



ON Semiconductor

Design Note – DN06054/D

# Reference Design for Solar Power MPPT Controller

| Device  | Application           | Input Voltage | Output Voltage | Output Current | Topology |
|---------|-----------------------|---------------|----------------|----------------|----------|
| NCP1294 | Solar Street Lighting | 12-24 V       | A 13.2V        | A 2.0A         | Flyback  |

Table 1: NCP1294 Output Statistics

| Characteristic       | Min | Typ | Max  | Unit |
|----------------------|-----|-----|------|------|
| Output Voltage       | 9   | 12  | 13.5 | V    |
| Output Current       | 0   |     | 2.0  | A    |
| Oscillator Frequency |     | 100 |      | kHz  |

1. < 2mA Current Consumption from Battery
2. Maximum Power Tracking < 5% Error
3. Can Charge 4 Batteries in Series or Parallel
4. Can be Configured for use with 10W to 30W Solar Panels
5. Can be used in Parallel with Other Systems

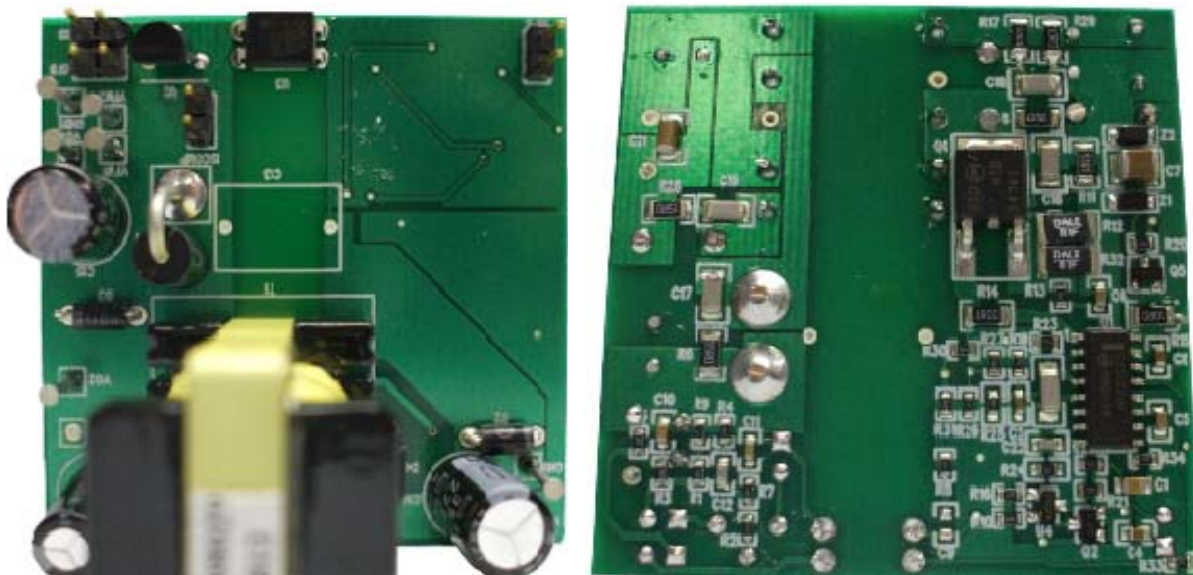


Figure 1: Solar Controller Evaluation Board

## System Description

The system under consideration is an off grid solar streetlamp. The solar streetlamp consists of high power LEDs, a lead acid battery, a solar controller, and a solar panel as shown in Figure 2.

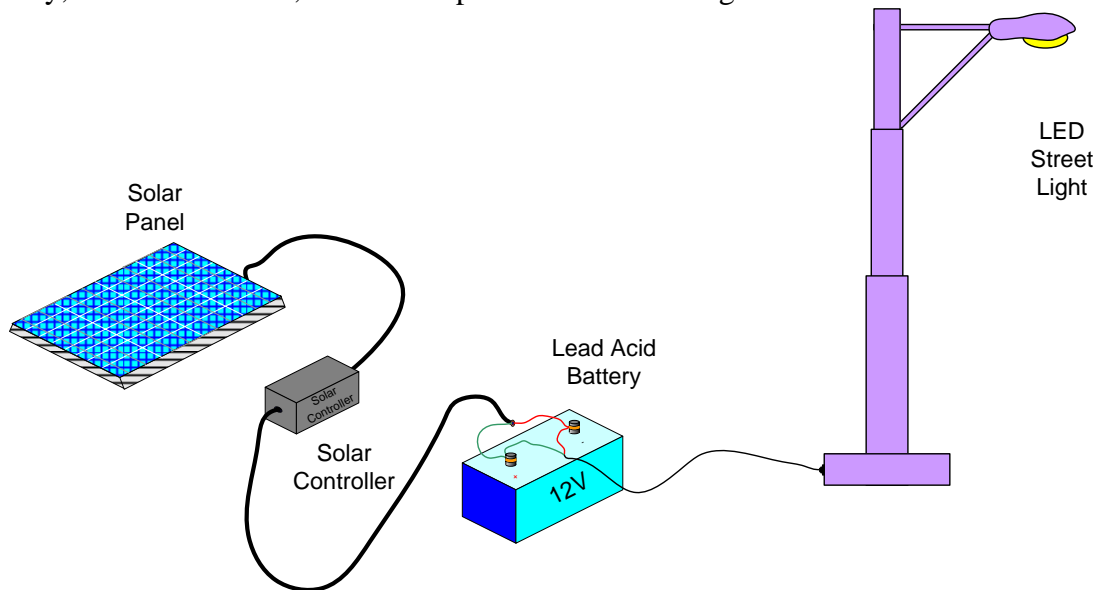


Figure 2: Basic off Grid Solar Streetlamp System

## Solar Panel Characteristics

Solar panels collect energy from the sun and convert it to electrical energy. Unfortunately, the sun is not consistent throughout the day due to cloud cover and the angle of the sun relative to the position of the solar panel. Further, the intensity of the sun varies with the season, geographic location, and reflections from adjacent surfaces. Figure 3 shows the monthly average daily total solar resource information on grid cells of approximately 40 km by 40 km in size [1].

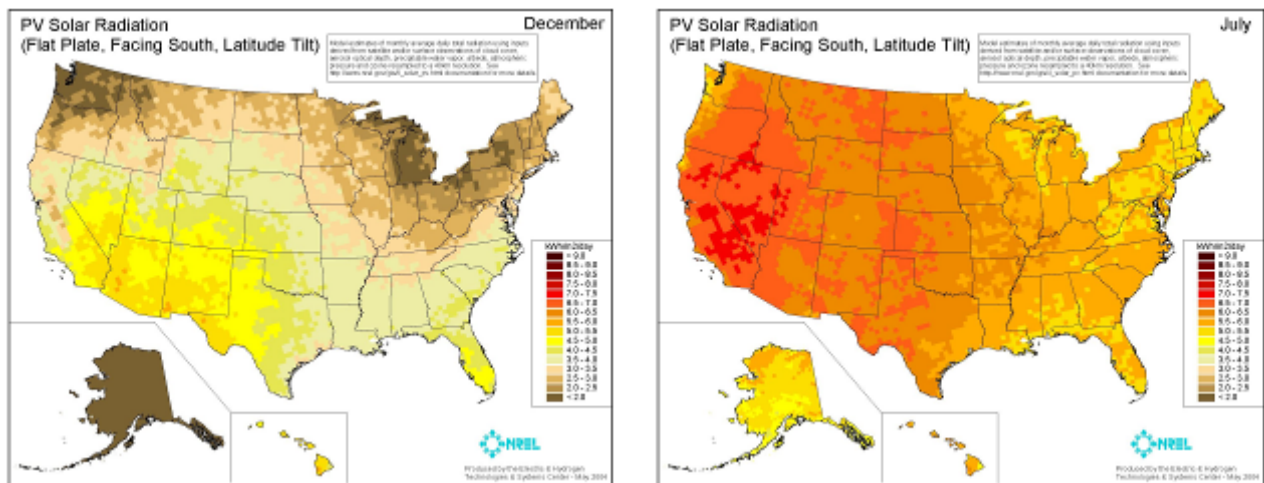


Figure 3: Monthly Average Daily Total Solar Resource in December (Right) and July (Left) [1]

Since the sun is not consistent, the solar panel rated for 30W peak power may only supply 24W in midday sun and 6 W in the evening sun. Figure 4 displays the voltage, current, and power characteristics of a solar panel at various times during the day with a resistive load. The voltage from solar panels can be configured by the manufacturer to supply almost any voltage and current depending on the solar cell configuration, but generally range from 20V to 48V.

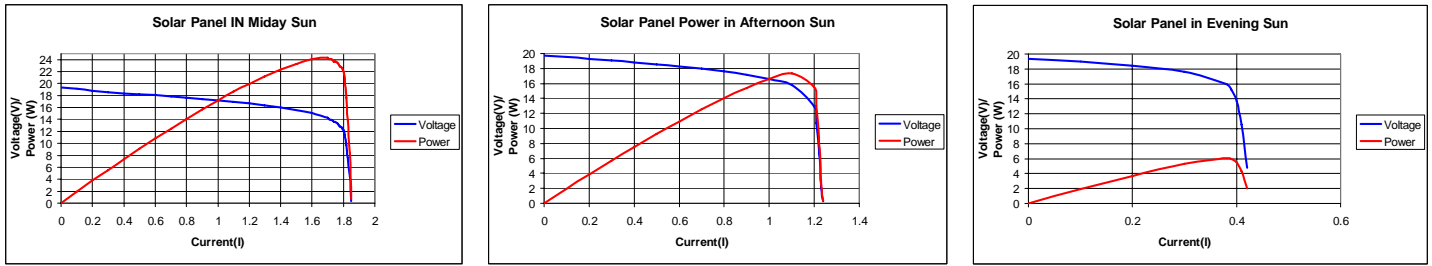


Figure 4: Solar Panel Available Power at Midday (Left) Afternoon (Middle) and Evening (Right)

## Controller Considerations

When designing the solar street lighting system, the worst-case scenarios must be considered if the light provided is for safety rather than convenience. Solar energy is measured in hours of the day at which the maximum rated performance from a solar panel can be obtained (peak\_power\_time). On average, Arizona has six peak hours of sun daily. Solar panels are rated for the peak power they produce, thus the required energy from solar panels can be calculated since the required load energy is known. Excess solar capacity needs to be considered for charge recovery from a cloudy day giving the designer a fixed number of days from which to recover from a series of cloudy days (Recharge-Time).

$$IDL_{Panelsize} = \frac{LoadEnergy}{Peak\_Power\_Time} \xrightarrow{Example} \frac{712Wh}{6h} = 119W \xrightarrow{Example2} \frac{672Wh}{6h} = 112W$$

$$RECHARGE_{Panelsize} = \frac{BatteryCapacity}{Recharge\_time} \xrightarrow{Example1} \frac{2.kW}{30} = 84W \xrightarrow{Example2} \frac{2.4kW}{30} = 80W$$

$$Total_{Panelsize} = RECHARGE_{Panelsize} + IDL_{Panelsize} \xrightarrow{Example1} 119W + 84W = 203W$$

$$\xrightarrow{Example2} 112W + 80W = 192W$$

The designer need only extract the peak power, deliver it to the battery, and then the system will be complete. Unfortunately, the solar panel characteristics make it difficult to find the peak power point as it moves with many variables. If the solar panel is simply connected to the battery and removed once it is charged, 20% - 30% of the peak power is lost depending on the state of charge of the battery. Commonly solar panels are the most expensive part of the system averaging \$4/W/USD. Solar panels are typically manufactured in 5W increments, thus each increment in power costs \$20/USD. The price of a linear charge controller may look attractive from the piece part standpoint, but may end with a less cost effective system. The panel size required for a linear charging system is calculated below.

$$LINEAR_{Panelsize} = \frac{Total_{Panelsize}}{LIN_{EFF} - PP_{Loss}} \xrightarrow{Example1} \frac{203W}{0.95 - 0.25} = 290W \xrightarrow{Example2} \frac{192W}{0.95 - 0.25} = 274W$$

The discrepancy between the peak power and the linear regulator power is 87W and 82W.

If an algorithm for peak power tracking is implemented, there will be an error from the true peak power point and the algorithm operating point. The peak power error (PP<sub>error</sub>) operation point results in unused energy from the solar panel, so the smaller the percentage of error, the greater the power extracted. The solar controller efficiency operates at 88% for the 12V system and 91% for the 24V system. The required solar panel size with peak power tracking is calculated below.

$$MPT_{Panel\ size} = \frac{IDL_{Panel\ size}}{\eta - PP_{ERROR}} \xrightarrow{\text{Example 1}} \frac{203W}{85\% - 5\%} = 254W \xrightarrow{\text{Example 2}} \frac{192}{91\% - 5\%} = 223W$$

For Example 1, the 254W requirement should be rounded to 255W and can be divided into three 85W solar panels. In Example 2, the 223W requirement should be rounded to 225W and can be divided into three 75W solar panels. The system level diagrams are shown in Figure 7.

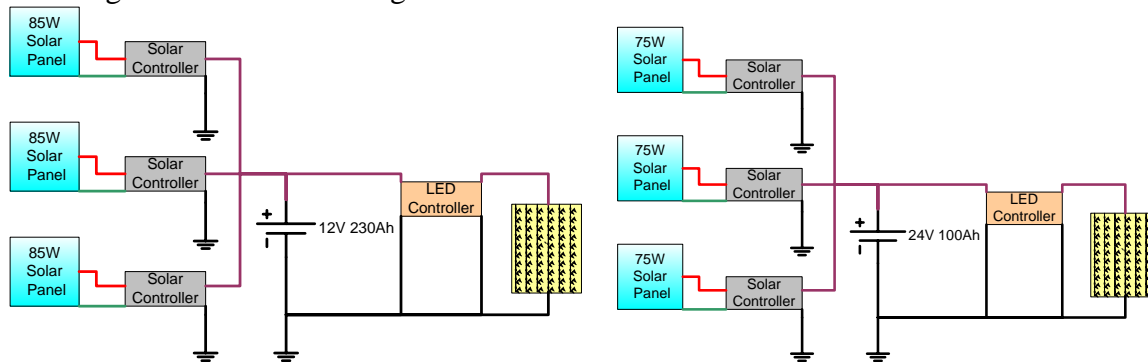


Figure 7: System Diagram

## Circuit Description

The input voltage for the solar controller enters from the solar panel through VIN and GND. The input voltage is filtered by C14. Input under voltage is sensed by R19, R25, and C2, which prevents the controller from operating when the solar panel cannot provide the minimum current. Input over voltage is detected by R27 and R26, which prevents the controller from turning on when the panel voltage is too high or an improper voltage source is connected. The frequency of operation is set by R22 and C1, and can be adjusted up to 1MHz. An external reference is provided that is capable of sourcing a minimum of 2mA when decoupled with C4. The NCP1294 allows the limiting of duty cycle, as well as providing voltage feed forward through R23 and C3. A linear regulator consisting of R20, Z1, and Q5 provide the startup current for the controller. Once the circuit is switching, the current for the controller is provided through R18, D2, C7, and clamped by Z2. The NCP1294 is equipped with power voltage line VC pin and power ground pin PG. The NCP1294 also has a logic voltage line VCC, which is filtered by R15 and C8 with a logic ground LGND to ensure optimal performance. Soft start of the controller can be programmed by adjusting C5. The switching of Q1 is accomplished with the gate pin and rise and fall times can be adjusted with R14. Snubbing of switching noise is provided on the primary side by C16, R11, D4, R17, C18, and R28. The current flowing through Q1 is sensed across R12 and R33 through the filtering of R13 and C6 at the ISENSE pin. Energy is delivered to the secondary side via D1 and D3 which are filtered by C15, C20, and C21. Snubbing is accomplished on the secondary side by C17, R6, R28, and C19. Isolated feedback is provided through U3, but can be modified to provide non-isolated feedback by connecting NIFB and removing ISFB, ISCOMP, ISI, R3, and R33. Phase and gain measurements during the prototyping stage can be accomplished with R9. Type 3 feedback is provided using U2, C11, R7, C12, R3, C10, R4, R5, C9, and R8. A standard ground bypass safety capacitor is provided in C13, but should be shorted if no-isolated operation is required.

## Peak Power Tracking

The NCP1294 allows the user to adjust the current limit via R21 and R24, which are compared to the pulse by pulse current limit measured at Pin 2. The solar panel as discussed earlier has I V characteristics shown in Figure 8 when the current is ramped up. During each on period of a DCM Flyback, the current in Q1 is ramped up from zero current to the maximum allowed internal current limit of the part. If the maximum power of the solar panel is exceeded, the voltage falls to zero. Ideally, the current limit of the part would be set such that it limited at the maximum power point, utilizing the entire capacity of the provided solar panels.

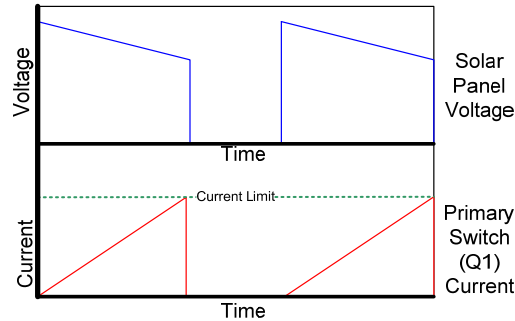


Figure 8: I V Characteristics of a Solar Panel in a Switching Application

The circuit in Figure 9 takes advantage of the IV characteristics of the solar panel to find the maximum power point on a cycle-by-cycle basis. During each cycle the current ramps up in the transformer when Q1 is on. Once the peak power has been exceeded, the voltage of the panel drops and is measured through R30, R31, and is compared to  $3.3V - 0.7V = 2.6V$  at the base of Q1. If the voltage falls below the 2.6V level, Q1 turns on and a voltage is dropped across R16 turning on Q2 and discharging the current limit set node. The designer can set two current limits adjustable by R24 and R16 if the on resistance is assumed to be  $\ll$  than the parallel combination of R16 and R24. If no lower limit is required, then R16 can be shorted to ground.

$$I_{LIMIT1} = \frac{V_{ref} * R24}{R24 + R21} \xrightarrow{\text{Example}} \frac{3.3V * 2.2k\Omega}{2.2k\Omega + 10k\Omega} = 595mV$$

$$I_{LIMIT2} = \frac{V_{ref} * R24 // R10}{R24 // R10 + R21} \xrightarrow{\text{Example}} \frac{3.3V * 687.5\Omega}{687.5\Omega + 10k\Omega} = 212mV$$

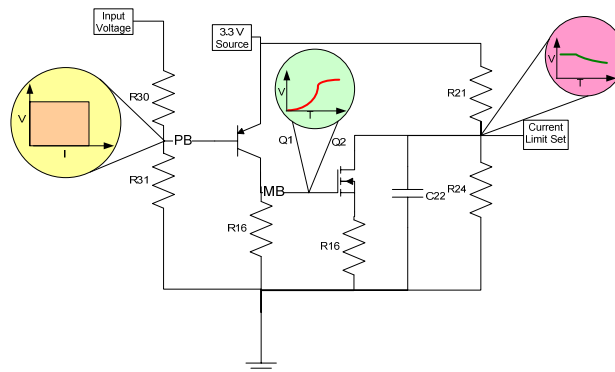


Figure 9: Peak Power Tracking Circuit

A 30W solar controller was designed to determine the maximum error in finding the peak power point using the methodology described above. The solar controller was then connected to a 30W solar panel. The solar panel I V curve data was gathered in a short duration using a resistive load. The solar panel was then connected to the solar controller, the solar controller was loaded with a battery type constant voltage load, and the solar panel I V characteristics were plotted in Figures 10 and 11. The resulting error in finding the maximum power point was less than 5%.

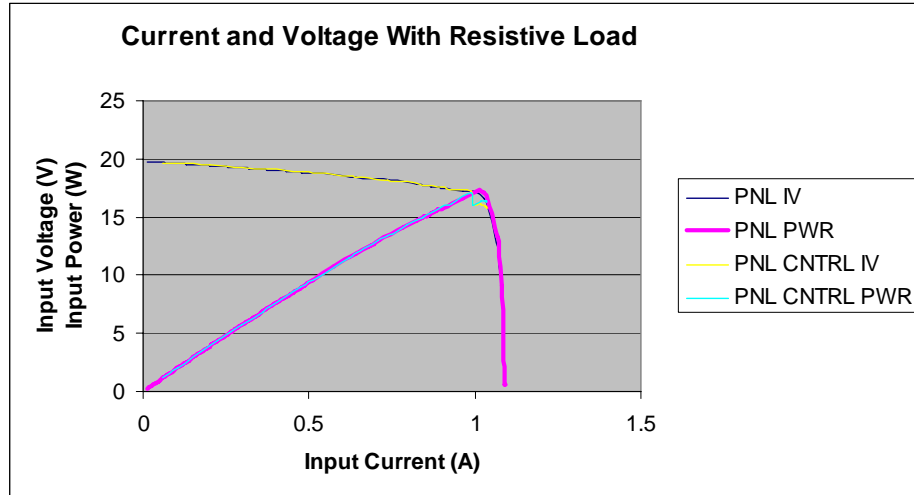


Figure 10: I V Characteristics of Solar Panel and Solar Controller

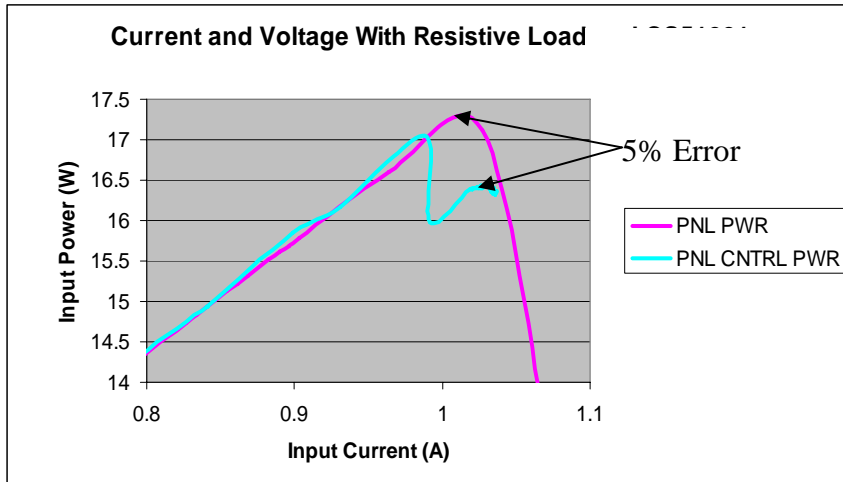


Figure 11: I V Characteristics of Solar Panel and Solar Controller Error

The control scheme should react and find the maximum power point in both the static and dynamic cases. The street light may have been installed when trees were small and over time they may shade the solar panel or have moving shadows that pass over the solar panel on windy day. Figure 12 shows the case where a tree is casting a shadow on the solar panel, a gust of wind moves the leaves to expose the solar panel to full sun, covers it completely, then provides the panel with more sun than the original level, all taking place in less than 6 seconds.



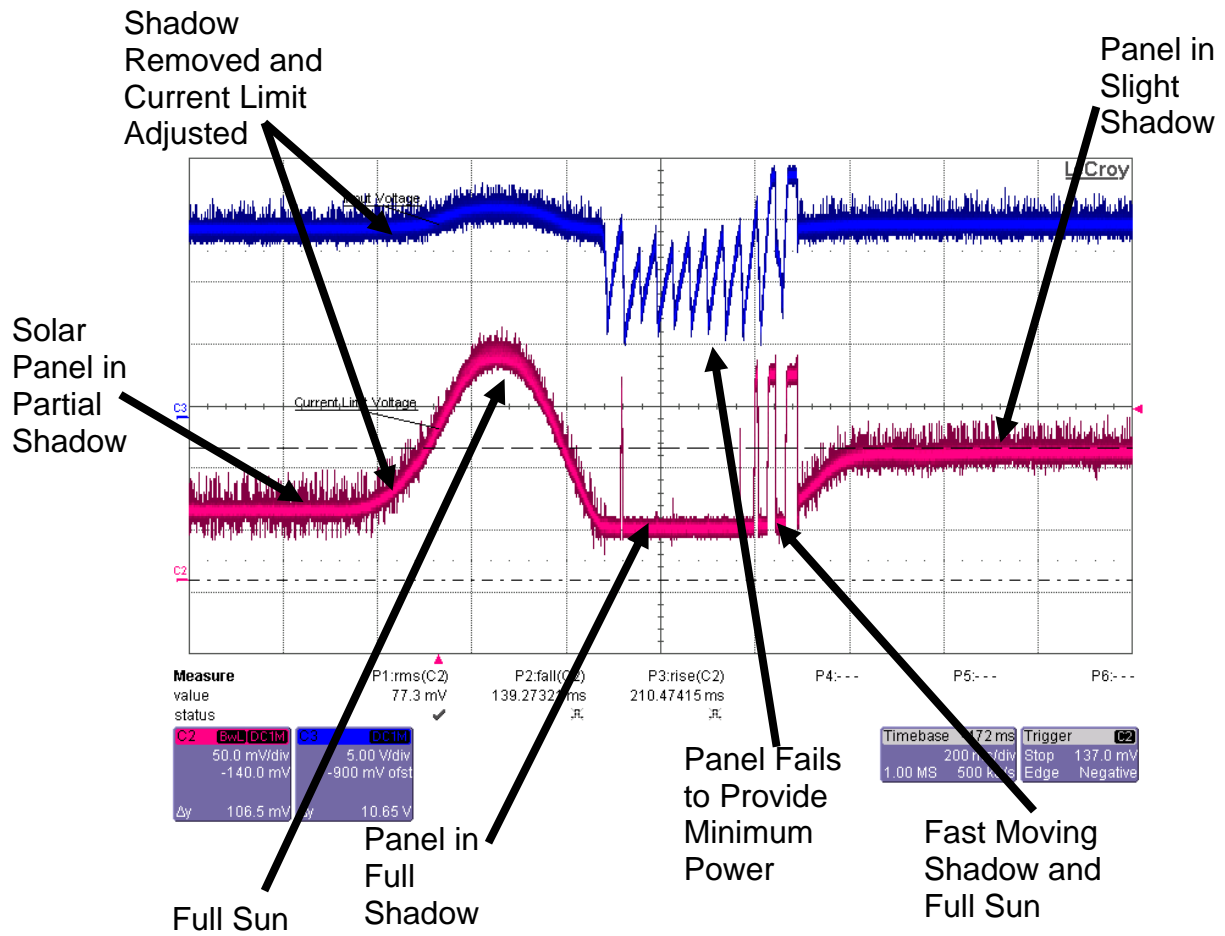


Figure 12: Shadow Reaction of Solar Controller



# Layout

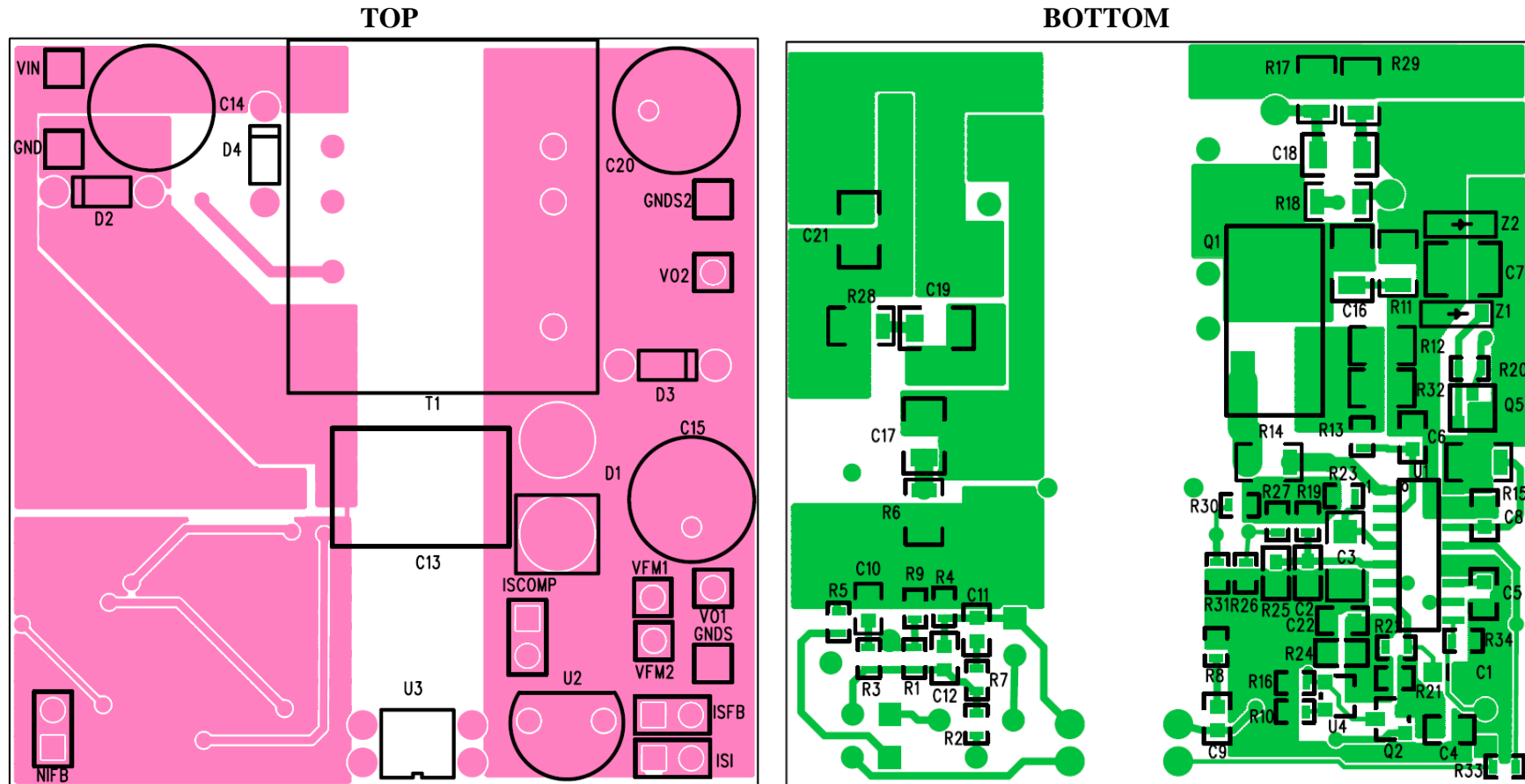


Figure 13: Layout of Solar Controller

# Schematic

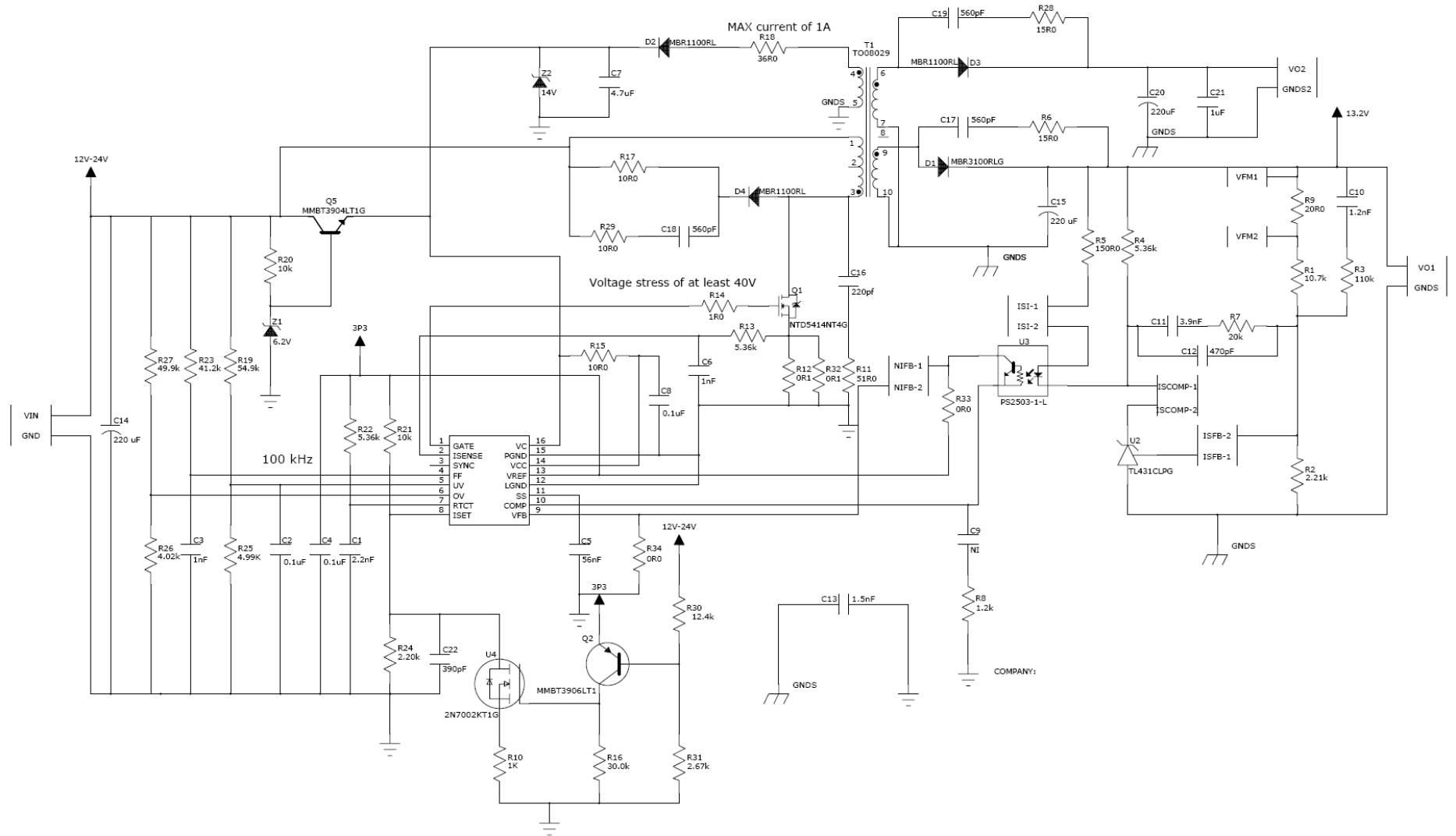


Figure 14: Schematic of Solar Controller

Table 2: Solar Controller Bill of Materials

| Designator | Quantity | Description                          | Value        | Tolerance | Footprint               | Manufacturer     | Manufacturer Part Number |
|------------|----------|--------------------------------------|--------------|-----------|-------------------------|------------------|--------------------------|
| D2-4       | 3        | Schottky 100V                        | 0.79 Vf      | NA        | Axial 5.2X2.7 mm        | ON Semiconductor | MBR1100RL                |
| U4         | 1        | Small Signal N MOSFET                | 60V 380mA    | NA        | SOT-23                  | ON Semiconductor | 2N7002KT1G               |
| C10        | 1        | Ceramic Chip Capacitor               | 1.2nF        | 10%       | 603                     | TDK              | C1608C0G1H122J           |
| C3         | 1        | Ceramic Chip Capacitor               | 1nF          | 10%       | 1206                    | Vishay           | VJ1206A102JXACW1BC       |
| C6         | 1        | Ceramic Chip Capacitor               | 1nF          | 10%       | 603                     | Vishay           | VJ0603Y102KXACW1BC       |
| C1         | 1        | Ceramic Chip Capacitor               | 2.2nF        | 10%       | 805                     | Vishay           | VJ0805Y222KXACW1BC       |
| C11        | 1        | Ceramic Chip Capacitor               | 3.9nF        | 10%       | 603                     | TDK              | C1608C0G1E392J           |
| C22        | 1        | Ceramic Chip Capacitor               | 390pF        | 10%       | 603                     | Vishay           | VJ0603A391JXACW1BC       |
| C12        | 1        | Ceramic Chip Capacitor               | 470pF        | 10%       | 603                     | TDK              | C1608X7R1H471K           |
| C5         | 1        | Ceramic Chip Capacitor               | 56nF         | 10%       | 603                     | Panasonic        | ECJ-1VB1C563K            |
| C9         | 1        | Ceramic Chip Capacitor               | NI           | 10%       | 603                     | AVX              |                          |
| C2 C4 C8   | 3        | Ceramic Chip Capacitor               | 0.1uF        | ±10%      | 603                     | Vishay           | VJ0603Y104KXJCW1BC       |
| C21        | 1        | Ceramic Chip Capacitor               | 1uF          | 10%       | 1206                    | Vishay           | VJ1206Y105KXJTW1BC       |
| C16        | 1        | Ceramic Chip Capacitor               | 220pf        | 10%       | 1206                    | Vishay           | VJ1206Y221JBBAT4X        |
| C17-19     | 3        | Ceramic Chip Capacitor               | 560pF        | 10%       | 1206                    | Vishay           | VJ1206Y561KBBAT4X        |
| C7         | 1        | Ceramic Chip Capacitor               | 4.7uF        | ±20%      | 1210                    | TDK Corporation  | C3225X7R1E475M           |
| C14-15     | 2        | AE Capacitor 35V                     | 220 uF       | 20%       | Through Hole 8mmX11.5mm | United Chemi-Con | ESMG350ELL221MHB5D       |
| C20        | 1        | AE cap 16V                           | 220uF        | ±20%      | 6.3mm x 11mm            | United Chemi-Con | ESMG160ELL221MF11D       |
| C13        | 1        | Ceramic Disk Capacitor               | 1.5nF        | +/- 20%   |                         | Panasonic        | ECKANA152ME              |
| U1         | 1        | Enhanced Voltage Mode PWM Controller | 3V Reference | NA        | SOIC 16                 | ON Semiconductor | NCP1294                  |
| D1         | 1        | Schottky Power Rectifier             | NA           | NA        | Axial Leaded            | On Semiconductor | MBR3100RLG               |
| Q5         | 1        | NPN Transistor                       | 40V 200mA    | NA        | SOT-23                  | ON Semiconductor | MMBT3904LT1G             |
| Q2         | 1        | PNP Transistor                       | PNP          | NA        | SOT-23                  | ON Semiconductor | MMBT3906LT1G             |
| Z2         | 1        | Zener Diode                          | 14V          | ±5%       | SOD-123                 | ON Semiconductor | MMSZ5244BT1G             |
| Z1         | 1        | Zener Diode                          | 6.2V         | ±5%       | SOD-123                 | ON Semiconductor | MMSZ5234BT1G             |
| Q1         | 1        | Power N-MOSFET                       | 60V 30A      | NA        | DPAK 4                  | ON Semiconductor | NTD5414NT4G              |

| Designator  | Quantity | Description                         | Value   | Tolerance | Footprint            | Manufacturer     | Manufacturer Part Number |
|-------------|----------|-------------------------------------|---------|-----------|----------------------|------------------|--------------------------|
| U3          | 1        | OTOCOUPLER                          | 6V 80mA | NA        | 4 PIN DIP            | CEL              | PS2503-1-L               |
| R33-34      | 2        | Resistor                            | 0R0     | NA        | 603                  | Vishay / Dale    | CRCW06030000Z0EA         |
| R8          | 1        | Resistor                            | 1.2k    | ±1.0%     | 603                  | Vishay / Dale    | CRCW06031K20FKEA         |
| R1          | 1        | Resistor                            | 10.7k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW060310K7FKEA         |
| R20-21      | 2        | Resistor                            | 10k     | ±1.0%     | 603                  | Vishay / Dale    | CRCW060310K0FKEA         |
| R3          | 1        | Resistor                            | 110k    | ±1.0%     | 603                  | Vishay / Dale    | CRCW0603110KFKEA         |
| R30         | 1        | Resistor                            | 12.4k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW060312K4FKEA         |
| R5          | 1        | Resistor                            | 150R0   | ±1.0%     | 603                  | Vishay / Dale    | CRCW0603150RFKEA         |
| R10         | 1        | Resistor                            | 1K      | ±1.0%     | 603                  | Vishay / Dale    | CRCW06031K00FKEA         |
| R2          | 1        | Resistor                            | 2.21k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW06032K21FKEA         |
| R31         | 1        | Resistor                            | 2.67k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW06032K67FKEA         |
| R9          | 1        | Resistor                            | 20R0    | ±1.0%     | 603                  | Vishay / Dale    | CRCW060320R0FKEA         |
| R7          | 1        | Resistor                            | 20k     | ±1.0%     | 603                  | Vishay / Dale    | CRCW060320K0FKEA         |
| R16         | 1        | Resistor                            | 30.0k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW060330K0FKEA         |
| R26         | 1        | Resistor                            | 4.02k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW06034K02FKEA         |
| R23         | 1        | Resistor                            | 41.2k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW060341K2FKEA         |
| R27         | 1        | Resistor                            | 49.9k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW060349K9FKEA         |
| R4 R13 R22  | 3        | Resistor                            | 5.36k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW06035K36FKEA         |
| R19         | 1        | Resistor                            | 54.9k   | ±1.0%     | 603                  | Vishay / Dale    | CRCW060354K9FKEA         |
| R12 R32     | 2        | Resistor                            | 0R1     | ±1.0%     | 1206                 | Vishay / Dale    | WSL1206R1000FEA          |
| R15 R17 R29 | 3        | Resistor                            | 10R0    | ±1.0%     | 1206                 | Vishay / Dale    | CRCW120610R0FKEA         |
| R6 R28      | 2        | Resistor                            | 15R0    | ±1.0%     | 1206                 | Vishay / Dale    | CRCW120615R0FKEA         |
| R14         | 1        | Resistor                            | 1R0     | ±1.0%     | 1206                 | Vishay / Dale    | CRCW12061R00FNEA         |
| R24         | 1        | Resistor                            | 2.20k   | ±1.0%     | 1206                 | Vishay / Dale    | CRCW06032K20FKEA         |
| R18         | 1        | Resistor                            | 36R0    | ±5.0%     | 1206                 | Vishay / Dale    | CRCW120633R0JNEA         |
| R25         | 1        | Resistor                            | 4.99K   | ±1.0%     | 603                  | Vishay / Dale    | CRCW06034K99FKEA         |
| R11         | 1        | Resistor                            | 51R0    | ±5.0%     | 1206                 | Vishay / Dale    | CRCW120651R0JNEA         |
| U2          | 1        | Programmable<br>Precision Reference | 2.5V    | ±0.4%     | TO-92                | On Semiconductor | TL431CLPG                |
| T1          | 1        | Transformer                         | 28.6 uH | 10%       | TH 10 PIN 24X21X32.5 | ICE              | TO08029                  |

[1] [NREL National Renewable Energy Laboratory webpage](http://www.nrel.gov/gis/solar.html). 2008

<<http://www.nrel.gov/gis/solar.html>>

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