

Maximum Power Solar Converter

*Author: John Charais
Microchip Technology Inc.*

INTRODUCTION

As the need for remote operation of electronic devices continues to increase, power for these devices becomes more of a concern. Remote applications are powered mostly by batteries that are either recharged or changed on a regular basis. The more remote the location is, the bigger the challenge becomes of replacing these batteries. Since the development of the modern photovoltaic cell in 1954, remotely powered applications that do not have to be serviced became possible.

The focus of this application note is to identify how to get the maximum power out of a solar panel to power a remote application. The Maximum Power Point Converter is essentially a DC-to-DC converter, where the DC input voltage is a solar panel and the output voltage is 28 volts. The intent of the converter is to show how to take the solar panel and generate a voltage capable of recharging a 24-volt battery. Although the chemistry of the battery and how to charge the battery properly are extremely important to the actual design, these details will not be covered in this application note. Also associated with this application note is a zip file with source code and Excel spreadsheet.

SOLAR PANELS

Solar Panels are an array of solar cells. The characteristics of the solar panel are essentially the same as those of the solar cells, only scaled up in voltage or current based on the number of solar cells used and the arrangement of the array. Solar panels come in a variety of shapes, sizes and efficiencies, but all have similar characteristics.

A solar panel will generate its maximum voltage when the panel is in full sunlight with no load. This voltage is commonly referred to as the open circuit voltage (VOC) of the panel. As the load of the solar panel increases, the output voltage of the solar panel will decrease in a nonlinear fashion until the maximum output current, the short circuit current (Jsc) of the panel, is reached.

Figure 1 illustrates two characteristic I-V curves for a solar panel under different lighting conditions. To get the maximum power out of the panel, it is best to operate the solar panel, on the knee of the curve.

From these graphs, you can see that depending on the illumination of the panel you want to operate the panel at different load points to maximize the output power. To complicate things even further, solar panels will have a negative VOC temperature coefficient and a positive JSC temperature coefficient. Figure 2 show the change in the I-V curves when temperature is taken into consideration.

The relationship between illumination and temperature make it difficult to estimate the proper point at which to operate the solar panel in order to maximize the output power. To solve this problem, the Max Power Point Converter continually measures and adjusts the power out of the solar panel in order to operate the panel at its maximum power point, independent of the panel's illumination or temperature.

FIGURE 1: SOLAR PANEL ILLUMINATION I-V CURVE

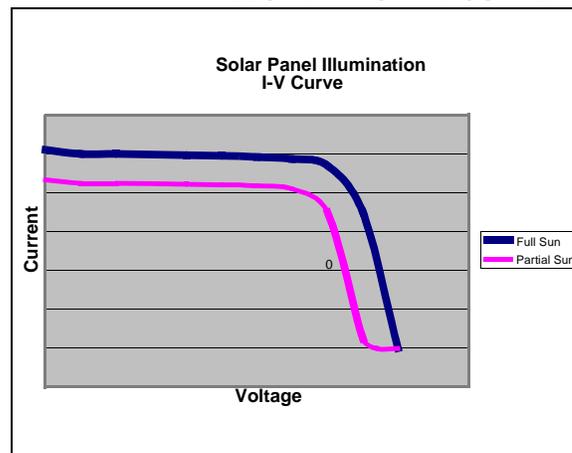
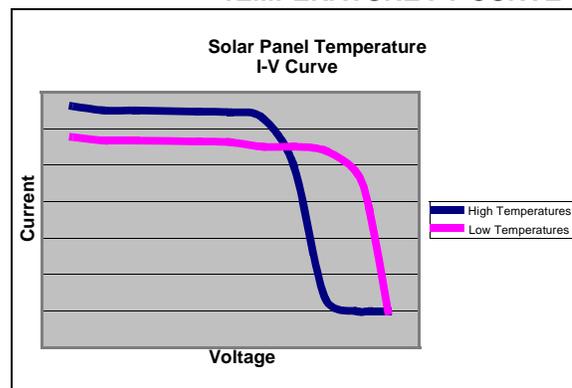


FIGURE 2: SOLAR PANEL TEMPERATURE I-V CURVE

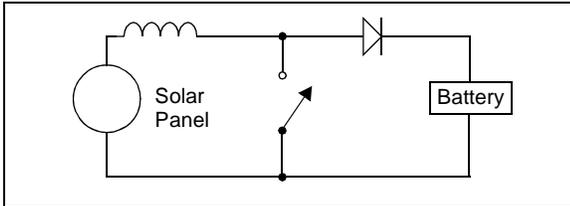


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OVERVIEW

For this project we will be using a 10-volt open circuit solar panel with a short circuit current of 2.5 amps. With an open circuit voltage of 10 volts, a boost converter is needed to charge the 24-volt battery. See Figure 3.

FIGURE 3: BOOST CONVERTER



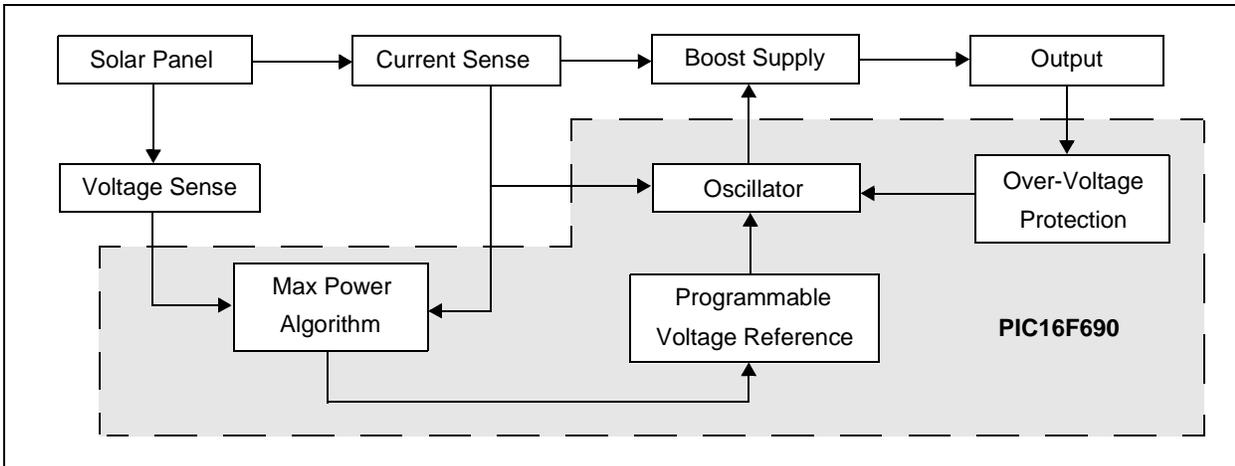
To get the solar panel to operate at its maximum power point, there are a few items needed. First, in order to know the output power of the solar panel, both the current and voltage of the solar panel have to be monitored. This will be accomplished by a high side current monitor and simple resistor divider on the solar panel's output voltage. There also needs to be a way to control the output power of the solar panel. This is done by manipulating the panel's output current. And lastly, a software algorithm is needed to know which way to manipulate the current, e.g., whether the current out of the solar panel should be increased or decreased.

To make the Maximum Power Point Converter work, the functions of the boost converter need to be merged with the solar panel's output load. The boost converter is either storing current in the boost inductor (switch closed) or it is delivering current from the boost inductor to the load (switch opened). When the boost inductor is storing current, the current comes from the solar panel. In essence, the boost inductor is the solar panel's load. By making the current stored in the boost inductor programmable, the load of the solar panel becomes programmable. This is the principal on how the Maximum Power Point Converter works. The Maximum Power Point Converter combines a boost converter, a programmable current oscillator and a software algorithm to maximize the power out of a solar panel.

HARDWARE OVERVIEW

Figure 4 shows the block diagram of the Maximum Power Point Converter.

FIGURE 4: MAXIMUM POWER POINT CONVERTER



THE CURRENT SENSE

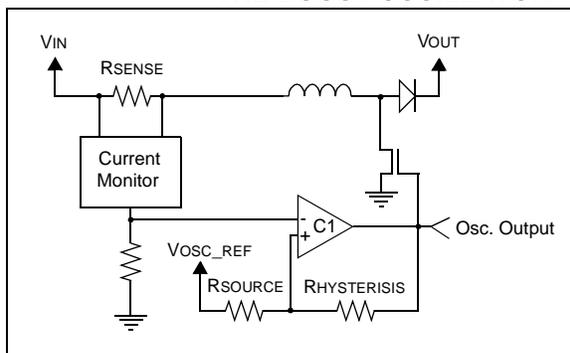
To know the instantaneous current in the boost inductor, a current sense resistor has been added in series with the boost inductor. Knowing the value of the current sense resistor and the voltage drop across it, the current in the inductor is obtained. The current sense resistor in our application is 10 mOhm. The sense resistor is kept intentionally small to reduce the inefficiency that it introduces to the boost converter. A high side current monitor is used to generate a voltage that is in the common mode range of the comparator.

THE OSCILLATOR

Figure 5 shows how the current sense works with a comparator and the components of the boost supply to make the oscillator.

The start-up condition of the oscillator is dictated by the software of the PIC16F690. Before the comparator is enabled, the port pin holds the gate of the boost FET low while the oscillator's reference voltage stabilizes. Once the reference voltage is stable, the comparator is enabled. This creates a start-up condition with no voltage at the negative comparator input while the positive input will be VOSC_REF multiplied by the divider ratio provided by RSOURCE and RHYSTERESIS.

FIGURE 5: SIMPLIFIED DIAGRAM OF THE BOOST OSCILLATOR



After the comparator is enabled, the positive input will be greater than the negative input, which causes the output of the comparator to immediately change to an output high. When the output of the comparator is high, the following will occur:

- The FET of the boost converter conducts.
- The positive input of the comparator equals VHH (see Equation 1).
- Energy is stored in the boost inductor.
- The current in the boost inductor increases at a linear rate.
- The voltage on the negative input of the comparator increases.

EQUATION 1:

$$V_{HH} = V_{OSC_REF} + (V_{DD} - V_{OSC_REF}) * R_{SOURCE} / (R_{SOURCE} + R_{HYSTERESIS})$$

At a predetermined current in the inductor, the negative input of the comparator becomes greater than the positive input, which causes the output of the comparator to become low. This current, IHH (for *hysteresis high*), is calculated by the following formula (Equation 2), where Gm is the gain of the current monitor:

EQUATION 2:

$$I_{HH} = V_{HH} / (G_M * R_{SENSE})$$

When the output of the comparator is low, the following will occur:

- The FET of the boost converter does not conduct.
- The positive input of the comparator equals VHL (see Equation 3).
- Energy is taken out of the boost inductor and delivered to the 24-volt load.
- The current in the boost inductor decreases at a linear rate.
- The voltage on the negative input of the comparator decreases.

EQUATION 3:

$$V_{HL} = V_{OSC_REF} * R_{HYSTERESIS} / (R_{SOURCE} + R_{HYSTERESIS})$$

The current in the inductor will keep decreasing until the voltage on the negative input equals the positive input of the comparator. This current, IHL (for *hysteresis low*), is calculated by the formula in Equation 4.

EQUATION 4:

$$I_{HL} = V_{HL} / (G_M * R_{SENSE})$$

When this point is reached, the comparator's output changes to a high and the cycle repeats.

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FIGURE 6: CURRENT VS. TIME IN THE BOOST INDUCTOR

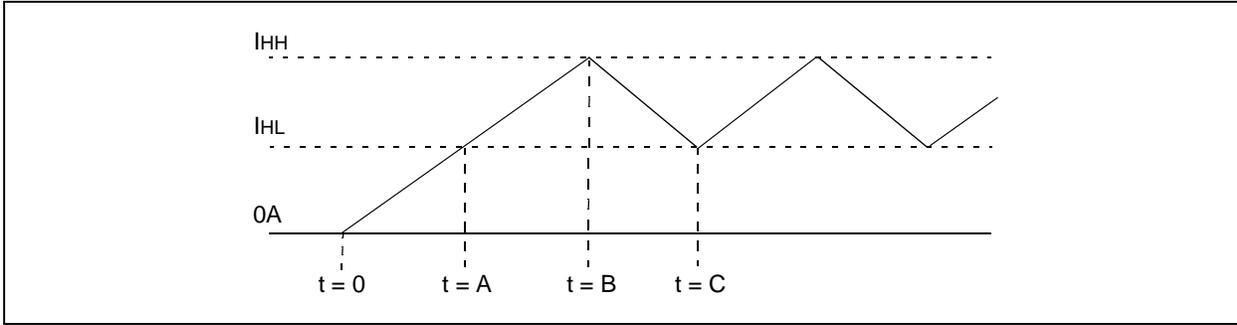


Figure 6 shows the current profile of the boost inductor with respect to time. The rate the current in the inductor changes, or the slope of the inductor current, is inversely proportional to the inductance. The larger the inductor is, the slower the current in the inductor changes. The combination of the amount of hysteresis and the size of the boost inductor will dictate the frequency of oscillation. The time it takes for the current to go from IHL to IHH is:

EQUATION 5:

$$T_B - A = (I_{HH} - I_{HL})L / V_{IN}$$

And the time it takes for the current to go from IHH to IHL is:

EQUATION 6:

$$T_C - B = (I_{HH} - I_{HL})L / (V_{OUT} - V_{IN})$$

The frequency of oscillation is determined by a combination of these two times:

EQUATION 7:

$$F_{SW} = 1 / (T_B - A + T_C - B)$$

PROGRAMMABLE VOLTAGE REFERENCE

The voltage reference for the PIC16F690's first comparator, C1, will be used to set the RMS current out of the solar panel. By making this reference programmable, it is possible to increase or decrease the current out of the solar panel independent of the solar panel's voltage. The power out of the solar panel will be controlled by monitoring the voltage and adjusting the current out of the solar panel's RMS current. To implement the programmable voltage reference, a RC filter, in combination with the PIC16F690's PWM, will be used.

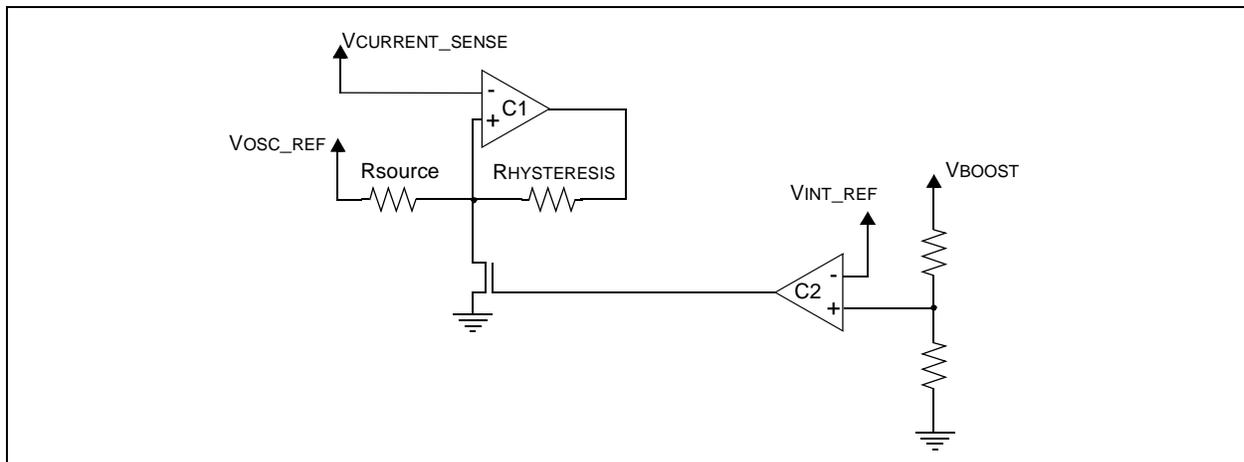
Ideally, the current out of the solar panel would be scalable from 0 amps to approximately 2.75 amps to slightly exceed the panel's full range of 0-2.5 amps, but the hardware setup of the oscillator does not allow for this to happen. Looking back to our equations for I_{HH} (Equation 2) and I_{HL} (Equation 4), it can be seen that if the programmable voltage reference is set to zero, I_{HL} will be zero, but I_{HH} is determined by the high output of C1 and the resistor divider set up by R_{SENSE} and $R_{HYSTERESIS}$. This creates an inherent DC offset current equal to half the ripple current in the boost inductor.

To get the programmable solar panel's current closer to the desired full dynamic range, we will have to decrease the current hysteresis of the boost supply. A side effect of decreasing the amount of hysteresis current is that the frequency of oscillation will increase. This is just one of the many trade-offs that goes into the selection of the components for the boost converter. The current hardware configuration of the Maximum Power Point Converter yields a programmable current range of 1-2.86 amps. This allows enough dynamic range at a slow enough switching frequency for the application at hand.

OVER-VOLTAGE PROTECTION

With a boost converter, special care needs to be taken to make sure that the output voltage does not exceed its desired level. To provide the over-voltage protection, the PIC16F690's second comparator, C2, is used. The comparator has its positive input connected to a resistor divider off the boost supply, and its negative input is set to an internally generated voltage of $\frac{1}{4} V_{DD}$. When the boost supply is greater than 28 volts, the comparator's output is high. As seen in Figure 7, the high output of the comparator is used to ground the positive output of comparator C1, setting the RMS current in the boost inductor to zero.

FIGURE 7: OVER-VOLTAGE PROTECTION



COMPONENT SELECTION

Keeping in mind that the goal of this project is to get the most power out of the solar panel, it would seem unwise to waste power by having an inefficient boost power supply. In order to optimize the efficiency of the boost supply, we first need to examine the losses associated with each component. Below are a series of power equations associated with each major component of the boost supply. For further analysis of the interaction of these equations, download the Excel spreadsheet associated with this application note.

SENSE RESISTOR

The power lost to the resistance of the sense resistor is I^2R . For most applications, “I” can be approximated as the average current in the inductor, which yields the following formula:

EQUATION 8:

$$P_{RES} = \left(\frac{I_{HH} + I_{HL}}{2} \right)^2 R$$

To get a more accurate power dissipation of the sense resistor, the power equation has to be integrated because the current is constantly changing.

EQUATION 9:

$$P_{RES} = \left(\frac{I_{HH} - I_{HL}}{3} \right)^2 + (I_{HH} - I_{HL}) * I_{HL} + I_{HL}^2 * R$$

INPUT AND OUTPUT CAPACITOR

The power lost because of a capacitor is due to equivalent series resistance (ESR) and the ripple current on the cap. For the input capacitor, the equation is:

EQUATION 10:

$$P_C = (I_{HH} - I_{HL})^2 ESR$$

SCHOTTKY DIODE

For the boost diode, there are 2 types of losses: reverse recovery losses and forward conducting losses. Depending on the switching speed for the given boost supply, the reverse recovery losses can be ignored for the most part, if a Schottky diode is used. The reason for this is because the reverse recovery current will be approximately 1-5 mAmps for 20-50 nSeconds. The forward conduction losses will dominate the reverse recovery and can be calculated by using the following equation:

EQUATION 11:

$$P_{SD} = V_F * (I_{HH} + I_{HL}) / 2 * V_{IN} / V_{OUT}$$

Where V_F is the forward voltage across the diode and V_{IN}/V_{OUT} is the ratio of the diode's conduction time.

BOOST INDUCTOR

There are 3 types of losses that occur in the inductor: winding losses, core losses and resistance losses. The winding and core losses have to do with the physical way the inductor is made and which core material is used. The best way to determine these losses is to consult the inductor manufacturer.

For this application note, the winding and core losses for the inductor were determined by using the “core loss calculator” located on the Coilcraft's web site. This calculator will also calculate the resistance losses via Equation 8.

EQUATION 12:

$$P_{IND} = P_I - P_{RES} + P_I - P_{WIND} + P_I - P_{CORE}$$

BOOST FET

The losses due to the boost FET can be broken up into two categories: conduction losses and switching losses. For the conduction loss, it is the resistance loss of the FET multiplied by the ratio of the FET's on/off time.

EQUATION 13:

$$PRDS = \left(\frac{I_{HH} + I_{HL}}{2} \right)^2 * RDS * (1 - V_{IN}/V_{OUT})$$

Or, for the more accurate loss:

EQUATION 14:

$$PRDS = \left(\frac{I_{HH} - I_{HL}}{3} + (I_{HH} - I_{HL}) I_{HL} + I_{HL}^2 \right) * RDS * (1 - V_{IN}/V_{OUT})$$

The switching losses can be broken up into 3 different categories: gate charge, output capacitance, and transition losses calculated by the following equations:

EQUATION 15:

$$P_{GATE} = F_{SW} * Q_G * V_{DRIVE}$$

EQUATION 16:

$$P_{COSS} = (C_{OSS} * V_{DS}^2 * F_{SW}) / 2$$

EQUATION 17:

$$P_{TRAN} = \frac{1}{2} (T_R + T_F) V_{OUT} * I_{IN} * F_{SW}$$

EQUATION 18:

$$P_{FET} = P_{GATE} + P_{COSS} + P_{TRAN}$$

F_{SW} is the switching frequency of the boost supply, Q_G is the FET's total gate charge, V_{DRIVE} is the voltage the gate is being driven to, and T_R/T_F is the FET's turn on/off rise/fall time.

The total power lost due to the switching power supply is:

EQUATION 19:

$$P_{TOTAL} = P_{RES} + P_{CIN} + P_{COUT} + P_{SD} + P_{I-RES} + P_{IND} + P_{IFET}$$

With the components on the current bill of material, the calculated efficiency of the boost supply is 96.56%, when the input voltage is 8 volts and the input current is 2.5 amps. Testing on the Maximum Power Point Converter has shown that the overall process converts efficiency to 94%. This is slightly less than what is calculated, because we only account for the efficiency of the boost supply, and did not account for the quiescent current draw of the FET driver, PIC16F690, current monitor, etc.

SOFTWARE

The software to control the Maximum Power Point Converter can be broken into two algorithms: Current Reduction and the dither routine, which are controlled via the Interrupt Service Routine (ISR). Both algorithms manipulate the current of the solar panel via the Programmable Voltage reference generated by the PIC16F690's 10-bit PWM.

By modifying the duty cycle of the PWM, the current out of the solar panel will scale linearly with respect to the duty cycle of PWM. To simplify the math for both algorithms, only the 8 MSBs of the PWM's duty cycle will be used, yielding 256 discrete current settings for the solar panel.

DITHER ROUTINE

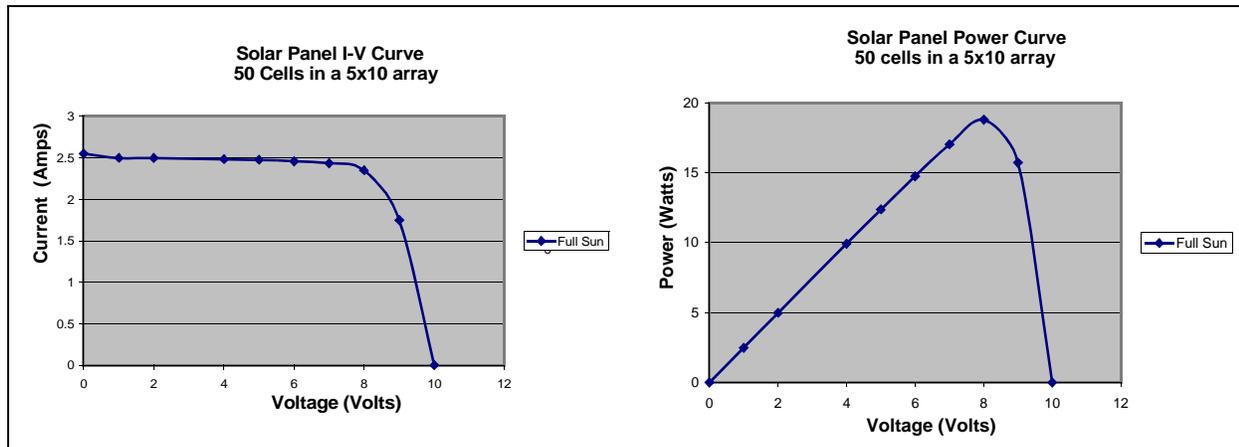
The dither routine is used to optimize the power out of the solar panel. The algorithm does not use the exact power out of the solar panel, but rather, a difference in the proportional power. For the dither routine, only the relative difference between two successive power calculations is important. Did the power increase or did the power decrease? The amount the power changed has no effect on the algorithm. For this reason, the exact power out of the solar panel is not required, which allows us to use the linear relationship of the PWM's duty cycle and the solar panels current. The proportional power out of the solar panel is calculated by multiplying the voltage of the solar panel by the duty cycle of the PWM. For simplicity, the 8 Most Significant Bytes (MSBs) of PWM's duty cycle is multiplied by the 8 MSBs of the A/D reading on the solar panels voltage.

Using the PWM duty cycle for the solar panel's current has two benefits. The first benefit is that it eliminates the need for additional hardware. To get the exact current out of the solar panel, an analog buffer on ROUT is needed, as well as an additional RC filter located on the buffer's output. The second benefit is that the PWM's duty cycle is already in a digital format speeding up the control loop, because there is no need to perform a second A/D conversion.

Figure shows the I-V curve and the maximum power curve of the solar panel the Maximum Power Point Converter was designed for. Starting with no load on the output, we have an open-circuit voltage of 10 volts. When the panel is operating at this voltage, the panel produces no power. By increasing the current taken out of the panel, we begin to collapse the solar panels voltage, but gain power. If the current out of the panel is increased beyond a certain point, the supply voltage will quickly collapse and the power out of the solar panel will decrease.

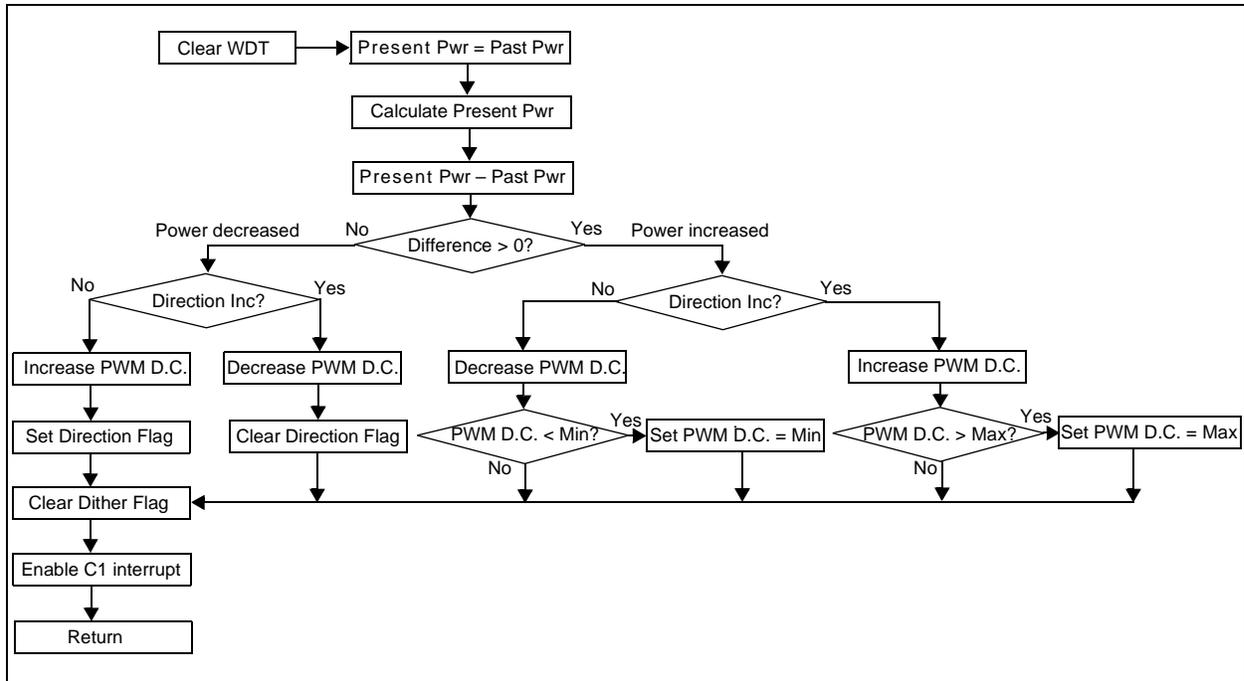
The first time through the dither routine, the proportional power of the solar panel is calculated by multiplying the voltage of the solar panel by the minimum duty cycle of the PWM. After the power has been calculated, the PWM's duty cycle is increased and the direction flag is set to indicate that the current out of the panel was increased (if the current out of the panel was decreased, the direction flag would be cleared). The second time through the dither routine, the power is again calculated and compared to the previous power calculation. If the power increases, the current will be adjusted in the same manner as indicated by the direction flag; in this case, the current would be increased. This will continue to happen until the power decreases. When the power decreases, the current is adjusted in the opposite manner as indicated by the direction flag (decreased), and then the direction flag is cleared.

FIGURE 8: DITHER ROUTINE



The algorithm works independent of the voltage or current from the solar panel. The key to the dither routine is whether the power increased or decreased due to the change in current. If the power increases, it continues to change the current in the same manner as indicated by the direction flag. If the power decreases, it changes the current out of the solar panel in the opposite manner as dictated by the direction flag. See Figure 9 for the flowchart of the full implementation of the dither routine.

FIGURE 9: FULL IMPLEMENTATION OF THE DITHER ROUTINE



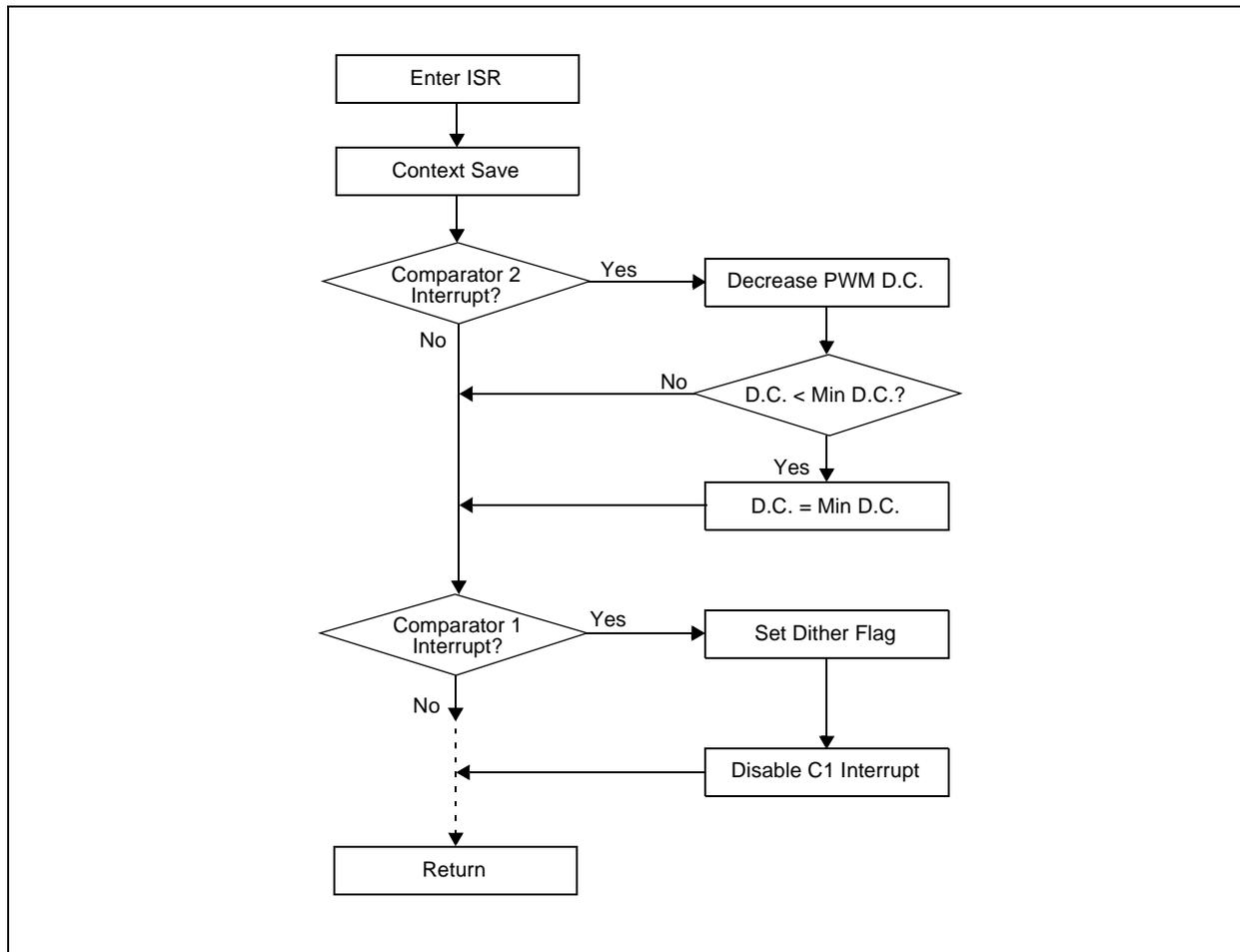
CURRENT REDUCTION

The function of the current reduction algorithm is to make the boost supply as efficient as possible. The load on the output, in part, dictates how much current should be taken out of the solar panel. Ideally, if the system was perfectly balanced, the minimum amount of energy would be taken out of the solar panel to maintain the proper voltage on the output load. If the over-voltage protection circuit becomes activated it essentially tells us there is too much energy being taken out of the solar panel. The current reduction algorithm is implemented to reduce the energy taken out of the solar panel, while allowing the dither routine to operate the solar panel at its peak power point. This will help the converter dissipate less heat due to the I^2R power losses of each component.

The full implementation of the current reduction algorithm can be seen in the flowchart of the ISR (Figure 10). The algorithm does nothing unless an over-voltage condition occurs, which is determined by the interrupt of comparator C2. When the interrupt occurs, the hardware automatically disables the oscillator and the current reduction algorithm slightly reduces the amount of energy to be taken out of the solar panel. When the over-voltage condition is no longer present, the oscillator will start again at a slightly lower current setting. This reduced current setting is desired to prevent the over-voltage condition from happening on every oscillation.

The next time through the dither routine, the current will again be adjusted up or down to operate the panel at its peak power point. The combination of the current reduction algorithm and the dither routine will optimize the power out of the solar panel for any given load.

FIGURE 10: INTERRUPT SERVICE ROUTINE FLOWCHART



ADDITIONAL SAFETY FEATURES

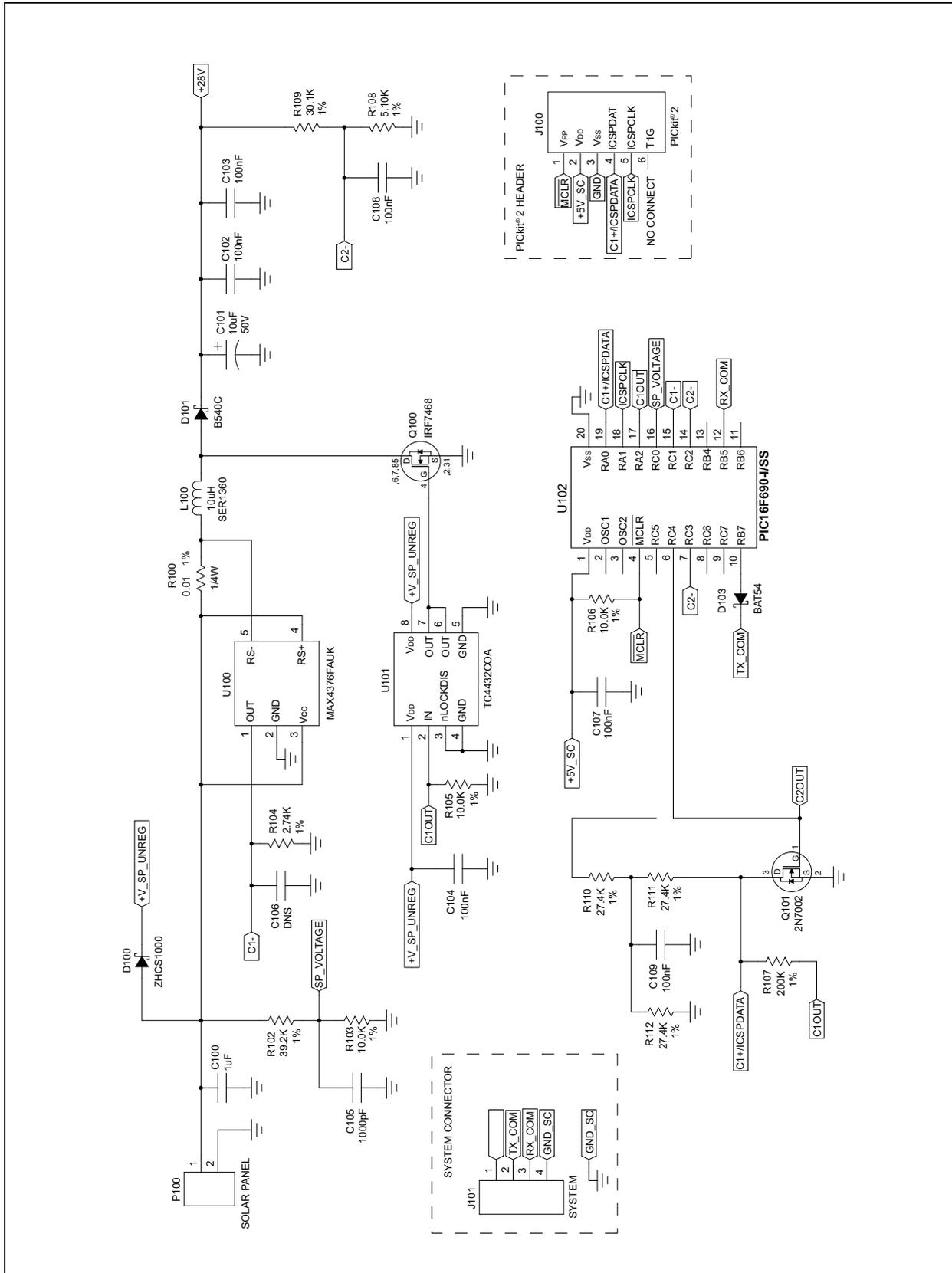
When comparator C1 is enabled, the comparator C1 interrupt is also enabled. Any change in the comparators state verifies that the oscillator oscillates and causes an interrupt. The state change of the comparator is used in conjunction with the Watchdog Timer (WDT) to ensure the oscillator never enters a state where the solar panel cannot supply enough current to reach its I_{HH} threshold. If this happens, the WDT of the PIC16F690 will reset the device. Servicing the comparator C1 interrupt causes the dither flag to be set and disables the comparator C1 interrupt. The comparator is disabled to prevent unnecessary time in the ISR after it has already been validated that the oscillator oscillates. The dither flag is checked only in the main software loop. If the dither flag is set, the dither routine will run and clear the WDT. At the end of the dither routine, the dither flag is cleared and the comparator C1 interrupt will be re-enabled.

CONCLUSION

As solar panels increase in efficiency, more and more applications will begin to use them as either a primary power source or as a backup power source. For applications where the ambient light is continually changing, the Maximum Power Solar Converter can be a very effective tool in increasing the total power delivered by the solar panel.

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APPENDIX A: SOLAR MAX POWER CONVERTER SCHEMATIC



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China - Xian
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India - Pune
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Korea - Seoul
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Malaysia - Kuala Lumpur
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Malaysia - Penang
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