Automation, Control and Intelligent Systems
2023; 11(3): 45-56
http://www.sciencepublishinggroup.com/j/acis
doi: 10.11648/j.acis.20231103.11
ISSN: 2328-5583 (Print); ISSN: 2328-5591 (Online)

Design GUI App on MATLAB for Comparison Analysis of LQR and Pole Placement Controller for Speed Control DC Motor

Alemie Assefa

Department of Electrical and Computer Engineering, Debre Berhan University, Debre Berhan, Ethiopia

Email address:
alemieastu@gmail.com

To cite this article:
Alemie Assefa. Design GUI App on MATLAB for Comparison Analysis of LQR and Pole Placement Controller for Speed Control DC Motor. *Automation, Control and Intelligent Systems*. Vol. 11, No. 3, 2023, pp. 45-56. doi: 10.11648/j.acis.20231103.11

Received: September 1, 2023; **Accepted**: October 17, 2023; **Published**: October 30, 2023

Abstract: This article presents the design of a graphical user interface (GUI) application on MATLAB for comparing the performance of two popular control techniques, Linear Quadratic Regulator (LQR) and Pole Placement, for DC motor speed control. The GUI app allows users to input system dynamics, desired speed references, and controller gains to visualize and analyze the behavior of the controllers in real-time. The app provides dynamic plots and performance metrics, enabling users to evaluate settling time, overshoot, steady-state error, and control effort. The GUI app serves as an educational tool and aids in the selection of the optimal control strategy for DC motor speed control. Through its user-friendly interface and real-time analysis capabilities, the GUI app contributes to the advancement of control systems engineering and promotes efficient and accurate control of DC motors. The simulation result shown from this paper depends on the parameters of LQR and Pole placement controllers (PPC). When the weighting matrices of the Q matrices is high, the speed response is good and when the location of poles are far from the origin of s plane the simulation result is good compared to the poles near to the origin and when the poles are purely real the performance of the result is better than when poles are the combination of both real and imaginary parts has been tested. From the simulation result the rise time and settling time is low for pure real and negative poles than complex conjugate poles.

Keywords: GUI, LQR, Pole Placement, DC Motor, PPC

1. Introduction

DC motors are widely used in various industries, ranging from robotics to electric vehicles, necessitating the development of efficient control strategies for precise speed control [1, 2]. This article focuses on designing a MATLAB based graphical user interface (GUI) application that facilitates the comparison of LQR and Pole Placement controllers for DC motor speed control and enables users to compare the performance of these control techniques in real-time. In a study the GUI app allows users to input system parameters, analyze the real-time response, and evaluate performance metrics to determine the most effective control strategy [3].

The GUI provides an intuitive platform for users to input system parameters, such as the motor's dynamics and desired speed reference, as well as the gains for the LQR and Pole Placement controllers.

Control systems engineering plays a vital role in achieving accurate and stable control of various systems, including DC motors. Two popular control techniques used for DC motor speed control are the Linear Quadratic Regulator (LQR) and Pole Placement. The GUI app provides an intuitive platform for analyzing the behavior and effectiveness of LQR and Pole Placement controllers, facilitating the selection of the optimal control strategy for DC motor speed control. By offering a user-friendly interface and real-time analysis capabilities, the GUI app contributes to the advancement of control systems engineering and promotes efficient and accurate control of DC motors.

By integrating dynamic plots, such as the motor speed response and control effort, the GUI offers users a visual representation of the controllers' performance [3]. Additionally, performance metrics like settling time, overshoot, steady-state error, and control effort are displayed, enabling a comprehensive comparison between the LQR and Pole Placement controllers.

2. Literature Review

Control of DC motors using various control techniques has been extensively studied in the field of control systems engineering. In particular, the comparison between Linear Quadratic Regulator (LQR) and Pole Placement controllers for DC motor speed control has garnered significant attention among researchers. Comparing the performance of Linear Quadratic Regulator (LQR) and Pole Placement controllers for DC motor speed control has been a topic of interest among researchers. Several studies have investigated the effectiveness and performance of these control techniques, providing valuable insights into their advantages and limitations.

Conducting an experimental investigation to compare the performance of LQR and sliding mode controllers for a DC motor speed control system. The authors implemented the controllers evaluated their performance using step response analysis [4]. The study revealed that the LQR controller provided better transient response characteristics with reduced settling time and overshoot compared to sliding mode controller.

The study compared the performance of LQR and PID controllers for a DC motor speed control application [32]. The authors implemented the controllers using MATLAB and evaluated their performance based on metrics such as settling time, overshoot, and control effort. The results indicated that both control techniques exhibited satisfactory performance, but the LQR controller demonstrated better response in terms of settling time and overshoot [5-7].

Some papers considered various performance metrics, including settling time, overshoot, and control effort, and applied a weighted sum optimization technique to determine the optimal controller gains. The results demonstrated that the LQR controller achieved superior performance in terms of settling time and overshoot, while the Pole Placement controller exhibited better control effort characteristics [8-11].

Overall, these studies [12, 13] emphasize the importance of comparing the performance of LQR and Pole Placement controllers for DC motor speed control. While the LQR controller often demonstrates better response characteristics in terms of settling time and overshoot, the Pole Placement controller may offer advantages in terms of control effort. Therefore, the choice between these control techniques depends on the specific requirements and objectives of the DC motor speed control application.

The performance of LQR controllers for a DC motor speed control system under varying load conditions. The authors examined the controllers' response in terms of stability, tracking accuracy, and disturbance rejection. The study revealed that the LQR controller maintained stability and accurate tracking performance under various load disturbances [14-16].

Several other studies have explored the performance comparison between LQR and Pole Placement controllers for DC motor speed control. These studies have highlighted the importance of considering factors such as settling time, overshoot, control effort, stability, and robustness when selecting the optimal control strategy for a specific application.

In summary, the literature review indicates that both LQR and Pole Placement controllers have been extensively studied for DC motor speed control. While the LQR controller [20] often demonstrates better response characteristics in terms of settling time and overshoot, the Pole Placement controller may offer advantages in terms of control effort and robustness.

3. Mathematical Modelling of DC Motor

The mathematical model of a separately excited DC motor typically consists of two main components: the electrical equation and the mechanical equation [16].

Consider a simplified model for the DC motor is shown in Figure 1.

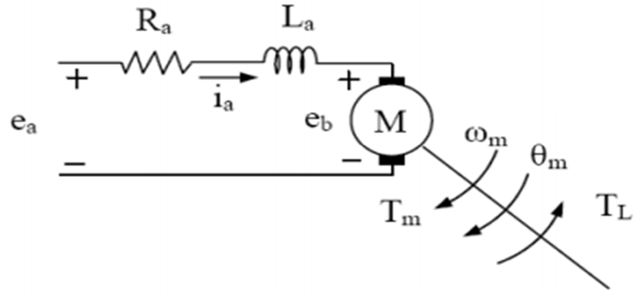

Figure 1. *Separately excited DC motor.*

Electrical Equation: The electrical equation describes the relationship between the voltage applied to the motor and the current flowing through its armature. This relationship is governed by the following equation:

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

Where, V_a is the applied voltage to the motor armature, R_a is the armature resistance, L_a is the armature inductance, i_a is the armature current, $\frac{di_a}{dt}$ represents the rate of change of armature current with respect to time and E_b is the back electromotive force (EMF) generated by the motor, which is proportional to the motor speed (ω_m) and can be expressed as $E_b = K_b \omega_m$.

Mechanical Equation: The mechanical equation characterizes the relationship between the motor's angular velocity (ω_m) and the torque (T_m) it produces. This relationship is defined by the following equation:

$$T_m = B\omega_m + J\frac{d\omega_m}{dt} \quad (2)$$

But the mechanical torque of the DC motor

$$T_m = K_t i_a$$

Where, T_m represents the motor torque, K_t is the torque constant, which relates the motor current to the generated torque, J is the moment of inertia of the motor's rotor and B is the motor damping coefficient, which accounts for mechanical losses.

The state space representation of a DC motor provides a concise mathematical description of its dynamics in terms of state variables and input/output relationships [17-19]. The state space model consists of a set of first-order differential equations that describe the evolution of the system states over time. For a separately excited DC motor, the state space representation can be derived based on the electrical and mechanical subsystems mentioned earlier.

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du \quad (3)$$

By combining the electrical and mechanical equations, the complete dynamic model of the DC motor [21-24] have three states i_a ω_m & θ_m, one input signal voltage applied to the motor armature (V_a) and one output signal motor angular velocity (ω_m). Therefore the state space representation of separately excited DC motor is

$$\frac{di_a}{dt} = -\frac{R_a}{L_a} i_a - \frac{K_b}{L_a}\omega_m + \frac{1}{L_a} V_a \quad (4)$$

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

$$\frac{d\theta_m}{dt} = \omega_m \quad (6)$$

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{d\omega_m}{dt} \\ \frac{d\theta_m}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_b}{L_a} & 0 \\ \frac{K_t}{J} & -\frac{B}{J} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ \omega_m \\ \theta_m \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ 0 \\ 0 \end{bmatrix} V_a \quad (7)$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ \omega_m \\ \theta_m \end{bmatrix}$$

The transfer function of the above state space representation can be determined using

$$\frac{\omega_m(s)}{V_a(s)} = C(sI - A)^{-1}B + D \quad (8)$$

$$\frac{\omega_m(s)}{V_a(s)} = \frac{K_t}{(L_a s + R_a)(Js + B) + K_b K_t} \quad \& \quad \frac{\theta_m(s)}{V_a(s)} = \frac{K_t}{s((L_a s + R_a)(Js + B) + K_b K_t)}$$

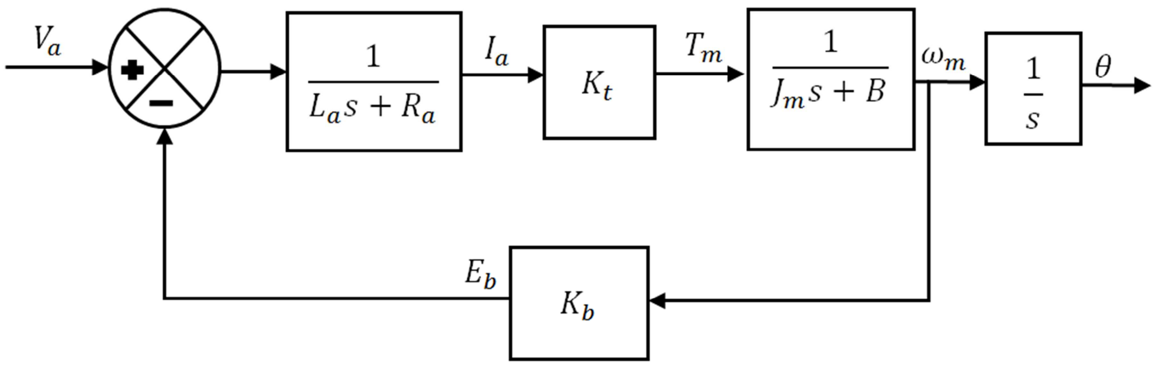

Figure 2. *Block diagram of DC motor.*

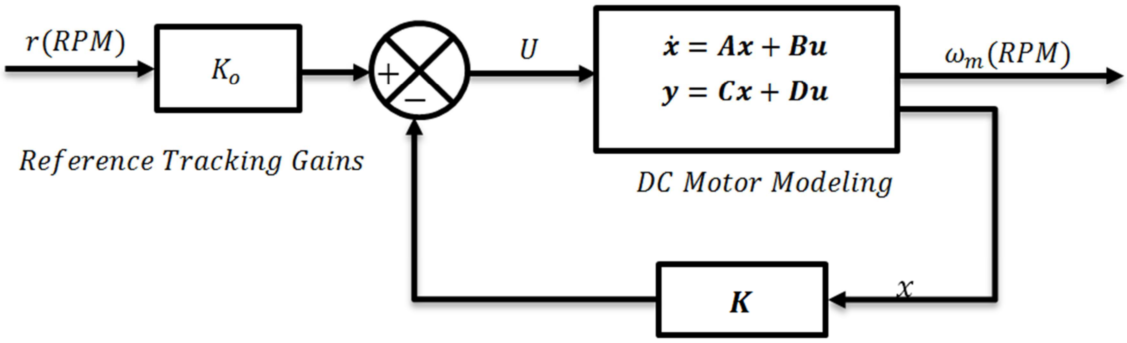

Figure 3. *General block diagram for DC motor with LQR controller.*

By utilizing the state space representation, control algorithms such as the Linear Quadratic Regulator (LQR) can be applied to design control strategies for the DC motor. The LQR control algorithm involves formulating an optimal control problem based on the system's state space representation and solving it to obtain the optimal control input that minimizes a cost function, typically associated with achieving desired performance criteria.

The state space representation allows for analysis, simulation, and control design of the DC motor system using a range of control techniques, including LQR, state feedback, and observer-based control.

4. General Block Diagram and Controller Design

The Linear Quadratic Regulator (LQR) is a well-known method that provides optimally controlled feedback gains to enable the closed-loop stable and high performance design of systems $\dot{x}$ or the derivation of the linear quadratic regulator for a linear system state-space representation.

4.1. LQR Controller Design

The Linear Quadratic Regulator (LQR) is an optimal control technique that minimizes a quadratic cost function. It calculates control signals based on system state and desired behavior, aiming to minimize both control effort and tracking errors simultaneously [20].

To design an LQR (Linear Quadratic Regulator) controller for the separately excited DC motor system described by the state space representation.

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

It need to define the state feedback gain matrix (K) that minimizes a quadratic cost function, typically associated with achieving desired performance criteria [25-29].

The cost function in LQR control can be formulated as:

$$J = \int_0^{\infty} (x^T Q x + u^T R u)\, dt \tag{9}$$

Where Q is the state weighting matrix, typically chosen as a positive definite symmetric matrix, to assign relative importance to the states R is the control weighting matrix, also a positive definite symmetric matrix, to assign relative importance to the control input.

The LQR controller design involves solving the algebraic Riccati equation to obtain the optimal feedback gain matrix (K).

The Riccati equation for the DC motor system can be expressed as:

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{10}$$

Where, A is the system matrix in the state space representation, B is the input matrix in the state space representation, P is the symmetric positive definite matrix solution of the Riccati equation and R is the control weighting matrix.

Once the symmetric positive definite matrix P is obtained, the optimal feedback gain matrix K can be calculated as

$$K_{3*3} = [\, K_1\, K_2\, K_3] = R^{-1}B^T P \tag{11}$$

Finally, the control input U can be computed as $u = -Kx$ that produces the lowest cost.

The LQR controller uses the state feedback gain matrix K to compute the control input that minimizes the cost function J and drives the system towards the desired performance criteria.

It is important to note that the choice of Q and R matrices in the cost function and the resulting feedback gain matrix K can significantly impact the control system's performance. The tuning of Q and R matrices is typically based on system requirements and desired trade-offs between control effort and state tracking.

Control signal for reference tracking using linear quadratic regulator (LQR) is given by

$$u = K_o r - K_Q x \tag{12}$$

$$\text{Where, } K_Q \leftrightarrow LQR\ Controller\ gain\ \&$$

$$K_o \leftrightarrow Reference\ gain$$

Substituting the reference control signal to the open loop state space equation. The resulting state space equation would be

$$\dot{x} = Ax + B(\, K_o r - K_Q x) = (A - BK_Q)x + BK_o r = A_{new}x + B_{new}u$$

$$y = Cx + D(\, K_o r - K_Q x) = (C - DK_Q)x + DK_o r = C_{new}x + D_{new}u$$

Where, $A_{new} = A - BK_Q$, $B_{new} = BK_o$, $C_{new} = C - DK_Q$ & $D_{new} = DK_o$

The overall closed loop transfer function of the new state space representation of DC motor can be determined using

$$\frac{\omega_m(s)}{r(s)} = K_o[\, C_{new}(sI - A_{new})^{-1}\, B_{new} + D_{new}] \tag{13}$$

$$\frac{\theta_m(s)}{r(s)} = \frac{K_o}{s}[\, C_{new}(sI - A_{new})^{-1}\, B_{new} + D_{new}] \tag{14}$$

4.2. Pole Placement Controller

Pole Placement Controller: Pole Placement is a control technique that involves placing the closed-loop system poles at desired locations in the complex plane. This technique enables engineers to shape the system's response by strategically selecting pole locations based on desired performance characteristics.

The mathematical expression for a pole placement controller depends on the specific system dynamics and desired pole locations. Consider a single-input, single-output (SISO) system with transfer function G(s) representing the open-loop transfer function of any linear system. The desired closed-loop characteristic equation can be represented as:

$$s^n + a_{n-1}s^{n-1} + a_{n-2}s^{n-2} + \cdots + a_1 s + a_0 = 0$$

where n is the order of the system and a_i are the desired coefficients.

To design the pole placement controller, the closed-loop transfer function is given by:

$$T(s) = K(s) * G(s)$$

where $K(s)$is the controller transfer function.

The general form of the pole placement controller transfer function is:

$$K(s) = \frac{(s-p_1)(s-p_2)...(s-p_n)}{G(s)} \quad (15)$$

Where p_i represents the desired pole locations.

To obtain the specific values for p_i, it needs to solve the characteristic equation with the desired pole locations and obtain the corresponding controller gains. The calculation of the controller gains depends on the chosen pole placement technique, such as the Ackermann's formula or other pole placement algorithms.

Control signal for reference tracking using pole placement controller (PPC) is given by

$$u = K_o r - K_P x \quad (16)$$

Where $K_P \leftrightarrow Pole\ Placment\ Controller\ gain$ &
$K_o \leftrightarrow Reference\ gain$

Substituting the reference control signal to the open loop state space equation. The resulting state space equation would be

$$\dot{x} = Ax + B(K_o r - K_P x) = (A - B K_P)x + BK_o r = A_{new}x + B_{new}u$$

$$y = Cx + D(K_o r - K_P x) = (C - DK_P)x + DK_o r = C_{new}x + D_{new}u$$

Where, $A_{new} = A - BK_P$, $B_{new} = BK_o$, $C_{new} = C - DK_P$ & $D_{new} = DK_o$

The overall closed loop transfer function of the new state space representation of DC motor can be determined using

$$\frac{\omega_m(s)}{r(s)} = K_o[C_{new}(sI - A_{new})^{-1} B_{new} + D_{new}]$$

$$\frac{\theta_m(s)}{r(s)} = \frac{K_o}{s}[C_{new}(sI - A_{new})^{-1} B_{new} + D_{new}] \quad (17)$$

5. GUI App Design on MATLAB

Graphical User Interfaces (GUIs) have revolutionized the way engineers and researchers interact with complex systems and analyze their behavior. In the context of comparing the performance of LQR and Pole Placement controllers for DC motor speed control, the development of a GUI becomes particularly valuable. This article focuses on designing a GUI application on MATLAB that enables users to conveniently assess and compare the effectiveness of these control techniques [3].

The GUI application serves as a powerful tool for engineers, researchers, and students in the field of control systems engineering [30-31]. It simplifies the process of evaluating control strategies for DC motor speed control, allowing users to assess the behavior of LQR and Pole Placement controllers in real-time. Ultimately, this GUI contributes to the advancement of control systems research and facilitates the development of efficient and accurate control techniques for DC motors.

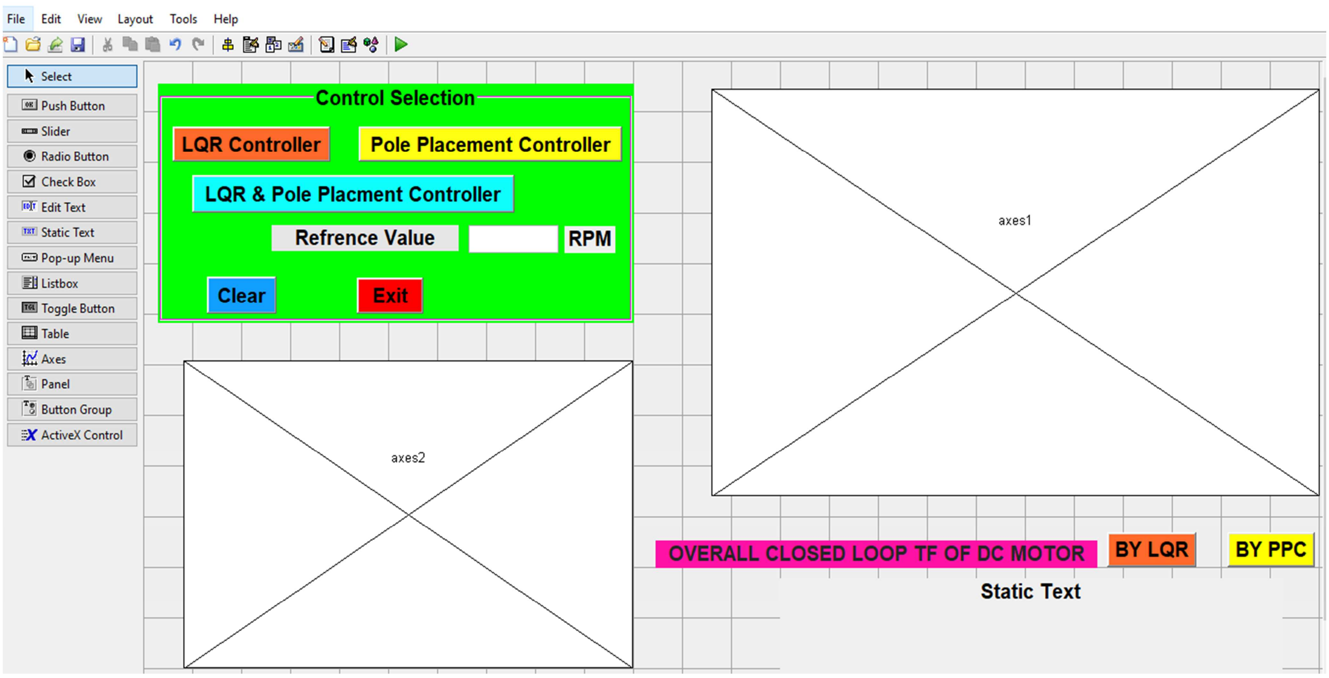

Figure 4. The general GUI block diagram on MATLAB for this paper.

The GUI App design on MATLAB for this paper is designed with the following components.

Desired Speed Reference: Numeric input field to set the desired speed reference for the motor.

Run Simulation Buttons: Upon clicking this button, the GUI app initiates the simulation using the specified parameters and displays the motor's response in real-time.

Compare Controllers Buttons: This button triggers the comparison of the LQR and Pole Placement controllers' performance based on the specified reference speed, displaying the results in terms of settling time, overshoot, steady-state error, and control effort.

Clear Buttons: This button is designed to clear all figure from GUI App axes.

Clear Buttons: This button is designed to remove the figure and close the GUI App.

BY LQR Button: This button is designed to calculate and display the closed loop transfer function of DC motor using linear quadratic regulator (LQR) controller.

BY PPC Button: This button is designed to calculate and display the closed loop transfer function of DC motor using pole placement controller (PPC).

Motor Speed Response plot (Axes1): A dynamic plot that shows the speed response of the motor over time for both the LQR and Pole Placement controllers.

All three State Response plot (Axes2): Another plot displaying the control effort exerted by each controller (PID and LQR controller) during the simulation.

Static Text field: The function of this field on GUI App design is just display the closed loop transfer function of DC motor both using LQR and PID controllers.

These components within the GUI will allow users to input relevant parameters, run simulations, visualize the motor's response, and compare the performance of the LQR and Pole Placement controllers.

6. Result and Discussion

To simulate and analysis of the effectiveness of LQR controller for DC Motor on MATLAB Software is based on the Table 1 DC motor parameters.

Table 1. *DC Motor Parameters.*

Parameter	Symbol	Value and Unit
Armature Resistance	R_a	1.1Ω
Armature Inductance	L_a	0.00891H
Back EMF Constant	K_b	0.22 $V/r/s$
Friction Coefficient	B	0.011 $N.m/r/s$
Motor torque Constant	K_t	0.22 $N.m/A$
Moment of Inertia	J	0.0044$Kg.m2$

The simulation result for DC Motor have been tested and analysed for variation of reference speed, different LQR parameters and different pole location.

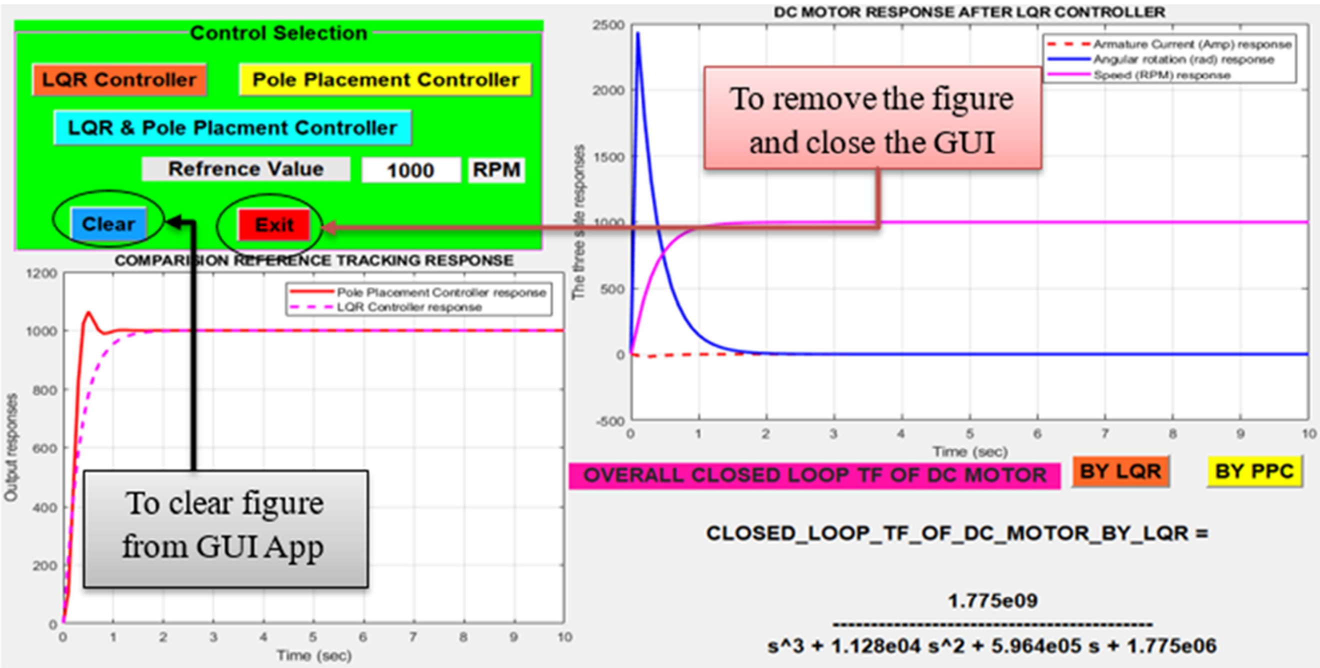

Figure 5. *Use of GUI button for DC Motor response graph.*

Condition 1: When the desired poles are the combination of real and imaginary poles

Case 1: The DC motor response for reference speed =1000RPM with LQR parameters $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 10 \end{bmatrix}, R = 0.1$ & $Desired\ poles\ of\ Motor\ = [-1 + 10i, -10 - 10i, -10]$

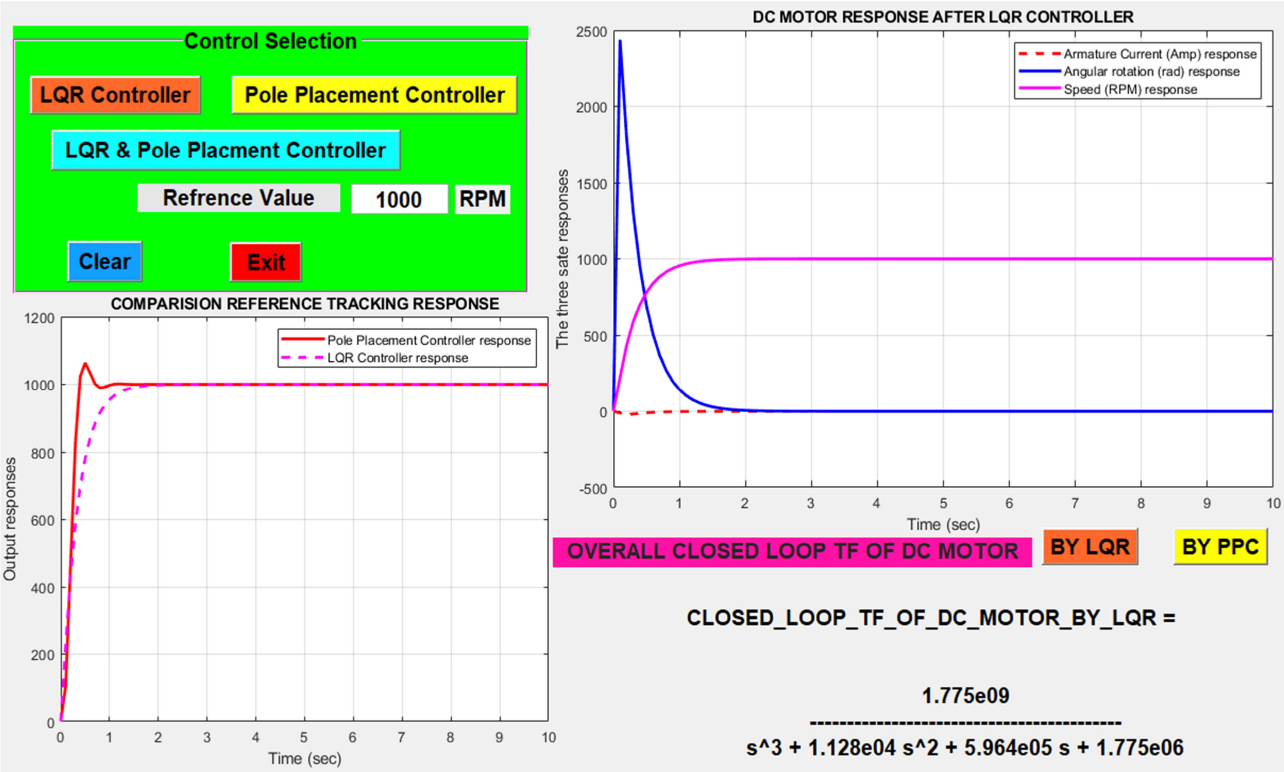

Figure 6. *DC Motor response with a reference speed =1000RPM for case 1 using LQR Controller.*

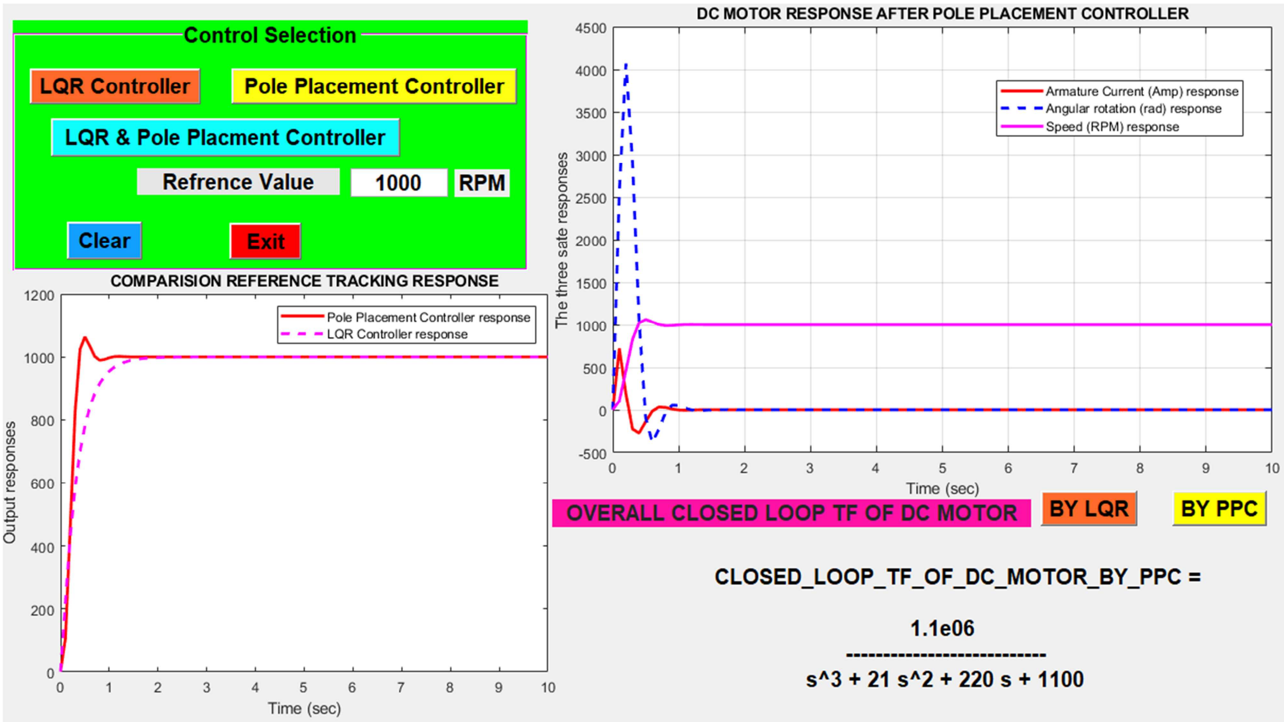

Figure 7. *DC Motor response with a reference speed =1000RPM for case 1 using Pole Placement Controller.*

Case 2: The DC motor response for reference speed =2000RPM with LQR parameters $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 10 \end{bmatrix}, R = 0.1$ $\&\ Desired\ poles\ of\ Motor\ = [-1+10i, -10-10i, -10]$

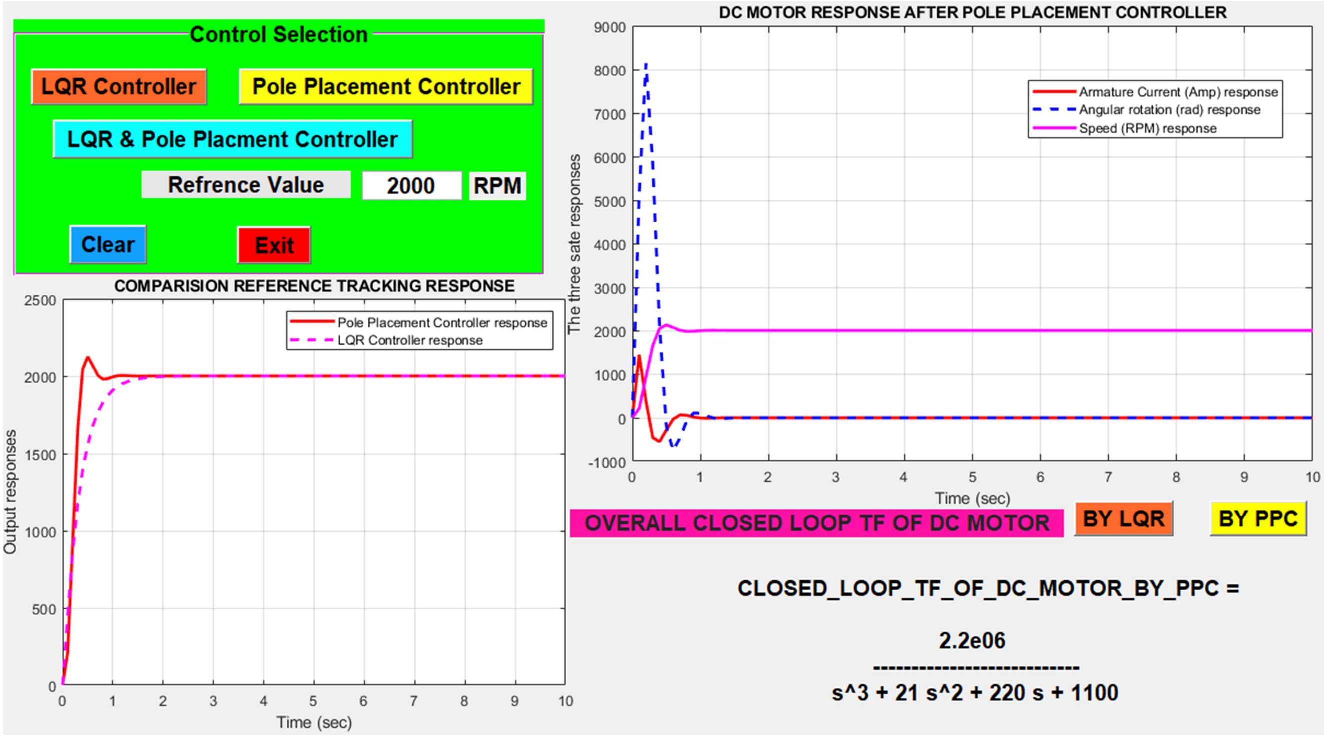

Figure 8. *DC Motor response with a reference speed =2000RPM for case 2 using Pole Placement Controller.*

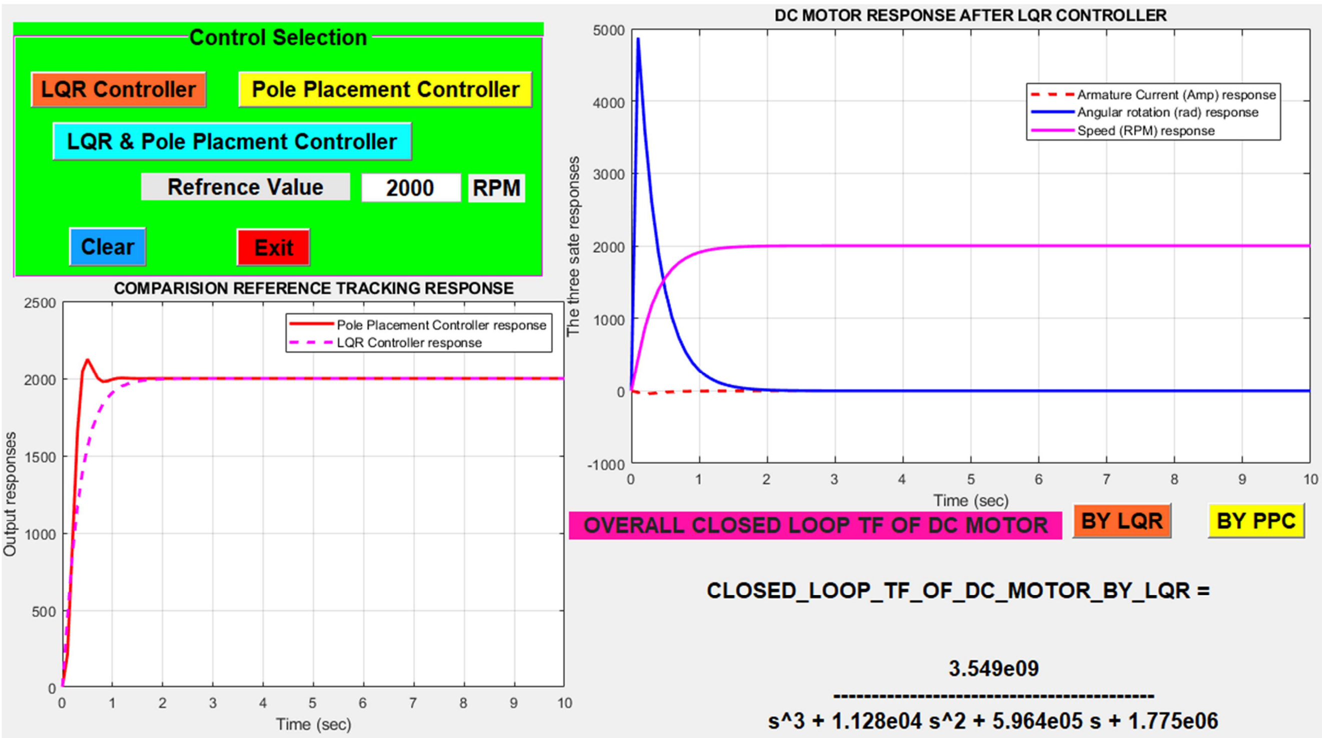

Figure 9. *DC Motor response with a reference speed =2000RPM for case 1 using LQR Controller.*

Condition 2: When the desired poles are real poles only with different weighting

Case 3: The DC motor response for reference speed =1000RPM with LQR parameters $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 10 \end{bmatrix}, R = 0.1$ $\&\ Desired\ poles\ of\ the\ system\ = [-10, -10, -10]$

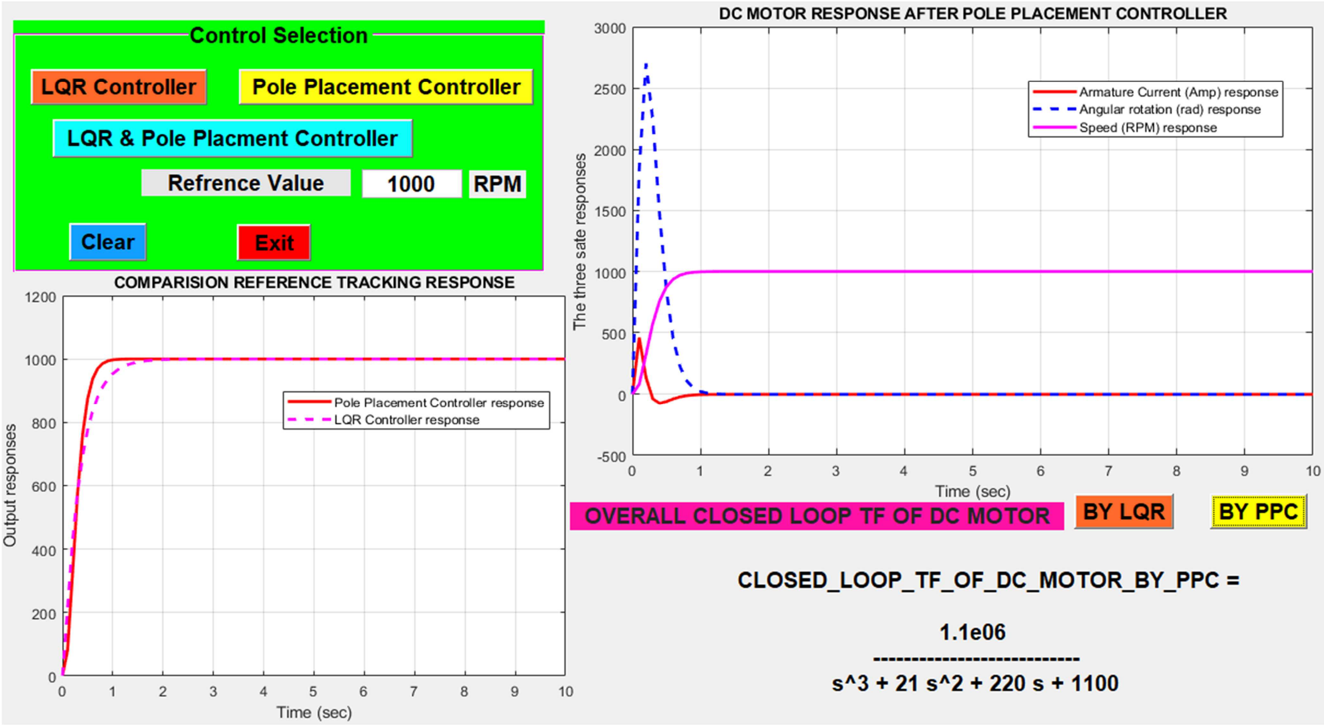

Figure 10. *DC Motor response with a reference speed =1000RPM for case 3 using Pole Placement Controller.*

Case 4: The DC motor response for reference speed =2000RPM with LQR parameters $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 10 \end{bmatrix}, R = 0.1$ & $Desired\ poles\ of\ the\ system\ = [-10, -10, -10]$

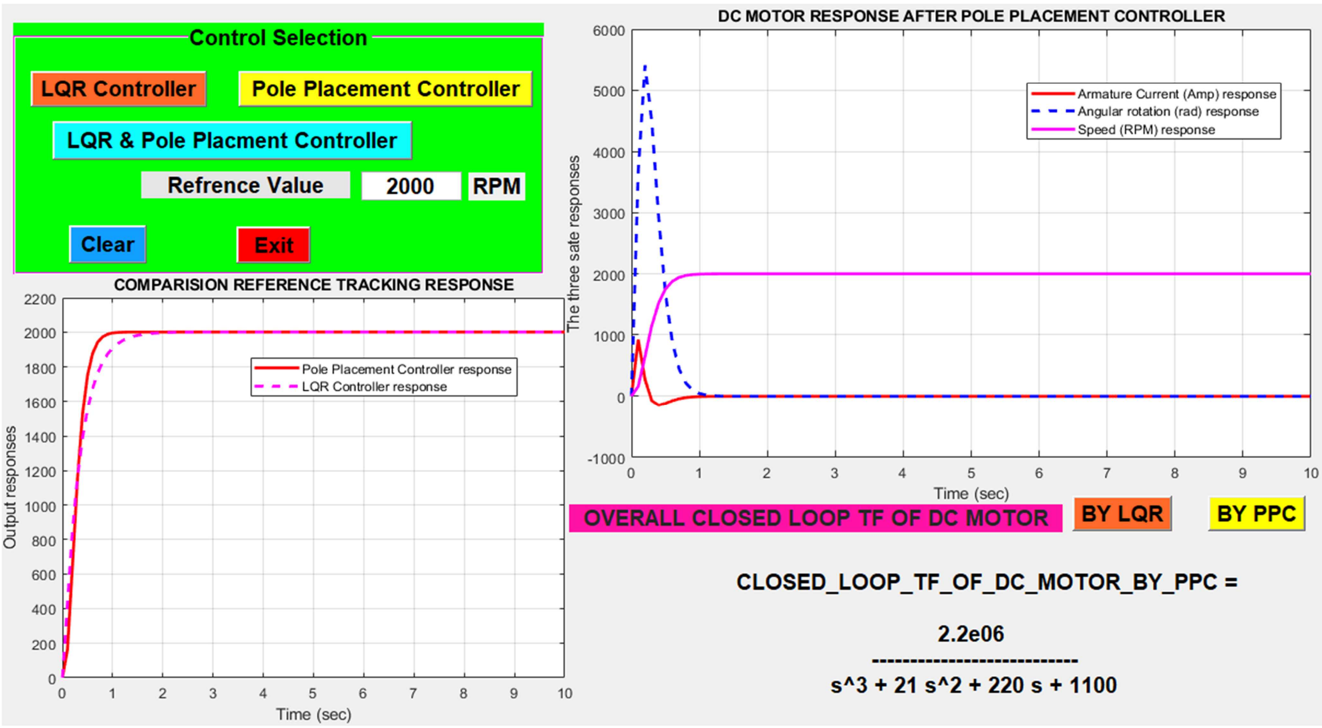

Figure 11. *DC Motor response with a reference speed =2000RPM for case 4 using Pole Placement Controller.*

Case 5: The DC motor response for reference speed =1000RPM with LQR parameters $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 100 \end{bmatrix}, R = 0.1$ & $Desired\ poles\ of\ the\ system\ = [-10, -10, -10]$

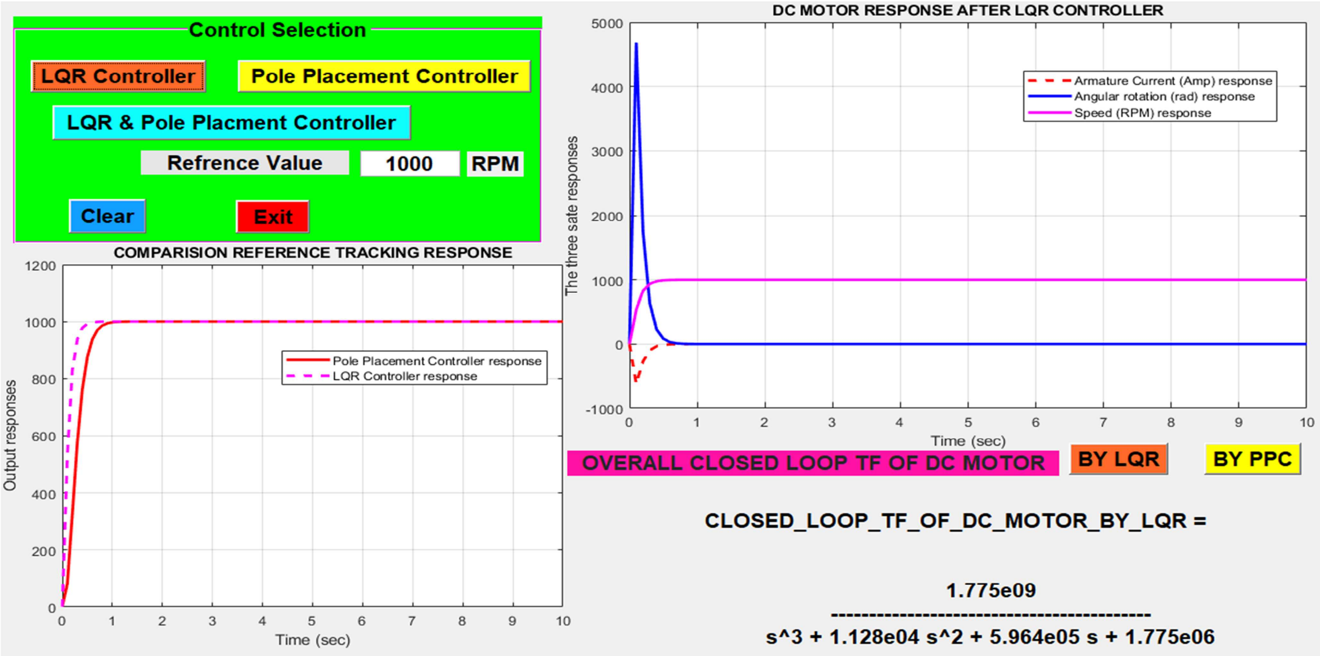

Figure 12. *DC Motor response with a reference speed =1000RPM for case 5 using LQR Controller.*

Case 6: The DC motor response for reference speed =2000RPM with LQR parameters $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 100 \end{bmatrix}, R =$ 0.1 & $Desired\ poles\ of\ the\ system\ = [-10, -10, -10]$

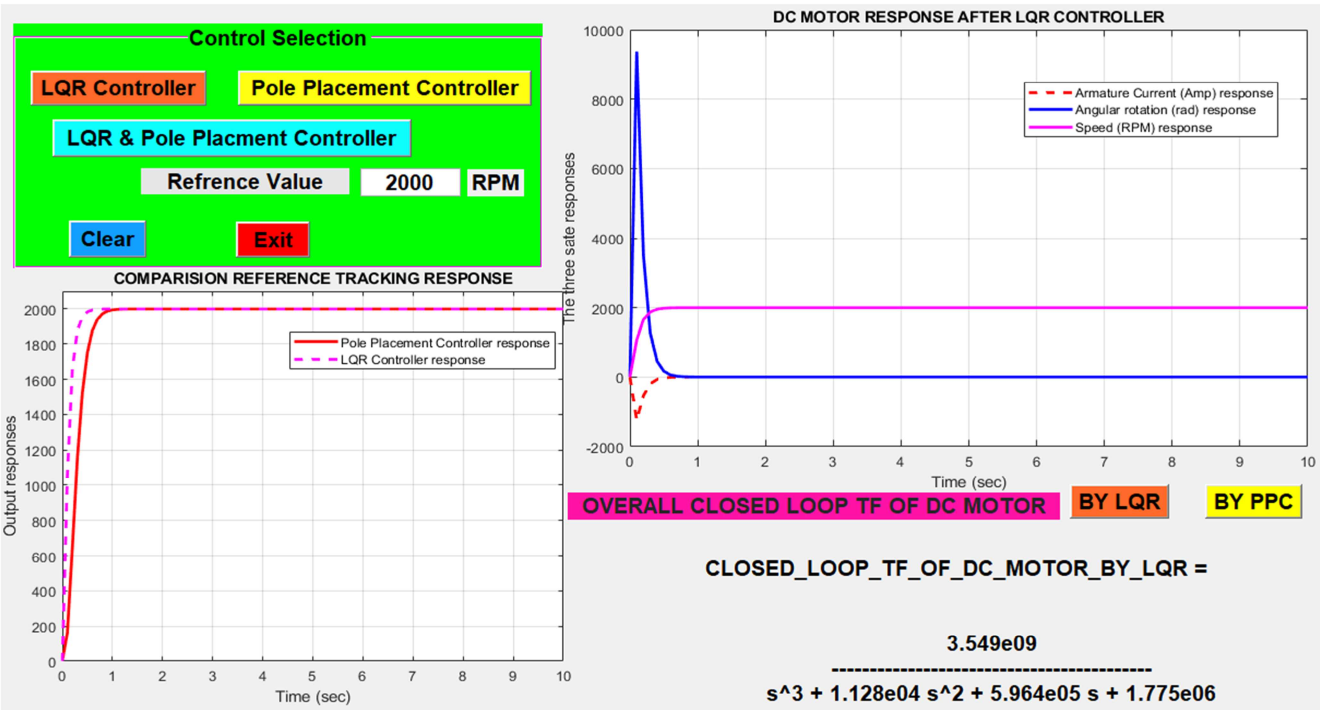

Figure 13. *DC Motor response with a reference speed =2000RPM for case 6 using LQR Controller.*

Generally the simulation result shows that the effectiveness of the simulation result highly depends on the LQR parameters and the desired location of poles for various reference speed of DC motor.

When the location of poles are far from the origin of s plane the simulation result is good compared to the poles near to the origin and when the poles are purely real the performance of the result is better than when poles are the combination of both real and imaginary parts. The simulation result also depends on the Q and R parameters of the LQR controller. When the weighting matrices of speed state is high the performance is very good and when the weighting matrices of the R matrices is low that is 0.1 the simulation result is very good this means that practically we don't worry about the fuel required by the motor. When the weighting matrices of the speed is low the simulation result also low so the performance of the system depends on the parameters of the controller.

Generally the simulation result enhances when the weighting matrices of the Q matrices is high and the location of poles should be far from the origin and the poles should be real part.

7. Conclusion

In this paper, the design of a graphical user interface (GUI) application on MATLAB for comparing the performance of LQR and Pole Placement controllers for DC motor speed control offers a valuable tool for control systems engineers, researchers, and students. By providing an intuitive platform to input system parameters, visualize real-time responses, and analyze performance metrics, the GUI facilitates informed decision-making regarding the selection of the optimal control strategy. The comparison between LQR and Pole Placement controllers allows for a comprehensive evaluation of settling time, overshoot, steady-state error, control effort, and robustness. This GUI application contributes to the advancement of control systems engineering by promoting efficient and accurate control of DC motors.

By empowering users to make informed decisions, this GUI app contributes to the advancement of control systems engineering and promotes efficient and accurate DC motor speed control. The development of a GUI app on MATLAB for comparing LQR and Pole Placement controllers for DC motor speed control will be a valuable tool for control systems engineers, researchers, and students.

The simulation result shown from this paper depends on the parameters of LQR and Pole placement controllers (PPC). When the weighting matrices of the Q matrices is high, the speed response is good and when the roots of the system are real poles with far from the origin the performance of the system has been increased.

References

[1] M. George, "Speed Control of Separately Excited DC Motor," pp. American Journal of Applied Sciences 5 (3): 227-233, 2008.

[2] J. K. F. H. T. B. M. Ruderman, "Optimal State Space Control of DC Motor," pp. The International Federation of Automatic ControlSeoul, Korea, July 6-11, 2008.

[3] A. S. A. a. A. D. ZAGORIANOS, "Matlab GUI Application for Teaching Control Systems," pp. Proceedings of the 6th WSEAS International Conference on ENGINEERING EDUCATION, ISBN: 978-960-474-100-7.

[4] G. P. Satyabrata Sahoo, "Analysis and Comparison of Speed Control of DC Motor using Sliding Mode Control and Linear Quadratic Regulator," pp. IJREE - International Journal of Research in Electrical Engineering, Volume: 02 Issue: 01 2015.

[5] Z. A. O. H. S. H. Saad A. Salman, "Stability and performance evaluation of the speed control of DC motor using state-feedback controller," pp. Indonesian Journal of Electrical Engineering and Computer Science, Vol. 22, No. 3, June 2021.

[6] D. D. Rajkumar dwivedi, PID Conventional Controller and LQR Optimal controller for Speed analysis of DC Motor: A Comparative Study, International Research Journal of Engineering and Technology (IRJET). Volume: 02 Issue: 08 | Nov-2015.

[7] A. S. A. M. Md. Firoz Ansari, Comparative Analysis of Speed Control of DC Motor using Closed Loop Unity Feedback, PID Controller and Linear Quadratic Regulator, IJLTEMAS, Volume IV, Issue III, March 2015.

[8] G. M. A. N. a. S. S. G. L. Yathisha, A Novel Method for the Design of LQR Controllers in Speed Control of DC Motor, IX Control Instrumentation System Conference (CISCON - 2012), 16-17 November 2012.

[9] S. G. Saisudha V., Analysis of speed control of DC motor using LQR method, I J C T A, 9 (15), 2016, pp. 7377-7385.

[10] R. M. A.-M. Hummadi, SIMULATION OF OPTIMAL SPEED CONTROL FOR a DC MOTOR USING LINEAR QUADRATIC REGULATOR (LQR), Journal of Engineering Volume 18, Issue 3, Pages 340-349, March 2012.

[11] Y. A. A. Shiboul, A. S. Dalabeeh and K. M. A. Shehhi, OPTIMAL STATE FEEDBACK CONTROLLER FOR SEPARATELY-EXCITED DC MOTOR, International Journal of Computer Science and Mobile Computing, Vol. 8 Issue. 6, June- 2019, pg. 187-199.

[12] B. Ch. Varaha Narasimha Raja, An Adaptive Analysis of Linear Quadratic Regulator(LQR) to Control the Speed of DC Motor, Proceedings of the IEEE conference on Advances In Communication, Navigation And Computer Networks.

[13] R. S. Vivek Shrivastva1, Performance Analysis of Speed Control of Direct Current (DC) Motor using Traditional Tuning Controller, International Journal of Emerging Technology and Advanced Engineering, Volume 4, Issue 5, May 2014.

[14] A. H. O. Ahmed, Optimal Speed Control for Direct Current Motors Using Linear Quadratic Regulator, Journal of Science and Technology - Engineering and Computer Sciences, Vol. 14, No. 2, December/ 2013.

[15] O. U. N. A. Ishak ERTUGRUL, Speed Control of Dc Motor Based on Linear Quadratic Regulator Method, IJREAT International Journal of Research in Engineering & Advanced Technology, Volume 4, Issue 5, Oct - Nov, 2016.

[16] T. Abut, Modelling and Optimal Control of a DC Motor, International Journal of Engineering Trends and Technology (IJETT) – Volume 32 Number 3- February 2016.

[17] N. R. S. Alfian Ma'arif, Control of DC Motor Using Integral StateFeedback and Comparison with PID: Simulation and Arduino Implementation, Journal of Robotics and Control (JRC) Volume 2, Issue 5, September 2021.

[18] G. M. Q. Q. M. J. Sarah N. Al-Bargothi, Speed control of DC motor using conventional and adaptive PID controllers, Indonesian Journal of Electrical Engineering and Computer Science, Vol. 16, No. 3, December 2019, pp. 1221~1228.

[19] E. S. Addasi, Modelling and Simulation of DC-Motor Electric Drive Control System with Variable Moment of Inertia, ACEEE Int. J. on Electrical and Power Engineering, Vol. 4, No. 1, Feb 201.

[20] R. Mohd Redha, Linear quadratic regulator (LQR) controller design for DC motor speed using matlab application, Faculty of Electrical & Electronic Engineering, Universiti Malaysia Pahang. 2008.

[21] A. Rhif, STABILIZING SLIDING MODE CONTROL DESIGN AND A PPLICATION FOR A DC MOTOR SPEED CONTROL, International Journal of Instrumentation and Control Systems (IJICS) Vol. 2, No. 1, January 2012.

[22] K. R. K. C. V. C. M. Sai Chetana, Comparative Analysis of PID, SMC, SMC with PID Controller for Speed Control of DC Motor, International Journal for Modern Trends in Science and Technology, Vol. 02, Issue 11, 2016, pp. 71-76.

[23] P. K. D. Dohare, Comparison of Performance Measures of Speed Control for a DC Motor using Fuzzy Logic Controller and Optimal LQR Controller, IJSTE - International Journal of Science Technology & Engineering | Volume 3 | Issue 11 | May 2017.

[24] R. R. I. M. R. M. A. Ahmad, Control Strategy of Buck Converter Driven Dc Motor: a Comparative Assessment, Australian Journal of Basic and Applied Sciences, 4(10): 4893-4903, 2010.

[25] D. H. S. &. A. R. K. Maithripala, Implementation of LQR controller for DC motor speed control, In 2015 Moratuwa Engineering Research Conference (MERCon) (pp. 252-257). IEEE. doi: 10.1109/MERCon.2015.7112229.

[26] P. M. M. G. Arnisa Myrtellari, Analysis and Performance of Linear Quadratic Regulator and PSO algorithm in optimal control of DC motor, International Journal of Latest Research in Engineering and Technology (IJLRET), Volume 2 Issue 4, April 2016, pp 88-93.

[27] T.-T. Nguyen, The linear quadratic regular algorithm-based control system of the direct current motor, International Journal of Power Electronics and Drive System (IJPEDS), Vol. 10, No. 2, June 2019, pp. 768-776.

[28] A. N. Gabriel Kost, Linear-quadratic Regulator (LQR) Controlling the Operation of the DC Motor in a Hybrid Wheeled Vehicle, Research on Precision Instrument and Machinery (RPIM) Volume 2 Issue 1, March 2013.

[29] S. M. Y.-K. e. Ghasemi, Speed control of separately excited DC motor using LQR controller, In 2019 IEEE International Conference on Electrical and Electronics Engineering (ICEEE) (pp. 1-6). IEEE. doi: 10.1109/ICEEE2019.8904680.

[30] P. Suhas Yadav, Fuzzy PID Controllers Using Matlab GUI Based for Real Time DC Motor Speed Control, INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY, 3 (4): April, 2014.

[31] G. R. P. Kshay C. Mahakalkar, Compensator Design for Speed Control of DC Motor by Root Locus Approach using MATLAB, International Research Journal of Engineering and Technology (IRJET), Volume: 03 Issue: 01 Jan-2016.

[32] N. K. A.-S. K. K. A. Ali A. Hassan, Comparative Study for DC Motor Speed Control Using PID Controller, International Journal of Engineering and Technology (IJET), Vol 9 No 6 Dec 2017-Jan 2018.