AN INVESTIGATION OF BATTERY VOLTAGE EQUALISATION TOPOLOGIES FOR AN ELECTRIC VEHICLE

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Abstract

The vehicle's battery system consists of a series connection of 26 12volt lead-acid batteries. This paper details the design and construction of a battery voltage equaliser which aims to balance the charge level of each individual battery within an hour. These batteries are divided into four banks of either six or eight batteries. Four 144W converters are required to transfer energy between the banks and the ends of the bus. 25 24W converters transfer energy between adjacent batteries. Due to the numbers of converters involved, the size, weight, cost, manufacturability, and efficiency are the key points of the design.

1. INTRODUCTION

The third electric vehicle (EV3) produced by the Electrical and Computer Engineering Department at the University of Canterbury is based on a "TOYOTA MR2". It is powered by 26 HAWKER Energy 12volt 26A-hour sealed lead-acid batteries connected in series to achieve a nominal 312V DC source and these batteries are conveniently divided into four banks by the constraints of their location in the car. The first bank consists of 8 batteries, which are located at the front boot of the MR2. The second bank consists of 6 batteries and is placed in the engine bay. The third and the fourth banks consist of 6 batteries each and are located in the rear boot. These battery locations are shown in *Figure 1.1*.

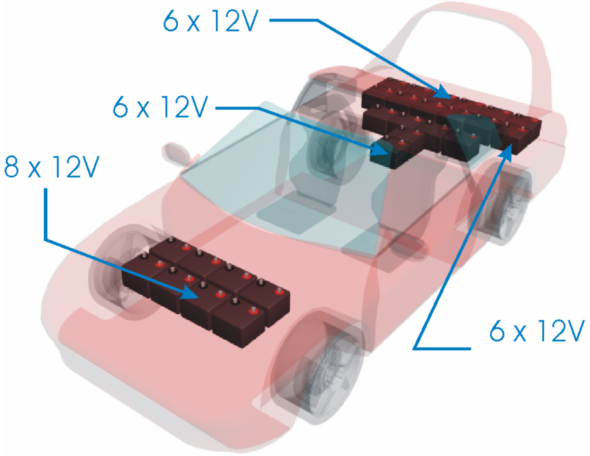

Figure 1.1. Battery location

This paper presents the design of a voltage equaliser for a series connected battery string. The need for a voltage equaliser is principally due to the differences in cell chemistry and temperature gradients along the battery string. During the charging process, some batteries will consequently reach full charge before others and before the overall battery terminal voltage reaches its nominal value[1]. Therefore, if the charger continues to charge the remaining batteries, it would result in overheating the fully charged batteries, thus reducing their life. The same principle can be applied to the discharging process. Any over-discharge would lead the battery into deep discharge, which can also reduce the life of the battery and decrease the travelling range of the electric vehicle.

Maintenance of cells at an equalised charge level is critical for enhancing battery life[1]. There are numbers of ways to monitor the charge level of the battery, and the most common techniques are coulometric measurement and open circuit measurement. The coulometric measurement counts the ampere-hours either coming out of or going into the battery bank. In its most basic form the battery capacity is assumed to be fixed. In reality the total battery capacity varies with the discharge current, the type of discharge, temperature and the age of the battery[2]. The open circuit voltage can be used to determine the state of charge and is more suited to battery monitoring in an electric vehicle since it can be measured directly from standard battery terminals and does not require sensors to be implanted in it. The open circuit voltage of a sealed lead-acid battery also relates directly to the battery's state of charge[3]. The main drawback of the open circuit voltage monitoring technique is that the open circuit voltage must stabilise before a reliable measurement can be made, and this can take from half an hour to several hours depending on the type of battery[3].

The objective of this project has been to design and build a battery equaliser specifically for the EV3, that can equalise the charge level of each individual battery within a series string battery. Since a number of equalisers have to be built for the entire battery string, the design of each equaliser must be small, light weight, cost effective, easy to use, flexible for mounting, maintenance free and highly efficient. An additional complication arises from the fact that these 26 batteries are not all located in a single compartment of the vehicle. In addition to having an equaliser capable of transferring energy between adjacent batteries, energy must also be able to be transferred between the battery banks(*Figure 1.1*) and between the top and bottom of the entire string.

In this paper the principle of operation of a voltage equaliser is described and simulation is used to demonstrate how a DC - DC converter can interface between two batteries and transfer the energy from one to the other. Possible equalisation topologies are discussed and a decision on the choice of voltage equaliser topology for the electric vehicle is made. The DC – DC converters making up the equaliser have been constructed and the efficiency with which they can transfer the energy has been measured.

2. PRINCIPLE OF OPERATION

The idea of a battery equaliser is to balance the charge level of two batteries by drawing energy from the one with the higher charge and transferring it to the other. The most efficient means of achieving this transfer is by using a high frequency DC - DC converter. In power electronics, every converter has their own energy storage unit, which can be an inductor, a capacitor, a transformer or some combination of these. By controlling the switching signal, this energy storage unit can be charged from the source then discharged to the load. In a battery equaliser the overcharged battery can be considered as the source and the undercharged battery as the load.

To illustrate this equalisation process, the buck-boost converter shown in *Figure 2.1*, which is connected to two battery models, has been simulated using PSpice. In this simulation the two rechargeable batteries are modelled as 1F capacitors. The two 100mΩ resistors model the internal resistance of the batteries and the wiring resistance between the converters and the batteries. Assuming that C1 represents the higher voltage battery. The operating principle of this equaliser is that first MOSFET Q1 is switched on by gate signal V1 and energy is drawn from the capacitor C1, which charges the inductor L1 via the wiring resistors R1 and R3. Then Q1 is switched off, and the stored energy in the inductor is discharged into C2 through the internal diode of Q2.

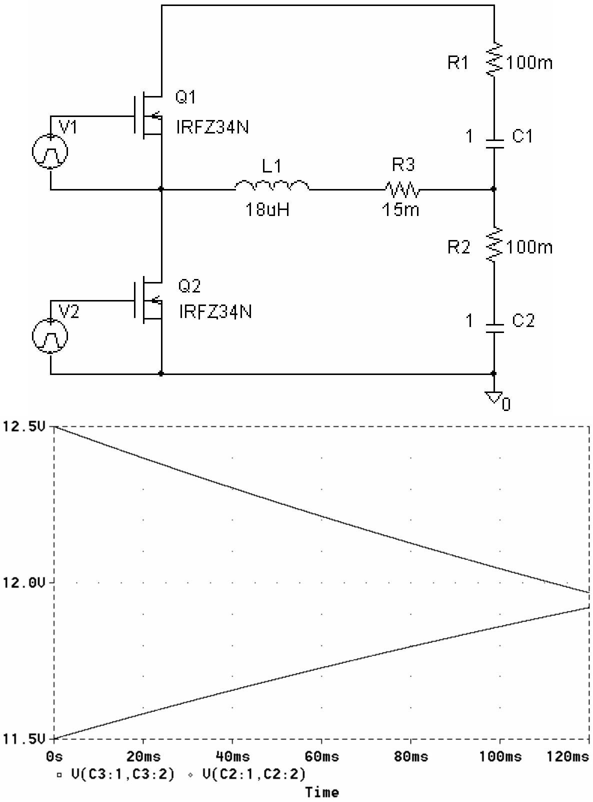

Figure 2.1. Buck-boost equalizer – schematic and operation

For the purpose of this simulation the initial capacitor voltages were set to 12.5 and 11.5V. The results of the simulation (*Figure 2.1*) show that the two battery voltages can be successfully equalised. It should be noted that an actual battery equalisation process would normally take place over a period of one to two hours, to limit the charge/discharge current and keep losses to a manageable level.

3. EQUALISER TOPOLOGIES

There are three possible equaliser topologies; the common bus, common core and ring equaliser. In the common bus equaliser, which is shown in *Figure 3.1*, a capacitor bank is placed on the common bus as a temporary energy store unit. Therefore, if any battery is overcharged, the overcharge energy can be transferred onto the common bus. On the contrary, if any battery is undercharged, that battery could be charged from the energy stored on the common bus. The energy transformation for each battery is done by an isolated DC – DC converter, which can be a flyback, push-pull, half-bridge or full-bridge converter.

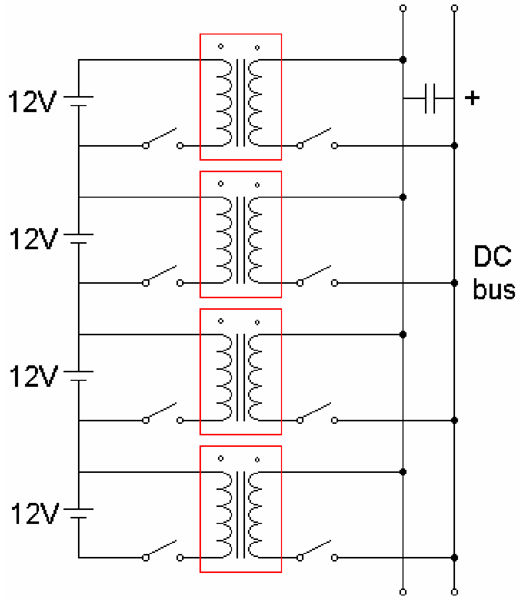

Figure 3.1. The common bus equaliser

The second topology is based on a common core technology that is shown in *Figure 3.2*. In the common core topology all windings have to be coupled to the common core, which is the energy storage unit in this topology. Any stored energy will be distributed via the diode to all undervoltage batteries right after the energy has been drawn from the overcharged battery. The largest portion of the stored energy will be directed to the lowest voltage battery without any additional control. In reality, this scheme has a fairly high sensitivity to the leakage inductance between secondary windings [1].

The third topology is the ring equaliser, which is shown in *Figure 3.3*. In the ring equaliser, the energy can only be drawn/transferred from/to adjacent batteries by a DC - DC converter. The top and bottom batteries of the string must also be linked by an isolated converter to complete the ring structure. The principal attraction of this topology is that only one converter needs to be isolated. The non-isolated converters connecting adjacent batteries can therefore be constructed in a compact lightweight low profile format.

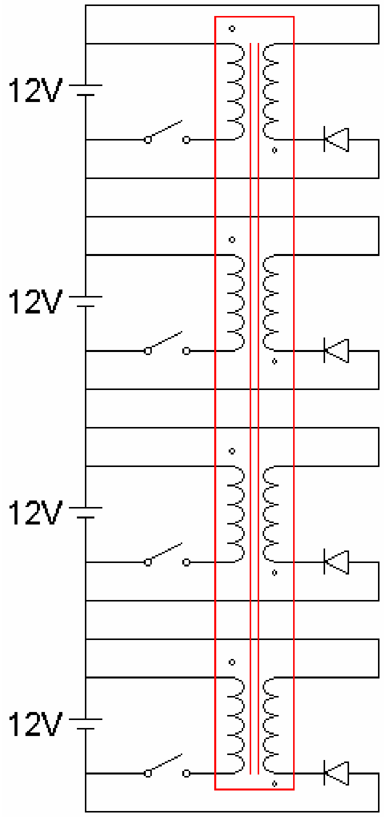

Figure 3.2. The common core equaliser

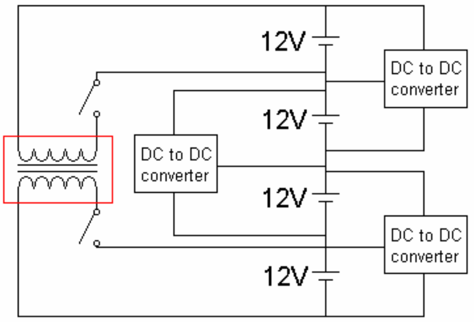

Figure 3.3. The ring equaliser

4. CONVERTER TOPOLOGY

To determine the most suitable equaliser topology for the EV3 application, an extensive analysis of each was undertaken. A summary of the results of that analysis is shown in *Table 4.1*.

	Common bus	**Common core**	**Ring**
For	• Good for long battery string • Easy for future expansion	• Good for long battery string	• Can be made in small size and light weight • Easy for future expansion
Against	• Converter requires transformer	• Converter requires transformer • Inflexible for future expansion • Inflexible for mounting	• Inefficient to transfer the energy to the remote battery

Table 4.1. Comparison of equaliser topologies

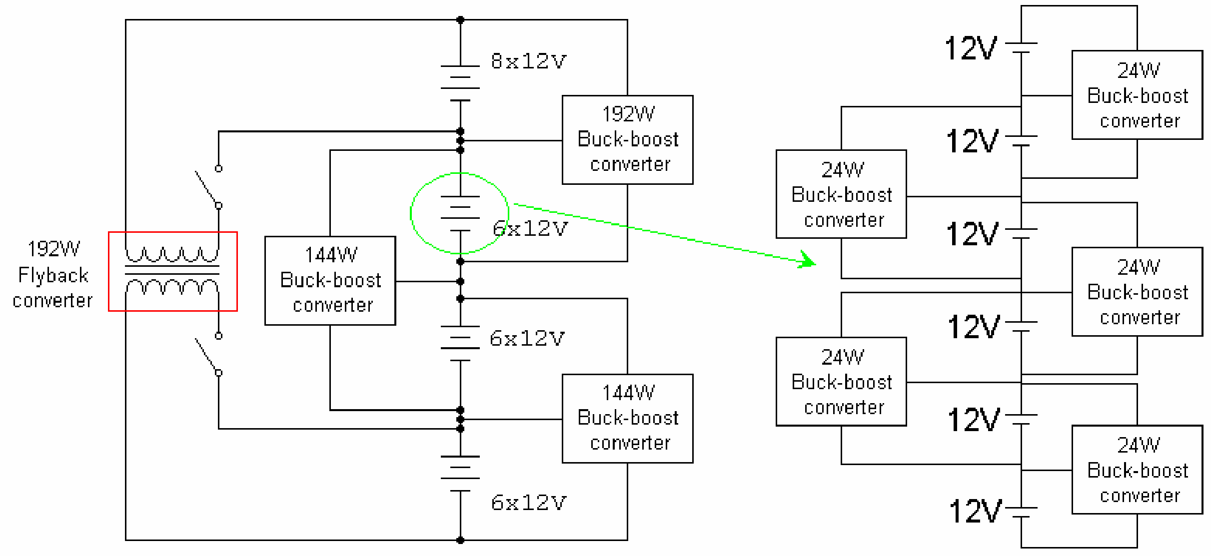

Figure 4.1. The proposed voltage equaliser structure

In summary, the common bus topology would be good for a single long string of batteries located physically close together. Probably the most negative aspect of this topology is that each and every converter requires a transformer. This would violate the need for a small compact easily manufactured converter. The common core topology has the obvious requirement that all 26 batteries must be located in the same compartment. The geography of the car will not allow this. For this application the ring structure is the most appropriate because most of the converters can satisfy the requirement of being small, non-isolated and easily manufacturable. In fact only one converter connected between the top and bottom of the battery string needs transformer isolation.

The key points for selecting the types of converters are the cost, manufacturability and efficiency. To equalise the charge between the adjacent banks or batteries, the buck-boost converter provides the advantage of a low component count and reasonably high efficiency. Compared with the Cuk converter, which typically has a slightly higher efficiency, the buck-boost converter's low component count gave it the advantage from a manufacturability point of view. For the selection of the isolated converter, the flyback converter was chosen because only one MOSFET is required on each side of the transformer to achieve bi-directional energy transformation. This configuration provides a significant advantage on component count and converter construction over the other isolated bidirectional topologies.

The proposed ring voltage equaliser structure is shown in *Figure 4.1*. Adjacent battery banks are linked by three 144/192W non-isolated buck-boost converters and one 192W isolated flyback converter links the top and bottom of the 26 battery string. Within each bank, the adjacent batteries are equalised by 24W non-isolated buck-boost converters. In this design, all the converters must be designed for bi-directional energy transfer, with average currents selected as 2A, so that 10% of total charge can be balanced in about an hour.

5. CONVERTER CONSTRUCTION AND TESTING

The entire battery string is conveniently divided into four banks by the constraints of their location in the car. The 192W flyback converter, the 144W buck-boost converters and the 192W buck-boost converter are designed to transfer energy between banks, and the 24W buck-boost converters are designed to equalise the battery voltage within each bank. All converters are constructed to operate at a maximum charge/discharge current of 2A which is controlled by a pulse by pulse current control loop.

5.1. The 24W Buck-boost converter.

Since a number of 24W buck-boost converters need to be built and ideally located in a recess in the top of each battery, the manufacturing process for a low profile design has to be as simple as possible. Therefore planar inductor technology was employed. The planar inductor can be constructed using either one E and one I core or two E cores, and the actual winding is made up by the loops of printed circuit board (pcb) tracks, where the higher inductance can be achieved by the multiple loops of a multilayer pcb. The biggest advantage of the use of the planar inductor is that since the windings are made up by the pcb tracks, the inductor can be made in a low profile, high precision and easily manufactured format. A major problem of the planar inductor is that since the multilayer pcb is used, any intermediate windings do not have as much heat dissipating area as the top and bottom layers. Therefore, as the current flows through the winding, heat will be built up, then as the track temperature increases, the winding resistance will also increase, and losses increase in the inductor. To overcome this problem, a wider pcb track has to be used in order to reduce the winding resistance and hence reduce the losses from the inductor. The trade off of using wider track is that it increases the size of the inductor and decreases the possible number of loops per layer. A range of inductors wound on a variety of cores were designed and tested appropriately. *Figure 5.1* shows a comparison of efficiency measurement against switching frequency for both E32 planar and RM8 cores.

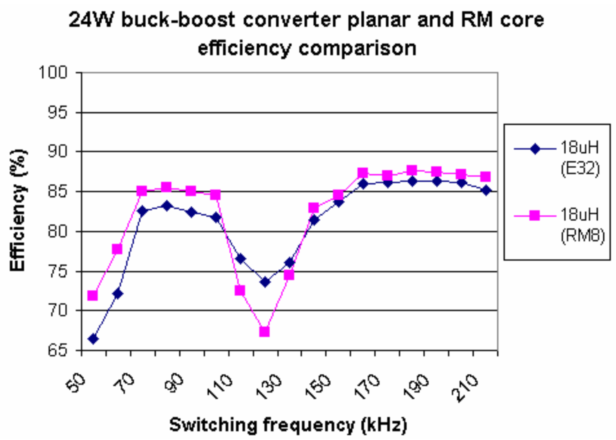

Figure 5.1. RM and planar inductors efficiency comparison

The experimental results of *Figure 5.1* show that the efficiency of the converter that uses the planar inductor is typically around 1.5 ~ 2% lower than the one which uses a standard inductor wound on an RM core. This extra loss from the planar inductor is caused by the higher winding resistance, whereas the litz wire that was used in the RM cored inductor has a much larger cross section area compared to the pcb track. The advantage gained by using a planar inductor to produce a low profile pcb outweighs the small loss in efficiency. Therefore the planar inductor is the choice and a photograph of this low profile buck-boost converter is shown in *Figure 5.2*. The overall height of the converter with the planar inductor is about 15mm, which is 10mm lower than an equivalent converter using an RM8 core. The 24W buck-boost converter shown in *Figure 5.2* has a measured efficiency of 86% at a switching frequency of 160kHz.

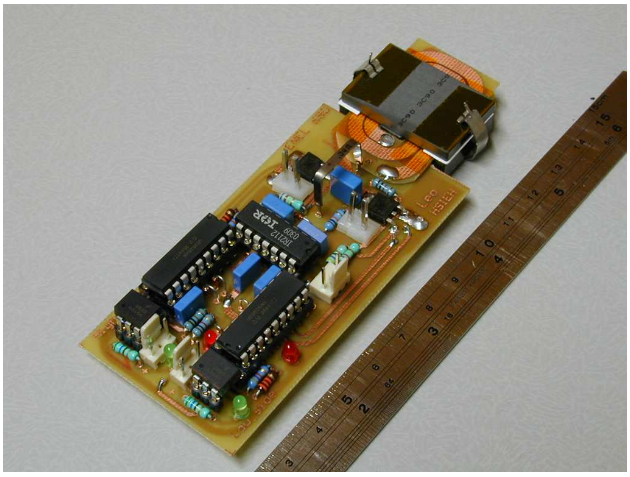

Figure 5.2. 24W buck-boost converter

Typical experimental equalisation results using the 24W buck-boost converter are shown in *Figure 5.3*. The initial voltage levels of each battery were 12.58V and 11.09V.

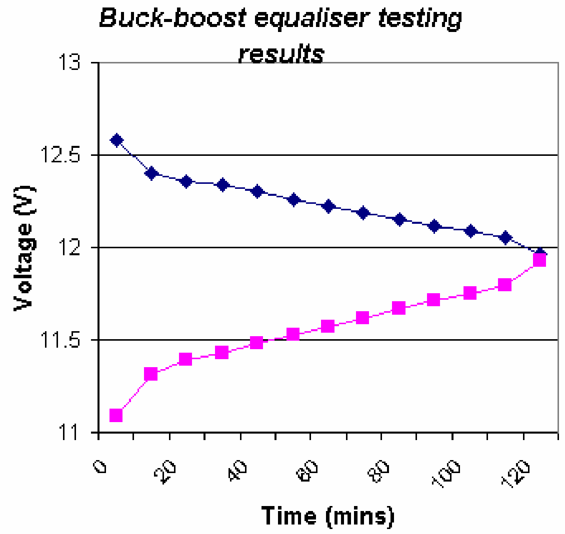

Figure 5.3. Experimental equalization results

5.2. The 144/192W Buck-boost converters.

The construction of the 144/192W buck-boost converters is similar to the 24W buck-boost converter. Since the input voltage has been changed to either 72V or 96V instead of 12V, the switching frequency has to be decreased in order to reduce the switching loss. To achieve the higher power transformation, a larger planar core and more turns are required in order to store sufficient energy and maintain the inductor in continuous conduction. Experimental measurements of efficiency against switching frequency for the 144/192W buck-boost converter are shown in *Figure 5.4*. To achieve a peak efficiency of 94% under 144W operation a switching frequency of 70kHz has been selected.

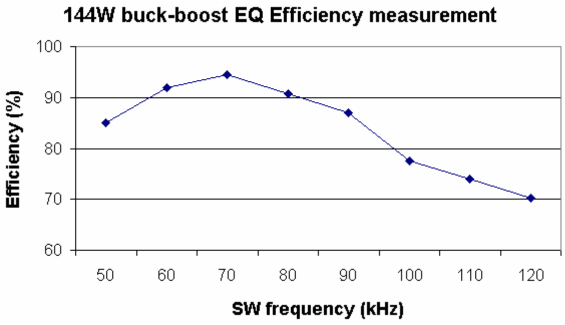

Figure 5.4. Efficiency against switching frequency for the 144W buck-boost converter

5.3. The 192W Flyback converter.

The purpose of the flyback converter is for transferring the energy between the top and the bottom battery banks. Since the bank voltages are 96 and 72V, the primary to secondary winding ratio must be 4:3. According to the experimental measurement, if the primary winding is less than 16 turns, the ratio of primary leakage inductance to the primary inductance would become too high, and has a significant impact on the converter's efficiency. The flyback transformer was wound (20 turns of primary winding and 15 turns for the secondary winding) on a standard RM14 core using litz wire. Experimental measurements of efficiency were carried out over a range of switching frequencies (*Figure 5.5*) and a switching frequency of 100kHz, which was chosen for the flyback converter, gave an efficiency of 94.5%.

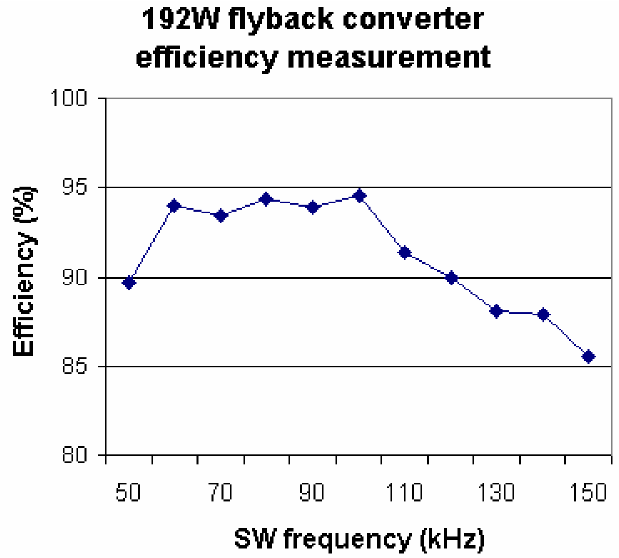

Figure 5.5 Efficiency against switching frequency for the flyback converter

The overall height of this flyback converter shown in figure 5.6 was measured as 35mm. The structure of the complete voltage equaliser requires only one flyback converter; therefore the requirement of a low profile compact design for this converter is not so stringent.

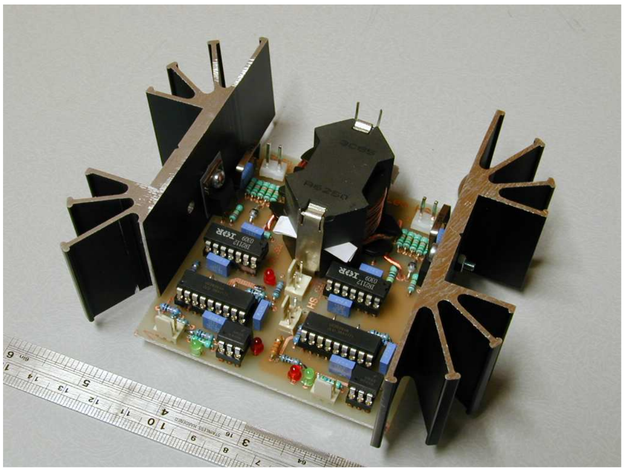

Figure 5.6. Physical construction of the 192W flyback converter

6. CONCLUSION

After comparing various topologies for a voltage equaliser, the ring structure was chosen as being the most suitable for the electric vehicle application. It has the major advantage of being able to be located across a number of separate compartments in the car. To achieve balancing 10% of total charge in an hour, all converters have been designed to carry a maximum charge/discharge current of 2A and are controlled by a pulse by pulse current control loop. The overall voltage equalising ring structure consists of three different types of converters; the 24W buck-boost converters for charging/discharging adjacent batteries, the 144/192W buck-boost converters for charging/discharging adjacent banks of batteries, and 192W isolated flyback converter which transfers charge between the top and bottom of the battery string. The 24W and 144/192W buck-boost converters have been designed using planar inductor technology to achieve a low profile and easily manufactured format. The efficiencies were recorded as 86% for the 24W buck-boost converter, 94% for the 144W buck-boost converter and 94.5% for the 192W flyback converter.

7. REFEREMCES

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