]
C   SUN == irradiance [W/m^2]
C   SUNR == reference irradiance [W/m^2]
C   SUNNOCT == irradiance at NOCT [K]
C   V == voltage [volts]
C   VMP == max. power point voltage [V]
```

```
C    VMR == reference max. power point voltage [V]
C    VOC == open circuit voltage [V]
C    UTIL == utilization of the array: ratio of actual power
C               to max. power

C**** variables used to determine the series resistance
C    ANEW,ALOW,AUP == A is the completion factor, the indexes
C                   stands for the limits: lower and upper, and for the current value: new
C    FNEW,FLOW,FUP == objective functions: at the interval
C                   limits and at the current value
C    GAMNEW,GAMLOW,GAMUP == curve fit factor: at the interval
C                   limits and at the current value
C    IONEW,IOLOW,IOUP == saturation current: at the interval
C                  limits and at the current value
C    RS,RSNEW,RSLOW,RSUP == series resistance: at the interval
C                   limits and at the current value

C**** variables used in operating current calculation
C    F == objective function for Newton's method
C    FPRIME == first derivative of F
C    IOLD,INEW == iteration variables

C**** variables used in maximum power evaluation
C    F1 == objective function
C    F1P == first derivative of F1
C    IMXO,IMXN == iteration variables

C*****************************************************************

C**** declaration of the variables:
     IMPLICIT NONE
     INTEGER ICONTROL
     REAL PAR,TIME,T,DTDT,S
```

```
      REAL*8 XIN,OUT
      REAL*8 I,CURRENT,V,IO,IOR,TA,
     &        A,Q_BZ,GAM,IL,ISC,TC,VOC,NS,NP,
     &        ISCR,VOCR,TCR,SUNR,VMR,IMR,MISC,EG,
     &        ILR,SUN,SERCELL,TCNOCT,TANOCT,SUNNOCT,
     &        AREA,TAU_AL,EFFREF,IMP,VMP,P,PMAX,MVOC,
     &        UTIL,VMI,VMA,VOLD,FF,CUR
      REAL*8  ANEW,ALOW,AUP,FNEW,FLOW,FUP,GAMNEW,GAMLOW
     &        IONEW,IOLOW,IOUP,RS,RSNEW,RSLOW,RSUP
      REAL*8  IOLD,INEW,F,FPRIME,GAMUP
      REAL*8  IMXO,IMXN,F1,F1P
      INTEGER FLAG,DUMMY,ISTORE,NSTORE,IAV,MEMO,N,FIRST
      INTEGER*4 INFO
      DIMENSION XIN(4), OUT(10), PAR(18), INFO(15)
C*****************************************************************
      COMMON /STORE/ NSTORE,IAV,S(5000)
C**** store is used to store values from previous timestep
      COMMON /ARRAY/ GAM,TC,Q_BZ,IL,IO,RS,IMP
C**** array is used to transfer data to function 'current'
      COMMON /PARAM/ SERCELL,TCR,IMR,VMR,ISCR,VOCR,MVOC,MISC,EG
C**** param is used to transfer data to subroutine 'series'
C*****************************************************************


C-----------------------------------------------------------------
C**** Set inputs
      SUN=XIN(3)/3.6
      TA=XIN(4)+273.15
      V=XIN(2)
      Cur=XIN(1)
C-----------------------------------------------------------------
C**** in this section a couple of checks on the inputs are
C**** performed. This is done at the second and following
C**** calls in timestep
```

```
C-----------------------------------------------------------------
C**** initial call in simulation
   IF (INFO(7).EQ.-1) THEN

      INFO(6)=10
      INFO(9)=0
      CALL TYPECK(1,INFO,4,18,0)
      Q_BZ=11604.45

C****  set parameters ***************************
      ISCR=PAR(1)
      VOCR=PAR(2)
      TCR=PAR(3)
      SUNR=PAR(4)
      VMR=PAR(5)
      IMR=PAR(6)
      MISC=PAR(7)
      MVOC=PAR(8)
      SERCELL=PAR(9)
      NS=PAR(10)
      NP=PAR(11)
      TCNOCT=PAR(12)
      TANOCT=PAR(13)
      SUNNOCT=PAR(14)
      AREA=PAR(15)
      TAU_AL=PAR(16)
      EG=PAR(17)
      RS=PAR(18)

      IF (RS.LT.0) THEN
C****    in this case RS is not provided as a parameter and
C****    has to be evaluated. This is done in subroutine "series"
        CALL SERIES(RS,Q_BZ)
```

```
      ENDIF

C****  evaluation of the 3 unknowns at reference condition
      GAM=Q_BZ*(VMR-VOCR+IMR*RS)/(TCR*LOG(1.-IMR/ISCR))
      ILR=ISCR
      IOR=ILR/EXP(Q_BZ*VOCR/(GAM*TCR))

C****  set up parameters for the entire array
      ILR=NP*ILR
      IOR=NP*IOR
      GAM=NS*GAM
      RS=(NS/NP)*RS

      A=GAM/(NS*SERCELL)

      MEMO=0
      FIRST=0
      GOTO 1000
    ENDIF

     IF(SUN.LE.0.01)THEN
       V=0.
       I=0.

C****   jump to the output section of the program
       GOTO 1000
      ENDIF


C-----------------------------------------------------------------
C**** first call in timestep
C****  evaluation of cell temperature from NOCT conditions
      EFFREF=IMR*VMR/(SUNR*AREA)
```

```
      TC=TA +(SUN*(TCNOCT-TANOCT)/SUNNOCT*(1.-EFFREF/TAU_AL))

C****  this part calculates how IL and IO vary with temp. and SUN
      IL=(SUN/SUNR)*(ILR+MISC*NP*(TC-TCR))
      IF(IL.LT.0.0) IL=0.0
      IO=IOR*((TC/TCR)**3)*EXP((Q_BZ*EG/(A))*((1./TCR)-(1./TC)))

C****  Open circuit voltage
      VOC=GAM*TC/Q_BZ*LOG(IL/IO+1.)
C****  Short circuit current
      ISC=IL

C****  all calculations are being skipped during time periods
C****  with no insolation
      IF(SUN.LE.0.0.OR.V.LT.0)THEN
       V=0.
       I=0.
       GOTO 1000
      ENDIF

C****     check if voltage greater than open circuit voltage
      IF(V.GT.VOC)THEN
        V=VOC
        I=0.
      ELSE
        I=IL-IO*(EXP(Q_BZ*(V+CUR*RS)/(GAM*TC))-1.)
      ENDIF

1000  CONTINUE
      P=I*V


C**** SET OUTPUTS ************************************
```

```
      OUT(1)=I
      OUT(2)=V
      OUT(3)=P
      OUT(4)=PMAX
      IF(PMAX.NE.0.)THEN
        UTIL=P/PMAX
      ELSE
        UTIL=0.
      ENDIF
      OUT(5)=RS
      OUT(6)=IL
      OUT(7)=IO
      OUT(8)=VOC
      OUT(9)=ISC
      OUT(10)=FF

      RETURN 1
      END

C*****************************************************************
      SUBROUTINE SERIES(RS,Q_BZ)
C**** determination of series resistance using bisection method

      IMPLICIT NONE
      COMMON /PARAM/ SERCELL,TCR,IMR,VMR,ISCR,VOCR,MVOC,MISC,EG

      REAL*8 SERCELL,TCR,IMR,VMR,ISCR,VOCR,MVOC,MISC,EG,Q_BZ
      REAL*8 ANEW,ALOW,AUP,FNEW,FLOW,FUP,GAMNEW,GAMLOW
      REAL*8 IONEW,IOLOW,IOUP,RS,RSNEW,RSLOW,RSUP,GAMUP


C**** parameters at the upper limit of the convergence interval
      RSUP=((SERCELL*TCR*LOG(1.-IMR/ISCR)/Q_BZ)+VOCR-VMR)/IMR
```

```
      AUP=1.
      GAMUP=SERCELL
      IOUP=ISCR*EXP(-Q_BZ*VOCR/(GAMUP*TCR))

C**** parameters at the lower limit of the convergence interval
      RSLOW=0.0
      GAMLOW=Q_BZ*(VMR-VOCR)/(TCR*LOG(1.-IMR/ISCR))
      ALOW=GAMLOW/SERCELL
      IOLOW=ISCR*EXP(-Q_BZ*VOCR/(GAMLOW*TCR))

      DO WHILE ((ABS(RSUP-RSLOW)).GT.0.0005)
         RSNEW=0.5*(RSUP+RSLOW)
         GAMNEW=Q_BZ*(VMR-VOCR+IMR*RSNEW)/(TCR*LOG(1.-IMR/ISCR))
         ANEW=GAMNEW/SERCELL
         IONEW=ISCR*EXP(-Q_BZ*VOCR/(GAMNEW*TCR))
         FUP=-MVOC+(GAMUP/Q_BZ)*(LOG(1.+ISCR/IOUP)+(TCR/(ISCR+
     >   IOUP))*(MISC-ISCR*((Q_BZ*EG/(AUP*TCR*TCR))+3./TCR)))
         FLOW=-MVOC+(GAMLOW/Q_BZ)*(LOG(1.+ISCR/IOLOW)+(TCR/(ISCR+
     >   IOLOW))*(MISC-ISCR*((Q_BZ*EG/(ALOW*TCR*TCR))+3./TCR)))
         FNEW=-MVOC+(GAMNEW/Q_BZ)*(LOG(1.+ISCR/IONEW)+(TCR/(ISCR+
     >   IONEW))*(MISC-ISCR*((Q_BZ*EG/(ANEW*TCR*TCR))+3./TCR)))
         IF((FLOW*FNEW).LT.0.0) RSUP=RSNEW
         IF((FLOW*FNEW).GT.0.0) RSLOW=RSNEW
         GAMUP=Q_BZ*(VMR-VOCR+IMR*RSUP)/(TCR*LOG(1.-IMR/ISCR))
         AUP=GAMUP/SERCELL
         IOUP=ISCR*EXP(-Q_BZ*VOCR/(GAMUP*TCR))
         GAMLOW=Q_BZ*(VMR-VOCR+IMR*RSLOW)/(TCR*LOG(1.-IMR/ISCR))
         ALOW=GAMLOW/SERCELL
         IOLOW=ISCR*EXP(-Q_BZ*VOCR/(GAMLOW*TCR))
      END DO

      RS=RSNEW
      RETURN
```

```
      END
```

TRNSYS TYPE for the lead acid battery (File: TYPE 74)

```
C***********************************************************
      SUBROUTINE TYPE74(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C     version from 12/22/89
C***********************************************************
C
C  THIS COMPONENT SIMULATES THE PERFORMANCE OF A LEAD-ACID
C  STORAGE BATTERY.  IT IS DESIGNED TO OPERATE IN CONJUNCTION
C  WITH A SOLAR CELL ARRAY AND A REGULATOR.
C
C  Q = STATE OF CHARGE [AH]
C  QM = RATED CAPACITY OF CELL [AH]
C  QC,QD = CAPACITY PARAMETERS ON CHARGE, DISCHARGE
C  F = FRACTIONAL STATE OF CHARGE = Q/QM (1.0 IS FULL CHARGE)
C  CP,CS = NUMBER OF CELLS IN PARALLEL, SERIES
C  P = POWER [WATTS]
C  IQ = CURRENT [AMPS
C  IQMAX,IQMIN = MAXIMUM CURRENT (CHARGE), MINIMUM CURRENT C
       (DISCHARGE)
C  V = VOLTAGE [VOLTS]
C  VC,IC = CUTOFF VOLTAGE ON CHARGE, CURRENT CORRESPONDING C         TO C
C  ICTOL = PARAMETER FOR ITERATIVE CALCULATIONS
C  VD = CUTOFF VOLTAGE ON DISCHARGE
C  ED,RD = DATA USED TO CALCULATE VD WHEN VCONTR .LT. 0.
C  VCONTR =  SPECIFICATION OF VOLTAGE CONTROL ON DISCHARGE.
C  POSITIVE MEANS VD=VCONTR.  NEGATIVE MEANS
C  VD=ED-ABS(IQ)*RD.
C  VDI = DIODE VOLTAGE FROM Z-P MODEL
```

```
C  VOC = OPEN CIRCUIT VOLTAGE AT FULL CHARGE
C  ESC,ESD = EXTRAPOLATED OPEN CIRCUIT VOLTAGES
C  GC,GD = COEFFICIENTS OF (1-F)IN V FORMULAS
C  RSC,RSD = INTERNAL RESISTANCES AT FULL CHARGE
C  MC,MD = CELL TYPE PARAMETERS WHICH DETERMINE THE SHAPES
C  OF THE
C  I-V-Q CHARACTERISTICS
C  ICOUNT=COUNTS THE NUMBER OF ITERATIONS INVOLVED IN
C  OBTAINING IC
C
C  THE BATTERY MODEL IS THE MODEL RECOMMENDED IN THE BEST
C  REPORT (THE HYMAN MODEL).  IT IS THE SHEPHERD MODEL
C  MODIFIED BY THE ADDITION OF A ZIMMERMAN-PETERSEN DIODE IN C    BOTH THE
CHARGE AND DISCHARGE EQUIVALENT CIRCUITS.
C*******************************************************************

   DIMENSION
   +  DTDT(1),    INFO(15),    OUT(9),    PAR(21),
   +  T(1),       XIN(1)
   REAL
   +  I1,       IC,       IC1,       ICTOL,
   +  IDF,       IQ,       IQMAX,       IQMIN,
   +  K1,       MC,       MD

C**************************************************************
   DOUBLE PRECISION XIN,OUT
   COMMON/SIM/ TIME0,TFINAL,DELT,IWARN
   COMMON/STORE/NSTORE,IAV,STORE(5000)
   INTEGER*4 INFO
C------------------------------------------------------
C**** Initialization--first call of component
   IF (INFO(7).LT.0) THEN
        INFO(9)=1
```

```
      INFO(6)=9
      INFO(10)=1
      CALL TYPECK (1,INFO,1,21,1)
      RETURN 1
   ENDIF
      INDEX=INFO(10)

C****  Set parameters
      QM=PAR(1)
      CP=PAR(2)
      CS=PAR(3)
      EFF=PAR(4)
      VC=PAR(5)
      VCONTR=PAR(6)
      IF (VCONTR.GT.0) THEN
       VD=VCONTR
C****   Check on minimum discharge voltage
       IF (VD.GT.2.5.OR.VD.LT.1.5) CALL TYPECK (-4,INFO,0,0,0)
      ENDIF
      ICTOL=PAR(7)
      ESC=PAR(8)
      ESD=PAR(9)
      GC=PAR(10)
      GD=PAR(11)
      MC=PAR(12)
      MD=PAR(13)
      ED=PAR(14)
      RD=PAR(15)
      I1=PAR(16)
      K1=PAR(17)
      QC=PAR(18)
      QD=PAR(19)
      RSC=PAR(20)
```

```
      RSD=PAR(21)
C****  Check on maximum charge voltage
   IF (VC.GT.2.8.OR.VC.LT.1.8) CALL TYPECK (-4,INFO,0,0,0)
   IF(TIME.EQ.TIME0) STORE(INDEX)=T(1)
   IF(INFO(7).EQ.0) THEN
C****  computation of state of charge of battery from
C****  the previous time step
      Q=STORE(INDEX)
      F=Q/QM
      H=1.-F
   ENDIF
C****  set inputs
      IQ=XIN(1)
C****  current for one cell
      IQ=IQ/CP

C--------------------------------------------------------
C**** first and following calls in time step
C****  Modified Shepherd Model
      VOC=(ESC+ESD)/2.
      IF (IQ.GE.0.) THEN
C****   Charging
       VDI=1./K1*ALOG(IQ/I1+1.)
       V=VOC+VDI-GC*H+IQ*RSC*(1.+MC*H/(QC/QM-H))
       BB=IQ*EFF
       AA=0.
      ELSE
C****   Discharging
       VDI=1./K1*ALOG(-IQ/I1+1.)
       V=VOC-VDI-GD*H+IQ*RSD*(1.+MD*H/(QD/QM-H))
       BB=IQ
       AA=0.
      ENDIF
```

```
      CALL DIFFEQ(TIME,AA,BB,Q,Q1,QBAR)
C------------------------------------------------------
      STORE(INDEX)=Q1
      P=IQ*V

C**** Output
      OUT(1)=Q1
      OUT(2)=Q1/QM
      OUT(3)=P*CP*CS
      OUT(4)=0.
      IF (P.GT.0.) OUT(4)=(1.-EFF)*P*CP*CS
      OUT(5)=IQ*CP
      OUT(6)=V*CS
      IF (VCONTR.LT.0.) VD=ED-ABS(IQ)*RD
      OUT(7)=VD*CS
      OUT(8)=VC*CS
      RETURN 1
      END
```

TRNSYS TYPE for the series type charge controller (File: TYPE 59)

```
C*********************************************************************
   SUBROUTINE TYPE59(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICONTROL,*)
C    version from: 12/22/89
C*********************************************************************
C**** Subroutine represents a charge controller for a system including
C**** PV-array, load and battery storage.
C**** The controler represents a series type controler.
C**** A blocking diode is included in the model. It prevents that the
C**** battery is being discharged through the cell. It is assumed that
C**** voltage drop at the diode is constant throughout the simulation
```

```
C**** and just depends on the diode material used in the system.
C**** The user has to provide this information as a parameter
C*********************************************************************

C    Variables:

C    VB -- battery voltage [volts]
C    VD -- low limit on voltage, when battery discharging
C    VC -- high limit on voltage, when battery charging: cutoff voltage
C    VDA -- limit on voltage, above battery can again begin to discharge
C              after being charged
C    VCA -- limit on voltage, above battery can again begin to charge
C              after being discharged
C    VDIODE -- voltage of diode
C    VCELL -- voltage send to cell
C    VLOAD -- voltage send to load
C    F -- fractional state of charge
C    FD -- discharge limit on F
C    FC -- charge limit on F
C    FDA -- limit on F above battery can be discharged again after
C              being charged
C    FCA -- limit on F below battery can be charged again after
C              being discharged
C    IBMIN,IBMAX -- min. and max. battery current permitted
C    IB -- battery current
C    ICAP -- integrated capacity from refrigeration cycle
C    IREFP  --  integrated power from refrigerator
C    ONTOL  --  tolerance in Wh above compressor switches off
C    OFFTOL --  tolerance in Wh above compressor switches on
C****************************************************************

      IMPLICIT NONE
      INTEGER ICONTROL,FAIL,FLAG
```

```
      INTEGER*4 INFO
      INTEGER ISTORE,NSTORE,IAV
      REAL TIME,T,DTDT,PAR,S
      REAL VC,VD,VDA,VCA,VDIODE
      REAL F,FD,FC,FDA,FCA,IBMIN,IBMAX
      REAL*8 ICAP,IREFP,TOL,DIFF,DUMP
      REAL*8 IB,VB,VCELL,VLOAD,DUMMY,XIN,OUT
      DIMENSION XIN(7), OUT(4), PAR(10), INFO(15)


      COMMON /STORE/ NSTORE,IAV,S(5000)
C**** store is used to store values from previous timestep

C***********************************************************

      INFO(6)=3
      INFO(9)=0

C-------------------------------------------------------
C**** Initial call of component
      IF(INFO(7).LT.0)THEN

C****    storage allocation
         INFO(10)=2
         CALL TYPECK(1,INFO,7,10,0)
         ISTORE=INFO(10)

C****    Iinitialization of auxiliary variables used in secant
C****    method
         S(ISTORE)=0.
         S(ISTORE+1)=0.

C****    SET PARAMETERS
```

```
      FD=PAR(1)
      FC=PAR(2)
      FDA=PAR(3)
      FCA=PAR(4)
      VDA=PAR(5)
      VCA=PAR(6)
      IBMAX=PAR(7)
      IBMIN=PAR(8)
      VDIODE=PAR(9)
      TOL=PAR(10)

      DUMMY=0.
      DUMP=0.
      FLAG=0
C-----------------------------------------------------
C**** first and following calls in time step
   ELSE

      DUMMY=S(ISTORE)

C****   Following calls in time step
C****   Set inputs
      VB=XIN(1)
      IB=XIN(2)
      F=XIN(3)
      VC=XIN(4)
      VD=XIN(5)
      ICAP=XIN(6)
      IREFP=XIN(7)
C****   check on discharge rate
      IF(IB.LT.0.)THEN
       IF(IB.LT.IBMIN)THEN
        FAIL=1
```

```
          ENDIF
         ELSE
          IF(IB.GT.IBMAX)THEN
           FAIL=2
          ENDIF
         ENDIF

C****    check provided energy
C****    FLAG=1 means to much energy was provided during the last
C****    timeperiod. The refrigeration cycle will be switched off.
C****    FLAG=0 means the refrigeration cycle is on.
         FLAG=INT(S(ISTORE+1))
         DIFF=ICAP-IREFP
         IF (DIFF .GT. TOL) THEN
          FLAG=1
         ELSEIF (DIFF .LT. 0.) THEN
          FLAG=0
         ENDIF
         S(ISTORE+1)=FLAG

C****    initially no restrictions are made, battery can either
C****    be charged or discharged
         IF(DUMMY.EQ.0.)THEN

C****      check on low limit of F and V
           IF((F.LT.FD).OR.(VB.LT.VD))THEN
C****        load will be disconnected from battery and from cell,
C****        but cell can still charge battery
C****        If DUMP=1. the refrigeration cycle will calculate the
C****        energy but store it as dumped energy

             VLOAD=0.
             VCELL=VDIODE+VB
```

```
           DUMMY=1.
           DUMP=0.

C****     check on high limit of voltage
          ELSEIF((F.GT.FC).OR.(VB.GT.VC))THEN
C****      cell will be disconnected from battery and load,
C****      battery will be discharged
           VCELL=-333.
C****      this is just a characteristic value that the cell
C****      recognizes that it is being disconnected
           VLOAD=VB
           DUMMY=2.
           IF (FLAG .EQ. 1) THEN
            DUMP=1.
           ELSE
            DUMP=0.
           ENDIF
          ELSE
C****      no restrictions

           VCELL=VDIODE+VB
           DUMP=0.
           IF (FLAG .EQ. 1) THEN
            VLOAD=0.
           ELSE
            VLOAD=VB
           ENDIF
          ENDIF

         ELSEIF(DUMMY.EQ.1.)THEN
C****     battery can only begin to discharge again, when VB is
C****     greater than VDA and F is greater then FDA
```

```
      IF((F.LT.FDA).OR.(VB.LT.VDA))THEN
       VLOAD=0.
       VCELL=VDIODE+VB
       DUMP=0.
      ELSE
C****   no restrictions

       VCELL=VDIODE+VB
       DUMMY=0.
       DUMP=0.
       IF (FLAG .EQ. 1) THEN
        VLOAD=0.
       ELSE
        VLOAD=VB
       ENDIF
      ENDIF

     ELSEIF(DUMMY.EQ.2.)THEN
C****  battery can only begin to charge again, when VB is
C****  less than VCA and F is less than FCA

      IF((F.GT.FCA).OR.(VB.GT.VCA))THEN
       VCELL=-333.
       VLOAD=VB
       DUMMY=2.
       IF (FLAG .EQ. 1) THEN
        DUMP=1.
       ELSE
        DUMP=0.
       ENDIF
      ELSE
C****   no restrictions
```

```
          VCELL=VDIODE+VB
          DUMMY=0.
          DUMP=0.
          IF (FLAG .EQ. 1) THEN
           VLOAD=0.
          ELSE
           VLOAD=VB
          ENDIF
         ENDIF
        ENDIF
      ENDIF

      S(ISTORE)=DUMMY

C**** SET OUTPUTS
      OUT(1)=VCELL
      OUT(2)=VLOAD
      OUT(3)=FAIL
      OUT(4)=DUMP

      RETURN 1
      END
```

TRNSYS TYPE for the parallel type charge controller (File: TYPE 66)

```
C***************************************************************
      SUBROUTINE TYPE66(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C*******************************************************************
C**** Subroutine represents a charge controller for a system including
C**** PV-array, load and battery storage.
C**** The controler represents a parallel type controler.
```

```
C*********************************************************************

     DOUBLE PRECISION XIN,OUT
     REAL PAR,TIME,T(1),DTDT(1)
     DIMENSION XIN(10),OUT(10),PAR(2),INFO(15),ICNTRL(2)
     INTEGER ICNTRL,IC
     INTEGER*4 INFO
     COMMON /STORE/NSTORE,IAV,STORE(5000)
     COMMON /SIM/ TIME0,TFINAL,DELTA,IWARN
     COMMON/LUNITS/LUR,LUW,IFORM,LUK
C      SMAX=PAR(1)
C      SMIN=PAR(2)
C      A - DEADBAND = PAR(3)
C      THIS PART REPRESENT A DISCHARGE CONTROLLER
          IF (INFO(7).EQ.-1) THEN
            ICNTRL(1)=1
            ICNTRL(2)=1
            INFO(11)=1
            INFO(10)=3
            IPR=0
            CALL TYPECK(1,INFO,7,4,0)
            STORE(INFO(10))=0
            STORE(INFO(10)+1)=0
            STORE(INFO(10)+2)=0
            RETURN 1
          ENDIF
          NST=INFO(10)
          STATEOLD=ICNTRL(1)
          STATENEW=STATEOLD
          SMAX=PAR(1)
          SMIN=PAR(2)
          A=PAR(3)
          CMAX=PAR(4)
```

```
      SOC=XIN(1)          ! STATE OF CHARGE
      IC=XIN(2)           ! CURRENT STATE
C     IC=0  - BATTERY DISCHARGE (MODE 0)
C     IC=1    NORMAL WORK (MODE 1)
C     IC=2    OVERCHARGE
      CPV=XIN(3)              ! CURRENT FROM PV
      VPV=XIN(4)              ! VOLTAGE FROM PV
      CREF=XIN(5)             ! CURRENT NEEDED BY REF.
      VREF=XIN(6)             ! VOLTAGE TO REF.( IS NOT USED)
      VBAT=XIN(7)             ! VOLTAGE FROM BATTERY
      CBAT=CPV-CREF           ! CURRENT TO BATTERY
      IF (IC.EQ.0) THEN
        IF (SOC.GT.SMIN+A) IC=1    ! SWITCH FROM  0 TO 1
        GOTO 11
      ENDIF
      IF (IC.EQ.1) THEN
        IF (SOC.GT.SMAX+A) IC=2   ! FROM 1 TO 2
        IF (SOC.LE.SMIN-A) IC=0   ! FROM 1 TO 0
        GOTO 11
      ENDIF
      IF (IC.EQ.2) THEN
        IF (SOC.LT.SMAX-A) THEN
          IC=1
          STATEOLD=0
        ENDIF
      ENDIF
C     Normal operation
11    CONTINUE
      IF (IC.EQ.1)  THEN
        OUT(1)=CBAT           ! CURRENT TO BATTERY
        OUT(2)=VBAT           ! VOLTAGE TO BATTERY
        OUT(3)=CPV            ! CURRENT TO REF
        OUT(4)=VBAT           ! VOLTAGE TO REF
```

```
          OUT(5)=0                 ! CONTROL CURRENT (MUST BE 0)
          STATEold=0
          STATEnew=0
           GOTO 99
        ENDIF
C       DISCHARGE
        IF (IC.EQ.0) THEN
         IF (STATEOLD.GE.0.5) THEN
          IF (CPV.LT.CMAX) STATENEW=0  ! SWITCH TO CHARGE BATTERY
         ELSE
          IF (CPV.GE.CMAX) STATENEW=1  ! TURN ON REF.
         ENDIF
         IF (STATEOLD.EQ.0) THEN         ! PV CHARGES BATTERY.
           OUT(1)=CBAT
           OUT(2)=VBAT
           OUT(3)=CPV
           OUT(4)=0
           OUT(5)=0
         ELSE
           OUT(1)=CBAT                 ! PV  CHARGES BATTERY AND REF
           OUT(2)=VBAT
           OUT(3)=CPV
           OUT(4)=VBAT
           OUT(5)=0
         ENDIF
         GOTO 99
        ENDIF
C       OVERCHARGE
        IF (IC.EQ.2) THEN
         IF (STATEOLD.LE.0.5) THEN
C       IT WAS DISCHARGE
          IF (CBAT.GE.0.0) STATENEW=1    ! BATTERY IS FULLY CHARGED
         ENDIF
```

```
    IF (STATEOLD.GT.0.5) THEN
      IF (CBAT.LT.0) STATENEW=0    ! PV CAN CHARGE BATTERY
    ENDIF
   IF (STATEOLD.EQ.0) THEN
     OUT(1)=CBAT
     OUT(2)=VBAT
     OUT(3)=CPV
     OUT(4)=VBAT
     OUT(5)=0
   ELSE
     OUT(1)=0
     OUT(2)=VBAT
     OUT(3)=CPV
     OUT(4)=VBAT
     OUT(5)=0
    ENDIF
   ENDIF
99 ICNTRL(1)=STATEOLD
   ICNTRL(2)=STATENEW
   OUT(6)=IC               ! STATE OF THE BATTERY
998 FORMAT(/' The batterywas fully charged',F6.2','and discharged at ',F5.2,'% of the time')
   RETURN 1
   END
```

TRNSYS TYPE for the cooling system (File: TYPE 73)

```
C***************************************************************
   SUBROUTINE TYPE73(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)

   DOUBLE PRECISION XIN,OUT
   DIMENSION XIN(5),OUT(8),PAR(1),INFO(15)
   INTEGER*4 INFO
```

```
      INTEGER ICNTRL,IDUMP

C*****************************************************************
C     This subroutine represents a vapor compression refrigeration
C     cycle combined with a brushless dc motor. As a result of this
C     type, we will get the input current as a function of the
C     input voltage, the room temperature and the freezer temperature.
C     This routine is valid only for a special combination
C     (Announced later) of cycle and motor parameters. The range in
C     which this routine is valid is:
C     - voltage between 0 and 20V
C     - ambient / room temperature between 10 and 40 C
C     - freezer temperature between -4 and 0 C
C*******************************************************************
C
C****** component specific variables
C     V = voltage in volts
C     Ta = ambient / room temperature in deg C
C     Tfr = freezer temperature in deg C
C     M0 .. M5 = coefficients for polynomial (It=f(V,Trm,Tfr))
C     M00 .. M20 = coefficients to determine M0 (M0=f(Trm,Tfr))
C     M01 .. M31 = coefficients to determine M1 (M1=f(Trm,Tfr))
C     M02 .. M32 = coefficients to determine M2 (M2=f(Trm,Tfr))
C     M03 .. M33 = coefficients to determine M3 (M3=f(Trm,Tfr))
C     M04 .. M34 = coefficients to determine M4 (M4=f(Trm,Tfr))
C     M05 .. M35 = coefficients to determine M5 (M5=f(Trm,Tfr))
C     C0 .. C4 = coefficients for polynomial (COP=f(V,Trm,Tfr))
C     C00 .. C30 = coefficients to determine C0 (C0=f(Trm,Tfr))
C     C01 .. C31 = coefficients to determine C1 (C1=f(Trm,Tfr))
C     C02 .. C32 = coefficients to determine C2 (C2=f(Trm,Tfr))
C     C03 .. C33 = coefficients to determine C3 (C3=f(Trm,Tfr))
C     C04 .. C34 = coefficients to determine C4 (C4=f(Trm,Tfr))
```

```
      Integer flag
      Real*8 V,Ta,Tfr,COP,CAP,eta,DUMP,CAPDUMP
      Real Vmin,Vstore
      Real MV0,MV1,MV2
      Real M0,M1,M2,M3,M4,M5
      Real M00,M10,M20,M01,M11,M21,M31,M02,M12,M22,M32
      Real M03,M13,M23,M33,M04,M14,M24,M34,M05,M15,M25,M35
      Real C0,C1,C2,C3,C4
      Real C00,C10,C20,C30,C01,C11,C21,C31,C02,C12,C22,C32
      Real C03,C13,C23,C33,C04,C14,C24,C34
C*******************************************************************

C****** Set Inputs
      V=XIN(1)
      Ta=XIN(2)
      Tfr=XIN(3)
      CUR1=XIN(4)
      DUMP=XIN(5)

C****** set the motor efficiency eta
      eta=0.9

C****** calculate the minimum voltage
C****** calculate the coefficiets MV0 to MV2
      MV0=0.3475-4.8749e-2*Tfr-3.74975e-3*Tfr**2
      MV1=4.435e-2+3.3501e-3*Tfr+3.37512e-4*Tfr**2
      MV2=-4.24999e-4-2.5e-5*Tfr-6.25e-6*Tfr**2

C****** calculate the minimum volyage     Vmin=MV0+MV1*Ta+MV2*Ta**2

      flag=0
******* check if input voltage < minimum voltage
      if (V .lt. Vmin) then
```

```
            Vstore=V
            V=Vmin
            flag=1
        endif

C****** calculate the coefficients M0 to M5 for the current calculation
        M00=0.5393400-0.7531403e-1*Tfr-0.4150383e-2*Tfr**2
        M10=0.7955132e-1+0.1831461e-2*Tfr+0.3723055e-4*Tfr**2
        M20=-0.5349341e-3+0.4925577e-4*Tfr+0.3084497e-6*Tfr**2
        M0=M00+M10*Ta+M20*Ta**2
        M01=0.2420253-0.8932678e-1*Tfr-0.7193248e-1*Tfr**2
     &  -0.1568414e-1*Tfr**3-0.8837680e-3*Tfr**4
        M11=0.3249278e-2+0.2009868e-1*Tfr+0.1202693e-1*Tfr**2
     &  +0.2491312e-2*Tfr**3+0.1337625e-3*Tfr**4
        M21=-0.5570044e-3-0.9656586e-3*Tfr-0.5732462e-3*Tfr**2
     &  -0.1205124e-3*Tfr**3-0.7105359e-5*Tfr**4
        M31=0.7205648e-5+0.1333949e-4*Tfr+0.8202517e-5*Tfr**2
     &  +0.1813732e-5*Tfr**3+0.1228688e-6*Tfr**4
        M1=M01+M11*Ta+M21*Ta**2+M31*Ta**3

        M02=-0.2407894e-1+0.5906843e-2*Tfr+0.6464932e-3*Tfr**2
        M12=-0.2636731e-2-0.1857755e-2*Tfr-0.2145157e-3*Tfr**2
        M22=0.1562658e-3+0.9752114e-4*Tfr+0.1382020e-4*Tfr**2
        M32=-0.1981315e-5-0.1404925e-5*Tfr-0.2219106e-6*Tfr**2
        M2=M02+M12*Ta+M22*Ta**2+M32*Ta**3

        M03=0.9773599e-3-0.6355449e-3*Tfr-0.2563748e-4*Tfr**2
        M13=0.342090e-3+0.1844913e-3*Tfr+0.1732689e-4*Tfr**2
        M23=-0.1774089e-4-0.1011879e-4*Tfr-0.1309981e-5*Tfr**2
        M33=0.2270733e-6+0.1504438e-6*Tfr+0.2225981e-7*Tfr**2
        M3=M03+M13*Ta+M23*Ta**2+M33*Ta**3

        M04=-0.1353613e-4+0.2119264e-4*Tfr-0.2033706e-5*Tfr**2
```

```
      M14=-0.1736821e-4-0.7236717e-5*Tfr-0.3860845e-6*Tfr**2
      M24=0.8676338e-6+0.4295446e-6*Tfr+0.4657939e-7*Tfr**2
      M34=-0.1119678e-7-0.6651886e-8*Tfr-0.8844703e-9*Tfr**2
      M4=M04+M14*Ta+M24*Ta**2+M34*Ta**3

      M05=-0.2340770e-7-0.1272806e-6*Tfr+0.1049813e-6*Tfr**2
      M15=0.3085858e-6+0.9075545e-7*Tfr-0.2664234e-8*Tfr**2
      M25=-0.1525100e-7-0.6232360e-8*Tfr-0.4642527e-9*Tfr**2
      M35=0.1981572e-9+0.1025284e-9*Tfr+0.1144823e-10*Tfr**2
      M5=M05+M15*Ta+M25*Ta**2+M35*Ta**3

C****** Calculate the current
      Cur=M0+M1*V+M2*V**2+M3*V**3+M4*V**4+M5*V**5

C****** calculate the coefficients C0 to C4 for the COP calculation
      C00=27.46059+2.836488*Tfr+0.156944*Tfr**2
      C10=-1.424066-1.961626e-1*Tfr-1.265663e-2*Tfr**2
      C20=3.416803e-2+5.412189e-3*Tfr+3.815587e-4*Tfr**2
      C30=-3.12657e-4-5.304732e-5*Tfr-3.953029e-6*Tfr**2
      C0=C00+C10*Ta+C20*Ta**2+C30*Ta**3

      C01=-6.813686-1.0977813*Tfr-7.2562158e-2*Tfr**2
      C11=0.460037+8.2911864e-2*Tfr+6.1038956e-3*Tfr**2
      C21=-1.2239169e-2-2.3818554e-3*Tfr-1.8997944e-4*Tfr**2
      C31=1.168953e-4+2.385522e-5*Tfr+2.01992816e-6*Tfr**2
      C1=C01+C11*Ta+C21*Ta**2+C31*Ta**3

      C02=0.874342+0.156789*Tfr+1.0991018e-2*Tfr**2
      C12=-6.23782687e-2-1.21939108e-2*Tfr-9.350255e-4*Tfr**2
      C22=1.705159e-3+3.5453289e-4*Tfr+2.9253592e-5*Tfr**2
      C32=-1.64908e-5-3.567798e-6*Tfr-3.1163785e-7*Tfr**2
      C2=C02+C12*Ta+C22*Ta**2+C32*Ta**3
```

```
      C03=-4.94305e-2-9.29327e-3*Tfr-6.708955e-4*Tfr**2
      C13=3.607627e-3+7.317108e-4*Tfr+5.7313358e-5*Tfr**2
      C23=-9.970261e-5-2.13617e-5*Tfr-1.7930097e-6*Tfr**2
      C33=9.687401e-7+2.1502586e-7*Tfr+1.9047263e-8*Tfr**2
      C3=C03+C13*Ta+C23*Ta**2+C33*Ta**3
      C04=1.0007998e-3+1.928476e-4*Tfr+1.4138368e-5*Tfr**2
      C14=-7.3877076e-5-1.526103e-5*Tfr-1.2066594e-6*Tfr**2
      C24=2.05229799e-6+4.4563212e-7*Tfr+3.759363e-8*Tfr**2
      C34=-1.997701e-8-4.4758553e-9*Tfr-3.968375e-10*Tfr**2
      C4=C04+C14*Ta+C24*Ta**2+C34*Ta**3

C****** calculate the COP
      COP=C0+C1*V+C2*V**2+C3*V**3+C4*V**4


      if (flag .eq. 1) then
            Cur=Cur/Vmin*Vstore
            COP=COP/Vmin*Vstore
            V=Vstore
      endif

C****** calculate the capacity with an assumed motor efficiency of eta=90%
      CAP=COP*V*cur*eta

C****** check if energy gets dumped
      CAPDUMP=0.
      IDUMP=IDINT(DUMP)
      IF (IDUMP .EQ. 1) THEN
       COP=0.
       Cur=0.
       CAPDUMP=CAP
       CAP=0.
      ENDIF
```

```
C****** Set Output
        OUT(1)=V
        OUT(2)=XIN(2)
        OUT(3)=XIN(3)
        OUT(4)=Cur
        OUT(5)=Cur-Cur1
        OUT(6)=COP
        OUT(7)=CAP
        OUT(8)=CAPDUMP

        Return 1
        END
```

TRNSYS TYPE for the refrigerator load (File: TYPE 60)

```
*******************************************************************
      SUBROUTINE TYPE60(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)

C     version from: 10/5/93
C******************************************************************
C     This subroutine describes the energy usage for a normal
C     refrigerator including ice making, door opening and
C     water cooling.
C******************************************************************

C     Variables:
C     k = conductivity walls
C     L = thickness walls
C     cpw = specific heat water (kJ/kg-K)
C     cpi = specific heat ice at 0C (kJ/kg-K)
C     mice = mass ice (kg)
C     Tice = min temperature for the ice (C)
```

```
C     Vref = volume refrigerator (m^3)
C     cpa = specific volume air (kJ/kg-K)
C     rhoa = density air (kg/m^3)
C     Ac = # air changes per minute [15(5)*area inside door for front (top)]
C     tdo = time door is open in min
C     mwat = mass water
C     Aidoor = inside door area (m^2)
C     Aref = area refrigerator (m^2)
C**************************************************************

      IMPLICIT NONE
      INTEGER ICNTRL
      INTEGER*4  INFO
      INTEGER ISTORE,NSTORE,IAV
      REAL TIME,T,DTDT,PAR,S
      DOUBLE PRECISION XIN,OUT
      DIMENSION XIN(4), OUT(5), PAR(11), INFO(15)
      REAL Ta,TaK,Tice,TiceK,Tref,k,L,cpw,cpi,mwat
      REAL Ac,tdo,mice,Aref,Vref,cpa,rhoa,P1,P2,P3,P4,Ptot

      COMMON /STORE/ NSTORE,IAV,S(5000)
C     store is used to store values from the previous timestep
C     Initial call of component

      IF (INFO(7) .LT. 0) THEN
C     storage allocation
        INFO(10)=1
        CALL TYPECK(1,INFO,4,11,0)
        ISTORE=INFO(10)
C     set PARAMETERS
        k=PAR(1)
        L=PAR(2)
        cpw=PAR(3)
```

```
      cpi=PAR(4)
      Aref=PAR(5)
      Tice=PAR(6)
      Vref=PAR(7)
      cpa=PAR(8)
      rhoa=PAR(9)
      Ac=PAR(10)
      tdo=PAR(11)
     ENDIF

C    set INPUTS
      Ta=XIN(1)
      Tref=XIN(2)
      mice=XIN(3)
      mwat=XIN(4)

*    conduction through walls (watts)
      P1=k/L*Aref*(Ta-Tref)

*    ice making (watts)
      TaK=273+Ta
      TiceK=273+Tice
      P2=mice*(cpw*TaK-cpi*TiceK)/86400

*    door opening (watts)
      P3=Vref*cpa*rhoa*(Ta-Tref)*Ac*tdo/86400

*    water cooling  (watts)
      P4=mwat*cpw*(Ta-Tref)/86400

*    total power (watts)
      Ptot=P1+P2+P3+P4
```

```
*     set OUTPUTS
        OUT(1)=P1
        OUT(2)=P2
        OUT(3)=P3
        OUT(4)=P4
        OUT(5)=Ptot

        Return 1
END
```

TRNSYS TYPE for integration and resetting (File: TYPE 71)

```
C*******************************************************************
   SUBROUTINE TYPE71(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICONTROL,*)

   IMPLICIT NONE
   INTEGER ICONTROL,IWARN
   INTEGER INFO
   INTEGER ISTORE,NSTORE,IAV
   REAL TIME,T,DTDT,PAR,S,STEP,IDUMP,EDUMP
   REAL TIME0,TFINAL,DELT,DTME,DUMP,TOL
   REAL ECAP,EREFP,CAP,REFP,DIFF,STDUMP
   REAL*8 XIN,OUT
   REAL ICAP,IREFP,STCAP,STREFP
   DIMENSION XIN(3), OUT(4), PAR(1), INFO(15)

   COMMON /SIM/ TIME0,TFINAL,DELT,IWARN
   COMMON /STORE/ NSTORE,IAV,S(5000)
C**** store is used to store values from previous timestep

C**********************************************************
```

```
      INFO(6)=3
      INFO(9)=0

C------------------------------------------------------
C**** Initial call of component
      IF(INFO(7).LT.0) THEN

C****    storage allocation
         INFO(10)=5
         CALL TYPECK(1,INFO,3,1,0)
         ISTORE=INFO(10)

C****    Iinitialization of auxiliary variables used in secant
C****    method
         S(ISTORE)=0.
         S(ISTORE+1)=0.
         S(ISTORE+2)=24.
         S(ISTORE+3)=0.

C****    set parameter
         TOL=PAR(1)

         RETURN 1
      ENDIF

      STEP=DELT
      ISTORE=INFO(10)
C-----------------------------------------------------
C**** first and following calls in time step
      IF (INFO(7).EQ. 0) THEN
         STCAP=S(ISTORE)
         STREFP=S(ISTORE+1)
         DTME=S(ISTORE+2)
```

```
      STDUMP=S(ISTORE+3)
   ENDIF

C****  Following calls in time step
C****  Set inputs
      CAP=XIN(1)
      REFP=XIN(2)
      DUMP=XIN(3)


C****  check provided energy
      IF (TIME .EQ. TIME0) THEN
       ICAP=0.
       IREFP=0.
       IDUMP=0.
      ELSE
       ECAP=CAP*STEP
       EREFP=REFP*STEP
       EDUMP=DUMP*STEP
       ICAP=STCAP+ECAP
       IREFP=STREFP+EREFP
       IDUMP=STDUMP+EDUMP
       DIFF=ICAP-IREFP
       IF (INT(TIME/DTME) .EQ. 1) THEN
        S(ISTORE+2)=DTME+24.
        IF (ICAP .GT. (IREFP-TOL)) THEN
         ICAP=DIFF
        ELSE
         ICAP=0.
        ENDIF
        IREFP=0.
       ENDIF
      ENDIF
```

```
      S(ISTORE)=ICAP
      S(ISTORE+1)=IREFP
      S(ISTORE+3)=IDUMP

C**** SET OUTPUTS
   OUT(1)=ICAP
   OUT(2)=IREFP
   OUT(3)=IDUMP
   OUT(4)=DTME
   RETURN 1
   END
```

Appendix D

TRNSYS DECKS

This Appendix contains the TRNSYS decks for the simulations of the PV-system

TRNSYS deck SContr.dck

```
*****************************************************************
*     PV system copmosed of PV module, battery,
*     refrigeration cycle and series controller
*                  SContr.dck
*****************************************************************

assign SContr.OUT 6
assign MIA.ALL 10
assign SContr.plt 15

* Simulation every hour for 24 hours
EQUAT 4
STEP=1
START=4354
STOP=4523
day=INT((TIME)/24.)


simulate START STOP STEP
```

```
*SOLVER 1
width 80
LIMITS 100 100
tolerance -0.01 -0.01

Equations 49
sun=[2,6]/3.6
suna=[2,6]/3.6*.72*3*2
*********** Reference Condition ************
Sunref = 1.000000E+03
*|Solar Radiation|W/m2|W/m2|0|1|1|1100|1
Tcref = 2.980000E+02
*|Cell Temperature|K|K|0|1|1|500|2
*|* ******** PV Module Parameters at Reference Condition ********
Iscref = 2.90000E+00
*|Short Circuit Current|Amp|Amp|0|1|1|5.90|3
Vocref = 2.000000E+01
*|Open Circuit Voltage|V|V|0|1|1|20.000|4
Imref = 2.670000E+00
*|Current @ Maximum Power Point|Amp|Amp|0|1|1|5.00|5
Vmref = 1.650000E+01
*|Voltage @ Maximum Power Point|V|V|0|1|1|20.00|6
Misc = 1.325000E-03
*|Temp. Coef. of Short Circuit Current |Amp/K|Amp/k|0|1|0|1.000|7
Mvoc = -7.750000E-02
*|Temp. Coef. of Open Circuit Current |V/K|V/K|0|1|-1.0|1.0000|8
********* PV Module Parameters at NOCT Conditions ***********
TcNOCT = 3.190000E+02
*| Cell Temperature @ NOCT|K|K|0|1|0|500|9
TaNOCT = 2.930000E+02
* Ambient Temperature @ NOCT in K
SunNOCT = 8.000E+02
* Solar Radiation at NOCT in W/m^2
```

| ************ PV Module Confeguration ************

NCS = 3.600000E+01

*|Number of Cells in the Module|||0|1|0|50|10

Area = 4.2700000E-01

*|Module Frontal Area|m2|m2|0|1|0|1.000|11

Ns = 1.000000E+00

*|Number of Modules Connected in Series|||0|1|0|4|12

Np = 3.000000E+00

*|Number of Modules Connected in Parallel|||0|1|0|4|13

Tau_Al = 0.90000E+00

* transmittance of cover * fraction of radiation incident on surface

EG = 1.12000E+00

* material band gap energy for silicon

*

* BATTERY

QM=250.0

* rated capacity of cell

CP=1.0

* # of cells in parallel

CS=6.0

* # of cells in series

EFF=0.95

* efficiency of battery

VC=2.3

* cutoff voltage on charge

VCONTR=-1

* specification of voltage control on discharge

ICTOL=0.01

* parameter for iterative calculations

ESC=2.25

* extrapolated open circuit voltage

ESD=2.1

* extrapolated open circuit voltage

GC=0.08

GD=0.08

* coefficients of (1-F) in V formulas

MC=0.864

MD=1

* cell type parameters which determine the shape of the I_V characteristic

ED=1.8

RD=2.4e-3

* data used to calculate VD when VCONTR .LT. 0

I1=2.5

K1=29.3

QC=-0.035*QM

QD=QM/0.85

*capacity parameters on charge/discharge

RSC=3/QM

RSD=0.5/QM

* Internal resistances at full charge

* Series Controller

FD=0.35

FC=1.

* minimum and maximum fractional state of charge

FDA=0.45

FCA=0.9

* limit on F above/below battery can be charged/discharged again

VDA=11.0

VCA=14.0

* limit on V above/below battery can be charged/discharged again

IBMAX=30.0

IBMIN=-30.0

* max. and min. current permitted

VDIODE=0.7

* voltage drop on diode

```
**********************************************************

UNIT 1 TYPE 9 DATA READER
PARAMETERS 20
-2 5 1 1 1 0 2 1 0 3 1 0 -4 1 0 5 0.1 0 10 0
INPUTS 0

**********************************************************
UNIT 2 TYPE 16 RADIATION PROCESSOR
PARAMETERS 9
*HMODE TMODE ITMODE DAY  LAT    SC  SHFT SMOOTH IE
  1   1    1   day  25.48 4871  0  1   -1
INPUTS 7
1,4  1,19  1,20  0,0  0,0   0,0  1,24
0.0  0.0   1.0   0.2  25.0  0.0  0.0

**********************************************************

equation 1
cur=[3,1]-[6,4]

**********************************************************
unit 3 type 62 PV array

Parameters 9
Iscref Vocref Tcref Sunref Vmref  Imref Misc    Mvoc   NCS

Parmeters 9
Ns Np  TcNOCT  TaNOCT  SunNOCT  Area  Tau_Al  EG  -1

Inputs 4
* Cur   V    Sun   Tamb
```

```
 3,1  5,1  2,6  1,5
 1    12.0 1000 20.0

************************************************************************
UNIT 6 TYPE 73 Refrigeration cycle with dc motor
Inputs 4
* Volt  Trm   Tfr  Cur
 5,2  1,5  0,0 0,0
 12.0  20.0 0.0  1.

************************************************************************
UNIT 4 TYPE 74 Battery
Parameters 7
QM  CP  CS  EFF  VC  VCONTR  ICTOL
Parameters 7
ESC  ESD  GC  GD  MC  MD  ED
Parameters 7
RD  I1  K1  QC  QD  RSC  RSD
Inputs 1
* Cur 4
 cur
 -2
DERIVA 1
115

********************************************************
UNIT 5 TYPE 59  Series Controller
Parameters 9
 FD  FC  FDA  FCA  VDA  VCA  IBMAX  IBMIN  VDIODE
Inputs 5
* VB   IB   F    VC   VD
 4,6  4,5  4,2  4,8  4,7
 12.0 -2.0 0.8  13.0 7.0
```

```
*********************************************************
UNIT 25 TYPE 25 PRINTER
PARAM 4
STEP START STOP 15
INPUT 9
4,2 3,2 4,6  5,2  3,1 4,5  6,4  1,5 2,6
SOC VPV VBAT VREF IPV IBAT IREF TA  SUN

UNIT 65 TYPE 65 ONLINE PROGRAM
PARAMETERS 14
3 2 -2 8 0 20 1 1 3
1 7 0 2 0
INPUTS 5
3,1   6,4   4,5   4,2   5,2
Ipv   Iref  Ibat  SOC   Vref
LABELS 4
[A]  [V]
Current
Voltage

end
```

TRNSYS deck PContr.dck

```
*******************************************************************
*     PV module, battery, refrigeration cycle,
*     Charge Controller
*                 PContr.dck
*******************************************************************
```

```
assign PContr.OUT 6
assign mia.all 10
assign PContr.plt 15

* Simulation every hour for 24 hours
EQUAT 4
STEP=1
START=4354
STOP=4523
day=INT((TIME)/24.)


simulate START STOP STEP
*SOLVER 1
width 80
LIMITS 100 100
tolerance -0.01 -0.01

Equations 40
sun=[2,6]
suna=sun/1000
*|*   *********  Reference Condition ************
Sunref =  1.000000E+03
*|Solar Radiation|W/m2|W/m2|0|1|1|1100|1
Tcref =  2.980000E+02
*|Cell Temperature|K|K|0|1|1|500|2
*|*   ******** PV Module Parameters at Reference Condition ********
Iscref =  2.90000E+00
*|Short Circuit Current|Amp|Amp|0|1|1|5.90|3
Vocref =  2.000000E+01
*|Open Circuit Voltage|V|V|0|1|1|20.000|4
Imref =  2.670000E+00
```

*|Current @ Maximum Power Point|Amp|Amp|0|1|1|5.00|5

Vmref = 1.650000E+01

*|Voltage @ Maximum Power Point|V|V|0|1|1|20.00|6

Misc = 1.325000E-03

*|Temp. Coef. of Short Circuit Current |Amp/K|Amp/k|0|1|0|1.000|7

Mvoc = -7.750000E-02

*|Temp. Coef. of Open Circuit Current |V/K|V/K|0|1|-1.0|1.0000|8

*********   PV Module Parameters at NOCT Conditions ***********

TcNOCT = 3.190000E+02

*| Cell Temperature @ NOCT|K|K|0|1|0|500|9

TaNOCT = 2.930000E+02

* Ambient Temperature @ NOCT in K

SunNOCT = 8.000E+02

* Solar Radiation at NOCT in W/m^2

| ************ PV Module Confeguration ************

NCS = 3.600000E+01

*|Number of Cells in the Module|||0|1|0|50|10

Area = 4.2700000E-01

*|Module Frontal Area|m2|m2|0|1|0|1.000|11

Ns = 1.000000E+00

*|Number of Modules Connected in Series|||0|1|0|4|12

Np = 3.000000E+00

*|Number of Modules Connected in Parallel|||0|1|0|4|13

Tau_Al = 0.90000E+00

* transmittance of cover * fraction of radiation incident on surface

EG = 1.12000E+00

* material band gap energy for silicon

*

*   BATTERY

QM=250.0

* rated capacity of cell

CP=1.0

* # of cells in parallel

CS=6.0

* # of cells in series

EFF=0.95

* efficiency of battery

VC=2.3

* cutoff voltage on charge

VCONTR=-1

* specification of voltage control on discharge

ICTOL=0.01

* parameter for iterative calculations

ESC=2.25

* extrapolated open circuit voltage

ESD=2.1

* extrapolated open circuit voltage

GC=0.08

GD=0.08

* coefficients of (1-F) in V formulas

MC=0.864

MD=1

* cell type parameters which determine the shape of the I_V characteristic

ED=1.8

RD=2.4e-3

* data used to calculate VD when VCONTR .LT. 0

I1=2.5

K1=29.3

QC=-0.035*QM

QD=QM/0.85

*capacity parameters on charge/discharge

RSC=3/QM

RSD=0.5/QM

* Internal resistances at full charge

```
*****************************************************
UNIT 1 TYPE 9 DATA READER
PARAMETERS 20
-2 5 1 1 1 0 2 1 0 3 1 0 -4 1 0 5 0.1 0 10 0
INPUTS 0

*****************************************************
UNIT 2 TYPE 16 RADIATION PROCESSOR
PARAMETERS 9
*HMODE TMODE ITMODE DAY  LAT    SC  SHFT SMOOTH IE
  1   1     1   day  25.48  4871   0   1    -1
INPUTS 7
1,4  1,19  1,20  0,0  0,0   0,0  1,24
0.0  0.0   1.0   0.2  25.0  0.0  0.0

*****************************************************

equation 2
F=[4,1]/QM
volt=[10,2]+0.7

UNIT 3 TYPE 62 PV ARRAY
Parameters 9
Iscref Vocref Tcref Sunref Vmref  Imref Misc    Mvoc   NCS
Parmeters 9
Ns Np TcNOCT TaNOCT SunNOCT Area  Tau_Al  EG  -1
Inputs 4
* Cur  V    Sun  Tamb
 3,1  VOLT  sun  1,5
 1    12   1000  20

UNIT 10 TYPE 66 CONTROLLER
PAR 4
```

```
*SocMax SocMin DeltaSoc Current needed to drive Ref
0.95 0.4 0.05 2
INPUTS 7
F  10,6  3,1  3,2  6,4  3,9  4,6
0.46  1  0.1  0.1  0.0  0.0  12

**********************************************************************
UNIT 6 TYPE 73 Refrigeration cycle with dc motor
Inputs 4
* Volt  Trm  Tfr  Cur
10,4   1,5  0,0  0,0
12.   20.  0   1.

**********************************************************************
UNIT 4 TYPE 74 Battery
Parameters 7
QM  CP  CS  EFF  VC  VCONTR  ICTOL
Parameters 7
ESC  ESD  GC  GD  MC  MD  ED
Parameters 7
RD  I1  K1  QC  QD  RSC  RSD
Inputs 1
* Cur 4
 10,1
 -2
DERIVA 1
 115

**********************************************************************
UNIT 8 TYPE 60 REFRIGERATOR
Parameters 6
* k  L  cpw  cpi  Aref  Tice
0.025  0.06  4190.  2110.  2.595  -10.
```

```
Parameters 5
* Vref cpa rhoa Ac tDo
0.127 1006. 1.18 4.03 30.
Inputs 4
* Trm Tref mice mwat
1,5 0,0 0,0 0,0
20. 5. 3. 3.

***********************************************************************
UNIT 24 TYPE 24 INTEGRATOR
INPUTS 3
*Iref CAP Power
6,4   6,7 8,5
0.    0.  0.

***********************************************************************
UNIT 25 TYPE 25 PRINTER
PARAM 4
STEP START STOP 15
INPUT 4
F 3,1  10,1  6,4
SOC IPV IBAT IREF

***********************************************************************
UNIT 65 TYPE 65 ONLINE PROGRAM
PARAMETERS 14
4 2 -2 8 0 20 1 1 3
1 7 0 2 0
INPUTS 6
3,1  6,4 10,1 F  6,1 10,6
CPV  CREF CBAT SOC Vref MODE
LABELS 4
[A] [V]
```

CURRENT

VOLTAGE

end

TRNSYS deck Simul.dck

```
*********************************************************************
*     PV system composed of PV module, battery,
*     refrigeration cycle, series controller and refrigerator
*              Simul.dck
*********************************************************************

assign Simul.OUT 6
assign MIA.ALL 10
assign Simul.plt 15

* Simulation every hour for 24 hours
EQUAT 4
STEP=1
START=1
STOP=8760
day=INT((TIME)/24.)


simulate START STOP STEP

*SOLVER 1
width 80
LIMITS 100 10
```

```
tolerance 0.001 0.001

Equations 50
sun=[2,6]/3.6
suna=[2,6]/3.6*.72*3*2
*|*   ********* Reference Condition ************
Sunref =  1.000000E+03
*|Solar Radiation|W/m2|W/m2|0|1|1|1100|1
Tcref =  2.980000E+02
*|Cell Temperature|K|K|0|1|1|500|2
*|*   ******** PV Module Parameters at Reference Condition ********
Iscref =  2.90000E+00
*|Short Circuit Current|Amp|Amp|0|1|1|5.90|3
Vocref =  2.000000E+01
*|Open Circuit Voltage|V|V|0|1|1|20.000|4
Imref =  2.670000E+00
*|Current @ Maximum Power Point|Amp|Amp|0|1|1|5.00|5
Vmref =  1.650000E+01
*|Voltage @ Maximum Power Point|V|V|0|1|1|20.00|6
Misc =  1.325000E-03
*|Temp. Coef. of Short Circuit Current |Amp/K|Amp/k|0|1|0|1.000|7
Mvoc = -7.750000E-02
*|Temp. Coef. of Open Circuit Current  |V/K|V/K|0|1|-1.0|1.0000|8
*********      PV Module Parameters at NOCT Conditions  ***********
TcNOCT =  3.190000E+02
*| Cell Temperature @ NOCT|K|K|0|1|0|500|9
TaNOCT = 2.930000E+02
*  Ambient Temperature @ NOCT in K
SunNOCT = 8.000E+02
*  Solar Radiation at NOCT in W/m^2
*|*   ************ PV Module Confeguration ************
NCS =  3.600000E+01
*|Number of Cells in the Module|||0|1|0|50|10
```

Area = 4.2700000E-01

*|Module Frontal Area|m2|m2|0|1|0|1.000|11

Ns = 1.000000E+00

*|Number of Modules Connected in Series|||0|1|0|4|12

Np = 6.000000E+00

*|Number of Modules Connected in Parallel|||0|1|0|4|13

Tau_Al = 0.90000E+00

* transmittance of cover * fraction of radiation incident on surface

EG = 1.12000E+00

* material band gap energy for silicon

*

* BATTERY

QM=100.0

* rated capacity of cell

CP=1.0

* # of cells in parallel

CS=6.0

* # of cells in series

EFF=0.95

* efficiency of battery

VC=2.3

* cutoff voltage on charge

VCONTR=-1

* specification of voltage control on discharge

ICTOL=0.01

* parameter for iterative calculations

ESC=2.25

* extrapolated open circuit voltage

ESD=2.1

* extrapolated open circuit voltage

GC=0.08

GD=0.08

* coefficients of (1-F) in V formulas

MC=0.864

MD=1

* cell type parameters which determine the shape of the I_V characteristic

ED=1.8

RD=2.4e-3

* data used to calculate VD when VCONTR .LT. 0

I1=2.5

K1=29.3

QC=-0.035*QM

QD=QM/0.85

*capacity parameters on charge/discharge

RSC=3/QM

RSD=0.5/QM

* Internal resistances at full charge

* Series controller

FD=0.35

FC=1.

* minimum and maximum fractional state of charge

FDA=0.45

FCA=1.

* limit on F above/below battery can be charged/discharged again

VDA=11.0

VCA=14.0

* limit on V above/below battery can be charged/discharged again

IBMAX=30.0

IBMIN=-30.0 * max. and min. current permitted

VDIODE=0.7

* voltage drop on diode

TOL=50.

* tolerance to switch the compressor on, off

****

```
UNIT 1 TYPE 9 DATA READER
PARAMETERS 20
-2 5 1 1 1 0 2 1 0 3 1 0 -4 1 0 5 0.1 0 10 0
INPUTS 0

***********************************************************
UNIT 2 TYPE 16 RADIATION PROCESSOR
PARAMETERS 9
*HMODE TMODE ITMODE DAY  LAT    SC  SHFT SMOOTH IE
  1    1     1   day  25.48  4871  0   1    -1
INPUTS 7
*               slope
1,4  1,19  1,20  0,0  0,0   0,0  1,24
0.0  0.0   1.0   0.2  20.0  0.0  0.0

***********************************************************

equation 1
cur=[3,1]-[6,4]

***********************************************************
unit 3 type 62 PV array

Parameters 9
Iscref Vocref Tcref Sunref Vmref  Imref Misc    Mvoc   NCS

Parmeters 9
Ns  Np  TcNOCT  TaNOCT  SunNOCT  Area   Tau_Al  EG   -1

Inputs 4
* Cur   V    Sun   Tamb
  3,1   5,1  2,6   1,5
  1    12.0  1000  20.0
```

```
**************************************************************************
UNIT 6 TYPE 73 Refrigeration cycle with dc motor
Inputs 5
* Volt Trm  Tfr Cur DUMP
 5,2  1,5  0,0 0,0 5,4
 12.0 20.0 -2. 1.  0.

**************************************************************************
UNIT 4 TYPE 74 Battery
Parameters 7
QM CP CS EFF VC VCONTR ICTOL
Parameters 7
ESC ESD GC GD MC MD ED
Parameters 7
RD I1 K1 QC QD RSC RSD
Inputs 1
* Cur 4
 cur
 -2
DERIVA 1
88.

*********************************************************
UNIT 5 TYPE 59  Series Controller
Parameters 6
 FD FC FDA FCA VDA VCA
Parameters 4
 IBMAX IBMIN VDIODE TOL
Inputs 7
* VB  IB  F   VC  VD  ICAP IREFP
 4,6 4,5 4,2 4,8 4,7 9,1  9,2
 12.0 -2.0 0.8 13.0 7.0 0.0  0.0
```

```
*****************************************************
UNIT 8 TYPE 60 REFRIGERATOR
Parameters 6
* k  L   cpw  cpi  Aref  Tice
0.025 0.06 4190. 2110. 2.595 -10.
Parameters 5
* Vref cpa rhoa Ac tDo
0.127 1006. 1.18 4.03 30.
Inputs 4
* Trm Tref mice mwat
1,5 0,0 0,0 0,0
20. 5. 3. 3.

*****************************************************
UNIT 9 TYPE 71 INTER\GRATION AND RESET
Parameters 1
TOL
INPUTS 3
*CAP REFP DUMP
6,7 8,5 6,8
80. 50. 0.

********************************************************
UNIT 25 TYPE 25 PRINTER
PARAM 4
STEP START STOP 15
INPUT 4
4,2 9,1 9,2  9,3
SOC ICAP IREFP IDUMP

*****************************************************
UNIT 65 TYPE 65 ONLINE PROGRAM
```

PARAMETERS 14

5 2 -2 8 0 120 1 1 3

52 7 0 2 0

INPUTS 7

3,1 6,4 4,5 4,2 5,4 6,7 8,5

Ipv Iref Ibat SOC DUMP CAP REFP

LABELS 4

[A] [W]

Current

WATTS

end