

Direct Torque Control Design with Fuzzy Sugeno-Proportional Derivative for 3-Phase Induction Motor Speed Control

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ABSTRACT

An induction motor is an electric motor that works based on induction currents. In general, induction motors are more used in the industry than DC motors due to the characteristics of induction motors, which are robust, reliable, easy to maintain, and relatively inexpensive. Rotational speed changes with load changes can lead to induction motor speed regulation, and slowing response time, but overshoot caused by external environmental factors should be minimized. Due to interference, a controller is needed that can work properly to optimize performance. The purpose of this research is to design a Kanno PD Fuzzy DTC controller that provides a fast and strong response on DTCs mounted on AC motors. Based on the research result obtained Fuzzy Sugeno provides a short computation time and its inference contains enough data and PD to speed up reaction time results. Therefore, the proposed method produces the rotational speed of the induction motor according to the specified settings of 100 rad/s with a settling time of 0.45 s, a rise time of 0.2 s, and no steady-state error. Based on the predicted state of the output response before it is sent to the controller, the steady-state error is obtained at 5 rad/s with a maximum overshoot of 5.4111%, a settling time of 0.1554 seconds, and a rise time of 0.1554 seconds.

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1. INTRODUCTION

Since the 19th century, induction motors have undergone improvements to the present. These improvements are made so that the operation works more optimally, for example by operating it as a synchronous-asynchronous machine, changing the number of poles in the stator winding, controlling with electronic systems, and so on [1]. Progress in the industrial sector in our country is growing rapidly, both large and small industries. Large industries use induction motors, because of their simple construction, robustness, relatively easy maintenance, lighter weight, high efficiency, and low cost compared to other motors such as DC motors. In an induction motor, there is no contact between the stator and the rotor except the bearing, then the power is quite large, the electric power is low and there is almost no maintenance [2,3]. In directing the speed of an induction motor at a decent speed and variable speed, frequency or torque is needed [4]. The power converter is used to set the induction motor parameters so that the motor speed can be affected by setting the input motor parameters [5].

Efforts to improve the limitations of the alternating current motor for control purposes consist of two methods, namely scalar and vector settings. In this study, the authors used vector control, in which

the vector control method to separate the flux from the rotor so that the speed control could work in a steady state and could not only adjust the speed angle and magnitude, but also the current, voltage, and flux [6]. This 3-Phase induction motor has a weak point, namely one of them, if it is disturbed, the speed is not constant. Giving this disturbance will cause changes in motor parameters so that the speed of the induction motor drops and does not reach the setpoint value [7,8].

To make the motor speed stable or have good performance, requires a controller to regulate the speed of a 3-Phase induction motor. There is research on 3-Phase induction motors that have been carried out, one of which uses DTC-based Fuzzy but there is still an overshoot of 2.67% with a rise time of 0.025 seconds and a settling time of 0.2 seconds. When the motor changes, the rotation reference becomes 74.51 rad/second with of 12.64 N-m occurs 94.6% overshoot, rise time 0.018 seconds and settling time 0.325 seconds [2]. In this study, there is still an overshoot and it is still oscillating, but the overshoot when the rotation reference changes occur is very large. In another study using the Flux Vector Control method based on PI Self Tuning. In this study, controlling the speed of an induction motor using a self-tuning PI controller for quadrature currents was able to reduce the motor speed overshoot from 132.8 rad/s to 119.2 rad/s [3]. So in this study, there is still overshoot, but the overshoot using self-tuning pi is smaller than the overshoot with conventional PI.

In another study, 3-Phase induction motors have been studied using Fuzzy Mamdani based on field-oriented control methods. In this study the test results and responses showed that the settling time was around 0.27 seconds, the rise time was around 0.29 seconds, the overshoot was around 2.7%, the undershoot was 0.5% and the steady state error was around 2% [7]. So in this study, there is still a fairly large overshoot and the steady state is close to 0. DTC is a control method based on adjusting the magnetic flux and stator torque and provides a fast and powerful response installed in AC motors. DTC was proposed by Isao Takahashi and Toshihiko Noguchi in 1980. DTC has easier construction, less computational requirement, and higher performance and execution. The DTC method makes it possible to directly set the switching conditions on the inverter with Space Vector Modulation. Even so, the conventional DTC setting scheme still uses a PI controller so that if there is a change in the load on the motor, the motor's speed response will decrease, not according to the given reference speed. [9].

As for the research regarding 3-Phase induction motors using DTC modeling, namely in this study the DTC controller settings can provide the performance is quite good where the overshoot and steady state are close to 0 and the rise time and settling time are quite fast but in this study oscillations still occur [10]. According to Cox (1994), there are several reasons why Fuzzy logic is used is because the idea of Fuzzy logic is easy, fully customizable, can bear wrong information, can show very complex nonlinear capabilities, and can help. usual control methods and given the normal language [11]. In Fuzzy logic there are usually several methods, namely the Mamdani method and the Sugeno method, However, in this study, the authors wanted to use Fuzzy Sugeno because the calculation time was short and the reasoning included quite extensive data [12].

Research using the Sugeno Fuzzy controller is a comparison between Fuzzy Sugeno and Fuzzy Mamdani on DC motors that do not have overshoot and to reach a set point, and when compared to computing between Fuzzy Sugeno and Mamdani to reach a steady state, Fuzzy Sugeno is faster. However, to reach the steady state mean (SE), Mamdani is faster than Sugeno and the delta error Mamdani is more stable than Fuzzy Sugeno.[12] In the research above, Fuzzy Sugeno has been able to get good results, but to further optimize better results, in this study adding a PD controller to speed up the system response in reaching the set point [13]. Based on the background description above, the authors are interested in conducting research using the Fuzzy Sugeno-PD DTC control for controlling 3-Phase induction motors.

2. RESEARCH METHOD

The flow of research begins with literature study, problem identification, data collection, variable determination in the form of transfer functions of 3-Phase induction motor systems, validation of mathematical models, designing DTC controllers, Fuzzy Mamdani controllers, combining DTC controllers, Fuzzy Mamdani with PD, analyzing the design results controller and the last is to draw conclusions based on the results of the research.

2.1 3-Phase Motor Induction

3-Phase induction motor is one of the motors in which an electric device converts electrical energy into mechanical energy with the converted electric power being 3-Phase electricity. This 3-Phase induction motor is quite widely used in today's industries and has also been used in households. This machine is used because it is very strong, and straightforward and the price is relatively cheap. According to the findings of experts towards the end of the 19th century, it is said to be an induction motor because the motor rotor current is an induced current as a result of the difference between the rotor rotation and the rotating field generated by the stator current. In general, there are 2 main construction parts in an induction motor, namely the stator and the rotor. The stator is the stationary part and the rotor is the rotating part. The construction of an induction motor can be seen in Figure 2.1 [1].

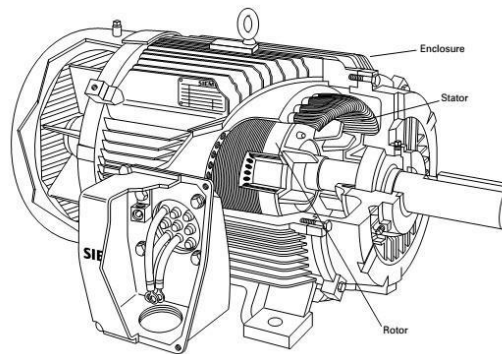


Figure 1. General structure of an ac motor

2.2 Mathematical Modeling

Table 1 is the parameter values that will be used to calculate the mathematical model of a 3-Phase induction motor.

Table 1. Parameter 3-Phase induction motor [25]

No	Name	Value
1	Motor Power (Hp)	3/2,4 Kw
2	Motor Voltage (line to line)(Volt)	460
3	Frekuensi (Hz)	60
4	Nomber Of Pole	4
5	Stator Resistance(Ohm)	1,77
6	Tahanan Resistance (Ohm)	1,34
7	Sator Inductance(mH)	0,3829
8	Rotor Inductance (mH)	0,3811
9	Magnetic Inductance (mH)	0,369
10	Moment of Inertia (Kg.M ²)	0,025
11	Full Load Current (A)	4
12	Full Load Speed (RPM)	1750
13	Full Load Efficiency (%)	88,5
14	Power Faktor (%)	80
15	Full Load Slip (%)	1,72

After doing the writing research, a mathematical model of the plant was obtained, especially the induction motor so that it tends to be simulated by the plant and the quality of the plant in the product used. The mathematical model of the induction motor used in this design can be obtained from formula (1). Equation (1) needs to be simplified again so that the simulation in Matlab is easy to manufacture. The simplification process is:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & \omega_e \cdot L_s & pL_m & \omega_e \cdot L_m \\ -\omega_e \cdot L_s & R_s + pL_s & -\omega_e \cdot L_m & pL_m \\ pL_m & (\omega_e - \omega_r) L_m & R_r + pL_r & (\omega_e - \omega_r) L_r \\ -(\omega_e - \omega_r) L_m & pL_m & -(\omega_e - \omega_r) L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (1)$$

A separation is made between variables that contain their derivatives, so that the form of the equation becomes:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s & \omega_e L_s & 0 & \omega_e L_m \\ -\omega_e L_s & R_s & -\omega_e L_m & 0 \\ 0 & (\omega_e - \omega_r) L_m & R_r & (\omega_e - \omega_r) L_r \\ -(\omega_e - \omega_r) L_m & 0 & -(\omega_e - \omega_r) L_r & R_r + p L_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} p L_s & 0 & p L_m & 0 \\ 0 & p L_s & 0 & p L_m \\ p L_m & 0 & p L_r & 0 \\ 0 & p L_m & 0 & p L_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (2)$$

In another form, the above equation can be as follows:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s & \omega_e L_s & 0 & \omega_e L_m \\ -\omega_e L_s & R_s & -\omega_e L_m & 0 \\ 0 & (\omega_e - \omega_r) L_m & R_r & (\omega_e - \omega_r) L_r \\ -(\omega_e - \omega_r) L_m & 0 & -(\omega_e - \omega_r) L_r & R_r + L_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (3)$$

Example

$$P = \begin{bmatrix} R_s & \omega_e L_s & 0 & \omega_e L_m \\ -\omega_e L_s & R_s & -\omega_e L_m & 0 \\ 0 & (\omega_e - \omega_r) L_m & R_r & (\omega_e - \omega_r) L_r \\ -(\omega_e - \omega_r) L_m & 0 & -(\omega_e - \omega_r) L_r & R_r + L_r \end{bmatrix} \quad (4)$$

$$Q = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad (5)$$

The above equation can be formed more simply, namely:

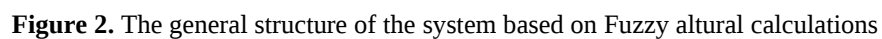
$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = P \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + Q \frac{d}{dt} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (6)$$

If you want to find the current value, the formula above becomes:

$$\frac{d}{dt} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} = -Q^{-1} P \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + Q^{-1} \begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} \quad (7)$$

2.3 Fuzzy Logic

In 1965, Lotfi A. Zadeh invented an intelligent control system, namely Fuzzy logic. the Fuzzy function is to distinguish a set according to the degree of membership from an uncertain boundary. This set theory is the development of a firm set theory that is created from the way humans understand an uncertain value. Fuzzy membership values are not only worth 0 or 1 but also produce a value that lies between 0 and 1. The Fuzzy structure can be seen in Figure 2.6 where the Fuzzy control design is divided into three stages, namely fuzzification, Fuzzy reasoning systems, and defuzzification [20].



DTC is a control method used to base the adjustment of the magnetic flux and stator torque and provides a fast and robust response for AC motors. The block diagram of the three-phase induction motor DTC system is shown in Figure 3.



PD control is a commonly used control system where each has different advantages and functions. Proportional control functions speed up the output of the system to reach the reference point by amplifying the driving error signal or error signal. Proportional control can produce an offset on the system by increasing the value of the proportional band or K_p . However, if the K_p value is too large, it will cause oscillations to arise because the system becomes unstable. P control can stand alone for system control.

Derivative control is usually called the rate controller which is symbolized by D. It is called the rate controller because the output on the derivative control is proportional to the rate of change of the error signal.

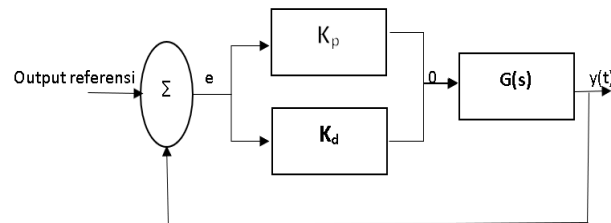


Figure 4. PD control

3. RESULTS AND DISCUSSION

The reference value for the stator flux is set at 1.46, while the reference value for speed is 100 rad/s. This speed reference value will later be used as a reference for the desired output response value of the system. The simulation response results are in the form of electromagnetic torque response, rotor speed, and estimated flux.

3.1 Results and Analysis of 3-Phase Induction Motor Speed System with DTC Controller

To analyze the output response of a 3-Phase induction motor system using DTC, it is necessary to do a simulation test first and in this circuit the reference value is 100 rad/s.

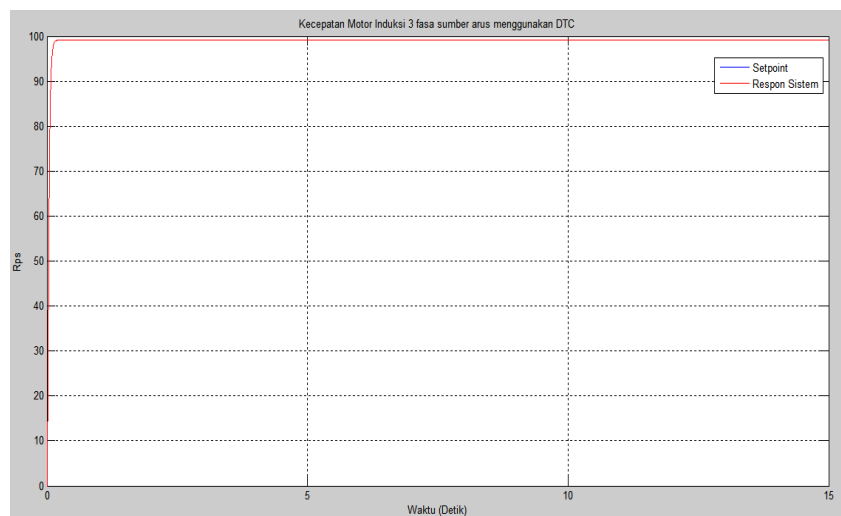


Figure 5. DTC control system output graph on 3-Phase induction motor

The rise time for a 3-phase induction motor with this trouble code is 0.0615 seconds. The settling time (t_s) for a 3-Phase induction motor using this fault code is calculated for an output response of 98%, an output reading of 97.1474 rad/s, and a time to reach 97.1474 rad/s of 0.113 seconds. The deceleration time (t_d) for a 3-Phase induction motor with DTC is calculated for a 50% output response, an output reading of 49.565 rad/s, and a time to reach 49.565 rad/s of 0.034 seconds. The steady-state error (E_{ss}) is obtained from the difference between the steady-state setpoint and the steady-state output. where the values are 100 rad/s and 99.13 rad/s respectively. Therefore, the steady-state error value for a 3-Phase induction motor with DTC is 0.87 rad/s.

3.2 Results and System Analysis of 3-Phase Induction Motor Speed with Fuzzy Sugeno DTC Controller

To analyze the output response of a 3-Phase induction motor system using DTC, it is necessary to do a simulation test first and in this circuit the reference value is 100 rad/s.

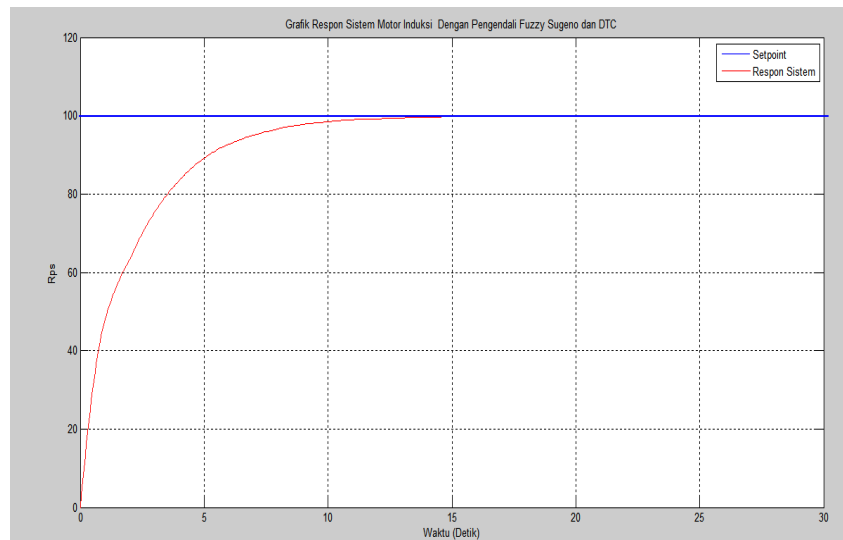


Figure 6. Graph of induction motor system response with Fuzzy Sugeno and DTC controllers

Therefore, the rise time of a 3-phase induction motor using DTC Fuzzy Sugeno is 5 seconds. The settling time (t_s) of a 3-Phase induction motor using DTC Fuzzy Sugeno is calculated for 98% output response. Here the output value is 98 rad/s and the time to reach 98 rad/s is 9.15 seconds. For the deceleration time (t_d) of a 3-Phase induction motor, use the DTC with an output response of 50% when the output value is 50 rad/s and the time to reach 50 rad/s is 1.1 seconds.

3.3 Results and System Analysis of 3-Phase Induction Motor Speed with Fuzzy Sugeno-PD DTC Controller

Furthermore, the PD controller is added to speed up the time needed to reach the proposed reference value of 100 rad/s because when controlled using the DTC-Fuzzy controller it still takes a long time to reach its steady-state value.

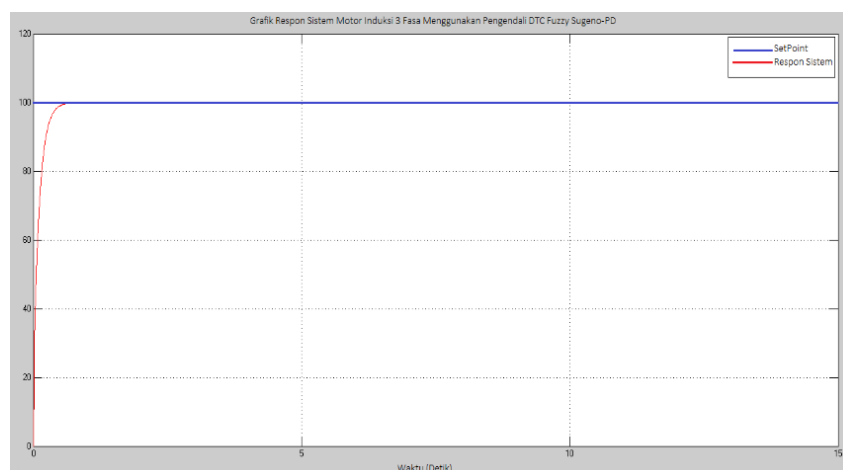


Figure 7. Graph of induction motor output using Fuzzy Sugeno-PD DTC controller

Therefore, the rise time of a 3-Phase induction motor using the Sugano PD Fuzzy DTC is 0.2 seconds. The settling time (t_s) of a 3-Phase induction motor using DTC Fuzzy Sugeno-PD is calculated when the output response is 98% where the output value is 98 rad/s and the time needed to reach 98 rad/s is 0.45 seconds. For Delay Time (t_d) on a 3-Phase induction motor using DTC Fuzzy Sugeno-PD, it is calculated when the output response is 50% where the output value is 50 rad/s and the time needed to reach 50 rad/s is 0.1 second. The system time response using the DTC Fuzzy Sugeno-PD controller can be seen in Table 4.5 which displays the values of rise time, steady time, delay time, maximum overshoot, and steady-state error.

3.4 Results and Analysis of 3-Phase Induction Motor Using DTC-Fuzzy Sugeno-PD Controller When Interrupted

To determine the performance of the Sugeno-PD Fuzzy DTC controller in overcoming disturbances in 3-Phase induction motors where disturbances are defined as changes in voltage up and voltage down. The disturbance given is 10% of the setpoint and the disturbance will be given at 10 seconds, then analyze the impact and changes in the system response from the controller.

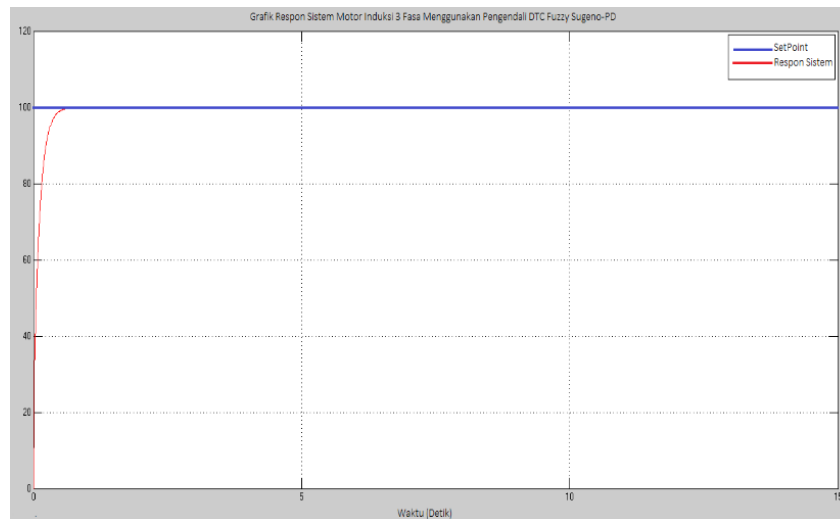


Figure 8. Graph of induction motor output using Fuzzy Sugeno-PD DTC controller with interference

Therefore, the rise time of a 3-Phase induction motor with a Sugeno PD Fuzzy DTC controller in this disturbance is 0.0268 seconds. Settling time (t_s) For a 3-Phase induction motor using DTC Fuzzy Sugeno-PD controller with this disturbance is calculated when the output response is 98% where the output value is 97.9706 rad/s and the time needed to reach 97.9706 rad/s is 0.488 seconds. For Delay Time (t_d) on 3-Phase induction motor using DTC. A Fuzzy Sugeno-PD controller with disturbance, is calculated when the output response is 50% where the output value is 49.985 rad/s and the time needed to reach 49.985 rad/s is 0.1088 seconds.

4. CONCLUSION

Conclude, based on the simulations performed and response analysis, that by using the Sugeno-PD DTC Fuzzy controller on a 3-Phase asynchronous motor, the controller was able to achieve performance with a setpoint of 100 rad/s. I can. The settling time is 0.45 seconds, the rise time is 0.2 seconds, and the delay time is 0.1 seconds. It can be seen that the Sugeno PD Fuzzy DTC controller can achieve results that match the setpoint while eliminating overshoots and steady-state errors. There is a 5 rad/s steady-state error, a 5.4111% overshoot, and still some oscillation from the state of the planned output response before being fed to the controller. The state of the planned output response when presented to the DTC controller has a steady-state error of 0.87 rad/s and a settling time of 0.113 seconds. Adding the DTC controller to the Sugeno Fuzzy controller gives better results as the result reaches the set point in 9.15 seconds of steady-state time with no steady-state error and no overshoot. From the simulation results obtained, it can be concluded that studies using the Sugeno Fuzzy DTC controller can eliminate overshoots, oscillations, and steady-state errors. Apart from that, it is also said to be superior to previous studies.

Based on the research conducted and the analysis performed on a 3-Phase induction motor using the Sugeno-PD DTC Fuzzy controller, the authors used the 7x7 membership function in further studies to estimate the resulting system response I suggest you can check if is better. 5x5 membership function. Alternatively, add a PID controller to further improve the output response.

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