Daniel Gonzalo Arboleda Avilés[1,*], Oscar Fernando Núñez Barrionuevo[2], Omar Fernando Sánchez Olmedo[2], Billy Daniel Chinchin Piñan[1], Daniel Alexander Arboleda Briones[3], Raúl Alfonso Bahamonde Soria[1].

[1]Renewable Energy Laboratory, Career of Chemical Sciences, Universidad Central del Ecuador, Quito-Ecuador.
[2]SAINCONTROL, García Moreno N11-328 y Matovelle, Quito-Ecuador.
[3]Mechatronic Department, Universidad Tecnológica Equinoccial (UTE), Quito-Ecuador.

***Autor de correspondencia:** dgarboleda@uce.edu.ec

Recibido: 30/10/18. Aceptado: 21/05/19

Química Aplicada y Analítica

Application of a direct current circuit to pick up and to store bioelectricity produced by microbial fuel cells

Abstract

Every year the demand for energy worldwide is increasing. There are some alternatives to reduce these problems, such as clean energy or renewable energy. A particular alternative is the microbial fuel cells. These cells are biochemical reactors that convert chemical energy into electricity. The present research evaluated the dairy serum to produce bioelectricity from micro fuel cells (MFC) that were constructed with low-cost materials and with isolated bacteria in anaerobic sediments, located in Ecuadorian national territory, producing maximum voltages of 0.830 V in the circuit and a maximum power density of 30 mW / m^2. This low voltage was worked with 50 mL MFCs and with an output voltage of 300 mV. Under these conditions, a FLYBACK lift circuit isolated by the transformer was designed. This new circuit could increase the voltage from 30 mV to enough voltage to light a 2.5 V LED. Therefore, the energy produced by the MFC can be directly used to light a LED and to charge capacitors. This study shows that these MFCs, together with the designed circuit, could be used potentially to generate clean energy.

Keywords: MFCs; COD; TOC; voltage; flyback; boost converter; DC - DC converters.

Aplicación de un circuito de corriente continua para la colección y almacenamiento de bioelectricidad producida por celdas de combustible microbianas

Resumen

Cada año la demanda de energía, en todo el mundo, va en aumento. Existen algunas alternativas para reducir estos problemas, tales como las energías limpias y renovables. Una alternativa muy específica es el uso de celdas de combustible microbianas. Dichas celdas son reactores bioquímicos que convierten la energía química en electricidad. La presente investigación evaluó el suero lácteo para la producción de bioelectricidad en celdas de combustible microbianas (MFC). Estas fueron construidas con materiales de bajo costo y con bacterias aisladas en sedimentos anaeróbicos, ubicados en territorio nacional ecuatoriano, produciendo voltajes máximos de 0,830 V en el circuito y una densidad de potencia máxima de 30 mW / m^2. Este bajo voltaje se trabajó con MFC de 50 mL y con un voltaje de salida de 300 mV. Bajo estas condiciones, se diseñó un circuito de elevación FLYBACK aislado por transformador. Este nuevo circuito aumentará el voltaje de 30 mV a un voltaje suficiente para encender un LED de 2.5 V. Por lo tanto, la energía producida por las MFC puede ser directamente utilizable para encender un LED y cargar los condensadores. Este estudio muestra que dichas celdas MFC, junto con el circuito diseñado, podrían utilizarse, potencialmente, para generar energía limpia.

Palabras clave: MFC; DQO; TOC; voltaje; flyback; boost converter; convertidores DC – DC.

Aplicação de um circuito de corrente contínua para coleta e armazenamento de bioeletricidade produzida por células a combustível microbianas

Resumo

Todos os anos a demanda por energia, em todo o mundo, está aumentando. Existem algumas alternativas para reduzir esses problemas, como energias limpas e renováveis. Uma alternativa muito específica é o uso de células combustíveis microbianas. Essas células são reatores bioquímicos que convertem energia química em eletricidade. O presente trabalho avaliou o soro lácteo para a produção de bioeletricidade em células a combustível microbianas (CCM), Estes foram construídos com materiais de baixo custo e bactérias isoladas em sedimentos anaeróbios, localizados no território nacional equatoriano, produzindo tensões máximas de 0,830 V no circuito e uma densidade de potência máxima de 30 mW / m^2. Esta baixa voltagem trabalhamos com CCM de 50 mL e com uma voltagem de saída de 300 mV. Sob essas condições, um circuito de elevação FLYBACK isolado por transformador foi projetado. Este novo circuito aumentará a tensão de 30 mV para uma tensão suficiente para ligar um LED de 2,5 V. Portanto, a energia produzida pelo MFC pode ser diretamente utilizável para ligar um LED e carregar os capacitores. Este estudo mostra que essas células CCM, juntamente com o circuito projetado, poderiam ser usadas para gerar energia limpa.

Palavras-chave: MFCs; DQO; TOC; voltagem; fly back; conversor boost; conversores DC - DC.

Introduction

The microbial fuel cells (MFCs) are an emerging technology that could contribute to the solution of several environmental problems such as the availability of uncontaminated water and the production of clean energy as part of renewable energies [1]. MFCs represent a technology with a recent focus for the generation of electricity and bioelectricity from biomass using bacteria [2, 3].

Furthermore, the Ecuadorian dairy industry is one of the economic sectors that generate the highest income in the country with a constant growth in the last 10 years. This increase in production volumes (5.6 million liters per day) is linked to an increase for waste produced, reaching about 19.2 million liters of wastewater daily nationally from the manufacture of cheese [4].

Dairy wastewater, as well as most agroindustry, generate high amounts of organic matter that are a serious environmental problem because they are related to the phenomenon that afflicts rivers and lakes, known as eutrophication, that is one of the consequences of the processes of pollution of the waters in rivers, reservoirs, lakes, and seas [5]. The main components of this wastewater are sugars, proteins, and emulsified fats that can be harnessed by the bacteria in their metabolism [6].

MFCs have the ability to take advantage of organic substrates to transform them into electricity using bacterial catalysis. The mechanism of electron transfer to the electrode can occur directly using specific bacteria called exo-electrogenic bacteria, among which are kind Geobacter and Shewanella [7].

A new way of storing electrical energy is the one that comes from domestic and industrial wastewater, being able to obtain two effects at the same time: decontaminate the wastewater avoiding with this action the contamination in the rivers and store the bioelectricity in a circuit of direct current [8].

Other researchers, in other experiences, have obtained the following data using domestic wastewater: 72 ± 1 mW m^{-2} at a fluid flow rate of 0.39 mL / min (with a degradation and removal of chemical oxygen demand in 42%) and an average power density of 43 ± 1 mW m^{-2} [9, 10, 11].

The output power found could be a function of the strength of the wastewater, according to a type of MONOD relationship with a constant average saturation [12, 13].:

$$k_s = 461 \text{ or } 719 \text{ mg} \frac{COD}{L}$$

MODEL MONOD: growth curve of an organism.

This curve studies the growth behavior of micro-organisms against time. Based on this curve, it is determined when the most significant amount of biomass is produced.

The dynamics of cell growth for biomass and substrate decrease during cultivation. This is described through the following equations:

$$\frac{d\,X(t)}{d\,t} = \mu\,(S)\cdot X\,(t) \qquad \text{Eq. (1)}$$

$$\frac{d\,S(t)}{d\,t} = -\frac{1}{Y}\cdot\frac{d\,X}{d\,t} \qquad \text{Eq. (2)}$$

Where X(0)=x0, S(0)=s0, X(t)=number of cells or biomass as a function of time, and μ(S)=specific speed of growth in S.

Equation (1) indicates that the growth rate of biomass is directly proportional to the amount of existing biomass, and equation (2) indicates that the substrate consumption rate is inversely proportional to the amount of existing biomass [14].

In this research, the energy produced by MFC was maintained at high proportions, even when several organic substrates were used. All of them approximately 1000 mg COD / L, including glucose (212 ± 2 mW·m^{-2}), acetate (286 ± 3 mW·m^{-2}), butyrate (220 ± 1 mW·m^{-2}), dextran (150 ± 1 mW·m^{-2}), starch (242 ± 3 mW·m^{-2}). These results show the versatility of power generation in an MFC with a variety of organic substrates and show that energy can be generated in high proportions in a continuous flow reactor system [15].

Studies of current harvesting have shown that the provided energy of MFC was approached by DC - DC switching converters as active extract energy. This is an advantage in the collection of continuous electrical power, which can be useful at home [6].

An electronic circuit is a device made with a set of elements, with a suitable topology, and with the aim of fulfilling specific functions, such as generating, transporting, or amplifying voltage or current signals. In several cases (the circuits used in the cited bibliography), it is observed that the materials are cheap if we consider Ecuador is a suitable application country [16, 48].

Considering previous work, in many of these cases, we start from two or more fuel cells connected in series or parallel [17]. For this reason, this research designed an economical, simple, and efficient circuit to amplify the voltage signal generated by one MFCs with the primary objective of having an adequate voltage to be used in the home as clean energy [18, 19, 29].

Materials and methods

Certain materials were recycled ones, and others were easily accessible to shoppers. Electrodes were obtained from carbon cylinders from Eveready® recycled dry batteries. The double chamber MFC - MEM (Membrane) was made with PVC pipes, and the electronic circuit elements and their parts are easy to find in a specialized store (figure 1).

Electronic equipment and Software

Table 1 shows the electronic components used in the design of the two voltage booster circuits (figures 3 and 4).

Table 1. Elements used in the simulation.

Symbol	Element	Description	Units
C1	Capacitor	1000	μF
D1	Quick switching diode	1N4148	---
D2	Diode	Light emitter	---
Q1	Switch	IRF840	---
R1	Resistance	100	Ω
R2	Resistance	20000	Ω
RV1	Potentiometer	1000	Ω
TR1	Pulse transformer	TRSAT2P28	---
U1	Controller	PIC12F683	---
VMFC	Power supply	0.3	V

Reagents

All reagents and solvents were available on the market and used as received, with purity correction of each. All solutions were prepared in deionized (DI) water purified by a Milli-Q ultrapure unit.

Preparation of the inoculum and biofilm formation

The MFCs were inoculated with a mixed consortium composed of electrogenic bacteria, recovered from anaerobic sediments (60 m deep) of the Paute River (Cuenca - Ecuador), of which 10 g of the sediment was suspended in 90 mL of iron chloride solution (0.05 M), sodium citrate (0.05 M), sodium acetate (0.03 M), ammonium chloride (0.03 M), potassium chloride (8.0 mM), sodium acid heptahydrate phosphate (0.7 mM), and sodium carbonate (0.05 M) during 72 h in anaerobic conditions to 37 °C ± 1 °C. Electroactive bacteria were isolated using solid media DSMZ 579 Geobacter.

The MFCs were monitored in the circuit implemented using a UNI-T TRMS multimeter (UT - 61D) for 72 h. Some samples were taken at intervals of time for the determination of total organic carbon (TOC), using a colorimetric method (Test 'N Tube Hach) with a spectrophotometer (Hach, model DR 1900).

The biofilm was growing on previously treated electrodes with 70% ethyl alcohol for 30 min and then washed with sterile water. Incubation was carried out in a 250 mL flask with 50% *v/v* BHI broth, 50% *v/v* whey and subsequent inoculation of bacteria isolated from the sediment consisting of 10 mL of anaerobic sediment with 10:3 dilution in electro-active bacteria medium previously incubated in anaerobiosis for 72 h and 37 °C [20].

Electrodes preparation

Carbon cylinders have 0.7 cm diameter and 1.8 cm height, which were subjected to a heat treatment in a red-hot lighter and immersed in a solution of nitric acid HNO3, 5.00 % *w/w* for 20 min and then treated with distilled water in an ultrasonic bath for 15 min.

The final isolation was made with epoxy resin (Loctite®, A.M.S.A S.A.). The connection between the wire and the electrode was evaluated by means of a multimeter.

Microbial fuel cells (MFC)

The MFC – MEM cell was built using standard PVC pipe connections with a nominal diameter of 38.1 cm and a commercial cellophane paper membrane as the protonic membrane, as shown in figure 1 [21].

The anodic chamber was adapted with two hoses of 0.5 cm diameter for inoculation and extraction of excess gas, while in the cathodic chamber, a hose was introduced for the entrance of air from a bubble pump.

Dairy serum was used as anolyte obtained from commercial pasteurized milk, using acid precipitation by the addition of a solution of sulfuric acid (H2SO4, 2.05 M) until pH 4.6 and 65 °C for 30 min and subsequent filtration for excessive amount removal of proteins and adjusted to pH 6.8 with a concentrated solution of potassium hydroxide KOH, 10 M.

Development and application of electronic circuits

To collect the energy of the MFCs, in this case, two voltage booster circuits were assembled (figures 5 and 6). Each one with a different configuration but with the same control system (microcontroller with PWM output). The pulse width modulation (PWM) determines the frequency and duty cycle flyback conversion [22].

For the experiment, the power source is the MFC, and the electronic device to be charged is a light-emitting diode, LED.

Circuits were assembled in protoboards, according to the values indicated in figures 5 and 6. A microcontroller was used as a control signal, which has programmed a PWM output (pulse-width modulation).

Figure 2 shows the diagram of the microcontroller program with its control output.

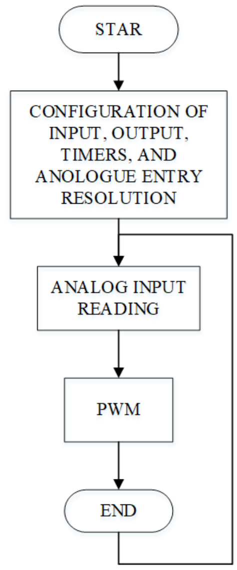

Figure 1. Flow diagram of the microcontroller program.

The objective of a static power converter is to obtain a waveform of voltage or controllable current to the output, using as input another voltage or current [23].

The first test assembly circuit is shown in figure 3, where the voltage increases due to the energy stored by the inductor L1. In this configuration, there are two important stages, which are determined by the operation of the M1 switch, which is controlled to operate in the conducting (closed) or disconnected (open) state. The complexity of applying this circuit is by the polarization voltage of the diode that must overcome the energy delivered by the MFCs.

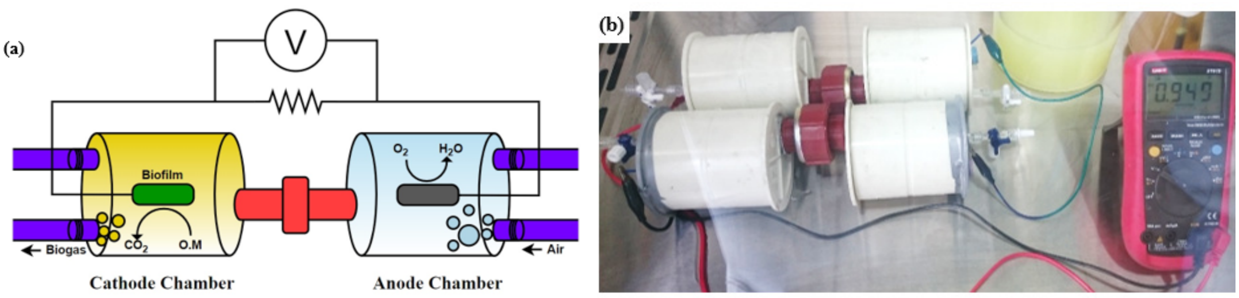

Figure 2. MFC-MEM. (a) Scheme used in the experiment. O.M: organic matter. (b) Real mfc-mem used.

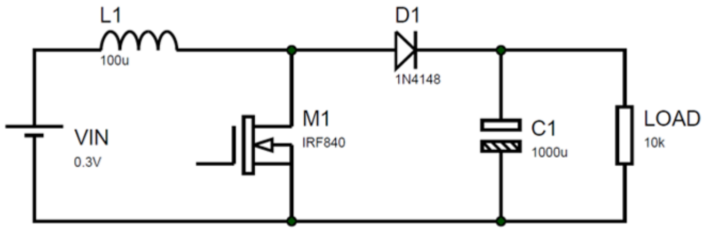

Figure 3. Diagram of converter circuit flyback Isolated based MFC energy harvesting system, where the voltage increases due to the energy stored by the inductor. L1 is the inductor. VIN is the energy delivered by the MFCs. M1 is the switch, which is controlled to operate in the conducting (closed) or disconnected (open) state. D1 quick switching diode. C1 energy storage capacitor.

The second configuration, the most suitable circuit and the one designed for the experiment, is a buck and boost converter isolated by FLYBACK transformer. This configuration does not use a diode until the amplification phase, where the voltage is already large enough to polarize the diode directly.

Figure 4 shows the circuit used. It consists of two mutually coupled coils, where their operation depends on the magnetization and demagnetization of them. This was achieved by the high-speed switching of the M1 switch.

The M1 switch, in this case, is a mosfet, the control was carried out using the PWM (pulse-width modulation) technique generated by a microcontroller, this signal reaches the gate of the M1 mosfet, controlling its switching between driving (closed) or disconnected (open) state.

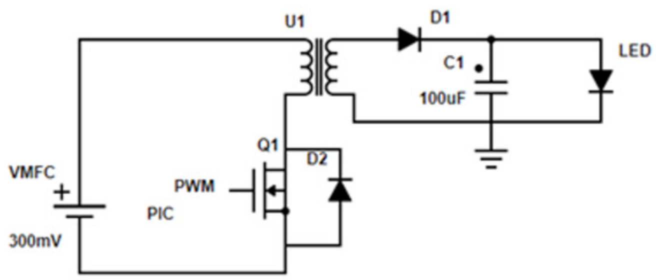

Figure 4. Diagram of elevator circuit by transformer, where VMFC is the MFC voltage. PWM pulse-width modulation. Q1 quick switching diode. D1, D2 diodes. U1 controller. C1 capacitor.

The second converter applied was an isolated flyback. This was the one that adjusted the most to the level of voltage generated by the cells. This type of converter is the most suitable for the collection of energy in this research. As can be seen, in figures 3 and 11, in which it was demonstrated the generation of bioelectricity by MFC, is a viable application to use it as clean energy, which may have practical applications, or for energy storage. The use of DC - DC converters can maximize the operation of the MFC cells in the efficiency of the collection and amplification of energy collected for practical uses.

The first part of this study showed that it was possible to obtain a voltage delivered by MFCs - MEM of 800 ± 50,3 mV and the voltage remained relatively stable for a period of 48 h, at which time MFC has degraded organic matter by 35.23 ± 6,5% and the decrease in TOC by 30.67 ± 5,2%.

Simulation

From the tests carried out, it could be observed that the circuit, which is more adapted to the characteristics of the MFCs, is the remote configuration. Therefore, before the implementation of the FLYBACK converter, a simulation was performed to observe the behavior of the circuit. This simulation was done based on open software, which can be obtained by the online way, called systemvision®. Figure 5 shows the simulated and assembly of the circuit.

In the various tests carried out, it can be concluded that the average power delivered by the cell is in the order of $P_{MFC} = 0.3$ mW, knowing that the power is given by:

$$P = V * I \qquad \text{Eq. (3)}$$

Where $V_{MFC} = 300$ mV, and $I_{MFC} = 1$ mA.

A light-emitting diode D2 was used as the charge for the circuit, which requires a voltage close to 3 V to turn on. As a switching element, a Q1 mosfet (IRF840) was used, which is controlled by a PIC12f683 (controller). The controller was programmed with a switching frequency of (1 / T), which is connected to the gate pin of the mosfet. In addition, a potentiometer was connected to a pin of the microcontroller, which varies the working frequency of the Q1 element. A better response of the circuit has achieved at the frequency of 1 kHz value with which the simulation was performed.

As the supply voltage for the circuit, the cell was replaced by a continuous voltage source of 300 mV and 1 mA of current. This source is an external power source with the primary objective of keeping the current and the voltage constant, equal to that provided by the MFC, to perform the measurements. These elements are detailed in table 1.

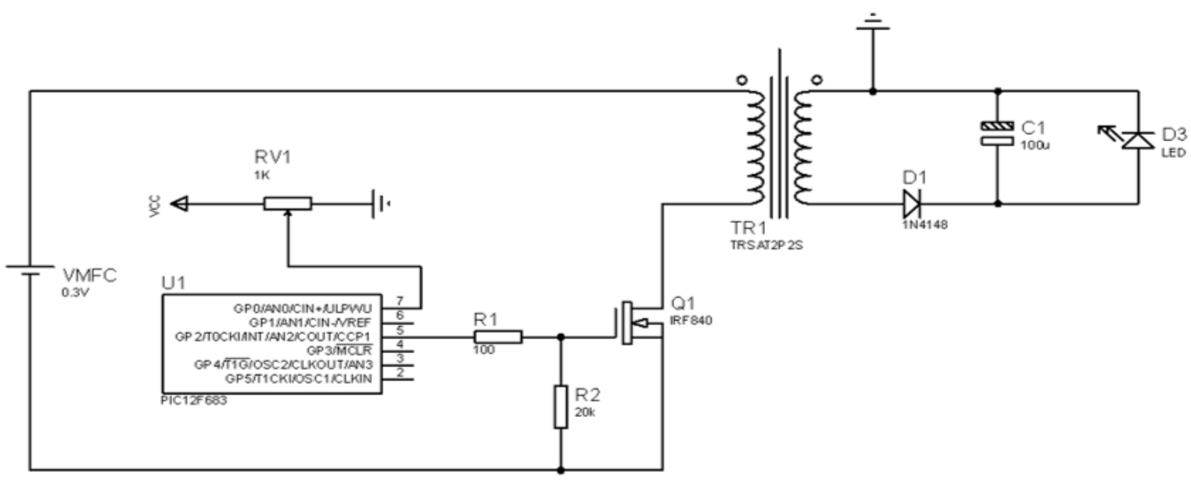

Figure 5. Diagram of circuit implemented. Voltage isolated elevator by transformer, where VMFC is the MFC voltage. RV1 potentiometer. U1 controller. R1, R2 resistances. Q1 switch. TR1 pulse transformer. D1 quick switching diode. C1 capacitor.

Results and discussion

MFCs evaluation

Potential evaluation

Several experimental tests were carried out with different associations and consortiums of bacteria (figure 6).

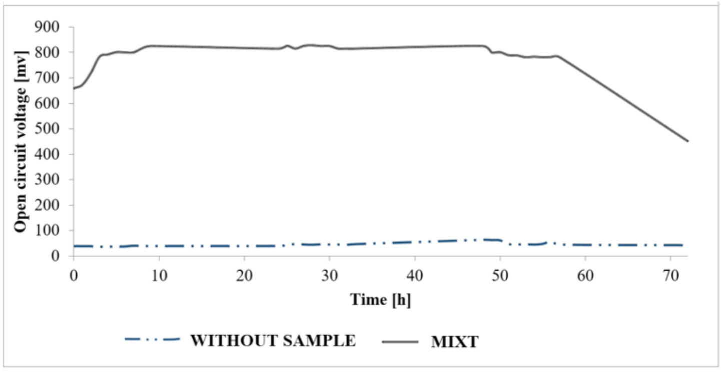

Figure 6. Graphical voltage [v] versus time [h]. Experimental result: MFC voltage, based energy harvester, with dairy serum without sample.

As can be seen in figure 6, the open-circuit voltage delivered by the MFCs-MEM is bordering the 800 mV and voltage keeps relatively stable for a period of 48 h, at which time the MFC has degraded the 35.23% organic matter and TOC decrease of 30.67%.

Polarization curves

To develop the circuit, the curves displayed in figure 7 were taken into consideration regarding the data provided by the polarization.

The characteristics of the generation of electricity by means of the MFCs through the polarization curve, where it has shown that the maximum power density is 30 MW·m^{-2} to 257 Ω and a current density of 0.415 mA×cm^{-2}, calculating the coulombic efficiency at this power density was 1.02%.

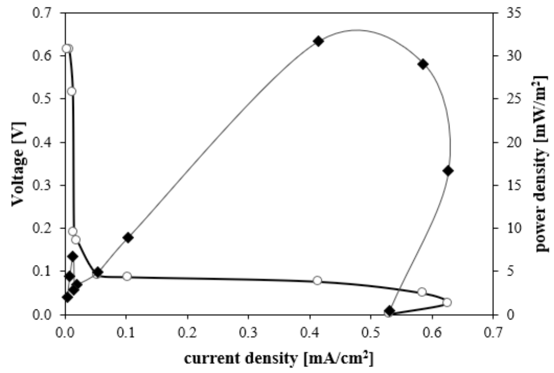

Figure 7. Polarization curve for a MFC-MEM on the first day with an initial toc of 45.24 g toc / l. Voltage (o) and power density (•) with a maximum power density of 30 mW / m2 and a current density of 0.415 mA / cm^2.

For the development and evaluation of the circuit, we worked with 50 mL cells with an architecture similar to the one described above. These MFCs delivered a voltage of 300 mV and a power of 0.3 mW.

Within the two circuits implemented, the most suitable circuit was the one of "transformer-isolated elevator" because the voltage delivered by the MFCs of 300 mV is not enough to directly polarize the diode D1 of the BOOST elevator converter configuration of figure 3, so the energy from the source cannot pass to the capacitor or the charge. An electrical power source should have a nominal output voltage that is higher than the band-gap of the semiconductor components used in the circuit. For example, for a germanium diode, a minimum of 0.3 V is required to turn on the diode [24].

The FLYBACK converter of the figures 4 and 5 is the circuit that was best adapted to the energy collection since it is not necessary to overcome the polarization voltage of the diode until a second stage when the signal can be amplified.

Circuit Simulation

The main objective of performing a simulation is to do virtual tests without running the risk of damaging any electronic element because, if that happened, it would imply an extra expense in the materials used in the assembly of the circuit.

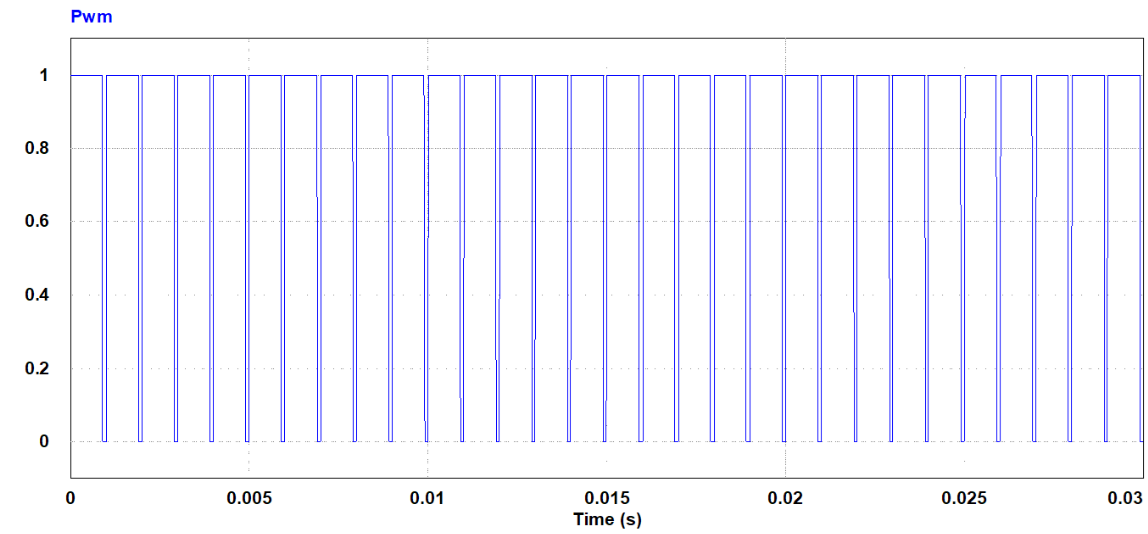

Figure 8. Duty cycle (high and low signal time), by control of magnetization and demagnetization of the transformer core. Where (PIC) is the controller, Q1 mosfet, RV1 potentiometer connected to the microcontroller PWM (Pulse-Width Modulation) signal in mosfet Q1.

With the use of the simulator, it would be easier to assemble the circuit in a prototype (protoboard), and there would be a high probability that the armed circuit would work correctly. Besides, with the simulator, it is easier to find errors when assembling the circuit, saving resources and time.

Once the circuit components have been calculated (Table 1) based on the input value and the desired output values, a simulation is carried out to check its operation before implementing the circuit.

To design an electronic circuit, which is too close to reality with the energy that provides, the MFCs, the following simulation was carried out. Figure 8 shows the results of the simulation.

Figure 8 shows the control signal generated by the controller (PIC) and which is connected to the Q1 mosfet, by varying the potentiometer RV1 connected to the microcontroller. The duty cycle (high and low time of the signal) can be varied, due to the magnetization and demagnetization control of the core of the transformer.

The implemented circuit can be divided into two stages marked by the configuration of the transformer, which is taken as an initial connection to the primary side of the transformer.

The cell signal in the transformer is treated initially by cutting and activating the switch (mosfet), allowing the magnetization of the core and the passage of energy to the secondary side. In figure 9a, the voltage can be seen on the primary side of the transformer. As it can be seen in figure 9b, the voltage delivered by the cell is continuous. The peaks and valleys shown correspond to the cut and saturation of the Q1 mosfet. The second stage of the circuit, connected to the secondary side of the transformer, uses the voltage delivered by the cell when it has already been raised by means of the diode D1. The energy pass is restricted in only one direction, and with the help of the capacitor C1, the shape of the voltage is softened.

Figures 10a and 10b show the difference between the input voltages VMFC (blue) and the output voltage V0 (green) (the voltage in the charge). We can see the voltage in the mentioned figures, the voltage of the VMFC is 0.3 V, while the output voltage V0 is close to 2.3 V, enough voltage to light a small charge such as a led.

MFCs evaluation

Circuit monitoring without Diode LED (D2)

Figures 11a and 11b show the circuit designed for the appropriate tests and data collection. It is worth mentioning that it is the same circuit, which was simulated through online software called systemvision®.

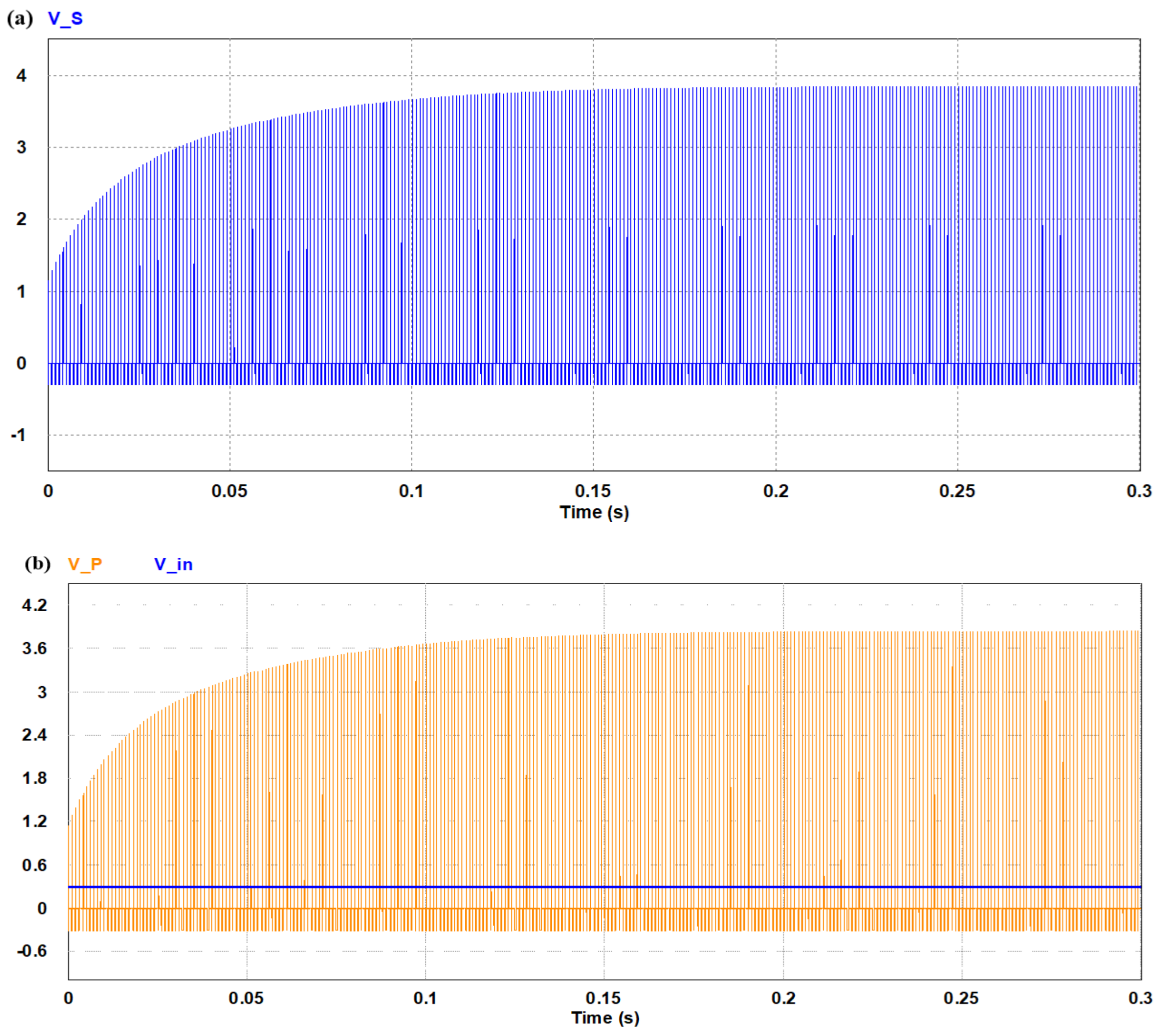

Figure 9. (a) Switched voltage from the second stage of the circuit, connected to the secondary side of the transformer, elevated by diode D1 and restricted energy passage in one direction only, with the help of capacitor C1. (b) First stage of voltage on the primary side of the transformer.

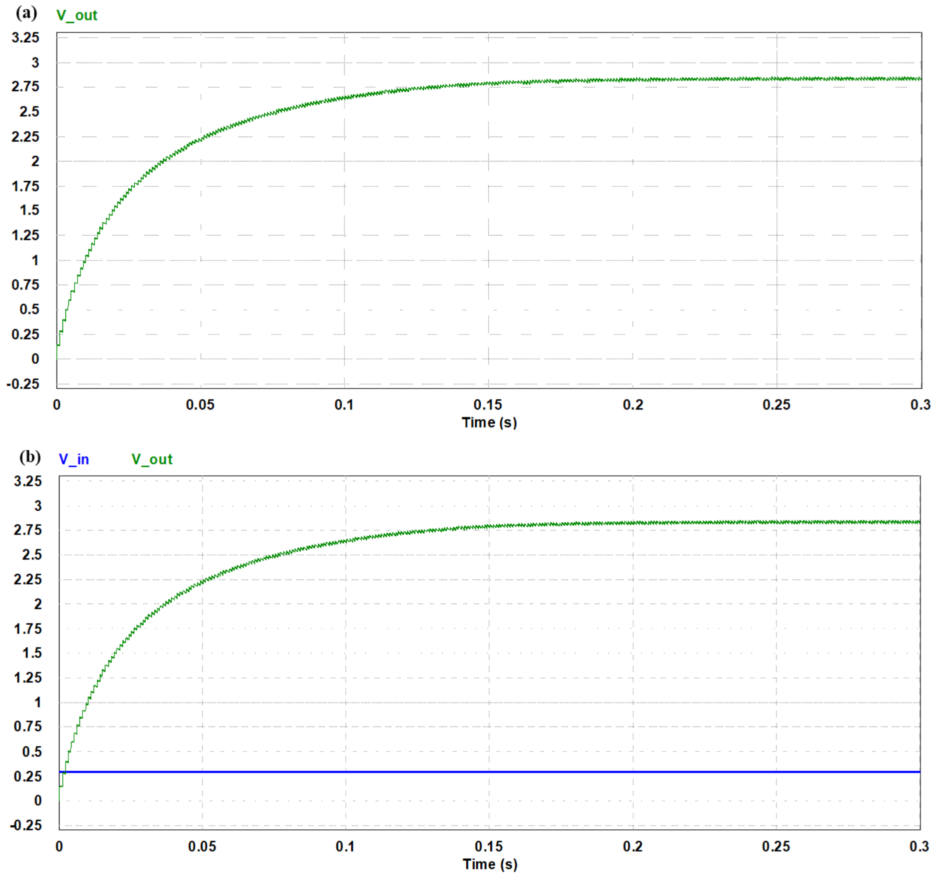

Figure 10. (a) Circuit evaluation without LED diode. Maximum Output voltage of the MFC after circuit application. (b) Output voltage V_0 vs Input voltage Difference between the input voltages VMFC (blue) and the output voltage V_0 (green) (the voltage in the charge) when the voltage of the VMFC is 0.3 V.

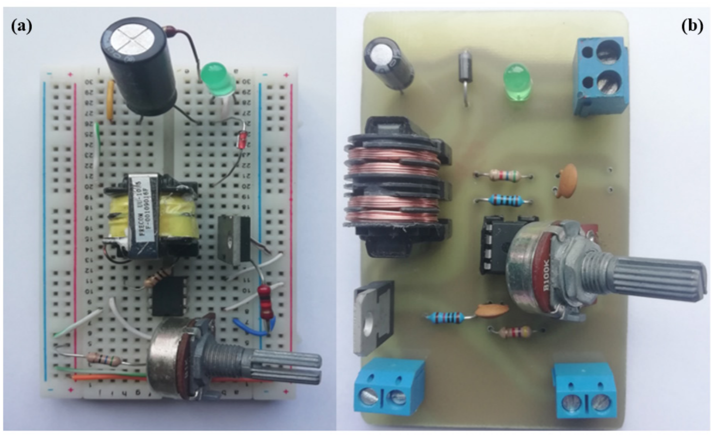

Figure 11. Physical circuit designed for the appropriate tests and data collection. (a) Protoboard circuit assembled. (b) Board circuit assembled

An MFC was taken as an energy source. Several voltage measurements were taken at the input and at the output of the circuit shown in the figures 11a and 11b.

Figure 12 shows the values obtained. As it is shown, the voltage delivered by the cell is close to 0.4 V and remains constant. The output voltage was taken initially without charge, then, all the voltage treated by the circuit was stored in the capacitor.

This can be appreciated in figure 4, where the voltage is delivered to capacitor C1 by the absence of charge D2. After 7 min, a led diode D2 was connected in parallel to the capacitor as the load of the circuit. As seen in figure 12, the output voltage drops from 6.5 V to 2.5 V, which voltage is enough to keep the charging diode on.

$V_{MFC} = 0.400$ V
$V_0 = 2.5$ V.

Where V_{MFC} is the input voltage generated by the MFC, and V_0 is the output voltage delivered by the diode (Amplified voltage by the circuit).

As can be seen in Figure 10, the voltage pick-up, obtained from the MFCS, can be used for low-voltage applications, using a transformer-isolated DC - DC flyback converter.

Circuit monitoring with diode LED (D2)

To check that the output voltage holds, several data were taken for 80 min with diode D2 connected to the circuit. Figure 13 shows the voltage of the MFC (blue) and the voltage of the charge V_0 (green).

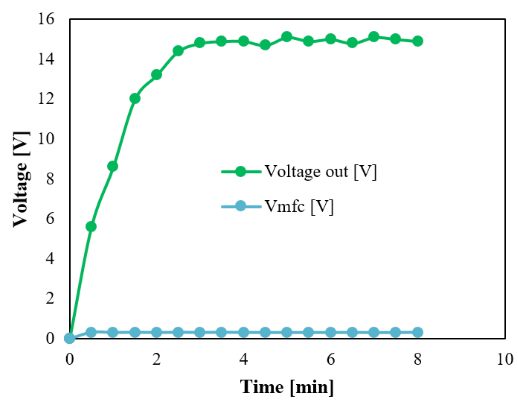

Figure 12. Voltage supplied by the MFC, close to 0.4 V being constant and the amplified voltage without load circuit, storing in the capacitor all the voltage treated by the circuit.

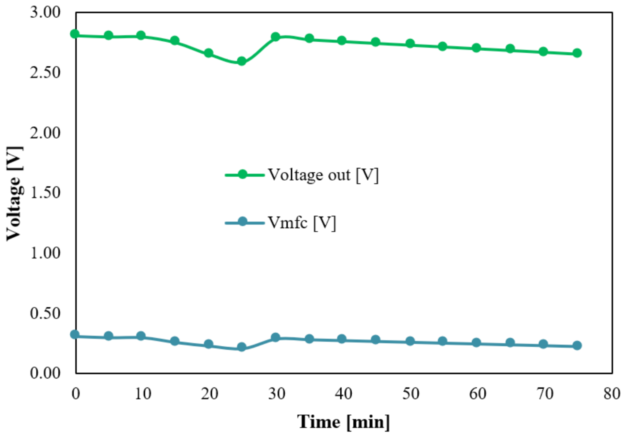

Figure 13. Voltage of the MFCs (blue) remained constant for about 80 minutes and the voltage of the load Vo (green) which is directly proportional to the voltage of the VMFC cells.

Figure 13 shows that the MFCs voltage remained constant for about 80 min (as it is shown in the output voltage Vo, which is directly proportional to the voltage of the VMFC cells). Then, if there is a voltage drop in the input, it would be watched in the output. In the same way, it is concluded that, if the cells are able to increase the voltage generation, more voltage can be obtained at the output of the circuit. In this way, this energy can ignite other small electrical devices that consume a higher amount of electrical energy. These voltage values were taken with a multimeter FLUKE model 322.

Final discussions

In this research, we have demonstrated that MFCs can generate clean energy or sustainable bioelectricity. Although removing 35.2 ± 6.5% of organic matter present in dairy serum, this process showed that the circuit was able to increase the voltage generated by the cell efficiently. Untreated organic matter by the MFCs could become part of a feed batch system of MFCs to degrade the remaining dairy serum further using advanced oxidation methods, or membrane technology, which are eco-friendly methodologies to obtain better quality water [25, 26].

Due to the power generated in the MFCs, which is limited, and it is not enough to feed continuously any electronic device of high consumption, it is necessary to use circuits of amplification and storage of energy. To generate enough power and operate electronic devices, some researchers have tried to build large MFCs [47, 48].

This task does not significantly improve the power output due to expansion problems in the MFCs. The power density does not remain constant when the electrode size is increased. To satisfy the energy needs of electronic devices, it is necessary to use capacitors, which would store the energy coming from the MFCs and then deliver it in short bursts of high power. The use of a capacitor does not produce power but allows the delivery of internal power [27].

The voltage provided by the MFC is in the order of millivolts [mV], so it is necessary to store that energy for use in everyday applications. The use of power electronics is crucial to manipulate and store this voltage. The MFC provides DC current of shallow values to reach a useful and adequate voltage; it is necessary the application and study of DC - DC converters specifically elevators (boost) or elevators-reducers (buck and boost) [28].

Therefore, in this research, it is specified that the implemented circuit demonstrates the production of clean energies or bio-electricity. This bio-electricity is produced through a metabolic process, characteristic of the bacteria used. Moreover, if more MFC are connected in series, there would be a higher production of clean energy.

Conclusions

This research showed a new system of energy collection from the generation of MFC, based on DC-DC converters. Two types of converters were implemented. The first, a boost converter that could not be applicable because the voltage level generated by the cells is not enough to polarize the elements directly to allow the passage of energy. And the second one, another booster converter, was implemented, which took advantage of the voltage generated by the MFCs, to allow the passage of bioelectricity. Although in this investigation, it was possible to turn on a led through an MFC, the expectation is to recreate the same system on a larger scale to feed larger sources, such as for lighting a home.

The present research shows that MFC generates bioelectricity (clean energy), but it should also be noted that the power generated in MFC is limited. This energy is not enough to keep continuously any electronic device on. To satisfy this need for energy, it is necessary to use capacitors, which would store the energy coming from the MFC and then deliver it in short bursts of high power. The use of a capacitor does not produce very high continuous power, but it does allow the delivery of internal power.

This article does not do a study of energy costs, but the clean energies would help to have a less polluted planet for future generations.

Acknowledgments

Our thanks to the Central University of Ecuador, the Government of Belgium for the contribution through the program of scientific projects “ARES”, and, especially, to the laboratory of renewable energies with its director, who had the leadership and vision to propose the topic of the present research project and choose a multidisciplinary human team, which allowed us to research and apply the necessary knowledge to contribute with the present work to have a planet with less pollution for our future generations.

References

[1] Z. Ge, J. Li, L. Xiao, Y. Tong y Z. He, «Recovery of Electrical Energy in Microbial Fuel Cells,» Environmental, science & Technology, pp. 137-141, 2014.

[2] B. Logan, Microbial Fuel Cells, WILEY, 2008.

[3] J. Trapero, L. Horcajada, J. Linares y J. Lobato, «Is microbial fuel cell technology ready? An economic answer towards industrial commercialization,» ELSEVIER, pp. 698-707, 2017.

[4] INSTITUTO NACIONAL DE ESTADISTICAS Y CENSOS, «Encuesta de Superficie y Producción Agropecuaria Continua ESPAC - 2014,» INEC, Quito, 2014.

[5] M. E. Romero Rengifo, «Desarrollo de un plan de manejo ambiental para la industria procesadora de leche Floralp ubicada en el cantón Ibarra-Imbabura,» Quito, 2009.

[6] M. Do, H. Ngo, Y. Guo, S. Liu, D. Chang, D. Nguyen, L. Nghiem y B. Ni, «Challenges in the application of microbial fuel cells to wastewater treatment and energy production: A mini review,» Science of the Total Environment, pp. 910-920, 2018.

[7] H. Wang, H. Luo, P. Fallgren, S. Jin y Z. Ren, «Bioelectrochemical system platform for sustainable environmental remediation and energy generation,» ELSEVIER, pp. 317-334, 2015.

[8] M. Alaraj, Z. Ren y J. D. Park, «Microbial fuel cell energy harvesting using synchronous flyback converter,» ELSEVIER, pp. 636-642, 2014.

[9] V. R. Nimjea, Chien-YenChen, H. R. Chen, C. C. Chen, Y. M. Huang, M. J. Tseng, K. C. Cheng and Y. F. Chang, «Comparative bioelectricity production from various wastewaters in microbial fuel cells using mixed cultures and a pure strain of Shewanella oneidensis, » Bioresource Technology, pp. 315-323, January 2012.

[10] S. Ishii, S. Suzuki, T. M. Norden-Krichmar, K. H. Nealson, Y. Sekiguchi, Y. A. Gorby y O. Bretschger, «Functionally Stable and Phylogenetically Diverse Microbial Enrichments from Microbial Fuel Cells during Wastewater Treatment,» PLOS, pp. 1-12, 2012.

[11] V. G. Gude, «Wastewater treatment in microbial fuel cells – an overview,» Journal of Cleaner Production, pp. 287-307, 2016.

[12] M. Gil Rodriguez, Depuración de aguas residuales: modelización de procesos de lodos activos, Madrid: CSIC - CSIC Press, 2006, p. 344.

[13] T. Krieg, L. Phan, J. Wood, A. Sydow, I. Vassilev, J. Krömer, K. Mangold y D. Holtmann, «Characterization of a membrane-separated and a membrane-less electrobioreactor for bioelectrochemical syntheses,» Bioprocess Engineering and Supporting Technologies, pp. 1705-1716, 2018.

[14] A. Trinidad Bello, «Modelos de crecimiento en biología, su significado biológico y selección del modelo por su ajuste,» Universidad Autónoma Metropolitana, México, D. F, 2014.

[15] B. M. B. L. SE Oh, «Cathode performance as a factor in electricity generation in microbial fuel cells,» Environmental science & technology - ACS Publications, p. 4900–4904, 2004 .

[16] P. K.Wu, J. C. Biffinger, L. A. Fitzgerald y B. R. Ringeisen, «A low power DC / DC booster circuit designed for microbial fuel cells,» Process Biochemistry, vol. 47, pp. 1620-1626, 2012.

[17] J. T. Maxwell, K. L. HsuAlex, P. Bart, Chadwick y Y. M. Arias Thode, «Scaling up benthic microbial fuel cells using flyback converters,» Journal of Power Sources, pp. 98-105, 2018.

[18] M. Forouzesh, Y. P. Siwakoti, S. A. Gorji, F. Blaabjerg y B. Lehman, «Step-Up DC – DC Converters: A Comprehensive Review of Voltage-Boosting Techniques, Topologies, and Applications,» IEEE Xplore, pp. 9143-9178, 2017.

[19] Y. E. Song, H. C. Boghani, H. S. Kim, B. G. Kim, T. Lee, B.-H. Jeon, G. C. Premier y J. R. Kim, «Electricity Production by the Application of a Low Voltage DC-DC Boost Converter to a Continuously Operating Flat-Plate Microbial Fuel Cell,» Energies — Open Access Journal, pp. 1-16, 2017.

[20] D. Gross et al., «Environmental chemistry through intelligent atmospheric data analysis,» Environmental Modelling & Software, vol. 25, pp. 760-769, June 2010.

[21] W. Logroño, M. Perez, G. Urquizo, A. Kadie, M. Echeverría, C. Recalde y G. Rákhely, «Single chamber microbial fuel cell (SCMFC) with a cathodic microalgal biofilm: A preliminary assessment of the generation of bioelectricity and biodegradation of real dye textile wastewater,» Chemosphere, vol. 176, pp. 378-388, June 2017.

[22] J. T. Babauta, M. Kerber, L. Hsu, A. Phipps, D. B. Chadwick y Y. M. Arias Thode, «Scaling up benthic microbial fuel cells using flyback converters,» Journal of Power Sources, pp. 98-105, 2018.

[23] A. López Cañon, R. Diez Medina y G. &. P. G. Perilla Galindo, «Convertidor multinivel DC / DC de alto voltaje en topología escalera,» Chemosphere, pp. 117-133, june 2017.

[24] P. K. Wu, J. C. Biffinger, L. A. Fitzgerald y B. R. Ringeisen, «A low power DC / DC booster circuit designed for microbial fuel cells,» Process Biochemistry, vol. 47, pp. 1620-1626, November, 2012.

[25] S. Sakthivel, B. Neppolian, M. V. Shankar, B. Arabindoo, M. Palanichamy y V. Murugesan, «Solar photocatalytic degradation of azo dye: comparison of photocatalytic efficiency of ZnO and TiO2,» Solar Energy Materials and Solar Cells, vol. 77, pp. 65-82, n° 330, April, 2003.

[26] R. X. Zhang, L. Braeken, T. Y. Liu, P. Luis, X. L. Wang y B. V. d. Bruggen, «Remarkable Anti-Fouling Performance of TiO2-Modified TFC Membranes with Mussel-Inspired Polydopamine Binding,» Applied Sciences, pp. 1-15, n° 13, January, 2017.

[27] j. D. Park y Z. Ren, «High efficiency energy harvesting from microbial fuel cells using a synchronous boost converter,» Journal of Power Sources, pp. 322-327, 2012.

[28] M. Gomez Valencia y A. Alzate Gomez, «Diseño estático de un convertidor DC / DC reductor-elevador bidireccional,» Tecnura, vol. 14, nº 26, pp. 7-14, June 2010.

[29] A. Dewan, C. Donovan, D. Heo y H. Beyenal, «Evaluating of performance the microbial fuel cells powering electronic devices,» Journal of power sources, pp. 90-96, 2010.

[30] F. Lobo, H. C. Wang y Z. Ren, «AC power generation from microbial fuel cells,» ELSEVIER, pp. 252-259, 2015.

[31] X. Elias, Reciclaje de residuos industriales, Madrid: Diaz de Santos, 2012.

[32] F. Davis, S. P. y J. Higson, «Biofuel cells-Recent advances and applications,» ELSEVIER, pp. 1224-1235, 2007.

[33] B. Min y B. Logan, «Continuous Electricity Generation from Domestic Wastewater and Organic Substrates in a Flat Plate Microbial Fuel Cell,» Environment Science & Technology, pp. 5809-5814, 2004.

[34] J. D. Park y Z. Ren , «High efficiency energy harvesting from microbial fuel cells using a synchronous boost converter,» ELSEVIER, pp. 322-327, 2012.

[35] H. Wang, Z. Ren y J. D. Park, «Power electronic converter for microbial fuel cells energy extraction;Effects of inductance, duty ratio, and switching frequency,» ELSEVIER, pp. 89-94, 2012.

[36] M. Hatzell, Y. Kim y B. Logan, «Powering microbial electrolysis cells by capacitor circuits charged using microbial fuel cell,» ELSEVIER, pp. 198-202, 2013.

[37] D. E. A. Thivierge, «Power conditioner for microbial fuel cells,» United States Patent, pp. 1-11, 2012.

[38] F. Hernández, et al., «Recent progress and perspectives in microbial fuel cells for bioenergy,» Fuel Processing Technology, pp. 284-297, 2015.

[39] B. Chandrasekhar y P. Naresh, «Analysis of Single Phase Boost Converter and Poly Phase Boost,» International Journal of Modern Engineering Research, pp. 1-5, 2016.

[40] Z. J. J. D. MuhannadAlaraja, «Microbial fuel cell energy harvesting using synchronous flyback converter,» Journal of Power Sources, vol. 247, pp. 636-642, February 2014.

[41] F. Davis, S. P. y J. Higson, «Biofuel cells-Recent advances and applications,» Biosensors and Bioelectronics, vol. 22, pp. 1224-1235, 15 February 2007.

[42] A. Dewan, C. Donovan, D. Heo y H. Beyenal, «Evaluating the performance of microbial fuel cells powering electronic devices,» Journal of Power Sources, vol. 195, pp. 90-96, 1 January 2010.

[43] X. Elias, «Reciclaje de residuos industriales,» SEGUNDA ed., 2. Ediciones Díaz de Santos, Ed., Madrid, Diaz de Santos, 2012, p. 1320.

[44] Z. Ge, J. Li, L. Xiao, Y. Tong y Z. He, «Recovery of Electrical Energy in Microbial Fuel Cells,» Environmental, Science & Technology, pp. 137-141, 4 September 2013.

[45] M. Hatzell, Y. Kim y B. Logan, «Powering microbial electrolysis cells by capacitor circuits charged using microbial fuel cell,» Journal of Power Sources, vol. 229, pp. 198-202, 1 May 2013.

[46] B. E. Logan, Microbial Fuel Cells, J. &. s. Wiley, Ed., Hoboken, New Jersey: WILEY, 2008, p. 216.

[47] A. M. López Cañón, R. F. Díez Medina, G. Perilla Galindo y Patiño Guevara, «Convertidor multinivel DC / DC de alto voltaje en topología escalera,» REDALYC, vol. 16, nº 1, pp. 117-133, 2012.

[48] B. Min y B. Logan, «Continuous Electricity Generation from Domestic Wastewater and Organic Substrates in a Flat Plate Microbial Fuel Cell,» Environment Science & Technology, pp. 5809-5814, 23 September 2004.

[49] J. D. Park y Z. Ren , «High efficiency energy harvesting from microbial fuel cells using a synchronous boost converter,» Journal of Power Sources, vol. 208, pp. 322-327, 15 June 2012.

[50] B. SE Oh, «Cathode performance as a factor in electricity generation in microbial fuel cells.,» Environmental science & technology - ACS Publications, pp. 4900-4904, August 2004.

[51] D. E. A. Thivierge, «Power conditioner for microbial fuel cells,» United States Patent, pp. 1-11, 31 July 2012.

[52] J. Trapero, L. Horcajada y J. Lobato, «Is microbial fuel cell technology ready? An economic answer tovwards industrial ccommercialization.,» Applied Energy, vol. 185, pp. 698-707, 01 January 2017.

[53] H. Wang, H. Luo, P. Fallgren y S. &. R. Z. Jin, «Bioelectrochemical system plataform for sustainable environmental remediation and energy generation,» Biotechnology Advances, vol. 33, pp. 317-334, May - August 2015.

[54] H. Wang, J. D. Park y Z. J. Ren, «Practical energy harvesting for microbial fuel cells,» Environmental Science & Technology, pp. 3267-3277, February 2015.

[55] H. Wang, Z. Ren y J. D. Park, «Power electronic converter for microbial fuel cells energy extraction;Effects of inductance, duty ratio, and switching frequency,» Journal of Power Sources, vol. 220, pp. 89-94, December 2012.

[56] J. Babauta, M. Kerber, L. Hsu, A. Phipps, B. Chadwick y M. Arias Thode, «Scaling up benthic microbial fuel cells using flyback converters,» Journal of Power Sources, vol. 395, pp. 98-105, 15 August 2018.

[57] M. Alaraj, Z. Ren y J. D. Park, «Microbial fuel cell energy harvesting using synchronouas flyback converter,» Journal of Power Sources, vol. 247, pp. 636-642, 01 02 2014.

[58] H. Wang, Z. Ren y J. D. Park, «Power electronic converters for microbial fuel cell energy extraction: Effects of,» Journal of Power Sources, vol. 220, pp. 89-94, 15 December 2015.

[59] F. Lobo, H. Wang y Z. Ren, «AC power generationfrom microbial fuel cells,» Journal of Power Sources, vol. 297, pp. 252-259, November 2015.

[60] F. Carvalho, A. Prazeres y R. Javier, «Cheese whey wastewater: characterization and treatment,» Science of The Total Environmen, pp. 385-396, 15 February 2013.

[61] R. M. Atlas, Handbook of Microbiological Media, Cuarta ed., Boca Raton: CRC press, 2010.

[62] F. Hernández Fernández, A. Perez de los Rios, M. Salazar García, L. Lozano Blanco, C. Godinez y J. Quezada Medina, «Recent progress and perspectives in microbial fuel cells for bioenergy,» Fuel Processing Technology, vol. 138, pp. 284-297, October 2015.

[63] V. Gnaneswar Gude, «Wastewater treatment in microbial fuel cells e an overview,» Journal of Cleaner Production, vol. 122, pp. 287-307, Mayo 2016.

[64] I. N. D. E. Y. C. Ecuador, «Encuesta de Superficie y Producción Agropecuaria Continua ESPAC - 2014,» INEC, Quito, 2014.

Article citation:
D. G. Arboleda-Avilés, O. F. Núñez-Barrionuevo, O. F. Sánchez-Olmedo, B. D. Chinchin-Piñan, D. A. Arboleda-Briones & R. A Bahamonde-Soria. "Application of a direct current circuit to pick up and to store bioelectricity produced by microbial fuel cells" *Rev. Colomb. Quim.*, vol. 48, no. 3, pp. 26-35, 2019. DOI: http://dx.doi.org/10.15446/rev.colomb.quim.v48n3.77011.