POWER MANAGEMENT SYSTEMS FOR USE WITH MICROBIAL FUEL CELLS

by

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The Navy has the need to power underwater sensor packages. Powering these systems with batteries requires constant upkeep that involve diving teams. This is a hazardous and expensive process so they want to explore alternate methods of powering these sensor packages. Microbial fuel cells (MFCs) are a potential energy source that could power devices placed underwater. MFCs are able to harvest energy from naturally occurring bacteria in open water environments. However, MFCs produce very little voltage and current. Traditional methods of power conversion are not able to allow an MFC to operate as a power source because of these limitations. This paper describes two power management systems have been designed for use with a microbial fuel cell (MFC). These systems create a power source suitable for powering electronic devices requiring higher voltage and power than what the MFC is able to supply on its own. Though the two systems use different methods they share a similar operating concept. The systems oscillate between two modes: (1) a period when energy from the MFC is accumulated in a supercapacitor and (2) when energy accumulated in the supercapacitor(s) is used to power external electronic devices. The power management system controls the operation of the integrated system, making decision about switching the modes of operation. The power supplies are entirely autonomous and the load and power management system require no external power besides the MFC. These power management systems were designed, built, and tested in the laboratory. In our application the power management systems increased the input potential from MFCs, which were as low as 300mV, to 3.3V and the input power from microwatts to milliwatts.
The specific motivation for this project was to develop a power management system between a microbial fuel cell and a hydrophone. The hydrophone used in this project is designed to float underwater and track sea turtle movements in Naval bases. There are many negative interactions between Naval vessels and sea turtles so tracking the turtles movement would be beneficial to both parties. Sensors are attached to the turtles and every time they go near a hydrophone a record is made. By using an array of hydrophones and taking data over an extended period of time the turtles movement can be mapped. These hydrophones are anchored to the sea floor and operate on batteries. This is a problem because whenever the batteries run out of power a diving team must be dispatched to retrieve the hydrophone and replace the batteries. This process is very costly and dangerous. If the batteries were not involved then the hydrophone would only need to be retrieved once enough data had been collected. This may be after several months or years of data collection, whereas if batteries are used then every hydrophone would need to be serviced much more frequently. The Navy is therefore researching other methods of powering these hydrophones besides batteries.

One alternative power supply that could apply to this application is the microbial fuel cell (MFC). MFCs harvest electrons released by electro-active bacteria to produce electricity [4]. An MFC can make use of the natural bacteria in a body of water to produce power, which makes it a unique small scale power supply for remote applications in aquatic environments. If an MFC could be used in place of batteries
then electronics in these environments could run off the power supplied by an MFC for an extended period of time without any human intervention, creating an autonomous system. An MFC needs very little maintenance and can potentially supply power as long as the microbes are alive. There are several drawbacks to MFCs, however. The voltage, current, and power supplied by an MFC is so low that almost no electronics would be able to run off a single MFC. Also, these MFC cannot be conventionally stacked in series to increase their total voltage. This means that a power management system is needed to provide an interface between an MFC and the electronics that need to be powered.

An MFC based power supply could be deployed with each hydrophone and supply power until the data collection process is finished. Early microbial fuel cells exist and the hydrophones exist but there are no power electronics to interface the two. The goal of this project was to investigate power management systems that could allow an MFC to be used as a viable power source. This document shows two different methods of implementing this power management system. These systems were designed, built, and tested in a laboratory setting. They were both able to successfully provide an interface between the MFC and the hydrophone load.

1.2 Microbial Fuel Cells

1.2.1 Introduction

Microbial fuel cells (MFCs) are another one of these novel, renewable, emerging energy sources. MFCs make use of electro-active bacteria to harvest energy from aquatic environments. This premise has been around since the 1970’s [4]. The idea that bacteria could be used to generate came from studying the corrosion that they caused. The bacteria would oxidodize their food source and produce electrons. If
these electrons could be scavenged then they could be used to produce electricity. This premise was investigated and in recent years MFC have been produced that had enough power output to be a possible power source [5, 6, 7, 8].

The basic operation of an MFC operating in an oceanic environment is shown in Figure 1.1. (The specific reactions are different for every bacteria so only the general principle is shown here. The exact reactions for the bacteria used in these experiments are defined in section 2.1.) The anode is buried in the seafloor. This is where the electro-active bacteria reside since they are anaerobes. The bacteria colonize the anode and begin oxidizing their food supply, usually glucose or lactate. When their food supply is oxidized, electrons are released. Normally, this electron would move straight to another electron receptor such as oxygen or nitrate. When the MFC is present the electron moves onto the anode instead of being taken up by another electron acceptor [4]. This electron is naturally drawn towards the positively charged cathode. On the way to the cathode the electron passes through the load where it can be put to use. From here it moves onto the cathode. The cathode is suspended in the ocean water where it facilitates the reduction of oxygen using the electrons from the bacteria. The electron is released back into the ocean and the cycle continues. As long as the bacteria are releasing electrons onto the anode and the cathode is releasing them back into the ocean then electric current will keep flowing.

A major problem that is hindering development of power systems involving MFCs is the fact that they cannot be connected in series. They can in a laboratory setting but not a real world setting. When each MFC is contained in it’s own cell they can be put in series like any other voltage source. However, when they are in the same body of water then only the cathode and anode connected directly to the load will participate in the reaction. All other anodes and cathodes will be short circuited together and have no impact on the system. This problem is demonstrated in Figure
1.2. This means that either the low output voltage is something that cannot be overcome or the MFCs must be stacked in series in a novel way.

1.2.2 Benefits and Drawbacks

Microbial fuel cells have several advantages over other energy sources.

• Sustainable power source

• Low maintenance

• Environmentally friendly

• Allows system to become autonomous

• "Direct conversion of substrate energy to electricity enables high conversion efficiency." [4]

• Operates at ambient and low temperatures [4]

• Applicable in water environments with no grid access

Even though MFCs have many benefits they also have drawbacks that can make them difficult to use.

• Supplies very low voltage. Working voltages typically around 500mV [9].

• Very low current available. Usually only a few milliamps but depends on size of MFC.

• Available power depends on environmental conditions. Temperature and nutrient fluctuations have a direct impact on the performance of the cell.

• Cannot be stacked in series to increase voltage (See Figure 1.2).
• Increasing the surface area of the MFC does not increase the current output linearly [7].

1.2.3 Publications

The experiments and designs within this document have been presented at a conference [10] and published in a peer reviewed journal [11].
Figure 1.1: Basic MFC Operation
Figure 1.2: Problem with Connecting MFCs in Series

(a)

(b)
CHAPTER 2
DESIGN

2.1 Microbial Fuel Cell Design

2.1.1 Principle of Operation

The microbial fuel cell can be implemented in the open ocean without supplying food or a bacteria to start the reaction. There are several different types of electro-active bacteria that naturally colonize the anode and begin producing electrons. For the laboratory MFC, however, one specific bacteria is being used and supplied with food. This will reduce the variables introduced into the system and facilitate in studying the performance of the MFC along with the power management system.

The basic structure and basic electro-chemical reactions in the laboratory MFC are shown in Figure 2.1.

The anode is colonized by Shewanella Oneidensis. These bacterium break down lactate supplied by the growth medium and release electrons as part of the byproduct. This oxidation reaction is the first step in creating current. The initial reaction is as follows:

\[
\text{Lactate} + H_2O \rightarrow \text{Acetate} + CO_2 + 4H^+ + 4e^- \quad (2.1)
\]

The release of electrons from the lactate are what produce the flow of current. These electrons flow from the anode, through the load and power management system, and then to the cathode. On the cathode an oxidation reaction occurs. The electrons that came from the anode react with water and oxygen in the cathode compartment to produce OH\(^-\). The reaction is as follows:
Figure 2.1: Basic MFC Structure and Reactions

\[ O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \]  

(2.2)

The protons, in the form of positively charged hydrogen ions, travel through the cation exchange membrane to neutralize the negatively charged cathode compartment. The \( OH^- \) produced in the above reaction then reacts with \( H^+ \) from the anode to form water:

\[ 4OH^- + 4H^+ \rightarrow 4H_2O \]  

(2.3)

It is very important to note that neither the anode material nor the cathode material are involved in any part of the above reaction. The anode and cathode remain intact and simply act as passive mediators in the electron harvesting process. Ideally, these elements will never have to be replaced and will not contribute to any
waste. Everything in the system happens naturally so the ecosystem housing the MFC will not be negatively impacted. A sacrificial anode can be used to increase the cell voltage of the MFC, but this anode will degrade and will have to be replaced. In order to have a long lifetime, no sacrificial anode is used in this MFC.

2.1.2 Physical Structure

The microbial fuel cell used in this study consisted of two polycarbonate compartments that were bolted together. Watertight seals were created using rubber gaskets between the polycarbonate walls. The compartments were symmetrical, each having a liquid volume of 1.014L. Each compartment contained a separate electrode which would facilitate the collection and dissipation of electrons. The electrodes were suspended in the center of the compartments so they did not have contact with any part of the physical structure of the MFC. The compartments were equipped with ports on top of the MFC to facilitate electrical connections with the electrodes. These ports on the anode side were sealed with silicone rubber so that an anaerobic environment could be created. The sides of the MFC contained ports to deliver and remove the nutrient solutions and accommodate gas exchange. Each compartment had different liquid and gas exchange needs. All outlets were equipped with flow breakers to prevent back contamination. Flow breakers prevent back contamination by breaking the constant stream of liquid and allowing fluid flow in only one direction. This prevents any bacterial growth in the non-sterile waste container from going back up into the MFC.

The compartments were separated by a cation exchange membrane (ESC-7000, Electrolytica Corporation). This membrane is needed to maintain the balance of charges between the two compartments. Positively charged ions must be allowed to travel to the cathode compartment after the bacteria oxidize them so that the elec-
trons may be stripped off the cathode. Current flow could not be maintained unless these electrons were continually being removed from the cathode. The membrane was preconditioned before use by being rinsed with water and kept in a 1 M NaCl solution for 24 hrs. This membrane could be reused after each test as long as it was cleaned. To reuse the membrane it was rinsed with tap water to remove deposits from the surface. Contaminants collect on the membrane so it needs to be thoroughly cleaned. Then the membrane was kept in 80°C water for 1 hr, rinsed again and inspected visually to make sure there were no deposits left on the surface. To store the membrane for a longer time, it was kept in a solution of 1 M NaCl.

2.1.3 The electrodes

The anode was made of a high density, isomolded graphite plate from Graphite-Store.com, Inc. The dimensions of the plate were 18 cm wide by 18 cm high by 0.6 cm thick with a projected surface area of 691.2 cm². The cathode was made of manganese-based catalyzed carbon bonded to a current-collecting screen made of platinum mesh This material was made by Electric Fuel Limited. Even though the commercial name of this electrode is ‘air electrode’ and the electrode can be used to
reduce oxygen in the gas phase, we used it as a submersed electrode to reduce oxygen in liquid media. The electrode was made of two pieces, each 9 cm wide by 19.3 cm high by 0.05 cm thick, and the total projected surface area was 694.8 cm$^2$. To hold the carbon materials firmly against the platinum wire mesh, the mesh was laminated using porous Teflon film. To improve the quality of the electrical connection, copper wires were woven into the platinum mesh and fixed there with a conductive silver epoxy. After the conductive epoxy dried it was covered with an insulating epoxy. Any contact between the electrolytic solution could cause a charge to develop which would obfuscate the results of the tests. It was very important that all energy supplied by the MFC was generated by the bacteria so the results would reflect the capabilities of the bacteria and nothing else.

2.1.4 Microorganism, Growth Medium, and Electrolyte Solution

In order to create a clearly defined, reproducible experiment a specific type of bacteria was used in the microbial fuel cell. In the anodic compartment, Shewanella Oneidensis (MR-1) was grown anaerobically. The growth medium for inoculation and continuous operation was Luria-Bertani (LB) broth (a solution of 10 g/L tryptone, 5 g/L NaCl and 5 g/L yeast extract), 0.35 g/L KH2PO4, 1.825 g/L Na2HPO4, 5 g/L NaCl, 9 g/L Na-Lactate (60% solution). The solution in the cathodic compartment was 1.825 g/L Na2HPO4 and 0.35 g/L KH2PO4.

2.1.5 MFC startup and operation

The very first step in starting the laboratory MFC was to take a frozen bacterial culture and innoculate a small amount of growth medium. This would allow the bacteria to bloom and develop a colony in ideal conditions before being introduced to the MFC environment. Once the bacteria was ready it was introduced into the
MFC. The MFC was operated in batch mode for one day with the growth medium for in the anodic compartment. This means that the MFC was left undisturbed to allow the bacteria to spread and establish a colony on the anode. After that, the growth medium was pumped continuously through the anodic compartment, at 15 mL/h, using a peristaltic pump. A waste container was connected to collect the used growth medium and waste from the bacteria. This container needed to contain some bleach to sterilize the waste fluid. If this was not done then the lab would be filled with a terrible odor. For the first few days, the MFC was operated in an open circuit condition. When the open circuit potential reached its operating voltage of about 700 mV then the energy harvesting components were attached to the cell.

2.1.5.1 Bacteria Inoculation

The following steps were taken to grow the bacteria while reducing the possibilities for contamination:

1. Mix a small batch of growth medium in several 100 mL Erlenmeyer flasks and cover each opening with foil.

2. Autoclave the flasks at 121° Celsius for 30 minutes to sterilize the growth medium.

3. Allow flasks to return to room temperature as to not kill the bacteria.

4. While flasks cool, remove frozen vials of Shewanella Oneidensis from freezer and allow to warm to room temperature.

5. Turn on the ultraviolet lights in the fume hood for at least 20 minutes to destroy any bacterial contaminants. The ultraviolet light damages the DNA in the bacteria to such an extent that the cell dies before it can repair itself.
6. Turn off the UV lights and clean the fume hood with alcohol.

7. Place all flasks and vials to be used into the fume hood and clean them with alcohol as well.

8. For each flask heat the opening with a bunsen burner, pour some bacteria in the flask, and quickly seal with foil.

9. Place flasks in an incubating shaker for 12 hours.

10. Inoculate MFC with bacteria between 12 and 24 hours after putting flasks in the shaker.

2.1.5.2 MFC Preparation and Inoculation

Every time the MFC was to be operated, the following activities were completed:

1. Cleaning all parts of the MFC and preparing the membrane.

2. Assembling the MFC and attaching the silicon tubing and the flow breakers.

3. Filling up the compartments with the deionized water.

4. Filling the MFC with water and autoclaving it at 121° Celsius for 30 minutes.

5. Cooling down the MFC after autoclaving and replacing the deionized water with the buffer solution in the cathodic compartment and with the growth medium in the anodic compartment.

6. Inserting the reference electrode (saturated calomel electrode, SCE) into the cathodic compartment.

7. Inoculating the MFC with Shewanella Oneidensis (MR-1) in LB medium.
8. Daily replacing 100mL of the buffer solution in the cathodic compartment with 100 mL of fresh buffer solution.

9. Pumping the air continuously to the cathodic compartment.

10. Pumping nitrogen continuously to the anodic compartment.

2.2 Power Management System Design Requirements

A power management system for use with a submersed microbial fuel cell has several design challenges. Many of these challenges are also being seen by other alternative energy sources.

First of all, the system has to operate entirely with the energy supplied by the MFC. Batteries cannot be used with any portion of the system. Recharging batteries with the MFC is not an option due to the low power delivered by the MFC. The maximum voltage seen on the laboratory MFC was about 800 mV. The average voltage seen was more around 650 mV. This problem cannot be overcome by stacking several MFCs in series like batteries, as discussed earlier. The voltage on the electrodes does not change as a function of electrode size either. This is a limitation that has a significant impact on the design of the power management system. The current that the MFC can supply is also very low, often in the range of a few milliamps. Several previous designs could potentially work if the available current and power was not so low.

The hydrophone load has several requirements that dictate the operation of the power management system. The hydrophone has the following requirements:

- Operating voltage: 3 - 5 Volts
- Estimated continuous power rating: 15 mW
- Estimated maximum power rating: 60 mW
- Design power rating: 100 mW

With these specifications and limitation in mind, other designs and options can be studied to determine the correct course of action.

2.3 Previous Work and Promising Components

2.3.1 Previous Work

There has not been much work done with extracting energy from sources with such low voltages. Batteries are the most frequently used mobile power source and typically have cell voltages above 1V. The small DC/DC converters on the market are usually designed with batteries in mind. Virtually all small voltage sources, besides the MFC, can be stacked in series to create higher voltages so that sub 1V voltages are not a concern. With more and more low voltage options showing up, some work has been done to make use of these sources.

Thermoelectric generators (TEG) are a low-voltage source that can supply voltages that are comparable to an MFC. John Damaschke developed a voltage converter to be used with a TEG which was published in 1997 [1]. The system used here could start up around 300mV and provide a stable output voltage of 5V to a 131 mW load. This initially sounds promising but this circuit will not apply to the MFC. The circuit is complicated and has several sub-sections: starter circuit, switching circuit, supply circuit, and the main circuit. The layout of these is shown in Figure 2.3. The starter circuit is a self-oscillating transformer circuit. This circuit basically draws current from the input and starts providing a boosted voltage to the switching circuit by means of a transformer. The switching circuit then takes over the circuit when it has enough voltage to begin switching its MOSFETs. This circuit is a modified boost
converter. Once this circuit begins outputting a regulated voltage then the entire circuit runs off that voltage and the starter circuit turns off. The principles used here are exactly what is needed for the MFC. These main functions are the ability for the system to start itself and then run of its own power supply with no batteries. However, there are reasons this circuit will not work with the MFC. This circuit consumes far more power than the MFC can supply. It is assumed that the energy source can supply enough current that the voltage will stay above 300mV during the entire operation. The losses in this circuit add up to 39mW. The MFC we are using can only supply up to a maximum of 1mW. The start up circuit alone in this system would not only use up all the available power from the MFC, but pull the voltage down to zero volts in the process making progress impossible. This circuit also needs an abrupt change in voltage to start up. A slowly charging MFC could not supply this quick change in voltage. This circuit will not work for the MFC.

The continuing progress in solar cell and fuel cell power supplies led to more work being done with low voltage boost converters. Several low-voltage design challenges and attempts to address them have been examined previously [2]. The target application for the circuit in [2] is a fuel-cell powered mobile phone. This application is similar to using the MFC to operate low-power electronics such as the hydrophone. This paper goes into detail on building and selecting components for maximum efficiency at low voltages. They key problem that they have here is startup. They come up with a good solution for their application. As shown in Figure 2.4, a mechanical switch is used in the startup process. When the switch is depressed, a short circuit to ground is created. This develops a positive charge across the inductor. Energy quickly accumulates and when the mechanical switch is opened then the stored current in the capacitor is diverted through the diode and into the capacitor. This creates an increased voltage on the output which is enough to start the regulator circuit.
The switching operations begin and a regulated voltage is seen delivered to the load. While this technique works for this application, it will not work for the MFC. The MFC is intended to be deployed in isolates places in open bodies of water. There will be no person available to physically depress a switch to start the circuit. This technique will therefor not work for the MFC.

2.3.2 Boost Converter

A boost converter seems like a good choice to increase the DC voltage from the MFC. A boost converter is a DC/DC voltage converter. This system can boost voltages using inductors and capacitors as energy storage devices and modulating the voltage across them with a semiconductor switch. Figure 2.5 shows the basic schematic of a boost converter. The schematic shows that when the switch is con-
ducting, the voltage across the inductor is positive and constant creating a positive, linear ramp current and in turn increasing the output voltage. When the switch is not conducting, the voltage across the inductor is constant and negative, causing the current in the inductor to ramp down. Control circuitry creates the pulse width modulated signal that controls the opening and closing of the switch. The constantly changing current meets a capacitor before the load. This capacitor creates a smooth, constant voltage for the load. All of these elements are designed to keep the output voltage at the desired level no matter what the input voltage is.

There are several problems with using only a boost converter. Current low-voltage boost converters usually need at least 800mV to start up [12, 13]. These cannot be used by themselves because the MFC voltage never gets high enough to allow them to turn on. Even if the MFC could achieve a high enough voltage to turn one of
these devices on then too much current would be drawn from the MFC and the voltage would be pulled down to zero. Another problem with commercial boost converters is that they have a maximum duty cycle of about 80%. With this duty ratio the minimum input voltage for an output voltage of 3.3V would be 660mV. The MFC voltage frequently dips below this and would therefore be unsuitable. The boost converter would either turn itself off or generate an output that was lower than expected.

2.3.3 Texas Instruments TPS61200

The TPS61200 series of boost converters is a special case. These integrated circuits can start up at 500mV, which appears promising. The problem with these is that they begin to draw current as the input voltage gets close to 500mV. This current is in excess of what the MFC can supply so if this device is connected directly to an MFC, the MFC voltage never increases to a level where the boost converter even turns on. If a super capacitor is placed in series with the MFC using a TPS61200 for the boost converter, the voltage on the super capacitor only rises to about 300mV.
and then the boost converter starts drawing all the current supplied by the MFC and the super capacitor voltage stops rising. This prevents the input voltage from getting high enough to start the boost converter. This problem was found through testing and is shown in Figure 2.6.

![Figure 2.6: Current Draw Prevents the MFC from Reaching Full Voltage](image)

2.3.4 Seiko Low-Voltage Charge Pump

The Seiko S-882Z charge pump is a major advancement in making use of low voltage energy sources. This charge pump uses fully depleted silicon on insulator technology in order to allow it to start operating at only 300mV. It is designed for low voltage applications such as solar cells and RF tag power. This charge pump
increases the input voltage up to between 1.8V and 2.4V on an externally connected capacitor. The exact topology of this charge pump is unknown, however tests were run to examine how it operates. The efficiency was low, but increased as the input voltage came closer to the voltage on the output capacitor. The efficiency also increased as the voltage on the capacitor increased. These results are discussed more in chapter 3. The intended uses for this charge pump use a small capacitor to deliver a short burst of power to a boost converter’s control circuit. This burst of power would allow the circuit to start switching, boost the input voltage, and then run off that higher voltage that it was producing. This device is a critical component of the power management systems discussed here. There are several different methods, discussed in [14], to use this charge pump. The methods for implementing this charge pump, proposed here in section 2.4, are not discussed in [14].

2.3.5 Super Capacitor

Energy storage is an essential part of this project. The MFC can only supply a maximum of 1mW and the intended load has a continuous power rating of 15mW. Due to conservation of energy, the MFC cannot directly power the load. Most energy storage methods do not apply to this project. Rechargeable batteries need charging circuits using voltages greater than the cell voltages of the batteries themselves. This already present a problem since energy needs to be stored before any voltage boosting can take place. Newer technologies that store energy as kinetic energy, such as flywheels and compressed air, can only be used for systems with a lot of power. Regular capacitors do not have the ability to store as much energy as will be needed, but supercapacitors do. As of 2010, supercapacitors have grown up to 5000F. They are currently being used as energy buffers in many different systems, such as vehicles and grid systems, and can be used as such in this MFC system [15]. Several of the
key benefits of supercapacitors fit the goals of the MFC power supply very well [16]. Unlike batteries, supercapacitors are easy to charge. Just like a capacitor, they can be placed in parallel with a voltage source and will develop the voltage of the source. Their equivalent series resistance (ESR) makes them ideal for adding current capacity to a system. This provides a solid way to increase the current capability of the MFC system. Supercapacitors can also work through a wide range of temperatures. The MFC may have to endure widely varying temperatures because it operates in bodies of water that can vary greatly in temperature depending on location and season. The useful life of a supercapacitor can be greater than 10 years and require no maintenance.
This help with the goal of the MFC power supply to be virtually maintenance free and have a long life cycle. These benefits make the supercapacitor a key component in the MFC power system.

2.4 Proposed Solutions

Two methods have been developed to make use of the MFC as a power source. The first solution uses one microbial fuel cell and the second puts two in series with electronics to increase the voltage. Both solutions use discrete steps of energy accumulation and energy delivery to provide an increased voltage and power to the load.

2.4.1 Single MFC Solution

2.4.1.1 Summary

The first solution uses a single MFC as the energy source. As shown in Figure 2.8, one MFC is connected directly to the S-882Z charge pump. The charge pump is used to slowly charge a large supercapacitor. Once this voltage reaches 1.8V it is delivered to the boost converter through a high-side driver. The boost converter is able to start up and provide a stable 3.3V to the load. Once the capacitor is drained to 1.3V then the capacitor is disconnected from the boost converter and begins to charge again.

2.4.1.2 Energy Accumulation

The MFC is connected directly to the input of the charge pump. Once the voltage from the MFC gets above 300mV the oscillation circuit in the charge pump begins and starts boosting the voltage on the supercapacitor. The charge pump limits the
current drawn from the MFC. Since this current is low, the MFC voltage remains high. The supercapacitor on the charge pump slowly charges up to 1.8V. Once this voltage is reached a comparator in the charge pump connects the supercapacitor with the output pin and energy distribution occurs.

2.4.1.3 Energy Distribution

The MFC is connected directly to the charge pump. The charge pump has a one pin that is used to charge the capacitor and another pin that delivers the voltage after the voltage has reached 1.8V. The on resistance of the MOSFET on the output pin can be up to 100 Ω so it will produce a lot of power loss when current goes through it. To avoid this problem this pin was used as the gating signal for a high-side driver circuit that separates the super capacitor and boost converter. This allows minimal
current to be sent through the inefficient charge pump MOSFET while diverting current flow through more efficient transistors. The high-side driver also allows the super capacitor and boost converter to remain separated until the super capacitor has been fully charged.

At this point, the output on the charge pump goes high which causes the high-side driver to conduct. The 1.8V on the super capacitor is then applied to the boost converter. The voltage is high enough to start the boost converter (ST L6920DB) and start boosting the voltage to 3.3V. This voltage is delivered to the load. After the super capacitor is drained to 1.3V, the comparator in the charge pump turns off the high-side driver and the super capacitor begins charging again.

![Diagram of Power Management System Delivering Power](image)

2.4.1.4 System Drawbacks

This power management system was successfully tested and works well with one MFC. However, this system has drawbacks that prompted the investigation of the circuit discussed in the next section. This circuit has to divert all power extracted from the MFC through the charge pump. The problem with this is that the charge pump is inefficient and does not draw a maximum amount of power out of the MFC. The charge pump was tested and was determined to have efficiencies around 20%. This efficiency is very low. Since all power is sent through this charge pump then
the total efficiency of the system will never be more than 20%. The following design was implemented so that the power delivered to the load would not pass through the charge pump. This would improve efficiency and power capacity. This design modification is discussed in the next section.

2.4.1.5 Parts List and Schematic

![Power Management System Schematic](image)

Figure 2.11: Power Management System Schematic

2.4.2 Multiple MFC Solution

2.4.2.1 Summary

This solution uses two MFCs that are essentially connected in series. This cannot be done by directly connecting them, as previously mentioned, so it is done so with electronics as a mediator. The MFCs each are connected to a supercapacitor through semiconductor switches (optical relays). The MFCs charge the main supercapacitors directly while a charge pump increases the voltage on a smaller supercapacitor which will turn on the relays. When the charge pump supercapacitor reaches 1.8V the supercapacitors are disconnected from the MFCs and connected in series. This delivers
Table 2.1: Parts List for First Power Management System

<table>
<thead>
<tr>
<th>Part</th>
<th>Manufacturer</th>
<th>Model Number</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Pump</td>
<td>Seiko</td>
<td>S-882Z</td>
<td>Input &gt;0.3V, Output 1.8V</td>
</tr>
<tr>
<td>Super Capacitor</td>
<td>NA</td>
<td>NA</td>
<td>2.2F</td>
</tr>
<tr>
<td>N-Channel Mosfet</td>
<td>Vishay/Siliconix</td>
<td>SI3460BDV</td>
<td>NA</td>
</tr>
<tr>
<td>P-Channel Mosfet</td>
<td>Vishay/Siliconix</td>
<td>SI3499DV</td>
<td>NA</td>
</tr>
<tr>
<td>DC/DC Converter IC</td>
<td>STM</td>
<td>L6920DB</td>
<td>Boost Converter: Input &gt;0.8V, Output 3.3V</td>
</tr>
<tr>
<td>Inductor</td>
<td>NA</td>
<td>NA</td>
<td>2µH</td>
</tr>
<tr>
<td>Capacitor</td>
<td>NA</td>
<td>NA</td>
<td>47µF</td>
</tr>
</tbody>
</table>

a high enough voltage to the boost converter to start operation. The boost converter then delivers a stable 3.3V to the load until the supercapacitors are disconnected and connected back to the MFCs to begin charging again.

Optical relays are used here instead of other semiconductor switches such as MOSFETs. Other devices need to have a certain gate-to-source voltage ($V_{GS}$) which cannot be dealt with here. Once the supercapacitors are connected in series then the $V_{GS}$ of several switches would be too high. Adding any devices to compensate for this increased $V_{GS}$ would either not work at such low voltages or add unnecessary strain on the system. Optical relays require more current than a low power MOSFET, but they also require a much lower voltage. The relays used in these experiments only needed 1.2V which could be supplied by the charge pump circuit.

There are several advantages to this circuit over the one described in Section 2.4.1.1. This circuit only uses the inefficient charge pump to power the optical relays.
The power to the load is only routed through the boost converter. This means that the load is operated with higher efficiency. Also, larger load can be operated because larger supercapacitors can be connected directly to the MFCs. Capacitor size on the charge pump is limited to less than about 10F. Whenever supercapacitors larger than 5F were connected to the charge pump the charging became inconsistent and the capacitors would not fully charge. But there is no limit on capacitor size when they are connected directly to the MFC. This means that very large capacitors can be used and more energy accumulated on the capacitors before they are connected.
to the charge pump. The disadvantages for this circuit include more parts, higher complexity, more materials, and higher cost.

2.4.2.2 Energy Accumulation

The first step is to accumulate energy from the MFCs. Switches S1 - S4 are normally-closed optical relays. As long as no current flows through the relays then the capacitors will be connected to the MFCs and disconnected from the boost converter. The Seiko S-882Z charge pump is connected to one of the MFCs. The current draw of the charge pump is only $290\,\mu\text{A}$ so it has very little effect on the charging of the main supercapacitors. This charge pump accumulates energy on its own supercapacitor that will activate the optical relays once charged. The super capacitor on the charge pump is very important to select correctly. This supercapacitor determines the time it will take between charging cycles. The super capacitor size in these tests was determined experimentally.

![Figure 2.13: Status of Optical Relays While Accumulating Energy](image-url)
2.4.2.3 Energy Distribution

Once the supercapacitor on the charge pump is charged to 1.8V then power is delivered to the optical relays through current limited resistors shown in Figure 3.8. When activated, switches S1-S4 are open and switches S5 and S6 are closed. As a result, capacitors C1 and C2 are disconnected from MFC1 and MFC2 and are connected in series through S6. Now the voltage across both main supercapacitors is the sum of the voltages on MFC1 and MFC2. This voltage is delivered through S5 to the boost converter. The combined voltage of both MFCs is enough to start the boost converter and begin delivering power to the load.

Figure 2.14: Status of Optical Relays While Delivering Energy to Load

2.4.2.4 Improvements Over Alternate Circuit

There are several improvements with this circuit versus the one that only uses one MFC. This circuit does not send all the power through the charge pump. A smaller amount of power goes through the charge pump that will power the optical relays. The power that will be delivered to the load all goes directly from the MFCs to the
main supercapacitors. This allows loads to be operated with higher efficiency with faster system charging times. This also allows higher power loads to be operated. This charge pump cannot charge supercapacitors over 5F. The MFC, however, can charge a supercapacitor of any size. This separation of sub-circuits allows very large supercapacitors connected directly to the MFCs but smaller supercapacitors can be used on the charge pump to only power the optical relays.

2.4.2.5 Parts List and Schematic

![Power Management System Schematic](image-url)
Table 2.2: Parts List for Second Power Management System

<table>
<thead>
<tr>
<th>Part</th>
<th>Manufacturer</th>
<th>Model Number</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Pump</td>
<td>Seiko</td>
<td>S-882Z</td>
<td>Input &gt;0.3V, Output 1.8V</td>
</tr>
<tr>
<td>Super Capacitor</td>
<td>NA</td>
<td>NA</td>
<td>1F</td>
</tr>
<tr>
<td>Super Capacitor</td>
<td>NA</td>
<td>NA</td>
<td>10F</td>
</tr>
<tr>
<td>Optical Relays</td>
<td>Clare</td>
<td>LBA716</td>
<td>1.2V LED</td>
</tr>
<tr>
<td>N-Channel Mosfet</td>
<td>Vishay/Siliconix</td>
<td>SI3460BDV</td>
<td>NA</td>
</tr>
<tr>
<td>P-Channel Mosfet</td>
<td>Vishay/Siliconix</td>
<td>SI3499DV</td>
<td>NA</td>
</tr>
<tr>
<td>DC/DC Converter IC</td>
<td>STM</td>
<td>L6920DB</td>
<td>Boost Converter: Input &gt;0.8V, Output 3.3V</td>
</tr>
<tr>
<td>Inductor</td>
<td>NA</td>
<td>NA</td>
<td>2µH</td>
</tr>
<tr>
<td>Capacitor</td>
<td>NA</td>
<td>NA</td>
<td>47µF</td>
</tr>
</tbody>
</table>
CHAPTER 3
RESULTS

3.1 MFC Results

A prototype MFC and a prototype power management system were developed and tested in the laboratory. The laboratory MFC consisted of two compartments, an anode and a cathode, which were separated by a proton exchange membrane. Each compartment had a liquid volume of 1.01L. The anode was made of a graphite plate, 18 cm wide 18 cm high 0.6 cm thick, with a surface area of 691.2 cm². The cathode was made of manganese-based catalyzed carbon bonded to a current-collecting screen made of platinum mesh. The cathode was made of two pieces, each 9 cm wide 19.3 cm high 0.05 cm thick, and the total surface area was 694.8 cm². The proton exchange membrane between the anode and the cathode allowed H⁺ ions to flow from the anode side to the cathode side to equilibrate the electrons being oxidized in the cathode. It also prevented the electrons in the anode from being oxidized immediately, instead allowing them to travel through the load of the MFC. This membrane is not needed in an open system because the sea floor isolates the reduced and oxidized environments. The bacteria Shewanella Oneidensis were grown on the anode side to produce electrons.

The voltage-current and power-current characteristic of the laboratory MFC were first tested as follows. The MFC was connected to resistive load and the resistance of the load was varied to vary the voltage and current of the MFC. The voltage and current of the MFC at different load were then measured with multimeters. The power of the MFC was calculated as product of the measured voltage and current. The measured voltage-current characteristic and power-current characteristic of the
MFC were plotted and shown in Figure 3.3. The voltage of the MFC was about 0.66V when the MFC current was zero. As the MFC current increased, the voltage of the MFC dropped. When the MFC current reached about 3.7mA, the voltage of the MFC dropped to 0.08V. The power of the MFC was zero when the MFC current was zero. When the MFC current was below 2.4mA, the power of MFC increased as the MFC current. When the MFC current was above 2.4mA, the power of the MFC decreased as the MFC current increased. The power of the MFC reached the maximum value of 1mW when the MFC current was 2.4mA.
Figure 3.2: Detailed Physical Setup of the Laboratory MFC
3.2 Power Management Results

3.2.1 Single MFC System

The power management system was developed and connected to the laboratory MFC and the hydrophone. The resultant system was tested through experiment. After the MFC was constructed it was operated for several days to ensure that the bacteria had established a colony. When the open-circuit voltage on the MFC reached approximately 700mV then the power management system and load were connected. In the experiment, the voltage of the MFC, the voltage of the super capacitor, and
the output voltage of the boost converter were first tested for a relatively long period-four days-to examine the long-term performance of the system. These voltages were recorded with a 500MHz digital oscilloscope (Tektronix TDS5054) and voltage probes in this four-day period.

Figure 3.4: Voltage of MFC, voltage of super capacitor, and output voltage of boost converter in the four-day period

As shown in Figure 3.4, after the experiment started the charge pump drew low current from the MFC to charge the super capacitor. As a result, the voltage of the super capacitor began to increase. Since the super capacitor was being charged, the output of the charge pump was low, and the high-side driver had the boost
converter disconnected from the supercapacitor. No voltage is being provided to the boost converter and therefore there is no output voltage to the hydrophone. Once the supercapacitor was charged to 1.8V then the output of the charge pump went high. The high-side driver begins to conduct and the supercapacitor is connected to the boost converter. The boost converter can easily start with an input voltage of 1.8V and produces a stable output of 3.3V to the hydrophone as the supercapacitor voltage drains. When the supercapacitor voltage gets down to 1.3V then the output of the charge pump goes low, the high-side driver stops conducting, and the boost converter is disconnected from the circuit. The output goes low and the supercapacitor begins charging again. This cycle of charging and discharging takes about 9.6 hours with a 1F super capacitor. The MFC voltage remains very constant throughout all the tests. This is because the charge pump only draws about 290 µA, which the MFC can easily supply.

Figure 3.5 is an expanded view of Figure 3.4 and shows greater details about MFC voltage, super capacitor voltage, and the boost converter output voltage. As shown in Figure 3.5, after the boost converter started up, it supplied a very stable voltage of 3.3V to the load. It can be seen in Figure 3.5 that as the boost converter delivered energy from the super capacitor to the load, the super capacitor voltage dropped. The power management system was able to supply power to the hydrophone for about 10 seconds at a time before the system disconnected the supercapacitor.

The power drawn from the MFC and the power delivered to the hydrophone in the four-day period were also recorded. In the test, the voltage and current from the MFC and the voltage and current to the hydrophone were recorded with the oscilloscope as well as voltage and current probes. The MFC voltage and current data were multiplied to calculate the power of the MFC, while the hydrophone voltage and current data were multiplied to calculate the power of the hydrophone. The MFC
power and hydrophone power in the four-day period are shown in Figure 3.6. It is shown there that the hydrophone drew about 95mW power from the boost converter when the boost converter started up, while the MFC only supplied 0.16mW power to the power management system constantly.

The size of the supercapacitor is what determines how long the system takes to charge. The change in charging time appeared to be linear with charging times of around 9.6 hours for 1F and 21.7 hours for 2.2F. This supercapacitor also determined how long the load could be operated after each charging session. Different loads

Figure 3.5: Detailed MFC voltage, super capacitor voltage, and boost converter output voltage
were tested to see how long they were powered. Extremely small loads, representing the most basic microcontroller circuits, were shown to be able to operate for several minutes. The tests show that a 10 $\mu$W load could be powered for up to 5.7 hours off a 2.2F supercapacitor. Larger loads, in the milliwatt range would usually be powered for a minute or less. A 10 mW load was powered for 83 seconds on a 2.2F supercapacitor. They hydrophone was able to run for 10 seconds off a 1F supercapacitor. The smaller supercapacitor was used for the hydrophone to decrease the charging time for the circuit.
The commercial boost converter has efficiencies that were expected from projected data from datasheets [13]. To measure this efficiency the input and output voltage and current were measured. The efficiency at an input voltage of 1.5V was 79%. This value was typical and expected. However, the efficiency of this power management system is low because of the Seiko charge pump. With the steady voltage in this experiment, the current draw was about 290\(\mu\) A at 560mV (160\(\mu\)W) throughout the tests. The output current to the super capacitor was also constant, operating at about 22A. So with the super capacitor being charged between 1.3V and 1.8V each time, the efficiency goes from 16.6 % and 24.4%. This is a limiting factor in this design. The entire charging cycle is dependent on this charge pump. The current draw of this part cannot be changed so it prevents the system from making full use of larger MFCs current capacity. No matter how much current is available, the current draw from the charge pump is constant. This makes it better suited for small MFCs like the one used in this experiment.

3.2.2 Multiple MFC System

The described power management system was built and tested in the lab. DC power supplies were used to simulate multiple MFCs. The schematic in Figure 3.8 highlights the subsystems in the circuit. The main supercapacitors were 10F and the supercapacitor connected to the charge pump was 1F. The load was the hydrophone.

Figures 3.9 through 3.11 show the test results of the power management system supplying power to the hydrophone. The beginning of Figure 3.9 shows supercapacitor C1 being charged by MFC1. The results for MFC2 and C2 are almost identical. The 10F capacitor charges up to MFC voltage within 2 hours. The rest of the time is spent waiting for the 1F supercapacitor on the charge pump to charge up to 1.8V.
Once the charge pump capacitor is charged then power is delivered to the optical relays. Supercapacitors C1 and C2 are connected in series through the optical relays and the voltage of the combined supercapacitors is delivered to the boost converter. The output voltage delivered to the hydrophone quickly jumps to 3.3V and then back down to zero and the system starts charging again.

Figure 3.10 is a detailed view of when the load is being powered. This figure shows the voltage of supercapacitor C1, the input voltage to the boost converter, and the output voltage delivered to the load. The voltage on the 10F supercapacitor C1 is 700mV, which is the output voltage of a healthy MFC. Once the charge pump activates the optical relays, the input to the boost converter goes high. It is shown that the voltage delivered to the boost converter is 1.4V, twice the voltage on C1,
because C1 and C2 are now connected in series. This voltage is finally boosted to 3.3V which is delivered to the load. The load continues to be powered until the supercapacitor on the charge pump is drained to 1.3V, at which point power is taken away from the optical relays and the main supercapacitors, C1 and C2, begin charging again.

Figure 3.11 shows the relation between the charge pump supercapacitor and the current delivered to the relays. The LEDs in the relays have a voltage drop of 1.24V. Current limiting resistors need to be selected to conserve power and protect the LEDs. According to the optical relay datasheet [17], it will take at least 0.21mA to run each
normally-closed relay and 0.85mA for each normally-open relay. Since the lowest voltage that the supercapacitor will supply the LEDs is 1.3V, that lowest drop must be used to select the current limiting resistors. The following equations were used to
Figure 3.10: Detailed Voltage of One Supercapacitor, Input to Boost Converter, and Output to Load

To find the limiting resistor for the normally-closed relay,

\[
R_{\text{min}} = \frac{V_{\text{min}} - V_{\text{LED}}}{I_{\text{LED total}}} = \frac{1.3 - 1.24}{3 \times 0.21mA} = 95\Omega
\]  \hspace{1cm} (3.1)
Table 3.1: Calculated and Measured Relay Current

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Calculated</th>
<th>Measured</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8V</td>
<td>21.8mA</td>
<td>19.6mA</td>
<td>10%</td>
</tr>
<tr>
<td>1.3V</td>
<td>2.3mA</td>
<td>3.5mA</td>
<td>52%</td>
</tr>
</tbody>
</table>

The following equations were used to find the current limiting resistor for the normally-open relays.

\[
R_{\text{min}} = \frac{V_{\text{min}} - V_{\text{LED}}}{I_{\text{LED total}}} = \frac{1.3 - 1.24}{2 \times 0.85mA} = 35.3\Omega
\] (3.2)

The closest 5% resistors were actually used were 91 Ω and 33 Ω. The calculated and measured currents delivered to the relays is shown in table 3.2.2.

The optical relays and current limiting resistors consume 39mW to at 1.8V down to 3mW at 1.3V while they are being powered. This is not a trivial amount of power loss. All this power contributes to the charge pump supercapacitor being drained quickly. If more efficient devices could be found then the optical relays then the load could be activated for a longer period of time. Figure 3.11 shows how the voltage on C1 is drained as current is sent to the relays.

Figure 3.9 demonstrates how the charge pump is limiting the efficiency of the circuit. Each MFC is connected to a 10F supercapacitor which charges in 2 hours. However, it takes 9.6 hours to charge the 1F supercapacitor on the charge pump. This means that the supercapacitors connected to the MFCs could accumulate a lot of power, but it is only worthwhile if there needs to be a higher output power.

The efficiencies for this circuit show that the load can be powered more efficiently. The charge pump circuit still has the same efficiency as before, about 20 %, but
Figure 3.11: Voltage and Current Delivered to Relays and Corresponding Output

this is only on the part of the circuit with the optical relays. The efficiency from the MFC to the load was typically 79%. This efficiency is almost the same as the boost converter efficiency before. Even though power is not going through the high-side driver circuit this time, there are still optical relays in between the boost converter and MFCs. However, the resistance of the high-side driver was almost exactly the same as the total resistance from the optical relays which was 0.04 Ω. So even though the efficiencies for these individual parts are the same, there is almost a 60% increase in the efficiency of the power delivered to the load as compared to the single MFC circuit. Also, the charge pump does not have to charge the main supercapacitors that will power the load. This is a huge benefit since the charge
pump had problems charging large supercapacitors but the MFCs have no problem charging supercapacitors of any size.

Figure 3.12: Photograph of the Tested System
CHAPTER 4

CONCLUSION

The two power management systems both proved to be successful. They were able to extract and accumulate energy at MFC voltage as low as 300mV and then deliver power to the hydrophone at 3.3V. The system is totally autonomous because no batteries are used. The first system increased the voltage of a single MFC by directing all power flow through the Seiko S882-Z charge pump. The low efficiency and charging limitations of this charge pump leave much to be desired. The second system was able to put MFCs in series by way of using optical relays to switch supercapacitors in series and parallel. This allowed the circuit to redirect some power so not all went through the inefficient charge pump. The MFCs in series were able to provide more energy and voltage to the boost converter so the boost converter was able to successfully start and provide power to the load.

The cycles of accumulating energy and bursting power to the load are not conducive to the hydrophone application. The hydrophone works best if it is always powered and can log time and date information when a sensor passes by. Any time that the hydrophone is not powered means that it could be missing sensors that are passing by. A better application for this power source would be data collection that does not need to be continually active. Low power sensor packages that would need to record data only a few times a day would benefit the most from this power source. As more discoveries are made in scaling up microbial fuel cells, higher power versions of the circuits presented here may become necessary. The need for accumulating and delivering power in cycles could vanish as the current capacity of these MFCs increases. However, small MFCs, such as those used in these experiments, need to go
through these cycles in order to power devices demanded more power than they can deliver.
REFERENCES CITED


