

# Dynamic Modeling of Direct Electron Transfer PQQ-GDH MWCNTs Bioanode Function

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**Abstract**— Herein a system capable of simultaneously sensing glucose and harvesting sufficient energy to power a digital device is presented. This system is powered by an enzymatic glucose biofuel cell consisting of pyrroloquinoline quinone glucose dehydrogenase (PQQ-GDH) modified bioanode and bilirubin oxidase modified biocathode. The electrical parameters from a single biofuel cell were amplified to 1.4 V using a charge pump circuit consisting of a capacitive element that senses glucose. Further a steady output DC supply of 3.2 V was obtained by interfacing a step up DC-DC converter circuit to the charge pump circuit. Such a system simultaneously senses glucose and harvests energy in various glucose concentrations operating under physiological conditions (37 °C and pH 7.4). The novel system shows a promising future for healthcare systems industry.

**Keywords**— glucose biofuel cell; charge pump circuit; step up DC converter circuit

## I. INTRODUCTION

With 29.1 million people in the US (9.3% of the populous) living with diabetes, continued research into improving glucose sensing systems is required. Moreover, an estimated yearly cost of \$245 B is spent on diabetes care in the U.S. alone, making it paramount to finding a permanent and cost-effective solution to managing diabetes and maintaining tight control over blood glucose. Glucose monitoring devices currently on the market suffer from various drawbacks [1]. The most common device, a glucometer, has several limitations, such as requirement of the user's to constantly prick their fingers to monitor their blood glucose. Additionally, these devices only provide a snap shot of blood glucose level, thereby it is rather an infrequent measurement of blood glucose. To overcome the current drawback of multiple finger pricking in a given day, the continuous glucose monitor (CGM) was introduced to allow for the periodic monitoring of interstitial glucose. These CGM employs an integrated needle biosensor that are implanted subcutaneously underneath the skin for a duration of up to 7 days. Although these devices periodically measure glucose, they still need to be replaced every 5 -7 days and still requires the use of a glucometer for calibration purpose and to maintain tight blood glucose measurement.

The shared common limitation of these devices is that they consist of battery operated potentiostat circuit which makes the device bulky, in addition to the frequent calibration

requirement. An ideal device could be installed once and would constantly measure the patient's glucose levels over an extended period of time without any discomfort to the patient or concern in regards to battery replacement. Moreover, the device should be independent of the battery operated potentiostat circuit. This has led to an extensive research to explore an alternate source of power and enzymatic biofuel cells as a power source have received significant attention due to their advantages and applications over conventional fuel cell and battery [2]. Enzymes are highly unstable and easily affected by external conditions such as temperature, pressure and humidity and an extensive research has been done to make these devices stable and long lasting [3]. Enzymatic glucose biofuel cells have found its application in various industries including biomedical industry in powering invasive devices such as pacemakers and glucose sensors [4, 5]. These biofuel cells however, do not produce sufficient electrical power density to sense glucose and/or power any microelectronic or bioelectronic devices. Therefore, there is a need for a closed loop sensing and an amplification circuit which are both powered by a single enzymatic glucose biofuel cell.

This paper focusses on a novel system that is powered by a single enzymatic glucose biofuel cell and simultaneously senses glucose and powers a digital glucometer. The system consists of two amplification circuits that amplifies the single biofuel cell parameters to both sense glucose and power a microelectronic device. The amplification circuits consist of a charge pump circuit and a step up DC-DC converter circuit. A transducer capacitor is connected to the output of a charge pump circuit and is used to sense glucose. Capacitors are storage elements and are used here to store charge until it can no longer hold any more charge which results into the capacitor discharging. This charge and discharge rate is governed by the power produced by the biofuel cell and amplified via a charge pump IC. Some researchers have used series and parallel combinations of these biofuel cells as a means to improve the electrical parameters [4, 6]. Although it amplifies the electrical parameters, it makes the device more bulky. Also, if the device fails, there is no way of knowing which individual biofuel cell is not functional without having to test each individual biofuel cell. Therefore, these amplification circuits are employed in this work to make the circuits less bulky and amplify the electrical parameters generated by the biofuel cell. Depending on the device to be powered, the output of the charge pump can be further amplified

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using a step up DC converter circuit. This glucose sensing system presented here reduce the bulkiness of the system. This novel system although is in its early stages, pose a possible solution to the drawbacks possessed by the commonly used glucose monitoring systems.

## II. EXPERIMENTAL

### A. Chemical and Components

Buckypaper comprising of multi-walled carbon nanotubes (MWCNTs) was purchased from Nanotech lab, NC. It was cut into two strips 0.5 cm x 0.5 cm long and wide respectively to serve as electrodes for enzyme immobilization process. 1-Pyrenebtanoic acid, succinimidyl ester (1-PBSE) was purchased from AnaSpec. Inc which was used as a cross-linker. Pyroquinoline quinone glucose dehydrogenase (PQQ-GDH), a glucose selective anodic enzyme was purchased from Toyobo co. ltd. Also, the oxygen reducing cathodic enzyme, Bilirubin oxidase was purchased from Sigma Aldrich. Potassium phosphate, calcium chloride, and D-(+)-Glucose, >=99.5% for experiments were purchased from Sigma Aldrich. Dimethyl sulfoxide (DMSO), >99.5% (GC) solvent for the crosslinker was purchased from Sigma Aldrich. Nafion® perfluorinated resin solution was purchased from Sigma Aldrich and was used to improve the longevity of the bioanodes [7].

### A. Energy harvesting using a biofuel cell

The buckypaper electrodes were formed by sandwiching a tungsten wire between two sheets of buckypaper to serve as a point of contact for external connection. Such method assists with ease of handling the buckypaper and extends the life of these electrodes. Further these electrodes were modified with 1-PBSE followed by respective enzyme solutions to form bioanode (PQQ-GDH enzyme) and biocathode (bilirubin oxidase) and the active surface area was calculated to be 0.04 cm<sup>2</sup>. Bilirubin oxidase enzyme allows for successful operation of the entire system at physiological conditions (37 °C and pH 7.4) as opposed to laccase enzyme which fails to operate beyond neutral pH.

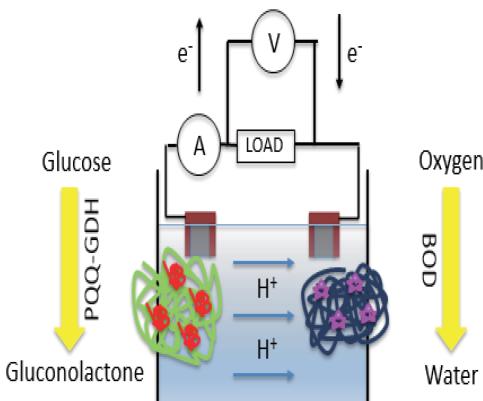


Figure 1. Enzymatic glucose biofuel cell harvesting energy from glucose.

Glucose is oxidized at the interface of bioanode and electrolyte consisting of glucose fuel to form gluconolactone along with the release of electrons and ions. These electroactive species travelled towards the cathode where oxygen is reduced by bilirubin oxidase to form water as illustrated in the reactions below:



The flow of electrons result into current being produced and hence, power is generated. The biofuel cell is further characterized in various glucose concentration solution and the peak open circuit voltage and short circuit current density along with peak power density is observed in the presence of 20 mM glucose solution [8]. However, this biofuel cell assembly by itself could neither sense glucose nor power any electronic device. Hence, amplification circuits in the form of charge pump and a step up DC converter circuit was implemented.

## III. RESULTS AND DISCUSSION

### A. Charge pump circuit

A charge pump circuit (S882z from Seiko Instruments Inc) and a 0.1 μF capacitor serving as the transducer are shown in the CAD schematic in Figure 2A. The board schematic obtained is used to fabricate the printed circuit board (PCB) shown in figure 2B. A single biofuel cell was able to supply the input supply between 0.3 V – 0.55 V to drive the oscillation circuit of the charge pump IC.

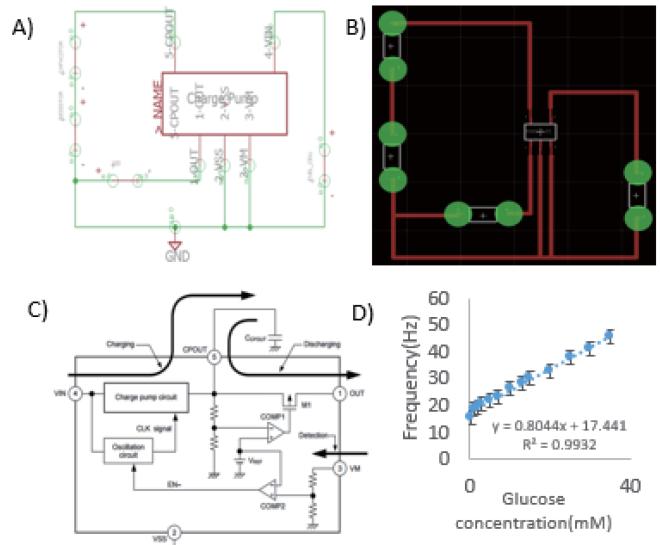


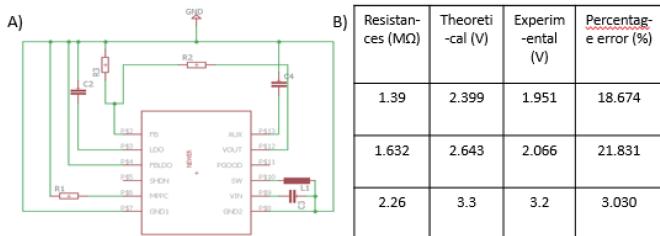
Figure 2. A) CAD schematic of charge pump circuit. B) Board file used to fabricate PCB C) Internal working of charge pump IC. D) Calibration curve of the glucose sensor monitored over a glucose concentration from 1 – 35 mM at 37 °C and pH 7.4.

Figure 2C shows the internal structure of the charge pump IC. The charge pump IC amplifies an input voltage of 0.3V or higher to 1.8V which is enough to power a microelectronic

device, such as a light emitting diode (LED). Moreover, the charging/ discharging cycle of the capacitor resulted in a voltage that toggles between 1.8 V and 1.2 V. This charge cycle across the capacitor is used to sense glucose. With increase in glucose concentration, the power produced by the glucose biofuel cell increased as well as the charge/ discharge cycle frequency. It is observed from the calibration curve that the charge/ discharge across the 0.1  $\mu$ F capacitor increased linearly with glucose concentration as shown in Figure 1D. Thus, glucose is sensed by monitoring the charge cycle across the capacitor by subjecting it to various glucose concentration at physiological conditions (37 °C and pH 7.4).

#### B. A step-up DC converter circuit

Although the charge pump circuit amplifies electrical parameters from a single biofuel cell, it supplies burst of power which is inconvenient to power any microelectronic or bioelectronic devices. Additionally, the output from the charge pump circuit ranges between 1.2 V and 1.8 V and this will be problematic for powering a microcontroller that can transmit data wirelessly. Clearly, there is a need for a steady DC supply. Here a step up DC-DC converter circuit (LTC3105 from Linear Technology Corporation) was employed. This circuit consists of a voltage divider circuit, which is used to amplify the output voltage based on the requirement as shown in the Figure 3A.



**Figure 3.** Eagle schematic of step up DC converter circuit. B) Theoretical and experimental comparison of output voltage with varying resistance values.

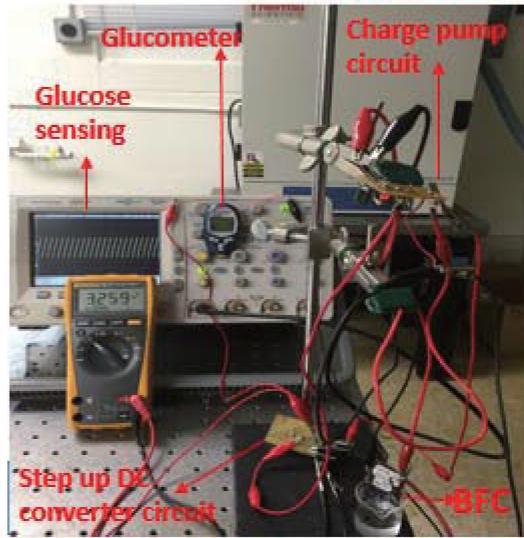
PSpice software is used to optimize the resistor value to yield the output DC voltage of 3.3 V. Under ideal conditions and disregarding the triggering voltage, the minimum input voltage required to achieve an output voltage of 3.3 V is observed to be 0.52 V. Furthermore, different resistors were connected in the voltage divider circuit to observe the change in output voltages. Theoretically, output DC voltage was calculated using the following equation:

$$V_{OUT} = 1.004 * \left( \frac{R_2}{R_1} \right) + 1$$

Figure 3B shows the discrepancy between the theoretical and practical output DC voltage values obtained. This discrepancy could be attributed to the energy loss in the form of heat at the orthogonal turns in the original PCB designs and the copper traces losses in the circuits. Moreover, signal losses could emerge due to long distance connection between the IC and the output measuring pins.

#### C. Interface circuit

For simultaneous glucose sensing and powering of a digital device, it is essential to interface both the charge pump circuit and a step up DC-DC converter circuit. The DC-DC converter circuit requires a triggering voltage of 1.4 V to start its operation following which a low operating voltage of 225 mV is sufficient to keep it operating. The biofuel cell is used to power both circuits as shown in the Figure 4.



**Figure 4.** Simultaneous glucose sensing and powering of glucometer

The primary power source that drives self-powered assembly is the enzymatic glucose biofuel cell. Such an assembly produced a steady output voltage of 3.2 V which was sufficient to power a digital glucometer. This novel glucose sensing system that uses a sensing circuit in the form of charge pump circuit and capacitor and powering circuit in the form of a step up DC converter circuit has the potential to replace glucose monitoring devices that run on battery operated mechanism and needs recalibration from time to time. Our system not only senses glucose but also generates enough energy to potentially power a biocompatible device, which is the future of glucose monitoring devices.

#### IV. CONCLUSION

We successfully build a self-powered glucose biosensor system that is capable of simultaneously sense glucose and power a digital device such as a glucometer. The system was driven by a single enzymatic glucose biofuel cell. The choice of PQQ-GDH and bilirubin oxidase enzyme enabled the system to operate at physiological conditions (37 °C and pH 7.4). The charge pump circuit amplified the voltage from a single biofuel cell to 1.2 V - 1.8 V and corresponding charge/ discharge cycle is observed across the transducer capacitor at various glucose concentration. Further, the voltage from the charge pump was amplified using a step up DC-DC converter circuit which generated an steady output DC voltage of 3.2 V. Such a system can play a major role in composite systems capable of

generating energy and using it towards bioimplantable and healthcare applications.

#### ACKNOWLEDGMENT

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#### REFERENCES

- [1] Y. Jyoti, A. Rani, V. Singh, and B.M. Murari. "Prospects and limitations of non-invasive blood glucose monitoring using near-infrared spectroscopy." *Biomedical signal processing and control*, 18, pp. 214-227, 30th April 1955.
- [2] G. Slaughter and T. Kulkarni. "Enzymatic glucose biofuel cell and its application," *Journal of Biochip & Tissue Chip*, 5, pp 1, January 2015.
- [3] M. Holzinger, A. Le Goff, and S. Cosnier. "Carbon nanotube/enzyme biofuel cells." *Electrochimica Acta*, 82, pp. 179-190, November 2012.
- [4] K. MacVittie, J. Halámková, L. Halámková, M. Southcott, W.D. Jemison, R. Lobel, and E. Katz. "From "cyborg" lobsters to a pacemaker powered by implantable biofuel cells." *Energy & Environmental Science*, 6, pp. 81-86, 2013.
- [5] G. Slaughter, and T. Kulkarni. "A self-powered glucose biosensing system." *Biosensors and Bioelectronics*, 78, pp. 45-50, 15th April 2016.
- [6] T. Miyake, K. Haneda, S. Yoshino, and M. Nishizawa. "Flexible, layered biofuel cells." *Biosensors and Bioelectronics*, 40, pp. 45-49, 15th February 2013.
- [7] B. Reuillard, C. Abreu, N. Lalaoui, A. Le Goff, M. Holzinger, O. Ondel, F. Buret, and S. Cosnier. "One-year stability for a glucose/oxygen biofuel cell combined with pH reactivation of the laccase/carbon nanotube biocathode." *Bioelectrochemistry*, 106, pp. 73-76, 31st December 2015.
- [8] T. Kulkarni, N. Mburu, and G. Slaughter. "Characterization of a Self-powered Glucose Monitor." *Sensors & Transducers*, 203, pp. 1, 1st August 2016.