

A tracking control design for a DC motor using robust sliding mode learning control

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ABSTRACT

The proposed robust sliding mode learning control (RSMLC) is a new control approach that uses immediate feedback from the closed-loop system to improve tracking performance. A recursive learning technique is integrated with the sliding mode controller to ensure that the tracking error and sliding variables asymptotically converge to zero, which can be guaranteed within the framework of the proposed control approach. Moreover, the proposed controller design does not require system uncertainty and its upper limits. Thus, these benefits can be significantly simplified and mitigated by the design and implementation of RSMLC for DC motor applications. In comparison with conventional sliding mode control (CSMC), the RSMLC structure does not contain an explicit switching element, so the chattering phenomenon will be eliminated. Meanwhile, it will preserve the CSMC's durability feature. Based on Lyapunov criteria, the stability and convergence analysis of the proposed controller were rigorously proved. Additionally, CSMC and SMLC controllers have been shown to outperform proportional integral derivative (PID) controllers in systems with nonlinear dynamics, high-order systems, or uncertainties. Finally, simulation studies of the DC motor system were carried out under the proposed controller. In contrast, the CSMC simulation results are also presented for comparison purposes and to verify the validity and effectiveness of the proposed RSMLC via CSMC and PID controllers.

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1. INTRODUCTION

According to the forms of commutation, the DC motor can be divided into brushed and brushless (BL) DC motors [1]. These motors are highly preferred due to their low maintenance and precise control, leading to their extensive use in robotics, automotive, aerospace, and automation equipment [2]. To assess the performance and characteristics of large DC motors, a prototype motor was designed, and adjustments were made to factors like the motor size to prevent defects and damage [3]. Also, for time-sensitive applications, networked control systems were used to establish connections with multiple sensors, actuators, and controllers via a shared data network, thus reducing the need for cumbersome wiring connections. By using controller gain conditioning, a method was developed to improve the network control framework's performance [4].

The speed control and load torque control of a series DC motor were challenged by utilizing two nonlinear feedback techniques based on feedback and input/output linearization methods. A linear feedback

controller, incorporating advanced state space switching for full state trajectory control, was employed [5]. To ensure effective tracking and control, the time-varying disturbance signals were estimated and cancelled using the extended proportional integral (PI) observer [6]. For optimizing the performance of a brushless DC (BLDC) drive, a fuzzy slider mode controller (FSMC) was employed, intelligently adjusting its gain through a fuzzy inference system (FIS) [7]. Furthermore, regarding the characteristics of the control system response, the performance of the BLDC motor controller based on an adaptive neuro-fuzzy inference system (ANFIS) was compared to that of the conventional PI, fuzzy tuned proportional integral derivative (PID), and fuzzy variable structure controllers [8]. Furthermore, the study emphasized the importance of braking force distribution and control in regenerative braking systems (RBS), specifically when adapted for the BLDC motor [9]. The focus was on optimizing the distribution of braking force using fuzzy logic control, as an alternative to the conventional PID control [10]. Due to the PID controller's shortcomings concerning non-customized performance metrics and a lack of process data, optimization algorithms like the genetic algorithm (GA), and cuckoo search (CS) were successfully utilized to tune PID controllers for monitoring the set-point in DC motor speed control by diminishing the integrated time absolute error (ITAE) in disturbance rejection [11]. Artificial bee colony optimization (ABC), a bio-inspired optimization technique, was suggested to develop a speed controller for the DC motor to achieve a result of improved static and dynamic performance [12]. Moreover, a networked predictive control (NPC) technique was designed and utilized for DC motor control to account for the impact of package dropouts and time-changing delays. Also, the closed-loop networked control systems (NCS) with uncertainties were characterized as a coupled switching control system using the Lyapunov function approach to maintain the system's robust stability as far as linear matrix inequalities [13].

On the other hand, within the sight of uncertainties and perturbations, an efficient sliding mode controller (SMC) for classical nonlinear control was designed to maintain the system's stability. Due to its robustness and rapid convergence against system perturbations and uncertainties, SMC was deployed to control the DC motor employed in various industrial applications as well as certain robots, such as the robotic hand [14], industrial robotic gripper [15], permanent magnet synchronous machine (PMSM) [16], and analysis was carried out while the load was changing to avoid being impacted by the loading circumstances [17]. The global SMC was used for the BLDC motor with unknown loads to manage second-order time-varying systems with constrained unpredictability in the parameters and disturbances and to drive the system states along the minimum time trajectory while staying within the input torque limit [18], and the levels of noise from torque ripple can be significantly reduced [19]. The primary drawback of conventional SMC is that it causes undesirable chattering issues in control, making it unsuitable for industrial applications [20]. Numerous effective control strategies, including an adaptive SMC [21], a high-order SMC [22], and an adaptive fuzzy strategy [23], have been thoroughly studied to lessen the effects of the chattering problem. As an illustration, the chattering issue was mitigated in [24] where second-order SMC was used to integrate the discontinuous switching term. Asymptotic convergence, though, was the cause of the tracking inaccuracy. Instead of using a switching element in the control input, a fast non-singular terminal SMC was utilized, which substantially eliminates the chattering problem. The tracking error's convergence neighbourhood size was affected by the unidentified disturbance, according to [25], [26].

This research is primarily driven by the application of DC motors in various contexts, aiming to develop an alternative approach to enhance the robustness of SMC in view of [27], [28] that will boost the effectiveness of the DC motor as far as dealing with the presence of outer uncertainties and minimizing the chattering phenomenon. Our robust sliding mode learning control (RSMLC), incorporates the concept of the "Lipschitz-like condition" as suggested in [27], [29] employing the Lipschitz-like condition forces our controller to be independent of previous knowledge about the uncertainty in the system. This is a result of the implicit implication of the uncertainties inherent in dynamics in the Lipschitz-like condition. Unlike conventional chattering-prone sliding mode control (CSMC), the suggested RSMLC approach eliminates the chattering phenomenon in the closed-loop system. Through comparisons with CSMC and simulation data, we demonstrate that the proposed RSMLC method effectively mitigates chattering effects and proves to be a reliable and efficient strategy.

The rest of this study is structured as follows. In section 2, we offer a comprehensive description of our research approach, which entails dynamic modeling of the DC motor system, the methodology used for designing SMC, the formulation of an RSMLC for the DC motor, as well as a discussion on the convergence and stability analyses that underscore the benefits of our proposed strategy. In section 3, we present the results and discussions pertaining to the effectiveness of the proposed controller. Finally, in the concluding section, we summarize our findings and identify potential avenues for future research.

2. RESEARCH METHOD

The primary objective of this study is to enhance the tracking performance of DC motors, with a specific emphasis on achieving precise speed control. To fulfil this objective, several steps have been undertaken. Firstly, the dynamic modeling of the DC motor system was conducted, providing a foundation for further analysis. Subsequently, the design of the SMC was carried out, followed by the formulation of the proposed RSMLC specifically tailored for the DC motor. To ensure system stability, an analysis of convergence was performed. The overall research methodology, along with the sequence of steps taken, is presented in a block diagram shown in the subsequent subsection.

2.1. Dynamic modeling of DC motor system

An illustration of a dynamic system's functioning is shown in Figure 1. Numerous applications necessitate highly accurate motor speed control, especially when guided by a reference signal. To verify the effectiveness of the model, it is subjected to a voltage reference signal spanning a broad range of voltages. The behavior of the DC motor is governed by a set of mechanical and electrical equations as follows:

$$V_a(t) = R_a i_a(t) + E_b(t) + L_a \frac{di_a(t)}{dt} \quad (1)$$

$$T_e - T_l = J \frac{dw}{dt} + b w \quad (2)$$

where the actual boundaries are portrayed as follows: V_a is the voltage supply (V); and for a constant electric field (separately excited or shunt); $T_e \propto I_f i_a$, $T_e = K_t i_a$, an induced electromagnetic torque (Nm); T_l load torque (Nm); $E_b \propto \phi w$, $E_b = K_b w$, E_b is the back emf (V); I_a armature current (Amp); $L_a = 2.7$ is the inductance of the armature (H); $R_a = 0.4$ is the armature resistance (Ω); $b = 0.0022$ coefficient of viscosity (Nms/rad); $K_t = 0.015$ torque constant (Nm/Amp); $K_b = 0.05$ motor constant (v-s/rad); $J = 0.0004$ moment of inertia ($kg.m^2$); w is the shaft speed (rad/s). Rewrite (1) and (2) that we got:

$$L_a \frac{di_a(t)}{dt} = V_a(t) - R_a i_a(t) - K_b w \quad (3)$$

$$J \frac{dw}{dt} = K_t i_a - b w - T_l \quad (4)$$

define the state space variables and the control signal variable as $x_1 = w$; $x_2 = i_a$; $U = V_a$. The state space variable derivation is thus as follows:

$$\dot{x}_1 = \dot{w} = \frac{d\dot{\theta}}{dt} = -\frac{b}{J}w + \frac{K_t}{J}i_a - \frac{1}{J}T_l \quad (5)$$

$$\dot{x}_2 = \dot{i}_a = \frac{di_a(t)}{dt} = -\frac{K_b}{L_a}w - \frac{R_a}{L_a}i_a + \frac{1}{L_a}U \quad (6)$$

then, upon substitution, we get:

$$\dot{x}_1 = -\frac{b}{J}x_1 + \frac{K_t}{J}x_2 - \frac{1}{J}T_l \quad (7)$$

$$\dot{x}_2 = -\frac{K_b}{L_a}x_1 - \frac{R_a}{L_a}x_2 + \frac{1}{L_a}U \quad (8)$$

the state-space model is given as:

$$\dot{X} = AX + BU + H \quad (9)$$

$$y = CX + DU \quad (10)$$

where $X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$; $A = \begin{bmatrix} -\frac{b}{J} & \frac{K_t}{J} \\ -\frac{K_b}{L_a} & -\frac{R_a}{L_a} \end{bmatrix}$; $B = \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix}$; $C = \begin{bmatrix} 1 & 0 \end{bmatrix}$; $D = 0$.

Furthermore, the variable $H(t)$ represents the lumped perturbation (i.e., load torque disturbance and modeling error), and is meant to be constrained such that $|H(t)| \leq H$. The DC motor's parameter value is

displayed above and used in the controller's simulation and design. The state-space model in (9) and (10) using the given parameters is represented as:

$$\dot{X} = \begin{bmatrix} -55 & 37.5 \\ -0.01852 & -0.1481 \end{bmatrix} X + \begin{bmatrix} 0 \\ 0.3704 \end{bmatrix} U \quad (11)$$

$$Y = [1 \ 0] X \quad (12)$$

So, the transfer function model can be created from the state-space model by using the MATLAB function $ss2tf(A = [-5.537.5; -0.01852 - 0.1481]; C = [10]; B = [0; 0.3704]; D = 0; [b, a] = ss2tf(A, B, C, D))$

$$w(s) = \frac{13.89}{s^2 + 5.648s + 1.509} v(s) \quad (13)$$

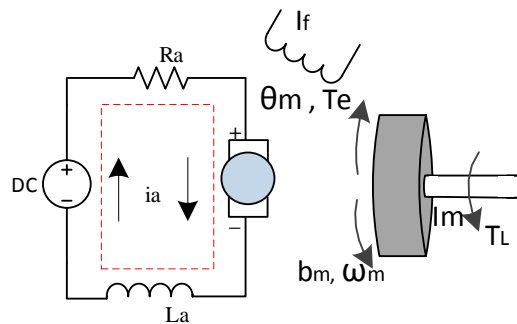


Figure 1. The schematic equivalent circuit diagram of the DC motor

2.2. SMC design

For the SMC, the model must be in a controllable state space form. As a result, the transfer function model's time domain representation in (13) is as follows:

$$\ddot{w} + 5.648\dot{w} + 1.509w = 13.89v$$

to make it simpler, the control design in (13) is modified as follows: $\ddot{x} + c_1\dot{x} + c_2x = c_3u$. Then, the state space variable is defined as (14).

$$x_1 = w, x_2 = \dot{w}, U = v \quad (14)$$

We obtain the state-space model in the controllable canonical form as:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -5.648x_2 - 1.509x_1 + 13.89U + H \quad (15)$$

where $H(t)$ is the uncertainty or unmodeled signal. The sliding mode controller combines reaching mode and sliding mode equations to guide the system's state trajectory. During reaching mode, the control input steers the trajectory towards the sliding surface. Once the trajectory reaches the sliding surface, the sliding mode control law maintains it on the surface and drives it towards the desired equilibrium point, so we select the sliding surface as:

$$s = \dot{e} + \lambda e = (\dot{w} - \dot{w}_d)\lambda + (w - w_d)$$

$$\dot{s} = (\ddot{w} - \ddot{w}_d) + (\dot{w} - \dot{w}_d)\lambda$$

where e is defined as error and (w_d) is the speed reference and $(\lambda > 0)$ is the performance parameter which kept the stability of the system on a sliding surface.

$$s = 0 \rightarrow \dot{s} = 0$$

Equivalent control can be found by substituting (15) into equation \dot{s} when $(\dot{s}) = 0$ as follow:

$$(x_2 - \dot{w}_d)\lambda - \ddot{w}_d + (-5.648x_2 + 13.89U + H) = 0$$

so the input signal appears in the first derivative, we select the robust control signal (U_n) to eliminate the known term:

$$U_n = (1/13.89)(1.509x_1 + (5.648 - \lambda)x_2 + \epsilon$$

since the derivative of the reference signal of the set point is zero, where (ϵ) deals with uncertainty. For some boundaries of uncertainty function (H), the total control signal will be:

$$U_{eq} = U_n + U_{sw}$$

where u_{sw} , known as sliding or control signal and define as:

$$U_{sw} = -(\epsilon + \beta) \text{sing}(s)$$

(β) is definite positive number.

2.3. Formulation of RSMLC for DC motor

We propose a controller that, in the existence of parameter fluctuation and external disturbances, can precisely track the speed of the DC motor trajectory. A description of the RSMLC design will be provided below. In the beginning, the tracking error is described as follows:

$$e(t) = x(t) - x_d(t) \quad (16)$$

where $x(t)$ indicates the quantifiable output (speed), $x_d(t)$ is the tracking reference, and the time parameter t will be omitted for simplicity. The following step is choosing the sliding surface:

$$s = \dot{e} + \lambda e \quad (17)$$

where $\lambda \in \Re$ and $\lambda > 0$. Then, the time derivative of (17) must contain the input signal to meet the sliding criteria, which are as follows:

$$\dot{s} = \Phi + c_3 U \quad (18)$$

where $\Phi = -c_1 x_2 - c_2 x_1 - H - \ddot{x}_r + \lambda \dot{e} + e$. The adopted robust sliding-based learning controller in this paper is taken from [21]:

$$u(t) = u(t - \tau) - \delta u(t) \quad (19)$$

where $\delta u(t)$ is the iterative learning term, and $u(t - \tau)$ is the anterior sample of the control signal specified as:

$$\delta u(t) = \begin{cases} \frac{1}{bs} \left(\rho_1 \hat{V}(t - \tau) + \rho_2 |\hat{V}(t - \tau)| \right), & \text{if } s \neq 0 \\ 0, & \text{if } s = 0 \end{cases} \quad (20)$$

where τ is the delay time, ρ_1 and ρ_2 are the control parameters to be designed, and $V(t)$ is the Lyapunov candidate function defined as:

$$V(t) = \left(\frac{s^2(t)}{2} \right). \quad (21)$$

$\left(\hat{V}(t - \tau) = \frac{V(t) - V(t - \tau)}{\tau} \right)$, is the delayed Lyapunov candidate estimated derivative $V(t - \tau)$ given by:

$$V(t - \tau) = \left(\frac{s^2(t - \tau)}{2} \right)$$

Remark 1: an insightful view of the proposed controller in (19) and (20), it can be deduced that when $s \neq 0$ the control signal will be continuous due to the learning part. Meanwhile, when $s=0$, only the prior signal will be responsible. Using residual signal model learning control (RSMLC) reduces chattering and protects against unexpected loads or unmodeled factors.

Remark 2: the delay time τ , as a rule, decided to be just about as little as the execution hardware permits. For example, it very well may be chosen as one sampling period.

2.4. Convergence analysis

The following Lemma has been introduced to demonstrate the stability of the entire system. Lemma: consider the model in (13) under the proposed RLSCMC law in (19) with correction form in (20), then a zero-value asymptotic convergence can be guaranteed for the tracking error e in (16). Proof: recalling the candidate Lyapunov function $V(t)$ from (21), then the time derivative along the system trajectory can be achieved as follows:

$$\begin{aligned}\dot{V}(t) &= s(t)\dot{s}(t) \\ &= s(t)(\dot{\Phi}(t) + b u(t)) \\ &= s(t)[\dot{\Phi}(t) + b u(t - \tau)] - s(t)b \delta u(t).\end{aligned}\quad (22)$$

substituting the learning term $\delta u(t)$ from (20) into (22) yields:

$$\dot{V}(t) = s(t)[\dot{\Phi}(t) + b u(t - \tau)] - \delta s(t)C_3 \left(\frac{1}{C_3 s(t)} (\rho_1 \hat{V}(t - \tau) + \rho_2 |\hat{V}(t - \tau)|) \right) \quad (23)$$

since $\dot{v}(t) = s(t)[\dot{\Phi} + c_3 u(t)]$, then it tends to be deduced that:

$$\dot{v}(t - \tau) = s(t)[\dot{\Phi} + c_3 u(t - \tau)] \quad (24)$$

substituting (24) into (23) yields:

$$\dot{v}(t) = \dot{v}(t, t - \tau) - \rho_1 \hat{v}(t - \tau) + \rho_2 |\hat{v}(t - \tau)| \quad (25)$$

the following assumption is introduced to proceed with system proof.

Assumption: the research assumption is that $\dot{v}(t)$ is a continuous function during the interval. It should be noted that this assumption is valid since τ would be a very short period. According to the Lipschitz-like condition in [18], there is a constant number which must be chosen to satisfy the condition for continuity:

$$|\dot{v}(t - \tau) - \dot{v}(t)| \leq \frac{1}{M} |\dot{v}(t - \tau)| \quad (26)$$

indeed, two possible cases in (26) should be investigated. The first case when:

$$\dot{v}(t) < \dot{v}(t - \tau) + \left(\frac{1}{M} - \rho_1 \right) |\dot{v}(t - \tau)| + \rho_2 |\dot{v}(t - \tau)| \quad (27)$$

as the control parameters are selected to satisfy the following conditions: $M \in \mathbb{R}, M \gg 1, \rho_1 > \frac{1}{M}$ then (27) is simplified into:

$$\dot{v}(t) < \dot{v}(t - \tau) \quad (28)$$

which implies that when $\dot{v}(t - \tau) > 0$ it keeps decreasing due to the learning controller. In other words, the proposed controller constantly reduces the instantaneous derivative of the Lyapunov function from a positive to a negative value. The next possible case is that when $\dot{v}(t - \tau) < 0$, which can be directly concluded that:

$$\dot{v}(t) < 0 \quad (29)$$

hence, the system stability proof is completed. Figure 2 shows the block diagram of the overall research methodology and the proposed SMLC strategy.

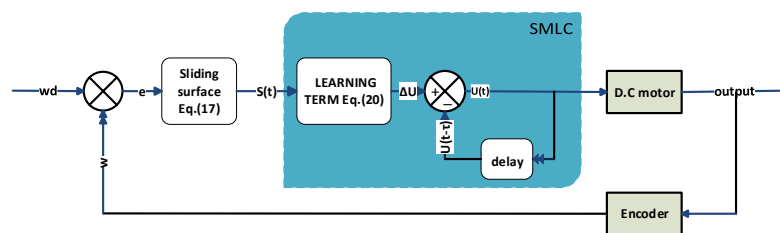


Figure 2. The block diagram of the proposed SMLC strategy

Remark 3: for comparison reasons, the CSMC is built based on the boundary layer technology as follows:

$$U_{eq.} = U_n + \beta \left(\frac{s_{csmc}}{|s_{csmc}| + \Delta} \right) \quad (30)$$

this equation is expressed, (where $\beta > 0$), (Δ) as the boundary layer thickness, and $((s_{csmc})/(|s_{csmc}| + \Delta))$ as the saturation function, which is utilized in place of the signum function to reduce the chattering effect [29]. In addition, the sliding variable is given as $s_{csmc} = \dot{e} + \lambda e + \int e dt$, where (e) is the tracking error defined in (16). By fulfilling the sliding condition ($s=0$), we can easily compute U_n as:

$$U_n = \frac{1}{C_3} \ddot{x} + \frac{c_1}{c_3} \dot{x} + \frac{c_2}{c_3} x \quad (31)$$

3. RESULTS AND DISCUSSION

In this section, we carry out simulation studies to validate the performance of the RSMC in a DC motor. First, the tracking outcomes for a nominal DC motor model are shown, and afterwards, the system performance is examined under various plant uncertainties using the RSMC system. We compared the tracking performance of the RSMC with that of CSMC in (31) for each test.

3.1. Tracking performance evaluation

Initially, the reference signal is placed as a step reference. It should be noted that such trajectories would excite the internal hysteresis nonlinearities. Thus, the tracking error would grow proportionally. Figure 3 shows the tracking response under the designed CSMC and PID under nominal conditions to step function input. Generally, we can see from the upper plot that the tracking performance for both methods is acceptable. Essentially notation in this figure is that CSMC owns a settling time (0.1855 s to track the reference, with free chattering, whilst the PID controller has (0.55 s). It showed, however, that chattering is an important issue under SMC. Meanwhile, the chattering effect is remarkably neglected under the RSMC with a fast response time (0.084 s) as shown in Figures 4 and 5 show the tracking error. To emphasize this fact Figure 3 is presented, which indicates the control efforts of each ordinary controller. This highlights the provision of an alternative control method that maintains SMC robustness and overcomes its limitations.

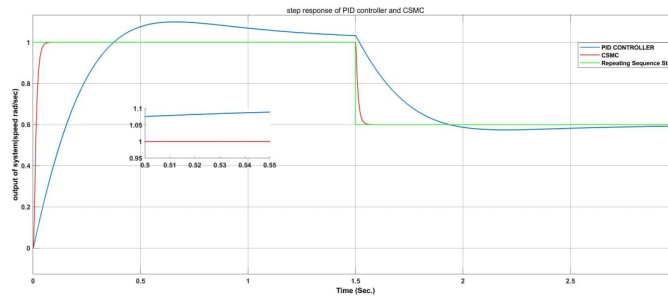


Figure 3. CSMC and PID controllers' response

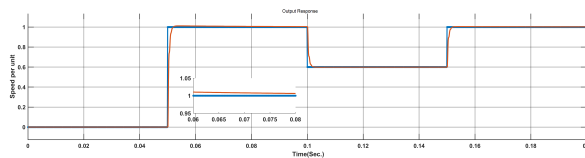


Figure 4. SMLC response

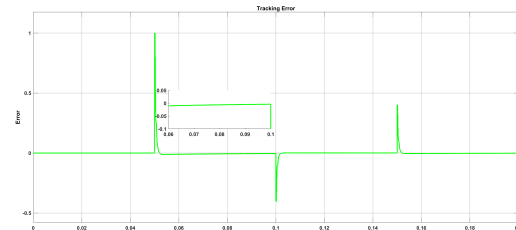


Figure 5. Tracking error

4. CONCLUSIONS

The DC motor model has been designed to control its speed using a CSMC controller based on the equivalent control approach, as well as the PID controller. The method of CSMC allows DC motor models to be calibrated to account for matched uncertainties more efficiently than the PID controller which must correct the gains for any unexpected perturbations. As indicated by these outcomes, the utilization of a load-torque varying and disturbances-sensitive control scheme is advised to meet the prerequisites forced on the framework for the entire scope of inertia. This is because the controller design does not need bounded uncertainties. The robustness of the RSMC was further tested in simulations and under different combinations of uncertain parameters. Results show that the method has good performance: in trajectory tracking tasks, the control system responds rather quickly, and steady-state errors are absent. Consequently, based on the simulation outcomes, we exhibit that the SMLC control strategy proposed in this research effectively settles the issue of a set of exchange load-torque in DC motors on the grounds that the control configuration is robust in terms of motor dynamics friction and load-torque variations and disturbances without deduced information on the differing scope of the varying range of the load and unmodeled perturbations, which are the principal commitment of this paper. Additionally, the control law is perfectly fitted to tracking trajectory tasks.

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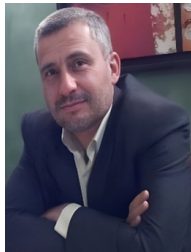
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