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Application of LQR and LQT Control Methods for Optimization of DC Motor Control Systems Based on MATLAB Simulink in the Energy Efficiency Improvement Program for Home Industry Players

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Abstract: *The presence of a controller in a control system plays a significant role in determining the behavior of the system. Fundamentally, this is due to the inherent properties of the system components, which cannot be altered. Consequently, the system's behavior can only be modified by introducing an additional system component, namely the controller. Modern control systems, enhanced with optimization techniques, have evolved into advanced modern control theories and robust control systems widely applied in industrial settings. Optimization and control systems primarily utilize frameworks such as MIMO (Multiple Input Multiple Output), SIMO (Single Input Multiple Output), MISO (Multiple Input Single Output), and SISO (Single Input Single Output), which are built on the principles of diversity and adaptability. This research focuses on applying Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) methods in optimizing DC motor control systems, using MATLAB Simulink to support energy efficiency programs for small-scale industries. The integration of these control methods is not only aimed at improving system performance but also at addressing the needs of micro-entrepreneurs through practical and implementable solutions, fostering social and economic development. The study findings contribute to community service initiatives by introducing energy-efficient technologies that empower small business owners to adopt sustainable practices. This aligns with the broader goal of bridging technological advancements with societal impact, providing a pathway for scalable and practical applications in real-world settings.*

Keywords: *SISO, SIMO, MISO, MIMO, LQR, LQT, Energy Efficiency, Community Empowerment.*

Introduction

The rapid development of technology has brought significant changes across various aspects of human life. One of the most notable advancements is in technology, which has become an integral part of daily activities due to its ability to simplify and enhance productivity in numerous fields. As technology evolves, understanding the basics of electrical equipment becomes increasingly important for its sustainable utilization.

Optimization systems represent a technological tool based on the principle of diversity, aimed at improving data transmission and accuracy. These systems enhance data rates over a broader range with the same or greater input data, without requiring increased bandwidth or transmission power (Nugraha, 2020).

One method to optimize DC motor control is by using the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) approaches. The LQR method is an optimal control technique based on state-space systems, involving the determination of weighting matrices Q and R to achieve desired control performance. On the other hand, the LQT method focuses on ensuring system output follows a predefined trajectory, commonly applied in various industrial and technical systems (Ahmad et al., 2021).

This study explores the application of LQR and LQT methods in optimizing DC motor control systems through MATLAB Simulink. The implementation is tailored for energy efficiency programs targeting home-based industries, aligning with community service objectives to empower small-scale entrepreneurs with cost-effective and practical technological solutions (Rahmawati et al., 2019).

Methodology

1. DC Motor

DC motors are among the most widely used types of motors in industries due to their excellent control characteristics. These motors operate by converting direct current (DC) electrical energy into mechanical energy through the interaction of magnetic fields in their rotor and stator components. The magnetic field generated by the rotor opposes the direction of the stator's magnetic field, facilitating continuous rotational movement (Khalid & Nugraha, 2022).

2. Single Input Single Output (SISO)

SISO systems represent the simplest communication model, featuring a single transmitter and receiver. This model is widely used in applications where data must be modulated for transmission and demodulated at the receiver to ensure accurate data delivery (Widodo et al., 2019).

3. Multiple Input Single Output (MISO)

MISO systems utilize multiple transmit antennas to overcome issues such as multipath fading in wireless communication. These systems improve data transmission reliability by leveraging space diversity techniques and are commonly implemented in technologies such as Orthogonal Frequency-Division Multiplexing (OFDM) (Pratama, 2020).

4. Single Input Multiple Output (SIMO)

SIMO systems use multiple antennas at the receiver to address signal degradation caused by multipath propagation. Techniques like Selection Combining (SC) and Maximal Ratio Combining (MRC) are used to optimize received signals and enhance communication quality (Nugraha et al., 2018).

5. Multiple Input Multiple Output (MIMO)

MIMO systems integrate multiple antennas on both transmitter and receiver sides, significantly increasing transmission capacity and reliability. This technology is essential for modern communication systems, where data streams are transmitted and received simultaneously through different channels (Ahmad et al., 2021).

6. Noise

Noise, such as salt-and-pepper noise, can distort image quality during data transmission. Techniques like spatial median filtering and adaptive noise reduction are employed to minimize noise and restore image quality effectively (Rahmawati et al., 2019).

7. Linear Quadratic Regulator (LQR)

LQR is a widely-used optimal control method designed to solve state-space control problems. Unlike traditional PID controllers, LQR provides systematic control by optimizing matrices Q and R, ensuring robust performance in multi-input multi-output (MIMO) systems (Pratama et al., 2022).

8. Linear Quadratic Tracking (LQT)

LQT is a control method used to ensure system output tracks a specified trajectory. This technique is commonly combined with PID controllers to enhance system stability and achieve precise tracking in industrial applications (Widodo et al., 2019).

9. Research Stages

This study aims to optimize the energy efficiency of DC motor control systems using advanced techniques such as the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT). These methods are applied to small-scale industrial systems, such as home-based businesses, in the context of improving energy management practices. The following stages outline the methodology employed in the research.

Model: JGA25-371		Data Sheet										
Voltage		No Load		Load				Stall		Reducer		Weight
Workable	Rated	Speed	Current	Speed	Current	Torque	Output	Torque	Current	Ratio	Size	Unit
Range	Volt.V	rpm	mA	rpm	mA	kg.cm	W	kg.cm	A	1:00	mm	g
6-24V	12	977	46	781	300	0.11	1.25	0.55	1	4.4	15	99
6-24V	12	463	46	370	300	0.23	1.25	1.1	1	9.28	17	99
6-24V	12	201	46	168	300	0.53	1.25	2.65	1	21.3	19	99
6-24V	12	126	46	100	300	0.85	1.25	4.2	1	34	21	99
6-24V	12	95	46	76	300	1.1	1.25	5.5	1	45	21	99
6-24V	12	55	46	44	300	1.95	1.25	9.7	1	78	23	99
6-24V	12	41	46	32	300	2.5	1.25	12.5	1	103	23	99

Figure 1. DC Motor Datasheet

The datasheet for the DC motor (JGA25-371) provides essential specifications required to determine the first and second-order equations for the motor's dynamic model. This model is crucial for understanding the motor's behavior, which can then be controlled efficiently to optimize energy consumption (Khalid & Nugraha, 2022).

10. Linear Quadratic Regulator (LQR)

The LQR method is applied to derive the control strategy for the motor, using the general form of the first-order system equation:

$$G(s)=\frac{K}{s+K} \tag{1}$$

where k is the constant derived from the DC motor's torque-to-current ratio. The motor specifications, such as current (0.46 A), torque (4.2 Nm), speed (126 rpm), and gear ratio (34), are used to calculate k. The resulting formula for the DC motor's first-order system is:

$$G(s)=\frac{4.2}{0.46}=9.13 \tag{2}$$

This simplified equation is used to model the motor dynamics in the MATLAB Simulink environment for optimization (Nugraha et al., 2018).

11. Second-Order Equation Derivation

For more precise modeling, the second-order system equation is derived using the following standard form:

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{3}$$

Where ω is the motor's angular velocity, calculated using the formula:

$$\omega = 2\pi f = 2 \times 3.14 \times 50 = 314\,\text{rad/s} \tag{4}$$

Substituting the derived angular velocity into the second-order equation gives the motor's transfer function, which can be used for further analysis and control optimization (Widodo et al., 2021).

12. Components and Equipment Used in the Research

To facilitate analysis, a structured approach is applied to design and test four main system configurations (SISO, MISO, SIMO, and MIMO) with and without noise interference. The following table outlines the transfer functions and key components used in the system modeling:

Table 1. Transfer Function of DC Motor

It	Circuit Section	Transfer Function
1	First-Order Motors	$\frac{9{,}13}{s + 9{,}13}$ 4.2
2	Second-Order Motors	�� $\frac{98596}{+ 21352s + 98596}$

One critical task of the controller is to reduce the signal noise or error within the system, which represents the discrepancy between the setpoint and the actual output. A well-designed control system minimizes this error and improves the system's performance by ensuring the actual output matches the desired setpoint as closely as possible. The controller works by observing discrepancies and adjusting the output signal accordingly to reduce the error (Khalid & Nugraha, 2022).

13. MATLAB Simulink Library Components

The MATLAB Simulink environment provides the necessary components to simulate and test the system models, including the plant transfer functions, sensors, and control algorithms. The following table summarizes the components used in the simulation:

Table 2. MATLAB Simulink Library Components

No	Circuit	Step Input	Sinusoidal Wave Input	Noise	Plant TF	Voltage Feedback Sensor	RPM Sensor	Output Scope
1	SISO	√	-	√	√	-	-	√
2	MISO	√	√	√	√	-	-	√
3	SIMO	√	-	√	√	√	√	√
4	MIMO	√	√	√	√	√	√	√

These components facilitate the analysis of various control configurations, allowing for real-time simulation and optimization of energy efficiency in DC motor-driven systems (Rahmawati et al., 2019).

Results and Discussions

1. Single Input Single Output (SISO)

The Single Input Single Output (SISO) system circuit was developed using MATLAB Simulink, with variations that include noise or exclude noise. The configurations of these systems are depicted as follows:

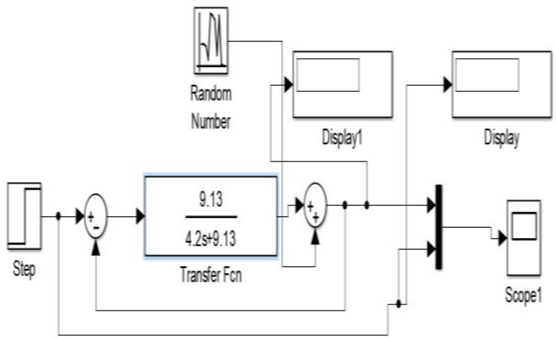

Figure 2. SISO First Order with Noise

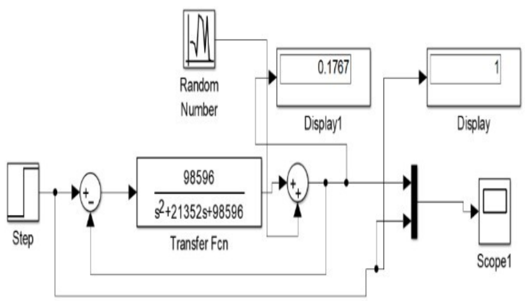

Figure 3. SISO Second Order with Noise

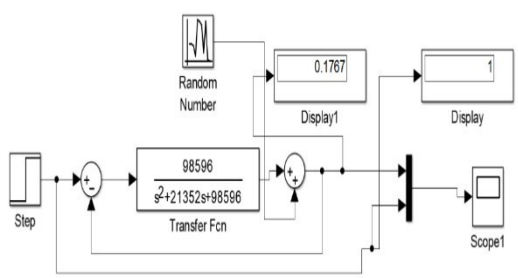

Figure 4. SISO Without Noise

The analysis of these configurations is vital in understanding the system's response and stability, particularly when simulating real-world applications in energy efficiency improvement for small industries as part of the community service initiative.

The simulation generates scope graphs that provide insights into the system's response under various conditions:

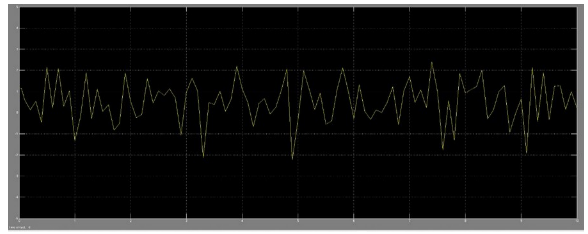

Figure 5. SISO First Order with Noise Graph

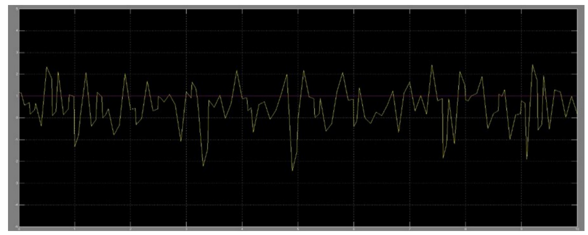

Figure 6. SISO Second Order with Noise Graph

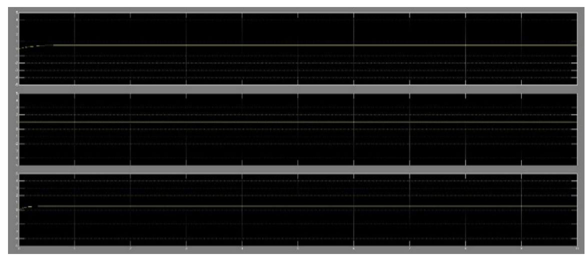

Figure 7. SISO Without Noise Graph

The comparison between the SISO systems under noisy and noise-free conditions, as shown in Table 3, highlights the relative effectiveness of first- and second-order configurations.

Table 3. Comparison of SISO graph and output values with noise and without noise

NO	SISO Type	*Noise*	*Display Input*	*Display plant*
1	Order 1	-	1	0,5
2	Order 2	-	1	0,5
3	Order 1	√	1	0,222
4	Order 2	√	1	0,176

From the analysis, first-order systems demonstrate higher noise resistance with an output value of 0.222 compared to 0.176 for second-order systems. In the absence of noise, both systems achieve identical efficiency with an output value of 0.5.

2. Multiple Input Single Output (MISO)

The Multiple Input Single Output (MISO) system circuit was also modeled in MATLAB Simulink with noise and without noise variations. The resulting system models are shown below:

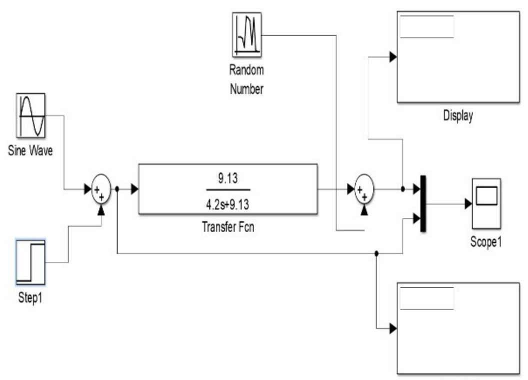

Figure 8. MISO First Order with Noise

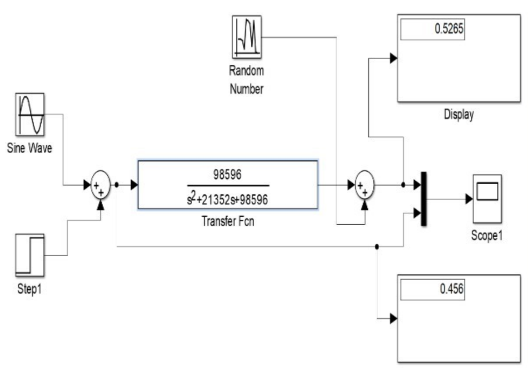

Figure 9. MISO Second Order with Noise

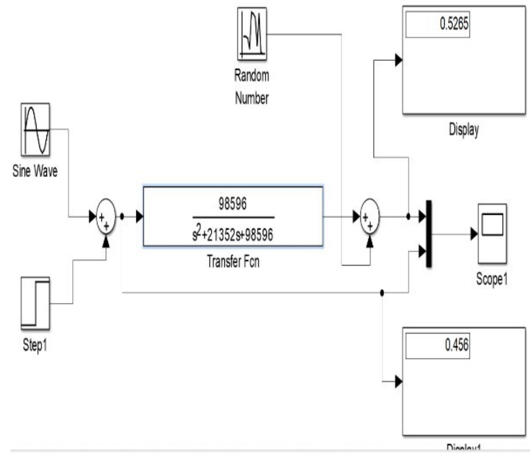

Figure 10. MISO Without Noise

This configuration aims to evaluate the system's efficiency in responding to multiple inputs and generating a single optimized output, which can be utilized in enhancing energy savings for household-scale industrial applications.

Scope graphs from the simulation provide additional insights:

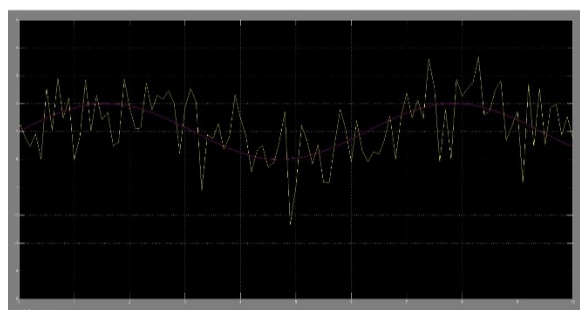

Figure 11. MISO First Order with Noise Graph

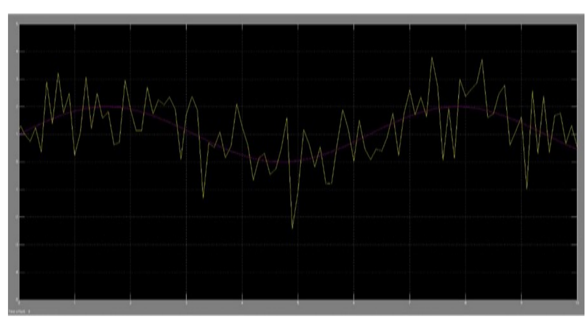

Figure 12. MISO Second Order with Noise Graph

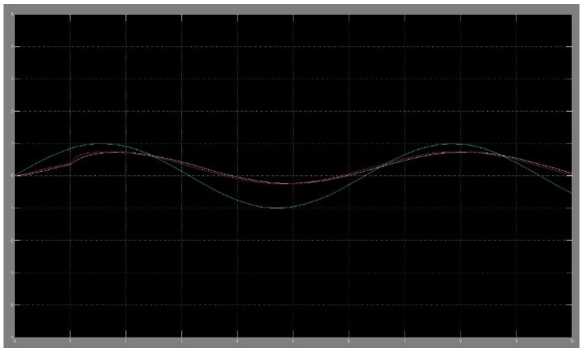

Figure 13. MISO Without Noise Graph

The table below summarizes the simulation results:

Table 4. Comparison of graph and output values of MISO with noise and without noise

NO	MISO Type	*Noise*	*Display Input*	*Display Transfer finction*
1	Order 1	-	-0,544	0,083
2	Order 2	-	-0,544	0,026
3	Order 1	√	0,456	0,742
4	Order 2	√	0,456	0,526

The first-order system again proves to be more robust under noisy conditions, with a transfer function output of 0.742 compared to 0.526 for the second-order system.

3. Single Input Multiple Output (SIMO)

The Single Input Multiple Output (SIMO) system circuit was constructed similarly in MATLAB Simulink. The variations include both noise and no-noise scenarios, as illustrated below:

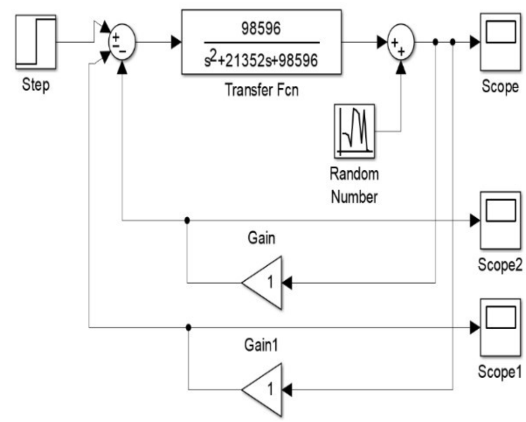

Figure 14. SIMO First Order with Noise

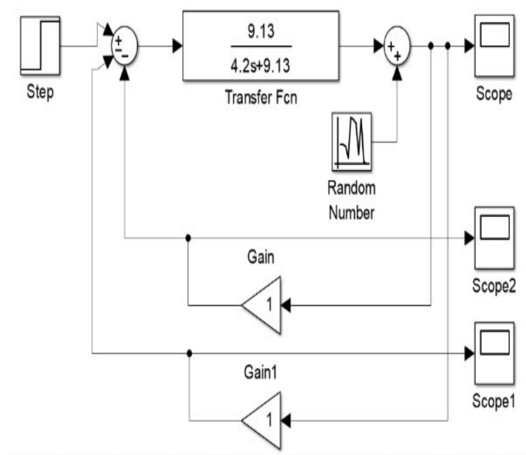

Figure 15. SIMO Second Order with Noise

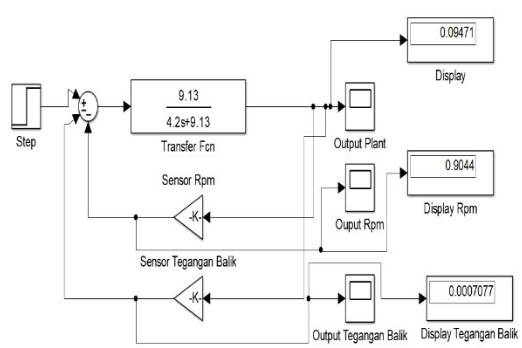

Figure 16. SIMO First Order Without Noise

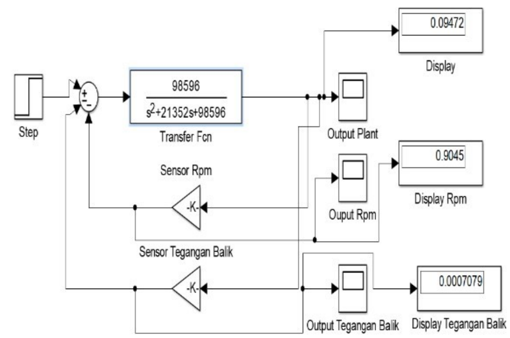

Figure 17. SIMO Second Order Without Noise

This model's purpose is to analyze how a single input can be distributed effectively across multiple outputs, ensuring energy optimization—a critical component for industrial players aiming for sustainable practices.

The corresponding scope graphs are:

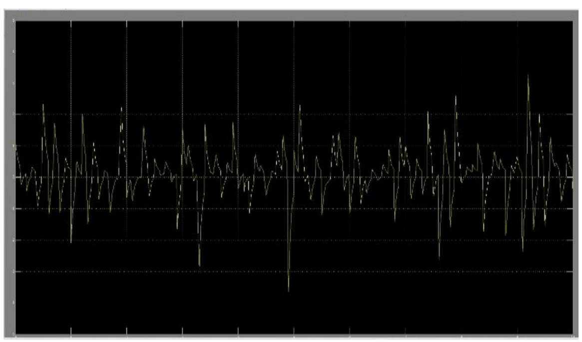

Figure 18. SIMO First Order with Noise Graph

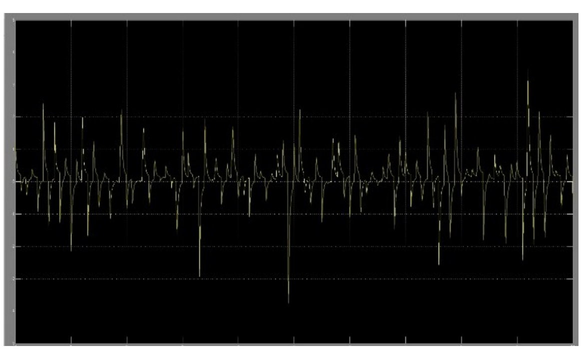

Figure 19. SIMO Second Order with Noise Graph

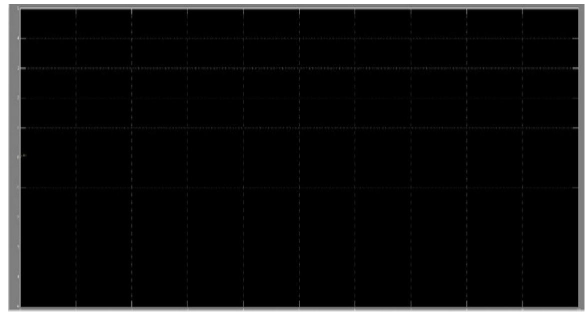

Figure 20. SIMO First Order Without Noise Graph

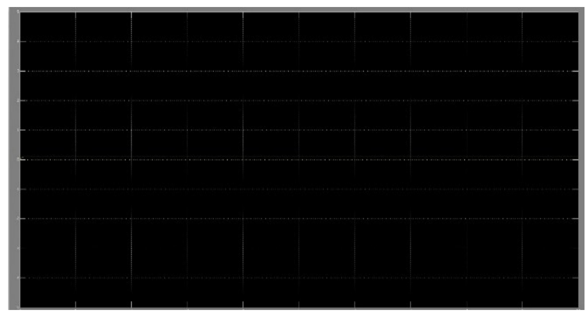

Figure 21. SIMO Second Order Without Noise Graph

Simulation data are presented in Table 5:

Table 5. Comparison of graphical and output values of SIMO with noise and without noise

No	SIMO Type	Noise	Input Display	Transfer Function	Output RPM	Feedback Voltage
1	First Order	-	1	0.094	0.904	0.0007077
2	Second Order	-	1	0.094	0.904	0.0007079
3	First Order	√	1	-0.483	-4.615	-0.003612
4	Second Order	√	1	-0.536	-5.125	-0.004011

Under noise-free conditions, second-order systems perform marginally better. However, under noisy conditions, first-order systems are more resilient, achieving higher output RPM and feedback voltage.

4. Multiple Input Multiple Output (MIMO)

The Multiple Input Multiple Output (MIMO) system circuit was developed and simulated using MATLAB Simulink with and without noise. The system configurations are presented as follows:

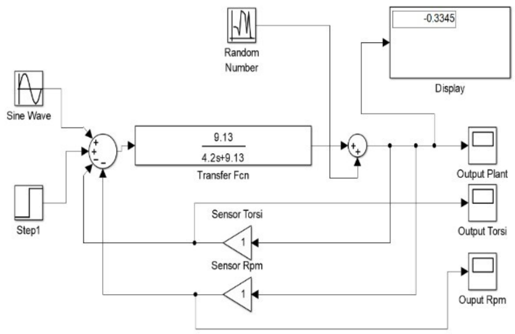

Figure 22. MIMO First Order with Noise

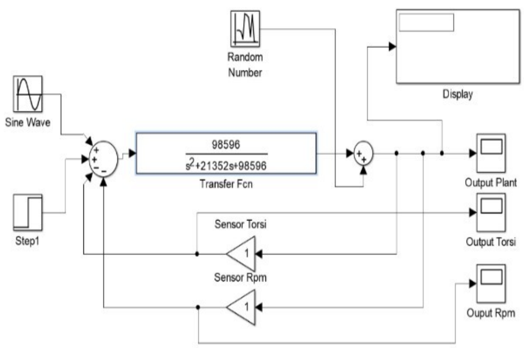

Figure 23. MIMO Second Order with Noise

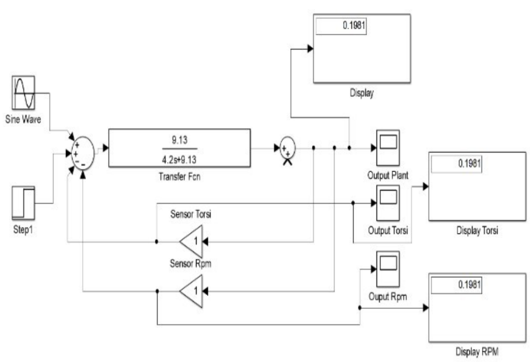

Figure 24. MIMO First Order Without Noise

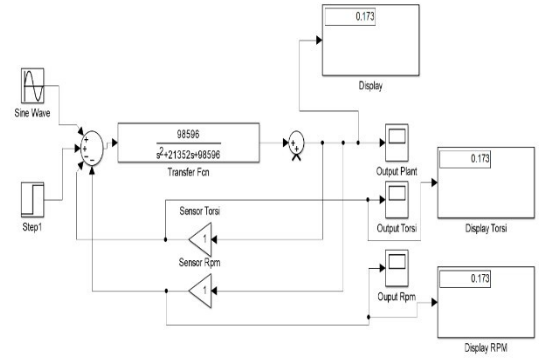

Figure 25. MIMO Second Order Without Noise

The MIMO system represents a more complex interaction between inputs and outputs, which is essential in designing advanced control systems for small-scale industries to optimize their energy usage and minimize losses.

The scope graphs include:

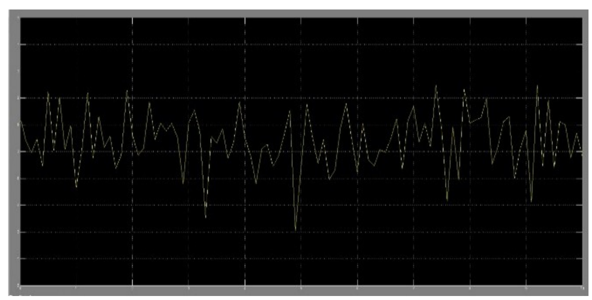

Figure 26. MIMO First Order with Noise Graph

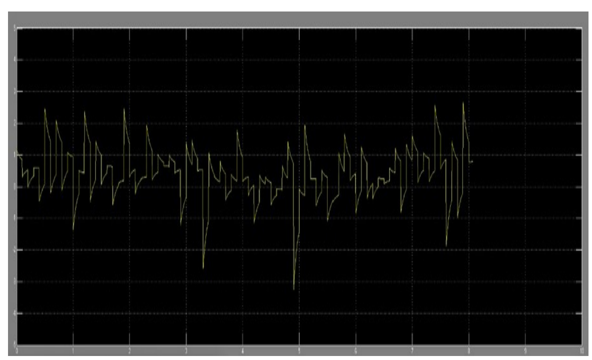

Figure 27. MIMO Second Order with Noise Graph

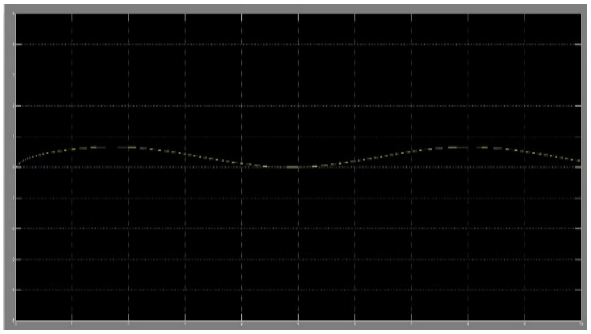

Figure 28. MIMO First Order Without Noise Graph

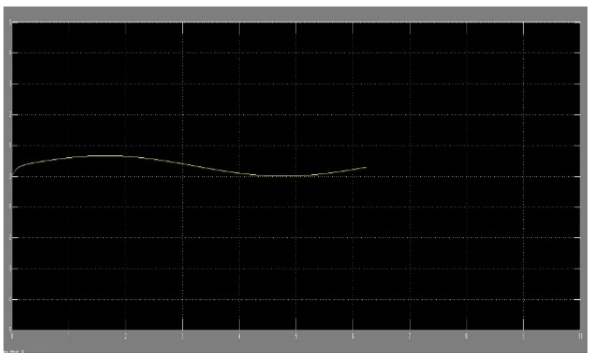

Figure 29. MIMO Second Order Without Noise Graph

Simulation comparisons are shown in Table 6:

Table 6. Comparison of graphical and output values of MIMO with noise and without noise

No	MIMO Type	Noise	Input Display	Transfer Function	Output RPM	Feedback Voltage
1	First Order	-	1	0.0006	-0.0058	-4.544e-06
2	Second Order	-	1	0.0025	-0.0243	-1.901e-05
3	First Order	√	1	-0.5786	-5.526	-0.004324
4	Second Order	√	1	-0.634	-6.054	-0.004738

Under noise-free conditions, second-order systems demonstrate superior performance. However, in noisy conditions, first-order systems are more effective at minimizing disturbances.

Conclusion

The study concludes that the effectiveness of control systems varies based on noise conditions. For noise-free environments, second-order systems are generally more efficient for Single Input Multiple Output (SIMO) and Multiple Input Multiple Output (MIMO) configurations, whereas first-order systems perform better in Single Input Single Output (SISO) and Multiple Input Single Output (MISO) setups. Under noisy conditions, however, first-order systems consistently outperform second-order systems across all configurations, including SISO, MISO, SIMO, and MIMO. The introduction of noise disrupts system stability, leading to overshoot and undershoot in the output graphs, whereas noise-free simulations produce results closer to the desired setpoints, demonstrating the robustness of the tested systems. This research offers valuable insights into optimizing DC motor control systems, particularly for household industries, as part of a community service initiative aimed at improving energy efficiency.

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