Design of an Auxiliary Power Distribution Network for an Electric Vehicle

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Abstract

This paper presents the design of an auxiliary power distribution network for an electric vehicle. Efficiency is a key element in the design for any electric vehicle and a 48Vdc distribution network will be used throughout the vehicle. The high efficiency Cuk converter has been selected as the most appropriate topology to supply the various distributed loads. To achieve the best compromise between efficiency and component sizes, a switching frequency of 100kHz is used. The results from simulations and experimental measurements are discussed and a range of proposals is also made to modify some of the existing loads to further improve efficiency.

1. Introduction

The University of Canterbury purchased a modern sports car "Toyota MR2" with the intention of converting it into an electric vehicle. This paper presents the design of the auxiliary power distribution network for the electric vehicle. In an electric vehicle, energy efficiency is extremely important and therefore the auxiliary power network must be designed for high efficiency. Another consideration is that due to the limited space and weight that can be carried in the vehicle, power supplies with minimal volume and weight are desired.

Current consumption investigations were made on the MR2's auxiliary loads. Transient current peaks occur when switching loads are switched in and out. These may load down the auxiliary converter and cause it to drop out, or shut down. In order to use the limited battery energy more efficiently, current limiting capability will be added to the converters to reduce the peak current demand. In addition, to improve efficiency, high intensity LEDs will replace the existing light bulbs in the vehicle.

The type of loads determines the power rating, number and placement of the auxiliary dc-dc converters that are connected to the auxiliary power distribution network in the vehicle. After initial investigations were conducted, the Cuk converter was selected as the most appropriate topology to supply the various distributed loads around the vehicle. This power supply is required to supply a 12Vdc, 30A output from a nominal 48Vdc input voltage.

To achieve a compromise between efficiency and component size, a switching frequency of 100kHz is used. The results from simulations and experimental measurements are discussed and a range of proposals is also made to modify some of the existing loads to further improve efficiency.

2. Auxiliary system in the electric vehicle

Figure 1 shows the auxiliary system that will be used in the electric vehicle. The nominal battery voltage of the electric vehicle will be 300Vdc. To provide auxiliary supplies the voltage will be stepped down to 12Vdc in two stages with an intermediate 48Vdc distribution network.

The advantage of this configuration is that the 48Vdc voltage distribution network is more efficient than the usual 12Vdc distribution system. This is because with a higher voltage bus smaller and lighter wires are required to supply the same power to the auxiliary loads. A 300Vdc distribution network, although more efficient, was not considered an option because of safety issues.

2.1 12V Auxiliary load current requirements

The power requirements of loads that are to be retained in the petrol-electric conversion need to be determined. The power rating was one of the factors that helped determine the type of dc-dc converters that will be used. Current consumption of loads is important for an electric vehicle as it determines the distance it can travel between recharging the batteries.

Transient current peaks occur in the measurements and they exist because loads are switched in and out. Figure 2 shows an example of measured hazard light current waveform. From the various current waveforms the peak and average currents were measured and tabulated for easy reference. Table 1 shows the summarised current consumption of the auxiliary loads in the vehicle. It is seen that the headlights, other external lights and power steering consume the major amount of power. Because of the limited energy stored in the supply batteries, efficient use of the power becomes the major concern in the design.
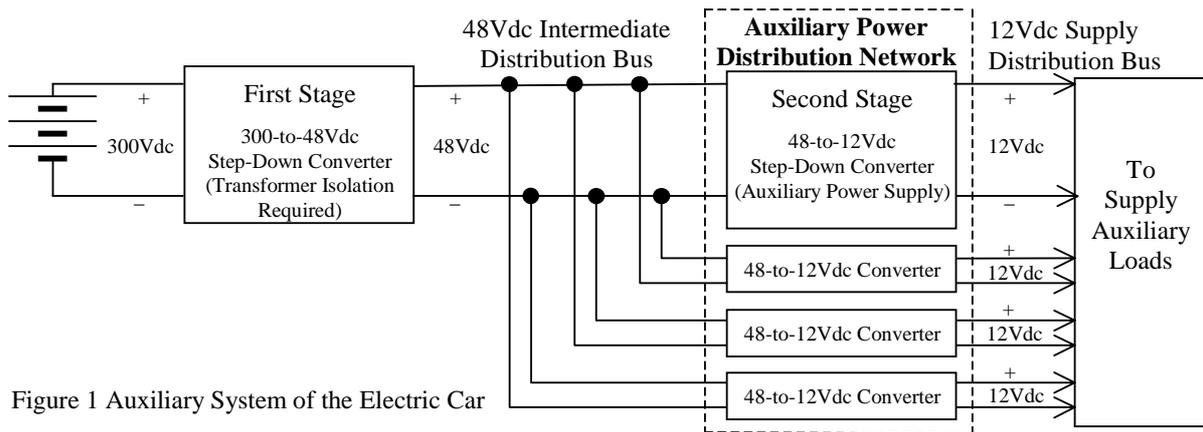
Figure 1 Auxiliary System of the Electric Car
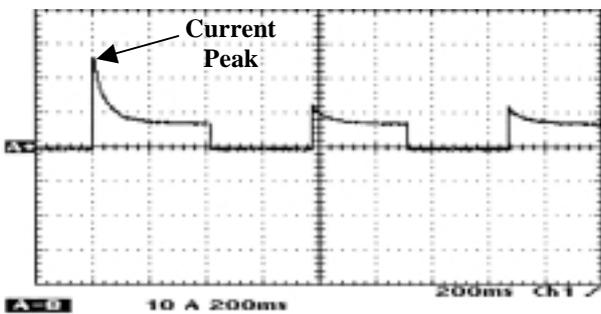
Figure 2 Current waveform of hazard lights

Table 1 Maximum Current Demand of the Loads

Loads	Maximum Current Consumed	
	Peak (Initial Spikes)	Average (Steady-State)
Headlights	27.4A	15A
External Lights	53.8A	31A
Internal Lights	10.3A	2.1A
Power Steering	49.2A	25A
Fan, Heater	25.6A	11.8A
All Other Electronics	42.1A	20A
Total	208.4A	104.9A

Current peaks must be reduced as they lead to a significant power loss in the system. In order to minimise the peaks, an experiment to check performance under current limiting conditions was undertaken on the loads. In the experiment, the auxiliary parts were tested under the condition of limiting the supply current to its average value and seeing whether it still functions the same. For example, power steering was tested using 25A as the limiting current. The power steering operated successfully at this level since the peak current occurred only when the steering operates in hard lock. Therefore an output that limits the current to 25A will be successful. All other auxiliary parts were found to operate properly in the current limit tests; thus, the power ratings of the converters are decided based on the average current values of the loads.

Another way of reducing power consumption in the car is to replace all the external and internal light bulbs in the vehicle, except headlights, with high intensity LEDs. Preliminary calculations that were carried out showed that current consumption of these loads decreased significantly if LEDs were used. For example, the current consumption of external lights would reduce from 31A (see Table 1) to 10A by replacing all the external lights by LEDs.

2.2 Power supply placement

Using the information provided in Table 1 and assuming that the high intensity LEDs are used, a decision was taken to use four converters with output current ratings that range from 20 to 30A. Specifically, as the average current consumed in power steering is around 25A, one converter with a 30A output will be placed beside it to supply the power. Another 30A power supply is going to be located in the front of the vehicle and supply the headlights and front external lights. A 20A converter will be placed behind the driver's seat to supply the internal lights and heater fans. Finally, the power of all other electronic equipments plus the external taillights is going to be supplied from a 30A power supply inside the boot of the vehicle. Figure 3 illustrates the placement of the four power supplies that will be used in the vehicle.

As an initial step in the project, a dc-dc converter with a 30A output current has been built and the design procedures are presented in the next section of this paper.
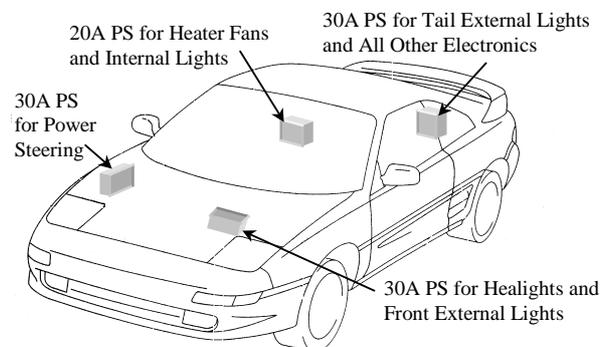
Figure 3 Power Supply Placements

3 Converter selection

The Cuk converter topology was selected because it has both continuous input and output current with low current ripple Since the input and output inductor currents are essentially constant in steady state, the switching current is confined entirely within the converter, in the transistor-coupling capacitor-diode loop. With careful layout, this loop can be made physically small, which will reduce the radiated RFI. In addition, the voltage and current waveforms in this converter are particularly clean, with very little ringing or overshoot, and therefore very little snubbing is required [1,2]. Figure 4 illustrates the schematic Cuk converter.
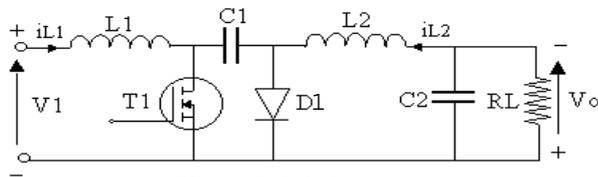
Figure 4. Cuk Converter

4. Converter design

4.1 Design objectives

The basic requirements of the Cuk converter are listed in Table 2. The normal functional voltage for auxiliaries in the vehicle is between 10.5V to 14Vdc. Therefore, the output voltage supplied from the converter is specified as 12Vdc ±10%, which is inside the normal operational range of the auxiliary loads. In the auxiliary loads investigation carried out in Section 2.1, it was found that large current ripples occurred (between 1.3 ~ 4.2Ap-p) while operating the auxiliaries; the output current is therefore specified as 30A±10%.

4.2 Component calculation

The theoretical equations of [4] were used to calculate the component sizes using a switching frequency of 100kHz. This switching frequency was selected because it provides a good compromise between efficiency and component sizes. Table 3 shows the calculation results.

4.3 Converter simulation

PSPICE is used to simulate the converter using the component values in Table3. The simulation was run until it reached steady state at a time of 9ms. Figure 5 shows the voltage and current waveforms generated from the simulations for two switching periods. Voltage ripple of 140mVp-p (2%) is obtained at the output of the converter as shown in Figure 5(a).

Table 2 Basic Requirements

Input Voltage	48Vdc
Output Voltage	12Vdc ± 10%
Output Current	30A ± 10%
Maximum Output Voltage Ripple	1.2V peak-to-peak (<10% of 12V)
Maximum Current Ripple of Inductance L2	3A peak-to-peak (<10% of 30A)
Minimum Efficiency	Preferably > 85%
Input Protection	Over voltage
Output Protection	Over voltage, Over current, Short circuit

Table 3 Calculation Results

Duty Ratio, D	33%
Inductance, L1	211.2µH
L2	52.8µH
Capacitance, C1	33µF
C2	15.86µF
Load RL	0.4Ω
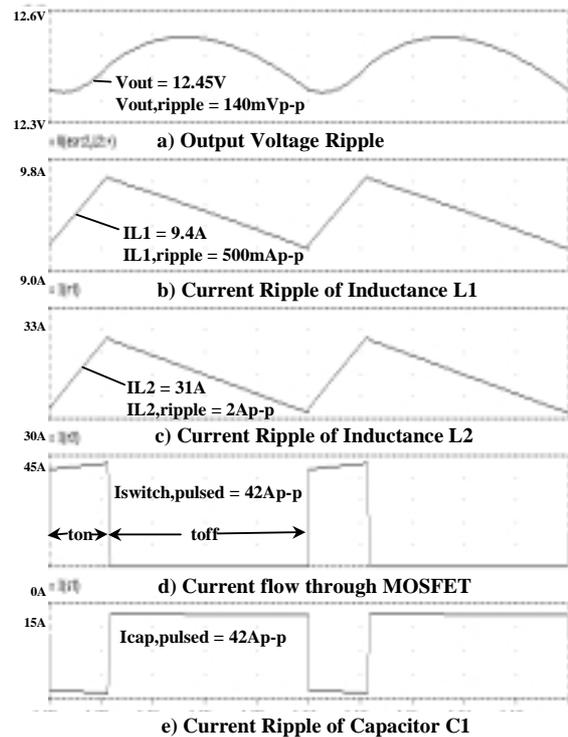
Figure 5. Simulated waveform of the Cuk converter.

Figures 5(b) and (c) show the inductor L1 and L2 current waveforms respectively. In inductor L2 the current ripple is 2Ap-p (6.7%).Large amount of pulsed current, 42Ap-p, flows through the switch and capacitor C1 on each PWM cycle as shown in Figure 5(d) and (e) respectively.
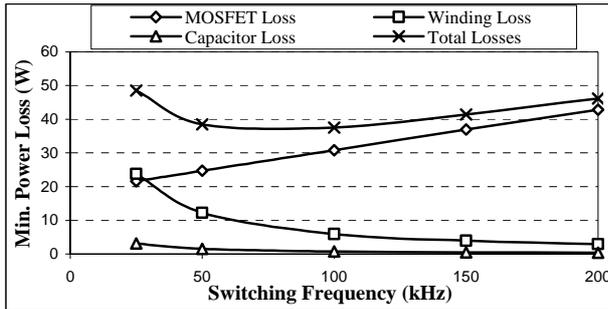
Figure 6 Estimated Cuk Converter Component Loss

Figure 7 Simulated Cuk Converter Efficiency

4.4 Circuit losses estimation

At various switching frequencies theoretical calculations were made to determine the component values and their losses [4]. Figure 6 illustrates the estimated component losses of the converter over a range of switching frequencies. MOSFET losses were estimated by adding the magnitude of conduction and switching loss in the switch. The power losses in the passive components were determined by finding the product of their series resistance and the current flowing through them. Using the information provided in Figure 6, PSPICE simulations were carried out to determine the overall efficiency of the converter over a range of switching frequencies as shown in Figure 7

4.5 Switching frequency selection

The need for a high efficiency converter dictates a careful selection of switching frequency. This in turn has an impact on the size of the passive components. Using Figures 6 and 7 a choice of 100kHz as the switching frequency was made. This choice is a compromise between choosing high efficiency and small components.

4.6 Inductor design

The basic inductor design procedure of Billings was followed [5]. Using the ripple current values given in Figure 5(b) and (c), the input parameters of the inductance design are determined and listed in the Table 4. Inductors L1 and L2 are wound on ETD49 and ETD59 ferrite core respectively. Theoretical calculations were carried out and found that without a air-gap, both inductor cores would be saturated at the 100kHz switching frequency.

Table 4 Input Parameters of Inductance Design

Inductor	L1	L2
Inductance	211.2uH	52.8uH
Peak Current	9.6A	32A
DC Current	9.4A	31A
Max. Temp.	100°C	100°C

Therefore an air-gap must be added in these cores to reduce magnetic flux density. However, the result is that extra windings are needed to regain the required inductance. To achieve the best compromise between the core size and the copper loss, an air-gap of 3mm was selected for both cores. This was verified from the tables and figures provided in the Philips Soft Ferrite data book [6].

4.7 Component selections

In the Cuk converter topology, all the current transferred from input to output must pass through capacitor C1. The converter delivers high currents and this results in an enormous ripple current flowing through the capacitance C1 during each PWM period. This is confirmed by PSPICE simulation as shown in Figure 5(e). Due to a large ripple current of up to 40Ap-p, electrolytic capacitors are not considered suitable. Plastic Film type MKT capacitors are used since they offer high AC stress properties. C1 is constructed from ten 3.3µF capacitors connected in parallel. The capacitors that form the output filter must also be able to handle an appreciable amount of ripple current of up to 3Ap-p. To handle this ripple current, ten 47µF electrolytic capacitors were connected in parallel to form the output capacitor C2.

To maximize the efficiency of the converter, the switch was chosen to have low conduction and switching losses. An Intersil RFP40N10 N-channel MOSFET was selected to provide higher than necessary current and voltage ratings with low $R_{DS,(ON)}$ of 0.04Ω and fast on and off switching times (47ns and 62ns respectively).

Since the converter is used in a step-down application, a high forward-voltage drop in the diode will result in an enormous power loss in the converter. An International Rectifier 30CPQ100 high efficiency, schottky diode was chosen as it offers a low forward-voltage drop of 0.86V and has the capability of handling large current and reverse blocking voltage of 30A and 100V respectively.
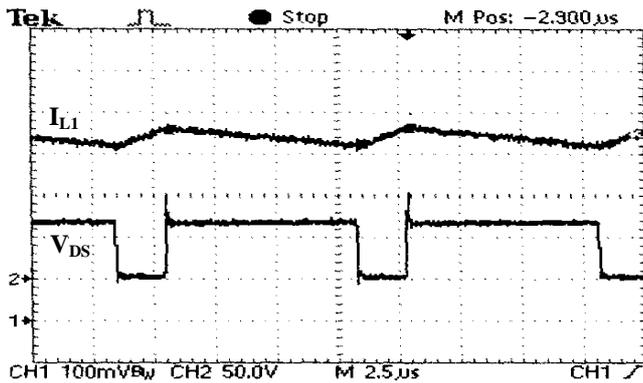
Figure 8 Input inductor current ripple (Top, 2A/div), and MOSFET switch voltage waveform (Bottom, 50V/div). Time scale: 2.5μs/div

Figure 9 Input inductor current ripple (Top, 2A/div), and Diode switch voltage waveform (Bottom, 50V/div). Time scale: 2.5μs/div

5. Prototype performance

The prototype model of the 12V, 30A converter has been built and tested for efficiency and steady state output voltage ripple. Under full load, the average current flowing through the Schottky diode is 30A. The diode's forward voltage drop of 0.86V limits the converter's theoretical maximum efficiency to 93.3%.

The measured efficiency of the switching converter at various loads is listed in Table 5. Under nominal operating conditions of 48V input, 30A output, the efficiency is measured to be 85.2%. The highest efficiency of 92.4% was obtained at 2/3 load (20A). The characteristic switching waveforms of Figure 8 and 9 show reasonably clean switching under the full load condition and confirms the correct operation of the converter.

Table 5. Measured Efficiency of the Converter

Load Condition	Vin (V)	Iin (A)	Vout (V)	Iout (A)	Effi. ζ (%)
1/3 Load	48.2	2.8	12.0	10.0	89.0
2/3 Load	48.1	5.4	12.0	20.0	92.4
Full Load	48.0	8.8	12.0	30.0	85.2

Ideally, the nominal voltage across the power devices (MOSFET and Diode) is 60Vp-p. As seen in the Figures 8 and 9, voltage spikes occur when the switches are turned on or off. Voltage clamps (RCD Snubbers) are designed and implemented across these power devices to reduce the voltage spikes and to limit the overall peak-to-peak voltage. Consequently, the voltage across the power devices is 95Vp-p and 92Vp-p respectively when using the voltage clamps. The current ripple of inductor L1 and the output voltage ripple are measured as 514mAp-p and 212mVp-p respectively. These values are close to the simulation results of 500mAp-p and 140mVp-p as given in Section 4.3. The measured output voltage is 12V±5%, which is within the specification of ±10%.

6. Conclusions

A distributed power network is to be used in an electric vehicle application. The 300Vdc nominal battery voltage is converted to 48V intermediate voltage. The use of high efficiency LEDs and power supply current limiting results in reduced energy consumption by the auxiliary loads. A Cuk converter has been designed and implemented that converts 48V to 12V at a maximum load current of 30A. The converter operates at 100kHz and has a maximum efficiency of 92.4% at 2/3 load. Comparison between waveforms captured from the prototype and simulation results are similar. This indicates that the simulation results are a good predictor for the experimental results.

7. References

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