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Sliding Mode Control of the Permanent Magnet DC Motor Based on Optimal Control Design

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Abstract. Permanent Magnet DC motors (PMDC) have become important for their many applications that require precise speed control. The motor speed may change suddenly due to external conditions and disturbance of load, so the speed profile will deteriorate and hence the performance will degrade. In this paper, a control design based on conventional and advanced controllers is established for the speed control of a PMDC motor. Firstly, conventional controllers based on proportional integral derivative (PID) were applied. Secondly, advanced controllers using Sliding Mode Control (SMC) are designed. In addition, a Particle Swarm Optimization (PSO) algorithm has been developed to improve the performance of proposed controllers by optimal tuning of their parameters. Third, the controllers were implemented practically in a real-time environment using a PC, an Arduino UNO, and actual PMDC motor and conditioning circuits. The computer simulation showed the superiority of the SMC controller over other controllers in terms of dynamic performance, steady-state and robustness characteristics when the motor is subjected to variation in load. The proposed controllers were validated in real-time to verify the simulation results via experimental setup.

INTRODUCTION

PMDC motors offer a broad variety of uses in electrical and mechanical domains, including robots, computer peripherals, air conditioners as well as other industrial uses [1]. The primary qualities and advantages that make employing PMDC motors so extensively disseminated and popular in current applications are great efficiency, low cost, ease of maintenance, ease of control of speed and a very basic construction [2]. Because of the increased power required to drive nonlinear loads, PMDC motors are commonly employed in variable speed drive applications. Disturbances or rapid variations in load might cause problems for these motors. The key problem is controlling the speed of these motors under these conditions. As a result, throughout the design process for an optimum speed control system under variable speed driving situations, disturbances must be considered [3]. A variety of controllers, including conventional and advanced controllers, can be used to regulate the speed of PMDC motors [4, 5]. The earliest controllers that could be utilized for PMDC motor speed control were PID controllers. They are employed in a wide range of applications because to their simplicity. Multiple novel strategies may be employed to address the difficulty of tweaking many design parameters for PMDC motor control. Traditional controllers are unable to handle real-time systems that display nonlinear behavior. To guarantee that the control system performs well, an advanced control system is necessary. Early in the 1950s, Emelyanov and several researchers proposed a variable-structure control (VSC), or SMC, feedback control strategy that provides an effective and robust approach for controlling nonlinear multivariable plants [6, 7]. Because of its low sensitivity to speed changes and disturbance load effects, SMC is a helpful approach for regulating complex and dynamic plants. The SMC has the potential to generate various significant efficiencies, such as rapid response, quick response to load disturbances and quick response to disturbances load. SMC's advantages have been applied to PMDC motor speed control. The design parameters of the SMC can be represented as the main drawback of this method, which should be adjusted properly. In the same way,

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these design factors have a significant impact on system response performance. An incorrect setting or value of these parameters can cause SMC performance to deteriorate or even cause instability issues. Because of that, an optimization method is required to solve the tuning problem to reduce the effort and the time wasted by trying and error and achieve the optimum values for SMC parameters. Optimization tuning approaches may be a reasonable choice. Some of the most recent and popular optimization algorithms in each of these subclasses are as follows: 1) Using evolutionary techniques such as Genetic Algorithm (GA), Biogeography-Based Optimization (BBO), Differential Evolution (DE), and Evolution Strategy (ES). 2) Based on swarm intelligence techniques like Ant Colony Optimization (ACO), Artificial Bee Colony Algorithm (ABC), Butterfly Optimization Algorithm (BOA), and Particle Swarm Optimization (PSO). 3) Based on physical techniques like Gravitational Search Algorithm (GSA), Black Hole (BH), and Colliding Bodies Optimization (CBO) [8].

In the optimization sector, the PSO approach has been presented as an optimum tuner.

This research has made three major contributions.

- A sliding mode control mechanism is proposed to deal with the controlling task of a PMDC motor speed with disturbance rejection in load.
- The particle Swarm Optimization algorithm is developed to improve the performance of proposed controllers by optimal tuning of their parameters.
- Experiments setup and real-time implementation have been made to validate the computer simulation.

Therefore, the objective of this project can be stated as follows:

- Modeling the PMDC motor for speed control purposes.
- Design and simulate of controllers for speed PMDC motor by using MATLAB Simulink program. These controllers are PID and SMC.
- Design and implementation the above methods controllers' practically in real-time for speed control purposes of PMDC motor.
- In addition to using PSO that corresponds with targets function of Integral Time Absolute Error (ITAE) to get the best parameters for these controllers and to improve the performance of proposed controllers compared to the other classical tuning methods.
- A comparison of PID and SMC controllers in terms of dynamic performance and robustness was undertaken.

This is how the article is structured: In the second part, the PMDC motor model is shown. The third part contains a description of the proposed controllers as well as the usage of the PSO method to determine the proposed controllers' optimal tuning parameters. A comparison and simulation study were conducted, as detailed in the fourth part, to ensure that the proposed approach is successful. The outcomes of a simulation were validated using real-time results in the fifth part. The work's conclusion is found in the sixth part.

MODEL OF PMDC MOTOR

PMDC motor is the most widely used type of drive, which is made up of two basic parts: a mechanical and electrical component. By mixing these components, a rotational speed may be produced. The circuit equivalent of PMDC motor, as shown in Figure 1, contains a power source called armature voltage $e_a(t)$ in volt, armature winding resistance R_a in ohm, armature winding inductance L_a in henry also the back electromotive force $e_b(t)$ in volt, the mechanical part which contains the motor shaft which has its moment of inertia of the motor J_m in addition to the load torque T_L is applied to the motor, motor torque T_m and damping ratio B_m. The shaft of the motor will start rotation by applying an armature voltage to the electrical part, so it can be translated as mechanical rotation called angular position $\theta(t)$ and angular speed of the motor shaft $\omega(t)$. PMDC motor modeling is used to generate the equation differential that represents the connection between output speed and input voltage [9, 10].

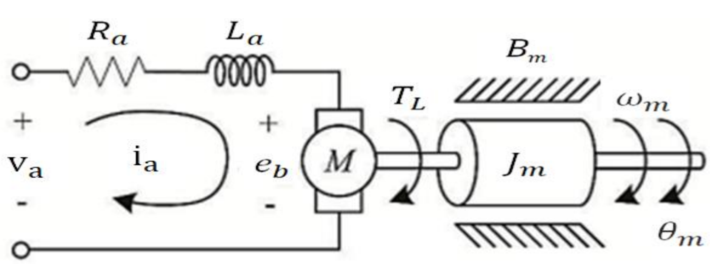


FIGURE 1. PMDC motor equivalent circuit [11].

The flux density of the air gap is constant since the PMDC motor's field winding is a permanent magnet. The PMDC motor's electrical equations are as follows:

$$v_a(t) = e_b(t) + R_a\, i_a(t) + L_a \frac{d}{dt} i_a(t) \tag{1}$$

$$e_b(t) = k_b\ \omega_m(t) \tag{2}$$

where:
k_b = BAN
B: Density flux (Wb/m^2).
A: The rotor's cross-sectional area (m^2).
N: The number of rotor conductors.

$$T_m(t) = J_m \frac{d}{dt}\ \omega_m(t) + B_m \omega_m(t) + T_L \tag{3}$$

$$T_m(t) = K_t\, i_a(t) \tag{4}$$

where:
$k_t = k_b$
Within the indicated speed range, the motor is assumed to work in one direction. As a result, non-linearity at zero crossing is ignored. The PMDC model in this circumstance may be described using the Laplacian transfer function below.

$$\frac{\omega_m(s)}{V_a(s)} = \frac{k_t}{J_m\, L_a S^2 + (J_m R_a + B_m L_a)\, S + B_m R_a + k_t\, k_b} \tag{5}$$

After simplifying the above equation.

$$\frac{\omega_m(s)}{V_a(s)} = \frac{\frac{k_t}{J_m\, L_a}}{\left(\left(\left(s + \frac{R_a}{L_a}\right)\left(s + \frac{B_m}{J_m}\right)\right) + \frac{k_t\, k_b}{L_a\, J_m}\right)} \tag{6}$$

Let

$$A_1 = \frac{k_t}{J_m\, L_a},\quad A_2 = \frac{R_a}{L_a},\quad A_3 = \frac{B_m}{J_m},\quad A_4 = \frac{k_t\, k_b}{L_a\, J_m}$$

$$\frac{\omega_m(s)}{V_a(s)} = \frac{A_1}{\left(((s + A_2)(s + A_3)) + A_4\right)} \tag{7}$$

Equation (7) in the time domain may be represented as:

$$\ddot{\omega}_m(t) = -(A_2 + A_3)\dot{\omega}_m(t) - (A_2 A_3 + A_4)\, \omega_m(t) + A_1\, v_a(t) \tag{8}$$

The model's state-space equations are

$$x_1 = \omega(t) \tag{9}$$

$$x_2 = \dot{\omega}(t) \tag{10}$$

$$\dot{x}_1 = \dot{\omega}(t) = X_2 \tag{11}$$

$$\dot{x}_2 = \ddot{\omega}(t) \tag{12}$$

$$y = \omega(t) \tag{13}$$

$$\dot{x}_2 = \ddot{\omega}_m(t) = -(A_2 + A_3)\dot{\omega}_m(t) - (A_2 A_3 + A_4)\, \omega_m(t) + A_1\, v_a(t) \tag{14}$$

PMDC MOTOR CONTROL ANALYSIS

PID Controller

PID controller is one among the most popular and often used. The PID controller enhances dynamic responsiveness as well as eliminating steady-state inaccuracy. In contrast, PID controllers account for more than 90% of all control utilized in industries. Algorithm PID has the advantage of having a few design parameters, and the ability to link the performance of the PID controller to these parameters. This algorithm receives a signal error and computes the proportional, integral and derivative of the error signal. The signal error e(t) is turned into the signal control u(t). The equation general for the PID controller is given by the equation below [12, 13]:

$$u(t) = K_p\, e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{15}$$

where:
K_p : The gain is proportionate.
K_i : The gain integral.
K_d : The gain derivative.

Sliding Mode Control

The employment of traditional control mechanisms may cause issues. Inconsistencies between the mathematical model and the real plant developed for the design controller are one element leading to this. This mismatch might prohibit you from achieving the appropriate level of performance. A set of dependable control processes was created to eliminate any discrepancies. The SMC methodology is one such approach to robust control design. Nonlinear systems, SMC has been used to solve multi-input multi-output (MIMO) systems, discrete-time models and infinite-dimension systems, and stochastic systems, among other control.

The sliding mode controller is chosen because of two reasons. First of all, the sliding mode algorithm is considered because it has the ability to exhibit stability against parameter variations, unmodelled dynamics and external disturbances. However, in a dynamic environment with disturbances and uncertainties, the conventional controller is not sufficient. In sum, the first reason for choosing the sliding mode controller is the ability to deal with nonlinearities, and the second reason is the ability to deal with disturbances and uncertainties.

During SMC, the most notable feature of SMC is its complete immunity to parametric uncertainty and load perturbations. SMC uses a high-speed switching control law to accomplish two aims. To begin, it directs the nonlinear plant's state trajectory onto a user-specified and user-chosen sliding or switching surface in the state space. Because a control path has one gain if the plant's state trajectory is "above" the surface and a control path has different gain if the trajectory of the drop is "below" the surface, this surface is called the switching surface. Secondly, the plant's state trajectory on this surface is preserved for all later times. During operation, the structure of the control system varies from one to the next, earning it the term variable structure control. The control is called the SMC [14, 15]. SMC is divided into two-part sliding modes and the reaching, as well as their phase pictures, are depicted in Figure 2. The SMC approach attempted to draw the system states back to the origin from the sliding surface. The reaching mode in surface sliding refers to SMC, this is a step from the starting point to the origin. SMC's goal is to trace output to a reference and generate a control signal $u(t)$, which reduces error tracking [5]. The signal $u(t)$ can be shown as in equation (16). It is made up of two sections. The first part is a control switching signal $u_{sw}(t)$, the second part indicates signal equivalent $u_{eq}(t)$

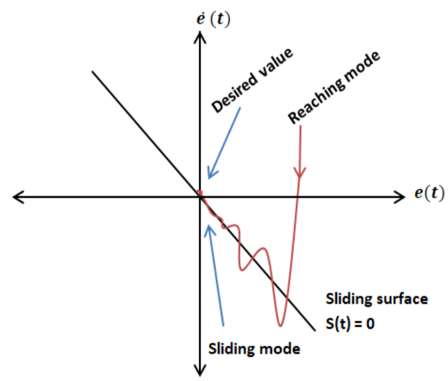


FIGURE 2. Portrait of the SMC's phase [5].

$$u(t) = u_{sw}(t) + u_{eq}(t) \tag{16}$$

The characteristics, and transfer functions of PMDC motor may be used to find an analogous control signal. Through the sliding surface signals switching control can be discovered. The following is the most commonly used equation for the sliding surface:

$$s(t) = C\,X_1 + X_2 = C\,e(t) + \dot{e}(t) \tag{17}$$
$$\dot{s}(t) = C\,\dot{X_1} + \dot{X_2} = C\,\dot{e}(t) + \ddot{e}(t) \tag{18}$$
$$e\,(t) = \omega_{ref} - \omega_{act} \tag{19}$$

where:
C: Parameter performance.
ω_{ref}: Speed reference.
ω_{act}: Speed actual from PMDC motor.

The sliding surface is revealed to be an activity that is relevant to tracking inaccuracy for any variation between the reference and the actual. C > 0 is a parameter performance that ensured the system's stability on the sliding surface. Because $s(t) = 0$ and $\dot{s}(t) = 0$ The derivative and the sliding surface are both equal to zero. After found the sliding surface, a control input has to be proposed to ensure that the sliding surface will be 0 in limited time. The switching control signal's equation may be written as follows:

$$u_{sw}(t) = K\,sgn(s) \tag{20}$$
$$Sgn\,(s(t)) = \begin{cases} +1\,, if\ s\,(t) > 0 \\ \ 0\,, if\ s\,(t)\ =\ 0 \\ -1, if\ s\,(t) < 0 \end{cases} \tag{21}$$

where:
K: Design parameters positive.
$sgn(s)$: Signum function.

Equation (11) and equation (14) may be substituted into equation to find equivalent control (18).

$$\dot{s}(t) = C\,X_2 - (A_2 + A_3)X_2 - (A_2A_3 + A_4)X_1 + A_1\,v_a(t) \tag{22}$$

SMC mobility on the surface must be ensured, this derivative sliding surface should be set to zero, and the accompanying control will be carried out utilizing the aforementioned condition.

$$v_a(t) = u_{eq}(t) = \frac{1}{A_1}\,[(A_2 + A_3 - C\,)X_2 + (A_2A_3 + A_4)\,X_1\,] \tag{23}$$

The $u(t)$ control signal will result in the following:

$$u(t) = \frac{1}{A_1}\,[(A_2 + A_3 - C\,)X_2 + (A_2A_3 + A_4)\,X_1\,] + K\,sgn(s) \tag{24}$$

To lower processing burden and relieve chattering, a modification in sign function is made as indicated in (25) where is a modest design constant positive also known as parameter tuning.

$$u(t) = \frac{1}{A_1}\,[(A_2 + A_3 - C\,)X_2 + (A_2A_3 + A_4)\,X_1\,] + K\left[\frac{S}{|S| + \delta}\right] \tag{25}$$

where:
δ : Positive tuning parameter $0 < \delta < 1$

Particle Swarm Optimization

Eberhart and Kennedy created the PSO approach in 1995 [16]. To increase its performance, a new parameter termed inertia weight was introduced [17]. When compared to optimization others, the PSO features a powerful global search, a few customizable parameters, a faster convergence rate, algorithm simplification and implementation ease [18]. Particle Swarm Optimization (PSO) algorithm is developed to improve the performance of proposed controllers by optimal tuning of their parameters. Compared to other optimization techniques, the PSO has been used due to its computation efficacy, fast convergence rate and its ability to find a solution that is close to optimal global.

The PSO techniques is based on swarm intelligence methods for studying the social behavior of moving species such as fish and birds. This algorithm is connected to a computer method that optimizes the problem of flocks of birds attempting to identify eating behaviors by repeating steps until the optimal answer is found. This implies that the candidate solutions are particles that move around in the search space according to the formula above [19]. Each particle has a variable velocity as it goes through the problem space. Each particle has a memory and it recalls its previous best location (referred to as the pbest). For each particle in the swarm, there are many pbest, with the swarm's global best (gbest) being the particle with the best fitness.

The primary notion underlying the PSO technique is that each particle is driven to its pbest and gbest positions at each time step using a random weighted acceleration. Each PSO particle in the search space has its own velocity, which updates dynamically based on their own flying adventure as well as data gained from the speed of their peers. After each iteration, the particles alter their speed and location based on their previous best location pbest and the best location of all other particles in the swarm gbest. Every particle has variables and dimensions that must be resolved. If the problem contains several variables, choose a particle dimension that is equal to all of them. The location and speed of the object are updated [20, 21]:

$$V_{i,j}(t+1) = W.V_{i,j}(t) + r_1 c_1 \left[Pbest_{i,j}(t) - X_{i,j}(t)\right] + r_2 c_2 [Gbest_{i,j}(t) - X_{i,j}(t)] \quad (26)$$

$$X_{i,j}(t+1) = V_{i,j}(t+1) + X_{i,j}(t) \quad (27)$$

where:

j: Number dimension, i: Particle index, W: Weight inertia has a wide range of values. [0 - 1], t: Iteration, $V_{i,j}(t)$: The particle's instant speed, $V_{i,j}(t+1)$: The particle next instant speed , $X_{i,j}(t+1)$: The particle next location, $X_{i,j}(t)$: The particle's instant location, c_1, c_2: The acceleration coefficients range values of [0 – 2] r_1, r_2: They're between values [0 - 1] according to the random coefficient. To reduce the speed error of PMDC motors, the algorithm PSO tuning approach for PID control and SMC control is utilized. Many objective functions, such as Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE) and Integral Time Squared Error (ITSE). However, the goal function employed in these algorithms to minimize the speed error is defined as [22]:

$$ITAE = \int_0^T t\,|e(t)|\,dt \quad (28)$$

$$e(t) = (\omega_{ref} - \omega_{act}) \quad (29)$$

where:

T: The time.

RESULTS SIMULATION

Tuning design parameters based on PSO optimization to boost the dynamic performance of the PMDC motor. In this paper, the performance of SMC and PID controllers is compared. Table 1 The parameters utilized for the PMDC motor. The performance of the PMDC motor was demonstrated using PID controller simulations. In these methods, the objective function ITAE is used to reduce the speed error. The PSO parameters employed in this experiment are shown in Table 2. The objective function PSO utilized in the PID controller is shown in Figure 3. Figure 4 shows the ideal value for the parameters PID control as well as in Table 3 represents values of optimal PID control.

TABLE 1. Parameters of the PMDC motor.

Description	Symbols	value
Back EMF Constant	K_b	0.0556 V. sec/rad
Torque Constant	K_t	0.0556 N. m / A
Inductance Winding Armature	L_a	0.0082 H
Resistance Winding Armature	R_a	11.27 Ω
Friction Constant	B_m	5.19 $\times 10^{-5}$ N. m. s/rad
Rotor Inertia of The Motor	J_m	7.668$\times 10^{-7}$ kg.m^2
The Voltage of Armature	V_a	24 volt
Load Torque	T_L	0.01N.m
The speed at No Load of Motor	ω_o	3800 r. p. m

TABLE 2. PSO Parameters for PID.

Parameters PSO	Value
Dimension number (*D*)	3
Weighted inertia (*W*)	0.854
Coefficients of acceleration (c_1)	2
Coefficients of acceleration (c_2)	2
Iteration	50
Swarm size	20

TABLE 3. Parameters for PID design that are optimal.

K_p	K_i	K_d
14.01074	6.12	0.1

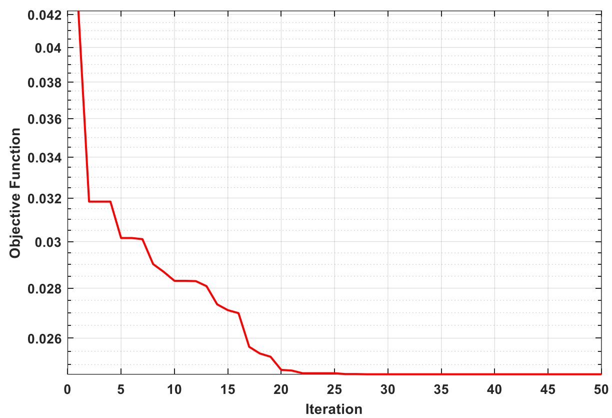


FIGURE 3. PSO objective function behaviors of PID.

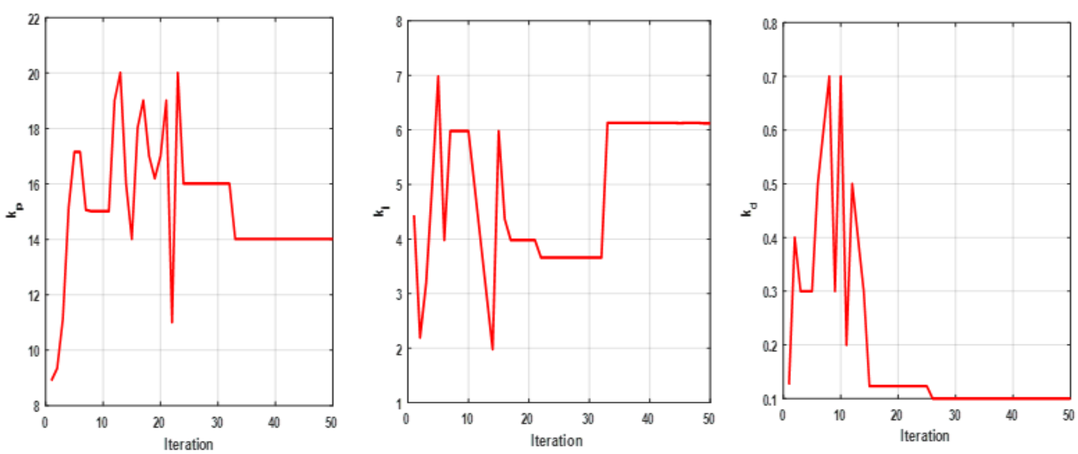


FIGURE 4. The optimal values of parameters for the PID controller.

The performance of the PMDC motor under the SMC controller was demonstrated through simulations. ITAE is the goal function in algorithms for minimizing the error speed. Table 4 lists the PSO parameters that were used in this investigation. Figures 5 and 6 demonstrate the cost function of the PSO used in the SMC controller, which indicates the optimal values of the SMC controller parameters. SMC parameters of the based on the PSO shown in Table 5.

TABLE 4. PSO Parameters for SMC.

Parameters PSO	Value
Dimension number (D)	3
Weighted inertia (W)	0.85
Coefficients of acceleration (c_1)	1.8
Coefficients of acceleration (c_2)	1.5
Swarm size	20
Iteration	50

TABLE 5. Parameters for SMC design that are optimal.

K	C	δ
150. 45237	80.765	0.9

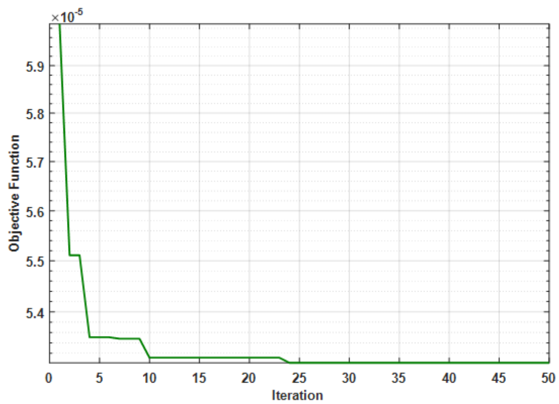


FIGURE 5. PSO objective function behaviors of SMC.

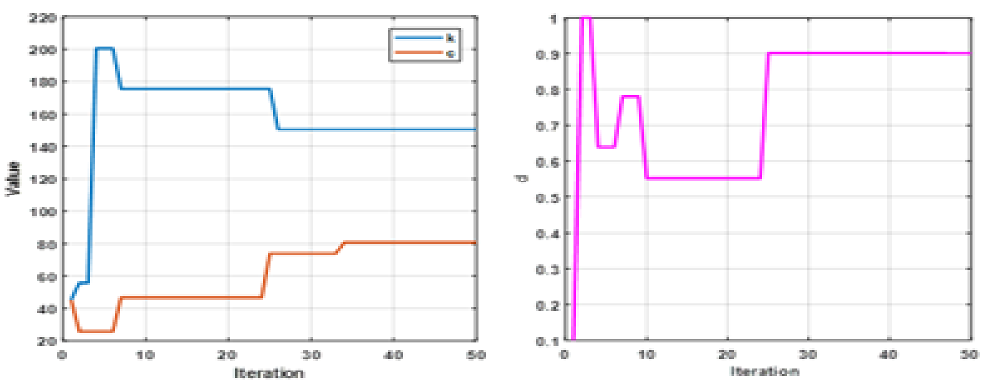


FIGURE 6. The optimal values of parameters the SMC controller.

Figures 7 and 8 show the simulated results of the PMDC motor speed under load and at a disturbance-free a multi-input reference speed is used. Respectively, based on the PSO tuning settings for SMC, PID controllers gain. In terms of tracking intended speed as well as the effect of disturbance load. PSO tuning speed based on SMC controller is better to PSO tuning speed based on PID controller, as shown in Table 6.

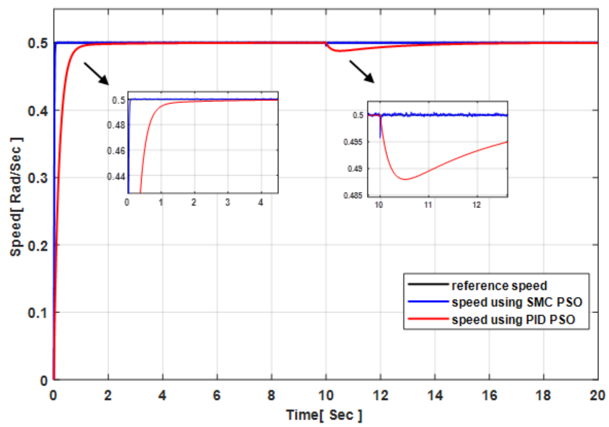


FIGURE 7. Speed response of PMDC motor under $T_L = 0.01$ Nm at 10 sec using SMC and PID controllers.

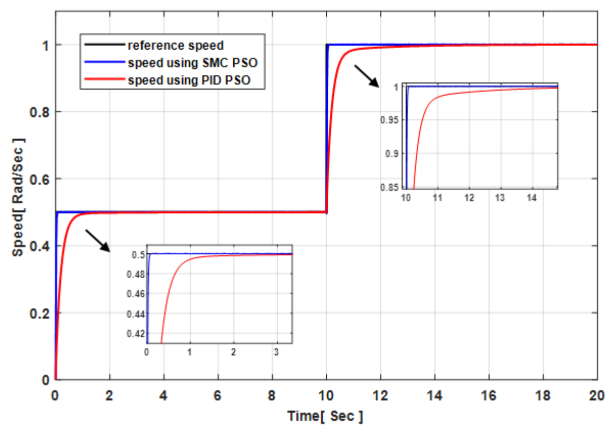


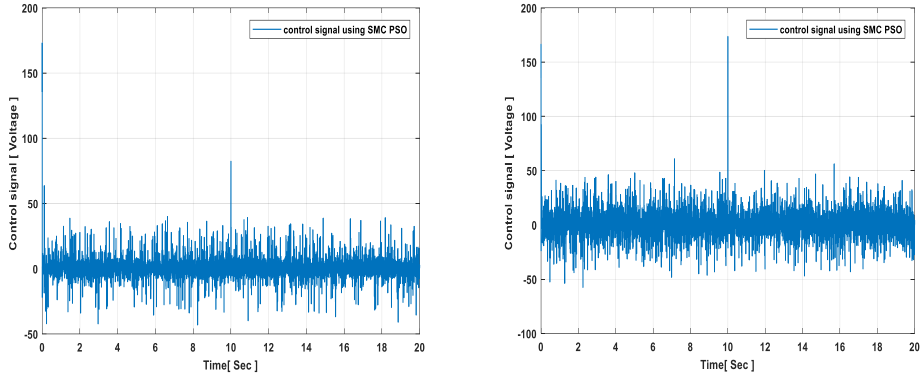
FIGURE 8. PMDC motor speed response employing SMC and PID controllers under multi-input reference speed at disturbance free.

TABLE 6. In MATLAB Simulink, the response of a PMDC motor.

Controllers	***Rise time t_r (sec)***	***Settling time t_s (sec)***
SMC	0.0251	0.18
PID	0.4011	4.6

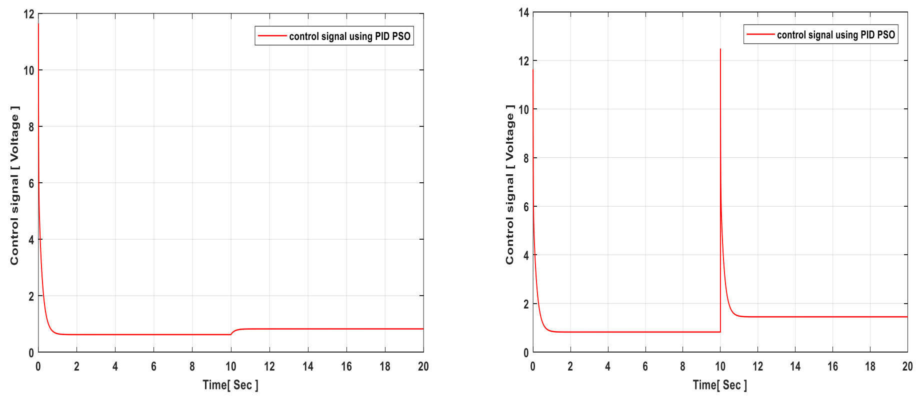
Figures 9 and 10 depict the PMDC motor's control signal for SMC and PID, respectively. As shown in Figure 9, it can note that the control signal contains the chattering but the response of motor speed is better than of PID control in term of simulation and practical results.

It is evident that the control signal based on SMC has high chattering behavior. This is due to the signum function used in control law with SMC. Actually, this chattering behavior has an adverse effect on the practical performance of DC motor. This control signal will add noisy behavior on actual speed and generate noisy sound; this is actually what has been observed during experimental results. In addition, this unwanted and evitable control signal leads to add burden on the switching components of the motor driver and in turn lead to early defect of its switching electronic components. The solution to reduce, not to remove, the effect of chattering is either to use smoothed switching functions or using super-twisting SMC that has been proposed in this study.



(a) (b)

FIGURE 9. Signal control, a) SMC under $T_L = 0.01$ Nm at (10) sec, b) SMC under multi-input reference at disturbance free.



(a) (b)

FIGURE 10. Signal control, a) PID under $T_L = 0.01$ Nm at (10) sec, b) PID under multi-input reference speed at disturbance free.

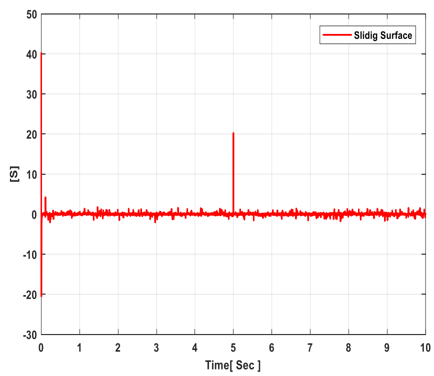


FIGURE. 11. sliding surface signal of SMC controller based on PSO under T_L=0.01Nm at (10) sec.

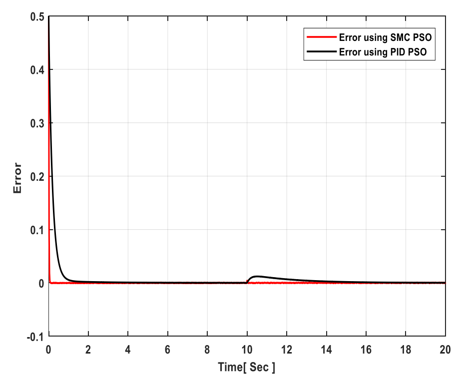


FIGURE. 12. Error of Speed response of PMDC Motor with SMC and PID controllers based on PSO under T_L=0.01Nm at (10) sec.

Figure 11 shows the sliding surface signal of SMC, and Figure 12 shows the PMDC motor's error signal for SMC and PID. Figure 13 shows the trace of trajectory-based on SMC in coordinate e-$\dot{e}$. The trajectory is composed of two parts; the reaching part and the sliding part. The first part guides the solution from the initial condition to the sliding surface, while the sliding part takes the trajectory to equilibrium points.

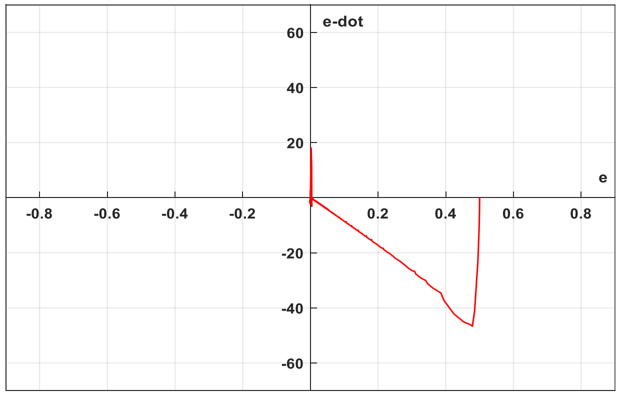


FIGURE 13. The trace of trajectory-based on SMC in coordinate e-$\dot{e}$.

Experimental Implantations PID and SMC of PMDC Motor

A wiring design for the hardware system is shown in Figure 14. A PMDC motor, computer, Arduino UNO, power supply, and driving circuits made comprised the experimental hardware platform. Table 1 lists the parameters of a PMDC motor. The control operation is carried out by using MATLAB software. You may link to an Arduino UNO using a feature in MATLAB. The Arduino UNO's (PWM) interface sends signals generated by the MATLAB-based controllers to drive circuits that regulate the voltage armature of the PMDC. The tachometer's feedback signal data is sent to the Arduino UNO's input analog port. All of the components shown in the hardware system are included in the hardware system in Figure 15. An experimental of PMDC performance using PID and SMC is shown Figure 14. As may be seen in the experimental assessment outcomes in Figures 16 and 17, the SMC controller gives a higher performance in transient response and rapid reaction in load disturbance. We see a convergence in response behavior in terms of (settling time, load disturbance) with a little variance in speed response as a result of other working conditions in the practical findings. Figures 18 and 19 show pulse-width modulation (PWM) transferred from the Arduino UNO's digital port to drive circuits during startup and throughout the operation.

There are many possibilities to explain the mismatch of the experimental results with the simulation (numerical results). Both simulation and experimental results are based on a modeling process. As a result, they are affected by the hypotheses in the model as well as by further resolution errors. Obtaining the correct results from an experimental setup is a challenging problem for any researcher. The difference is there due to the errors occurred from external disturbances, instrument, and the correct choice of coefficients in the numerical model with what is suitable for experimental tests. The experimental results are based on real-time system, which provides more precision and accuracy compared to any results obtained from any model utilizing any software.

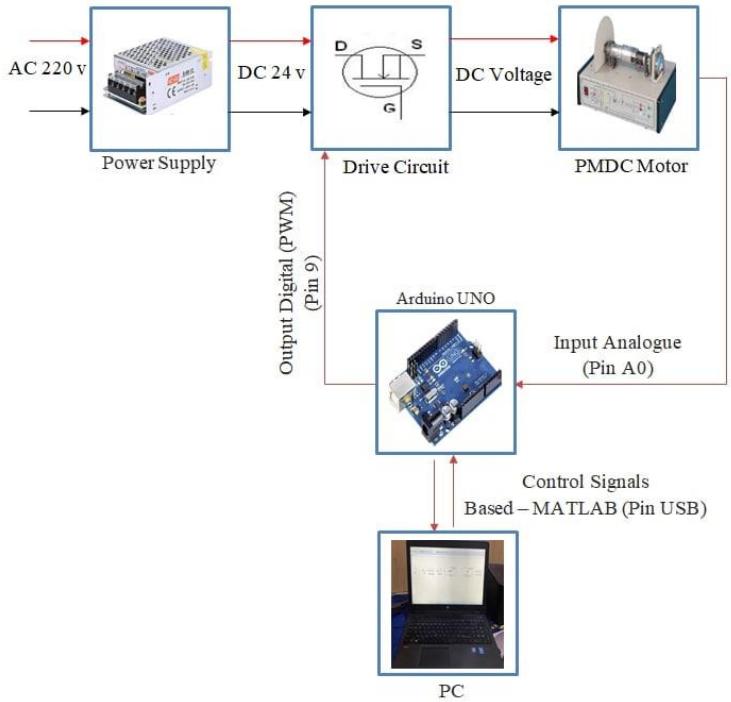


FIGURE 14. The wiring diagram of the hardware system.

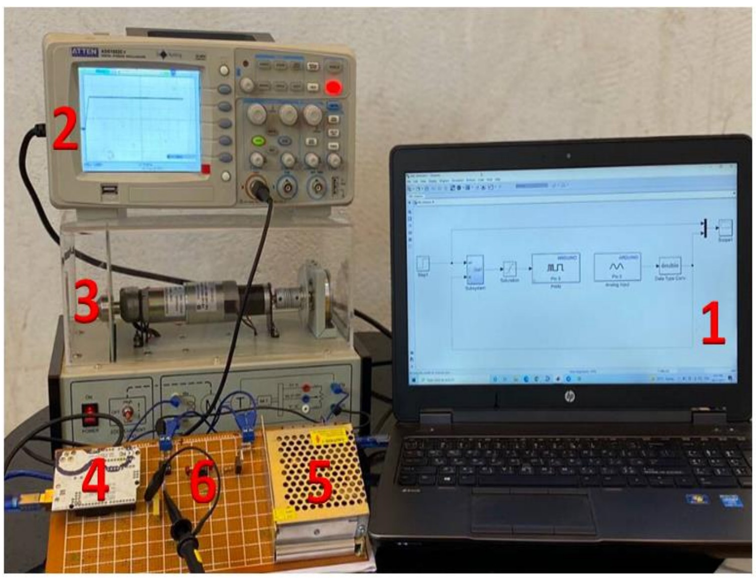


FIGURE 15. Overview of the experimental hardware set-up, 1) PC, 2) Oscilloscope, 3) PMDC motor, 4) Arduino UNO, 5) Power supply, 6) Drive circuit.

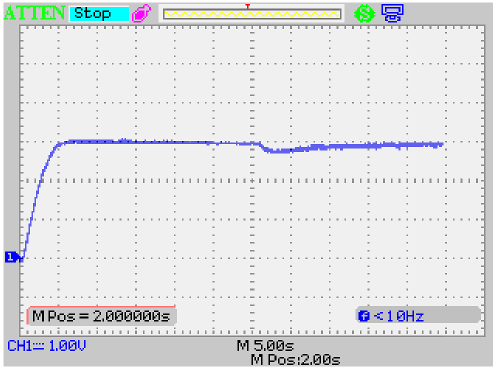


FIGURE 16. The experimental results using PID controller, under $T_L = 0.01N.m$ at 30 Sec.

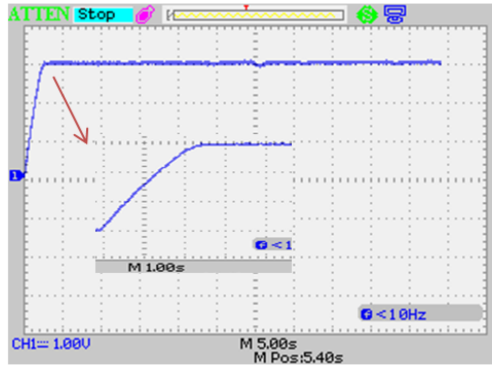
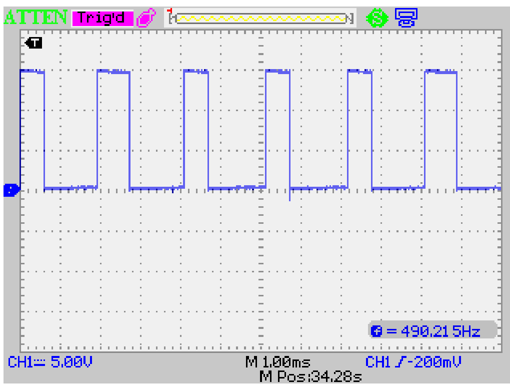
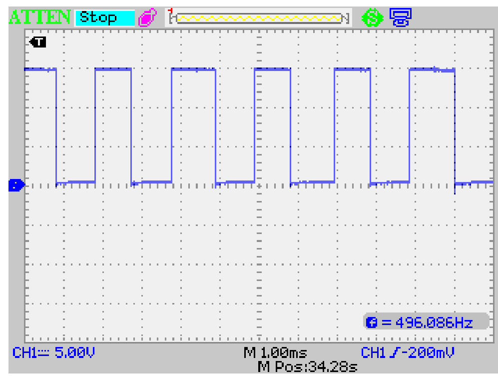


FIGURE 17. The experimental results using SMC controller, under $T_L = 0.01N.m$ at 30 Sec.

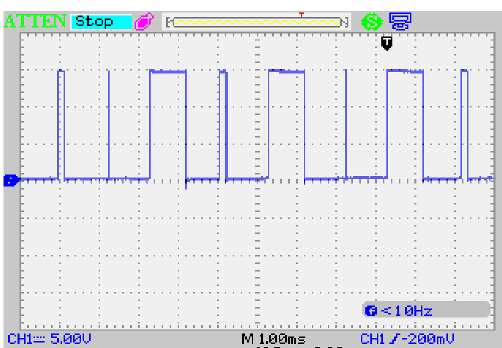


(a)

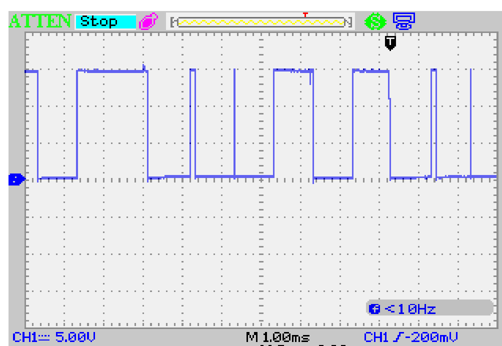


(b)

FIGURE 18. a) Signal generated by Arduino UNO-based PID controller (PWM) at start operation, b) Signal generated by Arduino UNO-based PID controller (PWM) at the load.



(a)



(b)

FIGURE 19. a) Signal generated by Arduino UNO-based controller (PWM) at start operation, b) Signal generated by Arduino UNO-based SMC controller (PWM) at the load.

TABLE 7. The experimental response of a PMDC motor.

control	*Rise time t_r (sec)*	*Settling time t_s (sec)*
SMC	0.9	2
PID	5	8

CONCLUSION

This study is devoted to the speed control of PMDC motor. Different classical and advanced control schemes have been proposed to achieve this objective. The PID controller is the classical controller, while SMC is the advanced controller. The PSO algorithm could enhance the performance of proposed controllers when it is used to tune the design parameters of such controllers. Furthermore, the SMC controller beats the PID controller in general, according to this optimization approach. The effectiveness of the proposed controllers is verified by simulations within the MATLAB/SIMULINK environment. The controller PID and SMC are more effective, according to simulation data. SMC has been found to be successful in terms of rising time, settling time and speedy disturbance reaction. In terms of attaining the required goals, the SMC controller is the most reliable and effective controller. To validate the simulation results, experiments were set up, and real-time implementation was carried out.

This research can be expanded for future work in either the control or optimization directions. To conduct a comparison in performance with SMC, other control schemes such as supper-twisting sliding mode control, adaptive backstepping control, model reference adaptive control and block backstepping control, or other recent control techniques can be suggested [23-41]. Other comparisons in performance can be made if other optimization techniques are addressed, like Social Spider Optimization (SSO), Whale-Optimization Algorithm (WOA), and Grey-Wolf Optimization [42-45].

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