

HIGH EFFICIENCY AUXILIARY POWER CONVERTERS

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Abstract

The auxiliary load DC-DC converters of the Sunshark solar car have never been examined. An analysis of the current design reveals it is complicated, and inefficient. Some simple measures to greatly improve the efficiency are present which will achieve an overall worthwhile power saving.

Two switch-mode power supply DC-DC converter designs are presented. One is a constant current supply for the LED brake and turn indicators, which allows them to be powered directly from the main DC bus, and switched only as necessary. The second is a low power flyback converter, which employs synchronous rectification among other techniques to achieve good efficiency and regulation over a large range of output powers.

Practical results from both converters, and an indication of the overall improvement in system efficiency will be offered.

1 INTRODUCTION

The University of Queensland's solar car Sunshark was placed fifth overall, and winner of its class in the last World Solar Challenge, run from Darwin to Adelaide in 1996 [1]. Since then, the team has undertaken a complete review and, where justified, update of the electrical systems of the car.

The main converters in the Sunshark Solar Car are the peak power point trackers (PPPTs) for the solar cell arrays, and the brushless DC (BLDC) motor drive. All of the 1-1.2kW generated by the solar array ultimately is processed by these converters (and of course the BLDC motor) before appearing as useful mechanical power at the wheel. High efficiency of these converters is paramount in achieving a competitive edge over the opposition. Much development work is expended in optimizing the performance of these key systems.

This paper however focuses on the work of another 4th year thesis student, who studied the signal conditioning circuitry and auxiliary converters.

1.1 Auxiliary converters

The auxiliary converters, necessary to provide low voltages for signal conditioning, microprocessor and telemetry circuitry, are usually neglected. The present configuration draws 10-15W during normal operation, and peaks at 60W when switched loads such as indicators are added.

If the 15W of auxiliary power usage can be reduced to 5W, this 10W saving equates to a 1% overall improvement in efficiency. This saving can bring about a small

but worthwhile improvement in average speed.

The present auxiliary converter setup consists of one main isolated step down converter (110-170Vdc to 12Vdc), rated at 75W. From this 12V rail, additional converters create +5, +/-12, and +/-15V rails. The indicators and horn also ran directly from this 12V supply. These additional loads, although only occasionally used, required the choice of the large 75W converter.

Generally the converter only operates at 10-15W, or about 15% of its rated 75W. Although a switch-mode converter, its efficiency at this level falls to between 70 and 75%. A further loss of efficiency occurs due to the double processing of power, with the series connection of DC-DC converter modules. A simple spreadsheet analysis showed that the overall efficiency of combined power conversion to the various voltage rails was between 50 to 55%.

1.2 Plan of Attack

The inefficiency of the auxiliary power system is addressed on a number of fronts.

- Reduce the total required auxiliary power, by choosing more efficient sensors, microcontrollers, and displays.
- Rationalize the total number of required auxiliary supply voltages, through the choice of sensors and redesign of signal conditioning circuitry. It was hoped to run only two supplies, +5V and +12 or +15V.

- Provide separate switched converters for the high current auxiliary loads, which are only occasionally turned on. These loads include the brake and turn indicators, and the horn.
- Finally, custom design these separate power supplies, ensuring they maintain their high efficiency, even at low load currents.

Two converter designs will be presented in this paper. The first is a simple modular switch-mode current source, a number of which will be built for each of the LED brake and turn indicators, to allow them to be separately powered and switched from the high voltage bus.

The second is a low power (3-10W) flyback converter to provide the auxiliary power supplies for telemetry, signal conditioning, and control. It will use various techniques such as synchronous rectification, a BiCMOS controller, and an active low current start up circuit to achieve high efficiency.

These two converters were both used in the CitiPower Sunrace held in January 1999. Although both worked, they both suffered reliability problems, due in part to poor installation. It is unfortunate that the current Sunshark team has not continued the development and commissioning work on these converters. The power supplies presently used in the Sunshark are still the same ones as used in the 1996 World solar challenge.

2 LED CURRENT SOURCE CONVERTER

2.1 LED vs. incandescent lights

Standard vehicles have incandescent lights for indicator and brake lights. These are usually bright enough for all driving conditions. However, each light draws a minimum 10 W. Hence, for a complete vehicle lighting system, as much as 60W is needed for this simple purpose. The availability of affordable high intensity LEDs has begun to see their use for vehicle stop lights. In the Sunshark, all indicator lights are LED based.

The apparent brightness of these LEDs is determined by the manner in which they are driven, not just by their current level. Because of the human eye's "persistence of vision", light can be pulsed and appear as bright as if the LEDs were driven with a continuous signal [2]. According to [3], rather than acting like an integrating photometer, the eye acts like a partially integrating and partially peak reading photometer. Therefore, the apparent brightness will always lie between the average luminous intensity and the peak intensity.

By pulsing at higher currents, the LEDs will be operating at their most efficient. LED efficiency drops at lower currents (typically less than 3mA). At very

high currents (typically greater than 50mA) their performance also starts to drop off due to junction heating effects.

A simple AB comparison was made between the LEDs and the original incandescent lights. Light from a 10W incandescent globe was matched by 12 LEDs grouped together and driven at 30mA. The power for this total arrangement is 0.6W. This suggests a sixteen-fold improvement in efficiency of LEDs over incandescent globes is possible.

2.2 LED current limiting

The simplest method for limiting the current in a string of LEDs is via a series resistor from a regulated voltage source. With a low voltage source such as 5V or 12V, several short strings of LEDs each with their own current limiting resistor are required. The percentage of the supply voltage dropped across the resistor must usually be around 20%, to ensure consistent brightness with different LEDs and source voltage variations. This immediately reduces the efficiency to 80%.

The other significant disadvantage, as already noted, is that this highly intermittent load must be supplied by the low voltage converters. The power supply must be rated to take this additional load, which may be significant if the other loads are small.

The current LED indicators in the Sunshark are implemented in this fashion. Each indicator consists of four series strings of five LEDs and a current limiting resistor powered from the 12V converter. The LEDs operate with a voltage drop of approximately 2V and a current of 30mA. Each indicator draws about 1.5W, and so the 12V power supply must be able to supply an additional 6W.

2.3 LED Switch mode current source

The alternative to oversizing the auxiliary converter for this very occasional load, is to build a separate converter which is only powered on when the indicators are needed. The next extension of this concept is to build a separate simple switch mode current source converter for each indicator. These current sources are individually enabled to light their connected string of LEDs. A regulated current source converter removes the need for a lossy resistor to set the LED string current, and improves the efficiency.

The power section of each converter is powered from directly from the high voltage DC bus. A buck or chopper topology was chosen since the DC bus voltage is 80V minimum, and the string of 12 LEDs needs at most 30V. No filter capacitor is placed across the LED string. A similar approach is often chosen for controlling the current in stepper motor windings and solenoids.

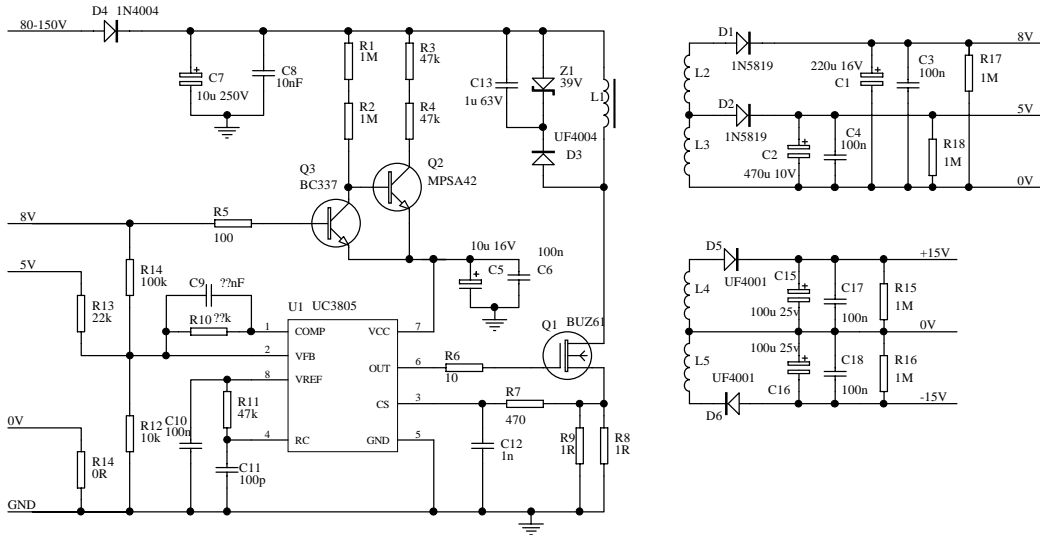


Figure 3: The schematic for the flyback converter.

Supply	5V	8V	+15V	-15V	Total
min	2.3W	0.05W	0.5W	0.5W	3.3W
typ	2.3W	2W	2W	0.5W	6.8W
max	4.5W	3W	2W	0.5W	10W

These four outputs were required to be isolated from the DC input voltage for safety reasons. The input voltage ranged from 80 to 150V.

A flyback converter is the most common choice for a low power isolated supply with multiple outputs. If the range of load variations on each output is not excessive, then regulating one output quasi-regulates the other outputs. Only one primary switch (a MOSFET) and PWM controller is required. Only one magnetic element is required. Each extra output requires a winding on this transformer, a diode, and a filter capacitor.

The disadvantages of such a converter are that switch utilization is poor, and the peak to average current ratio is high. At higher powers this reduces efficiency. The forward converter is usually chosen for power converters beyond 50W.

Despite this, most low power flyback converters are designed to operate in discontinuous conduction mode (DCM) rather than continuous conduction mode (CCM). Operation in DCM removes a right-half plane zero from the converter transfer function, and simplifies the feedback control loop design greatly [?]. The common example designs given by PWM controller chip manufacturers often give a DCM design for this reason.

3.1 Flyback Implementation

A flyback converter was implemented based on a BiCMOS variant of the industry standard UC3842 series of current mode controller chips. To show any improve-

ments undertaken a standard circuit was taken from the Unitrode UCC3805 application notes. The chip was run in the usual configuration of constant frequency, discontinuous current mode. It used a schottky diode with no synchronous rectification. A snubber was used to protect the switching MOSFET. A pregapped RM10 pot core was used for the transformer. The frequency was set to 50kHz as an initial value (see Figure. 3).

The circuit's feedback loop is not isolated at this stage, so the input and output of the converter share a common ground rail. The converter could be easily isolated by installing an opto isolator in the feedback loop.

As can be seen from Figure 4, efficiency remains below 85% at loads under 9W and drops off sharply below about 5 watts. Regulation, though, remains tight with the output voltage remaining within the $\pm 5\%$ design constraint over the entire load range.

To determine where the losses were, a survey was made of the various currents and voltages through all the possible loss-causing devices. For this purpose, the standard circuit was operated with only one secondary winding to provide a 5V output. The input was set to 100V and the load to 2.5W, one quarter the full load. The losses were then measured and tabulated to assess where the majority of the losses occurred.

	Loss	proportion
Snubber	125mW	16%
MOSFET	115mW	14%
Current Sense Resistor	10mW	1%
Secondary Coil Resistance	65mW	8%
Primary Coil Resistance	10mW	1%
Schottky Diode	475mW	60%
Total	800mW	100%

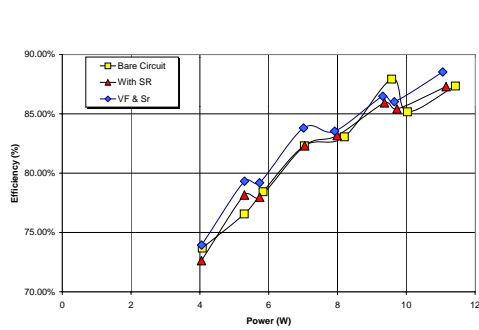


Figure 4: The efficiency gains achieved by operating the flyback converter with a synchronous rectifier, and at variable frequency.

The schottky diode loss clearly constitutes most of the losses in the regulator. If nothing else, the removal or reduction in this loss would improve efficiency dramatically. To overcome this loss, synchronous rectification has to be implemented.

This converter has four output rails, however synchronous rectification was only implemented on the 5V rail. The diode voltage drop is most significant on low output voltage rails. Furthermore, as the overall power rating is extremely small, the driver losses become a significant factor in the efficiency.

3.2 Synchronous Rectification

The circuit diagram for the synchronous rectifier is shown in Figure 5. A comparator senses when the voltage across the schottky diode is forward biased, and turns on the parallel P-ch MOSFET. When the current reverses, the voltage across the MOSFET goes negative, and the MOSFET is turned off.

A high speed LM319 comparator is used. Extra circuitry was required to protect the comparator inputs, and meet its input common mode and differential mode requirements. The emitter of the comparator output transistor is wired to primary side gate drive. This ensures that the synchronous MOSFET will always be turned off as the primary side MOSFET is turned on. This improvement proved necessary to avoid “cross conduction” between the MOSFETs. Before this modification, some ringing at the comparator input caused false turn-ons. This primary secondary connection removes any possibility of isolation as the circuit stands.

The improvement in efficiency exhibited by implementing synchronous rectification is shown in Figure 4. The improvement is marginal because of the losses associated with the driver’s power consumption negate most of the benefits attained from using synchronous rectification at these low powers.

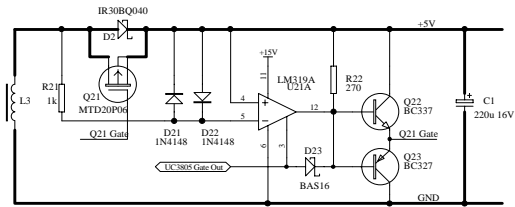


Figure 5: The schematic for the synchronous rectifier addition to the flyback converter.

The LM319 comparator used for the process, uses 105 mW from it’s supply rails. Furthermore, the pullup resistor can dissipate as much as 40 mW. The drive current needed to turn the synchronous rectification MOSFETs on and off is also equal to about 20 mW. Furthermore, the losses associated with the parasitic ringing of the MOSFET (as opposed to the Schottky diode) are significant. These losses reduce efficiency by between 2 and 4 percent depending on the load, before the benefits are included.

A more modern rail to rail low power high speed comparator with a totem-pole output may make a large difference in a future design. The Maxim MAX941 is a suitable contender. With the common mode range extending to its negative supply, this comparator would also allow an Nch MOSFET to be used in the return path.

3.3 Snubber Losses

The snubber makes a rather significant 15% contribution to the total loss. Reducing the snubber and accepting a higher switch voltage does reduce the power dissipation in the snubber. If the circuit is otherwise unchanged, the same energy is still stored in the inductor’s stray inductance each cycle. This energy is now dissipated in the inductor’s resistance as the ringing dies to zero.

The losses in the snubber can only be reduced if the leakage inductance of the transformer is reduced. This could be done with better winding strategies.

3.4 Variable Frequency Topologies

The switching losses increase as the square of the input voltage increases, for a constant frequency. This is because the energy stored in the MOSFET drain source capacitance and associated parasitic capacitances, $1/2 C_D V_D^2$, is dissipated every time the MOSFET turns on. Variable frequency operation overcomes this as it turns the switch on when the resonance of V_D has reached a valley, thus helping to reduce this switching loss (see Fig. 7).

The topology shown previously to drive the synchronous rectification circuits is the basis for the vari-

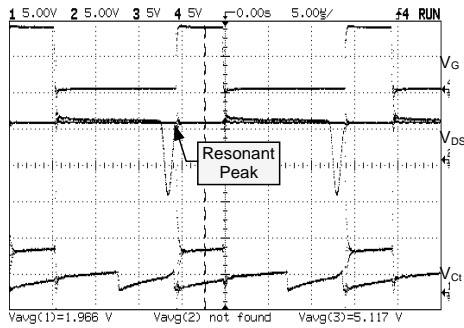


Figure 6: An oscilloscope plot showing the MOSFET switching on in the peak of the resonant V_{DS} waveform. This leads to high switching losses as the energy stored in MOSFET capacitances are discharged dissipatively.

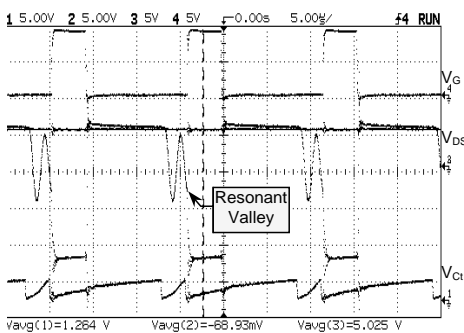


Figure 7: An oscilloscope plot showing the MOSFET switching on in the valley of the resonant V_{DS} waveform. This leads to the lowest switching losses as the converter approaches the conditions of soft switching.

able frequency driver.

There are two possible ways to vary the frequency on these current mode controller chips. The first of these involves sending a “synchronisation spike” to the timing pin to force an immediate reset. For the UCC3805 this is complicated as each switching period lasts two clock cycles, that is, the timing capacitor has to charge and discharge twice for one switching period to pass. The driver would have to send two narrow pulses to reset the chip to the beginning of the next switching cycle.

The other possibility is to place another current source on the timing pin, to cause it to speed up the charging of the capacitor. This was the topology adopted. After the synchronous rectifier has turned off, a current is applied to the timing capacitor to speed it up from that time onwards (until the switching MOSFET turns on). This should allow a crude form of control which should cause a switch on at close to the most efficient valley. However, as the time for this increase is variable, from load to load, fixing the time to turn off is difficult and only a rough calculation can be done.

Figure 4 shows the efficiency improvement achieved by

switching to a variable frequency topology. Two valleys are visible at 7 watts and 10 watts, rather than a uniform improvement. This is because the oscillator speed up circuit takes a finite amount of time to reset the chip. The chip may start its next cycle at a resonant valley or peak, dependent on the load (see Figs. 6 & 7). This gives rise to the oscillating nature of the losses.

4 CONCLUSIONS

Two switchmode converters were built as part of a revision of the Sunshark’s auxiliary power supplies. Both achieve large efficiency gains, but due to their immature state have not been included in the current car. A number of extra techniques tried on the auxiliary flyback to attempt to lift its efficiency higher had only marginal success, due to the extra power consumed in the process. It appears that at these low powers, the best method of conserving energy, is to minimise the power consumption to begin with, and then use a simple converter.

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