ENERGY HARVESTING FROM MICROBIAL FUEL CELL
USING SELF-SYNCHRONOUS FLYBACK CONVERTER

by
Muhammad, A Alaraj
Bachelor of Electrical Engineering, Qassim University, 2008

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Muhammad, A Alaraj

has been approved for the

Electrical Engineering Program

by

Jae-Do Park, Chair

Tim C. Lei

Jason Ren

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ABSTRACT

Microbial Fuel Cells (MFCs) use biodegradable matter, such as wastewater and animal droppings to generate electrical energy. To harvest the energy from MFC, power electronic converters have recently been used because of their advantages, such as the ability to store the harvested energy and the ability to control MFC voltage. Although power electronic converters have advantages to be used to harvest the energy, the diode based energy harvesters suffer from the low efficiency because of the diode losses. Replacing the diode with a MOSFET reduces the loss because MOSFET have lower conduction loss, but this replacement causes the synchronous MOSFET to be floating, which requires an isolated gate signal. This study presents harvesting energy from MFC using self-synchronous flyback converter, which improved the harvesting efficiency by 37.6% compared to a diode based boost converter.

The form and content of this abstract are approved. I recommend its publication.

Approved: Jae-Do Park
DEDICATION

I dedicate this work to Abrar, my lovely wife, who has always believed and supported me.
ACKNOWLEDGMENTS

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CHAPTER I
MICROBIAL FUEL CELL

Introduction

The main purpose of this thesis is to harvest the energy efficiently from Microbial Fuel Cell (MFC). MFC uses biodegradable matter, such as wastewater and animal droppings to generate electrical energy. Employing the bacteria to generate electricity is the basic idea of the microbial fuel cell. The bacteria oxidize their food source, and electrons are produced. When closing the circuit, electrons will circulate and electricity will be generated. In the recent researches, the MFC was improved to produce big enough power to be considered as a power source [21, 22]. MFCs can be built in the lab [5, 6] also in the ocean [1, 2], which is very useful to have a renewable source of electrical power under the ocean water. The U.S. Navy supported some researches on the MFC to be able to use it under water to power sensors [1, 2], and it might be used for other applications. One important problem of MFC is that it has a low output voltage and it cannot be connected in series with other MFCs to have a higher output voltage [3, 4], because of their nonlinear behavior.

Electrical Characteristics of MFC

Voltage-Current Polarization Curve

The polarization curve is the relation between the voltage and the current output of the MFC. Different MFCs might have different output power, but usually they have similar polarization curves. Figure I.1 shows two different MFCs, and it is clear that they have the same shape but different current and voltage values.
Figure I.1 Polarization Curve of Two Different MFCs [5].
Figure I.2  MFC Electrical Equivalent Circuit [5].

**Internal Resistance**

The voltage of the MFC when its terminals are open is generally 0.7 V. This voltage on the terminal of the MFC decreases when an external resistance is connected to the MFC, in other words, when a current flows through the MFC. The internal resistance of the MFC causes this voltage drop. The equivalent circuit of the MFC is shown in Figure I.2 [5]. The value of the internal resistance varies depending on factors such as reactor size and environmental conditions.

**Maximum Power Point**

There is a point of operation where the maximum power can be extracted from MFC. The maximum power extraction from MFC happens when an external resistance equal to the internal resistance is connected to MFC. The maximum power point can be seen in the polarization curves that are shown in Figure I.1. The internal resistance of the
MFC varies depending on the environmental conditions, but in most cases it can be assumed to be constant. Using algorithms that have been developed to track the maximum power point, the maximum power can be extracted using a variable resistor or using DC-DC converters [6, 7].

**Advantages and Disadvantages**

The MFC has many advantages that make it an important energy source and those advantages can be listed as follows:

- Sustainable power source.
- Clean power source from the environment point of view.
- Direct conversion of substrate energy to electricity [8].
- Works in ambient and low temperature [8].
- Operates in under water environment.

However, it also has some disadvantages that affect its operation:

- Low output voltage.
- Low output current, few milliamps depending on the size of the MFC.
- Depends on environmental conditions.
- Cannot be stacked in series to get higher output voltage, because of their nonlinear behaviour [3, 4].
CHAPTER II

MFC ENERGY EXTRACTION

Introduction

To use the energy generated by the MFC, an electrical circuit needs to be connected to harvest this energy. Different harvesters have been used in the recent years’ MFC research, including resistors and power electronic converters. This chapter will briefly review the previous work that has been done to extract the energy from the MFC.

MFC energy harvesters can be divided into passive harvesters and active harvesters. Each type of harvesters will be briefly discussed.

Passive Energy Extraction

Resistors

Extracting the energy from MFC using an external resistor is the most basic technique and has been widely used [12, 23, 24]. When an external resistor is connected to MFC, the current will start flowing through the resistor and the MFC voltage is given as:

$$V_{MFC} = I R_{ext}$$

where, $V_{MFC}$ is MFC output voltage which is the voltage across the external resistor, $I$ is the current passing through that resistor, and $R_{ext}$ is the resistance of the external resistor. When the current passes through the resistor, the extracted power will be dissipated in the resistor. This power dissipation shows the amount of extracted energy:
\[ E_{disp} = \int P_{disp} \, dt \quad \text{where,} \quad P_{disp} = I^2 R_{ext} \]

To dissipate the maximum amount of power on the external resistor, the external resistor must be equal to the internal resistance of the MFC. This can be seen in the following equations:

\[ P_{out} = I^2 R_{ext} \]

\[ I = \frac{V_{mfc}}{R_{int} + R_{ext}} \]

\[ P_{out} = \frac{V_{MFC}^2}{(R_{int} + R_{ext})^2} R_{ext} \]

\[ \frac{dP_{out}}{dR_{ext}} = 0, \ R_{ext} - R_{int} = 0 \rightarrow R_{ext} = R_{int} \]

A variable external resistance was tested in [12] with developed perturbation and observation (P&O) algorithm to track the maximum power point of the MFC, and the algorithm is able to set the external resistance equal to the internal resistance even it is changing. The disadvantage of using external resistor is that the extracted energy will burned in the resistor, which will not make the energy usable.

**Supercapacitors**

Using a supercapacitor is more useful than using a resistor because the supercapacitor stores the energy instead of burning it in the resistor. Supercapacitor is a simple way to harvest and store the energy from the MFC, by connecting it in parallel with the MFC. In [1, 2, 14], a capacitor and DC-DC converter are used to power wireless sensors. Different combinations have been used, but they share the idea of connecting the
capacitor directly to the MFC. Also, the capacitor was used in [13] to develop a MFC tester. To determine the charging and discharging frequency, and the optimum capacity of the capacitor for given charging and discharging potentials, and the optimum charging potentials when the discharge potentials and capacitor values are given.

**Charge Pumps**

Charge pumps were used to harvest the energy from the MFC. Charge pumps basically use capacitors and switches, and the operation of the charge pumps can be explained in the simple circuit shown in Figure II.1. Two modes of operation are present in the charge pumps. The first mode of operation is when the switches $S_1$ and $S_3$ are closed and the switch $S_2$ is opened. The capacitor is now in parallel with the supply and it will start charging to reach the supply voltage following the capacitor voltage-current equation:

![Simple Charge Pump Diagram](image-url)
After charging the capacitor the switches $S_1$ and $S_3$ open and the switch $S_2$ close, which is the second operation mode. During this mode the capacitor is in series with the supply and the output voltage is equal to:

$$V_{out} = V_{in} + V_c$$

Using charge pumps with the MFC has an advantage of being able to harvest the energy with higher voltage. In [11], the charge pump was applied directly to the MFC and a supercapacitor was connected at the output of the charge pump to store the energy. The charge pump is not a preferred choice because of the low efficiency at 16.6% - 24.4% [11], and the limited controllability.

**Active Energy Extraction**

**Power Electronics Converters**

Passive energy extraction from the MFC is not useful, because resistors burn the energy, and capacitors can lead the voltage to drop in the MFC. When a supercapacitor is connected to MFC, current flows and charges the supercapacitor, and at some point the voltage of the supercapacitor will be equal to the voltage of the MFC and the current will stop flowing, which will stop harvesting the energy from the MFC. The better way to extract the energy from the MFC is by active energy extraction using power electronics converters [5, 6, 15, 16, 19]. The energy can be stored in a capacitor and the voltage of the MFC can be maintained within the desirable limits when using converters. Inductance, duty ratio, and the switching frequency are the elements that affect the energy extraction and their effect was investigated in [15].
**Boost Converter**

The need to increase the voltage of the MFC made the use of the boost converter attractive [5, 16, 17, 18, 19]. The boost converter schematic is shown in Figure II.2. On the first time period $T_1$, when the switch $Q_1$ is closed and the switch $Q_2$ is open, the current will flow through the inductor $L$. The voltage across the inductor will start increasing and the current decreases following the basic inductance current voltage relation:

$$V_L = L \frac{di(t)}{dt}$$

where, $V_L$ is the voltage across the inductor $L$, and $i_L$ is the current passing through it. During the second time period $T_2$, the switch $Q_1$ should be opened and the switch $Q_2$ should be closed to forward the current to the load. During this time the current will start to flow through the switch $Q_2$ to charge the capacitor:

$$V_c = V_{in} + V_L$$

where, $V_c$ is the output capacitor voltage and the $V_L$ is the inductor voltage achieved on the first time period Switching between these two modes in high frequency will allow the energy to be stored in the capacitor with a boosted voltage. The switching frequency depends on the time spent in the two modes:

$$F_s = \frac{1}{T_s} , \quad where \ T_s = T_1 + T_2$$

The output voltage of the boost converter is:

$$V_{out} = \frac{V_{in}}{1 - D}$$
where, \( D \) is the duty ratio, which is related to the amount of time spent at each period and it can be calculated as follows:

\[
D = \frac{T_1}{T_1 + T_2}
\]

where, \( T_1 \) and \( T_2 \) are the times spent on the first and second period respectively. Notice that the maximum number of the duty ration is one. In [5], a simple boost converter was used with a MOSFET as \( Q_1 \) and a diode as \( Q_2 \). The reported efficiency was low at 43.8%. The main reason of this low efficiency is the diode drop, because the voltage across the diode is around 0.6 \( V \) and the current flows through this diode during the second time period. The diode losses can be calculated as follows:

\[
P_{loss} = V_D \, I_{mfe} \, (1 - D) \, T_s
\]
Loss of the diode is very high especially compared to the low power output of MFC, which is drawback of the diode-based boost converter. To avoid the high loss of the diode, a synchronous boost converter was used in [16]. The synchronous boost converter replaces the diode by a MOSFET, because the MOSFET has low on-resistance. The problem of using the synchronous boost converter is that the MOSFET in place of the diode will become a floating switch, which needs to be driven by a separate or isolated source. In [16] a transformer was used to drive the synchronous MOSFET by isolated signal, and an efficiency of 75.9% has been achieved.
CHAPTER III

FLYBACK CONVERTER

Introduction

The idea of using the synchronous boost converter with a transformer-based circuit to drive the synchronous floating switch makes the flyback converter a viable alternative, because the flyback converter already has a transformer that can be used to drive the synchronous floating switch. Hence, the synchronous flyback converter will be more efficient than the diode-based boost converter, by eliminating diode and using the main transformer for gating signal as well as power transfer. This chapter gives a background review on the flyback converter and its operation.

Basic Topology for Flyback Converter

Figure III.1 shows a basic flyback converter schematic. The flyback converter is derived from the boost converter, but with a transformer to step up the voltage. The transformer is also used to isolate the input and the output, which is required for some applications. The transformer must be designed to have a good coupling so that the primary and the secondary are linked with minimal leakage flux. The primary and the secondary of the transformer windings do not carry current simultaneously. Each side of the transformer will carry current only during a part of the switching period depending on the duty ratio.
The operation of flyback converter is defined by two modes: On-State and Off-State. Each mode of operation can be described with a separate equivalent circuit that will help to understand the operation of the flyback converter.

When the switch $S$ in Figure III.1 closes, the primary winding of the transformer is connected to the power supply’s positive terminal. During this time the diode on the secondary side will be reverse biased and open the secondary side of the transformer. Now, the input voltage will appear across the primary winding and the current will flow through the primary winding with this current-voltage relation:

$$V_L = L \frac{di_L(t)}{dt}$$

where, $V_L$ is the voltage across the primary inductor and $i_L$ is the inductor current passing through it. The secondary current will not flow because the secondary circuit is open. Hence, the flux will be established in the core by the primary current only. This is the on-
state mode and Figure III.2 shows the current carrying part of the circuit during this mode of operation. The energy will be stored in the magnetic field and it can be calculated using this relation:

\[ E_{\text{stored}} = \frac{1}{2} L_p I_p^2 \]

Where \( I_p \) denotes the magnitude of the primary current at the end of the conduction period. At the end of the first time period the switch \( S \) should be opened, which will cut the current path on the primary winding. By opening the current path, the voltage of the primary winding should be reversed according to the magnetic induction laws. Reversing the voltage polarity of the primary side will also reverse the polarity of the secondary side. This makes the diode on the secondary side forward biased, which will allow the current to pass through the secondary winding and charge the capacitor. This is the second mode of operation, and the equivalent circuit can be seen in Figure III.3.

**Continuous versus Discontinuous Flux Operation**

Operating the flyback converter such that the primary switch closes before the secondary current goes to zero is known as the continuous flux operation because the magnetic flux in the transformer core is never zero. In the continuous flux operation, the current that flows in the primary winding will not start from zero because of the existing magnetic flux. On the other hand, the discontinuous flux operation happen when the current at the secondary side of the transformer goes to zero before the primary switch is on. Having zero current in both sides of the transformer means zero flux in the core.
\[ V_{\text{pri}} = E_{\text{dc}}, \quad V_{\text{sec}} = E_{\text{dc}} \frac{N_2}{N_1} \]

Figure III.2 First Mode of Operation.

\[ V_{\text{pri}} = V_{\text{out}} \frac{N_1}{N_2}, \quad V_{\text{sec}} = V_{\text{out}} \]

Figure III.3 Second Mode of Operation.
Synchronous Flyback Converter

The basic flyback converter shares the disadvantage of the diode losses with the basic boost converter. For this reason the synchronous flyback converter is better choice to increase the efficiency since the MOSFET has much lower conduction losses. The synchronous flyback converter, shown in Figure III.4, has same structure as the basic flyback converter but with a MOSFET instead of the diode. The challenge with replacing the diode with a MOSFET is the driving of the synchronous MOSFET since it is a floating switch. The gate drive circuit of the synchronous MOSFET must turn it on when the primary switch is off, and must block the reverse current in case of discontinuous operation.

The reverse current must be considered because the MOSFET conducts bidirectional current, and if it is not turned off when the current reduces to zero, the energy stored in the capacitor will be discharged through the synchronous MOSFET to the transformer.
CHAPTER IV

PROPOSED SYSTEM

Introduction

The best way to harvest the energy is using power converters, which have many advantages over the other harvesters. They are able to maintain the voltage of the MFC at certain levels, which will be necessary to extract the maximum power from the MFC, and converters give the ability to store the harvested energy. However, their efficiency needs to be improved as much as possible.

Since a transformer was used to drive the synchronous MOSFET of the boost converter because it is a floating switch [6], the idea of using the flyback converter was considerable. Therefore the self-synchronized flyback converter [20] will be a good choice because it synchronizes the secondary MOSFET by itself, so the only thing needs to be driven is the primary MOSFET, which is easy to drive. To drive the primary MOSFET, a non-inverting hysteresis controller will be used.

This thesis claims that using the self-synchronized flyback converter will be more efficient than using the basic boost converter with a diode because of the MOSFET at the secondary side. The operation of the self-synchronized flyback converter and the non-inverting hysteresis controller will be discussed in details in this chapter.
Self-Synchronous Flyback Converter

The self-synchronized flyback converter [20] is basically a synchronous flyback converter with a designed driving circuit that will drive the synchronous MOSFET using the voltage across the output capacitor. The self-synchronized flyback converter is shown in Figure IV.1, and it can be seen that the synchronous MOSFET will be driven by using the output capacitor voltage. Since the capacitor to store the energy must be big enough to store the harvested energy, it takes time to build a voltage that can drive the MOSFET. At the beginning, when the output capacitor voltage is zero, the body diode of the MOSFET will be used as a switch until the capacitor builds a voltage equal to the minimum gate threshold voltage of the MOSFET. This means that at the beginning the circuit will act like a basic flyback converter.

Operation of the Self-Synchronous Flyback Converter

The operation is similar to the operation of the basic flyback converter discussed in the previous chapter. The only thing that will change is when the output capacitor builds some voltage. The synchronous MOSFET gate drive circuit will start operating. Note that the operation of the flyback converter will not change, so the only thing that needs to be discussed is the operation of the synchronous driving circuit.

The synchronous driving circuit [20] consists of two resistors: \( R'_1, R'_2 \); and three transistors: \( Q_1, Q_2, Q_3 \); and a diode \( D_a \). The transistor \( Q_1 \) operates as inverter. The transistors \( Q_2 \) and \( Q_3 \) operates as push-pull, which is needed to improve the transition of
the driving circuit. The diode $D_d$ is used to detect the polarity of the voltage across the MOSFET, which will be used to operate the transistor $Q_1$. To understand the operation of the synchronous driving circuit, its operation will be discussed step by step.

After opening the primary switch, current starts to flow in the secondary side passing through the body diode of the MOSFET. This makes the voltage $V_{AB} > 0$, which will make the diode $D_d$ forward biased with a higher voltage than the base-emitter voltage $V_{be}$ of the transistor $Q_1$. For this reason the diode $D_d$ will be forward biased as in Figure IV.2(b). The transistor $Q_1$ will remain turned off, and when the transistor $Q_1$ is off the base of the transistors $Q_2$, $Q_3$ will have the voltage of the $Q_1$ collector that is high. Having the voltage $V_c$ connected to the base of the transistors $Q_2$ and $Q_3$ through the resistor $R_2'$ will turn the transistor $Q_2$ on and turn the transistor $Q_3$ off. When the

---

**Figure IV.1** Self-Synchronous Flyback Converter.
transistor $Q_2$ is turned on, the voltage $V_c$ will be connected to the gate of the synchronous MOSFET as in Figure IV.2(c). Now, the gate-source voltage of the synchronous MOSFET is equal to the capacitor voltage and the MOSFET will be turned on as in Figure IV.2(d).

When $V_{AB} < 0$, either when the primary switch is closed or the current reversed its direction in case of discontinuous operation, the diode $D_d$ will be reversed biased as in Figure IV.2(e), and the base-emitter of the transistor $Q_1$ will be connected to $V_c$ through the resistor $R'_1$. This will turn the transistor on, and the base of the transistors $Q_2$ and $Q_3$ will be connected to a low voltage. This will turn the transistor $Q_2$ off, and the transistor $Q_3$ will be turned on. The gate of the synchronous MOSFET will now be connected to a low voltage and it will be turned off as in Figure IV.2(f).
Figure IV.2 Synchronous Driving Circuit Operation.
To be able to maintain the MFC voltage at the desirable level, the hysteresis controller can be used. The inverting hysteresis controller was used with the boost converter [5, 16]. When using the inverting hysteresis controller, a transistor must be added to invert the output signal. This transistor can be eliminated if the non-inverting hysteresis controller is used. The non-inverting hysteresis controller shown in Figure IV.3 can maintain the voltage of the MFC at the desirable level. Choosing the non-inverting hysteresis controller will reduce the number of elements used in the controller without affecting its function.

The resistors $R_2$ and $R_4$ in Figure IV.3 are chosen to be variable resistors to change the hysteresis band. Using these variable resistors the voltage of the MFC and the
operation frequency can be controlled. The high threshold voltage and the low threshold voltage determine the hysteresis band. To calculate the values of the \( V_{th-H} \) and \( V_{th-L} \), the following equations can be used:

\[
V_{th-H} = \frac{(R_1 + R_2) R_4}{(R_4 + R_3) R_2} V_{cc}
\]

\[
V_{th-L} = \frac{(R_1 + R_2) R_4}{(R_4 + R_3) R_2} V_{cc} - \frac{V_{cc} R_1}{R_2}
\]

when the MFC voltage hits the \( V_{th-H} \), the controller turns the MOSFET on, and when the MFC voltage hits the \( V_{th-L} \), the controller turns the MOSFET off.

**System Simulation**

After choosing the self-synchronized flyback converter and the hyteresis controller to harvest the energy from the MFC, a simulation must be done to make sure that this combination will work with the MFC. The MFC was simulated as a battery with a series resistance as an internal resistance. The code was used to simulate the system in the appendix and the results are shown in Figure IV.4.

The first waveform in Figure IV.4 is the primary MOSFET gate signal, which is controlled by the hysteresis band. The second waveform is the voltage of the primary winding of the transformer and notice that it is different than the MFC voltage because the primary inductor is disconnected from the MFC for part of the time depending on the duty ratio. The third waveform represents the primary and the secondary currents and notice that the secondary value depends on the turn ratio of the transformer.
**Overall System**

The overall system schematic of the proposed MFC energy harvester is shown in Figure IV.5. To evaluate the system efficiency, a boost converter has been tested under the same conditions for comparison.

At the beginning the hysteresis controller will turn the primary MOSFET on, and the current will flow through the primary winding. The voltage of the MFC will decrease as the current increase, and when the MFC voltage hits the lower threshold voltage the hysteresis controller will turn the primary MOSFET off. The synchronous gate drive will turn the synchronous MOSFET on and off depending on the current direction on the secondary side of the transformer.
Figure IV.5 Overall System.
CHAPTER V

EXPERIMENTAL RESULTS

Self-Synchronous Flyback Converter

The main purpose of using the self-synchronous flyback converter is to increase the efficiency of harvesting the energy from the MFC. To get high efficiency, the parameters of the self-synchronous flyback converter must be chosen carefully, so they consume less energy.

System Parameters

To build the circuit, the parameters must be chosen such that they have low power losses. For example, the MOSFETs must have low on-resistance and the comparator in the hysteresis controller must consume minimal power. For harvesting the energy all the resistances in the path of the current must be reduced to reduce the amount of the power loss.

The flyback transformer was made using the transformer-winding machine shown in Figure V.1. The primary inductance is an important element because it affects the switching frequency. For this experiment it was chosen to have low inductance to reduce the number of turns, which will reduce the resistance of the wire. A 50-turn primary inductor was made using the transformer-winding machine, which has an inductance of 7mH and 3.2Ω resistance. Also, the turns ratio is important because as the turns ratio increase the secondary current will decrease. Reducing the secondary current should reduce the secondary losses. This can be seen from the simple $P_{\text{loss}}$ equation:
\[ P_{\text{loss}} = I^2 R \]

If the secondary winding is doubled, the resistance will also be doubled. But the current will be reduced in half. Inserting those values in the loss equation will result in reducing the loss by half. So, as the turns ratio increases the efficiency should increase. For this experiment the turns ratio was 1:4.

The MOSFETs should have low on resistance to reduce the power loss. The ON Semiconductor N-channel MOSFET 4906NG was used on both switches, which has 6.5\,m\Omega on-resistance at 4.5\,V_{GS}. The PN2222A NPN & PN2907A PNP transistors were used for the transistors on the synchronous driving circuit. Also, the diode 1N755A was used as \( D_d \) in the synchronous driving circuit. The resistor \( R'_1 \) must be very high to limit the current that flow through it, just enough to drive the transistor \( Q_1 \). The resistor \( R'_2 \) should be high enough so that the current is limited when the transistor \( Q_1 \) is on. The values of the parameters that were used in this experiment are listed in table V.1.
Figure V.1  Winding Machine.
Table V.1 Table of Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer Turns Ratio</td>
<td>(1:4) (50 turn:400 turn)</td>
</tr>
<tr>
<td>Transformer Primary Inductance</td>
<td>7 mH</td>
</tr>
<tr>
<td>MOSFETs</td>
<td>4906NG</td>
</tr>
<tr>
<td>Comparator</td>
<td>LM2903</td>
</tr>
<tr>
<td>$R_1$</td>
<td>500 Ω</td>
</tr>
<tr>
<td>$R_2$</td>
<td>500 KΩ (Variable)</td>
</tr>
<tr>
<td>$R_3$</td>
<td>10 kΩ</td>
</tr>
<tr>
<td>$R_4$</td>
<td>5 kΩ (Variable)</td>
</tr>
<tr>
<td>$R_5$</td>
<td>1 kΩ</td>
</tr>
<tr>
<td>$R_1'$</td>
<td>1 MΩ</td>
</tr>
<tr>
<td>$R_2'$</td>
<td>100 KΩ</td>
</tr>
<tr>
<td>$D_d$</td>
<td>1N755A</td>
</tr>
<tr>
<td>$Q_1$ &amp; $Q_2$</td>
<td>PN2222A</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>PN2907A</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>1 F, 2.5 v</td>
</tr>
</tbody>
</table>
Filtering the MFC Voltage Ringing

The circuit was built in the lab, using the parameters chose on the previous section. When the built circuit was applied to the MFC and connected to the hysteresis controller, the voltage of the MFC started ringing as the switch goes off, and it becomes normal when the switch is on. This ringing is caused by the weakness of the MFC and it affected the hysteresis controller, since the voltage of the MFC exceeds the high and the low threshold voltages many times during the off period. This makes the hysteresis controller open and close the switch many times during the off period. This ringing on the MFC voltage and the hysteresis controller output waveforms can be seen in Figure V.2.
Figure V.3 Non-inverting hysteresis controller with capacitor at the input.

The MFC voltage ringing starts when the switch goes off, which means when the current stops flowing through the transformer primary winding. When the switch is off the current stops flowing and because the MFC is a weak source the voltage starts ringing. This problem increases since the hysteresis controller opens and closes the current path many times, which will make the ringing worse.

To solve this problem, a capacitor must be connected at the input of the hysteresis controller as shown in Figure V.3. Now when the switch is off and the path of the current is closed, the current will flow through the capacitor and charge it. When the switch is on, the capacitor will be discharged and the current will be added to the current from the MFC. The waveforms of the MFC voltage and the
MOSFET gate signal from the hysteresis controller after applying 0.1\( \mu F \) capacitor are shown in Figure V.4.

**Results**

The proposed system was built as shown in Figure V.5 and applied to the MFC for 25 minutes and the energy was harvested and stored in the output capacitor. The readings were taken each 5 minutes for the MFC voltage, MFC current, output capacitor voltage, switching frequency and exported to excel for the calculations and they can be seen in Table V.2. The resultant waveforms were recorded using Tektronix TPS2012 oscilloscope as shown in Figure V.6.
Figure V.5 Experiment Set.
Calculations

After getting the experiment results, the efficiency must be calculated. To calculate the efficiency the input and the output energy must be calculated because we know that the efficiency is equal to:

$$\eta = \frac{E_{out}}{E_{in}}$$

where the input energy can be calculated using:

$$E_{in} = \int V_{in} I_{in} \, dt$$

Where $V_{in}$ and $I_{in}$ are the input voltage and input current respectively. Now we have the input energy, which is the energy extracted from the MFC. The output energy in our experiment is stored in the output capacitor, and the energy stored in the capacitor can be calculated from:

$$E_{out} = \frac{1}{2} C V_c^2$$

Where $V_c$ is the capacitor voltage and $C$ is the capacitance of the capacitor.

The efficiency was calculated for every 5 minutes for this experiment and was plotted in Figure V.7. The average efficiency was 46.1%, and from Figure V.7, it is clear that the efficiency at the beginning is low because at the beginning the diode conducts, and when the output capacitor voltage reached 1.27 V the synchronous driving circuit started to work and the efficiency started increasing. As the output capacitor voltage increases the gate voltage will increase, which will turn the synchronous MOSFET on. The on-resistance of the MOSFET depends on the voltage at the gate. The on-resistance
Table V.2 Self-Synchronous FLYback Converter Experiment Results.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>$V_{mfc}$ [V]</th>
<th>$I_{mfc}$ [mA]</th>
<th>$V_c$ [V]</th>
<th>Frequency [KHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>.302</td>
<td>10.8</td>
<td>0.82</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>.309</td>
<td>10.7</td>
<td>1.27</td>
<td>4.2</td>
</tr>
<tr>
<td>15</td>
<td>.307</td>
<td>10.7</td>
<td>1.605</td>
<td>3.6</td>
</tr>
<tr>
<td>20</td>
<td>.307</td>
<td>10.7</td>
<td>1.886</td>
<td>3.3</td>
</tr>
<tr>
<td>25</td>
<td>.310</td>
<td>10.5</td>
<td>2.13</td>
<td>3</td>
</tr>
</tbody>
</table>

...decreases as the gate voltage goes high, and the MOSFET is completely turned on when the gate voltage is equal to the rated gate-source voltage on the data sheet.

The switching frequency is decreasing because of the capacitor across the input of the hysteresis controller. When the primary switch is off the current from MFC charges the filtering capacitor, which makes the MFC voltage need more time to hit the upper threshold of the hysteresis controller.
Figure V.6 Self-Synchronous FLYback Converter Experiment Waveforms. 
(a) Primary Switch State   (b) MFC Voltage   (c) Synchronous Switch State.
Figure V.7 Efficiency of the Self-Synchronous Flyback Converter vs. Time.
Table V.3 Boost Converter Experiment Results.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>$V_{mfe}$ [V]</th>
<th>$I_{mfe}$ [mA]</th>
<th>$V_c$ [V]</th>
<th>Frequency [KHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.311</td>
<td>10.9</td>
<td>0.89</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>0.312</td>
<td>10.7</td>
<td>1.3</td>
<td>6.3</td>
</tr>
<tr>
<td>15</td>
<td>0.312</td>
<td>10.5</td>
<td>1.555</td>
<td>6.4</td>
</tr>
<tr>
<td>20</td>
<td>0.312</td>
<td>10.5</td>
<td>1.704</td>
<td>6.45</td>
</tr>
<tr>
<td>25</td>
<td>0.311</td>
<td>10.4</td>
<td>1.825</td>
<td>6.47</td>
</tr>
</tbody>
</table>

**Boost Converter**

To compare the results of harvesting the energy from the MFC with the self-synchronous flyback converter, diode based-boost converter will be used. Comparing the results of the two converters will help to see the improvement of the self-synchronous flyback converter in terms of the efficiency. To make the comparison fair, the two converters have similar components. The inductor used with the boost converter was made in the lab using the winding machine. This inductor has $7mH$ inductance and $3.2\Omega$ resistance. Although this inductor is not efficient because of the high resistance compared to the inductor used in [5], it was used because we will use the same winding machine to make the transformer of the flyback converter. Low on-resistance 4906NG MOSFET has been chosen with the 1N755A diode to build the boost converter. The three main components for the boost converter were chosen and the circuit was built and tested in the lab.
The boost converter was connected to the MFC with the non-inverting hysteresis controller, and the energy was harvested and stored in 1 F supercapacitor. The experiment took 25 minutes and the readings were taken every 5 minutes. The MFC voltage, the MFC current, the capacitor voltage, and the switching frequency were recorded and they can be seen in table V.3. The waveforms shown in Figure V.8 were taken using Tektronix TPS2012 oscilloscope. The voltage of the MFC can be seen controlled by the hysteresis band of the hysteresis controller. The results was exported to excel and using the same calculations for the self-synchronous flyback converter, the efficiency was calculated and plotted as shown in Figure V.9, and the overall efficiency was calculated to be 33.5 %.

Figure V.8  Boost Converter Experiment Waveforms.
(a) Switch State   (b) MFC Voltage
As the output capacitor voltage increase, the switching frequency increase because of the higher resistance for injecting the power and this increase in the switching frequency can be seen in Table V.3.
Figure V.9 Efficiency of the Boost Converter vs. Time.
CHAPTER VI

COMPARISON AND CONCLUSION

Comparison

The two converters were operated at the same conditions to make the comparison fair. The MFC voltage is shown in Figure VI.1 in real time for both converters. The MFC current is also shown in Figure VI.2 for both converters in real time. Having the same voltage and current from the MFC means the same input power for both converters. The thing that is different between the two circuits is the switching frequency. They started at approximately the same switching frequency, but the switching frequency of the flyback converter was decreasing and was increasing for the boost converter. This switching frequency behavior difference is shown in Figure VI.3.

The self-synchronous flyback converter charged the output capacitor faster than the boost converter and Figure VI.4 shows a comparison between them. It is clear from the efficiency comparison in Figure VI.5 that the self-synchronous flyback converter has higher efficiency than the boost converter after 10 minutes of operation, which is because the synchronous driving circuit started to drive the synchronous MOSFET at this time. Even the synchronous driving circuit started to drive the synchronous MOSFET after approximately 10 minutes, the overall efficiency was improved by 37.6% to reach 46.1% compared to 33.5% for the boost converter. The self-synchronous flyback converter was able to store 2.27J out of 4.91J in the output capacitor compared to 1.665J out of 4.95J stored in the output capacitor by the boost converter.
Figure VI.1 MFC Voltage for Both Experiments vs. Time.

Figure VI.2 MFC Current For Both Experiments vs. Time.
Figure VI.3 Switching Frequency For Both Experiments vs. Time.

Figure VI.4 Output Capacitor Voltage for Both Experiments vs. Time.
Figure VI.5 Efficiency of Both Converters vs. Time.
Conclusion

The self-synchronous flyback converter was designed and built, and the energy was harvested from the MFC and stored in the capacitor in a good efficiency compared to the boost converter. The efficiency improved when the secondary diode was replaced by a MOSFET, because the diode has a high voltage drop across it (0.7 V). Replacing the diode by the MOSFET resulted in floating switch, which needs to be driven by an isolated source. The synchronous driving circuit [20] was used to drive the synchronous MOSFET.

The main advantage of using the DC-DC converters is the ability to control the voltage of the MFC. The non-inverting hysteresis controller was used for this thesis, but a capacitor was needed in the input of the hysteresis controller to filter the voltage of the MFC from the ringing caused by closing the current path each cycle, which is the way that the flyback converter works.

This thesis proved that replacing the secondary diode by a MOSFET improved the efficiency of harvesting the energy from the MFC. It also proves the advantages of using DC-DC converters, which are the ability to control the MFC voltage, the ability to store the energy in the output capacitor, and the efficient way to harvest the energy from the MFC.
This is the simulation code for the flyback converter:

clear all;
close all;

screenSize = get(0, 'ScreenSize');
position = [screenSize(3)/3 screenSize(4)/5 560 420];
set(0,'DefaultFigurePosition',position);

tMax = 0.01;
C = 40000e-6;
dt = 1e-6;

Vint = 0.7;
R = 120;
R2 = 0;

for n = 1:length(t)-1
    if sw(n) == 1,
        vR(n+1) = R * il(n);
        VL(n+1) = vs(n)-vR(n);
        il(n+1) = il(n) + (VL(n))/L1*dt;
        vo(n+1) = vo(n) + (-il)/C*dt;
        if il(n) >= Th_H,
            sw(n+1)=0;
            i2(n+1)=il(n+1)/N;
        else
            il(n+1) = il(n) + (VL(n))/L1*dt;
        end
    end
end

for n = 1:length(t)-1
    if sw(n) == 1,
        vR(n+1) = R * il(n);
        VL(n+1) = vs(n)-vR(n);
        il(n+1) = il(n) + (VL(n))/L1*dt;
        vo(n+1) = vo(n) + (-il)/C*dt;
        if il(n) >= Th_H,
            sw(n+1)=0;
            i2(n+1)=il(n+1)/N;
        else
            il(n+1) = il(n) + (VL(n))/L1*dt;
        end
    end
end
\begin{verbatim}
sw(n+1)=1;
i2(n+1)=0;

else
    vR2(n+1) = R2 * i2(n);
    vL(n+1)=(vR2(n+1)-vo(n+1))/N;
    i2(n+1) = i2(n) - (vo(n)/L2) * dt; \% Integration for current
    vo(n+1) = vo(n) + (i2(n)-il)/C*dt;
    vL(n+1)= (-vo(n+1))/N;
    if i2(n) <= Th_L,
        sw(n+1) = 1;
        il(n+1)=i2(n)*N;
    else
        sw(n+1) = 0;
        il(n+1)=0;
    end
end

end

tm = t*1000;
\% Result plotting
figure(1);
subplot(3,1,1);
plot(tm, sw, 'k');
grid on;
axis([0 tMax*1000 0 1.5]);
ylabel('Switch Status');

subplot(3,1,2);
plot(tm, vL, 'k');
grid on;
hold on;
ylabel('Primary Inductor Voltage [V]');

subplot(3,1,3);
plot(tm, il, 'k');
grid on;
hold on;
plot(tm, i2, 'r');
ylabel('Current [mA]');
xlabel('Time [msec]');

figure(2);
plot(tm, vo);
hold on;
grid on;
\end{verbatim}
REFERENCES


10. Alim Dewan, Haluk Beyenal, Zbigniew Lewandowski, Scaling up microbial fuel cells, Environmental Science & Technology 2008 42 (20), 7643-7648


