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Speed Control of Direct Current Motor via Pole Placement Control

Sallah Eldeen M. A. Sharief, Ibrahim M. H. Sanhoury

Department of Control Engineering, College of Engineering, Alneelain University
Khartoum, Sudan (E- mail: salah_aadam@yahoo.com)

Abstract: This paper describes a separately excited DC motor speed control using armature voltage control method, based on traditional Proportional- Integral- Derivative (PID) controller, and pole assignment, feedback control technique. The main objective of the proposed controller is to control the speed of a DC motor shaft rotation and overcome problems like overshoot, and increasing the system model order, that are caused by PID controller, with a step response. Results obtained with Ziegler – Nichols PID controller were compared with those obtained using pole placement. DC motor response contains a 24% overshoot with PID controller; compared with 0.0286% overshoot. In the response of pole placement controller, it is found that pole placement reduces system overshoot to 0.0015% of the closed loop system.

Keywords: *Separately excited DC motor; PID controller; pole placement controller.*

1. INTRODUCTION

DC motors are power actuators, which converts electrical energy into mechanical energy. They are in general divided into two categories: self-excited DC motors and separately excited DC motors (SEDM). They are normally used in applications that require wide speed ranges. The term speed control stand for intentional speed variation carried out automatically. DC motors are most suitable for wide range speed control and are therefore used in many adjustable speed drives. DC motors are widely used in applications where speed control of motor is required like, robot manipulators and home appliances. Since speed is directly proportional to armature voltage and inversely proportional to magnetic flux produced by the poles, so the rotor speed can be changed through adjusting the armature voltage or the field current [1].

The main objective of this work is to control the speed of separately excited DC motor. Different control algorithms had been studied, to control DC motor speed, such as Genetic Algorithm [2], neural network [3], fuzzy based approach [4]. Moreover, pole placement is just a few among these numerous works [5].

One of the commonly used controllers is (proportional – integral –derivative) PID controller, the most commonly employed PID design technique in industry is Ziegler-Nichols (ZN) method, which has the advantage of avoiding the use of controlled plant and uses the step response of the plant instead. PID controller using ZN method has good disturbance rejection. However, it has high percentage overshoot; therefore, the control signal becomes high in transient state, that causes saturation in the actuator. This controller also increases the system model order when used. Pole placement controller has been applied, to control the speed of (SEDM), and the result is compared with the output of PID controller, with unity feedback.

2. MATHEMATICAL MODEL OF SEDM

The DC motor converts direct current (DC) electrical energy into rotational mechanical energy. A major fraction of the torque generated in the rotor (armature) of the motor is available to drive an external load. Due to the high torque, speed controllability over a wide range, well-behaved speed-torque characteristics, DC motors are widely used in numerous control applications, including robotic manipulators, tape transport mechanisms, and servo valve actuators. Speed control can be achieved through variable supply voltage, resistors and electronic controls. The schematic diagram of separately excited DC Motor is shown in **Fig. 1** [7].

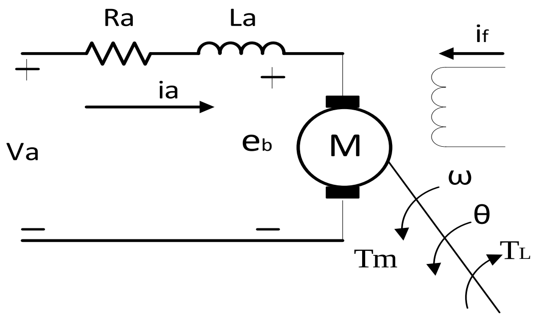

Fig. 1. A DC motor model

Table1. Parameters of SEDM [8]

Parameter	Value
Armature resistance, **R_a**	1 Ω
Armature inductance, **L_a**	0.5H
Moment of inertia , J	0.01 kg.m^2/s^2
Coefficient of Viscous friction, B	0.00003Nms
The back EMF constant, $\boldsymbol{K_b}$	0.023V/rad
The torque constant, $\boldsymbol{K_T}$	0.023Nm/A

where:

- V_a : Armature voltage (V)
- R_a : Armature resistance (Ω)
- L_a : Armature inductance (H)
- i_a : Armature current (A)
- e_b : Armature back EMF (V/rad)
- i_f : Field current (A)
- T_m : Motor torque (N.m)
- T_L : Load torque (N.m)
- θ : Rotor displacement (rad)
- ω : Angular speed (rad/sec)

The physical parameters of the SEDM are as follows:

Based on Newton's law combined with Kirchhoff's law, and assuming constant field excitation the armature circuit electrical equations are written as follow:

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

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + K_b \omega \quad (2)$$

$$T_m = K_T i_a = J \frac{d\omega}{dt} + B\omega \quad (3)$$

Equations (2) and (3) can be rearranged as follows:

$$\frac{di_a}{dt} = -\frac{R_a}{L_a} i_a - \frac{K_b}{L_a}\omega + \frac{V_a}{L_a} \quad (4)$$

$$\frac{d\omega}{dt} = \frac{K_T}{J} i_a - \frac{B}{J}\omega \quad (5)$$

Equations (4) and (5) represent the state space model of (SEDM) through 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 (ω).

$$\begin{bmatrix} \dot{i_a} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \frac{-R_a}{L_a} & \frac{-K_b}{L_a} \\ \frac{K_T}{J} & \frac{-B}{J} \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix} V_a \quad (6)$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} \quad (7)$$

The block diagram of armature controlled SEDM is shown in **Fig. 2**, from which the transfer function of the system is stated in equation (8):

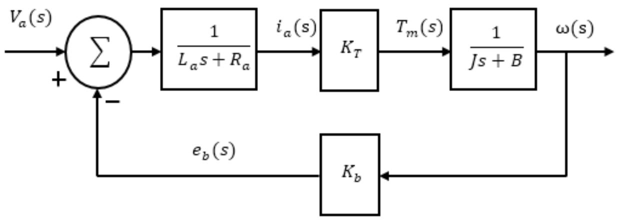

Fig. 2. Block diagram of armature control of (SEDM)

$$\frac{\omega(s)}{V_a(s)} = \frac{K_T}{(L_a s + R_a)(Js + B) + (K_T K_b)} \quad (8)$$

3. PID CONTROLLER DESIGN

PID controllers are the most widely used type of controllers for industrial applications. They have a simple structure and exhibit robust performance over a wide range of operating conditions. They are the most efficient of controllers when there is no complete knowledge of the process.

Equation 9 formulated the relationship between the input e(t) and output u(t) of PID controller [10].

$$u(t) = K_p(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de}{dt} \quad (9)$$

$$\frac{U(S)}{E(S)} = K_p + \frac{K_i}{s} + K_d s = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \quad (10)$$

4. ZIEGLER-NICHOLS TRADITIONAL TUNING METHOD

This method is applied to plants with step responses of the form displayed in **Fig. 3**. This type of response is typical of a first order system with transportation delay. The response can be characterized by two parameters; L is the delay time while T corresponds to the time constant. They are found by drawing the step response tangent at its point of inflection; and noting its intersections with the time axis and the steady state value. The plant model is represented using these parameters as in Equation 11:

$$G(S) = \frac{Ke^{-Ls}}{Ts+1} \quad (11)$$

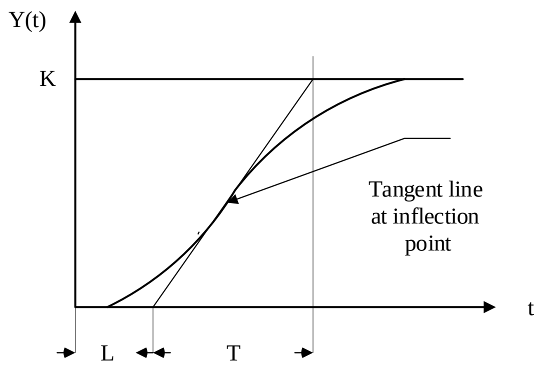

Fig. 3. Response curve for Ziegler-Nicholsmethod [9]

Table 2. ZN tuning rules based on step response of plant [12]

Type of controller	K_p	T_i	T_d
P	T/L	∞	0
PI	0.9T/L	L/0.3	0
PID	1.2T/L	2L	0.5L

In real-time process control systems, a large variety of plant models can be approximated by equation (11). If the system model cannot be physically derived, experiments can be performed to extract the parameters for the approximate model as in equation (11). For instance, if the step response of the plant model can be measured through an experiment, the output signal can be recorded as sketched in Figure 3, from which the parameters of k, L, and T can be extracted by the simple approach shown. More sophisticated curve fitting approaches can also be used. Ziegler-Nichols formula in Table (2) can be used to get the controller parameters [11].

From the first order model of the system: T=17.3913, L=0.514, which implies K_p=0.0355, T_i=1,028, T_d=0.257. Usually, initial design values of PID controller obtained by all means need to be adjusted repeatedly through computer simulation until the closed loop system performs or compromises as desired. These adjustments were done using simulation software, and the tuned values implies K_p=2, K_i=1.15 and K_d=0.38.

5. POLE PLACEMENT CONTROLLER DESIGN:

This section presents a commonly called pole placement or (pole assignment) technique. All state variables are assumed measurable for feedback. Conditioned on complete controllability, the poles of the closed loop system may be placed at any desired location by means of state feedback; through an appropriate state feedback gain matrix (**K**). For a control system given by:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \qquad (12)$$

Based on the pole placement, and through figure 4 the control signal will be:

$$u = -Kx \qquad (13)$$

Figure 4 shows the block diagram of a separately excited DC motor based on pole placement.

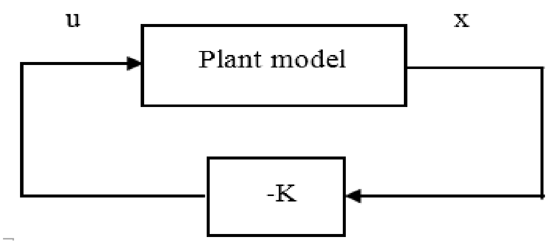

Fig.4. Closed loop control system [11]

The control signal (u) is determined by the instantaneous state, as it is clear in equation (13) and figure 4. Substituting equation (13) in equation (12) yields:

$$\dot{x}(t) = (A - BK)x(t) \qquad (14)$$

The solution of equation (14) is:

$$x(t) = e^{(\boldsymbol{A}-\boldsymbol{BK})}x(0) \qquad (15)$$

Where: $x(0)$ is the initial state; which can be caused by external disturbances. The Eigen values of matrix $(\mathbf{A} - \mathbf{BK})$ are called regulator poles; which determine the stability and transient response characteristics. If these regulator poles are placed in the left half of s-plane, then $x(t)$ approaches zero as (t) approaches infinity. The problem of placing the regulator poles (closed loop poles) at the desired location is called pole placement problem [12].

The closed loop transfer function of the system according to the selected data is given by equation (16), with two poles: (-1.002+1.9256i) and (-1.002-1.9256i).

$$\frac{\omega(s)}{V_a(s)} = \frac{4.6}{s^2+2.004s+4.712} \qquad (16)$$

The closed loop poles of equation (16) above have been shifted to (-2+0.77i) and (-2-0.77i) with trial and error method using simulation software. The corresponding transfer function is:

$$\frac{\omega(s)}{V_a(s)} = \frac{4.6}{s^2+4s+4.593} \qquad (17)$$

6. RESULTS AND DISCUSSION

Simulation software was developed to implement the presented results. These results are the SEDM response curves that were obtained before adding a certain controller; in existence of PID controller, and pole placement controller.

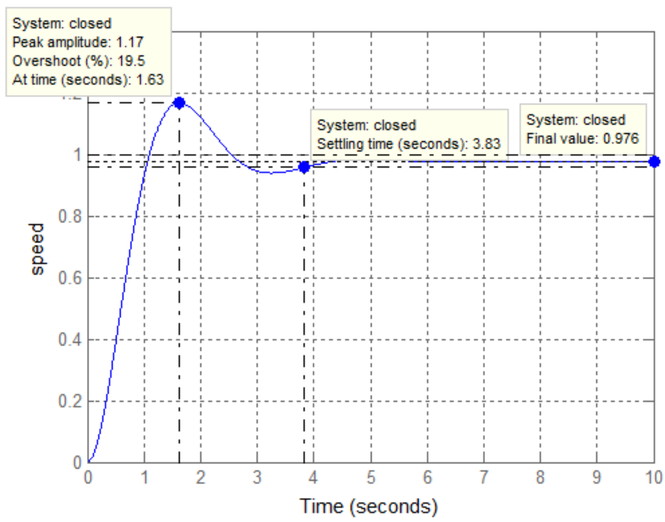

Fig. 5. Closed loop step response without a controller

Fig. 5 shows the closed loop response of the SEDM without a controller. The response has some imperfections, which are to be solved by the controller. These imperfections are: the steady state error and the 19.5 percent overshoot as shown **Fig. 5.** Also the response is slow with 3.83 second settling time.

As **Fig. 6** shows the PID controller improved the system response. It decreased settling time by 1.6 second, and set the steady state error to zero. On the other hand, it increased the overshoot by 23%. Inserting PID controller also increases the system order by one to become a third order system, as explained by the transfer function of equation 18, which made the system more complicated, although its response becomes effective. Increasing the system order and the response overshoot are unwanted behavior.

$$\frac{\omega(s)}{V_a(s)} = \frac{107480\,s^2+9.2s+5.29}{s^3+3.7520\,s^2+9.31204\,s+5.29} \qquad (18)$$

In the pole placement controller when the steady state error is set to zero, the overshoot dramatically decreased to 0.0285, in other words, it decreased to 0.0015%, and settling time is decreased in this method by 38.12% from the closed loop response before adding a controller, as shown in **Fig. 7**.

Table 3. Comparison between controllers response

Controller	Maximum OS (%)	Settling time (sec)	SS error
C.L response with unity feed back	19.5	3.83	0.024
PID controller	24	2.23	0
Pole placement controller	0.0286	2.37	0

Table 3 shows maximum overshoot, settling time and steady state error of the SEDM, obtained from simulation without a controller, with PID controller, and with pole placement controller. **Fig. 8** shows the step response of the system without a controller in the same window with the response in existence of both PID and pole placement controllers.

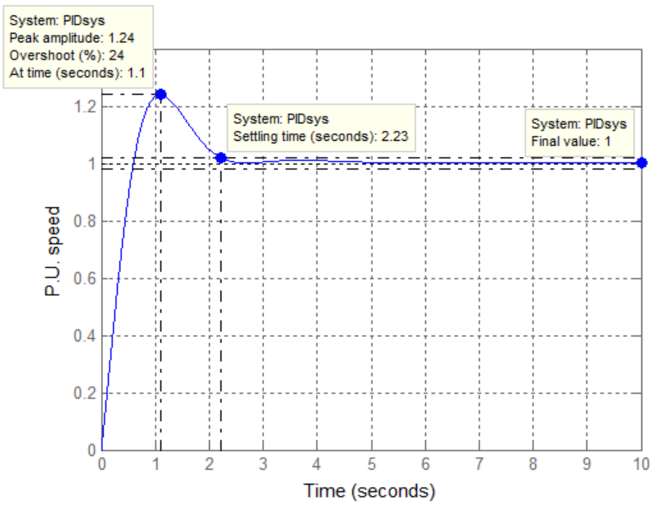

Fig.6. System response in the existence of PID controller

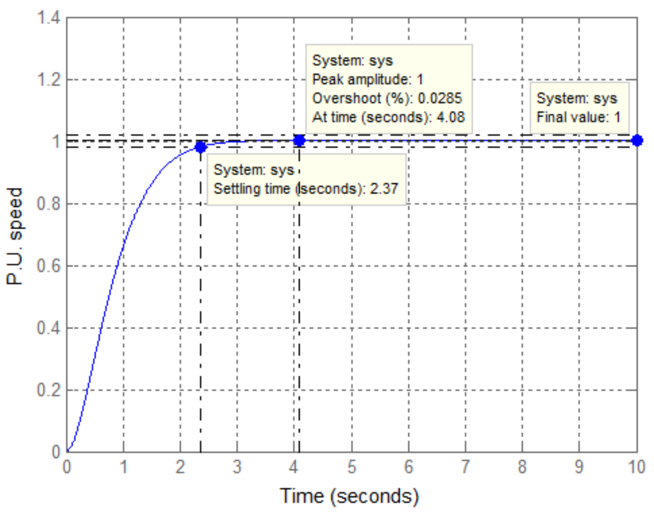

Fig.7: Step response with pole placement

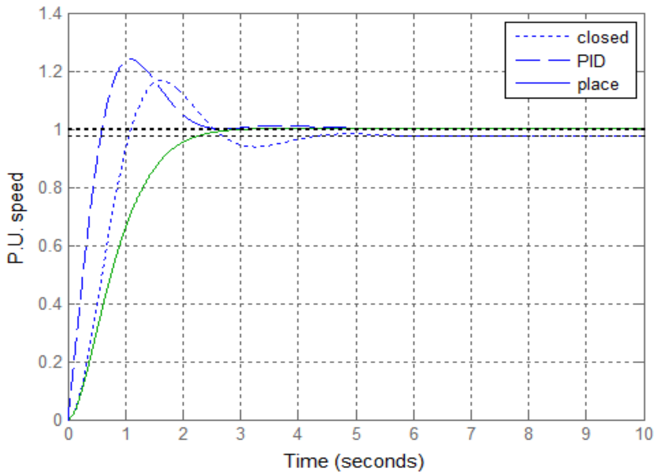

Fig.8: Response with &without controllers

7. CONCLUSIONS

In this paper, a pole placement controller is utilized to control the speed of separately excited DC motor. The proposed controller is benchmarked with the well-known PID controller, which has some problems like increasing the system response overshoot. The PID controller also increases the order of system model.

When comparing the PID and the pole placement controllers it is found that both of them diminish the steady state error, and accelerate the system response, but pole placement controller overcomes the problems of PID controller. It reduces the overshoot considerably, without increasing the system order; therefore, its performance is better compared to the PID controller.

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