Energy Harvesting With Microbial Fuel Cell and Power Management System

Andrew Meehan, Hongwei Gao, *Senior Member, IEEE*, and Zbigniew Lewandowski

***Abstract*—This paper presents a system that can harvest energy in the water and use the harvested energy to power electronic devices deployed in the water. The system consists of a microbial fuel cell (MFC) and a power management system. The MFC uses electrochemical reactions and bacteria that exist in the water to harvest energy and generate electricity. The power management system consisting of a charge pump, a super capacitor, two solid-state switches, and a boost converter accumulates the energy harvested by the MFC, stores the energy in the super capacitor, and bursts power to the load. The power management system also boosts the voltage of the MFC to a sufficient level for the electronic devices. The presented energy-harvesting system is self-powered, sustainable, environment friendly, and maintenance-free. The system has been tested and proven through experimental work.**

***Index Terms*—Boost converter, charge pump, hydrophone, microbial fuel cell (MFC), power management system.**

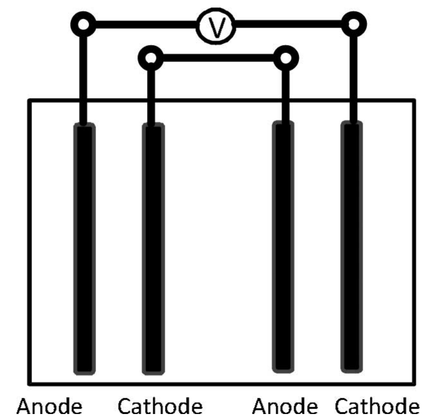

Fig. 1. Overall voltage of series-connected MFCs in an open water system.

I. Introduction

THERE are needs to harvest energy in the water and use the harvested energy to power electronic devices deployed in the water. For example, the U.S. Navy needs to detect and monitor sea turtle activities near naval bases so that the turtles are not endangered by naval ships. The navy uses electronic devices, so-called hydrophones, to do this. The hydrophones are anchored to the bottoms of the seas, and therefore, if they are powered by batteries, then the batteries have to be replaced frequently by diving teams, which is dangerous and expensive. The U.S. Navy considers using devices that can harvest energy from the water to power the hydrophones.

One type of devices that can harvest energy from the water is microbial fuel cells (MFCs). MFCs use bacteria that exist in the water and certain electrochemical reactions to generate electricity. They require no maintenance and have unlimited lifetime and are therefore more appealing than batteries for powering electronic devices deployed in the water. They can continue to produce electricity as long as the bacteria are alive and active, and therefore, can make the systems powered by MFCs autonomous. They do not produce harmful waste and are therefore environment friendly.

Though MFCs are very attractive power sources, they present certain challenges for real applications—they produce very low voltage and current.

The voltage of an MFC is usually insufficient for the load. For example, an MFC usually produces a few hundred milivolts, while a hydrophone requires 3.3 V to operate. The voltage can be increased in the laboratory by stacking several MFCs in series like batteries, but this cannot be done in an open water system such as in the sea. This is explained with Fig. 1, which shows that two MFCs are deployed in a water aquifer and are connected in series. Unlike series-connected cells in a battery pack where all the cells are separated, the series-connected MFCs will be placed in a common water body. As a result, the overall voltage of the series-connected MFCs is the voltage between the two electrodes on the extreme ends of the series, which will be the voltage of a single MFC.

The current of an MFC is usually insufficient for the load too. For example, an MFC usually supplies less than 2-mA current, while the hydrophone requires around 29 mA. In addition, it is impractical to increase the current capacity of an MFC by increasing the surface area of the anode or cathode. This is because an MFC has a very low maximum power density (maximum power of the MFC divided by the surface area), and the maximum power density becomes even lower when the surface area is bigger [1]. Therefore, increasing the current capacity of an MFC by increasing the surface area of the anode and cathode will result in a very large MFC that is expensive and hard to deploy. The relationship between the maximum power

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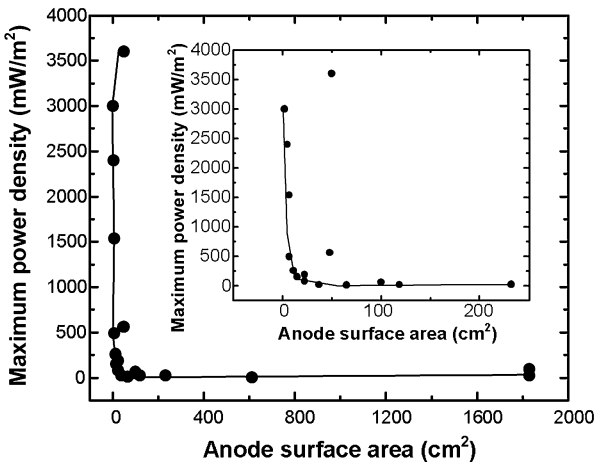

Fig. 2. MFC power density versus electrode surface area. The inset shows the data for smaller anode surface areas, those clumped together in the bottom-left corner of the larger image [1].

density and the surface area was studied in [1] and was shown in Fig. 2.

The low-voltage and low-current problem of the MFC requires a power management system to interface the MFC with the load. The power management system needs to boost the voltage of the MFC to meet the voltage requirement of the load. The power management system also needs to accumulate energy from the MFC over long time periods and provide sufficient current to the load in short time periods, i.e., burst power to the load.

This paper presents an MFC and a power management system to interface the MFC with a hydrophone. The design of the MFC and the design of the power management system are described in Section II. The experimental results of the resultant system are shown in Section III. The conclusions are drawn in Section IV.

II. MFC and Power Management System Design

The proposed system uses an MFC and a power management system to provide power to the hydrophone. The design of the MFC and the design of the power management system are described as follows.

A. MFC Design

The MFC consists of an anode and a cathode. In an open water system, the anode is buried in the floor and the cathode is suspended in the water.

The basic structure and basic electrochemical reactions in the MFC are shown in Fig. 3.

On the anode, a type of bacteria that exist in the water, *Shewanella Oneidensis*, break down lactate in the water and make lactate to release electrons and react with water. The reaction is as follows:

$$\mathrm{Lactate} + \mathrm{H_2O} \rightarrow \mathrm{Acetate} + \mathrm{CO_2} + 4\mathrm{H}^+ + 4e^-. \quad (1)$$

The electrons (e^-) produced in (1) travel onto the anode, and then, travel to the cathode through the load of the MFC. The

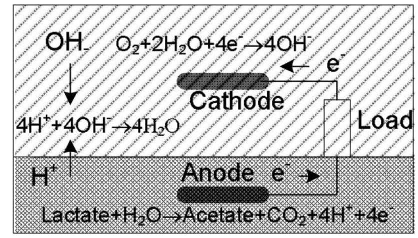

Fig. 3. MFC structure and reactions.

protons (H^+) produced in (1) travel to the cathode side through the water.

On the cathode, the electrons from the anode react with water and oxygen in the water to produce OH^-. The reaction is as follows:

$$\mathrm{O_2} + 2\mathrm{H_2O} + 4e^- \rightarrow 4\mathrm{OH}^-. \quad (2)$$

The OH^- produced in (2) then reacts with H^+ from the anode to form water

$$4\mathrm{OH}^- + 4\mathrm{H}^+ \rightarrow 4\mathrm{H_2O}. \quad (3)$$

Neither the anode material nor the cathode material participates in any of the aforementioned electrochemical reactions. As a result, neither the anode nor the cathode is consumed.

According to Fig. 2, the surface area should be selected carefully to achieve high power capacity and high power density. However, optimal design of the surface area is beyond the scope of the paper. A relatively large surface area of around 694 cm^2 was used in this paper because of availability of the anode and cathode material and the required short development time.

B. Power Management System Design

Using a charge pump to boost the low voltage (0.45 V) of an energy-harvesting system was reported in [2]. However, the charge pump used in [2] only boosted the voltage to 2.45 V, which is insufficient for powering hydrophones.

It seems straightforward to use a boost converter to increase the voltage of an MFC to the voltage level of the load. However, there are several problems with using only a boost converter to boost the voltage of an MFC. Currently available low-voltage boost converters usually need at least 800 mV to start up [3], [4]. Since an MFC usually produces voltage less than 0.7 V, these boost converters cannot be used to boost the voltage of the MFC. Some newly developed low-voltage boost converters, such as the Texas Instrument (TI) TPS61200 series of boost converters, can start up at 500 mV voltage [5], and therefore seem promising for increasing the voltage of an MFC. However, these boost converters begin to draw high current at start up. The current is in excess of the current the MFC can supply and causes the MFC voltage to drop quickly. As a result, when such a boost converter is connected to an MFC, the voltage of the MFC never increases to a level where the boost converter can start up.

Seiko recommended a charge pump plus a boost converter solution [6]. The charge pump draws low current from the source and uses the current to charge a capacitor. For example, a Seiko S-882Z charge pump can draw as low as a few hundred

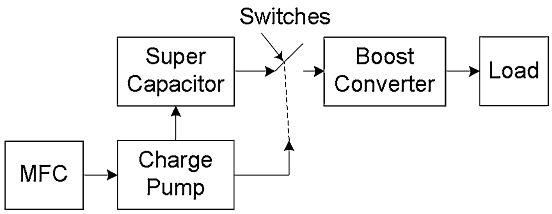

Fig. 4. Power management system block diagram.

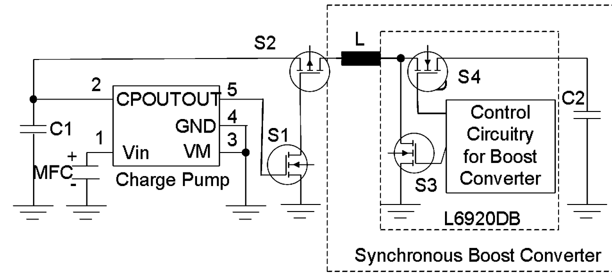

Fig. 5. Power management system schematic.

microamperes current from an MFC when the MFC is supplying as low as 0.3 V and can use the energy from the MFC to charge a capacitor to about 1.8 V. The boost converter is used to further boost the output voltage of the charge pump—the voltage of the capacitor. However, the boost converter cannot be directly connected to the capacitor. If so, then the boost converter will start to draw current from the capacitor when the capacitor is charged to a low-voltage level, such as 800 mV for commercially available low-voltage boost converters. Since the current drawn by the boost converter from the capacitor is higher than the current supplied by the charge pump to the capacitor, the voltage of the capacitor will drop. As a result, the capacitor voltage will stay low and the boost converter will not be able to start up.

The solution is to place solid-state switches between the capacitor and the boost converter. The switches turn OFF and therefore disconnect the boost converter from the capacitor when the capacitor voltage is low. On the other hand, the switches turn ON and therefore connect the boost converter to the capacitor when the capacitor voltage is high. The ON and OFF of the switches are controlled by the charge pump.

The devised power management system is illustrated in Fig. 4. The power management system consists of a charge pump (Seiko S-882Z), a 2.2-F super capacitor, a boost converter (built with ST Microelectronics L6920DB chip [7]), and solid-state switches. The charge pump draws low current from the MFC and charges the super capacitor. When the voltage of the super capacitor is lower than 1.8 V, the charge pump opens the switches between the super capacitor and the boost converter, and therefore, disconnects the boost converter from the super capacitor. In this case, the capacitor is charged by the charge pump, but does not source any current. Once the super capacitor voltage reaches 1.8 V, the charge pump closes the switches and therefore connects the boost converter to the super capacitor. In this case, the boost converter receives sufficient voltage and energy from the super capacitor, and therefore starts up, boosting the super capacitor voltage from 1.8 to 3.3 V, and thus supplying high enough current to the load.

The detailed schematic of the devised system is shown in Fig. 5. The two input pins of the charge pump, pin 1 and pin 4, are connected to the cathode and the anode of the MFC, respectively, and are used to draw current from the MFC. The output pin of the charge pump, pin 2, is connected to super capacitor $C1$ and used to charge the capacitor.

Pin 5 of the charge pump, which supplies 0 V voltage when the super capacitor voltage is lower than 1.8 V and supplies 1.8 V voltage when the super capacitor voltage reaches 1.8 V, is used to control the solid-state switches between the capacitor and the boost converter. Pin 5 is connected to the gate of an N-channel MOSFET $S1$, which turns ON when its gate-to-source voltage reaches 1.5 V. The drain of $S1$ is connected to the gate of a P-channel MOSFET $S2$, which turns ON when its gate-to-source voltage reaches -1.5 V. The drain and source of $S2$ are connected to the boost converter and super capacitor $C1$, respectively.

The charge pump starts to draw current from the MFC and charge the super capacitor when the MFC voltage reaches 0.3 V. Before the super capacitor voltage reaches 1.8 V, pin 5 of the charge pump supplies 0 V to the gate of $S1$, and therefore turns OFF $S1$ and, hence, $S2$. As a result, the boost converter is disconnected from the super capacitor and therefore shuts off. In this case, the capacitor is charged by the charge pump, but does not supply current to the boost converter. When the super capacitor voltage reaches 1.8 V, pin 5 of the charge pump supplies 1.8 V to the gate of $S1$ and turns ON $S1$. As a result, the gate voltage of $S2$ becomes 0 V and the gate-to-source voltage of $S2$ becomes -1.8 V. Consequently, $S2$ turns ON, connecting the synchronous boost converter that consists of inductor L, MOSFET $S3$, MOSFET $S4$, capacitor $C2$, and control circuitry for the boost converter ($S3$, $S4$, and the control circuitry are integrated in one single IC-ST Microelectronics L6920DB), to the super capacitor. In this case, the boost converter receives sufficient voltage and energy from the super capacitor and therefore starts up, thus providing 3.3 V voltage and sufficient current to the load. As energy is delivered from the super capacitor to the load through $S2$ and the boost converter, the voltage of the super capacitor drops. When the super capacitor voltage drops below 1.3 V, pin 5 of the charge pump supplies 0 V to the gate of $S1$. As a result, $S1$ and hence $S2$ turn OFF, disconnecting the boost converter from the super capacitor and therefore shutting off the boost converter. The boost converter starts up again when the super capacitor is charged to 1.8 V by the charge pump next time.

The parts in Fig. 5 are described in Table I.

A power management system consisting of a charge pump, a super capacitor, and a boost converter was introduced in [8]. Unlike the power management system introduced in this paper, the power management system proposed in [8] places the super capacitor at the input of the charge pump, i.e., in parallel with the MFC, rather than placing the super capacitor at the output of the charge pump. In addition, the power management system in [8] uses a boost converter to boost the voltage of the MFC/super capacitor, i.e., the input voltage of the charge pump,

Table I
POWER MANAGEMENT SYSTEM PARTS DESCRIPTION

Part	Manufacturer	Model Number	Specifications
Charge Pump	Seiko	S-882Z	Input:0.3V, Output 1.8V
Super Capacitor C1	Cooper/Bussman	B0820-2R5225-R	2.2F
N-Channel MOSFET S1	Vishay/Siliconix	SI3460BDV	V_{GS}:1.5V, V_{DS}:20V, I_D:8A, R_{ON}:0.04Ω
P-Channel MOSFET S2	Vishay/Siliconix	SI3499DV	V_{GS}:-1.5V, V_D:-8V, I_D:-5A, R_{ON}: 0.048Ω
Booster Converter IC	ST Microelectronics	L6920DB	Input:0.8V, Output:3.3V
Inductor L			2μH
Capacitor C2			47μF

rather than boosting the output voltage of the charge pump. Because the super capacitor is connected to the MFC directly, it is only charged to very low voltage, and therefore has much smaller energy content for a given capacitance. As a result, the power management system in [8] provides power to the load for a much shorter time period for a given capacitance or requires a much large super capacitor to provide power to the load for a given time period. By contrast, the power management system introduced in this paper places the super capacitor at the output of the charge pump. As a result, the super capacitor is charged to much higher voltage and therefore has much larger energy content for a given capacitance. This allows the boost converter to provide power to the load for much longer time period for a given capacitance. In addition, the boost converter in the power management introduced in [8] has to boost the low voltage of the MFC, such as below 0.3 V, to the voltage of the load, such as 3.3 V for a hydrophone. In this case, the boost converter has to have a very large duty ratio, such as more than 0.9. Such a large duty ratio is not supported by most commercially available low-voltage boost converter control ICs. Such a large duty ratio also compromises the efficiency of the boost converter.

III. EXPERIMENTAL 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. Each compartment had a liquid volume of 1.01 L. 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 cm^2. 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 cm^2. The prototype MFC along with the developed power management system and the hydrophone is shown in Fig. 6.

The voltage–current and power–current characteristics 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 Fig. 7.

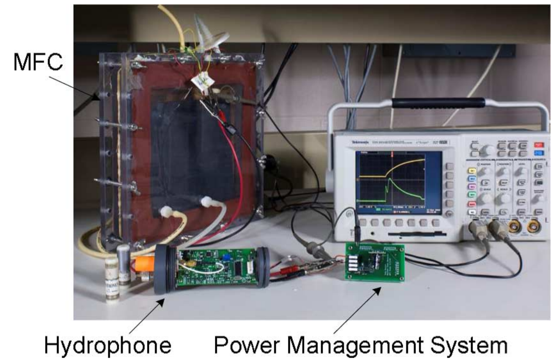

Fig. 6. MFC, hydrophone, and power management system.

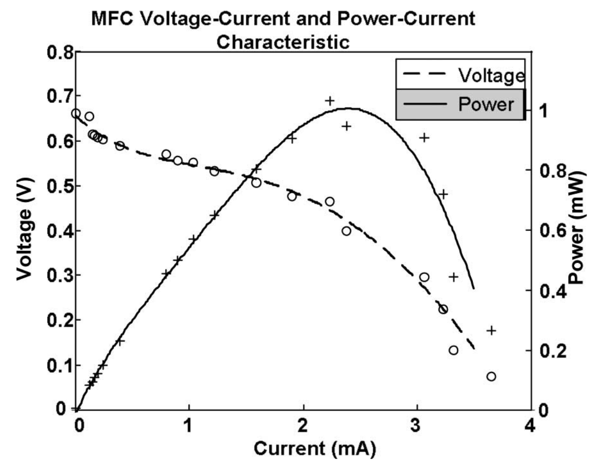

Fig. 7. Voltage–current and power–current characteristic of laboratory MFC.

The MFC voltage drops continuously as the MFC current increases. The MFC voltage is about 0.66 V at the open-circuit condition and drops to 0.08 V when the MFC current is 3.7 mA. Initially, the MFC power increases as the MFC current. After reaching the maximum value of 1 mW at the 2.4 mA MFC current, the MFC power decreases as the MFC current increases.

The power management system was also developed and connected to the laboratory MFC and the hydrophone. The resultant system was tested through experiment. 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 500-MHz digital oscilloscope (Tektronix TDS5054) and voltage probes in this four-day period. The recorded voltage data are shown in Figs. 8 and 9.

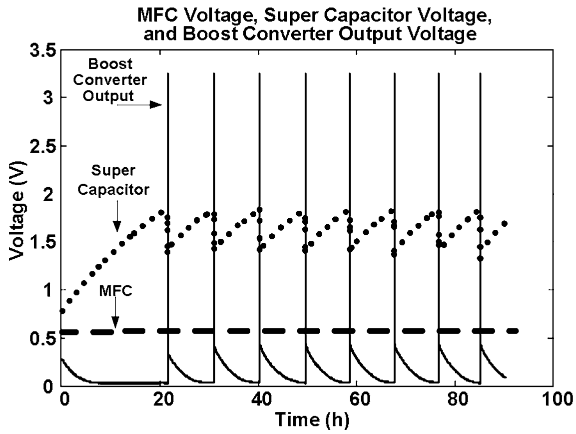

Fig. 8. Voltage of MFC, voltage of super capacitor, and output voltage of boost converter in the four-day period.

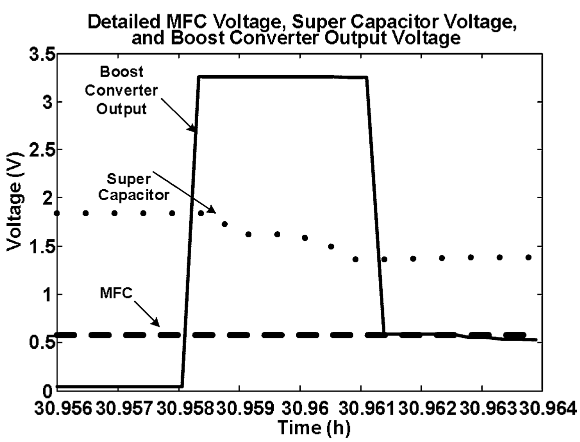

Fig. 9. Detailed MFC voltage, super capacitor voltage, and boost converter output voltage.

Fig. 8 shows the voltage of the MFC, the voltage of the super capacitor, and the output voltage of the boost converter in the four-day period.

When the super capacitor was charged to 1.8 V, the boost converter started up, supplying 3.3 V to the load. As energy was supplied to the load from the super capacitor, the super capacitor voltage dropped. When the super capacitor voltage dropped below 1.3 V, the boost converter shut off again. When the super capacitor was charged to 1.8 V next time, the boost converter started up again. Throughout the test, the charge pump drew very low current (about 290 μA) from the MFC to charge the super capacitor. As a result, the MFC voltage stayed relatively stable at 600 mV. It took about 9.3 h to charge the super capacitor from 1.3 to 1.8 V.

Fig. 9 is an expanded view of Fig. 8 and shows greater details about MFC voltage, super capacitor voltage, and the boost converter output voltage. As shown in Fig. 9, after the boost converter started up, it supplied a very stable voltage of 3.3 V to the load. It is also shown in Fig. 9 that as the boost converter delivered energy from the super capacitor to the load, the super capacitor voltage dropped. However, because of the high energy content in the super capacitor, the power management system could supply power to the load (hydrophone) for a very long period—about 10 s—before the boost converter was turned off.

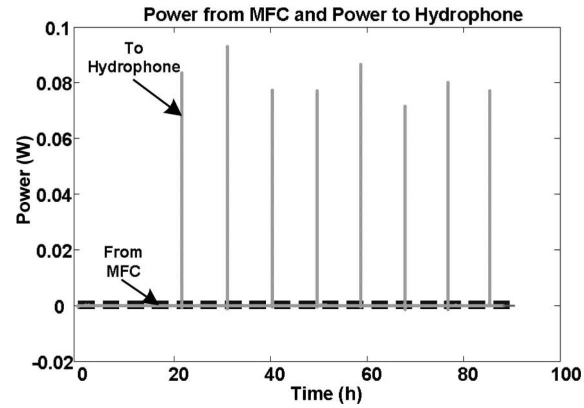

Fig. 10. Hydrophone and MFC power.

The power drawn from the MFC and the power delivered to the hydrophone in the four-day period were also tested. In the test, the voltage and current of the MFC and the voltage and current of 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 Fig. 10. As shown in Fig. 10, the hydrophone drew about 95 mW power from the boost converter when the boost converter started up, while the MFC only supplied 0.174 mW power to the power management system consistently.

The efficiency of the charge pump is 16.6%–24.4% according to the datasheet of the charge pump [6]. The efficiency of the boost converter is 85%–90% according to the datasheet of the boost converter [7].

IV. Conclusion

The experimental results have shown that the developed MFC can generate electricity using electrochemical reactions caused by *S. Oneidensis.* The results also show that an MFC can only produce very low voltage, current, and power, which are insufficient for electric load like hydrophones.

The experimental results also show that the developed power management system can successfully meet the voltage, current, and power demand of the load using the energy harvested by the MFC. The power management system can draw very low current from the MFC and accumulate the energy in a super capacitor. The power management system can boost the voltage of the super capacitor to meet the voltage demand of the load. The power management system can also deliver high enough power to the load from the super capacitor to meet the current or power demand of the load.

The proposed power system is suitable for applications that require self-contained, renewable, maintenance-free, and intermittent power source in water environment. Examples of such applications include powering sensors deployed in the water.

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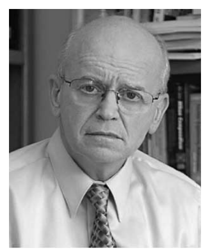

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