Sensorless Back EMF-Based Speed Estimation in a Brushed DC Motor Controller Using Low-Side Switching

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0 Abstract

This project demonstrates a method for estimating the speed of a brushed DC motor without the use of external sensors. By briefly switching off the motor's low-side MOSFET, the circuit exposes the back electromotive force, also called Back EMF, generated across the motor terminals. This voltage, which is directly proportional to the motor's speed, is sampled using an ADC connected to the motor's low-side path.

The system was implemented using a custom circuit with an integrated PsoC MCU, real-time firmware, and an LCD display to read Back EMF voltage and estimated speed. The acquired Back EMF readings were converted into speed estimates in RPM.

Multiple oscilloscope-based measurements were performed to analyze motor behavior under switching and steady-state conditions, including voltage drops and current flow through a N-type MOSFET FET and sense resistor. The results validate that reliable speed estimation can be achieved using only voltage measurements and low-side control, without the need for dedicated sensors like rotary encoders or Hall sensors.

1 Introduction

Accurate speed control and monitoring in DC motors is critical for many embedded and control system applications, especially when feedback is required but the use of physical sensors is impractical or costly. Traditional solutions like rotary encoders or Hall sensors add complexity, cost and mechanical fragility to embedded motor control systems. Therefore, sensorless estimation methods based on electrical measurements are attractive for low-cost and compact applications.

The goal of this project was to implement a method for estimating the rotational speed (RPM) of a brushed DC motor using the motor's own back electromotive force (Back EMF). The approach relies on briefly turning off the low-side N-channel Mosfet in the motor's low-side switch configuration. This allows the MCU's ADC to sample the Back EMF present across the motor teminals, which is directly proportional to the motor's speed. By periodically sampling this voltage and converting it into speed using calibration and scaling, it becomes possible to estimate RPM in real time without physical sensors.

This system was developed and tested on a custom breadboard-based circuit using a PSoC MCU, with firmware handling real-time switching, sampling and display of measured values. The project aims to validate the practicality of this approach by analyzing voltage and current behavior under different operating conditions and comparing derived speed estimates to expected motor performance.

2 System Overview

The system is designed to estimate the speed of a brushed DC motor without physical sensors by leveraging the Back EMF voltage that appears visible during short low-side switch-off periods.

2.1 Circuit Configuration

- The circuit is powered using three 1.5 V AA batteries, supplying a total of 4.5 V to the motor and control circuitry.
- The motor is driven in a low-side switching configuration using an N-channel MOSFET.
- A 0.62 Ω current sense resistor is placed between the MOSFET source and ground.
- A flyback diode is connected across the motor to safely conduct the inductive current during MOSFET turn-off.
- A pull-down resistor at 10 kΩ is added to the gate to protect the MCU GPIO pin from current spikes and transient during switching.
- A resistor is added for protection between ADC input and the motor's negative terminal to limit inrush current and protect the ADC during switching events.

2.2 Measurement Points

- Back EMF is measured between the MOSFET drain and ground when the MOSFET is turned off.
- Current is inferred by measuring the voltage across the current sense resistor during MOSFET on-time.

2.3 MCU and Firmware

- The PSoC MCU handles timed MOSFET switching and ADC sampling.
- Timing is implemented to sample the Back EMF during 30 ms low-side off window.
- A 16 x 2 LCD displays the estimated RPM and Back EMF voltage in real time.

2.4 Diagram

The internal firmware configuration was developed using PSoC Creator. The block diagram below shows how the MCU modules are connected to perform gate control, ADC sampling and LCD output. A digital output pin drives the MOSFET gate, while the ADC monitors the motor voltage during the off-time to capture Back EMF. The LCD module is used to display real-time voltage and estimated motor speed.

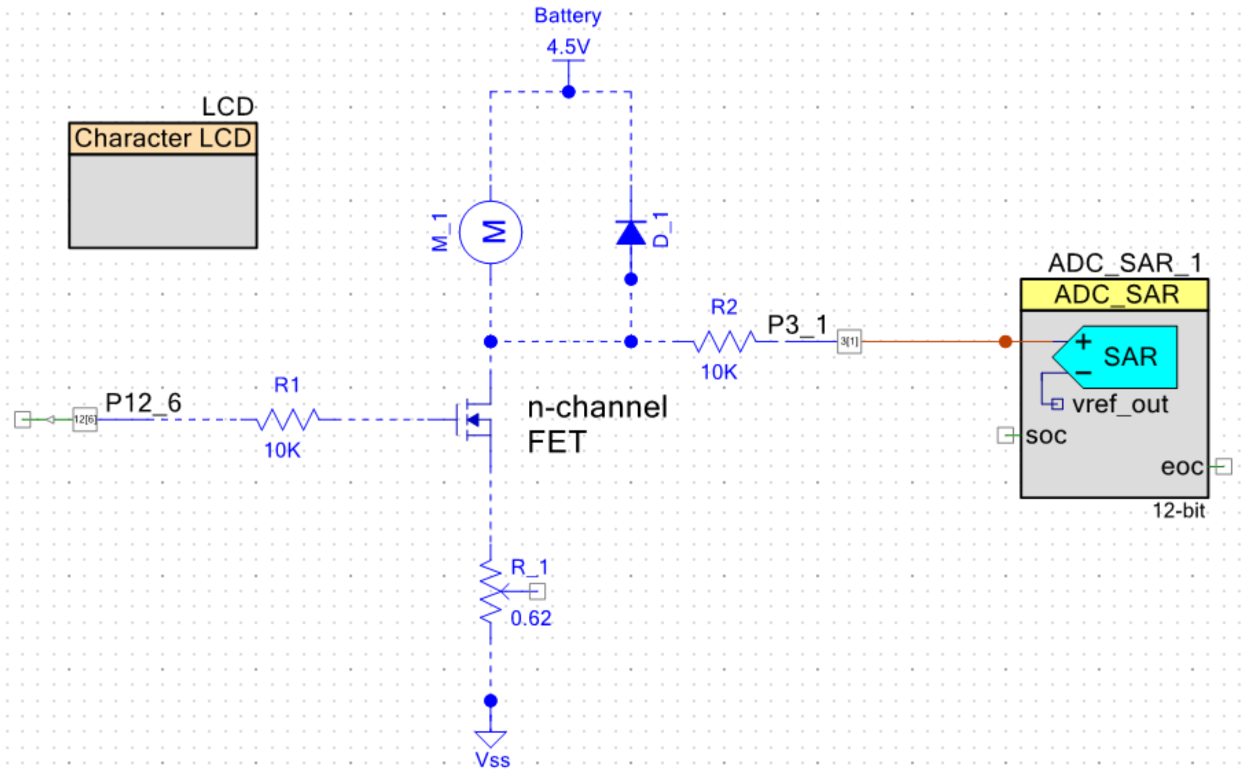

Figure 1 - PSoC Creator block diagram of the system

3 Methodology

3.1 Control Strategy

The motor is driven using low-side switching via a N-channel MOSFET controlled by the PSoC. The firmware enables the MOSFET for 3s to power the motor, then briefly disables it for 30-200 ms depending on the test case. A delay (around 30-50 ms) after turn-off allows transient effects to settle before ADC sampling begins. During this off-time, the motor coasts and generates a Back EMF voltage, which is proportional to its speed. The Back EMF voltage V_{EMF} can be written as:

$$V_{EMF} = K_e * \omega$$

Where K_e is the constant of proportionality and known as the Back EMF constant and ω is the rotational speed in RPM.

3.2 ADC Sampling and Speed Calculation

The ADC is triggered during the MOSFET-off window to sample the voltage at the MOSFET drain (i.e., motor negative terminal). This voltage is proportional to motor speed and is used to estimate RPM using the motor's known Back EMF constant K_e. The resulting speed and voltage are displayed on the LCD in real-time.

3.3 Oscilloscope Measurement

To verify operation and collect data for analysis:

- The voltage between MOSFET drain and ground was measured to observe Back EMF behavior during switching
- The voltage between MOSFET drain and ground was measured to observe the net voltage across the motor terminals, which can be found as:

$$V_{NET} = V_{Battery} - V_{EMF}$$

V_{NET}: Total voltage across motor terminals
$V_{Battery}$: Power supply voltage
V_{EMF}: Back EMF voltage

- The voltage between MOSFET source and ground (across the 0.62Ω resistor) was measured to calculate motor current during on-time.
- Multiple switching cases (e.g., between 30-200 ms off-times) were recorded to analyze how speed and Back EMF respond to different sampling windows.

4 Results

4.1 Back EMF Behavior During Low-Side Off Time

When MOSFET is turned off briefly (30-60 ms, etc.) the motor terminals are disconnected from ground, and the voltage between the drain and ground rises to the Back EMF level. This voltage correlates directly with motor speed.

Examples of graphs showing the voltage between Drain and Ground during the MOSFET off-window, where the Back EMF is visible for various off-times, are shown in figures 2, 3, 4, 5, 6 and 7.

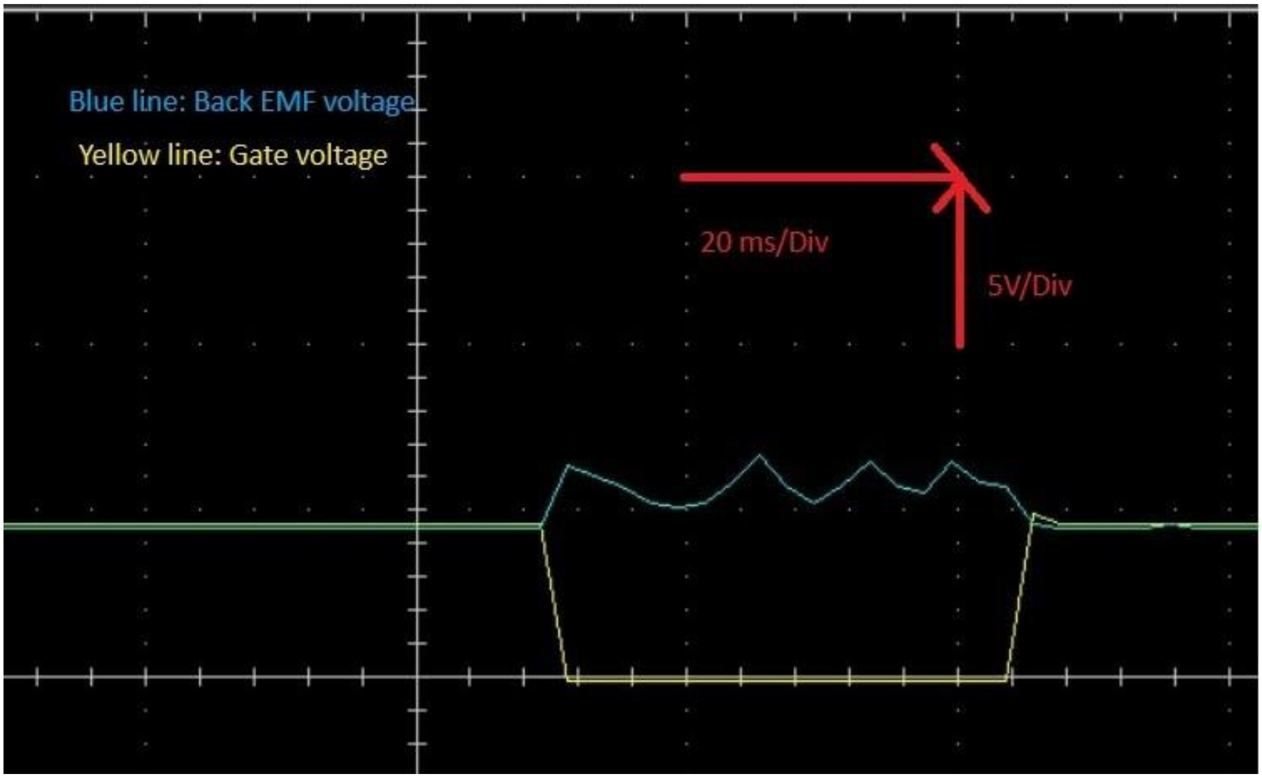

Figure 2 - Drain-to-Ground Voltage (30 ms off-time)

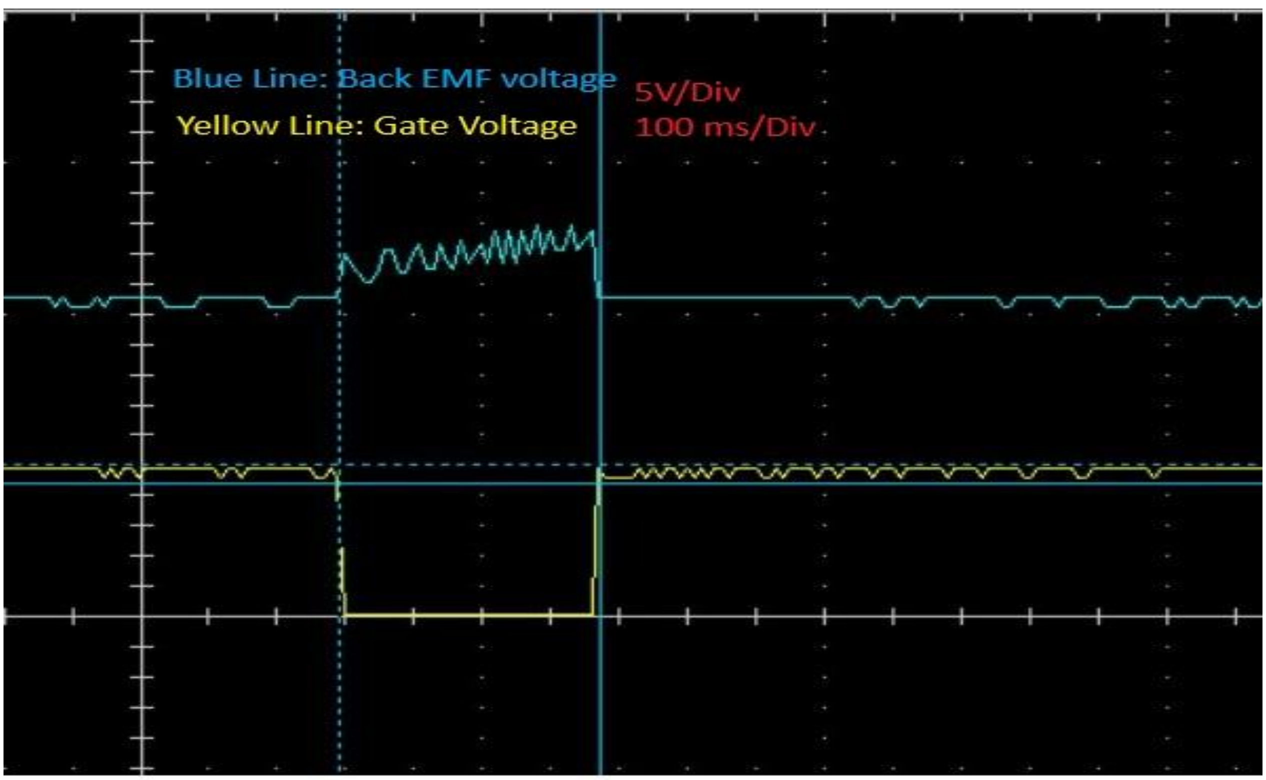

Figure 3 - Drain-to-Ground Voltage (70 ms off-time)

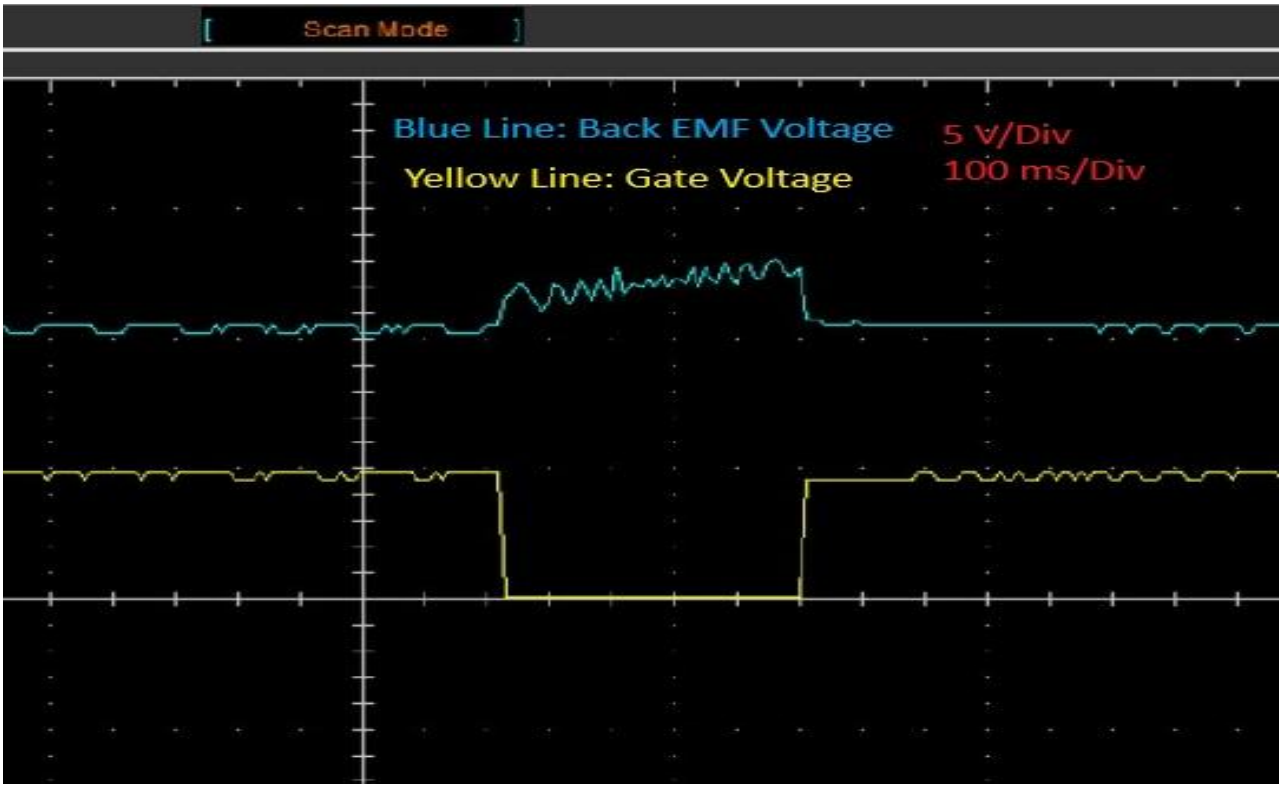

Figure 4 - Drain-to-Ground Voltage (90 ms off-time)

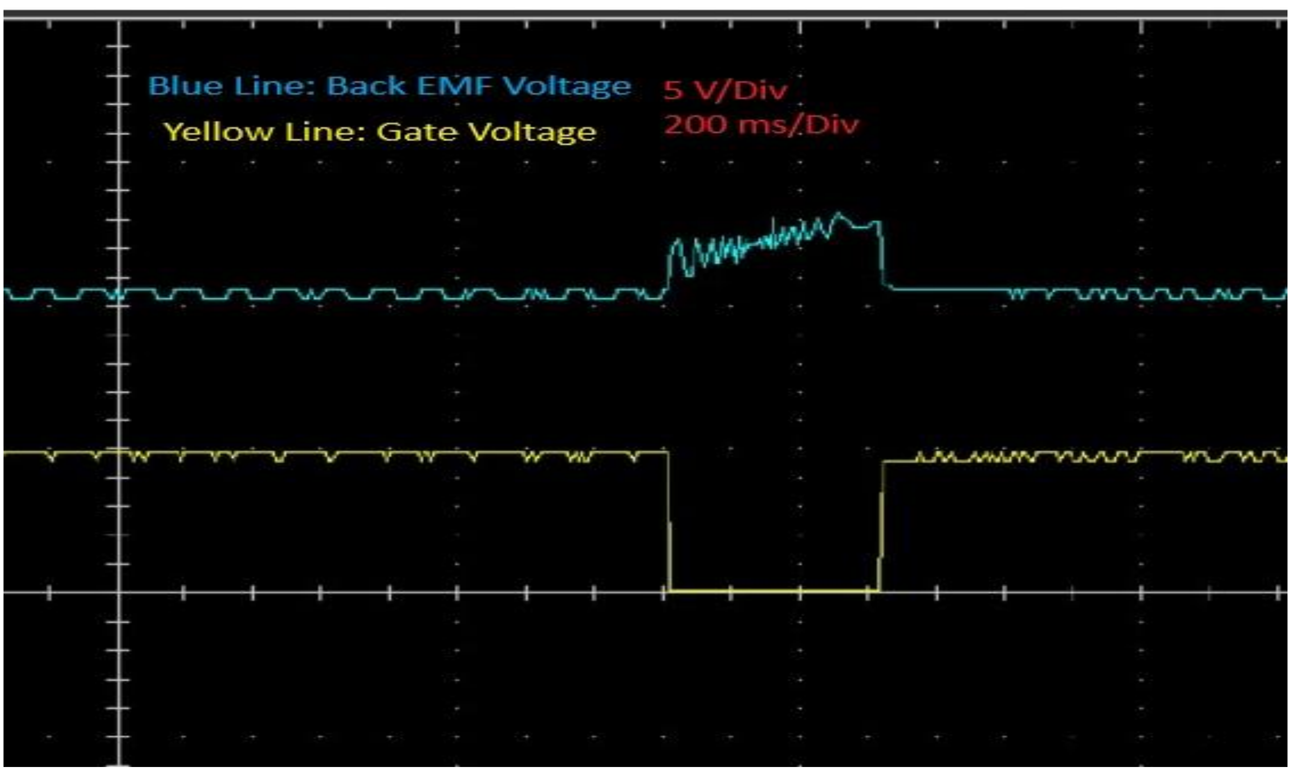

Figure 5 - Drain-to-Ground Voltage (120 ms off-time)

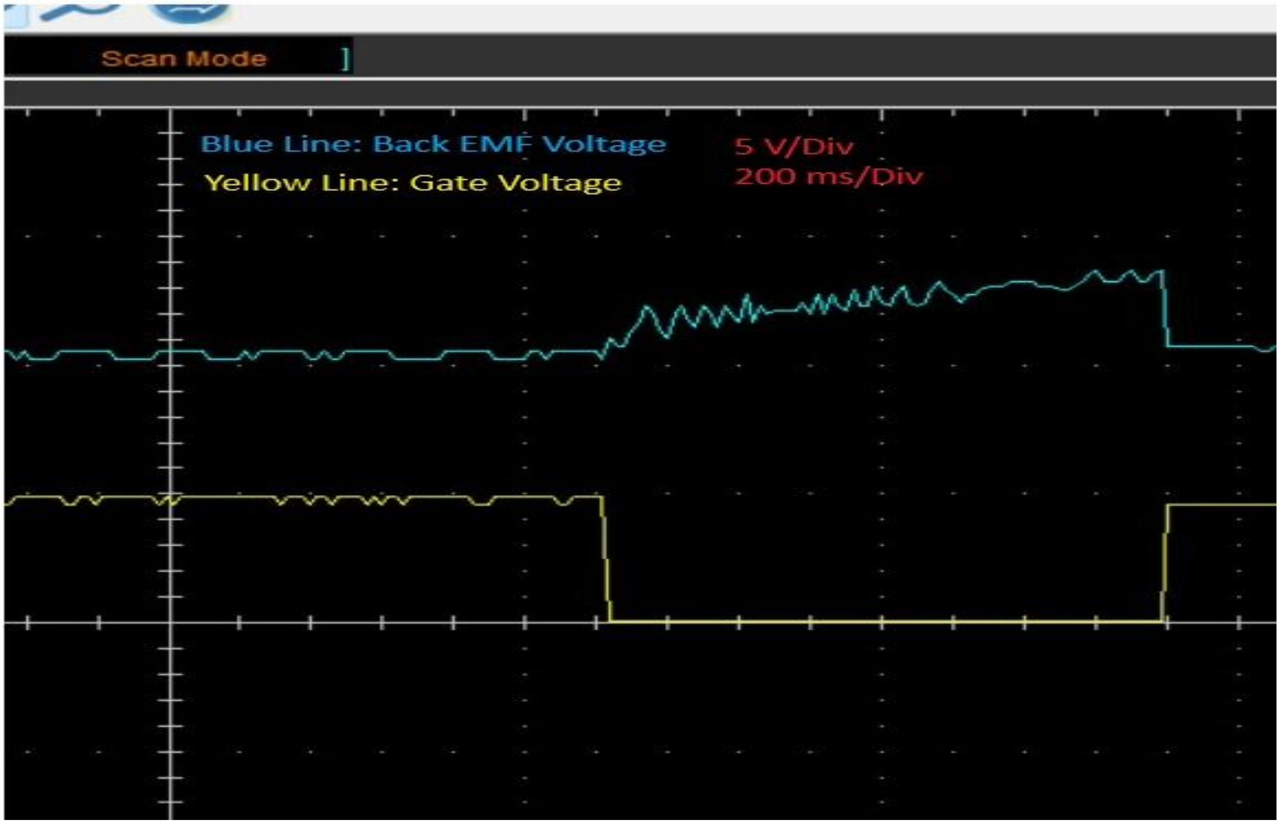

Figure 6 - Drain-to-Ground Voltage (150 ms off-time)

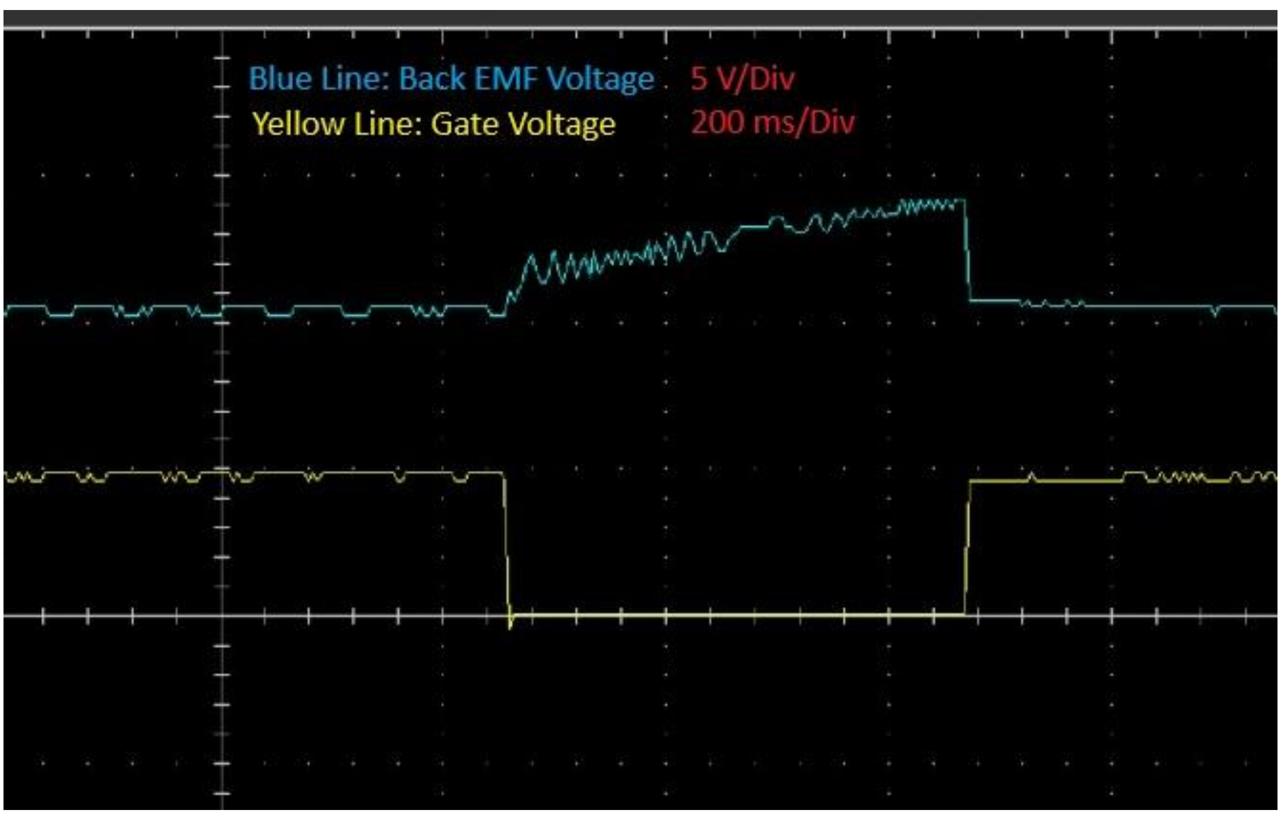

Figure 7 - Drain-to-Ground Voltage (2000 ms off-time)

The following graph shows the voltage between Drain and Ground when the MOSFET remains continuously on. It illustrates how the net voltage across the motor terminals significantly decreases and settled after a short amount of time due to increasing Back EMF:

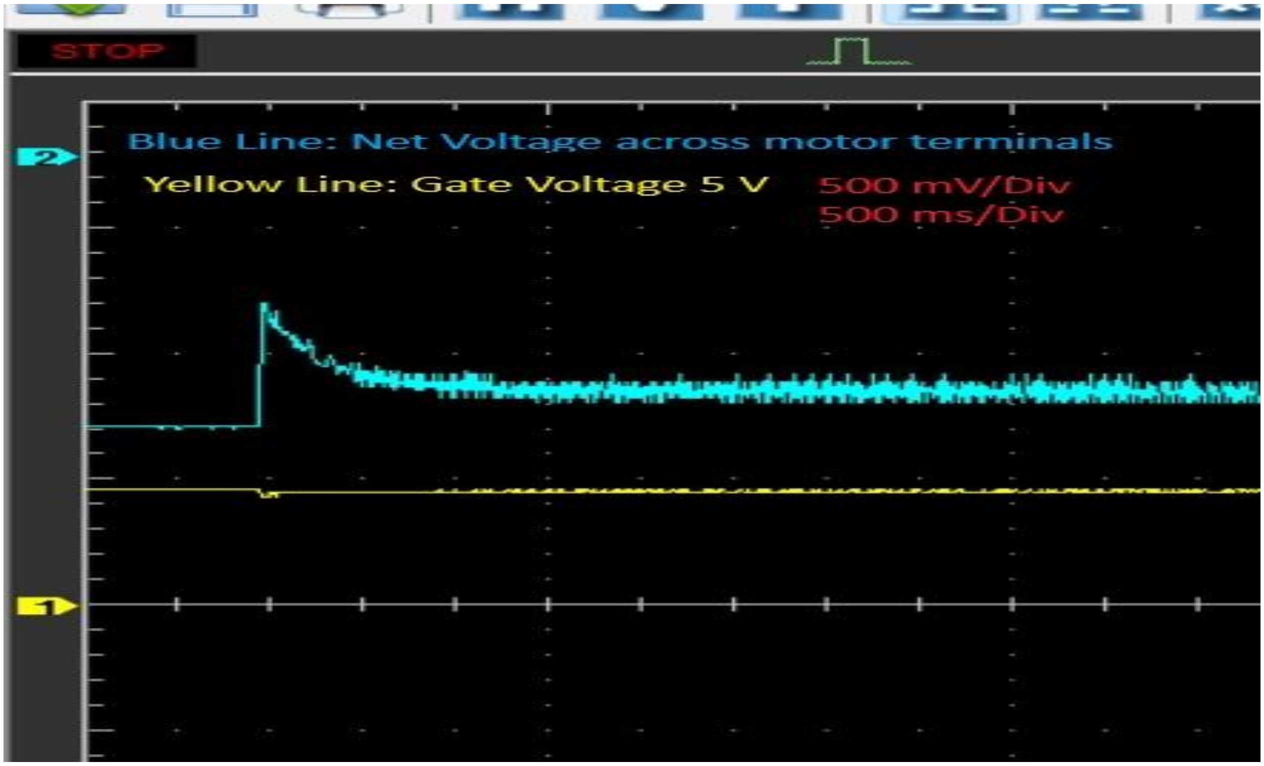

Figure 8 – Net voltage generated across motor terminal

4.2 Current Estimation Using Current Sense Resistor

A 0.62Ω current sense resistor (CSR) was placed between the MOSFET source and ground to allow indirect current monitoring. By measuring the voltage across the CSR during MOSFET on-time and applying ohm's low, an current profile was obtained.

While this measurement does not account for the voltage drop across the MOSFET itself, it serves as a practical method to observe current dynamics such as startup behavior, switching transient and load response.

The resulting current curve is lower than the total motor current but follows the same trend, providing useful validation of the system's electrical response.

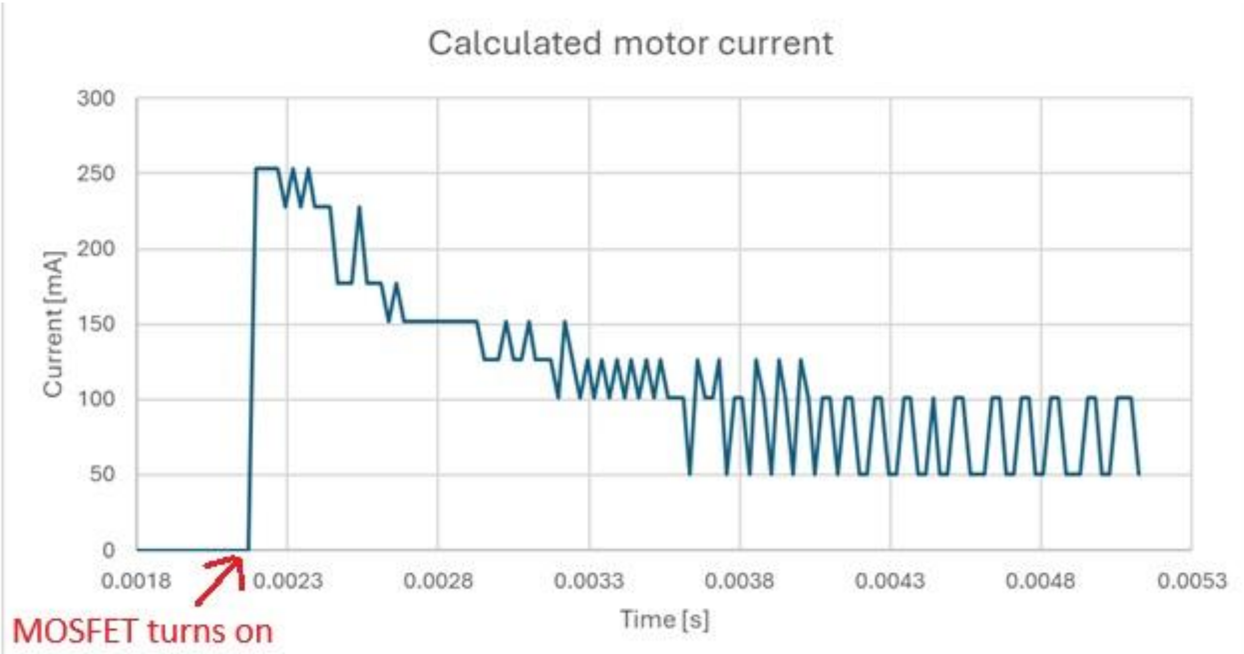

Figure 9 – Current through CSR

4.3 Calculated Motor Current from Drain-to-Ground Measurement

To estimate the full motor current more accurately, voltage was measured between the MOSFET drain and circuit ground during the on-state. This path includes both the MOSFET's on resistance $R_{on} = 0.18\Omega$ and the 0.62Ω CSR. The total resistance used for calculation was 0.8Ω (0.18Ω + 0.62Ω).

By applying Ohm's law to the measured drain-to-ground voltage, a better approximation of the motor's actual current draw was obtained. This approach reflects the total current flowing through the motor windings and switching path.

The current curve shows the motor's dynamic behavior during startup, including the initial inrush current and subsequent settling as Back EMF builds up and opposes the supply voltage. This curve closely follows expected characteristics for a low-inertia DC motor under no-load conditions.

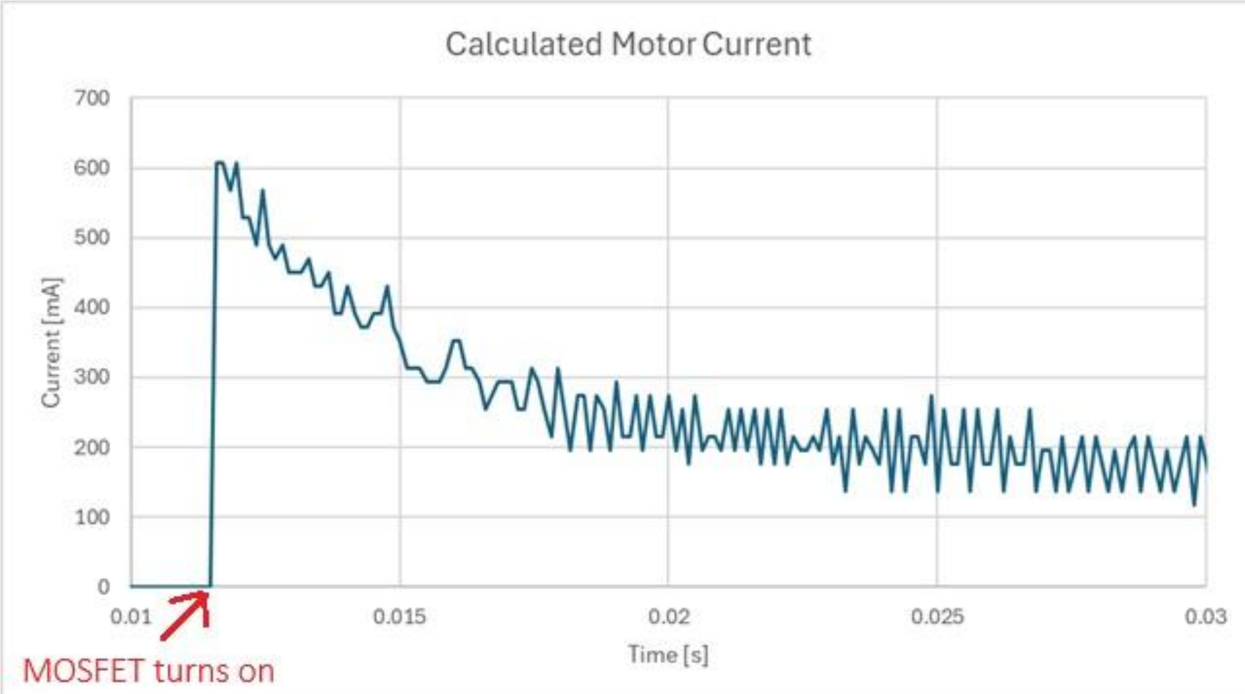

Figure 10 – Motor Current

4.4 Estimated Speed from Back EMF

To estimate the motor's rotational speed without sensors, the system samples the back electromotive force (Back EMF) that appears at the motor terminals when the low-side MOSFET is turned off. During this brief off-period, the motor acts as a generator, and the Back EMF is proportional to the motor speed according to the equation:

$$Back\ EMF = K_e * Speed$$

Where K_e is the constant of proportionality, also known as Back EMF constant, and it's measured in volts per thousand rpm. Based on datasheet value, the Back EMF constant K_e = 0.3466 mV/RPM was used for this motor.

The voltage was sampled via an ADC connected to the motor's low-side path during the MOSFET off-window. After each measurement, the Back EMF was computed and used to estimate speed:

$$Speed\ (RPM) = \frac{V_{supply} - V_{ADC}}{K_e}$$

This method subtracts the observed Back EMF from the supply voltage to account for voltage drop caused by motor loading, as supported by test observation.
The calculated speed was displayed in real time on an LCD screen, and confirmed to follow the expected behavior: The RPM increased rapidly after startup and stabilized as the motor reached steady-state speed.

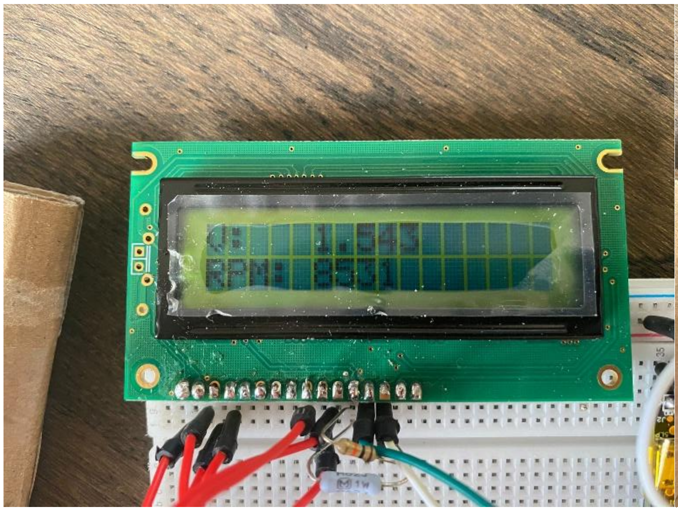

Figure 11 – Speed and Back EMF for 50ms off-time

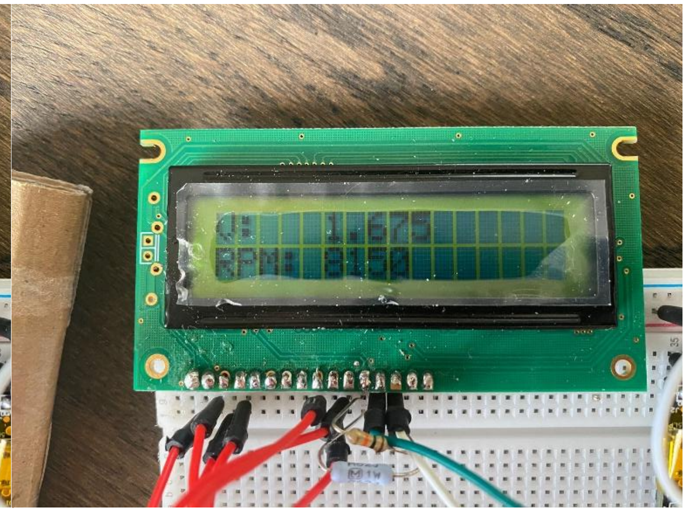

Figure 12 – Speed and Back EMF for 50ms off-time

To validate the Back EMF-based RPM estimation, LCD readings were recorded under different motor conditions. In the first case, the motor runs freely with no load, showing a stable Back EMF voltage and corresponding RPM, as shown in figure 11 and 12.

In the second case, external resistance was applied by gently pressing on the motor shaft. As expected, the RPM decreased due to the added mechanical load. At the same time, the Back EMF voltage rose significantly. This occurs because the motor draws more current in an attempt to maintain torque and resist the external force, which increases the Back EMF, as shown in figure 13 and 14.

These results confirm that the system is responsive to real-time changes in motor dynamics and accurately reflects speed variations without external sensors.

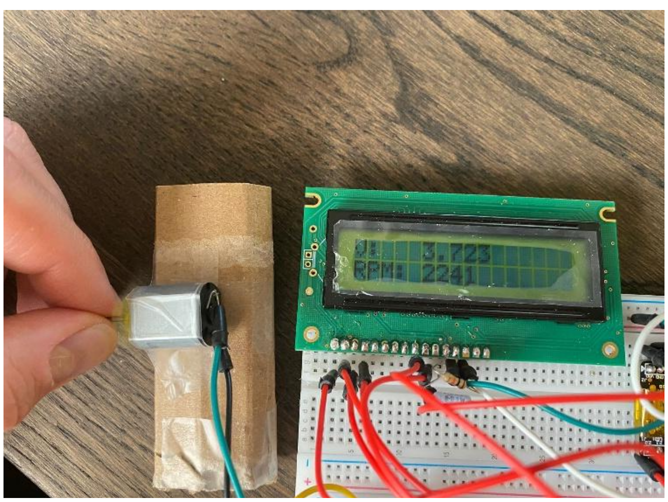

Figure 13 - Back EMF and Speed under external force

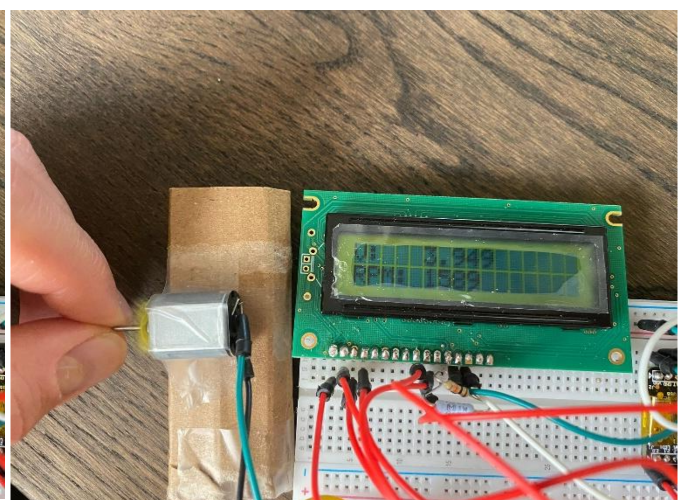

Figure 14 - Back EMF and Speed under external force

5 Discussion

Throughout the development of this system, some practical challenges were encountered that influenced both hardware and software design.

Floating ground and oscilloscope troubleshooting
One major issue was unexpected behavior in oscilloscope readings – especially negative voltages and floating baselines. This issue was traced to grounding inconsistencies between the MCU (powered via USB) and the motor supply (powered by batteries). Connecting all grounds to a common reference point resolved the issue and allowed consistent measurement.

Gate resistor and MOSFET switching stability
A 10 kΩ resistor was added between the PSoC GPIO and the MOSFET gate. This was not for turn-off purposes but rather to protect the GPIO pin from potential high-current transients during switching. It ensures the MCU is isolated from sudden voltage spikes caused by the capacitive nature of the MOSFET gate-to-source. The turn-off behavior of the MOSFET itself was confirmed through direct measurement of V_{GS}.

Back EMF accuracy and ADC timing
ADC timing also required careful adjustment for ADC sampling. Measuring too early after switching introduced transients, while waiting too long allowed motor speed to decay. A turn-off period between 40-60ms offered the best compromise between voltage stability and realistic speed capture.

Rise in Back EMF under external load
When external resistance was applied to the motor shaft, a decrease in speed was expected – and observed. However, the ADC also showed an increase in Back EMF voltage. This initially seemed counterintuitive, but was understood to be due to increased motor current trying to maintain torque, which caused a higher voltage drop across motor internal resistance. The behavior matches typical DC motor response under mechanical load.

Purpose and use of the current sense resistor
The 0.62Ω CSR was intentionally added between the MOSFET source and ground to serve as a stable, known resistance for current measurement. Unlike the MOSFET's R_{on}, which varies with temperature and gate voltage, the CSR provides consistent values for calculating current using Ohm's law. This simplifies interpretation of current profiles during startup and switching, and ensures more predictable and repeatable current measurements during testing.

6 Conclusion

This project succesfully demonstrated a sensorless method for estimating the speed of a brushed DC motor using Back EMF measurement and low-side switching. By briefly turning off the motor's low-side MOSFET and sampling the resulting Back EMF with an ADC integrated on PSoC MCU, reliable real-time speed estimates were achieved without the need for rotary encoders or Hall sensors

The system was implemented using a PSoC MCU, supporting coordinated gate control, analog sampling and LCD output. Through oscilloscope analysis and voltage/current measurement, the motor's electrical behavior was characterized during startup, steady-state and under external load.

Despite minor challenges like ADC timing and grounding inconsistencies, the method proved robust. The Back EMF voltage followed expected trends relative to speed, and motor current was successfully profiled through both the MOSFET and current sense resistor.

Overall, the project confirms that sensorless speed estimation using Back EMF and a low-side switching configuration is both feasible and effective for brushed DC motors, making it a valuable approach for compact and cost-sensitive embedded applications.