YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MKT5121 – SENSORS, ACTUATORS, AND INTERFACING

Term Project

Fluxgate Current Sensor

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1) INTRODUCTION

Current measurement is usually employed to measure the power to optimize the received energy from the resources, i.e., as feedback on MPPT controller, electric machines. In its simplest form, current measurement can be done by passing the current through a resistor named a sense resistor, as shown in Figure 1. This method can be used to measure both DC and AC current. The significant disadvantage of current measurement using a sense resistor is power dissipation in long-term high-current operations. In addition, the size and weight of the resistor are proportional to the measured current, the greater current to be measured the bigger resistor is necessary. A Hall effect sensor is applied to address such problems in current measurement. A Hall effect sensor is a type of sensor which detects the presence and magnitude of a magnetic field using the Hall effect, where a magnetic field will be generated around a current-carrying conductor wire. This magnetic field will be detected and converted into voltage by a hall sensor. There are many advantages to using hall sensors for current measurement. First, measurement becomes more accurate because the hall sensor does not have contact with the current-carrying conductor wire. Second, this method can be used for measuring AC and DC current. Third, the hall sensor can measure high currents with a small size device. And most important, there is no power dissipation.

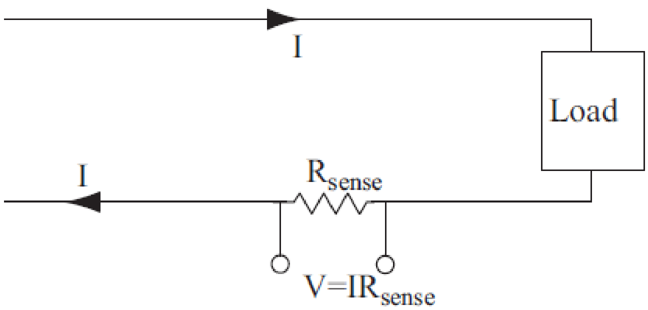

Figure 1 - A resistor as a current sensor

2) HALL EFFECT CURRENT MEASUREMENT

The electric current generates field magnetic around a current-carrying conductor wire. The direction of the magnetic field can be determined by the "right-hand rule". The magnetic flux density is calculated with the following equation:

$$B = \frac{\mu_0 \mu_r I}{2\pi r}$$

where B is the magnetic flux density (T), μ_0 is the vacuum permeability $4\pi * 10^{-7}\, Tm/A$, μ_r is the relative permeability, and I is the measured current (A). Magnetic flux density B can be measured by a Hall sensor. However, the magnetic field produced by the current-carrying conductor wire is very small. It is required a material with high permeability to strengthen the magnetic field, called a field concentrator shown in Figure 2. Field concentrator basically consists of a soft magnetic material with high permeability and low remanence that surrounds the conductor. The field concentrator is used for several reasons such as boosting the flux density, sensor positioning, and enabling closed-loop systems. The flux density is boosted with the effective permeability μ_r of the core usually has a typical flux amplification between a factor of 20 and 70.

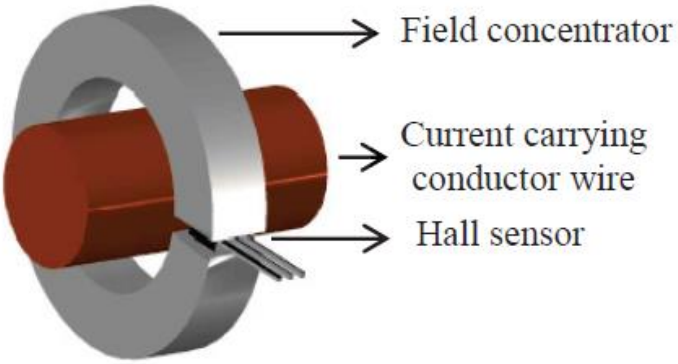

Figure 2 - Design of current measurement using hall sensor

Using a toroid will effectively collect all the flux and concentrate it. Therefore, using such a core allows us to make flexible systems for instance the wire can be moved inside the aperture without a remarkable influence on the output voltage of the sensor. However, this system shown in Figure 1 can be used for high DC currents. In this project, only a maximum 1A current can be obtained. Therefore, the toroid core is winded with wire through which the current passes. This system is shown in Figure 3.

Figure 3 - Field concentrator with windings

Current I flows through the conductor wire. The hall sensor is inserted into toroid gap. The cross section of the core has at least the size of hall sensor. The flux density produced by the conductor wire can be calculated from the previously given equation. However, there is a gap in toroid and this gap affects the magnetic flux. We can see this effect in Figure 4.

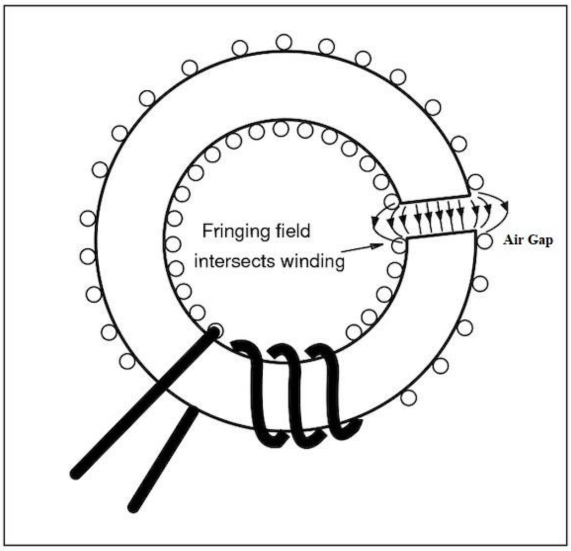

Figure 4 - Fringing field caused by air gap

Therefore, the new flux density can be calculated by considering the air gap effect using the following equation:

$$B=\frac{\mu_0\mu_r NI}{2\pi \;\; r-d \;\; +d\mu_r}$$

where d as the air gap thickness. This equation can be put into the same form as:

$$B=\frac{\mu_0\mu_e NI}{2\pi r}$$

where μ_e as the effective permeability, can be calculated:

$$\mu_e=\frac{\mu_r}{1+\frac{\mu_r d}{2\pi r}-\frac{d}{r}}$$

The output of the hall sensor is a voltage, and can be written as:

$$V_{out}=sB+V_{offset}=\left(\frac{s\mu_0\mu_e}{2\pi r}\right)I+V_{offset}$$

Where s is the sensitivity of the sensor. Quantities in the bracket are constant. Therefore, the output voltage of the sensor depends on the current through the wire. However, the toroid used in this project is small and the effect of the air gap is quite high. Also, there are lots of uncertainties and errors such as magnetic flux leakage, core material losses, and the primitive circuits built. Therefore, some assumptions and simplifications were made to calculate magnetic flux density.

The new equation is given by:

$$B = \frac{0.4\pi\mu_r NI}{MPL + \mu_r d}\ \mathrm{G}$$

where MPL is mean magnetic-path-length. For toroidal powder cores, the effective area (A) is the same as the cross-sectional area. By definition and Ampere's Law, the effective magnetic path length is the ratio of ampere-turns (NI) to the average magnetizing force. Using Ampere's law and averaging the magnetizing force gives the formula for effective path length.

$$MPL = \frac{\pi\ OD - ID}{\ln\left(\frac{OD}{ID}\right)}$$

Where OD: outside diameter of core (cm)

ID: inside diameter of core (cm)

Figure 5 represents the block diagram of the current measurement system. UGN3503 Hall effect (HE) sensor was used. Based on the datasheet information, the sensitivity of the UGN3503 sensor is in the range 0.75 to 1.75mV/G, and the magnetic flux linear range is ±900G. The relative permeability of the material that used for the field concentrator was not given in the datasheet. Since the magnetic flux density formula is known and the voltage output can be read, the simple system identification was applied to calculate the mean relative permeability of the toroid core. For the system identification, two different current values (1.36A and 0.66A) and different turn values between 3 and 15 were applied to the system and the sensing voltage was recorded. Then mean relative permeability was calculated. The values are given below in the table.

Table 1 - The system identification data

Turn	V_{out} (1.36A)	V_{out} (0.36A)	μ_r (1.36A)	μ_r (0.66A)	Average μ_r
3	0.025 V	0.015 V	16.68	21.03	18.85
6	0.069 V	0.034 V	23.75	24.16	23.95
9	0.113 V	0.059 V	26.21	28.48	27.34
12	0.152 V	0.078 V	26.47	28.20	27.33
15	0.244 V	0.122 V	35.29	35.55	35.91
				Total Avg.	26.68

The average relative permeability μ_r is 26.68 $\cong$ 27. The dimension of field concentrator toroid is shown in Figure 6.

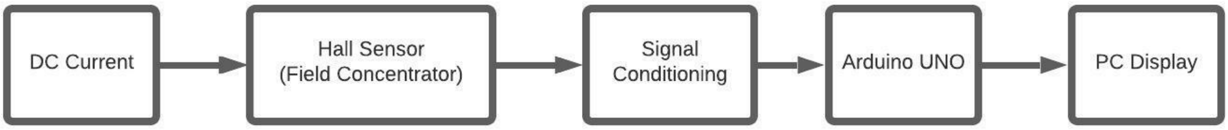

Figure 5 - Block diagram of the current measurement system

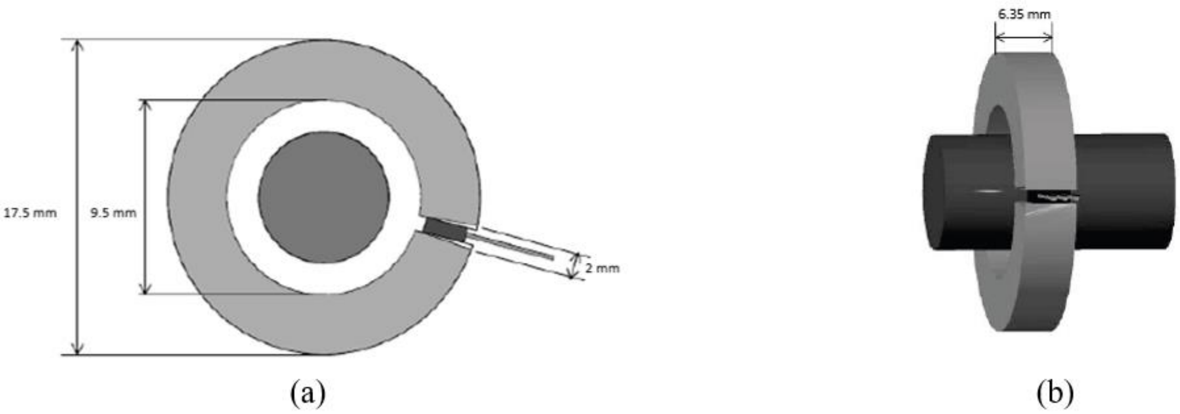

Figure 6 - The dimensions of field concentrator toroid, (a) diameter, and (b) thickness

After completing the fluxgate sensor design, a signal conditioning circuit (SC) was designed. The reason why this circuit is designed is that the voltage change in the sensor is quite small. The schematic diagram of the circuit is shown in Figure 7. Also, a potentiometer was added to the circuit to adjust the biased voltage that is read by the sensor when there is no primary current. Thus, the voltage can change between 0-5V, and the sensor does not saturate easily. There are two op-amps in LM358, so two inputs of the second op-amp were shorted and grounded to keep the signal noise down. The gain of the amplifier circuit is simply calculated as $G = 220/10 = 22$.

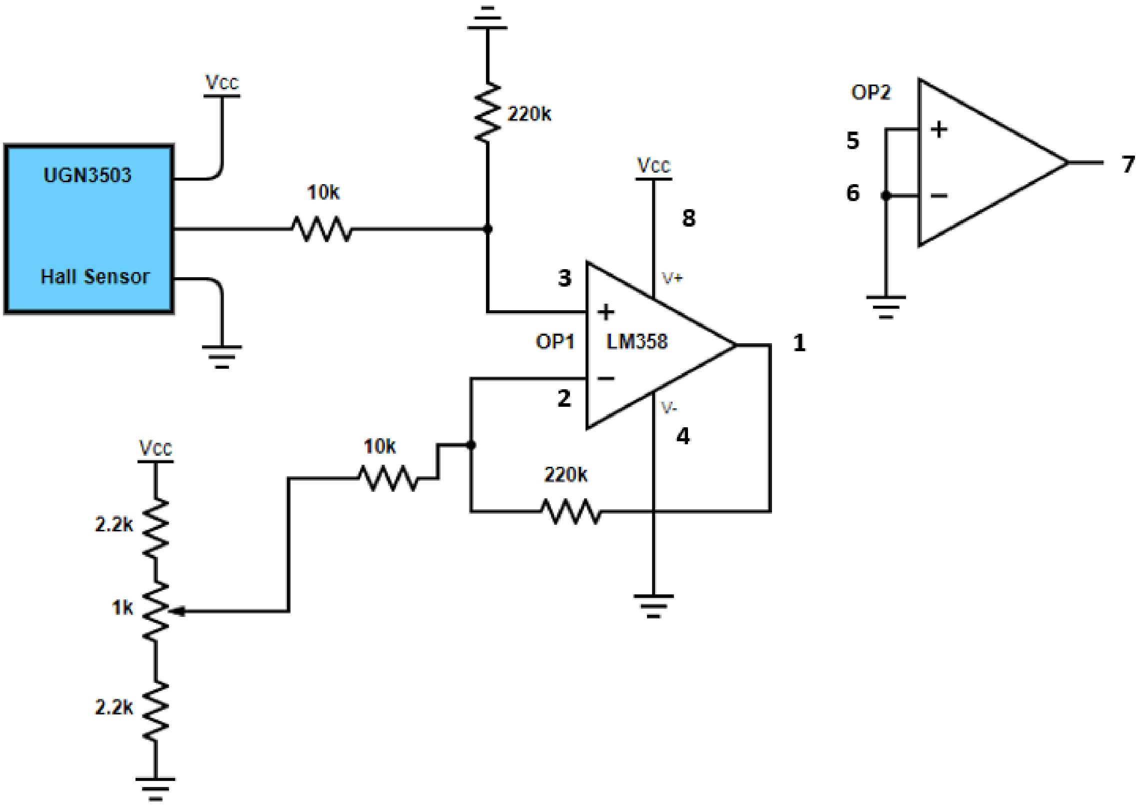

Figure 7 - Signal conditioning circuit

3) SETUP AND INTERFACE

First of all, the air gap that is the same as the thickness of the hall sensor was cut on the toroid. The winding cable, through which the current will be measured, was winded around the toroid. Then the system prototype was designed on the breadboard and some tests were done. Since we want our system to be more permanent and stable, the prototype circuit building on breadboard was moved on the stripboard. After the soldering of the whole system was done, the output voltage of the SC circuit was supplied into Arduino UNO. Arduino was programmed to read the output voltage. The microcontroller of the board has an ADC that reads changing voltage and converts it to a number between 0 and 1023. Therefore, to change values from 0-1023 to 0-5V values, we should scale the numbers by multiplying by 5.0 and by dividing by 1023.0 and multiplying that by sensor value. The schematic of the whole system is shown in Figure 8.

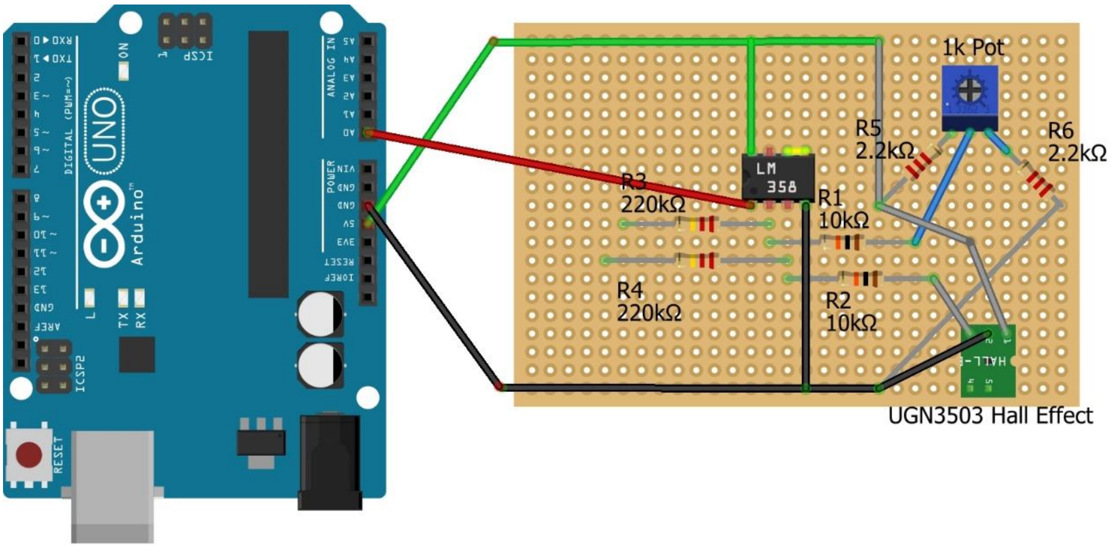

Figure 8 - Schematic of the system

Now that the output voltage of the system can be read, the interface design was done via MATLAB App. MATLAB can integrate with Arduino UNO and read the output value of it. MATLAB App is a quite useful tool to design interface and it can be used by anyone that does not experience a lot in coding as well. The real-time graphic measurements and real-time value reading can be done. In our system, the interface can read the primary current and Hall sensor voltage values and plot the real-time graphs of these values. The interface of the system is shown in Figure 9.

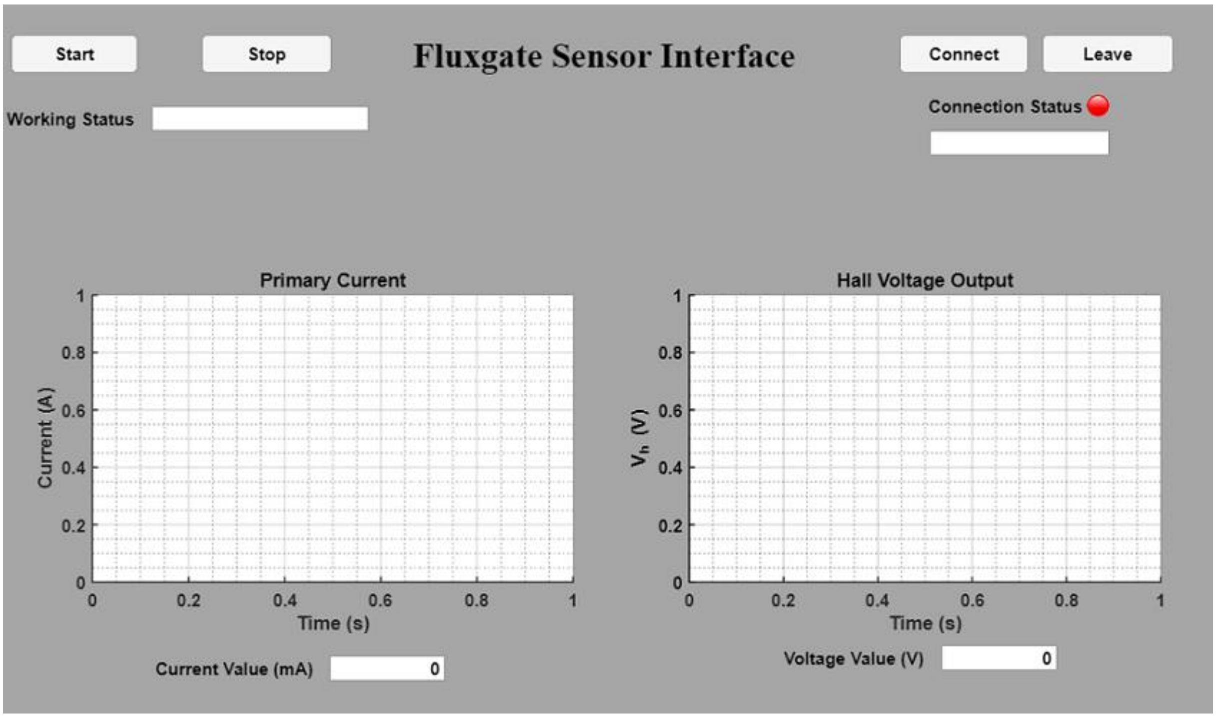

Figure 9 - Interface of the system

4) RESULT AND DISCUSSION

Field concentrator serves to strengthen the magnetic field caused by presence of electrical current in the wire. Without using a field concentrator, primary current 0.66A with a radius of 13.5 mm produced a magnetic field of 1.44G, whereas using a magnetic field concentrator generated a magnetic field of 72.17G. The sensitivity of the hall sensor is only 1.3 mV/G for typical value. Therefore, without the toroid sensor could not sense the applied primary current as expected.

Since 0.66A of applied primary current produce a flux density of 72.17G and suggested that the Hall effect sensitivity is 1.3 mV/G and, the Hall effect sensor produced an output voltage of 93.83 mV. However, the amplifier circuit amplified the voltage output, and the result is 2.06V. 5 different primary currents were applied to the system and result were obtained.

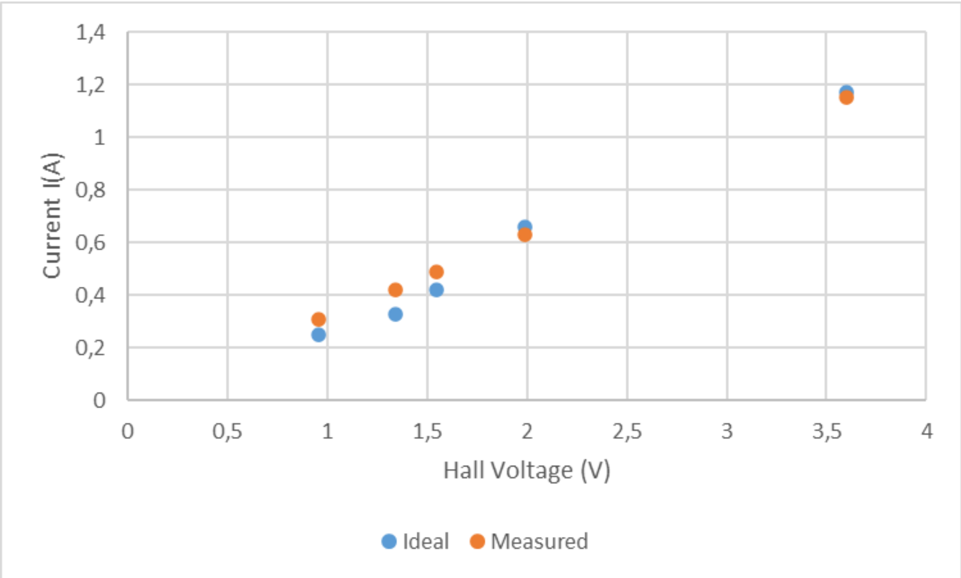

Figure 10 - Measured current vs output voltage of the amplifier circuit

In order to know the accuracy of the measurement, the relative error (RE) was calculated from the measured current and calculated current from ideal design used as reference (true value), as in equation:

$$RE = \left| \frac{I_{Measured} - I_{reference}}{I_{reference}} \right| x100\%$$

Figure 10 represents the measured current collected from interface with respect to the voltage output of the amplifier circuit. By using equation given above, the maximum relative error of the current measurement system was 21.43%. The table of the error calculation is given below:

Table 2 - Error calculation result

Reference Current	Measured Current	Relative Error (%)
0.25A	0.31A	19.35
0.33A	0.42A	21.43
0.42A	0.49A	14.28
0.66A	0.63A	4.76
1.17A	1.15A	1.74

When the error results were compared, one can understand that for higher current values the Hall sensor output is more stable, and the system can measure the current more correctly. The performance of the current measurement may be improved by choosing a better toroid core, hall sensor, and amplifier circuit.

The figures given below represents the measured current collected from the interface created by using MATLAB App.

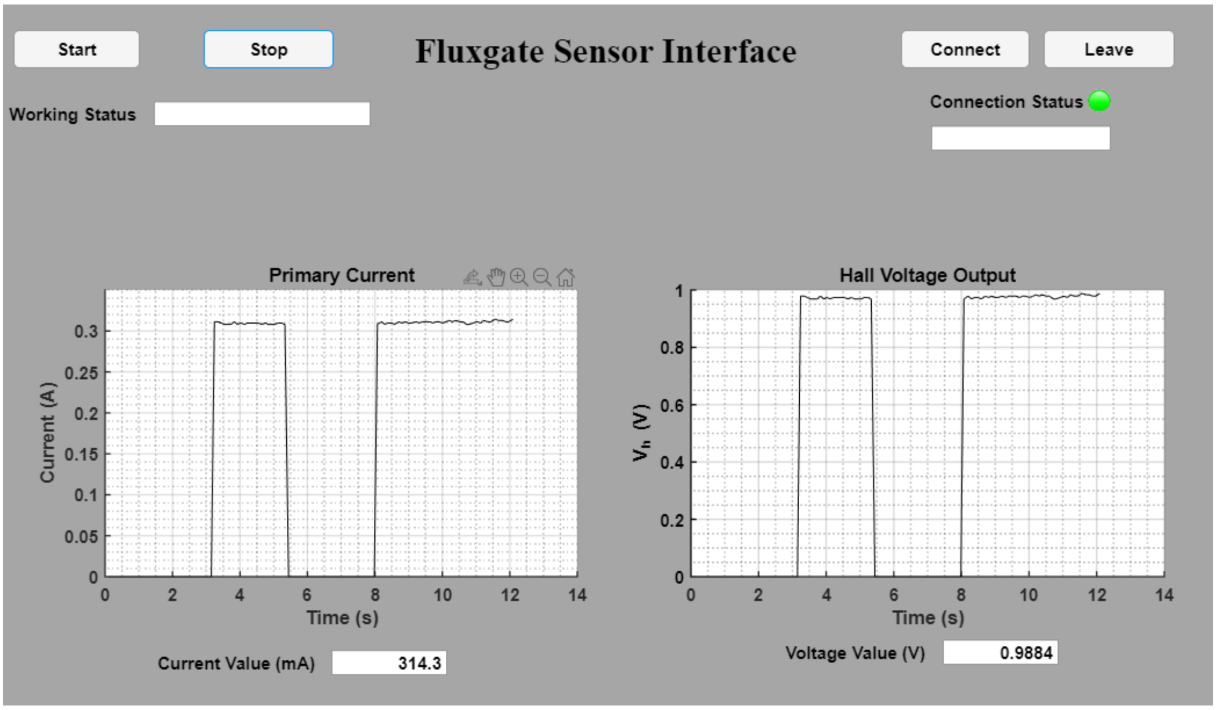

Figure 11 - Result of 0.25A reference

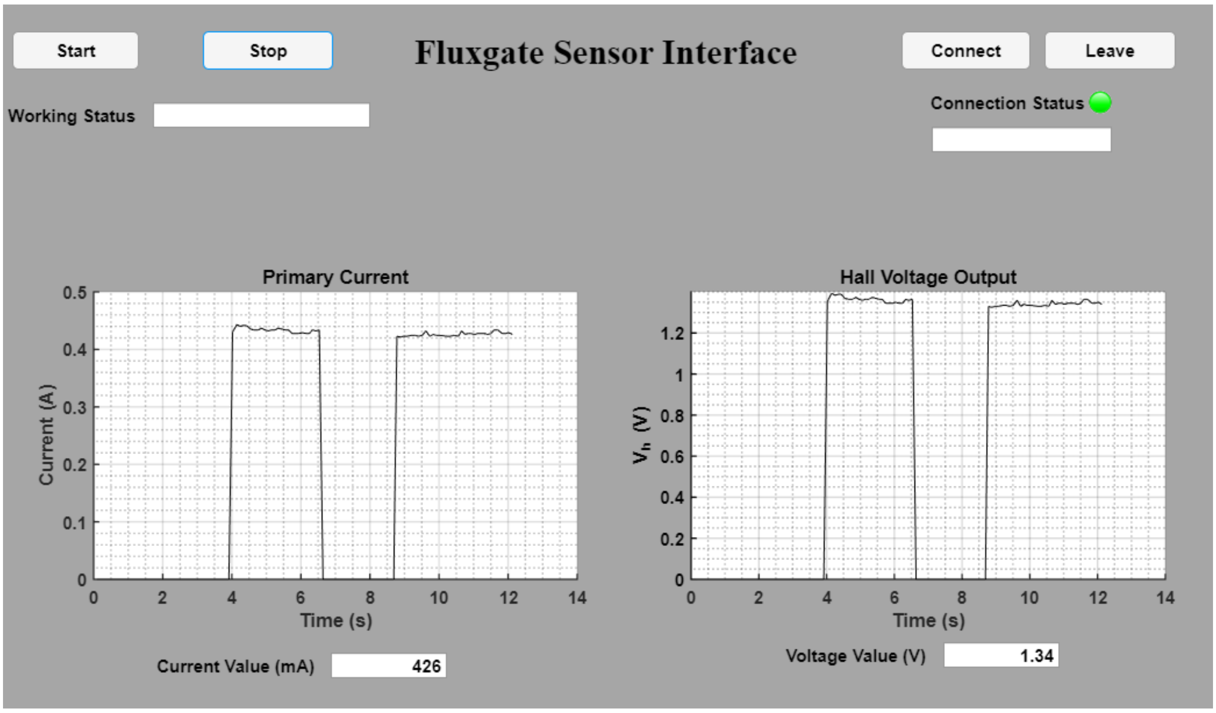

Figure 12 - Result of 0.33A reference

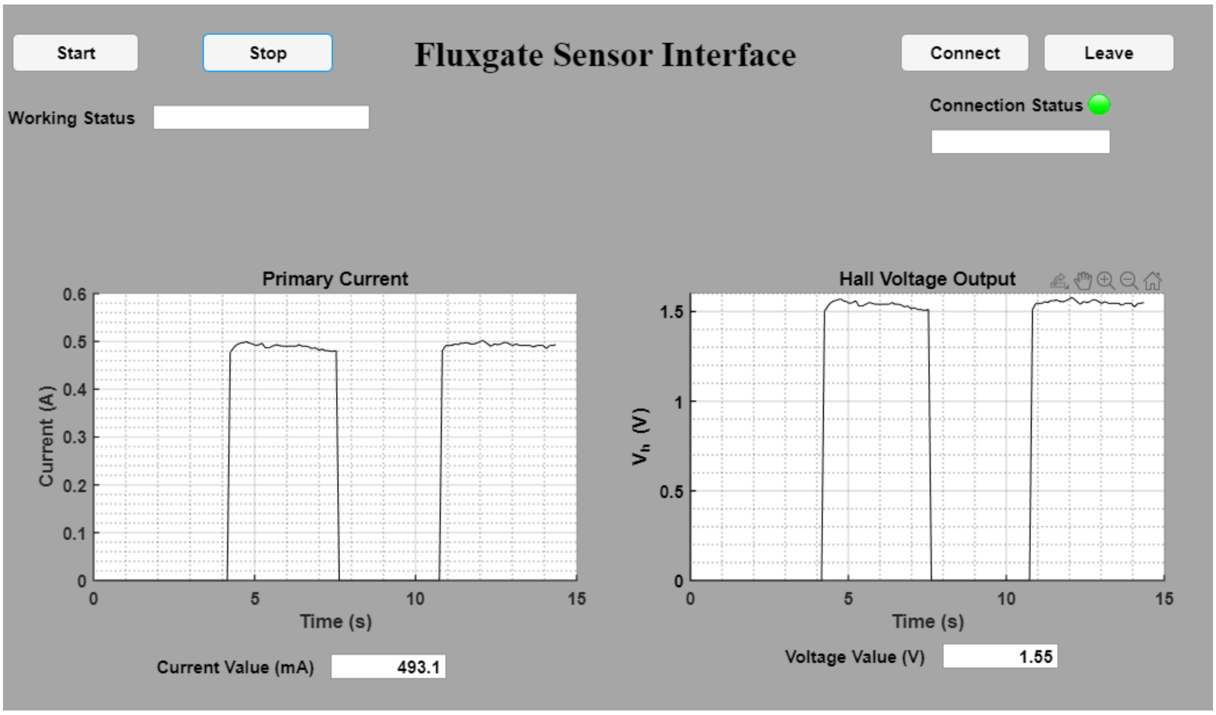

Figure 13 - Result of 0.42A reference

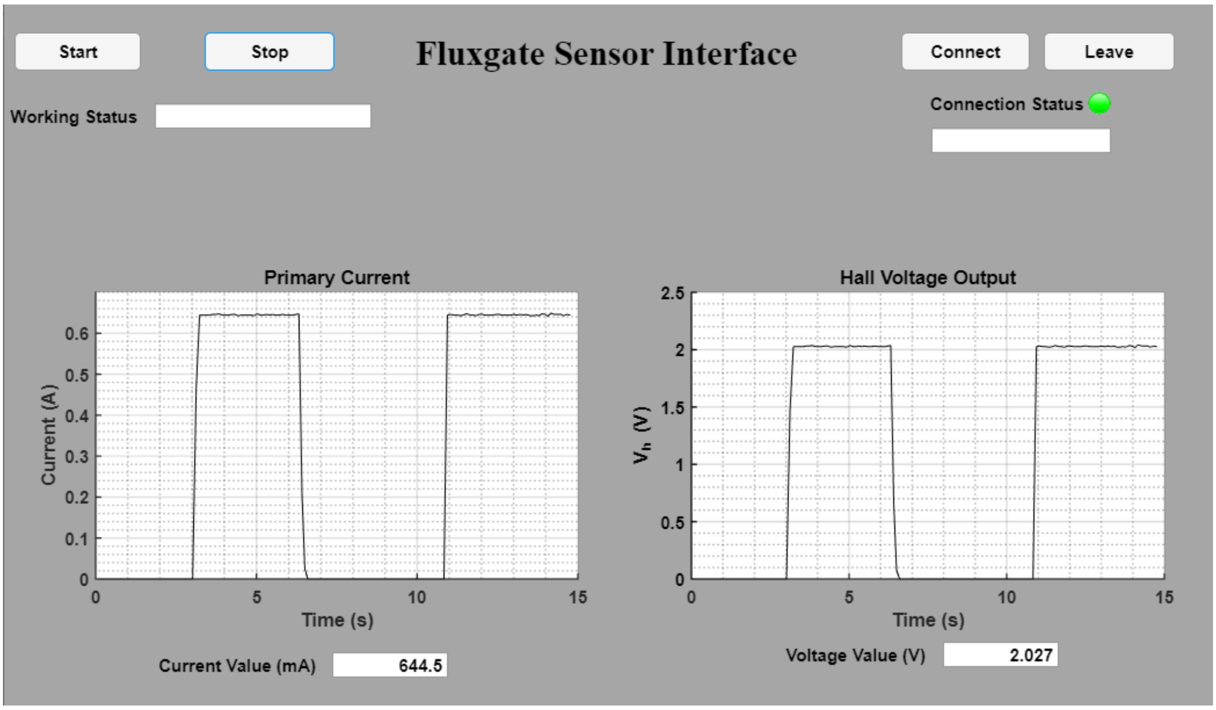

Figure 14 - Result of 0.66A reference

5) CONCLUSION

The fluxgate current measurement system was successfully created with the maximum current that can be measured at ±1A. The measurement results are displayed in MATLAB App interface on a PC in real-time graph, with 4.76% relative error of the system for 0.66A reference current.

6) REFERENCES

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