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TECHNICAL REPORT 3226
FEBRUARY 2021

**Proportional-Integral-Derivative (PID)
Controlled Flyback Converter
for Microbial Fuel Cell Energy Harvesting**

Maxwell M. Kerber
Joseph F. Schnecker, Jr.
Lewis Hsu, Ph.D.
NIWC Pacific

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

Microbial fuel cells (MFCs) can provide power at low output voltages, 0.2V-0.8V, from renewable and persistent fuel sources. This capability increases the reliability and sustainability of connected devices/sensors capable of utilizing power generated by these devices to monitor the environment for example a pH or temperature sensor. The challenge is to efficiently harvest the MFC power while boosting the voltage to a useful level. The proportional-integral-derivative (PID) flyback energy harvesting (EH) circuit presented in this report holds the MFC voltage at a user defined set point while being able to support delivery of a wide range of power levels (3mW-75mW tested here) into a 12V battery load. The control board power draw was 1.2mW. Energy harvesting efficiency was 80% for 75mW power level delivered to the battery load. Efficiency decreased to 56% at the 2.6mW power level, largely due to control circuit overhead power consuming a larger portion of the input power.

Start-up issues when encountering high MFC internal resistance, R_{mfc} , (a characteristic of low power MFC systems) occurred, which caused the EH board to turn on then off repeatedly. To expand the low power input range of the MFC EH board, a modification that limits the pulse width modulation duty cycle on start-up was made. This allowed the MFC EH board to operate from an MFC with internal resistance as high as 104 ohms, which is a slight increase from unmodified limit of 100 ohms. The modified EH board could start up and operate without unstable on-off cycling using an MFC power input as low as 1.7mW. Future testing with deployed MFCs needs to occur and is planned for future work. The preliminary PID control strategy using a microcontroller shows similar power requirements to the analog PID circuitry first examined. Based on this result, future work will focus on reducing power draw with a microcontroller-enabled PID control circuit since microcontrollers offers greater flexibility in start-up control and PID tuning.

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ACRONYMS

ADC	analog-to-digital converter
DAC	digital-to-analog converter
DC	direct current
DNP	do not populate
EH	energy harvester
IC	integrated circuit
MFC	microbial fuel cell
mux	multiplexer
NIWC Pacific	Naval Information Warfare Center Pacific
PCB	printed circuit board
pH	potential of hydrogen
PID	proportional-integral-derivative
POT	potentiometer
PWM	pulse width modulation
R _{mfc}	MFC internal resistance
V _{mfc}	MFC voltage

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1. INTRODUCTION

This section presents the purpose, microbial fuel cell (MFC) model, our energy harvesting (EH) approach, discontinuous conduction mode with a flyback converter and previous MFC EH efforts.

1.1 PURPOSE

In addition to wastewater treatment, MFCs produce power capable of powering ultra low power sensors. Efficient energy harvesting from MFCs continues to be a challenge for the technology due to the MFC's low output voltage and low power levels. Our approach to provide EH capabilities is to use a flyback converter operating in discontinuous conduction mode to impedance match the MFC's internal resistance to the DC/DC converter impedance. This solution allows for boosting low input voltages to usable levels with high efficiency.

1.2 MFC SOURCE MODEL

For bench testing, an MFC model utilizing a standard laboratory voltage source and a passive resistor is substituted in place of a real MFC. Figure 1 shows the specific model parameters used. The voltage source is set to the MFC open circuit voltage and R_{MFC} represents the MFC internal resistance. This model lacks the start-up phase of an MFC when the bacteria are just starting to create a biofilm. In practice, this start-up phase can be as long as a month after being deployed, and is characterized by a transition between a high internal resistance (low power) to a stabilized internal resistance under continuous operation. Instead, this model represents an MFC after the start-up phase, where the open circuit voltage and series resistance have stabilized.

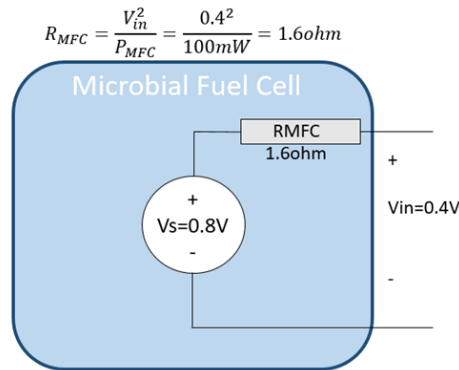


Figure 1. MFC model used for bench testing energy harvester circuit.

1.3 MFC FLYBACK EH BLOCK DIAGRAM

The goal for this research effort is to harvest energy from an MFC to power a load with a relatively wide range of possible internal resistances. Since MFCs have low operating voltages (between 0.2-0.8V), a boost converter is needed to change the voltage in order to charge a battery or power a load. This paper presents and discusses a flyback converter, which is a type of boost converter. Figure 2 depicts a top-level diagram of a flyback converter EH circuit. Here, the MFC powers the logic circuits and uses the MFC voltage to determine flyback operation point. Energy is then harvested and used to charge a battery. The flyback converter operates in "open loop," which means the converter output voltage is not monitored, in our case, the output voltage is the battery voltage. This differs from typical charging circuits that use feedback control to prevent overcharging when the battery is

full. For this application, the low power production of the MFC means there is a low chance of overcharging the battery. Therefore, the feedback overcharging protection circuit is omitted in favor of a trickle charging approach. This reduces the overall power draw of the EH and thus improves efficiency. If a sensor is attached to the battery, then the battery will discharge, providing power to the sensor. The MFC EH will usually supplement the battery's internal capacity by the slow recharging action instead of providing a full recharge capability. The EH output voltage, V_{out} , is limited to a maximum voltage using a zener diode in order to protect the flyback circuit and any sensitive downstream electronics.

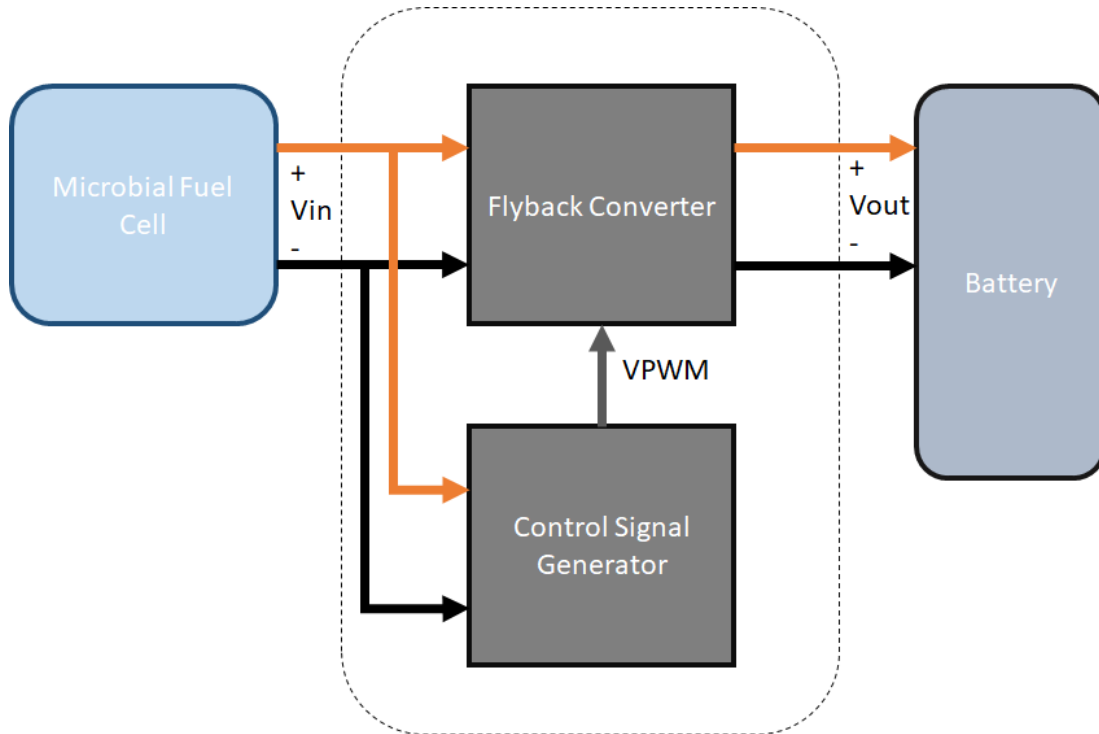


Figure 2. Top-level block diagram for an energy harvesting system using a flyback converter.

1.4 FLYBACK CONVERTER IN DISCONTINUOUS CURRENT MODE

The DC/DC flyback converter topology, in Figure 3, represents the bare bones converter circuit model. Here, V_{in} is the MFC voltage, also referred to as V_{mfc} , and V_{out} is connected to the load. VPWM is the pulse width modulation (PWM) control signal for turning the n-type metal oxide semiconductor (NMOS) transistor, M1, on and off, and L1, L2 represent the windings of a coupled transformer. When the voltage level of VPWM is high, M1 is on, so current flows through L1 and M1. Energy is being stored in the magnetic field surrounding the transformer winding based on its inductance. When the voltage of VPWM is low, M1 is off, so current flows through L2 and D1 to the load because of the energy transfer between the coupled transformer windings. The flyback converter operates in discontinuous current mode when the current in L2 stops before M1 turns back on.

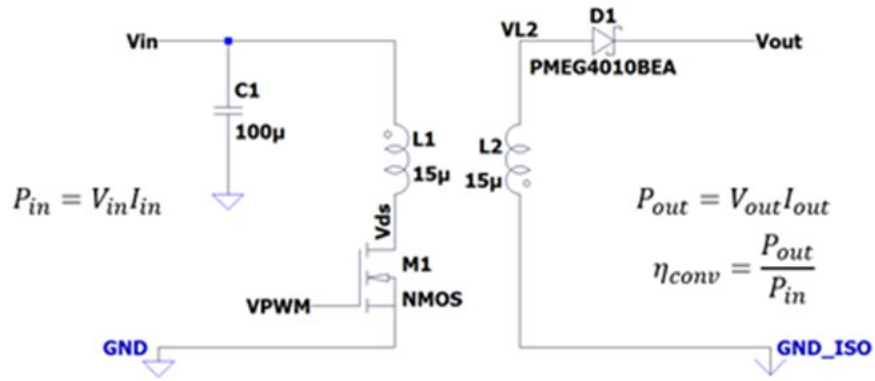


Figure 3. Flyback Converter Topology.

$$Z_{in} = \frac{2 * F * L}{D^2} \quad (1)$$

Equation 1. Flyback converter input impedance

The overall EH converter input impedance is given in Equation 1. This means that by changing L (the primary winding inductance if transformer has a 1:1 winding), F (frequency), and D (duty cycle) the circuit input impedance can be altered to match the internal impedance of the input voltage source (V_{in}). In the MFC system, this usually leads to operating at a V_{in} equal to half of the MFC open source voltage and optimum power transfer. In practice, L is usually fixed by the transformer choice, so the input impedance is changed by changing the PWM frequency and duty cycle.

1.5 PREVIOUS NIWC PACIFIC EFFORTS

This section discusses previous MFC EH flyback boards, which are the basis of the design in section 3.

1.5.1 10mW and 20mW Flyback Boards

Initially, the flyback EH boards had their logic supply power requirements come from the load battery via a buck converter. This meant that the load and MFC were not isolated. The MFC was not used to supply power to the logic components, so more energy could be harvested from the MFC. Two different versions of the flyback EH boards were made with different inductor values to address two different MFC power targets. The PWM frequency and duty cycle were fixed for these power levels. These boards just turned on and off when then MFC voltage was above and below set points respectively. An in-depth discussion of these boards and effort was published in Journal of Power Sources [1]. While the boards could potentially operate on high power MFC systems, at these specific power levels, the efficiency would suffer due to operation at non-optimal power point.

1.5.2 10mW and 20mW Fully Isolated Flyback Boards

The next version of the flyback EH boards was an extension of the original 10 and 20mW flyback boards with the added feature of not requiring logic power from the load battery. Instead, an ultra-low input voltage boost converter, Texas Instruments BQ25504RGTT, was used to generate the 2.5V logic power supply from the MFC voltage. This allowed the load battery to be fully isolated from the MFC. The boards still had fixed PWM frequency and basic on/off functionality. No attempt at dynamic impedance matching was made. The same boost converter for logic supply is used in the subsequent design presented in this technical report.

1.5.3 100mW Fully Isolated Flyback Boards

Since prior work was at lower MFC power levels, a higher power MFC EH board was designed and tested [2]. These boards differ from previous boards in that they have a transformer with lower inductance, different PWM frequency, and different duty cycles. This design replaced the low power 555 timer used as the PWM generator with an integrated circuit (IC) that allowed for a voltage-controlled duty cycle PWM signal output. This PWM IC is used again in the most “rev 2” boards discussed in this technical report. This board is referenced as “rev 1” in this document.

2. PID CONTROL IMPLEMENTATION

This section discusses PID basics and using operational amplifiers for an analog PID controller. The goal of the PID controller circuitry is to keep the flyback input voltage at a predetermined set point or close to half of the MFC open circuit voltage. At this voltage, the MFC can normally provide maximum power to a load and maximizes the amount of energy that can be harvested.

2.1 PID BASICS

PID control is used in a variety of industrial processes. For example, in a car's cruise control function, a PID controller uses feedback to continuously update a control signal that is related to the error between the reference set point and process variable. The control signal is the sum of three control factors: the proportional error, the integral of the error, and the derivative of the error [3].

2.2 PID CONTROLLER USING OPERATIONAL AMPLIFIERS

Reference [3] discusses PID control circuit using operation amplifiers. This circuit is the basis for controlling the V_{mfc} to the desired set point. The circuit is in Figure 4 and the PID controller parameters are in Equation 2. In this circuit, proportional gain is determined from the resistors, R_0 and R_1 . Integral gain is determined by the resistor, R_1 , and capacitor, C_1 . Derivative gain is determined from resistor, R_0 , and capacitor, C_0 .

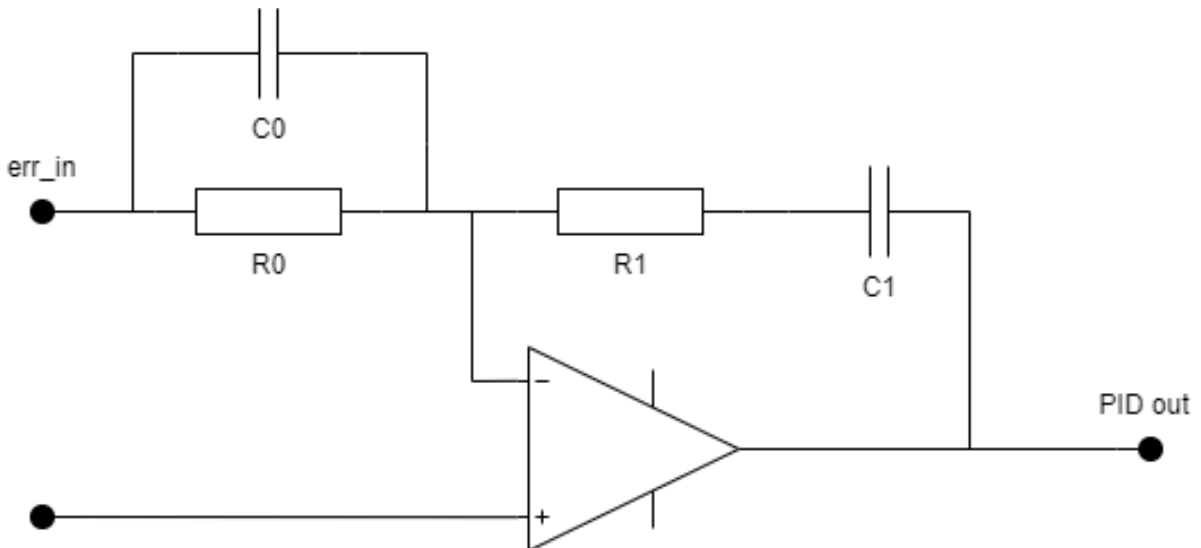


Figure 4. Opamp based PID controller.

$$k_p = \frac{R_1}{R_0}, \quad \tau_i = R_1 * C_1, \quad \tau_d = R_0 * C_0 \quad (2)$$

Equation 2. PID Controller Parameters

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3. EH CIRCUIT

This section discusses the EH circuit block diagram and schematic.

3.1 BLOCK DIAGRAM OVERVIEW

Figure 5 shows the basic EH block diagram. Blocks not shown are the control voltage rail generation, enable circuitry, delay circuitry and analog multiplexer (mux) circuitry. At a high level, this circuit works by using a PID control loop to keep the MFC output voltage constant by controlling the duty cycle of the PWM that is fed into the flyback EH. This constant voltage is selected to be close to half of the MFC open circuit voltage based on previous experimental results assessing the maximum power point of MFC systems.

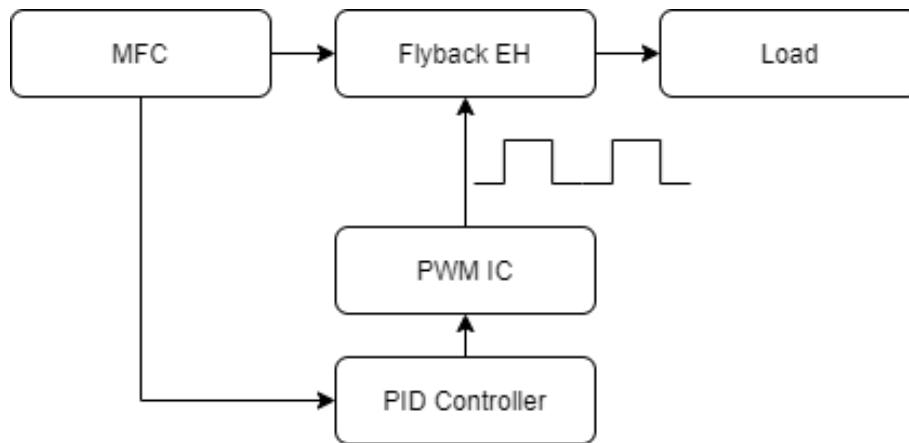


Figure 5. EH Block Diagram.

3.2 CIRCUIT SCHEMATIC

This section discusses the individual circuit blocks and presents the schematics.

3.2.1 DC-DC Boost Converter for 2.5V Logic Supply

The MFC is not only the source for energy harvesting, but also powers all the logic circuitry controlling the EH operation. The logic circuits that control the EH are powered by a positive 2.5V supply voltage. To obtain this supply voltage, a Texas Instruments BQ25504 IC boosts the MFC input voltage to 2.5V. The schematic for this boost converter is in Figure 6. This IC has low start-up voltage of around 450-500mV, and once operating can run down to input voltages of 50mV. This is an ideal range of start-up and operating voltages since the MFCs can easily provide energy at those voltage levels. A load switch controlled by “VBAT_OK” voltage signal output of the BQ25504 IC turns power on and off to the control circuitry. This allows downstream circuitry to start with a stable 2.5V and prevents premature turn on. This is important because some of the circuits will run at lower voltages, but some other functionality is only designed for a 2.5V supply. For example, the comparator voltage divider is set for 2.5V, which controls when the EH starts. A 2.5V positive supply rail was selected to allow for enough gate voltage to be applied to the flyback transistor to ensure it is fully on during switching.

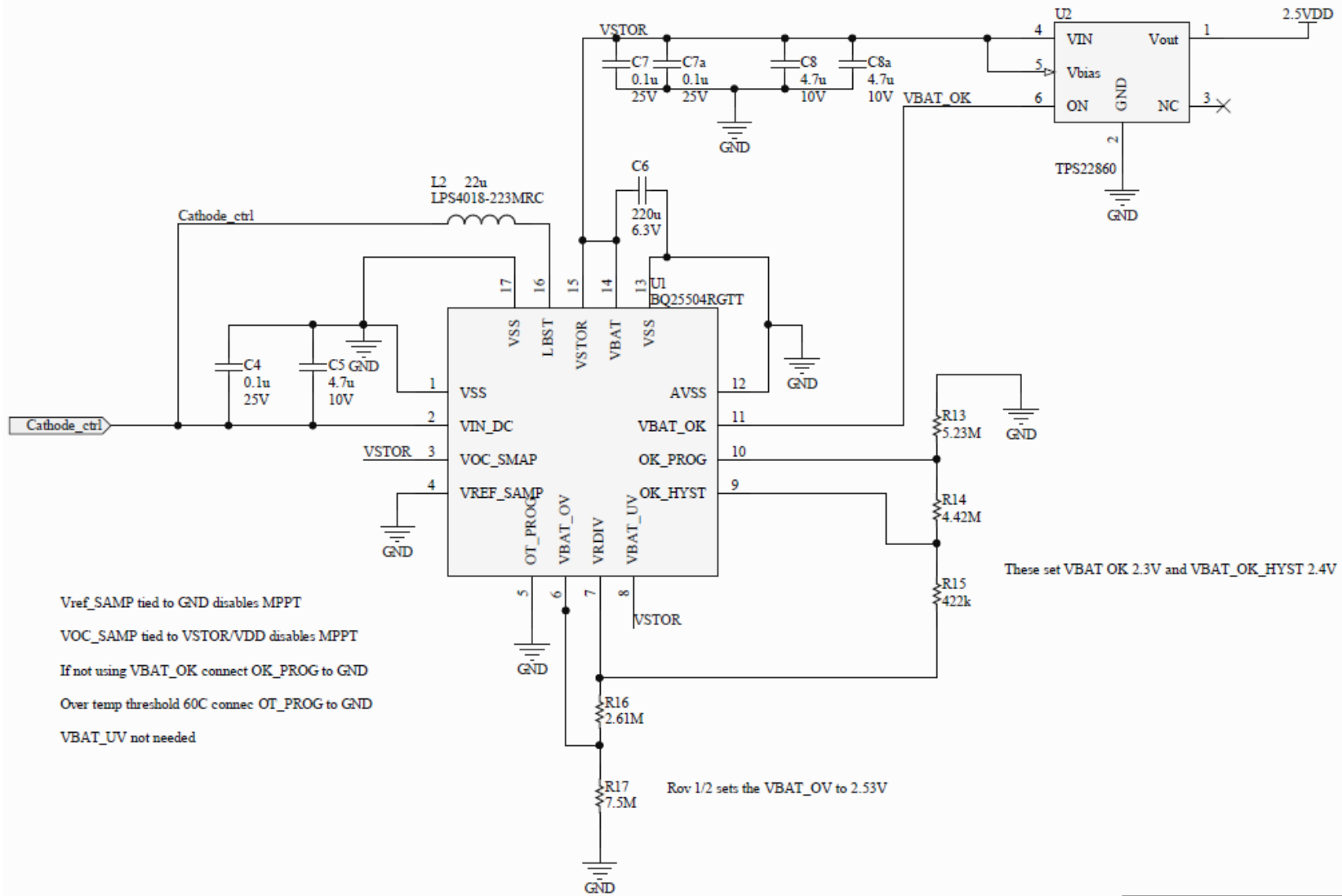


Figure 6. 2.5V Supply Circuit.

3.2.2 -2.5V Logic Supply

The -2.5V logic supply is an inverting charge pump IC that takes +2.5V as an input and sends out -2.5V as an output. This circuit is in Figure 7, where the node labelled VSS is -2.5V. The -2.5V supplies the negative op amp rail in the PID controller.

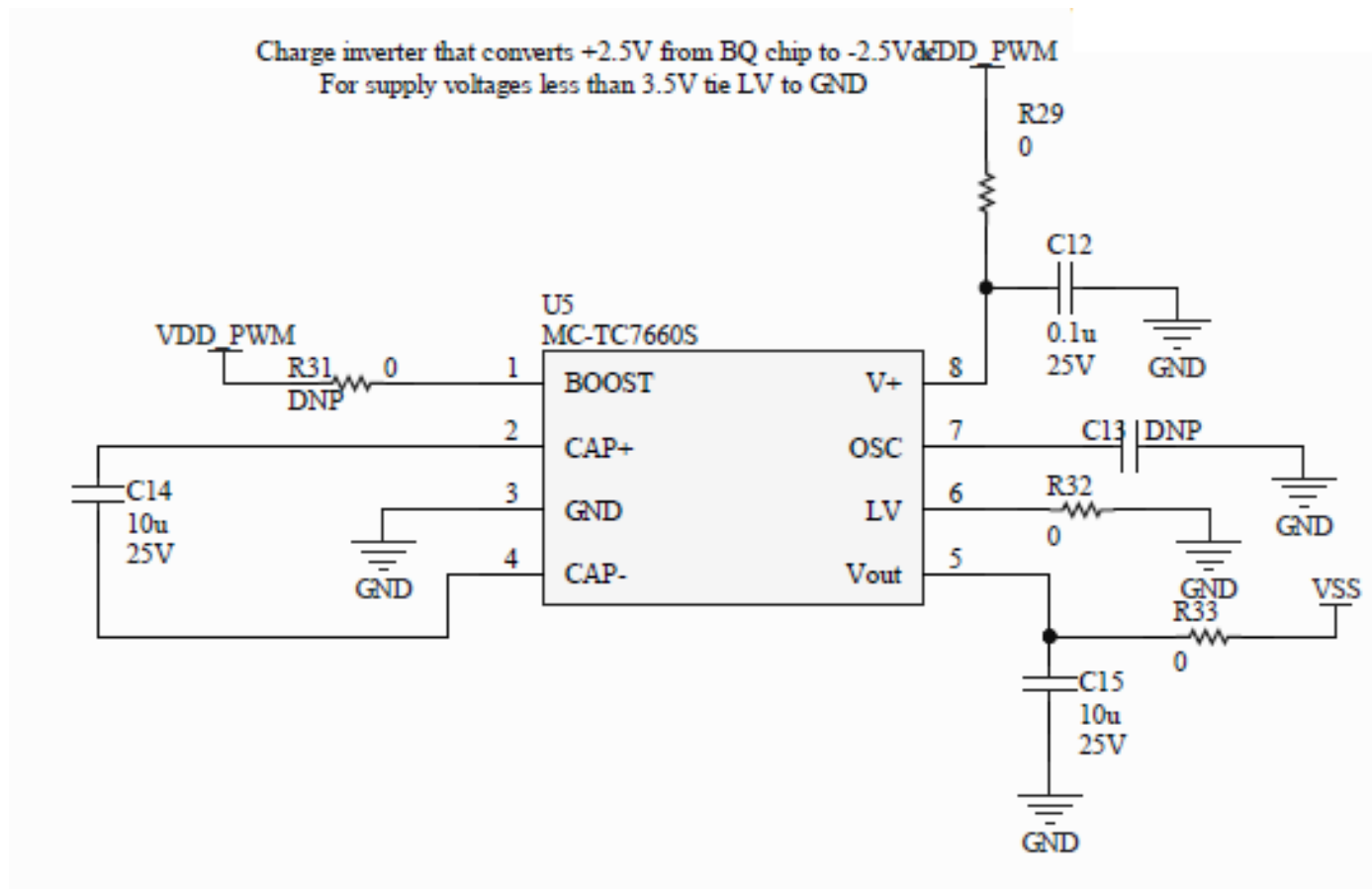


Figure 7. -2.5V Supply Rail Circuit.

3.2.3 Comparator for EH start/stop

Energy harvesting circuitry turns on when V_{mfc} reaches a user settable threshold, 500mV in our case. The EH circuitry is turned off when V_{mfc} falls below 100mV. The comparator circuit is equipped with a p-type metal oxide semiconductor (PMOS) load switch (Figure 8, Q1). The PMOS transistor is used as a load switch to manage the on and off power delivery to the EH circuitry downstream.

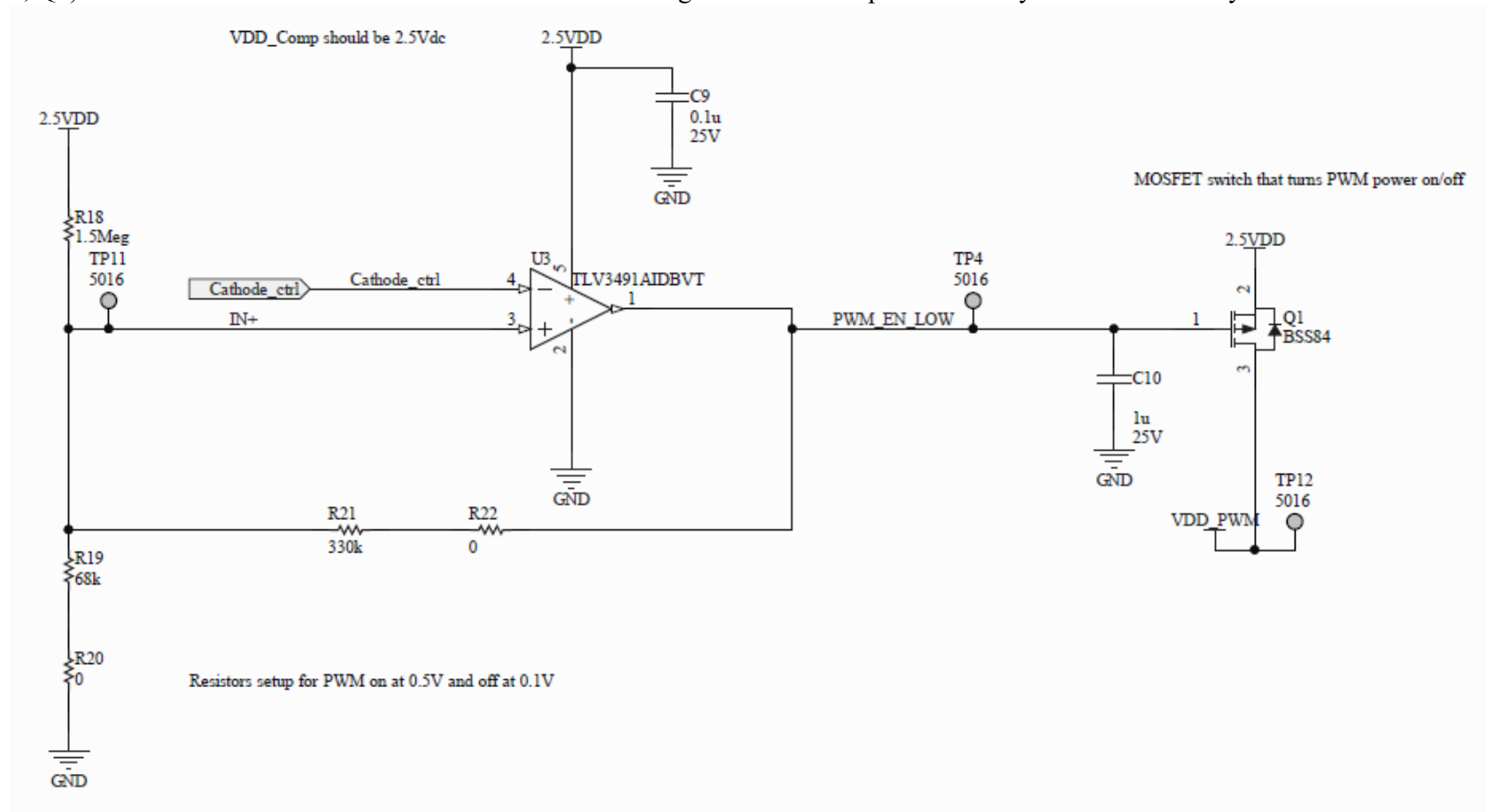


Figure 8. Comparator for Load Switch Circuit.

3.2.4 Start Delay and Analog Mux

Another comparator generates two start-up delays for two analog control multiplexers. Figure 9 shows schematic for delaying the PWM generator output and for delaying the connection of the V_{mfc} signal to the PID controller input.

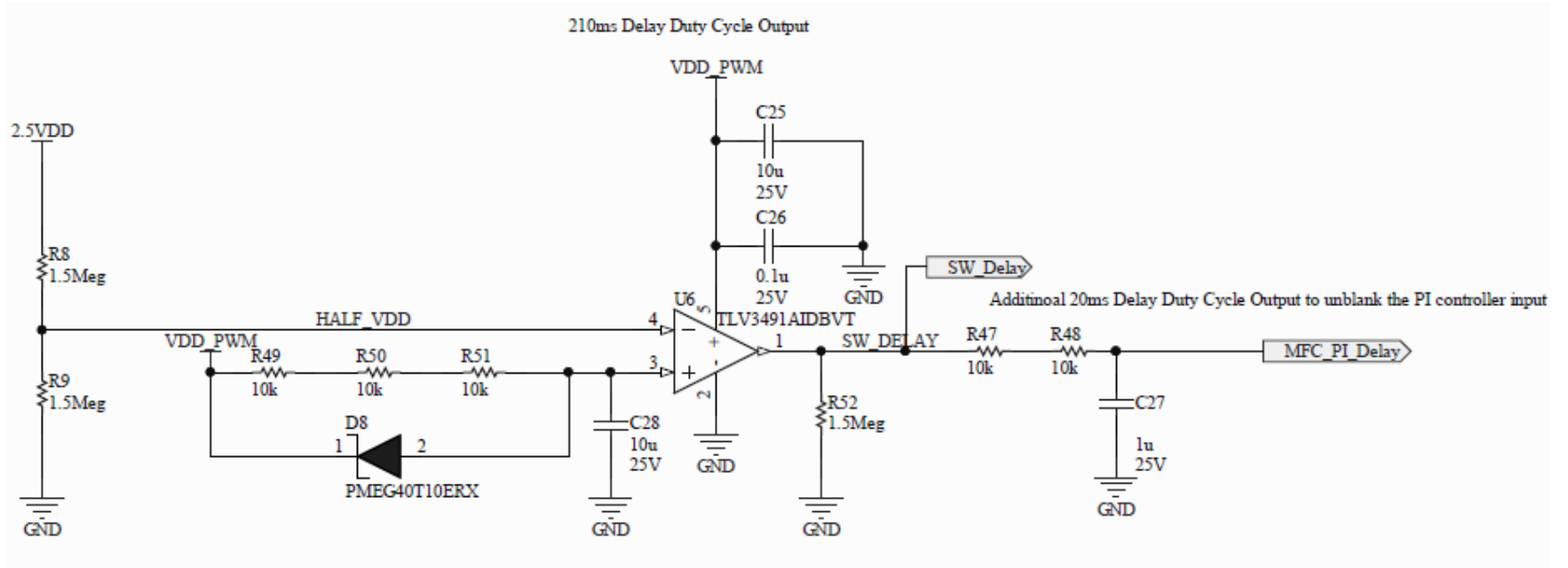


Figure 9. Analog Mux Control Signal Delay Circuit.

Figure 10 shows the analog multiplexer for blanking the PWM signal for a set time after power up. This is to prevent rogue voltages from affecting EH operation when applying initial power, which were observed from the PWM IC (Figure 15) during power up. Without this function, the rogue PWM voltages would turn on the flyback transistor prematurely and prevent lower power MFCs from starting up properly. At start-up, VPWM_output is grounded, i.e., set to zero, until a signal from the comparator in Figure 8 goes to a high voltage and connects VPWM_Gen from the PWM IC to VPWM_output. VPWM_output is connected to the flyback transistor and is normally the control signal for operation of the flyback EH.

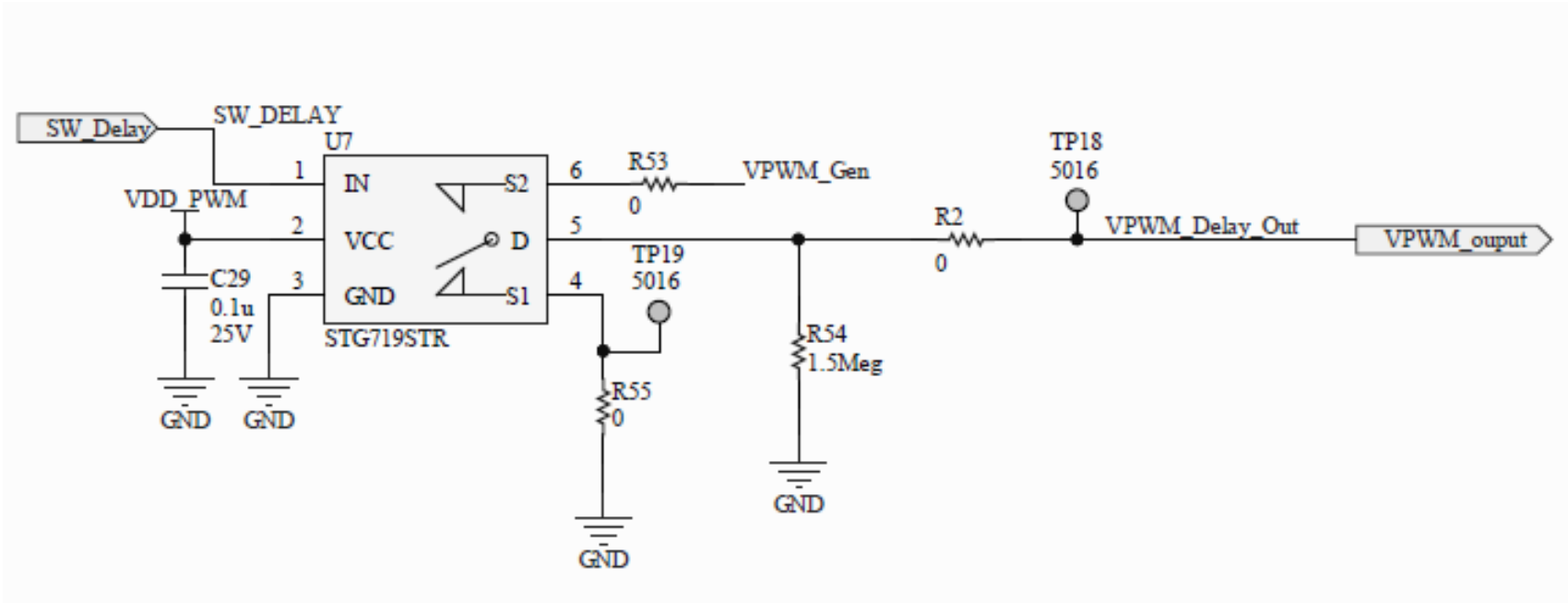


Figure 10. PWM Output Mux Circuit.

Figure 11 shows the analog multiplexer used to initialize the PID circuit input during power up. This circuit prevents the PID loop output from saturating to the 2.5V voltage rail during start-up and is another method to lower the minimum MFC power that can be handled by this PID EH board. Without this functionality, the system would begin attempting to correct the observed error and begin to cycle between a fully on and fully off state, which could be harmful to the MFC and ineffective as an EH circuit. Instead, the current strategy allows the input to the PID control loop to be grounded on power up so the PID loop will output -2.5V. This voltage signal is converted to 0V by the bipolar to unipolar circuit in Figure 14. A 0V input to the PWM IC means the duty cycle of the PWM signal is 5%, representing an input impedance of 348 ohms at our PWM frequency of 29kHz and inductor value of 15uH. This also helps apply the PID control to the wide range of MFC systems without requiring a fine tuning of the control signal gains.

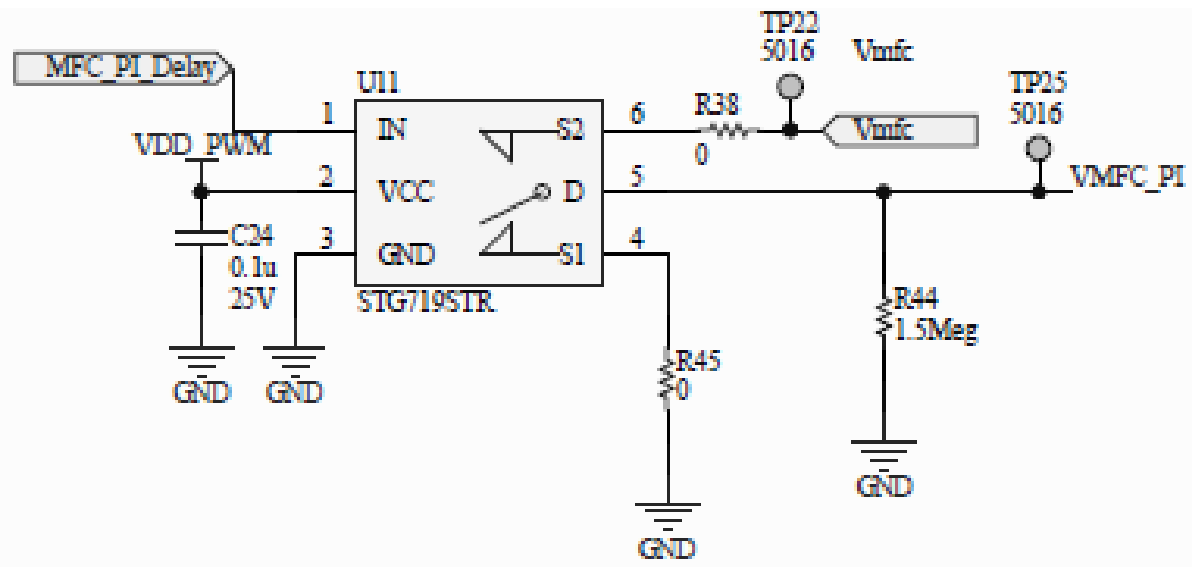


Figure 11. Analog Mux for Vmfc Input to PID Circuit.

3.2.5 Reference Voltages and PID Controller

The bipolar to unipolar circuit needs an offset voltage to scale the +/- 2.5V PID control, since the PWM IC input circuit can only accept a control signal from 0 – 1V. The circuit in Figure 12 is the reference for this circuit. Initially the voltage at the testing point, TP20, is set to 500mV. The circuit design allows for some flexibility for different scaling factors if there was a reason to modify the possible voltage range of the input control signal. This adjustment could be easily performed by modification to this specific circuit and some of the resistors in the circuit depicted in Figure 14.

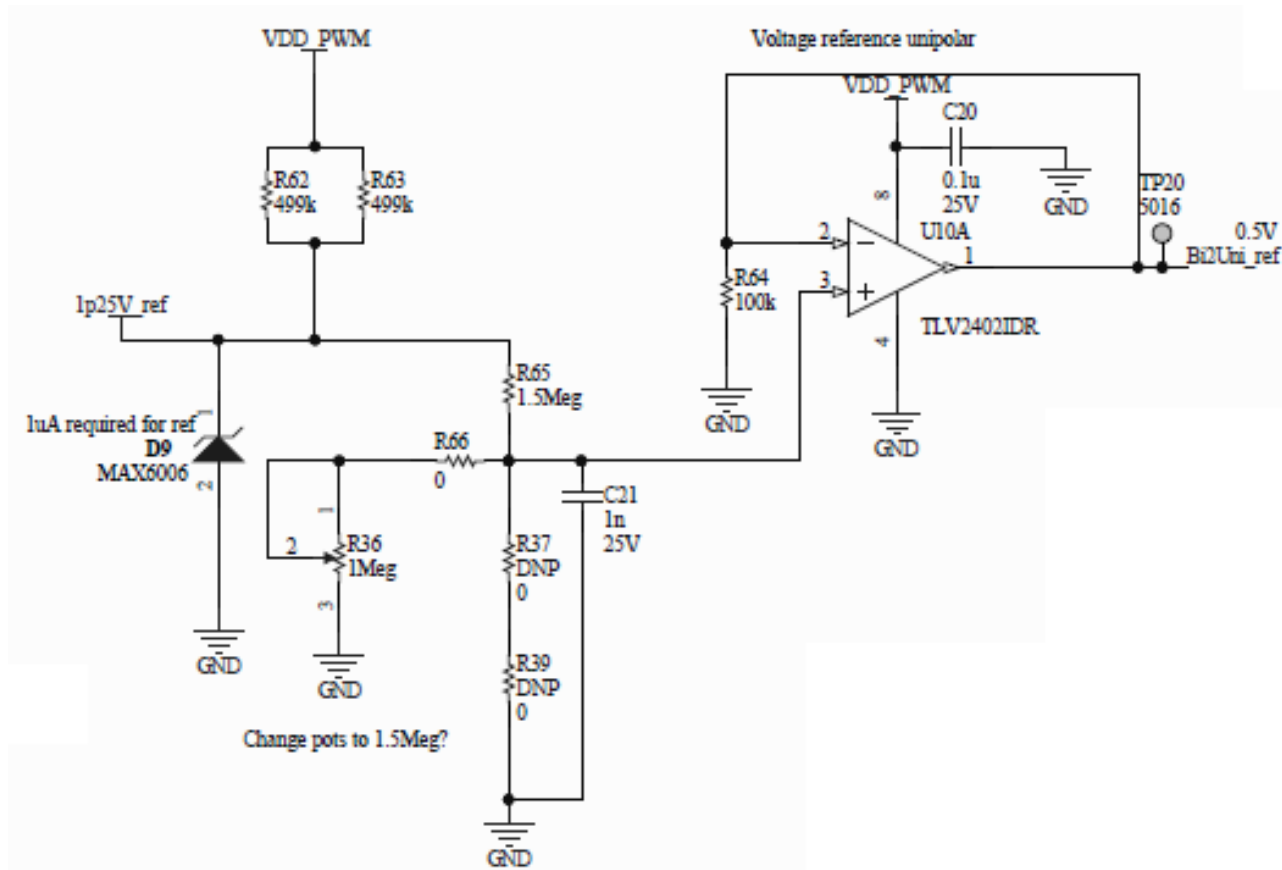


Figure 12. Bipolar to Unipolar Voltage Reference Circuit.

PID voltage set point circuit is shown in Figure 13. This set point is the target for the PID controller to keep V_{mfc} at by varying the flyback PWM duty cycle. Initially, the boards are set to 400mV by tuning the potentiometer, R43, and measuring $V_{mfc_ref_buff}$. For a fixed set point option, the user can populate the resistor, R42, and leave the resistor, R41, unpopulated R41, if there is concern about the potentiometer setpoint drifting over time. In this case, the resistors, R69 and R71, can be changed to get the desired set point.

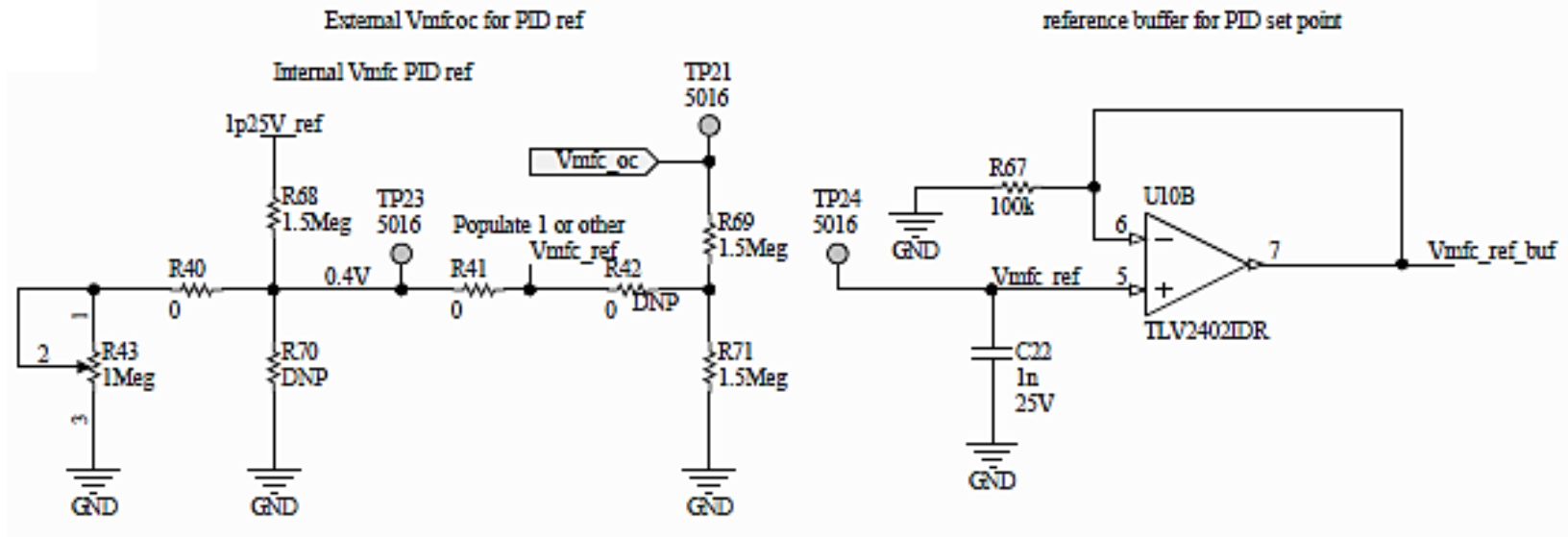


Figure 13. PID Voltage Reference Circuit.

The PID controller schematic is shown in Figure 14. From left to right, V_{mfc} is the input signal to the PID circuitry. The V_{mfc} signal is buffered, via a capacitor, then fed into an error amplifier which outputs the error as the difference between V_{mfc} and V_{mfc_ref} . The error term is then fed into the remaining PID controller circuitry. This circuit is the same one discussed in Figure 4. Finally, since the PID output range (-2.5V to +2.5V) does not match the PWM IC input range (0V to +1V), a bipolar to unipolar circuit is used to scale PID control signal to interface properly with the PWM IC.

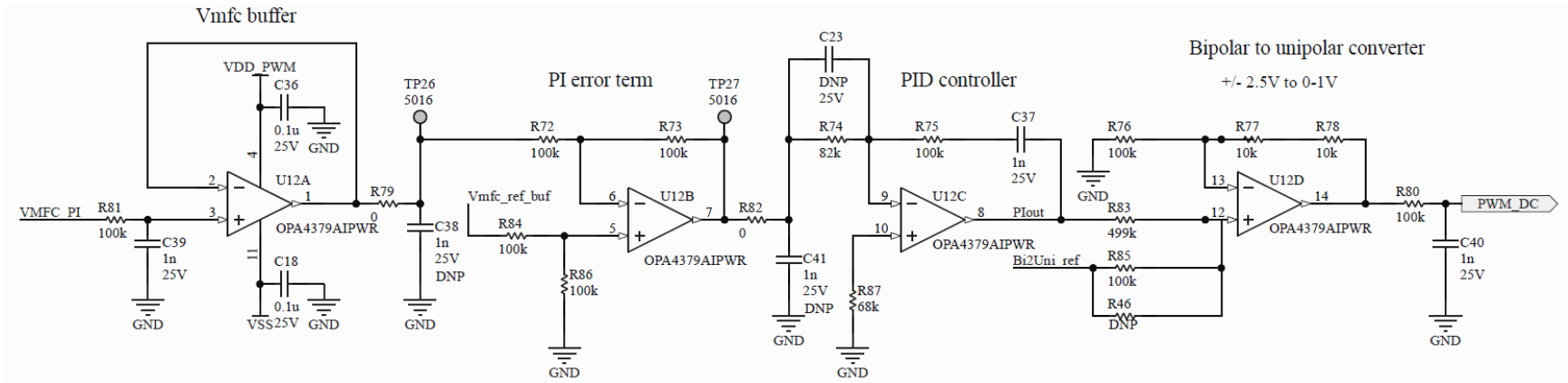


Figure 14. PID Circuit.

3.2.6 PWM IC

To generate the PWM signal that controls flyback switching parameters, a PWM IC (Linear Technology, Model LTC6992-2) is used. While several methods may exist to generate a voltage-controlled duty cycle PWM signal, this circuit (Figure 15) was one of the easier implementations. The resistors, R26 and R27, represent a voltage divider that can be utilized if a fixed PWM signal is preferred and allows the EH circuit to bypass PID control. The jumper resistor R28 is not populated for that functionality, noted by a DNP (Do Not Populate) designation in the circuit diagram.

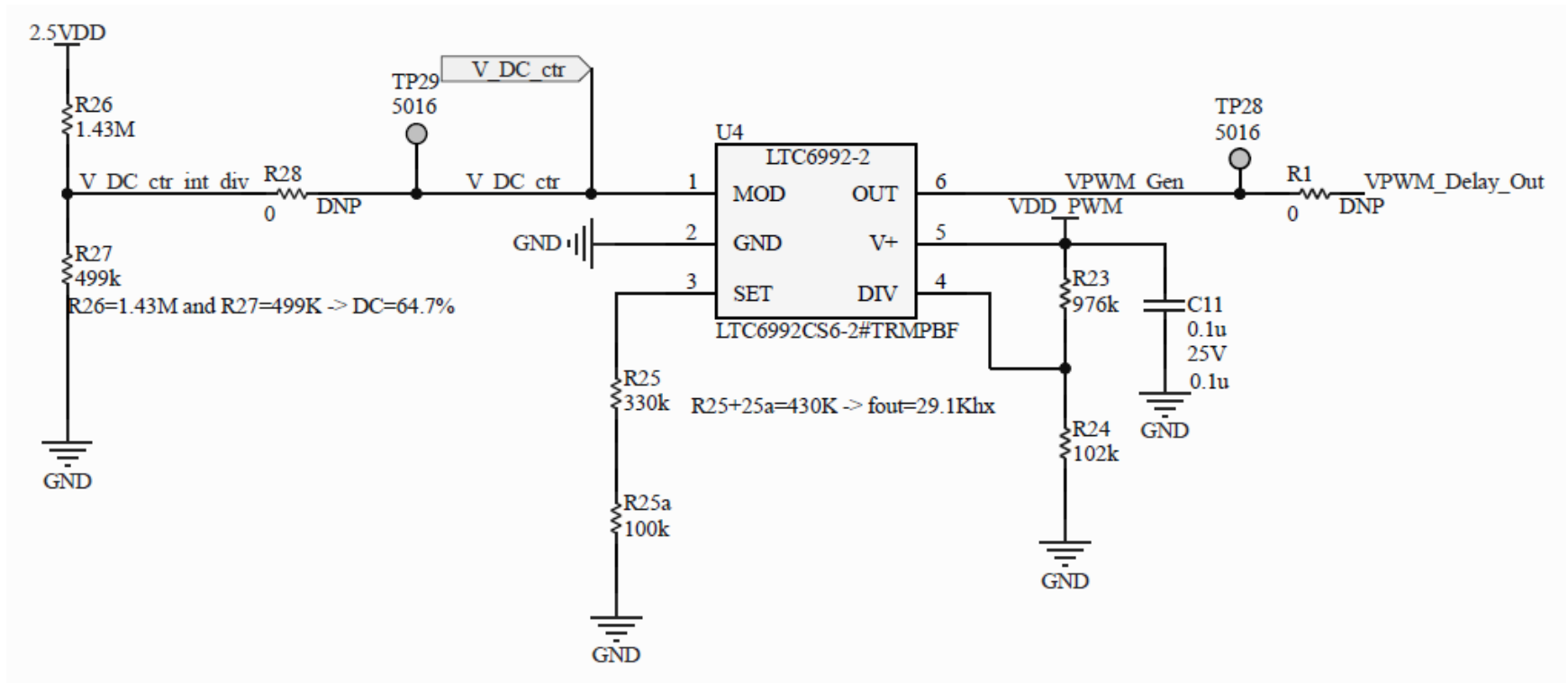


Figure 15. PWM Generator Circuit.

3.2.7 Flyback Energy Harvesting Circuit

The flyback converter energy harvesting circuitry is shown in Figure 16. A flyback topology was selected since circuit impedance could be easily controlled through modification of duty cycle, transformer inductance and frequency. Many of the DNP components on the primary side are for snubbing voltage when transistor M1 turns off. When M1 turns off, the current flowing in primary side inductor is suddenly stopped. This can cause a large voltage spike to appear on the primary side of the circuit (at TP9). This large voltage may exceed maximum voltage ranges of the transistor, M1, and cause component failure.

A battery is connected to the output of the secondary winding. Current pulses, whose sizes are dependent on the MFC power, charge the battery. A 2.2 μ F capacitor, C2, at the circuit output is placed to improve efficiency and power buffering capacity. A zener diode clamps the output voltage to prevent over-voltage spikes from damaging the secondary-side circuit components.

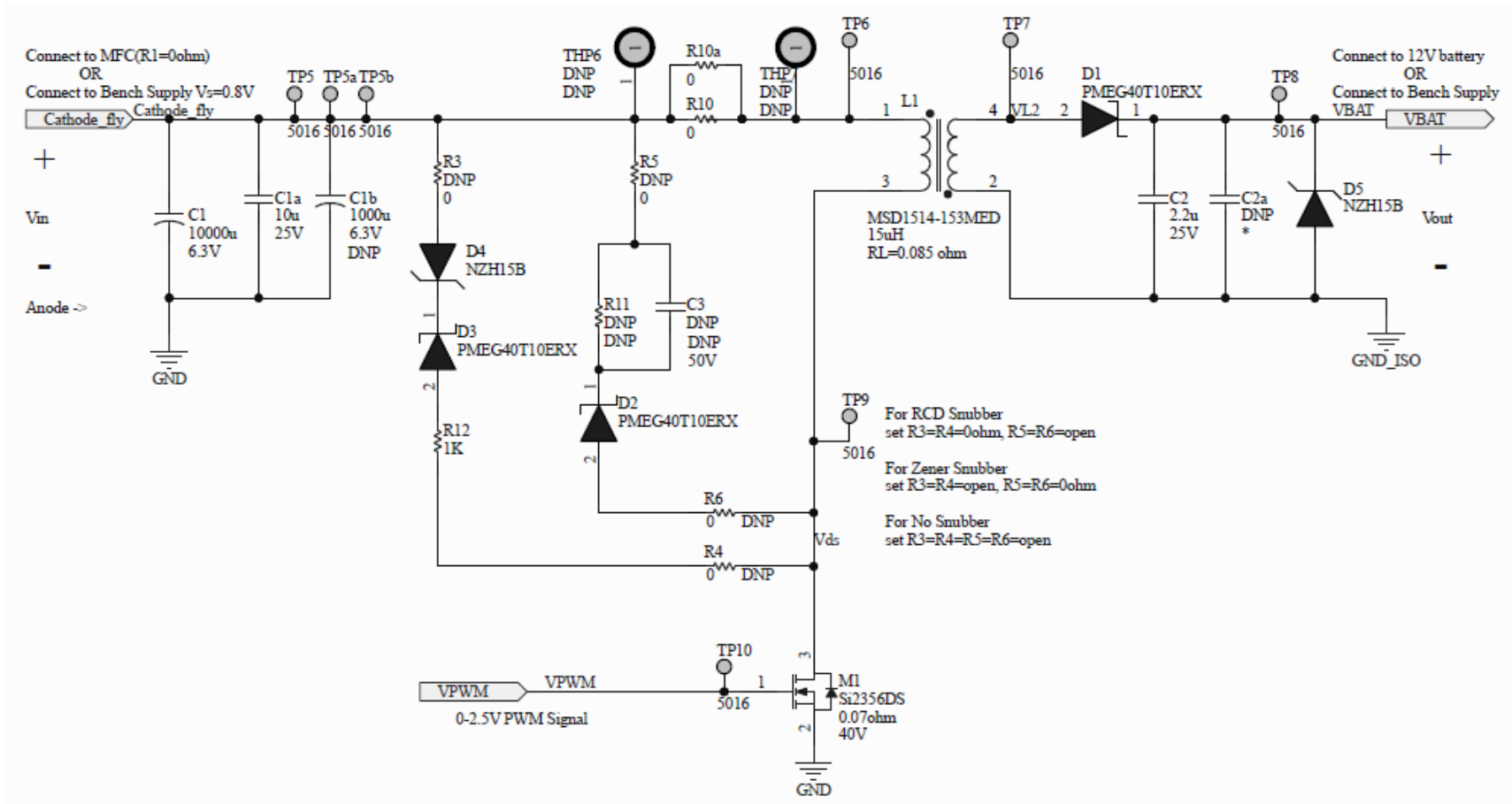


Figure 16. Flyback Topology Energy Harvesting Circuit.

3.3 PCB

This section discusses the PCB and important test points on the PCB.

3.3.1 Board

The circuit board size is 3.5 inches by 3.5 inches (Figure 17). All components are on a single side to accommodate ease for test probing. Numerous test points are on the board for probing. Some components are also not populated. One specific area that is not populated is to allow for alternative -2.5V rail generation circuits. A smaller area PCB is possible with components placed on both sides of the circuit board, the alternative negative rail circuits removed, fewer test points, and smaller passive component utilization. A limiting factor to minimum height is the 10,000uF capacitor at the input (Figure 16, C1). This large cap helps prevent erratic start-stop conditions from occurring for low power MFCs.

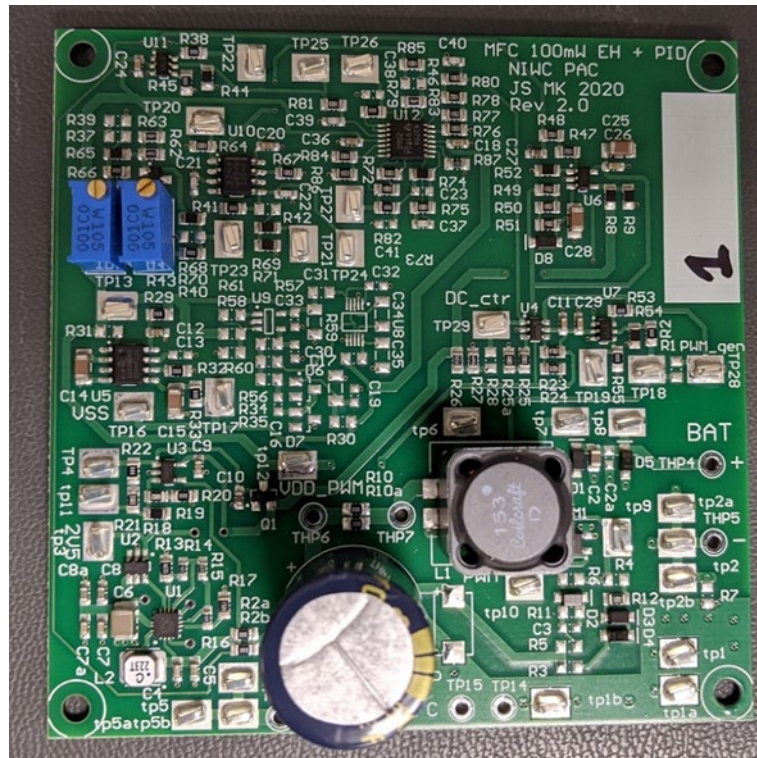


Figure 17. MFC Energy Harvesting PCB Rev 2.

3.3.2 Test Point Connections

A list of important test points is in Table 1.

Table 1. PCB Important Test Points.

Measurement	Test Point	Comment
MFC V+	tp5, tp5a-b, THP1	
MFC V-/Ground	tp14-15, tp1, tp1a-b, THP2	
2.5V	tp3	
2.5V after Pmos switch	tp12	This rail powers the EH circuits.
-2.5V logic rail	tp16	
PID set point	R84	The side that does not connect to R86. Use POT R43 to set.
Bi-Unipolar offset	tp20	Use POT R36 to set.
Duty Cycle Voltage	tp29	
PWM	tp10, tp18	
Bat +	tp8, THP4	
Bat – and Ground Iso	tp2, tp2a-b, THP5	

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4. MEASUREMENTS

4.1 TEST SETUP

This section discusses test setups for measuring board power draw and MFC energy harvesting power and efficiency.

4.1.1 Board Power Draw Setup

The power draw test setup for the PCB is shown in Figure 18. A separate power supply (Keithley 2400 source meter) was used to generate the input into the 2.5V boost circuit while another power supply (B&K Precision 9123A) was used to mimic MFC. A trace on the PCB was cut to make sure the source meter was the only supply connected to the boost circuit input. A series resistor of 15 ohms was used along with a 10,000uF capacitor to insure that the source meter would see the same input as the MFC if a real system was connected.

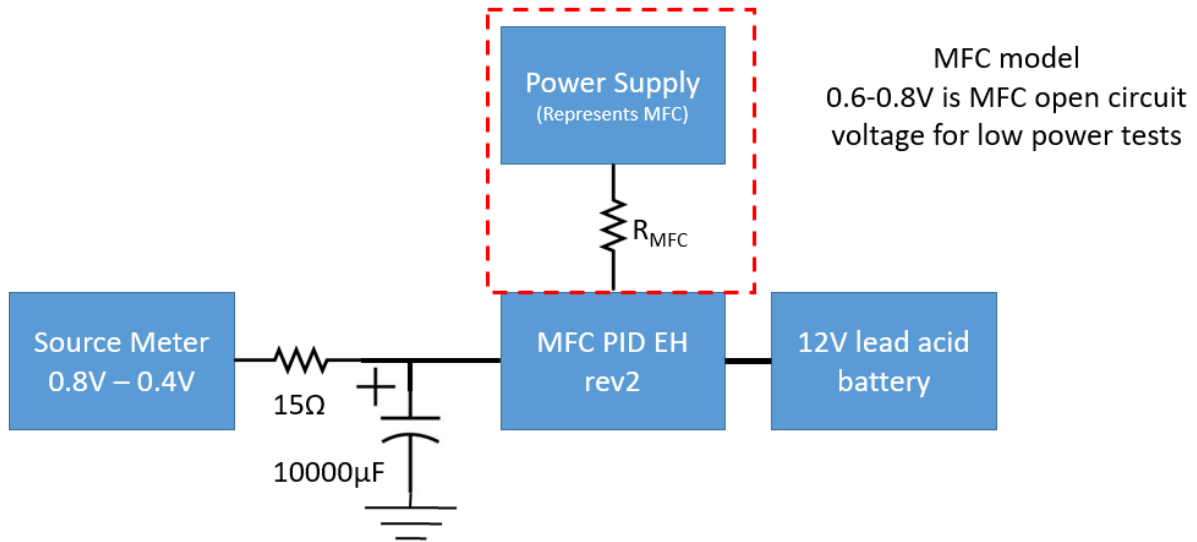


Figure 18. Power Draw Test Block Diagram.

4.1.2 Energy Harvesting Setup

The setup for energy harvesting measurement is shown in the block diagram depicted in Figure 19. Here the power supply represents the MFC open circuit voltage and the resistor R_{mfc} is the MFC internal resistance. R_{mfc} is varied to change the power level into the board. This MFC model supply will power the control circuits and will be the power source being harvested. A 12V lead-acid battery is used as a load to charge. The measurement bench setup picture is shown in Figure 20. An oscilloscope and current probe (Tektronix TBS2104 and TCP0030A, respectively) are used to measure PWM frequency, duty cycle, current flow to the battery, current flow from supply, and various board voltages. A resistor box is used for easy changes to R_{mfc} values.

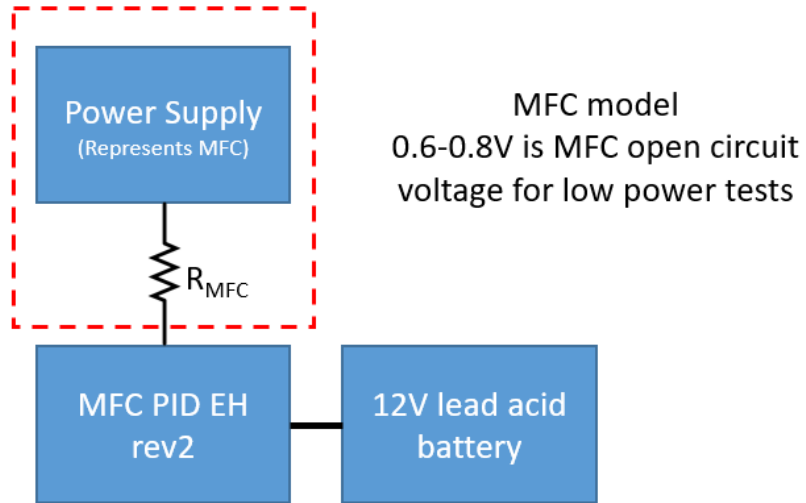


Figure 19. MFC EH Block Diagram Bench Setup.

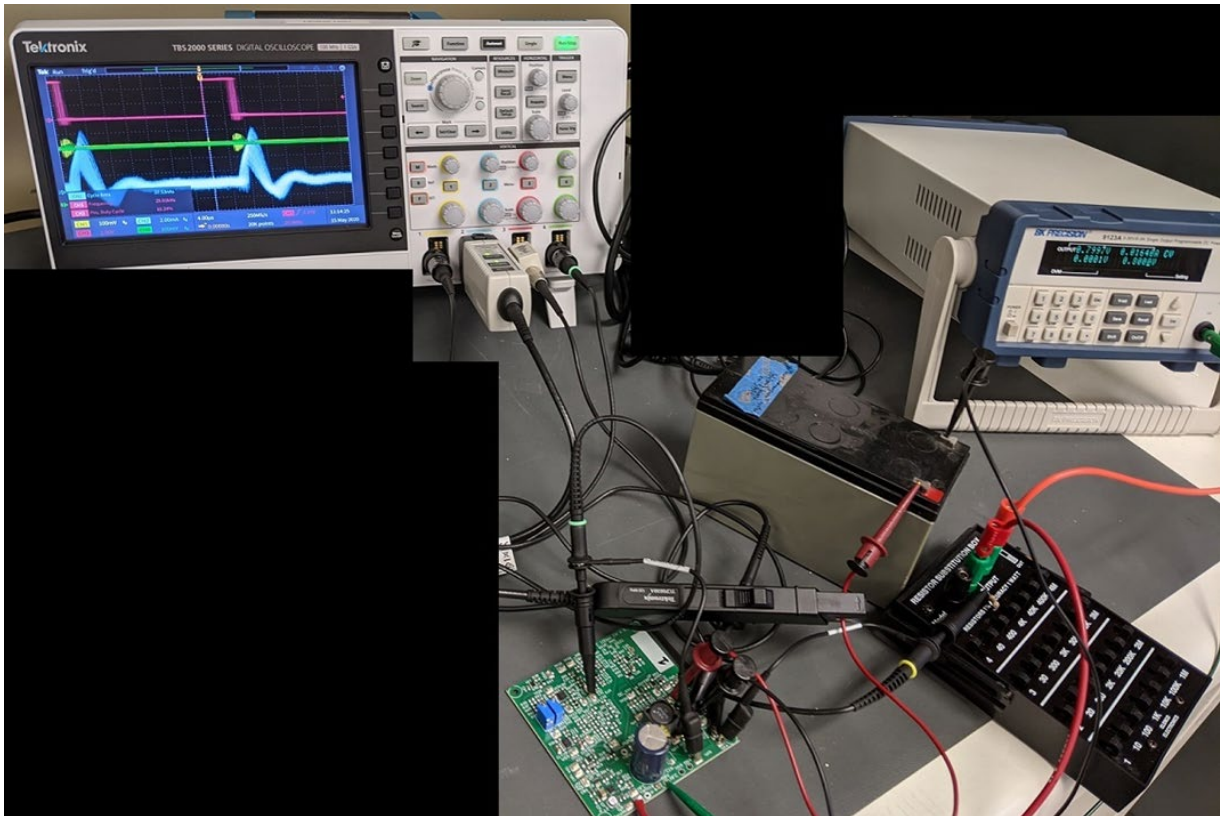


Figure 20. Bench Test Setup.

4.2 RESULTS

This section discusses “rev 2” board results from power draw and energy harvesting experiments.

4.2.1 Board Power Draw Results

The source meter voltage was stepped to three different values (0.8V, 0.6V and 0.4V) from an off state. All currents stated (Table 2) are the steady state current and not measured during start-up. The MFC supply was “on” and set to 0.8V with series resistance 14 ohms. No noticeable power draw difference was observed when MFC resistance was changed to 24 ohms. With the MFC supply “off,” the source meter current measurement is taken as the max seen on the meter since the most of the circuit is powered off except the comparator that enables the remaining EH circuit to power up. This causes the current to be more variable since the 2.5V boost IC is intermittently on to maintain the 2.5V rail. While the MFC supply is “on,” the current from the source meter was constant. A current probe connected to an oscilloscope was used to verify constant current at steady state.

With the MFC supply “on,” the power draw ranged from 0.98mW to 1.22mW for the different source meter voltages. With MFC supply “off,” only the 2.5V boost and comparator are powered. Under this condition, the max average power draw was 80uW. Since the PID loop is set to hold V_{mfc} at 0.4V, testing with source meter providing 0.4-0.6V is a good estimate for average power draw. Average power draw was about 1.2mW under these conditions. This value is likely the minimum power that the MFC has to supply to get the EH circuit operating at steady state. In practice, the MFC power needs to be higher so that the board does not enter an unstable power cycling mode due to possible higher start-up currents and so that enough excess power can be harvestable without shutdown. This overall minimum MFC power is measured and discussed later in more detail during targeted experiments to determine when the circuit enters unstable power cycling.

Table 2. Board Power Draw Results.

Measurement #	Source Meter [V]	Source Meter [mA]	Voltage into 2.5V Boost [mW]	Board Power Draw [mW]	Comment
1	0.8	1.26	0.781	0.98	MFC supply on
2	0.6	2.14	0.568	1.22	MFC supply on
3	0.4	3.5	0.348	1.22	MFC supply on
4	0.4	0.2	0.397	0.08	Max avg. on meter. MFC supply off.

4.2.2 Energy Harvesting Results

A typical EH measurement is shown in Figure 21. The blue trace is the current flow into the battery, the yellow trace is the MFC voltage, the red trace is PWM voltage signal, and the green trace is the current from the power supply. The cursors, 1 and 2, define the integration limits of the current flow into battery. These limits are determined to be when the PWM transitions from high voltage to low voltage and then back to high. As long as the current goes to zero before the next PWM cycle, the flyback operation is considered to be in discontinuous conduction mode.

The addition of the 2.2 μ F capacitor on the flyback output allows for greater power to the load battery, but the current waveform rings, i.e., shows unstable operation. Another calculation method for measuring the current into battery is to set the integral to end where the current waveform first goes to zero instead of where the PWM cycle ends. In this report, this method was not used, so the reported current integral areas might be understated depending the cursor. However, the authors believe the PWM method better represents the whole system even if the resultant power to battery is reported lower.

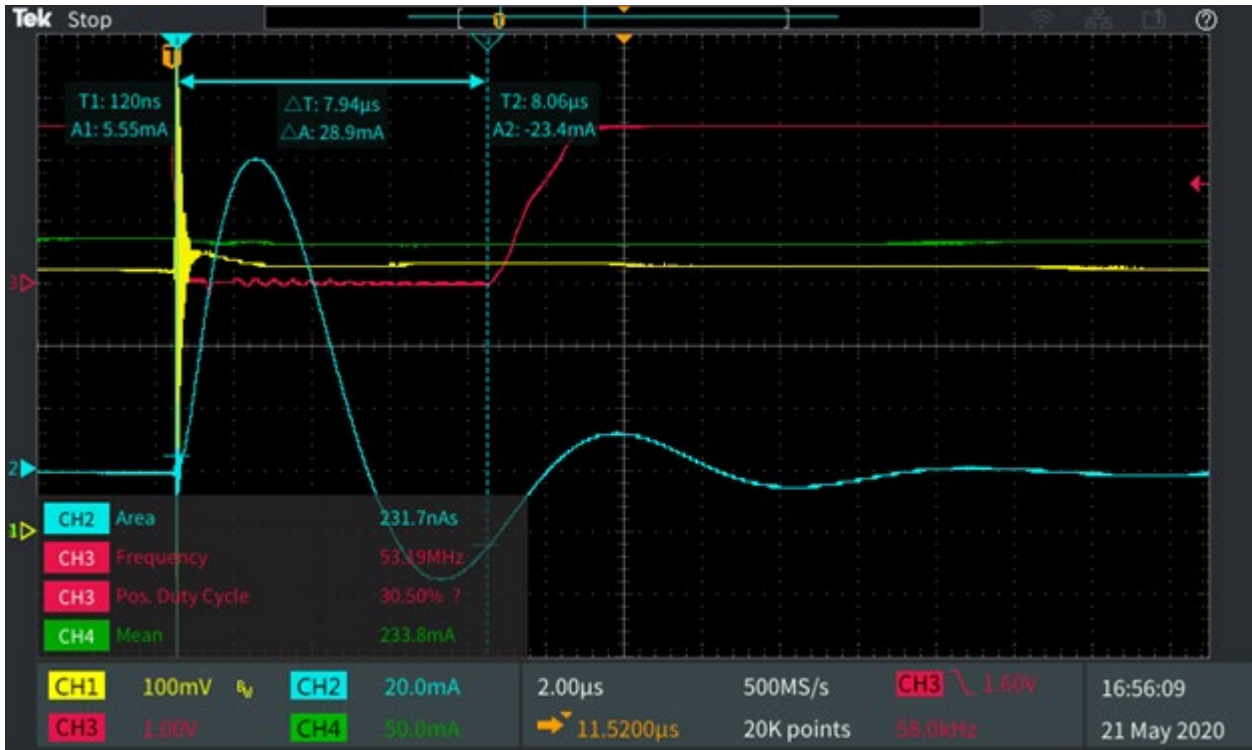


Figure 21. Rmfc = 1ohm, Current to battery rings.

A second measurement was made to measure the current area offset with the MFC supply “off,” since there is some area under the curve due to current probe drift and noise. This measurement is shown in Figure 22. The total current flowing into the battery is calculated as the difference of these two measurements. The trace color meaning in Figure 22 is the same as described above for Figure 21.



Figure 22. Offsets with MFC supply off for $R_{mfc} = 1 \text{ ohm}$.

At lower power tests, the current flowing into the battery stops before the next PWM signal (Figure 23). This confirms our theory that the flyback is operating in discontinuous current mode and the converter input impedance is governed by Equation 1.



Figure 23. $R_{mfc} = 32 \text{ ohm}$, Current to battery goes to zero before next PWM.

Results for the different Rmfc values (1, 2, 4, 8, 16, and 32 ohms) are summarized in Table 3. At lower Rmfc \leq 8ohm (simulating higher power MFCs) the observed efficiencies are around 80%. For Rmfc $>$ 8 ohms, efficiency begins to drop and goes as low as 56% (Rmfc = 32 ohms, 2.6mW delivered into the battery). Part of this efficiency drop is attributed to the logic circuit power overhead, as it starts to become comparable to the available power that can be delivered into battery.

Table 3. Varying Rmfc Energy Harvesting Results.

Rmfc [ohm]	Vmfc OC [V]	VPID Set [V]	Iin [A]	Pin [mW]	Iarea [nAs]	Iarea offset [nAs]	Iarea diff [nAs]	PWM Freq. [Hz]	Vbat [V]	Joule pulse [Ws]	Ibat avg [A]	Pbat [mW]	Eff %	Comment
1	0.8	0.4	234.0E-3	93.6	231.7	8.37	223.33	29000	11.62	2.6E-6	6.5E-3	75.3	80	512 average
2	0.8	0.4	146.0E-3	58.4	147.2	3.632	143.568	29000	11.62	1.7E-6	4.2E-3	48.4	83	512 average
4	0.8	0.4	82.6E-3	33.0	88.23	10.71	77.52	29000	11.62	900.8E-9	2.2E-3	26.1	79	512 average
8	0.8	0.4	44.5E-3	17.8	56.2	13	43.2	29000	11.62	502.0E-9	1.3E-3	14.6	82	512 average
16	0.8	0.4	22.1E-3	8.8	22.13	3.3	18.83	29000	11.62	218.8E-9	546.1E-6	6.3	72	512 average
32	0.8	0.4	11.8E-3	4.7	10.8	3	7.8	29000	11.62	90.6E-9	226.2E-6	2.6	56	512 average

The results show good efficiency for many different MFC internal resistances at higher power levels and the PID loop is able to keep the MFC voltage at a user controlled set point, 400mV, for these test results. The optional board function to keep V_{mfc} at half the MFC open circuit voltage was not tested on this revision of the board. "Rev 1" board tests on the bench showed that the PID will keep V_{mfc} at half the MFC open circuit voltage for optimum matching. When utilizing this strategy, the EH MFC has to have another reference MFC that is connected electrochemically so that it can be used for exclusively for open circuit measurements.

At some upper level, the MFC internal resistance is too high to maintain energy harvesting power so the board can enter a cyclic on-off state that may drain more power than gained through energy harvesting due to increased power draw during start-up. In our bench testing, this unstable and intermittent operation occurs for $R_{mfc} > 100$ ohms with supply set to 0.8V and $V_{set\ point} = 400mV$. The start-up issue and modification attempts are discussed in the next section.

5. ISSUES AND MODIFICATIONS

This section discusses start-up issue for low power MFCs and modifications to mitigate that issue. Included are some preliminary results

5.1 START-UP PID CONTROL ISSUE

At start-up, the MFC voltage is likely to be above the control set point and the PID loop control signal will increase the PWM duty cycle to its maximum (0.95 out of LTC PWM IC) in its attempt to lower the MFC voltage towards the set point. If the MFC is below an observed power, $<3\text{mW}$ in our tests, then the high duty cycle demand on start-up will draw enough power from the MFC to rapidly bring the MFC voltage below cut-off comparator threshold of 100mV (described in Section 3.2.3). In this case, the EH board will cut power to flyback energy harvesting circuitry in order to reduce the power draw and to allow the MFC to charge back up. Once the MFC voltage has recovered, it will start EH again and the start-stop cycle continues. Operating in this mode will draw more power than stable discontinuous mode harvesting because start-up of the EH circuit has an higher initial power draw compared to stable operation.

Figure 24 shows start-up under these conditions. The blue (current) and yellow (MFC voltage) curves are of most importance. The blue curve is the current flow to the battery load. As shown, the current flow here is off the observable scale ($>40\text{mA}$ peak) since the initial open circuit MFC voltage is far higher than the set voltage. Aggressive energy harvesting on initial start-up decreases V_{mfc} from about 550mV to approximately 320mV in 7.5ms . The lowest voltage observed for the V_{mfc} is significantly under the 400mV set point.

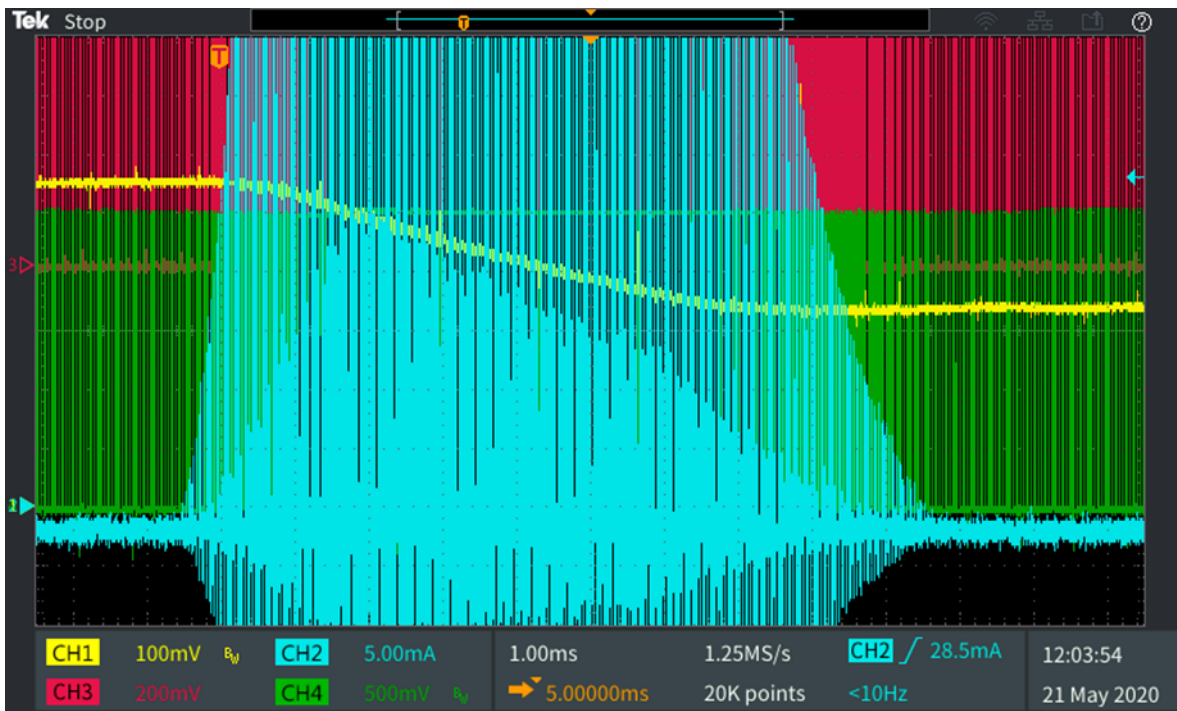


Figure 24. Typical start-up for unmodified board.

A closer look at the the PWM duty cycle is shown in Figure 25. Without board modification, the PWM signal (depicted as the green trace) has a duty cycle of 95%, which is the maximum duty cycle that can be generated by the PWM IC. This can cause an excess amount of current to be drawn from

the MFC, causing the MFC voltage to fall rapidly and under certain conditions, the MFC voltage would fall below the 100mV cutoff point, which triggers the unstable on-off cycling.

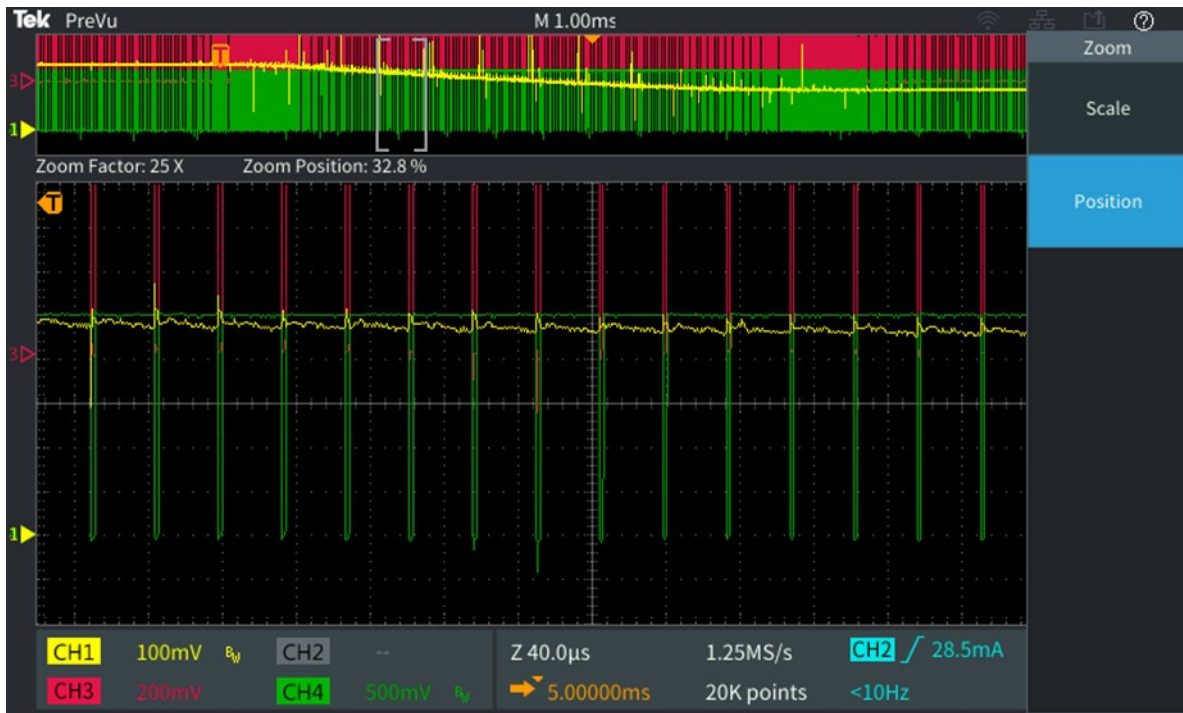


Figure 25. Zoom view of Figure 24 shows that the PWM duty cycle (green trace) is at 95% due to PID loop not having start-up limit on duty cycle maximum.

If R_{mfc} is high enough, the current from the MFC will not be enough to maintain V_{mfc} at 400mV, even with the lowest possible duty cycle from the PWC IC (5%). An extreme start-stop cycle is shown in Figure 26 where $R_{mfc} = 210$ ohms. Here, the yellow trace is MFC voltage, the blue trace is current flow to the battery, the green trace is the PMOS transistor gate voltage, and the red trace is the 2.5V logic supply voltage after the PMOS transistor (V_{DD_PWM} in schematics shown previously in this report). Once the EH circuitry is powered, the logic supply voltage shows a step increase to 2.5V from 0V. The MFC voltage continues to drop until reaching 100mV, at which point the 2.5V is turned off for the EH circuitry due to the cut-off circuit. The MFC voltage increases up to above 500mV as the system recovers and then triggers the start-stop cycle again.



Figure 26. Start-up issue due to low power MFC causing start stop cycle. $R_{mfc} = 210$ ohms, Yellow MFC voltage, Blue MFC current, Green Pmos gate voltage, and Red VDD_PWM.

5.2 MAXIMUM DUTY CYCLE LIMIT ON START-UP MODIFICATION AND RESULTS

Modifications to the flyback EH board were performed to increase the lowest power MFC that could be used with the EH board. The sections below discuss these modifications and results.

5.2.1 Modifications to Limit Maximum Duty Cycle on Power Up

The goal for these modifications is to limit the duty cycle from reaching 95% during start-up. This was done by changing how fast the bipolar to unipolar offset reaches the set point of 500mV. A Schottky barrier diode (BAT54) in parallel with the capacitor, C40, removes the negative voltages from being sent to the PWM IC. The C21 capacitance was increased to $\geq 10\mu\text{F}$ from the initial 1nF value in order to implement an increased delay to reach the 500mV setpoint of the bipolar to unipolar voltage reference. This increased delay limits the bipolar to unipolar circuit output to below 1V (95% duty cycle) and helps to minimize the EH board's PID signal on start-up. One drawback to this strategy is that the charge on the capacitor C21 is not discharged rapidly when the V_{mfc} turns. Thus, during the next start-up, the PWM signal will not have the same delay, which could be problematic if the system is unstable and going through start-up-shutdown cycling.

5.2.2 Results

Effects of the modifications described above are shown in Figure 27 and Figure 28. The yellow trace, V_{mfc} in Figure 27, shows a lower slope, with the lowest voltage observed at about 380mV. This is much closer to 400mV set point and much higher than before the modification. With this result, the EH circuit has an increased likelihood of successfully starting, i.e., lower power MFCs will not enter start-stop mode during start-up. Figure 28 shows the duty cycle was kept below 95%,

unlike the unmodified board, which maintained a duty cycle of 95%. This lower duty cycle caused the lower V_{mfc} slope and prevented the MFC voltage from triggering the unstable cycling condition for low power MFCs.

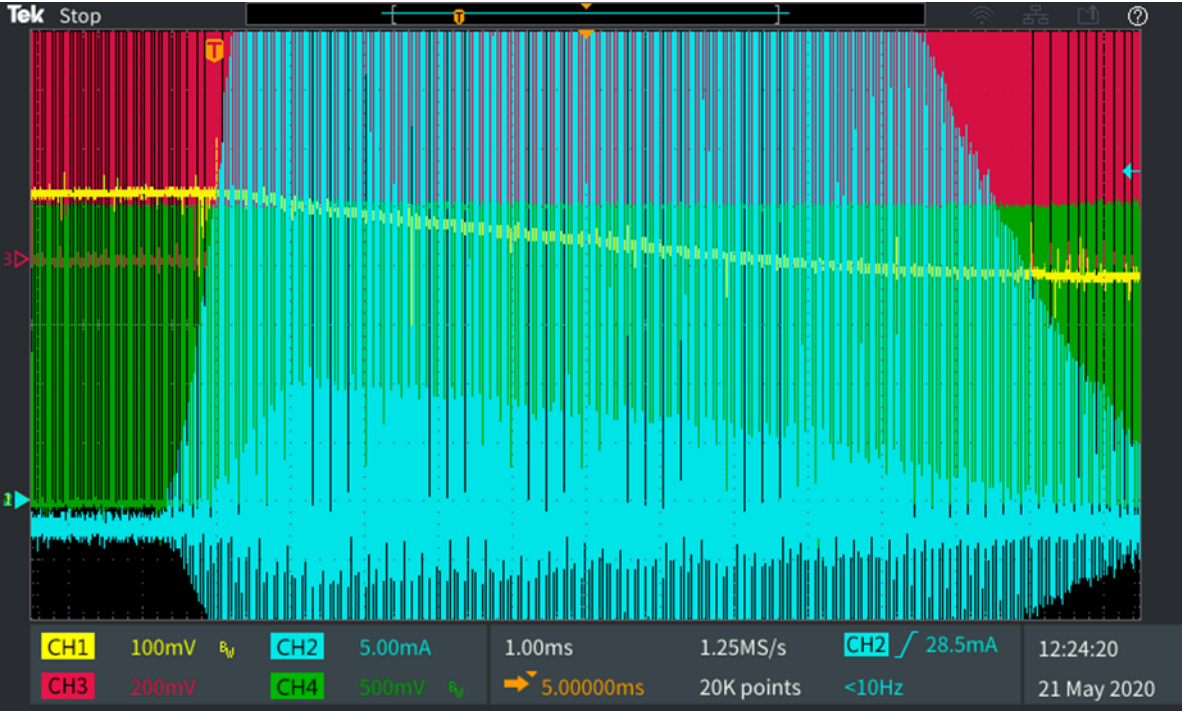


Figure 27. Start-up with modifications to limit PWM duty cycle. Same traces as Figure 24.

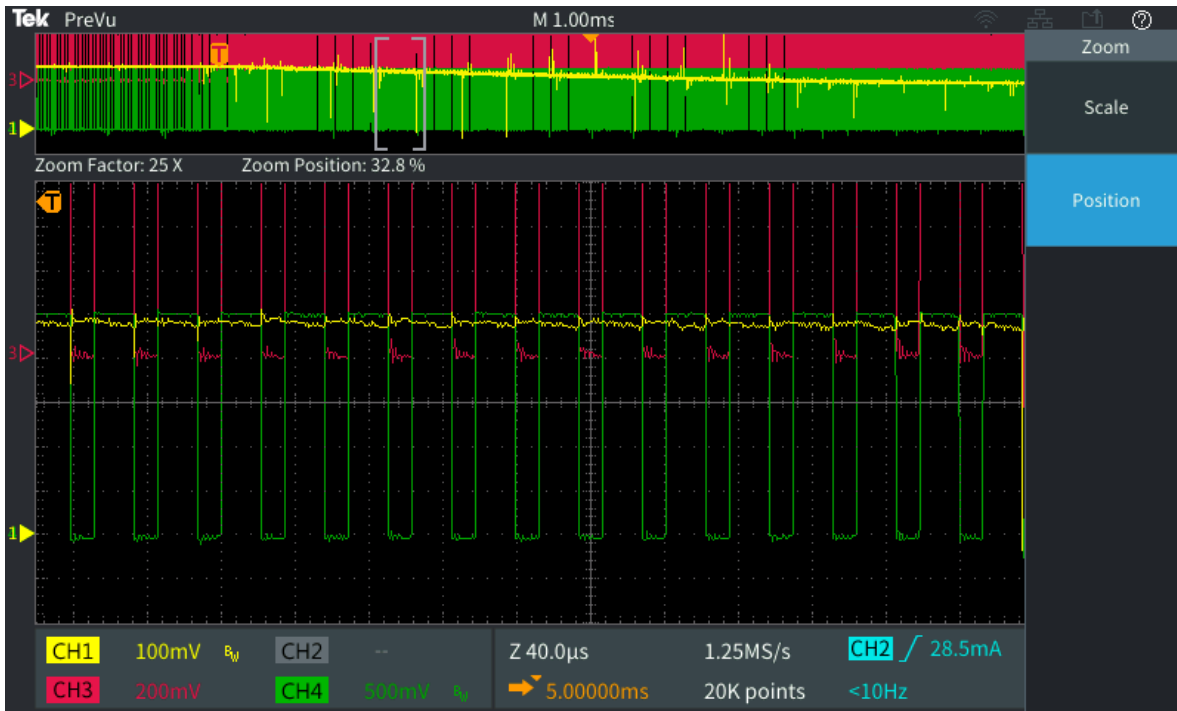


Figure 28. Zoom view of Figure 27 shows that the PWM duty cycle (green trace) is not at 95% due to modification.

The modified board was able to turn on with a R_{mfc} of 104 ohms, which is a slight increase from 100 ohms seen in the original circuit design. This suggests that the chance a lower power MFCs may encounter an unstable start-up condition is decreased. When R_{mfc} is equal to 104 ohms, the MFC supply current was 4.2mA, with the MFC supply voltage of 0.8V. The voltage the EH board sees in steady state is 0.4V, due to voltage drop across the resistor plus PID controller. Calculation of the minimum MFC power that is required for operation without start-up issues yields a power of 1.7mW. This minimum power is close to the stated steady state power draw of the board at 1.2mW.

When R_{mfc} was set to 110 ohms, the system began to exhibit the same start-up issues as the unmodified board. Therefore, increasing the delay to the reference set point may increase the upper limit of R_{mfc} for stable operation, but the gains appear negligible unless the duty cycle can be held near the minimum. Increasing the frequency along with the discussed modification was not tested, but could also be a method to increase upper limit of R_{mfc} .

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6. FUTURE

This section discusses future work for testing with actual fuel cells and performing PID control with a low power microcontroller.

6.1 TESTING REV 2 BOARD WITH FIELDDED MFCS

Thus far, bench testing using a power supply was performed on the MFC PID EH rev 2 boards. Since a real MFC has longer time scales than power supplies, the rev 2 boards should be tested with real MFCs. This would give a more realistic view of the EH PID control behavior with dynamic time constants. Previous testing on real MFCs with past version of the flyback EH PCBs were previously reported. [1, 2]. Testing, using rev 1 PCB, with a commercial wastewater MFC in ref [2] showed the need for dynamic PWM duty cycle to account for an unstable on/off cycling that was observed. This instability was caused by the mismatch of the PCB's target power (10mW) and the ability of the MFC to deliver enough power. NIWC Pacific has MFCs under development that can be used to test the rev 2 boards. A local commercial MFC company, Aquam, LLC, may also have operational MFCs that are available for testing.

6.2 DIGITAL PID CONTROLLER USING MICROCONTROLLER

Microcontrollers can implement a PID control strategy by using an analog-to-digital converter (ADC) to measure the MFC voltage, calculate the control response, and output the control signal in one IC. The issue with utilizing microcontrollers is higher power draw that might be needed accomplish all the required functions. Some microcontrollers are able to employ deep sleep states, which can be coupled with an increased time between ADC measurements (slower PID loop). This strategy may be able to yield a low power draw similar to what was achieved with the circuit described here.

The EH start/stop comparator functionality, discussed in section 3.2.3, can be onboard the microcontroller if the function is available or located as a separate circuit. In the latter case, a digital input pin on the microcontroller would be used to monitor the comparator output. The PWM generation can also be on the microcontroller chip. Generally on-chip PWM generators need high peripheral clock rates to get fine duty cycle resolution. The high clock rates will require more power draw. A mitigating strategy for this increased power draw is to use a digital-to-analog output signal from the microcontroller to control the current PWM IC described in this report.

An example microcontroller with all of the above, a digital-to-analog converter (DAC) and maintain DAC output in sleep mode is the PIC16F1769 and PIC16F1776. Preliminary testing with the PID control handled by the microcontroller using both the sleep mode and a DAC output to current PWM IC shows promise, requiring only 1.1mW at a 0.6V supply voltage while harvesting power. This compares favorably to measurements in Table 2 showing a power requirement of 1.2mW at 0.6V. When the microcontroller updates the control signal calculations, the PID loop power draw increases to 1.6mW briefly since the ADC function is used. The time between PID updates can be adjusted to minimize power at the expense of slower PID control signal updates. Power consumption of this microcontroller based strategy when MFC voltage is below turn-on point (100mV) is $\sim 64\mu\text{W}$. This power consumption again compares favorably with the $80\mu\text{W}$ measurement in Table 2. Since this was a preliminary test, detailed analysis and refinement of PID controller code were not performed.

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7. CONCLUSION

The PID flyback EH circuit works to hold the MFC voltage at a user defined set point while being able to support a wide range of power, 3mW-75mW tested, to the 12V battery load. The minimum EH control board power draw was 1.2mW. Efficiency for energy harvesting was 80% when delivering 75mW to the battery load and dropped as low as 56% at lower power due to control circuit overhead. Start-up issues at high R_{mfc} (low MFC power) were observed which caused the EH board to turn on then off repeatedly in an unstable cycling mode.

To increase the low power limit of the MFC board, a modification that limits the PWM duty cycle signal on start-up was made. This modification allowed the MFC EH board to operate from a model MFC with internal resistance of 104 ohms, representing a slight increase from unmodified limit of 100 ohms. The modified EH board could start-up and operate without unstable on-off cycling with an MFC power input as low as 1.7mW. Future testing with real MFCs needs to occur to further confirm our observations. Preliminary PID controller test results utilizing a microcontroller is promising and will be examined in future research.

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REFERENCES

1. Babauta, Jerome; Kerber, Maxwell; Hsu, Lewis; Phipps, Alex; Chadwick, Bart; Arias-thode, Meriah [2018]. Scaling up benthic microbial fuel cells using flyback converters. *Journal of Power Sources*. 395. 98-105. 10.1016/j.jpowsour.2018.05.042.
2. Schnecker, Joey, Jr.; Kerber, Maxwell; Hsu, Lewis [2019] Blackwater Microbial Fuel Cell Report. ONR Annual Report.
3. http://www.cds.caltech.edu/~murray/books/AM08/pdf/am06-pid_16Sep06.pdf.

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14. ABSTRACT Microbial fuel cells (MFCs) can provide power at low output voltages, 0.2V-0.8V. The challenge is to efficiently harvest the MFC power while boosting the voltage to a useful level. The proportional-integral-derivative (PID) flyback energy harvesting (EH) circuit presented in this report holds the MFC voltage at a user defined set point while being able to support delivery of a wide range of power levels (3mW-75mW tested here) into a 12V battery load. The control board power draw was 1.2mW. Energy harvesting efficiency was 80% for 75mW power level delivered to the battery load. Efficiency decreased to 56% at the 2.6mW power level, largely due to control circuit overhead power consuming a larger portion of the input power.					
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