Application of 6A05G Power Diodes in a Simple Yet Effective Voltage Adapter Module for Electric Cars

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Abstract

Some types of electric cars use 48V battery. The Rinus C1, the one we developed, uses six eight-volt-battery units connected in series. As this battery's voltage level is higher than the level needed by electrical / electronic devices in the car, a DC/DC converter or a voltage adapter is therefore required. In our case 12V voltage supply is required by the car lightings, electromagnetic door openers, a tablet PC and a multi-purpose USB charger. We have previously developed an efficient 48V/12V switched-mode DC/DC converter however an issue has been recognized: the complexity of on-board cabling of our circuit (although not so complex) rose the risk of module malfunction due to unintended cable displacement by a technician during the eCar assembly and maintenance. Having studied the case, we come to an idea that a simple voltage adapter may fit the need better. For this aim a general-purpose power-diode is predicted to be a good choice for the voltage dropping task considering its current capacity suitability to our client's requirement and its wide availability in the market. The current-voltage characteristics of a power diode (6A05G) is studied. Based on the data obtained, a simple voltage adapter module is successfully developed using a series of diodes as voltage droppers. The module is now used in the car. In addition to that, the module simplicity implies easier, faster and cheaper development.

Keywords

Voltage adapter, DC/DC converter, electric car, Mohammad Nasucha

1. Introduction

An electric car usually uses a battery bank with a voltage suitable for the motor and its controller but too high for the rest of the system. The eCar LED lighting, door openers, GPS device and other gadget(s) usually need 12V voltage. Thus, a DC/DC converter or a voltage adapter is required.

For the Rinus C1, the eCar we built, we previously developed a DC/DC converter module and it worked well. However an issue occurred: the complexity of on-board cabling of our circuit (although not so complex) rose the chance of module malfunction due to unintended cable displacement by a technician during the car assembly. Similar situation happened also during eCar maintenance activities. In our case, it happened that the module technically malfunctioned twice for the last two years. Having studied the case, we came to an idea that a simple voltage adapter should fit the need better. In conjunction to its behavior in dropping voltage, a power diode is predicted to be suitable for the task. The questions become: (i) Is it confirmed that the 6A05G power diodes are able to fit the needs of voltage dropping? (ii) If the answer of question number 1 is yes then can we make a practical and simple voltage adapter module using that diodes?

2. Previous Works versus The Proposed Alternative

It has been proven that the application of switching technique in voltage conversion circuits results in high efficiency. Voltage converters applying this technique have been widely used in many kind of machines or devices, both for industrial and personal uses. Research and development works on the switching concepts and techniques for different supply purposes have been continuing.

In the area of large power DC/DC conversion, the following research works were reported, among others. A research work was reported in (Bai, H. et al. 2012) where they proposed power factor correction for an 11 kW and 10 kW ZVS DC/DC converter for a high-efficiency battery charger in electric vehicles. A research work was also reported in (Andreiciks et al. 2013) where they designed a current source DC/DC converter for Interfacing a 5 kw Pem Fuel Cell.

In the area of small power DC/DC conversion, among others, the following writings addressed the research works that have been carried out. (Hansen and Hill 2000) reported switching regulator charges NiMH Batteries. (Chan-Soo et al. 2011) reported a low-power CMOS DC-DC buck converter with on-chip stacked spiral Inductor. (Fang et al. 2013) addressed the design of a step-down DC-DC converter ASIC applied to portable electronic products. (Mikic et al. 2015) reported the design and characterization of a step-down switched-mode power converter based on the regulator MC34063A. While (Nasucha 2016) addressed the development of a low-power step-down DC/DC converter module for electric cars.

In the area of conception, among others, the following research works were reported. DSP microcontroller-based fuzzy control of a DC/DC parallel resonant converter using phase-shift PWM technique was reported in (Iskender et al. 2006). While a mathematical modelling and analysis of transient and steady states of buck DC-DC converter in DCM was reported in (Babaei and Hamed 2013).

Due to its contribution to high efficiency the switching mode concept has been a favorable choice. Within our project of building an eCar (called Rinus C1), the switching mode concept has been also applied in the first place. A small power switching-mode DC/DC step-down converter module has been developed and used for the eCar for a while. However during the installation and car maintenance this situation was observed: (i) our circuit contained several onboard cables that connected the IC to the power transistors, (ii) during the installation the technician unintentionally broke some of those onboard cables causing circuit malfunction, (iii) during a car maintenance an unintended cable short circuit happened when a solid material was displaced across the converter module. In other words, the module complexity –although it is not so complexed– raised the chance of accidental malfunction.

Having faced the issue, in our case, it is then required to find out an effective solution. There are basically at least three way outs that can be chosen: (i) redesigning the switching-mode circuit so that it will be physically simpler and tidier, (ii) protecting the circuit (module) with a proper case, or (iii) designing and developing the circuit using other technique that allows simplicity.

The first or second solutions surely can be done as long as time permits. However the third choice is literally more challenging in the way that it can be an alternative for future practice. The fact that a diode drops voltage when it flows a forward current is here presumed to be the focal solution. Although it will result in lower conversion efficiency, the solution may still fit the need for a small power voltage converter because the energy loss will be somehow relatively small.

The 6A05G silicon power diode is here predicted to be a good choice considering that its forward current capacity suits client's requirement and that it is widely available in the market. Its price in the market is also inexpensive. For example its price on tokopedia.com in Indonesia today is more or less Rp1000 (8 cent in USD) per piece.

3. Method and Materials

Method applied and the material involved in this work are described in the following sub sections.

3.1. Method

The work has two goals: (a) to be confirmed that the 6A05G diode is a suitable voltage dropper for the simple voltage adapter module required, and (b) to have the module developed and ready to use. Therefore the whole work will consist of: (i) recognizing the client's requirement, (ii) learning and elaborating the 6A05G's relevant properties, (iii) obtaining actual diode's property values (data) through measurements, (iv) if actual data supports the hypothesis, then proceed with module design and development, and (v) testing the module.

3.2. Materials

The main component is the 6A05G power diode. If the actual measurements on this diode resulted in a confirmation on the hypothesis, the following components would be required to proceed with module development: resistors, fuses, switches, input terminals, main output terminals and a USB output socket. Measurements for both the diode and the module will be carried out using a digital ampere meter and voltmeter.

4. Determining Device Specifications

The client determined how the eCar would work and look, including what devices to be operating in the car. The researcher / designer then translates it into the device specifications for the Voltage Adapter Module in this regards.

4.1. Load Current Planning

Because the new module will be placed in the same eCar, with the same load situation, the previous load current planning applies. This is here re-shown by Table 1.

4.2. Module Main Specifications

In our previous work the module was to be connected to the two poles of the battery bank (48V). However for this work a different approach is taken. Considering that the voltage dropping by the diodes will cause energy loss, the input voltage needs to be brought as low as possible; of course still it has to be higher than the intended output voltage. It is an advantage that the battery bank has a number of terminals (as it consists of six 8-volt batteries) that it can actually serve several voltage values: 8, 16, 24, 32, 40 and 48 volt. Thus, it is decided to supply the module with 16 volt as it will cause least energy loss while it is still higher than the intended output voltage (12V).

The output voltage of the module is to be 12V, as required by the loads: LED lamps and door openers, GPS device, tablet PC, and mobile phone. The Voltage Adapter Module here developed will provide the same voltage (12V) for those as mentioned gadgets through a standard cigarette lighter socket. It means that the gadgets will require their standard 12V/5V converters.

In other words the Voltage Adapter Module is here to be designed based on the same load current planning as the one used in the previous work. It means that the module has to provide up to 5A continuous current at 12V. Table 2 shows this specifications.

4.3. Fuse Specifications

The input current fuse is therefore specified at 5A. The total capacity of the output fuse should ideally equal 5A. However as the output line is split into 4 lines (1.5 A for LED lamps, 1.5A for door openers, 0.65A for cigarette lighter 1, 0.65A for cigarette lighter 2 and another 0.65A for cigarette lighter 3), there should be a practical approach for the situation. Considering also common availability in the market it is decided to use 2A, 2A, 1A, 1A, 1A fuses for the as mentioned lines subsequently. This specifications is shown by Table 3.

Table 1. The load current planning, the same as the one documented in Nasucha (2016), applies.

Load	Charger Rated Output Power	Max. Current at 12V
All LED lamps	18W at 12V	18W / 12V = 1,5A
Door openers	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

Table 2. The Module Main Specifications

Input	Output
Vin = 16V	Vout = 12V; Iout = 5A (max)

Table 3. Fuse Specifications

Input Fuse	Output Fuses
Input Fuse: 5A	Output Fuse 1: 2A Output Fuse 2: 2A Output Fuse 3: 1A Output Fuse 4: 1A Output Fuse 5: 1A

5. The 6A05G's Relevant Properties

Research works on applications of diodes were reported although not specifically addressed their nature of dropping voltage. Application of 1200V-8A SiC JBS diodes in the motor system was reported in (Liu et al. 2013). Whereas characteristics and applications of silicon carbide power devices in power electronics was reported in (Kondrath and Kazimierczuk 2010).

As mentioned the 6A05G is predicted to be a good choice considering: (i) that its forward current capacity is suitable for the module requirement, and (ii) that it is widely available in the market. The current-voltage characteristics of this type of diode is explained in (Datasheet 2016) and here presented by Figure 1. The curve actually presents an exponential mathematical function that will show itself as a raising curve if drawn on a linear-scaled area. It is depicted by Figure 2.

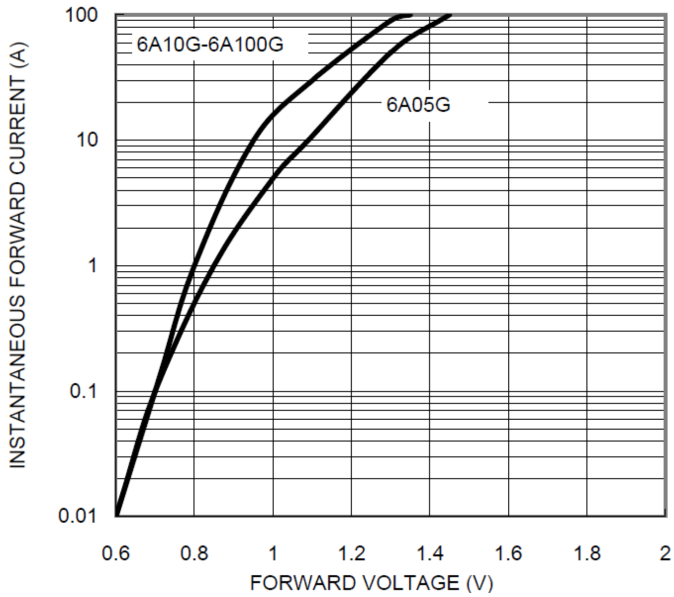


Figure 1. Forward current-voltage characteristics of 6A05G – 6A100G as depicted in (Datasheet 2016). It is shown that the diode starts flowing current when the anode-cathode voltage is around 0.6 volt. The more voltage applied the more current flows, in other words the more current to be flown by the diode the more voltage drops between its anode and cathode. The curve here is drawn on an algorithmic-scaled area.

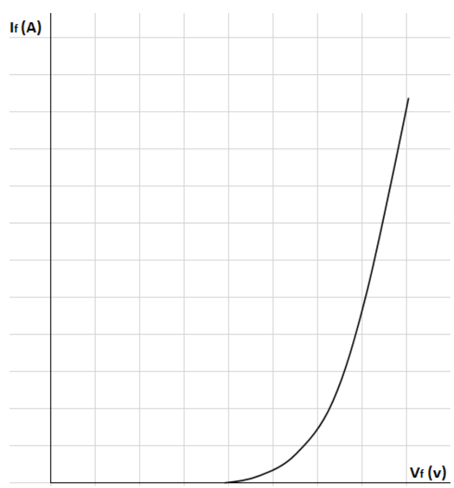


Figure 2. Forward current-voltage characteristics curve of a diode when drawn on a linear-scaled area.

As the information about 6A05G current-voltage characteristics is provided by the datasheet only in graph, the only way to find out the relation between current and voltage at a certain value is doing visual interpolation. This way is shown in Figure 3 whereas the results of this estimation are shown in Table 4. However the real values of voltage for chosen values of current will be known from measurements.

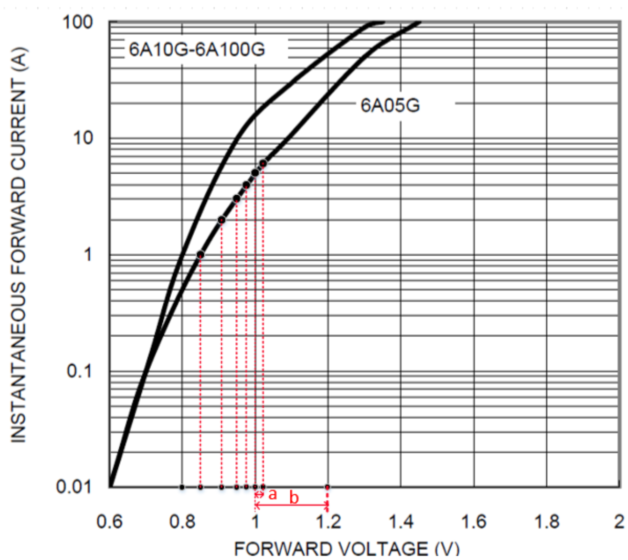


Figure 3. Estimating value of forward voltages for particular forward current values through interpolation.

Table 4. Estimated values of forward voltages for particular forward current values through interpolation as depicted in Figure 2.

Forward Current (A)	1.00	2.00	3.00	4.00	5.00	6.00
Forward Voltage (v)	0.85	0.91	0.95	0.98	1.00	1.02

6. Results of The 6A05G Measurement and Discussion

The diode alone was tested. Voltage between anode and cathode was measured for a certain amount of current. For the same current value the measurement were done ten times. The measurement were done for current = 1A, 2A, 3A, 4A, 5A and 6A. The results are shown by Table 5.

Table 5 shows actual forward voltage against forward current at particular values: 1A, 2A, 3A, 4A, 5A and 6A. The diode was supplied with the defined amount of current for 3 minutes –to approach real operational situation where it is heated up– then the anode-cathode voltage was read. The current source was then switched off for another 3 minutes to let the diode cool down. It was then switched on again for the next 3 minutes for the next voltage reading. The cabling was kept untouched during the whole measurement to ensure connection consistency. The room temperature was set around 25’C.

From the results shown, it is found that the drop voltage at the diode rises with the flowing current. The relation between voltage and current is positive but not linear. The portion of voltage increase is less than the portion of the current increase. This current-voltage characteristics is at the same tendency at the one expressed by Figure 2. However the most important message for the project is that these actual diode’s drop voltage data will be useful for predicting the total drop voltage that will happen in the module if a certain number of diodes are placed in series.

Table 5. This shows actual forward voltage against forward current of 6A05G at room temperature of 25'C ; current and voltage were read after 3 minute conduction.: (a) Current = 1A, (b) Current = 2A, (c) Current = 3A, (d) Current = 4A, _(e) Current = 5A, (f) Current = 6A. The diode was let off the current for 3 minutes before doing the next conduction. For this purpose the power supply was switched on and off while the junctions of the cables were kept untouched during the whole measurement process to ensure connection consistency.

Test No.	Continuous Forward Current (A)	Continuous Forward Voltage (V)
1	1	0.90
2	1	0.91
3	1	0.91
4	1	0.91
5	1	0.91
6	1	0.91
7	1	0.91
8	1	0.91
9	1	0.91
10	1	0.92
	Averaged	0.91

(a)

Test No.	Continuous Forward Current (A)	Continuous Forward Voltage (V)
1	2	0.96
2	2	0.97
3	2	0.97
4	2	0.97
5	2	0.97
6	2	0.97
7	2	0.97
8	2	0.97
9	2	0.98
10	2	0.98
	Averaged	0.97

(b)

Test No.	Continuous Forward Current (A)	Continuous Forward Voltage (V)
1	3	1.01
2	3	1.02
3	3	1.02
4	3	1.02
5	3	1.02
6	3	1.02
7	3	1.02
8	3	1.02
9	3	1.03
10	3	1.03
	Averaged	1.02

_(c)

Test No.	Continuous Forward Current (A)	Continuous Forward Voltage (V)
1	4	1.04
2	4	1.05
3	4	1.05
4	4	1.05
5	4	1.05
6	4	1.05
7	4	1.05
8	4	1.05
9	4	1.05
10	4	1.06
	Averaged	1.05

(d)

Test No.	Continuous Forward Current (A)	Continuous Forward Voltage (V)
1	5	1.06
2	5	1.07
3	5	1.07
4	5	1.07
5	5	1.07
6	5	1.07
7	5	1.07
8	5	1.07
9	5	1.07
10	5	1.08
	Averaged	1.07

_(e)

Test No.	Continuous Forward Current (A)	Continuous Forward Voltage (V)
1	6	1.08
2	6	1.08
3	6	1.09
4	6	1.09
5	6	1.09
6	6	1.09
7	6	1.09
8	6	1.09
9	6	1.09
10	6	1.09
	Averaged	1.09

(f)

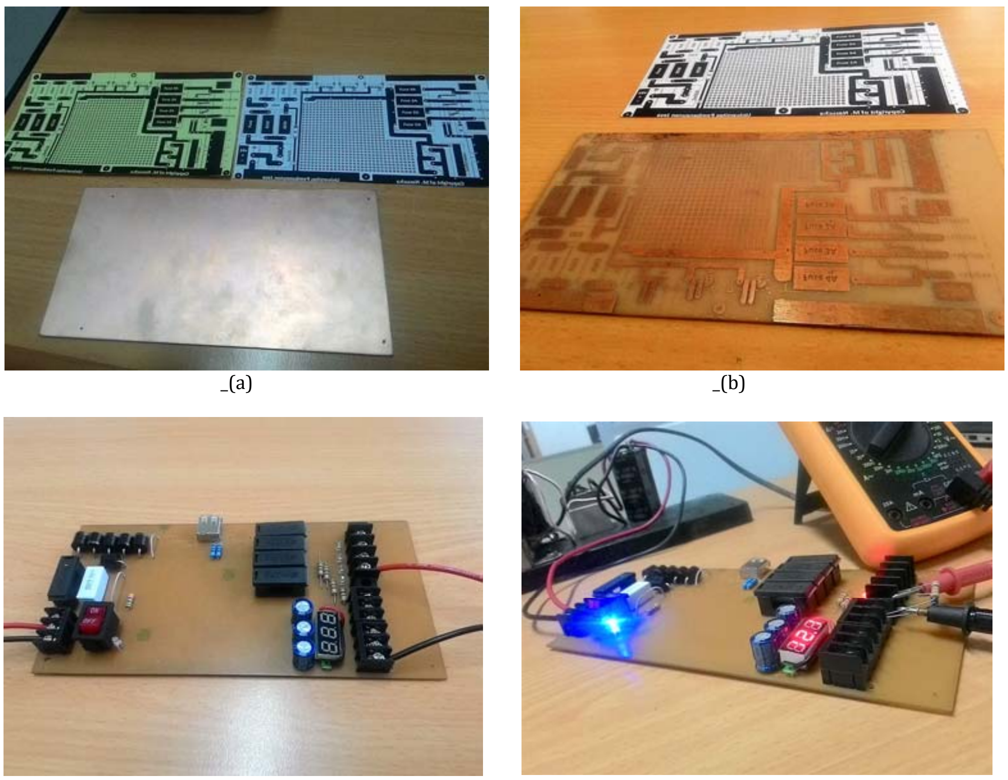
Table 6. Voltage predictions for the voltage adapter module that will be developed using the actual data of the Table 5. Actual voltage exists at the second cell of the battery bank usually slightly higher than 16V thus it is approached with 16.6V.

Load Current (A)	Diode's Individual Drop Voltage (V)	Predicted Total Drop Voltage (V) for			Predicted Module Output Voltage If Input Voltage = 16.6V		
		4 Diodes	5 Diodes	6 Diodes	4 Diodes	5 Diodes	6 Diodes
1	0.91	3.64	4.55	5.46	12.96	12.05	11.14
2	0.97	3.88	4.85	5.82	12.72	11.75	10.78
3	1.02	4.08	5.10	6.12	12.52	11.50	10.48
4	1.05	4.20	5.25	6.30	12.40	11.35	10.30
5	1.07	4.28	5.35	6.42	12.32	11.25	10.18
6	1.09	4.36	5.45	6.54	12.24	11.15	10.06

Based on those data, voltage predictions for different options are made and shown by Table 6. A number of diodes are to be placed on board in series. Considering that the required output voltage is around 12V, the application of four diodes is then chosen in order to provide the closest value.

7. Result of The Module Development and Discussion

Taking into account the positive findings as discussed in Chapter 6, the 6A05G diodes have been applied for the 18Vdc to12Vdc voltage adapter module. Four diodes are placed in series. Through a development cycle the module was then finished and ready to test. Figure 4 shows the stages of the development and the test.



_(a) _(b)

_(c) _(d)

Figure 4. Some photographs taken in the development cycle and the testing: (a) after completion of PCB layout design, (b) after the etching, (c) after the completion of assembling, and (d) when the module was being tested. There are six diodes shown in the picture, two of them are actually being short-circuited (unused). A small modification was also made for the output terminals: USB terminal was provided for the phone charger along with protection resistors.

Upon the completion of the module development, measurements were carried out in operation mode. The results of the measurement are shown in Table 7. It is found that module's output voltage varies with the load current, as predicted.

The voltage decreases when the load current increases. When the current ranges at 1 to 6A the output voltage will range at 12.80 to 11.42V. These values are lower than the prediction (see Table. 6 for the 4 diode option), logically caused by existence of other drop voltages at the protection resistor and at the line on the PCB. Considering that the real requirement –that the devices on the eCar have enough tolerance for the operating voltage– this voltage adapter module would fit the need.

Table 7. The table shows module's output voltage at different loads: (a) I = 1A, (b) I = 2A, (c) I = 3A, (d) I = 4A, (e) I = 5A, and (f) I = 6A at room temperature of 25'C. Four 6A05G diodes were placed in series and the whole onboard circuit resistance was around 0.1 ohm. The values were read when the module was operating for 3 minutes. The current supply to the module was cut for 3 minutes before doing the next operation. The junctions of the cables were kept untouched during the whole measurement process to ensure physical consistency.

Test No.	Load Current (A)	Input Voltage (V)	Output Voltage (V)
1	1	18.36	12.79
2	1	18.36	12.79
3	1	18.36	12.80
4	1	18.36	12.80
5	1	18.36	12.80
6	1	18.36	12.80
7	1	18.36	12.80
8	1	18.36	12.80
9	1	18.36	12.80
10	1	18.36	12.81
	Averaged output voltage =		12.80

(a)

Test No.	Load Current (A)	Input Voltage (V)	Output Voltage (V)
1	2	18.36	12.39
2	2	18.36	12.40
3	2	18.36	12.40
4	2	18.36	12.40
5	2	18.36	12.40
6	2	18.36	12.40
7	2	18.36	12.40
8	2	18.36	12.40
9	2	18.36	12.40
10	2	18.36	12.40
	Averaged output voltage =		12.40

(b)

Test No.	Load Current (A)	Input Voltage (V)	Output Voltage (V)
1	3	18.35	12.01
2	3	18.35	12.01
3	3	18.35	12.02
4	3	18.35	12.02
5	3	18.35	12.02
6	3	18.35	12.02
7	3	18.35	12.02
8	3	18.35	12.02
9	3	18.35	12.02
10	3	18.35	12.02
	Averaged output voltage =		12.02

(c)

Test No.	Load Current (A)	Input Voltage (V)	Output Voltage (V)
1	4	18.35	11.81
2	4	18.35	11.82
3	4	18.35	11.82
4	4	18.35	11.82
5	4	18.35	11.82
6	4	18.35	11.82
7	4	18.35	11.82
8	4	18.35	11.82
9	4	18.35	11.82
10	4	18.35	11.82
	Averaged output voltage =		11.82

(d)

Test No.	Load Current (A)	Input Voltage (V)	Output Voltage (V)
1	5	18.34	11.59
2	5	18.34	11.60
3	5	18.34	11.60
4	5	18.34	11.60
5	5	18.34	11.60
6	5	18.34	11.60
7	5	18.34	11.60
8	5	18.34	11.60
9	5	18.34	11.60
10	5	18.34	11.60
	Averaged output voltage =		11.60

(e)

Test No.	Load Current (A)	Input Voltage (V)	Output Voltage (V)
1	6	18.34	11.41
2	6	18.34	11.42
3	6	18.34	11.42
4	6	18.34	11.42
5	6	18.34	11.42
6	6	18.34	11.42
7	6	18.34	11.42
8	6	18.34	11.42
9	6	18.34	11.42
10	6	18.34	11.42
	Averaged output voltage =		11.42

(f)

The module has been installed onto the eCar successfully and the eCar is currently in normal operations as usual. Several machine maintenance activities have been also carried out and there has been no trouble with the module this far.

8. Conclusions

The drop voltage values of a 6A05G diode for different forward current values have been measured in this work. A simple voltage adapter module has been then developed using four diodes that are placed in series. The output voltage of the module is not stable, it decreases when the load current increases. However the module still fits the need. The module offers less physical complexity and therefore is expected to reduce the chance of unintended electrical incident during its installation and maintenance. The extra advantage includes the fact that the module can be developed faster, easier and less costly.

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