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DC-DC Boost Converter for Enhancing the Generated Output Voltage from Microbial Fuel Cell

Hager Meatimed[1,*], Aya S. Rady [2], S. A. Kamh[3] IEEE member, and S.M. Abd El-Azeem[3]

[1]Physics Dept., Faculty of Engineering and Technology, Modern Academy, Cairo, Egypt.

[2]Biophysics Res. Group, Physics Department, Faculty of Women for Arts, Science and Education, Ain Shams University, Cairo, Egypt.

[3]Electronic Res. Lab., Physics Department, Faculty of Women for Arts, Science and Education, Ain Shams University, Cairo, Egypt.

Abstract:

Microbial Fuel Cell (MFC) represents a promising approach for generating power inexpensively. Moreover, it is considered as an alternative green energy source. It could generate electrical energy by utilizing a wide range of organic substrates, as well as complex organic matter present in various environmental wastes depending on the bio-catalysis of microorganisms. However, the utilization of MFC in electronic applications is limited, due to its low output power density and output voltage. The present work aims to enhance the generated output voltage of a single MFC by applying DC-DC boost converter circuit. Before applying this circuit, a similar stacked series 6- MFCs are constructed for increasing its generated output voltage (on average 1.04V), where their produced output voltage reached about 6.24 V. In most electronic applications, the required voltage and current exceed these values. Hence, as a solution, a DC-DC boost converter circuit is recommended with an input voltage of 6 V based on the voltage harvested from the cascaded series 6-MFCs using a 6V/2A lead acid battery. In this work, the designed converter was operated in the discontinuous conduction mode (DCM) giving a variety of output voltage ranging from 15.8 V at load resistance (R_L) of 220 Ω up to 21.2 V at R_L of 620 Ω.

Keywords: Microbial fuel cell, Boost Converter, Energy harvesting, Output voltage**.**

1. Introduction

The demand for new energy sources increases and leads to the search for more renewable clean and green energy sources that can be used to fulfill life energy requirements [1, 2]. From these sources: solar, wind, tides, geothermal, and biomass energy [3-9]. One of the eco-friendly technologies and alternative suggested solutions for the energy depletion problem is the fuel cell. It is defined as an electrochemical device that converts chemical energy in fuels into electrical energy directly depending on the oxidation reaction of fuel at the anode

***Corresponding author**: Hager Meatimed, Physics Department, Faculty of Engineering and Technology, Modern Academy, Cairo, Egypt

E-mail: eng.hagar.shell.311@gmail.com

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site [10, 11]. It is basically constructs from two electrodes and an electrolyte to allow the transportation of protons (H^+). According to the type of utilized electrolyte in a fuel cell, the kind of chemical reactions [12], the catalysts required, and operating factors such as temperature are determined [13,14]. Depending on the type of electrolyte, fuel cells are divided into two main categories: metal fuel cells and organic fuel cells [15].

The present study deals with Microbial Fuel Cell (MFC), which is a type of organic fuel cell and one of the most promising renewable energy technologies which belong to the organic fuel cell category. It could generate electricity by harvesting electrons gained from a metabolized process by microorganisms [16-17]. It consists of an anaerobic anode (A) and aerobic cathode (K) - chambers that are connected by an external circuit and separated by a proton exchange membrane [17-21]. In the anode chamber, the decomposition of organic substrates, as well as complex organic matter present in various environmental wastes utilizing the electrogene bacteria [22], generates electrons (e^-) and H^+ that are transferred to the cathode through the circuit and membrane respectively [16]. The following equations summarize the flow of electrons through the external circuit that generates the electric current from MFC [23]:

$$\text{Organic matter} + H_2O \rightarrow CO_2 + H^+ + e^- \quad \text{(at anode)}$$

$$O_2 + H^+ + e^- \rightarrow H_2O \quad \text{(at the cathode)}$$

$$\text{Organic matter} + O_2 \rightarrow CO_2 + H_2O \quad \text{(overall)}$$

The generated electrical power density and the performance of MFCs are restricted by some physical and chemical parameters. These parameters include the total internal resistance, microbial metabolism in the anodic environment, rate of oxygen reduction on the surface of the cathode, electrode material, and dimensions as well, the type of proton exchange membrane. Moreover, the operational conditions such as, pH of the electrolyte (wastewater), conductivity, temperature…. etc. [24-26].

Depending on the parameters affecting the MFC-generated output voltage and its performance, For example , the selection of anode material where the microoranism are ineracted and compose the biofilm. Number of techologies have been introduce for improving the anode material as nanotechnolgy. The modification in electrode materials of MFCs have been reported through incorporation of nanomaterials. It includes metal-based and carbon nanoparticles, as well as conductive polymers, which may aid in the formation of thick microbial biofilms, resulting in improved electron transmission between biofilms and electrodes. Moreover, It could enchnce such as increasing active surface area, enhancing conductivity, and improving biocompatibility[27, 28].

Thus, number of research papers are concerned with their improvement. During 2000s, waste management, renewable energy production, and water supply are all possibilities with MFCs which are key challenges of the 21st. century[29,30]. From 2012 to 2013, many researchers tried to extract the maximum generated power from MFC using wastewater. The main strategy of some of them is to study the factors affecting the performance of the MFC. The achieved power density values were reported to be from 0.32 to 16.02 mW/m^2. Moreover, the generated voltage and current values were noticed to be 0.551 V and 0.47 mA, respectively[31]. Increasing power generation using stacking two MFCs together either in series or in parallel was carried out. The obtained power density values were reported to be from 464 to 542 mW/m^2, while the produced series working voltage value was noticed to be 1.22 V [20]. A few years later, from 2015 to 2016, the obtained output voltage values from MFC ranged from 40 mV up to 320 mV while using different bio-wastes[32]. Depending on certain bio-waste with different concentrations, the produced output voltage value ranged from 0.423 V to 0.723 V [33]. In the year, 2017 the area of research expanded to include studying the effect of each: the number and material type of electrode and the addition of resistors of different values in parallel with the cell [34-37]. During 2018 and 2019, studying the operation of different MFCs showed constant output voltage ranging from 60-550 mV while operating the cell for about a week[38]. Starting from the years 2020 and 2021, the researcher began to focus on solving the problem of low output power. Where their suggested solution could be summarized as either electrode preparation or energy harvesting from MFC. The produced output voltage values ranged from 0.26V to 0.78V [39, 40].

Despite all these trials, still now, the generation of practically usable power from MFCs [2] remains a major challenge for system application [41]. So, energy-harvesting circuits are needed for real-world applications. Nowadays, utilizing the DC-DC converters in energy harvesting systems is increased because of the vast applications which need high power. Boost converters can increase the voltage and reduce the number of cells [42-46].

So, this study aims to improve the MFC generated output voltage MFC, applying DC-DC boost converter circuit. Fig. (1). illustrates the block diagram for the MFC energy harvesting and boosting system. The main operation for which is boosting the stored energy (harvested from MFCs) via lead acid battery into another level before releasing it to the load [47, 48].

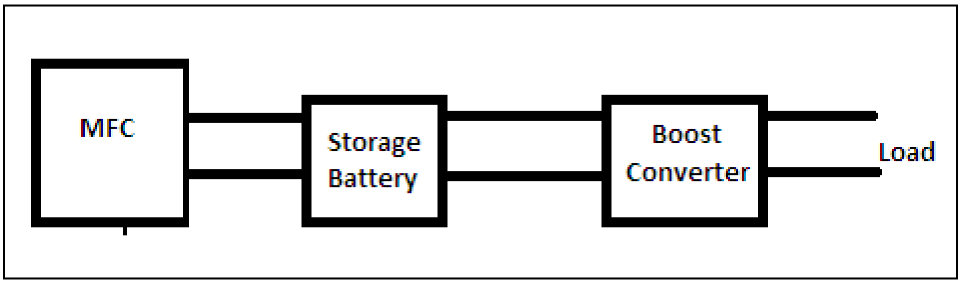


Fig. (1). Block diagram of the MFC energy harvesting and boosting system.

The proposed DC-DC converter (Fig.2) is constructed from the following circuit power elements: semiconductors switch (S), a diode [49], and an inductor (L) as well input /output capacitors (C_{in}, C_o), beside the load resistor (R_L). It could be operating in different modes [50, 51]; namely, continuous conduction mode (CCM) and discontinues conduction mode (DCM), as well the critical conduction mode (CrCM).

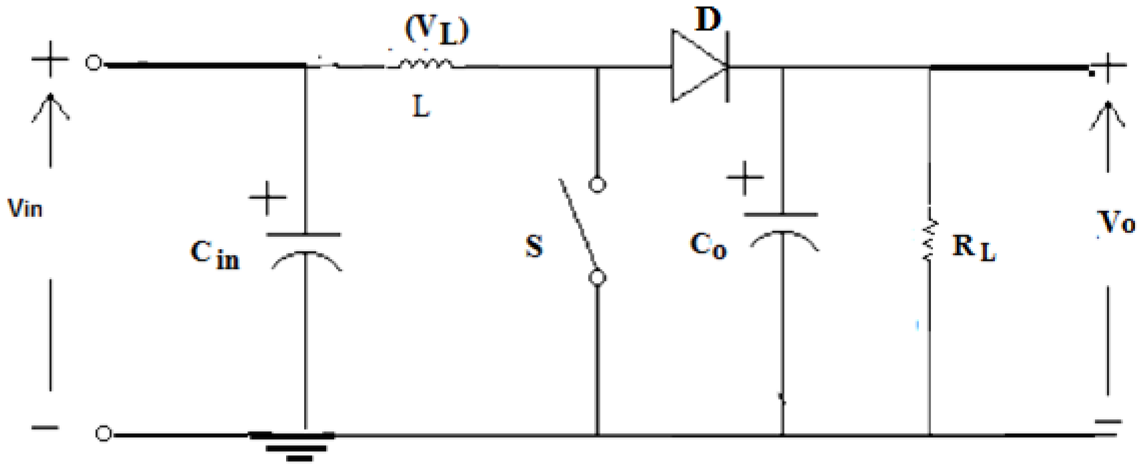


Fig. (2). Experimental set up of the boost converter circuit

In this work, the DC-DC boost converter circuit operates in DCM, where its output voltage (V_o) could be given by Eq. (1),

$$V_o = \frac{1}{2}\left[1+\sqrt{1+\frac{2R_L D^2}{f\ L}}\right]V_{in} \quad (1)$$

Where ,

V_o: Output voltage,

V_{in}: Input voltage,

D: switching duty cycle,

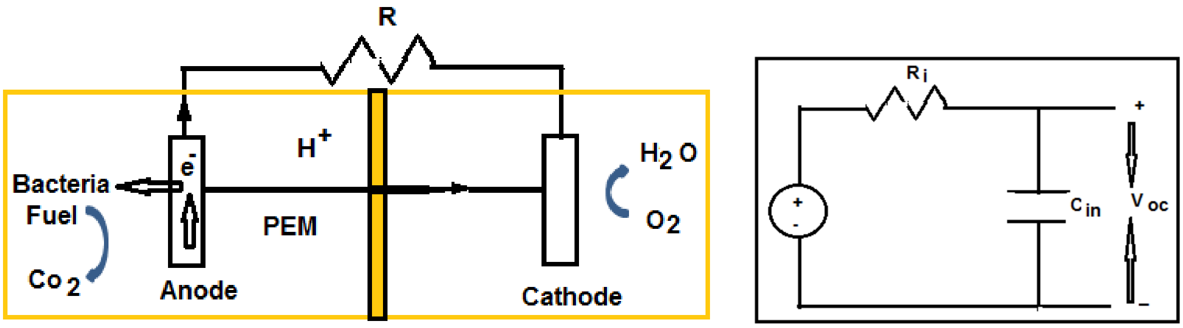
f: switching frequency,

L: Inductance and R_L is the load resistance.

1.1 Microbial Fuel Cell Electrical Equivalent Model

The proposed MFC can be electrically modeled as a voltage source with an internal resistance (R_i), open circuit voltage (V_{oc}), and internal capacitance (C_{in}) as shown in Fig. (3). The value of Ri is composed of several components including; anode, cathode, membrane, and electrolytic resistances. The V_{oc} varies nonlinearly depending on the solution pH, temperature, and substrate concentration [52].

The electrical performance of MFC could be investigated using polarization curves [53]. It described the variation of cell working voltage as a function of the current density. During the present work, the polarization curve of the designed MFC is experimentally reported and plotted.



(a) (b)

Fig. (3). MFC (a) schematic, and (b) electrical model

2. Experimental details

2.1 Microbial fuel cell set-up

The most common configuration of the double-chamber MFC is H-shaped [54], due to its flexibility and easy manipulation. The experimental setup for MFC is shown in Fig. (4). It consists of two plastic bottles (anode and cathode chambers) of 650 mL capacity connected by salt bridge which prepared by 10 % agar concentration mixed with NaCl of 1 M concentration. Aluminum (Al) and Copper (Cu) materials are used as anode and cathode electrodes. Moreover, the stacked 6-MFCs circuit is shown in Fig. (5), and Table. (1), illustrates the specifications of the designed MFC. Moreover, the work is extended to measure the bio-waste electrical conductivity and pH value, besides the total bacterial count (T.C), as well as the anaerobic plate count (APC) as illustrated in Table (2). Where the MFC output voltage is related to the microorganism content especially anaerobic bacteria [55-57]. The MFC bio-wastes are gathered and placed in a container with special color and mark. These containers are of a resistant and sealing material for infectious waste, and then they were subjected to incineration under the authority of the initiations.

Table. (1): Specification of the designed MFC

Wastewater source	Capacity of Anode/Cathode chamber	Anode/Cathode surface area	Molar concentration of salt bridge
Irrigation farmland	**650 mL**	**38.5 cm^2**	**1M**

Table. (2): The measured parameters of the used wastewater sample

Chracteristic parameters	**Physical parameterspe**		**Microorganism content**	
	pH	**EC(S/m)x10 $^{-4}$**	**T.C (cell/ml)**	**APC (cfu/ml)**
Value	7.72	1130	23x 10^4	60000

Fig. (4). Laboratory scale designed MFC

Fig. (5). Stacked series 6-MFCs circuit

2. Results and discussions

From the experimental work, the final results could be divided into three parts including;

i) Generating electrical power from single / stacked 6 -MFCs (Fig.5),

ii) Storing the generated output voltage (Fig.7), and

iii) Enhancing the generated output voltage based on DC-DC boost converter circuit (Fig.12).

The present study utilized a dual-chamber (H-shaped) microbial fuel cell for the electrical power generation. It is a simple design, easy to apply, and has an economic value (inexpensive constitutes that are available in the Egyptian market). The utilized MFC is monitored for 1400 hour (60 day). Along this time, the cell working voltage is measured and plotted versus the running time as shown in Fig. (6). Throughout this experimental work, no mediator for bacterial activation or organic substrate as compensatory for the biowaste mass transfer are supplied.

Depending on Fig. (6), from the starting point of measuring up to 220 hours, the cell working voltage fluctuated with an average value of 1.04 V. Reaching to 800 hours, the cell working voltage fluctuated with an average value of 0.95 V. After that, a noticeable reduction in cell working voltage is reported that reached a value of about 0.64 V within the last 200 hours. This reduction is regarded as the consumption of the organic matter involved in the bio-waste water which will affect the bacteria activity [58-60]. Thus, feeding of the anode with an additional organic substrate could increase the MFC generated output voltage and the sustainability scale [61].

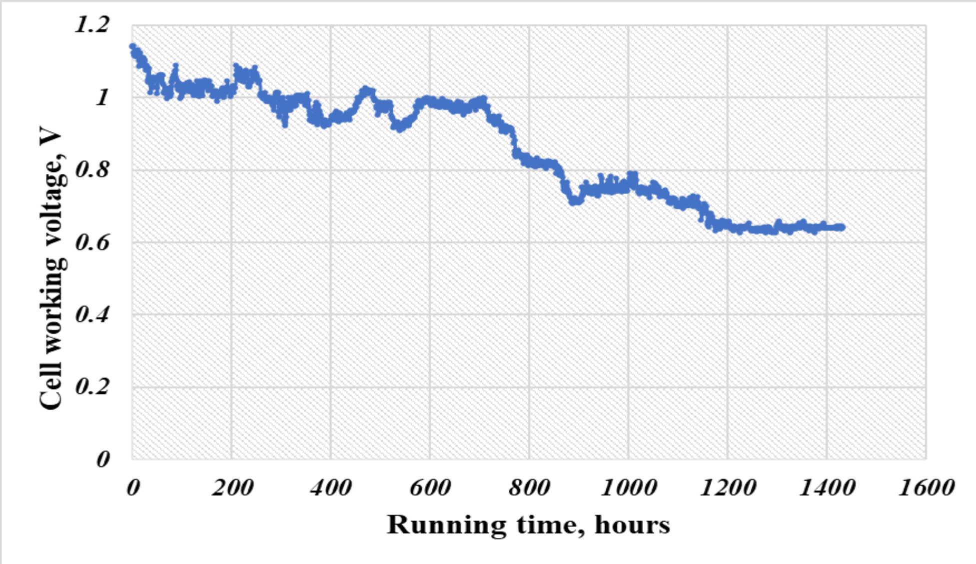


Fig. (6). Single MFC working voltage versus running time for a working cycle 60 day

During the work, owing to the lower value of the output cell working voltage (V_o) of a single MFC (with an average value of V_o=1.04 V), a lead acid storage battery having 6V/2A storage capacity is required, as well, a system of a stacked series 6 similar laboratory scaled MFCs are constructed considering the operating conditions, which are illustrated in Table. (1). The output cell working voltages of both; the single and stacked system are monitored and reported for a bout continuous 25-minute working time and represented in Fig. (7). From which, it is observed that V_o of the stacked system reaches about 6.24 V which is suitable for charging lead acid battery having 6V/2A storage capacity.

The noticed variation is almost linear for both. A small degree of oscillation was showed for stacked series 6-MFCs cell working voltage which could be attributed to the biodegradation rate of biomass by microorganism (especially the anaerobic bacteria activity) for each individual cell [53].

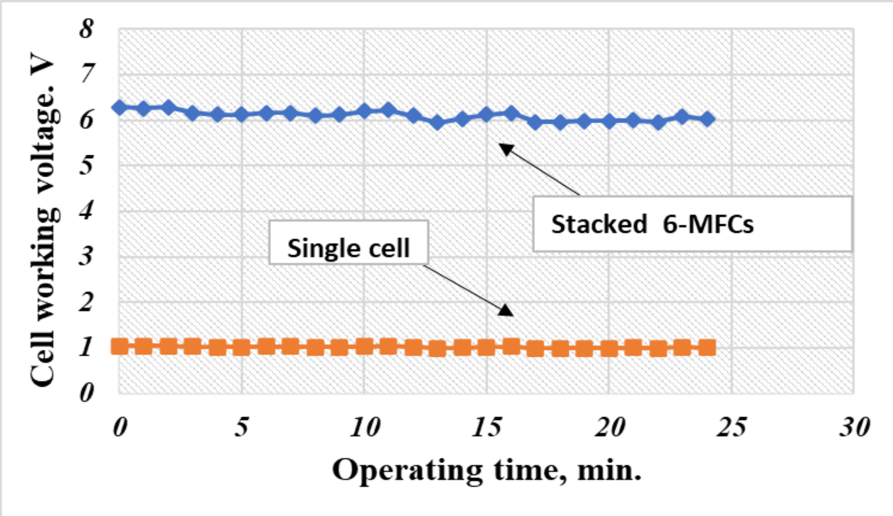


Fig. (7). Output voltage for the single and stacked series 6-MFCs

To elucidate the electrical performance for both single and stacked 6-MFCs, the polarization curve (cell working voltage-current density) is measured and plotted (Fig.8). It shows three main regions for cell working voltage reduction which could be defined as: Activation, Ohmic, and biomass concentration - loss regions. The activation loss region appears at low current density values, and the reduction in the cell working voltage is related to the energy lost for initiating chemical reactions and due to the electrons traveling to the terminal electron acceptor. Moreover, the linear part of the polarization curve is due to the Ohmic losses and is considered to be the most important part for the optimum fuel cell design. These losses are usually due to the internal connections, the diffusivity of the membrane, the resistance of ion conduction, etc. The last part of the curve (with the high current density and low cell working voltage) is due to the biomass concentration losses. These losses are also called mass transfer losses and are due to either limitation of the concentration of reactants or oxidants in the fuel cell [62, 63].

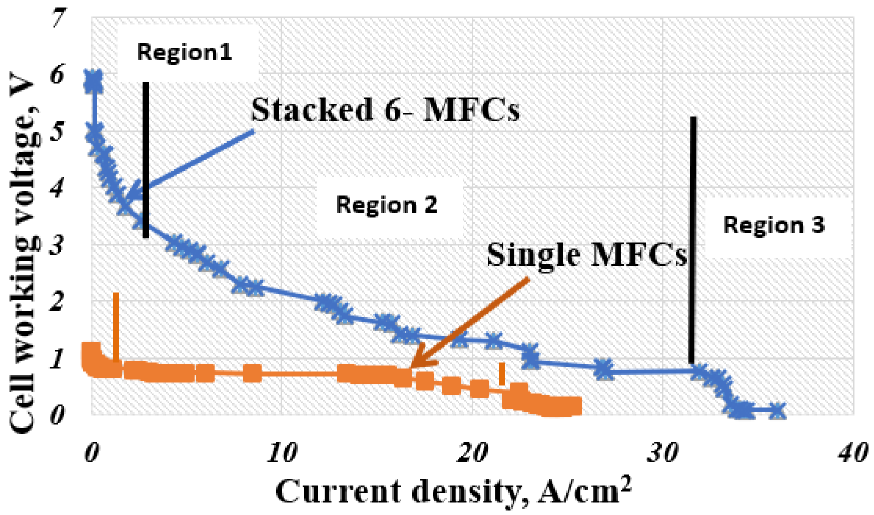


Fig. (8). Polarization curve of the laboratory scale single and stacked series 6-MFCs

Considering the output voltage of lead acid battery (Fig.9). To determine the real time, which is required for charging the battery, it is necessary to partially discharging it. This could be done using an external load to achieve the lowest voltage value (0.5V).

During the charging time from 0 up-to 20 min., the battery voltage increases linearly, while during the charging time from 20 up to 50 min., it increases exponentially reaching the value of 5.8 V. Increasing the charging time up to about 63 min., the battery voltage is almost saturated reaching the full storage capacity of 6V. At the same time, the battery current decreases from 300 mA down - to 50 mA.

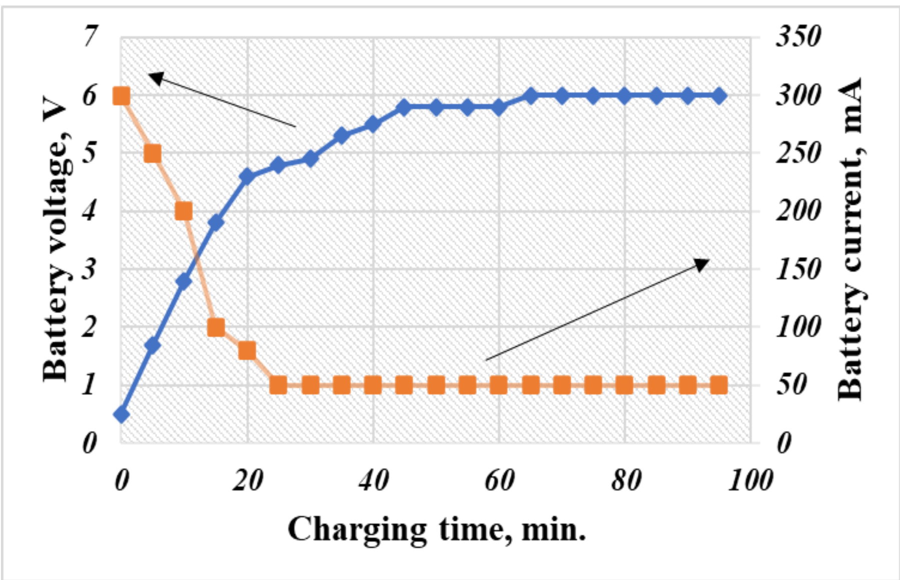


Fig. (9). Dependence of the lead acid voltage and current on the charging time

Considering the enhancement of MFCs generated output voltage using DC-DC boost converter circuit. DC-DC converter circuit is designed and tested based on the theoretical equation for the output voltage (Eq.1). For the proposed converter circuit, the influence of the following electrical parameters; f_s and D on V_o are studied. Depending on the obtained results, it is noticed that V_o values are function of both f_s and D (Figs.10 and 11).

Considering the impact of the switching frequency the output voltage on of the DC-DC boost converter, operating in discontinuous conduction mode (Fig.9). It is clear that, with increasing the operating frequency range (Band Width, BW) from 12 kHz up to 20 kHz, the obtained output voltage decreased from 20 V down to 12.7 V, according to Eq. (1). Concerning the effect of the switching duty cycle on the output voltage of the tested converter theoretically and experimentally (Fig.9). It is noticed that their results are in good agreement with each other. The obtained output voltage values increased from 12 V up-to 30.6 V with the variation of D values from 50 % up to 82 %, respectively.

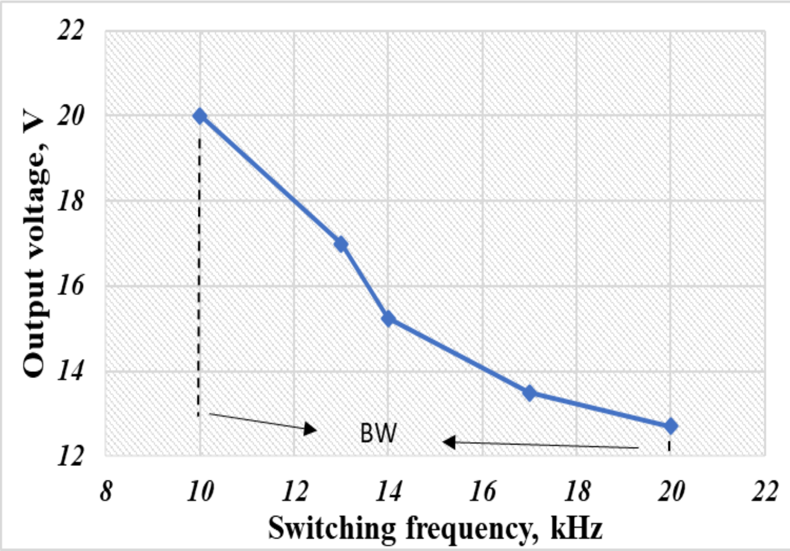


Fig. (10). Impact of the switching frequency on the output voltage of the DC-DC boost converter

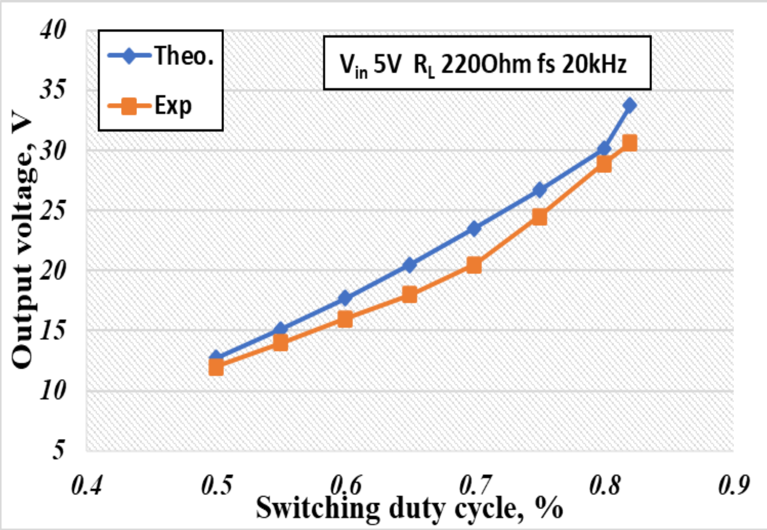


Fig. (11). Impact of switching duty cycle on the output voltage of boost converter circuit.

After the design and testing of the boost converter system (Fig.10 and 11), the converter was designed for enhancing the MFC output voltage with, D: 82% and fs of 20 kHz, as well the load resistance values are (220 and 620 Ω, as an example).

Considering the MFC output voltage based on DC-DC boost converter system (Fig.12), while applying the energy harvesting system (Fig.1). It is obviously shown that, the output voltage of the DC-DC boost converter reached the value of 21.2 V using R_L of 620Ω, while the value of 15.8 V was verified at R_L of 220 Ω. So, it could that the usage of the energy harvesting system could be improve the output voltage of the single MFC (1.04) to the value that enable it to be sued in the different life applications.

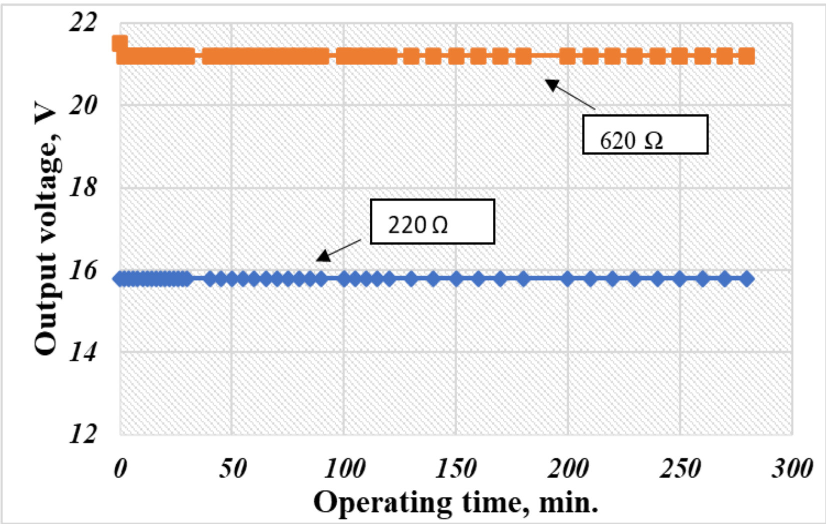


Fig. (12). DC-DC boost converter output voltage of, plotted at two different R_L values

Conclusions

The usage of MFC is limited in practical life applications, due to its low power density and output voltage. So, the present work aimed to improve the MFC output voltage applying DC-DC boost converter system. During the work, the following steps are carried out:

First; a single MFC is constructed with two plastic bottles (anode and cathode chambers) of 650 mL capacity connected by salt bridge which prepared by 10 % agar concentration mixed with NaCl of 1 M concentration. Aluminum and Copper materials are used as anode and cathode electrodes. The anode chamber is fed with an irrigation farmland as the bio-waste, while the cathode chamber is fed with tap water, giving an output working voltage of 1.04 V.

Second; for increasing the output working voltage of the single cell (1.04V), a system of stacked six series similar laboratory scaled MFCs are constructed. Their output working voltage is reached the value of 6.24 V.

Third; for using later the generated output voltage from the stacked system, a 6V/2A lead acid battery is used for storing the generated voltage.

Finally, a DC-DC boost converter operating in the discontinuous conduction mode (DCM) is recommended with an input voltage of 6V based on the voltage which is stored using lead acid battery. The obtained results showed a variety of output voltage values of 15.8 V and 21.2 V, while using load resistance values of 220 Ω and 620 Ω, respectively.

Recommendation for Future Work

Throughout the present work, several research directions are opened for future work including studying the impact of different MFC constructions and different bio-wastes collected from new areas on the generated output voltage and their sustainability. Also, for enhancing the generated MFC output voltage, another DC-DC converter types could be used.

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الملخص العربى

"تناول المحول الرافع للجهد لتعزيز جهد الخرج المتولد من خلايا الوقود الميكروبية"

هاجر معتمد مصطفي [1], آيه سيد راضي [2], ثناء عبد التواب قمح[3], سها محمد عبد العظيم أحمد[3]

(1) قسم الفيزياء، كلية الهندسة والتكنولوجيا، الأكاديمية الحديثة, القاهرة، مصر
(2) مجموعة أبحاث الفيزياء الحيوية، قسم الفيزياء، كلية البنات للآداب والعلوم والتربية،جامعة عين شمس، القاهرة، مصر.
(3) معمل أبحاث الإلكترونيات، قسم الفيزياء، كلية البنات للآداب والعلوم والتربية، جامعة عين شمس، القاهرة، مصر.

تعد خلايا الوقود الميكروبية (MFCs) أحد مولدات الطاقة المتجددة الصديقة للبيئة والتي تعتمد على البكتريا المتواجدة بالمخلفات الحيوية المختلفة بشكل أساسي في توليد الكهرباء. حيث يمكن أن تولد طاقة كهربائية من خلال إستخدام مجموعة واسعة من الركائز العضوية، وكذلك المواد العضوية المعقدة الموجودة في النفايات البيئية المختلفة اعتمادا على التحفيز الحيوي للكائنات الحية الدقيقة. ولكن ما زال استخدام تلك الخلايا محدود في التطبيقات الالكترونية، وذلك لانخفاض الجهد الكهربي الناتج منها. وفي هذا الصدد، يهدف العمل الحالي إلى تحسين جهد خرج خلايا الوقود الميكروبية بتطبيق نظام محول تعزيز الجهد (DC-DC boost converter). تم خلال البحث المعروض تشغيل المحول المصمم في وضع التوصيل المتقطع (DCM) عند قيم مقاومات حمل (R_L) 220 أوم و620 أوم بجهد دخل مستمر6 فولت. والذي تم توليده عن طريق توصيل عدد 6 خلايا متماثلة على التوالي لرفع الجهد الناتج من (1.04 فولت) باستخدام الخلية المفردة إلى 6.24 فولت باستخدام الخلايا المتصلة. وقد تم تخزين الجهد الناتج بإستخدام بطارية تخزين الجهد (6V/2A Lead acid battery). وقد لوحظ عن تشغيل المحول الرافع للجهد أن، قيم جهد خرج المحول تتراوح بين 15.8 فولت عند مقاومة الحمل 220 Ω إلى 21.2 فولت حال استخدام R_L 620 Ω.