Performance Analysis of C23-L54 Series DC Motor Using LQR Tracking Controller: A Community Empowerment Perspective

* Rachma Prilian Eviningsih[1],Anggara Trisna Nugraha[2]
[1] Electrical Engineering, Electronic Engineering Polytechnic Institute of Surabaya, Indonesia
[2] Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya, Indonesia
*Correspondence author: rachmaevin@pens.ac.id

Abstract: *Technological advancements continue to shape and enhance various aspects of human life, including efforts to address energy challenges in underserved communities. In the context of community empowerment, the integration of efficient and sustainable energy solutions has become critical. This study explores the application of Linear Quadratic Regulator (LQR) in optimizing the performance of three-phase induction motors for community-based energy systems. Using MATLAB and SIMULINK r2018a, the research develops a control model aimed at improving motor efficiency and stability, particularly in settings with limited technical resources.The research adopts state-space modeling as the analytical framework for complex control systems, allowing precise predictions of system behavior by considering internal dynamics. Initial simulations revealed that, without effective controllers, the system exhibited significant oscillations and instability when subjected to an input voltage of 0.5 V. This highlights the necessity of advanced controllers such as LQR to stabilize motor performance. Step signal testing with setpoints of 0.848 (Order 1) and 0.01905 (Order 2) demonstrates the controllers' effectiveness in achieving system stability and operational efficiency. The study underscores the potential of these technologies to empower communities by enhancing the reliability of small-scale energy systems, fostering economic opportunities, and supporting sustainable development. The findings provide a blueprint for deploying scalable energy solutions tailored to the unique needs of rural and underserved areas.*

Keyword*: Community Empowerment, Sustainable Energy Solutions, LQR Controller, Three-Phase Induction Motors, State-Space Modeling*

Introduction

Technological advancements are progressing rapidly, influencing every aspect of life and driving an unprecedented demand for innovative solutions compared to previous decades[1]. This surge has intensified global competition, particularly in the field of automation. Industry players continuously strive to upgrade systems to produce superior products or enhance production speed. One significant development in this context is the use of electric motors, which have become indispensable for advancing industrial capabilities.

Projections indicate that global demand for electric motors will grow by approximately 6.5% annually, with the Asia-Pacific region leading in sales volume. These figures underscore the critical role of electric motors, including DC motors, in improving production speed and quality while supporting industrial needs. To meet growing demands and facilitate human activities, various motor technologies have been developed, such as those used in Computerized Numerical Control (CNC) machines.

Among the types of motors, conventional DC motors are known for their excellent characteristics. However, they have notable drawbacks, including the need for routine maintenance of the commutator, periodic replacement of brushes, and high initial costs[2]. To address these challenges, brushless DC motors have been introduced, offering high efficiency, variable high speeds, and significantly lower maintenance costs [3][4].

This study focuses on designing a speed control system for brushless DC motors using MATLAB. MATLAB serves as a programming platform, graphical interface, and tool for creating block diagrams and simulating the speed control of brushless DC motors with a Linear Quadratic Regulator (LQR) controller. The implementation aims to enhance energy solutions in underserved communities by providing scalable, efficient, and cost-effective motor systems for sustainable development.

Methodology

1. DC Motor
   A DC motor is an electric motor that requires a direct current voltage supply to the field coil to be converted into mechanical motion energy[5][6]. The field coil in a dc motor is called the stator (the non-rotating part) and the armature coil is called the rotor (the rotating part). Direct current motors, as the name suggests, use direct unidirectional current. A DC motor is an electronic device that converts electrical energy into mechanical energy in the form of rotational motion[7]. In DC motors there is an armature with one or more separate coils. Each coil ends in a split ring (commutator)[8]. With the insulator between the commutator, the split ring can act as a double pole switch (double pole, double throw switch). DC motors work based on the Lorentz force principle, which states that when a current-carrying conductor is placed in a magnetic field, a force (known as the Lorentz force) will be created orthogonally between the direction of the magnetic field and the direction of current flow[9]. DC motor rotational speed (N).

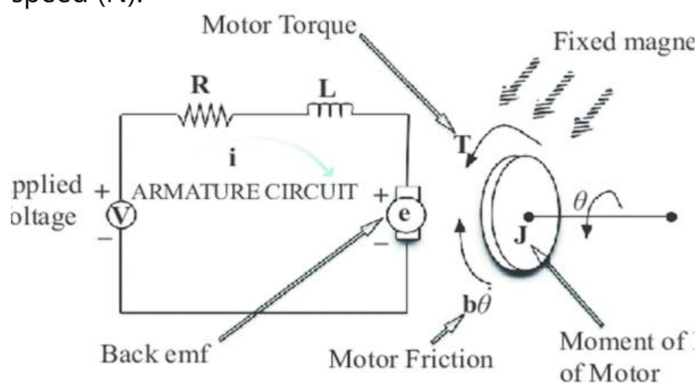


Figure 1. Schematic Diagram DC motor

2. Matlab Simulink
   SIMULINK is a component of MATLAB which plays a role in graphical programming[10]. The main use of SIMULINK is to simulate dynamic systems. The simulation process is carried out using a functional diagram which includes blocks connected with their respective functions equivalently. SIMULINK can be used as a means of modeling, simulating and analyzing dynamic systems using a graphical user interface. SIMULINK consists of several sets of toolboxes that can be used for linear and non-linear system analysis[11]. Some libraries that are often used in control systems include math, sinks, and sources. Before conducting research, the author first identified problems

regarding position control in the SISO, SIMO, MISO and MIMO systems which were vulnerable to interference so that they remained in the desired position.

3. Analytic ordo
   From the mathematical model of a system, the order of a system can be seen from the power of the variable s (in the Laplace transformation). A system is said to be first order if the transfer function has a variable s with the highest power of one. The physical form can be an RC electrical circuit, a thermal system, or other systems [12][13]. The first and second order system models can be written mathematically as follows in equations:

- Ordo 1

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

Keterangan :
C(s) = *Output*
R (s) = *Input*
K = constant
τs = *Rated Torque* (Nm)

- Ordo 2

$$\frac{C_{(s)}}{R_{(s)}} = \frac{Kt.Ke}{(Js+B)(R+Ls)+Kt.Ke}$$

Keterangan :
C(s) = *Output*
R(s) = *Input*
Kt = Torque constant
Ke = Voltage constant
J = rotor *inertia*
B = Friction constant
Ls = *inductance*
R = *Armatur* obstacle

4. State-space
   State-space is an analysis method for a complex control system. This method is used to analyze control systems with one input and one output or called SISO (Single Inputs and Single Outputs). In the state-space model the internal state (x) of the system is used to predict the output (t)[14][19]. so that y no longer depends only on system input but also on the internal state of the system. The input and output system in state-space is shown in Figure 2.

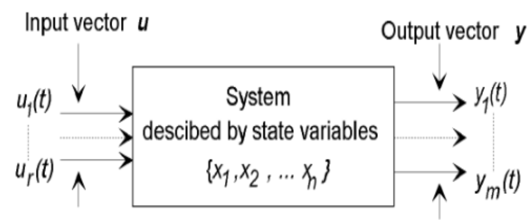


Figure 2.Input and output system inside state space

the state-space model is written as follows (Ogata, 2010):

$$x(t) = A(t)\,x(t) + B(t)\,u(t)$$

$$y(t) = C(t)\,x(t) + D(t)\,u(t)$$

Keterangan :
A(t) = Matrix state
B(t) = Matrix input
C(t) = Matrix output
D(t) = Matrix direct-transmission
u(t) = Input system
x(t) = State system
y(t) = Output System
$\dot{x}(t)$ = Differential

Below is diagram block form state-space

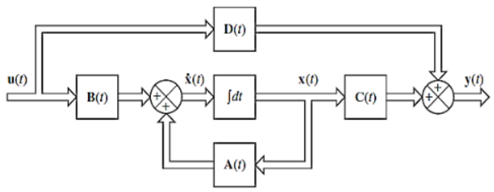


Figure 3. Block diagram state-space

5. Linear Quadratic Regulator (LQR)

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

Keterangan :
J = Cost function
Q = State weighting factor
R = Control variable factor weights
$[\ ]^T$ = Transpose

For LQR controller design, the first step is to choose a weight matrix of Q and R values. The input R is heavier than the state while the weight value of the Q state is more than the input[15][16]. Then the feedback K can be calculated and the closed loop response of the system can be found by simulation[18].
The LQR controller formula is as follows:

$$U = -Kx$$

Where:
K = Gain Feedback

From the state space system equation index and performance index, the optimal K matrix value for the performance index is obtained using the following formula:

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

Where:
P = Variable Algebraic Riccati Equation (ARE)
$[\ ]^{-1}$ = Invers

The Algebraic Riccati Equation (ARE) equation to get the P value is as follows:

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

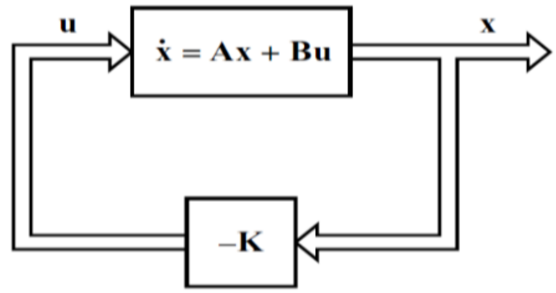


Figure 4. Block diagram LQR

The problems encountered in the control field are not only stabilizing the system, but how the system output follows changes in setpoints or specified references. In this case, if the plant output (x) is desired to be the same as the reference input, the system needs to be designed using setpoint tracking[17][20].

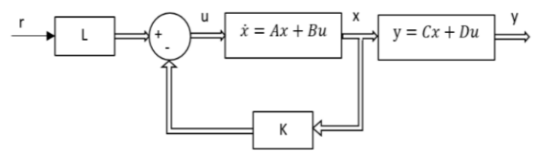
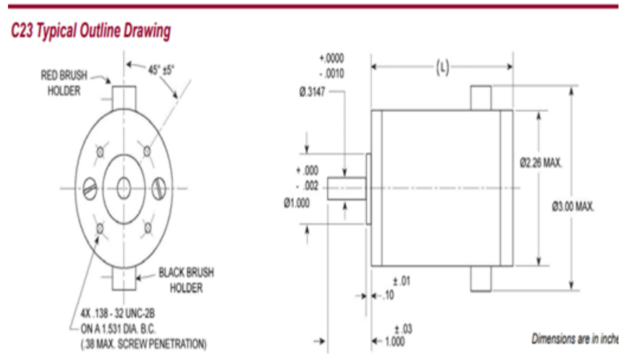


Figure 5. Block diagram control LQR

Results and Discussions

1. DC motor Specification

Search for and study references related to the themes discussed in this final research project, namely regarding mathematical modeling, SISO performance controllers, both from journals, research articles and the C23-L45 DC Motor DataSheet.



Part Number*		
Winding Code**		10
L = Length	inches	
	millimeters	
Peak Torque	oz-in	310.0
	Nm	2.189
Continuous Stall Torque	oz-in	34.0
	Nm	0.240
Rated Terminal Voltage	volts DC	12 -24
Terminal Voltage	volts DC	12
Rated Speed	RPM	1950
	rad/sec	204
Rated Torque	oz-in	25.3
	Nm	0.18
Rated Current	Amps	5.8
Rated Power	Watts	36.5
	Horsepower	0.05
Torque Sensitivity	oz-in/amp	6.06
	Nm/amp	0.0428
Back EMF	volts/KRPM	4.5
	volts/rad/sec	0.0430
Terminal Resistance	ohms	0.54
Terminal Inductance	mH	0.72
Motor Constant	oz-in/watt^1/2	8.2
	Nm/watt	0.058
Rotor Inertia	oz-in-sec²	0.0052
	g-cm²	367.2
Friction Torque	oz-in	5
	Nm	0.04
Thermal Resistance	°C/watt	4.7
Damping Factor	oz-in/KRPM	0.2
	Nm/KRPM	0.001
Weight	oz	46
	g	1304
Electrical Time Constant	millisecond	1.3309
Mech. Time Constant	millisecond	10.80095
Speed/Torque Gradient	rpm/oz-in	-19.83865

Figure 6. DC Motor Parameter

2. Validation Mathematic Model

To test the correctness of the data that has been collected, a simulation is carried out. This simulation uses Matlab SIMULINK r2018a software, the system is given a voltage input of 0.5 V, the response shows that the system is unstable and there are quite large oscillations. So based on simulation testing without a controller, the DC Motor Plant system needs to be equipped with a controller that can eliminate oscillations and stabilize the system using LQR

3. Model of Circuit

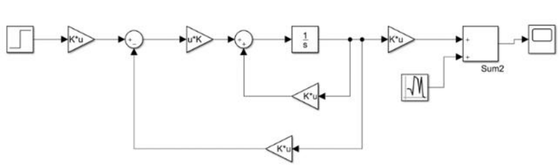


Figure 7. Simulink circuit

4. Result

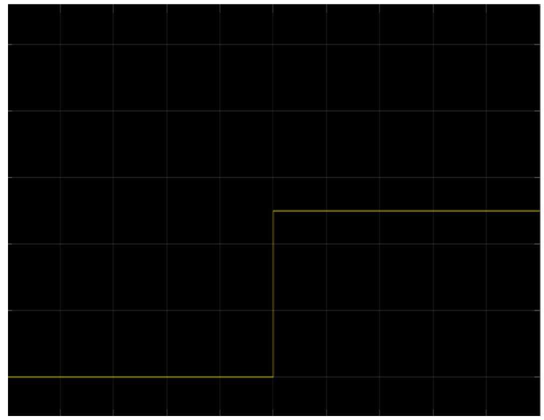


Figure 8. Simulink result LQR without noise

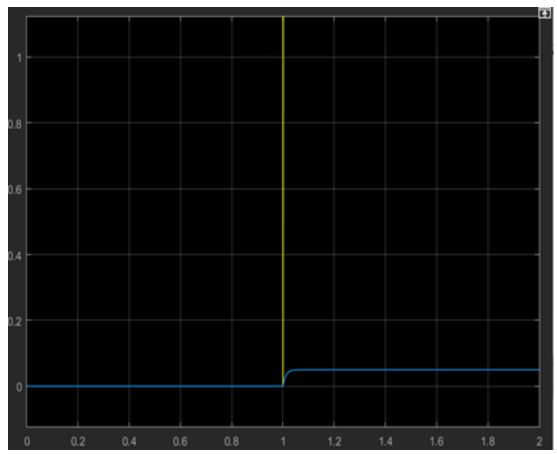


Figure 9. Simulink result LQR Tracking without noise

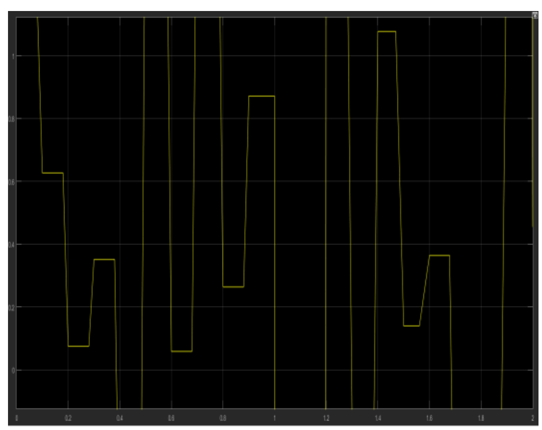


Figure 10. Simulink result LQR with noise

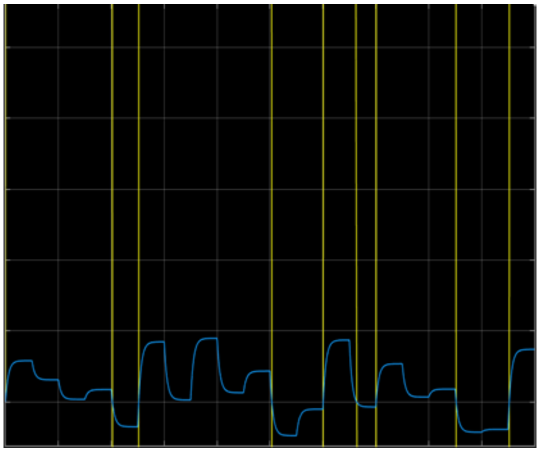


Figure 11. Simulink result LQR tracking with noise

Conclusion

Based on the research conducted, the findings demonstrate that MATLAB software effectively processes real-time system response data. Various tests were performed to evaluate the controller's performance, including setpoint changes, disturbance inputs, and sinusoidal reference signals.

The results indicate that the LQT controller outperforms the LQIT-GA controller in terms of transient response and achieving a smaller Integral of Absolute Error (IAE) during setpoint variation tests. The setpoint changes in the system did not adversely affect the performance of the LQT controller, showcasing its superior adaptability compared to LQIT-GA.

However, in disturbance response testing, neither the LQT nor the LQIT-GA controller was able to return to the predefined setpoint after responding to the disturbances introduced. This highlights a limitation in the performance of both controllers under such conditions.

In sinusoidal reference signal testing, the LQT controller again demonstrated better performance than the LQIT-GA controller, as evidenced by achieving a lower IAE value. This indicates the LQT controller's enhanced ability to handle varying reference signals effectively.

These findings underscore the potential of LQT controllers to enhance energy solutions in community-based applications, particularly in systems requiring precise and efficient motor control. Further improvements are recommended to address disturbance-handling capabilities, ensuring broader applicability in sustainable energy initiatives that aim to empower underserved communities through reliable and efficient technologies.

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