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Brushless Direct Current Motor for Current Control Based on Magnetizing and Freewheeling Modes

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Abstract - **Brushless DC (BLDC) motors are commonly used to power electric cars since they are so efficient. This motor, on the other hand, often has problems like fluctuating current and torque ripple. It can utilize both the hysteresis current control system and the freewheeling magnetization method to fix this problem. The goal of this method is to keep the current within the reference range while slowly raising and reducing it to avoid spikes. Simulations were utilized to verify the effectiveness of the proposed system. The results show that the proposed technique worked to keep the flow consisten. The motor operates more smoothly due to improved current. This method could really help electric cars run better.**

Keywords— **BLDC, Hysteresis Current Control, Magnetizing Freewheeling, Current Ripple, Electric Vehicle.**

I. INTRODUCTION

These BLDC motors are presently being employed more and more as the main motors in the development of electric vehicle technologies [1]. BLDC motors offer a good torque ratio and require minimal maintenance because they don't have any mechanical brush parts [2]. Because of these qualities, they are the best choice for many jobs that necessitate exceptional performance. BLDC motors are very efficient, but they still have significant issues related to torque quality. Significant current ripple exists in the stator windings, which is what causes this torque problem [3]. Due to this significant current ripple, the torque fluctuates significantly. If this condition isn't handled correctly, it could cause the motor to overheat and destroy the vehicle's mechanical parts, which would make the whole system much less efficient [4].

A lot of research has tried to overcome these challenges, but most of the solutions that have been suggested involve math and control systems that are too hard to use [5]. A straightforward yet precise method of controlling the current is necessary to ensure the motor operates as intended [6]. The Hysteresis Current Control (HCC) method is an excellent choice in this case since it is simple to learn and works well when loads change [7]. However, this method does not always perform optimally as it could if the system still used magnetizing-demagnetizing switching mechanisms. The biggest drawback with this method is that the reduction in current is too high, which makes the ripple bigger. But if the system still involves switching processes that magnetize and demagnetize, this method doesn't always function as effectively as it could. One main drawback with this method is that the reduction in current is too high, which makes the ripple in the current bigger [8]. This happens because while the device is in demagnetizing mode, the source voltage goes the other way from the induced voltage [9]. Some studies also show that employing this mode in steady-state circumstances can induce high torque ripple, even though it works well for fast braking [10]. The system must be regulated in a manner that is both uncomplicated and ensures that torque control is more precise and smooth [11].

In this paper, a hysteresis-based current control strategy utilizing both magnetizing and freewheeling modes is proposed. This paper suggests a hysteresis-based approach for current control that employs both magnetizing and freewheeling modes. To confirm the strategy's dependability, performance testing in this study was executed by extensive computational simulation validation, excluding hardware implementation. This study is expected to lead to an effective new approach for designing electric vehicle drive systems in the future.

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II. RESEARCH METHOD

A. Basic principles of BLDC motor

A BLDC motor is a synchronous motor that functions by the attraction and repulsion of magnets. This motor comprises two primary components: the rotor, a permanent magnet, and the stator, a winding. A Hall effect sensor is required to accurately detect the rotor position for the motor

to rotate smoothly. Typically, three sensors are fitted for each 120° electrical revolution. These sensors generate digital signals when traversed by the motor's permanent poles. The signal will register as "0" upon detecting the South Pole (S) and "1" upon detecting the North Pole (N). By interpreting these signal, the controller can ascertain which stator require energization.

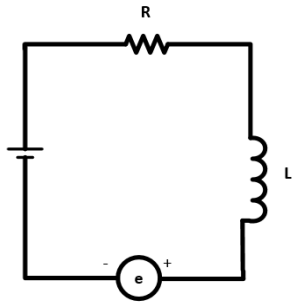


Figure 1. Equivalent circuit of a BLDC motor

Based on Figure 1, the equivalent circuit of a BLDC motor is depicted as a series circuit consisting of a resistor (R) and an inductor (L). This system receives a DC voltage supply converted throught an inverter. In simple terms, the resistor represents heat losses in the copper windings, while an inductor functions to store magnetic energy when current flows. The Back Electromotive Force (BEMF) component itself arises from the rotation of the rotor interacting with the magnetic flux and has a trapezoidal waveform. Because its value fluctuates with the motor's rotational speed, BEMF is a key factor determining current behavior and the amount of torque produced. The phase voltage (V) is calculated by summing the resistive voltage (V_R) and the inductive voltage (V_L) with the back electromotive force (e) generated by the motor. Consequently, the mathematical equation delineating the relationship between the input voltage and these components can be articulated as (1).

$$V = V_R + V_L + e \quad (1a)$$

$$V = i.R + L\frac{di}{dt} + e \quad (1b)$$

In order for the input voltage (V) in equation (1) to be supplied to the stator windings in accordance with the rotor speed, a switch arrangement is required that refers to the position information from the Hall effect sensor. These three sensors detect the rotor's magnetic poles and generate digital logic signals to determine the commutation sequence. This signal serves as the primary reference for the Three-Phase Inverter to activate the relevant switch pairs. The configuration of the power circuit used to realize the current distribution mechanism is shown in Figure 2.

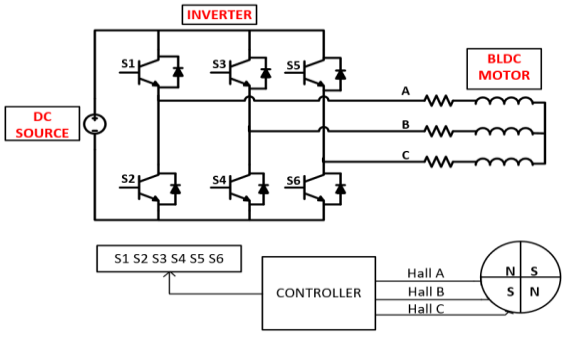


Figure 2. Basic principles of BLDC motor operation

As shown in Figure 2, the inverter circuit consists of six semiconductor switches configured in a full-bridge topology. In operation, the control system regulates the switching pattern to allow current to flow to only two phases of the motor alternately, while the third phase is left floating. To keep this process synchronized, the Hall sensor generates a digital signal that changes every 60˚ electrical degrees of rotation. This signal is what the controller uses to determine which pair of switches should be active. The complete relationship between the Hall sensor logic combination and the inverter switch activation sequence is detailed in Table 1.

Table 1.
The switching sequence of the three-phase inverter and the resulting motor current flow are based on Hall effect position feedback.

Step	Saklar	Hall sensor	Current (+)	Current (-)
1	S1-S6	1 0 0	I_a	I_c
2	S3-S6	1 1 0	I_b	I_c
3	S3-S2	0 1 0	I_b	I_a
4	S5-S2	0 1 1	I_c	I_a
5	S5-S4	0 0 1	I_c	I_b
6	S1-S4	1 0 1	I_a	I_b

The information in Table 1 illustrates the basic logic mapping of electronic commutation. For torque to be produced, these static rules must be executed synchronously as the rotor rotates. The relationship between changes in the Hall sensor signal, BEMF, and phase current injection within one electrical rotation cycle is illustrated in Figure 3.

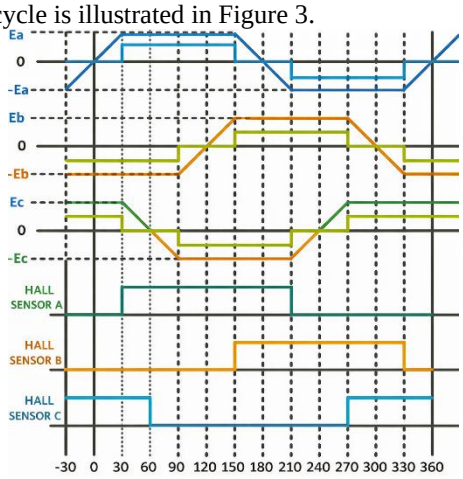


Figure 3. BEMF timing diagram, phase current, and Hall effect information flow

The Hall sensor's change serves as a reference for the inverter to inject current precisely when the back voltage reaches its peak. This timing is key for the engine to produce maximum power with minimal vibration. In practice, the inductive property of the stator windings causes the current to take time to rise or fall and cannot change suddenly. Therefore, a special control strategy is needed to form the ideal current, using magnetizing and freewheeling modes.

B. Magnetizing Freewheeling

Magnetizing mode is the moment when the system actively draws power from the DC source to the motor coils. In this phase, the controller closes the power switches according to the commutation sequence to connect the stator to the source

voltage (V). Due to the inductive nature of the stator windings, injecting the source voltage will result in a linearly increasing current response. Based on the fundamental equation (1), the rate of change of positive current in this mode is formulated as:

$$V = i(t).R + L\frac{di(t)}{dt} + e(t) \quad (2)$$

Because the source voltage (V) is much greater than the back EMF (e), the rate of change of current ($\frac{di}{dt}$) will be positive.

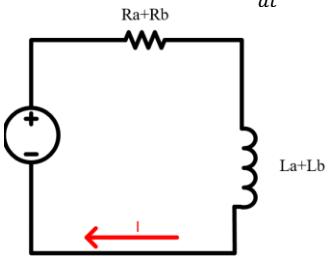


Figure 4 Illustration of magnetizing mode in a BLDC motor.

Freewheeling mode occurs when the voltage source (V) is temporarily disconected. When the voltage source (V) is removed, the magnetic energy stored within the stator inductor is not immediately lost, but rather decreases slowly by circulating current through the diode. This controlled current decay process is formulated as (3).

$$0 = i(t).R + L\frac{di(t)}{dt} + e(t) \quad (3)$$

Or if we're looking for its rate of change

$$-\frac{di(t)}{dt} = \frac{i(t).R+e(t)}{L} \quad (4)$$

Equation (4) shows that the rate of current decrease ($\frac{di}{dt}$) is negative, but its gradient is much gentler compared to forced braking. This slow decay is the advantage of freewheeling mode, which allows the current to persist longer in the stator.

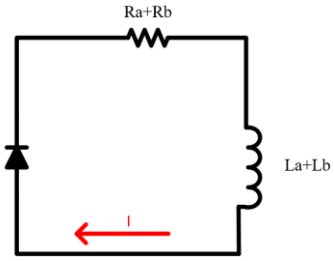


Figure 5. Illustration of freewheeling mode in a BLDC motor

The application of the two modes mentioned above to a three-phase inverter depends on the rotor position reading. Table 2 summarizes the switch configurations for each commutation sector.

Table 2.
Magnetizing and freewheeling mode switching logic

Step	Magnetizing	Hall effect	Current (+)	Current (-)	Freewheeling
1	S1-S6	1 0 0	Ia	Ic	D4-D3
2	S3-S6	1 1 0	Ib	Ic	D6-D3
3	S3-S2	0 1 0	Ib	Ia	D6-D5
4	S5-S2	0 1 1	Ic	Ia	D2-D5
5	S5-S4	0 0 1	Ic	Ib	D2-D1
6	S1-S4	1 0 1	Ia	Ib	D4-D1

In the magnetizing column, the listed switch pairs (for example, S1 and S6 in step 1) are conditioned to be closed (ON) to connect the voltage source to the stator windings, forcing the current to increase. Conversely, the freewheeling column shows the current circulation path throught the diodes when these switch pairs are opened (OFF). Although this table has mapped out which switches should be active, the decision of when the system should switch between magnetizing and freewheeling modes in an active sector is determined entirely by the current difference parameter or ΔI.

The parameter ΔI is a key variable in hysteresis control, representing the deviation between the measured actual current (I_{act}) and the reference current (I_{ref}). The control mechanism works by monitoring this ΔI to ensure it always stays within the set tolerance band (Δh). The reason for this is that when the real current drops below the lower limit of the hysteresis band, the system thinks the current is too low and turns on the magnetizing mode to rapidly increase the current. On the other hand, when the real current rises to the upper limit, the system sees that there is too much current and quickly turns on the freewheeling mode. This switch to freewheeling mode makes the current slowly drop, as shown in equation (4). This lowers the overall current ripple value (ΔI) and stops torque spikes from being too high.

The application of current control (ΔI) throught this magnetizing freewheeling strategy not only aims to maintain electrical limits but also has an impact on the mechanical performance of the motor. Therefore, understanding torque becomes important. Fundamentally, the electromagnetic torque (τ_e) in a BLDC motor is generated from the conversion of electrical power into mechanical power. The value is obtained by summing the instantaneous power in all three phases and dividing by the rotor's angular velocity (ω). This relationship is formulated in equation (5).

$$\tau_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \quad (5)$$

The above equation can be simplified by considering the characteristics of 120^0 conduction mode operation. In this mode, only two phases are actively conducting current at any one time (for example, phases A and B), with a constant but opposite current magnitude (I) and the BEMF value (e) at its flat peak. Assuming the back EMF voltage is $e = k.\omega$ represents angular frequency and I denotes current, the instantaneous power is expressed as:

$$P = (e.I) + (-e.-I) = 2.e.I \quad (6a)$$

$$P_{total} = 2.(k.\omega).I \quad (6b)$$

Since $\tau_e = \frac{P_{total}}{\omega}$, substituting the above power equation yields:

$$\tau_e = \frac{2.(k.\omega).I}{\omega} \quad (7)$$

By eliminating the variable ω and replacing the constant k with the torque constant (K_t), the resulting torque should be constant and linear with respect to current.

$$\tau_e = 2.k_t.I \quad (8)$$

In practical applications of hysteresis control, the current is improbable to remain entirely constant. The implementation of switching in a three-phase inverter to maintain the current within the tolerance band (Δh) will eventually result in current ripple (ΔI). According to the aforementioned linear connection, the existence of this current ripple (ΔI) will inevitably result in torque ripple ($\Delta\tau$) of a certain magnitude:

$$\Delta\tau = K_t . \Delta I \quad (9)$$

III. PROPOSED CONTROL STRATEGY

This is the main reason why the Magnetizing Freewheeling strategy is applied. minimizing ΔI will ultimately mitigate torque fluctuations (Δτ) by regulating the rate of current increase and decrease to ensure that it is not too drastic. To validate how effective this proposed strategy is in damping vibrations, the torque ripple percentage parameter ($\%\tau_{ripple}$) is used. This value is calculated by looking at the extreme difference between the highest and lowest torques compared to their average:

$$\%\tau_{ripple} = \frac{\tau_{max} - \tau_{min}}{\tau_{avg}} x\ 100\% \quad (10)$$

The less this percentage figure is, the smoother the motor spinning will be, which means that the hysteresis current control approach is operating perfectly. Equation (9) shows that the only approach to reduce torque ripple is to restrict the current variation (ΔI) itself. To effectively achieve the limiting of current fluctuation, a control technique is required that can respond to current variations immediately and accurately. Consequently, this research advocates for the implementation of the Hysteresis Current Control (HCC) technique combined with magnetizing freewheeling logic. This suggested plan uses the motor's natural transient properties, including the rate at which the current rises in magnetizing mode and the rate at which it falls in freewheeling mode, to make switching decisions. This mechanism makes sure that the real current is always kept within a safe range (Δh), as explained in the operational principle of hysteresis control (11).

$$(e(t) = I_{ref} - I_{act}) \quad (11)$$

Equation (11) above becomes the main input for the hysteresis comparator. The core task of a control system is to keep the error value ($e(t)$) always locked within the set hysteresis band (Δh). This mechanism is implemented by monitoring the actual current position in real-time to determine if it has reached the lower limit or the upper limit. Based on this monitoring, the controller will generate logic decisions to trigger transitions between magnetizing and freewheeling modes in order to instantly correct the current direction. Mathematically, this decision-making rule is represented by the switching function $S(t)$, which determines whether the inverter switch is active or inactive. That commutation logic is formulated as (12).

$$S(t) = 1\ (Magnetizing), jika\ e(t) > \Delta h$$
$$S(t) = 0\ (Freewheeling), jika\ e(t) < \Delta h$$
$$S(t) = S(t-1), jika\ \Delta h \leq e(t) \leq \Delta h \quad (12)$$

Equation (12) describes the working principle of a hysteresis comparator in regulating the switch status. The first condition ($S(t) = 1$) represents the magnetizing mode, where the switch is turned on because the error ($e(t)$) is large and positive, meaning the actual current is still far below the target and needs to be increased. Conversely, the second condition ($S(t) = 0$) represents the freewheeling mode, where the switch is turned off because the error is large and negative (the actual current exceeds the target), so the current needs to be decreased. The third condition functions as a memory to maintain the previous switch status as long as the error value remains within the safe limit ($\pm\Delta h$), preventing excessive switching that could damage components. The practical implementation of this switching algorithm certainly cannot stand alone; it requires integration with other control subsystems to fully respond to the motor's dynamics. To realize this, the hysteresis logic is placed at the core of the current control loop in a closed-loop system. The system design coordinates sensor readings, reference signal generation, and inverter switching execution within a single closed-loop unit. The overall topology of the proposed control strategy is illustrated in the block diagram in Figure 6.

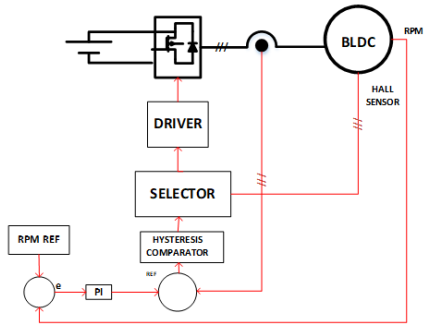


Figure 6 Block diagram of the simulation control system.

The control system model that was built has a double-loop structure. The outer loop controls speed, and the inner loop controls current via hysteresis. This process runs in order, with the PI controller first figuring out the difference between the reference speed and the actual speed to determine the desired current amplitude. Then, this amplitude is matched up with the position feedback from the Hall sensors to make a reference current signal that matches the commutation sequence.

This synchronization takes place on certain parts of the simulation. The control system block diagram has a Selector block that combines the Hall sensors' position measurements with the speed controller's reference current amplitude (I_{ref}). In the control system block diagram, there is a Selector block that integrates the position readings from the Hall sensors with the reference current amplitude (I_{ref}) generated by the speed controller. This block maps the Hall signals into three phase reference current signals (I_a, I_b, I_c). The formation logic is as follows: If a phase must be positive, the reference is $+I_{ref}$. If the phase becomes a return path, the reference is $-I_{ref}$. If the phase is in a floating condition, the reference is 0.

After the current reference is established, the system enters inner loop control. In the current loop, the difference between the reference current and the actual current read by the sensor is processed directly by the hysteresis comparator. This comparator is responsible for keeping the current within the tolerance band by sending a signal to the commutation logic block, which then activates the inverter drivers to force the actual current to follow the reference. The control strategy was then validated throught simulation.

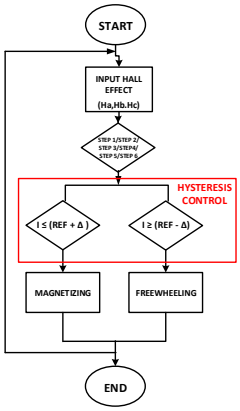


Figure 7 The algorithm proposed the current control strategy.

The system is designed using simulation to represent the BLDC motor using hysteresis current control. This strategy applies a tolerance-based switching method to regulate the current. The control system has two layers, or loops. The outer loop, called Speed Control, uses a PI (Proportional-Integral) controller to compare the reference speed (ω_{ref}) to the actual motor speed (ω_{act}). The output of this block is the reference current amplitude (I_{ref}), which shows how much torque the motor needs. The inner loop, or Current Control, is the most important part of the proposed approach. It takes the current amplitude from the outer loop and multiplies it by the commutation signal made by the Hall effect decoder block. The result is a three-phase current reference signal (I_a, I_b, I_c) that is in sync with the position of the rotor. The Hysteresis Controller block checks the actual current signal (I) that comes directly from the motor output against the reference current (I_{ref}). This is done at every phase of the simulation. The control method works based on inequality logic. This means that if the real current decreases below the lower limit, as shown in equation (9), the controller sends a logic signal 1 to the Ideal Switch block on the inverter. This is the Magnetizing mode, where the source voltage (V) is connected to the motor phase to make the current stronger. Equation (9) says that if the real current goes above the higher limit, the controller transmits a logic signal 0. This puts the system into freewheeling mode.

IV. RESULT AND DISCUSSION

The BLDC motor parameters and controller configuration used in this simulation study are summarized in Table 3. These parameters were chosen to represent the characteristics of a small-scale traction motor commonly used in light electric vehicles.

Table 3.
BLDC Drive System Simulation Parameters

Parameter	Value	Unit
DC Source	400	V
Reference speed	1500	RPM
Stator resistance	2,875	Ω
Stator inductance	8.5	mH
Rotor inertia	8	kg·m2
Number of Pole Pairs	4	Poles
Hysteresis Band	0.1	A

The effectiveness of the control strategy in regulating the stator current flow is demonstrated through a comparison of the current waveform responses in Figure 8. In figure 8 (a), it can be seen that open-loop operation produces a distorted current waveform with extreme spikes at each commutation sector transition. This is in stark contrast to the results shown in figure 8 (b), where applying the HCC algorithm successfully improved the quality of the current waveform. This regulation proves that the switching logic function formulated in Equation (12) effectively forces the actual current (I_{act}) to always remain locked within the tolerance band (Δh).

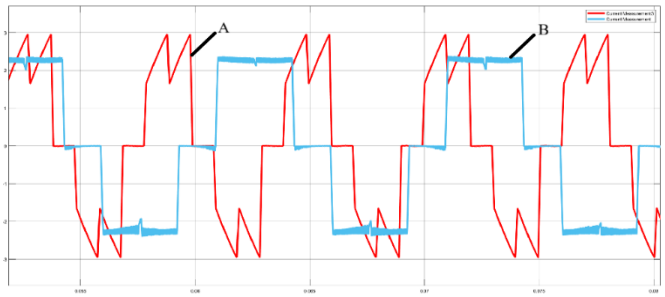


Figure 8. BLDC Motor Current with Hysteresis Current Control. (A) Current before hysteresis control and (B) current after hysteresis control.

The current improvement in Figure nine confirms the magnetizing and freewheeling mechanisms according to the theoretical basis. When the inverter pulse signal is high ('1'), the current experiences a sharp increase with a positive gradient ($\frac{di}{dt} > 0$), validating equation (6) where energy from the source V is fully injected into the inductor. Then, when the current reaches the upper limit and the signal changes to low ('0'), the current decays with a much gentler gradient. This phenomenon validates Equation (8), which proves that energy release throught the diode (Freewheeling) results in a slow current decay rate, effectively keeping the current ripple amplitude (ΔI) at a minimum.

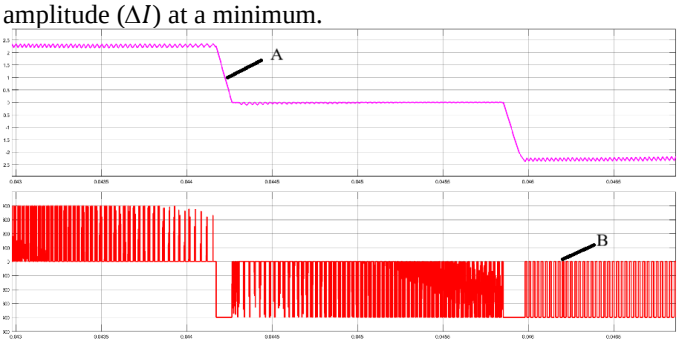


Figure 9. (A) Stator Current Response, showing the rising (magnetizing) and falling (freewheeling) patterns, and (B) PWM Voltage Signal as the switching trigger.

Figure nine (A) proves the mathematical advantage of freewheeling mode. This mode utilizes current circulation throught the diode, allowing the magnetic energy in the inductor to be released slowly. This keeps the ripple current amplitude (ΔI) at a minimum, which directly impacts the smoothness of the torque produced by the motor.

The improvement in current has a direct effect on torque, as seen in Figure 10. This shows that this procedure really does help the motor run more smoothly and far better than it did previously.

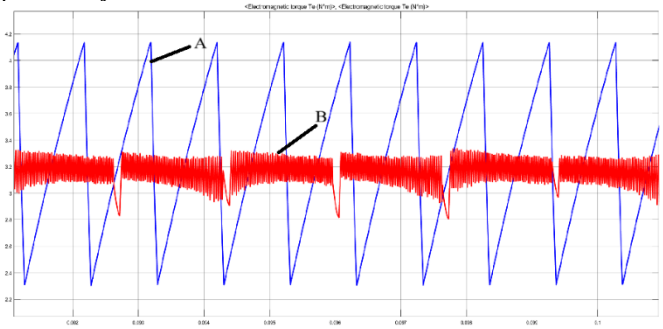


Figure 10. Electromagnetic Torque Response. (A) without hysteresis and (B) with Hysteresis

This proves that the proposed method is capable of overcoming the weakness of slow response in conventional linear controllers, making it a reliable solution for electric vehicle applications that demand high torque quality.

V. CONCLUSIONS

This study concludes that the proposed control method effectively resolves the persistent fluctuation. issue commonly found in BLDC motors. The results of the simulation show that this strategy may make the current much more regulated and always keep it within safe limits. This better quality of current has a direct effect on the motor torque, which makes it smooth and responsive. This approach is very good for use as a drive system in electric vehicles because it works so well.

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