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# Optimization of fractional PI controller parameters for enhanced induction motor speed control via indirect field-oriented control

***Introduction.*** *Induction Motors (IM) possess advantages such as stability, reliability, and ease of control, making them suitable for many purposes; the literature elucidates control methodologies for IM drives, primarily focusing on scalar and vector control techniques; the conventional method utilized in manufacturing is scalar control, which unfortunately demonstrates optimal performance solely in steady-state conditions. The absence of significant instantaneous torque control restricts flux and dissociated torque, resulting in subpar dynamic responsiveness. Indirect Field Oriented Control (IFOC) for IM drives has proven beneficial for various industrial applications, particularly electric vehicle propulsion. The primary advantages of this approach include the decoupling of torque and flux characteristics and its straightforward implementation.* ***The novelty*** *of the work consists of a proposal for a driving cycle model for testing the control system of electric vehicles in Mosul City (Iraq), and using a Complex Fractional Order Proportional Integral (CFOPI) controller to control IMs via IFOC strategies, the Artificial Bee Colony (ABC) algorithm was applied, which is considered to be highly efficient in finding the values of controllers.* ***Purpose.*** *Improvement IFOC techniques for the regulation of IM speed.* ***Methods.*** *Using the ABC algorithm in tuning the two unique CFOPI controller, and a Real Fractional Order Proportional Integral (RFOPI) controller, to regulate the speed of a three-phase IM via IFOC techniques.* ***Results.*** *The CFOPI controller outperforms the RFOPI controller in obtaining the best performance in controlling the IM.* ***Practical valu****e. The CFOPI controller demonstrates superiority over the RFOPI controller, as evidenced by the lower integral time absolute error in motor speed tracking during the driving cycle 2.1004 for the CFOPI controller compared to 2.1538 for the RFOPI controller.* References 27, tables 5, figures 4.

*Key words:* **complex fractional order proportional integral controller, real fractional order proportional integral controller, artificial bee colony algorithm, indirect field oriented control.**

***Вступ****. Асинхронні двигуни (АД) мають такі переваги, як стабільність, надійність і легкість керування, що робить їх придатними для багатьох цілей; література пояснює методології керування приводами АД, головним чином зосереджуючись на методах скалярного та векторного керування; звичайний метод, який використовується у виробництві, – це скалярне керування, яке, на жаль, демонструє оптимальну продуктивність лише в стаціонарних умовах. Відсутність значного миттєвого контролю крутного моменту обмежує потік і дисоційований крутний момент, що призводить до низької динамічної чутливості. Непряме поле-орієнтоване керування (IFOC) для приводів АД, довело свою користь для різноманітних промислових застосувань, зокрема для двигунів електромобілів. Основні переваги цього підходу включають відокремлення характеристик крутного моменту та потоку та його пряме впровадження.* ***Новизна*** *роботи полягає в пропозиції моделі циклу водіння для тестування системи керування електромобілями в місті Мосул (Ірак), і використання контролера комплексного дробового порядку пропорційного інтегралу (CFOPI) для керування АД за допомогою стратегій IFOC, було застосовано алгоритм штучної бджолиної колонії (ABC), який вважається високоефективним у пошуку значень контролерів.* ***Мета****. Удосконалення методики IFOC для регулювання швидкості АД.* ***Методи****. Використання алгоритму ABC для налаштування двох унікальних контролерів CFOPI та контролера реального дробового порядку пропорційного інтегралу (RFOPI) для регулювання швидкості трифазного АД за допомогою методів IFOC.* ***Результати****. Контролер CFOPI перевершує контролер RFOPI в отриманні найкращої продуктивності в управлінні АД.* ***Практична цінність****. Контролер CFOPI демонструє перевагу над контролером RFOPI, про що свідчить менша абсолютна похибка інтегрального часу у відстеженні швидкості двигуна під час циклу руху 2.1004 для контролера CFOPI порівняно з 2.1538 для контролера RFOPI.* Бібл. 27, табл. 5, рис. 4.

*Ключові слова:* **пропорційно-інтегральний контролер комплексного дробового порядку, пропорційно-інтегральний контролер дійсного дробового порядку, алгоритм штучної бджолиної колонії, непряме поле-орієнтоване керування.**

**Introduction.** Induction motors (IM) have advantageous characteristics like robustness, reliability, and ease of control, and are used in many different types of applications [1, 2]. These applications electric and hybrid vehicles, the literature clarified control methodologies for IM drives, predominantly encompassing scalar and vector control approaches [3, 4]. The lack of significant instantaneous torque control inhibits flux and dissociated torque, leading to suboptimal dynamic responsiveness [5]. In contrast, Field Oriented Control (FOC) regulates the frequency, amplitude, and instantaneous location of the flow linkage vectors of current and voltage [6, 7]. Therefore, it is effective for each stability and enhanced dynamic performance [8, 9]. The two fundamental groups of FOC methods are direct and indirect operations, defined by Blaschke in 1972 and Hasse in 1968, respectively [10].

**The aim of the paper** is using Indirect Field Oriented Control (IFOC) strategies for speed control of IM and decision the mathematical model of the system. Proposal for a driving cycle model for testing the control system of electric vehicles in Mosul City, Iraq. Applying the Artificial Bee Colony (ABC) algorithm to identify optimal certain elements for fractional order PI controllers.

**Review of the literature.** The authors compared the complex fractional order PI controller against the real fractional order PI controller to control the speed of the IM via the IFOC technique. The results showed that the Complex Fractional Order Proportional Integral (CFOPI) controller improved the Real Fractional Order Proportional Integral (RFOPI) controller by achieving a minimal error between the reference and actual speeds. Nevertheless, the controller variables were found by using trial and error [11]. The research presented here differentiates between the two different RFOPI speed controllers (FOPI and FO[PI]) of the IM drive. The results show the superiority of the FO[PI] controller compared to the FOPI and integer order PI under identical stability boundary constraints [12]. This study elucidates the use of Particle Swarm Optimization (PSO), Teaching Learning Based Optimization (TLBO) and Jaya optimization algorithms for the calibration of PI and RFOPI controllers employed in the IM driving model with comparison of the results from the aforementioned optimization. This indicates that Jaya yields superior reduction outcomes compared to the other two strategies [13]. An intelligent hybrid control system for scalar IM control use ANFIS optimization [14]. This study confirms the efficacy as well as the upside of a CFOPI model for ascertaining the parameters of a PID controller that manages the common rail tension in the injection system of a compressed fossil fuel engine. Parameters are derived by PSO process that integrates a cost factor evaluating effectiveness and reliability metrics [15]. A review of previous work in the field indicates that a few researchers have used CFOPI controllers to control IMs via IFOC strategies. Those who have investigated this type of controller utilized the trial and error method to ascertain optimal parameter values.

**Materials and methods.** The control architecture of IFOC (Fig. 1) is a vector control method widely accepted in high performance drive vehicles. The theory fundamentally relies on decoupling flux and torque by regulating the stator current component [16, 17]. The components of the control circuit in Fig. 1 are next [2, 18]: $R_r$ is the rotor resistance, $L_r$ is the rotor self-inductance, $T_m$ is the electromagnetic torque, $p$ is the number of pole pairs, $L_m$ is the magnetizing inductance, $\psi_{dr}$ is the rotor flux, $\omega$ is the angular frequency, $I_{abc}$ is the IM current, $i_d$, $i_q$ are the rotating currents in $d$-$q$ axis; $\omega_r$ is the IM angular speed.

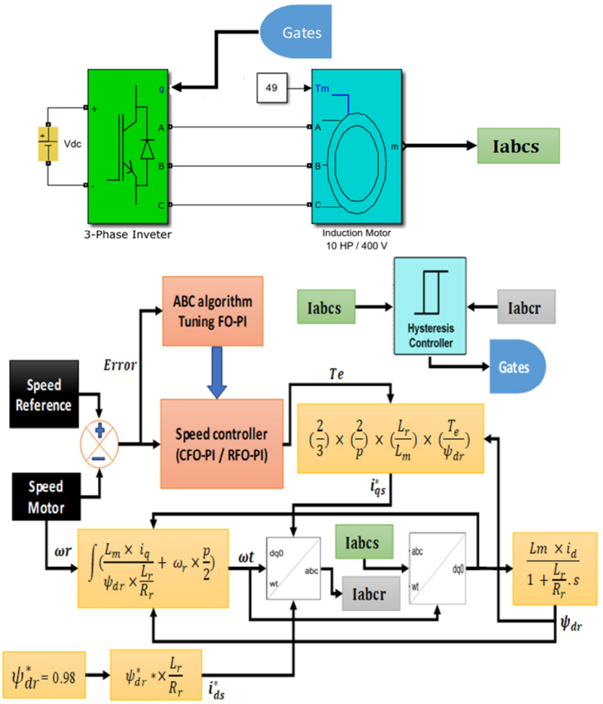

Fig. 1.The control architecture of IFOC of IM

**Types of FOPI controllers**. FOPI controllers are extensively utilized in various control projects to attain accurate system efficiency [19]. The bulk of the controllers possess real and complex components with fractional order integrals [20].

The general CFOPI controller is represented as [21, 22]:

$$G_c(s)=K_p+K_i\cdot\left(\frac{1}{s}\right)^{\alpha+j\beta}, \tag{1}$$

where $K_p$ is the proportional value; $K_i$ is the integral value; $\alpha$, $\beta$ are the non integer number (fractional values); $s$ is the fractional operator.

The complex integrator can be written as:

$$\left(\frac{1}{s}\right)^{\alpha+j\beta}=\left(\frac{1}{s}\right)^{\alpha}\cdot\left(\frac{1}{s}\right)^{j\beta}; \tag{2}$$

$$\left(\frac{1}{s}\right)^{\alpha+j\beta}=\left(\frac{1}{s}\right)^{\alpha}\cdot e^{j\beta\ln\left(\frac{1}{s}\right)}; \tag{3}$$

$$\left(\frac{1}{s}\right)^{\alpha+j\beta}=\left(\frac{1}{s}\right)^{\alpha}\cdot\left(\cos\left(\beta\ln\left(\frac{1}{s}\right)\right)+j\sin\left(\beta\ln\left(\frac{1}{s}\right)\right)\right). \tag{4}$$

If the complex operator is applied to a real input it will result in a complex response. So, in practice, it is realized by extracting the real part. The transfer function of CFOPI controller denoted as [23]:

$$\left(\frac{1}{s}\right)^{\alpha+j\beta}=\left(\frac{1}{s}\right)^{\alpha}\cdot\cos\left(\beta\ln\left(\frac{1}{s}\right)\right). \tag{5}$$

According to (1), when the real and imaginary parts are fractional values, the transfer function of the fractional controller has a real and imaginary form, as expressed as:

$$CFOPI(s)=K_p+K_i\cdot\left(\frac{1}{s}\right)^{\alpha}\cdot\cos\left(\beta\ln\left(\frac{1}{s}\right)\right). \tag{6}$$

The transfer function of RFOPI controller is:

$$RFOPI(s)=K_p+K_i\cdot\left(\frac{1}{s}\right)^{\alpha}. \tag{7}$$

According to (1), when the imaginary component is null, the transfer function of the fractional controller has a real style, as articulated in the subsequent equation:

**ABC algorithm** is engineered to mimic the actions of wild bees to get best solutions for constrained scenarios. The core ABC idea comprises 3 categories of bees: worker bees, spectator bees and spy bees. 50 % of the swarm consists of hired bees, while the other 50 % consists of observation bees. Just one artificial hired bee is supposed to exist for each food source [24]. The quantity of worker bees in the group correlates with the food sources in proximity to the hive. Foraging bees access their food supply and thereafter return to the hive to perform a dance in this area. The employed bee that has forsaken its food reserve metamorphoses into a scout and starts the search for a fresh source of food. Scouts methodically investigate their environment to identify a novel food source, driven by personal motivation, environmental indicators, or serendipity. Onlooker bees stay within the hive and assess which kind of food to utilize depending on the knowledge supplied by forager bees [25]. Table 1 explains the parameters of ABC algorithm.

Table 1

Selection of the settings for the ABC algorithm

| Parameters | Values |
|---|---|
| No. of bees and limit | 15 and 30 |
| No. of food sources | Round (no. of bees/2) |
| Population size and iteration number | 15 and 15 |
| Range of $K_P$ and $K_i$ | $0\le K_P\le 200$ and $0\le K_i\le 200$ |
| Range of real and imaginary part of CFO-PI controller | $0\le\alpha\le 1$ and $0\le\beta\le 1$ |

**Driving cycle for Mosul City (Iraq).** Definition of a driving cycle collection of data points illustrating vehicle speed in relation to time. Several driving cycles are employed globally for homologation, including the FTP-75 in the USA, the NEDC in Europe, and the J10-15 in Japan [26]. These cycles frequently encompass additional sub phases designed to illustrate low and high speed sequences or various driving environments such as urban, rural or freeway settings [27]. The proposed driving model was used to test the best type of fractional PI controllers and find the most efficient controller for tracking the required speeds of Mosul City's driving cycle. The proposed driving cycle includes reversing the electric vehicle's speed. The characteristics of the Mosul driving cycle the test duration is 12 min (Fig. 2). The load of 7.46 kW is kept constant during the driving cycle's execution and consists of the following durations as detailed in Table 2.

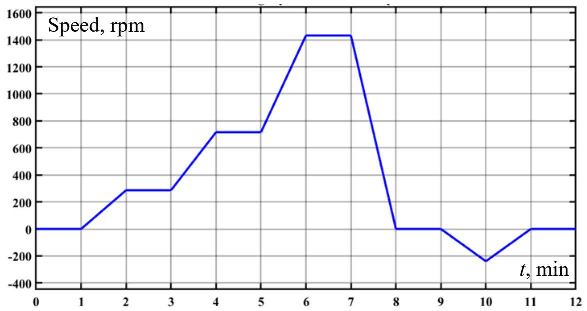

Fig. 2. Mosul City driving cycle

Table 2

Clarify the features of the driving cycle test for a control system in an electric vehicle

| Duration, min | Speed case, rpm | Duration, min | Speed case, rpm |
|---|---|---|---|
| [0–1] | Turn off speed | [7–8] | Decrease speed (breaking mode) [1432–0] |
| [1-2] | Increase speed [0–286] | [8–9] | Turn off speed |
| [2–3] | Constant at 286 | [9–10] | Reverse speed direction [0–238] |
| [3–4] | Increase speed [286–716] | [10–11] | Decrease speed [238–0] |
| [4–5] | Constant at 716 | [11–12] | Turn off speed |
| [5–6] | Increase speed [716–1432] | | |
| [6–7] | Constant at 1432 | | |

**Simulation and results.** This section shows the simulation method for controlling the speed of an electric vehicle using a three-phase IM, which parameters are shown in Table 3.

Table 3

Parameters of the IM

| Parameters | Value |
|---|---|
| Rated power $P$, HP | 10 |
| Voltage $V$, V | 400 |
| Frequency $f$, Hz | 50 |
| Angular speed $\omega_r$, rpm | 1440 |
| Stator resistance $R_s$, Ω | 0.7384 |
| Stator self-inductance $L_s$, mH | 3.045 |
| Rotor resistance $R_r$, Ω | 0.7402 |
| Rotor self-inductance $L_r$, mH | 3.045 |
| Magnetizing inductance $L_m$, H | 0.1241 |
| Inertia $J$, kg·m$^2$ | 0.0343 |
| Friction factor $F$, N·m·s | 0.000503 |
| Number of pole pairs $p$ | 2 |

It implements an IFOC technique with the proposed FOPI controller types. For an electric vehicle was developed to examine the different kinds of FOPI controllers by using performance Integral Time Absolute Error (ITAE) index:

$$ITAE = \int_0^t t \cdot \left| error(t)\mathrm{d}t \right| . \qquad (8)$$

The performance index showed that the CFOPI controller outperformed the RFOPI controller in obtaining the best results in tracking the driving cycle signal with the slightest error. Table 4 shows the parameters of all FOPI types by tuning ABC algorithm and identify the optimal variant, reflecting the characteristics of the roadways in Mosul (Iraq).

Table 4

Tuning the all types of FOPI controller using ABC algorithm

| Controller types | Transfer function | ITAE |
|---|---|---|
| CFOPI | $62.928 + 200 \cdot \left(\frac{1}{s}\right)^{0.982+j0.587}$ | 2.1004 |
| RFOPI | $59.724 + 198.565 \cdot \left(\frac{1}{s}\right)^{0.9}$ | 2.1538 |

Figure 3 shows the IM characteristics, when Mosul driving cycle is applied to the IM using the CFOPI controller by tuning parameters ABC algorithm.

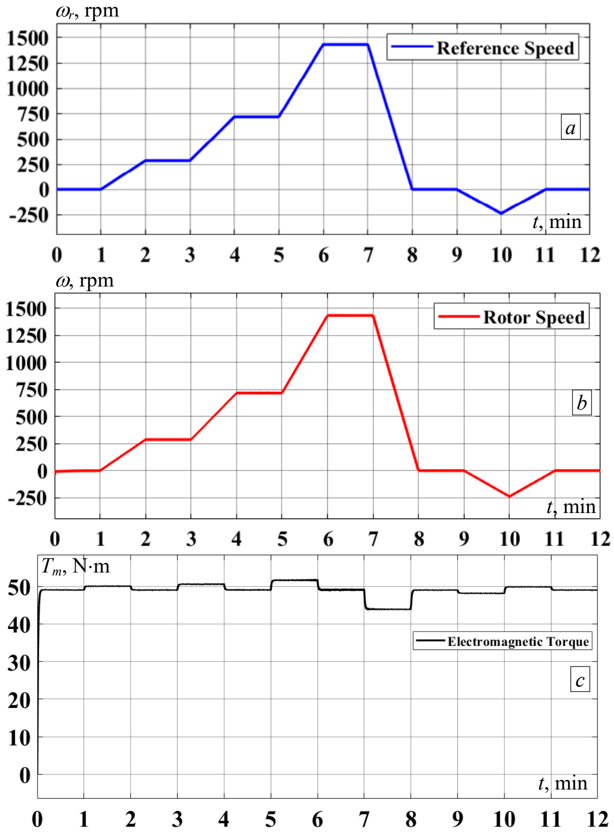

Fig. 3. The driving cycle response of the IM using the CFOPI controller: *a* – driving cycle reference; *b* – driving cycle of rotor speed IM; *c* – electromagnetic torque response

The different kinds of fractional controllers were evaluated using specific reference speeds (for lower-speed and high speed ranges) to facilitate a comparison among controllers. Table 5 indicates that the CFOPI controller surpassed the RFOPI controller, and Fig. 4 illustrates the time response for each reference speed.

Table 5

Comparison of fractional controllers at different reference speeds in terms of the time characteristics of the speed response

| Types of FOPI controller | Speed reference, rpm | Overshoot, % | Peak time, s | Settling time, s | Steady state error, % |
|---|---|---|---|---|---|
| RFOPI | 250 | 8 | 0.012 | 0.13 | 0 |
| | 750 | 5.6 | 0.016 | 0.717 | 0 |
| | 1200 | 5.67 | 0.024 | 0.95 | 0 |
| | 1440 | 6.18 | 0.068 | 0.98 | 0 |
| CFOPI | 250 | 7.6 | 0.012 | 0.12 | 0 |
| | 750 | 4 | 0.016 | 0.4 | 0 |
| | 1200 | 3.66 | 0.024 | 0.74 | 0 |
| | 1440 | 3.95 | 0.074 | 0.92 | 0 |

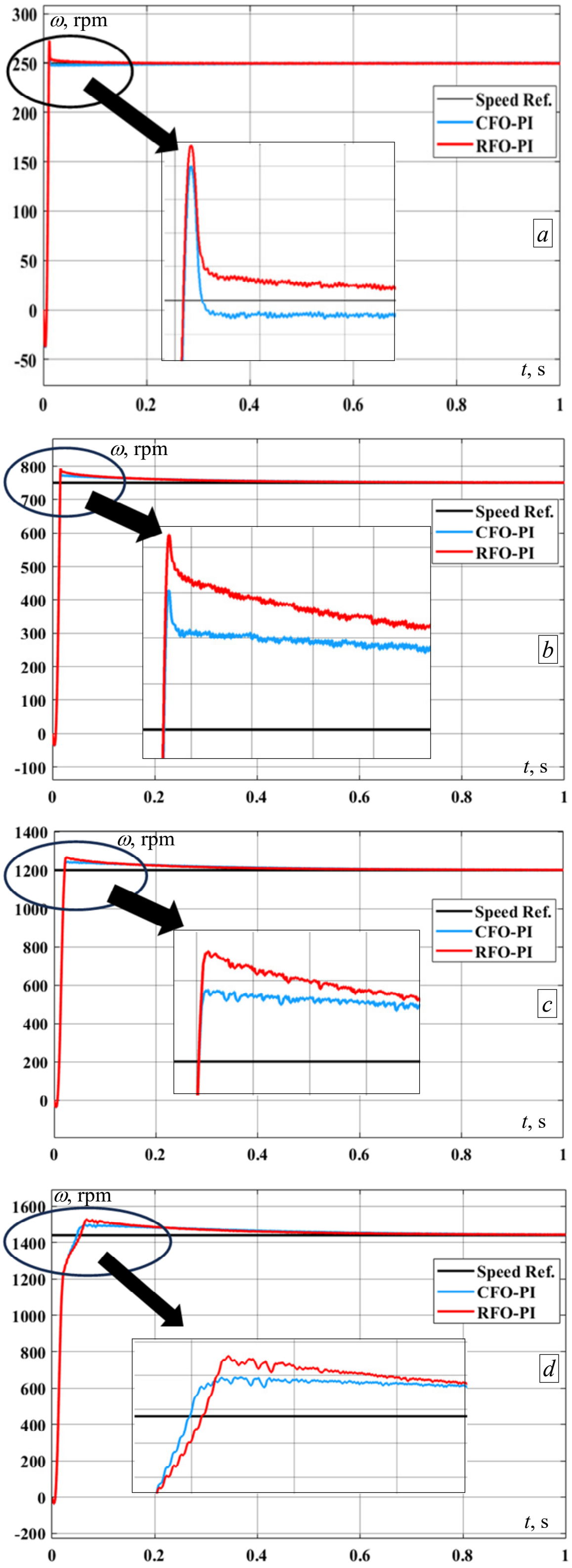

Fig. 4. Speed response of IM by CFOPI and RFOPI controllers for speed references:
*a* – 250 rpm; *b* – 750 rpm; *c* – 1200 rpm; *d* – 1440 rpm

**Conclusions**. IFOC strategy that uses 2 types of fractional controllers was used to control the speed of the three-phase IM via the voltage source inverter circuit, where the firing signal is generated using the hysteresis current method. It is comparative between the proposed controllers using the proposed driving cycle for the city of Mosul (Iraq), which includes several levels of speed values in both directions. And the other pattern is different reference speed levels, where low and high speeds were chosen in order to cover all cases of speed to using the IM in electric vehicle and using the ABC algorithm to find the parameters of the controllers through the results of the simulation turns out the superiority the CFOPI controller over the RFOPI controller, where the lowest ITAE in tracking the motor speed for driving cycle for the CFOPI controller is 2.1004, for the RFOPI controller is 2.1538.

The superiority of the CFOPI controller over the RFOPI controller where the overshoot in speed the limit that is considered one of the most. Important factor to speed control where the controller was CFOPI (7.6 %) and RFOPI (8 %) for reference speed 250 rpm; at reference speed 750 rpm (4 %) and (5.6 %), for 1200 rpm was (3.66 %) and (5.67 %) and for 1440 rpm was (3.95 %) and (6.18 %) respectively.

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**Conflict of interest.** The authors declare that there is no conflict of interest.

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