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1. M.S. ALI [1,2], 2. Mahidur R SARKER [3,4], 3. Ahmad ASRUL IBRAHIM[1], 4. Ramizi MOHAMED[1]

[1] Department of Electrical, Electronics and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia;
[2] Electrical Engineering Department, German-Malaysian Institute , Jalan Ilmiah, Taman Universiti,43000, Kajang, Selangor, Malaysia
[3] Institute of IR 4.0, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[4] Industrial Engineering and Automotive, Nebrija University, Campus de la Dehesa de la Villa, Calle Pirineos, 55, 28040 Madrid, Spain
ORCID. 1. 0000-0001-7142-7755, 2. 0000-0002-5363-6219, 3. 0000-0003-4997-3578, 4. 0000-0003-1534-6760

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A High Gain Variable Boost DC-DC Converter for Low-Voltage Hybrid Direct Methanol Fuel Cell Batteries

***Abstract**. Direct Methanol Fuel Cells (DMFCs) are emerging as primary power sources for portable applications due to their high energy density, easy-to-handle liquid fuel, and low temperature. They have a longer cell lifetime and are small and lightweight. However, there are several problems associated with typical DMFCs due to their slow dynamic response, long start-up time, and issues related to their unregulated low-level output voltage and current. This study describes the development of a DC-DC converter for a low-voltage (i.e., less than 5 V) DMFC. This study also presents a hybrid power source that consists of a battery and a DMFC and analyses, via software simulation, every component of the boost converter that influences its output. The proposed DC-DC converter is capable of boosting the voltage of the DMFC from 3 V to 60 V. The output voltage of this converter is regulated and applied to an LED lamp.*

Streszczenie.** Ogniwa paliwowe z bezpośrednim metanolem (DMFC) stają się coraz ważniejszym źródłem zasilania w zastosowaniach przenośnych ze względu na ich wysoką gęstość energii, łatwe w obsłudze paliwo ciekłe i niską temperaturę. Mają dłuższą żywotność ogniw i są małe i lekkie. Istnieje jednak kilka problemów związanych z typowymi DMFC ze względu na ich powolną reakcję dynamiczną, długi czas rozruchu oraz problemy związane z ich nieregulowanym napięciem i prądem wyjściowym niskiego poziomu. Niniejsze badanie opisuje rozwój konwertera DC-DC dla niskonapięciowego (tj. poniżej 5 V) DMFC. W niniejszym opracowaniu przedstawiono również hybrydowe źródło zasilania, które składa się z akumulatora i DMFC oraz analizuje, za pomocą symulacji programowej, każdy element przetwornicy doładowania, który wpływa na jego moc wyjściową. Proponowana przetwornica DC-DC jest w stanie podnieść napięcie DMFC z 3 V do 60 V. Napięcie wyjściowe tej przetwornicy jest regulowane i podawane na lampę LED.* (Przekształtnik DC-DC o zmiennym wysokim wzmocnieniu do niskonapięciowych hybrydowych akumulatorów ogniwem paliwowym z metanolem***)

Keywords: Direct methanol fuel cell, hybrid direct methanol fuel cell, DC-DC converter.
Słowa kluczowe: przekształtnik DC-DC, ogniowo paliwowe, .

Introduction

Portable electronic devices are important necessities of modern life. Devices such as portable lamps, super torch lights, and other portable electronics need power sources to operate. Therefore, the power source is one of the most important components in a portable application. For a long time, rechargeable batteries were the main power sources used in portable devices. However, they have several limitations, which include a short lifespan, a low power density, and a long charging time.

Recently, it is widely accepted that fuel cells overcome these limitations and can continuously generate power as long as fuel and oxygen are supplied to the cells [1][2][3][4]. The best candidate for portable applications is the direct methanol fuel cell (DMFC). The advantages of DMFCs are their higher energy density and longer lifespan compared to rechargeable batteries. In addition, the operating temperature is lower than that of other fuel cell technologies, and DMFCs can be designed to enable quick and easy fuel cartridge replacement. The potential of DMFCs to replace batteries as power sources are high because DMFCs' fuel source (methanol) theoretically has superior specific energy density [5][6][7].

However, the battery and fuel cell can work together: the battery becomes a temporary energy storage element to support the fuel cell during start up and sudden load changes because the fuel cell's transient response to abrupt load changes is poor [8][9][10]. The DMFC has a high energy density, and a battery has a high power density. Thus, combining these two density characteristics yields the best performance in a fast, robust system. In a hybrid system, the battery type is either lithium-ion or lead-acid of the two battery types, lithium-ion batteries have a better energy density than acid batteries [11].

Considering that a fuel cell has a relatively slow response, a secondary energy storage component such as a battery is needed to maintain system voltage during transient events and at start-up. However, this energy storage topology requires additional control circuitry to manage the power flow operations under charging and discharging conditions [12]. The output power of the system should be smooth and constant. A secondary energy source (i.e., a battery) is used to smooth the output power during operation because the converters used in the system operate at a constant voltage.

Generally, fuel cells produce an unregulated DC output voltage, and a DC-DC converter is required to regulate the output voltage to the desired value. Usually, a boost converter is used to step-up the output voltage of the fuel cell at the optimum value by charging the temporary energy storage component in the portable application. In addition, by using a DC-DC converter interface between a fuel cell and the load, the current's slew rate and ripple can be reduced [13][14][15]. With respect to commercial viability, the product's cost of goods is a concern and will influence the end user's price. To reduce the cost of the product, the number of components used in the system should be keep to a minimum, but maintaining optimal system efficiency is of paramount importance. The size and weight of the product are also important and must be suitable for portable applications.

In conclusion, the main problem with DMFCs is that they cannot be used with any portable device if their output voltage and current are below 5 V and 890 mA, respectively. Normally, the output of a DMFC is unregulated, unstable, and exhibits current ripple. Incorporation of a suitable power conditioning circuit can improve the output characteristics of a DMFC. The problem associated with the low output voltage and current of the DMFC can be solved by implementing a hybrid-powered DC-DC converter between the DMFC and battery. The battery can be used to power the pulse width modulation circuit controlling the switching element of the DC-DC converter, while the output of the DMFC becomes the input to the DC-DC converter. The variable boost converter, along with its filtering element, provides suitable power conditioning to improve the voltage and current output of the DMFC in addition to providing a simple circuit to reduce power loss. With this implementation, the output voltage can be stepped up according to the load, and as a result, the output current will be more stable. However, no prior research has been published on the creation of a variable boost converter for the low voltage hybrid DMFC. Thus, this study proposes a novel variable boost converter for the low voltage DMFC/battery hybrid that is relatively low cost and has size and weight characteristics suitable for portable applications. The proposed topology can step-up the low voltage from the fuel cell, and the output voltage can be regulated to any desired voltage to operate an LED lamp that requires up to 60 V.

A Review of Hybrid Fuel Cell and Battery Topologies for Portable Applications

Hybrid sources can combine the high power density of batteries with the high energy density of fuel cells to improve the runtime of portable electronic devices. As shown in Figure 1, the synchronous boost converter is connected to the fuel cell to boost the voltage output from that cell up to DC-bus voltage levels (typically 3.3 V for electronic devices) [16]. In real applications, a fuel cell normally consists of four to six stacks that are connected in series to attain acceptable input voltage levels on full load (2-2.4 V). On the battery side, the H-bridge buck-boost converter is employed to manage charging and discharging of the battery. This H-bridge buck-boost converter is combined with analog circuitry that allows this converter to be operated as either a buck converter when the battery is fully charged or a boost when the battery is nearly discharge.

A complete active hybrid DMFC system combines a DMFC stack and a Li-ion battery to share the applied load and exploit the high energy density of the fuel cell and the superior power density of the battery. This system is a significant step towards bringing the next generation of portable energy sources in step with modern electronic design automation. A conventional battery charger hybridization circuit relies on the battery as a primary power source. The DMFC stack operates only when charging the battery. The system operation begins with the DMFC stack charging the battery, and then the battery discharges to satisfy the demand of the load. Then, two diodes are configured in the circuit such that the current from the DMFC only goes to the output regulation converter. Additional current for this system is supplied by the battery. This supplementary current goes through three converters: the battery charger, the battery output converter, and the output regulation converter [17].

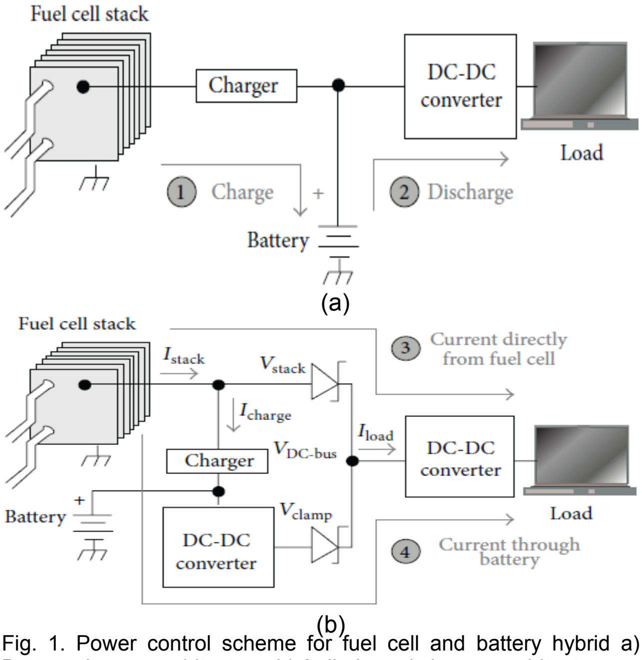

Fig. 1. Power control scheme for fuel cell and battery hybrid a) Battery charger architecture, b) 2-diode and charger architecture.

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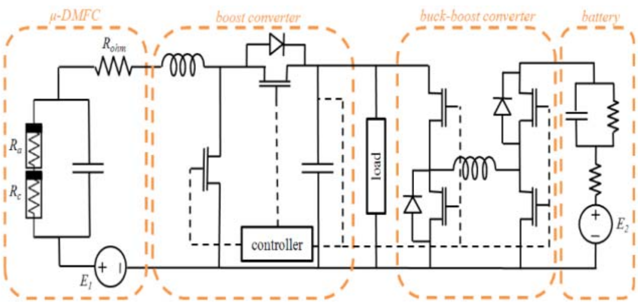

Fig. 2. A hybrid DMFC/Battery circuit [].

Designing the Boost Converter

Basic Design of the Boost Converter

The basic construction of a boost converter circuit normally consists of an inductor *L* as the storage device, a transistor as a switching device *S*, a diode *D* to ensure current only flows in one direction, and a capacitor C used to limit the output ripple and load resistance R, as shown in Fig 3 below [19][20]. The design of the boost converter needs to consider the current conduction mode, input and output voltages, input and output currents, output ripple and component rating. Basic design normally starts with a detailed calculation of every value of the components to be used in order to produce the desired output voltage. Selection of the suitable frequency range for the PWM is also considered in the calculation [21].

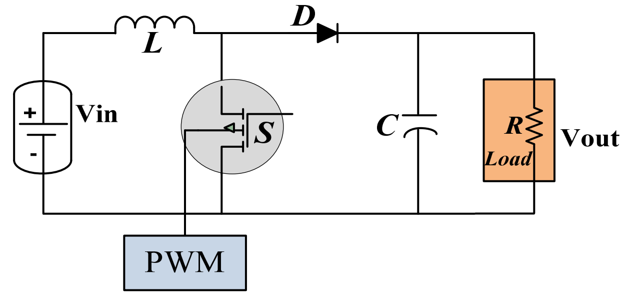

Fig. 3. Conventional boost converter.

Selection of the Inductor

Inductor is the main component needed to boost the voltage. Without inductor the voltage cannot be boosting. Large induction needed for high voltage gain boost converter and its increase the start-up time. Normal inductor used for boost converter is inductor with ferrite core and low DC resistance along the coil to ensure saturation current rating for highest efficiency. The selection of induction value for boost converter, Lc, is normally refer to the relationship between minimum duty cycle, D, maximum input voltage, V_i, equivalent load, R, and switching frequency, F_s. This relationship is defined as:

(1) $$Lc = R*D\,(1-D)^2/2*Fs \quad \text{H}$$

Selection of the Diode

First element must be consider in diode selection is the power rating of the diode. The power rating of the diode must be equivalent to the power of boost converter. If the diode with low power rating, then the diode unable to handle the reverse output voltage of the boost converter and become damage. Other element need to be consider are fast switching characteristic, low reverse-recovery and low power lost. These diode characteristic can be achieve depend to the manufacturer because difference manufacturer will produce different quality of the diode.

Selection of the Capacitance

The capacitor used to stabilize and achieve the desire boost voltage. So, the value need to be consider in capacitor selection are the value of capacitance, F, and the value of capacitor voltage. The value of the farad will affect the charging and discharging time of the capacitor. The smaller farad will give faster charging and discharging. Besides that, the value of the capacitor voltage must be equivalent with desire boost voltage. If the capacitor voltage lower than desire boost voltage, then the desire voltage never achieve. Other criteria for selecting the capacitor is its capacitance and equivalent series resistance, ESR, must be lower as possible because it's influenced the efficiency and the performance of boost converter. To reduce ESR, it is also possible to connect capacitors in parallel and output filter capacitors are also chosen to meet the output voltage ripple [22].

Proposed Topology Description

Fig 4 shows the block diagram for the overall topology of the proposed variable boost converter for the DMFC/battery hybrid system. This topology consists of two power sources (i.e., the fuel cell and the battery). The DMFC is the primary power source to the buck-boost converter, and the battery acts as a secondary power source and supplies power to the PWM circuit. The second stage of this topology is a variable boost converter. This variable boost converter is used to step-up the DC voltage from the fuel cell to drive the load. The power from the battery is used to power the PWM circuit because the battery's voltage is more stable, and its transient response is faster than that of the DMFCs. Additionally, the variable PWM is used to regulate the boost converter, and output voltage is dependent on the load.

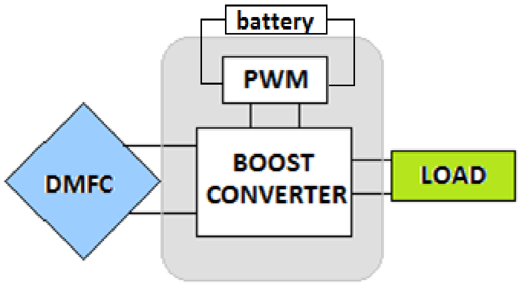

Fig. 4. Overall system topology.

Fig 5 illustrates the construction of the variable boost converter. Open loop control is deployed in this system. The DMFC stack produces almost 3 V, which is supplied as an input voltage to the boost converter. Two DMFCs were connected in parallel and used in this system to increase the current stability. The purpose of this boost converter is to step-up the voltage from the DMFC and to provide an optimum voltage for the load. When the power MOSFET $Q1$ is conducting, current is drawn through the inductor, thereby storing energy in that inductor. When the power MOSFET $Q1$ stops conducting, the inductor's voltage "flies back", or reverses, because the current through the inductor cannot change instantaneously. The voltage across the inductor increases to a value that is higher than the combined voltage across the diode and the DMFC. Once that combined voltage is exceeded, the diode starts conducting and the voltage across the capacitors becomes greater than the input voltage. There are four small (4.7 μF) capacitors connected in parallel that are used in the boost converter circuit to stabilize the voltage and reduce ripple current. There is also a diode used in this circuit to ensure that current flows exclusively in one direction.

Additionally, the resistor and super LEDs act as loads in this circuit, which also contains capacitors. The power MOSFET $Q1$ is controlled by the PWM circuitry and functions as a switching transistor for the variable boost converter. These PWM circuits will operate at up to 1 kHz, which can control the switching of the power MOSFET $Q1$, thus enabling the variable boost converter capability. The PWM frequency influences the charging rate of the capacitors. This PWM circuit is powered by 9 V battery. Thus, there are no problems with the PWM circuits at start-up, but the transient response of the DMFC is slow during that period. The specifications of the DMFC are as follows:

- Number of cells for one stack: 6
- Voltage per cell: 0.6 V nominal, 0.4 V minimum
- Voltage of each stack: 3.6 V nominal, 3.0 V minimum
- Current of each stack: 200 mA nominal, 100 mA minimum

The DC-DC boost converter must meet the following requirements:
• Step-up voltage up to 60 V.
• Converter filtering using capacitors.
• The converter is designed to maximize the power transferred to the capacitors by reducing components used in the circuit, which results in less power loss during operation.
• Regulation of the output voltage.

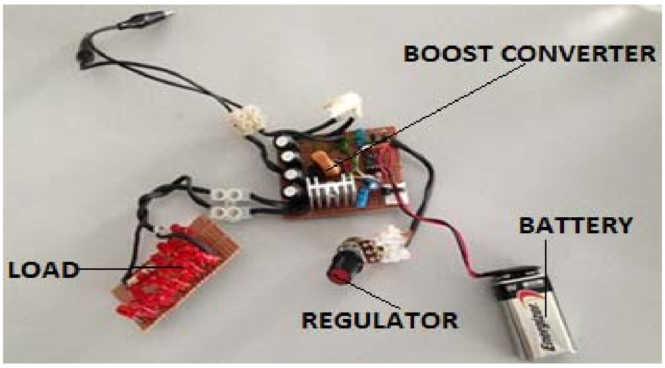

Fig. 5. Variable boost converter constructions.

The components used in the boost converter circuit are as shown in Table 1.

Table 1. Components list for boost converter

Component name	Value	Equipment quantity
Inductor	22H	1
Diode	100V	1
Power MOSFET	IRFZ44VPBF	1
Capacitor	4.7 µF	1
LED	Load	12
Battery cell	9V	1

The PWM is the main controller in this topology and is used in this project to control the switching elements for the boost converter. An IC NE 555 was utilized in this PWM circuit to provide a pulse with a regulated duty cycle. The output voltage of the boost converter is controlled by varying the duty cycle of the PWM. A TEKTRONIX digital oscilloscope with a bandwidth of 250 MHz was employed for the measurement of these pulses. The NE 555 timer used in the PWM circuit is configured as a stable oscillator. This means that once power is applied, the timer will oscillate without any external trigger. The 100 kΩ variable resistor was used to control the discharge signal from the timer. Fig 6 shows the PWM circuit configuration, and Fig 7 shows the overall system construction. The components used in the PWM circuit are shown in Table 2.

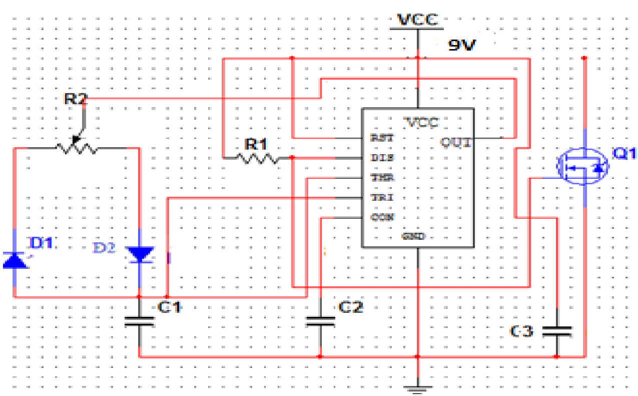

Fig. 6. Proposed sematic diagram of this system.

Table 2. Components list for pwm circuit

Component name	Value	Equipment quantity
IC	NE555	1
Resistor	10 kΩ~100 kΩ	1
Diode	100 V	1
Capacitor	1 µF	1

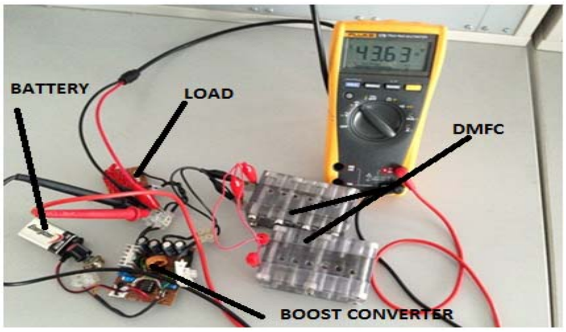

Fig. 7. Overall system connection and measurement.

Results and discussion

Simulation Analysis of the Boost Converter Components

Any change of components in the boost converter circuit, in terms of value or arrangement, will change the output of the boost converter. For this section, the influence of every components of the boost converter was analysed with the Multisim 10.1 software.

Influence of the Changed Arrangement of the Diode

In the basic construction of the boost converter, only one diode is used to ensure that the current flows in only one direction after switching. For this analysis, the single diode was replaced by four diodes, as shown in Figure 8. The analysis results show that the output voltage of the boost converter takes a longer time to reach the steady stage when using the four diodes. Fig 9 shows the output waveform of the output voltage of the boost converter when using both the single diode and four diodes. In rectifier applications, this type of circuit is known as a half-wave rectifier and full-wave rectifier. The output voltage for the single diode is larger than that of the four diodes, and the current also drops when using the four diodes.

Influence of Changing the Value and Arrangement of the Capacitor

In the boost converter circuit, the capacitor is the main component to reach and stabilize the output voltage at the desired voltage. The output voltage is dependent on the capacitor voltage value, and the farad value influences the stability of the output voltage. In this analysis, four conditions were chosen to show its influence on the output voltage. For the first condition, a comparison was made by using a single capacitor and varying the farad value between low and high. From the result shown in Fig 10 and Fig 11, the circuit used the higher farad value took longer to reach the steady stage. Using a lower farad value can give fast access to the steady stage, but it does produce more ripple. To improve this condition, the capacitors were arranged in parallel. Comparison between the lower and higher farad values was performed.

Three capacitors were connected in parallel in the circuit. The results show that the three capacitors with the low farad value were faster to arrive at the output voltage steady stage when compared to the higher farad value, which took too long. At a time of 180 ms, output for the lower farad value, as shown in Fig 12, had already reached almost 60 V; the output of the higher farad value, shown in Fig 13, was still at 40 V at that time.

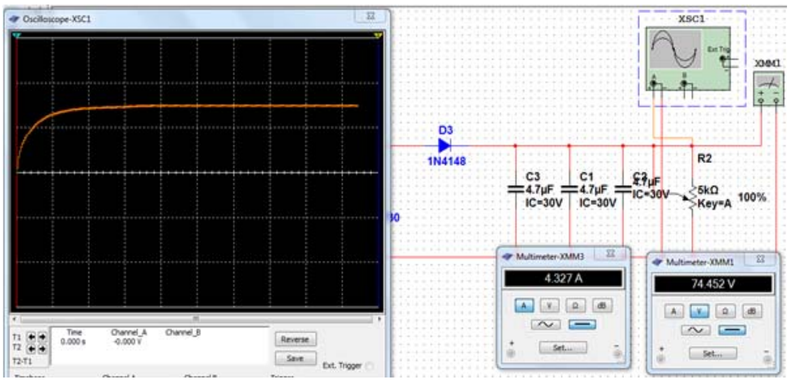

Fig. 8. Output voltage waveform by using single diode.

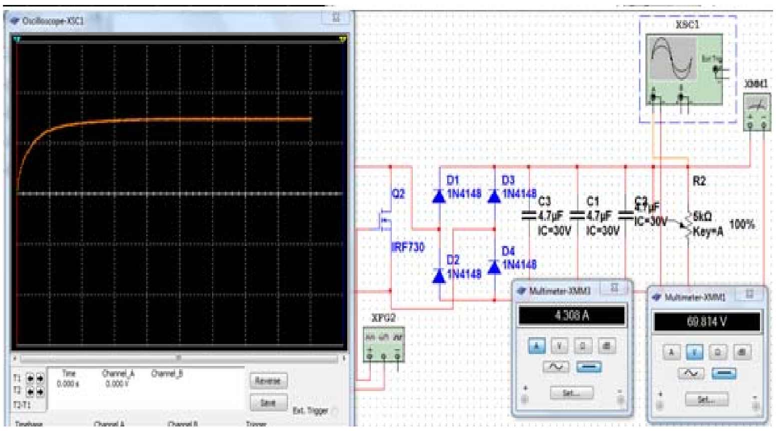

Fig. 9. Output voltage waveform by using four diodes.

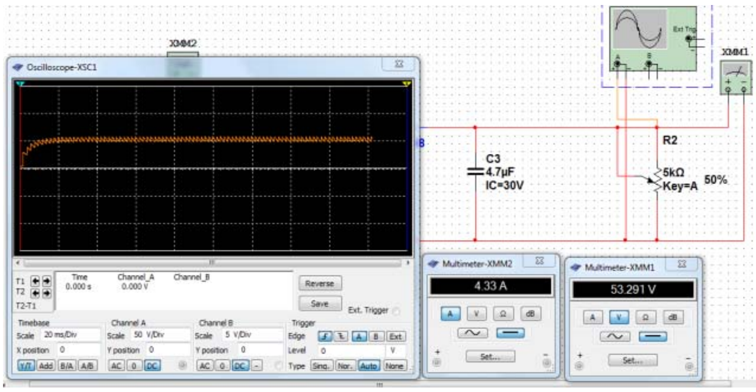

Fig. 10. Output waveform used lower farad (4.7µF).

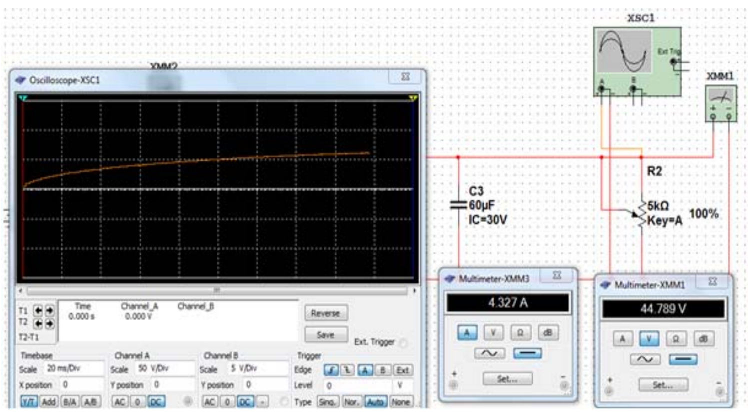

Fig. 11. Output waveform used higher farad (60µF).

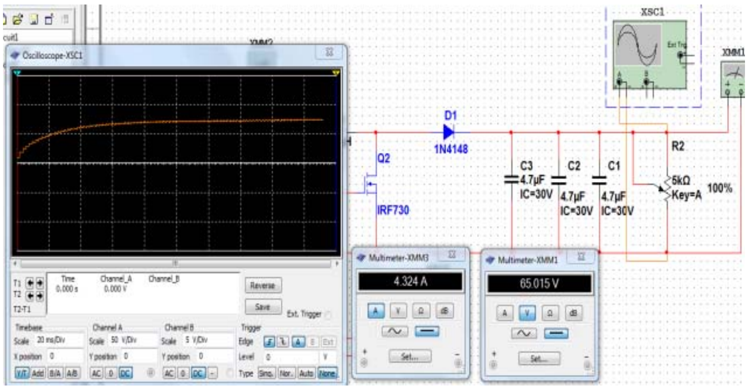

Fig. 12. Output waveform used three capacitors with low farad (4.7µF).

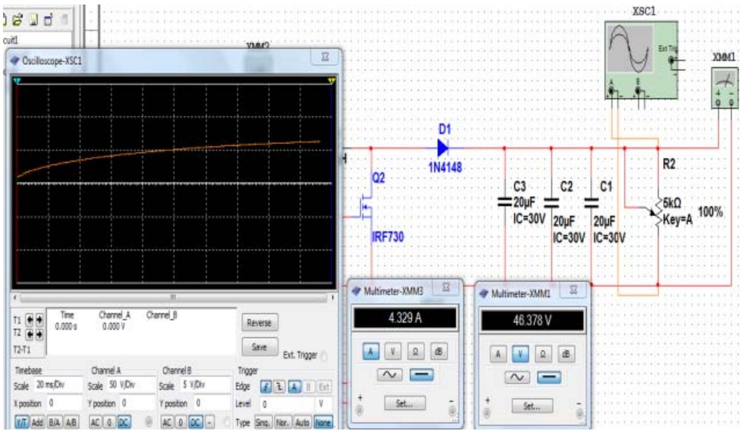

Fig. 13. Output waveform used three capacitors with high farad (20µF).

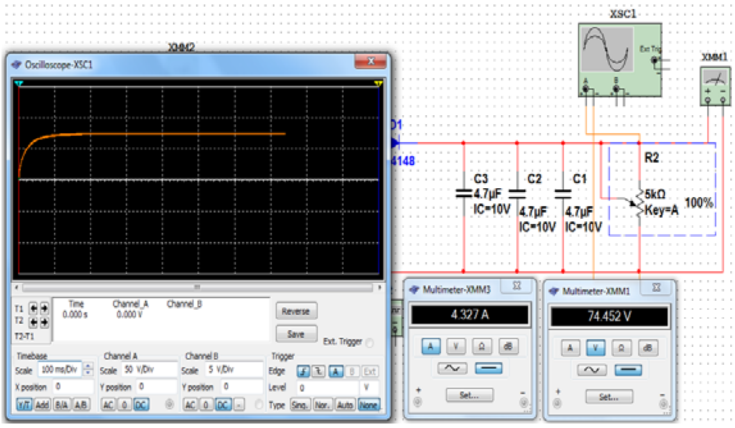

Fig. 14. Output waveform using 10V capacitor.

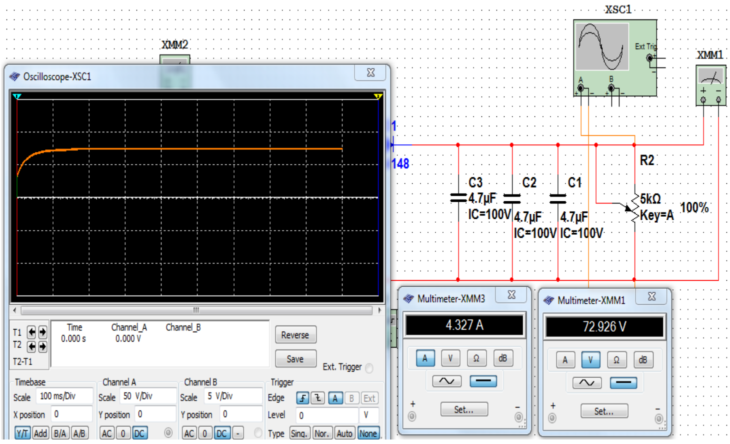

Fig. 15. Output waveform using 100v capacitor.

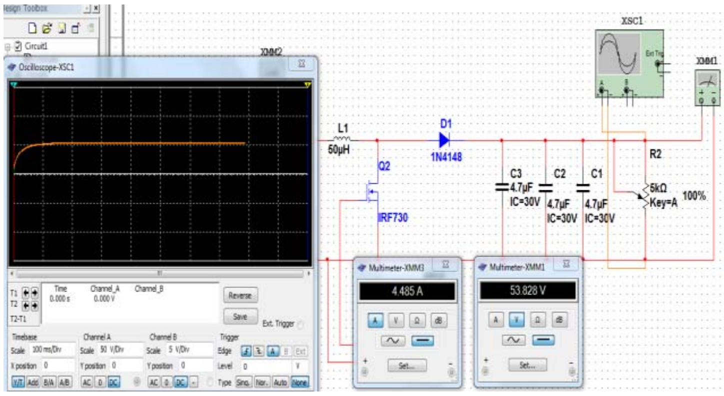

Fig. 16. Output wave form using 50μH inductances.

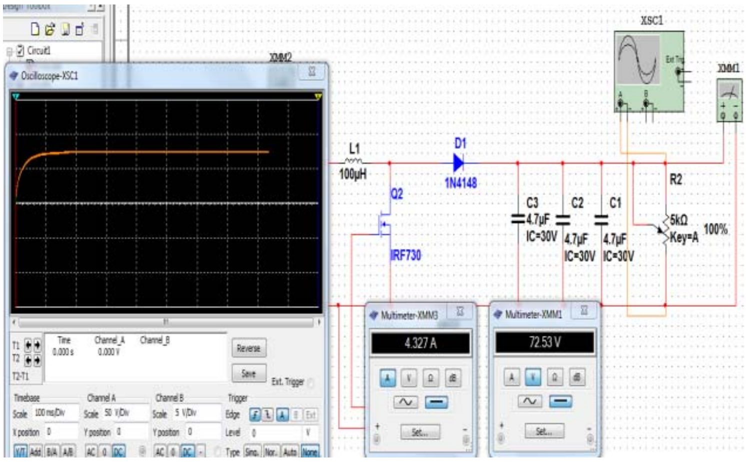

Fig. 17. Output wave form using 100μH inductances.

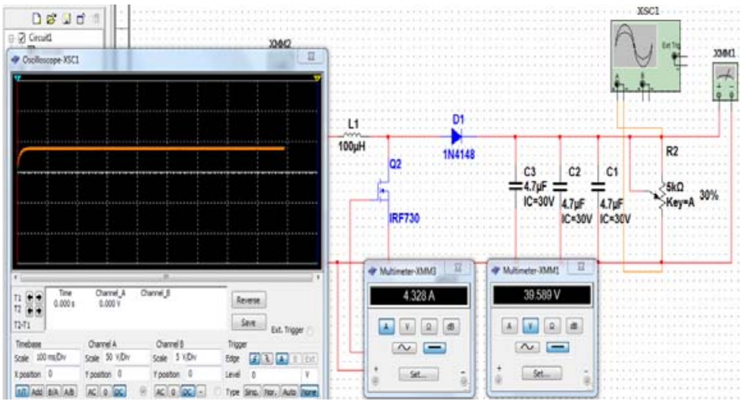

Fig. 18. Output wave form using 30% of 5kΩ resistor.

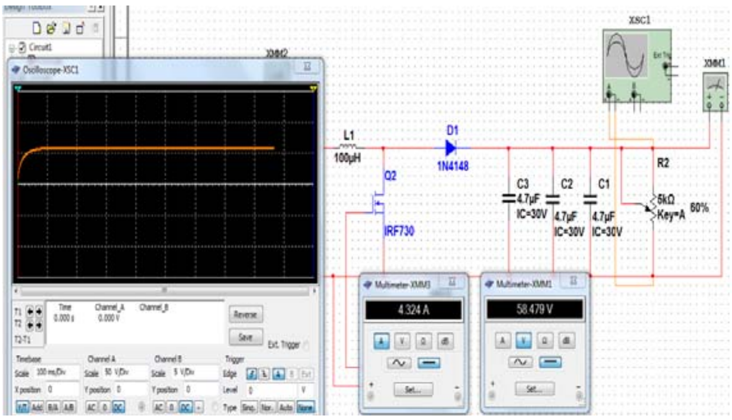

Fig. 19. Output wave form using 60% of 5kΩ resistor.

In addition, the value of the capacitor voltage also influences the output of the boost converter. In this analysis, two values of capacitor voltage were chosen for comparison. The results from Fig 14 and Fig 15 show that, when the value of the capacitor voltage increases, the charging time and the time to reach the output voltage steady stage will also increase.

Influence of Changing the Value of the Inductor

Another element that influences the output of the boost converter is the inductor. Changes to the inductor's value will also change the characteristics of the boost converter. In this analysis, two values for the inductor were chosen for comparison. The results from Fig 16 and Fig 17 show that, when the value of the inductor increases, the output voltage of the boost converter also increases.

Influence of Changing the Value of the Resistor

The final element that influences the output of the boost converter is the resistor, or load resistance. In this circuit simulation, a 5 kΩ variable resistor was used to show the effect of the resistor on the boost converter. This resistor was regulating at 30% and 60% to make the output comparison. The results from the output voltage, shown in Fig 18 and Fig 19, show that increasing the value of the load resistor also increases the output value of the boost converter.

Hardware Analysis of the Proposed Topology

Fig 20 shows the data for the relationship between the input and output voltages of the boost converter that is powered by the DMFC. The proposed variable boost converter can step-up the voltage to 60 V from a DMFC voltage of 3 V. As the input voltage increases, the output voltage increases as well and is directly proportional.

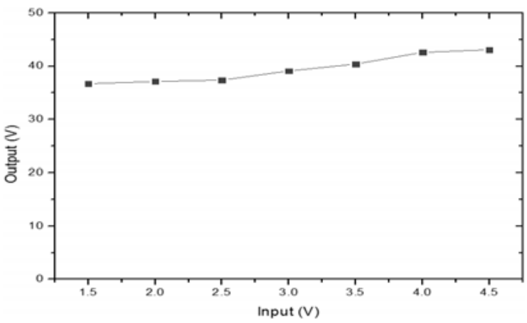

Fig. 20. Graph relationship between the input and output voltage of boost converter.

The frequency of the PWM is fixed at 120 Hz. The waveform of the DMFC's output voltage is shown in Fig 21, where the voltage measured by an oscilloscope is 2.84 V, and ripple is observed in the waveform.

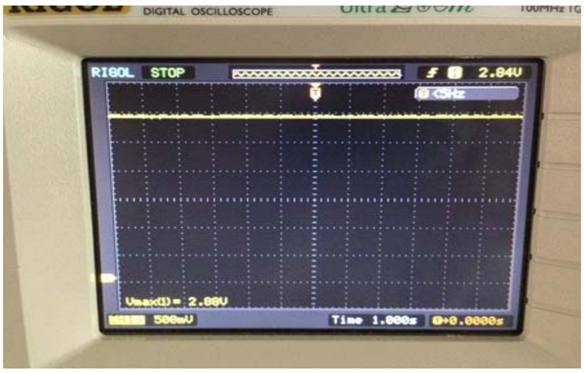

Fig. 21. Waveform of output DMFC.

Fig 22 shows the output voltage waveform of the proposed variable boost converter at 31.6 V; the converter produces a smooth DC voltage as evidenced by the waveform, in which ripple was eliminated through use of the filtering element.

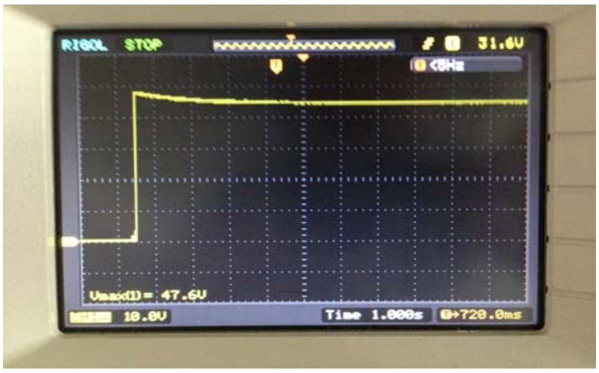

Fig. 22. Waveform of output voltage.

Fig 23 contains the data illustrating the relationship between the frequency of the PWM and the input and output voltages of the variable boost converter. When the frequency of the PWM is varied from 85 Hz to 145 Hz, the input and output voltages of the boost converter change simultaneously. At 0 Hz, the input voltage of the fuel cell is approximately 1.61 V, and the output voltage of the boost converter remains unchanged. At a frequency of 85.7 Hz, the boost converter will step-up the voltage from 1.61 V to 21 V. The lowest frequency that can be produced by the NE555 IC during a stable PWM operation is 85.7 Hz. The highest frequency attainable is 145 Hz, and the output voltage is 34 V at an input voltage of 2.59 V. The highest output voltage that can be produced by the proposed boost converter is approximately 57 V. This occurs within the frequency range between 135 Hz and 140 Hz and corresponds to an input voltage of approximately 2.6 V. The graph in Fig 23 shows the relationship between the PWM frequency and the output voltage of the proposed variable boost converter. This frequency was measured from the gate terminal of the power MOSFET to the ground. There is a turning point of the boost voltage that occurs within the frequency range of 140 Hz to 145 Hz.

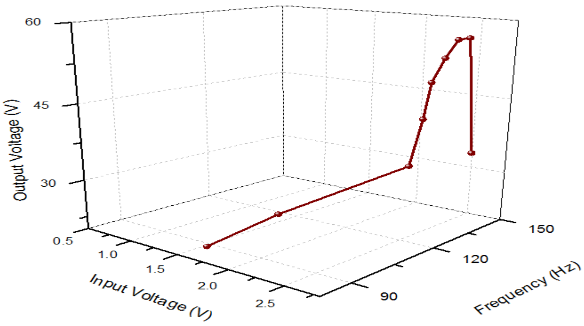

Fig. 23. Graph relationship between PWM frequency with input and output voltage.

Fig 24 shows a comparison of the output voltage data, along with a graph of the boost converter performance as a function of the power source utilized. With reference to Figure 24, the output voltage of the boost converter when using a power supply as a power source is higher than the output voltage for the case where a DMFC is used as a power source. This is because the current density of the power supply is more than that of the DMFC and, in terms of stability, the power supply was producing in continuous current mode. The graph of the output boost converter when using a power supply shows a linear relationship at the upper range in contrast with the DMFC used as a power source. The gradient of the curve for the power supply is greater than the DMFC gradient. Table 3 presents the percentage of efficiency obtained from this study.

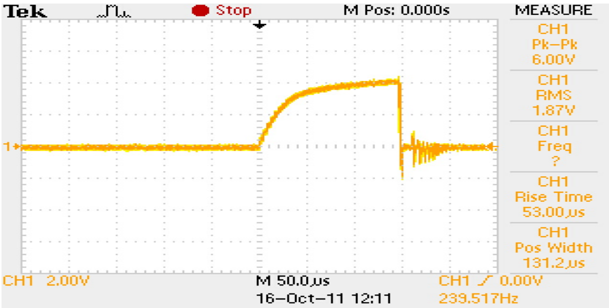

Fig. 24. PWM waveform using 90% of 100kΩ resistor.

Table 3. Tested efficiency of boost converter by using power supply

	Input Condition			Output Condition			
Test	Voltage (V)	Current (mA)	Power (W)	Voltage (V)	Current (mA)	Power (W)	Efficiency (%)
1	1.5	90	0.135	63.6	2.0	0.128	95
2	2.0	120	0.240	64.7	3.0	0.191	80
3	2.5	150	0.375	65.0	4.2	0.270	72
4	3.0	180	0.540	65.2	6.5	0.421	70

Using a TEKTRONIX digital oscilloscope, the waveform of the PWM was captured. The frequency of the PWM signal was controlled by varying the resistance of the variable resistor. Fig 25 shows the PWM waveforms at resistances of 90 kΩ and 7 kΩ, respectively. At a resistance of 73 kΩ, the maximum PWM frequency of 4.7 kHz is achieved. Finally, Table 4 presents the comparison of the results obtained from this study with those of previous researchers. This study has successfully developed a high-efficiency variable boost converter for the low voltage range of DMFC-Battery hybrids.

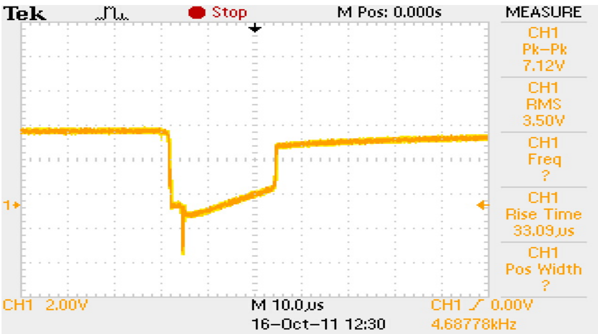

Fig. 25. PWM waveform using 73% of 100kΩ resistor.

Table 4. Comparison with previous researchers

References	Type of fuel cell	Type of power management	Input voltage	Output voltage	Controller applied
[4]	Active DMFC + smart battery	Buck boost	14-36V	16.5V/ 1.52A	MSP430FS 438 microcontroller
[23]	DMFC + super capacitor	Boost & buck boost	14V	20V	DSP controller
[24]	Active DMFC + battery	Buck boost	39V	20V	TMS470 microcontroller
[25]	DMFC	Direct supply	3V	3V	-
This study	Pasive DMFC + Capacitor + battery	Boost	0-12V	60V	IC NE 555

Conclusions

In this paper, a variable boost converter is analyzed. This proposed variable boost converter is able to boost the voltage up to 60 V from the DMFC's low voltage output of approximately 3 V. Incorporation of a battery into the system eliminates several deficiencies of the DMFC, e.g., instability, low voltage output, and lack of regulation. Although the PWM produced by the NE555 has a stable oscillation, the stepped-up output voltage generated by the variable boost converter still stable, and there are no distortions to the switching. The regulated output voltage produced by this proposed variable boost converter can be set at any desired voltage to control the brightness of an LED lamp. From the analysis of every component of the boost converter, it can be concluded that every element or component in the boost converter circuit influences the output. This high gain boost converter can be applied as a more efficient system of power management for portable power supplies by using the DMFC if this topology is adopted with an artificially intelligent closed loop control to control the switching element because of the decreasing and unstable output of the DMFC.

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Authors: *M.S. ALI is a PhD student at the Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM), E-mail: mohdshamsul@gmi.edu.my*
Dr. Mahidur R. Sarker is currently working as Research Fellow to the Institute of IR 4.0, Universiti Kebangsaan Malaysia (UKM). E-mail:mahidursarker@ukm.edu.my.
Dr. Ahmad Asrul Ibrahim is currently working as Senior Lecturer of Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM), E-mail: ahmadasrul@ukm.edu.my.
Dr. Ramizi Mohamed is an Associate Professor of Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM), E-mail: ramizi@ukm.my.

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