Bulletin of Electrical Engineering and Informatics
Vol. 13, No. 5, October 2024, pp. 3112~3120
ISSN: 2302-9285, DOI: 10.11591/eei.v13i5.7755

Integral-proportional derivative approach for brushless direct current motor speed control

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Article Info

Article history:

Received Oct 21, 2023
Revised Feb 26, 2024
Accepted Mar 20, 2024

Keywords:

Brushless motors
Control engineering
DC motors
Electric vehicles
Velocity control

ABSTRACT

This paper proposed the integral-proportional-derivative (I-PD) as an extension of the conventional proportional-integral-derivative (PID) method that has been used in many brushless direct current (BLDC) applications to control the BLDC motor that can deal with desired speed (reference) changes. It has elucidated a comprehensive comparative analysis between PID, intending to delineate the most efficacious control approach based on a thorough evaluation. This paper scrutinizes four principal methods: proportional-integral (PI), integral-proportional (I-P), PID, and I-PD. Our findings indicate that in the presence of voltage spike constraints, I-P or I-PD emerges as the optimum choice for both four-pole and six-pole motors. Where maximum difference (MaxDiff) is the principal consideration, PI, and I-P are identified as the most suitable methods. Conversely, when the primary objective is to minimize root mean square error (RMSE), PI proves superior for four-pole motors, while PID is preferable for six-pole types. Notably, I-P demonstrates excellent performance in terms of settling time for both motor types. In summation, I-P stands out as the preeminent choice if the objective is to select a singular method that ensures optimal performance across all parameters for a four-pole or six-pole motor.

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1. INTRODUCTION

The first brushless direct current (BLDC) motor with solid-state commutation was introduced in 1962. The distinguishing feature of BLDC motors is the absence of a physical commutator. Their demand will grow significantly in the upcoming decade. They offer low maintenance, reduced noise, and deliver high torque relative to their size [1]. The BLDC motor operates based on lorentz’s force law [2]. For several decades, these motors have seen extensive use. They provide benefits over common direct current (DC) and induction motors, such as the ability to run at swift rotational velocities, rapid response due to low rotor inertia (like changing rotation direction), handling quick acceleration, increased reliability due to the absence of brushes, impressive efficiency, and quieter operation, even though they are not entirely silent [3].

However, there are currently significant challenges, such as their reliability and durability, which revolve around their lack of fault tolerance, electromagnetic interference, acoustic noise, flux ripple, and torque ripple. Feedback control has been identified as a potential solution for these issues. However, in the past five years, several areas have been overlooked, like simple control schemes, enhancing robustness, and reducing electromagnetic interference to the controllers. Regarding the speed and position control strategy, some approaches have been proposed based on feedback control, such as the proportional-integral-derivative (PID) method, intelligent control, and other control schemes. The voltage, current, and commutation logic control need to be considered once we want to control the position and speed of a BLDC motor. Disturbances such as load dynamics and torque ripples are the challenges in this control process. The number of poles and the winding types can also change the control parameters. Therefore, researchers must delve more deeply into the control strategy to get the best control scheme with the best efficiency and simplicity. The best control strategy is still an open issue to achieve low computation control, providing the best result.

Several associations have established efficiency standards for motors in different regions. The international electrotechnical commission (IEC) regulates these standards in Europe, while the National Electrical Manufacturers Association (NEMA) does so in the USA. Presently, four IEC standards relate to motor efficiency [4]. The IEC 60034-30-1 defines four classes of motor efficiency: IE1 as standard efficiency, IE2 as high efficiency, IE3 as premium efficiency, and IE4 as super premium efficiency. These standards apply to 50 Hz or 60 Hz motor drives, single-phase or three-phase, specifically for BLDC motors with an output power exceeding 120 W, determining their efficiency levels [5]. Torque ripples can occur when operating a BLDC motor for various reasons [6]. They can be induced by inefficient commutation strategies and internal gate control schemes during the motor control process. Ideally, torque ripple remains constant due to the in-phase back electromagnetic fields (EMF) and quasi-square wave stator current. However, practically achieving this is challenging since non-zero stator winding inductance generates torque ripples.

Numerous studies have recently focused on mitigating torque ripples in BLDC motors. The field orientation control employs d-axis and q-axis analysis as inputs to the controller [7]–[10]. Direct torque control selects the voltage vector based on variables related to flux and torque, which a controller processes into the control system to analyze commutation points [11]–[14]. Method in [15]–[18] alters the switching logic upon detecting overcurrent, increased speed, or overload [15]–[18]. Another approach deals with the input voltage control [19]–[23] by adjusting the pulse width modulation (PWM). An artificial neural network analyses several motor parameters [6], [24]–[26]. The drive inverter topology incorporates a multilevel inverter and a modified z-source typology [27]–[30]. The sliding mode control technique is applied in designing the controller [31], while adaptive model control utilizes an offline model-based drive for speed control by reducing torque ripples [32]. Modified PWM control [33], [34] employs the PWM chopping method for a low-cost digital control technique. Another control technique for DC motors by extending model reference adaptive control can be seen in [35]. Performance of BLDC motor with various diameter has been discussed in [36].

Furthermore, efficient motor speed control and the commutation logic pattern are carried out by collecting inputs from both the drive and the motors [37]. There are several approaches to managing harmonic content in drive power supplies, so it is reasonable to utilize the PWM technique [38]. Space vector PWM (SVPWM) control is the preferred choice of various PWM techniques. Using current control strategies with PWM and hysteresis controllers plays a crucial role in enhancing the performance of motor drives. Current control techniques employing unipolar PWM can be divided into five modes: H-PWM-L-ON, H-ON-L-PWM-ON-PWM, PWM-ON, PWM-ON-PWM, and H-PWM-L-PWM [39]. The mentioned control methods are mainly based on PID control since it is simple. However, its performance usually still needs improvement, especially once the disturbances (such as load dynamics or torque ripples) exist.

In the implementation, the problems that remain to be investigated are how to get a fast response with the dynamic disturbance but still accurately fulfil the required target (such as speed and position). This capability is the main requirement in vehicles, drones, and many applications that employ drones where the desired output changes dynamically. PID is primarily used at the implementation level, such as for drone flight control, and electric vehicles. This paper explores various BLDC motor control techniques based on PID that currently have been used in many applications and provide a new contribution by offering its extension based on integral-proportional-derivative (I-PD) to control both input voltage and switching pattern instead of using one method to control each target. This extension tends to maintain the simple structure of conventional PID control and low-cost computation and improve the performance of BLDC motors regarding the disturbances that are so dynamic in many applications using these motors by still fulfilling the required output. Simulation-based analysis using MATLAB and laboratory experiments have been conducted to reinforce the conclusions. The performance of the I-PD method will be compared with conventional PID control.

2. METHOD

The required BLDC motor speed is the controlled objective in the control design. There are two winding types in BLDC motors: wye and delta. Due to the different voltage and current characteristics, delta-wound motors can provide higher torque at low speeds than their wye-connected counterparts. This paper focused on the delta-wound type since it is commonly applied in a variety of fields and might be favoured in certain situations: high torque applications, industrial machines, automotive, variable speed drives, fans and pumps, and other general applications like home appliances, aerospace applications, and medical devices, based on specific needs and design criteria. The motor as the plant was a 1350 KV BLDC motor with a 14N12P configuration. An optocoupler is used to measure the motor speed.

We do experiments in MATLAB simulation and directly test. In the experiments, either simulation or direct motor test, variation of BLDC motor input voltage controls the speed, proving that speed control can be done with a switching pattern and input voltage control. The speed motor test was done to take the data representing the relation among voltage, current, power, and motor speed. This paper compares the variation control method based on PID and I-PD for analysis. I-PD is proposed in this paper as a new approach for BLDC motors. More implementation examples of integral-proportional (I-P) and I-PD can be seen in [40]–[42]. The technique proposed in this paper controls switching patterns by considering the sector or field of the commutation and DC voltage input for the BLDC motor based on I-PD. The performance of each control was compared and analyzed. The error, as the difference between the desired speed (reference) and measured speed (actual output), is compared to the existing DC output voltage as input to the first controller for speed. The production of the first controller is used to control the DC input voltage.

The experiment through simulation following the control block diagram shown in Figure 1. For the BLDC motor as a part of a plant, we used a BLDC motor MATLAB model with the following specifications: composite three-phase port for electric connection, delta-wound, perfect trapezoid of back-EMF profile with 0.0175 Wb maximum flux linkage, various pole number (4 or 6), stator self-inductance per phase 0.1 mH, and stator mutual inductance 0.01 mH. Furthermore, for the three-phase converter model, we combined buck-converter and inverter buck-converter for DC-to-DC converter, which provides dynamic DC voltage to the inverter input. The buck-converter used a synchronous converter modelling option, 48 V DC input, with a switching device based on metal-oxide-semiconductor field effect transistor (MOSFET) and LC filter with 220 μH inductance, 10 μF capacitance, and 0.25 Ω capacitor effective series resistance. The inverter had three-phase ports and MOSFET as a switching device. The switching had 0.001 Ω drain-source on resistance, 0.00001/Ω off-state conductance, and 0.5 V threshold voltage, and the integral diode had 0.8 V forward voltage, 0.001 Ω on resistance, and 0.00001/Ω off conductance.

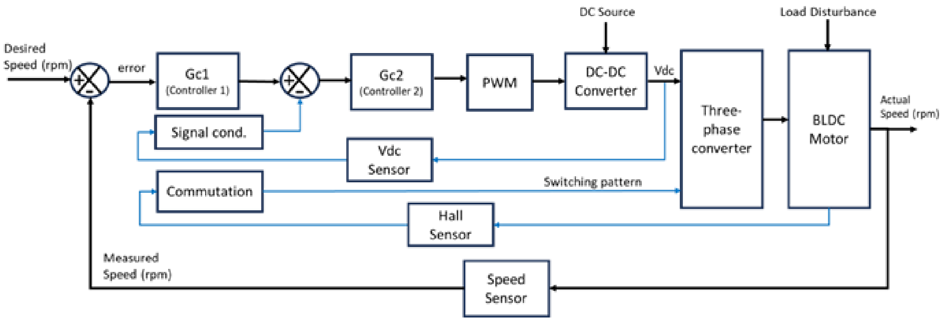


Figure 1. Block diagram of the BLDC motor speed control system

Controller 1 (Gc1) and controller 2 (Gc2) are PID and I-PD control variations, which are compared in section results and discussion. Table 1 lists their mathematic models. These controllers drive the PWM to generate the gate signal of the DC-DC converter that subsequently adjusts the motor speed. Furthermore, for the commutation pattern, 6×6 or 36 different commutation logic patterns are selected based on the hall sensor connected to the BLDC motor.

Table 1. Mathematic models of PID and I-PD control output

PID-based control	I-PD-based control (proposed)
$Gc1_{PI} = K_P\left(1 + \frac{Ki}{s}\right)e$	$Gc1_{I-P} = K_P\left(\frac{K_i}{s}e - y\right)$
$Gc1_{PID} = K_P\left(1 + \frac{Ki}{s} + K_d s\right)e$	$Gc1_{I-PD} = K_P\left(\left(\frac{K_i}{s}\right)e - (1 + K_d s)y\right)$

There are some performance analyses for those multiple methods, such as the maximum difference (MaxDiff) and root mean square error (RMSE) between dynamic references (desired speed) and measured speed, overshoot/undershoot, and settling time. The MaxDiff represents the variance between the line and our dataset, MaxDiff=max $|\boldsymbol{r_i} - \boldsymbol{y_i}|$ where r_i and y_i are the sampling times of the desired and actual speeds, respectively. In (1) shows the RMSE formula. These analyses were done by using MATLAB.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(r_i - y_i)^2}{n}} \tag{1}$$

3. RESULTS AND DISCUSSION

Figure 2 shows a small experiment in the control engineering laboratory to see the relationship between delta-wound BLDC motor speed with power, voltage, and current. Figure 3(a) shows the results. Both voltage and current increase once the motor speed increases. This data became the consideration for controlling the input voltage of the three-phase converter, resulting in the variation of current to run the motor dynamically according to the desired output or set-point. The previous approach tends to control only the switching pattern for this purpose. This paper combines them in the simulation experiment: control the three-phase input voltage, which subsequently contains the injected current to the motor, and the switching pattern based on the commutation.

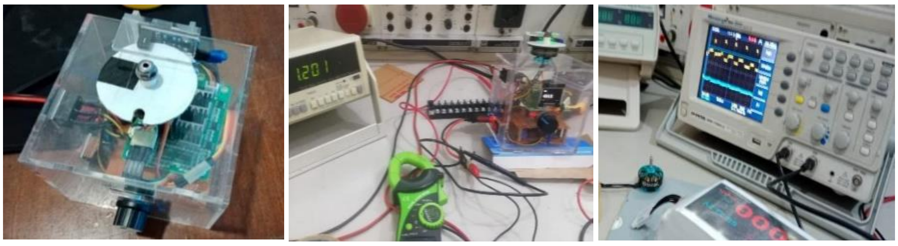
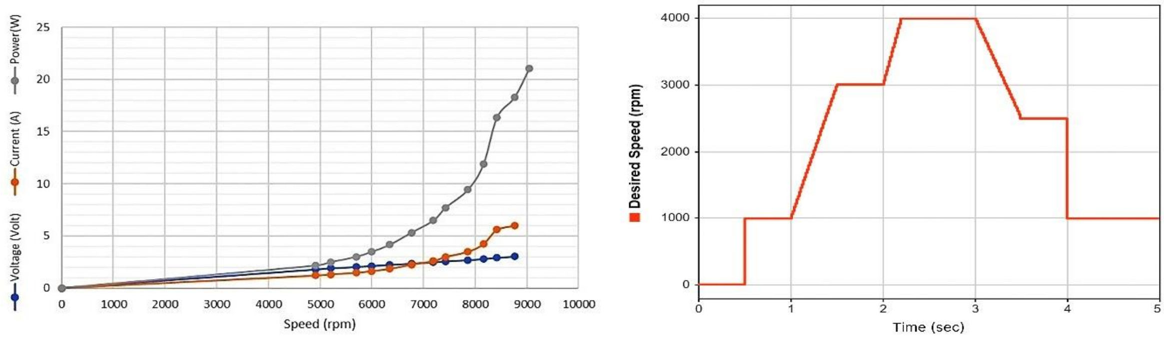


Figure 2. Experiment to investigate the delta-wound BLDC motor speed

For the simulation experiments, Figure 3(b) provides the desired dynamic speed as a reference for the controller to adjust the system to achieve the requirements. It varies the step and ramp set-point and the raising and the falling dynamics. The BLDC rotor has a delta-wound configuration, and the back EMF profile is perfect for trapezoids with a maximum flux linkage of 0.0175 Wb. Four-pole and six-pole numbers have been analyzed. Stator self-inductance per phase, stator inductance fluctuation, stator mutual inductance, and stator resistance are set at 0.1 mH, 0 mH, 0.01 mH, and 0.1 Ω, respectively.

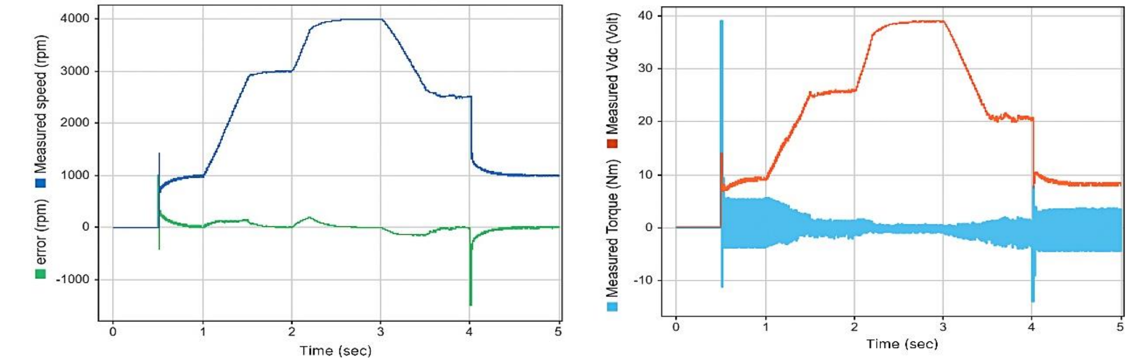


(a) (b)

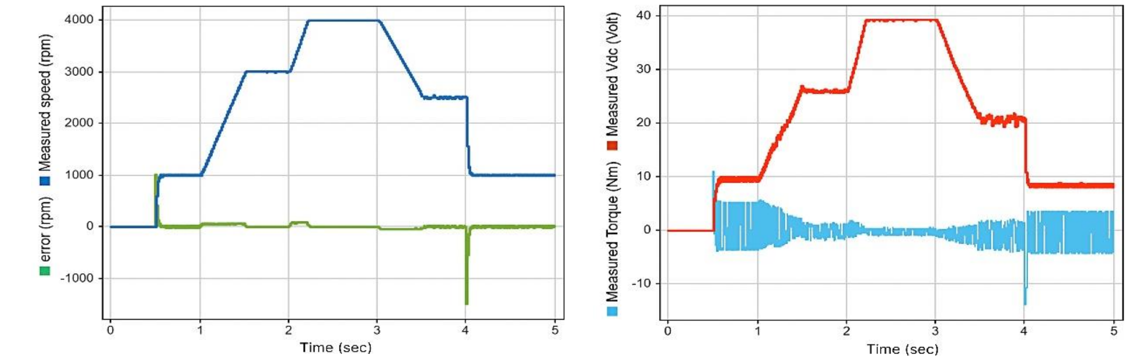
Figure 3. Motor speed characterictis and various set-point design: (a) relationship delta-wound BLDC motor speed with power, voltage, and current and (b) desired speed as the reference or set-point

The analysis was done with four-pole and six-pole BLDC motors. Figure 4 depicts comparative plots of six-pole BLDC motor control methods employed to regulate the input voltage for a three-phase converter, injecting the three-phase current into the BLDC motor. These methods encompass the proportional-integral (PI), I-P, PID, and I-PD, all employed their ideal forms instead of their parallel counterparts. The four-pole BLDC motor control results in similar plot features to the six-pole.

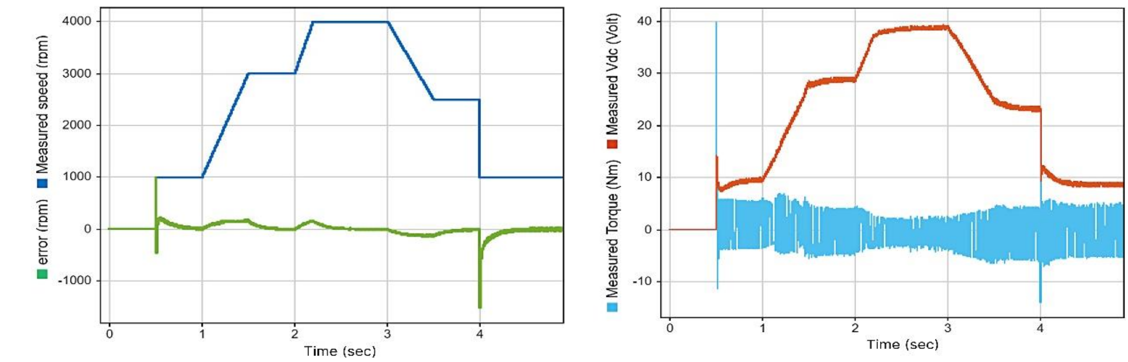
In the six-pole BLDC motor plots depicted in Figure 4, all methods demonstrate the capability to track reference changes. Specifically, during the rising step reference, an overshot is observed in the PI method (Figure 4(a)) at a simulation time of 1 s. In contrast, none of the methods result in an overshot for the ramp reference. Similarly, undershooting is absent across all methods during the falling step reference. The dynamic torque is comparatively lower in the PI (Figure 4(a)) and I-P (Figure 4(b)) control methods. Furthermore, a significant spike is noticeable in the voltage across the direct current (Vdc) plots for both PI (Figure 4(a)) and PID (Figure 4(c)) methods, where it shows a minor spike when using I-P (Figure 4(b)) dan I-PD (Figure 4(d)) method.



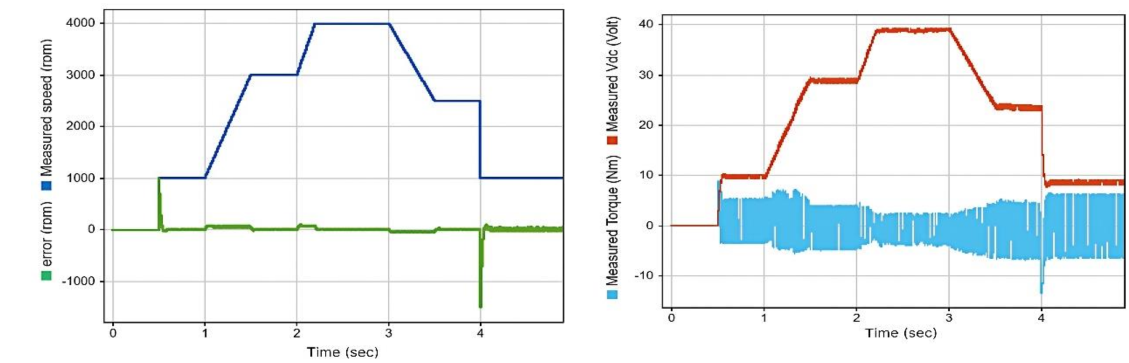
(a)



(b)



(c)



(d)

Figure 4. System performance (six-pole) of speed control to adjust input voltage (Vdc) and switching patterns of delta-wound BLDC with six pole pairs: (a) PI control method, (b) I-P control method, (c) PID control method, and (d) I-PD control method

A more detailed performance analysis is presented in Tables 2 and 3. Table 2 provides a comparative study of the control method concerning MaxDiff and RMSE. It reveals that the PI and I-PD control performances in a four-pole BLDC motor exhibit the smallest MaxDiff. This performance is analogous to that observed in a six-pole BLDC motor. Regarding RMSE in the four-pole BLDC motor, the smallest RMSE is recorded at 21.76 rpm under PI control, while in the six-pole motor case, the smallest RMSE is 26.51 rpm when utilizing I-PD control.

Table 2. MaxDiff and RSME comparison

Control method	Pole number	Max diff (rpm)	RMSE (rpm)
PI	4/6	1,500/1,510	21.76/45.53
I-P	4/6	1,500/1,510	44.97/51.58
PID	4/6	1,510/1,520	26.62/31.32
I-PD	4/6	1,510/1,520	26.51/40.71

Table 3. The performance of controlled system with reference changes

Type	Reference changes (rpm)	Pole	Overshoot	Undershoot	Settling time (s)
PI	1,000 (step at 0.5 s)	4/6	310 rpm (31%)/430.3 rpm (43%)	-	0.08/0.7
	3,000 (ramp at 1.5s)	4/6	No overshoot no overshoot	-	0/0.1
	4,000 (ramp at 2.2 s)	4/6	No overshoot/no overshoot	-	0.14/0.1
	2,500 (ramp at 3.5 s)	4/6	-	No undershoot/no overshoot	0.05/0.1
	1,000 (step at 4 s)	4/6	-	No undershoot/no overshoot	0.1/0.1
I-P	1,000 (step at 0.5 s)	4/6	No overshoot/no overshoot	-	0.02/0.03
	3,000 (ramp at 1.5s)	4/6	15 rpm (1.5%)/no overshoot	-	0/0
	4,000 (ramp at 2.2 s)	4/6	8 rpm (0.8%)/no overshoot	-	0/0
	2,500 (ramp at 3.5 s)	4/6	-	1 rpm (0.01%)/no undershoot	0/0
	1,000 (step at 4 s)	4/6	-	60 rpm (6%)/no undershoot	0/0.02
PID	1,000 (step at 0.5 s)	4/6	430.4 rpm (43.04%)/451.4 rpm (45.14%)	-	0.16/0.14
	3,000 (ramp at 1.5s)	4/6	No overshoot/no overshoot	-	0.1/0
	4,000 (ramp at 2.2s)	4/6	No overshoot/no overshoot	-	0.14/0
	2,500 (ramp at 3.5s)	4/6	-	No undershoot/no overshoot	0.05/0.02
	1,000 (step at 4s)	4/6	-	No undershoot/no overshoot	0.16/0.15
I-PD	1,000 (step at 0.5s)	4/6	80 rpm (8%)/40 rpm (4%)	-	0.03/0.03
	3,000 (ramp at 1.5s)	4/6	20 rpm (2%)/20 rpm (2%)	-	0.01/0
	4,000 (ramp at 2.2s)	4/6	15 rpm (1.5%)/15 rpm (1.5%)	-	0/0.01
	2,500 (ramp at 3.5s)	4/6	-	15 rpm (1.5 %)/20 rpm (2 %)	0.01/0
	1,000 (step at 4s)	4/6	-	100 rpm (10%)/95 rpm (9.5%)	0.02/0.02

Table 3 lists data relating to the overshoot during the rising edge, undershoot during the falling edge, and the settling time. Notably, in cases of both four-pole and six-pole motors, no overshoot is observed during the rising ramp at simulation times of 1.5 s and 2.2 s under PI and PID techniques. In contrast, the I-P method uniquely exhibits no overshoot for the rising step at 0.5 s. Moreover, during the ramp-down and falling step at respective times of 3.5 s and 4 s, all three methods, namely I-P, PID, and I-PD, exhibit either no or minimal undershoot. Furthermore, the I-P shows the best performance for the settling time for the four-pole and the six-pole motor.

4. CONCLUSION

This paper has presented the proposed I-PD as an extension of the conventional PID method used in many BLDC applications to control the BLDC motor that can deal with desired speed (reference) changes. It has elucidated a comprehensive comparative analysis between PID. Our results underscore the importance of tailoring the control strategy to meet specific controller requirements. For instances where voltage spike constraints are a priority, I-P or I-PD methods prove most effective for both four-pole and six-pole motors. When minimizing the performance of MaxDiff is the primary objective, our findings recommend adopting PI and I-P methods. Conversely, for those emphasizing the lowest RMSE, PI is the preferred choice for four-pole motors, while PID is the optimal selection for six-pole motors. Additionally, regarding settling time, the I-P method exhibits superior performance for both motor types. In conclusion, for achieving the best overall performance, regardless of the motor’s pole configuration, the I-P method emerges as the most favourable choice. These insights contribute valuable guidance to BLDC motor control, facilitating informed decisions for controller selection in various applications.

ACKNOWLEDGEMENTS

The authors thank the Faculty of Engineering Universitas Tanjungpura regarding the research funding through DIPA T.A. 2023 with contract number 5326/UN22.4/PT.01.03/2023.

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