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Research Article

Analysis of Optimization Algorithms Used in Permanent Magnet Synchronous Motor Control According to Different Performance Indices

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ABSTRACT

Permanent magnet synchronous motors (PMSM) can be produced at lower costs with new developments in magnet technology and are widely used in many industrial areas due to their low energy consumption. The widespread use of PMSM brings with it the requirement for high accuracy control performance. In order to achieve high performance accuracy, vector control technique is generally preferred. However, the parameter values of the controllers used in this technique are very important for motor performance. Tuning these parameters by optimization techniques instead of classical methods has become a popular topic. Nowadays, modern control methods show more effective control behavior than classical control methods, which has made the use of modern control methods widespread and studies on modern control methods have intensified.

In this study, the analysis of different optimization algorithms used in the control of an PMSM according to their performance indices is investigated in Matlab-Simulink environment. As a result of simulation with different optimization algorithms under the same conditions, the analysis of optimization algorithms using different performance indices such as integral of the absolute value of the error (IAE), integral of the square of the error (ISE), Integral of the Square of the Error Multiplied by Time (ITSE), and Integral of the Absolute Error Multiplied by Time (ITAE) is carried out.

Keywords: *PMSM, optimization, Matlab-Simulink, performance indices.*

Sabit Mıknatıslı Senkron Motor Kontrolünde Kullanılan Optimizasyon Algoritmalarının Farklı Performans İndislerine Göre Analizi

ÖZET

Sabit mıknatıslı senkron motor (SMSM), mıknatıs teknolojisindeki yeni gelişmelerle daha düşük maliyetlerle üretilebilmekte ve düşük enerji tüketimi sayesinde birçok endüstriyel alanda yaygın olarak kullanılmaktadır. SMSM'nin kullanım yaygınlığı, yüksek doğrulukta kontrol performansı gereksinimini de getirmektedir. Yüksek performans doğruluğu elde etmek için genellikle vektör kontrol tekniği tercih edilmektedir. Ancak bu teknikte kullanılan denetleyicilerin parametre değerleri motor performansı

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açısından çok önemlidir. Bu parametrelerin klasik metotlar yerine optimizasyon teknikleri ile ayarlanması popüler bir konu haline gelmiştir. Günümüzde modern kontrol metodlarının klasik kontrol metodlarına göre daha etkin bir kontrol davranışı göstermesi, modern kontrol metodlarının kullanımını yaygınlaştırmış ve modern kontrol metodları ile ilgili çalışmalar yoğunluk kazanmıştır.
Bu çalışmada bir SMSM'nin kontrolünde kullanılan farklı optimizasyon algoritmalarının performans indislerine göre analizi Matlab-Simulink ortamında incelenmiştir. Farklı optimizasyon algoritmaları ile aynı koşullarda yapılan benzetim sonucunda hatanın mutlak değerinin integrali (IAE), hatanın karesinin integrali (ISE), hatanın karesinin zamanla çarpımının integrali (ITSE), ve mutlak hatanın zamanla çarpımının integrali (ITAE) gibi farklı performans indisleri kullanılarak optimizasyon algoritmalarının analizi gerçekleştirilmiştir.

Anahtar Kelimeler: *SMSM, optimizasyon, Matlab-Simulink, performans indisi.*

I. INTRODUCTION

By not using brushes and collectors in permanent magnet synchronous motors (PMSM), operating and repair costs are reduced, while high efficiency and torque are achieved. Thanks to the developments in magnet technology, their advantages such as lighter and smaller designs, lower moment of inertia in the lightweight engine and better dynamic performance as a result of this small footprint design have enabled these machines to be used in a wider range in the market.

In order to operate PMSMs, speed and location information is required. Sensors that meet this requirement cannot behave stably at high speeds. Additionally, additional costs arise when sensor control is required. For this reason, sensorless speed control has gained great importance recently [1].
Due to the increasing complexity and size of today's problems, it is becoming increasingly difficult to obtain solutions with analytical methods. Instead of analytical methods in solving optimization problems, heuristic methods that find the best among the solutions and find this result in the optimal time are recommended. These approaches are mostly inspired by nature. The most common optimization-based heuristic approaches are Artificial Neural Networks, Genetic Algorithm, Particle Swarm Optimization, etc. are algorithms [2-5].

Optimization algorithms are classified as deterministic, which follows a consistent path to a solution, and probabilistic, which involves randomness. While traditional methods are generally deterministic, AI-based optimizations are probabilistic [6].

While each algorithm has advantages over each other, it also has disadvantages. These advantages and disadvantages vary depending on the problem to be applied. If the optimization method most suitable for the problem to be solved is selected, the problem will be solved faster and more precisely and, most importantly, more accurate results will emerge [7].

One of the most important issues encountered in optimization algorithms is the determination of the objective function. The error occurring in control methods is minimized by performance indices such as the integral of the absolute value of the error (IAE), the integral of the square of the error (ISE), the Integral of the absolute error multiplied by time (ITAE) and the Integral of the square of the error multiplied by time (ITSE) [8].

In a study, Proportional-Integral-Derivative (PID) controller (ITAE) was used to optimize the gain parameters used in indirect rotor field oriented control (IFOC) system design. It has been observed that under variable speed conditions, the amount of settling, rising and overshooting is constantly changing. It is clearly shown in the study how the PID controller parameters obtained after running different algorithms 30 times affect the system [9]. In a research, the performances, features and advantages of Artificial Bee Colony (ABC), Differential Evolution (DG) and Particle Swarm Optimization (PSO) algorithms were comparatively examined and evaluated using criteria such as ISE, ITSE, IAE, ITAE.

Additionally, a detailed analysis was performed on an objective function that included settling and overshoot times as well as error values [10]. Another artificial intelligence method used in this regard is the artificial fish shoal algorithm. Cheng and Hong used the ITAE index in their study. PID parameters were adjusted by minimizing this index [11]. In one study, they reviewed the architecture of Two-degree-of-freedom (2-DOF) PID controllers and presented the findings of a simulation process to optimize the settings of these controllers for an PMSM direct drive model, including torque ripple. With the help of genetic algorithm, they optimized the settings of these controllers according to two factors. The first of these is to minimize speed deviations caused by torque fluctuations, and the second is to minimize the absolute sum of squares of errors (ISE) [12]. In another study, the coefficient parameters of the Proportional-Integral (PI) controller used in the vector control technique are aimed to find the best values by using optimisation algorithms such as Artificial Bee Colony (ABC), Particle Swarm Optimisation (PSO), Weighted Average of Vectors (INFO), Genetic Algorithm (GA), Differential Evolution (DE), Symbiotic Organisms Search (SOS). In line with these results, a comparative analysis was made for optimization algorithms [13]. In another study, they proposed a new method to find the best values of the parameters used in tuning the Proportional-Integral-Derivative (PID) controller. IAE, ISE, ITAE and ITSE performance indices were used. It was observed that ITSE and ITAE values and ISE and IAE values were similar [14]. Ant Colony Optimization algorithm was used to find the variables of the PID controller. In the research, the results of 5 different performance indices (IAE, ITAE, ITSE, MSE and ISE) were examined. ITAE has been observed to have a high success rate [15].

In this study, an analysis is presented on the performance of different optimization algorithms used in the control of a permanent magnet synchronous motor. In the simulations carried out in the Matlab-Simulink environment, different optimization algorithms were examined under the same conditions using different performance indices such as IAE, ISE, ITSE and ITAE. It is aimed that this analysis will contribute to determining the most effective optimization algorithm in engine control and designing more effective systems in industrial areas.

II. MATERIAL AND METHOD

A. Permanent Magnet Synchronous Motor (PMSM)

Today, developments in material technology and design programs used in electric motor production, as well as the ability of power electronic components used in motor drive systems to reach sufficiently high speeds and decreasing costs, have expanded the usage areas of permanent magnet synchronous motors. Permanent Magnet Synchronous Motors is a motor that uses permanent magnets in an air gap to create the magnetic field rather than using field windings. Therefore, since there is no need for additional power supply or field windings, the cost is reduced and the losses arising from the excitation windings are eliminated. PMSM engines have significant advantages that have attracted interest from both researchers and industry for use in many applications. PMSMs have begun to become more widely used and widespread in the industry due to their advantages such as taking up less space compared to other motors, compact structure, high efficiency and well-developed drivers. Permanent magnets are the most important components of this motor and largely determine the capability and limitations of the PMSM [16].

A. 1. Vector control of permanent magnet synchronous motor

Since the armature and excitation axes in direct current electric motors are perpendicular to each other, when the armature response is neglected, the armature and excitation currents are completely independent of each other [19].

In vector control applications, three-phase quantities are first converted into a fixed axis set perpendicular to each other (Clarke transformation), and then into an axis set rotating perpendicular to each other and at synchronous speed (Park transformation). In these transformations, expressions in αβ terms are obtained for the fixed axis, while expressions in d-q terms are obtained for the synchronous axis [17].

In the vector control method, PMSM is done by transferring the motor model to the rotor reference plane. In this regard, the rotor reference plane of the PMSM equivalent circuit can be expressed as in Figure 1 [18].

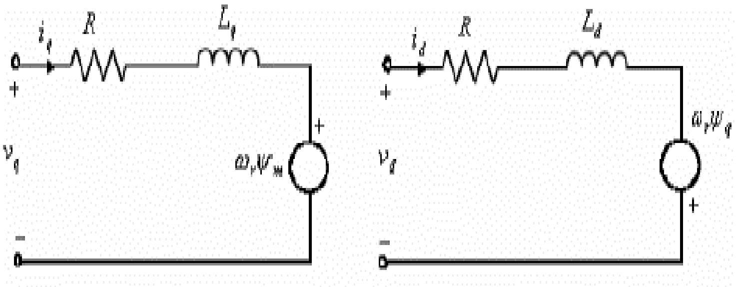


Figure 1. *Equivalent circuit of PMSM in rotor reference plane*

When we use the equivalent circuit of PMSM in Figure 1, the motor voltages are as in equation (1).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{pmatrix} R & 0 \\ 0 & R \end{pmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt} \begin{pmatrix} L_d & 0 \\ 0 & L_q \end{pmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_r \begin{bmatrix} \psi_q \\ \psi_d \end{bmatrix} \quad (1)$$

V_d, V_q = d-q components of the input voltage

i_d, i_q = d-q components of phase currents

L_d, L_q = d-q axis inductances

ψ_q, ψ_d = d-q axis magnetic fluxes

R = Stator resistance

ω_r = Rotor angular speed;

The magnetic fluxes of the motor for the d and q axes are calculated as in equation (2).

$$\begin{bmatrix} \psi_q \\ \psi_d \end{bmatrix} = \begin{pmatrix} L_d & 0 \\ 0 & L_q \end{pmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \psi_m \\ 0 \end{bmatrix} \quad (2)$$

ψ_m = Common magnetic flux due to permanent magnet;

When equation (1) is arranged, the currents of the motor in the d and q axes can be placed on the left side of the equation and the equation can be written in state space form.

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \left\{ \begin{bmatrix} V_d \\ V_q \end{bmatrix} - \begin{pmatrix} R & 0 \\ 0 & R \end{pmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_r \begin{pmatrix} 0 & L_q \\ -L_d & 0 \end{pmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \omega_r \begin{bmatrix} 0 \\ \psi_m \end{bmatrix} \right\} \begin{pmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{pmatrix} \quad (3)$$

In equation (3), it can be seen that the control quantity of the motor is expressed as the currents (i_d and i_q) in the rotor reference plane.

The electromagnetic torque produced by the motor is as in equation (4).

$$T_e = \frac{3}{2} \frac{P}{2} \left[\psi_m i_q + (L_d - L_q) i_q * i_d \right] \quad (4)$$

P= Pole number;

In equation (4), it can be seen that the torque produced by the motor varies according to the rotor magnetic flux and the currents i_d and i_q to the rotor reference plane. Since the rotor magnetic flux in PMSM is provided by magnets, the rotor magnetic flux ψ_m is constant. In addition, since the inductances of the d and q axes are equal to each other in the surface magnet synchronous motor (L_d=L_q), the torque expression in equation (4) can be written as in equation (5).

$$T_e = \frac{3}{2}\frac{P}{2}\left[\psi_m i_q\right] \tag{5}$$

Therefore, in a synchronous motor whose magnets are placed on the rotor surface, the torque depends only on the rotor reference plane q-axis (i_q) current. The angular speed of the rotor can be expressed by equation (6).

$$\frac{d\omega_r}{dt} = \frac{T_e - T_L - B\omega_r}{J} \tag{6}$$

T_L = Load torque

J = Torque of inertia

B = friction coefficient;

The rotor position is as in equation (7) [19].

$$\frac{d\theta_r}{dt} = \omega_r \tag{7}$$

B. OPTIMIZATION

Optimization is the technique of obtaining the best result within given limitations. For this purpose, classical derivative-based search algorithms such as steep descent, Newton, Quaxi-Newton, Conjugate-Newton can be used. This type of algorithms searches for a problem with many local minima in a way that minimizes the objective function according to its initial value. Additionally, swarm-based heuristic algorithms have been developed by modeling the behavior of living and inanimate objects in nature. These algorithms try to find the most suitable point by making more general searches. Essentially, each individual in the herd is first assigned a possible solution value. Each individual's possible solution is then evaluated with the objective function. Then, the individuals in the herd are moved according to the structure of the algorithm and the new possible solutions of each individual are re-evaluated with the objective function. Then, depending on the characteristics of the algorithm, the possible analyzes of the herd are renewed by optimizing the old and new possible solutions or their values in the objective function. In this way, the most appropriate values are tried to be obtained [20]. Performance indices are generally used to determine this objective function.

C. PERFORMANCE INDICES

When designing a system, a performance index is often needed, which determines the system that will give the optimal performance value based on performance parameters. In adaptive control systems, system parameters are constantly changed to ensure appropriate performance, so a parameter that can be used to determine the appropriate value is needed [21]. There are performance indices such as IAE, ISE, ITAE and ITSE in the literature. The equations of these performance indices are given below, respectively. In addition, each of these performance indices was used as an objective function.

IAE(Integral of Absolute Value of Error);

$$f(IAE) = \int_0^T |e(t)| dt \quad (8)$$

ISE(Integral Square Error);

$$f(ISE) = \int_0^T e^2(t) dt \quad (9)$$

ITAE (Integral of Time Absolute Error);

$$f(ITAE) = \int_0^T t * |e(t)| dt \quad (10)$$

ITSE (Integral of Time Square Error)

$$f(ITSE) = \int_0^T t * e^2(t) dt \quad (11)$$

III. SIMULATION STUDY

In this study, speed control was carried out using vector control technique for PMSM. The image of the model made in Matlab/Simulink environment is seen in Figure 2. As seen in the Figure 2, 3 PI controllers are used in the vector control structure. These are controllers that adjust speed, flux and torque. Since we are performing speed control in this application, we focus on the PI controller parameters that adjust the speed. In addition, the performance indices used in the model are also given. Reference speed value is 500 rpm. value and the engine is required to follow this speed. Engine parameter values used in the system are given in Table 1.

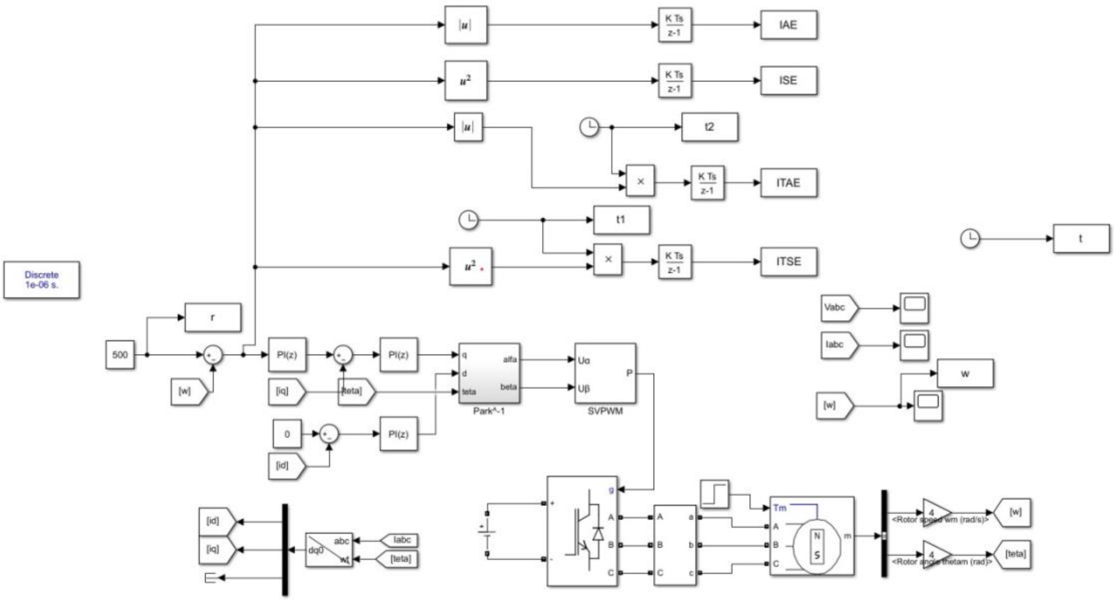


Figure 2. *Vector control algorithm diagram and performance indices of PMSM*

Table 1. *Parameters of PMSM*

Parameters(Symbol)	**Values**
Pole number P	4
Rated speed (rpm)	500
Torque of inertia (kg/m2)	0,0008
Friction coefficient (Nm·s)	0
Stator resistance Rs(Ω)	2,875
Ld-Lq inductance (H)	0.00153
Rotor flux Ψf (Wb)	0,175

To determine the PI controller parameters that adjust the speed, Artificial Bee Colony (ABC), Differential Evolution (DE), Runge-Kutta (RK), Genetic Algorithm (GA), Arithmetic Optimization Algorithm (AOA) and Jellyfish Search (JS) optimization algorithms were used in the study. The advantages of optimization algorithms were analyzed by creating objective functions with performance indices. The abbreviations and parameter settings of the algorithms used in the study, including population size (Np), iterations (It), lower and upper limits of decision variables, crossover probability (Pc), lower and upper limits of scaling factor (beta_min, beta_max) and mutation probability (Pm) are given in Table 2.

Table 2. *Parameter settings of optimization algorithms*

Optimization Algorithms	**Parameter Settings**
ABC	Np:30, İt:200
DE	Np:30, It:200 beta_min=0.02, beta_max=0.08, Pc=0.2
JF	Np:30, İt:200
RK	Np:30, İt:200
AOA	Np:30, İt:200,
GA	Np:30, İt:200 Pc = 0.8, Pm = 0.1
Lower limit	[0 0]
Upper limit	[1 500]

To determine real-time PI parameters in the simulation model, optimization algorithms are run sequentially and PI parameter values obtained from the Simulink model are constantly updated. Optimization algorithms give the best fitness value after approximately 200 iterations. These values are as seen in Table 3. According to these best fitness values, it is shown in bold colour in Table 3 that the ITAE performance index gives the best minimum value in all six optimisation algorithms.

Table 3. *Performance index values measured according to optimization algorithms*

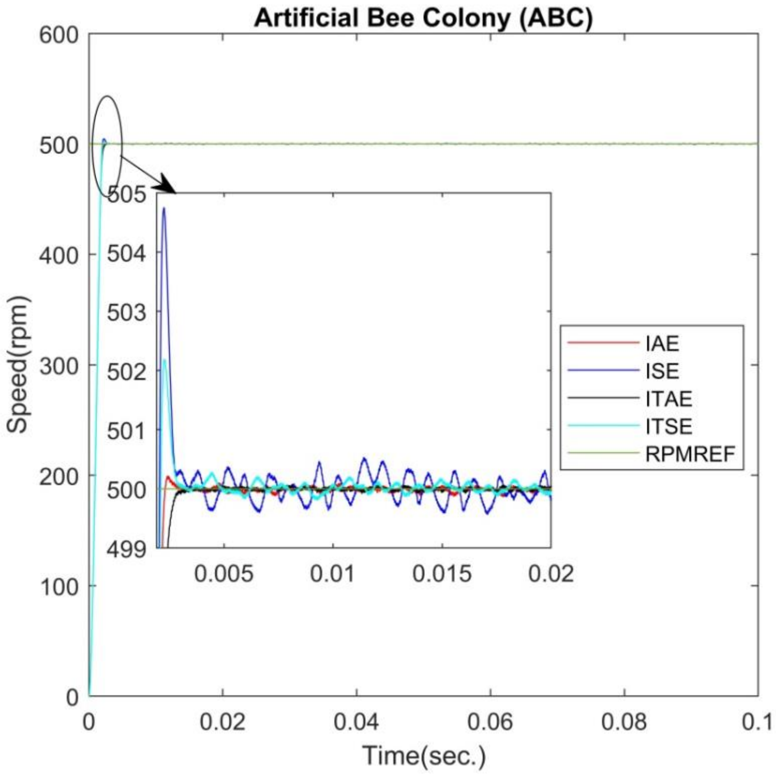
Optimization Algorithms	**Performance İndex**			
	IAE	***ISE***	***ITAE***	***ITSE***
ABC	0,5433	199,7384	**4,6423e-04**	0,1003
DE	0,5433	199,7869	**0,0023**	0,1003
JF	0,5438	199,7527	**4,6544e-04**	0,1003
RK	0,5437	199,7195	**4.4794e-04**	0,1004
AOA	0,5826	200,2047	**0,0023**	0,1089
GA	0,5479	199,9497	**0,0023**	0,1024

In addition, PI parameters are obtained according to these fitness values. The obtained PI parameters are the best parameters for the proposed system. These parameters are given in Table 4.

Table 4. *PI parameter coefficients found according to optimization algorithms*

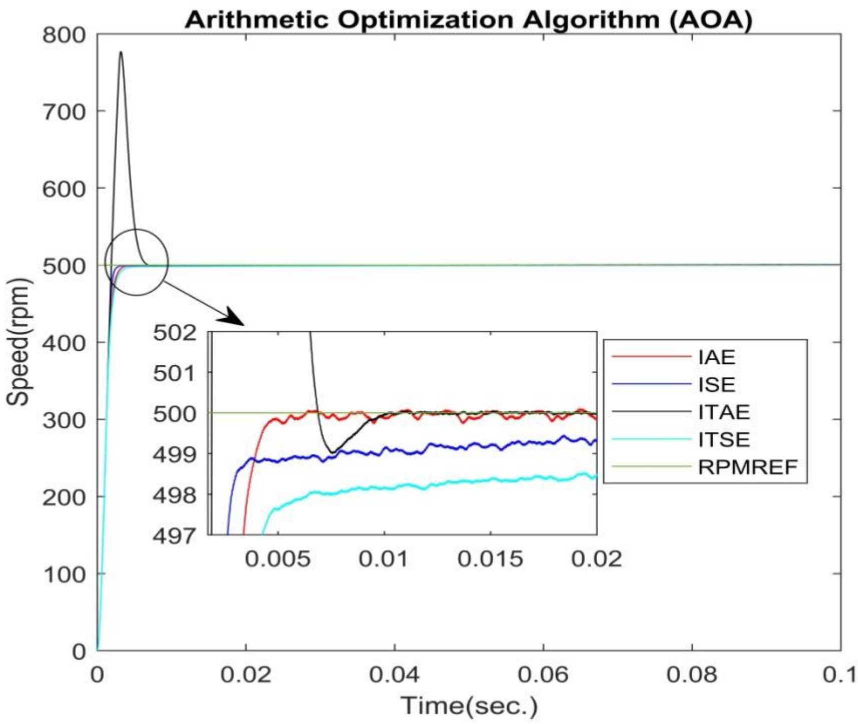
Optimization Algorithms	**(IAE)**		**(ISE)**		**(ITAE)**		**(ITSE)**	
	kpw	***kiw***	***kpw***	***kiw***	***kpw***	***kiw***	***kpw***	***kiw***
ABC	0,938	0,073	0,950	0	1	0,024	0,923	0
DE	0,966	10,504	0,971	8,190	0,548	492,991	0,962	8,476
JF	0,998	0,682	0,992	1,986	0,947	0,197	0,999	0,120
RK	0,999	0,077	1	0,229	1	0,094	0,999	0,066
AOA	0,376	5,788	0,607	3,770	0,491	411,066	0,339	5,694
GA	0,796	1,044	1	0,855	0,537	483,272	0,445	9,088

The speed-time graphs were obtained when the system is operated according to these PI parameters from the algorithms are given in Figure 3, respectively.



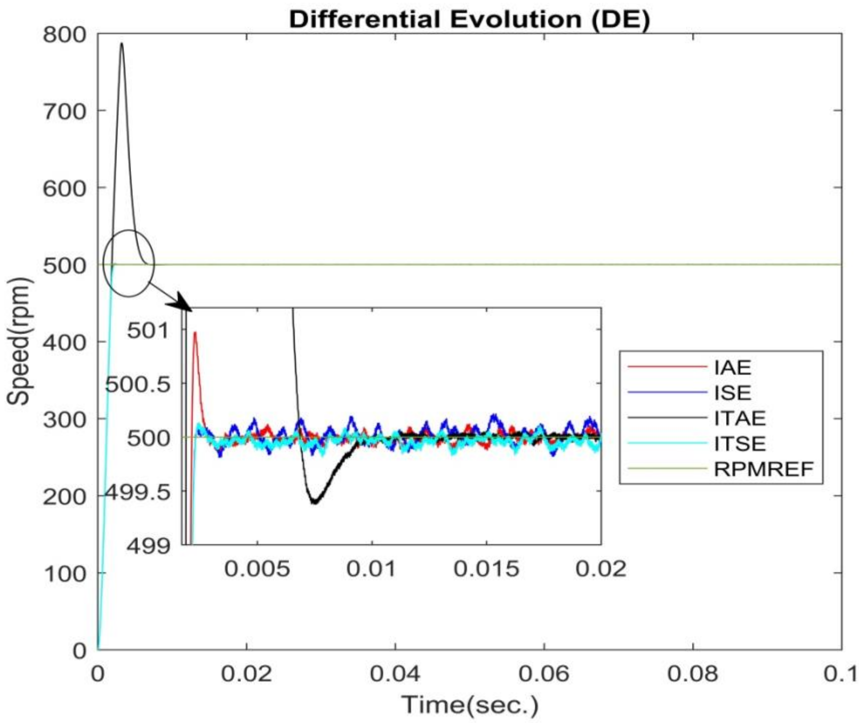
Artificial Bee Colony (ABC)
Speed(rpm)
Time(sec.)
IAE
ISE
ITAE
ITSE
RPMREF

(a)



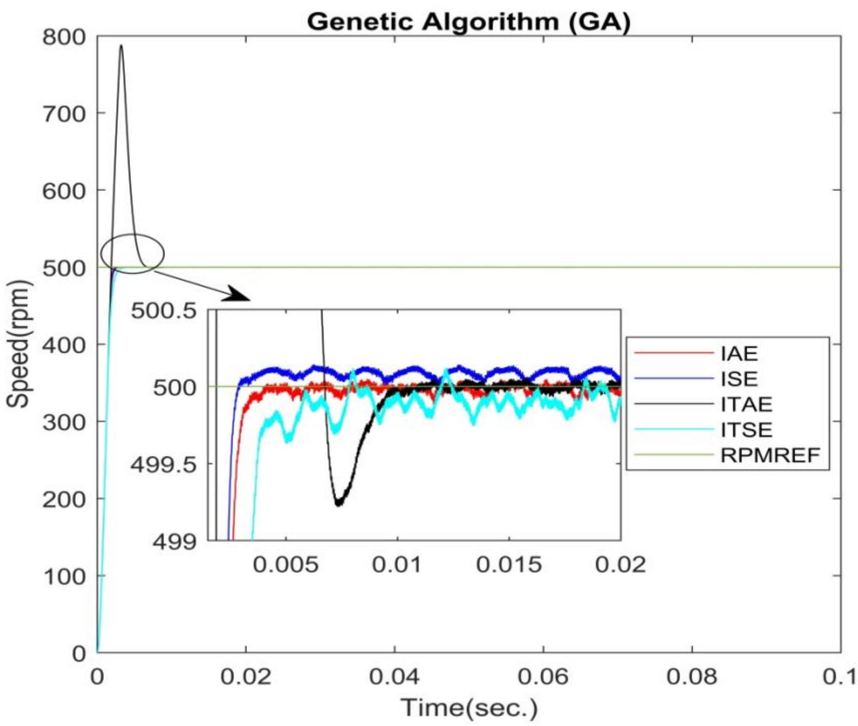
Arithmetic Optimization Algorithm (AOA)
Speed(rpm)
Time(sec.)
IAE
ISE
ITAE
ITSE
RPMREF

(b)



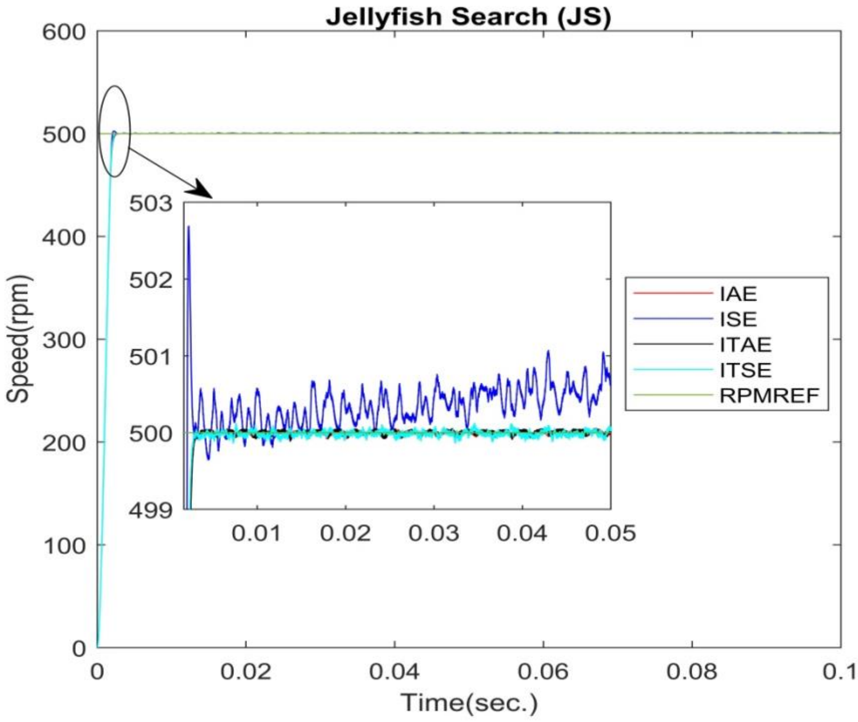
Differential Evolution (DE)
Speed(rpm)
Time(sec.)
IAE
ISE
ITAE
ITSE
RPMREF

(c)

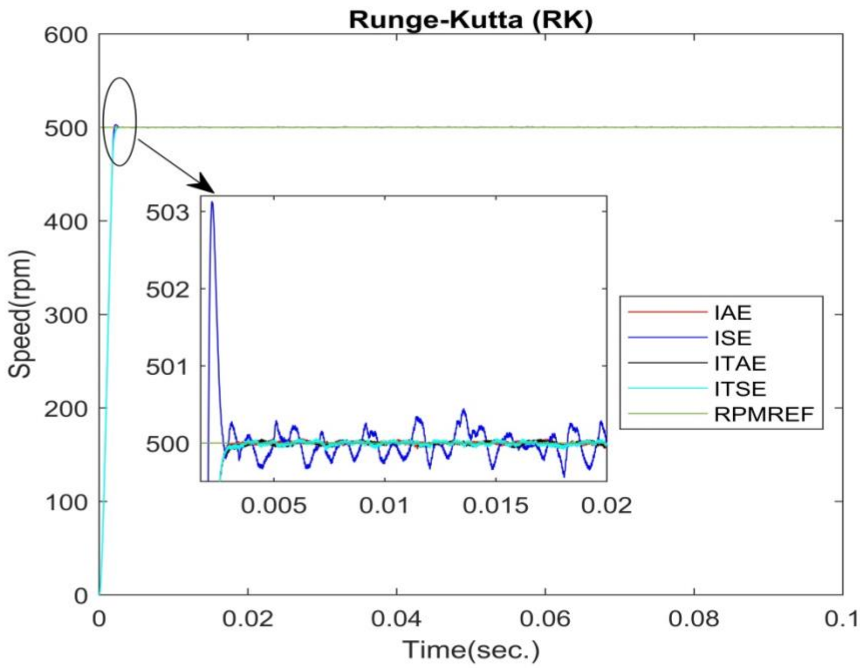


Genetic Algorithm (GA)
Speed(rpm)
Time(sec.)
IAE
ISE
ITAE
ITSE
RPMREF

(d)



(e)



(f)

Figure 3. ***(a)*** *Speed/time graphs of ABC according to four performance indices* ***(b)*** *Speed/time graphs of AOA according to four performance indices* ***(c)*** *Speed/time graphs of DE according to four performance indices* ***(d)*** *Speed/time graphs of GA according to four performance indices* ***(e)*** *Speed/time graphs of JS according to four performance indices* ***(f)*** *Speed/time graphs of RK according to four performance indices*

As seen in Figure 3, the system output reaches the desired reference speed after some oscillation. It is seen in Figure 3 that ITAE performance index minimises this oscillation. In some algorithms of ITAE, the percentage of overshoot is higher than other performance indices as seen in Figure 3.

Table 5. *Unit step response values of performance indices according to optimization algorithms.*

Optimization Algorithms	**Rise time tr (ms)**				**Settling time ts (ms)**				**Overshoot (%)**			
	IAE	***ISE***	***ITAE***	***ITSE***	***IAE***	***ISE***	***ITAE***	***ITSE***	***IAE***	***ISE***	***ITAE***	***ITSE***
ABC	1.718	1.724	**1.717**	1.718	2.895	3.27	**2.885**	2.92	0.002	0.048	**0**	0.022
DE	1.717	1.717	**1.715**	1.716	2.724	**2.292**	9.39	2.94	0.01	**0.001**	2.88	**0.001**
JF	**1.715**	1.723	1.718	**1.715**	2.943	2.825	2.988	**2.79**	**0**	0.027	**0**	**0**
RK	**1.715**	1.723	1.717	**1.715**	2.899	**2.72**	2.825	2.9	**0**	0.031	**0**	**0**
AOA	1.946	1.757	**1.715**	2.044	**5.6**	37.39	9.93	92.81	**0**	**0**	2.77	**0**
GA	1.729	1.716	**1.715**	1.852	3.685	**2.856**	9.578	7.849	**0**	**0**	2.884	**0**

The best values of rise time (tr), settling time (ts) and overshoot percentage of the obtained velocity-time graphs are highlighted in bold colour in Table 5. According to the data in Table 5, it is observed that the performance indices of the six algorithms in the PI controller design are close to each other in the unit step response values, especially in the rise and settling time.

As can be clearly seen from the speed time graphs and Table 3, if the PMSM vector control technique is operated under these conditions, it provides the best performance in the ITAE performance index.

IV. CONCLUSION

In this study, various optimization algorithms were used to increase the performance of permanent magnet synchronous motors. As a result of experiments conducted under the same conditions using Genetic Algorithm (GA), Arithmetic Optimization Algorithm (AOA), Runge-Kutta (RK), Jellyfish Search (JS), Differential Evolution (DE) and Artificial Bee Colony (ABC) algorithms, IAE, ISE, ITAE, the performance of the optimization algorithms was evaluated using the and ITSE performance indices. The results showed that the ITAE performance index provides significant improvements in optimization performance compared to IAE, ISE and ITSE. Especially when Figure 3 is examined, it is seen that it oscillates less than other performance indices while reaching the reference speed and when the conformity values obtained from the ITAE performance index are examined in Table (3), it is seen that it gives more minimised results than other performance indices.

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