MAXIMUM POWER TRACKING FOR PV SYSTEMS

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ABSTRACT

In this paperphoto voltaic (PV) electricity is one of the best options for most impartment and ecological future energy requirements of the world. Organic photovoltaic (OPV) cells are hopeful views for common renewable energy unpaid to light weight, low cost, and flexibility. An organic solar cell or organic photovoltaic (OPV) cell is a photovoltaic cell that uses organic electronics-a branch of electronics that deals with conductive organic polymers or small organic molecules for light absorption and charge transport. The plastic used in OPV cells has low production costs in high volumes. Combined with the flexibility of organic molecules, OPV cells are potentially cost-effective for photovoltaic applications.Solar photovoltaic (PV) panels are a great source of renewable energygeneration. The biggest problem with solar systems is relatively low efficiency and highcost. In this research work hopes to alleviate this problem by using novel power electronicconverter and control designs. An electronic DC/DC converter, called "Quasi-Double-Boost DC/DC Converter," is designed for a Solar PV system. A Maximum Power PointTracking (MTTP) algorithm is implemented through this converter. This algorithm allowsthe PV system to work at its highest efficiency. Different current sensing and sensorlesstechnologies used with the converter for the MPPT algorithm are offered and tested.Design aspects of the system and components will be discussed. Results fromsimulations and experiments will be presented. These results will show that theproposed converter and MPPT control algorithm improves overall PV system efficiencywithout adding much additional cost.

Keywords : Maximum Power, PV System, MPPT, DC, System Layout, PV panels, I-V Curves, CCM, DCM

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1. INTRODUCTION

The past few years have been filled with news of fuel price hikes, oil spills, andconcerns of global warming. One of the few positives that can be taken from this is thatit is changing the average person's mindset towards renewable energy. People arefinding the benefits of having their own renewable energy system more attractive thanthey ever have before. The biggest form of renewable energy to benefit from this issolar PV systems because of their many merits, such as cleanness and relative lack ofnoise or movement, as well as their ease of installation and integration when comparedto wind turbines. However, the output power of a PV panel is largely determined by thesolar irradiation and the temperature of the panel. At a certain weather condition, theoutput power of a PV panel depends on the terminal voltage of the system. Tomaximize the power output of the PV system, a high-efficiency, low-cost DC/DCconverter with an appropriate maximum power point tracking (MPPT) algorithm iscommonly employed to control the terminal voltage of the PV system at optimal valuesin various solar radiation conditions.There are three main DC/DC converter technologies used with most PV systems(Bernardo, 2009; Morales-Saldana, 2006; Mrabti, 2009; Nabulsi, 2009; Shanthi, 2007).The first of these converters is the buck converter (Bernardo, 2009; Mrabti, 2009). Buckconverters are step-down converters that output a voltage lower than the voltage thatis input to the converter. The standard buck converter has an output that is equivalentto the input voltage multiplied by the duty cycle or

$$V_{out} = D * V_{in} \text{ ………. } 1.1$$

Buck converters work for low voltage applications. They can be implemented inMPPT algorithms (Bernardo, 2009), as long as the PV panels output voltage is greaterthan the voltage required by the load. To maximize the efficiency of the PV panel fromnear zero to the maximum output, the entire range of the duty cycle needs to be usedfor the implementation of the MPPT algorithm.The second commonly used converter in PV systems is a boost converter(Shanthi, 2007). Boost converters are step-up converters that output a voltage higherthan the voltage that is input to the converter. The standard boost converter has anoutput that is equivalent to the input voltage divided by the duty cycle.

$$Vout= Vin / (1- D) \text{ ……….. } 1.2$$

Basic boost converters work well with the MPPT control as long as the load canaccept a voltage from the minimum output of the PV panel all the way up a certainvalue (e.g., 5 times) subject to practical limits of the duty cycle (e.g., 80%). However, inmany applications, a high boost ratio is required for the DC/DC converter to connect thelow-voltage PV panel to a relatively high-voltage load or power grid. This cannot besatisfied by using basic boost converters.The third commonly used converter in solar PV systems is a cascaded boostconverter (Morales-Saldana, 2006; Nabulsi, 2009). Cascaded boost converters have anoutput that is equivalent to the input voltage divided by the duty cycle to the nth power,where n refers to the number of boost converters that are cascaded.

$$V_{out} = V_{in} / (1\text{-}D)^n \quad \ldots\ldots\ldots..1.3$$

Cascaded boost converters work well in applications that require high voltageboost ratios. One problem with both the boost and the cascaded boost converters isthe oscillations and relative instability under changing and startup conditions as shownin (Rensburg, 2008).In order to utilize the potential with any of these converters in a PV system, theconverter needs to be controlled by a MPPT algorithm. Various MPPT algorithms (Hua,1998; Hussein, 1995; Koutroulis, 2001; Pan, 1999) have been proposed based on powermeasurements, including the hill-climbing (HC) method (Koutroulis, 2001), perturb-andobserve(P&O) method (Hua, 1998), and incremental conductance (IncCond) method(Hussein, 1995). The HC and P&O methods achieve the same fundamental thought indifferent ways (Salas, 2006). These two algorithms are widely used because of theirsimplicity; however they can fail under rapidly changing atmospheric conditions. Theincremental conductance method can track the maximum power point (MPP) moreaccurately than the HC and P&O algorithms can, however it is relatively complicated toimplement.Every addition, converter and MPPT algorithm add additional cost to the entirePV system. However the cost in minimal compared to the PV panels and can usually beoffset by improved efficiency. Improving efficiency is the easiest way to cut cost with aPV system. A good MPPT algorithm and a high efficiency converter are a must toimprove efficiency but should not be the only changes to the standard setup. Oneshould also employ higher output voltages to lower line losses and allow for moreefficient AC conversion. The second easiest way to improve overall system cost is in thecomponents themselves. A higher and more stable line voltage will mean smaller ACinverters with grid tie systems that will not need any boosting capabilities at all. Theremoval of expensive components such as current sensors also helps to keep cost at aminimum and improves the system reliability. The system needs to be robust enoughthat when the consumer wants to expand their energy production by adding morepanels, they don't need to replace their entire system. The DC/DC converter and MPPTcontrol algorithm proposed in this work will implement all of these improvements inhopes creating a highly efficient, low-cost, and highly reliable solar PV system for cleanand renewable power generation.

2. SYSTEM LAYOUT

The overall PV system layout can be seen in Figure 1. The system consists of aPV panel or panels, a quasi-double-boost DC/DC converter, a MPPT control algorithmand some sort of load.

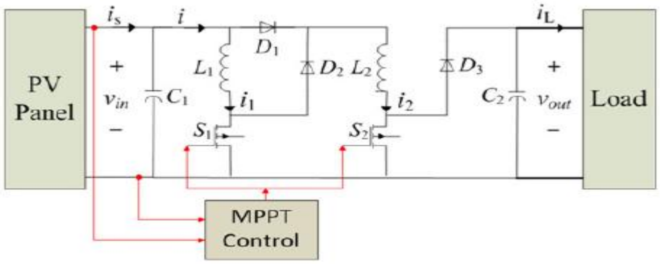


Figure 1.The layout of the overall PV System

2.1The PV Panel

PV panels generate electricity through what is called the "Photovoltaic Effect"(Wenham, 2009). In the simplest form the Photovoltaic Effect can be described asfollows: Light particles called photons are constantly emitted from the Sun. This can beseen by the brightness on a sunny day when many of these particles make it to earth'ssurface. The effect comes into play when these particles hit a PV material, such as asolar cell. When the photons impact this material it excites the atoms within thematerial, which causes an electron-hole pair to form. A band gap built into the materialcauses the electron to move along a certain predefined path. This electron-hole paircreation happens many times over, throughout the panel. All of these flowing electronsgenerate a current that is directed out of the panel to some type of load. Thus, thephotovoltaic effect converts light into the more useful form of power, electricity.Solar cells output power in what is called an I-V curve. A typical I-V curve of asolar cell can be seen in Figure 2 (Wenham, 2009). This curve represents what thecurrent output by the solar cell would be as the output voltage is varied and vise versa.Below the I-V curve, the P-V curve is also shown in Figure 2. This curve can be easilyobtained from the I-V curve through the equation P = V x I.

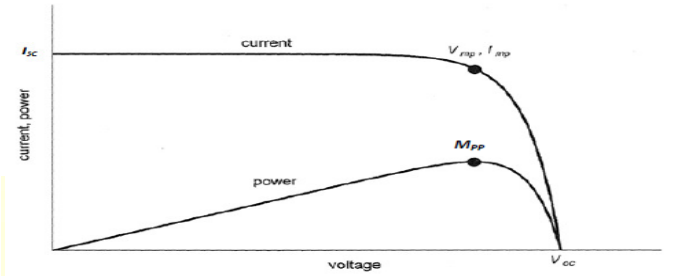


Figure2 : A rep I- V cure for a solar cell showing the MPP

There are three other important aspects of a solar cell also shown in Figure 2.The first two are the open circuit voltage (Voc) and the short circuit current (Isc) of thecell. The open circuit voltage is the voltage that is output to the cell terminals when thecell is exposed to light and there is no current flowing between the terminals. This isalso the maximum voltage that can be produced by the cell, which makes knowing thisnumber useful when designing a circuit or load to connect to the cell terminals. Theshort circuit current is the current that will flow when the cell is under light and theterminals are shorted together. This is the maximum current that can be output by thespecific solar cell. The third important aspect of a solar cell is the MPP. This is the pointwhere the cell is operating at maximum efficiency and outputting the highest poweravailable. The MPP also has voltage at maximum power (Vmp) and current at maximumpower (Imp) points associated with it. The way these points move and change with theenvironmental conditions around the cell will be discussed in more detail later.

Each individual cell is relatively little in size and can only produce a small amountof power. The Voc of an individual solar cell is usually approximately 0.6 V(Wenham,2009). The cells become much more useful when combined in an array to create a PVpanel. When connected together the cells properties add together to create an I-Vcurve that has the same appearance as that of an individual cell but is larger inmagnitude. The cells in an array are usually connected in series to obtain a higher andmore appropriate terminal voltage.The PV panels used in this research are BP Solar model SX 3175 (Appendix 1).Each panel consists of 72 individual solar cells connected in series to obtain a ratedpower of 175 W, which corresponds to a maximum power current and voltage of 4.85 Aand 36.1 V, respectively. The panel has an open circuit voltage of 43.6 V and a shortcircuit current of 5.3 A.

2.2 Modeling of the PV Panel

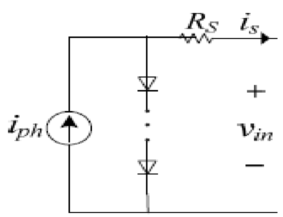


Figure 3: the PV Panel model

A PV panel model is developed using the work in (Tsai, 2008) as a starting point.The panel is modeled as a current source as shown in Figure 3 that follows equation 2-1

$$i = I_{ph} - I_S(T)(\exp\{q(V_{in} + i \cdot R_S)/kTA\} - 1) \qquad \text{……….2.1}$$

where i is the PV panel output current; Iph is photocurrent; IS(T) is the reverse saturationcurrent; q (= 1.6×10-19) is an electron charge; Vin is the terminal voltage of the PV panel;RS is the PV panel series resistance; A is the ideal factor of the PN junction of the PVdiode, which varies in the range of [1, 2]; and k (= 1.38×10-23J/K) is the Boltzmannconstant. The photo current is then found using equation 2-2.

$$I_{ph} = \left[I_{sc} + K_i(T - T_{ref})\right] \cdot \lambda \qquad \text{…….2.2}$$

where ISC is the short circuit current provided by the PV panel at a referencetemperature and an irradiance of 1kW/m2; Ki (= 3mA/°C) is the temperature coefficient,λ is the solar irradiance in kW/m2; and T and Tref are measured temperature andreference temperature, respectively. The output current is then

$$I_S(T) = I_S(T_{ref})\exp\{K_S(T - T_{ref})\} \qquad \text{…………2.3}$$

where IS(Tref) is the reverse saturation current (Tref = 295K) and Ks (≈ 0.072/°C) is thetemperature coefficient of the PV panel.

2.3The Quasi-Double-Boost DC/DC Converter

Many DC/DC converter topologies were considered prior to designing thesystem. Ultimately a double-boost DC/DC converter (Rensburg, 2008) was chosenbecause of the requirement for a high voltage regulation ratio (200/28) as well as theconverter's output stability over the entire duty cycle range. As shown in Figure 1, thedouble-boost DC/DC converter consists of two inductors, two switches and threediodes. The boost function is achieved by switching the two switches simultaneously.However, the following analysis reveals that the voltage regulation ratio is not exactlydouble boost previously derived (Rensburg, 2008).

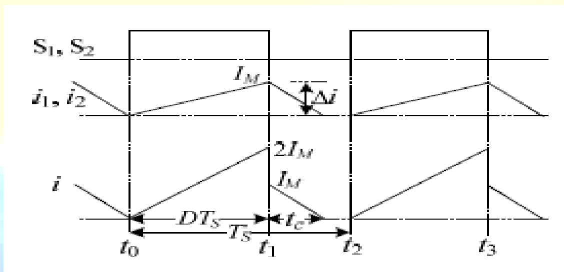


Figure 4.The current waveform in DCM mode.

The converter can work in a continuous current mode (CCM) or a discontinuouscurrent mode (DCM). The DCM is studied since the CCM is a special case of the DCM.The waveforms in the DCM are shown in Figure 4, where S1 and S2 are the gate signals ofthe two switches; TS and D are the switching period and duty ratio of the DC/DCconverter, respectively; tc is the duration that the inductor currents decrease to zerofrom the maximum value; and IM is the maximum inductor current. Neglecting theripples of vin and vout, the following formula can be obtained for the switch on and offperiods, respectively.

$$I_M = \frac{V_{in} D T_S}{L} \quad \text{.........2.4}$$

$$V_{in} - V_{out} = -2L\frac{I_M}{t_c} \quad \text{........2.5}$$

where L1 = L2 = L; Vin and Vout are the average values of vin and vout, respectively. Thenthe voltage regulation ratio can be obtained from (2-4) and (2-5) as follows.

$$\frac{V_{out}}{V_{in}} = \frac{2DT + t_c}{t_c} \quad \text{............ 2.6}$$

The average value of the input current I in a period can be calculated as:

$$I = \left(D + \frac{t_c}{2T_S}\right) I_M$$ ……….2.7

According to the power conservation law, Vin*I = Pout, then

$$\frac{V_{out} \times V_{out}}{R} = V_{in}\left(D + \frac{t_c}{2T_S}\right) I_M$$ ……2.8

where R is the equivalent resistance of the load. Substituting (2-4) and (2-7) into (2-8), then

$$\frac{D + \frac{t_c}{2T_S}}{\frac{t_c}{2T_S} \times \frac{t_c}{2T_S}} = \frac{D \cdot T_S \cdot R}{L}$$ ……2.9

The conduction time tc can be derived from (2-9).

$$t_c = \frac{1 + \sqrt{1 + 4D^2 T_S \left(\frac{R}{L}\right)}}{D\left(\frac{R}{L}\right)}$$ ……. 2.10

Equation (2-10) indicates that the conduction time during the switch off period isrelated with R, L, T, and D. The following formula can be obtained by substituting (2-10)into (2-6).

$$\frac{V_{out}}{V_{in}} = \frac{1 + \sqrt{1 + 4D^2 T_S \left(\frac{R}{L}\right)}}{2}$$ ……… 2.11

Equation (2-11) indicates that in the DCM, the voltage ratio is not onlydetermined by the duty ratio, but also determined by the output current and theinductance value. If the equivalent load resistance varies from time to time, the dutyratio should be changed to sustain the desired voltage gain.

When tc = (1−D) TS, the converter works in the critical mode, substituting tcinto(2-9), then the critical inductance LC is:

$$L_C = \frac{D(1-D)^2}{(1+D)} \cdot \frac{RT_S}{2}$$ ------2.12

Equation (2-12) indicates that the critical inductance depends on the duty cycleand load. Equation (2-12) also indicates that there exist a supremum (i.e., the leastupper bound) value LM such that for any L > LM, the circuit will work in the CCM for anyduty ratios. This unique maximal critical inductance can be derived by setting the first derivative of LC with respect to D as zero.

$$\frac{\partial L_C}{\partial D} = 0 \qquad \text{……….} \; 2.13$$

Then

$$L_M = 0.113 \cdot \frac{RT}{2} \qquad \text{…..}2.14$$

Therefore, (2-14) can be used to design the inductor so that the circuit alwaysworks in the CCM when the load is fixed. On the other hand, if the inductance is fixed,then there exists a critical duty cycle (DC), when D < DC, the converter works in the DCM;otherwise, the converter works in the CCM, in which (2-6) can be further simplified as:

$$\frac{V_{out}}{V_{in}} = \frac{1+D}{1-D} \qquad \text{…..}2.15$$

Equation (2-15) indicates that the voltage regulation ratio is not simply twicethat of the basic boost converter as claimed in (Rensburg, 2008). Thus, the originaldouble-boost converter named in (Rensburg, 2008) is called the quasi-double-boostconverter from here on.

3 THE MAXIMUM POWER POINT TRACKING ALGORITHM

The P&O algorithm is a relatively simple yet powerful method for MPPT. Thealgorithm is an iteration based approach to MPPT (Salas, 2006). A flowchart of themethod can be seen in Figure 5.The first step in the P&O algorithm is to sense the current and voltage presentlybeing output by the PV panel and use these values to calculate the power being outputby the panel. The algorithm then compares the current power against the power fromthe previous iteration that has been stored in memory. If the algorithm is just in thefirst iteration the current power will be compared against some constant placed in thealgorithm during programming. The system compares the difference between currentand previous powers against a predefined constant.

This constant is placed within thealgorithm to ensure that when the method has found the MPP of the PV panel, the dutycycle will remain constant until the conditions change enough to change the location ofthe MPP. If this step is not included the algorithm would constantly change the dutycycle, causing the operating point of the panel to move back and forth across the MPP.The movement across the MPP is an unwanted oscillation that can be disruptive topower flow and could also cause unwanted loss from not having the operating pointright over the MPP at all times. The next step in the algorithm is determining whetherthe current power is greater than or less than the previous power. The answer to thistells the algorithm which branch of the flowchart to take next. No matter whichdirection the algorithm takes, the next step is to compare the voltages in the currentand previous iterations. The voltage comparison tells the algorithm which side of theMPP the operating point is at thereby allowing the algorithm to adjust the duty cycle inthe right direction, either a positive or negative addition to the current duty cycle. Thefinal step of the method is to actually change the duty cycle being output to theconverter, and wait for the converter to stabilize before starting the process all overagain.

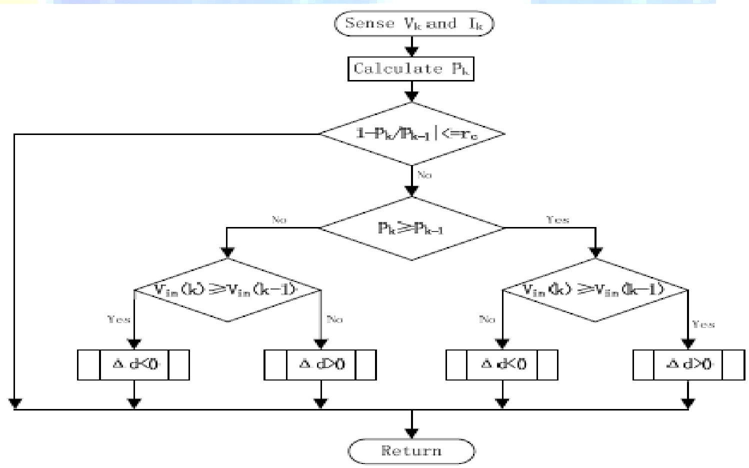


Figure 5.Flowchart

There are multiple ways to try to optimize the P&O algorithm. The first and mostimportant is to choose the constants within the system carefully. The first constant (rcin the flowchart) that tells the algorithm whether or not the MPP has changed, needs tobe sized just right. It needs to be big enough to stop the oscillation effect once the MPPhas been found but small enough to ensure that the algorithm will move to the correctpoint when the MPP changes even slightly. Another important constant to optimize isthe amount the duty cycle changes (Δd) with each perturb. This needs to be smallenough to allow for a sufficient number of steps within the full duty cycle range. It is

also important to make this number small enough that when the MPP is reached onechange won't be enough to throw it over the MPP causing the same oscillations thatwere avoided by sizing rccorrectly. This also means that the amount of change in theduty cycle should be correlated with the first constant as well as. This all makes it sound

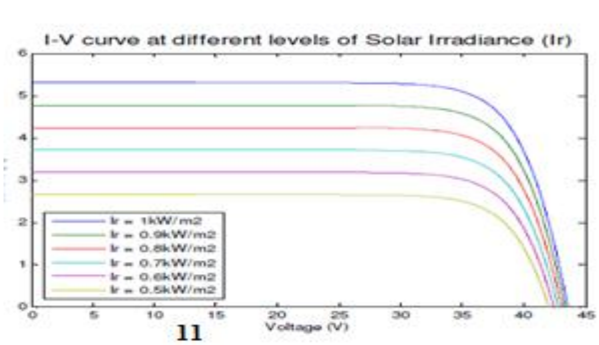
as though it would be best to have Δd as small as possible, but this would also causeproblems. The system needs to be able to respond to rapid changes in theenvironment, such as cloud cover. If a cloud suddenly shades part of the panel thealgorithm should be able to quickly account for the change in MPP and move theoperating point to the new MPP. Having the amount of change in the duty cycle periteration very small would mean that it would take a great number of iterations to reachthe new MPP. Every iteration where the panel is not operating at the MPP can beconsidered a loss in power. Therefore it is important to have Δd be large enough toallow the algorithm to converge to a new MPP quickly. This shows that there is a largetrade off between speed and efficiency with this algorithm. The algorithm in use hereincreases or decreases the duty cycle by 0.125% per iteration.The last main way to optimize this algorithm is to change the time betweenwhen one iteration ends and the next one begins. There needs to be enough timebetween the iterations to be sure that the converter or panel has reached a steady stateafter a variation in duty cycle. If there is not enough time the power calculation may bebeing made from fluctuating voltage and currents. The fluctuations would cause thecalculated power to be wrong, which could make the rest of the algorithm change theduty cycle in the wrong direction. Here again careful decisions need to be made though,because if the time between iterations is too long then there will be convergence issueswith the system under rapidly changing conditions.

4. RESULTS

Simulation studies are carried out in MATLAB Simulink to validate the converterand MPPT control for a PV system as is presented in Appendix 2.

4.1Validation of the PV Panel Model

The PV panel model is firstly tested to make sure it is accurate. The results fromthe first test can be seen in Figure 11. In this test the I-V curves are found after differentlevels of solar irradiance were applied to the model. It can be seen here that while thevoltage remains nearly the same, the current changes greatly with varying irradiance.In the second test, simulations are performed for the PV panel model withdifferent cell temperatures. The results are shown in Figure 7. These results from themodel provide a great visual depiction of how small an effect a temperature change haswhen compared to a change in irradiance, shown in Figure 6.The Quasi-Double-Boost DC/DC Converter.The DC/DC converter is the next part of the system that needs to be tested. Theconverter tests are preformed with a constant voltage source of 36 volts.



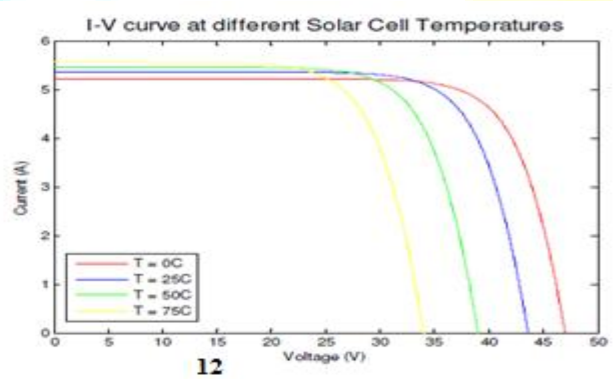
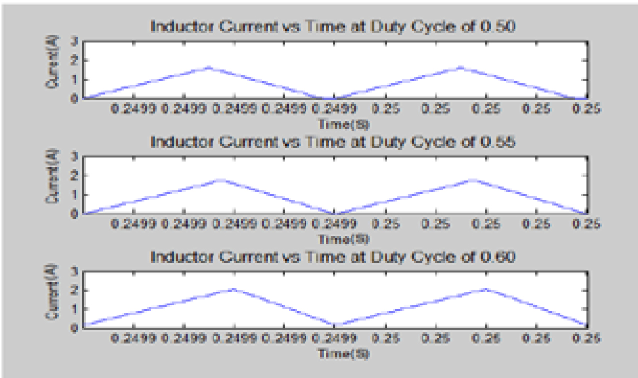


Figure 6. I-V curves at different levels of solar irradiance generated by the PV panel model.Figure 7. I-V curves at different levels of solar cell temperatures generated by the PV panel model.

This is bothfor ease of testing and for the accuracy of the results. Other system parameters are setas follows: the switching period of the converter is 50 μs (20 kHz); the inductors are 560μH and the load resistance R is 330 Ω.The first aspect of the converter is its characteristics in different operatingmodes: CCM and DCM. This can be tested by looking at the inductor currents aroundthe critical duty cycle found in equation (2-12). With the parameters set above andequation (2-12) it can be calculated that the critical duty cycle is 0.568. Figure 8 showsa converter duty cycle on each side of the critical value. From Figure 8 it is shown thatwhen the duty cycle is 0.60, which is higher than the critical value the converteroperates in CCM. The figure also shows that when the duty cycle is lower than thecritical value at 0.50, the converter operates in DCM. At a duty cycle of 0.55 which isclose to the critical value but still below it the converter is only ever so slightly acting inDCM.



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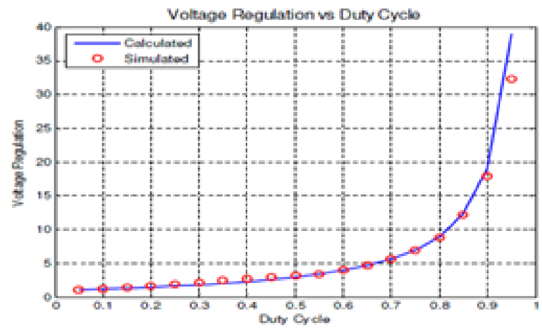

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Figure 8.The inductor current of the converter in DCM and CCM, Figure 9. Comparison of the calculated and simulated results of voltage regulation for the DC/DC converter.

The next property of the converter to look at is the voltage regulation. To testvoltage regulation the converter is ran at specific duty ratios while input and outputvoltages are measured. The regulation ratio is then compared to the ratio calculated byequation (2-15) in Figure 9. As is shown in the graph, the simulated results for thevoltage regulation are close to what had been calculated. The one main difference iswhen the duty cycle is at 95%. At this point the simulated value is a gain of 32.4 whilethe calculated value is a gain of 39. This is believed to be due to the simulation beingmore accurate to real life where the higher voltage causes more losses though thecomponents in the converter.

4.2 The MPPT Control

The P&O MPPT method is implemented in Simulink and added to the convertercircuit and PV panel model. The MPPT control unit takes as its input voltage and current measurements from the PVpanel simulation. The control unit then computes the power and sends the informationalong with the PV panel voltage value into the P&O algorithm. The algorithm thendecides whether the duty cycle output to the circuit should be increased, decreased orkept the same. This new duty cycle is then output to the converter. The process is ableto hold the PV panel at its maximum power output under changing conditions.In order to test the MPPT control algorithm the entire PV system has to besimulated. The best way to test the MPPT algorithm is by simulating the PV panel undervarious light conditions all while running the converter. This allows the tracking systemto sense the changes in the panel output and correct for them using the duty cycle ofthe converter. Figure 10 shows the results of a 40 second simulation of the entire PVsystem. It can be seen that the irradiance was first increased from 0 to 1 kW/m2 andthen decreased back down to 0 in a stair step fashion. In the second part of Figure 10 the algorithms reaction to the irradiance is shown in the form of the duty cycle itoutputs. The third graph on Figure 10 shows the resulting solar power output from thepanel.

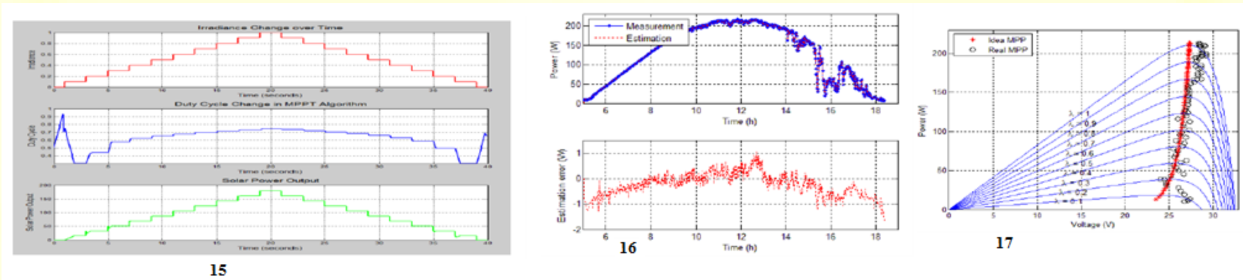


Figure 10. Simulation results of the MPPT control algorithm, Figure 11.The power estimation results, Figure 12. The MPPT results of the PV system.

There are a few interesting outcomes worth noting from the results shown inFigure 10. The first thing that is noticed is the rapid increase in the duty cycle at thebeginning of the simulation. This is something that will only be seen in a simulation and is a result of the PV panel model being so accurate to real life. When a PV panel is notgiven any light at all it can actually work in a reverse. This is best described while talkingabout a panel hooked up to a battery directly. The reverse leakage current through thediodes within a solar cell can actually take power away from the battery and emit itthrough the PV panel when no light is present. The same is true for this simulationwhere the capacitor starts with a slight charge on it. The algorithm is actually doingexactly what it is supposed to, just backwards. When there is 0 kW/m2 irradiance the PVpanel model is actually taking power out of the capacitor and it is flowing backwardsthrough the circuit. Even though the amount of power is very small (~-3e-30) thealgorithm senses it and tries to compensate for it. This compensation is seen in Figure10 by the duty cycle rapidly increasing at both the beginning and end of the simulation.Here the algorithm is actually trying to completely shut off the switches within theconverter in order to lessen the loss of power. Since the control algorithm only allowsthe converter to operate at a duty cycle from 5% to 95% when the duty cycle shown inFigure 10 increases to 95% it is reset at 72.5%. Shortly after this reset the irradianceincreases to 0.1 kW/m2, which causes all backward power flow to cease. This allows thealgorithm to settle at the duty cycle which allows the most power flow from the panel tothe converter.There are two main reasons that the backward power flow seen in Figure 10 isonly a simulation result. In the real system the controller will be powered from the PVpanel in order to minimize losses when it is not needed. This means that when there iszero irradiance the controller will not be running and, therefore, the converter willalready be in its off state, not allowing reverse power flow. The second reason thisshould not be seen in the real system is that there is almost never a time when there isabsolutely no irradiance. At night the sun reflects off the moon, there are manmadelights everywhere and even the stars give off some irradiance that will be seen on thepanel. While this isn't enough to see a usable amount of power, it is usually enough tostop the panel from allowing power to flow in reverse.The next thing to take notice of in Figure 10 is how good the system actually is attracking the power output of the PV panel. At very low irradiance values the algorithmhas a slight lag before it settles at the correct value since the duty cycle has to change somuch. This can be seen both when the irradiance is increasing and when it is decreasingat values of 0.1 and 0.2 kW/m2. This is only seen at these low values and is almostcompletely eliminated at higher irradiance values. At the higher values of irradiance thealgorithm is very quick at tracking to the new irradiance value once a change hasoccurred. With the simulation only being 40 seconds in total length and havingirradiance changes in steps over the full range of values, the algorithm preformed evenbetter than expected. This shows that the algorithm should have no problem adjustingfor a quickly changing MPP on partly cloudy days. The next step is to simulate the othercurrent-sensorless technologies.

4.3 Current-Sensorless MPPT Control

Simulation studies are carried out in MATLAB Simulink to validate the proposedcurrent-sensorless MPPT quasi-double-boost converter for the PV system. Thesesimulations are completed by using real solar radiation data obtained from NationalRenewable Energy Laboratory (NREL) to validate the proposed system and controlalgorithm. The data was collected from the South Table Mountain site in Golden,Colorado, on May 31, 2010. During the simulation, the output power of the PV panel isestimated by the proposed current-sensorless

MPPT algorithm and is compared withthe measured output power by using both voltage and current transducers, as shown inthe Figure 11.The proposed current-sensorless algorithm estimates the real output power withgood precision; the estimation errors are less than 1 W during most of the day. Withoutknowing the solar radiation, the proposed MPPT algorithm controls the PV system totrack the MPP of the PV panel by using the estimated current and measured voltage.Figure 12 shows the operating points, i.e., the real MPPs, of the panel at various solarradiation conditions during the day, which are close to ideal MPPs.

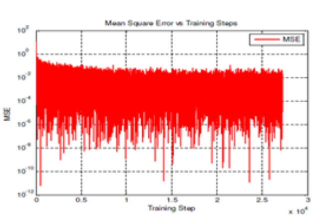
Inductor Current Sensing TechnologySimulation studies are also carried out to validate the inductor current sensing

technology and the resulting MPPT control algorithm. These simulations werepreformed within MATLAB's Simulink using the neural network laid out as in Figure 10.The code for the neural network design can be seen in Appendix 2. In order to gatherdata to train the system, the converter simulation presented above was run again. The

simulation used a varying duty cycle incremented in small steps and the resultinginductor voltage drop along with the input voltage and current were recorded. Theseresults were then used to train the artificial neural network. The resulting mean squareerror (MSE) output from training can be seen in Figure 13, where the MSE is calculatedby

$$MSE = \frac{1}{2}E^2 \quad \ldots\ldots 4.1$$

WhereE is the error between the actual input current and the input current estimatedby the artificial neural network.



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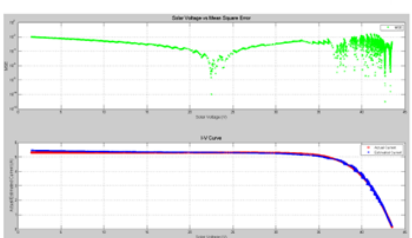

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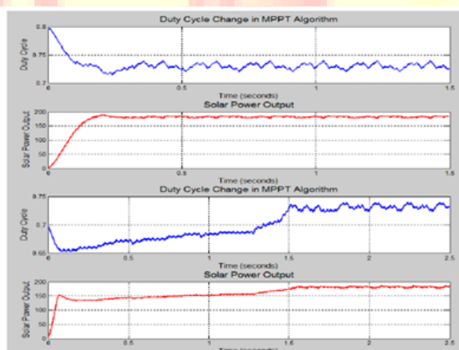

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Figure 13. Mean square error output during the neural network training, Figure 14.Comparison of actual and estimated input current, Figure 15. Simulation results of the inductor sensing MPPT control algorithm.

Figure 13 shows that the mean square error stays below 10-1.5 for all inputs bythe end of the training period. To obtain a better understanding of what this actuallymeans the weights found in testing, the neural network is applied to the data setrecorded through the converter simulation and the estimated input current is comparedagainst the actual recorded input current. The results of this comparison are shown in Figure 14.

Figure 14 shows the I-V curve output for both the estimated and the actual PVpanel current. It can be seen that the two curves are very similar. While the two curvesdo not exactly match they are close enough to run the MPPT system. The importantaspect of the curve for the MPPT algorithm is not the exact current value, but that thecurrent is linear in the movement throughout the curve. The algorithm only careswhether the current is increasing or decreasing. This can further be seen by simulatingthe MPPT system while using the artificial neural network to estimate the input currentwithin the algorithm. Figure 15 shows the results of running the system with theestimated current as an input to the MPPT algorithm. The irradiance is set to 1 kW/m2and the duty cycle is began to different values, one higher (80%) than the valueexpected for the maximum power output and one lower (70%). The algorithm finds theMPP in both directions to be 184 W, at a duty cycle of 74% which are the same as theresults seen in Figure 10. When comparing the results after the algorithm has reachedthe MPP in Figure 15 and in Figure 10, it is again seen that they are the same. Thisshows that the algorithm with the inductor current sensing technology is working asgood as the algorithm with the standard sensing technology, though it may be slightlyslower. The inductor current sensing algorithm still manages to find both new MPPwithin 1.6 seconds. This is quick enough for the system to work under any normalworking conditions. The next step was to apply the results observed in the simulationsto the actual system.

4.4 Sensing Technology Comparisons

All three of the sensing technologies work when simulated but each one has prosand cons when compared against each other. When comparing both current sensorlesstechniques there is not really one that stands out over the other. Both work in thelower power application presented here but do not improve on the traditional resistorsense technology. Where the biggest improvement would be seen is in high power,high current applications. This is where the resistor sense technology would incur themost losses. However at these higher powers and currents the current sensorless andinductor current sense designs would not have any extra losses when compared to a lowpower system. Being used in a higher power system may even improve the accuracy ofboth systems. The higher current in the current sensorless design would give thesystem a more defined voltage ripple to perform calculations off of, improving overallresults. The inductor current sense system would also have a higher inductor voltagedrop to read into the neural network which would allow the system to obtain betteraccuracy in the current estimation. This would be due to there being a higher inductorvoltage change correlated to the higher current. The higher current would howeverrequire retraining of the neural network to ensure proper operation.In low power applications with low current the standard resistor sensetechnology is recommended, both for ease of use, cost effectiveness, and reliability. Inapplications where the power level may change overtime, such as modular systemswhere panels may be added and removed the traditional system is also recommended.This is because both current sensorless technologies would have to be modified eachtime the input power level changed. With the traditional sense technology as long asthe voltage drop across the resistance does not exceed the input rating of the voltagetransducer used to measure it the system will continue to work without anymodification at any power level. In higher power applications that would cause largepower losses across a resistive element it is recommended that both the currentsensorless and the inductor current sense technology be evaluated for performancewith the overall system. High power applications are where these systems will excelover the traditional current sense technology.

5 CONCLUSIONS

In order to maintain the highest power output from a PV panel at all times a highefficiency converter coupled with a MPPT system must be used. In this research a highefficiencyquasi-double-boost DC/DC converter was designed and implemented. A fastreacting and accurate MPPT algorithm was implemented to control the converter andmake sure the PV panel is always outputting the maximum power available at a giventime. Results are presented showing the output power improvement over a standardpanel with a fixed load. Three separate current sensing and sensorless methods arepresented to ensure the entire system operates with the highest possible efficiency.In future work it is recommended that all three current sensing technologies beimplemented with identical converters and PV panels, so they can truly be tested against one another.

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