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Enhancing LQR and LQT Control Strategies for the Output Performance of PG36M555 DC Motors

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Abstract

A DC motor is commonly utilized as an actuator due to its ability to produce high torque. Controlling the motor's speed is one of the primary methods to manage its performance. Among various wireless communication options, radio waves are preferred since they do not require a clear line of sight between the transmitter and receiver. Employing multiple antennas offers benefits such as enhanced reliability and increased data transmission rates. This study focuses on designing and simulating four types of systems: SISO, SIMO, MISO, and MIMO. The performance of these configurations is evaluated and compared using Signal-to-Noise Ratio (SNR) and channel capacity, with variations in antenna count. Simulations were carried out in MATLAB to analyze how different antenna quantities (4, 8, and 16) affect channel capacity across an SNR range of 0 to 30 dB. The simulation outcomes reveal a substantial rise in system capacity, reaching up to 214 bits/Hz/sec when a 16x16 MIMO setup is applied at 30 dB SNR.

Keyword: Matlab, LRT, LQT, Performance, DC Motor, PG36M555

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1. Introduction

Direct Current (DC) motors remain one of the most widely utilized actuators in industrial and engineering applications due to their simple structure, high starting torque, ease of speed control, and reliable dynamic response. They are commonly deployed in robotics, manufacturing automation, transportation systems, and small-scale electromechanical devices where precise motion control is required. Despite these advantages, achieving high-performance operation in DC motor systems requires appropriate control strategies to ensure stability, fast transient response, minimal steady-state error, and robustness against disturbances. Without proper control optimization, DC motors may exhibit slow response, steady-state deviation, or sensitivity to parameter variations and external

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noise. Consequently, the development of efficient control methods for DC motor systems remains a significant research topic in modern control engineering [1] [2] [3].

In contemporary industrial environments, automated control systems are increasingly implemented to improve operational efficiency, productivity, and reliability. Automated systems allow machines to execute predefined tasks accurately with minimal human intervention, reducing operational errors while increasing consistency and repeatability. In both large-scale industries and emerging mid-level enterprises, automation plays a crucial role in maintaining competitiveness and reducing production costs. The integration of intelligent control algorithms into actuator systems such as DC motors is therefore essential to meet the growing demand for high precision and fast response in automated processes [4] [5].

One of the central challenges in modern control engineering is the design of optimal controllers capable of delivering superior dynamic performance under physical and operational constraints. Optimal control theory provides a systematic framework for determining control inputs that minimize a predefined performance index while satisfying system dynamics. Instead of relying solely on heuristic tuning, optimal control methods mathematically formulate the control objective in terms of state variables and control effort, enabling a balanced trade-off between performance and energy consumption. The primary goal is to reduce deviations from the desired reference signal while maintaining system stability and minimizing control energy [6] [7].

Among the various optimal control techniques, the Linear Quadratic Regulator (LQR) has emerged as one of the most effective state-space-based methods for linear dynamic systems. LQR determines the optimal feedback gain matrix by minimizing a quadratic performance index composed of weighted state and control variables. The selection of weighting matrices Q and R plays a crucial role in shaping the system response, as these matrices define the relative importance of state error and control effort. Proper tuning of Q and R enables designers to achieve fast settling time, reduced overshoot, and improved steady-state accuracy. Due to its mathematical rigor and systematic formulation, LQR has been successfully applied in numerous engineering domains, including induction motor speed regulation, power system frequency control, aerospace stabilization systems, and robotic motion control [8] [9].

In addition to LQR, the Linear Quadratic Tracker (LQT) extends the optimal control concept by incorporating reference tracking capabilities. While LQR focuses primarily on state regulation toward zero, LQT introduces an additional feedforward term to enable accurate tracking of time-varying reference signals. This feature makes LQT particularly suitable for applications where maintaining precise speed or position trajectories is critical. By combining state feedback and feedforward compensation, LQT enhances tracking performance while preserving the optimality framework derived from quadratic cost minimization [10] [11] [12]. Although optimal control techniques such as LQR and LQT have been extensively studied in theoretical contexts, their practical performance must be evaluated through modeling and simulation before real-world implementation. Mathematical modeling of the DC motor is therefore a fundamental step in control system design. By representing the motor dynamics using differential equations and state-space formulations, it becomes possible to analyze system behavior under various control strategies. First-order modeling is often employed for simplified representation of speed dynamics, allowing clear observation of transient and steady-state characteristics. Simulation environments such as MATLAB/Simulink provide a flexible platform for implementing these models and evaluating controller performance under controlled scenarios, including the presence of disturbances or measurement noise [13] [14] [15] [16].

Despite the established advantages of optimal control methods, challenges remain regarding robustness against noise and parameter uncertainty. In practical systems, external disturbances,

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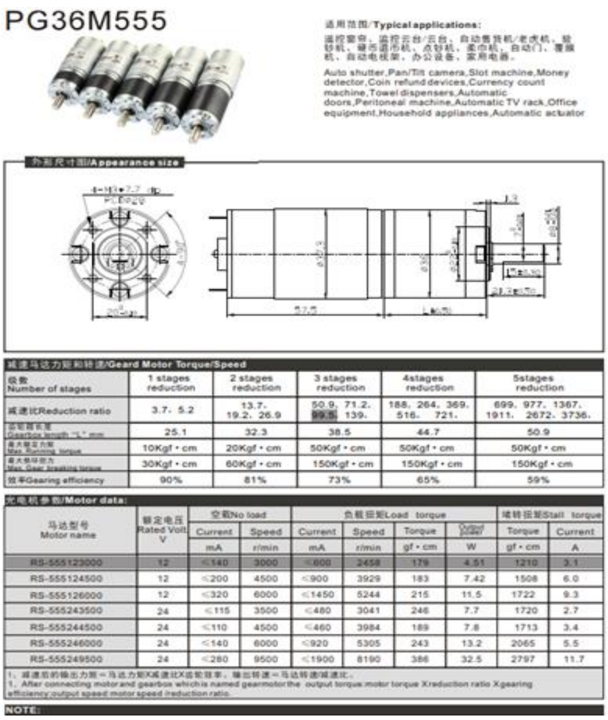
sensor noise, and modeling inaccuracies may degrade controller performance. Therefore, evaluating how LQR and LQT strategies respond to noise conditions is essential for assessing their reliability in realistic environments. Comparative analysis between uncontrolled systems, LQR-controlled systems, and LQT-controlled systems provides valuable insight into the strengths and limitations of each approach [17] [18].

This study focuses on modeling and simulating the PG36M555 DC motor using first-order mathematical representation and implementing both LQR and LQT optimal control strategies. The system response is evaluated in terms of settling time, overshoot, steady-state error, and robustness to noise disturbances. Simulations are conducted using MATLAB/Simulink to compare motor performance under three conditions: without control optimization, with LQR control, and with LQT control. By systematically analyzing these configurations, this research aims to determine the effectiveness of optimal control strategies in enhancing DC motor dynamic performance. The findings are expected to contribute to the development of efficient and reliable control solutions for small-scale electromechanical systems requiring high precision and stability.

2. Research Method

Implementing experimental methods in this research plays a crucial role, as it enables a direct assessment of how a control strategy performs when applied to a real-world system. Unlike simulations or theoretical approaches, this method provides firsthand insights into system behavior under actual operating conditions [16]. As a result, it becomes possible to make more precise evaluations concerning factors like effectiveness, responsiveness, and overall system efficiency. Moreover, experimental testing offers valuable insights into the practical strengths and limitations of the control approach when deployed in realistic scenarios. It generates tangible and quantifiable data that support or challenge theoretical expectations, allowing researchers to verify the viability of the method in practice [17]. This hands-on validation is particularly important for systems that require a high degree of precision, stability, and operational reliability.



Geard Motor Torque/Speed

Number of stages	1 stages reduction	2 stages reduction	3 stages reduction	4stages reduction	5stages reduction
Reduction ratio	3.7、5.2	13.7、19.2、26.9	50.9、71.2、99.5、139、	188、264、369、516、721、	699、977、1367、1911、2672、3736、
Gearbox length "L" mm	25.1	32.3	38.5	44.7	50.9
Max. Running torque	10Kgf・cm	20Kgf・cm	50Kgf・cm	50Kgf・cm	50Kgf・cm
Max. Gear breaking torque	30Kgf・cm	60Kgf・cm	150Kgf・cm	150Kgf・cm	150Kgf・cm
Gearing efficiency	90%	81%	73%	65%	59%

Motor data:

Motor name	Rated Volt V	No load		Load torque				Stall torque	
		Current	Speed	Current	Speed	Torque	Output power	Torque	Current
		mA	r/min	mA	r/min	gf・cm	W	gf・cm	A
RS-555123000	12	≤140	3000	≤800	2458	179	4.51	1210	3.1
RS-555124500	12	≤200	4500	≤900	3929	183	7.42	1508	6.0
RS-555126000	12	≤320	6000	≤1450	5244	215	11.5	1722	9.3
RS-555243500	24	≤115	3500	≤480	3041	246	7.7	1720	2.7
RS-555244500	24	≤110	4500	≤460	3984	189	7.8	1713	3.4
RS-555246000	24	≤140	6000	≤920	5305	243	13.2	2065	5.5
RS-555249500	24	≤280	9500	≤1900	8190	386	32.5	2797	11.7

1. After connecting motor and gearbox which is named gearmotor the output torque=motor torque Xreduction ratio Xgearing efficiency output speed=motor speed /reduction ratio.

NOTE:

Figure 1. Datasheet Motor DC PG36M555

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2.1. First Order Mathematical Modeling

Mathematical modeling is done to obtain the response results of the DC motor. The mathematical model of the first-order system can be written as the following equation

$$\frac{C(s)}{R(s)} = \frac{K}{\tau s + 1} \quad (1)$$

$$K = \frac{\tau}{i} \quad (2)$$

Description:
τ = Torque
i = Ampere

So the calculation on the DC motor DC Motor PG36M555 based on the specifications from the datasheet obtained is:

$$K = \frac{\tau}{i} = \frac{0.2}{2.1} = 0{,}095 \quad (3)$$

Substitute the results of equation 3 into equation 1 to obtain the mathematical model of the PG36M555 DC Motor.

$$G(s) = \frac{K}{\tau s + 1} = \frac{0{,}174}{0.687s + 1} \quad (4)$$

2.2. Linear Quadratic Regulator (LQR)

Linear Quadratic Regulator (LQR) is a method used in modern control theory [19]. Analysis of such systems is done using the state space approach. Due to the simple approach of the state space method, multi-input multi-output systems use this method. The state space equation for the system is generally written as:

$$\dot{X} = AX + Bu \quad (5)$$

In principle, the LQR method searches for a control signal u that minimizes the performance index J.

$$J = \int (X^T Q_x + u^T R_a) dt \quad (6)$$

LQR finds the optimal control input law u*. The constraints imposed by the Q and R matrices minimize the performance index. The closed-loop optimal control law is defined as:

$$u^* = -Kx \quad (7)$$

Here, K represents the optimal feedback gain matrix, which functions to minimize the performance index of the system. This gain matrix plays a key role in determining the appropriate placement of the closed-loop poles to achieve optimal system behavior. The value of K is influenced by the system matrices A and B, as well as the weighting matrices Q and R [20]. To calculate the feedback gain K, the Algebraic Riccati Equation (ARE) must be solved. The solution to this equation

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yields P, a symmetric and positive definite matrix. This matrix P is essential in defining the optimal control law and directly impacts the computation of the gain matrix K.

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{8}$$

$$K = AX - BKx = (A - BK)x \tag{9}$$

Equation (8) and (9) become:

$$x = AX - BKx = (A - BK)x \tag{10}$$

The block diagram showing the LQR configuration is shown in Figure 2.

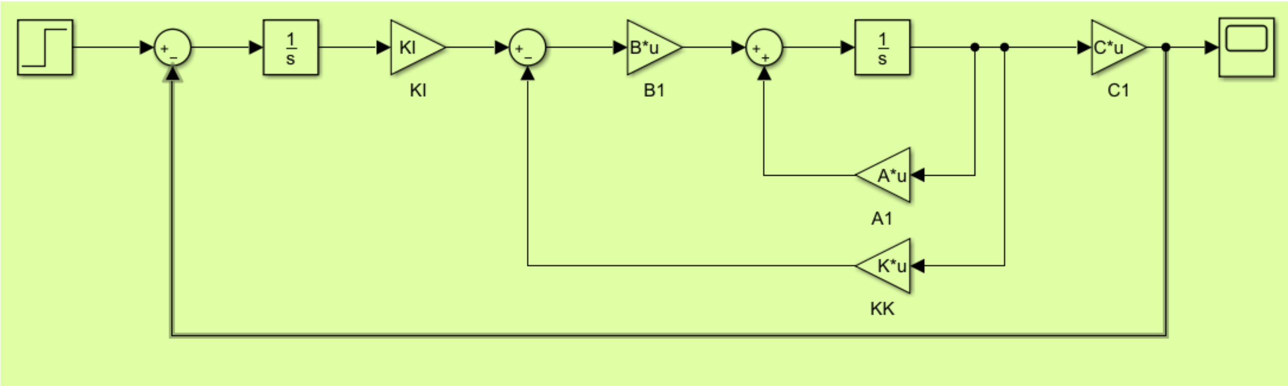

Figure 2. LQR Diagram Block

2.2. Linear Quadratic Tracker (LQT)

The LQT consists of the usual state feedback of a linear dynamic system together with an additional feed-forward control term. The feed-forward control term depends on the reference signal vector, r(t). The vector r(t) is given by:

$$r(t) = [V_{ref}(t) \;\; 0]^T \tag{11}$$

Where, V_ref is a time-varying reference voltage signal. The LQT scheme minimizes the squared performance index to produce the optimal control decision which can be formulated in the following equation.

$$J = \frac{1}{2}\int_0^T [(x(t) - r(t))^T Q\big(x(t) - r(t)\big) + d(t)^T R d(t)]dt \tag{12}$$

Where, Q and R are the intermediate state and control weighting matrices, respectively. They are chosen such that; Q = QT ≥ 0 and R = RT > 0. Due to the quadratic nature of the cost function, the control signal is proportional to the quadratic variation of the equation. Thus, if the state-variations are large; minimization and, hence, the convergence rate is faster.

$$d(t) = -Kx(t) + K_{ff} v_{ref}(t) \tag{13}$$

Where,

$$K = R^{-1}B^T P \tag{14}$$

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$$K_{ff} = R^{-1}B^T((A - BK)^T)^{-1}H^TQ \quad (15)$$

The gain vector, K, helps to relocate the system poles to synthesize the optimal controller. The optimal gain vector depends on the symmetric positive definite matrix, P, shown in (14). The matrix, P, for a given system can be obtained by solving the Riccati Algebra Equation, shown in.

$$A^TP + PA - PBR^{-1}B^TP + H^T\text{QH} = 0 \quad (16)$$

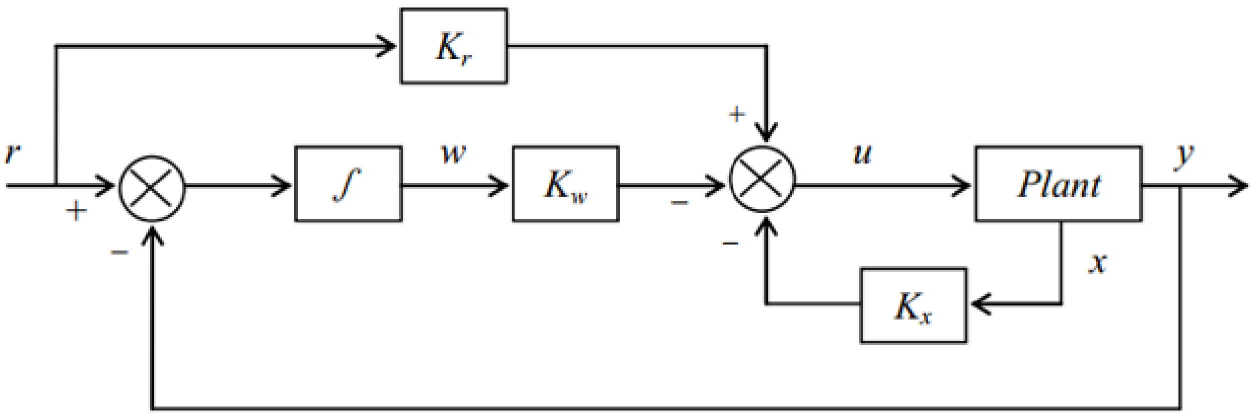

Figure 3. LQT Diagram Block

2.3. Block diagram first order DC Motor PG36M555

In the first order motor block diagram, the aim is to find out the original response results of the DC motor if the PG36M555 DC Motor is not added to the method carried out in the Simulink software.

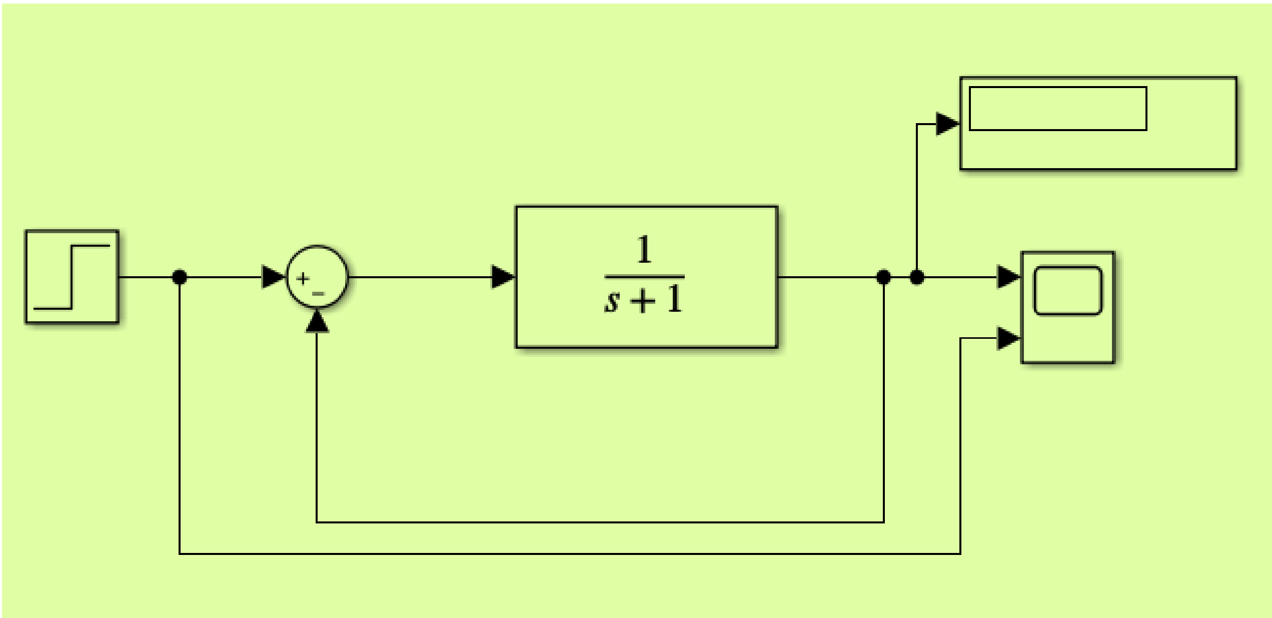

Figure 4. Block diagram first order in Simulink

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Figure 4 shows a first-order block diagram of a DC motor consisting of an input and an output. The input used is a step response type. The transfer function in the diagram can contain a first-order DC motor modeling. The response results will be displayed on the scope and display to find out the maximum response value produced.

2.4. Block diagram LQR DC Motor PG36M555

In the LQR block diagram of the PG36M555 DC Motor, the aim is to find out the response results of the DC motor if the DC motor is given the addition of the LQR optimization method which is carried out on the Simulink software.

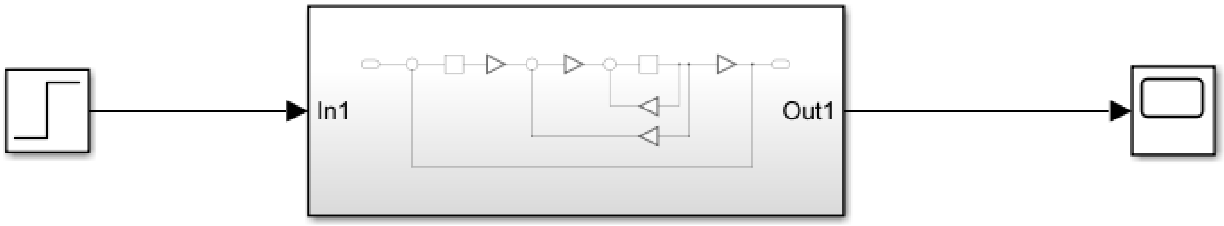

Figure 5. Block diagram LQR Motor in Simulink

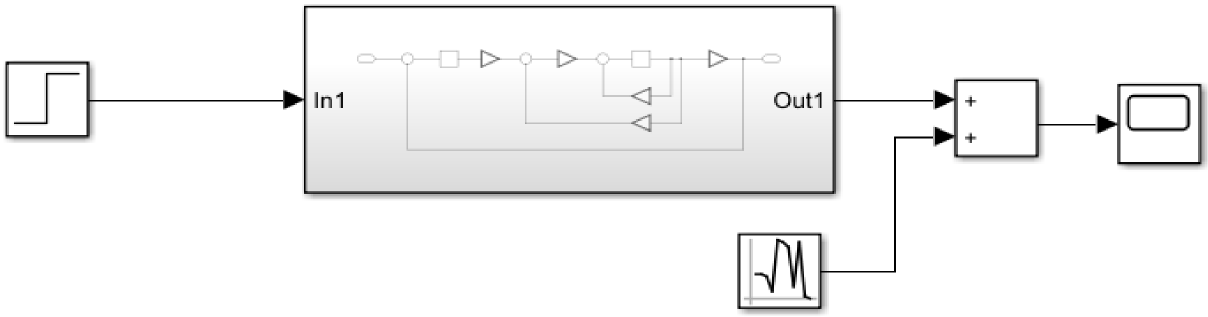

Figure 6. Block diagram LQR Motor in Simulink with noise

2.5. Block diagram LQT DC Motor PG36M555

In the LQT block diagram of the PG36M555 DC Motor, the aim is to find out the response results of the DC motor if the DC motor is given the addition of the LQT optimization method which is carried out on the Simulink software.

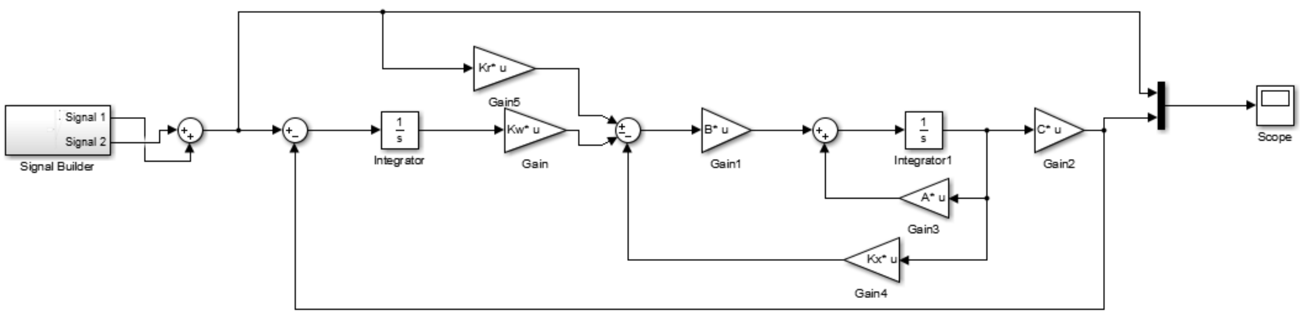

Figure 7. Block diagram LQT Motor in Simulink

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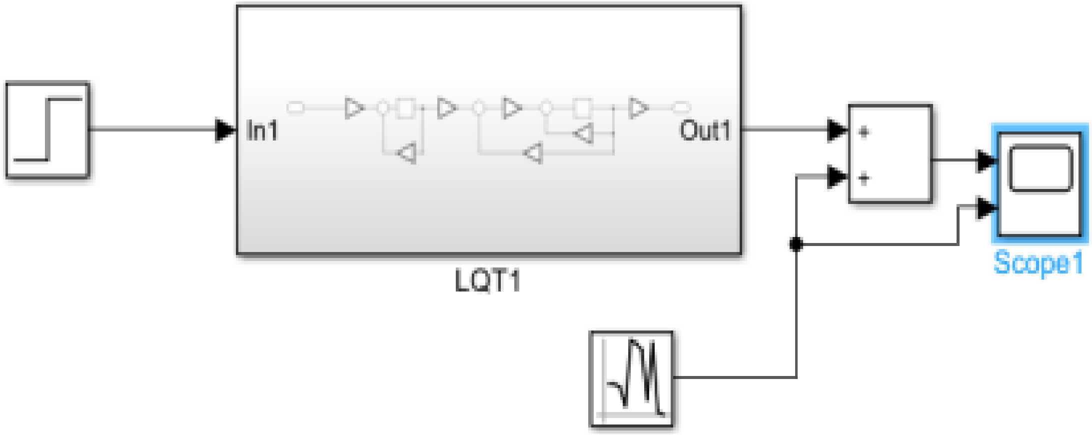

Figure 8. Block diagram LQT Motor in Simulink with noise

3. Results And Discussion

This section discusses the results of the PG36M555 DC motor response in the first-order mathematical model and when given the LQR method with and without noise. The response results are obtained using simulations in the Simulink Matlab software.

3.1. First Order Response Results of PG36M555 DC Motor

Figure 9. Response Results of PG36M555 DC Motor

In the output response of the first-order modeling shown in Figure 9, the motor's response appears to deviate significantly from the desired setpoint. The orange waveform represents the actual motor response, while the blue line indicates the target setpoint. The intended value is 0.5, yet the motor only reaches approximately 0.07. The observed PG36M555 DC motor demonstrates linear behavior, as indicated by the absence of ripples in the signal. The system reaches a steady state around the 2-second mark after being powered on. However, the overall response is considered relatively slow [10] [14] [15].

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3.2. PG36M555 DC Motor Response Results Using LQR Method

Figure 10. DC Motor Response Results Using LQR Method

In the output response shown in Figure 10, the PG36M555 DC motor demonstrates a significantly improved performance when the LQR method is applied. The response curve aligns precisely with the desired setpoint value of 0.5. The motor successfully reaches the setpoint at approximately 1.2 seconds without experiencing any overshoot or undershoot. This indicates that applying the LQR control method leads to a much more accurate and stable response compared to the system without LQR implementation [2] [3] [11].

3.3. Comparison Results of DC Motor Response Using LQR

Figure 11. Comparison Results of DC Motor Response Using LQR Method and Without Method

In the comparison output response shown in Figure 11, the PG36M555 DC motor displays noticeably different behaviors when controlled with and without the LQR method. The orange

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waveform represents the desired setpoint, the blue curve shows the motor's response without LQR, and the yellow curve indicates the response with LQR applied. As clearly illustrated in the figure, the motor response under LQR control outperforms the response without it. Not only does the LQR-controlled system closely follow the setpoint without any overshoot or undershoot, but it also reaches steady-state significantly faster, highlighting the improved performance and stability brought by the LQR approach [16] [17] [18].

3.4. PG36M555 DC Motor Response Using LQR Method with Noise

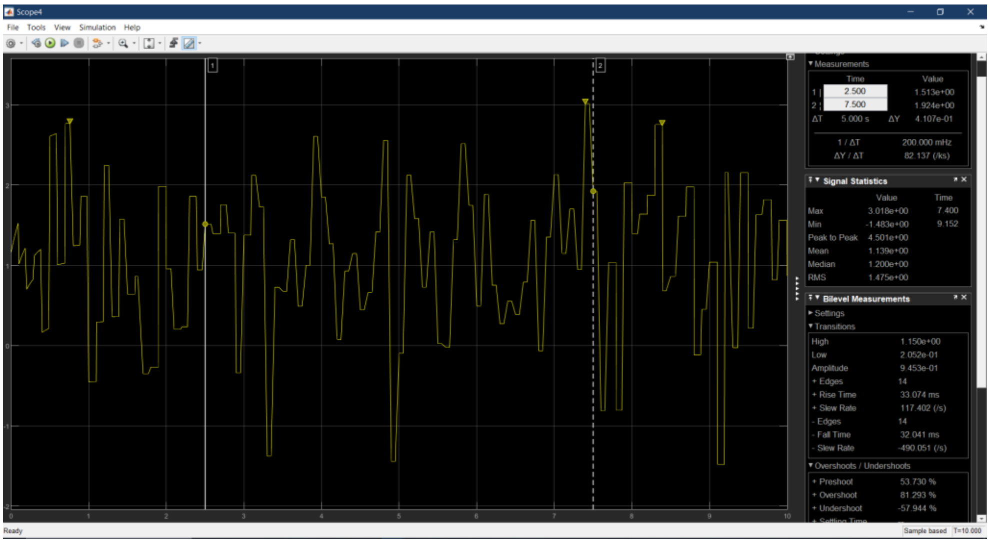

Figure 12. DC Motor Response Results Using LQR Method with Noise

Based on the results shown in Figure 12, the yellow signal representing the response of the PG36M555 DC motor under LQR control undergoes a noticeable change in shape after noise is introduced. The signal becomes highly distorted, displaying significant ripples and closely mimicking the characteristics of the injected noise. As a result, the motor response loses its linearity and deviates significantly from a stable steady-state condition at the intended setpoint [1] [2].

3.5. PG36M555 DC Motor Response Results Using LQT Method

Figure 13. DC Motor Response Results Using LQT Method

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In the output response modeling shown in the figure above, the PG36M555 DC motor controlled using the LQT method successfully reaches the desired setpoint of 0.5. The response time to reach steady state is exceptionally fast, recorded at just 8.36 microseconds. However, the response exhibits a 4.7% overshoot and a slight 0.8% undershoot, indicating minor deviations before stabilizing at the target value [4] [6].

3.6. Comparison Results of DC Motor Response

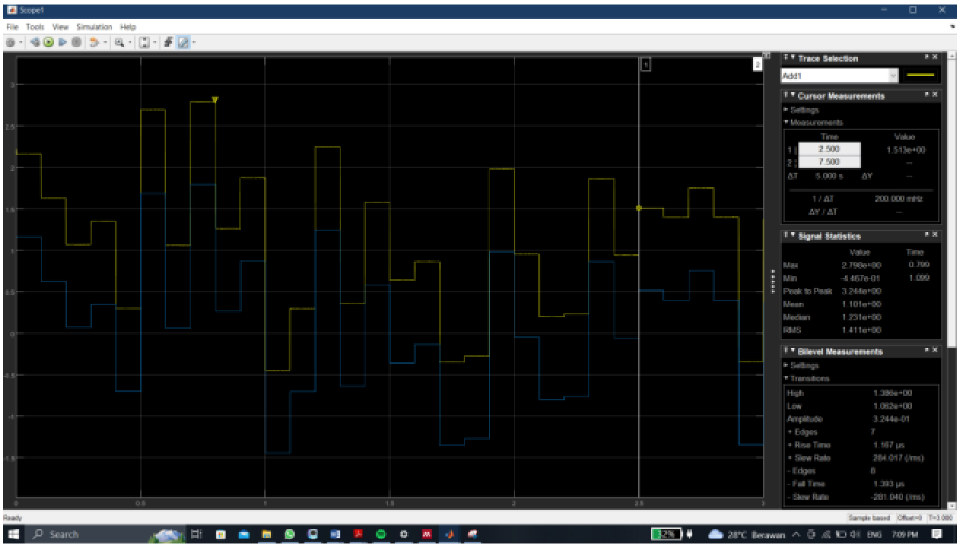

Figure 14. Comparison Results of DC Motor Response Using LQT Method and Without Method

As shown in Figure 14, the yellow signal representing the response of the PG36M555 DC motor using the LQT method undergoes a significant change in shape after noise is introduced. The signal becomes heavily distorted, exhibiting numerous ripples and closely following the pattern of the applied noise. Consequently, the response loses its linear characteristics and deviates substantially from a stable steady-state condition at the intended setpoint [13] [18].

3.7. PG36M555 DC Motor Response Using LQT Method with Noise

Figure 15. DC Motor Response Results Using LQT Method with Noise

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In the comparative output response shown in Figure 15, the Maxon EC-I 40 70 Watt DC motor displays distinct differences in behavior when operated with and without the LQT control method. The orange waveform represents the desired setpoint, the blue curve illustrates the motor's response without LQT, and the yellow curve shows the response with LQT applied. From the figure, it is evident that the motor's performance with LQT is significantly better, demonstrating a response that more closely follows the setpoint and overall improved system behavior compared to operating without the LQT method.

4. Conclusion

This study presents a systematic modeling and simulation-based evaluation of optimal control strategies to enhance the dynamic performance of the PG36M555 DC motor. A first-order mathematical model was developed to characterize the motor dynamics, and its open-loop response was analyzed as a baseline reference. The uncontrolled system exhibited slow transient behavior and substantial steady-state deviation, reaching only approximately 0.07 of the intended 0.5 setpoint and requiring nearly 2 seconds to stabilize, thereby highlighting the necessity of control optimization. The application of the Linear Quadratic Regulator (LQR) significantly improved system performance, enabling accurate setpoint tracking without overshoot or undershoot and reducing the settling time to approximately 1.2 seconds, confirming the effectiveness of optimal state-feedback control in improving stability and precision. Furthermore, the Linear Quadratic Tracker (LQT) achieved even faster convergence, reaching steady state in approximately 8.36 microseconds, albeit with minor overshoot (4.7%) and undershoot (0.8%), demonstrating superior tracking capability under nominal conditions. However, robustness analysis under noise disturbances revealed that both LQR and LQT experienced performance degradation, with output signals becoming distorted and deviating from steady-state stability. These findings indicate that while optimal control strategies substantially enhance nominal dynamic response and tracking performance, their sensitivity to noise remains a practical limitation. Overall, this work provides a comprehensive comparative assessment of LQR and LQT implementations for commercial DC motor systems and offers practical insight into their advantages and constraints in real-world control applications.

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