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An examination of the impact of the selected error criterion on the ACO performance in BLDC drives

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الملخص:

أصبحت محركات التيار المباشر بدون فرشاة (BLDC) شائعة بشكل متزايد في تطبيقات التحكم في الحركة. نتيجة لذلك، هناك حاجة إلى وحدة تحكم منخفضة التكلفة ولكنها فعالة في سرعة المحرك. محركات (BLDC) يتم استخدامها في الأجهزة الصناعية والمنزلية باستخدام تقنية محرك السيارات التقليدية، مثل الروبوتات والثلاجات وأنظمة تكييف الهواء. تشتهر محركات التيار المباشر بدون فرشاة (BLDC) بكفاءتها العالية وصيانتها المنخفضة. يهدف هذا العمل إلى تصميم وحدة تحكم PID غير تقليدية عبر استخدام أمثلية خوارزمية قرية النمل "Ant Colony Optimisers (ACO) " من أجل الحصول على أداء سرعة فعال لمحرك BLDC من نوع "Maxon EC flat". علاوة على ذلك، عندما يستخدم ACO لضبط التحكم في PID ، فإن الوظيفة الموضوعية مطلوبة. لذلك، في هذا العمل، يتم تطبيق أربع أنواع من دوال الهدف أو مؤشرات الأخطاء وهي متوسط الخطأ التربيعي (MSE)، الخطأ التربيعي المتكامل (ISE)، الخطأ المطلق المتكامل (IAE) و الخطأ المطلق المتكامل للوقت (ITAE) وتم مقارنة أدائها من حيث استقرار سرعة المحرك. في بيئة المحاكاة، يتم استخدام وحدة التحكم PID للتحكم في سرعة محركات BLDC في ظل ثلاث ظروف اختبار وهي الأحمال الصغيرة والمتوسطة والعالية من القصور الذاتي. توضح نتائج المحاكاة أنMSE تقدم أفضل أداء في حالات التحميل بالقصور الذاتي المنخفضة والعالية. في حين أن IAE كانت متفوقة مقارنة بالمعايير الأخرى عند تطبيق الأحمال المتوسطة. علاوة على ذلك، تُظهر هذه الورقة مشكلة مقايضة استهلاك الطاقة بسرعة الاستقرار. بعبارة أخرى، فإن تحقيق استقرار سريع عبر أي نوع من مؤشرات الأخطاء لا يضمن قدرًا منخفضًا من الطاقة المستهلكة.

الكلمات المفتاحية: محرك DC بدون فرشاة (BLDC) ، وحدات تحكم PID ، التحكم في السرعة، مستعمرة النمل (ACO) ، PID، الأحمال الداخلية، لحظة القصور الذاتي.

Abstract

Brushless direct current (BLDC) motor drives are becoming increasingly popular in motion control applications. As a result, a low-cost but effective BLDC motor speed controller is required. They are used in industrial and home appliances with conventional motor drive technology, such as robots, refrigerators and air conditioning systems. Brushless direct current (BLDC) drives are well known for their high efficiency and low maintenance. This work aims to design a non-conventional PID controller via Ant Colony Optimisers (ACO) in order to obtain an efficient speed performance for a BLDC motor "namely, Maxon EC flat". Moreover, when ACO is used for tuning of PID control, the objective function is required. Therefore, in this work, four different objective functions which are MSE, ISE, IAE, and ITAE are applied and their performance was compared in terms of motor' speed stability. In a simulation environment, the PID controller is used to control the speed of BLDC motors under three testing conditions which are Small, medium, and high inertia loads. The simulation results demonstrate that MSE offers the best performance under low and high inertial loading cases. Whereas, IAE has been superior compared with other criterions when medium loads are applied. Moreover, this paper shows a stability speed- power consumption trade-off problem. In other words, achieving a fast stability via any type of error indices doesn't guarantee a low amount of consuming energy.

Keywords: Brushless DC motor (BLDC), PID controllers, Speed Control, Ant Colony (ACO), PID, Inner Loads, Moment of Inertia

I. Introduction

Nowadays, BLDC motors have been intensively used and involved in many industrial applications such as automotive technologies, medical and aerospace applications due to their light weights, superior efficiency and low power density [1] and also for their capability to provide different ranges of speeds [2].

In practical applications, the BLDC drive design involves a complex process that includes modeling, control scheme selection, simulation, parameter tuning, etc. Numerous contemporary control solutions have recently been put forth for the speed control design of BLDC motors [3]. Conventional PID control, on the other hand, uses a conventional speed control system and has a simple, stable, easy-to-adjust, and high reliability algorithm [4, 5]. But in reality, most industrial processes exhibit varying degrees of nonlinearity, parameter variability, and system mathematical model uncertainty.

Due to the PID control parameters' poor robustness and difficult tuning, it is challenging to reach the ideal state in real-world production settings.

In order to deal with the speed control instability, many speed control techniques have been proposed by researchers to cope with this problem. Each method has its unique advantages and drawbacks in terms of optimization objectives, computational requirements and the properties of target plant model [6]. The speed of the motor has to be adjusted by controllers in order to obtain the desired performance. The speed controllers can be conventional controllers such as PIDs in their three popular forms (P, PI and PID), it has been stated that over 90% of the controllers applied for industrial control applications are PID controllers [5], they have the advantage of being easy to use and having clear functionality and acceptable performance. However, the nonlinear characteristics of the DC motors such as saturation [7] and friction [8] play a vital role in degrading the performance of these controllers. Therefore, many non-conventional control strategies have been intensively introduced by researchers as solutions to the problem of non-linearity, these strategies include using of particle swarm optimization [9, 10], Ant-Colony optimization [11, 12], Genetic Algorithm [13, 14], Fuzzy Logic controllers [15-17] and Artificial Bee Colony (ABC) algorithm.

Gunawan et al. [18] presented an optimal approach for obtaining the best FOPID parameter values using PSO and GA algorithms. The simulation results show that the PSO algorithm outperforms the Nelder-Mead and genetic algorithms in terms of control performance. Singh et al. [19] presented an ACO-based parameter optimization strategy for FOPID controllers. The algorithm has been applied to integer and fractional order plants, and the results show high control precision and quick response. Kurniawan et al. . [20] proposed a solution algorithm based on the Cross Entropy method (CEM) to determine the parameters of the FOPID controller for a PMDC motor model system with good performance.

Mirzal et al. [21] examined a GA-tuned PID with various objective functions, including ISE (Integral of the Square Error), IAE (Integral of Absolute Magnitude of Error), ITSE (Integral of Time multiplied by the Square Error), ITAE (Integral of Time multiplied by the Absolute Error), and MSE (Mean of the Square Error), are compared. The IAE objective function has the lowest overshoot (OS), while ITAE has the shortest settling time, according to comparison results for overshoot and settling time. The influence of the selected objective function on the tuning operation was also examined by Kumar and Gupta [22]. The PSO tuned PID in the AVR system was performed by comparing IAE, ITAE, ISE, and MSE in [22], as opposed to this. Their outcome demonstrates that MSE has the best rise and peak times, ITAE has the lowest overshoot, and ISE has the shortest settling times.

The effectiveness of the various objective PID functions tuned by ACO for BLDC motor speed control will be assessed in this paper. ACO PID tuned with various error indices is compared on a particular BLDC motor (namely, Maxon EC flat), which has a quicker dynamic response than other types. This paper also demonstrates how an ACO PID controller can be used to control a motor's speed while maintaining a constant speed regardless of changes in inertial load.

The paper is organized as follows: Section II shortly describes the concept of Ant Colony optimization and the tuning formulas of the PIDs implemented in this work.. Section III explains the Dynamic model of the BLDC motor system. Section IV describes the principles of PID control. Sections V and VI present the experimental setup and simulation results that shows the performance evaluation of the proposed Ant Colony and PID techniques in controlling of speed under different inertia loading criteria and different applied error criterion, while Section VII concludes the paper.

II. ANT COLONY OPTIMISATION TECHNIQUE

Marco Dorigo first introduced ant colony optimization (ACO) in his Ph.D. thesis in the 1990s. This algorithm is based on an ant's foraging behavior when looking for a path between their colony and a source of food. It was originally used to solve the well-known traveling salesman problem. Later, it is used to solve various difficult optimization problems.

Ant colony optimization (ACO) is a promising metaheuristic that has received a great deal of empirical and theoretical attention. The ACO has been and continues to be a useful paradigm for developing efficient combinatorial optimization algorithms [23]. ACO algorithms search for optimal or near-optimal solutions to difficult optimization problems using a colony of artificial ants [24]. The ants can communicate indirectly via a chemical substance called pheromone [23], which is both accumulative and evaporative, but eventually achieves the cooperative goal.

The ants take a shorter path, which accumulates the pheromone trail faster than the longer one. As a result, the faster the pheromone trails increase on the short path, the more likely it is that the ants will also travel this path. Pheromone trails can continuously deposit and evaporate over time. At the same time, the ants can continuously secrete the pheromone during their travel process, allowing the pheromone trails to be updated. The pheromone trails on the path that few ants travel are decreasing, but the pheromone trails on the path that more ants travel are increasing. Fig. 1 depicts the main idea of the proposed algorithm.

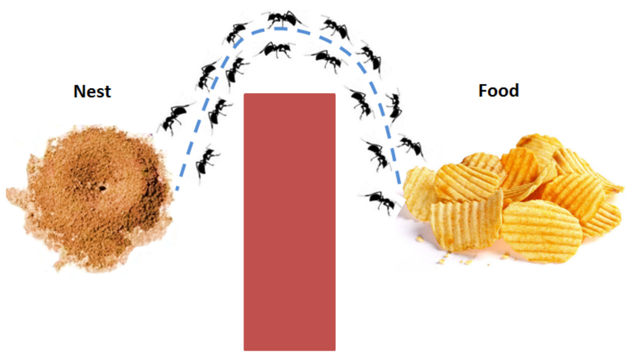

Fig. 1: The main idea of ACO technique.

The ant colony optimization algorithm is a meta-heuristic computational optimization technique that is inspired by nature. It was first mentioned by Marco Dorigo [12, 25]. It is an ant colony's indirect communication using a pheromone trail. Ant behavior can be explained as follows [26].

1. First, each individual ant attempts to solve the specified optimization problem; the optimal solution is reached when the ants collaborate as a colony.

2. Ants interact indirectly while searching for a solution by leaving a pheromone trail behind them. Given a problem, each ant is assigned a state from which it begins its journey and moves to adjacent states in order to find the shortest path.

3. The path of the ant's traverse is determined by its internal state, the pheromone trail, and information received from its surroundings.

4. The pheromone is then released by the ants, and the quality of the path is determined by the amount of pheromone released.[27]

5. Finally, the ant system employs a pheromone matrix to find the best solution.

The most important step in implementing the Ant Colony algorithm in the control system is to choose the cost function that will be used to assess the fitness of each controller term (K_p, K_i, K_d). Furthermore, in this work, the suggested cost function is dependent on four popular performance criteria which are: the Integral of the Square of the Error (ISE), the Integral of the Absolute magnitude of Error (IAE), the Integral of Time multiplied by the Absolute value of the Error (ITAE), and the Mean Squared Error (MSE). The objective functions can be described by the following equations:

$$\mathrm{ISE} = \int_0^t (e(t))^2 \, dt$$

$$IAE = \int_0^t e(t)dt$$

$$ITAE = \int_0^t t.|e(t)|dt$$

$$MSE = \frac{1}{t}\int_0^t (e(t))^2 dt$$

Fig. 2.خطأ! لم يتم العثور على مصدر المرجع. shows the main stages followed for obtaining the optimal values for the ACO-PID controller. It is worth mentioning that the best solution is heavily dependent on the best performance of the selected cost function as well as the sufficient number of ant's iterations.

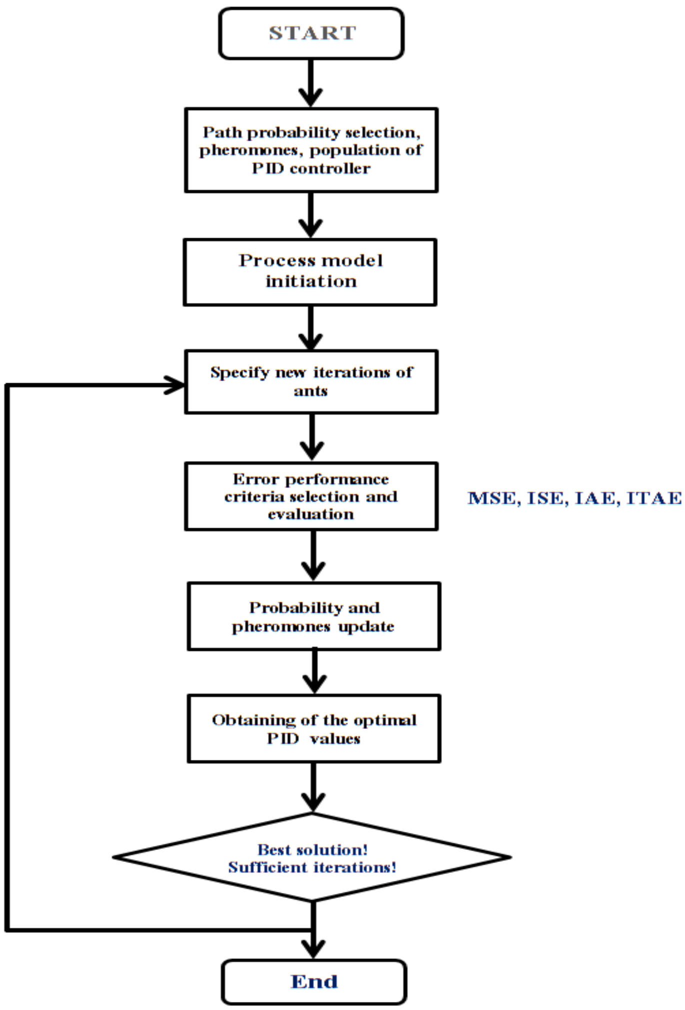

Fig. 2: Flowchart of Ant Colony optimiser.

III. Dynamic model of BLDC drives

A typical electromechanical system for BLDC motors can be represented via Kirchoff's law by the following equation:

$$V = Ri + L\frac{di}{dt} + E_b \qquad (1)$$

where: V represents the supply voltage of the motor

i and L represent the armature current and inductance

E_b represents the back electromagnetic force

The equation (1) can be rewritten as follows:

$$\frac{di}{dt} = \frac{-Ri}{L} - \frac{E_b}{L} + \frac{V}{L} \qquad (2)$$

But $E_b = K_e w$

Where: K_e represents the electrical torque

$$\therefore \frac{di}{dt} = \frac{-Ri}{L} - \frac{K_e w}{L} + \frac{V}{L} \qquad (3)$$

$$T_E = K_f w + J\frac{dw}{dt} + T_L \qquad (4)$$

Where:

T_E: the electrical torque

K_f: the friction constant

J: the rotor inertia

T_L: the assumed mechanical load

The equation (4) can be rearranged as follows:

$$\frac{dw}{dt} = -\frac{T_E}{J} + \frac{K_f w}{J} + \frac{T_L}{J}$$

But $T_E = K_t w$

Where: K_t is the torque constant

$$\therefore \frac{dw}{dt} = -\frac{K_t w}{J} + \frac{K_f w}{J} + \frac{T_L}{J} \qquad (5)$$

Taking the Laplace transform for equations (3 and 5) and using direct substitutions, the following equation can be obtained:

$$V = \left\{\frac{s^2JL+sK_fL+sRJ+K_fR+K_eK_t}{K_t}\right\} w$$

Since the transfer function for any motor system represents the ratio of the output (speed) to the input (supply voltage)

Thus $G(s) = \frac{W}{V} = \frac{K_t}{s^2JL+sK_fL+sRJ+K_fR+K_eK_t}$ (6)

Since the BLDC motor used in this research (EC flat 200189) has three phases. Therefore, equation (6) can be rewritten as follows:

Thus $G(s) = \frac{W}{V} = \frac{K_t}{s^2JL+sK_fL+s.3\times RJ+3\times K_fR+K_eK_t}$ (7)

Considering the following attempts:

The friction constant can be neglected since has a very small influence, therefore, K_f tends to zero.

The rotor inductance has a small influence, thus, it can also be neglected.

Based on the aforementioned assumptions, the equation (7) can be rewritten as follows:

$$G(s) = \frac{W}{V} = \frac{K_t}{s^2JL + s.3\times RJ + K_eK_t}$$

Or $G(s) = \frac{W}{V} = \frac{\frac{1}{K_e}}{s^2\frac{JL}{K_eK_t}+s\frac{3\times RJ}{K_eK_t}+1}$

Or $G(s) = \frac{W}{V} = \frac{\frac{1}{K_e}}{s^2(\frac{3\times R}{3\times R})\frac{JL}{K_eK_t}+s\frac{3\times RJ}{K_eK_t}+1}$ (8)

The mechanical and electrical time constants can be expressed by the following mathematical forms:

$$\tau_m = \frac{3.RJ}{K_e K_t} \quad (9)$$

$$\tau_e = \frac{L}{3.R} \quad (10)$$

Substituting in equation (8) by the equations (9) and (10), the final transfer function for the BLDC motor can be obtained which can be represented as a second order system (see equation 11)

$$G(s) = \frac{W}{V} = \frac{\frac{1}{K_e}}{s^2\tau_m\tau_e + s\tau_m + 1} \quad (11)$$

IV. PID control

PID controller is the most popular control algorithm in the applications of industrial control, it has been preferred by designers for its simplicity in structure, easiness to use. Therefore, there are many sophisticated control techniques were derived from it, such as model predictive control [28]. It can be defined as summation of the integral error, derivative error and multiplying error with constant. The general PID formula can be represented by the following equation:

$$u(t) = K_p e(t) + K_i \int_0^\tau e(\tau) + K_d \frac{de(t)}{dt} \quad (12)$$

Where: $u(t)$ is the controller output

K_p, K_i and K_d are the proportional, integral and derivative parameters, respectively.

e is the error of the system, and τ is the instantaneous time.

V. Experimental Setup

A brushless DC motor (namely Maxon EC flat, product number: 200189) was implemented in this work. The actual specifications for the motor was extracted from the datasheet from Maxon company, these specifications are given in Table 1 which will be used later for calculating of the elements of motor's mathematical model.

Table 1: ACTUAL MAXON MOTOR SPECIFICATIONS.

DC Maxon Motor Data	Unit	Value
Supply voltage	Vdc	12
NO load speed	rpm	4350
Maximum NO load current	Milli Amps	163
Nominal Speed at rated torque	rpm	2800
Rated torque	mNm	54.7
Nominal current	Milli Amps	2.02
Stall torque	mNm	219
Stall current	Amps	8.58
Terminal resistor	Ω	1.4
Terminal inductance	mH	0.56
Torque constant	mNm/Amp	25.5

Speed constant	rpm/Vdc	374
Speed/torque gradient	rpm/mNm	20.5
Mechanical time constant	ms	19.9
Rotor inertia	gcm^2	92.5

The experimental work has been divided into three parts based on the size of inertia load, thus there are three inertia loading cases which are: small, medium and maximum loads. Moreover, it is worth mentioning that the speed of the BLDC motor will be examined under three loading conditions. The PID terms will be tuned and optimized via the four popular error criterions in order to find which error indices can provide the best Ant Colony optimization.

The experiment has been iterated 30 times and each iteration has a number of 30 ants which means that the total number of ants is 900.

In order to find the parameters of the BLDC model, the first step is to determine the electrical time constant (τ_e) via equations 9 and Table 1.

$$\tau_e = \frac{L}{3.R} = \frac{0.56 \times 10^{-3}}{3 \times 1.4} = 133.34 \times 10^{-6}$$

The mechanical time constant (τ_m) has a known value from the actual specification of the motor.

$$\tau_m = 0.0199$$

The last step is to find the electrical torque (K_e) via rearranging for equation (9) and Table 1.

$$K_e = \frac{3.RJ}{\tau_m K_t} = \frac{3 \times 1.4 \times 9.25 \times 10^{-6}}{0.0199 \times 25.5 \times 10^{-3}} = 0.077\ \frac{V - sec}{rad}$$

Therefore, the final transfer function G(s) can be expressed as follows:

$$G(s) = \frac{12.99}{2.65 \times 10^{-6}\,S^2 + 0.0199\,S + 1}$$

It is worth mentioning that the above mathematical transfer function was calculated when a full (maximum) rotor inertia ($i.e\ J = 9.25 \times 10^{-6}$) is applied.

By assuming that the BLDC motor can be operated with 20% and 50% of the nominal rotor inertia ($i.e\ J = 1.85 \times 10^{-6}$ as a small inertia and $J = 4.625 \times 10^{-6}$ as a medium inertia), thus two transfer functions can be obtained which represent the BLDC with small and medium inertia loads respectively.

$$G(s) = \frac{65.31}{2.65 \times 10^{-6}\,S^2 + 0.0199\,S + 1}\ \text{(small inertia)}$$

$$G(s) = \frac{26.12}{2.65 \times 10^{-6}\,S^2 + 0.0199\,S + 1}\ \text{(medium inertia)}$$

VI. Results and Discussions

The simulation is carried out via Matlab toolbox (R2013a). three loading conditions have been applied to the motor in order to testify its control performance when ACO technique is used. It can be notified from Table 2 and Table 3 that the MSE provides the fastest cost value as well as the shortest rise time, while ISE has the lowest overshoot but offers longer rise time in comparison with other criteria. Moreover, both IAE and ITAE require a large amount of energy consumption in order to control the maxon motor and that refer to their high overshoot and undershoot.

It can also be notified from tables that both IAE and MSE provide almost similar performance in terms of rise and settling times. However, all error indices provide similar peak time which means that the selection of error criteria will not directly lead to significant variations in the value of peak times.

Table 2: Small inertia load.

Error indices	Tuned Controller parameters			Cost Best
	P	I	D	
ISE	9.6	2.9	0.82	305.7
IAE	7.9	8.0	0.01	758.5
ITAE	7.17	5.9	0.41	259.7
MSE	8.79	8.49	0.01	170.9

Table 3: Time domain specifications at the small inertia load.

Parameters	ISE	IAE	ITAE	MSE
Rise time (s)	0.77	0.25	0.32	0.22
Settling time (s)	6.4	1.813	2.69	1.83
Max overshoot; Undershoot (%)	1.14;0	2.79;1.3	1.95;1.15	1.3;0
Peak time (s)	5	4.16	4.53	4.9

When a medium inertial load is applied to the motor (see Table 4 and Table 5), it's clear that the objective function that uses integral of absolute errors (IAE) offers quicker rise and settling times and shorter peak time compared with other error indices.

ITAE requires a significant amount of energy consumption because it has the highest overshoot and undershoot. This implies that the more energy required to control the plant, the higher the control effort required.

In the case of implementation of maximum loads (see

Table 6 and Table 7), the ACO PID controller performance with MSE criterion has been superior to that of other criterions. However, the objective function of ISE doesn't provide a cost-effective solution in terms of power consumption.

Table 4: Medium inertia load.

Error indices	Tuned Controller parameters			Cost Best
	P	I	D	
ISE	7	6.57	7.9	448.2
IAE	6.27	9.4	0.01	742.3
ITAE	8.79	8.49	0.01	206.2

MSE	9.5	5.1	0.41	231.1

Table 5: Time domain specifications at the medium load.

Parameters	ISE	IAE	ITAE	MSE
Rise time (s)	0.42	0.36	0.32	0.48
Settling time (s)	2.83	1.33	4.37	2.9
Max overshoot; Undershoot (%)	1.98;0.39	2.47;2.15	9.63;1.99	1.59;0
Peak time (s)	4.76	3.26	3.55	4.9

Table 6: Maximum inertia load.

Error indices	Tuned Controller parameters			Cost
	P	I	D	Best
ISE	6.27	9.4	0.01	637.81
IAE	6.97	6.06	1.73	951.71
ITAE	7.78	7.28	0.01	260.2
MSE	8.79	9.19	1.52	405.07

Table 7: Time domain specifications at the maximum load.

Parameters	ISE	IAE	ITAE	MSE
Rise time (s)	0.45	0.87	0.64	0.44
Settling time (s)	2.2	1.48	3.02	2.63
Max overshoot; Undershoot (%)	7.07;1.61	1.67;0.92	1.55;1.53	1.51;0.11
Peak time (s)	1.19	2.54	1.42	1.88

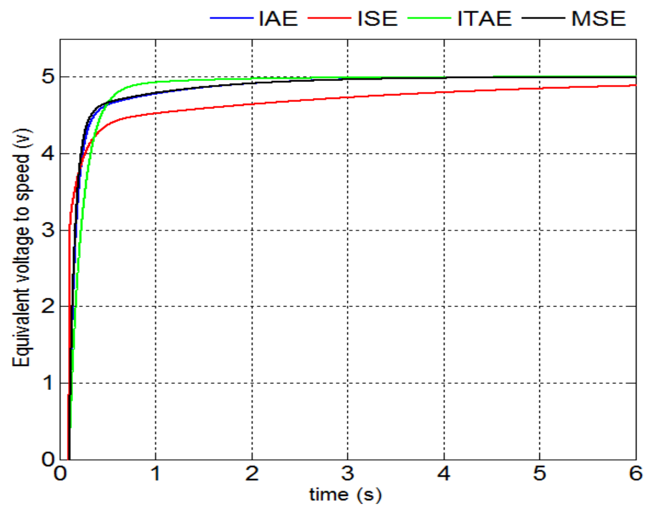

Fig. 3: Step response profile with four error indices and under small inertia loads.

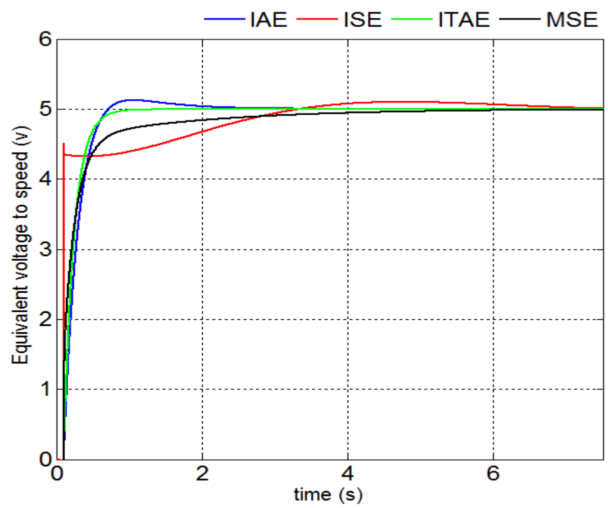

Fig. 4: Step responses profile with varying error indices and under Medium inertia loads.

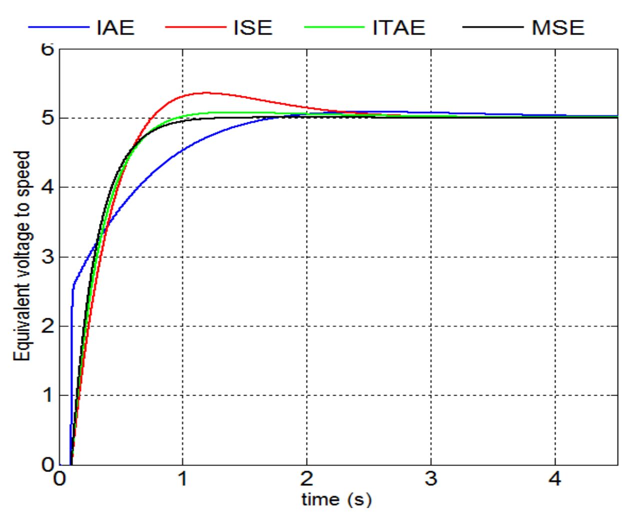

Fig. 5: Step responses profile with varying error indices and under high inertia loads.

VII. Conclusion

A BLDC motor drive (typically, Maxon EC flat) was implemented by using Matlab toolbox, Ant Colony optimization technique was designed to control the speed of the drive under varying inertial loads. Also, the performance of four error indices have been applied and their impact on motor's stability was examined in terms of time domain specifications, the results showed the capability of mean squared error (MSE) in providing an optimum performance under small and high loads, whereas the integral of the absolute magnitude of the error (IAE) provides a sufficient performance at medium loads compared with other indices, it provides a quick stability for the motor's speed, but it's solution cannot be cost-effective in terms of power consumption due to high overshoots and undershoots.

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