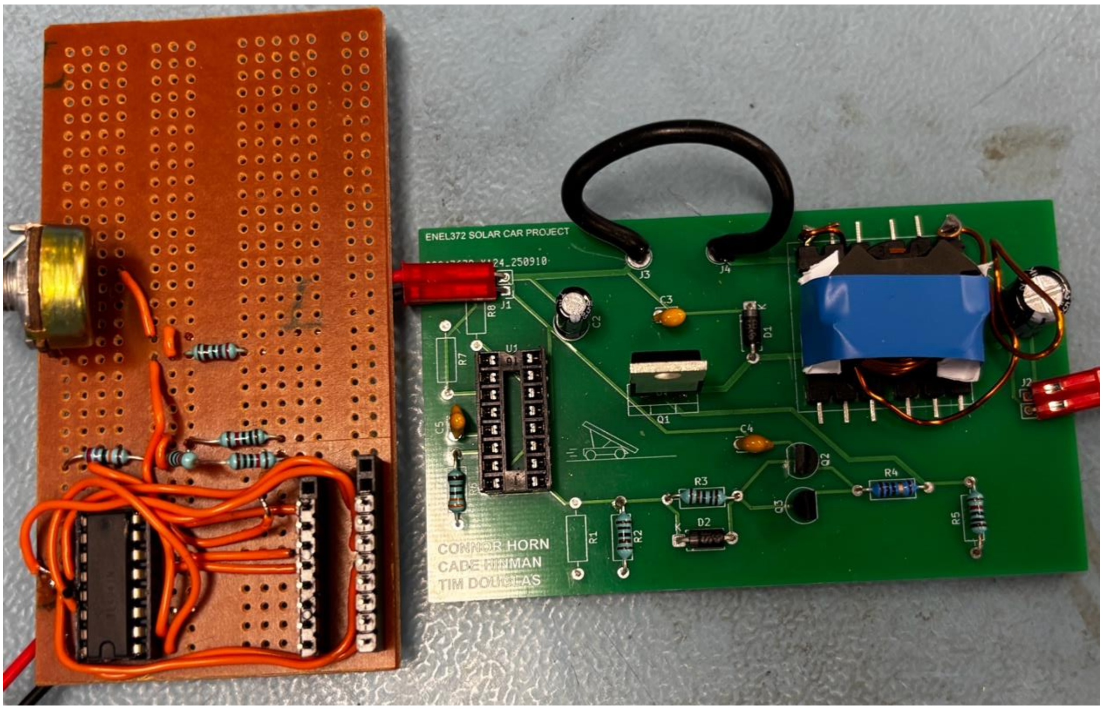
POWER AND ANALOGUE ELECTRONICS
SOLAR CAR REPORT
ENEL372



GROUP 02

13 OCTOBER 2025

TIM DOUGLAS

CADE HINMAN

CONNER HORN

Introduction & Background

This report involves the design and application of a DC-DC converter known as a Buck Converter for a model solar-powered car. The aim of the project is allowed for efficient power transfer from the solar panel to the DC motor output. A buck converter circuit reduces voltage while increasing current, enabling smooth power delivery from the source to the load. This is achieved by rapidly switching a MOSFET, while using an inductor to store and release energy with capacitors to smooth the voltage ripple. The Solar car model consists of a 10W solar panel fitted to an aluminium chassis, with a DC motor and a gearbox with a servo motor for steering. The servo motor is powered by an external battery, whereas all the driving power is purely from the solar panel and transmitted to the gearbox and motor. The power available from the solar panel is due to voltage and current, with a DC Motor drawing varying amount of current based on the torque requirement. During initial startup the current is high due to no back emf being present, during regular running the current settles based on the applied load, extra friction or mass can alter the current demand. To achieve maximum efficiency during operation, the solar panel must operate near its maximum power point. This is achieved by holding the panel voltage to be constant. During the load changes and changing the motor demand, the duty cycle of the buck converter must be adjusted to alter the current draw by the solar panel. Altering the duty cycle, the converter regulates motor supply voltage, while ensuring maximum voltage efficiency.

The Solar Car Project must follow these outlined constraints:

- A buck Converter circuit must be used
- Control Chip must be the TL494
- N-Channel MOSFET IPP034NO3L should be used
- Diode SB240S should be used
- RM8 Inductor Core must be used, and design and self wound
- Maximum capacitance in the circuit is 350 µF

These constraints have been met by using a buck converter circuit, using an TL494 control chip with a IPP034NO3L with a SB240S diode. A block diagram showing the overall system and the component relationships can be seen in Figure 1.

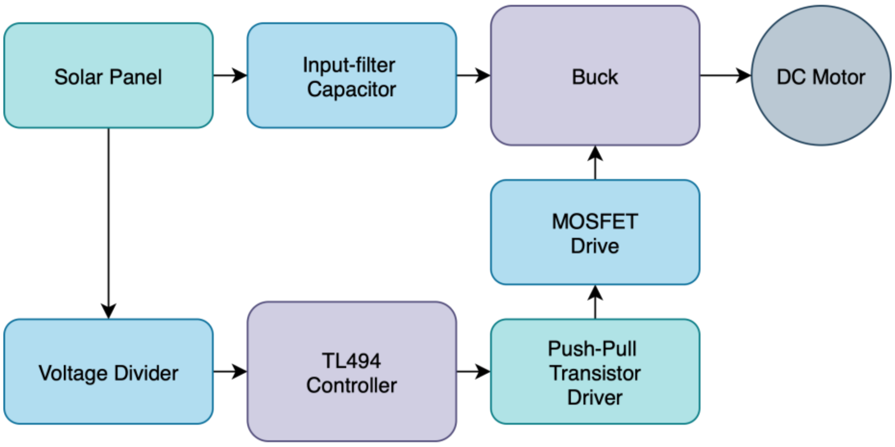


Figure 1: Block diagram of Solar-Car system

Circuit Design Decisions and Calculations

The design of the buck converter circuit has four key components that make up the circuit. The buck converter itself, the PWM signal generator, push-pull transistor amplifier (gate driver) and the controlling area. The PWM signal generator is used to switch the buck at a certain frequency, calculations were based around 40 kHz switching frequency. The gate driving circuit takes the PWM signal to increase the current so the MOSFET can switch. The controlling area ensures the solar panels voltage is constant while adjusting the duty cycle for the PWM signal.

Buck Design

The buck converter that has been designed and used for this circuit, steps down the solar panel input voltage to a more suitable level to drive a DC motor. The main design focus for the buck design is the Inductor, its role in the circuit is to store energy when the MOSFET is on, release the energy when the MOSFET is turned off. This operation of the inductor is used to ensure smooth continuous current supply to the DC motor while ensuring efficiency.

Some of the key components within the converter circuit (Figure 2) include an input and an output capacitor. These are used for filtering voltage ripple and stabilizing both input and output voltages. An N-Channel MOSFET is used for efficiently switching the current at high frequency and a Schottky Diode which is forward biased diode during the off period is used to provide a path for inductor current when the MOSFET is off, retaining continuous current to flow.

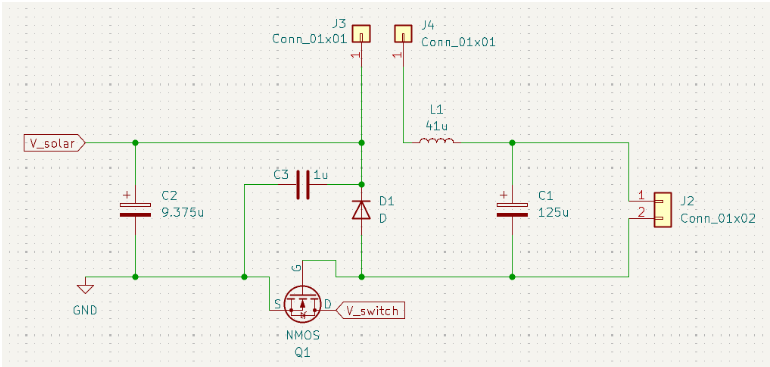


Figure 2: Buck converter circuit

The inductor within the buck circuit has been designed for continuous inductor current or CCM (Continuous Conduction Mode). This means that the average output current is greater than half of the inductor current ripple. The inductor current becomes discontinuous when the inductor current waveform drops to zero or below. CCM can be calculated using equation 1.

$$I_o = \frac{\Delta I_L}{2} \tag{1}$$

Equation 1 can be used to then find and calculate a value for inductance that will satisfy CCM. As the solar panel voltage is not always constant due to available sunlight, having the inductance equation relying on output voltage, this can instead use that the input voltage multiplied by duty ratio is equal to the output voltage. This allows the voltage from the solar panel (Vs) to remain constant while retaining maximum efficiency. A basic assumption is that the converter is 100% efficient in this case. The minimum inductance can be calculated using Equation 2.

$$L > \frac{V_s D(1-D)}{2 f_s I_o} \tag{2}$$

Where Vs is the input voltage from the solar panel, D is the duty cycle, fs is the switching frequency and I_o is the output current. As the inductor current must be continuous for all situations, assumed is the worst case duty cycle of 0.5, substituting into equation Y, now forms equation 3.

$$L > \frac{V_s}{8 f_s I_o} \tag{3}$$

Alongside using Equation R, values used to calculate an inductance value include a supply voltage of 15V, 40kHz switching frequency and 1.5A as the average output current. Substituting these values gave a minimum inductance value of 31.25 µH to be self wound around a ferrite RM8 Core. This is the absolute minimum value for inductance to entirely prevent the inductor current becoming discontinuous, while also minimizing inductor current ripple.

To prevent inductor saturation, an air gap needs to be large between the two halves of the ferrite RM8 core. With a magnetic field strength of 300 mT, maximum current of 2.25A and a minimum area of $63 \times 10^{-6}\ mm^2$. Substituting into equation 4.

$$NA_{MIN} = \frac{Li_{max}}{B_{max}} \tag{4}$$

Gives a number of turns needed to keep a minimum inductance value of 31.25 µH is 37.202 turns, this can be rounded to 40 turns. To find the necessary air gap with the number of turns around the core, the necessary reluctance was calculated to be 51.2×10^6 Amp-Turns / Weber using equation 5.

$$R = \frac{N^2}{L} \tag{5}$$

The length of the copper wire used within the core was calculated to be 648mm, using the permeability of free space (μ_0) of $4\pi \times 10^{-7}$and a relative permeability (μ_r) of 1600 for a ferrite material, using equation 6.

$$L = R\mu_0\mu_r A \tag{6}$$

Assuming that air gap dominates reluctance, we can then calculate the necessary airgap using equation 7.

$$R = \frac{L}{\mu_0 A} = \frac{2L_{airgap}}{\mu_0 A} \tag{7}$$

To give an airgap value (L_{airgap}) of 202.6µm or around 2 pieces of paper between the 2 halves of the RM8 core. When measuring the inductance one the core had be wound, resulted in lower amount of turns due to size constraints, of 20 and a higher inductance value of 41µH. This meets one of the requirements that a self wound RM8 core is to be used in the buck circuit.

The two capacitors used in the buck converter are split into input and output. The input capacitor is used to ensure constant current is drawn from the solar panel. If the solar panels current draw is too much, it will reduce the voltage, reducing the maximum power outputted. Assuming 100% efficiency, and assuming the worst case duty cycle is 0.5, the minimum input capacitance can be calculated using equation 8.

$$C_{in} > \frac{I_o}{4f_s\Delta V_s} \tag{8}$$

The minimum input capacitance can be calculated using I_o of 1.5A, ΔV_s of $\pm$ 1V and a switching frequency of 40 kHz. This results in a minimum capacitance of 9.375 µF, due to sizing limitations, in practise a 10 µF capacitor was used instead. To further voltage ripple, an output capacitor is used to smooth the voltage by filtering the voltage ripple due to the constant switching. The output capacitance can be calculated by rearranging equation 9 for C_{out}.

$$\Delta V_0 = V_o\left(\frac{1-D}{8LC_{out}f_s^2}\right) \tag{9}$$

Using the worst case duty cycle of 0.5, f_s of 40kHz, and a voltage ripple of 1%, or 0.07V, as the desired output is around 7V. This gives an Output capacitance of 125µF, which meets the requirement of maximum capacitance in the circuit can be 350 µF.

PWM

The PWM signal used to control the MOSFET within the buck circuit was generated using the built in pins within the TL494 control chip. The TL494 provides a PWM output and includes in built amplifiers that are used to compare feedback voltage with reference voltage to regulate the duty cycle.

The TL494 also provides a consistent 5V reference output, making it the perfect control chip for closed loop control applications, like the Solar Car.

The circuit was designed for a 40 kHz switching frequency. This frequency was chosen as it provided sufficient switching speeds that are able to smooth motor current, while preventing switching losses. Using the TL494 datasheet, relevant values for the timing capacitor (CT) and timing resistor (RT) are able to be selected from Figure 3. The CT and RT values can be seen in Figure 4, which shows the TL494 PWM Circuit.

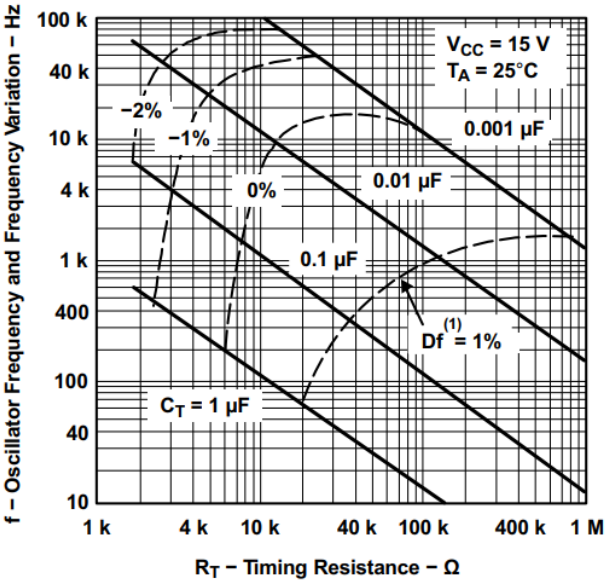


Figure 3: Oscillator Frequency and Frequency Variation vs Timing Resistance Curve

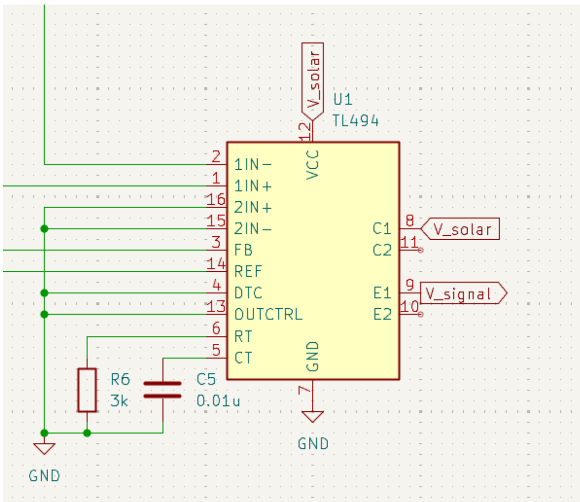


Figure 4: TL494 PWM Circuit

Gate Driven Circuit

A push-pull transistor setup was utilised to act as a gate driver to achieve switching for the main MOSFET. The TL494 was unable to supply sufficient current to meet the charge and discharge demand at 40kHz. To overcome this, a complimentary push-pull pair of NPN and PNP transistors were implemented. This was used to amplify the current from the TL494 to an appropriate output, thus allowing for the 40kHz demand to be satisfied at the main MOSFET gate. This ultimately allowed for the MOSFET to switch both quickly and efficiently, thus reducing switching losses and heat generated.

This configuration means that when the TL494 output is high, one transistor supplies current to the MOSFET, thus charging the gate. In the case where the output is low, the complementary transistor discharges the gate. This sequence allows for strong drive in both directions alongside clean switching transition from high to low. For the circuit detailed in this report, this setup was first tested on a breadboard, and once desired operation was confirmed, this was then implemented on a PCB. The schematic for the finalised configuration can be seen in Figure 5.1 and 5.2.

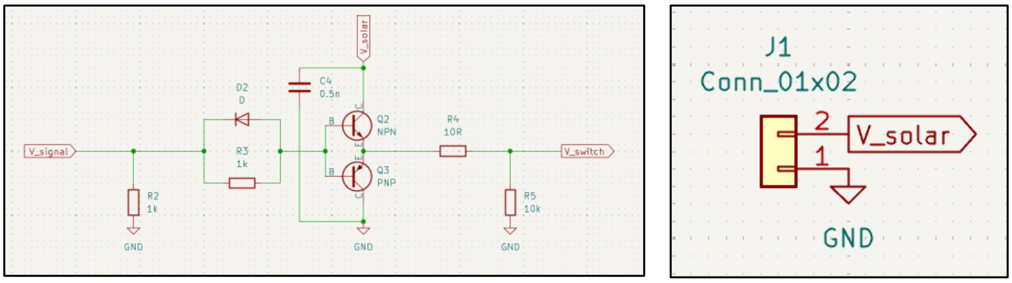


Figure 5.1 and 5.2- Push-Pull transistor configuration

Without the push-pull stage, the TL496 would be unable to control the current enough to reliably charge or discharge the MOSFET gate at 40kHz. In addition to this, the complimentary nature of the NPN and PNP transistors ensures bidirectional drive and thus efficient and clean switching. Therefore, this push-pull configuration acts as a link between the TL494 and main power MOSFET that translates the control signal into a high-current drive which is able to both fully saturate and turn the MOSFET off within each switching cycle. This switching signal that occurs in the circuitry seen in Figure 4.1 is then sent to main power stage and ultimately delivered to the DC motor as seen in Figure 6.

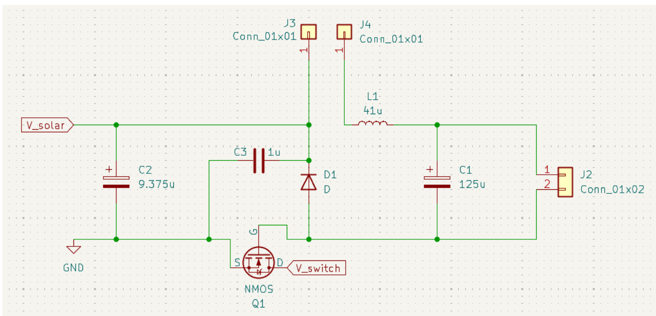


Figure 6: Main power stage schematic

Control Section

The control section of the circuit is responsible for maintaining a constant voltage from the solar panel. This was done with the TL494's internal error amplifier, which compares the feedback voltage with the 5V reference voltage. The output from the error amplifier then adjusts the PWM duty cycle, allowing for control over the energy transferred to the motor.

For this circuit, the feedback voltage is received through a voltage divider. This voltage divider, in theory, was designed to take an input of around 20V from the solar panel and scale it down to approximately 5V for the TL494 feedback pin. To achieve this input-to-output ratio, a variety of resistor configurations could be used; however, in this design, it was decided to use three 10kΩ resistors, with two in series and those in parallel with the remaining 10kΩ resistor. This setup can be seen in Figure 7 connected to pins 2 and 3 with a 1µF capacitor between these pins. Despite the calculations confirming this configuration, for unknown reasons, the converter's output voltage to the motor remained in the range of 7–8V.

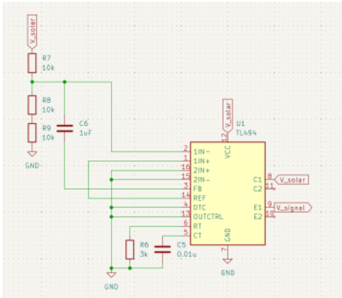


Figure 7: V-solar Voltage Divider

Despite this setback, the 7–8V output was sufficient to drive the motor, just not efficiently. During troubleshooting, it was also observed that the feedback loop was not stable. To address this, a compensation capacitor was added between the output and inverting input of the error amplifier to reduce oscillations. This ensured smooth variations in duty cycle, even under varying loads.

The feedback loop is a crucial part of the circuit, as it allows the system to dynamically respond to changes in sunlight and motor load. This ensures that the solar panel operates near its maximum power point, resulting in more efficient energy conversion.

Demonstration that the circuit works

Figure 8 shows the inductor current (green) and the switching signal at the MOSFET (yellow). As shown, the inductor current rises when the switch is on and drops when the switch is off. The inductor current is also far from saturation, ensuring continuous conduction.

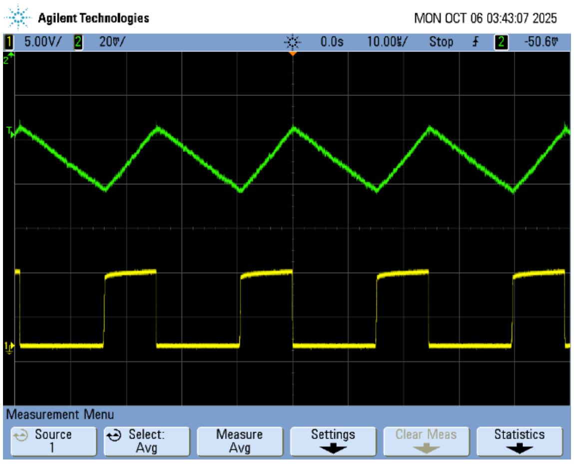


Figure 8: Inductor current and V_{gs}

Figure 9, 10, and 11 show how a consistent voltage is maintained across multiple levels of light hitting the solar panel. There is a small variation likely due to the input filter capacitor being too small.

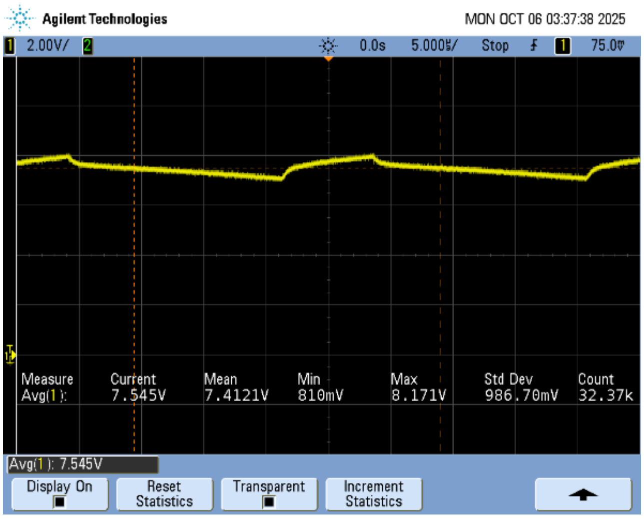


Figure 9: Solar panel voltage with growth and bloom lights on

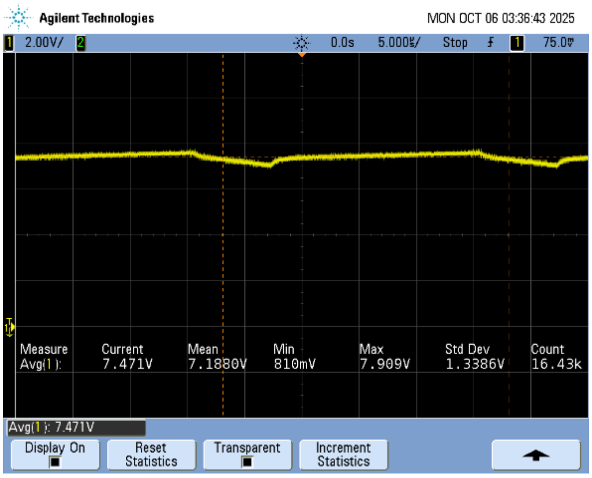


Figure 10: Solar panel voltage with bloom lights on

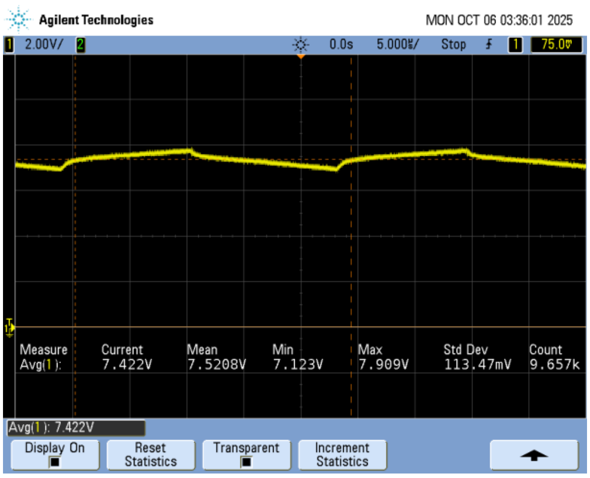


Figure 11: Solar panel voltage with growth lights on

Figure 12 shows the signal from the TL494 (green) and the signal out of the push-pull emitter (yellow). It can be seen from the scale in the top left corner that the push-pull emitter is sufficiently boosting the signal high enough to drive the MOSFET.

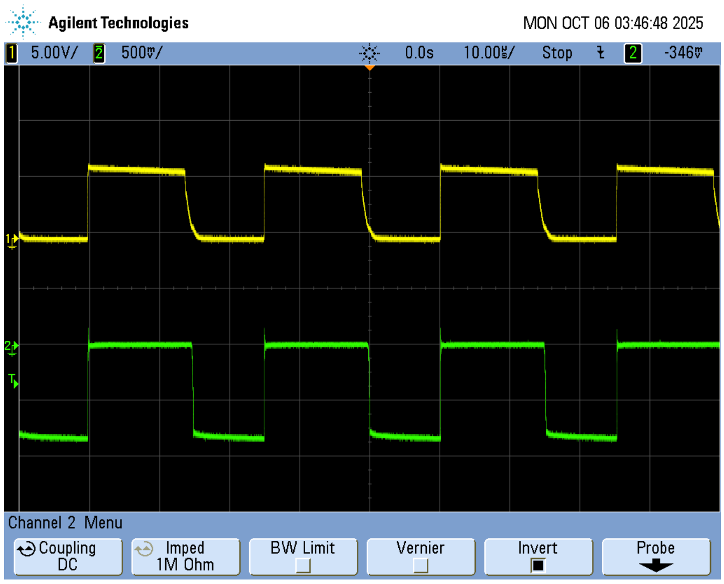


Figure 12 Signal from TL494 and push-pull emitter

Discussion

The aim of this project was to design an efficient buck converter circuit to power a motor from a 10W solar panel. The goal was to achieve a feedback controlled converter that ensured a constant solar panel voltage was maintained in order to maximise the power output.

In its initial stages the circuit had a couple issues, namely the lack of feedback so the system was working in an open loop configuration. This meant that while the converter worked, it did not maximise the efficiency of the solar panel. This issue was solved by adding an additional daughterboard made from Veroboard that acted as a shield for the existing TL494 socket. On to this, the TL494 was mounted, and the correct feedback circuitry was attached. The second issue was also related to the control circuitry. The measured solar panel maximum power point (MPP) was at approximately 17V however the converter pinned it at around 20V due to incorrect values on the input voltage divider. However, after the resistors were changed to the correct values the input voltage would not go any higher than 7V. This behaviour was ultimately unfixable, possibly due to a broken TL494. Aside from missing feedback circuitry, the configuration of the MOSFET on the PCB was slightly incorrect, with the gate and drain pins being the wrong way around. This was fixed by physically crossing the two legs over, avoiding the need to redesign the PCB.

In future the PCB could be improved with better ground plane design and more advanced trace routing/component placement. The output of the buck contains a significant amount of noise that can be found in most of the circuit. While it is impossible to prevent all noise, a better ground plane design would lower the likelihood of developing noisy inductive loops.