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Comparative Analysis using Linear and Non-linear Controllers for Speed Control of Separately Excited DC Motor

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Abstract
The main objective of this work is to optimize the time domain specifications i.e., less settling time, less or NO undershoot, less or NO overshoot and less rise time. This work deals with speed control of a separately excited DC motor utilizing both linear and non-linear control methods. In linear controller we considered PID controller. In Non-linear controller we considered Sliding mode controller (SMC). The main aim of this work is to design a SMC based on variable structure system which is a robust non-linear controller and insensitive to external disturbances and parametric changes. A dynamic model of separately excited DC motor of both linear PID and non-linear SMC are implemented by MATLAB/SIMULINK for speed control. The separately excited DC motor with both PID controller and SMC controller are compared and analyzed based on time domain characteristics.

Keywords: DC motor, PID controller, SMC controller

1. Introduction

The development of DC motors has evolved over time. Thomas Davenport invented the first DC motor in 1980. Since then, several types of DC motors have developed. One of the significant advancements in DC motors is the development and widespread adoption of brushless DC motors. The classification of the DC motor comprises of three types: separately excited, self-excited, and permanent magnet DC motors. These DC motors possess characteristics of precision and adaptability, accompanied by uncomplicated control strategies that contribute to the overall system's efficiency and resilience. The utilization of DC motors spans across a wide range of sectors, including defense, industries, and robotics, among others. These preferences are driven by their inherent simplicity, ease of implementation, reliability, and cost-effectiveness, making them a fundamental component in industrial applications.

1.2 Working Principle of DC Motor

A DC motor converts electrical energy into mechanical energy through the interaction between magnetic fields and electrical currents.

When a current-carrying conductor is placed in a magnetic field, it experiences a force perpendicular to both the direction of current and the magnetic field. The force created on the conductor caused it to move and generate mechanical energy.

1.3 Advantages of DC Motor:

1. **Easy speed control:** DC motors produce smooth and accurate speed control, making them perfect for applying that need for variable speed.
2. **High starting torque:** DC motors are useful for applications requiring a significant initial force, like industrial machines, on the account of their high starting torque.
3. **Cost-Effectiveness:** DC motors can be cost-effective compared to other types of motors.
4. **Widely available:** DC motors are extensively utilized and available in various sizes, making them versatile for different applications.
5. **Reliability:** DC motors are renowned for their reliability and toughness, requiring little upkeep in the range of settings.

1.4 Disadvantages of DC Motor:

1. **Brush and commutator wear:** DC motors with brushes and commutators experience wear over-time, leading to maintenance issues and limited lifespan.
2. **Limited power capacity:** DC motors are typically less appropriate for high-power applications than certain other motor types.
3. **Electromagnetic interference:** The sparking at the brushes and commutator can generate electro-magnetic interference, which may be undesirable in certain applications.
4. **Complexity for high voltage:** Scaling up DC motor to handle high voltages can become complex and may require additional engineering solutions.

1.5 Applications for DC Motor:

1. **Automotive Systems:** Powering window regulators, windshield wipers, and fans.
2. **Robotics:** Driving wheels and joints in robots.
3. **Industrial Automation:** Employed in conveyor systems, pumps, and manufacturing equipment.
4. **Medical Devices: used in** Applications like infusion pumps, surgical tools, pumps, and other medi-cal equipment.
5. **Aerospace:** Control surfaces, landing gear systems, and other components in aircraft.
6. **Computer Hardware:** Used in disk drives and cooling fans.

Figure 1: Applications of DC motor

2. Classification of DC Motor

DC motors are distinguished into three types. They are:

1. Separately excited DC motor.
2. Self-excited DC motor.
3. Permanent magnet DC motor.

2.1 Separately Excited DC Motor

An electric motor that has separate electrical power sources for the armature winding and field winding is known as a separately excited DC motor. Better performance and speed regulation come from this design's ability to precisely control the armature and field currents. In this setup, a magnetic field is produced by energizing the field winding with an independent power source. Rotation is produced by the electromagnetic forces acting on the armature winding, which is connected to another power source. Because of their independence from power sources, separately excited DC motors can be effectively controlled and fine-tuned for a variety of demanding applications, including robotics, machine tools, and specific industrial processes that call for high precision and dynamic performance [1].

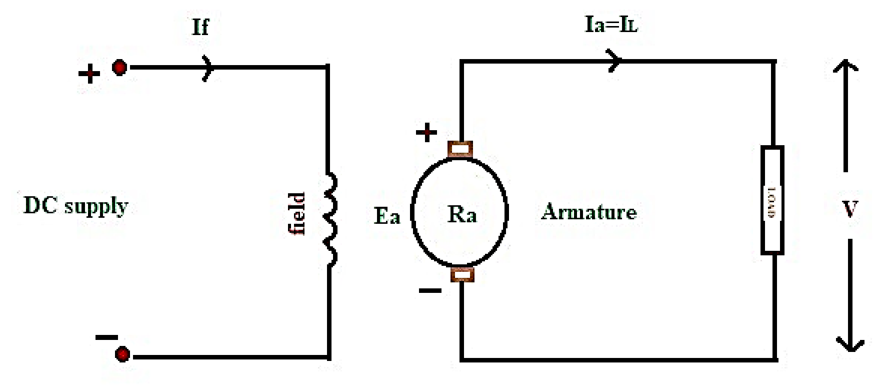

Figure 2: Circuit representation of separately excited DC Motor

2.1.1 Advantages:

1. **Precise Speed Control:** Applications requiring precise speed adjustments can benefit from the separate control of the armature and field currents, which enables precise speed regulation.
2. **Regenerative Braking:** The motor is able to engage in regenerative braking, in which the motor reverses the direction of motion from kinetic energy to electrical energy by acting as a generator.
3. **Independent Torque and Speed Control:** The ability to control the field and armature currents independently provides flexibility in adjusting torque and speed.
4. **High Efficiency:** Offers good efficiency and performance, especially under varying load conditions.
5. **Smooth Operation:** The accurate regulation of both the field and armature currents results in a stable and seamless operation.

2.1.2 Disadvantages:

1. **Complex Control System:** The independent control of field and armature currents requires a more complex control system, which may increase the overall system cost and complexity.
2. **Brush and Commutator Wear:** Like other DC motors, separately excited motors use brushes and a commutator, which can experience wear and require maintenance.
3. **Electromagnetic Interference:** Separately excited DC motors may produce electromagnetic interference, affecting nearby electronic devices.

4. **Cost:** When compared to other DC motor types, these motors can be more costly especially for high-power applications.
5. **Size and Weight:** Separately excited DC motors may be larger and heavier than alternative motor types with similar power rating.

2.2.3 Applications:

1. **Industrial Automation:** Used in automated operations that need torque and speed control, like conveyor systems and robotic arms.
2. **Electric Vehicles:** A feature of electrical bicycles and cars that permit for precise management over torque and speed of DC motors for optimal operation.
3. **Paper Mills and Textile Industries:** Utilized in paper and textile manufacturing equipment because the motor's speed can be adjusted to meet production demands.
4. **Medical Equipment:** Used in a variety of medical devices where very accurate motor speed control is essential.
5. **Aerospace:** Employed in some aerospace applications where exact control and lightweight characteristics are necessary
6.

2.2 Self-excited DC Motor

A self-excited DC motor is a kind of electric motor in which the armature winding and field winding are connected in parallel or series, enabling the motor to produce its own magnetic field. Series-wound and shunt-wound DC motors are the two primary varieties of self-excited DC motors. The series motor produces a high starting torque but has erratic speed characteristics. However, this results in more stable speed regulation. Due to their affordability and ease of use in producing dependable rotational motion, self-excited DC motors are often found in a vast range of applications, consisting of low-power devices, small tools, and household appliances.

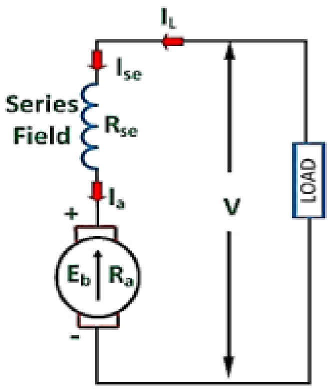

Figure 2.2: Circuit representation of Self-excited DC Motor

2.2.1 Advantages:

1. **Simplicity:** Since their designs are rather straightforward, they can be produced affordably and with ease.
2. **Ease of Control:** Self-excited DC motors are generally simpler to supervise than other types of motors, allowing for efficient speed and torque adjustments.
3. **Wide Range of Speed Control**: These motors are appropriate for a variety of applications where speed adjustment is essential because they provide a broad range of speed control.
4. **High Starting Torque:** It is beneficial for the motor, where it must start under load, that it frequently displays high starting torque.

5. **Low Maintenance:** With fewer components, they tend to have lower maintenance requirements, contributing to increased reliability.

2.2.2 Applications:

1. **Poor Speed Regulation:** These motors can exhibit poor speed regulation, making it challenging to maintain a consistent speed under varying loads.
2. **Brush and Commutator Wear:** The presence of brushes and commutators in self-excited DC motors shows wear and tear over time, necessitating regular upkeep and replacement.

2.2.3 Disadvantages:

1. **Automotive Industry:** DC motors are employed in automotive applications, particularly in electric vehicles, windshield wipers, and power windows.
2. **Robotics:** Self-excited DC motors are appropriate for certain robotic applications on account of their precise control capabilities and compact design.
3. **Medical Devices:** They can be found in medical equipment like pumps and surgical tools where precise control and reliability are essential.
4. **Entertainment Systems:** Some consumer electronics, such as turntables and tape decks, use self-excited DC motors for their rotational motion control.

2.3 Permanent Magnet DC Motor:

A permanent magnet DC motor is a type of DC motor where the stator contains permanent magnets. By using the permanent magnets, it creates a magnetic field for the operation of the DC motor. PMDC motors are widely used in various applications on account of their simplicity, reliability, and high efficiency.

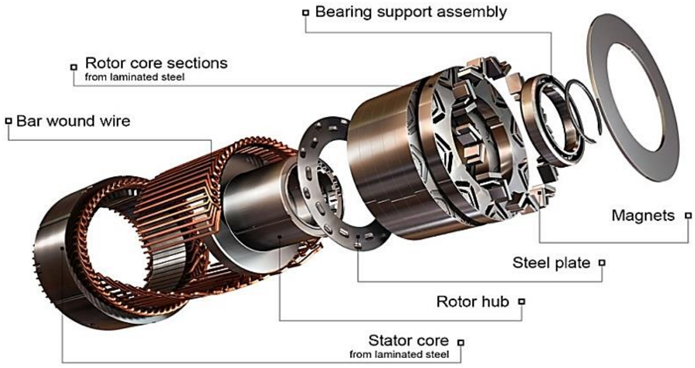

Figure 2.3: Permanent magnet DC Motor

2.3.1 Applications:

1. **Automotive:** PMDC motors are employed in various automotive systems, such as power windows, windshield wipers, and electric mirrors.
2. **Home Appliances:** Found in household appliances like vacuum cleaners, blenders, and electric shavers due to their compact size and efficient operation.
3. **Electric Scooters and Bikes:** PMDC motors are often used in electric scooters and bikes for their compact size, lightweight, and efficiency.
4. **Medical Devices:** Used in a variety of medical devices, including blood analyzers, dental instruments, and infusion pumps.
5. **Automation and Robotics:** Used in smaller robotic applications and automation systems where compact size and precise control are essential.

3. Speed Control Technique

Speed control is the intentional speed variation of a DC motor, either manually or automatically. The Speed control methods of the DC motor are

1. Flux controlled method.
2. Armature controlled method.

3.1 Flux Control Method

In the field control method, the DC motor's speed is increased by weakening the field. By connecting the motor in series with a variable resistance, we can achieve the higher speed than the base speed.

The field flux control method provides speeds that are above the base speeds. In the field control method, the power remains constant over a given speed range. By keeping power constant and then weakening the flux, the torque decreases and speed increases [2].

The Field control method is used for open-loop control systems, which gives smooth performance and steady output.

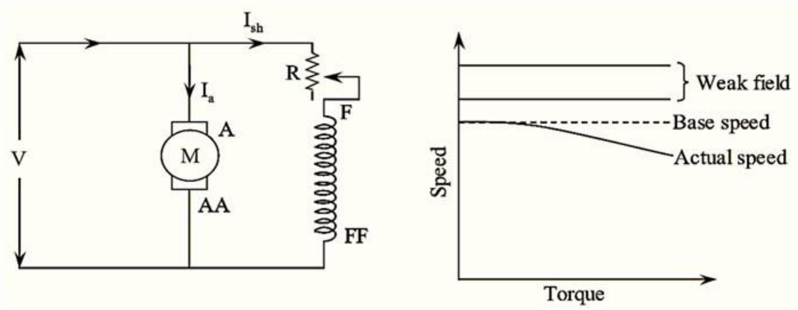

Figure 4.1: Flux Control Method

3.2 Armature Control Method

In the armature control method, by connecting a variable resistance in series with the armature, the voltage can be adjusted. As a result of the armature voltage drop being smaller, the armature current flow through the circuit is subsequently decreased. After that, the speed is directly related to the voltage. Then the voltage drops as a result.

The armature control method provides speeds that are below the base speed. The armature control method, the field and torque remain constant over a given speed range. By keeping torque constant, we can vary the power by varying the armature voltage, and then the speed increases. It is a closed-loop control system. This method gives a vast range of speed variations; it operates in both directions and with stability[2].

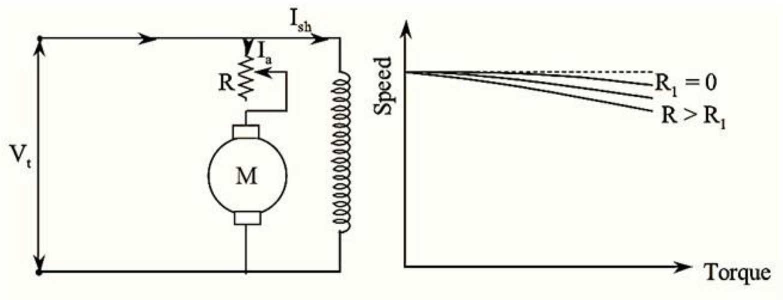

Figure 4.2: Armature Control Method

3.2.1 Applications of Armature Control Method:

1. **Machine Tools:** Armature control is often employed in machine tools, such as lathes, where accurate speed and torque control are necessary for machining processes.
2. **Conveyor Systems:** In manufacturing and material handling systems, armature control ensures precise control over conveyor belt speeds, allowing for efficient movement of products along the assembly line.
3. **Robotics:** Armature control is utilized in robotic systems enabling precise and coordinated movements in different robotic applications.
4. **Textile Industry:** In textile machinery, such as spinning and weaving machines, armature control helps in controlling the speed and tension of the process, ensuring consistent and high-quality production.
5. **Electric Vehicles:** In some electric vehicle configurations, armature control is employed for the motor drive to achieve efficient speed and torque control, contributing to better overall vehicle performance.

3.3 Modeling of DC Motor

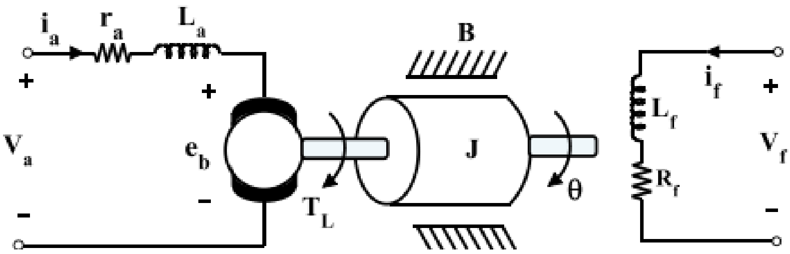

Figure 4.3: Schematic diagram of separately excited DC Motor

The armature control method is taken into consideration for speed control in these separately excited DC motors. The torque and field in the armature control method are constant within a specified speed range. We can regulate the armature current by altering the armature voltage. Here, we obtain a constant field current in the independently excited DC motor, resulting in a rated flux [3].

Then DC motor equations:
From KVL equation from the above DC motor

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

Torque equation:

$$T_e = K_t i_a = J \frac{d^2\theta}{dt^2} + \frac{d\theta}{dt} + T_L \qquad (2)$$

Back EMF equation:

$$e_b = K_b \omega \qquad (3)$$

By using Laplace transform from Eq., 1, 2, 3. We get

$$\frac{\omega(s)}{U(s)} = \frac{\frac{K_t}{JL_a}}{s^2+\left(\frac{r_a}{L_a}+\frac{B}{J}\right)s+\left(\frac{r_aB+K_bK_t}{JL_a}\right)} \quad (4)$$

Whereas,
R_a= armature resistance (“Ω”)
L_a= armature inductance, (“H”)
I_a= armature current, (“A”)
I_f= field current (“A”)
E_b = back emf (“volts”)
θ = angular displacement of the motor shaft, (“rad”)

3.4 Parameters & Specifications of DC Motor

Table 1: Parameters of DC Motor

PARAMETERS	***SPECIFICATIONS***	***VALUE***
R_a	Armature resistance	0.78Ω
L_a	Armature inductance	0.016H
J	Moment of inertia	$10kg.m^2/sec^2$
B	Frictional coefficient	0N-m/rad/sec
K_t	Motor Torque constant	0.6Nm/A
K_b	Back emf constant	0.6V-s/rad
K_1	Integral constant	1
K_2	Proportional constant	0

4. Control System

A control system comprises devices that are able to manage commands, direct, or regulate other devices' behavior in order to achieve a desired outcome. Two broad categories can be used to categorize the various types of control systems. These are

1. Linear controller.
2. Non-linear controller.

4.1 Linear Controller

A linear control system is one that satisfies additive and homogeneity properties. Stated differently, the system operates on the superposition principle, which states that the total set of inputs equals the sum of the individual responses. There are several types of linear controllers, including PID, PD, PI, and integral (also known as derivative) controllers [3].

4.2 PID Controller

The terms proportional, integral, and derivative refer to PID controllers. Proportional mode is employed as a quick variable adjustment that lowers errors and quickens the integral mode's response, which is achieved at null balance. The derivative mode, which is dependent on how quickly the controlled variable progresses, provides rapid correction. PID controllers are employed in closed-loop systems. PID regulators are frequently utilized because of their dependability and flexibility.

Proportional (P): Adjusts for the current error, which is the discrepancy between the process variable's actual value and the intended set point.
Integral (I): Addresses any steady-state error by accounting for the cumulative effect of previous errors over time.
Derivative (D): Helps avoid overshooting by forecasting future errors based on the error's rate of change.
Proportionality improves steady-state response. The derivative controller improves system stability. The integral controller improves the stability of the system. The PID controller improves both steady-state and transient responses.
The transfer function of the PID controller

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d s$$

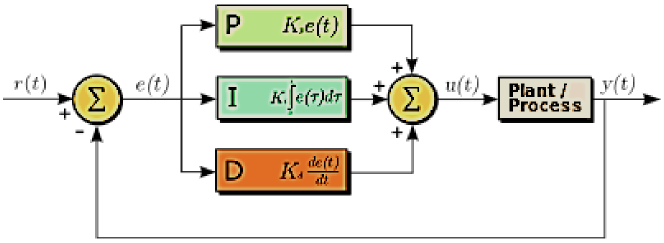

Figure 4.2: PID Controller

4.2.1 Applications:

1. **Temperature Control:** HVAC systems, ovens, and other temperature-controlled environments often utilize PID controllers to regulate temperature accurately and respond to changes in external conditions.
2. **Robotics:** PID controllers are employed in robotic systems to control motor movements, ensuring smooth and precise motion. They help in tasks such as position control and trajectory tracking.
3. **Chemical Processes:** In chemical engineering, PID controllers are applied to control variables like concentration, pressure, and flow rates, optimizing chemical reactions and ensuring product quality.
4. **Aviation and Aerospace:** PID controllers play a role in controlling aircraft and spacecraft systems, contributing to stability and responsiveness in flight control systems.

4.3 Non-linear Controller:

The non-linear controller is a control system that does not satisfy the properties of homogeneity and addictiveness. Systems that do not follow the superposition principle are called non-linear controllers. Examples of non-linear controllers are sliding mode control, fuzzy control, LARDC control, etc.
Nonlinear controllers are useful in applications ranging from advanced robotics and aerospace systems to biological processes and complex industrial systems because they use complex algorithms, frequently based on mathematical models, to adapt and respond to these complexities. In complex and demanding settings, their ability to manage complex relationships enables more precise and flexible control.

4.4 Sliding Mode Control (SMC)

A SMC is known for its accuracy, resilience, ease of tuning and applications. SMC is based on variable structure systems, which provide a strong nonlinear control that is resistant to changes in the parameters and outside disturbances[1]. Because of their robustness and uncertainty-handling capabilities, SMCs are well-suited for a vast range of applications, especially in systems where precise control is crucial. SMC

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is characterized by its ability to create a sliding surface on which the dynamics of the system behave as desired.
A two-part controller design underpins the sliding mode control.

1. The first step is to plan a sliding surface in such a way that the motion complies with design requirements.
2. Making the switching surface appealing to the system state is the focus of the second, which is choosing a control law.

The concepts of SMC are

1. It is important to design the switching function so that the SMC outputs the desired dynamic values.
2. It is rare to realize a regulator that ensures the framework's sliding mode.

There are usually two phases involved with the sliding mode controller:

1. Sliding Phase: A new control law is applied to maintain the system's state on the sliding surface once it has arrived.
2. Reaching Phase: Using a control law, the system's state is pushed in the direction of the sliding surface[4].

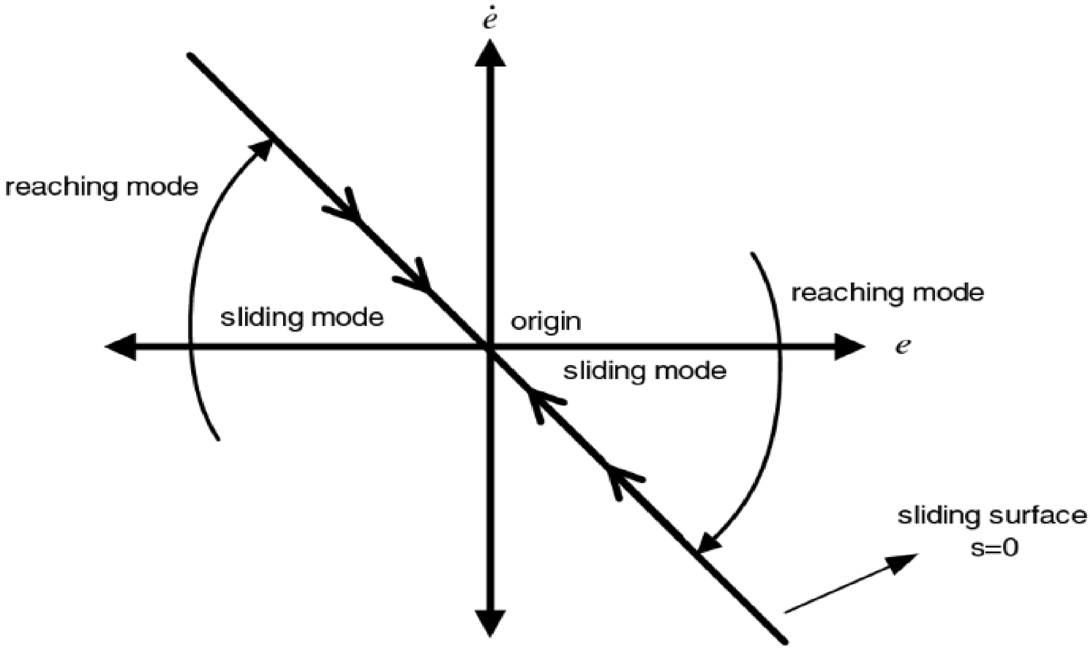

Figure 5.4: Graphical Representation of SMC Controller

4.4.1 Applications of Non-Linear Controller:

1. **Robotics:** Nonlinear controllers are used in robotics for systems with complex and nonlinear dynamics, allowing for more precise and adaptable control.
2. **Aerospace and Flight Control:** Nonlinear control is employed in aircraft and spacecraft to manage dynamic and nonlinear behaviors, enhancing stability and control accuracy.
3. **Flexible Structures:** Systems with flexible or deformable structures, like bridges or flexible robotic arms, often require nonlinear control for effective stabilization and performance.
4. **Autonomous Vehicles:** Nonlinear control strategies are utilized in autonomous vehicles to handle the complexity of real-world environments and dynamic driving conditions.

5. Simulation

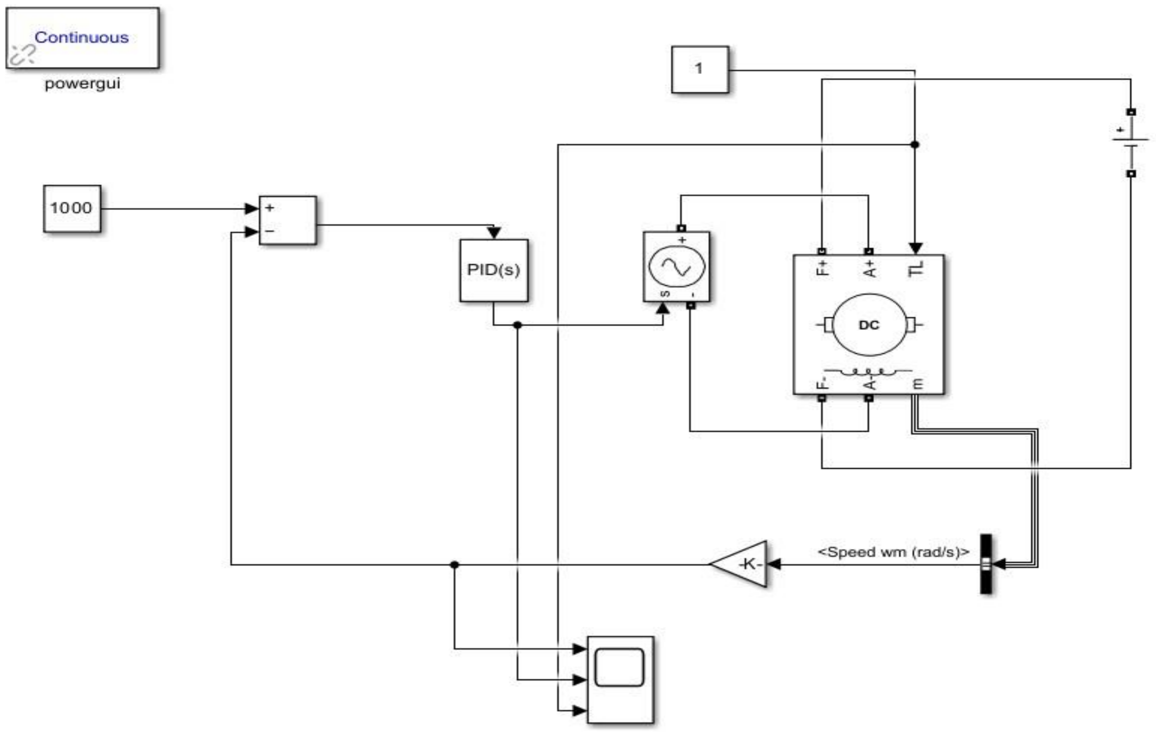

Figure 5.1: Simulation of DC motor using PID Controller

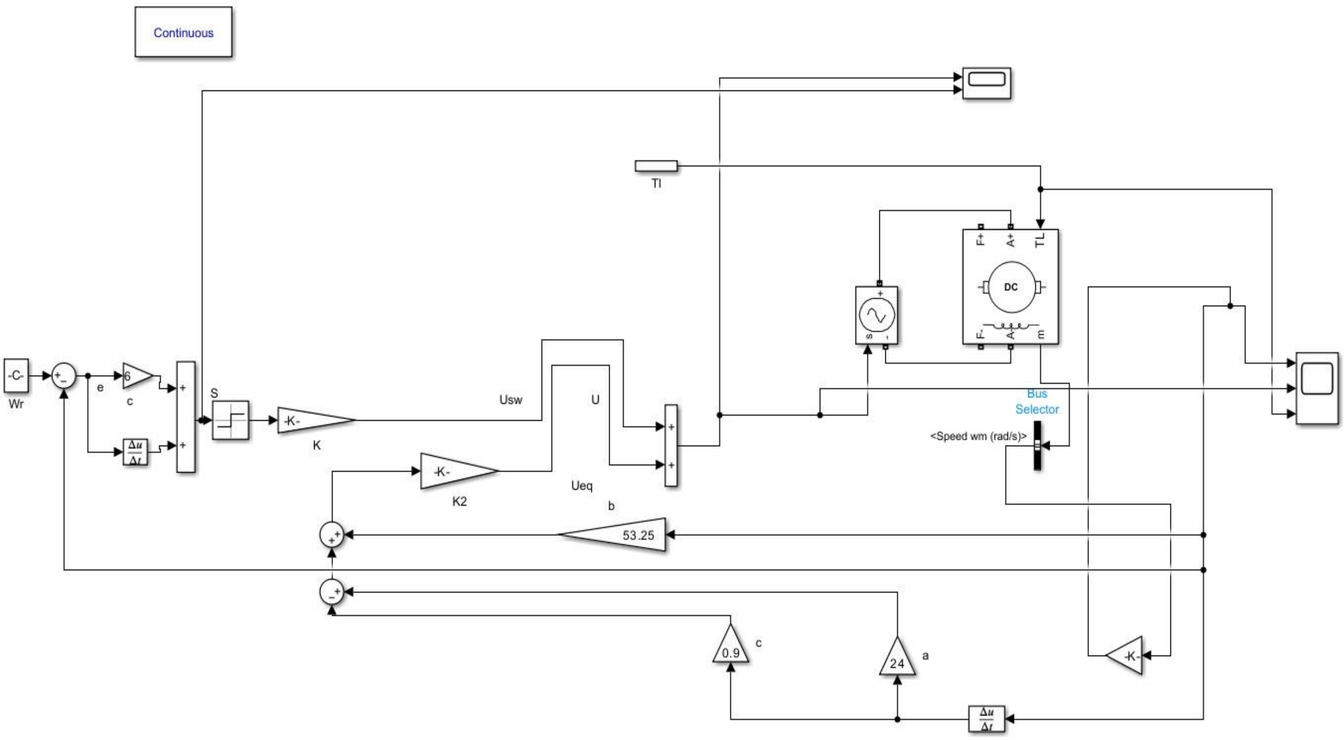

Figure 5.2: Simulation of DC motor using SMC Controller

6. Results

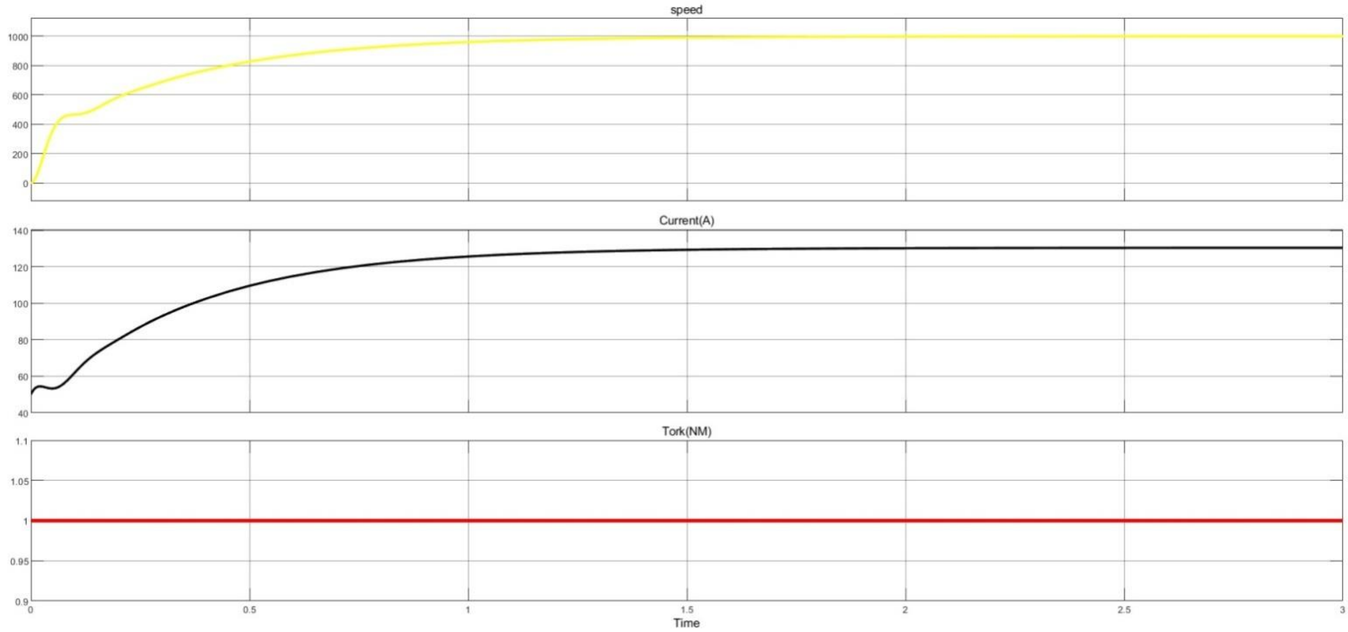

Figure 6.1: Speed response of DC motor using PID controller

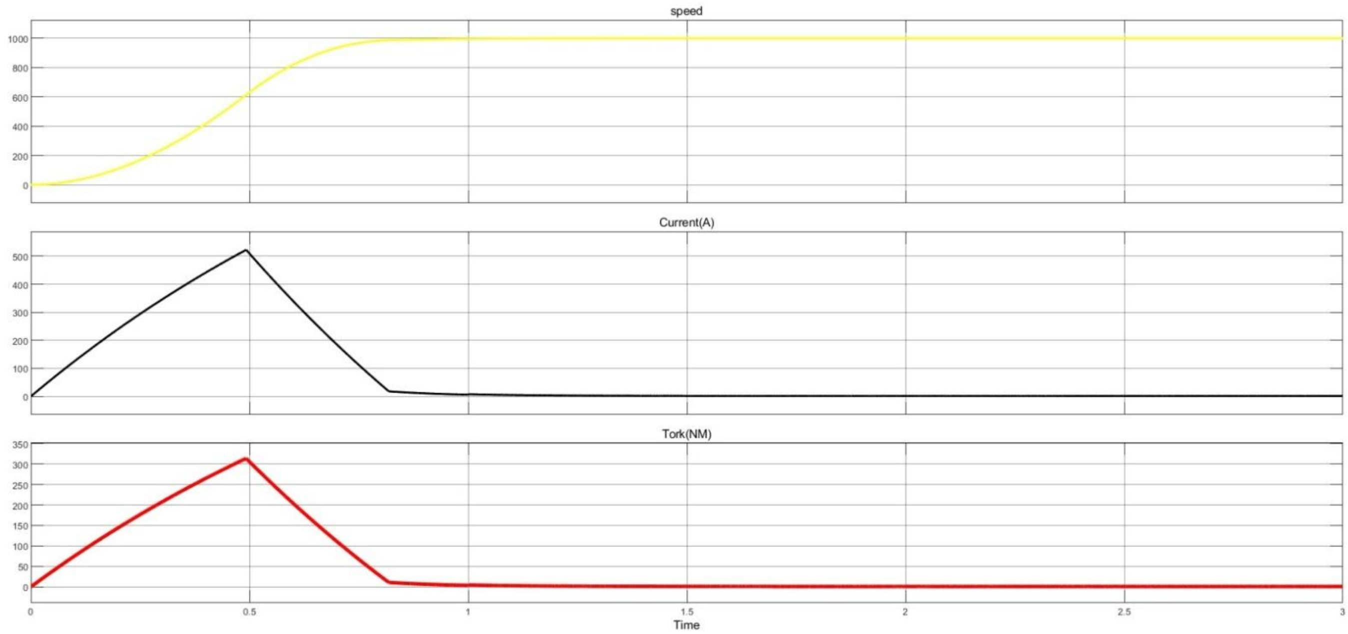

Figure 6.2: Speed response of DC motor using SMC Controller

7. CONCLUSIONS

The performances of both controllers are analyzed on the basis of the time domain specifications, i.e., undershoots, overshoots, rise time, and settling time. The performance of the DC motor without a controller didn't reach the expected outcome and had a relative error of 200 rpm. The outcome of a DC motor with a PID controller on the basis of time domain specifications, it reached the expected outcome but had more settling time and rise time. In the result of a DC motor with an SMC controller on the basis of time domain specifications reached the outcome and had NO or LESS settling time and rise time. In comparison, based on both controllers, the SMC controller has improved the characteristics of time domain specifications. The SMC controller is accurate, and it is observed that the SMC controller response is faster than the PID controller.

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