Journal for Maritime in Community Service and Empowerment ISSN:
Vol. xx, No xx, Month-year

Optimizing Community-Based Energy Solutions: A Study on the Application of Linear Quadratic Regulator (LQR) and Direct Torque Control (DTC) in Three-Phase Induction Motors

* Anggara Trisna Nugraha[1], Yudha[2]
[1,2] Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya, Indonesia
*Correspondence author: anggaranugraha@ppns.ac.id

Abstract: *This study explores the development of a method for controlling the speed of three-phase induction motors using Linear Quadratic Regulator (LQR) and Direct Torque Control (DTC). By combining LQR and DTC, this method enables direct control of torque and stator flux, which plays a crucial role in optimizing energy systems for community-based applications. The rotor speed, torque, and flux are estimated using DTC, with input provided from stator voltage and current. The motor's speed is compared to a reference speed, generating an error, which, along with the speed change rate (delta error), serves as input for the LQR controller. Simulation results demonstrate rapid speed response under startup conditions, load changes, and setpoint variations, highlighting the robustness of the control system in real-world applications, such as rural energy systems. During load change conditions, the speed response shows minimal deviation, ensuring stable operation even under disturbances. For a load torque of 30 N·m, the maximum overshoot is 4.6735%, with a peak time of 0.007 seconds and a settling time of 0.111 seconds. The motor speed errors for reference speeds of 1450 rpm, 725 rpm, 725 rpm, and 362.5 rpm are 0.03%, 0.03%, 0.08%, and 0.027%, respectively, compared to the actual motor speed. This research contributes to the development of efficient, low-cost energy solutions that could be adapted for community-based projects, particularly in rural and underserved areas, helping to optimize local power generation and distribution systems for sustainable development.*

Keyword: *Induction Motor, LQR, DTC, Speed rotation*

Introduction

In today's rapidly advancing technological era, control systems play a vital role in human life, contributing significantly to the development of science and technology. Control systems, particularly in the industrial sector, facilitate numerous processes that enhance efficiency and reliability. These systems are essential in modern industries where precise control of machinery, energy, and processes is crucial to ensure the consistency and quality of production. For instance, automatic control systems are indispensable in various industrial operations, such as managing pressure, temperature, humidity, viscosity, and process flow. Additionally, they are integral to machine tool operations, handling mechanical parts, and assembly processes in manufacturing industries.

In the context of community-based energy solutions, particularly in rural or underserved areas, control systems in energy management are becoming increasingly important. As access to reliable energy remains a challenge in many regions, optimizing energy usage through advanced technologies can have a significant impact on improving local infrastructures, contributing to both social and economic development. One area where control systems can have a direct impact is in the operation of three-phase induction motors, which are widely used in industrial applications, including small-scale local power generation systems. These motors are known for their reliability, low maintenance needs, and ability to handle large amounts of power while consuming minimal electrical energy.

Three-phase induction motors are extensively used in various industries due to their efficiency, durability, and ability to operate without physical contact between the stator and rotor, except for the bearings. These characteristics make them ideal for both industrial and community applications, where reliability and low maintenance are essential. As communities in remote or underserved areas seek to improve local infrastructure and access to energy, understanding and optimizing motor performance through advanced control systems can help in developing sustainable energy solutions.

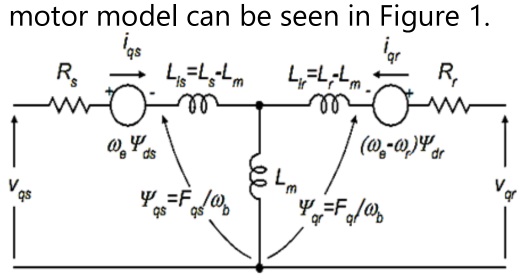
While there are many existing methods for controlling the speed of three-phase induction motors, including frequency and network adjustments, vector control, and others, there is a gap in utilizing hybrid control techniques that integrate Direct Torque Control (DTC) and Linear Quadratic Regulator (LQR), both of which have primarily been applied to DC motors. The integration of these methods can provide enhanced control over motor performance, ensuring more efficient energy consumption and improved system stability, which is crucial for community-based energy projects.

The goal of this study is to combine DTC and LQR controllers to regulate the speed of three-phase induction motors under various conditions, including startup, steady state, and changes in load torque. By focusing on the practical applications of these control techniques, this research aims to contribute to the development of efficient, cost-effective energy solutions that can be used in community-level energy systems, improving both technical performance and social benefits. The results of this study have the potential to optimize local energy production, reducing reliance on traditional, non-renewable energy sources and fostering greater energy independence within communities.

Methodology

1. Induction Motor DQ Model

Conventionally, to analyze the 3phase induction motor model, it is developed based on a transformer model assuming the source voltage is sinusoidal and in steady state conditions [5]. Therefore, another, more flexible model is needed to analyze induction motors. Induction motors in dq coordinates are used to analyze motors and are more flexible. Equation of induction motor voltage with symmetric voltage in dq coordinates [6] and Flux included in the coil [7][16]. These equations can be expressed in matrix form [8]. The diagram of the induction motor model can be seen in Figure 1.



(a)

Figure 1. Equivalent circuit induction motor

2. State space Induction motor

From several mathematical models above, these equations can be simplified to obtain the next state space model depicted in the form of a vector matrix of state equations. Form the state space equation of an induction motor especially the squirrel-cage type used in this research. From the induction motor voltage equation with Symmetric stress in d-q coordinates [6] and Flux included in the coil[7] can be expressed in matrix form as follows:

$$V_{qd} = Z_{qd} I_{qd}$$

With:

$$V_{qd} = |v_{qs} \quad v_{ds} \quad 0 \quad 0|^T$$

$$I_{qd} = |\mathrm{i}_{qs} \quad \mathrm{i}_{ds} \quad \mathrm{i}_{qr} \quad \mathrm{i}_{dr}|^T$$

After creating a simulation model of a 3 phase induction motor [2][17] it is necessary to carry out validation to see that the motor response produced is in accordance with the actual motor characteristics according to the parameters in table 1.

Table 1. motor characteristics

Power	7,5	HP/kW
	5,6	kW
Voltage, ***V***	380	Volt(L-L,rms)
Phase (F)	3	phasa
Stator resistance, ***Rs***	1,77	Ohm
Rotor resistance, ***Rr***	1,34	Ohm
Stator reactance, ***Xs***	5,25	Ohm
Rotor reactance, ***Xr***	4,57	Ohm
coupled reactance, ***Xm***	1,39	Ohm
Inertia Moment , ***J***	0.025	$Kg.m^2$
Pole, ***P***	4	
Frequency, ***f***	50	Hertz
Slip, ***S***	3	Persen
friction coefficient,***B***	0.01	N.m.sec/rad
Full Load current, ***I***	4	Ampere
Full load Slip (s)	1,72	Ohm

3. Design System

In this research, the system to be controlled is a 3 phase induction motor with a squirrel cage rotor type. The 3 phase induction motor system model with LQR and DTC control can be seen in Figure 2.

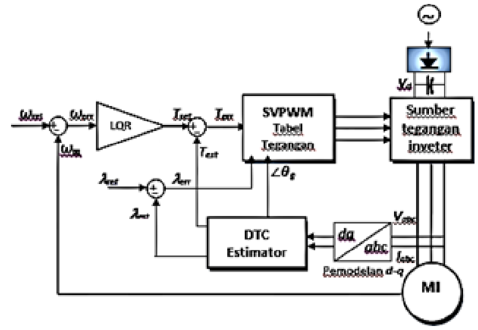


Figure 2. Simulation induction motor 3 phase with LQR and DTC

From Figure 2 it can be seen that the design of the induction motor speed control system is divided into several parts, namely.

- Induction motor
- 3 phase inverter and PWM switching
- Calculation of rotor flux, Theta, Iqs, Id
- LQR control
- DTCs

4. Base principal vector control

Vector control is a method of arranging the field coil in an induction motor, where the coupling system is changed to a decoupling system. With this system the gain current and motor load current can be controlled separately, so that torque and flux can also be regulated separately, just like a dc motor. Implementing flux vectors in 3 phase induction motors requires calculations or simulations on the orientation of the stator, rotor and torque. To facilitate the simulation of the motor from transient to stable conditions, the abc coordinates of the motor are changed into the image/vector model to dq form [7][8][18].

5. 3 phase Inverter and switching PWM (SPWM)

The inverter as an electronic switching circuit can change a direct voltage source into an alternating voltage with adjustable voltage and frequency [10]. To run a 3-phase AC motor with LQR control, a power circuit is needed as the starting medium. The PWM inverter technique is very appropriate to use as an implementation of model design. A three-phase three-arm inverter power circuit which has six switches and a DC voltage source [19]. A voltage source type DC to AC converter (voltage-type inverter) must fulfill two conditions, namely that the switches located on one arm must not conduct simultaneously to cause a short circuit current, and continuity on the AC side current must always be maintained. This can be seen in figure 3.

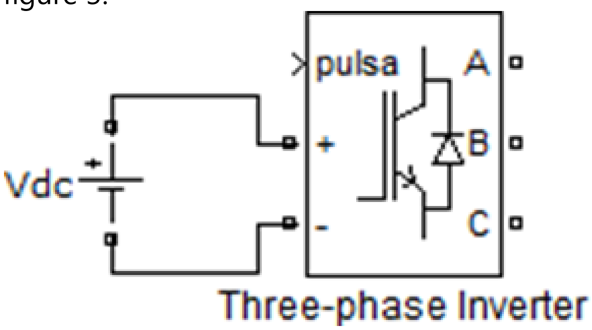


Figure 3. 3 phase inverter

The current controlled inverter circuit is modeled with a Universal Bridge block from a power electronic device. The current regulator is built with Simulink blocks, which consist of three hysteresis controllers. The motor currents are provided by the measurement output from the 3 phase induction motor block which can be seen in Figure 4.

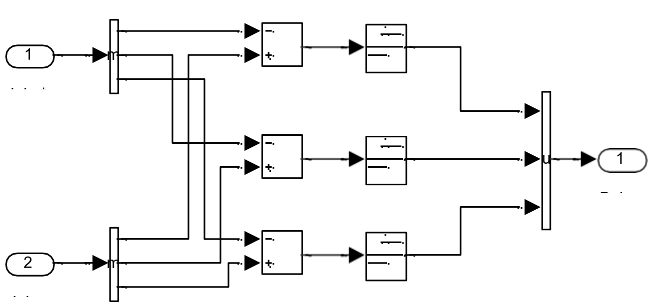


Figure 4. Current regulator

The conversion between abc-dq and dq-abc reference frames is executed by abc-dq and dq-abc blocks, as shown in figures 5 and 6

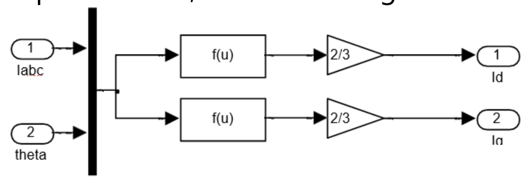


Figure 5. Transform abc-dq

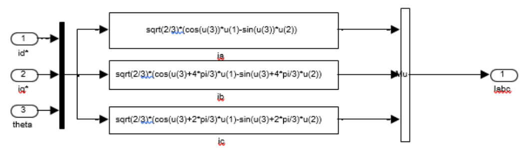


Figure 6. Transform dq-abc

The rotor flux is calculated with the flux calculation block as shown in figure 7

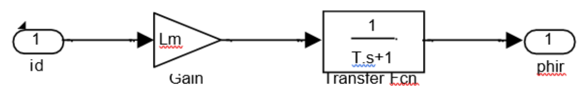


Figure 7. fluks calculation

The position of the rotor flux (θe) is calculated with the Theta calculation block, as in figure 8

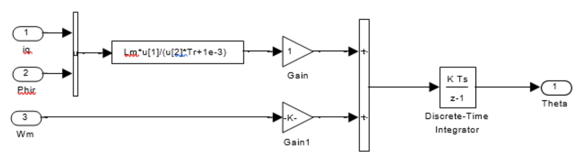


Figure 8. Theta calculation

The stator q-axis reference current (iq*) is calculated with the iq* calculation block as in figure 9.

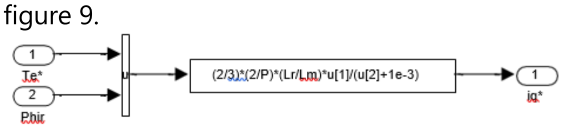


Figure 9. The stator q-axis reference current

The stator d-axis reference current (id*) is calculated with the id* calculation block as in figure 10.

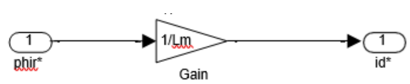


Figure 10. The stator d-axis reference current

6. Linear Quadratic Regulator (LQR)

An optimal system is a system that has the best performance against a certain reference. An optimal control system requires the existence of an optimization criterion that can minimize measurement results with deviations in system behavior from its ideal behavior [9][20].

The optimization method with a linear quadratic regulator (LQR) is to determine the input signal that will move a linear system state from an initial condition x(t0) to a final condition x(t) that minimizes a quadratic performance performance index. The cost functional in question is the time integral of the quadratic form of the state vector x and the input vector u as in the equation:

$$[XTQX + UTRU]$$

where Q is a positive semi-definite matrix and R is a positive definite matrix. On the basis of the above, the parameter variations of the linear quadratic regulator design problem can be determined, also for the final conditions, which may have an effect on the cost function.

The principle of using the LQR method is to obtain the optimal control signal from state feedback u= -[k].[x]. The feedback matrix k is obtained by solving the Riccati equation. One obstacle

The use of the LQR method is to solve the Riccati equation which is not easy if solved manually, therefore computer assistance is needed, in this case with the Matlab program package [14].

In optimal control systems, the model that is widely used is the equation of state. The representation of the system in the form of state space equations can be seen in Figure 3. In the equation of state, the differential equations are first order simultaneously, and are written in matrix vector notation:

[X]' = [A][X] + [B][U]

[Y] = [C][X] + [D][U]

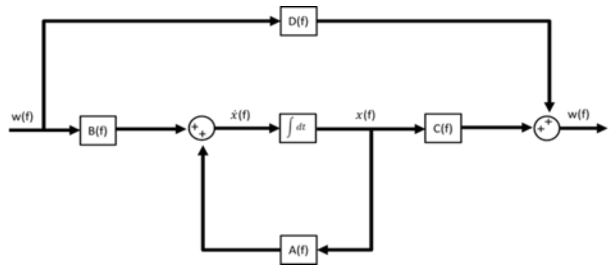


Figure 11. Representation system

7. Value Matrix

The weight matrices are the Q and R matrices. The selection of the Q and R matrices is done by trial and error. By condition, the matrix Q is a symmetric, positive semidefinite and real matrix (Q > 0). Matrix Q is a matrix of order 4×4 which is written as an equation

Matrix Q is a diagonal matrix with q components, and if the separation is carried out, the identity matrix is multiplied by the constant q. Determining the dimensions of matrix Q is based on the number of states of matrix A [11][12].

Meanwhile, the R matrix is a symmetric, positive definite and real matrix (R > 0). Matrix R is a matrix of order 1×1 which is written as an equation. Matrix R is a diagonal matrix with r components, and if the separation is carried out, you will get an identity matrix which is multiplied by the constant r. To calculate the optimal gain value K, the help of the Matlab program is used. To get gain K, you must first choose the weight matrices Q and R. The selection of the weight matrices Q and R is based on the smallest relative residual value. The calculation of the relative residual value can be done by trial and error. Namely by changing the value of the Q matrix.

Figure 12. block diagram of LQR

8. Direct Torque Control

In an induction motor with a cage rotor type, for a fixed time the rotor becomes very large, the leakage flux changes slowly compared to changes in the stator leakage flux. Therefore, under conditions of rapid change, the rotor flux tends not to change. Rapid changes of electromagnetic torque can result from rotating stator flux, as the direction of the torque. In other words, the stator flux can instantly speed up or slow down by using the appropriate stator voltage vector[13][14]. Torque and flux control together and decouple is achieved by direct regulation of the stator voltage, of the torque and flux response errors. DTC is usually used according to the voltage vector in this case to maintain torque and stator flux with two hysteresis regions[15]. To determine the motor rotation, the circuit equation can be used and the motor current is measured in a reference frame that can be selected in the stator frame

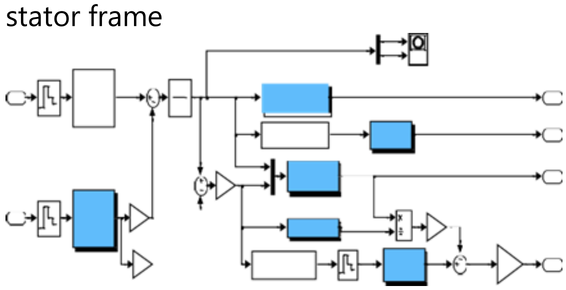


Figure 13. block diagram DTC

Results and Discussions

Simulation results of LQR control on a 3 phase induction motor with DTC using Simulink Matlab with the following data: sampling time 100 ·s, reference flux taken at nominal value

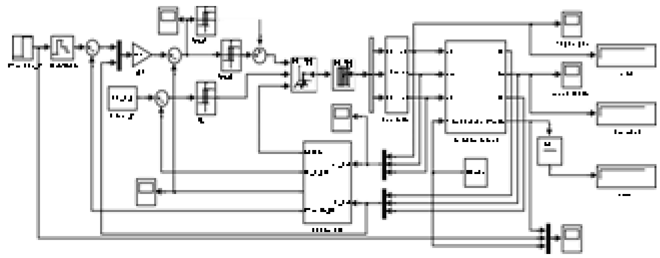


Figure 14. Simulation

The simulation is set for start conditions, steady state and changes in rotation reference and if there is a change in load.

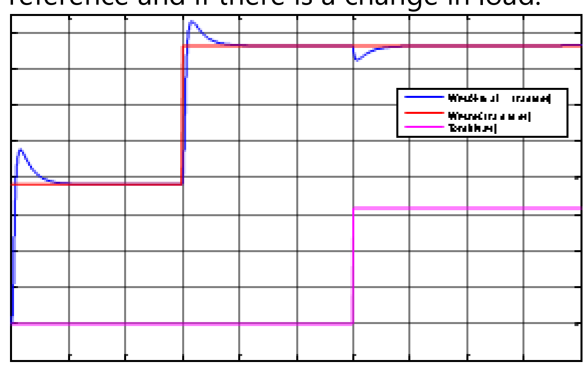


Figure 15. result Simulation

Figure 15: is the motor rotation response when starting, changes in speed reference and changes in load, Over-shoot resulting at start, changes reference speed and load changes as well as the time required to reach steady state conditions can be seen in the following table:

Table 2. Respon rotation

Condition	***Parameter***	
	Overshoot	**(i_{ss})**
Start	9,43 rad/det	**0,12**
Speed reference change	15,74 rad/det.	**0,12**
Load change (torsi)	**4,85 rad/det.**	**0,12**

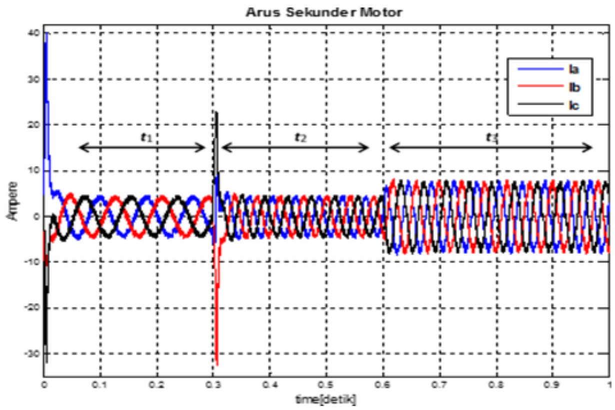


Figure 16. Stator current

Figure 16. is the stator current in each change condition that occurs, the t1 area shows a rotation time of 38.09 rad/second at zero load (motor without load), the t2 area shows a motor rotation time of 76.18 rad/second at zero load, and the t3 area shows a rotation time of 76.18 rad/sec for a full load of 31.63 N.m

Table 3. Respon current

area	*Parameter*	
	Rotation	**Current**
t1	38,09 rad/det.	**5,10 A**
t2	38,09 rad/det.	**5,10 A**
t3	**76,18 rad/det.**	**8,2 A**

For transient conditions and changes in reference speed, the current overshoot is 40, 29 Amperes and 10.5 Amperes.

Table 4. Respon voltage motor

Rotation	*Parameter*	
	Periode (T)	**Vm**
38,09 rad/det. (t=0 s/d 0,3s)	0,091 s	466,6
76,18 rad/det. (t=0,3 s/d 1s)	0,044 s	466,6

It can be seen that when the reference speed changes to become faster, the motor voltage frequency also increases large (ƒ = 1)

This is the response of electromagnetic torque where when starting and changing the speed setting, a torque ripple of 310 N.m and 280 N.m occurs.

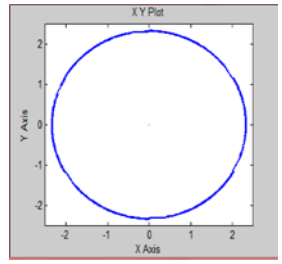


Figure 17. Fluks stator depand pole coordinate d and q

In Figure 17, it can be seen that the rotation speed of the induction motor occurs when there is a change in load torque. From figure 5 the motor rotation speed is controlled by LQR and DTC

Conclusion

Based on the simulation results conducted in this study, the following conclusions can be drawn:

1. Startup Condition: When the motor starts with no load and a rotational speed of 0.5 nominal rotations (38.09 rad/s), an overshoot of 9.43 rad/s (19.84%) is observed. The rise time is 0.007875 seconds, and the settling time is 0.12 seconds. This indicates that the motor responds quickly but exhibits a noticeable overshoot at startup, a common characteristic in energy optimization systems for community-based applications where rapid activation is essential.
2. Change in Reference Speed: When the reference speed increases by 100% to 76.18 rad/s, with no load, the motor experiences an overshoot of 15.74 rad/s (17.12%), with a rise time of 0.0094 seconds and a settling time of

0.12 seconds. This scenario demonstrates the motor's ability to adapt to changes in operational conditions, a crucial feature for optimizing energy systems in rural or community-based projects where demand may fluctuate.

3. Full Load Condition: Under full load (31.63 N.m torque) at a speed of 76.18 rad/s, the motor exhibits an overshoot of 4.45 rad/s (5.51%), with a peak time of 0.0086 seconds and a settling time of 0.12 seconds. This scenario reflects the motor's robustness in maintaining speed and stability even under varying load conditions, which is vital for community-based energy solutions where energy demands can vary throughout the day.
4. Control Method Alternatives: There are several alternatives for controlling the speed of induction motors, such as frequency and network adjustments, vector control, and others. However, the hybrid control method that integrates Linear Quadratic Regulator (LQR) and Direct Torque Control (DTC) has not been widely explored in induction motors. These techniques have primarily been used in DC motors, which has limited their application in community-based energy solutions.

In the context of community service, especially in rural or isolated areas where energy infrastructure is often limited or inefficient, applying LQR and DTC control methods to induction motors presents a promising approach. This hybrid control can optimize motor performance, reduce energy consumption, and improve the reliability of local energy systems.

1. Objective of the Study: The aim of this research is to combine DTC and LQR controllers to regulate the speed of three-phase induction motors under various operational conditions—such as startup, steady-state operation, and changes in load torque. By focusing on these key conditions, the study aims to contribute practical solutions to optimize energy systems for community-level applications. Effective energy management in such settings can lead to increased energy efficiency, reduce costs, and promote sustainability in local power generation systems.

References

[1] Endro Wahjono. Soebagio.*Fuzzi Logic Direct Torque Control Untuk Motor Induksi Yang digunakan Pada kendaraan Listrik (Electrik Vehicle).*Politeknik Elektronika Negeri Surabaya. 2009.

[2] Oktavianus Kati. *Pengendali Sliding Mode Control (SMC) Motor Induksi 3 Phasa dengan Direct Torque Control (DTC Menggunakan Algoritma Genetika.* Universitas Hasanuddin. 2011.

[3] Ching-Chang Wong, shih-Yu Chang. *Parameter Selection in The Sliding Mode Control Design Using Genetic Algorithms.* Tamkang Journal of

Sience and Engineering. Vol. 1, No. 2, pp. 115-122. 1998.

[4] Jeremia Purba.*Simulasi Pengaturan Kecepatan Motor Induksi Tiga Phasa Dengan Direct Torque Control Dengan Menggunakan Matlab 7.0.1.* Universitas Sumatera Utara. 2009.

[5] Epyk Sunarno, Soebagio, Mauridhi Heri Purnomo. *Pengaturan Kecepatan Motor Induksi Tanpa Snesor Kecepatan dengan Metoda Direct Torque control Menggunakan Observer Recurrent Neural Network.*

Politeknik Elektronika Negeri Surabaya.2009

[6] Panji Kurniawan. *Perancangan Dan Simulasi Metode Direct Torque Control (DTC) Untuk Pengatuan Kecepatan Motor Induksi 3 Phasa.* Institute Teknologi Sepuluh November Surabaya.2009.

[7] *Era Purwanto, Ananto Mukti Wibowo, Soebagio, Mauridhi Hery Purnomo. Pengembangan Metoda Self Tuning Parameter PID Controller Dengan Menggunakan Genetic Algorithm Pada Pengaturan Motor Induksi Sebagai Penggerak Mobil Listrik.* Seminar Nasional Aplikasi Teknologi Informasi (SNATI). ISSN: 1907-5022. 2009.

[8] M. Abid, Y. Ramdani, A. Aissaoui, A. Zeblah. *Sliding Mode Speed and Flux control of an Induction Machine.* Journal of Cybernetics and Informatics. ISSN:1336- 4774. Vol. 6. 2006.

[9] Lewis, F.L. *Optimal Control*. Kanada: John Wiley & Sons, Inc.1996.

[10] Wahyu, Thomas dan Agung, Wahyu. 2003. Analisis dan Desain Sistem Kontrol dengan MATLAB. Yogyakarta : Penerbit ANDI.

[11] Heru Dibyo Laksono. *Simulasi Tingkah Laku Kecepatan Motor DC di titik Operasi Mempergunakan Metoda Linear Quadratic Regulator (LQR).* Jurusan Teknik Elektro Universitas Andalas Padang.. No. 29 Vol.2 thn. XV April 2008.

[12] Soebagio, *Model mesin AC pada koordinat d-qn*, Materi Kuliah Mesin Listrik Lanjut, ITS, 200.

[13] D. Casadei, Giovanni Serra, "FOC and DTC: two variable scheme for induction motors torque control", *Trans. On Power Electronics*, Vol. 17, No. 5, September 2002.

[14] Ferdinandus, Aprildy Randy Andrew, Anggara Trisna Nugraha, and Jamaaluddin Jamaaluddin. "Setting Neuro-Fuzzy PID Control In Plant Nonlinear Active Suspension." Journal of Physics: Conference Series. Vol. 1114. No. 1. IOP Publishing, 2018.

[15] Nugraha, Anggara Trisna. Desain Kontrol Path Following Quadcopter Dengan Command Generator Tracker Model Following. Diss. Institut Teknologi Sepuluh Nopember, 2017.

[16] Saputra, Fahmi Yahya, et al. "Efficiency Of Generator Set On Changes In Electrical Load On Fishery

Vessels." MEIN: Journal of Mechanical, Electrical & Industrial Technology 1.2 (2024): 1-4.

[17] Fauzi, Ahmad Raafi, et al. "Performance of Permanent Magnet Synchronous Generator (pmsg) 3 Phase Radial Flux Results Modification of Induction Motor." MEIN: Journal of Mechanical, Electrical & Industrial Technology 1.2 (2024): 5-11.

[18] Rahman, Farhan Wahyu Nur, et al. "Application of Ant Colony Optimization Algorithm in Determining PID Parameters in AC Motor Control." Brilliance: Research of Artificial Intelligence 4.2 (2024): 538-549.

[19] Mu'in, Misbakhul, et al. "ANALISIS ALIRAN DAYA DAN CAPASITOR PLACEMENT PADA SISTEM KELISTRIKAN PT BLAMBANGAN BAHARI SHIPYARD DENGAN SOFTWARE ETAP." Jurnal 7 Samudra 8.1 (2023).

[20] Amrullah, Muhammad'Ubaid, et al. "RANCANG BANGUN MONITORING KUALITAS AIR TAMBAK UDANG VANAME DENGAN KONTROL PADDLE WHEEL BERBASIS MIKROKONTROLLER." Jurnal 7 Samudra 8.2 (2023): 117-122.