MODELING OF A
PHOTOVOLTAIC POWERED
REFRIGERATION SYSTEM

by
Gerold Furler

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requirements for the degree of

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(Mechanical Engineering)

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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 too 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.

But what would the Lab be without the students and our secretaries? You make it a great place to be. I especially want to mention Øystein, we had a blast in practicing for the Crazy Lake Run last spring, and then Kevin, it was fun to seeing you fall over your handlebars in Governors dodge (I fell twice) and seeing you disappearing in the mud. I died laughing.
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.

But most of all I want to thank my girl friend Michal. I am looking forward to tell you how much your loving support through the tons of letters and calls meant to me in the last months. This time showed me even more what I have in you.

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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<th>Description</th>
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<tr>
<td>A</td>
<td>area</td>
<td>( \text{m}^2 )</td>
</tr>
<tr>
<td>A</td>
<td>static frictional loss coefficient</td>
<td>( \text{N-m} )</td>
</tr>
<tr>
<td>( A_c )</td>
<td>air changes per minute</td>
<td>( \text{m}^2 )</td>
</tr>
<tr>
<td>( A_{\text{ref}} )</td>
<td>refrigerator area</td>
<td>( \text{m}^2 )</td>
</tr>
<tr>
<td>B</td>
<td>dynamic frictional loss coefficient</td>
<td>( \text{N-m-sec} )</td>
</tr>
<tr>
<td>CAP</td>
<td>refrigeration capacity</td>
<td>( \text{kW}, \text{Btu/hr} )</td>
</tr>
<tr>
<td>COP</td>
<td>coefficient of performance</td>
<td></td>
</tr>
<tr>
<td>( C_p )</td>
<td>cells-modules in parallel</td>
<td></td>
</tr>
<tr>
<td>( c_{\text{pair}} )</td>
<td>specific heat of air</td>
<td>( \text{kJ/kg-K} )</td>
</tr>
<tr>
<td>( c_{\text{ice}} )</td>
<td>specific heat of ice</td>
<td>( \text{kJ/kg-K} )</td>
</tr>
<tr>
<td>( C_s )</td>
<td>cells-modules in series</td>
<td></td>
</tr>
<tr>
<td>( c_{\text{wat}} )</td>
<td>specific heat of wat</td>
<td>( \text{kJ/kg-K} )</td>
</tr>
<tr>
<td>( E_a )</td>
<td>electromagnetic force</td>
<td>( \text{V} )</td>
</tr>
<tr>
<td>( E_c )</td>
<td>constant open circuit voltage of the battery when charging</td>
<td>( \text{V} )</td>
</tr>
<tr>
<td>( E_d )</td>
<td>constant open circuit voltage of the battery when discharging</td>
<td>( \text{V} )</td>
</tr>
<tr>
<td>( E_D )</td>
<td>battery constant</td>
<td>( \text{V} )</td>
</tr>
<tr>
<td>F</td>
<td>fractional state of charge of the battery</td>
<td></td>
</tr>
<tr>
<td>( G_c )</td>
<td>current capacity on charge</td>
<td></td>
</tr>
</tbody>
</table>
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
K_t  - 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
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>m&lt;sub&gt;ice&lt;/sub&gt;</td>
<td>mass ice</td>
<td>[kg]</td>
</tr>
<tr>
<td>M&lt;sub&gt;p&lt;/sub&gt;</td>
<td># of PV modules in parallel</td>
<td></td>
</tr>
<tr>
<td>M&lt;sub&gt;s&lt;/sub&gt;</td>
<td># of PV modules in series</td>
<td></td>
</tr>
<tr>
<td>m&lt;sub&gt;wat&lt;/sub&gt;</td>
<td>mass water</td>
<td>[kg]</td>
</tr>
<tr>
<td>n</td>
<td>polytropic exponent</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>speed</td>
<td>[1/sec]</td>
</tr>
<tr>
<td>N&lt;sub&gt;s&lt;/sub&gt;</td>
<td># of cells in series times # modules in series</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
<td>[kPa]</td>
</tr>
<tr>
<td>P&lt;sub&gt;in&lt;/sub&gt;</td>
<td>input power</td>
<td>[watts]</td>
</tr>
<tr>
<td>P&lt;sub&gt;loss&lt;/sub&gt;</td>
<td>loss of energy for the battery</td>
<td>[watts]</td>
</tr>
<tr>
<td>P&lt;sub&gt;o&lt;/sub&gt;</td>
<td>output power</td>
<td>[watts]</td>
</tr>
<tr>
<td>Q</td>
<td>actual capacity of a battery cell</td>
<td>[Ah]</td>
</tr>
<tr>
<td>Q&lt;sub&gt;d&lt;/sub&gt;</td>
<td>capacity parameter on discharge</td>
<td>[Ah]</td>
</tr>
<tr>
<td>Q&lt;sub&gt;m&lt;/sub&gt;</td>
<td>rated capacity of battery</td>
<td>[Ah]</td>
</tr>
<tr>
<td>Q&lt;sub&gt;rej&lt;/sub&gt;</td>
<td>rejected energy</td>
<td>[kJ], [Btu]</td>
</tr>
<tr>
<td>Q&lt;sub&gt;lat&lt;/sub&gt;</td>
<td>latent heat</td>
<td>[W]</td>
</tr>
<tr>
<td>Q&lt;sub&gt;load&lt;/sub&gt;</td>
<td>total heat of the load</td>
<td>[W]</td>
</tr>
<tr>
<td>Q&lt;sub&gt;sen&lt;/sub&gt;</td>
<td>sensible heat</td>
<td>[W]</td>
</tr>
<tr>
<td>R</td>
<td>resistance</td>
<td>[ohms]</td>
</tr>
<tr>
<td>RPM</td>
<td>revolutions per minute</td>
<td>[1/min]</td>
</tr>
<tr>
<td>R&lt;sub&gt;s&lt;/sub&gt;</td>
<td>series resistance</td>
<td>[ohms]</td>
</tr>
<tr>
<td>R&lt;sub&gt;c&lt;/sub&gt;</td>
<td>internal resistance at full charge when charging battery</td>
<td>[ohms]</td>
</tr>
<tr>
<td>R&lt;sub&gt;d&lt;/sub&gt;</td>
<td>internal resistance at full charge when discharging battery</td>
<td>[ohms]</td>
</tr>
<tr>
<td>R&lt;sub&gt;D&lt;/sub&gt;</td>
<td>battery constant</td>
<td>[ohms]</td>
</tr>
<tr>
<td>R&lt;sub&gt;sh&lt;/sub&gt;</td>
<td>shunt resistance</td>
<td>[ohms]</td>
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<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
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<td>--------</td>
<td>--------------------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
<td>[sec]</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
<td>[°C], [°F]</td>
</tr>
<tr>
<td>T</td>
<td>d.c. motor torque</td>
<td>[Nm]</td>
</tr>
<tr>
<td>Ta</td>
<td>ambient temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>Tc</td>
<td>cell temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>tdo</td>
<td>daily opening time</td>
<td>[min]</td>
</tr>
<tr>
<td>Trf</td>
<td>freezer temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>Tloss</td>
<td>rotational losses</td>
<td>[Nm]</td>
</tr>
<tr>
<td>To</td>
<td>output torque</td>
<td>[Nm]</td>
</tr>
<tr>
<td>Tref</td>
<td>refrigerator temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>Trm</td>
<td>room temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>UAcon</td>
<td>overall heat transfer coefficient area product, condenser</td>
<td>[W/K]</td>
</tr>
<tr>
<td>UAev</td>
<td>overall heat transfer coefficient area product, evaporator</td>
<td>[W/K]</td>
</tr>
<tr>
<td>UL</td>
<td>heat transfer loss coefficient</td>
<td>[W/m²-K]</td>
</tr>
<tr>
<td>V</td>
<td>volume</td>
<td>[m³]</td>
</tr>
<tr>
<td>V</td>
<td>voltage</td>
<td>[V]</td>
</tr>
<tr>
<td>Vbat</td>
<td>battery voltage</td>
<td>[V]</td>
</tr>
<tr>
<td>Vc</td>
<td>maximum charge voltage for the battery</td>
<td>[V]</td>
</tr>
<tr>
<td>Vcell</td>
<td>voltage of a battery cell</td>
<td>[V]</td>
</tr>
<tr>
<td>Vd</td>
<td>maximum discharge voltage for the battery</td>
<td>[V]</td>
</tr>
<tr>
<td>Vdi</td>
<td>voltage drop over diode</td>
<td>[V]</td>
</tr>
<tr>
<td>Vdispl</td>
<td>displacement volume</td>
<td>[m³]</td>
</tr>
<tr>
<td>Vmp</td>
<td>voltage at maximum power</td>
<td>[V]</td>
</tr>
<tr>
<td>Voc</td>
<td>open circuit voltage</td>
<td>[V]</td>
</tr>
<tr>
<td>Vref</td>
<td>refrigerator volume</td>
<td>[m³]</td>
</tr>
</tbody>
</table>
$V_t$ - terminal voltage  \quad [V]

$v$ - specific volume  \quad [m^3/kg]

$W_{pol}$ - polytropic work  \quad []

$w$ - mass flow rate  \quad [kg/sec], [lbs/hr]

**Greek symbols**

$\eta$ - efficiency

$\eta_c$ - efficiency of PV a cell

$\eta_{mot}$ - motor efficiency

$\eta_{vol}$ - volumetric efficiency

$\rho$ - density  \quad [kg/m$^3$]

$\omega$ - angular velocity  \quad [1/sec]

$\gamma$ - curve fitting parameter

$\epsilon$ - bandgap energy  \quad [eV]

$\mu_{V,oc}$ - temperature coefficient for open circuit voltage  \quad [V/K]

$\mu_{I,sc}$ - temperature coefficient for short circuit current  \quad [A/K]

$\tau$ - transmittance

$\alpha$ - absorptance

$\phi$ - magnetic flux  \quad [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.
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.

![Electrical circuit for a PV generator](image)

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].

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

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].

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

where

$I_o$ is the diode reverse saturation current

$V$ is the output voltage,

$R_s$ is the series resistance,

$\gamma$ 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 $I_l$, $I_o$, $R_s$, $\gamma$ 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](image)

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/m² and an ambient temperature of 25 °C. With these measured values, the four parameters $I_l$, $I_o$, $\gamma$ 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, $I_{sc}$.

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

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.

$$I_o = I_l \exp\left(-\frac{V_{oc}}{\gamma}\right) \quad [2.4]$$

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.

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

Equations [2.4] and [2.5] can only be solved when the curve fitting parameter $\gamma$ is known. The manufacturers do not provide a value for $\gamma$ 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, $\mu_{s,c}$, and the open circuit voltage, $\mu_{V,oc}$. These coefficients describe the temperature behavior of the module shown in Figure 2.3.

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

$$
\gamma_{ref} = \frac{\mu_{V,oc} T_{c,ref} - V_{oc,ref} + \epsilon N_s}{\mu_{s,c} T_{c,ref} - \frac{3}{I_{l,ref}}} \quad [2.6]
$$

where

$\epsilon$ 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.

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

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

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

With these equations, the I-V curves for different radiation levels can be obtained. Figure 2.4 shows the characteristic for different insolation levels.
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/m²). 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.

![I-V characteristics for differently connected PV arrays](image)

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

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

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

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

\[
\gamma_{tot} = M_s \gamma \tag{2.12}
\]

\[
R_{s,tot} = \frac{M_s}{M_p} R_s \tag{2.13}
\]
where

\[ M_p \] is the number of modules in parallel,

\[ M_s \] is the number of modules in series.

The outputs of interest are:

\[
\begin{align*}
I_{tot} &= M_p I \\
V_{tot} &= M V
\end{align*}
\]

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.
\[ \tau \alpha G_T = \eta_c G_T + U_L (T_c - T_a) \]  

where

\( \tau \) is the transmittance of the cover,
\( \alpha \) is the absorption coefficient,
\( G_T \) is the incident solar radiation,
\( \eta_c \) is the efficiency of the module,
\( U_L \) is the loss coefficient of the module,
\( T_a \) is the ambient temperature.

The ratio \( \tau \alpha/UL \) 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 \( ^\circ \)C. The measurement is made under no load conditions. In this case the efficiency, \( \eta_c \), is zero, which leads to Equation [2.17] for the ratio \( \tau \alpha/UL \). Once \( \tau \alpha/UL \) is known, Equation [2.18] can be applied to calculate the cell temperature at other operating conditions.

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

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

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 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.
The cell temperature for 1000 W/m² 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.
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.

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

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

![Electrical circuit for a lead acid battery cell](image)

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 \( E_d \).

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

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].

\[
V_{di} = \frac{1}{K_{di}} \ln \left( \frac{I_{cell}}{I_{di}} + 1 \right) \tag{3.2}
\]

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.

\[
V_{cell} = V_{oc} - V_{di} - G_d (1 - F) + I_{cell} R_d \left( 1 + \frac{m_d (1 - F)}{Q_d - (1 - F)} \right) \tag{3.3}
\]

\[
V_{cell} = V_{oc} + V_{di} - G_c (1 - F) + I_{cell} R_c \left( 1 + \frac{m_c (1 - F)}{Q_c - (1 - F)} \right) \tag{3.4}
\]

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.

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

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].

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

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 of charge.

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

$$\frac{dQ}{dt} = I_{cell}$$  \[3.7\]
\[
\frac{dQ}{dt} = I_{cell} \eta \quad [3.8]
\]

where

\( \eta \) 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].

\[
P_{loss} = (1 - \eta) P \quad [3.9]
\]

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.

\[
I_{bat} = C_p I_{cell} \quad [3.10]
\]

\[
V_{bat} = C_s I_{cell} \quad [3.11]
\]

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 ($\eta$). 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].

\[
V_c = \text{const.} \quad [3.12] \\
V_d = E_D - |I_{\text{cell}}| R_D \quad [3.13]
\]

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.

![Diagram of PV system configuration including a series controller](image)

**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.

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.
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:

![Power flow diagram of a brushless d.c. motor](image)

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.

<table>
<thead>
<tr>
<th>A: Electrical Losses</th>
<th>Description for losses</th>
<th>Effects of load</th>
<th>Effects of load</th>
</tr>
</thead>
<tbody>
<tr>
<td>- winding and resistant losses (I^2 R)</td>
<td></td>
<td>- increase with the load</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B: Rotational Losses</th>
<th>Description for losses</th>
<th>Effects of load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mechanical losses</td>
<td></td>
<td>- constant at constant speed</td>
</tr>
<tr>
<td>- friction losses (Tloss = A + B ω)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Core (or iron) losses</td>
<td></td>
<td>- constant at constant speed and field flux</td>
</tr>
<tr>
<td>- hysteresis loss (Ph = Kh Bx f V)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- eddy current losses (Pc = K1 B^2 f^2 t^2 V)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C: Stray Load Losses</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>negligible for motors below 200 hp</td>
<td></td>
</tr>
</tbody>
</table>

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:

![Equivalent electrical circuit of a brushless d.c. motor](image)

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

The terminal voltage, $V_t$, is expressed by:

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

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].

\[ V_t = R I_t + E_a \]  \[4.2\]

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:

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

where

- \( K_b \) is the back EMF constant,
- \( \omega \) is the angular velocity.

The electromagnetic torque equation is given by:

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

and
\[ T = T_{loss} + T_o \]  

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]:

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

where

- \( A \) is the static friction coefficient,
- \( B \) is the dynamic friction coefficient.

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

\[ \eta = \frac{P_o}{P_{in}} \]  

where the following relationships can be found:

\[ P_o = T_o \omega \]  

and
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.

![Motor efficiency versus voltage for different torques](image)

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.

![Graph showing motor efficiency versus torque](image)

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.
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:

\[
E_a = K_b \phi \omega
\]
\[\text{[4.10]}\]
\[
T = K_t \phi I_t
\]
\[\text{[4.11]}\]

where

\( \phi \) is the magnetic flux with it's unit \([\text{V-sec} = \text{Wb}]\).
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 $k_f$.

$$\phi = k_f I_t$$  \hspace{1cm} [4.12]

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

$$T = K_t k_f I_t^2 = M_{AF} I_t^2$$  \hspace{1cm} [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.

![Graph showing speed-torque and current-torque characteristic for a series motor]

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 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](image-url)
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.

\[ CAP = w \ (h_1 - h_4) \quad [5.1] \]
\[ CAP = UA_{ev} \ (T_{fr} - T_{ev}) \quad [5.2] \]

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, \( \eta_{vol} \). \( \eta_{vol} \) 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.

\* The equation is not exactly correct because the evaporator temperature increases from the state of saturated vapor to state 1.
Figure 5.3: Compression cycle for a reciprocating compressor

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

[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].
\[ \eta_{vol} = [1 + m - m \left( \frac{P'_{\text{con}}}{P'_{ev}} \right)^{\frac{1}{n}} \frac{v_1}{v_1}] \]  

where

- \( m \) is the ratio of the clearance volume over the displacement volume \( V_{\text{displ}} \),
- \( n \) 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

\[ w = \rho_1 V_{\text{displ}} N \eta_{vol} \]  

where

- \( \rho_1 \) 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:

\[ W_{pol} = P'_{ev} v_1 \left( \frac{n}{(n-1)} \right) \left( \frac{P'_{\text{con}}}{P'_{ev}} \right)^{\frac{n-1}{n}} - 1 \]  

\[ 5.6 \]
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, $T_{rm}$.

\[
Q_{rej} = w (h_2 - h_3) \quad [5.7]
\]

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

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.

\[ h_3 = h_4 \] \[5.10\]

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 l/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.

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

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.
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:
\[ \text{COP}_{\text{data}} = \frac{3.413 \text{ CAP}_{\text{data}} \eta_{\text{mot}}}{P_{\text{in}}} \]  \hspace{2cm} [5.11] \\

where

\[ \eta_{\text{mot}} \] is the motor efficiency.

Because \( P_{\text{in}} \) was given in kW, whereas the \( \text{CAP} \) 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 \( \text{CAP} \) and the \( \text{COP} \) and compares these values with the provided data. Figure 5.5 illustrates the \( \text{CAP} \)-comparison as a function of the evaporator temperature for different condenser temperatures. Figure 5.6 shows the \( \text{COP} \)-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](image)
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 $UA_e$ means the equipment is physically large and expensive.

With a small $UA_e$ (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 $UA_e$ 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.

![Graph showing the relationship between CAP and COP with varying room and freezer temperatures](image)

Figure 5.9: CAP versus room temperature for different freezer temperatures
To study the influence of the room and freezer temperature on the \textit{CAP} and the \textit{COP} the compressor speed was fixed to 1000 l/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 \textit{CAP} and the \textit{COP} increase with an increase of the freezer temperature.

\section{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:

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

[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:

\[
Q_{sen,w} = m_{ice} c_{p,wat} T_{rm}
\]  

[5.13]

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

\[
Q_{lat} = m_{ice} 273 (c_{p,wat} - c_{p,ice})
\]  

[5.14]
The sensible heat to cool the ice to its final temperature \((Q_{sen,i})\) is:

\[
Q_{sen,i} = m_{ice} \cdot c_{pice} \cdot T_{ice}
\]  

[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].

\[
Q_2 = \frac{m_{ice} \cdot (c_{pwat} \cdot T_{rm} - c_{pice} \cdot T_{ice})}{86400}
\]  

[5.16]

where

- \(m_{ice}\) is the mass of the ice,
- \(c_{pwat}\) is the specific heat of water at 20 C,
- \(c_{pice}\) 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.

\[
\dot{Q}_3 = \frac{m_{wat} \cdot c_{pwat} \cdot (T_{rm} - T_{ref})}{18000}
\]  

[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.

\[ \dot{Q}_4 = \frac{V_{\text{ref}} c_{\text{pair}} (T_{\text{rm}} - T_{\text{ref}}) A_c t_{\text{do}}}{86400} \]  

[5.18]

where

- \(V_{\text{ref}}\) is the volume of the refrigerator,
- \(c_{\text{pair}}\) is the specific heat of air,
- \(A_c\) are the air changes per minute,
- \(t_{\text{do}}\) 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].

\[ \dot{Q}_{\text{load}} = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{Q}_4 \]  

[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.
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.
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.

\[
P_o = \frac{\pi RPM T_o}{30} = w W_{pot} \quad [6.1]
\]

\[
w = \frac{\rho V_{disp} RPM \eta_{vol}}{60} \quad [6.2]
\]

where
$RPM$ is the revolutions per minute,
$T_o$ is the output torque,
$\rho$ is the density of the refrigerant,
$V_{disp}$ is the displacement volume,
$\eta_{vol}$ is the volumetric efficiency,
$W_{pol}$ is the polytropic work.

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

$$COP = \frac{CAP}{P_o} \tag{6.3}$$

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.
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.
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 6.3: Behavior of the torque 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.

![Graph showing compressor input power versus freezer temperature](image)

**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.

![Graph showing 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.](image)

**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.
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.

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.
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 l/min. The speed and capacity versus voltage is illustrated in Figure 6.14.
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/m². 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.

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 for a PV system including PV array, battery and refrigeration load for an incident solar radiation of 1000 W/m²

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.
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.
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:
- $\phi$: incident solar radiation
- $T_a$: ambient temperature
- $V$: voltage
- Flag: switches the convergence promotion on - off

OUTPUTS:
- $V$: voltage
- $I$: current
- $P$: output power
- $P_{\text{max}}$: maximum output power
- $R_s$: series resistance
- $I_l$: light current
$I_0$ reverse saturation current
$V_{oc}$ open circuit voltage
$I_{sc}$ short circuit current
$FF$ fill factor

PARAMETERS:

$I_{sc, \text{ref}}$ short circuit current at reference conditions
$V_{oc, \text{ref}}$ open circuit voltage at reference conditions
$T_{c, \text{ref}}$ cell temperature at reference conditions
$\phi_{\text{ref}}$ incident solar radiation at reference conditions
$V_{mp, \text{ref}}$ voltage at maximum power at reference conditions
$I_{mp, \text{ref}}$ 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
$\phi_{\text{NOCT}}$ NOCT incident solar radiation
$AREA$ module area
$\tau \alpha$ transmittance - absorptance product
$\epsilon$ 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.

![Information flow diagram for the lead acid battery component](image)

**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\(_{\text{loss}}\)  power losses
I\(_{\text{bat}}\)  battery current
V\(_{\text{bat}}\)  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
\(\eta\)  charging efficiency
V\(_{c}\)  cutoff voltage on charge
V\(_{\text{contr}}\)  specification of the cutoff voltage on discharge
I\(_{c,\text{tol}}\)  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} \quad \text{curve fitting parameter}
Q_c \quad \text{capacity parameter on charge}
Q_d \quad \text{capacity parameter on discharge}
R_c \quad \text{internal resistance on charge}
R_d \quad \text{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.

![Information flow diagram for the series controller](image)
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
\( V_{\text{diode}} \)  
  diode voltage drop

\( \text{TOL} \)  
  value related to the heat gains of the refrigerator to raise from the lower to the upper thermostat limit

The inputs \( V_{\text{bat}}, I_{\text{bat}} \) 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 hysteresis to prevent an oscillation of the system. The parameters \( I_{b,\text{max}} \) and \( I_{b,\text{min}} \) do not have an influence on the behavior of the system. When the current is greater than \( I_{b,\text{max}} \) or smaller than \( I_{b,\text{min}} \), the output "Fail" is set to 1 or 2. Inside this range "Fail" remains zero. \( V_{\text{diode}} \) 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 \( \text{TOL} \) and the inputs \( ICAP \) and \( IQ_{\text{load}} \) cause the cooling system to operate or not. \( \text{TOL} \) 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. \( IQ_{\text{load}} \) 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 \( \text{TOL} \), 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.

$$
k_{ref} \left( T_{rm} - T_{ref} \right) = m \, cp \, dT_{ref} / dt \tag{7.1}
$$

$$
mc_p = \rho_{air} \, V_{ref} \, c_{p_{air}} + m_{wat} \, c_{p_{wat}} + m_{ice} \, c_{p_{ice}} \tag{7.2}
$$

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,
- $c_{p_{wat}}$ is the specific heat of water,
- $c_{p_{ice}}$ is the specific heat of ice,
- $c_{p_{air}}$ is the specific heat of the air,
- $A_{ref}$ is the area of the refrigerator,
\( V_{\text{ref}} \) is the volume of the refrigerator,
\( \rho_{\text{air}} \) is the density of air,
\( T_{\text{rm}} \) is the room temperature,
\( T_{\text{ref}} \) is the refrigerator temperature.

Introducing the temperature difference \( \Theta \)

\[
\Theta = T_{\text{rm}} - T_{\text{ref}} \tag{7.3}
\]

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

\[
\frac{L m c_p}{k A_{\text{ref}}} \ln \frac{\Theta_i}{\Theta} = t \tag{7.4}
\]

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

\[
\begin{align*}
k &= 0.025 \text{ W/m-K} & L &= 0.06 \text{m} & m_{\text{wat}} &= 2 \text{kg} \\
m_{\text{ice}} &= 3 \text{kg} & c_{p\text{wat}} &= 4190 \text{J/kg-K} & c_{p\text{ice}} &= 2110 \text{J/kg-K} \\
c_{p\text{air}} &= 1006 \text{J/kg-K} & A_{\text{ref}} &= 2.595 \text{m}^2 & V_{\text{ref}} &= 0.127 \text{m}^3 \\
\rho_{\text{air}} &= 1.18 \text{kg/m}^3 & T_{\text{rm}} &= 30 \text{ C} &
\end{align*}
\]

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
- $I_{pv}$: current from PV array
- $V_{pv}$: voltage from PV array
Iref  current from cooling system
Vref  voltage from cooling system
Vbat  battery voltage

OUTPUTS:
I bat  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
DeltaSOC  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 \textit{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 \textit{Mode}. If the battery was on discharge (input \textit{Mode} = 0), the SOC must be greater than the sum of \( S_{\text{min}} \) plus \( \Delta S_{\text{SOC}} \) to allow discharging again, which would then cause the output \textit{Mode} to be one. If the battery operated under normal conditions (input \textit{Mode} = 1), the state of charge is compared to the limits \( S_{\text{min}} \) and \( S_{\text{max}} \). If the deep discharge or the overcharge level is reached \textit{Mode} is set to either zero or two. The third case (input \textit{Mode} = 2) indicates that the overcharge condition existed at the last calculation. If the current state of charge is smaller than the difference of \( S_{\text{max}} \) minus \( \Delta S_{\text{SOC}} \), the battery can be operated under normal conditions and the \textit{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-order.

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

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](image)

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.

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

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](image)

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

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.

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

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](image_url)
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.

\[
COP = d_{000} + d_{100} T_{fr} + d_{200} T_{fr}^2 + ... + d_{k00} T_{fr}^k + \\
[d_{010} + d_{110} T_{fr} + d_{210} T_{fr}^2 + ... + d_{k10} T_{fr}^k] T_{rm} + ... + \\
[d_{0m0} + d_{1m0} T_{fr} + d_{2m0} T_{fr}^2 + ... + d_{km0} T_{fr}^k] T_{rm}^m + ... + \\
[d_{001} + d_{101} T_{fr} + d_{201} T_{fr}^2 + ... + d_{k01} T_{fr}^k + \\
[d_{011} + d_{111} T_{fr} + d_{211} T_{fr}^2 + ... + d_{k11} T_{fr}^k] T_{rm} + ... + \\
[d_{0m1} + d_{1m1} T_{fr} + d_{2m1} T_{fr}^2 + ... + d_{km1} T_{fr}^k] T_{rm}^m \} V + ... + \\
[d_{00n} + d_{10n} T_{fr} + d_{20n} T_{fr}^2 + ... + d_{k0n} T_{fr}^k + \\
[d_{01n} + d_{11n} T_{fr} + d_{21n} T_{fr}^2 + ... + d_{k1n} T_{fr}^k] T_{rm} + ... + \\
[d_{0mn} + d_{1mn} T_{fr} + d_{2mn} T_{fr}^2 + ... + d_{kmn} T_{fr}^k] T_{rm}^m \} V^n
\]
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](image)

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

\[
CAP = \frac{COP}{VI \eta_{mot}}
\]  \[7.10\]

where

\( \eta_{mot} \) 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.

![Graph showing curve fit capacity and accuracy for varying motor efficiency](image)

**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 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.

![Flow diagram](image)

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

**INPUTS:**

- **V** voltage
- **T<sub>a</sub>** ambient temperature
- **T<sub>fr</sub>** freezer temperature
- **Dump** dumped energy indicator
OUTPUTS:

\begin{align*}
V & \quad \text{voltage} \\
T_a & \quad \text{ambient temperature} \\
T_{fr} & \quad \text{freezer temperature} \\
I & \quad \text{current} \\
\text{CAP} & \quad \text{refrigeration capacity} \\
\text{COP} & \quad \text{coefficient of performance} \\
\text{CAP}_{\text{Dump}} & \quad \text{dumped refrigeration capacity}
\end{align*}

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 $\text{CAP}_{\text{Dump}}$ 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](image)

**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
- \( Q_{\text{tot}} \)  total capacity

PARAMETERS:

- \( k \)  conductivity of the refrigerator walls
- \( L \)  thickness of the refrigerator walls
- \( c_{\text{wat}} \)  specific heat of water
- \( c_{\text{ice}} \)  specific heat of ice
- \( A_{\text{ref}} \)  area of the refrigerator
- \( T_{\text{ice}} \)  temperature for the ice
- \( V_{\text{ref}} \)  volume of the refrigerator
- \( c_{\text{air}} \)  specific heat of air
- \( \rho_{\text{air}} \)  density of air
- \( A_c \)  number of air changes per minute
- \( t_{\text{do}} \)  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
- CAPDump: dumped refrigeration capacity

OUTPUTS:
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.
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
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.

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.
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.
REFERENCES


12 Magnetic Technology Company, *Direct Drive - Engineering Handbook*

13 Barber Colman Company, *Motor Data*, Motor Type EYQM No. 33300-51


15 Chlumsky, *Reciprocating and Rotary Compressors*, SNTL, 1965


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.

\[ I_{sc,\text{ref}} = 2.9 \, \text{A} \quad V_{oc,\text{ref}} = 20 \, \text{V} \quad T_{c,\text{ref}} = 301 \, \text{K} \]
\[ \phi_{\text{ref}} = 1000 \, \text{W/m}^2 \quad V_{MP,\text{ref}} = 16.5 \, \text{V} \quad I_{MP,\text{ref}} = 2.67 \, \text{A} \]
\[ \mu_{I,sc} = 0.001325 \, \text{A/K} \quad \mu_{V,oc} = -0.0775 \, \text{V/K} \quad T_{c,\text{NOCT}} = 319 \, \text{K} \]
\[ T_{a,\text{NOCT}} = 293 \, \text{K} \quad \epsilon_g = 1.12 \, \text{eV} \quad \text{area} = 0.427 \, \text{m}^2 \]
### Data for the lead acid battery

The data are from TRNSYS [2].

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_c )</td>
<td>2.25 V</td>
</tr>
<tr>
<td>( G_d )</td>
<td>0.08</td>
</tr>
<tr>
<td>( E_{\text{const,d}} )</td>
<td>1.8 V</td>
</tr>
<tr>
<td>( I_{\text{di}} )</td>
<td>2.5 A</td>
</tr>
<tr>
<td>( Q_c )</td>
<td>(-0.0035, Q_M)</td>
</tr>
<tr>
<td>( R_c )</td>
<td>(3/Q_M)</td>
</tr>
<tr>
<td>( E_d )</td>
<td>2.1 V</td>
</tr>
<tr>
<td>( M_c )</td>
<td>0.864</td>
</tr>
<tr>
<td>( R_{\text{const,d}} )</td>
<td>2.4E-3 (\Omega)</td>
</tr>
</tbody>
</table>

### Data for the brushless d.c. motor

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_b )</td>
<td>0.04 V/rad-sec</td>
</tr>
<tr>
<td>( F_{\text{stat}} )</td>
<td>4.38E-3 Nm</td>
</tr>
<tr>
<td>( K_t )</td>
<td>0.04 Nm/A</td>
</tr>
<tr>
<td>( F_{\text{dyn}} )</td>
<td>2.54E-6 Nm-sec</td>
</tr>
<tr>
<td>( R )</td>
<td>4.52 (\Omega)</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.95</td>
</tr>
<tr>
<td>( M_d )</td>
<td>1</td>
</tr>
<tr>
<td>( M_{\text{d}} )</td>
<td>0.95</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Condensing Temperature in deg F</th>
<th>Evaporator Temperature in deg F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>80</td>
<td>14600</td>
</tr>
<tr>
<td>90</td>
<td>13100</td>
</tr>
<tr>
<td>100</td>
<td>11600</td>
</tr>
<tr>
<td>110</td>
<td>10100</td>
</tr>
<tr>
<td>120</td>
<td>8700</td>
</tr>
</tbody>
</table>

### Power in watts

<table>
<thead>
<tr>
<th>Condensing Temperature in deg F</th>
<th>Evaporator Temperature in deg F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>80</td>
<td>1380</td>
</tr>
<tr>
<td>90</td>
<td>1440</td>
</tr>
<tr>
<td>100</td>
<td>1490</td>
</tr>
<tr>
<td>110</td>
<td>1510</td>
</tr>
<tr>
<td>120</td>
<td>1530</td>
</tr>
<tr>
<td>Condensing Temperature in deg F</td>
<td>Evaporator Temperature in deg F</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>80</td>
<td>183</td>
</tr>
<tr>
<td>90</td>
<td>170</td>
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<tr>
<td>100</td>
<td>156</td>
</tr>
<tr>
<td>110</td>
<td>142</td>
</tr>
<tr>
<td>120</td>
<td>128</td>
</tr>
</tbody>
</table>
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 coefficient of the short circuit current
muVoc [V/K] = temperature coefficient 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
taulpha = 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
\[ \text{Imp}=2.67 \]
\[ \text{Vmp}=16.5 \]
\[ \text{mulsc}=1.325\times10^{-3} \]
\[ \text{muVoc}=-0.0775 \]

\{other fixed parameters\}
\[ \text{taualpha}=0.9 \]
\[ \text{Ac}=0.427 \]
\[ e=1.12 \]
\[ \text{Ns}=36 \]

\{variables\}
\[ V=12 \]
\[ \text{GT}=1000 \]
\[ \text{Ta}=25+273 \]

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

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

\{calculation of numbers at any cell tempatur\}
\[ a/\text{aref} = \text{Tc}/\text{Tcref} \]
\[ \text{IL} = \text{GT}/\text{GTref}*(\text{ILref}+\text{mulsc}*(\text{Tc}-\text{Tcref})) \]
\[ \text{Io/Ioref} = (\text{Tc}/\text{Tcref})^{3}*\exp(e*\text{Ns}/\text{aref}*(1-\text{Tcref}/\text{Tc})) \]

\{efficiency\}
\[
\eta = I \times V / (A \times G T)
\]
\[
\eta_{\text{ref}} = I_{\text{mp}} \times V_{\text{mp}} / (A \times G T_{\text{ref}})
\]
\[
\eta = \eta_{\text{ref}} + \mu_{\text{mp}} \times (T_c - T_{\text{ref}})
\]
\[
\mu_{\text{mp}} = \eta_{\text{ref}} \times \mu_{\text{Voc}} / V_{\text{mp}}
\]

\[
\{ \text{cell temperature; assume } \tau_{\alpha UL} = \tau_{\alpha UL} = \text{constant} \}
\]
\[
\tau_{\alpha UL} = (T_c \text{NOCT} - T_a \text{NOCT}) / G T \text{NOCT}
\]
\[
T_c = T_a + G T \tau_{\alpha UL} \times (1 - \eta / \tau_{\alpha UL})
\]

---

**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:

- \(C_p\) = # of cells in parallel
- \(C_s\) = # of cells in series
- \(E_d\) [V], \(R_d\) [ohms] = constants to calculate the voltage limit on discharge
- \(e\) = charging efficiency
- \(E_{sd}, E_{sc}\) [V] = extrapolated open circuit voltages
- \(F\) = fractional state of charge
- \(G_d, G_c\) = small valued coefficients of \(F\) for charge, discharge
- \(H\) = depth of discharge
- \(I_{bat}\) [A] = battery current
- \(I_{cell}\) [A] = cell current
- \(I_{di}, K_{di}\) = curve fitting parameters
- \(m_d, m_c\) = cell type parameters which determine the shape of the IV-capacity characteristics
- \(Q_c\) [Ah] = capacity on charge
- \(Q_d\) [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 discharge
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}
\[
\begin{align*}
V_{\text{ocbat}} &= (E_{\text{sc}} + E_{\text{sd}})/2 \\
V_{\text{di}} &= 1/K_{\text{di}} \ln(\text{abs}(I_{\text{cell}})/I_{\text{di}} + 1) \\
R_{\text{sc}} &= 3/Q_m \\
R_{\text{sd}} &= 0.5/Q_m \\
Q_{c} &= -0.035*Q_m \\
Q_{d} &= Q_m/0.85 \\
F &= Q/Q_m \\
H &= 1-F \\
V_d &= E_d - \text{abs}(I_{\text{cell}}) \times R_d \\
V_{\text{cell}} &= \text{BAT\_VOLT}(V_{\text{ocbat}}, V_{\text{di}}, G_d, G_c, H, I_{\text{cell}}, R_{\text{sd}}, R_{\text{sc}}, m_d, m_c, Q_d, Q_c, Q_m) \\
V_{\text{bat}} &= C_s \times V_{\text{cell}} \\
I_{\text{bat}} &= C_p \times I_{\text{cell}}
\end{align*}
\]

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:}
\begin{align*}
E_a [V] &= \text{electromagnetic force} \\
eff &= \text{motor efficiency} \\
F_{\text{dyn}} [\text{Nms}] &= \text{dynamic friction constant} \\
F_{\text{stat}} [\text{Nm}] &= \text{static friction constant} \\
I_t [A] &= \text{terminal current} \\
K_b [V/\text{rad-sec}] &= \text{back EMF constant}
\end{align*}
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] = terminal 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}

{steady 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}

\[ \text{wdot} = \rho_1 \cdot V_{\text{displ}} \cdot N_{\text{dot}} \cdot \eta_{\text{vol}} \]

\[ \rho_1 = \frac{1}{v_1} \]

{state 2s}

\[ s_{2s} = s_1 \]

\[ h_{2s} = \text{Enthalpy}(R22, s=s_{2s}, P=P_{\text{con}}) \]

{isentropic efficiency}

\[ \eta_{\text{eff, isent}} = \frac{h_{2s} - h_1}{h_2 - h_1} \]

{state 2}

\[ v_2 = v_1 \cdot (P_{\text{ev}} / P_{\text{con}})^{(1/n)} \]

\[ T_2 = \text{Temperature}(R22, v=v_2, P=P_{\text{con}}) \]

\[ h_2 = \text{Enthalpy}(R22, P=P_{\text{con}}, T=T_2) \]

{State 3}

\[ P_{\text{con}} = \text{Pressure}(R22, x=1, T=T_{\text{con}}) \]

\[ h_3 = \text{Enthalpy}(R22, T=T_3, P=P_{\text{con}}) \]

{State 4}

\[ h_4 = h_3 \]

{calculate refrigeration capacity and the rejected power}

\[ \text{CAP} = \text{wdot} \cdot (h_1 - h_4) \]

{calculate capacity error}

\[ \text{CAP}_{\text{error}} = \text{CAP} - \text{CAP}_{\text{dat}} \]

{calculate COP}

\[ \text{power}_{\text{dat}} = W_{\text{power}} \cdot 3.413 \cdot 0.7 \quad \text{(Btu/hr; value from katalog, motor efficiency = 70%)} \]
COPdat = CAPdat/powerdat

\[ \text{power} = \text{wdot} \times Wpol \quad \{ \text{Btu/hr; not including the motor efficiency} \} \]
\[ \text{COP} = \frac{\text{CAP}}{\text{power}} \]

{calculate the polytropic work}
\[ Wpol = \frac{(Pev' \times v1 \times n/(n-1)) \times ((Pcon'/Pev')^((n-1)/n)-1)}{144/778} \]

{calculate work error}
\[ \text{enthdiff} = h2 - h1 \]
\[ \text{errorwork} = \text{enthdiff} - Wpol \]

{calculate the isentropic efficiency out of datas}
\[ \text{COPdat} = \frac{(h1 - h4)/(h2s - h1) \times \text{effisendat}}{\text{h1}} \]

---

**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:}
\[ \text{CAP} \ [\text{kW}] = \text{refrigeration capacity} \]
\[ \text{COP} = \text{coefficient of performance} \]
\[ \text{dPev} \ [\text{kPa}] = \text{pressure difference at inlet valve of the compressor} \]
\[ \text{dPcon} \ [\text{kPa}] = \text{pressure difference at outlet valve of the compressor} \]
\[ \text{etavol} = \text{volumetric efficiency} \]
\[ h1 = \text{enthalpy at state 1} \]
\[ h2 = \text{enthalpy at state 2} \]
\[ h3 = \text{enthalpy at state 3} \]
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}
\( n = 1.061 \) \{\text{polytropic exponent}\}
\( dP_{ev} = 70 \) \{\text{kPa, assumed value}\}
\( dP_{con} = 7 \) \{\text{kPa, assumed value}\}

\( \text{RPM} = 60 \times \text{RPS} \)

\( UA_{ev} = 0.01 \)
\( UA_{con} = 0.01 \)

\{\text{calculate the volumetric efficiency}\}\]
\( \text{etavol} = (1 + m - m \times (P_{con} / P_{ev})^{(1/n)}) \times \text{volratio} \)
\( P_{con}' = P_{con} + dP_{con} \)
\( P_{ev}' = P_{ev} - dP_{ev} \)
\( \text{volratio} = v^1 / v^1' \)
\( v^1' = \text{Volume}(R12, h = h1, P = P_{ev}') \)

\{\text{calculate refrigeration capacity}\}\]
\( \text{CAP} = \text{wdot} \times (h1 - h4) \)
\( \text{CAP} = UA_{ev} \times (T_{fr} - Tev) \)

\{\text{State 1}\}\]
\( h1 = \text{Enthalpy}(R12, T = Tev, x = 1) \)
\( v1 = \text{Volume}(R12, T = Tev, x = 1) \)
\( P_{ev} = \text{Pressure}(R12, T = Tev, x = 1) \)

\{\text{evaporator}\}\]
\( \text{wdot} = \rho_1 \times \text{Vdispl} \times \text{RPS} \times \text{etavol} \)
\( \rho_1 = 1 / v1 \)

\{\text{State 2}\}\]
\( v2' = v1' \times (P_{ev} / P_{con})^{(1/n)} \)
\( h2' = \text{Enthalpy}(R12, P = P_{con}', v = v2') \)
\( h2 = h2' \)
\[ T_2 = \text{Temperature}(R_{12}, h = h_2, P = P_{\text{con}}) \]

\{ heat transfer condenser \}
\[ Q_{\text{con}} = (h_2 - h_3) \cdot w_{\text{dot}} \]
\[ Q_{\text{con}} = U A_{\text{con}} \cdot (T_{\text{con}} - T_{\text{rm}}) \]

\{ State 3 \}
\[ P_{\text{con}} = \text{Pressure}(R_{12}, x = 0, T = T_{\text{con}}) \]
\[ h_3 = \text{Enthalpy}(R_{12}, x = 0, P = P_{\text{con}}) \]

\{ State 4 \}
\[ h_4 = h_3 \]

\{ calculate COP \}
\[ \text{COP} = \frac{C A P \cdot 1000}{T_0 \cdot \omega} \]

\{ calculate the polytropic work \}
\[ W_{\text{pol}} = (P_{\text{ev}}' \cdot v_1' \cdot n/(n-1) \cdot ((P_{\text{con}}'/P_{\text{ev}}')^{(n-1)/n}) - 1) \]
\[ T_0 \cdot \omega = w_{\text{dot}} \cdot W_{\text{pol}} \cdot 1000 \]

\{ Part for the brushless d.c. motor \}
\{ V_t = 15 \} \quad \{ V; \ terminal\ voltage \}
\[ R = 0.52 \quad \{ \text{ohms; resistance} \} \]
\[ K_b = 0.15 \quad \{ V/\text{rad/sec; back EMF constant} \} \]
\[ K_t = 0.15 \quad \{ \text{Nm/A; torque sensitivity} \} \]
\[ F_{\text{stat}} = 4.38 \times 10^{-3} \quad \{ \text{Nm; static friction constant} \} \]
\[ F_{\text{dyn}} = 2.54 \times 10^{-6} \quad \{ \text{Nms; dynamic friction constant} \} \]

\{ steady state equations \}
\[ V_t = I_t \cdot R + E_a \]
\[ E_a = K_b \cdot \omega \]
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))
goto 20
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)
mulsc=1.325e-3 \ (A/K; temperature coefficient of the short circuit current)
muVoc=-0.0775 \ (V/K; temperature coefficient 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=I-L-ID \ (-Ish; the shunt current is assumed to be negligible)
ID=Io*(exp((V+I*Rs)/a)-1)
P=I*V

{calculations of numbers at reference conditions}
$IL_{\text{ref}}=I_{\text{sc}}$
$I_{\text{ref}}/\exp(-V_{\text{o}}/a_{\text{ref}})=IL_{\text{ref}}$

$Rs=(a_{\text{ref}}/\ln(1-I_{\text{mp}}/IL_{\text{ref}})-V_{\text{mp}}+V_{\text{o}})/I_{\text{mp}}$
$a_{\text{ref}}=(\mu_{\text{Voc}}*T_{\text{cref}}-V_{\text{o}}+e*N_{\text{s}})/(\mu_{\text{ls}}*T_{\text{cref}}/IL_{\text{ref}}-3)$

{calculation of numbers at any cell temperature}
$a/a_{\text{ref}}=T_{c}/T_{\text{cref}}$
$IL=GT/GT_{\text{ref}}*(IL_{\text{ref}}+\mu_{\text{ls}}*(T_{c}-T_{\text{cref}}))$

$I_{\text{o}}/I_{\text{ref}}=(T_{c}/T_{\text{cref}})^{3}\exp(e*N_{\text{s}}/a_{\text{ref}}*(1-T_{\text{cref}}/T_{c}))$

{efficiency}
$\eta=I*V/(A_{c}GT)$
$\eta_{\text{mpref}}=I_{mp}*V_{mp}/(A_{c}GT_{\text{ref}})$

$\eta_{mp}=\eta_{\text{mpref}}+\mu_{mp}(T_{c}-T_{\text{cref}})$
$\mu_{mp}=\eta_{\text{mpref}}*\mu_{\text{Voc}}/V_{mp}$

{cell temperature; assume $\tau_{\alpha}/U_{\text{L}}=\tau_{\alpha}/U_{\text{L}}=\text{constant}$}
$\tau_{\alpha}/U_{\text{L}}=(T_{cNOCT}-T_{aNOCT})/GT_{NOCT}$
$T_{c}=T_{a}+GT*\tau_{\alpha}/U_{\text{L}}*(1-\eta/\tau_{\alpha})$

{Part of the refrigeration cycle}

{Refrigerant = R12}
$T_{\text{rm}}=30$
$T_{fr}=0$
$V_{\text{displ}}=1e^{-5}$

$m=0.094$ {clearance volume/displacement volume}
$n=1.061$ {polytropic exponent}
$d_{\text{Pev}}=70$ {kPa, assumed value}
dPcon=7 \quad \{ \text{kPa, assumed value} \}

RPM=60*RPS

UAev=0.01
UAcon=0.01

\{ \text{calculate the volumetric efficiency} \}
etavol=(1+m-m*(Pcon'/Pev')^{(1/n)})*\text{volratio}
Pcon'=Pcon+dPcon
Pev'=Pev-dPev
\text{volratio}=v_1/v_1'
v_1'=\text{Volume}(R12,h=h_1,P=Pev')

\{ \text{calculate refrigeration capacity} \}
CAP=wdot*(h_1-h_4)
CAP=UAev*(Tfr-Tev)

\{ \text{State 1} \}
h_1=\text{Enthalpy}(R12,T=Tev,x=1)
v_1=\text{Volume}(R12,T=Tev,x=1)
Pev=\text{Pressure}(R12,T=Tev,x=1)

\{ \text{evaporator} \}
wdot=\rho h_1*V_{\text{displ}}*RPS*\text{etavol}
\rho h_1=1/v_1

\{ \text{State 2} \}
v_2'=v_1*(Pev'/Pcon')^{(1/n)}
h_2'=\text{Enthalpy}(R12,P=Pcon',v=v_2')
h_2=h_2'
T_2=\text{Temperature}(R12,h=h_2,P=Pcon)
\begin{align*}
\text{heat transfer condenser} \\
Q_{\text{con}} &= (h_2-h_3) \cdot \dot{w} \\
Q_{\text{con}} &= UA_{\text{con}}(T_{\text{con}}-T_{\text{rm}}) \\
\\
\text{State 3} \\
P_{\text{con}} &= \text{Pressure}(R_{12}, x=0, T=T_{\text{con}}) \\
h_3 &= \text{Enthalpy}(R_{12}, x=0, P=P_{\text{con}}) \\
\\
\text{State 4} \\
h_4 &= h_3 \\
\\
\text{calculate COP} \\
\text{COP} &= \frac{\text{CAP} \cdot 1000}{T_0 \cdot \omega} \\
\\
\text{calculate the polytropic work} \\
W_{\text{pol}} &= \frac{(P_{\text{ev}}^*v^1^*n/(n-1)*((P_{\text{con}}'/P_{\text{ev}}')^A((n-1)/n)-1))}{T_0 \cdot \omega} = \dot{w} \cdot W_{\text{pol}} \cdot 1000 \\
\\
\text{Part of the brushless d.c. motor} \\
R &= 0.52 \quad \{\text{ohms; resistance}\} \\
K_b &= 0.15 \quad \{\text{V/rad/sec; back EMF constant}\} \\
K_t &= 0.15 \quad \{\text{Nm/A; torque sensitivity}\} \\
F_{\text{stat}} &= 4.38E-3 \quad \{\text{Nm; static friction constant}\} \\
F_{\text{dyn}} &= 2.54E-6 \quad \{\text{Nms; dynamic friction constant}\} \\
\\
\text{steady state equations} \\
V_t &= I_t \cdot R + E_a \\
E_a &= K_b \cdot \omega \\
\\
T_m &= K_t \cdot I_t \\
T_m &= T_{\text{loss}} + T_o
\end{align*}
\[ T_{\text{loss}} = F_{\text{stat}} + F_{\text{dyn}} \cdot \omega \]
\( \text{eff} = \frac{P_o}{P_{\text{in}}} \)

\[ P_o = T_o \cdot \omega \]
\[ P_{\text{in}} = V_t \cdot I_t \]

\[ \omega = \frac{2 \pi \cdot \text{RPM}}{60} \]
\[ V = V_t \]

{Part of the lead acid battery}

{variables}
\( C_p = 1 \)  \# cells parallel
\( C_s = 6 \)  \# cells in series
\( G_d = 0.08 \)  \{Coefficient of \( (1-F) \) in V formulas\}
\( G_c = 0.08 \)  \{Coefficient of \( (1-F) \) in V formulas\}
\( m_d = 1 \)  \{Cell type parameter which determines the shape of the I-V-Q characteristic\}
\( m_c = 0.864 \)  \{Cell type parameter which determines the shape of the I-V-Q characteristic\}
\( I_{d i} = 2.5 \)
\( K_{d i} = 29.3 \)
\( E_{s d} = 2.1 \)  \{Extrapolated open circuit voltage\}
\( E_{s c} = 2.25 \)  \{Extrapolated open circuit voltage\}
\( Q_{m} = 250 \)  \{Rated capacity of cell\}
\( V_c = 2.3 \)
\( \text{eff} = 0.95 \)
\( E_d = 1.8 \)
\( R_d = 2.4e^{-3} \)
\( F = 1 \)
\{equations\}

\begin{align*}
    x &= 0 \\
    \text{Vocbat} &= \frac{E_{sc} + E_{sd}}{2} \\
    \text{Vdi} &= \frac{1}{K_{di}} \ln (\text{abs}(I_{cell})/I_{di} + 1) \\
    R_{sc} &= \frac{3}{Q_{m}} \\
    R_{sd} &= \frac{0.5}{Q_{m}} \\
    Q_{c} &= -0.035 \times Q_{m} \\
    Q_{d} &= \frac{Q_{m}}{0.85} \\
    F &= \frac{Q}{Q_{m}} \\
    H &= 1 - F \\
    \text{Vd} &= E_{d} - \text{abs}(I_{cell}) \times R_{d} \\
    V_{cell} &= \text{BAT} - \text{VOLT}(\text{Vocbat}, \text{Vdi}, G_{d}, G_{c}, H, I_{cell}, R_{sd}, R_{sc}, m_{d}, m_{c}, Q_{d}, Q_{c}, Q_{m}) \\
    \text{Vbat} &= C_{s} \times V_{cell} \\
    I_{bat} &= C_{p} \times I_{cell} \\
    \text{Vbat} &= V_{t}
\end{align*}
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)

SUBROUTINE TYPE62(TIME,XIN,OUT,T,DTDT,PARINFO,ICONTROL,*)

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

***** Definition of the variables:

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

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

\[
\text{FLAG} = \text{switch: if FLAG=1 then convergence promotion is on} \\
\text{if FLAG=0 then convergence promotion is off}
\]

\( \text{GAM} \) = curve fit factor

\( I \) = current [amps]

\( IL \) = light current [A]

\( \text{ILR} \) = reference light current [A]

\( \text{IMP} \) = current at max. power [A]

\( \text{IMR} \) = reference current at max. power [A]

\( IO \) = reverse saturation current [A]

\( \text{IOR} \) = dito at reference [A]

\( \text{ISC} \) = short circuit current [A]

\( \text{ISCR} \) = dito at reference [A]

\( \text{MEMO} \) = memorizer if convergence promotion is on or off

\( \text{MISC} \) = temperature coefficient: short circuit current [A/K]

\( \text{MVOC} \) = temperature coefficient: open circuit voltage [V/K]

\( N \) = pointer to a relative address in program

\( \text{NP} \) = number of modules in parallel

\( \text{NS} \) = number of modules in series

\( P \) = power [W]

\( \text{PMAX} \) = power [W]

\( \text{Q_BZ} \) = electron charge/Boltzmann constant [C*K/J]

\( TA \) = ambient temperature [Kelvin (K)]

\( \text{TANOCT} \) = ambient temperature at NOCT [K]

\( \text{TAU_AL} \) = transmittance-absorptance product

\( TC \) = cell temperature [K]

\( \text{TCR} \) = reference cell temperature [K]

\( \text{TCNOCT} \) = cell temperature at NOCT [K]

\( \text{SUN} \) = irradiance [W/m^2]

\( \text{SUNR} \) = reference irradiance [W/m^2]

\( \text{SUNNOCT} \) = irradiance at NOCT [K]

\( V \) = voltage [volts]

\( \text{VMP} \) = 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 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, IISC, TC, VOC, NS, NP,
& ISCR, VOCR, TCR, SUNR, VMR, IMR, MISC, EG,
& ILR, SUN, SERCELL, TCONCT, 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**** 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.
ENDIF

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(ILL .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
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,GAMLLOW
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+
   IONEUP)) *(MISC-ISCR*((Q_BZ*EG/(AUP*TCR*TCR))+3./TCR))
   FLOW=-MVOC+(GAMLOW/Q_BZ)*LOG(1.+ISCR/IOLOW)+TCR/(ISCR+
   IONELOW)) *(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*IONEW).LT.0.0) RSUP=RSNEW
IF((FLOW*IONEW).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
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 (DISCHARGE)
C V = VOLTAGE [VOLTS]
C VC,IC = CUTOFF VOLTAGE ON CHARGE, CURRENT CORRESPONDING 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 BOTH THE
C 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
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
ENDIF

C**** Check on minimum discharge voltage
IF (VD.GT.2.5.OR.VD.LT.1.5) CALL TYPECK (-4,INFO,0,0,0)

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)
Il=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.O.) 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 DIFEQ(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,DTDTAR,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 controller represents a series type controller.
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
and just depends on the diode material used in the system.
The user has to provide this information as a parameter

Variables:

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

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******************************************************************  
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***** initialization 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
        END
ENDIF
ELSE
IF(IB.GT.IBMAX)THEN
    FAIL=2
ENDIF
ENDIF

C**** check provided energy
C**** FLAG=1 means too much energy was provided during the last
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
  ENDIF
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 controller represents a parallel type controller.
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
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=I
    STATEOLD=0
  ENDIF
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
ICNTRL(1)=STATEOLD
ICNTRL(2)=STATENEW
OUT(6)=IC  ! STATE OF THE BATTERY
998 FORMAT(' The battery was 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***** 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 (I_t=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,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 coefficients 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 voltage   Vmin=MV0+MV1*Ta+MV2*Ta**2

   flag=0

****** check if input voltage < minimum voltage
   if (V .lt. Vmin) then
Vstore=V
V=V_{\text{min}}
flag=1

dif

C****** calculate the coefficients $M_0$ to $M_5$ for the current calculation

$M_{00}=0.5393400-0.7531403e^{-1}\times T_{fr}-0.4150383e^{-2}\times T_{fr}^2$
$M_{10}=0.7955132e^{-1}+0.1831461e^{-2}\times T_{fr}+0.3723055e^{-4}\times T_{fr}^2$
$M_{20}=0.5349341e^{-3}+0.4925577e^{-4}\times T_{fr}+0.3084497e^{-6}\times T_{fr}^2$
$M_0=M_{00}+M_{10}\times T_d+M_{20}\times T_e^2$
$M_{01}=0.2420253-0.8932678e^{-1}\times T_{fr}-0.7193248e^{-1}\times T_{fr}^2$
$& \quad -0.1568414e^{-1}\times T_{fr}^3-0.8837680e^{-1}\times T_{fr}^4$
$M_{11}=0.3249278e^{-2}+0.2099868e^{-1}\times T_{fr}+0.8202517e^{-3}\times T_{fr}^2$
$& \quad +0.2491312e^{-2}\times T_{fr}^3+0.1337625e^{-2}\times T_{fr}^4$
$M_{21}=-0.5570044e^{-3}-0.9656586e^{-3}\times T_{fr}-0.5732462e^{-2}\times T_{fr}^2$
$& \quad -0.1205124e^{-1}\times T_{fr}^3-0.7105359e^{-1}\times T_{fr}^4$
$M_{31}=0.7205648e^{-5}+0.1333949e^{-4}\times T_{fr}+0.8202517e^{-5}\times T_{fr}^2$
$& \quad +0.1813732e^{-5}\times T_{fr}^3+0.1228688e^{-5}\times T_{fr}^4$
$M_1=M_{01}+M_{11}\times T_d+M_{21}\times T_e^2+M_{31}\times T_e^3$

$M_{02}=-0.2407894e^{-1}+0.5906843e^{-2}\times T_{fr}+0.6464932e^{-3}\times T_{fr}^2$
$M_{12}=-0.2636731e^{-2}-0.1857755e^{-2}\times T_{fr}-0.2145157e^{-3}\times T_{fr}^2$
$M_{22}=0.1562658e^{-3}+0.9752114e^{-4}\times T_{fr}+0.1382020e^{-4}\times T_{fr}^2$
$M_{32}=-0.1981315e^{-5}-0.1404925e^{-5}\times T_{fr}-0.2219106e^{-6}\times T_{fr}^2$
$M_2=M_{02}+M_{12}\times T_d+M_{22}\times T_e^2+M_{32}\times T_e^3$

$M_{03}=0.9773599e^{-3}-0.6355449e^{-3}\times T_{fr}-0.2563748e^{-4}\times T_{fr}^2$
$M_{13}=0.342090e^{-3}+0.1844913e^{-3}\times T_{fr}+0.1732689e^{-4}\times T_{fr}^2$
$M_{23}=-0.1774089e^{-4}+0.1011879e^{-4}\times T_{fr}-0.1309981e^{-5}\times T_{fr}^2$
$M_{33}=0.2270733e^{-6}+0.1504438e^{-6}\times T_{fr}+0.2225981e^{-7}\times T_{fr}^2$
$M_3=M_{03}+M_{13}\times T_d+M_{23}\times T_e^2+M_{33}\times T_e^3$

$M_{04}=-0.1353613e^{-4}+0.2119264e^{-4}\times T_{fr}-0.2033706e^{-5}\times T_{fr}^2$
M14=-0.173682e-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
C0=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
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
\[ C03 = -4.94305 \times 10^{-2} - 9.29327 \times 10^{-3} T_{fr} - 6.708955 \times 10^{-4} T_{fr}^2 \]
\[ C13 = 3.607627 \times 10^{-3} + 7.317108 \times 10^{-4} T_{fr} + 5.7313358 \times 10^{-5} T_{fr}^2 \]
\[ C23 = -9.97026 \times 10^{-5} - 2.13617 \times 10^{-5} T_{fr} - 1.7930097 \times 10^{-6} T_{fr}^2 \]
\[ C33 = 9.687401e-7 + 2.1502586e-7 T_{fr} + 1.9047263e-8 T_{fr}^2 \]
\[ C3 = C03 + C13 T_a + C23 T_a^2 + C33 T_a^3 \]
\[ C04 = 1.0007998e-3 + 1.928476e-4 T_{fr} + 1.4138368e-5 T_{fr}^2 \]
\[ C14 = -7.3877076e-5 - 1.526103e-5 T_{fr} - 1.2066594e-6 T_{fr}^2 \]
\[ C24 = 2.05229799e-6 + 4.4563212e-7 T_{fr} + 3.759363e-8 T_{fr}^2 \]
\[ C34 = -1.997701e-8 - 4.4758553e-9 T_{fr} - 3.968375e-10 T_{fr}^2 \]
\[ C4 = C04 + C14 T_a + C24 T_a^2 + C34 T_a^3 \]

C**** calculate the COP
\[ \text{COP} = C0 + C1 V + C2 V^2 + C3 V^3 + C4 V^4 \]

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%
\[ \text{CAP} = \text{COP} \times V \times \text{cur} \times \eta \]

C**** check if energy gets dumped
\[ \text{CAPDUMP} = 0. \]
\[ \text{IDUMP} = \text{IDINT(DUMP)} \]
IF (IDUMP .EQ. 1) THEN
    COP = 0.
    Cur = 0.
    \text{CAPDUMP} = \text{CAP}
    \text{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)

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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*(Tref-Ta)*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**** Initialization of auxiliary variables used in secant 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+EREPF
      IDUMP=STDUMP+EDUMP
      DIFF=ICAP-IREFP
      IF (INT(TIME/DTME) .EQ. 1) THEN
         S(ISTORE+2)=DTME+24.
      ENDIF
      IF (ICAP .GT. (IREFP-TOL)) THEN
         ICAP=DIFF
      ELSE
         ICAP=0.
      ENDIF
      IREFP=0.
   ENDIF
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
This Appendix contains the TRNSYS decks for the simulations of the PV-system.

**TRNSYS deck 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|1W/m2|101111111110011
Tcref = 2.980000E+02
*Cell Temperature|K|K|10111150012

*|* ******* PV Module Parameters at Reference Condition *******
Isc.ref = 2.900000E+00
*Short Circuit Current|Amp|Amp|0|0|0|5.9013
Vocref = 2.000000E+01
*Open Circuit Voltage|V|V|0|120.00014
Imref = 2.670000E+00
*Current @ Maximum Power Point|Amp|Amp|0|0|0|5.0015
Vmref = 1.650000E+01
*Voltage @ Maximum Power Point|V|V|120.00016
Misc = 1.325000E-03
*Temp. Coef. of Short Circuit Current |Amp/K|Amp/k|0|0|0|1.00007
Mvoc = -7.750000E-02
*Temp. Coef. of Open Circuit Current |V/K|V/K|0|0|1.011.00008

********** PV Module Parameters at NOCT Conditions **********
TcNOCT = 3.190000E+02
*Cell Temperature @ NOCT|K|K|0|110115009
TaNOCT = 2.930000E+02
* Ambient Temperature @ NOCT in K
SunNOCT = 8.000000E+02
* Solar Radiation at NOCT in W/m^2
### PV Module Configuration

- **NCS** = 3.600000E+01
- **Area** = 4.2700000E-01
- **Ns** = 1.000000E+00
- **Np** = 3.000000E+00
- **Tau_AI** = 0.90000E+00
- **EG** = 1.12000E+00
- **QM** = 250.0
- **CP** = 1.0
- **CS** = 6.0
- **EFF** = 0.95
- **VC** = 2.3
- **VCONTR** = -1
- **ICTOL** = 0.01
- **ESC** = 2.25
- **ESD** = 2.1

* transmittance of cover * fraction of radiation incident on surface

* material band gap energy for silicon

* battery parameters

- **QM** = rated capacity of cell
- **CP** = # of cells in parallel
- **CS** = # of cells in series
- **EFF** = efficiency of battery
- **VC** = cutoff voltage on charge
- **VCONTR** = specification of voltage control on discharge
- **ICTOL** = parameter for iterative calculations
- **ESC** = extrapolated open circuit voltage
- **ESD** = 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 0 2 1 0 3 1 0 -4 1 0 5 0 1 0 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

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

Inputs 4
* Cur V Sun Tamb
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 1.0

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
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/m20111111101]
Tcalf = 2.980000E+02
*Cell Temperature[11111115002
*|*  ********** PV Module Parameters at Reference Condition **********
Iscref = 2.900000E+00
*Short Circuit Current[AmplAmb011115.903
Vocref = 2.000000E+01
*Open Circuit Voltage[V10111120.0004
Imref = 2.670000E+00
*ICurrent @ Maximum Power Point\(I_{Pmax}\) = 1.650000E+01
Vmref = 1.650000E+01
*IVoltage @ Maximum Power Point\(V_{Pmax}\) = 20.0016
M misc = 1.325000E-03
*ITemp. Coef. of Short Circuit Current \(I_{SC} \) = 0.00017
M voc = -7.750000E-02
*ITemp. Coef. of Open Circuit Current \(I_{OC} \) = 0.00018

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

TcNOCT = 3.190000E+02

*Cell Temperature @ NOCT\(I_{T_c} \) = 50.09
TaNOCT = 2.930000E+02

* Ambient Temperature @ NOCT in K

SunNOCT = 8.000E+02

* Solar Radiation at NOCT in W/m\(^2\)

****** PV Module Configuration ******

NCS = 3.600000E+01

*Number of Cells in the Module\(N_{cell}\) = 50
Area = 4.2700000E-01

*Module Frontal Area\(A_{front}\) = 0.00011

Ns = 1.000000E+00

*Number of Modules Connected in Series\(N_{series}\) = 12

Np = 3.000000E+00

*Number of Modules Connected in Parallel\(N_{parallel}\) = 13

\(\tau_{A_i} \) = 0.900000E+00

* transmittance of cover * fraction of radiation incident on surface

EG = 1.120000E+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
-25 1 1 1 0 2 1 0 3 1 0 -4 1 0 5 0 1 0 0
INPUTS 0

UNIT 2 TYPE 16 RADIATION PROCESSOR
PARAMETERS 9
*HMODE TMODE ITMODE DAY LAT SC SHFT SMOOTH IE
    1 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 Tc ref Sunref Vmref Imref Misc Mvoc NCS
Parameters 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
42-28020113
17020
INPUTS 6
3.1 6.4 10.1 F 6.1 10.6
CPV CREF CBAT SOC Vref MODE
LABELS 4
[A] [V]
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/m20111110011
TcRef = 2.980000E+02
*|Cell Temperature|K|K|10111150012

*|* PV Module Parameters at Reference Condition |**********|

IscRef = 2.900000E+00
*|Short Circuit Current |Amp/Amp011115.903
VocRef = 2.000000E+01
*|Open Circuit Voltage |V/V10111120.0004
ImRef = 2.670000E+00
*|Current @ Maximum Power Point |Amp/Amp011115.005
VmRef = 1.650000E+01
*|Voltage @ Maximum Power Point |V/V10111120.006
Misc = 1.325000E-03
*|Temp. Coef. of Short Circuit Current |Amp/K/Amp/k0110101.0007
Mvoc = -7.750000E-02
*|Temp. Coef. of Open Circuit Current |V/K/V101111.01100008

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

TcNOCT = 3.190000E+02
*|Cell Temperature @ NOCT |K|K|10111150009
TaNOCT = 2.930000E+02
* |Ambient Temperature @ NOCT in K
SunNOCT = 8.000000E+02
* |Solar Radiation at NOCT in W/m^2

*|* PV Module Configuration |**********|

NCS = 3.600000E+01
*|Number of Cells in the Module |01111150110
Area = 4.2700000E-01
*!Module Frontal Area=2.10.10.1.0.00.11
Ns = 1.0000000E+00
*!Number of Modules Connected in Series=1.0.1.4.1.12
Np = 6.0000000E+00
*!Number of Modules Connected in Parallel=1.0.1.0.4.1.13
Tau_A = 0.90000E+00
* transmittance of cover * fraction of radiation incident on surface
EG = 1.120000E+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 0 2 1 0 3 1 0 -4 1 0 5 1 0 1 0 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

unit 3 type 62 PV array

Parameters 9
Iscref Vocref Tcref Sunref Vmref Imref Misc Mvoc NCS

Parameters 9
Ns Np TeNOCT 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 INTEGRATION 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
52 -280 120 113
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