Journal of Electrical, Marine and Its Application Technology **Vol. …...., No. …….**
ISSN xxxxxx **Publication Periode**

Analysis and Implementation of a DC Motor System Based on Arduino-Simulink Matlab Using Linear Quadratic Regulator (LQR) Control

Fadli Hadi Nugroho
Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya
fadli.hadi@student.ppns.ac.id

Abstract

This study presents the comprehensive process of identifying a DC motor system using experimental techniques facilitated by MATLAB's identification tools. Following the acquisition of a mathematical model for the DC motor system, an optimal control technique, specifically the Linear Quadratic Regulator (LQR), is designed to evaluate the step response of the system and enhance its dynamic performance. In this research, a DC motor identification module integrated with Arduino is developed to simplify and streamline the modeling process of DC motors, adopting first-order and second-order model approximations. This module acts as a bridge between Arduino hardware and MATLAB's Simulink environment, enabling seamless input-output data acquisition for system identification purposes. The identification process resulted in a DC motor model constructed using a second-order Auto Regressive with Xogenous inputs (ARX) structure, which was subsequently used as the basis for the LQR control design. The LQR control technique was implemented by computing the Q matrix elements through the multiplication of the system's transpose C matrix with its original C matrix, while the R matrix parameter was experimentally tuned to a value of 0.000001 to achieve optimal balance between system performance and control effort. Comparative analysis demonstrated that the LQR control method significantly improved the system's response, achieving a time constant of 0.02 seconds, which outperformed the conventional PID controller in terms of responsiveness and stability.

Keywords: Identification system, DC Motor, LQR.

1. Introduction

To understand and analyze the characteristics of a system, it is essential to conduct system identification, which involves creating a mathematical model based on the behavior and properties of its components (Wang et al., 2015). Through the identification process, a transfer function can be derived, enabling an evaluation of the system's response to various inputs. By understanding the system's behavior through its transfer function, appropriate actions or treatments can be devised to ensure that the system behaves as desired. System identification is fundamentally an experimental approach to determining the dynamic model of a physical system.

A system model is typically built using observed data (Ljung, 2002). System identification is a critical step in scientific research, often serving as the initial phase of any comprehensive system analysis (Shakouri & Radmanesh, 2009). However, obtaining a reliable model is a non-trivial process, requiring adherence to established methodologies. There are two primary approaches to obtaining a mathematical model of a physical system: analytical methods and experimental techniques.

Several experimental techniques exist for obtaining the model of a DC motor system. One common approach involves observing the input and output data of the motor under controlled conditions (Tang et al., 2017). Another approach leverages artificial intelligence algorithms, such as recurrent neural networks (RNN), to develop dynamic models based on minimizing the error during the learning process, where the motor's parameters are known (Ismeal et al., 2014). For example, prior research has utilized back electromotive force (EMF) as an input variable and the rotational speed as the output variable for system identification (Kamdar et al., 2015). This relationship between input and output can then be evaluated using MATLAB's system identification toolbox.

A DC motor often exhibits nonlinear behavior, especially when subjected to load variations. Conventional controllers, such as PID controllers, are widely used because they perform effectively in controlling linear systems (Wang & Yang, 2016; Viola et al., 2017; Shanmugasundram et al., 2014). For example, prior studies have implemented PID controllers for induction motor control using field-oriented control (FOC) techniques to improve torque control signals (Ellis, 2004; Ardana, 2013). However, for more complex systems or those requiring enhanced performance, optimal control techniques like the Linear Quadratic Regulator (LQR) have been employed by researchers to achieve superior control performance (Haron, 2013; Srivastava & Pandit, 2015).

This study focuses on a permanent magnet DC motor as the plant to be identified and controlled using the optimal LQR control technique. A black-box identification approach is employed (Ljung, 1999), wherein the motor system's input-output relationship is analyzed to derive a suitable mathematical model. Additionally, a

DOI xxxxxx

novel identification module for the DC motor is developed using Arduino hardware integrated with MATLAB-Simulink, enabling efficient data acquisition and model development.

2. Material and methods

2.1. Methods

In control systems, the process of system identification can generally be described through a structured framework, as illustrated in Figure 1. System identification typically involves four primary steps:

a) Availability of input-output data: Data from the plant to be identified must be collected, forming the basis of the identification process.
b) Model structure selection: The appropriate model structure must be determined, considering the system's dynamics and the desired accuracy.
c) Parameter estimation: Parameters of the selected model structure are estimated based on the input-output data using optimization or curve-fitting techniques.
d) Model validation: The identified model is validated to ensure that the structure and parameter values accurately represent the system's dynamics.

The inclusion of relevant figures, tables, and equations to support this process provides a clear and systematic approach for readers, aiding in understanding and reproducibility.

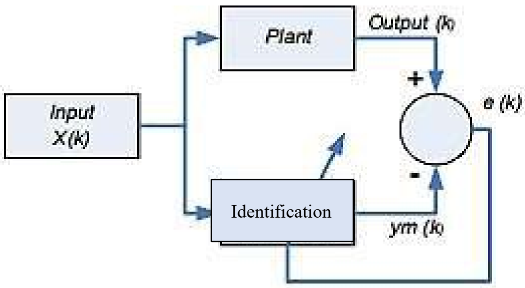

Figure 1. Block Diagram of Identification

In this study, the identification process for a DC motor system is conducted using an open-loop configuration facilitated by Arduino hardware interfaced with a personal computer (PC) running MATLAB-Simulink. The identification method employed is the static identification approach, which is widely used due to its simplicity and effectiveness in obtaining basic system models.

The open-loop configuration is implemented by applying a step input to the motor and observing its output response. This approach allows for the isolation of the system's inherent characteristics without the influence of feedback dynamics. The static identification process is particularly well-suited for systems where linear approximations can provide valuable insights into the system's behavior under specific conditions.

2.2. System Characteristics

System characteristics refer to the unique dynamic behavior of a system, often described as its performance specifications. These characteristics are observed as the system's output response to a given input signal or test signal. The output response provides critical insights into the system's behavior and is classified into two main types: time response characteristics and frequency response characteristics. In this research, the focus is placed on observing the time response characteristics of the DC motor.

The primary purpose of analyzing the time response characteristics is to evaluate the output response of the system as it evolves over time. Generally, the performance specifications of a time response can be divided into two observation phases:

a) Transient response specifications: These describe the system's behavior during the transition period before reaching steady state, including parameters such as rise time, settling time, and overshoot.
b) Steady-state response specifications: These refer to the behavior of the system once it has reached equilibrium, focusing on parameters like steady-state error.

In this study, the analysis of system characteristics is further approached using first-order and second-order system models, which are fundamental in understanding dynamic systems' behavior in engineering applications.

2.3. Mathematical Model of a DC Motor

Journal of Electrical, Marine and Its Application Technology **Vol. …...., No. …….**
ISSN xxxxxx **Publication Periode**

The speed regulation of a DC motor, particularly one using permanent magnets for field excitation, can be achieved by controlling the voltage applied to the armature winding (Yu & Hwang, 2004). Since the magnetic field is generated by a permanent magnet, its field strength remains constant. The circuit diagram representing the configuration of a DC motor is illustrated

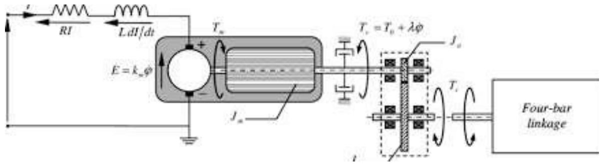

Figure 2. configuration of a DC motor

For the purpose of deriving an analytical model of the DC motor, the transfer function of the system is obtained by analyzing the motor's electrical and mechanical dynamics. This transfer function forms the foundation for understanding the motor's behavior and its interaction with various control strategies.

$$\frac{\Omega(s)}{Ea(s)} = \frac{K_{TM}}{(JRa)s + RaB + K_{TM}\,Kg}$$

2.4. Optimal Control Using Linear Quadratic Regulator (LQR)

The Linear Quadratic Regulator (LQR) is an optimal control strategy designed to drive the system states to a desired final value, typically zero, while minimizing a defined cost function. This cost function balances the trade-off between control effort and system performance, ensuring both stability and efficiency in the system's dynamic response. The primary goal of LQR is to determine the optimal state feedback gain (K) (Zadeh, 1956), which directly influences the control input to achieve the desired system behavior. Below is the block diagram of LQR Configuration.

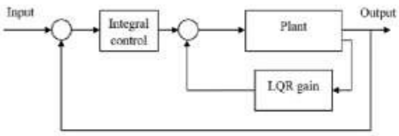

Figure 3. configuration of a LQR

2.5. Identification Motor DC System

System Identification (SID) is an advanced tool integrated within MATLAB (Mathworks Inc.), designed for the identification, simulation, and analysis of dynamic systems. Utilizing a Graphical User Interface (GUI), SID facilitates the process of system identification by allowing researchers to model and analyze the behavior of complex systems through a user-friendly platform. This tool is essential in obtaining accurate mathematical models that reflect the real-world performance of systems(Nugraha et al., 2024).

In the context of this study, a DC motor identification and control module based on Arduino has been successfully developed and integrated with Simulink. This integration enables seamless data acquisition and system identification of the DC motor, laying the foundation for the creation of a robust mathematical model(Nugraha, 2022). The developed module facilitates a comprehensive analysis of the motor's dynamics, ensuring that the resulting model closely aligns with the system's real behavior.

The process begins by collecting input-output data from the DC motor using the Arduino platform, which is then fed into the Simulink environment for further analysis. The Simulink toolbox plays a crucial role in the system identification process, enabling the conversion of experimental data into mathematical models. This procedure involves estimating system parameters that define the motor's behavior. After the initial identification, the transfer function of the DC motor is derived based on the system's response. The accuracy of the model is validated by comparing the theoretical transfer function with the actual system response from the plant. This verification process ensures that the identified model represents the true dynamics of the motor, which is crucial for implementing precise control algorithms such as Linear Quadratic Regulator (LQR).

Table 1. System models DC Motor

DOI xxxxxx

First-order system models	$\frac{0,4748}{s+1.989}$
Second-order system models	$\frac{9.359}{s^2+21,36s+39,21}$

3. Results and discussion

3.1. Optimal Control Using Linear Quadratic Regulator (LQR) on a DC Motor System

Before applying the Linear Quadratic Regulator (LQR) for optimal control of the DC motor system, it is essential to first analyze the system in an open-loop configuration. This step involves deriving the transfer function of the system and subsequently converting it into a state-space model. The process of identifying and validating the system's dynamics is crucial for the effective implementation of LQR, which aims to optimize system performance by minimizing a cost function and stabilizing the system's state. The identification of the DC motor system was performed using two different modeling approaches: a first-order model and a second-order model. Both approaches were tested by applying a step input signal and analyzing the system's response. The results were compared to assess the effectiveness of each approach in capturing the motor's dynamic behavior.

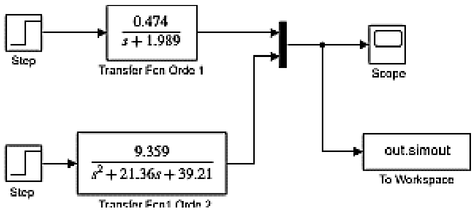

Figure 4. the Simulink response of the DC motor system with a step input signal

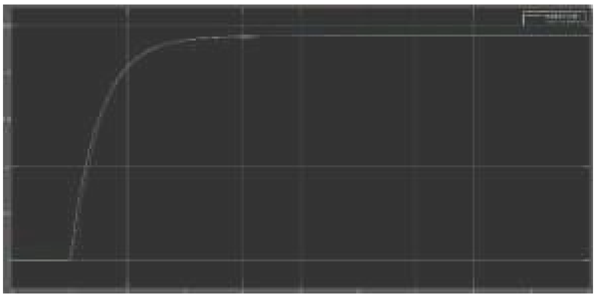

Figure 5. comparison of the system responses from the first-order and second-order models

The next step is to use Matlab, changing the model of the transfer form function into state space form with using the command "[A,B,C,D] = tf2ss(num,den)". The result of the conversion into a form state space is in Table 2.

Table 2. conversion into a form state space

Transfer function model	State Space model
$\frac{0,4748}{s+1.989}$ First-order system models	A = -1.989 B = 1 C = 0,4780 D = 0
$\frac{9.359}{s^2+21,36s+39,21}$ Second-order system models	A = $\begin{bmatrix} -21,36 & -39,21 \\ 1 & 0 \end{bmatrix}$ B = $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$

	$C = \begin{bmatrix} 0 & 9{,}359 \end{bmatrix}$ D = 0

Simulink block modeling in shape of state space is presented in Fig 6

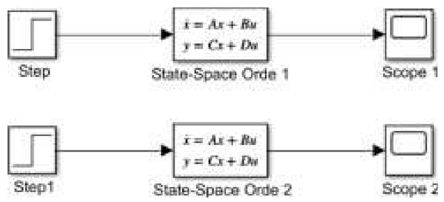

Figure 6. Simulink block modeling in shape of state space

Table 3. Matrix element K

State Space model	Matrix element K
A = -1.989 B = 1 C = 0,4780 D = 0	K = 472.0152
$A = \begin{bmatrix} -21{,}36 & -39{,}21 \\ 1 & 0 \end{bmatrix}$ $B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ $C = \begin{bmatrix} 0 & 9{,}359 \end{bmatrix}$ D = 0	$K = \begin{bmatrix} 116.8 \\ 9319.9 \end{bmatrix}$

Program listing on m-file Matlab to search for Matrix K elements in second order model approach using LQR.

```
%transfer function sistem
pendekatan orde dua
num2 = 9.359;
den2= [1 21.36 39.21];
G=tf(num2,den2)
%step respons sistem pendekatan
orde dua
figure(1)
step(G)
%konversi kedalam model state space
[A,B,C,D] = tf2ss(num2,den2);
modelMotor=ss(A,B,C,D);
modelMotor=tf(modelMotor)
%pembobotan Matriks Q dan R
7
R=0.000001;
Q=transpose(C)*C;
%mencari element Matriks K dengan
LQR
K=lqr(A,B,Q,R)
sys=ss(A,B,C,D);
```

DOI xxxxxx


```
Af=A-B*K;
T=ss(Af,B,C,D);
T=tf(T)
%step respons sistem setelah umpan
balik Matriks K dengan LQR
figure(3)
step(T)
```

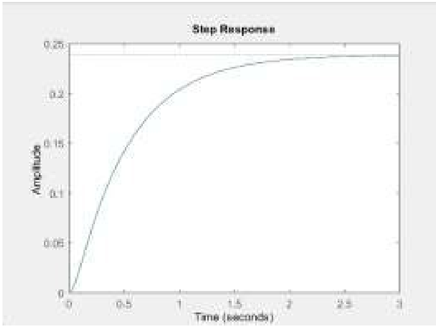

Figure 7. Step response of the DC Motor system is a second order approach

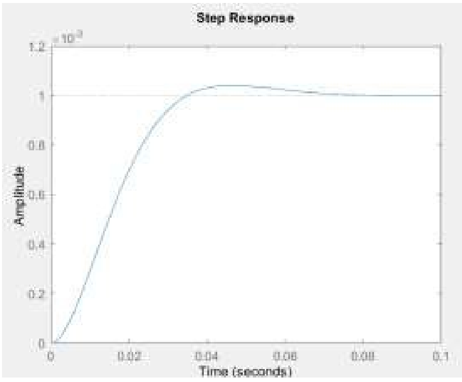

Figure 8. Step response of the DC Motor system is a second order approach after K Matrix feedback with LQR.

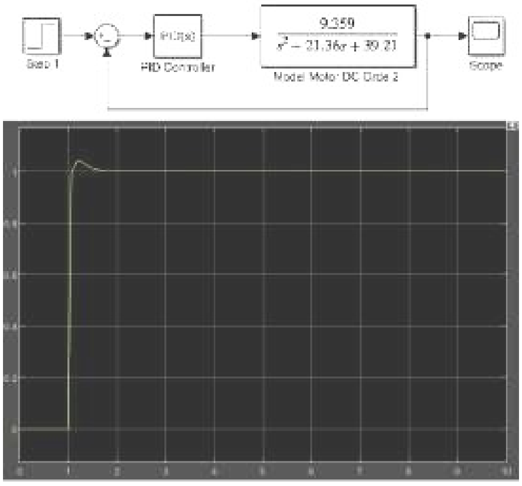

Figure 9. Step response system with PID control on a new order approximation system with parameters Kp = 81.76, Ki = 364.98 and Kd = 4.04.

Based on the analysis of the step response, it was observed that the second-order model of the system in the open-loop condition, without any feedback, failed to reach a steady-state condition upon receiving a step input signal. The system's response in this open-loop configuration showed a delay in settling to the steady state, which is typical for systems that do not incorporate feedback control mechanisms.

DOI xxxxxx

In contrast, when the system was closed-loop with LQR control, significant improvements in performance were observed. Specifically, using LQR with feedback gains of k1 = 116.8 and k2 = 9319.9, the system's time constant (τ) was achieved when the response reached 63.2% of the steady-state value in approximately 0.03 seconds. This response time indicates a much faster convergence to the steady state compared to the open-loop configuration, demonstrating the effectiveness of LQR control in optimizing system dynamics.

To further evaluate the performance of the LQR controller, a comparison with PID control was made. The PID controller, with proportional gain (Kp) of 81.76, integral gain (Ki) of 364.98, and derivative gain (Kd) of 4.04, was implemented as shown in Figure 9. The PID-controlled system exhibited a settling time of approximately 0.05 seconds. This result demonstrates that the LQR control is more optimal, reducing the response time by approximately 0.02 seconds when compared to PID control.

4. Conclusion

The optimal control technique discussed in this paper is the Linear Quadratic Regulator (LQR), which is widely used for controlling dynamic systems due to its ability to minimize a defined cost function. In the context of the DC motor system analyzed in this study, the Q matrix elements are determined by multiplying the transpose of the system matrix C with the system matrix C itself, ensuring that the system's state weighting reflects its dynamic behavior. Meanwhile, the R matrix elements, which represent the control effort penalty, are experimentally tuned to a value of 0.000001 to achieve the desired system performance.

Based on the experimental results of implementing the LQR control system, it can be concluded that the LQR controller provides a more optimal time constant response (τ) compared to the conventional PID control. Specifically, the LQR control reduces the system's settling time by approximately 0.02 seconds, demonstrating its superior performance in achieving faster response times and better system stability.

Credit authorship contribution statement

Author Name: Conceptualization, Writing – review & editing. **Author Name**: Supervision, Writing – review & editing. **Author Name**: Conceptualization, Supervision, Writing – review & editing.

References

Wang X, Yin T, Chen J, et al. Rapid design of Motor DC speed control system based on Matlab[J]. Applied Mechanics & Materials, 2015, 743:168-171.

L. Ljung, "Prediction error estimation methods", Circ. Syst. Signal Process. 21 (2002) 11–21.

G. H. Shakouri and H. R. Radmanesh, "Identification of a continuous time nonlinear state space model for the extenal power system dynamic equivalent by neural network," Electrical Power and Energy Systems, vol. 31, pp. 334-344, 2009.

Tang, Wei-Jie, Zhen-Tao Liu, and Qian Wang. "Motor DC speed control based on system identification and PID auto tuning." Control Conference (CCC), 2017 36th Chinese. IEEE, 2017.

Ismeal, Godem A., Karol Kyslan, and Viliam Fedák. "Motor DC identification based on Recurrent Neural Networks." Mechatronics- Mechatronika (ME), 2014 16th International Conference on. IEEE, 2014.

Kamdar, Sauyma, Harsidh Brahmbhatt, Tigmanshu Patel, and Manish Thakker. "Sensorless speed control of high speed brushed Motor DC by model identification and validation." In Engineering (NUiCONE), 2015 5th Nirma University International Conference on, pp. 1-6. IEEE, 2015.

Wang, Jun-Sheng, and Guang-Hong Yang. "Data-Driven Output- Feedback Fault-Tolerant Compensation Control for Digital PID Control Systems With Unknown Dynamics." IEEE Transactions on Industrial Electronics 63, no. 11 (2016): 7029-7039.

Viola, J., L. Angel, and J. M. Sebastian. "Design and robust performance evaluation of a fractional order PID controller applied to a Motor DC ." IEEE/CAA Journal of Automatica Sinica 4, no. 2 (2017): 304-314.

Shanmugasundram, R., K. Muhammad Zakariah, and N. Yadaiah. "Implementation and performance analysis of digital controllers for brushless Motor DC drives." IEEE/ASME transactions on mechatronics 19, no. 1 (2014): 213-224.

G. Ellis, Control system design guide : a practical guide. 3rd ed 2004, Amsterdam ; Boston: Elsevier Academic Press.

Nugraha, Anggara Trisna, et al. "Comparison of Buck-Boost Converter with Sepic Converter for Optimization of Wind Power Plant Output Voltage." International Conference on Applied Science and Technology on Engineering Science 2023 (iCAST-ES 2023). Atlantis Press, 2024.

Raka Ardana, I Wayan. Simulasi Sistem Kontroler Pid Untuk Motor Induksi Menggunakan Perangkat Lunak Matlab / Simulink. Majalah Ilmiah Teknologi Elektro, vol. 7, no. 2, May, 2013.

Haron, Hartini Sharninayati. "Linear quadratic regulator (LQR) controller design for DC servo motor." PhD diss., Universiti Tun Hussein Onn Malaysia, 2013.

Srivastava, Saurabh, and V. S. Pandit. "A scheme to control the speed of a Motor DC with time delay using LQR-PID controller." In Industrial Instrumentation and Control (ICIC), 2015 International Conference on, pp. 294-299. IEEE, 2015.

L. Ljung, System Identification Theory for the User, 2nd ed., Prentice Hall, CA: Linkoping University Sweden, 1999.

L. A. Zadeh, “On the Identification Problem,” IEEE Transactions On Circuit Theory, vol. 3, no 4, pp.277-281.1956.

Nugraha, Anggara Trisna. RANCANG BANGUN TEKNOLOGI PEMURNI AIR. Deepublish, 2022.

Yu, Gwo-Ruey, and Rey-Chue Hwang. "Optimal PID speed control of brush less Motor DC s using LQR approach." Systems, Man and Cybernetics, 2004 IEEE International Conference on. Vol. 1. IEEE, 2004.

Peng, Jinzhu, and Rickey Dubay. "Identification and adaptive neural network control of a Motor DC system with dead-zone characteristics." ISA transactions 50.4 (2011): 588-598.

Ogata, Katsuhiko. Modern Control Engineering Third Edition. New Jersey, Prentice Hall, Upper Saddle River. 1997.

DOI xxxxxx