Simple, Inexpensive Solar PV Power Optimizer

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Abstract

A simple solar panel power optimizer can be made with about $2 of electrical components, compared to more than $30 for most Maximum Power Point Tracking controllers. Solar panel voltage is kept near the

maximum power point voltage by intermittently disconnecting the load. The solar panel charges a capacitor during the “off” part of the cycle. During the “on” part of the cycle, the capacitor discharges, adding to the panel current. While not a true Maximum Power Point Tracker, the circuit can update the maximum power point voltage by periodically sampling the open circuit voltage.

Nomenclature

ISEC	Insulated Solar Electric Cooker (Cooking)
MECS	Modern Energy Cooking Services
MPP	Maximum Power Point
MPPR	Maximum Power Point Resistance
MPPT	Maximum Power Point Tracking
MPPV	Maximum Power Point Voltage
OCV	Open Circuit Voltage

Introduction

The extensive progress on Maximum Power Point Tracking (MPPT) for the optimization of solar panel power extraction has been well documented in two review articles (Podder, 2019; Esram, 2007) and will not be summarized here. Within the taxonomy of MPPT, we present here a Constant Voltage method with optional fractional Open Circuit Voltage (OCV) updating. Our power optimization method is not true MPPT because it does not actually measure power and approximates Maximum Power Point (MPP) conditions. Our circuit is not able to find a Global Maximum Power Point when partial shading conditions produce multiple power maxima. The output is voltage pulses, or can be made to be DC with the inclusion of an inductor.

The value of our circuit is simplicity and cost, consisting of between 10 and 26 electrical components with a total cost of about $2: appropriate for users who would otherwise not use any power optimizers. For instance, there is a considerable and growing market for off-grid solar electric cooking technologies, that must either buy expensive MPPT technologies or incur power losses by connecting the thermal load directly to the solar panel without optimizing. Since 2015, we have been developing a low power, low cost solar electric cooking technology with the goal of being locally manufactured in developing countries, (Watkins, 2017; Gius 2019; Osei 2021). The beauty of our power optimization circuit is that it can be produced inexpensively in small numbers by hand anywhere simple electrical components are available.

A decrease of solar intensity on a solar panel results in a near-proportional reduction of current, while the voltage profile remains relatively constant as displayed Fig.1, left.

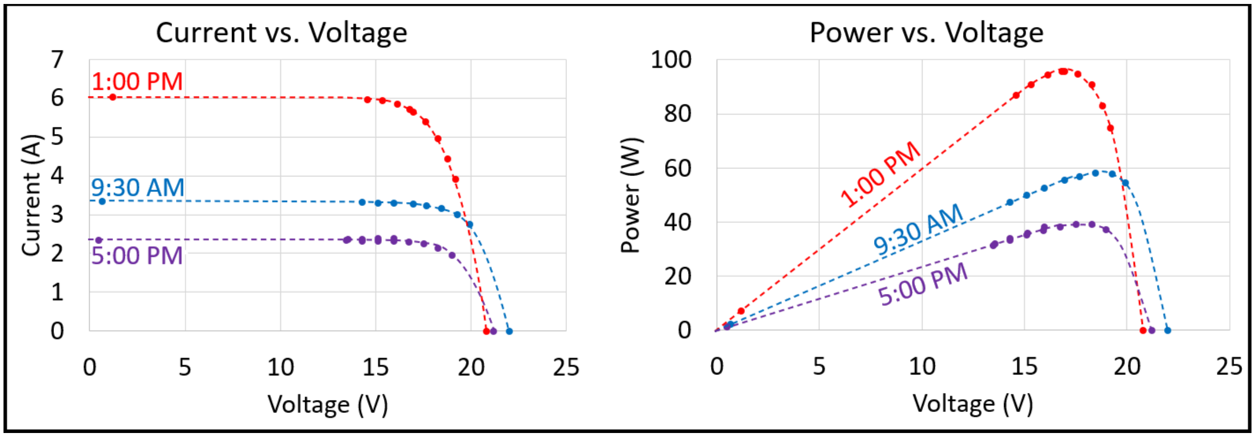


Figure 1. Data for a sunny day at different times, left. The slight decrease in voltage for 1:00 PM (approximately solar noon) likely results from an increase in solar panel temperature. The power produced varies as a function of the voltage on the solar panel, with a maximum power at about 80% of the maximum voltage (open circuit voltage), right. (Guis 2019)

The power produced, the product of current and voltage, corresponds to the area of the rectangle defined by the working point (letter "x" on Fig 2, left): where the solar I-V production curve intersects the load curve (the straight line of the resistive load on Fig.2, left). For instance, the displayed 100 W solar panels have a maximum power point (MPP) (V = 17 V, I = 5.7 A) under full sunlight, achieving maximum power only with a load of 3 Ohms, or Maximum Power Point Resistance (MPPR). The working point should remain close to 17 V for all solar intensities (blue circles, Fig 2, right), requiring the MPPR to increase. However, for a simple resistive load, the resistance is constant causing a voltage drop proportional to the current reduction. The decreased solar intensity thus moves the working point to the left, resulting in near quadratic loss of power to the load resistor (red circles, Fig. 2, right). The power loss is actually slightly less than quadratic because the supplied current increases slightly with the leftward shift of the working point.

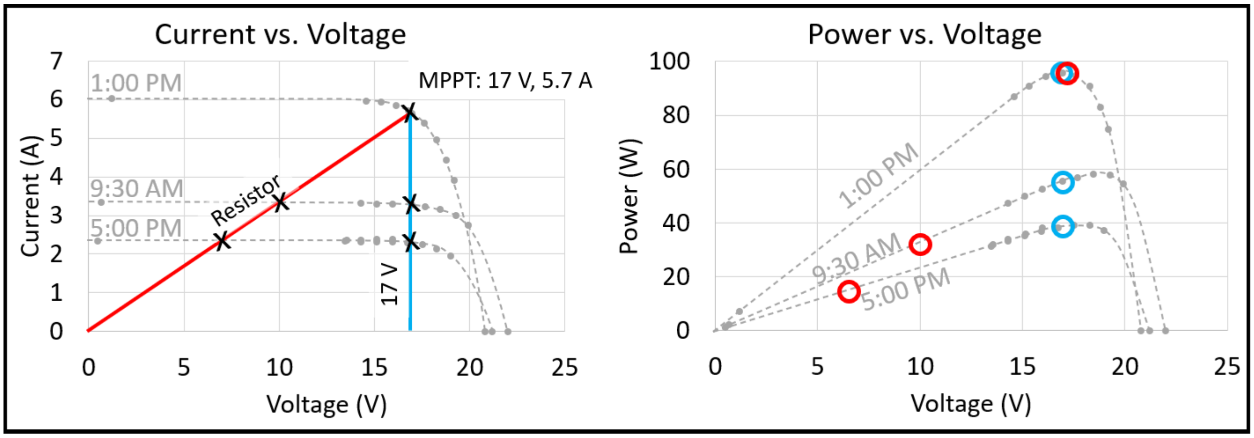


Figure 2. The working points ("x" at left) are where the solar panel I-V curve intersects the red load curve. The power produced (right) is the area of the rectangle defined by the working point. If the load is a simple resistor with a resistance that optimizes power for full sunlight, power will be lost for lower solar intensities (right, red circles).

A simulation using the "one diode" model on PSIM simulation tool (Fig. 3), compares the theoretical maximum solar PV power (blue) to delivered power from a solar panel directly connected to the resistive load that maximizes power under full sunlight (orange).

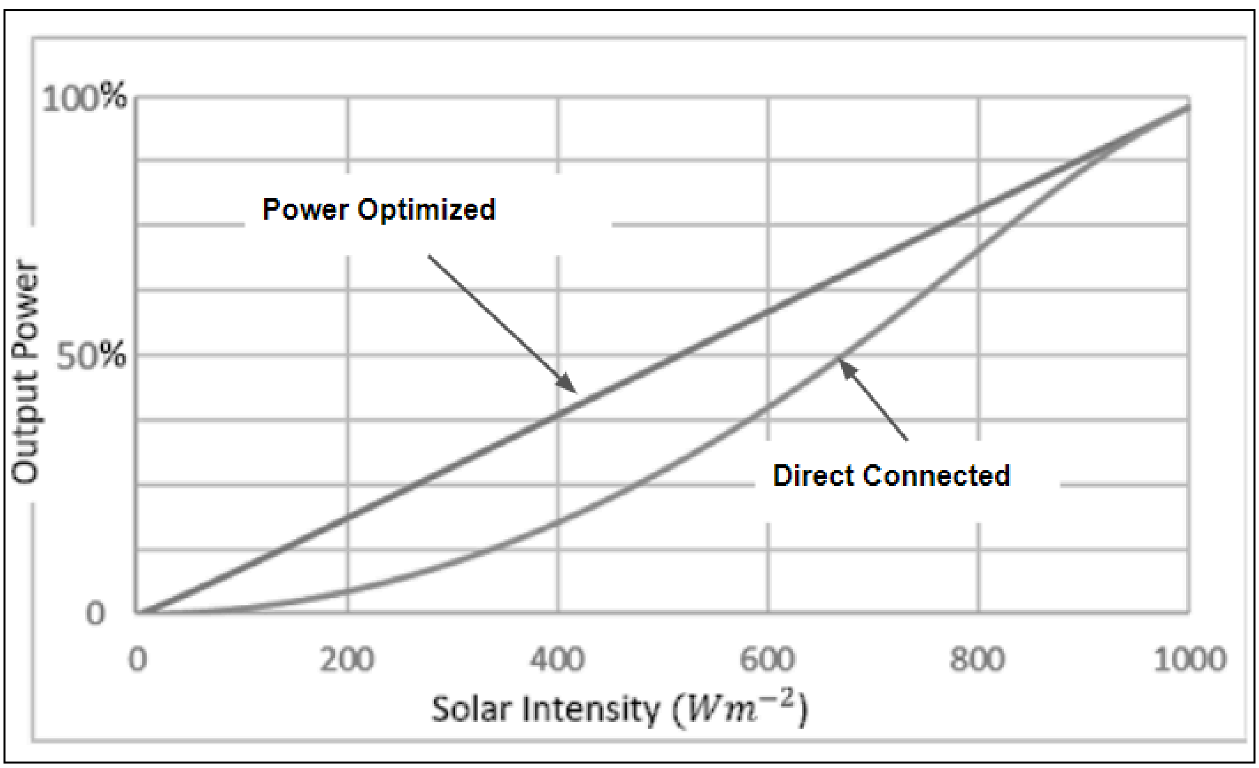


Figure 3, Comparison of maximum solar PV power (blue) and power delivered to a directly-connected resistive load (orange) of MPPR under full sunlight, in a simulation using the "one diode" model on PSIM simulation tool, courtesy of EMPO-NI Off Grid Solutions

In a previous publication (Gius, 2019) we showed how a heater made of diodes maintains near constant voltage for all currents, considerably increasing delivered solar panel power in reduced sunlight. The blue circles on Figure 2, right, are an idealization of this condition. However, diode heaters thermally degrade, are more difficult to make into heaters than resistors, and have a voltage that is not perfectly constant, but somewhat temperature dependent.

Maximum Power Point Trackers maintain MPP conditions by using DC/DC converters and processors to match the load's impedance to the solar panel under changing solar intensity and solar panel temperature. Most MPPTs continuously calculate the power produced while slightly changing the voltage conversion to continuously maximize power output.

The clean cooking movement aims to replace combustion cooking with (among other fuels) solar electricity. The least expensive application of solar electric cooking is a solar panel directly connected to a heater. Simple resistive cooking technologies including 12V/24V DC hotplates and DC pressure cookers are already internationally available. These and other DC devices are often powered by a directly-connected solar panel (Kashyap 2023, Batchelor 20219), providing present demand for an inexpensive "impedance matching" solar electric power optimizer.

Experimental

Optimizing Solar Panel Power

Our solar PV power optimizer maintains solar panel voltage near the maximum power point voltage (MPPV) by intermittently disconnecting the load to store charge in a capacitor across the solar panel (C1 in Fig. 4). When solar intensity decreases, rather than reducing the current to the load, there is a reduction in the duty cycle (duty ratio) of full current pulses, essentially increasing the effective resistance of the load. Thus, the power to the load will decrease linearly with a decrease in solar intensity rather than near quadratically. The reduction in duty cycle results in a time-average load impedance that matches the MPP of the solar panel under all solar intensities.

The duty cycle can be controlled by a processor that directly measures power output, achieving true MPPT. However, the operating point can be maintained *near* MPP without a processor by using a comparator (IC1, in Fig. 4) to define the solar panel target voltage. IC1 compares the solar panel voltage (pin 3, determined by R1, R2) to a target voltage (pin 2 determined by R3 and R4). When the panel voltage drops below the target voltage, the comparator (IC1) disconnects the load, until C1 charges to a voltage high enough for the comparator to reconnect the load through M1. Q1 and Q2 constitute an "isolator" between the comparator and the power MOSFET, M1. While Q1 and Q2 may not be necessary, including the isolator makes the transition more abrupt, reducing the time for M1 to switch states, reducing power loss in M1, and reducing the operating temperature of M1. Using the components in Table 1 under solar power 200 W (34 V, 6 A), without the isolator, M1 melted despite being connected to a heat sink. With the isolator, minimal power was lost: the heat sink was found to be unnecessary, though still recommended.

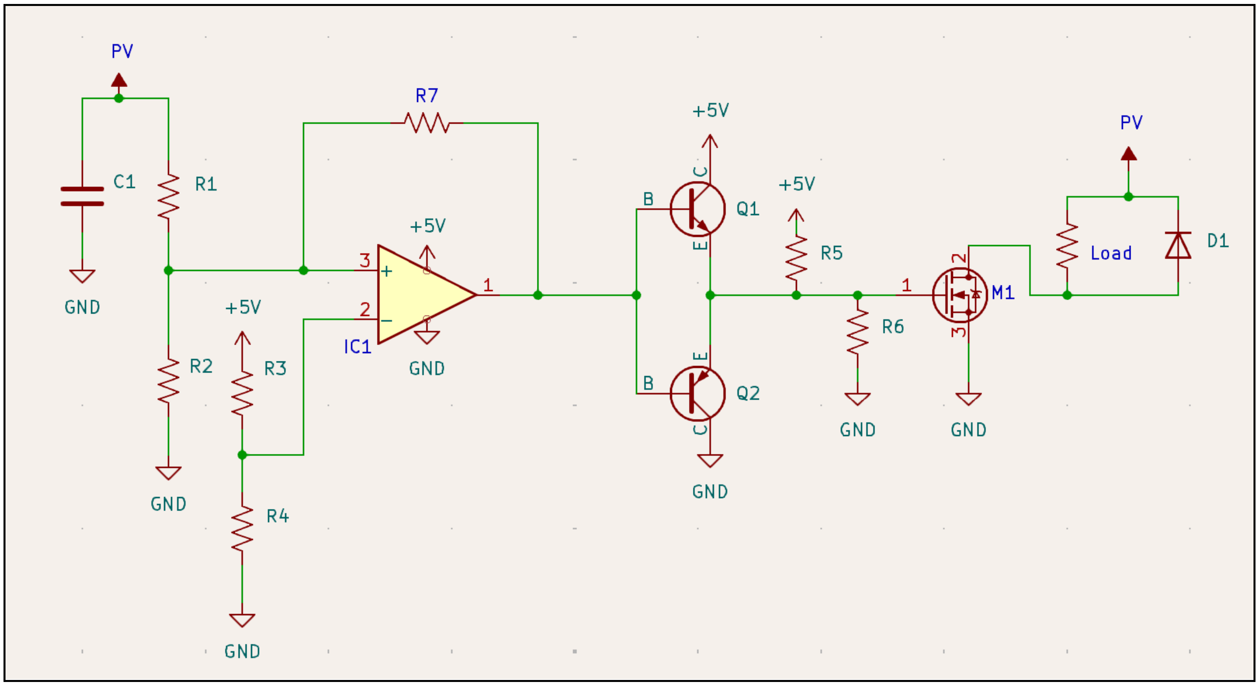


Figure 4, Schematic of simple power optimizer. IC1 compares the solar panel voltage (pin 3) to a target voltage (pin 2). When the panel voltage drops below the target voltage (determined by R1, R2, R3 and R4), the comparator (IC1) disconnects the load, allowing C1 to charge to a higher voltage.

R1	R2	R3	R4	R5	R6	R7*	C1	IC1	Q1	Q2	M1	D1	5V
56K	10K	10K	10K	1K	100K	220K	470µ	LM358	2N4401	2N4403	STP36NF06L	SK36	LM78L05

*Table 1. Components in Fig. 4 Power Optimizing Circuit applied to a single, 100 W solar panel with MPP: 18 V, 6 A. *We found that hysteresis resistor, R7, was not necessary, but its inclusion reduced time in the transition state. Total component cost is $1.26 when components are purchased in quantities of 1000.*

Choosing Target Voltage

The solar panel's operating voltage (determined by the choice of R1, R2, R3 and R4, Fig 4) should be as close as possible to MPPV. MPPV decreases a little with decreased solar intensity, but decreases considerably with increased solar panel temperature.

A true MPPT circuit continuously updates the target voltage with a processor. However, the circuit can also adjust the solar panel target voltage to new conditions with the fraction OCV method: the MPP voltage is a fixed portion of the OCV, usually between 70% and 80%. For our solar panels V_mpp = ~ 0.79 V_oc.

R3 is now connected to the solar panel positive voltage instead of a steady 5V reference. R3 and R4 have new resistances (Table 2) to select the target voltage that is the correct ratio of the OCV. The timing chip (IC2, Fig.5) disconnects the load long enough to drive the solar panel to OCV and samples the new target voltage via M2, charging C2 via diode D2, which holds the charge on C2 until the next sampling pulse. This "sample and hold" innovation allows a single power optimizer to respond to environmental changes and be universally applied to different solar panel configurations. For instance, if the user doubles input voltage by connecting two solar panels in series, OCV sampling could double the operating voltage.

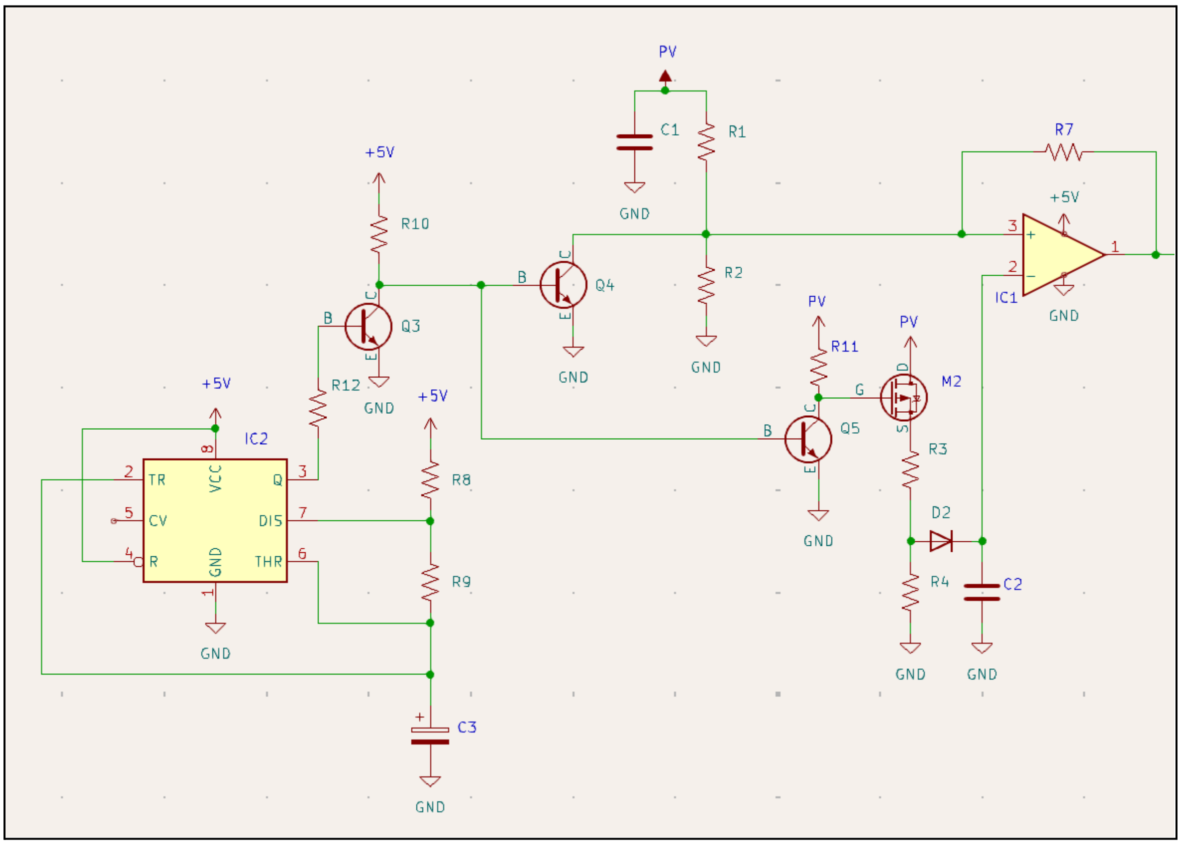


Figure 5, Open circuit voltage sampling to update the solar panel target voltage replaces the constant target voltage on pin 2 shown in Fig 4. Timing chip IC2 sends a high signal every 10 s (for instance) that disconnects the load resistor from the solar panel (M6 grounds the positive input of IC1), long enough to bring the panel voltage (PV) to Open Circuit Voltage (OCV), updating the charge on C2 to the correct fraction of V_oc via D2 by closing M2

R1: 56K	R2: 10K	R3: 680	R4: 100	R7: 220K	R8: 2M	R9: 10K	R10: 1K	R11: 10K	C1: 470µ
C2:	C3:	IC1:	IC2:	Q3:	Q4:	Q5:	D2:	M2:	R12:

246µ	10µ	LM358	NE555	2N4401	2N4401	2N4401	SK36	BS250P	220

Table 2, suggested components for the sample and hold circuit (Fig. 5). Adding the sample and hold circuit costs an additional $1.50.

The choices of R3, R4, C2, the amount of time M2 is connected, and the sampling frequency depend on each other and on the input impedance of IC1. If the comparator's input impedance at pin 2 is high enough, C2 can be small, allowing R3 and R4 to be large enough to always be connected with negligible power loss, eliminating the need for M2, Q5, and R11.

Additional Options:

DC Output can be achieved by adding an inductor in series with the load, maintaining the current through the load and diode D1 between voltage pulses, when M1 disconnects power. Near constant DC output makes the power optimizer appropriate not only for loads that can handle voltage pulses, but also for loads that require constant DC voltage. The advantage to using this constant DC output power optimizer over connecting the solar panel directly to the DC load is that the power optimizer provides the DC power at or near the solar panel's MPP for all load impedances lower than MPPR. The increased impedance offered by the inductor also requires more time to discharge C1, lowering the comparator's switching frequency, reducing the thermal load on M1.

5V USB and 12V power outlets: The 5V DC necessary for the operation of the circuit comes from a dedicated circuit component that can be powered by a number of methods, but will most likely be provided by a circuit component powered by the same PV panel the circuit controls. This same component can provide 5V for a USB charging port. Additional ports could also supply 12V, etc. Studies (Wilson, 2018) have found that users are more likely to use alternative cooking technologies if the technology can charge appliances.

Results

Figure 6 displays the solar panel voltage and the voltage on the gate of MOSFET M1 as a function of time for the circuit in Figure 4, using the components indicated in Table 1.

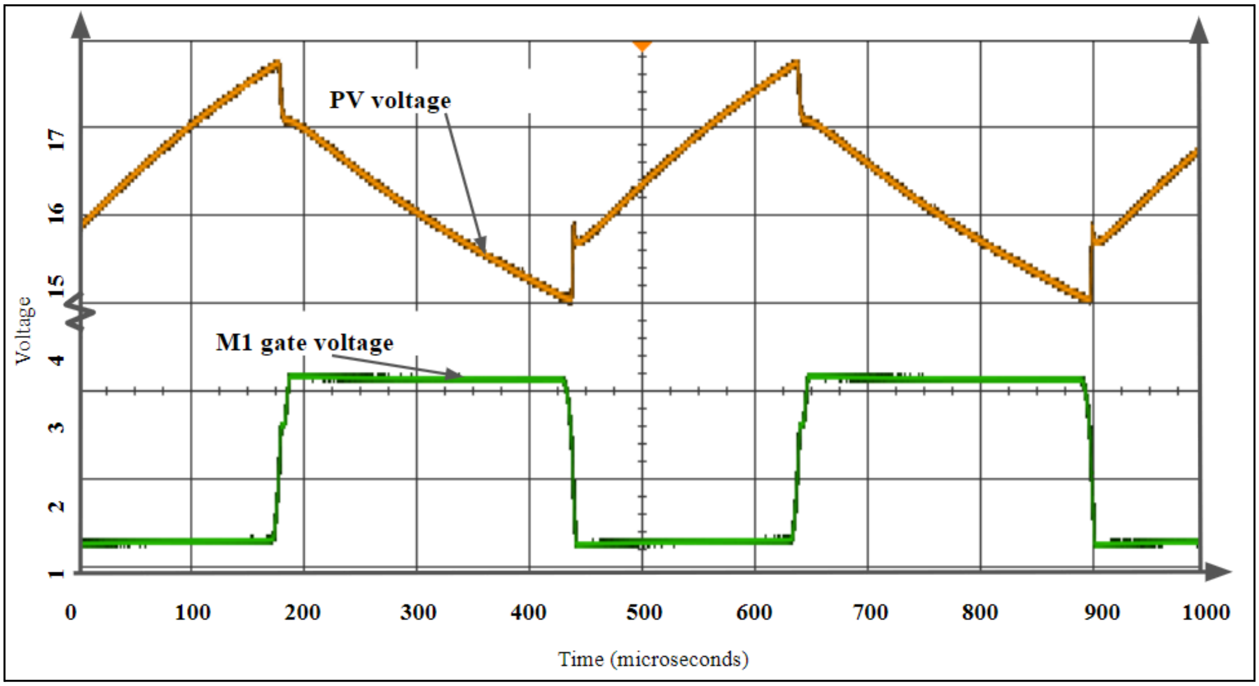


Figure 6: Oscilloscope traces for solar panel voltage (top) and voltage on M1 gate, below.

The power measured from the 100 W solar panel directly connected to a 3.0 Ohm resistor (Fig. 7, lower data points) is compared to power measured through the optimizer detailed in Fig. 4 and Fig. 6; overlaid on the expected trends from Fig. 3. Solar intensity was varied by changing the angle of the solar panel with respect to incident sunlight. Relative intensity was determined by comparing the short circuit current for each angle.

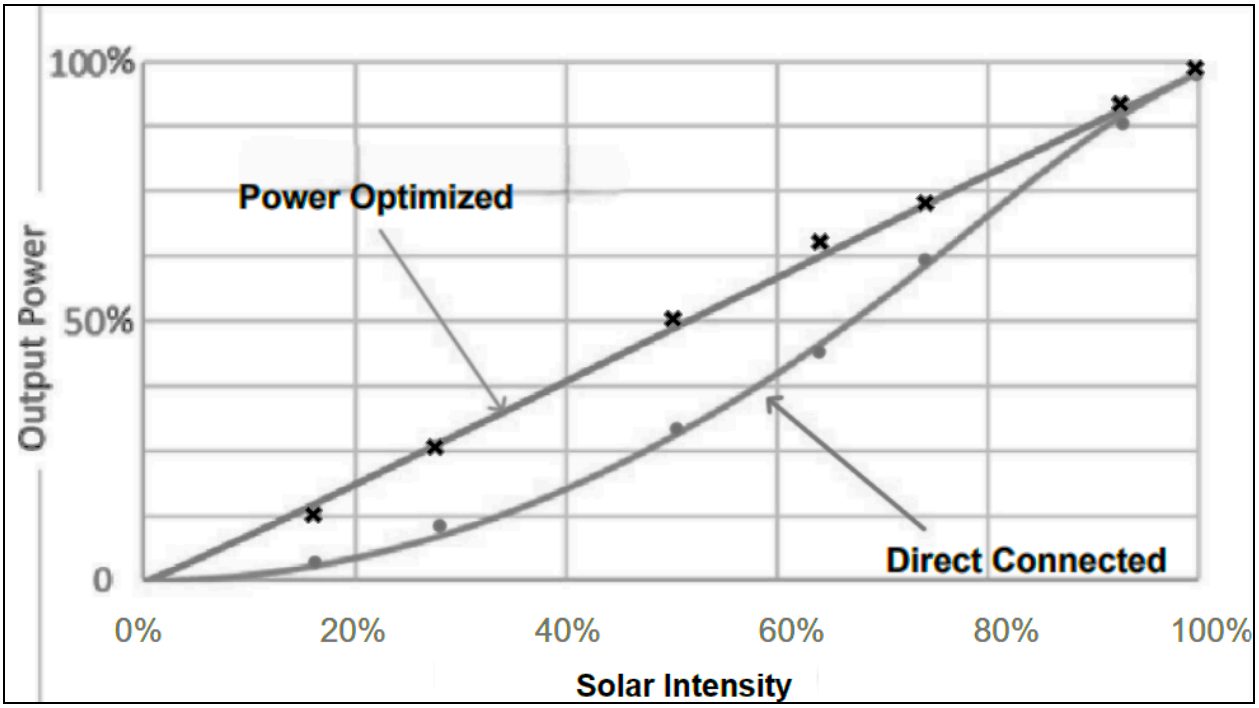


Figure 7. Power measurements overlaid on the theoretical curves of Fig. 3. Our 100 W solar panel was directly connected to a 3 Ohm resistor (circles), and connected via the optimizer detailed in Fig. 4 and Fig. 6 ("x" data points).

Figure 8 displays the solar panel voltage (across capacitor C1) and the target voltage across C2 (pin 3 on comparator) during an OCV sampling pulse for the components in Table 2. OCV was sampled every 14 s, for a period of 80 ms. The 1 MegaOhm input impedance of the scope used to record these traces drained more current from capacitor C2 than the comparator, resulting in greater voltage drop during the 14s, better illustrating the change in voltage for both traces during the recorded sampling pulse (Fig. 8). Without scope, the voltage change during the update is smaller by a factor of 5.

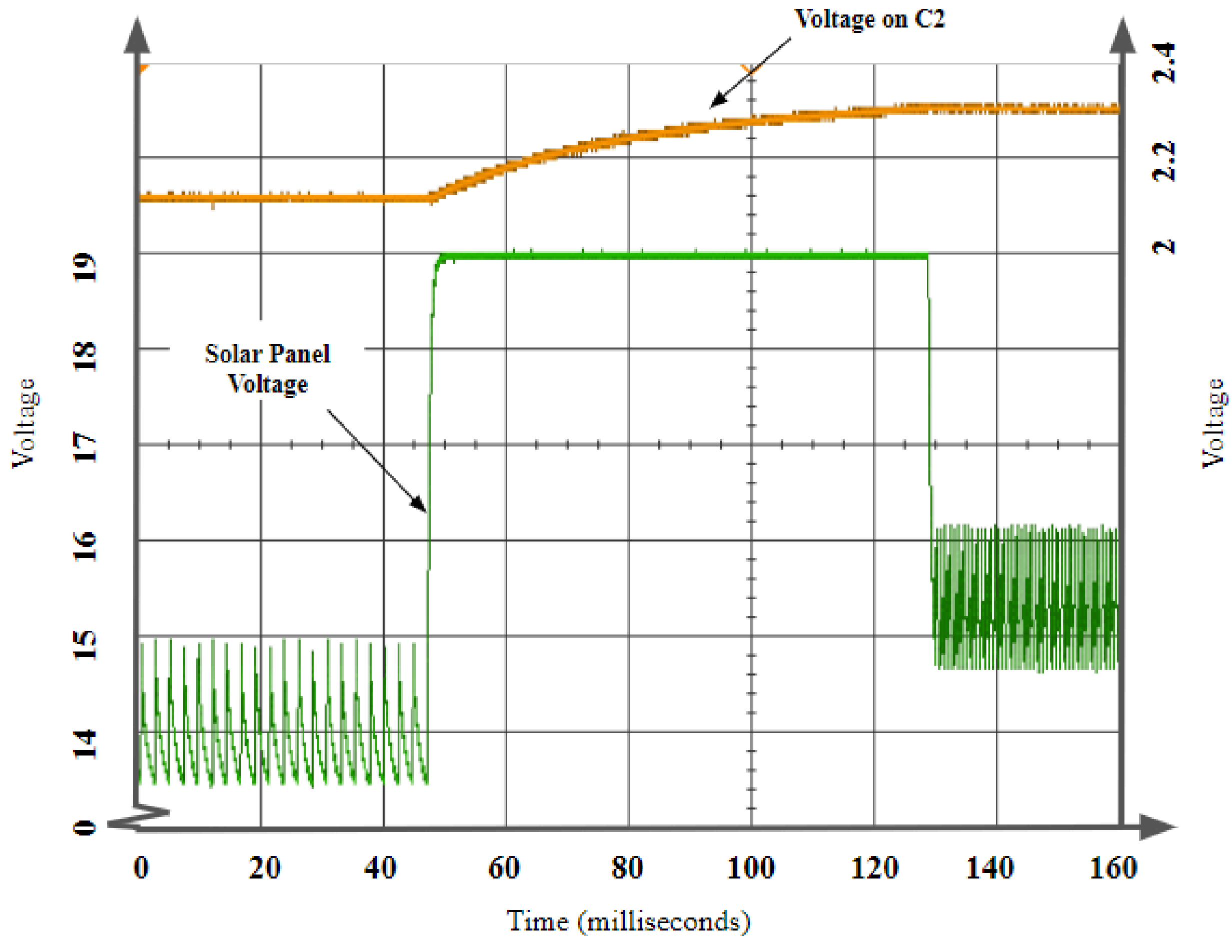


Figure 8 displays the solar panel voltage and the voltage on C2, during an OCV sampling pulse for the components in Table 2.

Figure 9 displays the voltage on the load with and without a 2 mH inductor.

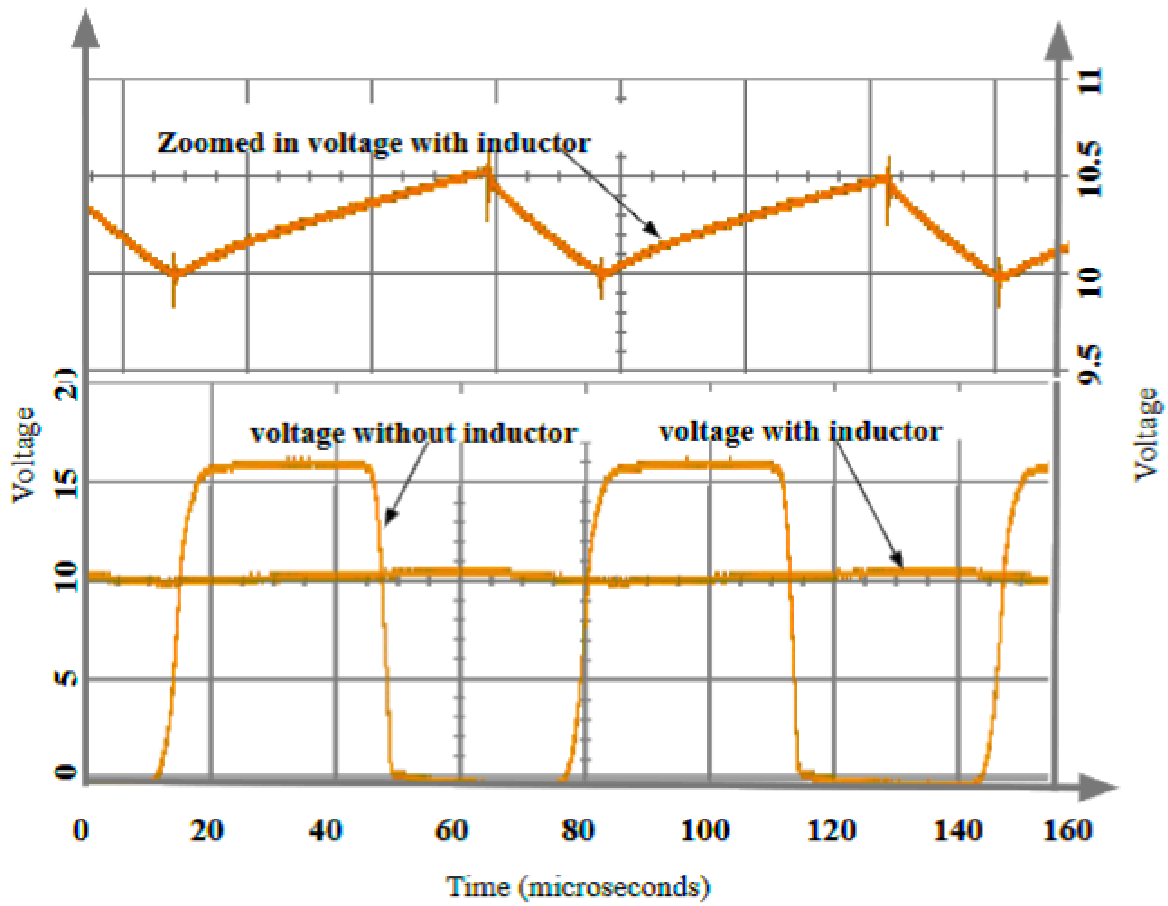


Figure 9 The voltage on the load with and without a 2 mH inductor. The two traces were taken separately. Adding the inductor increases the capacitor discharge time (when voltage on the load increases) and thus increases the period of oscillations.

Discussion

What did we build?

Figure 2 illustrates how maintaining MPP conditions requires the load resistance to increase with decreasing solar intensity. By intermittently disconnecting the load, our circuit increases the effective resistance by time averaging the load resistance with infinity, yielding R_effective = V/I_ave. The circuit optimizes power by matching the impedance of the load to that of the solar panel's MPP conditions.

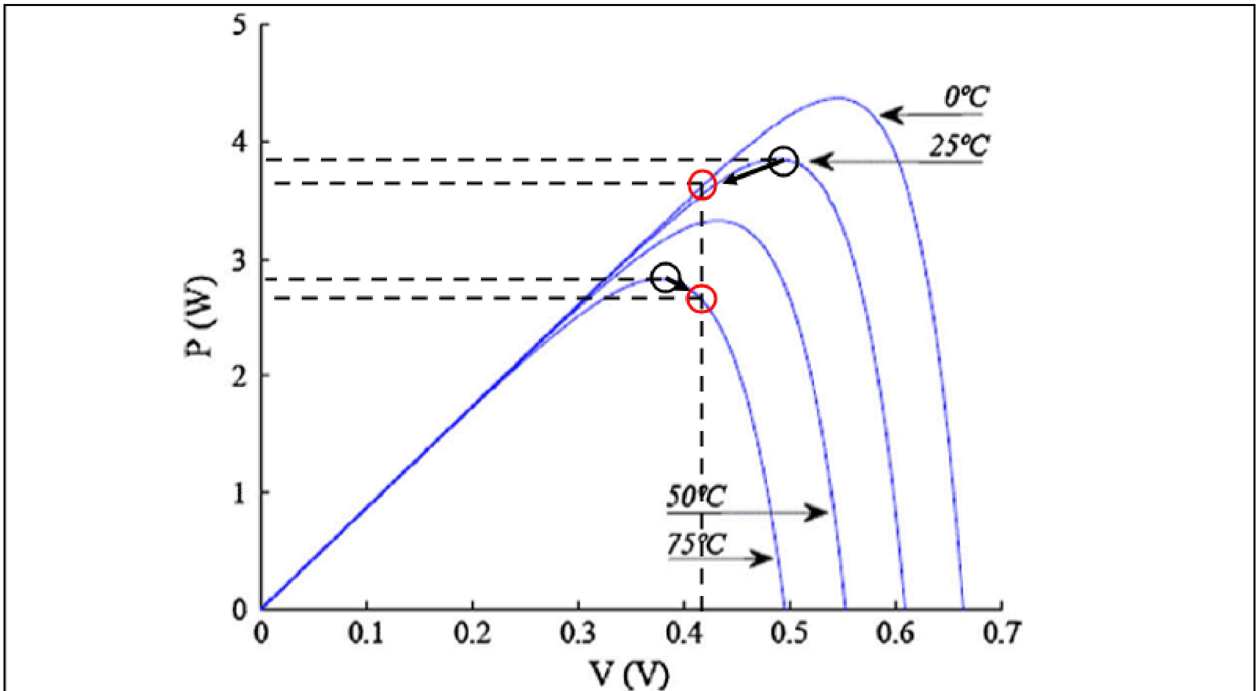
Improved versatility. Figures 1 and 2 illustrate the importance of picking the correct resistance for a load directly connected to a solar panel. However, few resistive loads are tailored to a solar panel's MPPR, resulting in power loss when the load resistance is higher or lower than MPPR. Impedance matching is further complicated by the reduction of MPPR with increased solar panel temperature, as well as solar intensity. This power optimizing circuit increases the effective load impedance to the solar panel's MPPR at all times, and only requires that the resistance of the load is less than MPPR, freeing the user to pick any resistive load below that determined by the solar panel specifications. This versatility means that invariably, the power increase achieved with our power optimizer is better than that displayed in Figure 7.

Do you need fractional OCV sampling? Not necessarily.

If the solar panel temperature varies between 25 and 75 degree Celsius, corresponding to a 25% decrease in V_{mpp}, (Fig. 10), an intermediate voltage (vertical dotted line) can be chosen to minimize the losses from the two temperature extremes to about 5%. However, the 0C and 25C curves don't exist in a tropical location because the temperature under full sunlight would be far greater than 25 C; thus, full sunlight temperature would likely vary by less than 20C in the same area, considerably reducing the power loss at either temperature extreme. Lower temperatures will be possible, but only under reduced sunlight, corresponding to reduced solar panel current. Power losses due to the variations in MPPV will be small if the target voltage is carefully chosen, for three reasons:

1) Reduced temperature will largely coincide with reduced sunlight intensity. Reduction in temperature increases MPPV, while the reduction in intensity reduces MPPV.
2) The Power-Voltage curve is flatter on the low voltage side of peak power, so if the target voltage is determined in hot, sunny weather, the increase in MPPV for cool, sunny weather will minimally reduce power output.
3) Reduced intensity already has reduced power, making fractional power losses less important than fractional power losses at full solar intensity.

Without OCV sampling the operating voltage must be customized for each solar panel assembly for the projected full sunlight and high temperature conditions, complicating installation and reducing flexibility. With OCV sampling, the circuit only needs to be customized to the fractional OCV coefficient of the solar panel.



Output power-voltage (PV) curves of solar panel under different operating temperatures. [11]

Figure 10, Shifting of Solar Panel power curve with temperature (Manoharram, 2013).

<u>Prioritizing Loads</u>

If several loads are connected to the same power optimizer output, the loads will all have the same voltage. However, if each load is connected to separate optimizers without OCV, each optimizer can be set to slightly different target voltages, assigning priority to the device associated with the lowest target voltage.

<u>No DC/DC convertor necessary?</u>

Although we state that no buck or boost convertor is necessary, the optimizer circuit with the inductor is itself a DC/DC buck convertor, where the input voltage from the solar panel controls the conversion ratio. Figure 9 illustrates this behavior. The ~ 60% duty cycle results from the solar intensity providing 60% the MPP current, which in a directly-connected resistive load would result in the voltage also being 60% of MPPV (9 V) and an output power of 36% maximum power - with (60%-36%) power being lost in the solar panel. The power optimizing circuit maintains maximum available power by reducing the output voltage only by rt.0.6 (to 11.6 V), while increasing the current by the same factor (not shown).

Conclusion

A simple solar PV power optimizer can be inexpensively made where simple electronic components are available. The circuit has no buck/boost converter and no processor, and does not calculate the power; and thus is not a true maximum power point tracker (MPPT). However, in the absence of partial shading conditions (PSC), the performance of this simple circuit deviates minimally from that of true MPPT. With between 10 and 26 circuit components totalling less than \$3 in cost, our solar PV power optimizer is a small fraction of the cost and complexity of a true MPPT.

Acknowledgements

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