Development of a Low-power Step-down DC/DC Converter Module for Electric Cars

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***Abstract*—An electric car uses at least two high power DC/DC converters, one applied as the motor speed controller and one applied for the battery charger. It also usually needs another DC/DC converter, a small one, used to down step the battery voltage to a lower voltage for supplying power to non-machine-related devices such as LED lamps, door openers, GPS device, tablet PC, and mobile phone. For the Rinus C1 electric car we built, we needed a small power DC/DC converter that converts 48V battery voltage to 12V gadget-ready voltage. Having gone through requirement definition, reference study, design, assembling and experimental test, the module has been successfully developed –using MC34063A ASIC of Motorola– and is currently in use.**

***Keywords*—DC/DC converter, buck converter, electric car**

I. Introduction

DC / DC converters are used in various systems. High power DC/DC converters are used, in example, in a wind power system such as those discussed in [1]. The design of a 5kW DC/DC converter for a hydrogen fuel cell system is reported in [2]. High power DC/DC converters are also applied for electric cars. A 10kW DC/DC converter for an electric vehicle battery charger has been designed and is reported in [3]. In our case, when building the Rinus C1 electric car, we used a ready-to-use battery charger and a ready-to-use motor speed controller (both employs a high power DC/DC converter) however we designed and developed by our own the low-power DC/DC converter module for the non-machine-related devices. We particularly needed this module to supply 12 DC voltage for car LED lamps, electric door openers, a tablet PC, a GPS and a mobile phone.

The car has been built in 2013 where our first version of the module was actually a passive voltage adapter using resistors. The one discussed in this paper is our second version, developed in 2015.

The whole development process consisted of requirement definition, reference study, design, assembling and experimental test.

II. Defining Requirement

Prior to design, the input and output properties of the DC/DC converter had to be specified. The specification included the voltage and the current values. The specification itself depended on the maximum load current to serve.

A. Load Current Planning

The power source of the converter module would be the car's battery, which is, in our case 48V. The two input pins of the module would be connected to the two battery terminals. The output voltage of the module was to be 12V, as required by the load: LED lamps and door openers. For GPS device, tablet PC, and mobile phone the converter module would provide the same voltage (12V) through a standard cigarette lighter socket, so that they would need a 12V/5V adapter (another step-down DC/DC converter) as usual.

The load current planning is shown by Table 1. The total current consumption was planned to be 4.95A where the individual charger down steps 12V to 5V, assumed with 90% efficiency. It is good to keep this assumption value a bit lower than some newer achievements, such as efficiency of 95% reported by K. Fang, Y. S. Lu and F. Yu in [4] for a low-power step-down DC/DC converter they developed.

TABLE 1. LOAD CURRENT PLANNING FOR THE DC/DC CONVERTER MODULE

Load	Charger Rated Output Power	Max. Current at 12V
All LED lamps	18W at 12V	18W / 12V = 1,5A
Door opener	18W at 12V	18W / 12V = 1,5A
Cigarette lighter 1 (GPS or mobile phone charger)	7W at 5.2V	(7w/0.9*) / 12V = 0.65A
Cigarette lighter 2 (Tablet PC charger)	7W at 5.2V	(7w/0.9*) / 12V = 0.65A
Cigarette lighter 3 (Mobile phone charger)	7W at 5.2V	(7w/0.9*) / 12V = 0.65A
		Total current: 4.95A

*The individual charger down steps 12V to 5V, assumed with 90% efficiency.

B. Input and Output Specification

The load current planning implied the magnitude of the current to be supplied by the module. The input voltage had to be specified in accordance with the power supply, in our case, the car battery voltage. This input and output specification is shown by Table 2.

TABLE 2. SPECIFICATION OF MODULE INPUT AND OUTPUT

Input	Output
Vin = 48V	Vout = 12V Iout = 5A (max)

When comes to circuit protection, it needs to be prudent in predicting the input current because the input current and output current are more or less of the same value. The

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difference is that the output current flows off the module to the load continuously while the input current flows from the battery into the module in “pulse mode”. It means that, in this case, the maximum input current is also 5A but in pulse mode.

Particularly in determining the input fuse property, it is required to notice that a fuse responds to heat; where the heat itself grows with current and time. It should mean that, e.g. a 5A fuse will respond to a 5A pulse-mode current more slowly than to a 5A continuous current. This is the reason why a lower capacity fuse should be chosen for the input current.

III. Designing The Circuit

A. Overview on Step-down Conversion Concept

The concept of converting a DC voltage to a lower voltage with high efficiency using an inductor, a capacitor and a diode has been widely used and discussed, for example in [5]. The topology is shown by Figure 1.

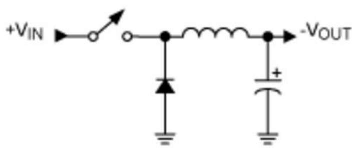

Fig. 1. The switch-mode step-down converter (buck converter) topology as discussed in [5].

While a linear voltage regulator produces a lower voltage by dropping the unused voltage onto a resistor (or a resistor equivalence), a switch-mode step-down converter regulates its output voltage by switching the input current on and off. The output voltage will depend on the ratio between the t_{ON} and the pulse period. The output voltage Vout is determined by Vin, T_{OFF} and the T_{ON} in such a way that:

$$\text{Vout} = \left(\frac{ton}{ton + toff}\right).\ Vi \tag{1}$$

While

$$\left(\frac{ton}{ton+toff}\right) = D \tag{2}$$

Where D is the duty cycle. Thus

$$\text{Vout} = D.Vin \tag{3}$$

The idea about how to control the duty cycle itself is shown by Figure 2. Every time the ramp signal (v1) becomes higher than the constant voltage (v2), switch is on.

Furthermore this idea can be brought to reality, in example, with the help of an op-amp that operates as a comparator for v1 and v2. The op-amp works in such a way that whenever the ramp signal > Vout controller it will produce a full output voltage. This is depicted by Figure 3.

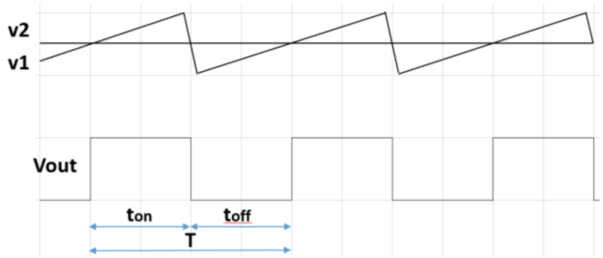

Fig. 2. The idea of how to control the duty cycle. The output voltage will exist whenever v2 > v1.

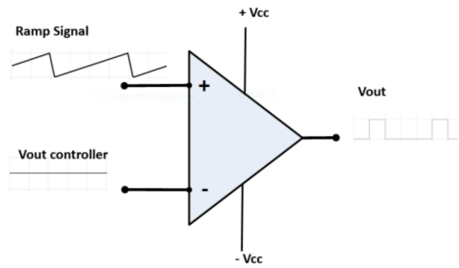

Fig. 3. The circuit to realize the idea in Figure 2. It is also known as Pulse-width Modulation (PWM) circuit.

B. Overview on Previous Works

Works on DC/DC converter circuit design have been carried out by parties, including E. Babaei and M. M. Hamed in [6], I. Iskender, Y. Üçtug and H.B. Ertan in [7] and L. Chan-Soo et al in [8].

E. Babaei and M. M. Hamed in [6] reports particularly a valuable proof, through a deep mathematical analysis, about the relation among output voltage ripple, load resistance, inductance and capacitor capacitance in buck converter topology. It is reported that the output voltage ripple relates inversely with inductance, capacitor capacity and the load resistance, meaning that, the more inductance and capacitor capacity we can manage the less ripple we will get. This confirmation gave an implication to our design, that is, we determined the load current we wanted to allow, a certain ripple voltage value we wanted to accept and then we decided the value of inductance and capacitor based on our previous experiments.

I. Iskender, Y. Üçtug and H.B. Ertan in [7] reports a microcontroller-based fuzzy control approach to adjust the output voltage of the dc-dc converter using phase-shift PWM technique. The results indicate that the fuzzy control performs well in terms of voltage regulation and also controlling the rise- and fall-time of the output waveform.

L. Chan-Soo, et al. in [8] reports their design of a very small-power DC/DC converter with an on-chip inductor that operates properly with the inductance of 7.6 nH and mW power range.

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K. Fang, Y. S. Lu and F. Yu report their design of a particular ASIC for a DC/DC controller in [4].

Furthermore, designs of DC/DC converter based on Motorola MC34043A have been carried out by parties too, including J. Hansen and J. Hill as reported in [9], M. Mikic et al as reported in [10] and S. D. Das et al as reported in [11].

C. Our Circuit Design using MC34063A

It is good to find that several sophisticated DC/DC converter controller ASICs have been widely available with cheap price, e.g. the MC34063A of Motorola. This ASIC's architecture is shown by Figure 4.

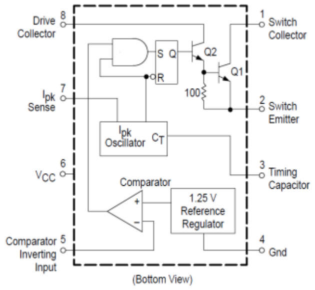

Fig. 4. The architecture of MC34063A of Motorola as depicted in [12]

Our Circuit

The circuit of our module is shown by Figure 5. Referring to the figure, (a), the area within the cutting-line rectangle, is representing the MC34063A while (b), the area outside the rectangle, is representing the circuit we had to take care of.

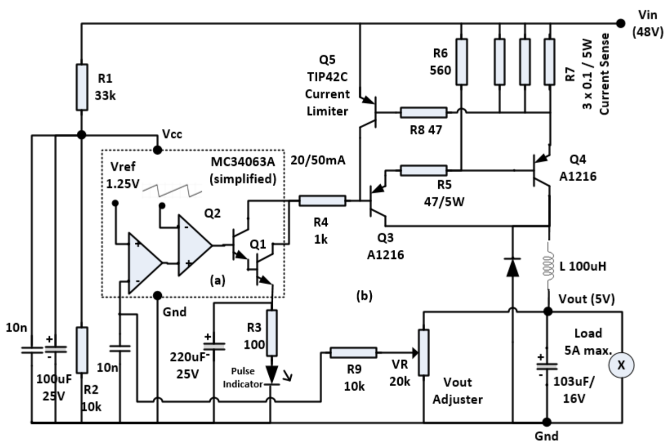

Fig. 5 The whole circuit of the converter module. (a) represents circuit within the MC34063A while (b) represents the part to be taken care of during our work. Some component values suggested in [12] were considered.

Controlling Vout using Vref Technique

The Vref feature provided in the MC34063A works as follows:

- Vref is internally set as 1.25V.
- Its counterpart is the comparator inverting input (Vpin5).
- If there is no voltage difference between Vref and Vpin5, the controller will keep current duty cycle.
- If Vpin5 < Vref then the controller will increase the duty cycle.
- If Vpin5 > Vref then the controller will decrease the duty cycle.

In this manner, a sensing mechanism can be made in such a way so that the controller will not change its duty cycle if the output voltage is already in 'shape' (reaches the intended value). This Vout-sensing mechanism is shown in Figure 6.

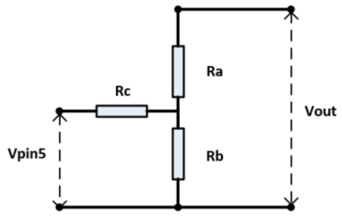

Fig. 6. Vout sensing mechanism

The two pins at the right side are to be connected to the Vout of the converter module while the two pins at the left side are to be connected to the pin 5 of the MC34065A as a feedback. For this configuration, with the fact that the chip impedance at the pin 5 is very much higher than Rc, applies the following:

$$\frac{Ra + Rb}{Rb} = \frac{Vout}{Vpin5}$$

$$\frac{Ra}{Rb} + 1 = \frac{Vout}{Vpin5}$$

$$\frac{Ra}{Rb} = \left(\frac{Vout}{Vpin5}\right) - 1 \qquad (4)$$

In equilibrium Vpin5 has to be as high as Vref of the chip is, thus

$$\frac{Ra}{Rb} = \left(\frac{Vout}{Vref}\right) - 1 \qquad (5)$$

The Current Amplifiers

As the chip is capable of driving current up to 1.5A, one-stage current amplifying (Q4) should actually do for the final task. However an external over-load current sensing (R7, R8 and Q5) has been incorporated so another stage (Q3) was added in order to provide an enough drop voltage between Q4's emitter and Q3's base. In this way, the low drop voltage at Q5's emitter and collector when an overload happens can affect the conduction state of Q4 and Q5.

Determining R3, R4 and R5 Values

R3, R4 and R5 are used to protect Q1, Q3 and Q4 from exceeding current. Their values shall be not too small to ensure the protection effective but also not too big to ensure Q4 able to deliver the maximum collector current as required. Proper values for R3, R4 and R5 can be predicted by analyzing related currents and voltages, with the help of Figure 7.

According to Figure 7, the following applies:

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$$\text{VLED} + \text{VR3} + \text{VCE1} + \text{VR4} + \text{VBE3} + \text{VR5} + \text{VBE4} + \text{VR7} = \text{Vin} \quad (5)$$

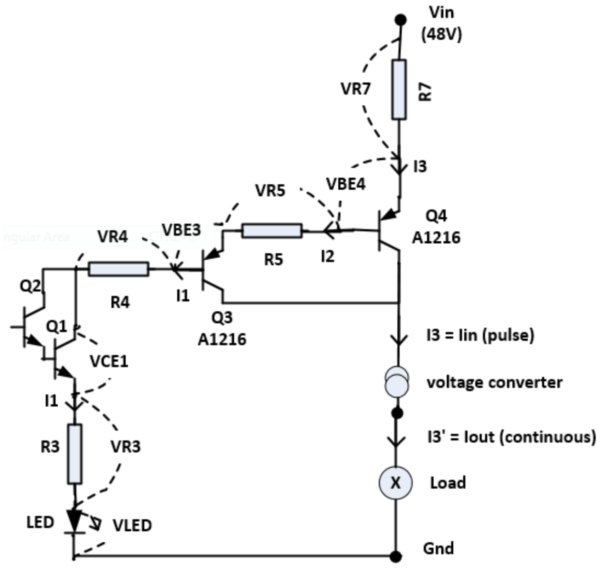

Fig.7. Voltages and currents related to R3, R4 and R5 values

In practice approximation can be made by the following approach:

- VBE of each transistor at conduction mode ~ 0.7V
- VCE of the Q1 (in darlington mode) ~ 1.0V
- VLED (blue) ~ 2.2V
- Collector current ~ emitter current of a transistor

In this sense the equation (5) becomes

$$2.2 + \text{VR3} + 1.0 + \text{VR4} + 0.7 + \text{VR5} + 0.7 + \text{VR7} = \text{Vin}$$

$$\text{VR3} + \text{VR4} + \text{VR5} + \text{VR7} = \text{Vin} - 4.6 \quad (6)$$

Breaking down each voltage into product of current and resistance, it becomes:

$$\text{I1}\,(\text{R3} + \text{R4}) + \text{I2.R5} + \text{I3.R7} = \text{Vin} - 4.6 \quad (7)$$

Considering the amplification carried out by Q3 and Q4,

$$\text{I2} = \frac{I3}{hFE(Q4)} \quad (8)$$

and

$$\text{I1} = \frac{I2}{hFE(Q3)} \quad (9)$$

Thus

$$\text{I1} = \frac{I3}{hFE(Q3).hFE(Q4)} \quad (10)$$

Working on (7), (8) and (10) with substitution it is found that

$$\left(\frac{I3}{hFE(Q3).hFE(Q4)}\right).(\text{R3} + \text{R4}) + \left(\frac{I3}{hFE(Q4)}\right).\text{R5} + \text{I3.R7} = \text{Vin} - 4.6 \quad (11)$$

In other words

$$\left(\frac{R3+R4}{hFE(Q3).hFE(Q4)}\right) + \left(\frac{R5}{hFE(Q4)}\right) + \text{R7} = \frac{Vin-4.6}{I3} \quad (11)$$

According to [13] the hFE of an A1216 transistor at VCE = -4V and Ic = 8A is 30 at the minimum. As for the A1216 in different VCE and Ic situations the hFE shall be physically measured.

With the help of equation (11), the data of hFE (Q4) and hFE(Q3) and setting I3 as 5A (maximum current) the values for R3, R4 and R5 can be chosen. They can then be fine-tuned through experiment.

As for the overload protection, the TIP42C has been chosen to amplify the signal from the current sense resistor. The properties of this transistor are explained in [14].

IV. Designing the PCB

The PCB has been designed manually using the Microsoft Visio 2013 and the result is here shown by Figure 8.

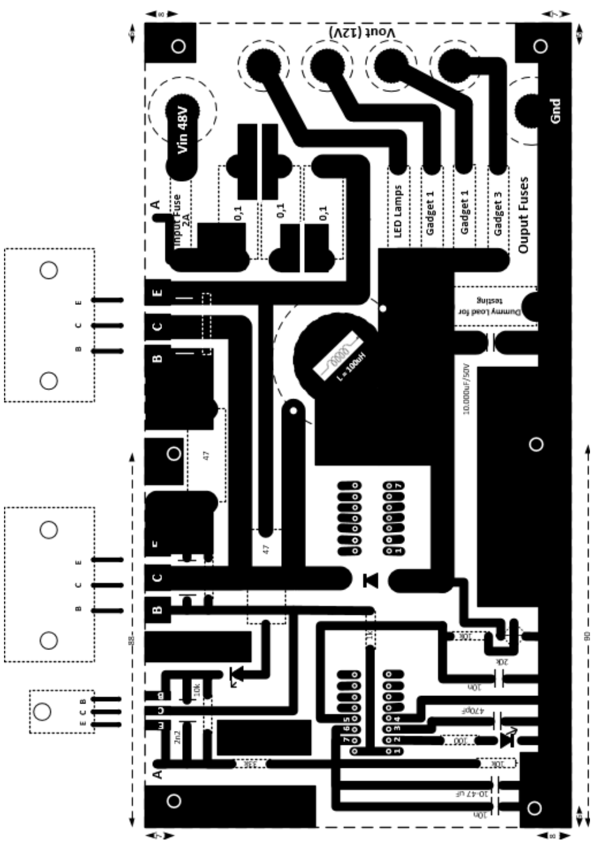

Fig. 8. The PCB design: The PCB size is 189mm x 100mm. Some component names and values are kept as they are to help technician when assembling. A group of free pins in the middle of the PCB is dedicated for storing a spare MC34063A IC for future replacement.

V. Development of the Module

In addition to circuit design and PCB design, the module development needed some mechanical considerations in regards to its shield dimension and shape, in order to make it easier when being installed into the electric car. The physical

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appearance of the module when it has been developed is shown by Figure 9.

Figure 9. Physical appearance of the module. The Vout terminals have not been soldered at the time the photograph taken. Underneath the PCB is the heatsink on which the transistors are firmly placed.

VI. Experimental Result

During the test the input voltage, the output current and output voltage were measured. The testing results are shown by Table 3, Table 4, Table 5 and Table 6.

Table 3. Result of Test with RLoad = 10 ohm

		Vin (V)	RLoad (ohm)	ILoad (A)	Vout (V)
Test Number	1	48.28	10	1.21	12.12
	2	48.14	10	1.20	12.11
	3	48.24	10	1.21	12.12
	4	48.24	10	1.21	12.11
	5	48.16	10	1.20	12.09
	6	48.22	10	1.21	12.11
	7	48.24	10	1.21	12.12
	8	48.16	10	1.20	12.09
	9	48.14	10	1.20	12.08
	10	48.12	10	1.20	12.06
Averaged		48.19	10.00	1.21	12.10

Table 4. Result of Test with RLoad = 4.7 ohm

		Vin (V)	RLoad (ohm)	ILoad (A)	Vout (V)
Test Number	1	48.17	4.7	2.57	12.07
	2	48.17	4.7	2.57	12.06
	3	48.18	4.7	2.57	12.06
	4	48.15	4.7	2.57	12.06
	5	48.11	4.7	2.56	12.04
	6	48.18	4.7	2.57	12.06
	7	48.17	4.7	2.57	12.06
	8	48.18	4.7	2.56	12.04
	9	48.11	4.7	2.56	12.04
	10	48.18	4.7	2.57	12.06
Averaged		48.16	4.70	2.56	12.06

Table 5. Result of Test with RLoad = 2.2 ohm

		Vin (V)	RLoad (ohm)	ILoad (A)	Vout (V)
Test Number	1	48.00	2.2	5.46	12.01
	2	48.01	2.2	5.46	12.01
	3	48.01	2.2	5.46	12.01
	4	48.01	2.2	5.46	12.01
	5	48.02	2.2	5.46	12.00
	6	48.01	2.2	5.46	12.01
	7	48.01	2.2	5.48	12.06
	8	48.04	2.2	5.46	12.02
	9	48.00	2.2	5.46	12.00
	10	48.02	2.2	5.46	12.01
Averaged		48.01	2.20	5.46	12.01

Table 6. Summary (Rload = 10 ohm, 4.7 ohm and 2.2 ohm)

Vin (V)	Rload (ohm)	Iload (A)	Vout (V)
48.19	10.00	1.21	12.10
48.16	4.70	2.56	12.06
48.01	2.20	5.46	12.01

VII. Conclusion

The low-power step-down DC/DC converter has been developed and successfully produces the intended output voltage with high stability. The result produced by this work can be a solution to the same requirement (48VDC to 12VDC conversion) out of many contexts, not limited to the application for electric cars.

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APPENDIX A
PHOTOGRAPHS OF RINUS C1 ON ROAD

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