A MAXIMUM POWER POINT TRACKER OPTIMIZED FOR SOLAR POWERED CARS

by

ANITA V. RAJAN

SUBMITTED TO THE DEPARTMENT OF
ELECTRICAL ENGINEERING AND COMPUTER SCIENCE IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF

BACHELOR OF SCIENCE

IN ELECTRICAL SCIENCE AND ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1990

Signature redacted

Signature of Author____________________________________
Department of Electrical Engineering and Computer Science
May 11, 1990

Signature redacted

Certified by____________________________________
Gill A. Pratt
Thesis Supervisor

Signature redacted

Accepted by____________________________________
Leonard A. Gould
Chairman, Department Committee on Undergraduate Theses

A MAXIMUM POWER TRACKER OPTIMIZED FOR SOLAR POWERED CARS

by

ANITA V. RAJAN

Submitted to the

Department of Electrical Engineering and Computer Science

May 21, 1990
in Partial Fulfillment of the Requirements for the
Degree of Bachelor of Science in
Electrical Science and Engineering

ABSTRACT

The following is an efficiency study of a key component in a solar powered car: the maximum power point tracker (MPPT). An MPPT is necessary where power is delivered from solar cells to batteries. A design optimization for the tracker is crucial for its use in solar powered cars since these vehicles have a very limited amount of input power. Unfortunately, the power stage of a maximum power tracker, consisting of inductors, capacitors, diodes, and MOSFETs, may waste a small yet significant percentage of the total power out of the solar cells. Most trackers today are about 95% efficient. The objective here is to raise the efficiency to 98%.

Once the input and output current and voltages have been picked, each component of the tracker can be optimized for maximum efficiency. After examining the conduction, switching, and gate losses of the MOSFET and diode, the optimum design can be found. The key to making the tracker most efficient is to look at the entire package of parts and optimize several variables at once: frequency, number of devices in parallel (a method of reducing resistive losses), and heat sinking. Using this information, other circuit configurations can be analyzed and external variables can be manipulated to obtain the maximum efficiency. Additional crucial parameters such as weight, cost and space taken up by the tracker must be considered in the design. In the end, based on the key equations which are derived, a super efficient maximum power point tracker can be designed and built to the specifications of the user.

Thesis Supervisor: Gill A. Pratt

Title: Research Associate, Department of Electrical Engineering and Computer Science

TABLE OF CONTENTS

1 INTRODUCTION

The purpose of this research is to discover the optimal operating efficiency of a maximum power point tracker (MPPT), a device which maximizes the power transferred from solar cells to a battery pack. Many MPPT's are not configured for maximum efficiency because, in their application, power lost is not a vitally important consideration. In these trackers, which are usually between 85% to 95% efficient, the main design restriction is to ensure that the device does not overheat. The following study is important because it serves to optimize the MPPT for its use in a solar powered car, in which there are severe limitations on the amount of available power. The following study proposes methods of optimizing the efficiency of the tracker, observing the power lost and the rise in device temperature, while considering such limitations as weight and cost. It is hoped that a 98% efficient tracker can be designed.

To make the effort more simplistic, the research will provide a resourceful program with which to determine the optimal working parameters and components of the tracker. Rather than providing one answer *to all problems,* this approach will suit the average user who wishes to set his own guidelines. For instance, the user will be able to decide which type of heat sink to use on the tracker, what the range of duty cycle should be, how much average power transfer his tracker will allow, the number of paralleled components the tracker will have, and so on. He may wish to also base his limitations on cost and weight rather than maximum efficiency. In spite of allowing many working variables, this study will provide a viable solution to eliminate device inefficiencies, so that anyone hoping to build a 98% efficient maximum power point tracker can employ the efforts of this paper.

2 OPTIMIZATION OVERVIEW

The objective of this study is to derive an MPPT which is at least 98% efficient. This means that the components which waste the most power will be narrowed down and their losses defined. Then, methods of eliminating or reducing the losses will be studied. The steps are as follows:

1. Define the purpose of the MPPT and the MPPT power stage.
2. Define the types of losses which may be generated.
3. Pin-point these losses in the key components and add these to the program.
5. Pick the ideal configuration (type and number of each component) based on the efficiency performances.
6. Look at alternative circuit configurations to eliminate losses.
7. With all the losses added together and the least power consuming configuration discovered, determine the efficiency of the MPPT.

To combine the losses and derive methods by which the tracker efficiency can be maximized, this study includes the creation of a computer program which can be found in the Appendix. The intent of the program is to make the analysis of the components and their losses simpler. Every possible input variable which can be altered is included in a list called 'invals'. Some of these variables and their corresponding abbreviations are:

- the name of the metal-oxide semiconductior field effect transistor (MOSFET) — fet-name
- the name of the diode — diode-name
- the snubber diode name — sdiode-name
- the output voltage — v-out
- the input voltage — v-in
- the maximum power transfer — pow-max
- the thermal resistance — r-th
- the ambient temperature — t-amb
- the number of parallel MOSFETs — n-fet

- the number of parallel diodes — n-diode
- the maximum junction temperature of each device — t-max
- the frequency of operation — freq
- the value of the snubber inductance — l-snub
- and others

All the losses, and the steps to derive the losses, are included in the program. Since the key to this study is to assemble all of the components under scrutiny and look at the efficiency and optimization of the whole maximum power point tracker, an equation for finding the efficiency is also included in the program.

The purpose of the program is not just to calculate and print numbers for the power loss or efficiency. The program is equipped to plot any graph given a set of defined variables. This way, the user may make plots to compare power losses, efficiencies, rise in current, rise in temperature, and many other factors, for any set of changing variables.

Most of the ensuing graphs will have a plot of a variable versus the input voltage, v-in. The effects of sweeping v-in from v-min at 30 volts to v-max at 120 volts will be observed. The battery voltage, v-out, will be fixed at 60 volts, to simulate a typical solar vehicle battery voltage. Thus, as will be explained in section 3, the left side of v-in = 60 volts will be the 'boost' mode and the the right side of v-in = 60 volts will be the 'buck' mode. There are other parameters which will be assigned values for this study although all variables are at the user's discretion. The following are some of the operating conditions:

The curves will be drawn in increments of 100 watts from 100 to 500 watts. The whole purpose of the maximum power point tracker is to transfer power from the solar cells to batteries. The size the solar surface area of an average solar car ranges from seven square feet to thirty-seven square feet. The surface area of a terrestrial solar cell is usually 4x4 inches. Therefore, if the car's surface area can accommodate between 60 and 400 cells, with an average of 1.25 watts each, a single tracker needs to be able to transfer anywhere from 100 watts to 500 watts.

The frequency of operation is fixed at 20 kHz, because aside from space and weight concerns, the greatest efficiencies are obtained at the lowest frequencies. Furthermore, 20 kHz is the lowest switching frequency that is guaranteed to be inaudible.

Adding up the losses for the MOSFET and the diode is essential for calculating the efficiency, but a major problem encountered is the rise in temperature of the components. Thus, even if the losses do not seem too large, the components' temperature may rise well above the rated junction temperature of 150°C. Because of this, and to better observe the diode and MOSFET limits, operation at junction temperatures of each device is not considered above 150°C. This allows the user to observe the minimum and maximum operable duty cycles and currents so that neither of these need to be an input parameter.

To maintain conservative estimates of power loss, the ambient temperature, t-amb, is set at 50°C. It is unlikely that the MPPT board temperature will ever be so hot, however it is difficult to determine the exact value of t-amb.

Now that the conditions have been set, the first step is to understand the maximum power point tracker.

3 THE MAXIMUM POWER POINT TRACKER

3.1 PURPOSE

A maximum power point tracker is an electronic device which maximizes the power out of an array of solar cells and transfers this to a set of batteries. An MPPT is useful and necessary when working with solar cell power output applications. Solar cells, or photovoltaic cells, have a peculiar characteristic associated with their power output. The cells' current and output voltage are affected by light intensity and temperature: the cells' current increases with increasing light intensity, measured in watts per meter squared, and the cells' voltage drops with increasing cell temperature (see figures 3.1a and 3.1b). Thus, the power output from the solar cells, the product of the cell current and voltage, will drop relative to the input solar energy when the cell temperature increases and the light intensity drops.

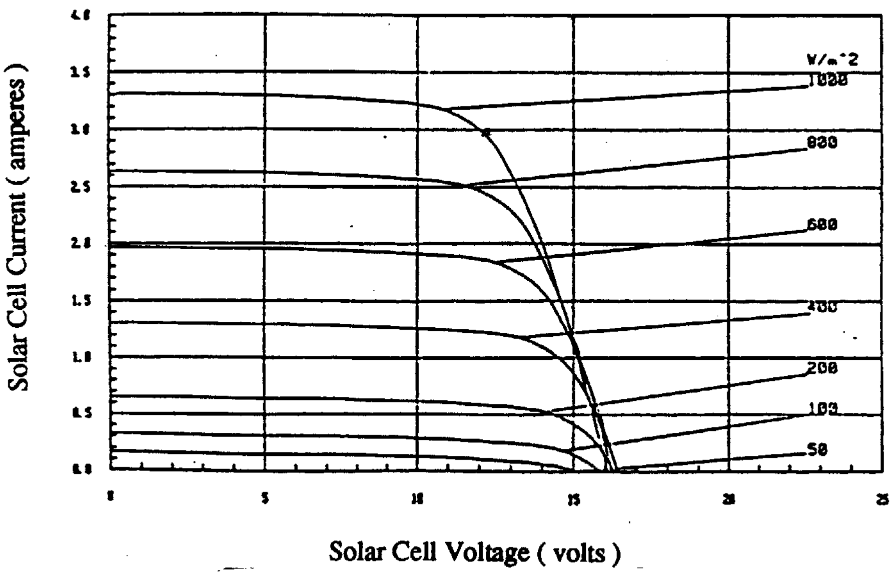

Figure 3.1a: Current vs voltage of 15 solar cells at various light intensities

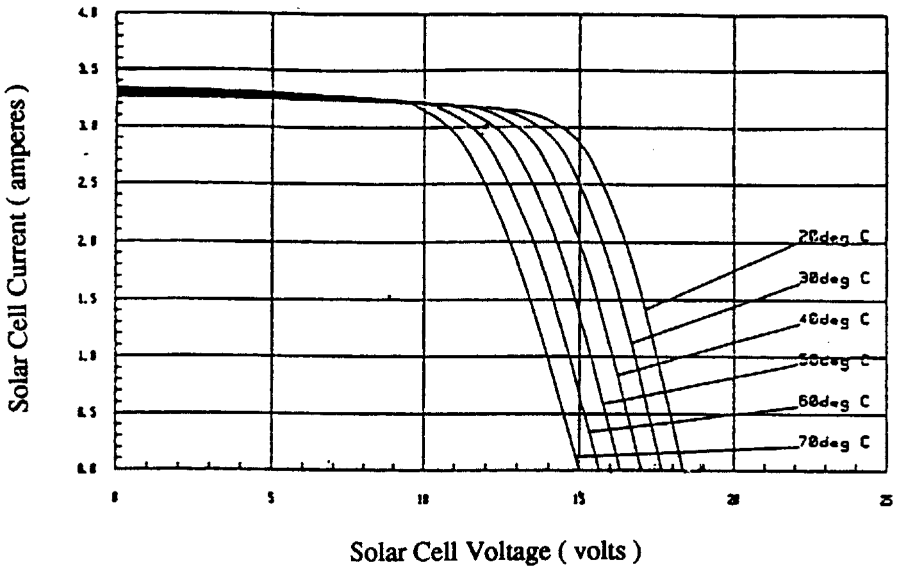

Figure 3.1b: Current vs voltage of 15 solar cells at various cell temperatures

Figures 3.2a and 3.2b show the relationship between the solar cell power output and the cell voltage and current, respectively. The figures show the cells' changing maximum power point, the peak of each curve. It is this variability in the cells output power which makes it necessary to use an electronic device which can constantly track the solar peak power point.

The power out of the solar cells is dependent on the cells' efficiency. This efficiency ranges between 10% and 16% for most 'efficient' terrestrial cells. In the case of 13% efficient cells, this means that for every 1000 watts per square meter (W / m-2) of solar radiation, the solar cells put out will only be 130 W / m-2. For this reason, every watt out of the solar cells needs to be harnessed and used efficiently.

The maximum power point tracker can be extremely useful in dynamic applications. In solar powered cars, where the chief method of propulsion is the solar array output power, the power from the solar cells needs to be transferred to the batteries very efficiently. It is this power which must drive the car at average speeds of 30 miles an hour. For this reason, every device which uses the solar output power must be optimized for maximum. The MPPT is made up of two stages: the control stage and the power stage. Although the control stage of the tracker is more complicated in design, it is the power stage, consisting of MOSFETs, diodes, capacitors and inductors, which is the more inefficient stage of the device.

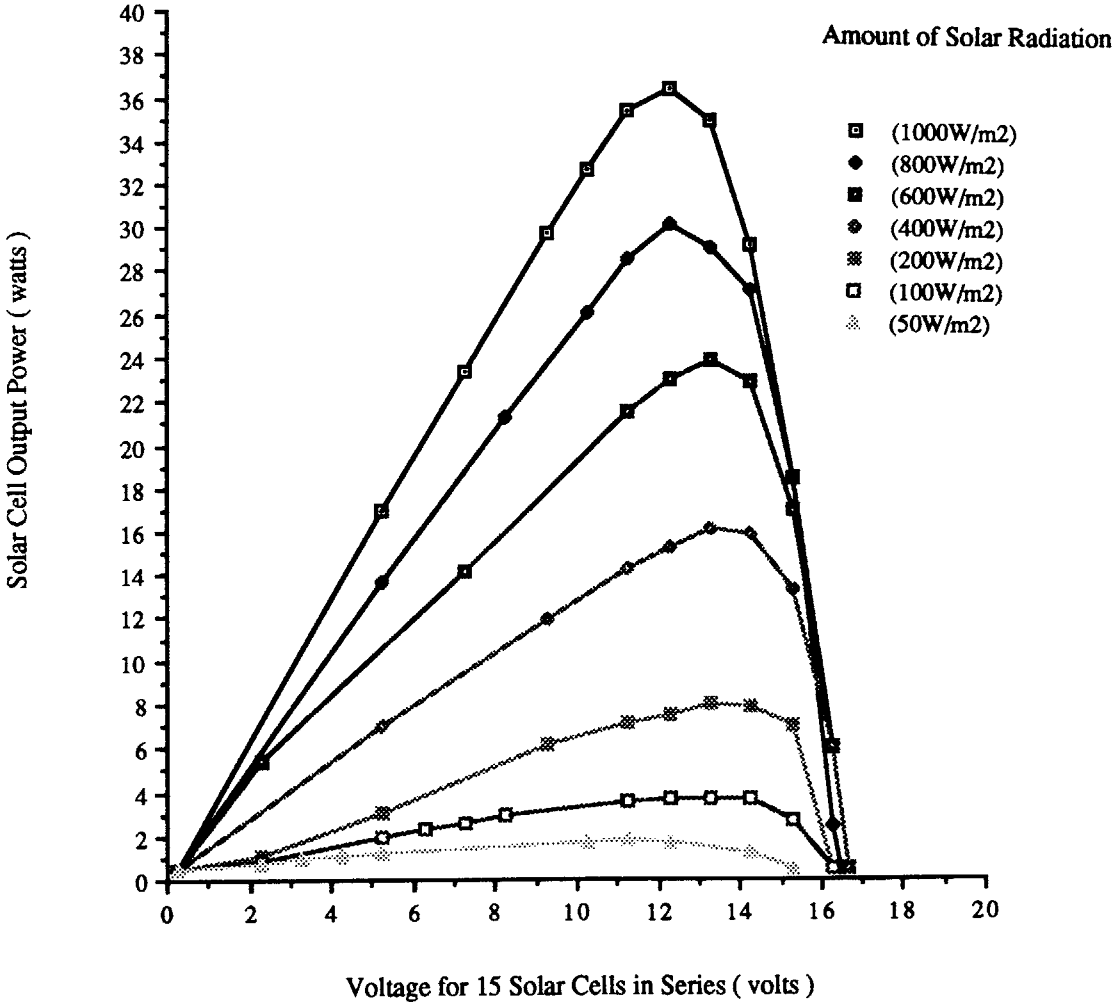

Figure 3.2a: Solar cell output power versus voltage at various light intensities

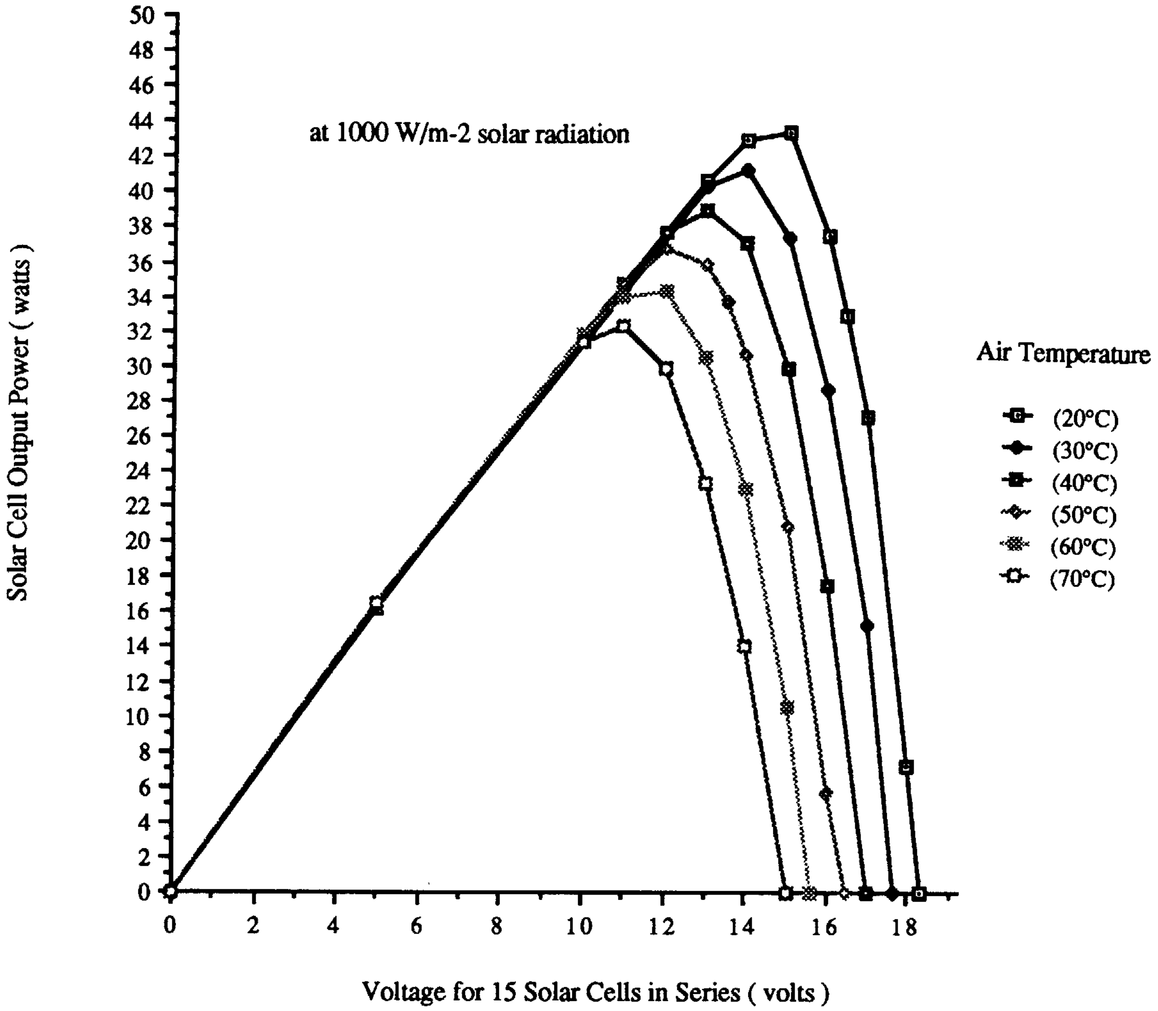

Figure 3.2b: Solar cell output power versus voltage at various temperatures

3.2 THE POWER STAGE

In the MPPT power stage, the MOSFET and diode act as two opposite switches which are turned on and off at a particular frequency. In one configuration of this stage, when the MOSFET is on, the inductor in the circuit stores the solar cells' output energy. When the MOSFET is turned off and the diode is on the inductor is allowed to dump the stored energy into the battery, or the battery's filter capacitors.

The MPPT power stage, with the solar voltage on one side and the battery voltage on the other, resembles a DC to DC converter. Depending on the voltage of the solar cells and batteries, the MPPT can be configured as a boost converter or a buck converter as seen in figure 3.3 and figure 3.4. In a buck converter, power flows from the higher voltage terminal to the lower voltage terminal. In a boost converter, the power flows in the reverse direction (Kassakian, Schlecht, and Verghese, 1990).

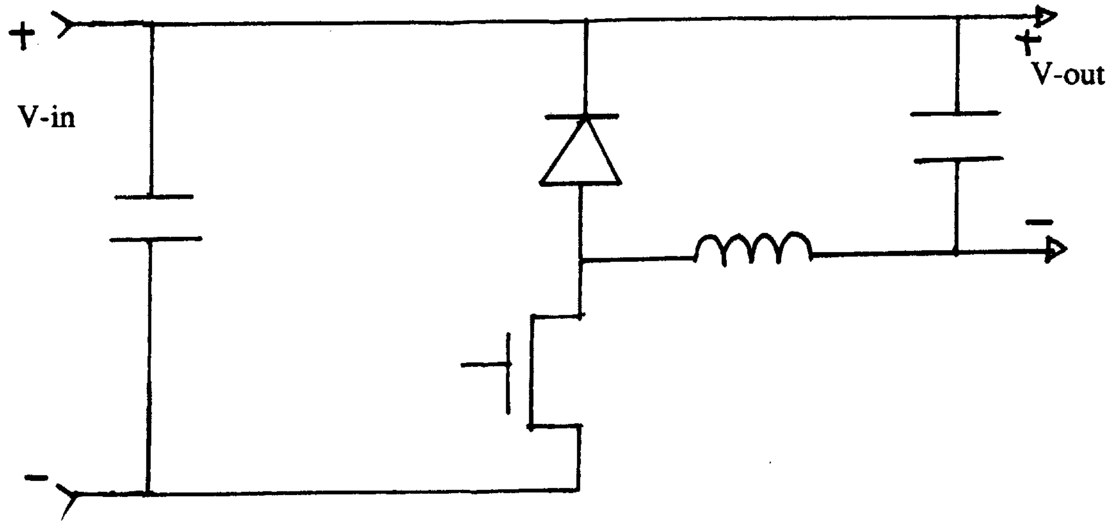

Figure 3.3: The power stage of an MPPT in the buck converter configuration

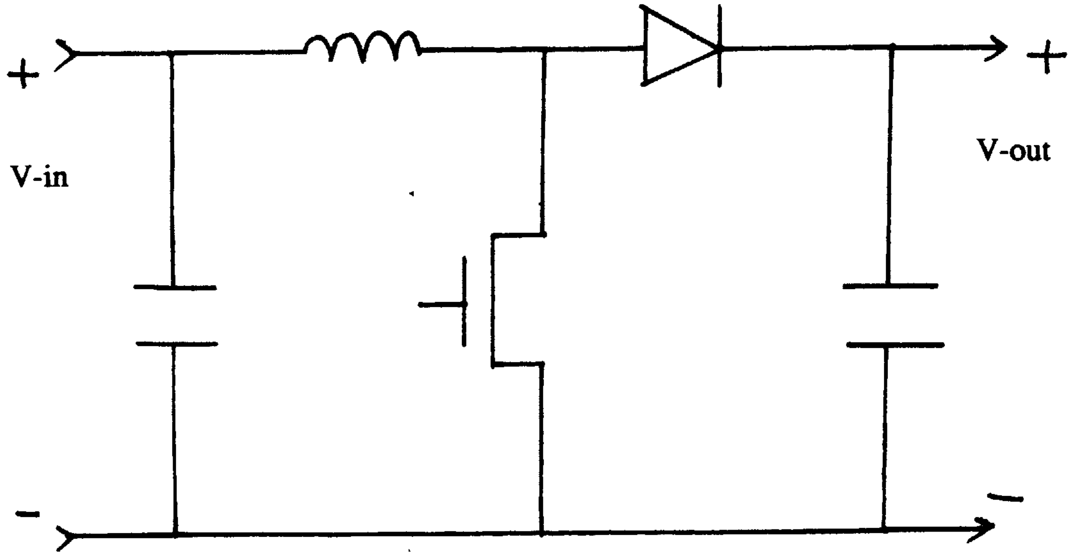

Figure 3.4: The power stage of an MPPT in the boost converter configuration

It is important to distinguish the boost converter from the buck converter. For instance, when v-out is greater than v-in, the MPPT must function in the boost configuration, whereas when the input voltage is larger, the MPPT must be in its buck configuration. As stated in section 2, most of the graphs in this study have the output voltage fixed at 60 volts. The curves to the left side of v-in = 60 volts, in each graph, simulate an MPPT in the boost mode and those to the right side of this point simulate the MPPT in the buck mode.

The type of converter used for the MPPT affects the definition of certain variables. For instance, the duty ratio, d, is the ratio at which the MOSFET is turned on and off. It is defined by the operation of the boost and buck converters. In a buck converter,

$$d = \text{v-out} / \text{v-in} \tag{3.1}$$

and in a boost converter,

$$d = 1 - (\text{v-in} / \text{v-out}) \tag{3.2}$$

(Kassakian, Schlecht, and Verghese, 1990)

Since the position of the each component in the tracker, as well as the value of d, changes from one configuration to the other, it is important to define the currents and voltages in the MOSFET and the diode for each converter. In the boost converter:

$$\begin{aligned} \text{i-fetrms} &= \text{sqrt}\,(d) * \text{i-in} \\ \text{v-fet} &= \text{v-out} \\ \text{i-diode} &= \text{i-in} \\ \text{v-diode} &= \text{v-out} \end{aligned} \tag{3.3}$$

and in the buck converter:

$$\begin{aligned} \text{i-fetrms} &= \text{sqrt}\,(d) * \text{i-out} \\ \text{v-fet} &= \text{v-in} \\ \text{i-diode} &= \text{i-out} \\ \text{v-diode} &= \text{v-in} \end{aligned} \tag{3.4}$$

where i-out = power / v-out and i-in = power / v-in.

With the majority of the static elements and variables in the maximum power point tracker defined, we next define the power losses which are incurred by each configuration and to try to optimize the tracker's efficiency based on these losses.

4 TYPES OF LOSSES

In the maximum power point tracker each element generates some intrinsic power loss. The capacitors heat up, the inductors lose power to hysteresis and eddy currents, and the MOSFETs and diodes have a combination of factors which make them inefficient. It must be remembered that components heat up when power is lost. Since the components have a shorter life if they get too hot (close to 150°C), it is wise to observe the temperature rise of each component in addition to the amount of power lost. For this project, the important devices to analyze are the MOSFET and the diode since the other two are defined by the user's requirements .

There are several types of power losses in MOSFETs and diodes. The most noteworthy of these are: switching losses, conduction losses and gate losses. Switching losses are usually due to the charging of parasitic capacitors, the turn on delay of the device, and the parasitic inductance of the device. Factors which are instrumental in varying the amount of wasted power are the frequency of switching and the load current transmitted through the device. Due to the fact that increased frequency increases the switching losses, it is natural to attempt to keep the frequency as low as possible.

The diode and MOSFET conduction losses are regulated by the devices' resistance. The load current being passed through the diode or MOSFET and the duty cycle of each device are a crucial part of this loss because they are the key parameters in the conduction loss equation.

The gate loss is one item which exists only in the MOSFET. This loss is generated by the intrinsic nature of the MOSFET to have a gate charge. The loss is affected by the device's switching frequency.

With the types of losses having been roughly outlined for the diode and the MOSFET, the governing power loss equations for each device must be derived. With these equations in hand it will be simpler to find the most efficient combination to be used in the maximum power point tracker. Once the combination of MOSFETs and diodes has been decided, we will look at variations in the circuit which can reduce the losses and produce an efficiency maximized MPPT.

5 THE MOSFET

5.1 PURPOSE AND FUNCTION

The metal-oxide-semiconductor field effect transistor, or MOSFET, placed at the input side of a buck converter or the output side of a boost converter (see figures 3.3 and 3.4), is ideal for this circuit topology because it can act as a high frequency switch. This switch can be turned on and off to change the amount of time for which power is transferred from the input capacitor to the output inductor, in the buck converter, and vice-versa in the boost converter. The MOSFET can handle switching frequencies well above 20,000 Hertz so that operation is above the audible region.

5.2 DIFFERENT TYPES AND THEIR CHARACTERISTICS

There are a number of common MOSFETs used in switching DC to DC converter applications. Two such MOSFETs, manufactured by International Rectifier, are the IRPF-150 and the IRFP-250. The IRFP series of MOSFETs is ideal because of the style of packaging, the low on-state resistances, Rds-on, and the efficient switching capabilities. The package style allows the device to be mounted on a heat sink, or straight onto a printed circuit board (International Rectifier, 1987).

The general guideline for picking which MOSFET should be used in a particular application is to decide which device suits the maximum operating voltage. For device applications up to 80 volts, the ideal MOSFET is the IRFP-150. Although it is designed for a maximum voltage of 100 volts, it is safest to keep the voltage 20% below the rated maximum. For operation up to 160 volts, the IRFP-250 is the best MOSFET.

The two MOSFETs can be distinguished by their other device characteristics as well. The IRFP-150 has a rated static on-state drain to source resistance (Rds-on) at 0.055Ω and can handle up to 40 amps, whereas in the IRFP-250, Rds-on is 0.085Ω and the maximum rated current is 33 amps. The maximum junction temperature for the devices is 150°C. Other device characteristics can be seen in Table 1:

Fet Name	Drain to Source Capacitance	Gate to Source Charge	Total Gate Charge
IRFP-150	500.e-12 Farads	27.e-9 Farads	63.e-9 Farads
IRFP-250	275.e-12 Farads	37.e-9 Farads	79.e-9 Farads

Table 1: MOSFET characteristics (International Rectifier, 1987).

These two MOSFETs are the only two MOSFETs considered in the ensuing analysis since they are best suited for the application.

5.3 THE MOSFET LOSSES

The losses incurred by MOSFETs are generated by the following three factors: switching transients, conduction or duty cycle, and gate charge.

5.3.1 The Switching Losses

There are usually two main switching losses: these are losses caused by turning the MOSFET on and off. Fortunately, the turn-off losses can be eliminated from discussion because of the internal MOSFET and diode "parasitic" capacitors, which allow for smooth current transition when the MOSFET is turned off. Figure 5.1 shows the power stage of the MPPT, where the main filter inductor and capacitors are replaced by a voltage and current source. The current which flowed through the MOSFET commutates to the two parasitic capacitors, Cfo and Cdo, and the voltage at the X in figure 5.1 drops until the diode conducts. The lossless process hinges on driving the gate of the MOSFET properly, so that its current falls to zero long before the voltage rises significantly.

The turn-on losses, however, cannot be disregarded. There are three components of the MOSFET which contribute to this type of MOSFET switching loss: the parasitic capacitance Cfo, the turn-on time t-on, and the parasitic inductance Lp.

The first part of the turn-on loss is due to the power lost from discharging Cfo, which was charged in the turn-off cycle. An amount of power equal to :

$$\text{Power-on-loss-1} = 4\,/\,3\ (0.5\ \text{Cfo} * \text{V-fet} * \text{V-fet}) * \text{freq} \qquad (5.1)$$

is lost in each MOSFET, where 'freq' is the frequency of switching and V-fet is the voltage at the MOSFET. V-fet depends on the configuration of the power stage; in the boost mode, V-fet is equal to the output voltage, and in the buck mode, V-fet is equal to the input voltage.

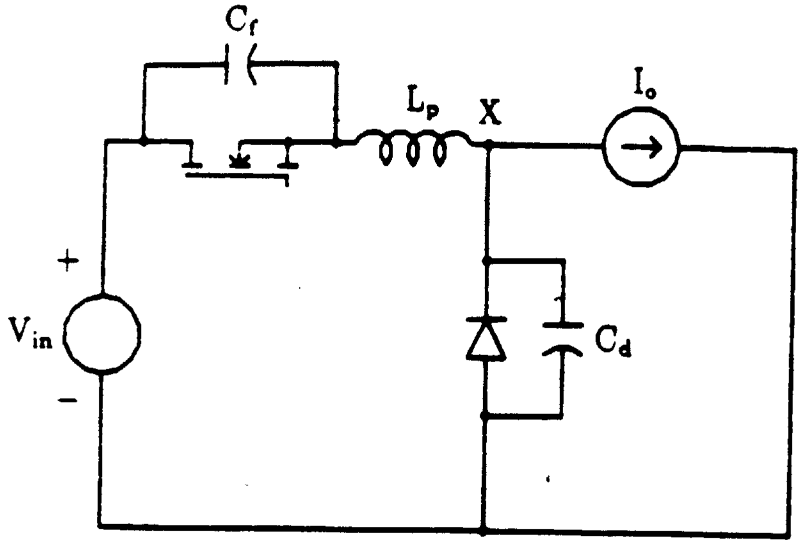

Figure 5.1: A simplified MPPT Power stage topology (Schlecht and Casey, 1987)

The power lost due to the turn-on time delay of the MOSFET, t-on, can be approximated by the following equation:

Power-on-loss-2 = (0.5 * V-fet * I * t-on) * freq

where I is the current through the MOSFET. 't-on' is given as the time needed to transfer the load current from the diode to the MOSFET, as well as the time needed to collapse V-ds, the FET's drain to source voltage. When V-ds is zero the MOSFET is on.

In addition to the above-mentioned turn-on losses, there is a small parasitic inductance, Lp, in the usual power stage circuit. Lp causes the following power loss:

Power-on-loss-3 = (0.5 * Lp * I * I) * freq

where Lp is typically 15 nanoHenrys (Schlecht and Casey, 1987).

5.3.2 The conduction power loss

Passing current through a device which has a resistance will always result in a conduction loss. Unfortunately, in the case of the MPPT, such a loss can result in a significant drop in efficiency. The MOSFET's conduction loss is characterized by the following equation:

$$\text{condloss} = \text{rfet} * \text{I-rms} * \text{I-rms}. \tag{5.2}$$

The rms (root-mean-squared) current, I-rms, is a product of the load current through the MOSFET, either I-in in the boost mode or I-out in the buck mode, and the MOSFET duty cycle, d. Rfet is the drain to source on-state resistance of the MOSFET. As stated before, the static on-state resistance is 0.055Ω for the IRFP-150 and 0.085Ω for the IRFP-250.

Unfortunately, when the MOSFET is being used, rfet does not stay at its static value. Due to temperature effects, the case and the junction of the MOSFET heat up and make the resistance of the device increase. Figure 5.2 shows the effect of the FET's junction temperature on the resistance.

To determine rfet so that Equation (5.2) can be solved involves a lengthy procedure. First the MOSFET junction temperature, ftemp, must be calculated.

$$\text{ftemp} = \text{t-amb} + \text{r-th} * \text{condloss} \tag{5.3}$$

where t-amb is the ambient temperature during operation and r-th is the thermal resistance of the MOSFET in °C / watt (Horowitz and Hill, 1985). The thermal resistance is usually obtainable from device specifications. If no heat sink is used with the MOSFET, r-th is usually quite large — between 40°C / watt and 60 °C / watt. With a heat sink, the device's r-th is equivalent to the thermal resistance from the case to sink plus the thermal resistance from the sink to the air. This junction to ambient thermal resistance of the MOSFET usually ranges from 30°C / watt for a poor heat sink to 5°C / watt for a good heat sink (Horowitz and Hill, 1985).

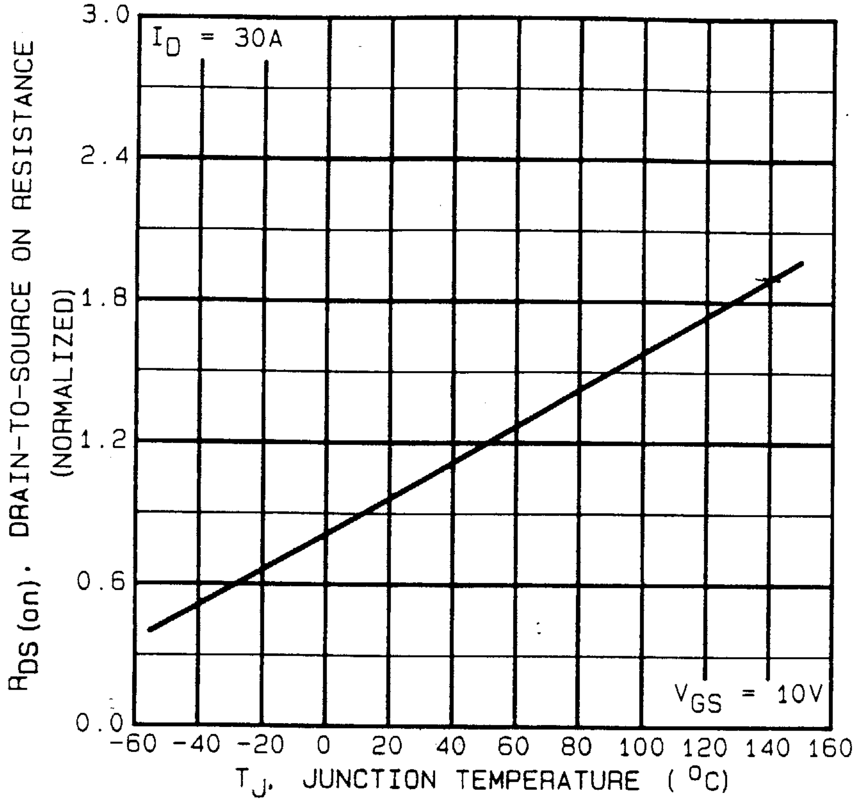

Figure 5.2: Normalized On-Resistance versus Temperature for the IRFP-250 (International Rectifier, 1987)

An equation which relates the MOSFET's on-state resistance to the junction temperature may be derived from figure 5.2. The governing equation is as follows:

$$\text{rfet} = \text{ftemp} * \text{slope} + \text{zero} \qquad (5.4)$$

where "slope" is the slope of the line in the above graph and zero is the intercept of the line with the y-axis. For the IRFP-150, Equation (5.4) becomes:

$$\text{rfet} = 0.00037 * \text{ftemp} + 0.046 \qquad (5.5)$$

and for the IRFP-250

$$rfet = 0.00068 * ftemp + 0.068. \tag{5.6}$$

The actual procedure for calculating rfet, and thus the conduction loss of the MOSFET, is an iterative one; an initial conduction loss contributes to a rise in junction temperature which causes rfet to increase. The rise in rfet contributes to an increase in condloss. The limit to the analysis is set so that ftemp increases until the previous value of ftemp is within 0.1 °C of the new value. Figure 5.3 is a graph of the junction temperature of a single MOSFET versus the input voltage.

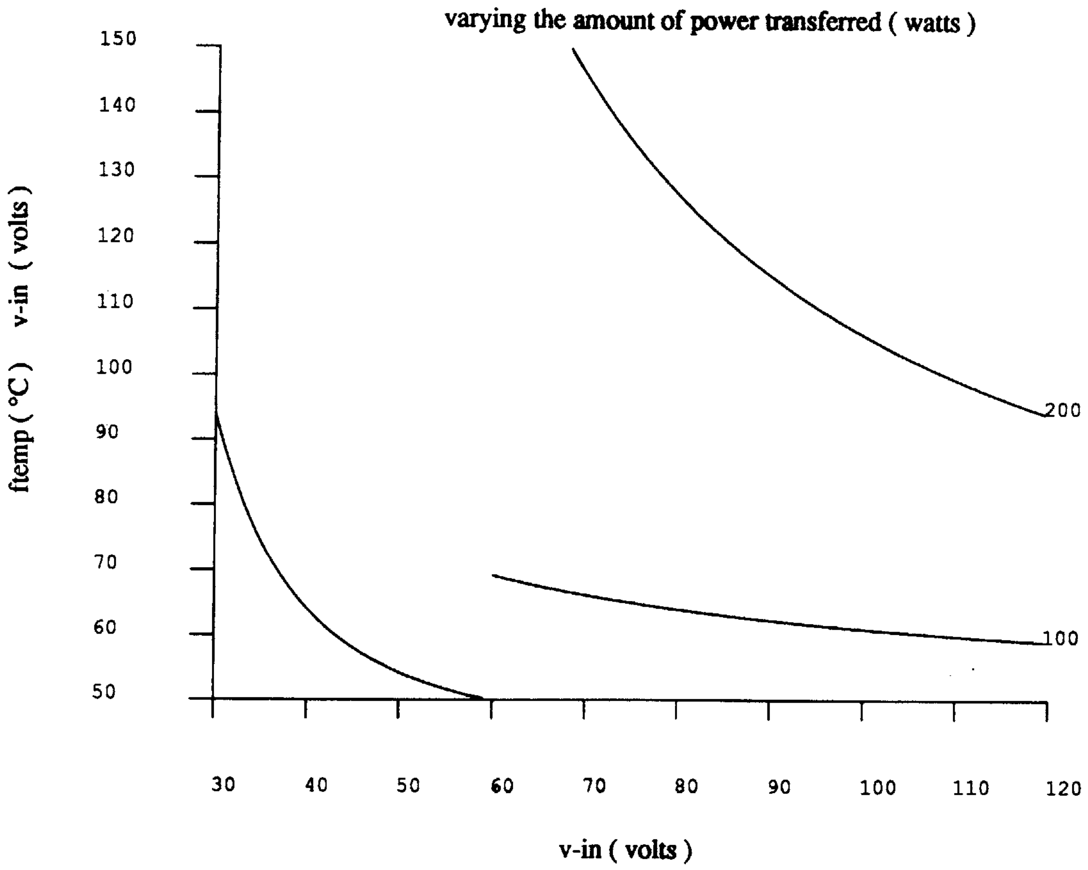

Figure 5.3: The MOSFET temperature vs. v-in for 1 MOSFET

Figure 5.3 demonstrates a problem with the rise in junction temperature for a single MOSFET device. When no heat sink is used (r-th = 60 °C / W), the single MOSFET is unreliable for operation at high amounts of power tranfer.

5.3.3 The gate loss

The third type of power loss which is intrinsic in the MOSFET is the gate charge loss. This is caused by the existence of a gate charge, Qg, in the MOSFET. The gate charge plays an important role when the MOSFET is being turned on. A certain amount of energy is transferred from the drive circuit to the gate of the MOSFET when the gate is being fired to turn the MOSFET on. The average energy transferred is equal to :

$$0.5 \text{ E-gate loss} = Qg * Vgs \qquad \text{(International Rectifier, 1987)}$$

where Vgs, the gate to source voltage, is about 12 volts. Since the energy lost from the drive circuit is then lost from the MOSFET, the total energy lost to fire the gate is:

$$\text{E-gateloss} = 2 * Qg * Vgs$$

The power lost because of this gate charge is thus,

$$\text{gate-loss} = freq * (2 * Qg * Vgs). \qquad (5.7)$$

The gate loss associated with operation with one MOSFET is 0.0178 watts.

6 THE DIODE

6.1 PURPOSE AND FUNCTION

The diode or diodes in the MPPT may be in various positions in the MPPT power stage as seen in figures 3.3 and 3.4. The diode is ideal for the power stage of the MPPT, because it acts like a switch which can be controlled by the voltage at the anode. When this voltage is more positive than the cathode terminal by an amount greater than the forward voltage drop the diode turns on and conducts. If the circuit current through the diode goes negative while the diode is on, the diode turns off.

In the MPPT power stage circuit, the diode complements the MOSFET so that power can be transferred from the solar cell array to the batteries. When the MOSFET is turned off, the diode is allowed to conduct, so that energy can be transferred from the inductor to the capacitor. Thus the diode with a duty cycle equivalent to (1-d), where d is the MOSFET duty cycle, helps complete the cycle of power transfer from the solar cells to the batteries.

6.2 DIFFERENT TYPES AND THEIR CHARACTERISTICS

The diode has several intrinsic characteristics which must be observed before it can be found suitable for use in the MPPT. The diode must have a low forward voltage drop so that conduction losses are minimal. The maximum reverse voltage must be greater than the input voltage. The diode's reverse recovery time, that is the time for the diode to turn off, should be not more than 30-40 nanoseconds. Finally, the diode should be able to handle the maximum load current in the MPPT, typically between three and twelve amps.

The types of diodes which may be used in the MPPT are described in Table 2.

Diode name	Vrmax	Iavgmax	Cdo	ninpack
UES-1404	200 Volts	8 Amps	100.e-12 F	1
UES-1504	200 Volts	16 Amps	100.e-12 F	1
UES-2404	200 Volts	8 Amps	100.e-12 F	2
UES-3015C	150 Volts	15 Amps	100.e-12 F	2
UES-3015S	200 Volts	30 Amps	100.e-12 F	1
FEP30-P	200 Volts	15 Amps	100.e-12 F	2

Table 2: The important characteristics for possible diodes in the MPPT.

In this table, Vrmax is the maximum reverse voltage, Iavgmax is the maximum average current which can be tolerated by the diode, Cdo is the diode capacitance, and ninpack is the number of diodes in each diode pack.

6.3 THE DIODE LOSSES

6.3.1 The conduction loss

A diode's conduction loss is based chiefly on its forward voltage drop, Vf. The equation for this loss is:

$$\text{diodeloss} = Vf * (1-D) * I \qquad (6.1)$$

where (1-D) is the diode's duty cycle and I is the forward current passing through the diode. In the boost mode, I is I-in, and in the buck mode it is I-out.

The forward voltage drop of the diode is a characteristic drop in voltage across the diode when current is passed through it. Each diode has its own characteristic curve relating the forward current to the forward voltage. Figure 6.1 shows the curves for the UES1404. To obtain a usable relationship between this current and voltage it is necessary to approximate the curve at 25°C with a line. The relationship between the two then takes the following form:

$$\text{Vforward} = Vf = (\ \log10\ (I) - \text{intercept}\ )\ /\ \text{slope} \qquad (6.2)$$

where "intercept" is the y-intercept when the forward voltage, Vf, is zero, and "slope" is the slope of the line which approximates the curve. Table 3 provides information about the intercept and slope for each of the diodes in Table 2.

Diode name	intercept	slope
UES-1404	-3.5	5.00
UES-1504	-4.66	6.66
UES-2404	-2.97	4.37
UES-3015C	-2.60	4.30
UES-3015S	-4.59	6.99
FEP30-P	-3.72	5.55

Table 3: The slope and intercept for each diode under consideration for the MPPT.

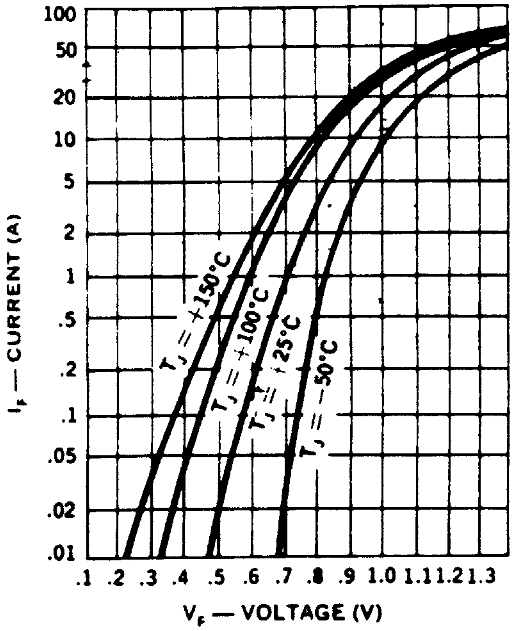

Figure 6.1: Typical curves at various ambient temperatures for forward current versus forward voltage (for the UES1404 Unitrode diode).

The diode's junction temperature has a serious role in determining the final value of Vf. Although the maximum temperature for a diode is 150°C, the forward voltage drop decreases as the junction temperature increases. Equations 6.3a, 6.3b, and 6.3c describe the computer code for scaling the forward voltage drop by the absolute temperature of the diode junction (Horowitz and Hill, 1985):

```
define centigrade ( t )   ( 273. + ( t ) )                                 (6.3a)

define scaletemp  ( t )   (centrigrade ( 25. ) / centigrade ( t ) )        (6.3b)

define vf ( dp, i, t )    (scaletemp ( t ) * \                             (6.3c)
                          ( ( log 10 ( i ) - ( dp ) -> intercept ) / ( dp ) -> slope ) )
```

where t is typically replaced with the diode's junction temperature. The second line of Equation (6.3c) is equivalent to Equation (6.2). Since the user may pick any diode in the table, a diode pointer, (dp), is used to obtain the necessary information (intercept or slope) about the chosen diode.

The diode junction temperature, dtemp, is derived the same way as the MOSFET's junction temperature:

```
dtemp = t-amb + r-th * diodeloss                                   (6.4)
```

The thermal resistance, r-th, for an average diode without a heat sink is typically 60°C / Watt, whereas when a heat sink is used r-th can range from 5°C / Watt to 20°C / Watt.

Equations (6.1), (6.3), and (6.4) can be combined to determine the diode's conduction loss. Given a certain operating current and a specified diode, Vf is first computed with dtemp at the ambient temperature, t-amb. For a given amount of power transfer, when the voltage drops, the current increases. Therefore, the value of Vf is used to compute the initial diode loss. The value of Equation (6.1) is then used to calculate dtemp given a certain thermal resistance. The value of dtemp is then used to find a new value for Vf. The cycle continues until the new value for dtemp is not more than 0.1°C above the previous value. It is at this final diode temperature that the actual value of the diode conduction loss, Equation (6.1), is computed.

Figures 6.2a-f show the relationship between the input voltage and the diode conduction loss for each diode in Table 2. A parallel combination of diodes is used for the analysis since some diode packs contain 2 diodes. The graphs show that the UES3015S is the most efficient diode, of all the diodes in Table 2. Unlike the others, this diode can handle higher amounts of transferred power given no heat sinking (r-th = 60 °C); it has better thermal conductivity since there is only 1 diode in the pack.

Figure 6.3 shows the diode temperature of the UES3015S. The graph shows that on the buck side the diode is limited by the MOSFET's rise in temperature, whereas on the boost side the diode is affected by its own rise in junction temperature. Even 2 parallel UES3015S diodes cannot overcome the high current generated by a large amount of power transfer.

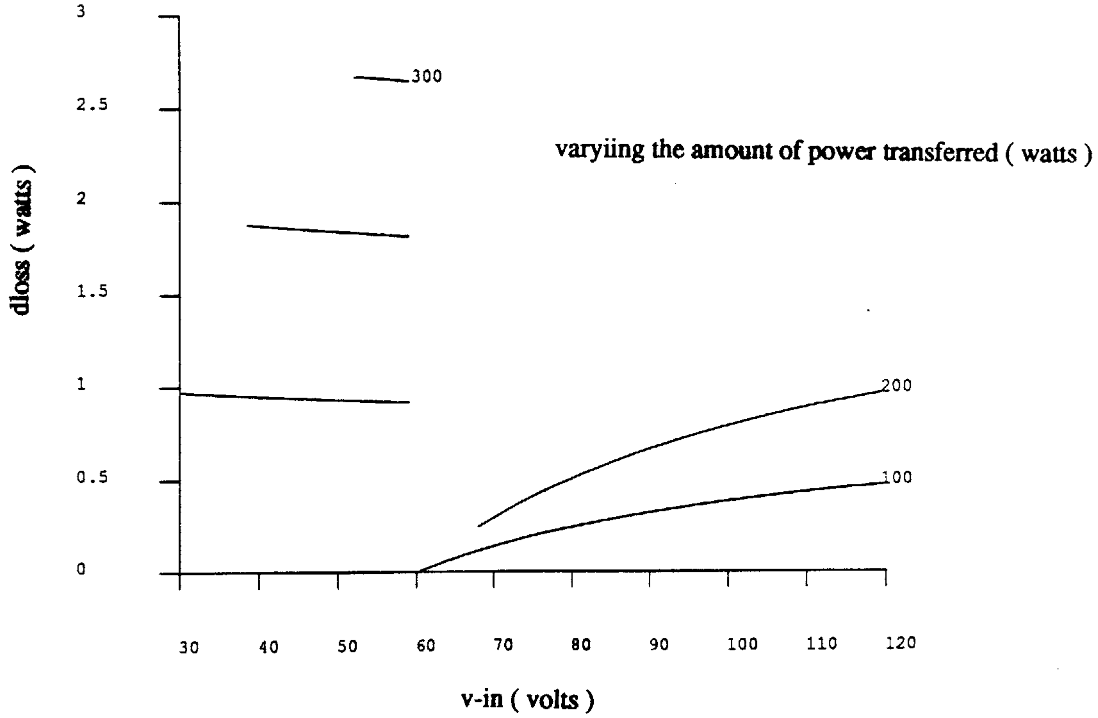

Figure 6.2a: The diode power loss versus v-in for the UES3015S

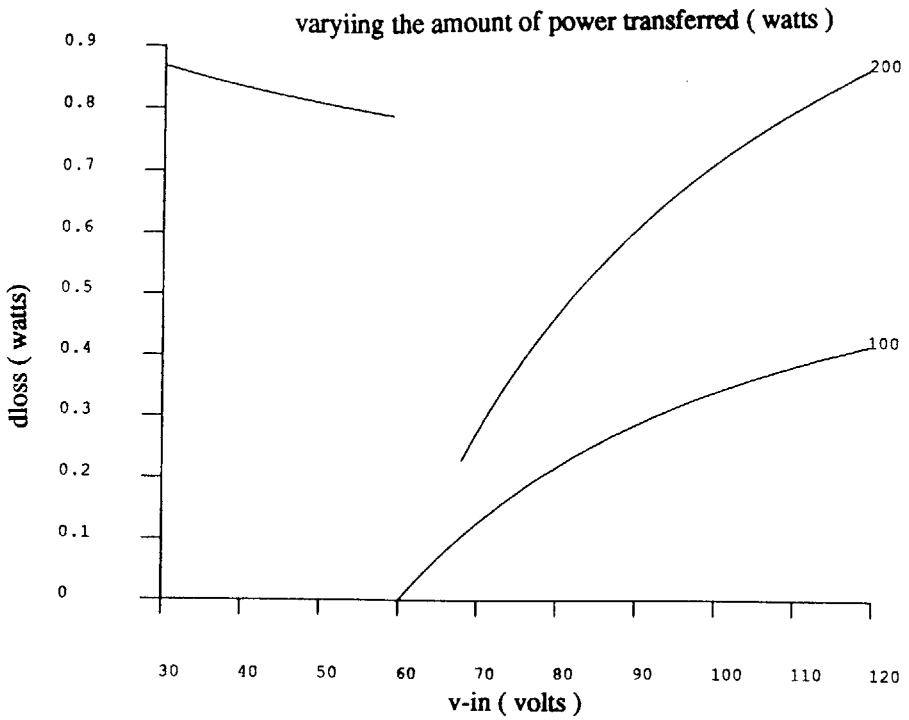

Figure 6.2b: The diode power loss versus v-in for the UES3015C

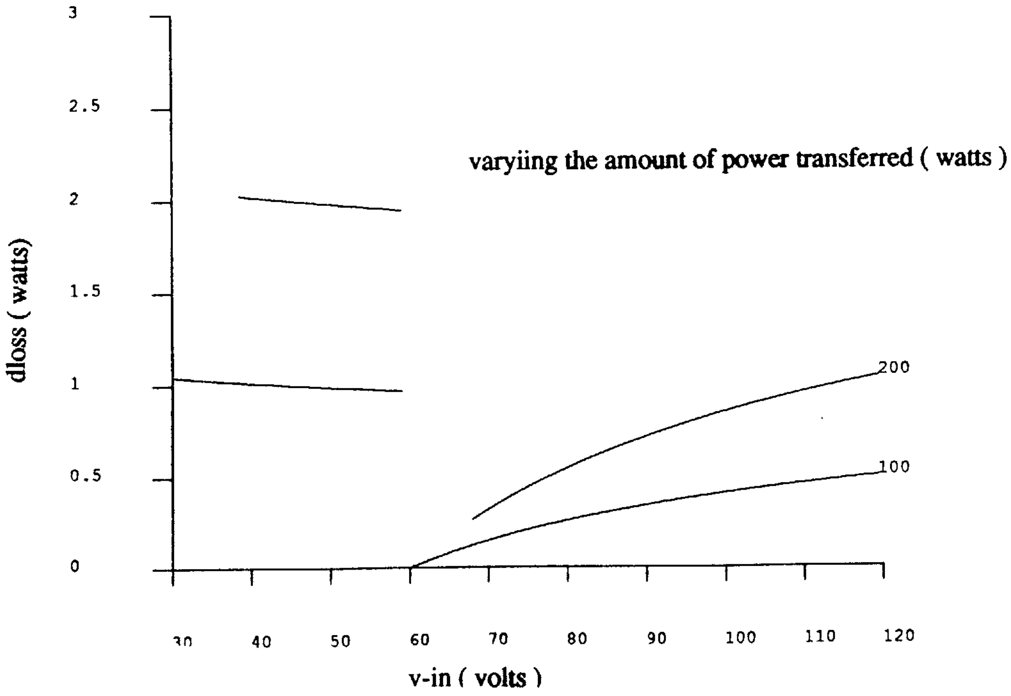

Figure 6.2c: The diode power loss versus v-in for the UES1404

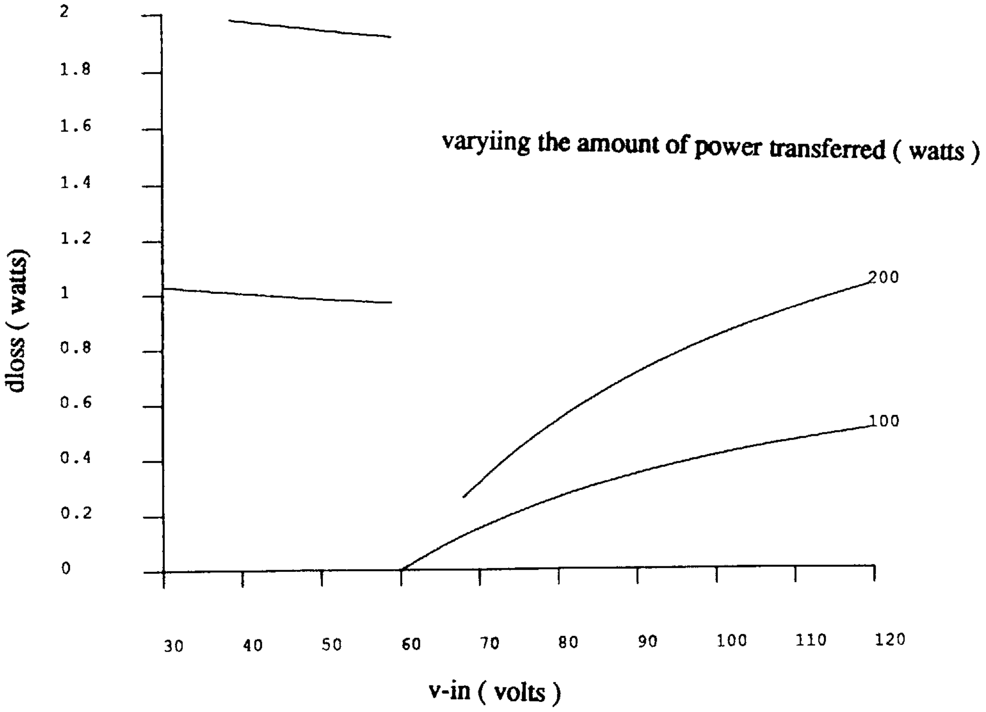

Figure 6.2d: The diode power loss versus v-in for the UES1504

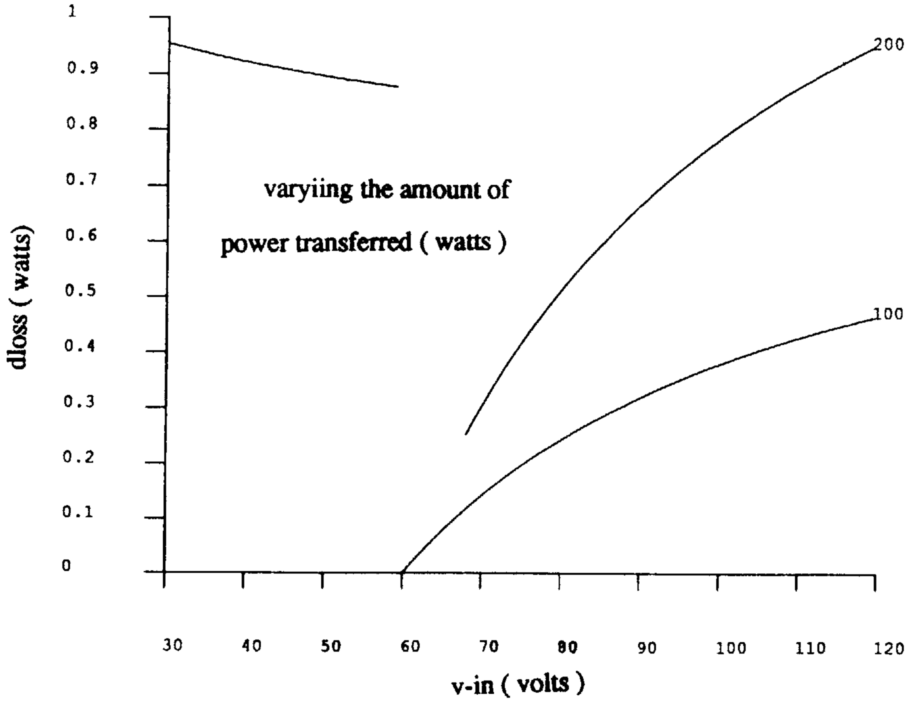

Figure 6.2e: The diode power loss versus v-in for the UES2404

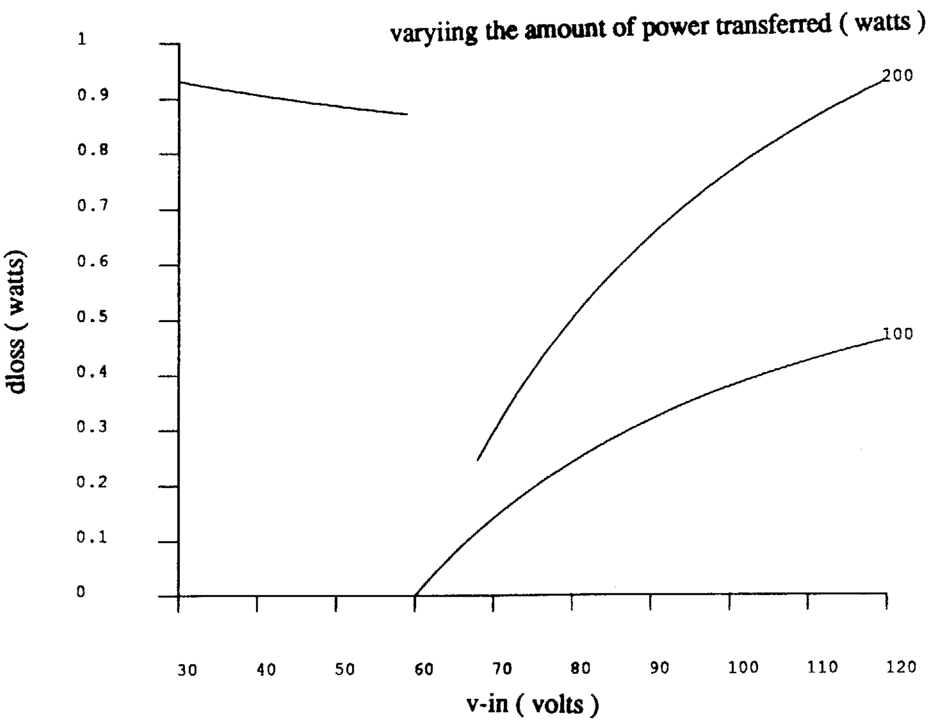

Figure 6.2f: The diode power loss versus v-in for the FEP30-P

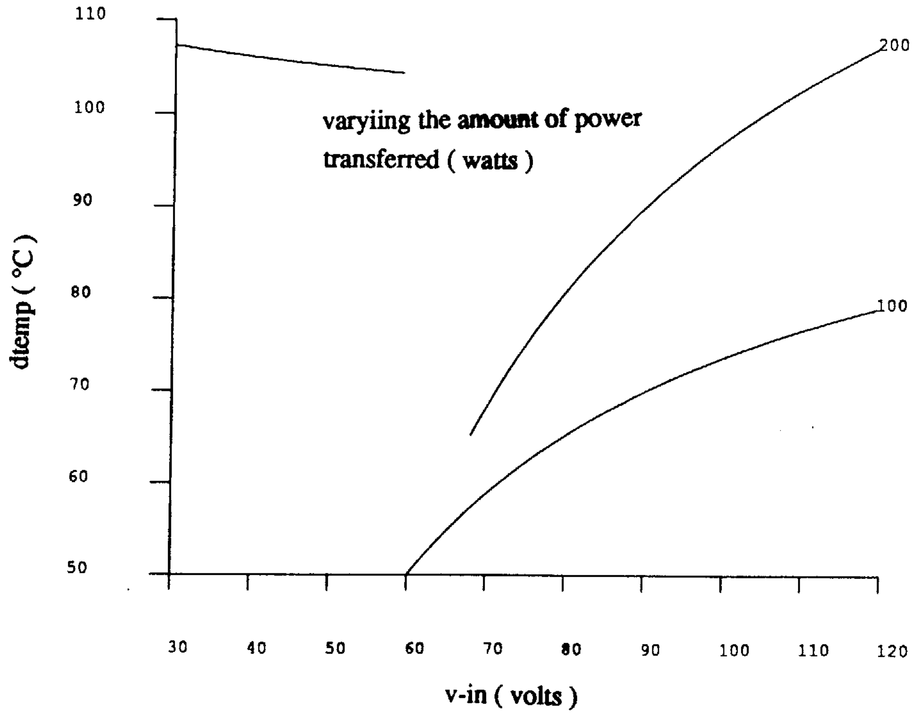

Figure 6.3: The diode temperature versus v-in for the UES3015S

6.3.2 The Charge loss

The other major loss in the diode is due to the diode switching loss. As noted in table 2, the diode has an intrinsic parasitic capacitance, Cdo. When the diode is turned off, the parasitic capacitor is charged up as a means of directing the current. The final charge of the diode capacitor is:

$$Qd = 2 * Cdo * v\text{-}diode$$

where v-diode is the voltage across the diode. Since Qd comes from the principal voltage source, the energy from the source is Qd * v-diode. Not all of the energy from the source is transferred to the diode. The actual amount transferred is:

$$E\text{-}diodeloss = Qd * v\text{-}diode — 4 / 3 (0.5 * Cdo * v\text{-}diode * v\text{-}diode) =$$

$$E\text{-}diodeloss = 8 / 3 (0.5 * Cdo * v\text{-}diode)$$

as stated by Schlecht and Casey (Schlecht and Casey, 1987).
The total power loss due to the capacitance in the diode is:

$$dc\text{-}loss = 8 / 3 * (0.5 * Cdo * v\text{-}diode) * freq \qquad (6.5)$$

where "dc-loss" is called the diode charge loss (Schlecht and Casey, 1987). Even though this charge originates in the diode, the power loss occurs in the MOSFET. Typically, this loss is much less than the conduction loss, ranging between 0 watts and 0.1 watts; however, it must be included in the overall calculation.

7. REDUCING THE LOSSES

7.1 PARALLELING COMPONENTS

From the preceding figures and data, it is evident that the losses associated with a single MOSFET and a single diode are not the only consideration in the performance of the MPPT. In fact, for all practical purposes, the losses are minimal. It is the rise in temperature of the components which is critically important. When operating over 100 watts of power transfer in the boost mode and over 200 watts of power transfer in the buck mode, a lot of current passes through a single device. For this reason, the junction temperature rises and hits the peak rating of 150°C very quickly. Thus, an MPPT configured with 1 diode and 1 MOSFET, cannot operate at practical power levels and it would seem impossible, no matter what the configuration, to arrive at a practical 98% efficient tracker.

The most plausible solution to the problem of power loss and thermal rise is to attempt to eliminate the larger losses so that the junction temperature in the ocmponents will not rise too fast. The answer is to limit the diode and MOSFET conduction losses. The only method of effectively reducing these power losses is to reduce the resistance of each device. The best way to do this is to place two or more of each device in parallel. The procedure code for determining 'floss', the conduction loss for paralleled MOSFETs, is given in Equation (7.1). In the equation, nfet is the number of paralleled MOSFETs and i-fetrms is the rms current of the MOSFET as described in Section 3.2. Here rfet is the resistance of the paralleled combination of MOSFETs; it is affected by ftemp, which is influenced by the number of MOSFETs in parallel. To acquire the characteristics of a MOSFET, a MOSFET pointer, called (fp), is used. This way, the user can enter a MOSFET name from Table 1 and the program will pick the named MOSFET and extract the characteristics which are demanded.

```
#define TEPSILON .1

double fequil(fp, nfet, t_amb, r_th, i_rms)                (7.1)
    struct fet *fp;
    int nfet;
    double t_amb;
    double r_th;
    double i_rms;
```

```
{
    double oldtemp = 0.;
    double temp;
    double power;
    double r;

    for (temp = t_amb; fabs (temp - oldtemp) > TEPSILON;

         temp = t_amb + r_th * power
     {
         if (temp > t_max)
             return (-1.);

         oldtemp = temp;

         power = condloss(fp, nfet, temp, i_rms) / nfet;
     }

     return (temp);
 }

#define rfet(fp,temp) ((temp) * (fp)->slope + (fp)->rzero)

#define condloss(fp,nfet,temp,i_rms) \
        ((i_rms) * (i_rms) * rfet (fp, temp) / ((double) nfet))

 ftemp = fequil (fp, n_fet, t_amb, r_th, i_fetrms);

 if (ftemp < 0.)
     continue;

 floss = condloss (fp, n_fet, ftemp, i_fetrms);
```

The procedure code for determining 'dloss', the conduction loss for paralleled diodes, is given in Equation (7.2).

(7.2)

```
#define TEPSILON .1

double dequil(dp, ndiode, t_amb, r_th, i_max, d)
    struct diode *dp;
    int ndiode;
    double t_amb;
    double r_th;
    double i_max;
    double d;
```

cont. (7.2)

```
{
    double oldtemp = 0.;
    double temp;
    double power;
    double r;

    for (temp = t_amb; fabs (temp - oldtemp) > TEPSILON;
          temp = t_amb + r_th * powe
    {
        oldtemp = temp;

        if (temp > t_max)
            return (-1.);

        power = diodeloss(dp, ndiode, temp, i_max, d) /
                 (ndiode / dp->ninpack);
    }

    return (temp);
}

#define centigrade(t)    (273.+(t))
#define scaletemp(t)     (centigrade(25.) / centigrade(t))

#define vf(dp,i,t)       (scaletemp(t) * \
                         ((log10(i) - (dp)->intercept)
                         / (dp)->slope))
#define diodeloss(dp,n,t,i,d)    ((d) * vf(dp,(i)/(n),t) * (i))

dtemp = dequil (dp, n_diode, t_amb, r_th, i_diode, (1. - d));

if (dtemp < 0.)
    continue;

dloss = diodeloss (dp, n_diode, dtemp, i_diode, (1. - d));
```

When the effect of paralleling components is analyzed in a graph, it is important that the thermal rise of the diode does not affect the MOSFET analysis and vice versa. To eliminate this bias, the following figures employ four paralleled MOSFETs while the number of diodes is changed, or four paralleled diodes when the number of MOSFETs is changed.

Figures 7.1 and 7.2 show that parallel components not only reduce the losses but effectively increase the performance of the maximum power point tracker. For instance, in figure 7.1a only 200 watts can be transferred in the buck converter, whereas in figure 7.1d the amount of transferred power goes up to 500 watts. Figure 7.2a shows that while using one diode only 100 watts can be transferred in the boost converter, whereas figure 7.2d shows that when four diodes are paralleled upto 500 watts may be transferred.

Figure 7.1 also shows that the difference in the power lost between 3 and 4 MOSFETs is not extremely large. Therefore, for monetary reasons, it is advisable to use 3 MOSFETs, rather than 4, in the main power stage (an entire study on the savings in cost versus savings in efficiency could be performed, but that is not the intent of this thesis. Figure 7.2 shows the radical difference in the practicality of using between one and four diodes. Since three diodes does cannot transfer upto 500 watts of power in the boost mode, it is wiser to use four diodes. However, the graphs also show that the buck configuration wastes less power; thus, is the user is certain that he or she will only use the MPPT in that configuration, it is alright to use three diodes. It should be noted that, in general, diode losses tend to be higher than MOSFET losses.

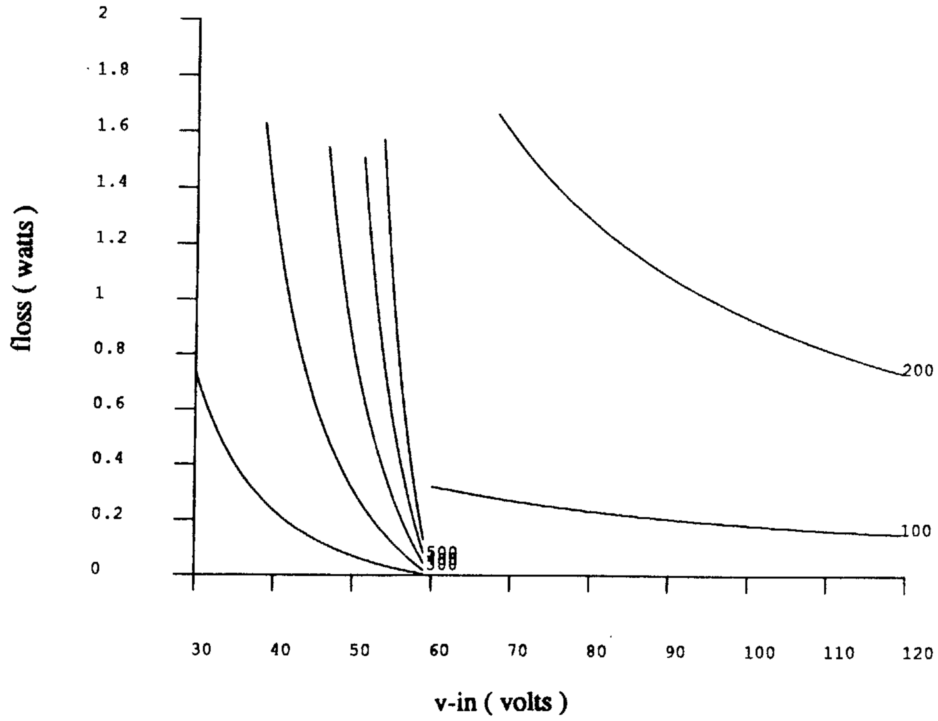

Figure 7.1a : MOSFET conduction power loss, floss, versus v-in for 1 MOSFET

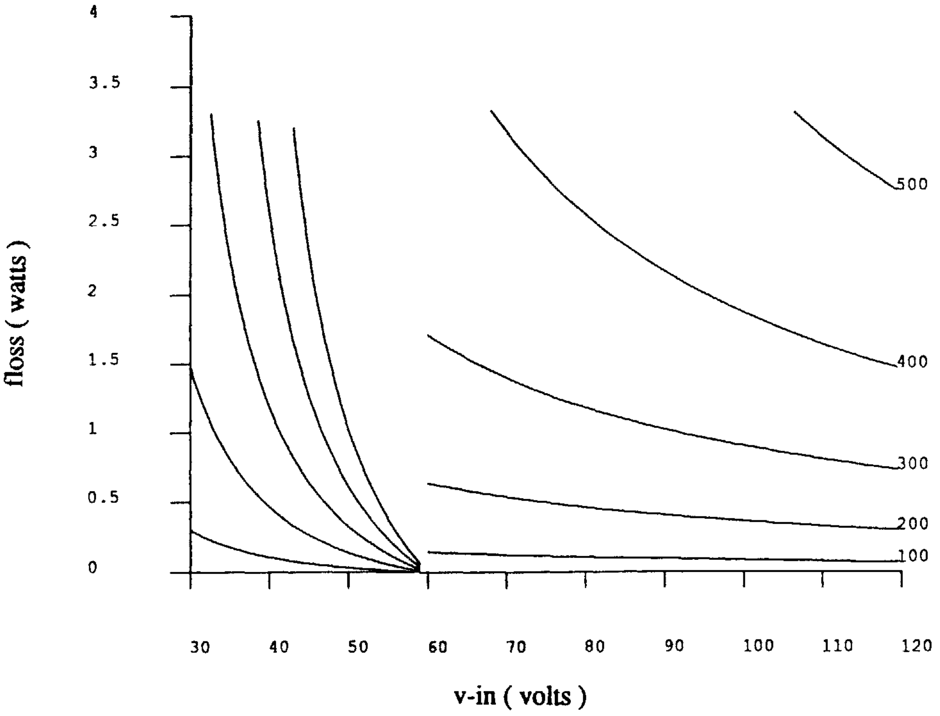

Figure 7.1b : MOSFET conduction power loss, floss, versus v-in for 2 MOSFETs

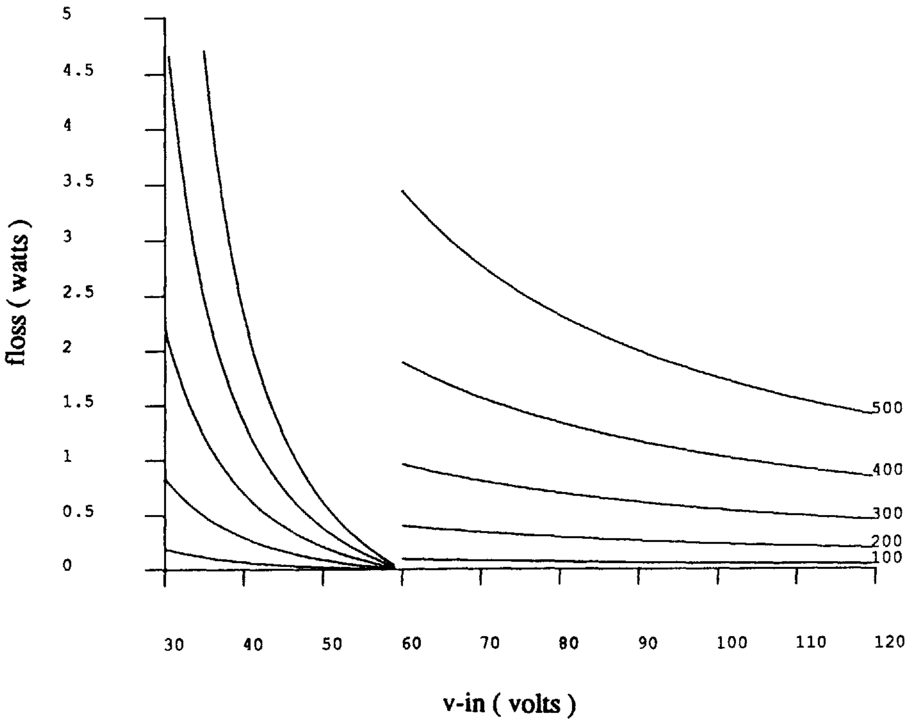

Figure 7.1c : MOSFET conduction power loss, floss, versus v-in for 3 MOSFETs

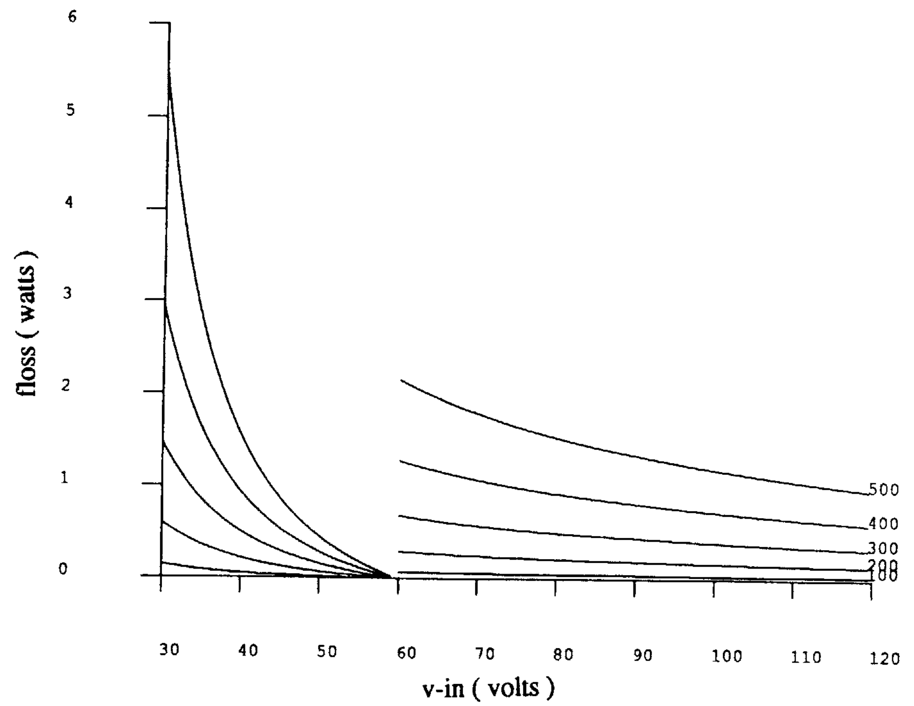

Figure 7.1d : MOSFET conduction power loss, floss, versus v-in for 4 MOSFETs

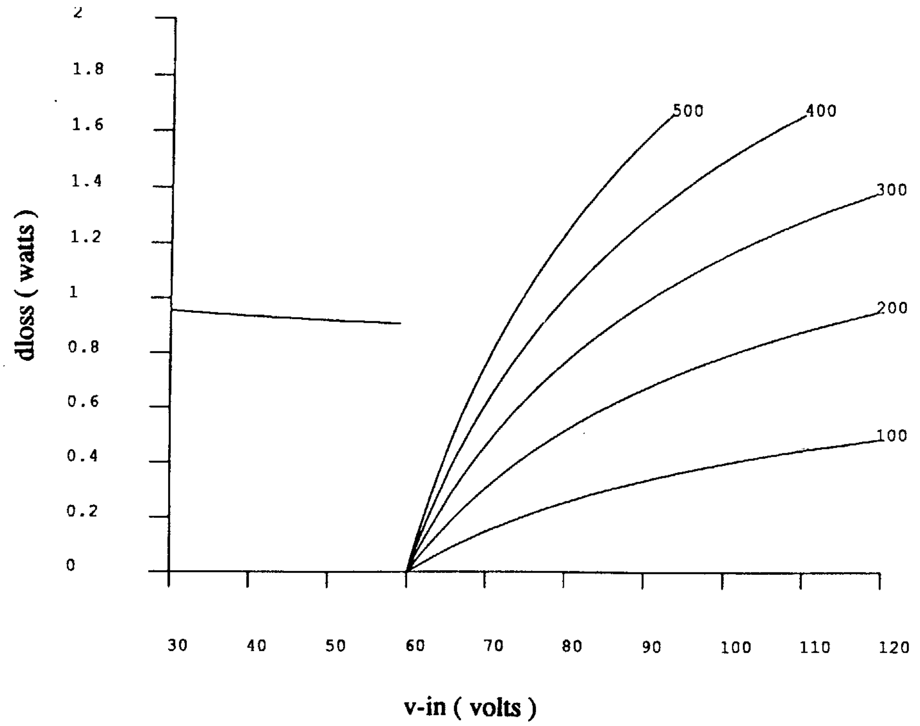

Figure 7.2a : Diode conduction power loss, dloss, versus v-in for 1 diode

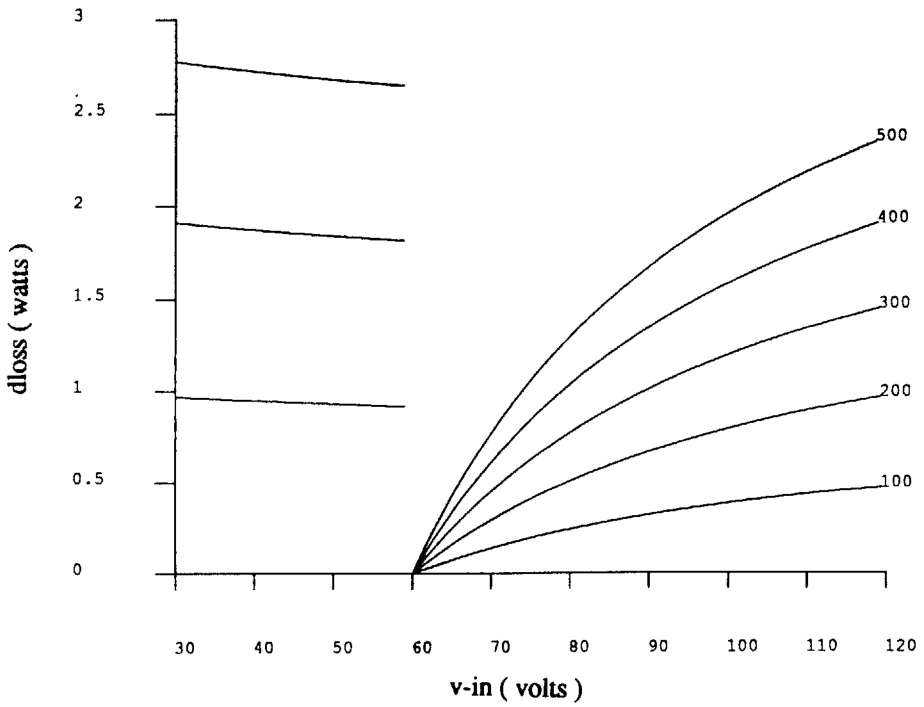

Figure 7.2b : Diode conduction power loss, dloss, versus v-in for 2 diodes

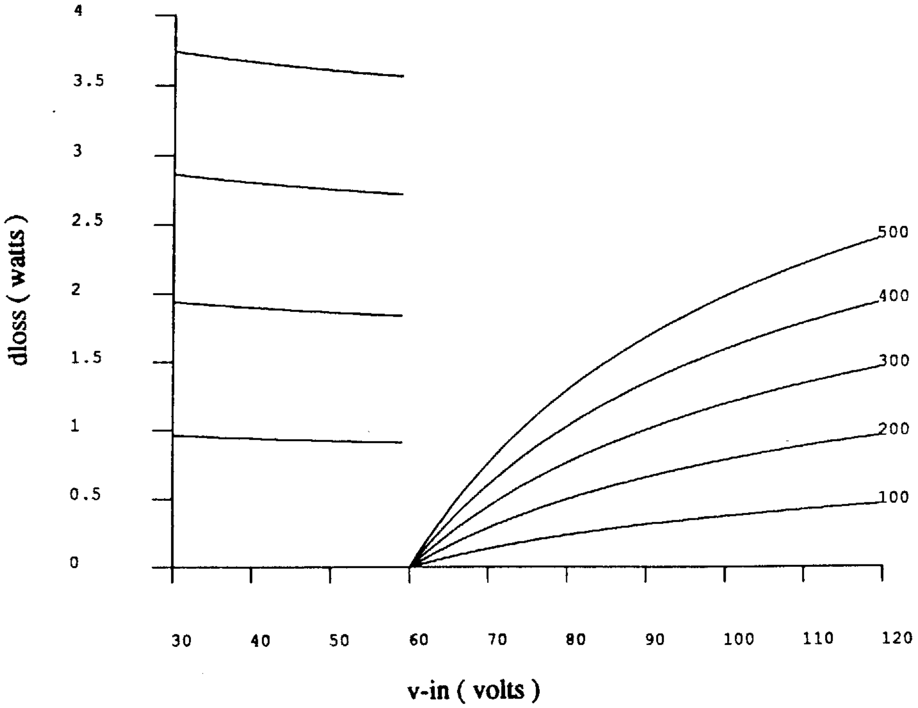

Figure 7.2c : Diode conduction power loss, dloss, versus v-in for 3 diodes

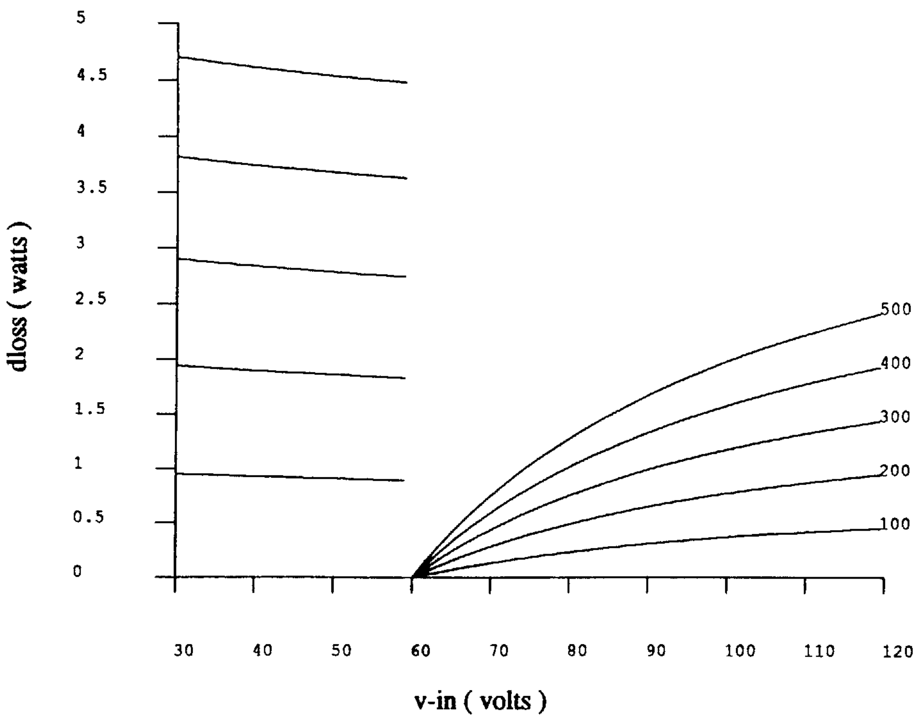

Figure 7.2d: Diode conduction power loss, dloss, versus v-in for 4 diodes

Figures 7.3 and 7.4 show that the rise in the junction temperature of each device is also controlled by using a combination of 3 paralleled MOSFETs and 4 paralleled diodes. Comparing these figures to figure 5.3 and figure 6.3 proves the effectiveness of having a paralleled combination of components.

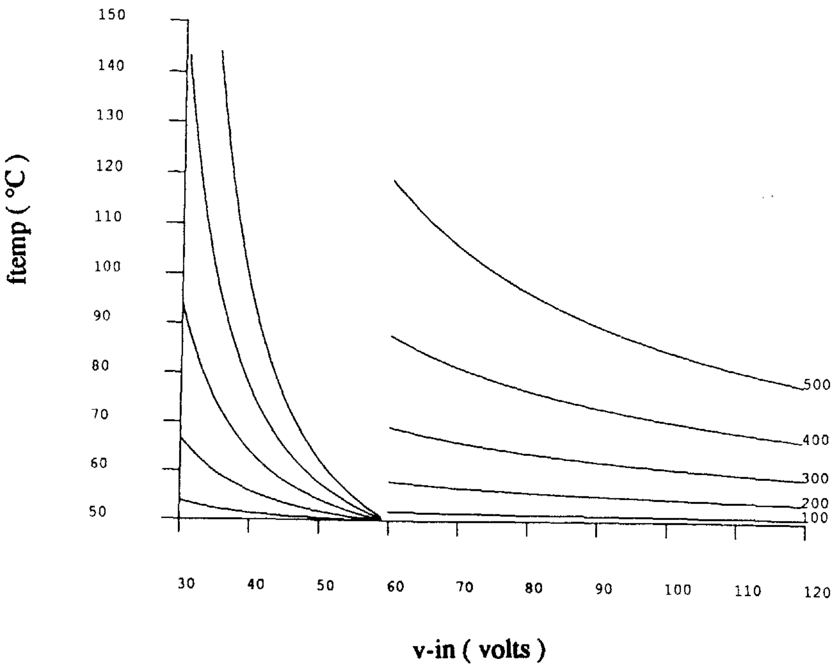

Figure 7.3: The junction temperature of each MOSFET when the main power stage uses 3 paralleled MOSFETs.

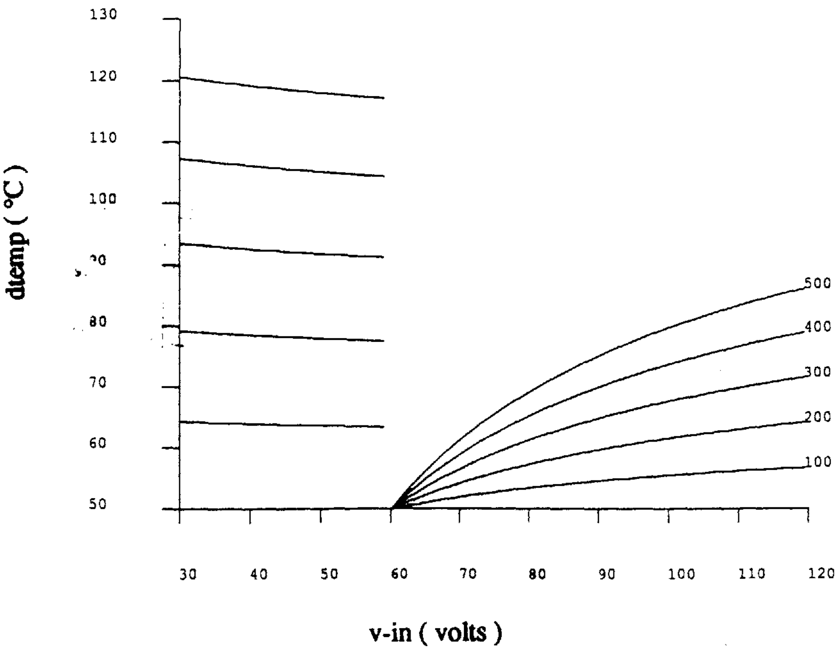

Figure 7.4: The junction temperature of each diode pack when paralleling 4 diodes.

7.2 USING A SNUBBER CIRCUIT

7.2.1 The structure and function of the snubber

Although the MPPT configured with three MOSFETs and four diodes in its power stage has reduced conduction losses, other losses are still prevalent. Unfortunately, the turn-on losses, gate losses and the diode charge losses increase due to the combination of MOSFETs and diodes. Furthermore, a problem is encountered because the diodes have a turn-off time which is longer than the MOSFETs' turn-on time. Therefore, there is a period of time during which both the MOSFETs and the diodes are conducting. This causes a great deal of noise, seen as current and voltage spikes, to occur. Since spikes can destroy components and contribute to large amounts of power loss, it is important to eliminate this problem caused by the diode turn-off transient.

A snubber circuit, which is placed critically between the main diodes and MOSFETs, is the answer to the problem. This snubber circuit, shown in figures 7.5 and 7.6, is made up of one MOSFET, one diode and a small air core inductor, which has a value of 10 microHenrys for this study.

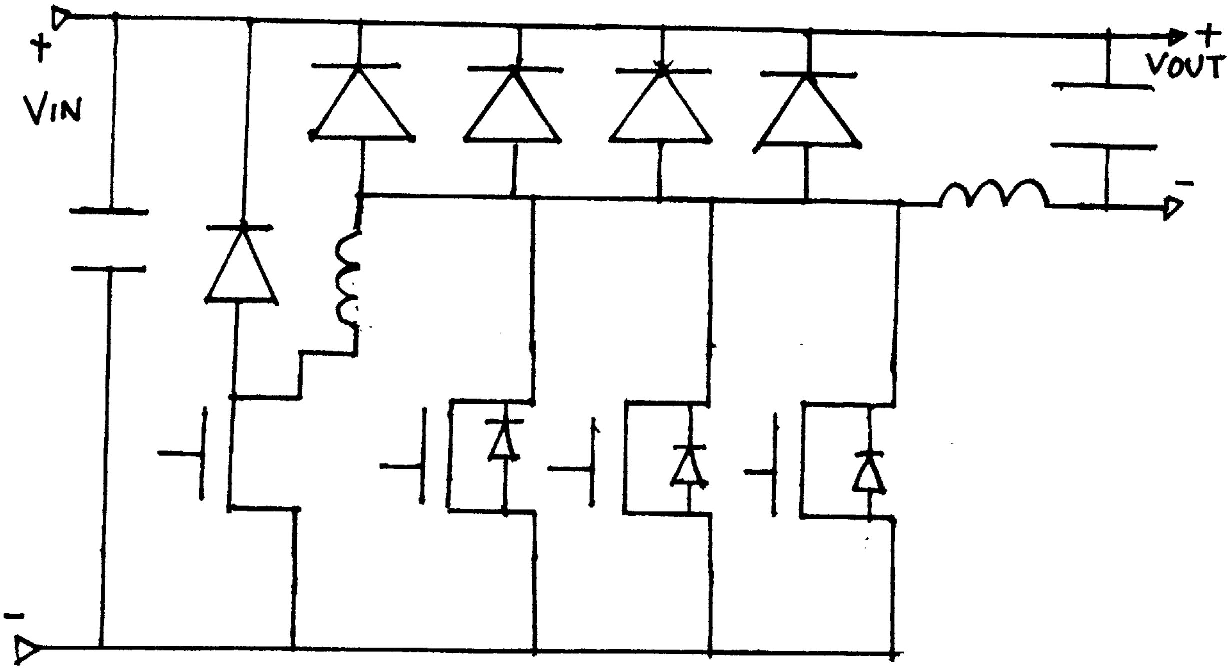

Figure 7.5: The MPPT power stage (as a buck converter) with a snubber circuit.

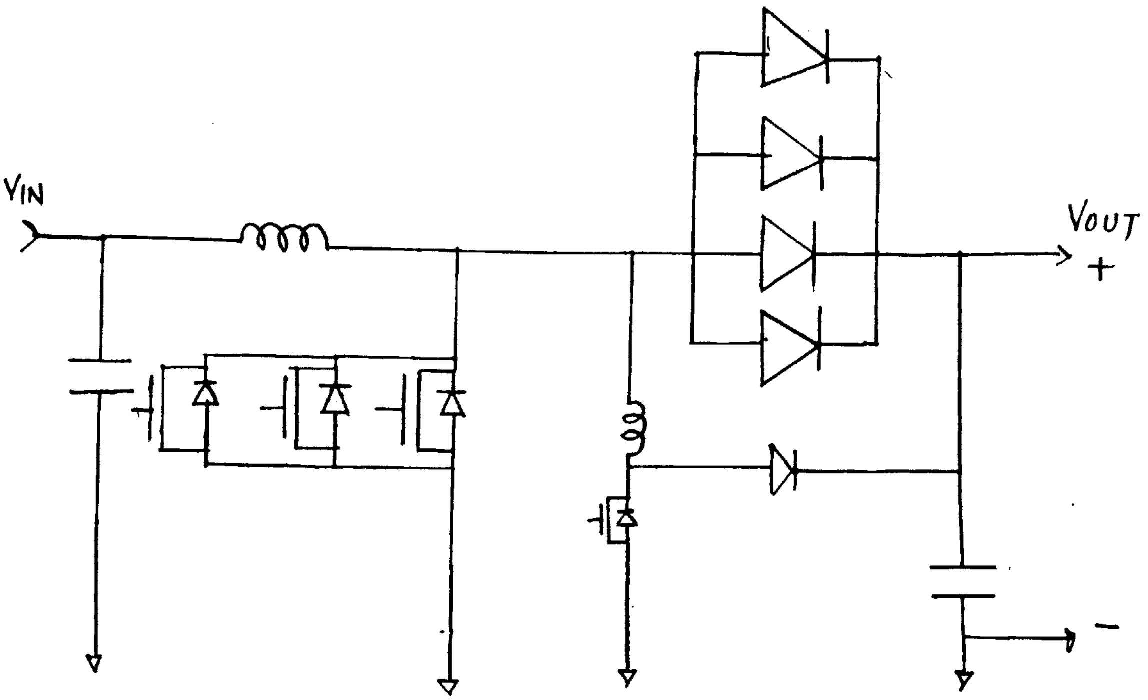

Figure 7.6: The MPPT power stage (as a boost converter) with a snubber circuit.

The process of limiting the noise and power lost in the main MOSFETs and diodes, for a boost mode MPPT, is as follows:

* The paralled MOSFETs are on.

* The MOSFETs are turned off and the main diodes conduct.

* The snubber MOSFET is turned on,causing the main diode to turn off, and the current which passed through the diodes now goes through the snubber inductor. When the inductor voltage reaches v-out (for the boost converter) the snubber MOSFET is turned off and the snubber diode is turned on, allowing the energy in the snubber inductor to be transmitted to the batteries.

*Just before the snubber MOSFET turns off, and as soon as the drain to source voltage drops low, the main stage paralleled MOSFETs are turned on.

The time for which the snubber MOSFET and the snubber diode are on is equivalent. In the boost mode this time, called the snub-time, is:

snub-time = i-in * l-snub / v-fet (7.3)

and in the buck mode this time is:

snub-time = i-out * l-snub / v-fet (7.4)

where v-fet is the MOSFET voltage and l-snub is the inductance of the snubber coil.

7.2.2 The losses created and eliminated by the snubber

The snubber circuit minimizes the switching power dissipation by allowing the main 3 MOSFETs to turn on only after the MOSFETs' source voltage has dropped to zero. The turn-on power which was previously lost in the three main MOSFETs is eliminated because the MOSFETs' source-to-drain voltage is initially zero and because there is no turn-on time delay. There is a small amount of turn-on loss associated with the snubber MOSFET, called the on-loss. In the program, this power, given in Equation (7.5), is equivalent to Equation (5.1).

```
#define onloss (fp, v, freq)  (( 4. / 3.) * .5  *  (fp)->cf0 * v * v * (freq))  (7.5)
on_loss = onloss (fp, v_fet, freq)
```

The turn-on loss of the snubber MOSFET is not affected by t-on or Lp because the current is zero when the snubber MOSFET is initially turned on. The snubber's turn-on loss is typically less than 0.1 watts.

The single MOSFET in the snubber circuit and the three MOSFETs in the main stage of the MPPT each have power losses caused by the gate charge. For the single snubber MOSFET the gate charge which contributes to the loss is the total gate charge, qg. The snubber circuit, though, causes the gate loss in the main MOSFETs to be minimal, since the source voltage is zero when the MOSFETs are turned on. Thus, the paralleled MOSFETs have a gate-loss associated with their gate to source charge and the single snubber MOSFET has a gate-loss associated with the total gate charge. In the program, the gate loss equation looks like the following:

```
#define gateloss (q, freq)  (2. * (freq) * (q) *12.)                    (7.6)
gate_loss = gateloss (fp-> qg, freq) + n_fet * gaate loss (fp->qs, freq)
```

where Vgs is 12 volts. Given the operating parameters the gate loss adds an additional 0.912 watts to the total power lost in the MPPT.

The snubber circuit also causes the diode-charge loss, or dc-loss, to be eliminated in the main paralleled diodes. As explained in section 6.3.2, this loss occurs when a diode is turned off. Since at turn-off, v-diode, which equals v-fet, is zero, the diode charge loss becomes zero. The remaining snubber diode, however, does have a small dc-loss, which is equivalent to that described in Equation (6.5). This equation is restated in Equation (7.7):

```
#define dcloss (dp, v, freq)  ((8. / 3.) * .5 *  (dp)->cd0 * (v) * (v) * (freq)    (7.7)
dc_loss = dcloss (sdp, v-diode, freq)
```

The snubber MOSFET and diode also have a small conduction loss. The MOSFET's conduction loss, called sfloss, is:

```
sftemp = fequil (fp, 1, t_amb, r_th, i_snubrms);

if (sftemp < 0.)
    continue;                                                (7.8)

sfloss = condloss (fp, 1, sftemp, i_snubrms);
```

and the diode's conduction loss is:

```
sdtemp = dequil (sdp, 1, t_amb, r_th,
                  i_snubdiode, snub_time * freq);
if (sdtemp < 0.)
                                                              (7.9)
    _ _
sdloss = diodeloss (sdp, 1, sdtemp, i_snubdiode,
                     snub_time * freq);
```

where

i-snubrms = .707 * i-in * sqrt (snub-time * freq)
i-snubdiode = .5 * i-in

for the boost mode and

i-snubrms = .707 * i-out * sqrt (snub-time * freq)
i-snubdiode = .5 * i-out

for the buck mode.

The following figures, figures 7.7 and 7.8, show the amount of power lost due to sfloss and sdloss. Contrary to floss and dloss, as v-in decreases in the buck mode the power lost in the snubber diode and snubber fet increases. This occurs because the conduction loss in the snubber MOSFET and diode increases with current and the current goes up as the voltage decreases for a given amount of power transfer.

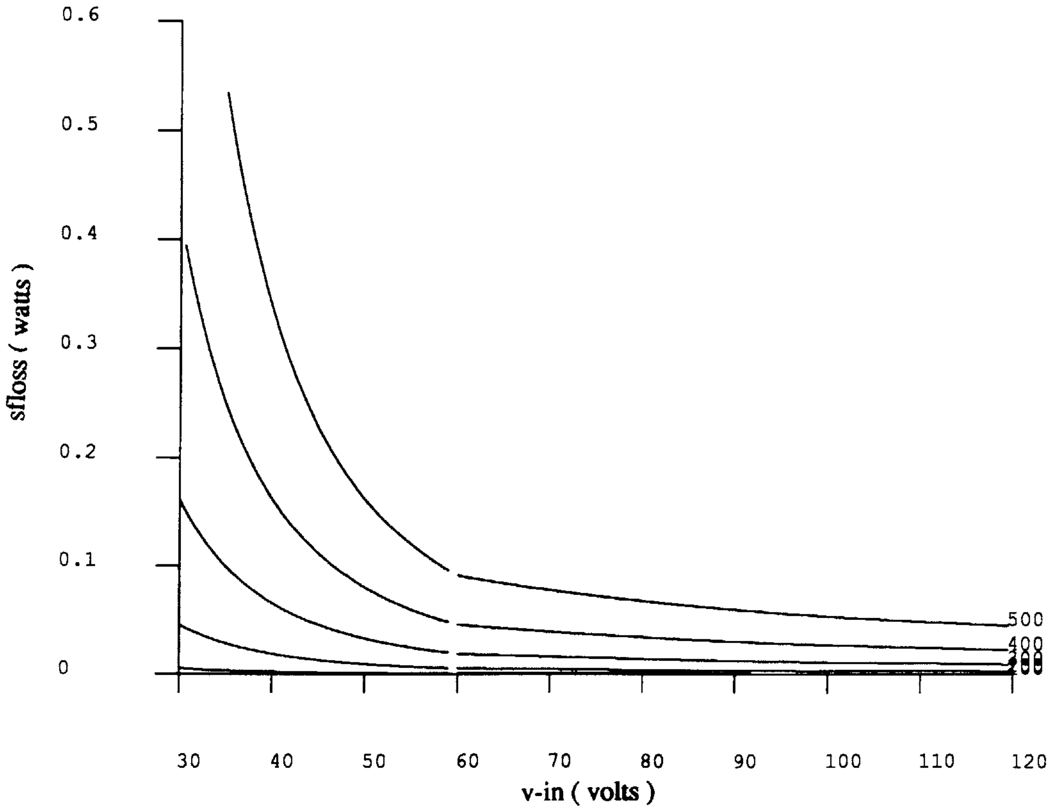

Figure 7.7: sfloss versus v-in

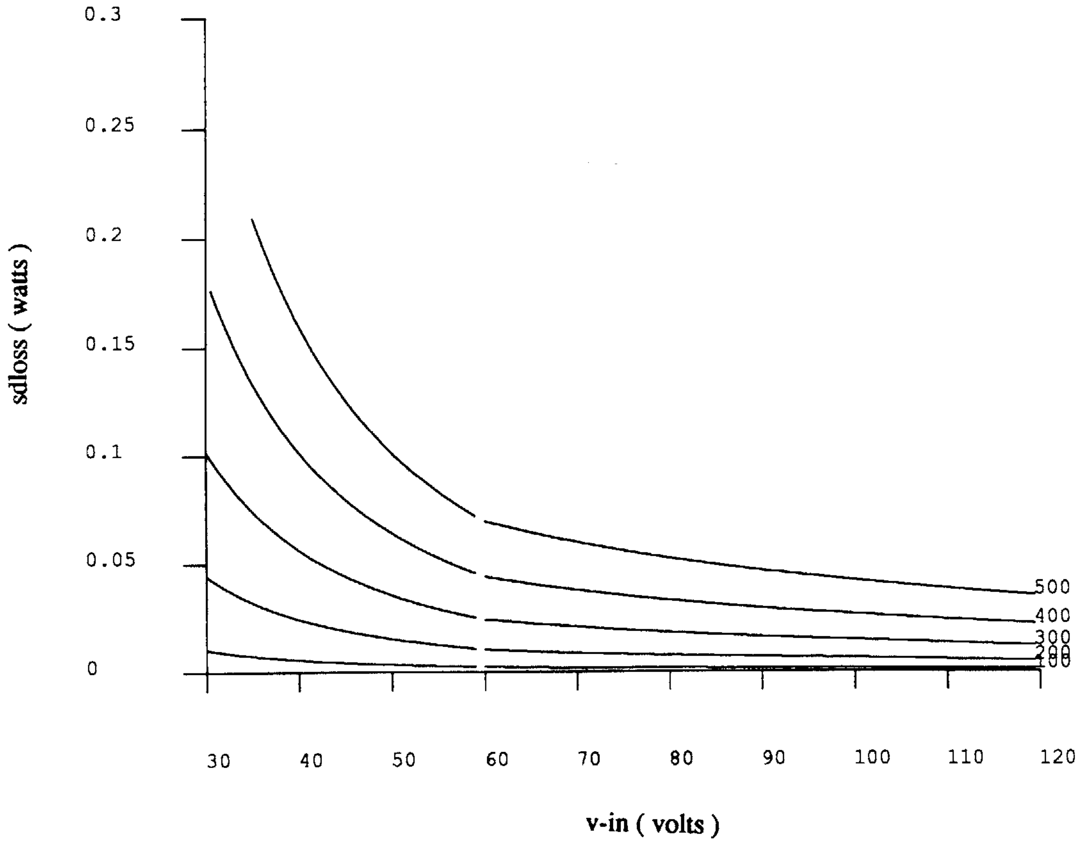

Figure 7.8: sdloss versus v-in

In order to derive the total power lost in the MPPT under the mentioned conditions all of the losses must be summed up. Thus the total power lost, called tloss, is equal to:

$$\text{tloss} = \text{floss} + \text{dloss} + \text{sfloss} + \text{sdloss} + \text{on-loss} + \text{gate-loss} + \text{dc-loss} \qquad (7.7)$$

Figure 7.9 shows the relationship between the total lost and v-in. This graph proves that the overall power loss in a buck converter is much less than a boost converter.

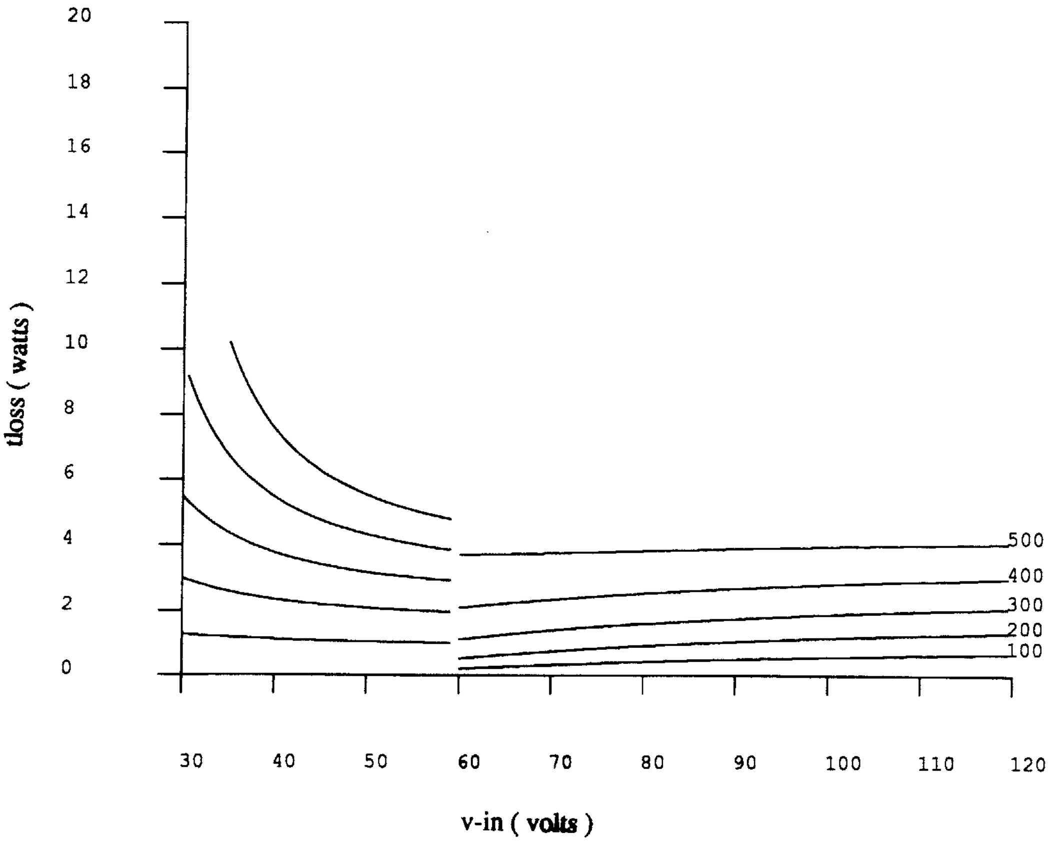

Figure 7.9: t-loss=floss + dloss + sfloss + sdloss + on-loss + gate-loss + dc-loss versus v-in.

The efficiency of the entire MPPT is the most crucial analysis for this study. The efficiency, eff, is determined by :

$$\text{eff} = 1 - (\text{tloss} / \text{power}) \qquad (7.8)$$

where the efficiency percentile is found by multiplying eff x 100%. In Equation (7.8), 'power' is the total power transferred.

Figure 7.10 serves as the final answer to the entire preceding discussion. It is a graph of the MPPT power stage efficiency versus v-in. The graph shows that the buck converter is much more efficient than the boost converter for all power levels. Even for 500 watts of power transfer, the buck converter is above 99.1% efficient. The boost converter permits the MPPT to operate above an efficiency of 98% for most values of d. At 500 watts, when d approaches 0.58 in the boost converter, the efficiency drops quite fast. Figure 7.10 also shows that the MPPT efficiency is greatest when the input and output voltage are close together. This is true for both the boost and the buck converter.

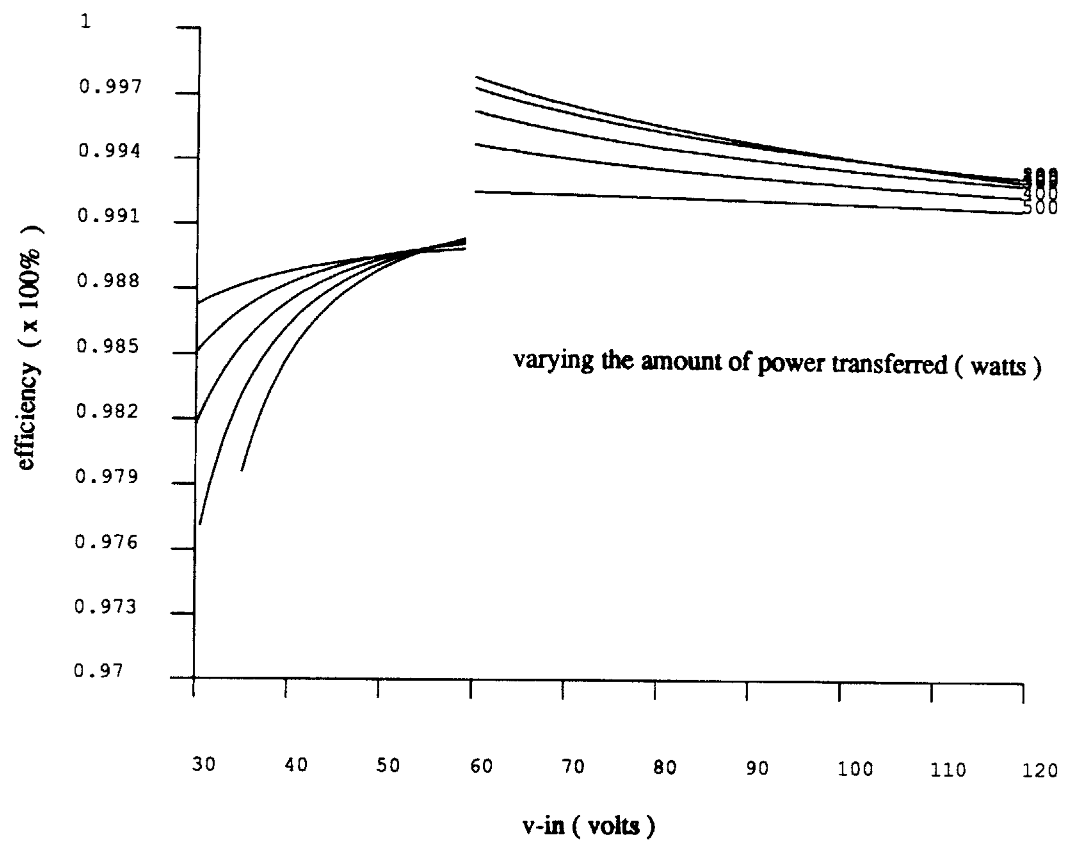

Figure 7.10: MPPT eff versus v-in

In the boost converter when there are small amounts of power being transferred, such as 100 watts, there is a drop in efficiency which is larger than that in the larger amounts of power transfer. This is because relative to the power being transferred, the losses are significant. In spite of all of this, the important fact to note is that paralleling three MOSFETs and four diodes maintains an MPPT efficiency well above 98% for most values of d.

7.3 OTHER METHODS OF DECREASING THE POWER LOSS

In spite of finally arriving at a maximum power point tracker whose efficiency exceeds 98%, it is vitally important that other variables, such as those which were fixed in section 2, are analyzed. The following analyses will explain what happens if a heat sink is added, if the number of parallel components changed, or if the ambient temperature is changed. Furthermore, by sweeping across variables other than the transferred power, one can learn more about the types of losses at low power, and the effect of t-amb.

7.3.1 Varying r-th

In the previous sections, r-th was fixed at 60°C/watt, the thermal resistance of the MOSFET and diode without a heat sink. Since the addition of a heat sink can be a cheap and easy way of limiting the loss of power, the effect of heat sinking needs to be analyzed. Figure 7.11 shows the difference in the MPPT's efficiency between operation with a good heat sink (r-th=10 °C/w) and no paralleled components and operation with no heat sink and no paralleled components. When a good sink is used, the MPPT can be made to operate above 98% at most power levels for the buck converter. Interestingly, in the buck mode, when v-in is near 60 volts, the tracker's efficiency drops dramatically. This is because the diode's efficiency increases when its junction temperature increases; in this case, the heat sink is making the diode run cooler.

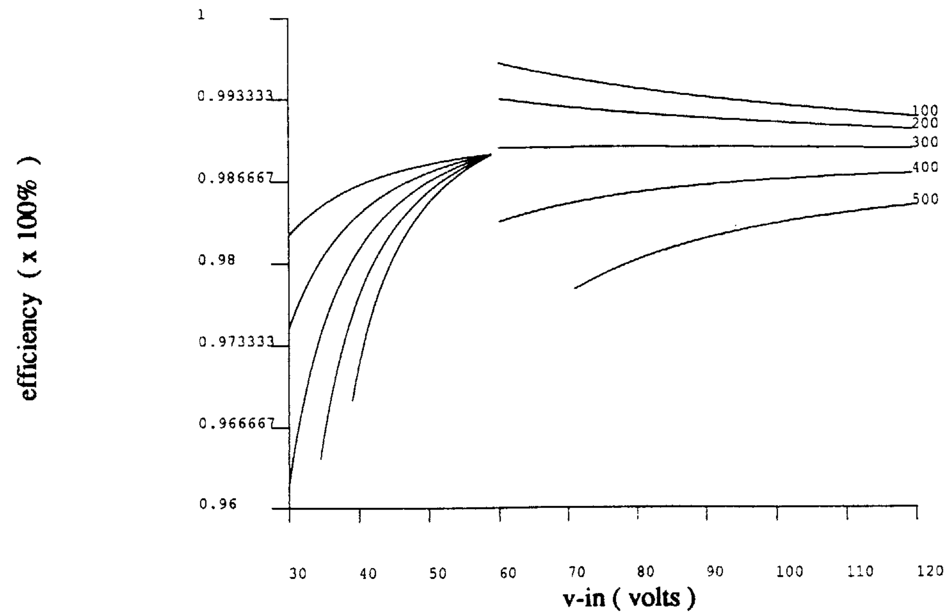

Figure 7.11a: The MPPT's efficiency versus v-in for a single diode and MOSFET when r-th=10°C/w.

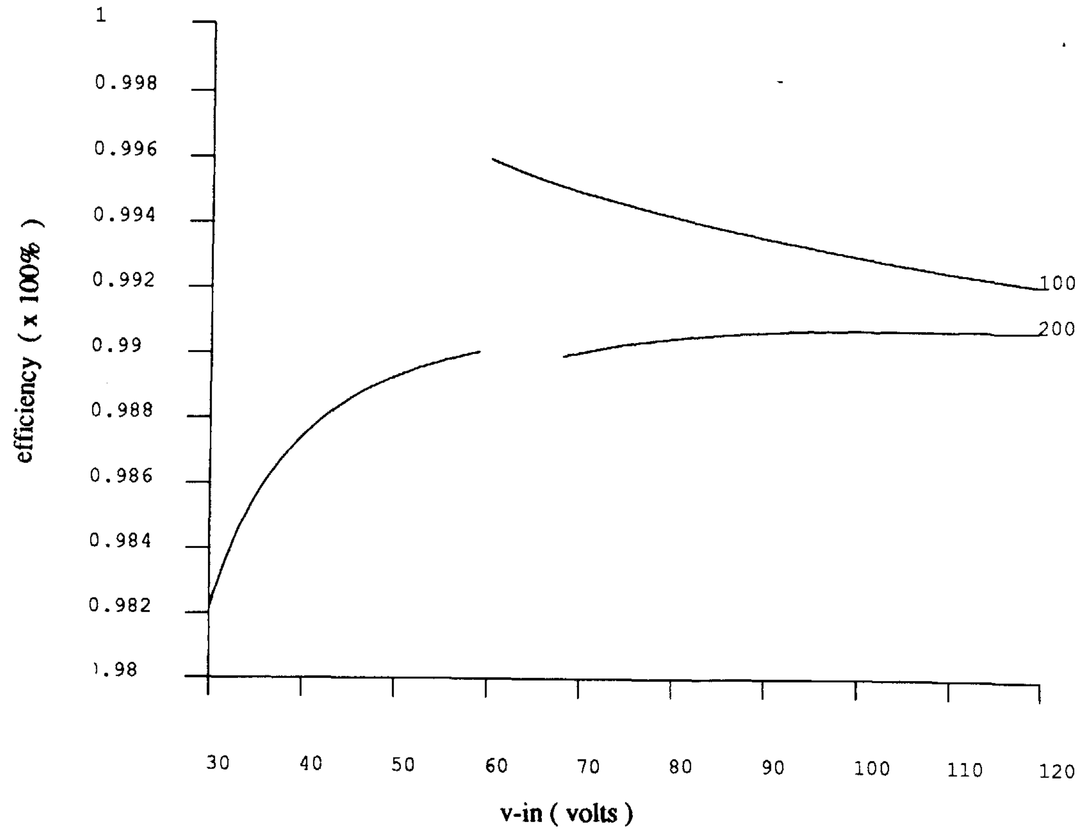

Figure 7.11b: The MPPT's efficiency versus v-in for a single diode and MOSFET when when r-th = 60°C/w.

Figure 7.12 shows that if the x-axis of a graph is the amount of power transferred, one can determine how many MOSFETs is most efficient at a certain level of power transfer for the boost converter. If only 50 watts are being transferred from the solar cells to the batteries, one MOSFET and four diodes can make the tracker 98.9% efficient. However more components are necessary when more power is transferred. There is not much difference in the efficiency when using three, four, or five MOSFETs, thus it is possible to use only three MOSFETs and have a practical MPPT.

Figure 7.13a and figure 7.13b compares the efficiency and the number of MOSFETs which can be used in a buck converter which has no heat sink (r-th = 60°C/w) and one with a good heat sink (r-th = 10°C/w). For both graphs, v-out is fixed at 60 volts and v-in is fixed at 90 volts and four parallel diodes are used. The efficiency and performance does not change for low amounts of power transfer. When the power transferred is greater than 200 watts, the MPPT with a heat sink is more efficient for 1 and 2 diodes. However, the heat sink does not really increase the efficiency when 3,4,or 5 MOSFETs are used. This data merely reinforces the fact that the maximum achievable efficiency, with or without a heat sink, is just above 99% for operation with 3 to 5 MOSFETs and four diodes.

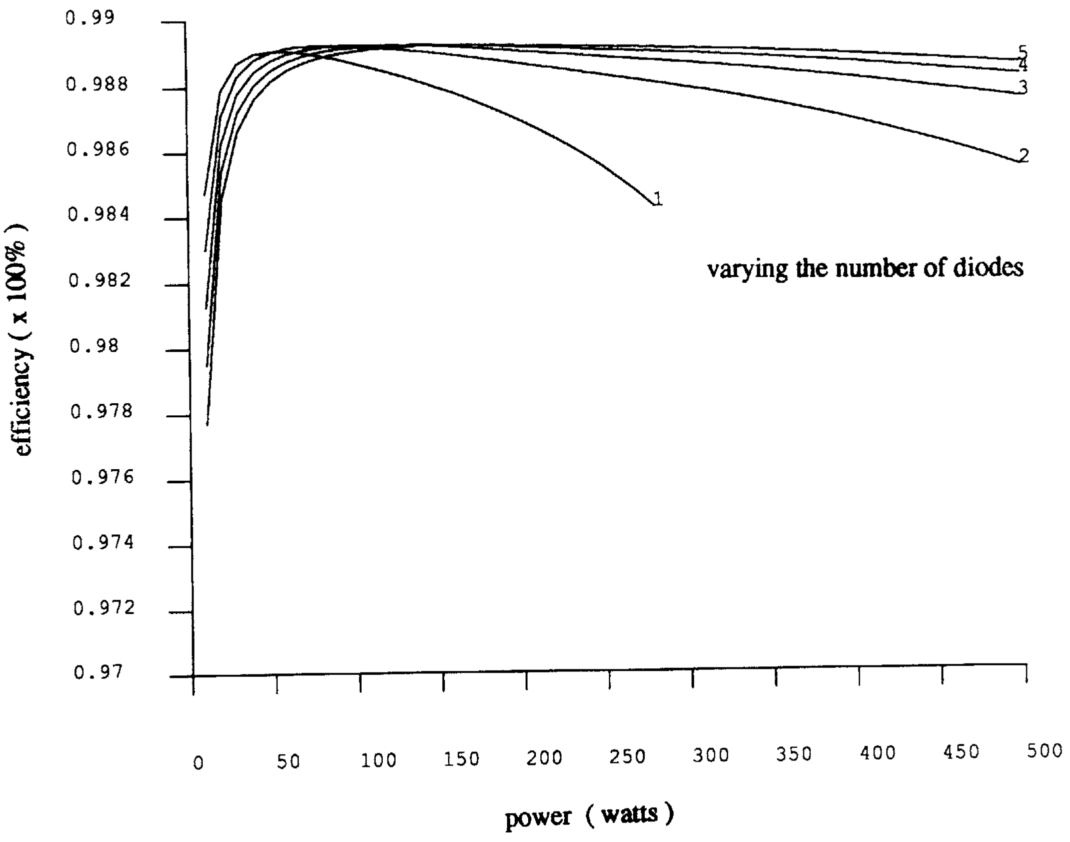

Figure 7.12: Efficiency versus power transfer for a boost converter.

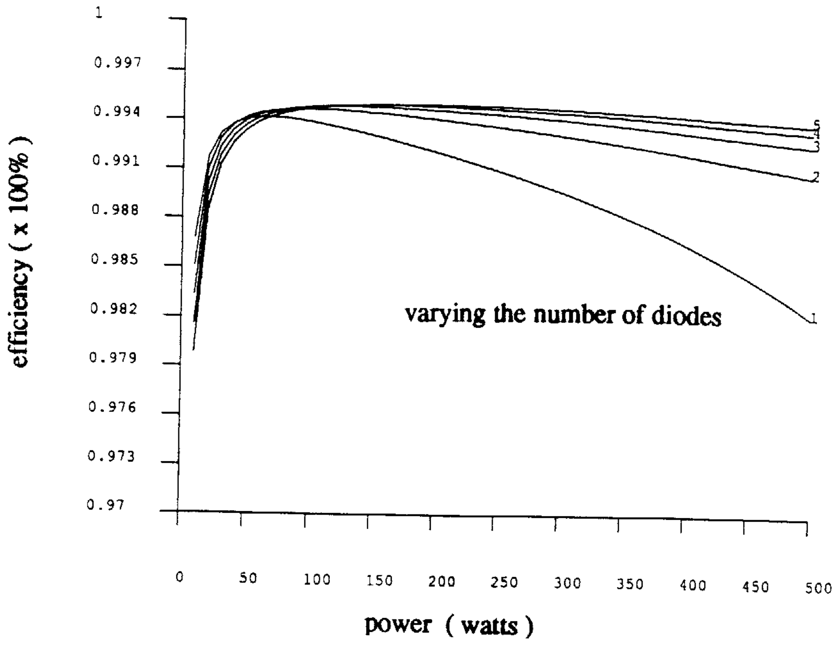

Figure 7.13a: Efficiency versus power transfer for the buck converter with r-th=60°C/w.

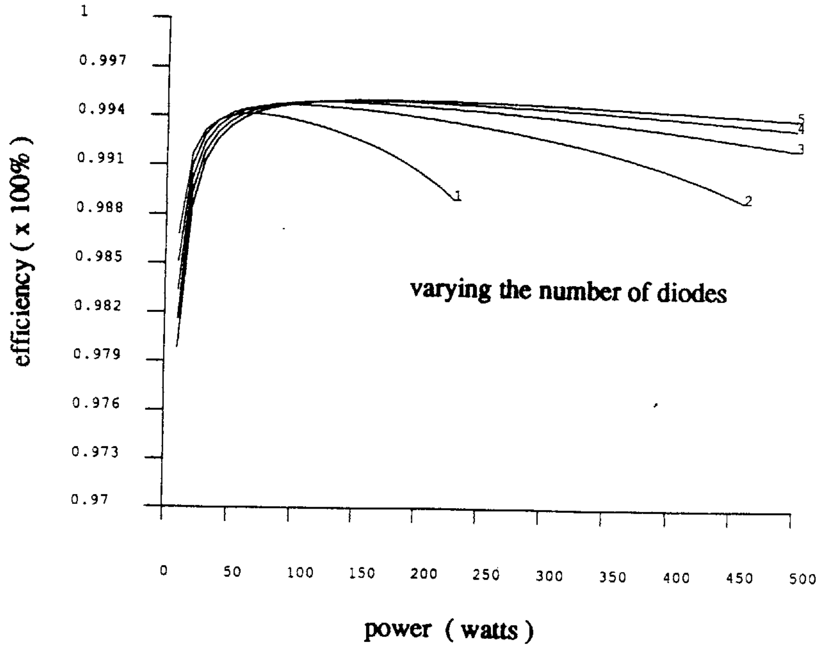

Figure 7.13b: Efficiency versus power transfer for the buck converter with r-th=10°C/w .

In Figure 7.14 the diode conduction loss is plotted against the thermal resistance while the number of diodes is varied from 1 to 6. The following are fixed: 500 watts of power transfer and three MOSFETs and a buck configuration.

Figure 7.14 is the most important figure to observe since it provides an answer as to which combination of diodes is more efficient for a certain amount of heat sinking. From the graph, the user can choose whether to use more diodes or more heat sink to improve the tracker's efficiency. For example, using one diode wastes less power between 40°C/w and 60°C/w than even five parallel diodes.

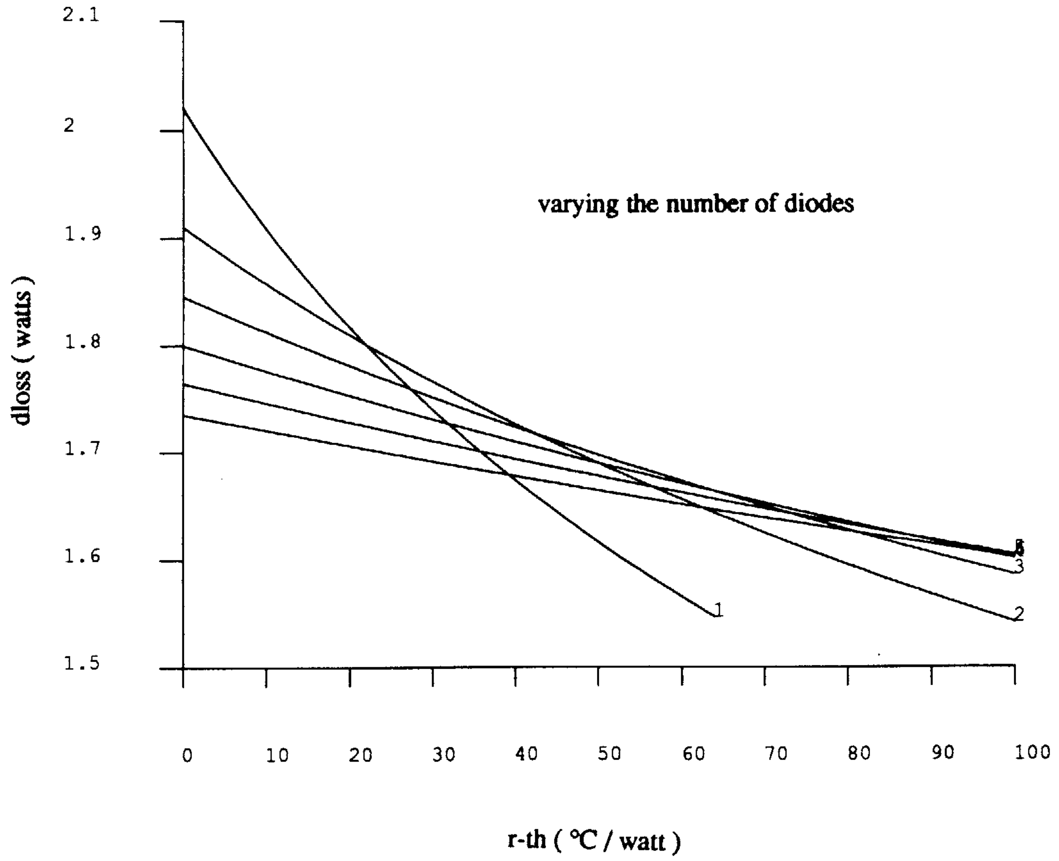

Figure 7.14: d-loss versus r-th while sweeping from 1 to 6 diodes.

7.3.2 Varying t-amb

The exact value of t-amb, the ambient temperature for the maximum power point tracker, cannot be determined for all operations. If the MPPT is used in a desert, for instance, the user needs to be aware of what is happening to the components in the MPPT. Therefore, it is important to observe the rise in temperature of the diode and MOSFET as related to the ambient temperature. Figures 7.15a and 7.15b show the effect of ambient temperature on the diode and MOSFET in a buck converter with the power transfer fixed at 500 watts.

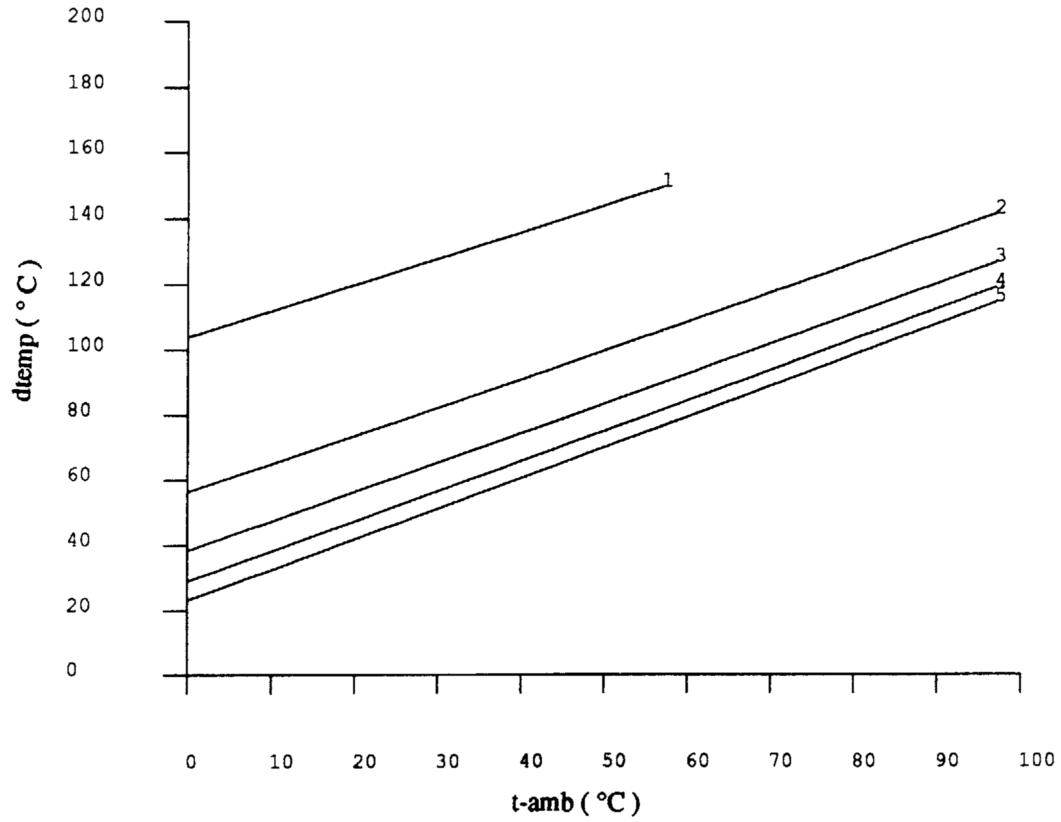

Figure 7.15a: The diode temperature versus t-amb while varying the number of diodes.

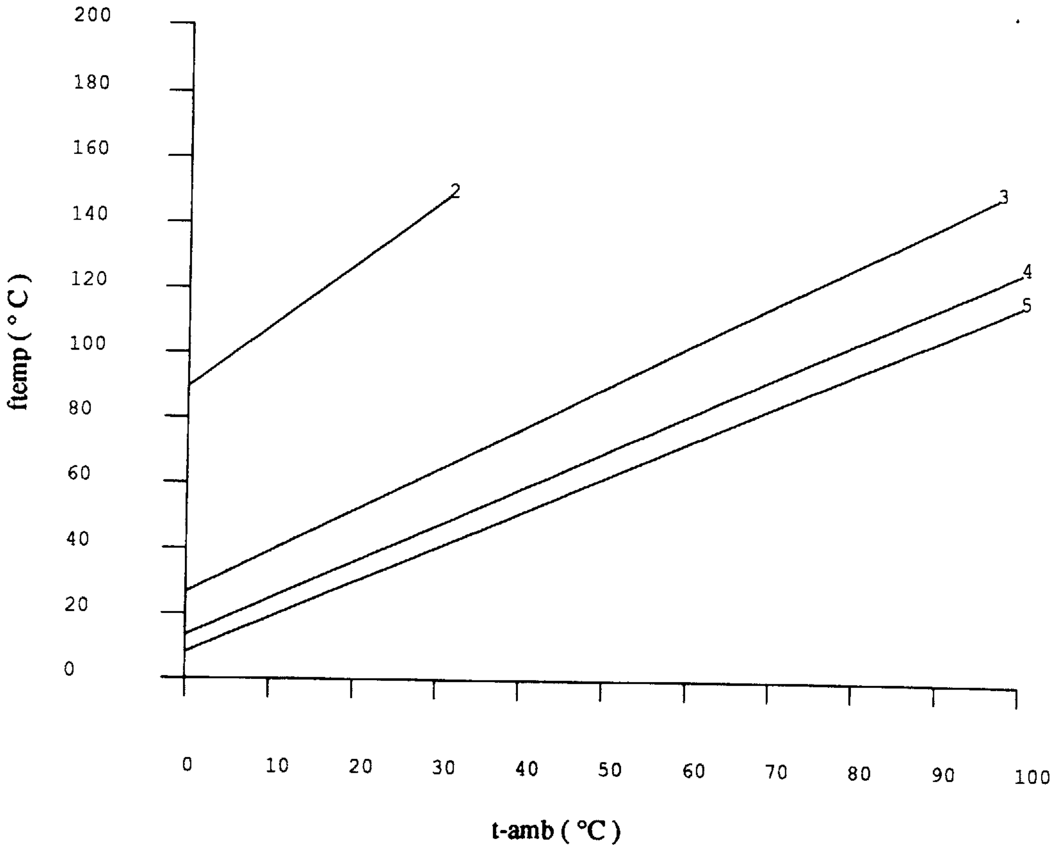

Figure 7.15b: The MOSFET temperature versus t-amb while varying the number of MOSFETs.

The efficiency of the MPPT, given that four diodes and three MOSFETs are used, the power transferred is 500 watts, and the ambient temperature changes from 0°C to 100°C, is given in figure 7.16.

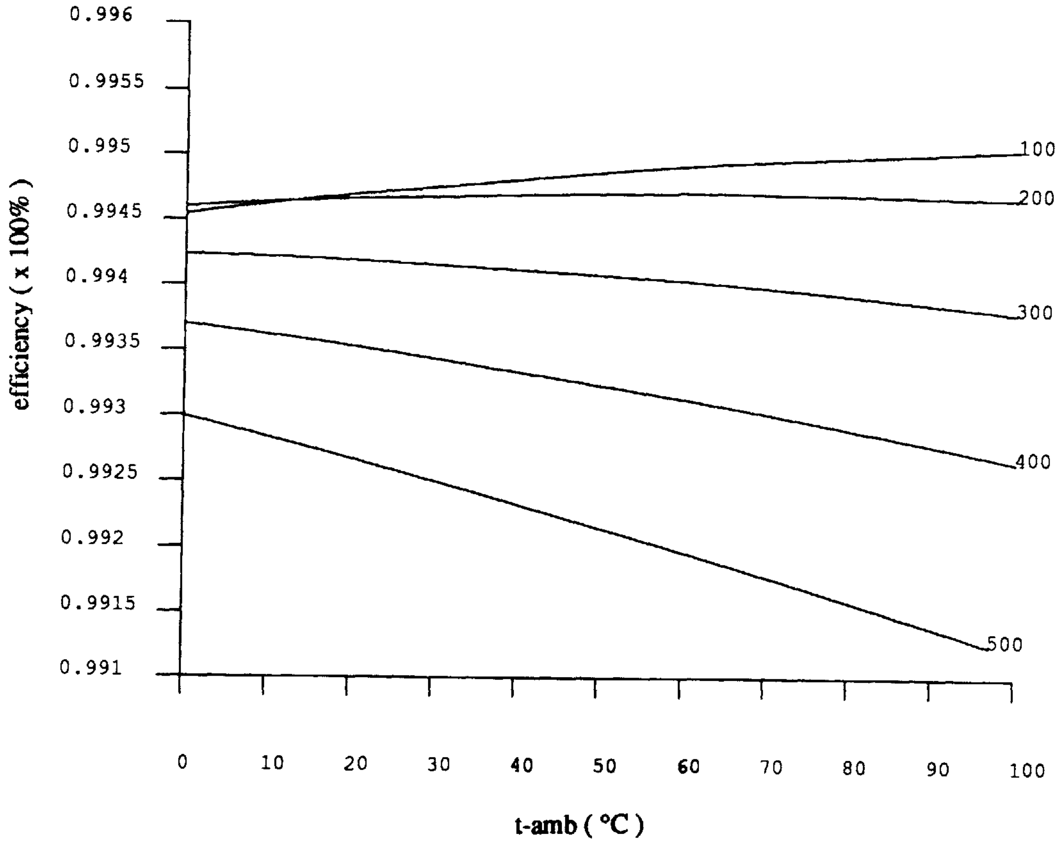

Figure 7.16: Efficiency versus power transfer sweeping t-amb.

8 CONCLUSION

All the necessary information to design a maximum power tracker which is greater than 98% efficient has been obtained. The basic power stage configuration consists of the main inductor and capacitor, three MOSFETs in parallel, four diodes in parallel, and a snubber circuit. When a heat sink is used, the number of components can be decreased.

The preceding analysis includes information about the maximum power point tracker which complements the amazing efficiency which can be achieved. For instance, the discussion proved that the buck converter is much more efficient than the boost converter and requires less components in parallel to make it practical. For the goals of this research, the buck converter is much more useful however the boost converter has its advantages for ordinary applications. The graphs proved that in order to achieve maximum efficiency in the boost and the buck modes, the system voltages, v-in and v-out, need to be as close together in value as possible. A heat sink can replace expensive MOSFETs to maintain high efficiency for large amounts of power transfer. Furthermore, if no heat sink is used and the thermal resistance increases to 100°C / watt, using three MOSFETs and four diodes will still keep the tracker over 98% efficient.

Unfortunately, there are a number of optimizations that were not included in this study. Thus, many projects can continue from this research. Possible topics of interest which can be pursued are as follows:

The inductors and capacitors of the main stage of the MPPT are need to be optimized according to the user's requirements. The inductor is most efficient if it is an air core inductor because it avoids hysteresis and eddy current losses, as well as most weight limitations. The only power that could be lost is due to the coil's resistance. This can be optimized for best efficiency by using the largest wire size. In reality, though, a gapped ferrite core is often used since the user is usually limited by space. The size of the capacitors on the input and ouput is defined by the voltage at either end. The capacitor needs to be a high ripple type so that it can handle the high switching frequency and the amount of energy needed to be stored per cycle. These details are left up to the user's discretion.

Although the research outlined in this paper does not discuss weight-related power losses, it is important to realize that in dealing with power usage limitations with solar cars, weight is a serious consideration; the car's total weight is directly related to power used. For applications in a solar land speed record car, where the power needed to drive one pound of weight is 0.426 watts, it is necessary to decide if the power saved adding a heat sink overcomes the power lost due to the weight of the components (Worden, 1989). In an MPPT, the tracker weight can be optimized by the number and type of the components being used. The critical components which may affect the weight of the tracker are the inductor and the capacitor. In the 'big picture' these two elements must also be analyzed for their weights.

Another project which is necessary for the commercial use of a maximum power point tracker is a cost versus efficiency analysis. When the price of the tracker needs to be minimized, it is vital that the MPPT's cost be optimized for the best efficiency. The study would include deciding whether more MOSFETs and diodes or more heat sink should be used. In the end, the user needs to be satisfied with the efficiency as well as other parameters in his design.

9 REFERENCES

General Instruments Power Semiconductor Division, (1990) *Databook 1990,* New York: General Instruments, 1989, pp.198-199.

Gray, P.E. and Searle, C.L., (1969) *Electronic Principles - Physics, Models, and Circuits,* New York: John Wiley & Sons, Inc., 1969.

International Rectifier, (1987) *Hexfet Desinger's Manual,* El Sengundo, CA: International Rectifier, 1987, pp. C-477 - c-506, I-63 - I-66.

Horowitz, P. and Hill, W, (1985) *The Art of Electronics,* Cambridge: Cambridge University Press, 1985.

Kassakian, J.G., Schlecht, M.F. and Verghese, G.C., (1990) *Principles of Power Electronics,* Massachusetts Institute of Technology: 1990, pp. 251-286.

Merrigan, J.A., (1982) *Sunlight to Electricity,* Cambridge, MA: The MIT Press, 1982, pp. 58-66.

Schlecht, M.F. and Casey, L.F., (1987) "Comparison of the Square-Wave and Quasi-Resonant Topologies". *Proc. of the Second Annual IEEE Applied Power Electronics Conference and Exposition.* San Diego: APEC '87, 1987, pp. 124-134.

Unitrode Corporation, (1989) *Semiconductor Databook and Application Notes.* Watertown: Unitrode Corporation, 1989, pp. 2-97 - 2-115 and 12-166 - 12-168.

Worden, J.D., (1989) *Solar Powered Land Speed Record Vehicle Design,* 1989, pp.33-34.

10 APPPENDIX

```
#include <stdio.h>
#include <math.h>

#include "diode.h"
#include "fet.h"

extern double t_max;
```

```
#define centigrade(t)       (273.+(t))
#define scaletemp(t)        (centigrade(25.) / centigrade(t))

#define vf(dp,i,t)          (scaletemp(t) * \
                            ((log10(i) - (dp)->intercept) / (dp)->slope))

#define diodeloss(dp,n,t,i,d)   ((d) * vf(dp,(i)/(n),t) * (i))

struct diode
{
    char *name;
    double intercept;
    double slope;
    double vrmax;
    double iavgmax;
    double cd0;
    int ninpack;
};

extern struct diode diodes[], *getdiode();

extern double dequil();

#define dcloss(dp, v, freq) ((8./3.) * .5 * (dp)->cd0 * (v) * (v) * (freq))
```

```
struct fet
{
    char *name;
    double rzero;
    double slope;
    double cf0; /* Effective drain to source capacitance */
    double qs;  /* Gate to source charge */
    double qg;  /* Total gate charge */
};

#define rfet(fp,temp) ((temp) * (fp)->slope + (fp)->rzero)

#define condloss(fp,nfet,temp,i_rms) \
        ((i_rms) * (i_rms) * rfet (fp, temp) / ((double) nfet))


#define onloss(fp, v, freq) ((4./3.) * .5 * (fp)->cf0 * (v) * (v) * (freq))

#define gateloss(q, freq)       (2. * (freq) * (q) * 12.)

extern struct fet fets[], *getfet();

extern double fequil();
```

```
#include "include.h"

struct diode diodes[] =
{
    "UES1404",  -3.5,   5,      200,    8,      100.e-12,       1,
    "UES1504",  -4.66,  6.66,   200,    16,     100.e-12,       1,
    "UES2404",  -2.97,  4.37,   200,    8,      100.e-12,       2,
    "UES3015C", -2.6,   4.3,    150,    15,     100.e-12,       2,
    "UES3015S", -4.59,  6.99,   150,    30,     100.e-12,       1,
    "FEP30-P",  -3.72,  5.55,   200,    15,     100.e-12,       2,
    0,          0,      0,      0,      0,      100.e-12,       0
};

struct diode *
getdiode(name)
    char *name;
{
    struct diode *dp;

    for (dp = diodes; dp->name; dp++)
    {
        if (! strcmp (dp->name, name))
            return (dp);
    }
    fprintf (stderr, "No diode info for %s\n", name);
    exit (0);
}


#define TEPSILON .1

double dequil(dp, ndiode, t_amb, r_th, i_max, d)
    struct diode *dp;
    double ndiode;
    double t_amb;
    double r_th;
    double i_max;
    double d;
{
    double oldtemp = 0.;
    double temp;
    double power;
    double r;

    for (temp = t_amb; fabs (temp - oldtemp) > TEPSILON; temp = t_amb + r_th * powe
    {
        oldtemp = temp;

        if (temp > 10. * t_max)
            return (-1.);

        power = diodeloss(dp, ndiode, temp, i_max, d) / (ndiode / dp->ninpack);
    }

    if (temp > t_max)
        return (-1.);
```

```
    return (temp);
}
```

```
#include "include.h"

struct fet fets[] =
{
    "IRFP-250", .068, .00068,   275.e-12,       37.e-9, 79.e-9,
    "IRFP-150", .046, .00037,   500.e-12,       27.e-9, 63.e-9,
    0,          0,      0,      0
};

struct fet *
getfet(name)
    char *name;
{
    struct fet *fp;

    for (fp = fets; fp->name; fp++)
    {
        if (! strcmp (fp->name, name))
            return (fp);
    }
    fprintf (stderr, "No fet info for %s\n", name);
    exit (0);
}

#define TEPSILON .1

double fequil(fp, nfet, t_amb, r_th, i_rms)
    struct fet *fp;
    double nfet;
    double t_amb;
    double r_th;
    double i_rms;
{
    double oldtemp = 0.;
    double temp;
    double power;
    double r;

    for (temp = t_amb; fabs (temp - oldtemp) > TEPSILON; temp = t_amb + r_th * powe
    {
        if (temp > 10. * t_max)
            return (-1.);

        oldtemp = temp;

        power = condloss(fp, nfet, temp, i_rms) / nfet;
    }

    if (temp > t_max)
        return (-1.);

    return (temp);
}
```

```
#include "include.h"

double r_th, i_out, i_in, t_amb;
double v_in, v_out, d;
double i_fetrms, i_diode;
double dtemp, ftemp;
double eff;
double power;
double sw_min2, sw_max2, sw_step2;
double sw_min1, sw_max1, sw_step1;
double floss, dloss, tloss;
double n_fet, n_diode;
char fet_name[100], diode_name[100], sdiode_name[100];
double t_max;
char x_axis[100], y_axis[100], sweep1[100], sweep2[100];
double d_vf;
double freq;
double on_loss, gate_loss, dc_loss;
double v_fet, v_diode;
double i_snubrms, snub_time, i_snubdiode;
double sfloss, sftemp;
double sdloss, sdtemp;
double l_snub;

struct var
{
    char *name;
    char *format;
    char *ptr;
} vars[] =
{
    "l_snub",    "%lf",  (char *) & l_snub,
    "sftemp",    "%lf",  (char *) & sftemp,
    "sdtemp",    "%lf",  (char *) & sdtemp,
    "sfloss",    "%lf",  (char *) & sfloss,
    "sdloss",    "%lf",  (char *) & sdloss,
    "snub_time","%lf",  (char *) & snub_time,
    "i_snubrms","%lf",  (char *) & i_snubrms,
    "i_snubdiode","%lf",(char *) & i_snubdiode,
    "v_fet",     "%lf",  (char *) & v_fet,
    "v_diode",   "%lf",  (char *) & v_diode,
    "gate_loss","%lf",  (char *) & gate_loss,
    "dc_loss",   "%lf",  (char *) & dc_loss,
    "on_loss",   "%lf",  (char *) & on_loss,
    "fet_name",  "%s",   (char *) fet_name,
    "diode_name","%s",   (char *) diode_name,
    "sdiode_name","%s",  (char *) sdiode_name,
    "sweep1",    "%s",   (char *) sweep1,
    "sweep2",    "%s",   (char *) sweep2,
    "x_axis",    "%s",   (char *) x_axis,
    "y_axis",    "%s",   (char *) y_axis,
    "freq",      "%lf",  (char *) & freq,
    "v_in",      "%lf",  (char *) & v_in,
    "v_out",     "%lf",  (char *) & v_out,
    "power",     "%lf",  (char *) & power,
    "sw_min1",   "%lf",  (char *) & sw_min1,
```

```
    "sw_max1",  "%lf",  (char *) & sw_max1,
    "sw_step1", "%lf",  (char *) & sw_step1,
    "sw_min2",  "%lf",  (char *) & sw_min2,
    "sw_max2",  "%lf",  (char *) & sw_max2,
    "sw_step2", "%lf",  (char *) & sw_step2,
    "r_th",     "%lf",  (char *) & r_th,
    "t_amb",    "%lf",  (char *) & t_amb,
    "t_max",    "%lf",  (char *) & t_max,
    "n_fet",    "%lf",  (char *) & n_fet,
    "n_diode",  "%lf",  (char *) & n_diode,
    "eff",      "%lf",  (char *) & eff,
    "ftemp",    "%lf",  (char *) & ftemp,
    "dtemp",    "%lf",  (char *) & dtemp,
    "floss",    "%lf",  (char *) & floss,
    "dloss",    "%lf",  (char *) & dloss,
    "tloss",    "%lf",  (char *) & tloss,
    "i_fetrms", "%lf",  (char *) & i_fetrms,
    "i_diode",  "%lf",  (char *) & i_diode,
    "d",        "%lf",  (char *) & d,
    "d_vf",     "%lf",  (char *) & d_vf,
    0,          0,      0
};

struct var *xp, *yp;
struct var *swp1, *swp2;

struct var *
getvar(s)
    char *s;
{
    struct var *vp;

    for (vp = vars; vp->name; vp++)
        if (! strcmp(vp->name, s))
            return (vp);


    fprintf (stderr, "Don't understand variable %s\n", s);
    exit (0);
}

parsevar()
{
    char s[128];

    struct var *vp;

    if (scanf ("%s\t", s) == 1)
    {
        vp = getvar (s);

        if (scanf (vp->format, vp->ptr) == 1)
            return (1);
        else
        {
            fprintf ("Bad line for %s\n", s);
```

```
                exit (0);
            }
        }
        else
            return (0);
}


char obuf[BUFSIZ];

main()
{
        struct fet *fp;
        struct diode *dp;
        struct diode *sdp;
        double *swdp1, *swdp2;
        int didpoint;


        setbuf (stdout, obuf);

        while (parsevar())
            ;

        xp = getvar(x_axis);
        yp = getvar(y_axis);
        swp1 = getvar(sweep1);
        swp2 = getvar(sweep2);
        swdp1 = (double *) swp1->ptr;
        swdp2 = (double *) swp2->ptr;

        fp = getfet(fet_name);

        dp = getdiode(diode_name);

        sdp = getdiode (sdiode_name);

        for (*swdp1 = sw_min1; *swdp1 <= sw_max1; (*swdp1) += sw_step1)
        {
            didpoint = 0;

            for (*swdp2 = sw_min2; *swdp2 <= sw_max2; (*swdp2) += sw_step2)
            {
                i_out = power / v_out;
                i_in = power / v_in;

                if (v_out == 0. || v_in == 0.)
                    continue;

                if (v_out > v_in)    /* Boost */
                {
                    if (v_out - .5 <= v_in)
                        dobreak();

                    d = 1. - v_in / v_out;
```

```
        i_fetrms = sqrt(d) * i_in;

        v_fet = v_out;

        snub_time = i_in * l_snub / v_fet;

        i_snubrms = .707 * i_in * sqrt (snub_time * freq);

        i_snubdiode = .5 * i_in;

        v_diode = v_out;

        i_diode = i_in;
    }
    else                    /* Buck */
    {
        if (v_out + .5 > v_in)
            dobreak();

        d = v_out / v_in;

        i_fetrms = sqrt(d) * i_out;

        v_fet = v_in;

        snub_time = i_out * l_snub / v_fet;

        i_snubrms = .707 * i_out * sqrt (snub_time * freq);

        i_snubdiode = .5 * i_out;

        v_diode = v_in;

        i_diode = i_out;
    }

    ftemp = fequil (fp, n_fet, t_amb, r_th, i_fetrms);

    if (ftemp < 0.)
        continue;

    floss = condloss (fp, n_fet, ftemp, i_fetrms);

    sftemp = fequil (fp, 1, t_amb, r_th, i_snubrms);

    if (sftemp < 0.)
        continue;

    sfloss = condloss (fp, 1, sftemp, i_snubrms);

    dtemp = dequil (dp, n_diode, t_amb, r_th, i_diode, (1. - d));

    if (dtemp < 0.)
        continue;

    dloss = diodeloss (dp, n_diode, dtemp, i_diode, (1. - d));
```

```
            sdtemp = dequil (sdp, 1, t_amb, r_th, i_snubdiode, snub_time * freq);

            if (sdtemp < 0.)
                continue;

            sdloss = diodeloss (sdp, 1, sdtemp, i_snubdiode, snub_time * freq);

            d_vf = vf(dp, i_diode / n_diode, dtemp);

            on_loss = onloss(fp, v_fet, freq);

            dc_loss = dcloss (sdp, v_diode, freq);

            gate_loss = gateloss(fp->qg, freq) + n_fet * gateloss (fp->qs, freq);

            tloss = floss + dloss + sfloss + sdloss + on_loss
                        + gate_loss + dc_loss;

            if (power == 0.)
                eff = 1.;
            else
                eff = 1. - (tloss / power);

            dopoint (*(double *)(xp->ptr), *(double *)(yp->ptr));

            didpoint = 1;
        }
        if (didpoint)
            dolabel (*swdpl);
    }
    fflush (stdout);

    exit (0);
}

double ox, oy;

dopoint(x, y)
    double x, y;
{
    ox = x;
    oy = y;

    printf ("%lg\t%lg\n", x, y);
}


dolabel(d)
    double d;
{
    printf ("%lg\t%lg\t\"%lg\"\n", ox, oy, d);
}

dobreak()
{
```

```
    printf ("%lg\t%lg\t\" \"\n", ox, oy);
}
```