Discrete-Time Observer Based Nonlinear Control for a BLDC Motor

S. Rezaei, M. Ghahestani, N. S. Gogani, M. Ehsani, V. Behnamgol, R. Barzamini, B. Sohani

Abstract— **Controlling brushless DC motors enhances their efficiency and accuracy. Recently, the nonlinear control of these motors has garnered significant attention from researchers. This article presents the extraction of the nonlinear model of a brushless DC motor and the conversion of three-phase coordinates to d-q space, leading to the design of a nonlinear controller and a discrete-time observer. To maximize efficiency, a linear feedback nonlinear controller is designed to control the current along the d-axis, while a feedback nonlinear controller is used to control the shaft angle. The shaft position controller utilizes load torque estimation information. The developed observer is designed in discrete time to estimate system states and load torque. Software and processor in the loop simulation results confirm the performance of the observer-based control system. Additionally, the discrete-time nature of the observer facilitates easy implementation, and the article concludes with the results of the controller implementation based on the proposed observer and the processor in the loop simulation.**

I. INTRODUCTION

Brushless DC (BLDC) motors have become increasingly popular and are now a key focus of research, thanks to their notable advantages such as compact design, high efficiency, minimal maintenance needs, robust performance, reliability, and a superior torque-to-weight ratio. These motors are now commonly integrated into a wide range of industrial and domestic technologies, including robotics, electric transportation, military systems, aerospace, manufacturing, ventilation systems, tumble dryers, and refrigerators. However, despite their widespread adoption, several critical challenges remain that limit their full potential in industrial and commercial settings. Issues such as limited fault tolerance, electromagnetic interference, audible noise, magnetic flux fluctuations, and torque irregularities continue to hinder their overall reliability and lifespan. To overcome these challenges, implementing closed-loop vector control strategies has emerged as a promising solution for enhancing the performance of BLDC motors [1, 2].

Linear controllers, including PID, are simple and effective and are widely used to adjust the performance of motors, including BLDC motors [3, 4]. A BLDC motor represents a complex, highly coupled nonlinear dynamic system [5]. In real-world scenarios, mechanical load characteristics—such as friction and inertia—can vary with the nature of the applied load. As a result, relying solely on linear control methods often falls short of delivering optimal performance [6]. To improve the performance of PID controllers for BLDC motors, we can refer to Fuzzy-PID controllers [7] and the modified firefly algorithm-particle swarm optimization-based fractional order PID [8]. In [9], a nonlinear control strategy for managing radial position and motor torque in a bearingless BLDC motor is proposed, utilizing feedback linearization theory. To address speed fluctuations in small BLDC motors operating under varying load conditions, a Sliding Mode Controller was introduced in [10]. Additionally, [11] explores a discrete-time sliding mode control technique enhanced by particle swarm optimization, aimed at improving the performance of BLDC motors in electric vehicle applications. Sliding mode control is a robust method for controlling uncertain systems, particularly in power electronics systems such as electric motors and generators [12]. When implemented on a microprocessor with a fixed sampling interval, true sliding mode control cannot be fully realized. Instead, a quasi-sliding mode arises, whose characteristics are analyzed in [13]. The ideal sliding surface becomes a finite sliding region, often represented as a sector. The dimensions of this sector are influenced by factors such as the sampling period and the magnitude of the switching gains.

Using an observer to estimate non-measurable information, including load torque, can improve the closed-loop control system of motors [14]. If a disturbance observer is used, it is better to design it in a discrete-time form to avoid the need to readjust the gains during its implementation in the processor. For example, in the design of discrete-time observers, the choice of sampling time is considered from the beginning of the design stage, making implementation easier [15, 16].

The purpose of this paper is to control the position of brushless direct current motors based on the extended observer. For this purpose, a non-linear feedback controller will be used. The back-stepping control method is very useful when some states are controlled by other states in nonlinear cascade systems [17]. This is why the back-stepping algorithm is used to control some motors, such as permanent magnet synchronous motor speed [18]. Load torque can affect control accuracy. Therefore, an observer will be used to estimate this variable. For ease of implementation, the proposed observer is designed in discrete-

Samaneh Rezaei has a MSc from Department of Electrical and Computer Engineering, MUT University, Tehran, Iran (e-mail: samrezai1994@gmail.com).

Mina Ghahestani is a PhD student of Science and Research Branch, Islamic Azad University, Tehran, Iran (email: mina.ghahestani@iau.ac.ir)

Nazanin Seyed Gogani is a PhD student of Islamic Azad University, Damavand, Iran (e-mail: n.seyedgogani@iau.ac.ir).

Mohsen Ehsani has a PhD from Islamic Azad University, Damavand, Iran (e-mail: Ehsani.Mohsen.bbb@gmail.com).

Vahid Behnamgol is a researcher at energy research center of Islamic Azad University, Damavand, Iran. Corresponding Author (e-mail: vahid_behnamgol@damavandiau.ac.ir).

Rohollah Barzamini is an assistant professor of Central Tehran Branch, Islamic Azad University, Iran (email: barzamini.eng@iauctb.ac.ir).

Behnaz Sohani is an assistant professor of Wolfson School of Mechanical, Electrical & Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK (e-mail: b.sohani@lboro.ac.uk).

time form, and at the end of the implementation, the processor will be in the loop.

In the second part of the article, the mathematical model of the motor will be discussed. In the third part, the controller and observer used in this research are described and presented, and the simulation and implementation results will be presented in the fourth and fifth parts. Finally, the conclusion will be presented in the sixth section.

II. MOTOR MODEL

In [20], a discrete model of a brushless motor is introduced. The model of the motor in the form of a vector matrix in the state space is as follows:

$$i_q(k+1) = i_q(k) + T\left[\frac{V_q}{L} - \frac{R}{L}i_q(k) - p i_d(k)\omega(k) - \frac{p\lambda}{L}\omega(k)\right] \quad (1)$$

$$i_d(k+1) = i_d(k) + T\left[\frac{V_d}{L} - \frac{R}{L}i_d(k) - p i_q(k)\omega(k)\right] \quad (2)$$

$$i_0(k+1) = i_0(k) + T\left[\frac{V_0}{L} - \frac{R}{L}i_0(k)\right] \quad (3)$$

$$\omega(k+1) = \omega(k) + T\left[\frac{3p\lambda}{2J}i_q(k) - \frac{b}{J}\omega(k) - \frac{T_L}{J}\right] \quad (4)$$

$$\theta(k+1) = \theta(k) + T\,\omega(k) \quad (5)$$

The list of symbols is presented in Table 1.

TABLE I. LIST OF SYMBOLS USED IN THE MOTOR MODEL

Abbreviation	Parameter
R	Coil resistance
J	Inertia
b	Coefficient of friction
L	Self-inductance
P	Number of motor poles
λ	Flux
T	Sampling time
ω	Angular velocity
θ	Angle
i_q,i_d	Motor currents in dq coordinates

Equations (1) to (3) represent the currents converted from three-phase abc state to dq0 state. Equation (4) describes the angular velocity, and equation (5) is the mechanical angle of the motor in discrete state.

III. CONTROLLER AND OBSERVER DESIGN

A. Shaft Angle Controller

To control the angle of the motor shaft, we use a feedback controller. In this case, we will have three subsystems for control. The first stage starts with the innermost subsystem. In this step, to reach the desired angle, we define the error function as:

$$e_1 = \theta_d - \theta \quad (6)$$

To check stability, we first consider the function (7) as the Lyapunov function:

$$v_1 = \frac{1}{2}e_1^2 \rightarrow \dot{v}_1 = e_1\dot{e}_1 = e_1\left(\dot{\theta}_d - \omega\right) \quad (7)$$

The control input from the first subsystem can be calculated as:

$$\omega_d = k_1 e_1 + \dot{\theta}_d \quad (8)$$

The second step of the back-stepping method begins with the introduction of the error function:

$$e_2 = \omega_d - \omega \quad (9)$$

The Lyapunov function includes the error functions of the first and second stages:

$$v_2 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 \rightarrow \dot{v}_2 = e_1(\dot{\theta}_d - \omega) + e_2\left(k_1\dot{e}_1 + \ddot{\theta}_d - \dot{\omega}\right) \quad (10)$$

The control input of the second stage contains the desired value i_{qd} as:

$$i_{qd} = \frac{2J}{3P\lambda}\left(k_2 e_2 + \frac{e_1}{e_2}\dot{\theta}_d - \frac{e_1}{e_2}\omega + k_1\dot{e}_1 + \ddot{\theta}_d + \frac{b}{J}\omega + \frac{T_L}{J}\right) \quad (11)$$

Tracking error in third stage is introduced as:

$$e_3 = i_{qd} - i_q \quad (12)$$

By defining the error function according to the above equation, the Lyapunov function of the third step is given by:

$$\begin{aligned} v_3 &= \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{1}{2}e_3^2 \rightarrow \\ \dot{v}_3 &= e_1\left(\dot{\theta}_d - \omega\right) + e_2\left(k_1\dot{e}_1 + \ddot{\theta}_d - \dot{\omega}\right) \\ &+ e_3\left(\frac{2k_2 J}{3P\lambda}\dot{e}_2 + \frac{\dot{e}_1 e_2 - \dot{e}_2 e_1}{e_2^{\,2}}(\dot{\theta}_d + \omega)\right. \\ &+ \frac{e_1}{e_2}(\ddot{\theta}_d - \dot{\omega}) + k_1(\ddot{\theta}_d - \dot{\omega}) + \theta_d^{(3)} \\ &\left. + \frac{b}{J}\dot{\omega} + \frac{\dot{T}_L}{J} - \frac{V_q}{L} - \frac{R}{L}i_q - \frac{P\lambda}{L}\omega - P i_d\omega\right) \end{aligned} \quad (13)$$

The control input of the third stage is the same control input applied to the motor to control the shaft angle, which obtains the desired value V_{qd} from the Lyapunov function of the third stage:

$$V_{qd} = L\Bigg(k_3 e_3 + \frac{e_1}{e_3}\left(\dot{\theta}_d - \omega\right) + \frac{e_2}{e_3}\left(k_1 \dot{e}_1 + \ddot{\theta}_d - \dot{\omega}\right)$$
$$+ \frac{2k_2 J}{3P\lambda}\dot{e}_2 + \frac{\dot{e}_1 e_2 - \dot{e}_2 e_1}{e_2^{\,2}}(\dot{\theta}_d + \omega) + \frac{e_1}{e_2}(\ddot{\theta}_d - \dot{\omega}) \tag{14}$$
$$+ k_1(\ddot{\theta}_d - \dot{\omega}) + \theta_d^{(3)} + \frac{b}{J}\dot{\omega} + \frac{\dot{T}_L}{J} - \frac{R}{L} i_q - \frac{P\lambda}{L}\omega - P i_d \omega \Bigg)$$

We calculate the discrete form of the controller equation:

$$V_{qd}(k) = L\Bigg(k_3 e_3(k) + \frac{e_1}{e_3}\left(x_2(k) - \omega(k)\right)$$
$$+ \frac{e_2}{e_3}\left(k_1 x_1(k) + x_3(k) - \frac{3P\lambda}{2J} i_q(k) + \frac{b}{J}\omega(k) + \frac{T_L}{J}\right)$$
$$+ \frac{2k_2 J}{3P\lambda} x_5(k) + k_1\left(x_3(k) - \frac{3P\lambda}{2J} i_q(k) + \frac{b}{J}\omega(k) + \frac{T_L}{J}\right)$$
$$+ x_4(k) + \frac{x_1(k)e_2(k) - x_5(k)e_1(k)}{e_2^{\,2}(k)}(x_2(k) + \omega(k)) \tag{15}$$
$$+ \frac{e_1}{e_2}\left(x_3(k) - \frac{3P\lambda}{2J} i_q(k) + \frac{b}{J}\omega(k) + \frac{T_L}{J}\right)$$
$$+ \frac{b}{J}\left(\frac{3P\lambda}{2J} i_q(k) - \frac{b}{J}\omega(k) - \frac{T_L}{J}\right) + \frac{R}{L} i_q(k) - P i_d(k)\omega(k) \Bigg)$$

The gain coefficients k_1, k_2, k_3 of the feedback controller are adjusted to achieve the desired value of the position. According to the presented Lyapunov stability theory, the controlling coefficients should be positive $k_1, k_2, k_3 > 0$.

B. d-Axis Current Controller

According to the mentioned principles and the desire to maintain torque without reducing it and eliminating the interference effect, the current component in the d direction should be zero to create maximum efficiency. For this purpose, we use a linear feedback controller. Equation (16) represents the current state equation in the d axis:

$$\frac{d}{dt} i_d = \frac{V_d}{L} - \frac{R}{L} i_d - p i_q \omega \tag{16}$$

The above state equation is a nonlinear equation of the motor states. Using the linear feedback controller theory, we remove the nonlinear parts and then design the controller for the linearized system. The nonlinear part of the above equation is included $p\, i_q \omega$, which we control by removing it and using a simple controller:

$$V_d = R i_d - P\omega i_q - k_4 i_d \tag{17}$$

The linearizer feedback controller equation (17) is applied to system equation (16). The gain range of the linear feedback generator is as $k_4 > 0$. According to the linearizer feedback controller designed in equation (17), it can be seen that no derivative or integration operation has been done, so its discrete form is as follows:

$$V_d(k) = R i_d(k) - P\omega(k) i_q(k) - k_4 i_d(k) \tag{18}$$

C. Load Torque Observer

To design the discrete-time observer, the system model considered for the observer should first be written in discrete-time form:

$$\begin{cases} \omega(k+1) = \omega(k) + T\left[\dfrac{3p\lambda}{2J} i_q - \dfrac{b}{J}\omega - \dfrac{T_L}{J}\right] \\ T_L(k+1) = T_L(k) \end{cases} \tag{19}$$

Now we need to design the extended discrete-time observer for this discrete-time system. The discrete form is designed as follows:

$$\begin{cases} \hat{\omega}(k+1) = \hat{\omega}(k) + T\left[\dfrac{3p\lambda}{2J} i_q(k) - \dfrac{b}{J}\hat{\omega}(k) - \dfrac{\hat{T}_L}{J}\right] \\ \quad + L_1(\omega(k) - \hat{\omega}(k)) \\ \hat{T}(k+1) = L_2(\omega(k) - \hat{\omega}(k)) + \hat{T}(k) \end{cases} \tag{20}$$

With the design, it is necessary to check the stability of the observer using the dynamics of the observer error. To check the dynamics of observer error, the difference between the actual and estimated value should be calculated. Assuming a discrete system in the form:

$$\begin{cases} x(k+1) = \hat{A}\hat{x}(k) + \hat{B}u(k) + L(y(k) - \hat{y}(k)) \\ y(k) = C\hat{x}(k) \end{cases} \tag{21}$$

To properly determine the matrix L, it is necessary to check the dynamic error of the observer:

$$e(k) = x(k) - \hat{x}(k) \tag{22}$$

$$e(k+1) = x(k+1) - \hat{x}(k+1) \tag{23}$$

$$\begin{aligned} &e(k) = x(k) - \hat{x}(k) \\ &e(k+1) = \hat{A}e(k) + (A - LC - \hat{A})x(k) + (B - \hat{B})u(k) \end{aligned} \tag{24}$$

$$\begin{cases} \hat{A} = A - LC \\ \hat{B} = B \end{cases} \tag{25}$$

According to the explanations provided in the observer design section using pole placement, for the stability of a discrete system, it is necessary to place all the eigenvalues of the matrix $\hat{A} = A - LC$ inside the unit circle.

IV. NUMERICAL SIMULATION RESULTS

The simulation results of the loop model are presented in this section. The load torque is estimated using the proposed discrete-time observer. Considering an arbitrary position, the back-stepping controller for proper positioning in the presence of the TL load and the linearizer feedback controller for zeroing the direct current d, with the aim of creating maximum efficiency for the motor model, are applied. The sampling time is 5 milliseconds, and the values of motor parameters are listed in Table 2.

TABLE II. MOTOR PARAMETER VALUES

Value	Symbol	Motor Parameters
1.02	R	Coil resistance
0.004	J	Inertia
0.0049	b	Friction coefficient
0.0086	L	Self-inductance
4	P	Number of bridges
0.07	λ	Flux

Figure 1 shows the estimation of load torque using continuous and discrete-time observers. It can be seen that this variable was estimated with appropriate accuracy and in a short period of time. The difference between the estimation made using the continuous-time observer and the discrete-time observer is evident. Therefore, considering that in the implementation stage, the information of the discrete-time observer should be used, it is better to use the same observer in the design and simulation stage and adjust the controller gains based on the discrete-time estimation.

In the following, by using continuous-time and discrete-time estimation information and by applying feedback and linear feedback controllers, the position and speed of the motor shaft and the current in the direction d in Figures 2 to 4 and the control signals issued in Figures 5 and 6 have been drawn. In these figures, the effect of using discrete-time estimation in output control and the difference of control signals in the case of using continuous-time estimation and discrete-time estimation is evident.

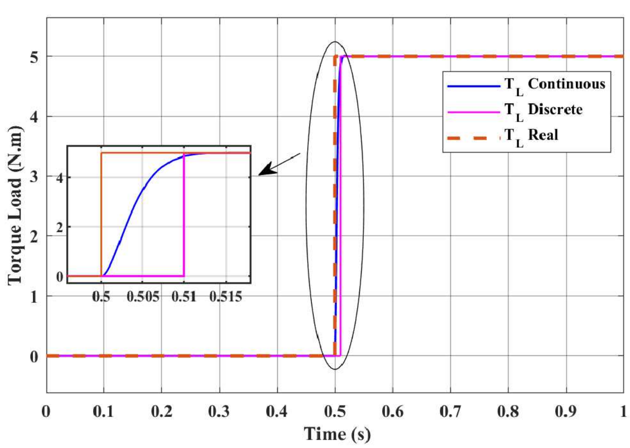

Figure 1. Estimation of Load Torque Using Continuous-Time and Discrete-Time Observers

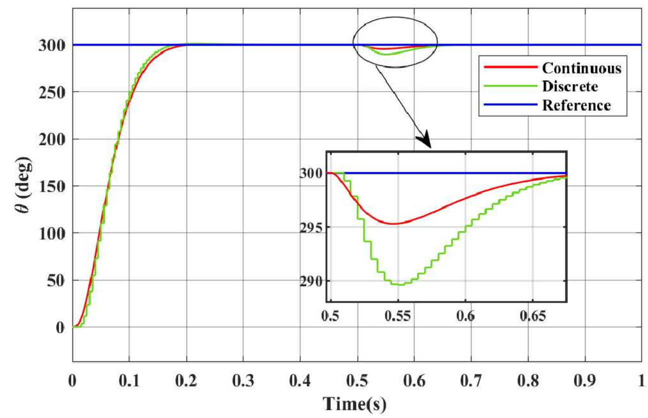

Figure 2. The Angular Position of the Shaft by Applying the Backstepping Controller Based on Continuous-Time and Discrete-Time Observers

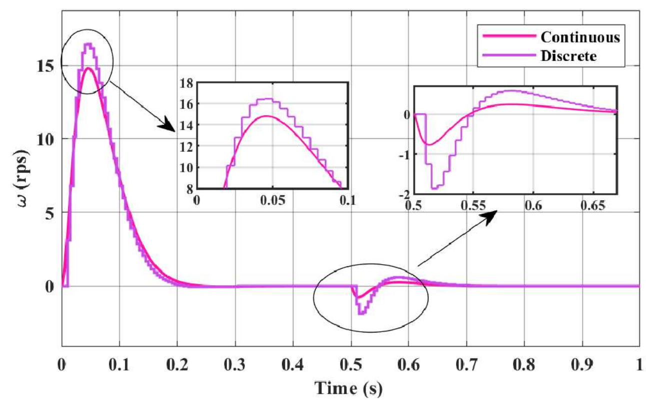

Figure 3. Angular Speed of the Shaft by Applying Backstepping Controller Based on Continuous-Time and Discrete-Time Observers

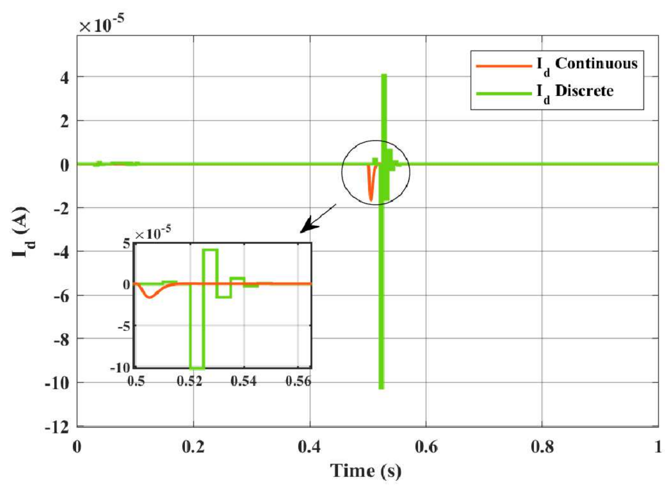

Figure 4. d-Axis Current by Applying Linearizer Feedback

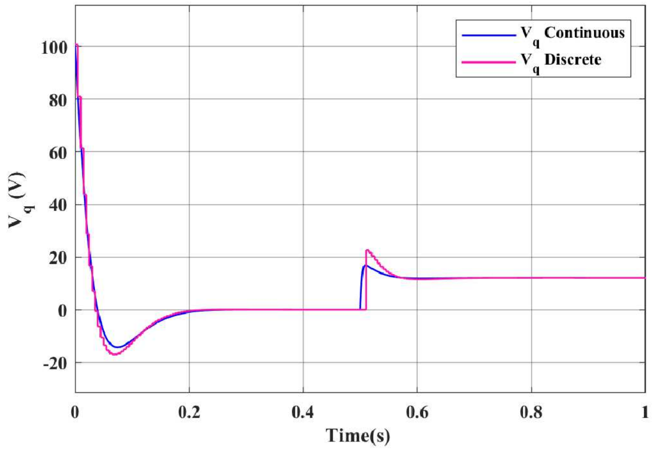

Figure 5. The Vq Control Signal Issued by the Feedback Controller Based on Continuous-Time and Discrete-Time Observers

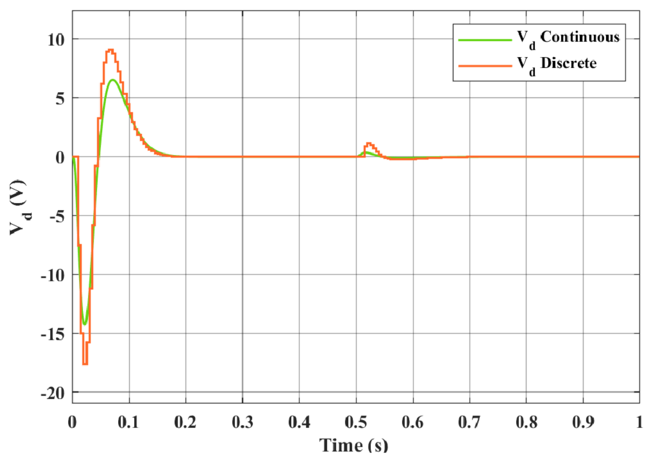

Figure 6. Control Signal Vd Issued by Linearizer Feedback Controller

V. PROCESSOR IN THE LOOP SIMULATION RESULTS

Simulating the processor in the loop requires the discretization of continuous equations and the design of the discrete-mode controller and determining the appropriate sampling time to connect the processor with the operating system. It is a communication protocol to implement UART. By placing the controller code on the processor and communicating with MATLAB software, the results are as follows.By applying the voltage signal issued by the feedback controller based on the observer that is drawn in Figure 7, the angular position of the shaft follows the desired position as seen in Figure 8. Also, by applying the voltage signal issued by the linear feedback controller that is drawn in Figure 9, the current in the d direction converges to zero as seen in Figure 10. According to Figure 10, it can be seen that the d-axis current has moved away from the zero value and then this error has been compensated and controlled. This behavior is not observed in the simulation, and this problem is due to the absence of a delay in applying the controller signal to the system dynamics. By making the communication delay time smaller, the amount of divergence in the error will be smaller.

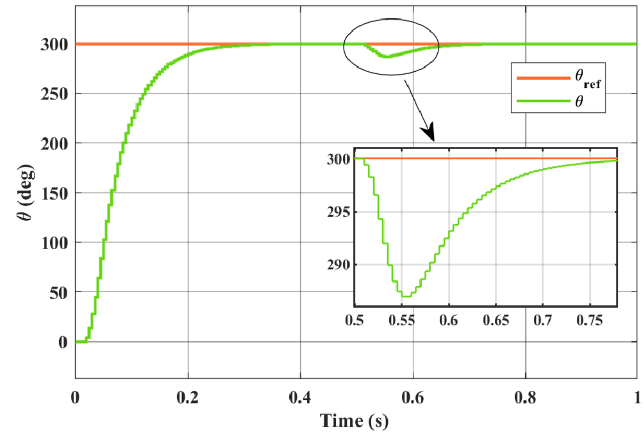

Figure 7. Angular Position of the Shaft by Applying the Backstepping Controller Based on the Discrete-Time Observer in the Simulation of the Processor in the Loop

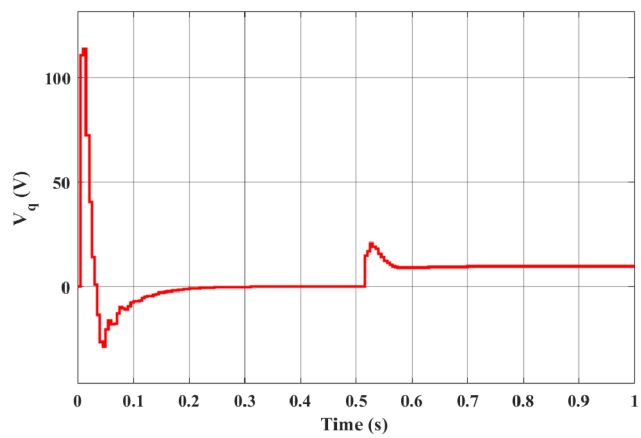

Figure 8. The Vq Control Signal Issued by the Discrete-Time Observer-Based Feedback Controller in the Processor-in-the-Loop Simulation

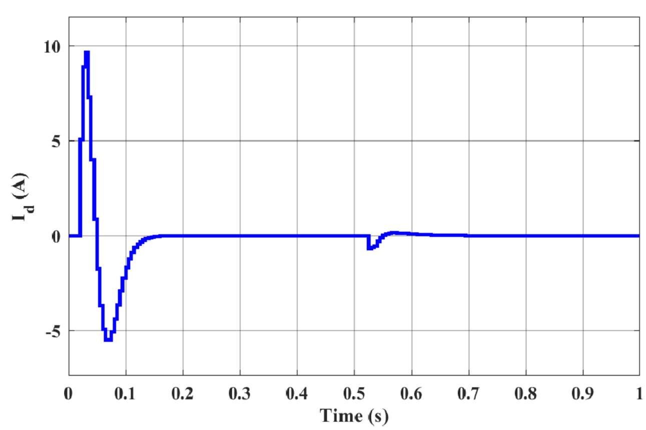

Figure 9. d-Axis Current by Applying Linearizer Feedback Controller in Processor-in-the-Loop Simulation

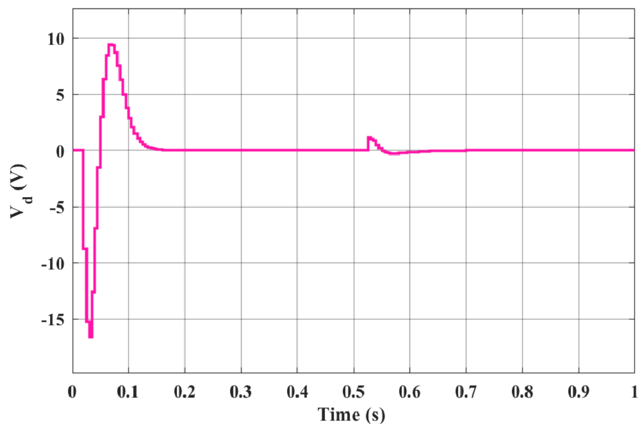

Figure 10. The Control Signal Vd Issued by the Linearizer Feedback Controller in the Processor Simulation in the Loop

VI. Conclusion

In the case of external disturbances such as load torque and to achieve precise control of BLDC motors, a solution is using an extended state observer. It is better that the observer is designed in discrete-time form in the design stage so that there is no need to readjust the controller gains in the implementation stage. In this paper, the feedback linearization was used to control the current, and the back-stepping method based on the discrete-time observer was used to control the angular position of the shaft. The simulation results showed the difference caused by the use of continuous-time and discrete-time observers. Also, a difference was observed due to the communication delay between the results of the processor simulation in the loop and the computer simulation. In general, the proposed control method is able to control the current and the position of the shaft and does not need to readjust the gains in the implementation phase.

References

[1] D. Kumar and R. A. Gupta, "A comprehensive review on BLDC motor and its control techniques," International Journal of Power Electronics, vol. 14, no. 3, pp. 292-335, 2021.

[2] D. Mohanraj et al., "A Review of BLDC Motor: State of Art, Advanced Control Techniques, and Applications," IEEE Access, vol. 10, pp. 54833-54869, 2022, doi: 10.1109/ACCESS.2022.3175011.

[3] M. Mahmud, S. M. Motakabber, A. Z. Alam, and A. N. Nordin, "Control BLDC motor speed using PID controller," International Journal of Advanced Computer Science and Applications, vol. 11, no. 3, 2020.

[4] S. Usha, P. M. Dubey, R. Ramya, and M. V. Suganyadevi, "Performance enhancement of BLDC motor using PID controller," International Journal of Power Electronics and Drive Systems, vol. 12, no. 3, pp. 1335, Sep. 2021.

[5] N. Hemati, J. S. Thorp, and M. C. Leu, "Robust nonlinear control of brushless DC motors for direct-drive robotic applications," IEEE Transactions on Industrial Electronics, vol. 37, no. 6, pp. 460-468, Dec. 1990, doi: 10.1109/41.103449.

[6] S. C. Chen and C. Y. Kuo, "Design and implementation of double-integral sliding-mode controller for brushless direct current motor speed control," Advances in Mechanical Engineering, vol. 9, no. 11, Nov. 2017, doi: 10.1177/1687814017737724.

[7] H. Maghfiroh, A. Ramelan, and F. Adriyanto, "Fuzzy-PID in BLDC motor speed control using MATLAB/Simulink," Journal of Robotics and Control (JRC), vol. 3, no. 1, pp. 8-13, 2022.

[8] B. N. Kommula and V. R. Kota, "Design of MFA-PSO based fractional order PID controller for effective torque controlled BLDC motor," Sustainable Energy Technologies and Assessments, vol. 49, Feb. 2022, doi: 10.1016/j.seta.2021.101644.

[9] H. Grabner, W. Amrhein, S. Silber, and W. Gruber, "Nonlinear Feedback Control of a Bearingless Brushless DC Motor," IEEE/ASME Transactions on Mechatronics, vol. 15, no. 1, pp. 40-47, Feb. 2010, doi: 10.1109/TMECH.2009.2014058.

[10] K. Guo, M. Yang, X. Li, P. Shi, and P. Wang, "Research on a New Adaptive Integral Sliding Mode Controller Based on a Small BLDC," IEEE Access, vol. 10, pp. 73204-73213, 2022, doi: 10.1109/ACCESS.2022.3188665.

[11] F. Wang, Q. Mei, and X. Xin, "Discrete sliding mode control method for particle swarm optimization-based brushless DC motor of electric vehicle," Journal of Vibroengineering, vol. 25, no. 5, pp. 1025-1039, Aug. 2023.

[12] M. Ehsani, et al., “Adaptive Dynamic Sliding Mode Algorithm for BDFIG Control,” Iran. J. Electr. Electron. Eng., vol. 19, no. 1, 2023.

[13] K.-W. Lim, T.-S. Low, M. F. Rahman, and L.-B. Wee, "A discrete time variable structure controller for a brushless DC motor drive," IEEE Transactions on Industrial Electronics, vol. 38, no. 2, pp. 102-107, Apr. 1991, doi: 10.1109/41.88902.

[14] M. Ehsani, A. Oraee, B. Abdi, V. Behnamgol, and M. Hakimi, "Adaptive dynamic sliding mode controller based on extended state observer for brushless doubly fed induction generator," International Journal of Dynamics and Control, Jun. 2024.

[15] M. Darabi Moghadam, A. Vali, S. M. Hakimi, V. Behnamgol, and G. Derakhshan, "Design and Implementation of Discrete Time Observer Based Backstepping Controller for a 2DOF Servomechanism," Journal of Control, vol. 16, no. 3, pp. 1-9, Dec. 2022.

[16] M. Javaheripour, A. Vali, V. Behnam Gol, and F. Allahverdi Zadeh, "Line of Sight (LOS) rate estimation in strap down seekers using discrete-time extended state observer," Journal of Control, vol. 16, no. 2, pp. 55-67, Jul. 2022.

[17] N. S. Gogani, V. Behnamgol, S. M. Hakimi, and G. Derakhshan, "Finite time backstepping super twisting controller design for a quadrotor," Engineering Letters, vol. 30, no. 2, pp. 674-680, 2022.

[18] V. Behnamgol, M. Ehsani, A. Oraee, R. Barzamini, and B. Sohani, "Finite time power regulation of BDFIG using adaptive nonlinear method," Power Control Data Process. Syst., vol. 2, no. 2, 2025.

[19] S. Trefilov, "Non-linear discrete model of BLDC motor for studying the range of permissible values of the voltage vector in the state space," International Conference on Modern Trends in Manufacturing Technologies and Equipment: Mechanical Engineering and Materials Science (ICMTMTE 2020)