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Robust hall sensor signal conditioning for BLDC motor control using RC filters and optocoupler isolation

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ABSTRACT

Brushless DC (BLDC) motors require accurate rotor position feedback to guarantee reliable electronic commutation. However, hall-effect sensor signals are often degraded by high-frequency switching noise from the inverter, which can cause false commutations and control errors. Moreover, a direct connection to control hardware may introduce ground loops and jeopardize sensitive electronics. This study proposes a hardware-based hall signal conditioning method that integrates RC low-pass filters, designed with a 1.59 kHz cutoff frequency, to attenuate inverter-induced noise, and 4N35 optocouplers to provide galvanic isolation. Unlike existing approaches that rely primarily on algorithmic noise rejection or digital filtering, the proposed solution offers a compact, low-latency hardware implementation suitable for real-time embedded control. Experimental validation using a dSPACE DS1104 board shows a 14.7 dB improvement in signal-to-noise ratio (SNR) and a 36% reduction in timing jitter, ensuring clean and isolated hall signals for stable six-step commutation. These improvements directly translate into smoother torque production, enhanced speed stability, and increased protection of control electronics, making the method applicable to both research and industrial BLDC motor systems operating in noisy environments.

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1. INTRODUCTION

Brushless direct current (BLDC) motors have become essential in many industrial, robotic, and automotive applications, thanks to their high efficiency, long life, and low energy consumption under load [1], [2]. However, proper motor function depends on accurate rotor position control, which is usually achieved with hall-effect sensors. These sensors generate logic signals that are used to switch the motor phases. In an ideal theoretical setting, the transitions of these signals enable perfectly synchronized commutation, guaranteeing constant torque and stable rotation [3], [4]. However, in practical environments, these sensors can produce low-amplitude or corrupted signals, compromising the reliability of the control system and overall motor performance. In embedded systems or electrically noisy environments, signals from hall-effect sensors often have insufficient amplitude to be reliably detected by digital control circuits [5]-[7]. This phenomenon can be exacerbated by factors such as cable length, electromagnetic interference, or sensor power supply hazards. The result is switching errors, motor instability, increased energy losses, and, ultimately, reduced performance. However worthy of consideration software observation methods may be, they alone are not capable of ensuring the robustness required under real experimental conditions, where the quality of the input signal is a decisive factor [8]. Therefore, there is a gap in the literature regarding simple, low-cost, and efficient material solutions that can pre-condition the hall signal before it is numerically processed [9], [10]. Devices like optocouplers, operational amplifiers, or Schmitt trigger type comparators can ensure an efficient solution for amplifying and isolating such weak signals, but they are not exhaustively researched within the specific context of the BLDC motors.

In the literature, authors have devoted several works to improving the poor reliability of hall sensor signals in BLDC motor control systems. For example, Park *et al.* [11] presents an online strategy for estimating and compensating for switching errors due to poor hall sensor signals, based on phase current analysis for dynamic correction of the switching offset. On the other hand, Zhang and Lin [12] implemented an error compensation method for position errors using the least squares and back-EMF retroaction, with the aim to correct the effects of a bad signal sensor alignment or amplitude. Complementarily, research published on MDPI Energies [13] studied angular errors induced by low-resolution hall sensors and proposed a vector observer capable of producing more faithful sinusoidal control signals. Furthermore, Ebadpour *et al.* [14] put forward a compensation and diagnostic strategy including state analysis of hall signals and a velocity observer, to reconstruct a reliable signal in the event of sensor failure or loss. However, most of this work focuses on algorithmic or software solutions, and neglects physical signal processing, in particular electrical conditioning (filtering, amplification, isolation), which is essential in high-noise or low-power environments [15], [16]. It should be noted that, although there are many studies on algorithmic strategies for compensating for hall effect sensor defects, such as software correction of position errors, interference detection, or state observation, few address the major issue of hardware signal processing prior to digital conversion. In noisy industrial environments, purely software-based solutions reach their limits because they require a sufficiently clean and reliable input signal.

In view of this problem, the aim of the present work is to design and experimentally test a signal conditioning hardware solution capable of compensating for the low amplitudes of the signals supplied by hall-effect sensors. The aim is to propose a simple, reproducible architecture that can be integrated into a real control loop, guaranteeing the reliability of the logic transitions required for motor phase switching [17]. For this end, a solution comprising amplification, filtering, and galvanic isolation with the aid of optocouplers is created, then implemented and tested on a dSPACE DS1104 board. This work also seeks to compare the performance of the optimized system with that of conventional control design methodologies, in order to prove the practical benefits of material conditioning in the real context of BLDC motor control [18], [19].

This study presents a practical solution with an experimental prototype whose aim is to resolve the shortcomings of low-amplitude signals produced by hall-effect sensors, which are often the cause of malfunctions when addressing BLDC motors. The aim is to design a safe signal processing architecture, integrated into an integrated control chain and tested in a real-life environment. The remainder of the article is structured in the following manner: Section 2 presents the model and the mathematical representation of the BLDC motor. Section 3 gives the methodology employed in the design and implementation of the material and software solution, encompassing the conditioning of the signal and its integration on the dSPACE DS1104 card. Section 4 describes the experiment carried out and the results, highlighting the performance of the system developed compared with conventional methods. Finally, section 5 provides a critical analysis of the results and opens up prospects for future research, particularly in constrained environments, on the robustness and optimization of BLDC motor control systems.

2. MATHEMATICAL MODELING OF THE BLDC MOTORS

The equivalent model of the BLDC motor drive system, assuming a symmetrical three-phase stator winding, is shown in Figure 1 [20]. The terminal voltage equation for the three stator phases can be expressed as (1).

$$\begin{cases} V_a = Ri_a + L\frac{di_a}{dt} + e_a \\ V_b = Ri_b + L\frac{di_b}{dt} + e_b \\ V_c = Ri_c + L\frac{di_c}{dt} + e_c \end{cases} \tag{1}$$

The electromagnetic torque developed by the motor is given by (2).

$$T_{em} = \frac{e_a i_a + e_b i_b + e_c i_c}{\Omega} \tag{2}$$

Where V_a, V_b, V_c (V) are the voltages across the three-phase stator windings; i_a, i_b, i_c (A) are the corresponding phase currents; R (Ω) is the stator phase resistance; L (H) is the stator phase inductance; e_a, e_b, e_c (V) are the back electromotive forces (EMFs) for each phase; T_{em} (N.m) is the developed electromagnetic torque; and Ω (rad/s) is the rotor angular velocity.

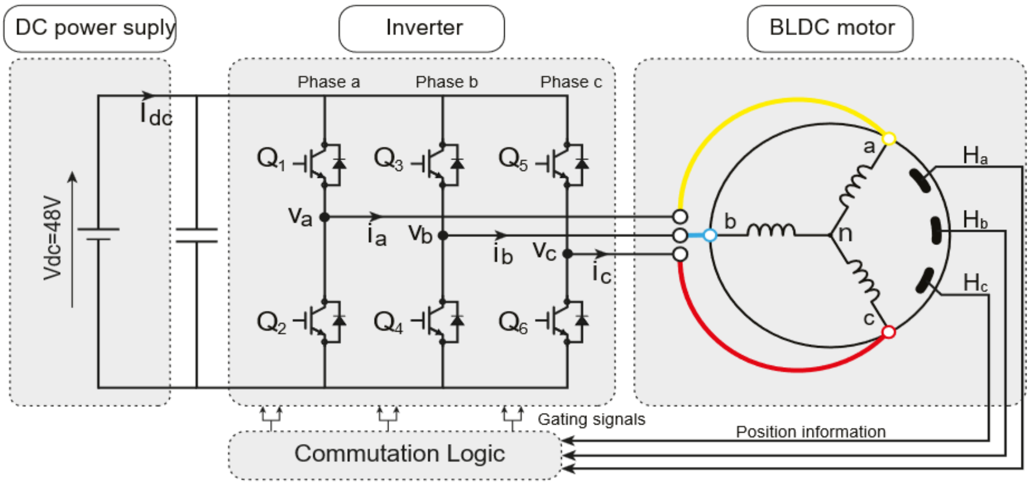


Figure 1. Diagram of the complete BLDC motor control bridge

3. METHOD

The objective of this section is to present the various methods, techniques, and algorithms used in this study. It is structured in two complementary parts. The first part is devoted to a presentation of the experimental approaches, the equipment used, and the justification of the hardware choices made, particularly in relation to the realization of the brushless motor commutation table. The second part describes the codes used. It also includes logograms of the algorithms used to power and control the BLDC motor.

3.1. Identification of the motor commutation table

This section presents the various experimental tests carried out to determine the commutation table and control algorithm for the brushless motor. The experimental architecture shown in Figure 2 was used for this analysis. To improve the quality of the signals from the hall-effect sensors, an active filtering solution based on an RC filter was implemented [21]. This selection was motivated by the need to eliminate high-frequency interference and attenuate rapid signal variations likely to disrupt the switching process. The RC filter used is a low-pass filter whose cut-off frequency is given by (3).

$$f_c = \frac{1}{2\pi RC} \tag{3}$$

Where R = 1 kΩ and C = 100 nF, giving a cutoff frequency of approximately $f_c \approx 1.59$ kHz. This frequency preserves the useful form of the signal and eliminates unwanted noise. Table 1 lists all the components used and experimental values, including optocoupler input and output resistances and filter parameters [22]. This filtering device enables more accurate signal acquisition by the mixed-signal digital oscilloscope, guaranteeing reliable identification of the switching sequence. The RC filter, with a cut-off frequency of 1.59 kHz, effectively eliminates interference while preserving the speed of hall signals. The 4N35 optocoupler, with a maximum transfer frequency of around 20 kHz, ensures reliable galvanic isolation without degrading signal dynamics. This choice guarantees clean, fast signal processing at the BLDC motor's operating frequency.

Table 1. Experimental values to be used

Symbol	Description	Value
R_L	Optocoupler output resistor	1.5 KΩ
R_{in}	Optocoupler input resistor	200 Ω
R	Filter resistor	1 KΩ
C	Filter capacity	100 nF

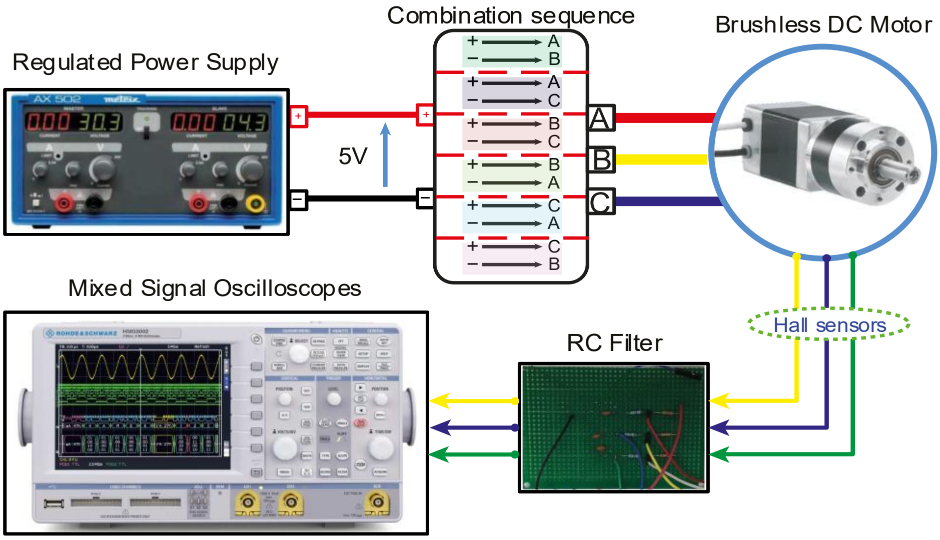


Figure 2. Experimental test for BLDC motor commutation table identification

3.2. Find the motor switchboard using an oscilloscope

The first test carried out as part of this study aims to detect the commutation table of the brushless DC motor (BLDC), based on the signals provided by the hall sensors integrated in the motor [23]. These generate three digital signals relating to the relative position of the rotor, making it possible to construct a binary combination coded on 3 bits. The results of this identification stage are shown in Table 2.

Table 2. Hall sensor 3-bit patterns mapped to commutation steps

Hall C	Hall B	Hall A	Commutation Step
0	0	1	1
0	1	1	2
0	1	0	3
1	1	0	4
1	0	0	5
1	0	1	6

3.3. Determining switching states for inverter control

This second experimental test enabled us to detect and confirm the six-step switching Table 3 used to drive the BLDC motor inverter. Each hall sensor configuration (CBA) is associated with a defined motor phase activation sequence (positive, negative or floating) and a pair of switches (Q1-Q6) to be activated. This table guarantees correct commutation according to rotor position, and thus stable, efficient motor operation [24].

Table 3. Phase switching for six-step commutation

Step	Hall Pattern (CBA)	Phase C	Phase B	Phase A	Commutateurs
1	001	+	-	Z	Q5 – Q4
2	011	+	Z	-	Q5 – Q2
3	010	Z	+	-	Q3 – Q2
4	110	-	+	Z	Q3 – Q6
5	100	-	Z	+	Q1 – Q6
6	101	Z	-	+	Q1 – Q4

3.4. Code in flowchart form

Figure 3 shows a flow chart of the switching algorithm implemented in MATLAB/Simulink to control a BLDC motor using hall sensors. The code first de-zeros the pulse width modulation (PWM) signals from the IGBT transistors to enable safe starting. It then reads the duty cycle values and hall sensor states (Ha, Hb, Hc), giving us the rotor position. The signals are converted to a position-dependent binary code (POS) of value 1 to 6, corresponding to the six switching states of a three-phase motor. Based on the read value from the POS, a respective configuration of IGBT transistors is enabled in order to create the suitable sequence of voltage for the motor phases so that the rotating field could be created. When there is an erroneous reading, the system automatically shifts to safe mode, disconnecting all the outputs. This type of algorithm guarantees commutation with the positioning of the rotor in a stable form, a requirement to drive BLDC motors [25], [26].

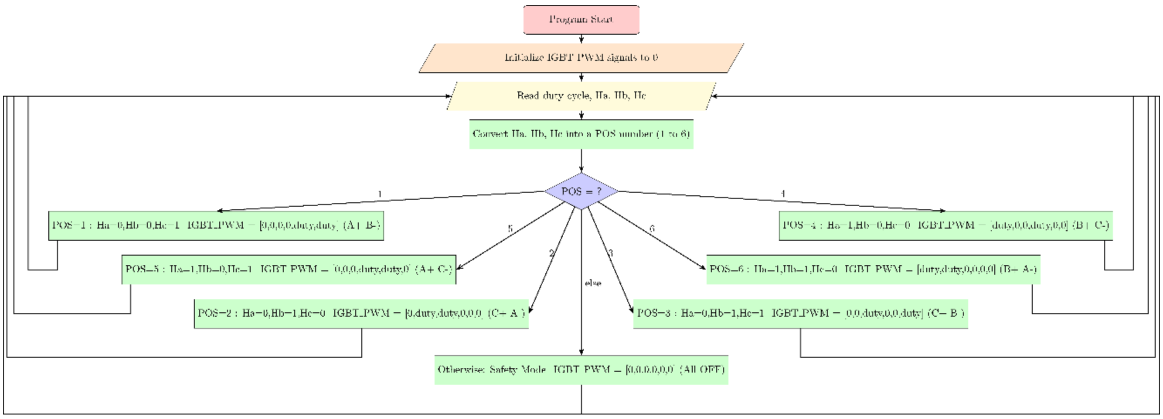


Figure 3. Flowchart of the code use

4. RESULTS AND DISCUSSION

4.1. System overview

Figure 4 shows the test bench set up for the experimental validation of the method for processing signals from hall effect sensors in a BLDC motor control system. This device consists of an EA-PS 9360-80 programmable power supply providing a 48 V DC voltage to a Semikron inverter, which powers the BLDC motor equipped with hall sensors. The signals from these sensors go through an optocoupler module and an RC filter before being fed into the dSPACE DS1104 card through a PWM card for acquisition and real-time processing under the MATLAB/Simulink and ControlDesk environment. This configuration allows for the faithful reproduction of real operating conditions, including electromagnetic disturbances due to power switching, in order to accurately evaluate the efficiency of the proposed conditioning solution. The set-up includes the following elements:

- Power supply: a programmable DC power supply model EA-PS 9360-80 delivering a stabilized voltage of 48 V with a maximum capacity of 80 A, used to power the inverter.
- Inverter (semikron box): converts DC voltage into the three-phase signals required for motor operation. The output terminals (A, B, C) are connected directly to the brushless motor.
- BLDC motor: the motor used is equipped with three integrated hall-effect sensors to detect rotor position. These sensors operate at a voltage of 5 V, with often noisy output signals.
- Signal conditioning: Hall sensor signals are first electrically isolated using a 4N35 optocoupler, then filtered and amplified by an active RC filter to eliminate noise and improve position detection quality.
- Acquisition and control: the conditioned signals are then sent to the dSPACE DS1104 board, which integrates a high-performance DSP to run the real-time control algorithm. This algorithm is developed in MATLAB/Simulink and automatically generated for the target hardware.
- User interface: dSPACE's ControlDesk software provides the human-machine interface, data acquisition, parameter setting, and real-time analysis of the system's dynamic behavior.

Tests were performed at different set speed values and load conditions to evaluate the robustness of the hall signal processing. The test bench presented here proves that the proposed solution is effective; hence, it perfectly integrates with the BLDC motor control chain.

4.2. Hall signal improvement

Figure 5 gives a comparative view of the signals from the hall-effect sensors before and after implementation of the proposed solution. Figure 5(a) reveals noisy, irregularly shaped signals, with a signal-to-noise ratio (SNR) measured at around 49%, indicating significant instability. Figure 5(b), on the other hand, shows a clear improvement after integration of the active RC filter and the 4N35 optocoupler, with perfectly square, stable signals and an SNR of almost 90%.

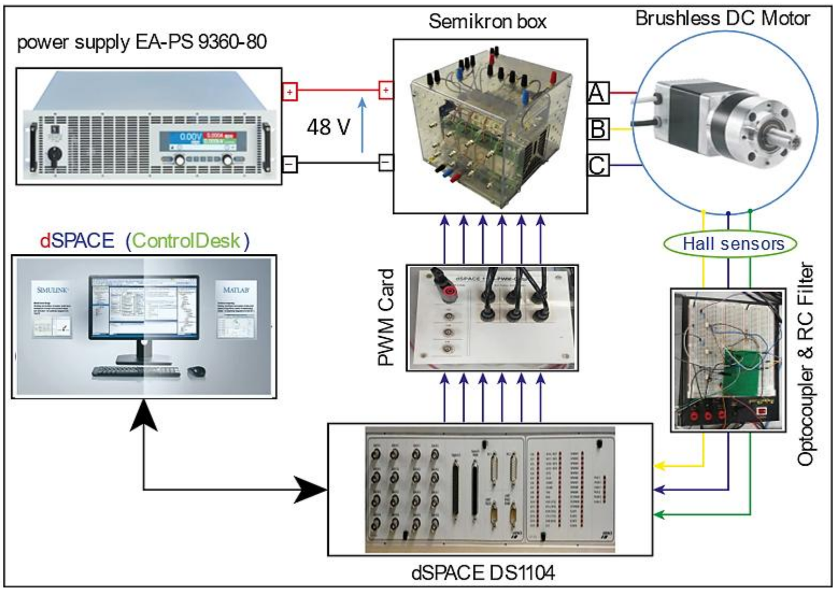
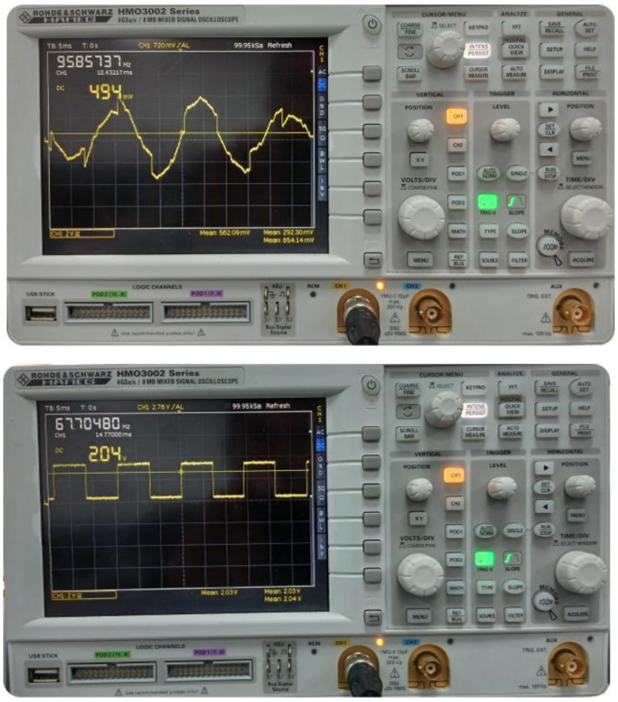


Figure 4. Operating diagram of a brushless motor with a modified solution

(a)



(b)

Figure 5. Hall-effect sensor signals before and after conditioning: (a) noise signals from hall sensors before processing and (b) stabilized signals after optoelectronic filtering

The summary of key indicators measured before and after treatment in comparative Table 4 below supports this observation. This significant improvement is due to the combined action of the 4N35 optocoupler isolating and protecting the control circuits from electrical disturbances, while the active RC filter eliminates the high-frequency interference that originally caused the distortion of the signals. This kind of architecture gives more reliability to rotor position detection and so improves the accuracy of speed control. Finally, the results obtained are consistent with those reported in previous studies on sensor signal filtering in BLDC motor control systems, while presenting a solution that is simpler and more economical to implement. These results provide a sound basis for future extensions, such as the use of adaptive digital filters or performance analysis under different load and speed conditions.

Table 4. Comparative analysis of sensor signal stability

Measured parameter	Before treatment (Figure 5(a))	After treatment (Figure 5(b))
Signal-to-noise ratio (SNR)	49%	90%
Jitter level	High	Low
Signal form	Distorted and noisy	Square and stable

4.3. Robust BLDC commutation through RC-filtered hall signals and dSPACE control

Figure 6 shows the signals obtained with the dSPACE DSP1104 board, highlighting the synchronization of the hall sensors and the PWM control signals applied to the IGBT switches of the three-phase inverter. The first three figures show the signals from hall sensors A, B, and C, which detect the rotor position with a typical phase shift of 120° electrical between them. These signals are crucial for identifying motor phase switching times. At the same time, the other six diagrams show the PWM signals that are generated to control the IGBT transistors (Q1 to Q6), evenly distributed over the inverter's upper and lower arms. These control signals are associated directly and synchronously with the logic state of the hall sensors, facilitating correct phase switching as a function of rotor position. The display also incorporates the duty cycle variation, in percent, which modulates the average voltage amplitude received by the motor and, consequently, the torque and speed of rotation. The overall results verify the consistency of operation between position sensing, control signal generation, and motor control. This experimental configuration based on the DSP1104 board, provides a stable environment for the implementation and real-time verification of elaborate BLDC motor control strategies, such as vector modulation or adaptive control.

- (Ha, Hb, Hc – hall sensors A, B, C): Indicate the rotor position at any given moment, allowing the IGBT activation sequence to be determined.
- IGBT PWM (Q1, Q2, Q3): PWM signals applied to the upper switches of each phase, synchronized with the hall signal transitions.
- IGBT PWM (Q4, Q5, Q6): PWM signals applied to the lower switches of each phase, also synchronized with the hall sensors.
- Duty cycle: Instantaneous value of the duty cycle applied to the PWMs, directly influencing the voltage and therefore the speed of the motor.

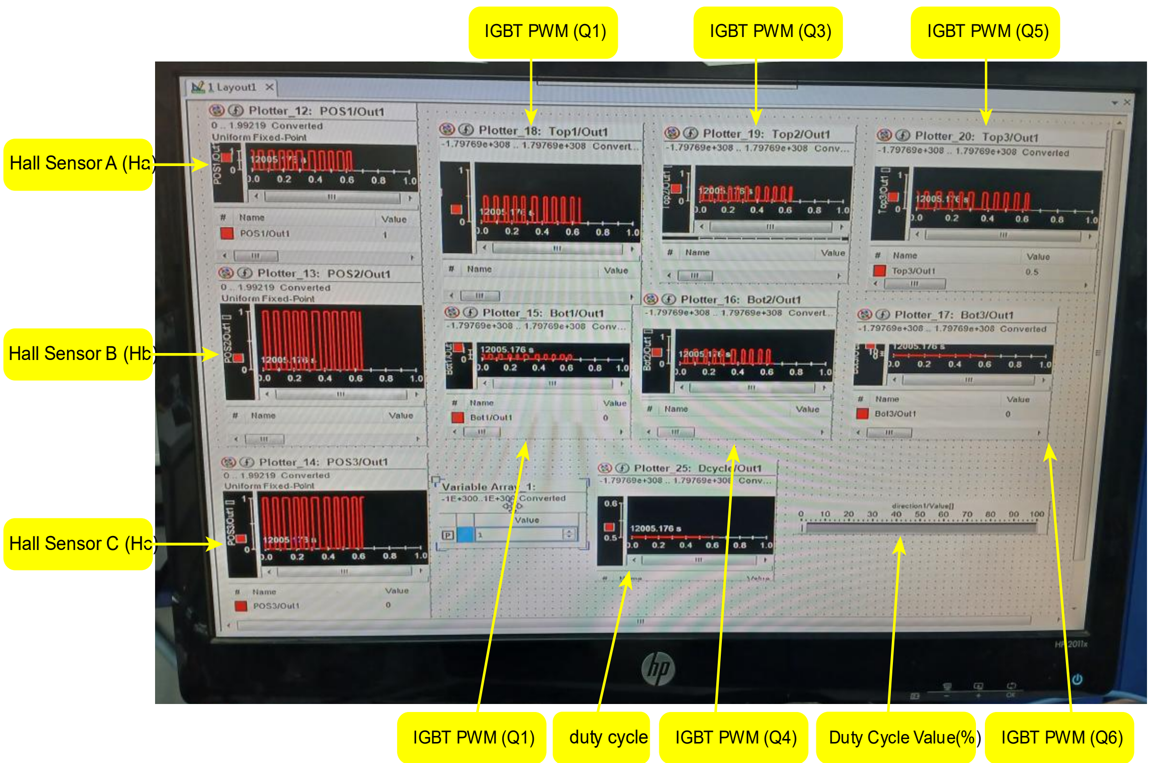


Figure 6. Signals acquired by the dSPACE card and ControlDesk

5. CONCLUSION

This research proposed an innovative experimental solution to compensate for periodic hall sensor signal faults in BLDC motor speed commutation. By combining a 4N35 optocoupler and an active RC filter, this hardware architecture was implemented and tested on a specific test bench, demonstrating a significant increase in the quality of switching signals and, consequently, in control precision. However, certain limitations have been identified, such as sensitivity to electromagnetic disturbances and the need for fine calibration of filters according to different engine operating modes. These observations pave the way for promising developments, such as the integration of adaptive digital filters capable of adjusting in real time to changing conditions, or the use of intelligent control strategies, such as fuzzy controllers or predictive controls. Outside the experimental environment, this hardware methodology offers a rigid, adaptable, and potentially maintainable, reconfigurable foundation for the requirements of embedded systems in fields as diverse as industrial automation, electric vehicles, and robotics. To this end, this study makes an important contribution to increasing the robustness of BLDC control chains, calling for further research into miniaturization, integration logic, and overall performance of filter systems for large-scale practical implementation.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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El Fadil Hassan	✓	✓	✓	✓		✓	✓			✓	✓	✓	✓	
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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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