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Performance Comparison of Sliding Mode Control and Conventional PI Controller for Speed Control of Separately Excited Direct Current Motors

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Abstract- Direct Current (DC) motors have been used extensively in industry mainly because of the simple strategies required to achieve good performance in speed or position control applications. This paper addresses controlling of speed of a separately excited DC motor which remains among the vital issues. A separately excited DC motor is generally controlled by Proportional plus Integral (PI) controller. PI controller is simple but sensitive to parameter variations and external disturbance. Due to the robustness of Sliding Mode Control (SMC), especially against parameters variations and external disturbances, and also its ability in controlling linear and nonlinear systems; a separately excited DC motor sliding mode speed controller technique is proposed in this paper. Performance of these controllers has been verified through simulation results using MATLAB/SIMULINK software. The simulation results showed that SMC was a superior controller than PI controller for speed control of a separately excited DC motor.

***Keywords*:** *Direct Current Motors, Speed Control, Proportional plus Integral Controller, Sliding Mode Control.*

مستخلص:

محركات التيار المستمر (DC) تستخدم على نطاق واسع فى الصناعة ويرجع السبب الأساسى لذلك لبساطة إستراتجيات التحكم المطلوبة للتحكم فى تطبيقات السرعة أو الوضع لتحقيق أداء جيد. فى هذه الورقة تم تناول التحكم فى سرعة محرك التيار المستمر ذو التغذية المنفصلة و التى لا تزال من بين القضايا المهمة. يتم التحكم فى سرعة محرك التيار المستمر ذو التغذية المنفصلة بصورة واسعة بإستخدام الحاكمة التناسبية–التكاملية (PI). حيث تمتاز الحاكمة التناسبية–التكاملية بالبساطة و لكنها تتأثر بالتغير فى المعاملات و الإضطربات الخارجية. نسبة للمتانة التى يمتاز بها تحكم الوضع الإنزلاقى (SMC) و خصوصاً ضد التغير فى المعاملات و الإضطربات الخارجية, و أيضاً مقدرته للتحكم فى الأنظمة الخطية و الغير خطية, لذلك تم إستخدام تقنية تحكم الوضع الإنزلاقى للتحكم فى سرعة محرك التيار المستمر ذو التغذية المنفصلة فى هذه الورقة. تم التحقق من أداء هذه المتحكمات من خلال نتائج المحاكاة المتحصلة عليها بواسطة برنامج MATLAB/SIMULINK. نتائج المحاكاة أوضحت تفوق تحكم الوضع الإنزلاقى على الحاكمة التناسبية–التكاملية للتحكم فى سرعة محرك التيار المستمر ذو التغذية المنفصلة.

Introduction

Direct current motors have been widely used in many industrial applications such as electric vehicles, steel rolling mills, electric cranes, robotic manipulators, and home appliances due to precise, wide, simple, and continuous control characteristics. Therefore, the control of speed of a DC motor is an important issue and has been studied since the early decades in the last century [(1)]. DC motors are generally controlled by conventional Proportional plus Integral controllers, since they designed easily, have low cost, inexpensive maintenance and effectiveness.

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With only the classical PI controller applied to control of a DC motor, a good performance characteristic of the controller can be obtained, if all the model parameters of DC motor and operating conditions such as external load torque, disturbances are exactly known (2). However, the performance of PI controller for speed or position regulation degrades under external disturbances and machine parameter variations. Furthermore, the PI controller gains have to be carefully selected in order to obtain a desired response (3). This makes the use of traditional PI controller a poor choice for industrial variable speed drive applications where higher dynamic control performance with little overshoot and high efficiency is required (4-7).

The above issues can be solved by advanced control techniques such as sliding mode control. Sliding mode control was first proposed in early 1950's in Soviet Union by Emelyanov and several co-researchers. After seventies, SMC has become more popular control strategies and powerful control technology to deal with the nonlinear uncertain system. The main reason of this popularity is the attractive superior properties of SMC, such as good performance even in the case of nonlinear systems, applicability to Multi-Input Multi-Output (MIMO) systems. The best property of the SMC is its robustness. Loosely speaking, a system with a sliding mode control is insensitive to parameter variations and external disturbances (8-14).

Nevertheless, this type of control has a disadvantage, which is the chattering phenomenon. The chattering phenomenon is understood to be an oscillatory motion in the neighbourhood of the sliding surface. There are two possible mechanisms which produce chattering.

First, chattering may be caused by the switching nonidealities, such as time delays or time constants. Second the presence of parasitic dynamics (actuator and sensor dynamics) in series with the plant. The chattering phenomenon problem is considered as a major obstacle for sliding mode control to become one of the most significant discoveries in modern control theory. Several solutions have been proposed in the research literature to eliminate or reduce the chattering (15-17).

The organization of this paper is as follows. In section II, the state space model of a separately excited DC motor is given. The basic concept of SMC is briefly reviewed in section III. The section IV, the speed control of a separately excited DC motor using SMC technique is discussed. The simulation results are stated in section V. The last section contains the conclusion.

The State Space Model of DC Motor

Direct current motors are widely used for industrial and domestic applications. The control of the speed of a DC motor with high accuracy is required. There are various DC motor types. Depending on type, a DC motor may be controlled by varying the input voltage or by changing the input current. In this paper, the separately excited DC motor model is chosen due to its good electrical and mechanical performances compared to other DC motor models. The separately excited DC motor is driven by applied armature voltage. Figure 1 shows a separately excited DC motor equivalent model (1-4).

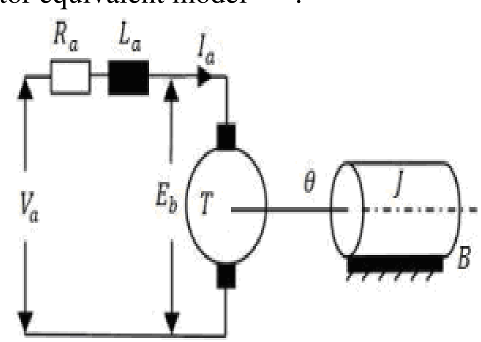

Figure 1: A separately excited DC motor model

The dynamics of a separately excited DC motor may be expressed as:

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$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_b$$
$$V_a = R_a i_a + L_a \frac{di_a}{dt} + K_b \omega \qquad (1)$$

$$T = K_T i_a = J\frac{d\omega}{dt} + B\omega \qquad (2)$$

where V_a is the input terminal voltage (armature voltage) in volt, E_b is the back emf in volt, R_a is the armature resistance in ohm, L_a is the armature inductance in H, J is the moment of inertia of the motor in kgm^2/s^2, T is the motor torque in Nm, B is the viscous friction coefficient in Nms, K_T is the torque factor constant in Nm/A, K_b is the back emf constant in Vs/rad, ω is the angular speed in rad/s, and i_a is the armature current in A. Equations (1) and (2) are rearranged to obtain-

$$\frac{di_a}{dt} = -\frac{R_a}{L_a} i_a - \frac{K_b}{L_a}\omega + \frac{V_a}{L_a} \qquad (3)$$

$$\frac{d\omega}{dt} = \frac{K_T}{J} i_a - \frac{B}{J}\omega \qquad (4)$$

In the state space model of a separately excited DC motor, Equations (3) and (4) can be expressed by choosing the angular speed (ω) and armature current (i_a) as state variables and the armature voltage (V_a) as an input. The output is chosen to be the angular speed [1-4].

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} \dot{i}_a \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \frac{-R_a}{L_a} & \frac{-K_b}{L_a} \\ \frac{K_T}{J} & \frac{-B}{J} \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} V_a$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} \qquad (5)$$

Table 1 lists the numerical values for the parameters of the separately excited DC motor studied in this paper.

Basic Concept of SMC

The theory of sliding mode control has been developed firstly in the Soviet Union in early 1950s [18]. However, sliding mode control did not receive wide acceptance among engineering professionals until the mid 1970s when a book by Itkis [8] and a survey paper by Utkin [19] were published in English. Since then, and especially during the late 80's, the control research community has shown significant interest in sliding mode control.

Table I: Parameters of the separately excited DC motor

Parameters	Values
Armature resistance, R_a	5Ω
Armature inductance, L_a	0.01H
Moment of inertia, J	$0.0025kgm^2/s^2$
Viscous friction coefficient, B	0.136Nms
The back emf constant, K_b	0.245Vs/rad
The torque factor constant, K_T	0.245Nm/A

This increased interest is explained by the fact that robustness has become a major requirement in modern control applications. Sliding mode control concepts have subsequently been utilized in the design of robust regulators, tracking system, state observers, model reference systems and fault detection schemes. The ideas have successfully been applied to problems as diverse as control of electric motors, aircraft and space craft flight, control of flexible structure, robot manipulators, and chemical processes. In general, the phase trajectory of a sliding mode control can be investigated in two parts, representing two modes of the system as shown in Figure 2.

The first part, the trajectory starting from anywhere on the phase plane moves toward sliding surface and reaches the surface in finite time. This is known as reaching, hitting, or non-sliding phase and the system is sensitive to parameter variations and disturbance rejection in this part of the phase trajectory. The second part is the sliding phase in which the state trajectory moves to the origin along the sliding surface and the

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states never leave the sliding surface. During this period, the system is defined by the equation of the sliding surface and thus it is independent of the system parameters and external disturbances [8-12].

In general, the sliding mode controller design approach usually consists of two steps. First, the sliding or switching surface(s) is designed such that the system motion in sliding mode satisfies design specifications. Second, a control law is designed making the switching surface attractive to the system state.

Sliding surface can be either linear or nonlinear. For simplicity, only a linear sliding surface is used in this paper.

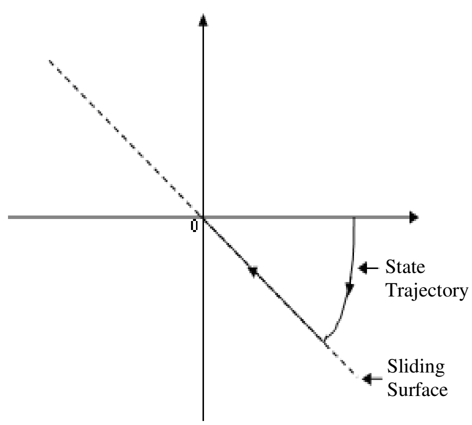

Figure 2: Phase portrait of a sliding motion

Slotine [12] proposed a form of general equation to determine the sliding surface which ensures the convergence of a variable towards its desired value as:

$$s = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \qquad (6)$$

where n is the system order, e is the tracking error, and λ is a strictly positive constant that determine the bandwidth of the system. Having chosen the sliding surface at this stage, the next step would be to choose the control law (u) that will allow the error vector ($e, \dot{e}$) to reach the sliding surface. To do so, the control law should be designed in such a way that the following condition, also named reaching condition, is met:

$$s\dot{s} < 0 \qquad (7)$$

In order to satisfy this condition, the basic discontinuous control law of sliding mode control is given by:

$$u = -K sign(s) \qquad (8)$$

where K is a positive constant known as the hitting control gain or parameter, s is the sliding surface, and sign is the signum function defined as [8-14]:

$$\text{sign (s)} = \begin{cases} 1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \end{cases} \qquad (9)$$

The discontinuous control law described by Equation (9) presents high robustness, insensitive to parameter fluctuations and disturbances. However, using a sign function often causes chattering phenomenon in practice. Several solutions have been proposed in research literature to alleviate the chattering phenomenon [9-11].

Design of Sliding Mode Speed Control of DC Motor

In this section, the design procedure for the speed control of a separately excited DC motor which is under control by SMC technique is discussed. Thus, the state space model of a separately excited DC motor is obtained as shown in Equation (5). The speed control goal is to force the speed ω to track the desired speed reference ω_d. For the sliding mode controller technique, the sliding surface is chosen as:

$$s = \dot{\omega}_e + \lambda\omega_e \qquad (10)$$

where ω_e is the tracking speed error. λ is a strictly positive constant that determine the bandwidth of the system. The given speed control problem can be treated as a regulator problem, where the desired acceleration is chosen to be zero. In this paper to reduce the chattering phenomenon of the sliding mode control, the signum function is replaced by pseudo sliding with smooth control action. The pseudo function is defined as [20]:

$$u = K\frac{s}{|s| + \delta} \qquad (11)$$

where δ is a small positive design constant also called as tuning parameter used to reduce chattering phenomenon (0<δ<1), K is a positive constant, and the sliding surface has the same definition as Equation (10).

Simulation Results

In this section, the overall model of a separately excited DC motor with sliding mode control was implemented in MATLAB/ Simulink. Simulation results of the SMC were compared with the PI controller. Simulations were based on the facts that whether the sliding mode controller is better and more robust than the PI controller or not. Firstly the response of a separately excited DC motor is observed under normal condition, secondly under load torque change, finally under high moment of inertia, respectively.

Simulation results for the nominal system are presented in Figure 3, which shows the rotor speed responses for SMC and PI controller when a separately excited DC motor is operating at a reference speed of 10 rad/s. In terms of the rotor speed control trajectories shown in Figure 3, two different controllers have a similar performance in term of fast tracking of the desired speed. The sliding mode controller shows a little overshoot which is reasonable and then tracks the reference speed closely. However, the settling time and rise time for SMC is shorter than for PI controller.

In order to testify the robustness of the controlled system, a 0.5Nm load torque was suddenly added at time 0.3s and then removed at time 0.4s while the command speed was set as 10rad/s. Figure 4 gives the rotor speed responses under these conditions. The PI controller had the worse rotor speed response at these two instants. However, the system controlled by the SMC demonstrated an excellent rotor speed response whether the load was added or removed. Again the SMC performed a better tracking ability than the PI controller. Therefore, it could be concluded that the PI controller is not robust to load torque variations.

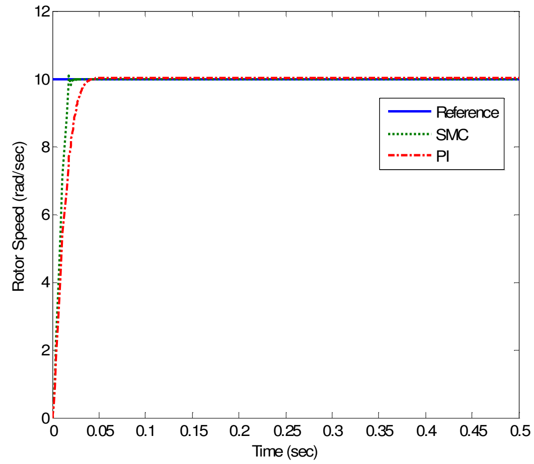

Figure 3: Speed responses of SMC and PI controller for step command

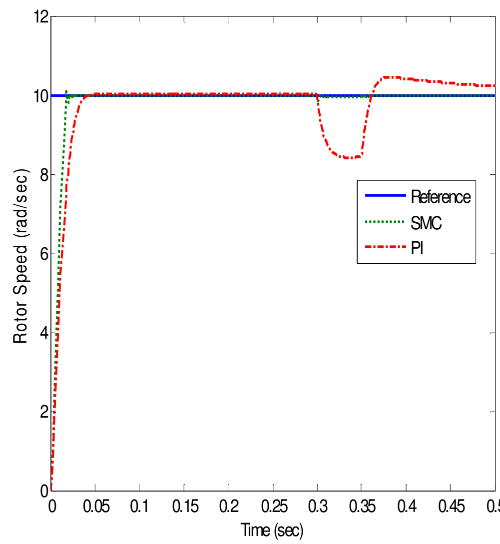

Figure 4: Speed responses of SMC and PI controller against sudden change in torque load

To analyze the sensitivity of the sliding mode controller to parameter variations, the moment of inertia of the separately excited DC motor had been substantially modified throughout the test. The motor was commanded to accelerate from rest to a reference speed of 10 rad/sec under no torque load. Figure 5 shows the motor responses of SMC and PI controller when the moment of inertia was increased by 100% of its original value. It can be seen that the PI controller exhibited poor dynamic response. Furthermore, when carefully study Figure 5 according to the rise time, settling time and overshoot, the best performance belonged to sliding mode controller. This means that the sliding mode controller was insensitive to parametric variations and a robust tracking performance was achieved in presence of the uncertain parameters.

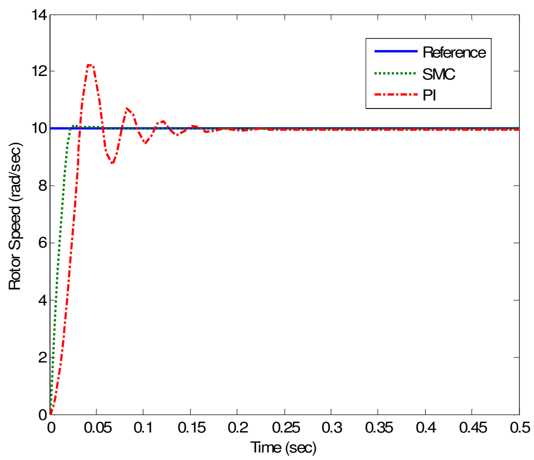

Figure 5: Speed responses of SMC and PI controller with variation in J

Conclusion-

Sliding mode control and PI controller have been considered in this paper for controlling the speed of a separately excited DC motor. The performance of the controllers was validated through simulations. A comparison method had been studied to show the relative advantages and limitations of each controller. From the comparative simulation results, one can conclude that the two controllers demonstrated nearly the same dynamic behavior under nominal condition.

However, simulation results show that the sliding mode controller realized a good dynamic behavior of the motor with a rapid rise time and settling time, and had better performance than the PI controller. But the comparison between the speed control of a separately excited DC motor by the sliding mode controller and PI controller showed clearly that the sliding mode controller gives better performance than the PI controller against parameter variations and external load torque.

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