Journal of Marine Electrical and Industrial Technology **Vol. 2, No. 1**
ISSN 3047-7778 **March 2025**

Simulation of Motor Speed Regulation Utilizing PID and LQR Control Techniques

Muhammad Izzul Haj[1], Dimas Eka Saputra[2], Rama Arya Sobhita[3], Anggara Trisna Nugraha[4]
[1] Mechanical Engineering, Chung Yuan Christian University, Taiwan (g11273061@cycu.edu.tw)
[2] Design and Manufacture Engineering, Shipbuilding Institute of Polytechnic Surabaya, Indonesia (deka@student.ppns.ac.id)
[3] Marine Electrical, Shipbuilding Institute of Polytechnic Surabaya, Indonesia (ramasobhita@student.ppns.ac.id)
[4] Marine Electrical, Shipbuilding Institute of Polytechnic Surabaya, Indonesia (anggaranugraha@ppns.ac.id)

Abstract

Ensuring precision and efficiency in motorized industrial systems is crucial, particularly in automated machinery applications. This study explores methods to improve the performance of induction motor control systems using advanced control techniques. The primary objective is to achieve reliable regulation of motor speed and position in industrial environments. Two control strategies—Proportional-Integral-Derivative (PID) and Linear Quadratic Regulator (LQR)—are implemented and analyzed to assess their effectiveness in maintaining stability and operational efficiency. The optimal PID performance was achieved with gains of Kp = 10, Ki = 5, and Kd = 2, resulting in minimal overshoot and effectively reducing both transient and steady-state errors. In the LQR test, minimal overshoot was observed with the Q matrix, resulting in a stable response with a settling time of 2–2.8 seconds. However, increasing the R value slowed the system response due to reduced control effort, emphasizing the trade-off between energy efficiency and speed. In contrast, the well-tuned PID controller provided a smoother response with less overshoot and undershoot, stabilizing within 4 seconds. While LQR offers theoretical advantages, the PID controller delivered superior practical performance in this case, with quicker stabilization and smoother control. This research contributes to the development of intelligent control systems, demonstrating the significance of advanced control strategies in optimizing motor-driven industrial operations.

Keywords: Controller, LQR, PID

1. Introduction

Induction motors are widely used in numerous industrial applications due to their durability, energy efficiency, and reliability (Prastyawan & Nugraha, 2022). In many manufacturing processes, precise motor control is essential for maintaining system stability and ensuring optimal performance. Applications requiring accurate control of motor speed and position, such as conveyor systems, HVAC systems, and factory machinery, rely heavily on induction motors for their versatility and cost-effectiveness.

Controlling induction motors involves regulating parameters such as speed, torque, and position to ensure efficient operation (Nugraha et al. 2022; Anggara et al., 2021). Advanced control methods, such as Proportional-Integral-Derivative (PID) controllers and Linear Quadratic Regulator (LQR) controllers, can be employed to enhance the precision and stability of the motor system (Febrianto & Nugraha, 2021). These strategies help maintain motor performance within desired limits, improving overall system efficiency.

The performance of induction motors in industrial environments is often influenced by various factors, including load fluctuations, disturbances, and mechanical imperfections (Fitzgerald et al., 1996; Priyambodo & Nugraha, 2021). To address these challenges, robust control techniques are required to minimize their effects and maintain motor stability over time. This study aims to evaluate the effectiveness of PID and LQR control strategies in regulating induction motor performance, with a focus on improving system stability and response times.

The research examines the integration of mechanical and electrical components to develop a control system that optimizes the motor's operation. By comparing PID and LQR control methods, the system's behavior under different operating conditions is assessed to determine which approach yields the best performance. Simulation and experimental results will showcase the capabilities of these control strategies, contributing to the advancement of more efficient and reliable motor control systems for industrial applications.

2. Materials and methods

2.1. Linear Quadratic Regulator (LQR)

The Linear Quadratic Regulator (LQR) is a widely recognized method for optimal control in state-space systems. This technique is highly effective in engineering and is frequently applied in fields such as robotics, manufacturing, and automation. One of the key advantages of LQR is its ability to provide an optimal solution to control problems defined within the system's state space. LQR is particularly advantageous in Multi-Input Multi-Output (MIMO) systems, where the complexity of interactions between multiple inputs and outputs demands a sophisticated control approach. Typically, the state-space model of this type of system can be expressed in the following manner.

$$\dot{X} = AX + Bu \tag{1}$$

Fundamentally, the LQR approach aims to determine a control input uuu that minimizes the performance criterion J.

$$J = \int (X^T Q_x + u^T R_a) dt \tag{2}$$

The Linear Quadratic Regulator (LQR) determines the optimal control input law u*. The weighting matrices Q and R impose constraints that shape the minimization of the performance index. The resulting closed-loop optimal control law is given by:

$$u^* = -Kx \tag{3}$$

In this context, K denotes the optimal feedback gain matrix. It is formulated to minimize the performance index by appropriately assigning the closed-loop poles to ensure the desired system dynamics. The computation of K is based on the system matrices A, B, and the weighting matrices Q and R. To determine K, the Algebraic Riccati Equation (ARE) must be solved. The solution to the ARE is the matrix P, which is symmetric and positive definite, and is defined as follows:

$$x = AX - BKx = (A - BK)x \tag{4}$$

A major benefit of LQR lies in its ability to address control problems in MIMO systems. These systems require multiple control inputs to influence multiple outputs simultaneously, which makes control inherently complex. By formulating the system in state-space form, LQR facilitates the systematic design of control laws that account for all interactions efficiently (Dermawan et al. 2023). This makes LQR a critical tool in fields such as robotics, aerospace engineering, and industrial automation, where MIMO systems are common.

A crucial aspect of the LQR method is its reliance on two key parameters: the weight matrices Q and R. These matrices play a vital role in determining the optimal control action for the system. The matrix Q is usually a positive-definite, positive-semidefinite, or real symmetric matrix, while R is typically a positive-definite or real symmetric matrix. These matrices represent the relative importance of the state error (as defined by the Q matrix) and the control effort (as defined by the R matrix). Adjusting these parameters allows for tailoring the control system to meet specific performance goals, such as minimizing state deviations or reducing energy consumption.

In contrast to controllers like the Proportional-Integral-Derivative (PID) controller, which has standardized tuning methods like Ziegler-Nichols or Cohen-Coon, LQR does not have a universally accepted method for directly tuning its weight matrices (Dermawan et al. 2023; Wibowo & Nugraha, 2023). Instead, determining the optimal Q and R matrices often requires experimentation or optimization techniques, which can be computationally demanding but result in more precise control for complex systems (Nugraha, Ramadhan, & Shiddiq, 2022).

2.2. Proportional Integral Derivative (PID)

The Proportional-Integral-Derivative (PID) control system is widely utilized across various engineering fields, especially in automation and instrumentation, due to its simplicity and versatility (Agna et al. 2023; Apriani et al. 2022)

It works by adjusting three key parameters, Proportional (P), Integral (I), and Derivative (D), to optimize a system’s output response to a given input signal (Priyambodo & Nugraha, 2021; Putra et al., 2024). The main advantage of PID control lies in its broad applicability, ranging from simple temperature regulation to more complex motor speed control systems (Realdo, Nugraha, & Misra, 2021). However, its limitations are evident, particularly in systems with high complexity or non-linearity, where advanced control techniques such as Linear Quadratic Regulator (LQR) may offer better performance.

The PID controller's core components play crucial roles in regulating the system's behavior:

1. Proportional (P) Control: The proportional component adjusts the output based on the present error, which is the difference between the desired setpoint and the actual output. The larger the error, the greater the corrective action.
2. Integral (I) Control: This component addresses accumulated past errors by summing them over time, helping to eliminate steady-state errors that might persist despite proportional control action.
3. Derivative (D) Control: The derivative component predicts future errors by examining the rate of change of the error, providing damping to stabilize the system and reduce overshooting.

Each of these components offers specific advantages but can also present challenges when improperly tuned. Effective PID control depends on properly adjusting the P, I, and D parameters for the system at hand. Tuning these parameters is particularly important for dynamic systems, such as motor speed control, to avoid issues like instability, slow responses, or excessive energy consumption (Rasyid, 1999). Proper tuning ensures that the system reacts effectively to inputs, with minimal overshoot or oscillations (Putra & Nugraha, 2021).

In motor speed control applications, PID controllers are frequently employed because they provide smooth and stable regulation. By adjusting the P, I, and D parameters, the PID controller maintains the motor speed at the desired setpoint, compensating for disturbances or changes in load. The feedback loop continuously compares the motor's actual speed with the target and adjusts the input accordingly, ensuring efficient motor operation with minimal fluctuation in speed.

Despite its advantages, PID control may not be the best solution for all types of systems. While it is highly effective in many simple or moderately complex applications, it may struggle with Multi-Input Multi-Output (MIMO) or nonlinear systems, where more advanced strategies like LQR could be more effective. Determining the optimal PID parameters remains essential for achieving optimal system performance, particularly in dynamic environments like motor speed regulation.

2.3. DC Motor

Induction motors are widely used in various industrial applications due to their straightforward design and reliability (Ruddianto et al., 2021). These motors operate on the principle of electromagnetic induction, discovered by Michael Faraday, where a current passing through the stator generates a magnetic field that interacts with the rotor, creating motion. An induction motor typically consists of two primary components: the stator, which generates a rotating magnetic field, and the rotor, which rotates within this field. Induction motors are categorized into single-phase and three-phase types, with three-phase motors being more commonly used in industries because of their higher efficiency and greater capacity to handle larger loads.

The key benefits of induction motors are their simplicity in design and minimal maintenance needs. Unlike synchronous motors, induction motors do not require commutators or brushes, making them more durable and reducing maintenance costs. Additionally, induction motors are energy-efficient over extended operation periods, as they do not require external drive systems. However, a limitation of induction motors is in speed control. Since the speed of an induction motor is directly related to the frequency of the power supply, precise speed control necessitates the use of more advanced control techniques.

Induction motor performance can be optimized through various control methods, including speed and position regulation (Shiddiq, Ramadhan, & Nugraha, 2021). One of the most common methods is the Proportional-Integral-Derivative (PID) controller, which adjusts the error between the setpoint and actual values of the system by applying proportional, integral, and derivative actions. While PID controllers are effective and simple to implement in many cases, they have limitations, particularly in handling external disturbances and system uncertainties, which are often encountered in induction motor applications. As a result, more adaptive and robust control approaches are required for optimal performance.

An alternative advanced control strategy is the Linear Quadratic Regulator (LQR), which is an optimal control method designed for regulating linear dynamic systems. LQR minimizes a cost function that incorporates the energy used by the system and deviations from the desired state. For induction motors, LQR can control the motor's position and speed while considering various external influences that could affect performance. Unlike PID, LQR offers a more stable and efficient solution under non-ideal operating conditions or in complex systems. Research has demonstrated that LQR typically provides superior stability and control efficiency compared to PID in induction motor applications.

Several studies have investigated the application of different control strategies to enhance induction motor performance and efficiency. For instance, comparisons between PID and LQR for controlling three-phase induction motors have shown that LQR delivers better speed control and faster responses to disturbances. Nonetheless, PID remains a popular choice in applications where extreme response times or complex systems are not required. Combining these two techniques in controlling induction motors offers valuable insights for developing more efficient motor control systems for various industrial applications, including manufacturing and HVAC systems.

2.4. Method

A. System Modeling

This tool implements DC motor position control using a DC motor circuit for modeling purposes. The analysis of this system is divided into two main components: the electrical system and the DC motor system. The electrical system is discussed because it plays a crucial role in the operation and behavior of the DC motor. According to Kirchhoff's current law (KCL), the total current entering a junction in a circuit is equal to the total current leaving that junction.

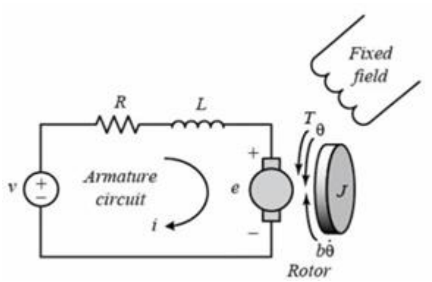

Figure 1. System Model

By applying KCL, we can ensure that the correct amount of current is supplied to the motor, which directly affects its torque and speed. Understanding the electrical system's behavior is vital because it influences the overall dynamics of the DC motor, including its response to control inputs and how efficiently it operates in the system. The relationship between the electrical system and the motor system must be analyzed to design effective controllers and achieve accurate position control.

B. MATLAB Simulink program

```
b = 0.1;
R = 3;
L = 3;
K = 0.1;
J = 0.1;

A =[0 1 1 ; 0 -b/J K/J ; 0 -
K/L -r/L];
B =[0;0;1/L];
C = [1 0 0];
D = 0;

R = 0.01;
Q = [1000 0 0 ; 0 10 0 ; 00
0];
Klqr = lqr(A,B,Q,R);
```

C. Modeled Simulink

- DC Motor Model

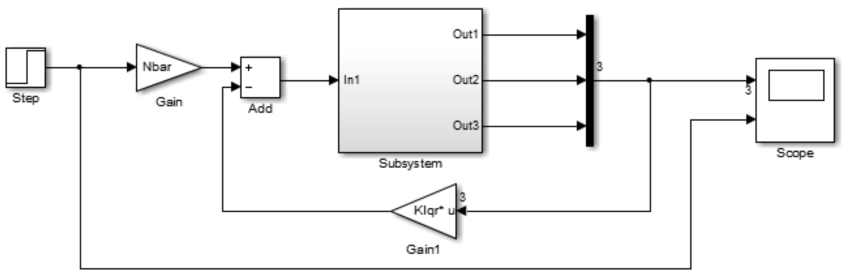

Figure 2. DC Motor Block Diagram.

- Subsystem of DC motor

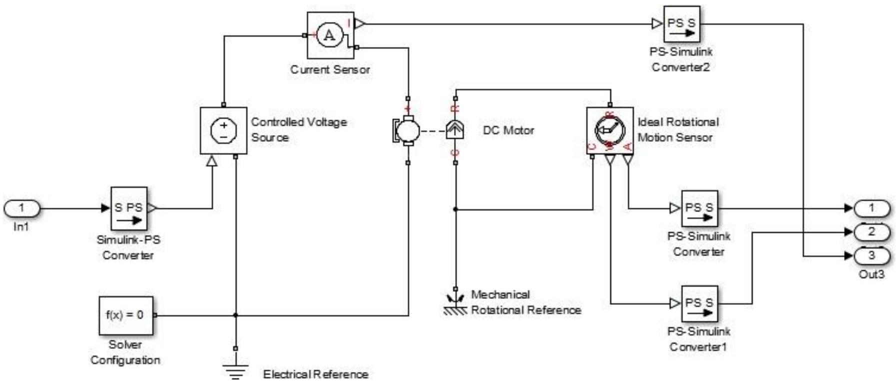

Figure 3. Subsystem of DC Motor.

3. Results and discussion

3.1. LQR Control

The input applied to the system generated a response that is captured in Figure 4. By comparing the graph of the system's response to the input, we observed the system's performance. The system exhibited a relatively fast response, reaching a stable state in under 2 seconds. This indicated that the control system was effective in quickly stabilizing the motor position, demonstrating its efficiency in adjusting to the desired setpoint. The ability to achieve stability so quickly suggested that the system's design and control strategy were well-tuned for rapid response and minimal oscillations.

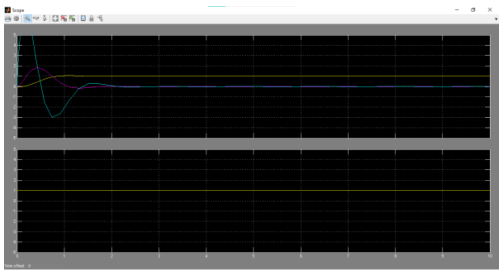

Figure 4. LQR Control

Then, we experimented with varying the values of the Q and R matrices to implement the Linear Quadratic Regulator (LQR) control strategy. For the first variation, the Q matrix was set to: [10 0 0; 0 10 0; 0 0 10]. After applying this variation, the resulting system response was captured in the graph. From Figure 5, we observed that the system response had become slower compared to the previous response. The simulation results showed that a stable system response with a steady-state time of about 2–3 seconds and a very small overshoot. The control signal in the second subplot was also almost identical for all variations, with a final value of about 2–2.5 units This suggested that the increased values in the Q matrix may have caused the system to prioritize minimizing state errors more aggressively, which could result in a slower but more stable approach to reaching the desired setpoint.

The Q matrix influenced the weighting of state errors, and in this case, the higher values in the diagonal elements of the Q matrix likely contribute to a more cautious or slower response in order to reduce state deviations more effectively.

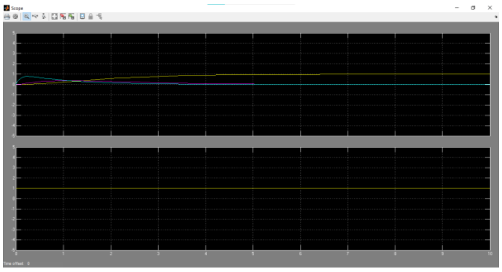

Figure 5. The first variation of the Q matrix

For the second variation of the Q matrix on Figure 6, we set the values as follows: [10 0 0; 0 100 0; 0 0 10]. Upon applying this variation, the system's response graph showed a significant deterioration in performance. Unlike the previous response, this variation caused the system to struggle in reaching stability, with the response not settling even after 10 seconds. This suggested that the increased value in the second row and second column of the Q matrix, which corresponded to the state error associated with the second state variable, might have introduced an overemphasis on minimizing error for that particular state.

As a result, in the first subplot, the three curves showed almost identical behavior with a steady-state time of about 2–2.8 seconds and minimal overshoot. All curves reach the same final value, indicating the stability of the system concerning the reference. The control signal in the second subplot was also consistent among the variations of Q, with final values ranging from 2 to 2.5 units. This emphasized that the Q matrix adjustment has an effect, but it was small, so further adjustment was needed.

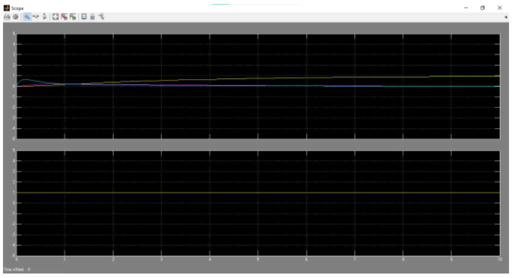

Figure 6. The second variation of the Q matrix

Then, for the next, we did a variation of the value of R where the value of R was changed to 1. After applying, the resulting system response was captured in the graph. From this graph, we observed that the system response was slower compared to when the R value was set to 0.01. The increase in the value of R generally represented a higher weighting on the control effort, meaning that the system was now putting more emphasis on minimizing the control input (or effort) rather than focusing on the state error.

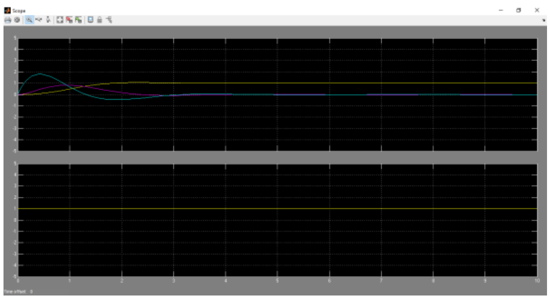

Figure 7. Variation matrix R

As a result of Figure 7, the control system became less aggressive in adjusting to the desired setpoint, leading to a slower response. While the system might show a more energy-efficient performance due to the reduced control effort, it also took longer to reach the stable state compared to when R was smaller. This highlighted the trade-off between control effort and speed of response, with a higher R value typically leading to more conservative control actions and, consequently, slower system response.

3.2. PID Control

In PID control, determining the optimal values for the proportional (Kp), integral (Ki), and derivative (Kd) parameters often involves a trial-and-error method. For the first data collection on figure 8, the values of Kp = 15, Ki = 10, and Kd = 2 were used. The resulting graph of the system's response showed that while the system did eventually reach the setpoint, it continued to exhibit oscillations and undershooting for about 1.3 seconds. This indicated that, although the motor reached the desired setpoint, it did not stabilize smoothly. The presence of oscillations and undershoots suggested that the system remained unstable and that the PID parameters required further adjustment. The instability could be due to the proportional term (Kp) being too large, causing the system to overcorrect and oscillate around the setpoint. Similarly, the integral term (Ki) might be contributing to the issue by aggressively correcting past errors, while the derivative term (Kd) might not be sufficient to dampen the oscillations. As a result, further fine-tuning of these parameters was needed to achieve a more stable and smoother response, reducing both overshoot and oscillations.

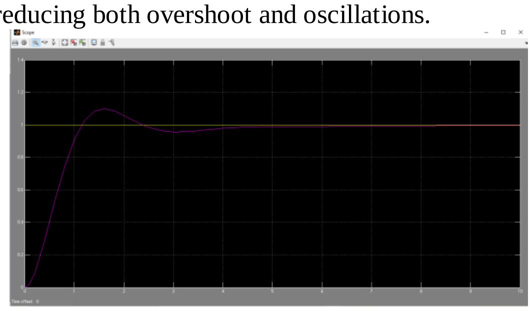

Figure 8. Kp = 15, Ki = 10, Kd = 2

In the second experiment on Figure 9, the PID control parameters were set to Kp = 10, Ki = 5, and Kd = 2. The resulting response graph indicated that the system successfully reached the setpoint without producing any oscillations or undershoots. Additionally, the system stabilized smoothly and achieved steady-state operation within the 4th second. This demonstrated that the adjustments to the PID parameters had improved the system's stability and responsiveness. The absence of oscillations and the quicker stabilization suggested that the control parameters were now well-tuned, allowing for effective and efficient motor control.

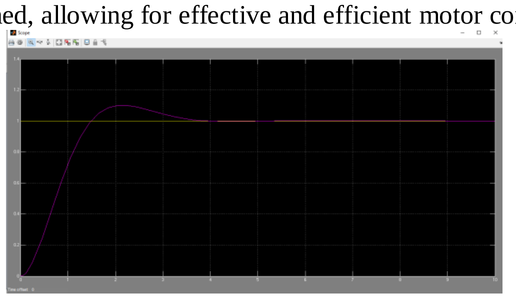

Figure 9. Kp = 10, Ki = 5, Kd = 2

In the third experiment on Figure 10, the PID control parameters were set to Kp = 6, Ki = 4, and Kd = 2. The resulting response graph shows that the system successfully reaches the setpoint without any oscillations or undershoots. However, unlike the previous experiment, the system took a bit longer to stabilize, reaching steady-state operation at around the 7th second. Despite the longer settling time, the absence of oscillations and overshooting indicated that the control parameters are more balanced, providing a stable response. This suggests that the PID controller was effectively managing the motor control, but a further adjustment of the parameters could be made to reduce the time required for stabilization.

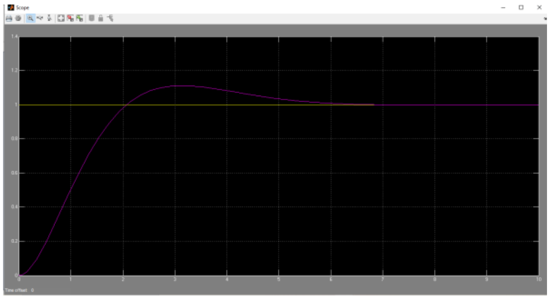

Figure 10. Kp = 6, Ki = 4, Kd = 2

4. Conclusion

Based on the experimental results, the following conclusions can be made:

1. System Stability with LQR and PID Control: Both LQR and PID controllers ensured stable system performance, minimizing overshoot, settling time, and steady-state error. Both methods effectively controlled the system with minimal fluctuations, maintaining desired behavior under varying conditions.

2. Optimal Performance with PID Control: The best PID performance was achieved with Kp = 10, Ki = 5, and Kd = 2, offering a good balance between responsiveness and minimal overshoot about 1.5 second, effectively reducing both transient and steady-state errors in 4 second.

3. Comparison of Control Strategies: In the LQR test, minimal overshoot was observed with the Q matrix, resulting in a stable response and a settling time of 2–2.8 seconds. However, with a higher R value, the system responded more slowly due to reduced control effort, emphasizing the trade-off between energy efficiency and speed. In contrast, the PID controller with Kp = 10, Ki = 5, and Kd = 2 yielded a smoother response with less overshoot and undershoot than LQR, stabilizing within 4 seconds. While LQR offers theoretical advantages, the well-tuned PID provided superior practical performance in this case.

References

Anggara Trisna Nugraha, et al., 2021. Solutions for Growing the Power Factor Prevent a Reactive. Electricity Tariff and Decrease in Warmth on Installation with Bank Capacitors. Applied Technology and Computing Science Journal 4.1: 35-46.

Astrom K. Hagglund, 1995. PID Controllers: Theory, Design, and Tuning. Research Triangle Park, Instrument Society.

Febrianto, Roby, and Anggara Trisna Nugraha, 2021. PERANCANGAN BATTERY CHARGER MENGGUNAKAN ENERGI PENGGERAK MIKRO HIDRO BERBASIS ARDUINO UNO. Seminar MASTER PPNS. Vol. 6. No. 1.

Fitzgerald, A.E., Charles Kingsley Jr., Stephen D. Umans, 1996. Mesin-mesin Listrik, Edisi keempat, terjemahan Djoko Achyanto Msc. EE. Erlangga.

Nugraha, Anggara Trisna, Rachma Prilian Eviningsih, 2022. Konsep Dasar Elektronika Daya. Deepublish.

Dermawan, Deny, et al, 2023. Pengontrol Kecepatan Respon Motor dengan PID dan LQR. Seminar MASTER PPNS. Vol. 8. No. 1.

Putra, Z. M. A., Nugraha, A. T., Widiarti, Y., Safaroz, W., Sobhita, R. A, 2024. Design of Unipolar Pure Sine Wave Inverter with SPWM Method Based on ESP32 Microcontroller as a Support of The EBT System on Ship. In E3S web of conferences (Vol. 473, p. 01008). EDP Sciences.

Dermawan, Deny, et al, 2023. Kendali Kecepatan Motor Dengan Kontrol PID Menggunakan Metode Metaheuristik." Seminar MASTER PPNS. Vol. 8. No. 1.

Wibowo, Muhammad Ferdiansyah, Anggara Trisna Nugraha, 2023. PERENCANAAN SISTEM PROPULSI ELEKTRIK PADA FAST PATROL BOAT 28 METER. Proceedings Conference on Marine Engineering and its Application. Vol. 6. No. 1.

Agna, Diego Ilham Yoga, Rama Arya Sobhita, Anggara Trisna Nugraha, 2023. Penyearah Gelombang Penuh 3 Fasa Tak Terkendali dari Generator Kapal AC 3 Fasa. Seminar MASTER PPNS. Vol. 8. No. 1.

Apriani, Mirna, et al, 2022. Coastal Community Empowerment Recovery of cockle shell waste into eco-friendly artificial reefs in Mutiara Beach, Trenggalek, Indonesia. Frontiers in Community Service and Empowerment 1.4.

Prastyawan, Rikat Eka, Anggara Trisna Nugraha, 2022. PENERAPAN TEKNOLOGI INFORMASI UNTUK PEMBELAJARAN TEST OF ENGLISH FOR INTERNATIONAL COMMUNICATION PREPARATION. Jurnal Cakrawala Maritim 5.1: 4-8.

Nugraha, Anggara Trisna, Moch Fadhil Ramadhan, and Muhammad Jafar Shiddiq, 2022. DISTRIBUTED PANEL-BASED FIRE ALARM DESIGN. JEEMECS (Journal of Electrical Engineering, Mechatronic and Computer Science) 5.1.

Priyambodo, Dadang, and Anggara Trisna Nugraha, 2021. Design and Build a Photovoltaic and Vertical Savonius Turbine Power Plant as an Alternative Power Supply to Help Save Energy in Skyscrapers." Journal of Electronics, Electromedical Engineering, and Medical Informatics 3.1: 57-63.

Putra, Muhammad Dwi Hari, and Anggara Trisna Nugraha, 2021. RANCANG BANGUN BATTERY CHARGER DENGAN SISTEM CONSTANT VOLTAGE BERBASIS KONTROL PI. Seminar MASTER PPNS. Vol. 6. No. 1.

Realdo, Adam Meredita, Anggara Trisna Nugraha, Shubhrojit Misra, 2012. Design and Development of Electricity Use Management System of Surabaya State Shipping Polytechnic Based on Decision Tree Algorithm. Indonesian Journal of Electronics, Electromedical Engineering, and Medical Informatics 3.4: 179-184.

Ruddianto, Ruddianto, et al, 2021. The Experiment Practical Design of Marine Auxiliary Engine Monitoring and Control System. Indonesian Journal of Electronics, Electromedical Engineering, and Medical Informatics 3.4: 148-155.

Shiddiq, Muhammad Jafar, Moch Fadhil Ramadhan, and Anggara Trisna Nugraha, 2021. PERENCANAAN PEMBANGKIT LISTRIK ENERGI BAYU KINCIR SAVONIUS GUNA MEWUJUDKAN PEMANFAATAN RENEWABLE ENERGY PADA JEMBATAN SURAMADU. Seminar MASTER PPNS. Vol. 6. No. 1.