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Fractional-based iterative learning-optimal model predictive control of speed induction motor regulation for electric vehicles application

Introduction. *A new control strategy based on the combination of optimal model predictive control (OMPC) with fractional iterative learning control (F-ILC) for speed regulation of an induction motor (IM) for electric vehicles (EVs) application is presented. OMPC uses predictive models to optimize speed control actions by considering the dynamic behavior of the IM, when integrated with the F-ILC, the system learns and refines the speed control iteratively based on previous iterations, adapting to the specific characteristics of the IM and improving performance over time. The synergy between OMPC and F-ILC named F-ILC-OMPC enhances the precision and adaptability of speed control for IMs in EVs application, and optimizes the energy efficiency and responsiveness under varying driving conditions.* ***The novelty*** *lies in the conjunction of the OMPC with the ILC-based on the fractional calculus to regulate the speed of IMs, which is original.* ***Purpose.*** *The new control strategy provides increased performance, robustness and adaptability to changing operational conditions.* ***Methods.*** *The mathematical development of a control law that mitigates the disturbance and achieves accurate and efficient speed regulation. The effectiveness of the suggested control strategy was assessed via simulations in MATLAB conducted on an IM system.* ***Results.*** *The results clearly show the benefits of the F-ILC-OMPC methodology in attaining accurate speed control, minimizing steady-state error and enhanced disturbance rejection.* ***Practical value.*** *The main perspective lies in the development of a speed control strategy for IMs for EVs and the establishment of reliable and efficient electrical systems using ILC-OMPC control. This research has the prospect of a subsequent implementation of these results in experimental prototypes.* References 24, tables 2, figures 9.

Key words: **optimal model predictive control, iterative learning control, induction motor, speed control, electric vehicles.**

Вступ. *Представлено нову стратегію керування, яка базується на поєднанні прогнозного керування оптимальною моделлю (OMPC) з дробовим ітеративним навчальним керуванням (F-ILC) для регулювання швидкості асинхронного двигуна (АД) для застосування в електромобілях. OMPC використовує прогнозні моделі для оптимізації дій керування швидкістю, враховуючи динамічну поведінку АД. При інтеграції з ILC на основі дробів система вивчає та вдосконалює керування швидкістю ітеративно на основі попередніх ітерацій, адаптуючись до конкретних характеристик АД та підвищення продуктивності з часом. Синергія між OMPC і F-ILC під назвою F-ILC-OMPC підвищує точність і адаптивність регулювання швидкості для АД в електромобілях, а також оптимізує енергоефективність і чутливість за різних умов руху.* ***Новизна*** *полягає в поєднанні OMPC з ILC на основі дробового числення для регулювання швидкості АД, що є оригінальним.* ***Призначення.*** *Нова стратегія управління забезпечує підвищену продуктивність, надійність і адаптивність до мінливих умов експлуатації.* ***Методи.*** *Математичний розвиток закону керування, який пом'якшує збурення та досягає точного та ефективного регулювання швидкості. Ефективність запропонованої стратегії керування була оцінена за допомогою моделювання у MATLAB, проведеного на системі АД.* ***Результати.*** *Результати чітко показують переваги методології F-ILC-OMPC у досягненні точного контролю швидкості, мінімізації стаціонарної помилки та покращеного усунення перешкод.* ***Практична цінність****. Основна перспектива полягає в розробці стратегії регулювання швидкості АД для електромобілів і створення надійних і ефективних електричних систем з використанням керування ILC-OMPC. Дане дослідження має перспективу подальшого впровадження цих результатів в експериментальні прототипи.* Бібл. 24, табл. 2, рис. 9.

Ключові слова: **оптимальна модель прогнозного керування, ітераційне навчальне керування, асинхронний двигун, керування швидкістю, електромобілі.**

Abbreviations

DTC	Direct Torque Control	IM	Induction Motor
EV	Electric Vehicle	ILC	Iterative Learning Control
FCS-PTC	Finite Control Set-Predictive Torque Control	MPC	Model Predictive Control
F-ILC	Fractional Iterative Learning Control	OMPC	Optimal Model Predictive Control
IFOC	Indirect Field-Oriented Control	SVM	Space Vector Modulation

Introduction. EV is a vehicle that uses one or more electric motors for propulsion. In contrast to traditional vehicles that rely only on internal combustion drive fueled by gasoline or diesel, EVs include reduced greenhouse gas emissions, lower operating costs due to lower maintenance and electricity costs compared with gasoline, and the potential for using renewable energy sources to charge batteries.

Several types of electric motors are commonly employed in these vehicles. The choice of motor depends on factors such as vehicle type, performance requirements, and cost. IMs offer several advantages when used in EVs, contributing to their widespread adoption in the automotive industry. It has a simple and robust design, and the simplicity of the IMs results in lower maintenance requirements. In addition, IMs can operate at high efficiency levels and are self-starting, eliminating the need for additional starting mechanisms.

The motor's driver (traction inverter and controller) is a crucial component of an EV. It regulates the power supplied to the electric motor based on the driver's input and other factors. It can adjust the voltage and current to control the speed of the electric motor. Speed control is part of a larger vehicle control system that manages various aspects, including safety, stability, and efficiency. This overarching system integrates inputs from multiple sensors and subsystems to ensure a smooth and controlled driving experience.

There are many methods for controlling the speed of EVs that can be applied to a variety of electric motors. One can site some of them, like the PID controller which involves proportional, integral and derivative components to regulate the system. It helps in achieving the desired speed regulation of EV motors [1].

In [2], authors proposed a back-stepping control technique with SVM strategy for IM. A load torque observer was designed to enhance speed tracking, and system stability was studied using Lyapunov theory.

The authors [3] have used a model reference adaptive system observer to ensure the continuity of the drive of a permanent magnet synchronous motor and improve its reliability by eliminating the speed sensor. The performance and robustness of the system were tested using real driving scenarios.

Other researchers have used the zeta converters in improving the speed control of brushless DC motors for small EVs. The goal was to develop EVs that reduce emissions by utilizing renewable fuels. The study proposed the use of a PI controller assisted by a hysteresis current controller to regulate the motor's speed [4].

The paper [5] presented a new approach for estimating the speed of in-wheel EV with two independent rear drives. This study focused on the use of variable-speed IMs. The objective is to improve the dynamic performance of the control system using type-1 and type-2 fuzzy logic controllers in a model reference adaptive system.

The authors of [6] have developed and tested a DTC control for EVs for a six-phase motor with adaptive speed estimator, and extensive SVM.

Another DTC scheme with a predictive speed and flux control of an IM for an EV was used in [7], authors proposed also a sliding mode observer to accomplish a sensorless estimation technique in aim to achieve efficient torque control and higher efficiency. The design has included the implementation of the sliding mode observer, with stator currents transformation, and flux angle estimation.

The main work in [8] was the design of a speed-sensorless control based on finite control set-predictive torque control (FCS-PTC) in IM drive system. An adaptive fading-based extended Kalman filter observer was used to estimate the angular speed and the flux that are required for the FCS-PTC algorithm. The load torque is estimated to improve speed estimation performance, and it is used in the feed-forward control loop to enhance load disturbance rejection. It was shown that FCS-PTC offers advantages such as easy implementation, handling of nonlinearities, and inclusion of constraints.

The fractional PID controller is a type of control system that extends the traditional PID controller by introducing fractional-order calculus into the proportional, integral, and derivative terms [9]. This type of controller has attracted great interest from researchers thanks to its advantages.

In [10] the authors address the issue of torque ripples generated by a motor when using a PID controller, which can lead to increased noise in the system. They proposed a fractional-order-based PID control scheme that offers faster tracking and reduces the magnitude of torque ripples compared to traditional PID control. Authors of [11] have applied a new controller for EV speed control which was based on a fuzzy fractional-order PID algorithm and the Ant Colony Optimization technique for parameter's tuning was used. The controller's performance was evaluated using the new European driving cycle.

The goal of the paper is the design of a new strategy for speed control of an IM using a combination of OMPC and ILC. The objective is to achieve accurate and efficient speed regulation of the motor in EVs application. OMPC leverages predictive models to optimize speed control actions, it provides a real-time optimization approach that predicts future motor behavior and generates control signals accordingly. When combined with ILC, the system benefits from iterative learning, enabling it to refine speed control based on previous experiences, which enables the system to learn from previous iterations and improve performance over time. The ILC uses the error information from previous control cycles to update the control inputs and reduce tracking errors in subsequent iterations. The proposed control strategy was evaluated through simulations of an IM system. The results demonstrate the effectiveness of the OMPC–ILC approach in achieving precise speed control with reduced steady-state error and improved disturbance rejection compared with other control methods.

IM model and theory of the control. The powertrain of an EV is a system that propels the vehicle by converting electrical energy from the battery into mechanical energy for driving (Fig. 1). It typically consists of several key components that work together to achieve efficient and controlled vehicle movement [12, 13].

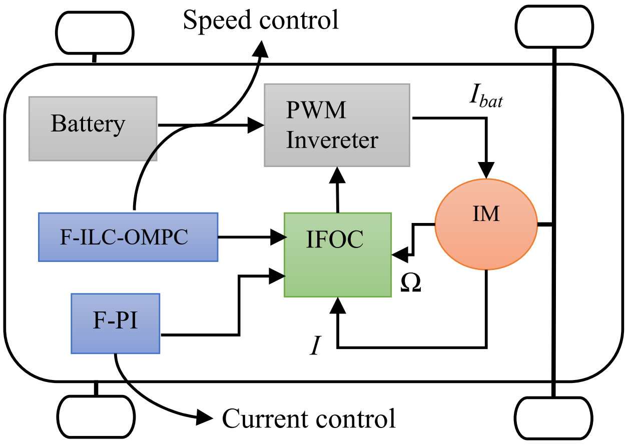

Fig. 1. EV powertrain

IM belongs to electric motors which are predominant in EVs, thanks to its simplicity, reliability, and robustness. The mathematical model of the motor's electric and mechanical dynamics is given by the equations (1)–(4) [14]:

$$\begin{cases} v_{ds} = R_s i_{ds} + \dfrac{\mathrm{d}\varphi_{ds}}{\mathrm{d}t} - \omega_e \varphi_{qs}; \\ v_{qs} = R_s i_{qs} + \dfrac{\mathrm{d}\varphi_{qs}}{\mathrm{d}t} - \omega_e \varphi_{ds}; \\ v_{dr} = R_r i_{dr} + \dfrac{\mathrm{d}\varphi_{dr}}{\mathrm{d}t} - (\omega_e - \omega_r)\varphi_{qs}; \\ v_{qr} = R_r i_{qr} + \dfrac{\mathrm{d}\varphi_{qr}}{\mathrm{d}t} + (\omega_e - \omega_r)\varphi_{qs}; \end{cases} \tag{1}$$

$$\begin{cases} \varphi_{ds} = L_s i_{ds} + L_m i_{dr}; \\ \varphi_{qs} = L_s i_{qs} + L_m i_{qr}; \\ \varphi_{dr} = L_r i_{dr} + L_m i_{ds}; \\ \varphi_{qr} = L_r i_{qr} + L_m i_{qs}; \end{cases} \tag{2}$$

$$J\frac{\mathrm{d}\Omega}{\mathrm{d}t} = T_{em} - T_L - f\,\Omega; \tag{3}$$

$$T_{em} = p\left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}\right), \tag{4}$$

where v_d, v_q, i_d, i_q, φ_d and φ_q are the *dq* components of the rotor (symbol «*r*») and stator (symbol «*s*») voltage, current and flux linkage, respectively; L_r, L_s, R_r, R_s are the rotor and stator self-inductances and resistances; p is the pairs number of poles; ω is the angular speed; L_m is the magnetizing inductance; J is the motor moment inertia; Ω is the speed; T_{em} is the motor torque; T_L is the load torque; f is the viscous friction coefficient

Indirect field-oriented control. Also known as vector control, it's a popular control strategy used in the field of electric motor control. The primary objective of IFOC is to control the stator currents of a three-phase AC IM in a manner that simplifies the control task. Speed control is achieved by regulating the torque-producing current based on the desired speed (Fig. 2).

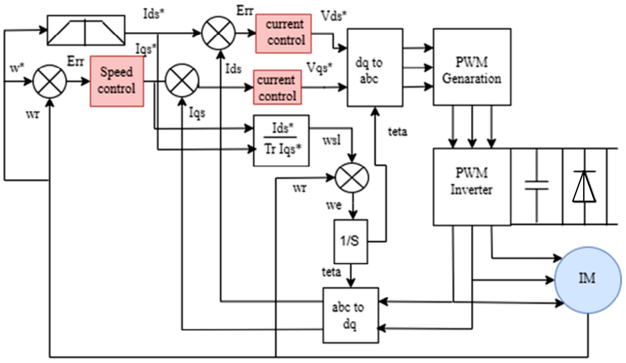

Fig. 2. Block diagram of control strategy IFOC

IFOC provides several advantages, including high dynamic performance, efficient torque control, and the ability to operate over a wide speed range. It is widely used in applications where precise control of motor performance is crucial, such as in EVs.

Iterative learning control. The control law within the framework of ILC is presented as the mathematical relationship or the algorithm that determines how to adjust control inputs at each iteration to reduce errors and enhance performance over time. The underlying objective of this control law is to assimilate insights derived from errors encountered in previous iterations and to make adjustments to control inputs for a more efficient convergence towards the desired performance. The PID-type ILC control law is given as follows [15, 16]:

$$U_{k+1}(t) = U_k(t) + K_p e_k(t) + K_i \int e_k(t)\mathrm{d}t + K_d \dot{e}_k(t), \tag{5}$$

where $U_k(t)$ is the control input at the current iteration; $U_{k+1}(t)$ is the control input at the next iteration; $e_k(t)$ is the error between the desired and actual outputs at the current iteration.

In (5), the control input for the next iteration $U_{k+1}(t)$ is modified based on the current control input $U_k(t)$ and the error $e_k(t)$ observed in the current iteration. This adjustment is scaled by the learning parameter (K_p, K_i and K_d) that determine the magnitude of the control input adjustment. It is worth highlighting that the actual structure of the control law may be more intricate and could encompass additional terms or considerations depending on the unique attributes of the system and the task at hand. The selection of the learning (K_p, K_i and K_d) is pivotal and may necessitate tuning to attain optimal performance in a specific application.

Optimal model predictive control. MPC is an advanced control strategy used in various industries to optimize the performance of dynamic systems. OMPC is an extension of MPC that emphasizes finding an optimal control policy while considering system constraints, dynamic models, and performance objectives [17, 18].

These models are used to predict the future behavior of the system based on current and past states and inputs.

The dual mode represents a control strategy that relies on predictions using two distinct modes. The first mode is applied when the system is distant from the steady state, while the second mode comes into play as the system approaches the desired operating point.

The control law can be elaborated as [17, 19]:

$$U_k = -KX_k + C_k \cdot K \le n_c; \tag{6}$$

$$U_k = -KX_k \cdot K > n_c, \tag{7}$$

where n_c is the control horizon; C_k is the perturbations; X_k is the state space model; K is the state feedback gain, it can be determined by using the MATLAB command [K] = dlqr (A, B, Q, R), where Q and R are the real symmetric matrices, semi-positive definite, and positive definite, respectively.

The cost function is expressed as:

$$J = X_k^T S_k X_k + C_{\to k}^T S_{cx} C_{\to k} + 2X_k^T S_{cx} C_{\to k}, \tag{8}$$

where S_k, S_c and S_{cx} are the parameters of the cost function after solving using a standard Lyapunov identity to form the predicted cost.

To ensure good performance and tracking of the reference r, we propose setting ($Y_k = r$), we added some terms (X_{ss}) and (U_{ss}) at each step k, that express the desired stable state as follows ($X_k = \hat{X}_k + X_{ss}$) and ($U_k = \hat{U}_k + U_{ss}$):

$$Y_k = CX_x; \tag{9}$$

$$X_{ss} = AX_x + BU_{ss}; \tag{10}$$

$$\begin{bmatrix} Y_{ss} \\ 0 \end{bmatrix} = \begin{bmatrix} C & 0 \\ A-I & B \end{bmatrix} \begin{bmatrix} X_{ss} \\ U_{ss} \end{bmatrix}; \tag{11}$$

$$\begin{bmatrix} X_{ss} \\ U_{ss} \end{bmatrix} = \begin{bmatrix} C & 0 \\ A-I & B \end{bmatrix}^{-1} \begin{bmatrix} r \\ 0 \end{bmatrix}. \tag{12}$$

We define:

$$\begin{bmatrix} X_{ss} \\ U_{ss} \end{bmatrix} = \begin{bmatrix} M_x \\ M_u \end{bmatrix} \begin{bmatrix} r \\ 0 \end{bmatrix}. \tag{13}$$

Therefore, we have:

$$X_{ss} = M_x \cdot r; \tag{14}$$

$$U_{ss} = M_u \cdot r. \tag{15}$$

By substituting X_{ss} and U_{ss} into (6):

$$U_k - U_{ss} = -K(X_k - X_{ss}) + C_k; \tag{16}$$

$$U_k = -KX_k - K\,M_x \cdot r + M_u \cdot r + C_k. \tag{17}$$

So:

$$U_k = -KX_k + (K\,M_x - M_u)\cdot r + C_k, \tag{18}$$

where A, B, and C are the matrices that define the system dynamics and relationships between state, input, and output:

$$\begin{cases} \dot{X} = AX + BU; \\ Y = CX + DU, \end{cases} \quad (19)$$

where X is the state vector of dimension n; U is the system input (or control) of dimension m; Y is the system output of dimension r; A is the state matrix (or evolution matrix) dim $[A(.)] = n \times n$; B is the input matrix dim $[B\,(.)] = n \times m$; C is the output matrix (or observation matrix) dim $[C\,(.)] = r \times n$; D is the feed forward matrix dim $[D\,(.)] = r \times m$.

Design of the combination of F-ILC and OMPC (F-ILC-OPMC). Now we will elaborate the proposed control strategy for the speed control of an IM using the proposed combination of OMPC and iterative learning control.

From the OMPC we substitute the control law formulation of U_k determined in (15) into the ILC (5); so one can find the new ILC control law as follows:

$$U_{k+1}(t) = \alpha + \beta, \quad (20)$$

where:

$$\alpha = \left[-KX_k + \left(KM_x - M_u\right) \cdot r + C_k\right]; \quad (21)$$

$$\beta = K_p e_k(t) + K_i \int e_k(t) \mathrm{d}t + K_d \dot{e}_k(t). \quad (22)$$

The second term of (20) named β constitutes the PID-type ILC as defined in its original form in (5). In our case, we propose a fractional order controller which is FOP ID-type of ILC as it is illustrated in Fig. 3.

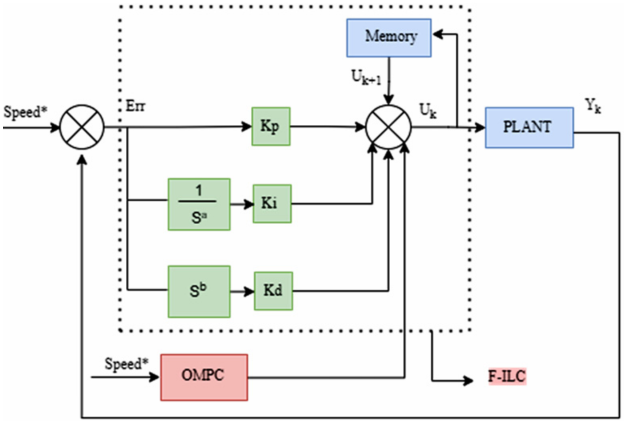

Fig. 3. Block diagram of the fractional control law F-ILC-OMPC

In standard PID controllers, the order of the terms is restricted to integer values (1 for proportional, integral, and derivative). However, fractional-order PID controllers allow the use of fractional orders, which allow additional degrees of freedom for tuning and optimizing control systems [20].

In addition, the use of fractional orders allows more flexibility in shaping the frequency response and adapting the controller to specific system dynamics. For this purpose, we use it in the ILC law control:

$$\beta = \left[K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\gamma}\right] e_k(t), \quad (23)$$

where λ, γ are the fractional orders for the integral and derivative terms, respectively; s is the Laplace variable.

The full controller is depicted in Fig. 3.

Simulation and analysis. The regulation of the IM's speed relies on the subsequent closed-loop equations:

$$G(s) = \frac{1}{Js + f}; \quad (24)$$

$$H(s) = \frac{G}{G+1}, \quad (25)$$

where H is the closed-loop speed; G is the open loop speed transfer function.

In a state-space representation, a dynamic system is described by a set of first-order differential or difference equations, so that H is transformed in state-space and we use A, B, and C to determine the control law.

The F-ILC-OMPC is injected in the speed loop of the IFOC (Fig. 4). The IM parameters are reported in Table 1 [21].

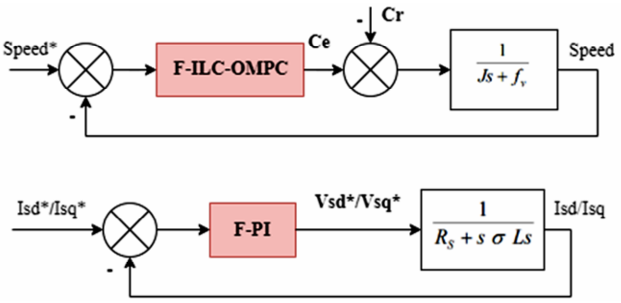

Fig. 4. Control loop of speed with F-ILC-OMPC and current with F-PI

Table 1

IM's parameters

Rated shaft power P_n, kW	3
Line-to-line voltage V_n, V	220 / 380
Rated speed N_n, rpm	1500
Pairs number of poles	2
Stator self-inductance L_s, mH	261
Rotor self-inductance L_r, mH	261
Magnetizing inductance L_m, mH	249
Stator resistance R_s, Ω	2.3
Rotor resistance R_r, Ω	1.55
Machine inertia J, kg·m^2	0.0076
Viscous friction coefficient f, kg·m^2/s	0.0007

Performance assessment is conducted using MATLAB simulations to illustrate the responses of the rotor speed, electromagnetic torque and stator phase current under the F-ILC-OMPC controller.

The system's speed tracking response is examined under the conditions of a multi-step speed references with [400, 900, 1500, –1500] rpm at [0 s, 0.5 s, 1 s, 1.5 s]. A load torque of 7 N·m disturbs the system at time 0.7 s.

Figures 5, 6 show the pursuing curve of the actual speed compared to its reference, in addition, the stability of the system is tested when it's disturbed by the application of the resisting torque. With this scenario, it's clear that the system ensures a stable and efficient tracking performance since the rise time is about 0.0243 s and with an overshoot about only 0.33 %.

The behavior of the electromagnetic torque is shown in Fig. 7. This curve shows a fast dynamic response during the regulation process, the goal is typically to ensure that the motor operates at the desired torque level (7 N·m), and maintaining stability and efficiency.

The direct and quadratic components of the stator currents of the IM (Fig. 8) refers to the controlled or adjusted current flowing through the stator windings of the motor during the test scenario. A simple two F-PI regulators was sufficient to achieve the desired stator currents regulation and no sharp peaks was induced (Fig. 9).

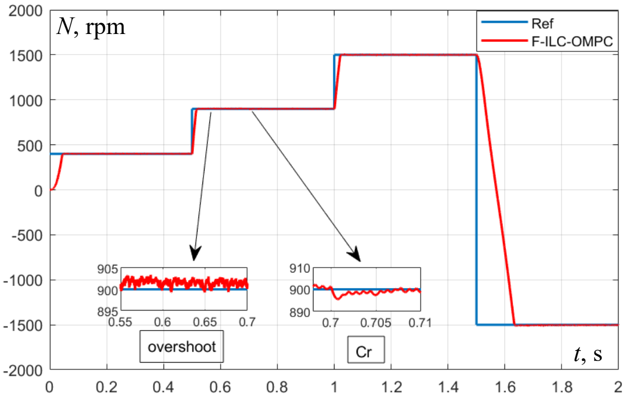

Fig. 5. Speed response of IM with F-ILC-OMPC controller

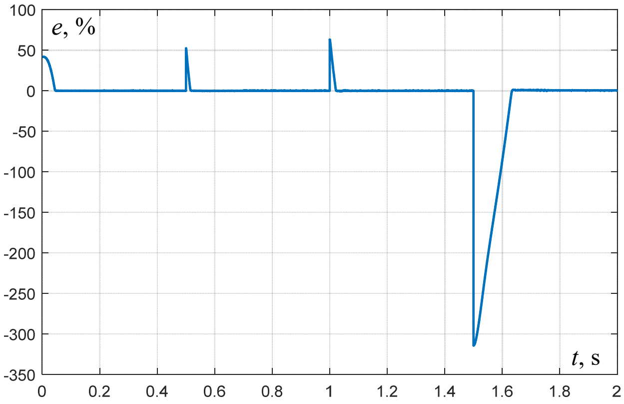

Fig. 6. Error between the actual speed and the reference

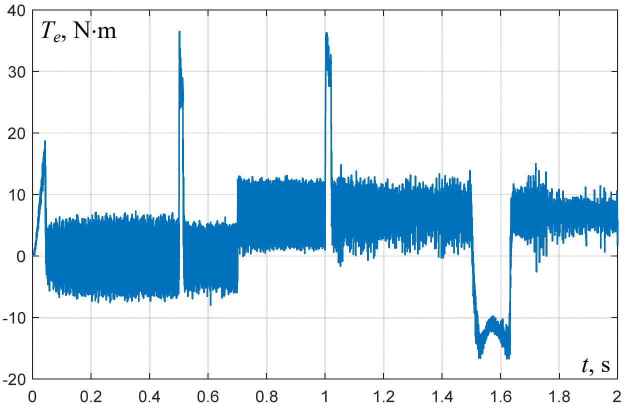

Fig. 7. Electromagnetic torque response

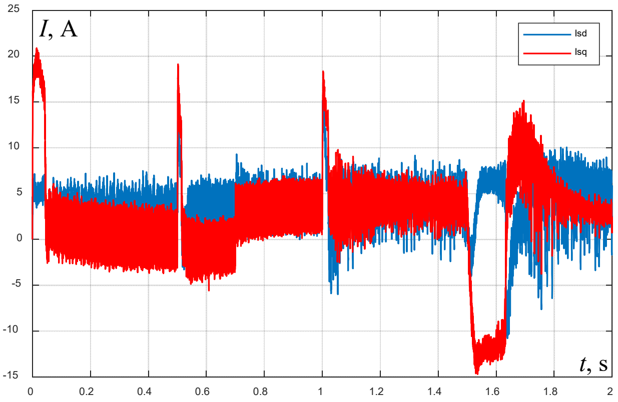

Fig. 8. Currents I_{sq}, I_{sd} of IM with ILC-OMPC controller

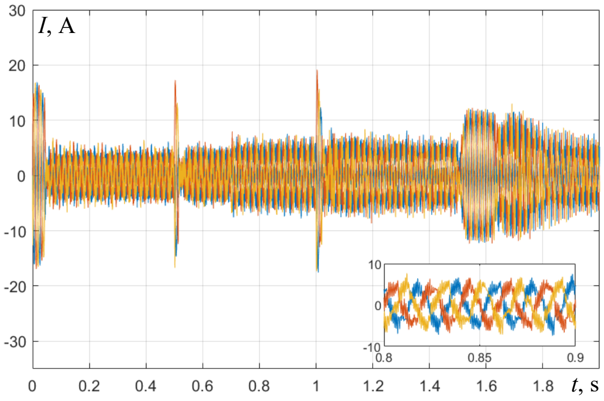

Fig. 9. Three phase stator currents of IM

The results obtained using our proposed method is juxtaposed with other references in Table 2. Various controllers were used for the control of electrical machines, and we have endeavored to make the comparison as fair as possible.

Table 2

Comparison with other references

Controller	Rise time, s	Overshoot, %	Settling time, s	Disturbance rejection time, s	Ref.
DTC-slide mode NPC	0.9	10	2	–	[7]
MFPCC	0.7	6	2	1	[22]
ASMC-MPTC	0.25	–	0.3	0.4	[23]
FPIM-OESW	0.38	2	0.5	–	[24]
F-ILC-OMPC	0.0243	0.33	0.048	0.071	Proposed method

Conclusions. The proposed F-ILC-OMPC approach was evaluated through simulations using an IM. The results demonstrated that the combination of F-ILC and OMPC yields higher speed control performance compared with other control methods. It achieves faster response times, better tracking accuracy and improved disturbance rejection. As expected, OMPC with F-ILC strategy offers an effective solution for the speed control of IMs and can be exploited in EVs application. It leverages predictive modeling, real-time optimization, and iterative learning to achieve precise and efficient speed regulation in the electrical motored system.

In summary, the combination of OMPC and F-ILC offers a promising approach for speed control of IMs, providing enhanced performance, robustness, and adaptability to varying operating conditions.

Conflict of interest. The authors declare that they have no conflicts of interest.

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