International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 16, No. 1, March 2025, pp. 106~116
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v16.i1.pp106-116

Rounding function-based zero crossing detection for a sensorless BLDC motor control

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Article Info

Article history:

Received Jul 3, 2024
Revised Sep 12, 2024
Accepted Oct 23, 2024

Keywords:

BEMF sensing
BLDC motor
Feedback circuit
Rounding function
Sensor less control
Zero crossing

ABSTRACT

Permanent magnet brushless DC (PMBLDC) motors are favored for their low maintenance, high reliability, and efficiency, making them ideal for industrial, domestic, military, aerospace, and robotics applications. Sensor less control is the most preferred technique for PMBLDC motors due to its reliability and cost-effectiveness, eliminating the need for physical sensors. A crucial aspect of sensor less control is accurately detecting the point of zero crossing of the back electromotive force (BEMF) signals. Traditional methods, such as rotor position estimation, input observers, and AI-based strategies, can suffer from high ripples and computational inefficiencies. This paper introduces an approach using the rounding function to determine the point of zero crossing, aiming to enhance precision and reduce computational overhead. The rounding function converts continuous BEMF signals into discrete signals, minimizing ripples and facilitating accurate zero-crossing detection. This method improves detection accuracy while simplifying computation demands. Validation was performed through a MATLAB Simulink simulation and an experiment using the F28379D microcontroller, gate driver, and a six-switch inverter. The results demonstrate the effectiveness of the proposed approach, showing agreement between experimental and simulation outcomes.

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1. INTRODUCTION

Permanent magnet brushless DC or PMBDC motors are widely used for various applications due to their high speed, low maintenance, small size, and reliability. Typically, PMBLDC motors rely on Hall effect sensors for rotor position detection enabling commutation. This commutation sequence is essential for strategizing different control techniques for PMBLDC motors, as noted in [1]-[9]. However, having sensors increases overall cost, complexity, and potential reliability issues. To overcome the drawback of sensor-based control, sensor less control techniques, which estimate rotor position using electrical signals such as BEMF, have garnered significant attention. Back electromotive force or BEMF is the voltage generated by the rotating motor, which is proportional to the rotor speed and can be used to infer the rotor's position.

A critical aspect of sensor less control is accurately detecting the zero-crossing point of the BEMF signals. Several methods for detecting BEMF zero-crossing have been proposed and explored through simulations. For instance, zero-crossing detection using pulse width modulation (PWM) was explored by [10], who developed a technique that detects rotor position through PWM-based zero-crossing detection to drive the motor. To enhance position estimation, flux linkage estimation was studied by [11], who integrated converter-fed power factor correction with flux linkage to achieve a precise switching pattern. Building on these approaches, observer-based BEMF techniques were employed by [12], utilizing terminal current sensors and DC bus voltage for sensor less control, calculating both speed and rotor position via line-to-line voltage. Similarly, [13] proposed a hybrid adaptive neuro-fuzzy inference system (ANFIS)-based particle swarm optimization (PSO) method to determine BEMF zero-crossing from terminal voltage, where PSO iteratively adjusts ANFIS properties to minimize the error between sampled output and actual training data. Further advancements in rotor position estimation include artificial neural networks (ANN)-based multilayer perceptron method [14], which effectively determines rotor position using artificial neural networks. Subsequently, [15] introduced a three-phase phase-locked loop (PLL) strategy. enabling continuous rotor position prediction without reliance on zero-crossing points.

Despite the advancements in sensor less control techniques, challenges remain, particularly in terms of accuracy, complexity, and performance at low speeds. Existing techniques often struggle with accurate zero-crossing detection, especially under varying operating conditions. For instance, performance issues at high speeds have been observed, as [16] reported satisfactory results with a method that compares zero-crossing with the voltage neutral point but noted performance delays at higher reference speeds. Likewise, accuracy and complexity challenges have been highlighted by researchers [17]-[20] who explored techniques such as unknown input observers and third harmonic BEMF. These methods, however, often struggle with accuracy and require significant computational resources. Additionally, real-time validation issues have been a focal point in the studies conducted by [21]-[25]. These investigations revealed difficulties in detection at low speeds and the necessity for high computational power, further complicating real-time implementation. Consequently [26], worked on rotor position estimation at a full stop aimed to improve efficiency using the saturation effect of the stator. To curtail some of these issues, a compensation technique to overcome commutation error due to conduction loss and fluctuation current using line voltage feedback was implemented by [27]. while rounding function-based zero crossing detection used for a single-phase AC signal was demonstrated in [28] but an error was observed in the phase-shifting.

In response to these challenges, this paper introduces a rounding function technique to address the issues of motor starting problems, detection inaccuracies, and computational complexity. This technique senses the BEMF feedback by using the rounding function, effectively mitigating noise and providing an accurate zero-crossing detection. This simplifies the detection process by converting continuous BEMF signals into discrete forms, reducing computational complexity. A real-time experiment was implemented using a comparator feedback circuit for zero-crossing detection, aiming to improve precision and efficiency. Section 1 introduces, and reviews related work based on the problem-solving process, section 2 of this paper discusses the system description, the introduced technique is discussed in section 3, the results and discussion are given in section 4, and section 5 is the conclusion.

2. PMBLDC MOTOR MODELLING AND SYSTEM DESCRIPTION

The three-phase PMBLDC motor is represented using an analytical model, assuming the iron core saturation effect and homogeneous air gap are neglected. The standard driving strategy is the three-phase six-switch configuration, with six insulated-gate bipolar transistors (IGBTs) S_1, S_3, and S_5 on the high side and S_2, S_4, and S_6 on the low side as shown in Figures 1 and 2 respectively. The voltage in (1)-(3) are outlined considering the three-phase neutral point N of the Y-connected windings.

$$V_{AN} = R_s i_A + L\frac{di_A}{dt} + M\left[\frac{di_B}{dt} + \frac{di_C}{dt}\right] + e_A \tag{1}$$

$$V_{BN} = R_s i_B + L\frac{di_B}{dt} + M\left[\frac{di_A}{dt} + \frac{di_C}{dt}\right] + e_B \tag{2}$$

$$V_{CN} = R_s i_C + L\frac{di_C}{dt} + M\left[\frac{di_A}{dt} + \frac{di_B}{dt}\right] + e_C \tag{3}$$

The (1) through (3) can then be expressed in matrix form as in (4).

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BC} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \tag{4}$$

Let the (5),

$$L_{AB} = L_{AC} = L_{BA} = L_{BC} = L_{CA} = L_{CB} = M \tag{5}$$

where the mutual and self-inductances are denoted, respectively, by L and M. The (5) can be used in place of (4) to obtain the (6).

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \tag{6}$$

Consequently, the equation for a three-phase current can be defined by (7).

$$i_A + i_B + i_C = 0 \tag{7}$$

The inductance matrix of the system can alternatively be shown as in (8).

$$Mi_B + Mi_C = -Mi_A \tag{8}$$

Hence, the (9)-(12).

$$V_{AN} = R_s i_A + (L - M)\frac{di_A}{dt} + e_A \tag{9}$$

$$V_{BN} = R_s i_B + (L - M)\frac{di_B}{dt} + e_B \tag{10}$$

$$V_{CN} = R_s i_C + (L - M)\frac{di_C}{dt} + e_C \tag{11}$$

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \tag{12}$$

E_A, E_B, and E_C are the phase back-EMFs, while V_{AN}, V_{BN}, and V_{CN} are the phase voltages, and phase current are represented as i_A, i_B, and i_C. The phase resistance is equal and represented as R_S, for a symmetrical phase winding.

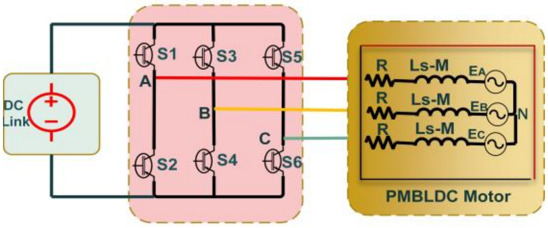

Figure 1. Inverter topology

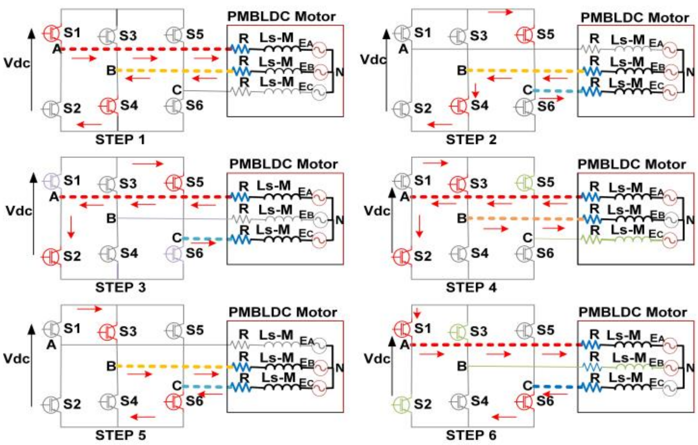

Figure 2. Commutation sequence

3. ROUNDING FUNCTION BASED ZERO CROSSING DETECTION

In PMBLDC motors, rotor position information is crucial for precise voltage regulation via the inverter, dictating which switches are activated. Traditionally, Hall sensors are used, but this work proposes a sensor less control approach, which infers rotor position through algorithms and electrical measurements. The common method for sensor less control involves detecting BEMF, which correlates with rotor speed and position. The introduced technique uses a rounding function to process BEMF signals using a ceiling function. The ceiling function, which records a real number to the smallest following integer, effectively transforms the BEMF signal into a discrete form. Thereby simplifying zero-crossing detection. This method is cost-effective and reduces computational complexity compared to traditional techniques. The rounding function accurately detects zero-crossing points of the three-phase trapezoidal BEMF signal. This innovative approach improves sensor less PMBLDC motor control by ensuring accurate and efficient operation. Figure 3 shows the complete model in MATLAB/Simulink, while Table 1 shows the switching patterns.

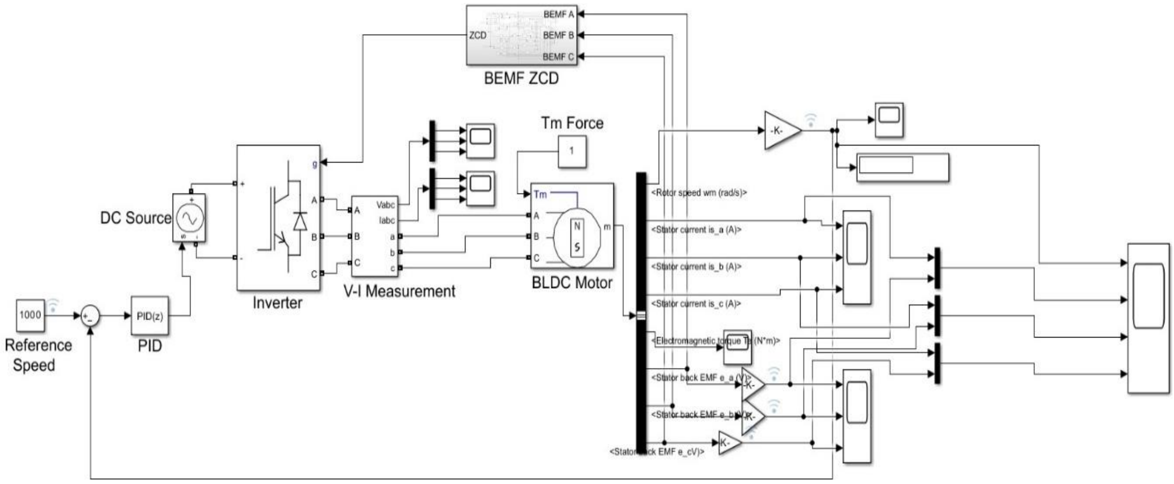

Figure 3. Complete model

Table 1. Switching patterns

Steps	Switches	Active phases	Silent phase
1	S_1S_4	AB	C
2	S_5S_4	CB	A
3	S_5S_2	CA	B
4	S_3S_2	BA	C
5	S_3S_6	BC	A
6	S_1S_6	AC	B

3.1. Laboratory setup

A real-time experiment was conducted to justify the introduced technique. The setup consists of a Genfan 3-blade propeller fixed to the rotor to test the smoothness and performance of the 24 V PMBLDC motor with parameters shown in Table 2 and a DC link source. The main controller is a C2000 piccolo TMS320F28379D microcontroller coupled to a 3P.Si8272.V1.2 gate driver connected to a three-phase six-switch inverter and a BEMF feedback detection circuit made of the voltage divider and op-amp as arranged in Figure 4. The voltage and current are measured using a fluke multimeter, differential probe and CC-800 current probes respectively. The resultant output was observed and recorded with a Tektronix (MDO3024) digital oscilloscope, while the speed of the motor was recorded utilising the tachometer.

3.2. Zero crossing detection circuit

Zero crossing detection is essential in controlling a PMBLDC motor, specifically in sensor less control applications. The detection circuit demonstrated in Figure 5 helps establish the precise moments when the BEMF crosses zero volts, indicating the correct timing for commutation. Here, a zero-crossing detection circuit using a comparator, and resistor is employed and illustrated in Figure 6. The detection circuit using a comparator was chosen because it displays an output signal similar to that produced by the rounding function.

Table 2. Motor parameters

Parameters	Values	Units
Rated voltage	24	V
Rated speed	1000-3000	RPM
Rated torque	2	Nm
Number of poles	8	-
Phase resistance	2.7850	Ohms
Phase inductance	0.000835	H
Voltage constant	44.8867	V.peakL-L/Krpm
Torque constant	0.42864	Nm/A peak
Flux linkage	0.0535795	Vs

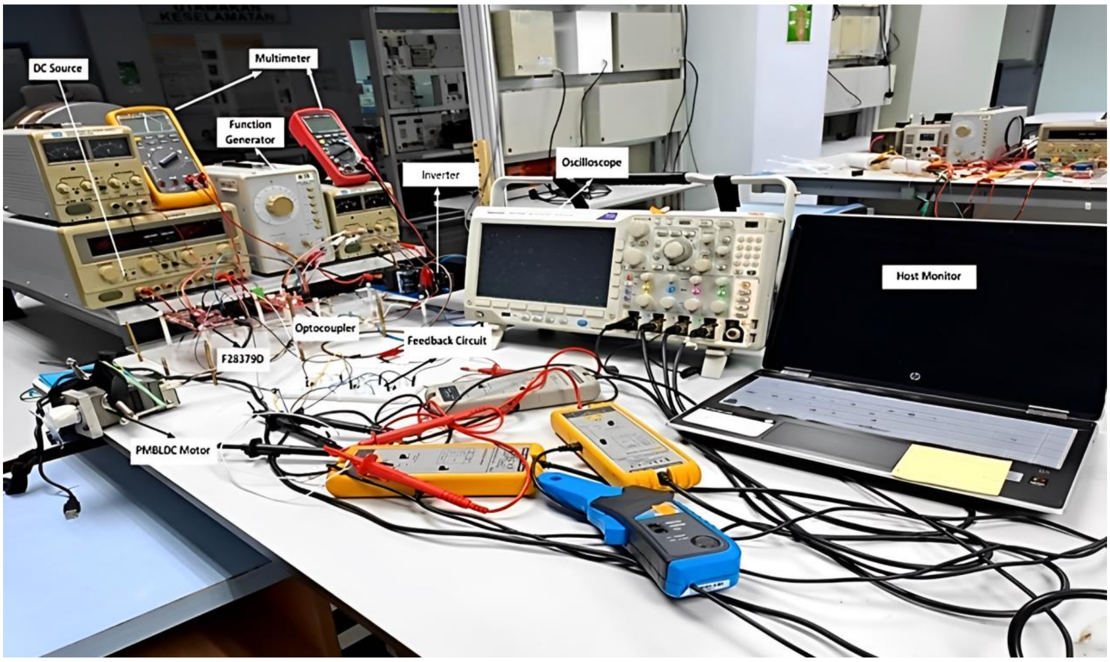

Figure 4. View of the experiment setup

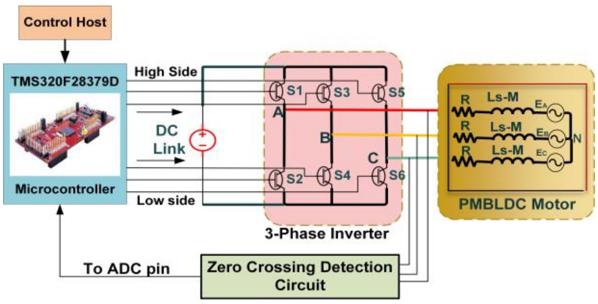

Figure 5. Sensorless control scheme

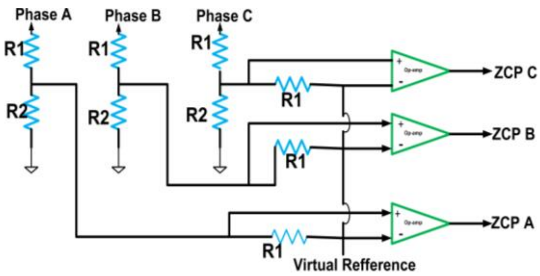

Figure 6. Feedback circuit

The voltage divider reduces the feedback of the BEMF voltage from the motor windings to a required value needed by the op-amp and ADC, the voltage divider formula can be deduced as in (13):

$$V_o = V_i \times \frac{R_2}{R_1+R_2} \quad (13)$$

where V_o is the voltage divider output, V_i is the voltage of motor terminals, while R_1 and R_2 are the values of resistors 1 and 2 respectively. The op-amp employed as a comparator compares the BEMF voltage from the voltage divider to a reference voltage. The comparator changes its output state when the BEMF crosses zero, indicating the zero crossing. The output signal from the op-amp is connected to the ADC pin of the microcontroller. This work demonstrates the zero-crossing point detection using a function generator GAG 809 used to inject a sinusoidal signal comparing the comparator output to the sinusoidal signal to ascertain the point of zero crossing.

3.3. BEMF detection

To detect the BEMF, the floating phase detection technique was employed, this involves monitoring the BEMF of the non-energized (floating) phase, while the other two phases are actively driven. A PMBLDC motor typically has three phases (A, B, and C), and at any given time, one phase is floating (not connected to the power supply), while the other two phases are energized. This strategy involves obtaining the zero crossing of the BEMF by comparing the motor terminal voltage to the neutral point. If the motor neutral point is unavailable, a virtual neutral point is built to sample the terminal voltage of the floating phase as illustrated in Figure 7.

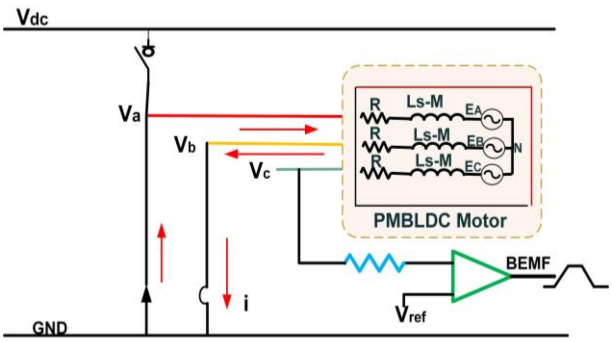

Figure 7. BEMF detection scheme

4. RESULTS AND DISCUSSION

For demonstration purposes, a sinusoidal signal is utilized and compared with the rounding function output signal to confirm the point of zero crossing detection (ZCD) for the three-phase systems as shown in Figure 8. A 24 V DC link voltage was applied to the inverter and a 2 Nm load torque was applied to serve as the motor load. The proposed technique exhibits good reference tracking as indicated in Figure 9 and it was able to minimize computation complexity.

To ensure precision, and to confirm that the three-phase currents are in phase with the BEMF signal, the signals were matched as shown in Figure 9. In the physical experiment, a zero-crossing feedback circuit was built and investigated before connection to the ADC pin for PWM synchronization. The accuracy of zero-crossing detection is shown in Figure 10.

The phase A current waveform illustrates the six switching commutations, while the line-to-line voltage is the difference between any two phases of a motor, having three phases A, B and C. Subsequently, measurement was taken between phases V_{AB}, V_{CA} and V_{BC} consecutively as demonstrated in Figure 11. In this approach, the control utilizes a six-step commutation energizing the phases in pairs for 120° each within a 360° electrical cycle leading to three distinct steps.

The commutation of a PMBLDC motor phase voltage has six switching sequences because of the nature of the commutation method employed in trapezoidal control. The commutation process, otherwise known as 120° commutation, is a technique where motor phases are sequentially energized to drive the motor as a result of a rotating magnetic field created. Here, the process occurs in six steps in one electrical cycle 360°, each corresponding to 60 electrical degrees. Likewise, the phase voltage and current must be in phase. This configuration confirms that the electrical supply to the motor is converted effectively to mechanical energy. Phase voltage and current are compared ensuring they are in phase as shown in Figure 12. The most precise technique for estimating the BEMF is measuring the floating phase. Figure 13 illustrates phase C BEMF, and the currents I_A and I_B respectively. Whereas, Figure 14 indicates waveforms of the comparator output and currents.

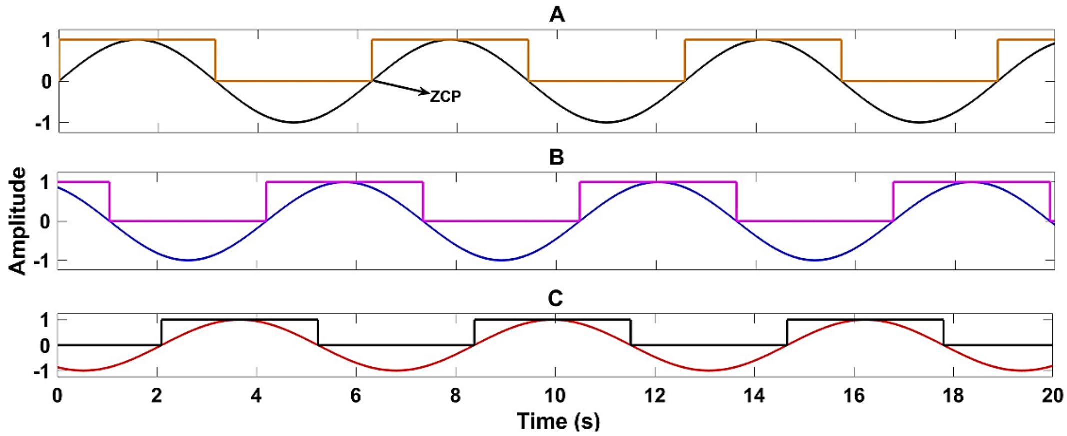

Figure 8. Three-phase ZCD

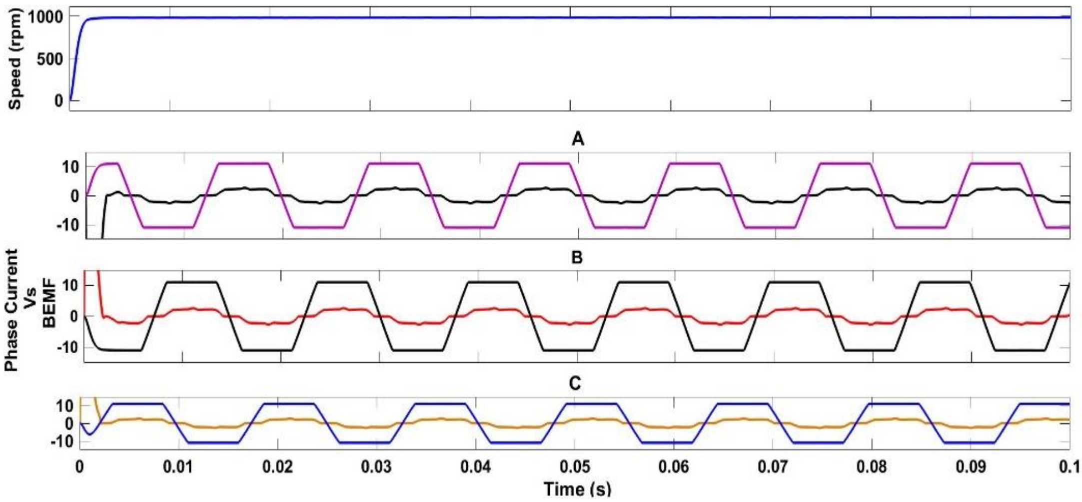

Figure 9. Speed, BEMF A, B, C, and phase current

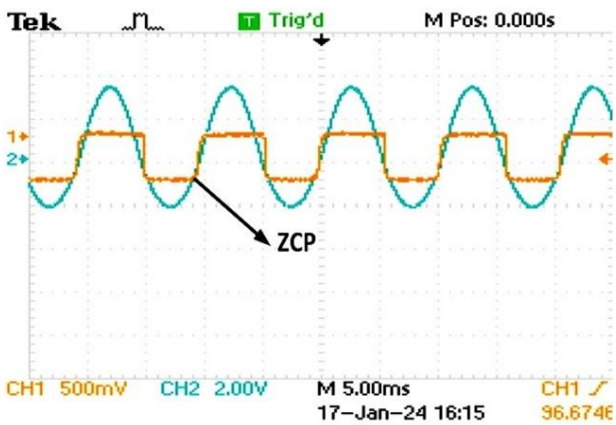

Figure 10. Zero crossing point

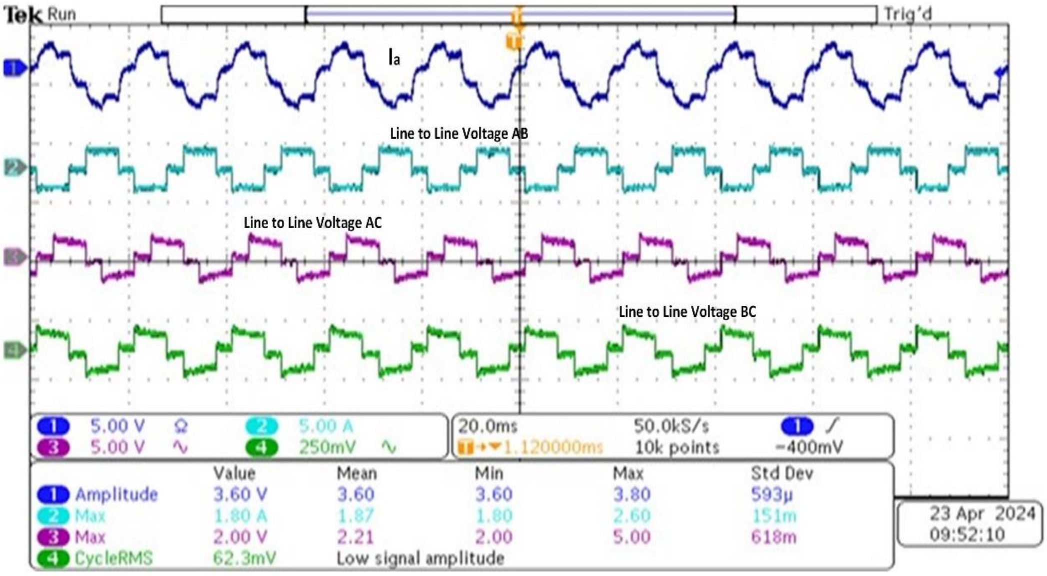

Figure 11. Motor terminal voltage and currents

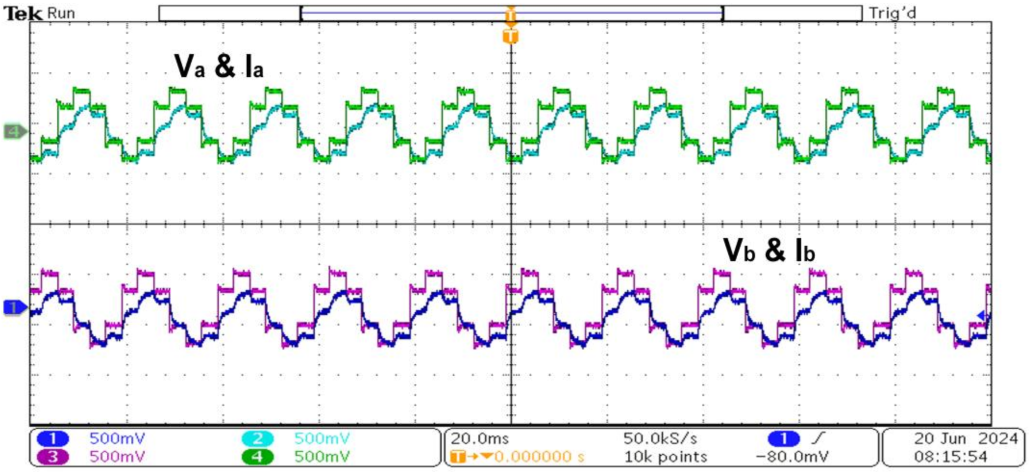

Figure 12. Phase A and B voltage and current in phase

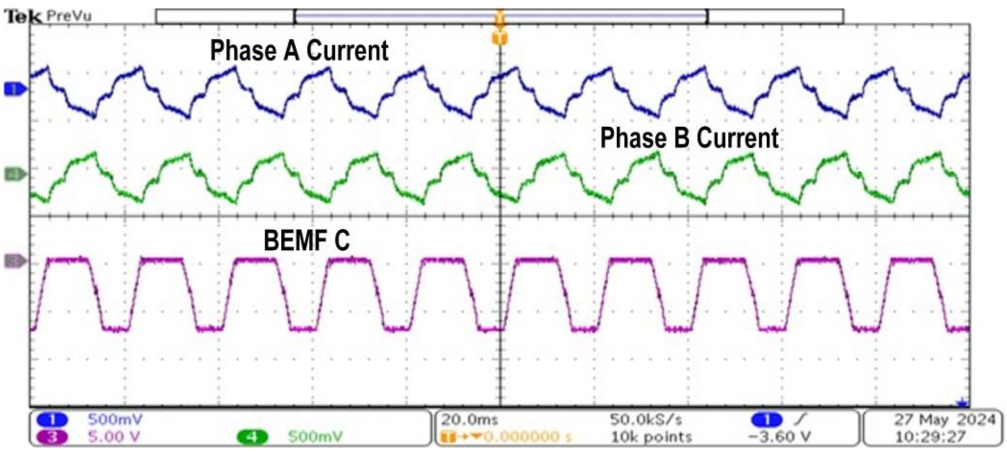

Figure 13. BEMF C and currents Ia and I_b,

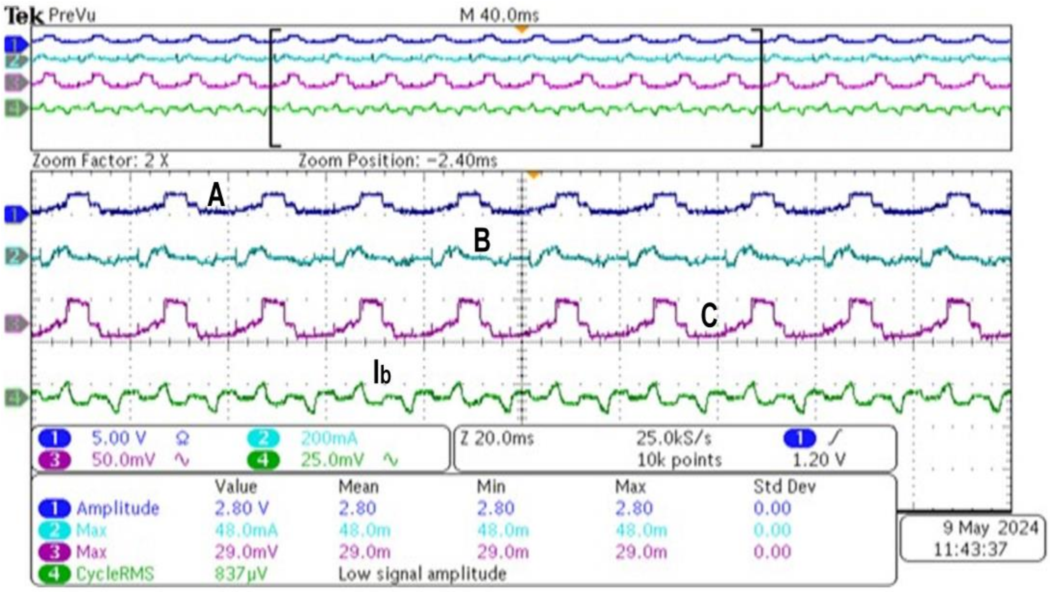

Figure 14. Comparator output A, B, C, and current I_b

5. CONCLUSION

Conclusively, the rounding function-based zero-crossing detection technique offers a robust, efficient, and adaptable solution for PMBLDC motor control, reducing noise and enhancing precision and computational efficiency. Validated through simulation and physical experiments, this technique accurately detects rotor position by employing a feedback circuit with an op-amp and resistors. The BEMF detection is embedded in a microcontroller, which integrates with an optocoupler and inverter for effective motor control. Sensor less control is simulated in MATLAB/Simulink, while the CCS platform was used to run the motor in physical experiments. Simulation and real-time results are in agreement. Future work will optimize the algorithm further and explore advanced control strategies for broader applications.

ACKNOWLEDGEMENTS

The authors would like to thank Universiti Sains Malaysia and Petroleum Technology Development Fund of Nigeria for providing the financial support under research grant project no: 203.PELECT.6071509.

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