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Design and implementation of a state feedback controller for enhanced speed stability of permanent magnet DC motors under load variations

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Abstract

This study presents the design and simulation of a State Feedback Controller (SFC) for speed regulation of a Permanent-Magnet DC (PMDC) motor using a state-space modeling approach. The objective is to achieve stable and accurate speed control under dynamic load disturbances that typically degrade the performance of conventional open-loop systems. The Direct Current (DC) motor is modeled in state-space form, with armature current and angular speed selected as the main system states. Controller gains are designed using the pole placement method to ensure fast response and improved stability. The proposed SFC is evaluated through MATLAB®/Simulink® simulations by examining motor speed, armature current, and input voltage responses under step-load variations. Simulation results show that the SFC maintains the motor speed at the reference value of 3,430 rpm even during sudden load increases, whereas the uncontrolled motor experiences significant speed drops and oscillations. Performance analysis confirms notable improvements in transient response. The rise time is reduced from 1.1864 s to 0.4220 s, and the settling time decreases from 2.1132 s to 0.7517 s, indicating faster and more stable system behavior. In addition, smoother current transitions and more efficient voltage regulation are achieved compared to the open-loop configuration. Overall, the results demonstrate that state-space control using pole placement provides a robust and responsive alternative to conventional PID controllers for DC motor speed control under load disturbances. Future work will focus on experimental validation and the exploration of advanced control strategies such as Linear Quadratic Regulation and adaptive control.

Keywords:
DC motor, speed control, state feedback controller, state-space model, MATLAB® Simulink®

1 Introduction

The rapid advancement of technology has driven significant progress in industrial automation and control systems, leading to an increasing demand for motor control strategies that are not only efficient and precise but also adaptive. Electric motors, especially Direct Current (DC) motors, are fundamental in modern applications such as robotics, electric vehicles, and renewable energy systems due to their precise speed regulation capabilities. However, maintaining a stable DC motor speed under dynamic load conditions is still challenging. Open-loop systems cannot compensate for disturbances, and traditional PID controllers often underperform due to fixed gains, lacking real-time adaptability [1,2].

For high-performance systems like electric vehicles and robotic arms, stable and accurate speed control is crucial for both performance and safety [3,4]. Advanced methods such as State Feedback Controllers (SFCs) have emerged as promising alternatives, offering improved robustness and dynamic response by using state-space modeling and pole placement strategies [5]. These approaches allow real-time adjustment of input voltages to minimize steady-state error and enhance transient performance, especially in nonlinear or load-varying environments [6,7].

This study focuses on the design and implementation of an SFC for a Permanent Magnet DC Motor (PMDC) using a state-space approach. The methodology involves mathematical modeling, controller synthesis via pole placement, and performance validation using MATLAB® Simulink®. The evaluation considers rise time, settling time, steady-state error, and load disturbance rejection performance aspects crucial to real-world applications, including wind-turbine pitch systems and electric mobility solutions. Based on these challenges, this research develops a control strategy that ensures stable and accurate speed regulation of a PMDC under dynamic load variations. The main goal is not only to design and implement an SFC using a state-space approach but also to validate its effectiveness compared to conventional methods.

1.1 Review of the literature

In recent years, various control strategies have been explored to enhance the speed regulation of DC motors. One such approach involves optimizing PID controllers using metaheuristic algorithms, such as the Whale Optimization Algorithm (WOA), to achieve improved transient response and reduced steady-state error [8]. Another innovative approach is the integration of neural networks in adaptive PID feedback systems, which enable real-time learning and adjustment to varying load conditions [9].

Furthermore, inverse optimal control techniques have been proposed for speed regulation using DC/DC converters, offering an alternative method to maintain speed stability under fluctuating loads [10,11]. Sensorless control strategies have also gained traction, with studies highlighting their potential in optimizing energy consumption while maintaining efficient motor performance [12,13]. Additionally, researchers have explored the integration of fuzzy logic with traditional controllers to improve precision in motor applications, such as antenna positioning systems [14,15]. These developments motivate the adoption of an SFC to address the limitations of conventional controllers in handling dynamic load variations.

2 Research method

This research was designed using an experimental–simulation approach based on the state-space method to develop a mathematical model of a PMDC Motor and to design an SFC through the pole placement technique. The implementation and validation of the proposed controller in this study are limited to simulation-based analysis using MATLAB®/Simulink®. Simulations were conducted under varying dynamic load scenarios. Research data were obtained by recording key variables such as motor speed, armature current, and armature voltage. The simulation results were analyzed quantitatively by evaluating performance parameters including rise time, settling time, steady-state error, overshoot, and the system's capability to reject load disturbances. Furthermore, the performance of the SFC was compared with both the uncontrolled system and conventional PID control to assess the superiority of the proposed approach in terms of adaptability and stability.

To support the simulation and implementation of DC motor speed control, several essential components and tools were employed. MATLAB® software version R2023a served as the primary platform for system modeling, simulation, and control analysis. The motor used in this study was a PMDC, known for its linear characteristics and quick response to input-voltage changes.

For real-time speed measurement, the system was equipped with a speed sensor in the form of an optical encoder, which provided accurate data regarding rotor speed variations. A variable DC voltage source was used as the power supply, allowing voltage adjustments as needed during testing. For real-time control implementation, a microcontroller, either Arduino Uno or STM32, was employed to execute the control algorithms developed in simulation and to connect directly with the hardware for real-world validation of system performance.

The research workflow is outlined in Fig. 1. In this flowchart, “Yes” proceeds when the system meets the controllability criteria required for state-feedback control design, while “No” indicates the need to revise the system model or parameters before proceeding.

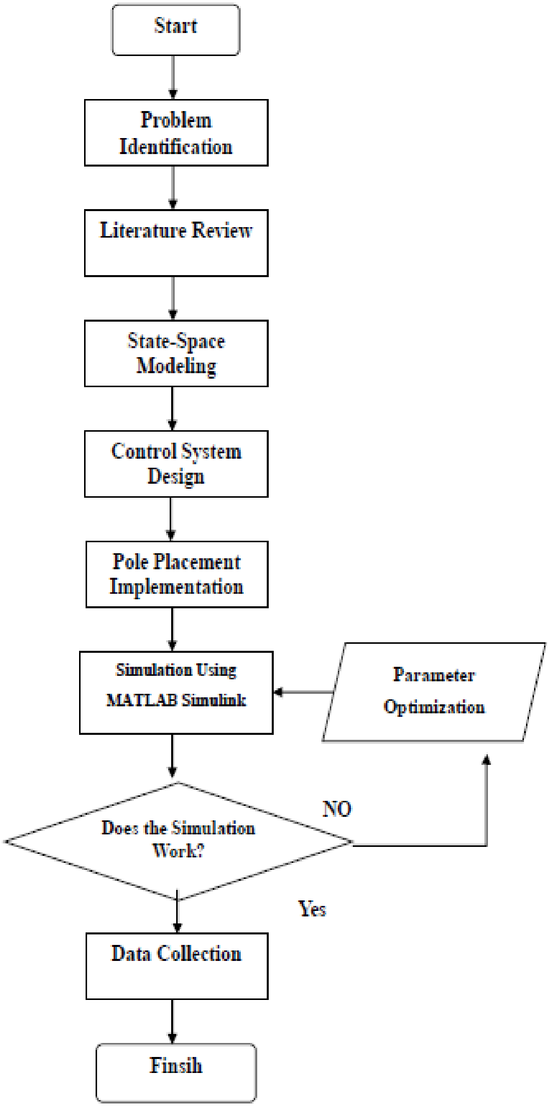

Fig. 1. Research workflow

2.1 Research design

The research design of this study was structured to systematically address the problem of speed instability in DC motors under dynamic load variations. The process began with identifying the main issue: the inability of conventional controllers to maintain stable motor speed under load disturbances. A comprehensive literature review was then conducted to gather insights from prior studies on DC motor control strategies, including traditional PID controllers and advanced methods such as state-feedback and intelligent control approaches.

Subsequently, a mathematical model of the PMDC was developed using the state-space method to represent the electrical and mechanical dynamics of the motor [16,17]. Based on this model, an SFC was designed using the pole placement technique to achieve the desired closed-loop performance. To enhance system stability and efficiency, parameter optimization was performed by fine-tuning the state feedback gains, ensuring an appropriate balance between fast response and minimal overshoot [18,19].

After the controller design stage, data were collected through MATLAB®/Simulink® simulations under different dynamic load conditions. Key variables, including motor speed, armature current, and armature voltage, were recorded to capture the system’s response. The final stage involved data analysis, where the simulation results were evaluated using performance indicators such as rise time, settling time, steady-state error, overshoot and disturbance-rejection capability. The outcomes were then compared with both the uncontrolled system and a conventional PID controller to validate the effectiveness and superiority of the proposed approach.

At the modeling stage, it was necessary to define the physical and electrical parameters of the PMDC Motor used in this study. These parameters form the basis of the state-space model and significantly influence the system’s dynamic behavior. The detailed motor specifications employed in the research are presented in Table 1.

Table 1. Motor parameters used in the state-space model

Equipment	Specifications
Rated voltage (V)	24
Rated current (A)	5.4
Rated power (W)	120
No- Load speed (RPM)	4000
Rated speed (RPM)	3430
Resistance (Ω)	4.67
Inductance (H)	0.017

In the design of an SFC using the pole placement method, the system utilizes feedback loops where state variables, such as speed and armature current, are used as control inputs. The controller is designed to regulate the armature voltage (Va) based on the control equation, Eq. (1).

$$V_a = K_i . q - K_1 . i - K_2 . \omega \qquad (1)$$

where V_a is armature voltage, K_i is integral gain (position error), K_1 is the feedback gain for armature current, K_2 is the feedback gain for angular speed, i is armature current, ω is angular velocity (speed), and q is rotor position.

This equation indicates that the armature voltage is controlled by a combination of state variables, each multiplied by its respective feedback coefficient. By adjusting these coefficients, the system can achieve the desired performance, such as improved dynamic response and optimal system stability. In the design of a SFC, the system's block diagram is illustrated in Fig. 2. One of the methods used for pole placement is Ackermann’s Method.

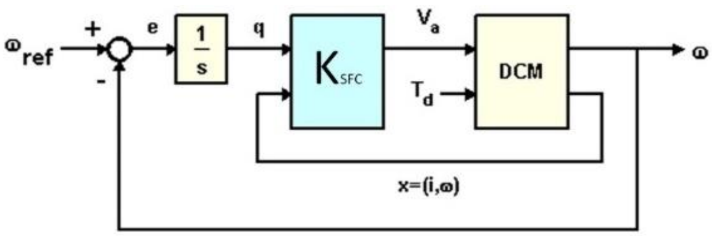

Fig. 2. Block diagram of an SFC on a DC motor

To apply this method, the motor model must be in a controllable state. The controllability of the system is evaluated using the controllability matrix (M) defined as Eq. (2).

$$M = [B \mid AB \mid ... \mid A^{n-1}B] \qquad (2)$$

where A is the system matrix from the state-space model, B is the input matrix, and n is the order of the system.

Once the system is confirmed to be controllable, the feedback gain (K) is determined using Ackermann’s formula (Eq. (3)).

$$K = [0 \;\; 0 \;\; ... \;\; 0 \;\;\; 1][B \mid ... \mid AB \mid ... \mid A^{n-1}B]^{-1}\varphi(A) \qquad (3)$$

where K is the feedback gain vector $[K_1 \quad K_2 \quad ... \quad K_n]$, M is the controllability matrix as defined above, $\varphi(A)$ is the desired characteristic polynomial matrix evaluated at A, and $[0 \quad 0 \quad ... \quad 1]$ is a selector row vector used in Ackermann's method to extract the correct row.

The design of a SFC is illustrated in Fig. 2, where Ackermann's Method is applied for pole placement. This method requires the motor model to be in a controllable state, which is verified by computing the controllability matrix. Once controllability is confirmed, the feedback gain is determined using Ackermann's formula, derived from the characteristic polynomial corresponding to the desired pole placement.

2.2 Parameter optimization

The system's performance is first evaluated through initial simulations, followed by an optimization process aimed at achieving a stable and efficient response [20]. State feedback gains (K1, K2, Ki), initially computed using Ackermann's formula, are fine-tuned through iterations to balance quick responsiveness with system stability and avoid excessive oscillations [21], [22].

Careful adjustment of closed-loop pole placement ensures fast and stable response with minimal overshoot and delay. This enhances the system's ability to handle step inputs and continuous load torque variations effectively [23]. A crucial part of the optimization also includes refining the load torque compensation mechanism.

The controller is tested with time-based torque changes to ensure it adapts and maintains motor speed under varying load conditions. The MATLAB® script shown in Fig. 3 automates the computation of feedback gains and configures the controller for different scenarios. Final simulations validate that the optimized parameters meet the desired system behavior.

```
%Integral Action
Ai = [A zeros(2,1);-C 0]
Bi = [B;0]
Ci = [C 0]

%Peletakan nilai poles
pcl = [-10 -10 -10]

%Ackermann Formula
K = acker(Ai,Bi,pcl)
ksfw = K(1) % state feedback (current)
ksfi = K(2) % state feedback (speed)
KI = -K(3) % integral gain
```

Fig. 3. The MATLAB® script used for computing and optimizing

2.3 Data Collection and Analysis

After the optimization process was completed, simulation results were systematically collected from MATLAB®/Simulink® by recording the time-domain responses of motor speed, armature current, and armature voltage under varying dynamic load conditions. These data were then analyzed to evaluate the effectiveness of the SFC compared with both the uncontrolled system and the conventional PID controller. Several key performance indicators were used in the analysis. Rise time measures how quickly the motor speed reaches 90% of the reference value, while settling time indicates the duration required for the speed to stabilize within a specified tolerance band around the reference [24].

The steady-state error quantifies the difference between the final motor speed and the desired setpoint [17], [23]. Another important metric is overshoot, which refers to the extent to which the motor speed temporarily exceeds the reference value before reaching a steady state [25]. In addition, disturbance rejection capability was assessed to determine how effectively the controller maintained speed stability during load variations. By combining these evaluation metrics, the collected data provided a comprehensive basis for validating the improvements in adaptability, stability, and overall performance achieved by the proposed SFC.

3 Results and discussion

3.1 DC motor simulation testing

In the simulation study, the DC motor was subjected to varying load-torque values to observe the motor's speed response before and after implementing the SFC under different load-torque conditions. Fig. 4 shows the load-torque profile used in the testing scheme.

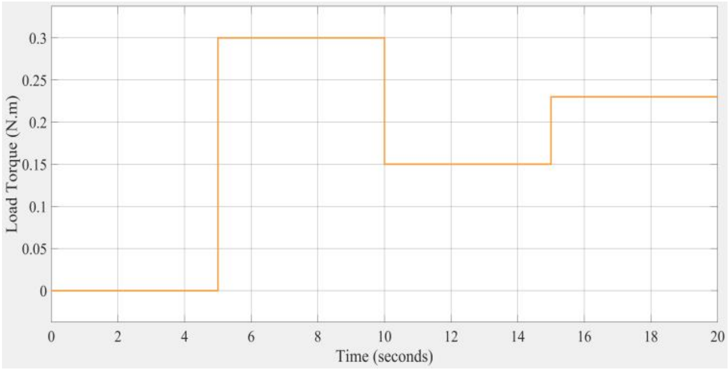

Fig. 4. Load-torque profile for DC-motor testing

The load-testing scheme is divided into several time intervals. In the 0–5 s interval, the motor operates under no-load conditions. Then, the load torque increases to 0.3 N·m during the 5–10 s interval. At 10–15 s, the load torque decreases to 0.15 N·m. Finally, during the 15–20 s interval, the load torque is set to 0.23 N·m.

3.2 DC-motor simulation without state-feedback control

Simulation testing was first conducted on the DC-motor system without applying the state-feedback controller to observe its natural response to input signals and load variations. In the absence of control, the DC motor is supplied with a constant voltage of 24 V without any adaptive mechanism to adjust the voltage supply in response to load variations. As a result, the motor speed experiences significant fluctuations when the load torque changes. Fig. 5 shows the simulated speed response in the open-loop case.

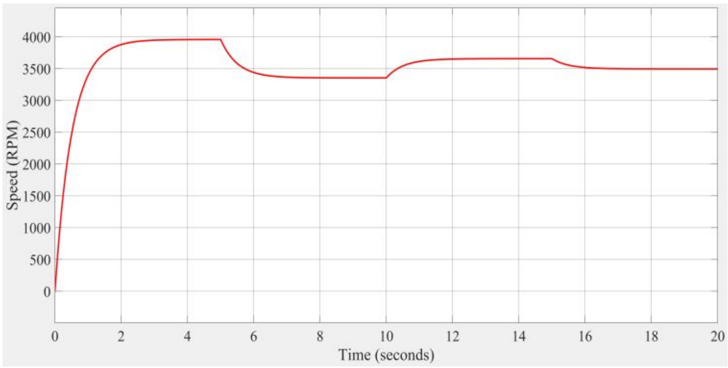

Fig. 5. DC-motor speed response without the SFC (open-loop)

During the 0–5 s interval under no-load conditions, the motor reaches a steady-state speed of 3,931 rpm, as the generated electromagnetic torque is sufficient to overcome internal losses. When the load torque increases to 0.3 N·m (5–10 s), the speed drops sharply to 3,356 rpm due to the higher resistive torque. As the load decreases to 0.15 N·m (10–15 s), the speed recovers to 3,656 rpm, and at 0.23 N·m (15–20 s), the speed reduces slightly to 3,495 rpm. The open-loop speed data are summarized in Table 2.

Table 2. DC Motor Speed Response Without Control

Time interval (s)	Load torque (N·m)	Speed (rpm)
0 – 5	0.00	3,931
5 – 10	0.30	3,356
10 – 15	0.15	3,656
15 – 20	0.23	3,495

The motor speed drops drastically when the load increases and rises again when the load decreases. Without a voltage-regulation mechanism, the motor is unable to maintain the reference speed stably.

The armature current exhibits significant surges in response to load-torque changes. At no load, the initial current is around 0.34 A just enough to overcome system losses. When the load torque increases to 0.3 N·m, the current sharply rises to about 5.52 A, as more power is needed to produce the required electromagnetic torque. A reduced load of 0.15 N·m lowers the current to around 2.93 A, while a load of 0.23 N·m during the 15–20 s interval raises it again to about 4.3 A. These variations are illustrated in Fig. 6.

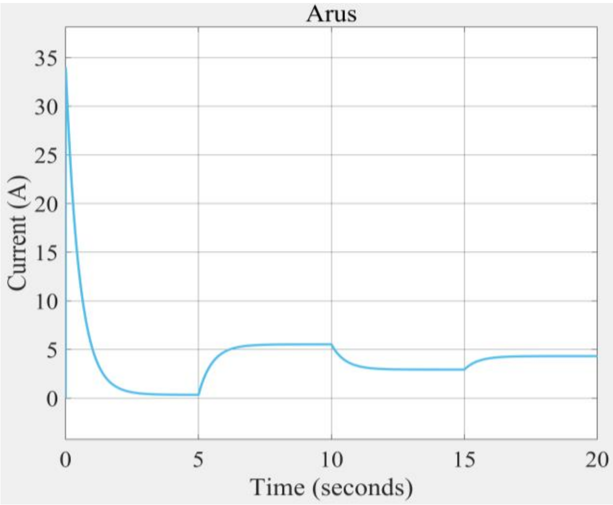

Fig. 6. Armature-current response in a DC motor without control for load fluctuations

Without control, the current undergoes large fluctuations in response to changes in load torque, indicating inefficient power utilization. The voltage supplied to the DC motor remains constant at 24 V. Since there is no adjustment for load variations, the motor is unable to compensate for speed reductions when the load increases. The constant voltage supply cannot enhance the electromagnetic torque generated by the motor, causing the motor speed to drop whenever the load increases. This is illustrated in Fig. 7. The supply voltage remains constant at 24 V, demonstrating the inability of the open-loop system to adapt to load changes.

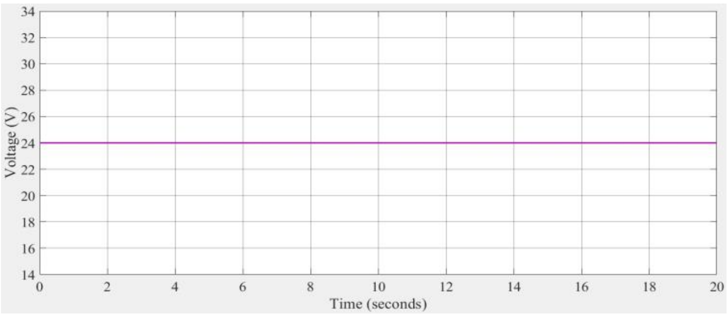

Fig. 7. Voltage response of a DC motor without a control system to load fluctuations

3.3 DC-motor simulation with state-feedback control

When the SFC is applied, the system becomes more adaptive in responding to load variations. The SFC adjusts the supply voltage in real time so that the motor maintains the reference speed of 3,430 rpm, even as the load torque fluctuates during the simulation. Fig. 8 shows the closed-loop speed response. When the SFC is implemented, the system can adjust the input voltage to keep the speed stable at 3,430 rpm despite load variations (Table 3).

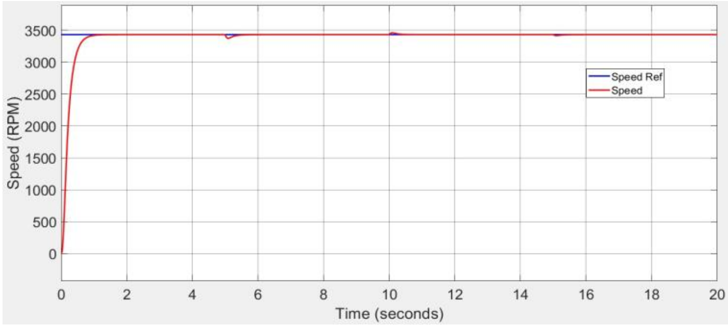

Fig. 8. DC motor speed response with a SFC to load fluctuations

Table 3. DC motor speed response with SFC implementation

Time interval (s)	Load torque (N·m)	Speed with SFC (rpm)
0 – 5	0.00	3,430
5 – 10	0.30	3,430
10 – 15	0.15	3,430
15 – 20	0.23	3,430

Implementation of the SFC results in more stable armature current and reduced fluctuations compared to the uncontrolled system. At no load, the initial current is around 0.294 A slightly lower due to optimized voltage supply. When the load torque reaches 0.3 N·m, the current rises to about 5.53 A**,** but remains steadier because voltage adjustments maintain torque and speed. As the load decreases to 0.15 N·m, the current drops to around 2.91 A, and it increases to roughly 4.31 A at 0.23 N·m. This improved current stability indicates better power efficiency under SFC, as shown in Fig. 9.

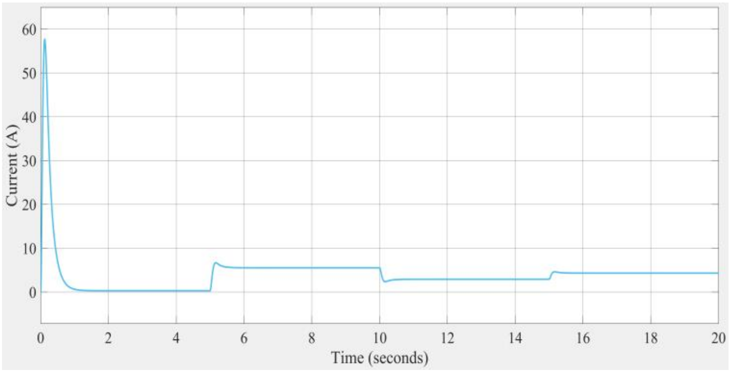

Fig. 9. Armature-current response of a DC motor with the SFC to load fluctuations

Under the SFC, current fluctuations are smaller, indicating improved power utilization and stability. The supply voltage in the SFC system adjusts dynamically to maintain the reference speed. Under no-load conditions, the voltage remains at about 20.8 V, which is lower than in the uncontrolled system because high voltage is not required to sustain the reference speed. When the load increases to 0.3 N·m, the voltage rises to about 24.5 V to provide additional power and maintain speed. A decrease in load to 0.15 N·m causes the voltage to drop back to about 22.6 V, while an increase to 0.23 N·m raises the voltage to about 23.6 V. These variations demonstrate that the SFC effectively adjusts the power supply to ensure optimal motor performance. The voltage-variation profile is presented in Fig. 10.

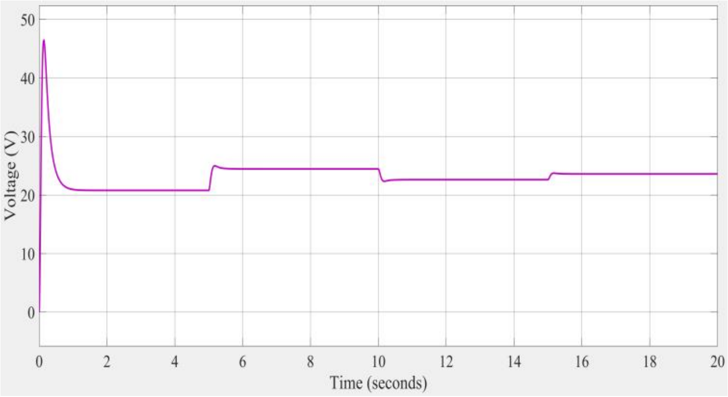

Fig. 10. Armature-voltage response of a DC motor with the SFC to load fluctuations

Dynamic adjustment of the supply voltage enables the closed-loop system to maintain the desired speed despite changes in load torque. This behavior indicates that the closed-loop poles placed through the SFC significantly improve the damping characteristics of the system. As a result, the motor is able to maintain a constant speed despite load torque variations. The reduction in rise time and settling time demonstrates that the proposed pole placement strategy enhances transient performance and disturbance rejection capability. Similar improvements in dynamic response under load disturbances have also been reported in recent DC motor speed control studies. Salman et al. [27] demonstrated that a state-feedback controller produced stable system responses under both disturbed and undisturbed conditions. Olusegun et al. [17] confirmed that an LQR-based SFC effectively suppressed periodic load torque disturbances while achieving superior dynamic performance compared to conventional PID controllers. Al-Mahturi et al. [28] applied the pole placement technique in state feedback design for DC motor speed control, demonstrating improved performance under load disturbance conditions. Furthermore, comparative studies [29][30] reported that modern closed-loop controllers significantly reduce rise time and settling time while providing better load disturbance rejection, confirming the effectiveness of advanced control strategies in maintaining desired motor speed under varying load conditions. Similar improvements in dynamic response under load disturbances have also been reported in recent DC motor speed control studies.

4 Conclusion

The proposed state-feedback controller successfully maintained the DC-motor speed at the reference value despite external load disturbances, fulfilling the requirement for robustness. The system's dynamic response improved significantly: the rise time decreased from 1.1864 s to 0.4220 s, and the settling time improved from 2.1132 s to 0.7517 s. Furthermore, adaptive regulation of the armature voltage enabled the motor to sustain a stable current under varying load conditions. Although direct power consumption was not measured, the reduction in current and voltage fluctuations suggests better energy utilization. Overall, the implementation of the SFC enhanced both system stability and efficiency compared to the uncontrolled system, validating its effectiveness in practical scenarios. The proposed method is therefore recommended for applications demanding precise and stable DC-motor speed control, such as robotics, industrial automation and electric vehicles.

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