Disturbance Observer Design for Controlling the Speed of Three Phase Induction Motor

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Abstract— **Induction Motor is a type of motor that is most widely used in industry compared to other electrical motors, because this type of motor has several advantages such as construction simplicity, sturdiness, cheap prices and low maintenance need. But the main challenge is to keep the speed remain constant when the induction motor is given many various values of load until particular value of the load nominal is given, so the response of the motor will change variously even if a controller has been given, thus controlling the speed of three phase induction motor is much more difficult to do. Therefore, in this research, we applied Disturbance Observer (DOB) method using Proportional Integral Derivative (PID) controller. This method was chosen because it can automatically reduce or even eliminate the disturbance, which is in the form of load and the measurement noise. The use of PID controller was expected to enhance the motor's time settling. The test result of the Disturbance Observer method shows that it can reduce the measurement noise in every loading scenario. While the simulation result shows that the response of PID controller + DOB are capable of approaching the nominal load response with a response specification of 0.1 % of plant error, overshoot or undershoot of 1.5 %, time settling (ts) 5 % by 7.1 seconds and time rises (tr) of 2.2 seconds.**

Keywords*— *Disturbance Observer, Proportional Integral Derivative, Induction Motor

I. INTRODUCTION

Three-phase induction motor is an electrical motor that is most widely used in industry. This is due to its construction simplicity, sturdiness, cheap prices, and maintenance easiness, thus it begins to replace the use of DC motors in the industry. The only drawback of induction motor is its inability to maintain a constant speed when there are load changes. This condition happens because there is no linear relationship between the current and generated torque.

The use of three-phase induction motors in some industries requires the high performance ability of the induction motor to maintain its speed despite changes in load. Examples of applications of the induction motor that is in the paper industry. One example of the use of induction motor is in paper production facility where the thickness of all produced paper must be even. Thus requiring a constant accuracy and speed of the driving motor, while it is very possible that there is a huge load change. The motor speed of conveyors for example, must be maintained in order to remain constant despite changes due to various given load, or other disturbances that may caused by changes in the circumstances that can not be predicted (outdoor area).

Several studies on speed controlling of induction motor has been done. [1] used a fuzzy logic controller to improve the performance of PID controller on induction motor speed controller. Similarly, a study conducted by [2] to develop a fuzzy controller which was used to obtain the PID parameters. But they only got results for the speed setting, without considering the generated disturbances when the motor is used for particular needs.

II. THEORY

A. PID Controller

PID controller is often found in almost every motor speed setting. The wide use of PID controller is basically motivated by few reasons. PID controller has a simple control structure, where there are three main parameters that must be tuned, the Kp, Ki, and Kd. The effect of the changes in each parameter to the controlling dynamics is easily understood by the operator.

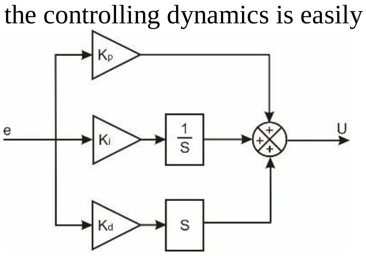

Fig. 1. PID controller structure

The equations of PID control signal is the sum of each elements of proportional, integral and derivative which are multiplied by error signal [3] as shown in the equation (1).

$$u(t) = K_p\left(e(t) + \frac{1}{\tau_i}\int e(t)\,dt + \tau_d\frac{de(t)}{dt}\right) \quad (1)$$

If the value of Kp is multiplied with each of the PID constants, the Equation (2) is obtained.

$$u(t) = \left(Kp\; e(t) + \frac{Kp}{\tau_i}\int e(t)\,dt + Kp\tau_d\frac{de(t)}{dt}\right) \quad (2)$$

While the value of Ki, and Kd are obtained as in Equation (3):

$$Ki = \frac{Kp}{\tau_i} \quad (3)$$

$$Kd = Kp.\tau_d \quad (4)$$

Thus by substituting Equation (3) and (4) into Equation (2), we can obtain a complete PID control signal parameters as shown in Equation (5).

$$u(t) = \left(Kp\ e(t) + Ki \int e(t)\,dt + Kd\frac{de(t)}{dt}\right) \quad (5)$$

The design of PID controller is basically to specify parameter values of Kp, Ki, and Kd so that the response system design results in accordance with the desired performance specifications. In designing the PID controller analytically there are several stages:

1. Determining a mathematical model of plant. The order of the mathematical order is a second order. If a mathematical model obtained has a higher order (more than two), then the mathematical model used is the reduction model in second order.
2. Determining the desired performance specifications. This design is a design with approach to the response time, the measure of the quality of the response that is used is a measure of the quality of the response time, the Settling Time (ts),% Over-shoot, and % Error Steady State.
3. Determining Kp, Ki and Kd

The characteristic of the PID controller is greatly influenced by the large contribution of the three parameters P, I and D. The selection of Kp, τ_I and τ_d constants will result in the dominance of the properties of each element. These constants and dominants will contribute greatly to the overall system response.

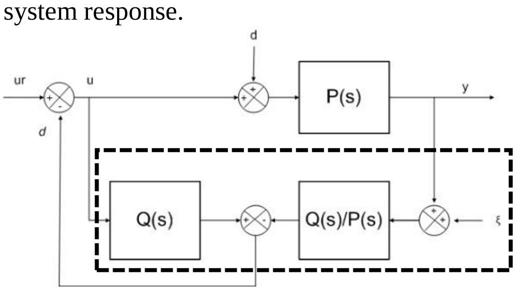

Fig. 2. Block Diagram of Disturbance Observer

B. Disturbance Observer Method

DOB Method is one of the most widely used motion control methods. By using a low-pass Q (s) filter and a nominal plant model, DOB estimates disturbance and estimation signals are used to eliminate disturbance. So DOB makes the P (s) plant behavior between the control signal and the plant output undisturbed by parameter uncertainty, disturbance and noise sensors. Figure 2 shows the DOB structure. Ur, u, d, ξ, and y signals respectively show control signals, disturbance, measurement noise and output signals. While signal δ is the result of estimation signal. The control signal (ur) is supplied by the external loop controller. Q (s) is a low-pass filter and Pn (s) is the nominal model of the plant [4]. Ideally, the DOB would weaken the disturbance at low frequencies and make the plant controlled by an external loop close to the nominal model. The behavior of the disturbance observer can be analyzed by taking into account the transfer function from ur, d, dan ξ to y output. The block diagram of the disturbance observer can be seen in figure 2.

This ability can be shown by paying attention to the transfer function [4]:

$$y = Gyur(s)v + Gyd(s)d + Gy\zeta(s)\zeta \quad (6)$$

$$Gyur(s) = \frac{P(s)Pn(s)}{Pn(s)+Q(s)(P(s)-Pn(s))} \quad (7)$$

$$Gyd(s) = \frac{P(s)Pn(s)(1-Q(s))}{Pn(s)+Q(s)(P(s)-Pn(s))} \quad (8)$$

$$Gy\zeta(s) = \frac{P(s)Q(s)}{Pn(s)+Q(s)(P(s)-Pn(s))} \quad (9)$$

From the above three functions of transfer it can be seen that the DOB design to determine the rejection performance of disturbance depends on the selection of the filter Q(s). The third behavior of the system transfer function above when the filter value Q(s) at low frequency close to 1 indicates that y ≈Pn(s)v + ζ so the DOB effect on the system as follows:

a. Guy(s) ≈ Pn(s), this means the system dynamics from u to y will be the same as the nominal model.
b. Gdy(s) ≈ 0, this indicates that at low frequencies the disturbances will be muted.
c. Gζy(s) ≈ Pn(s), this indicates that the noise sensor will still be forwarded.

While when the value of the filter Q(s) close to 0 then the equation becomes y ≈P(s)v + P(s)d, so the disturbance observer will make the output signal does not affect the noise sensor. In control system applications the main dominating disturbances are low frequency, while the noise sensor will dominate the high frequency. Order filter Q(s) should be higher or equal to nominal system order Pn(s). The filter structure widely used in DOB design is a binomial filter expressed by the following equation [5].

$$Q(s) = \left\{1 + \left[\sum_{k=1}^{N-r} ak(Ts)^k\right]\left[\sum_{k=1}^{N-r} ak(Ts)^k\right]^{-1}\right\} \quad (10)$$

where,

N : filter order
r : relative order

In this research the filter used is Binomial filter of order 1. The reason for choosing 1st order filter is because by choosing a low order it will get a simple structure and can save computation time. By entering the value of N = 1 and r = 1 then we will get the desired filter equation.

$$Q(s) = \frac{1}{\tau_f(s)+1} \quad (11)$$

Where,

τ_f : *Time Constant filter*

The ability of DOB in dampening disturbance will be greatly determined by the time constant of the filter used, the smaller the constant time the bandwidth of the filter will be wider and the range of DOB work in resisting the disturbance will be wider too. However from Equation (3) shows wide bandwidth resulting in a system more sensitive to noise. In the implementation of the time constant value of the filter will be set up to produce the best capability limit. The DOB method is generally implemented using a two-loop structure as shown in Figure 3 [2].

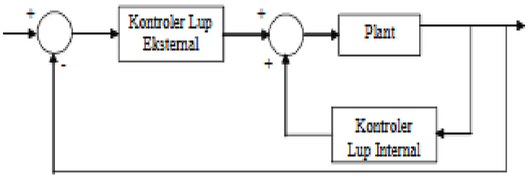

Fig. 3. Block Diagram of Disturbance Observer

With the above structure, internal loop controllers produce corrective control signals to reduce disturbance to the maximum extent possible to make the actual plant a nominal model. So if the internal loop controller is working properly then the actual plant with internal loop controller can be considered as a nominal model. While the external loop controller is designed to improve overall system performance, where the controller is designed based on the nominal model. Many studies with DOB methods use PID controllers as external loop controllers [4], [5]. The PID controller is chosen because of its ability to increase the speed of the system response. Since the internal loop has made the actual plant a nominal model, the PID controller is designed based on the nominal model.

III. System Design

A. System Overview

The expected system specifications achieved in the design of this Final Project is the motor speed response capable of following the set point either when given minimum or maximum load. The designed system structure is shown in Figure 4.

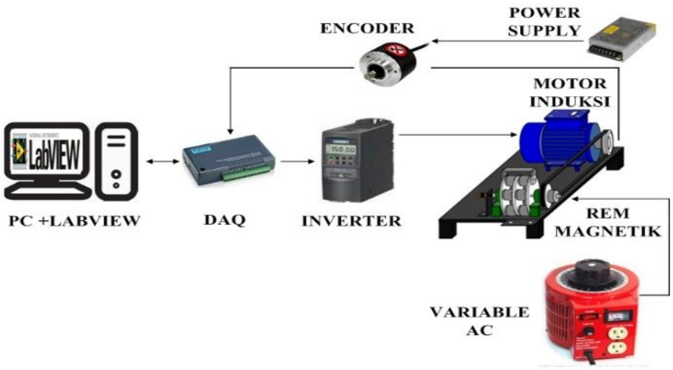

Fig. 4. System Architecture

While the block diagram of the system to be designed can be seen in Figure 5.

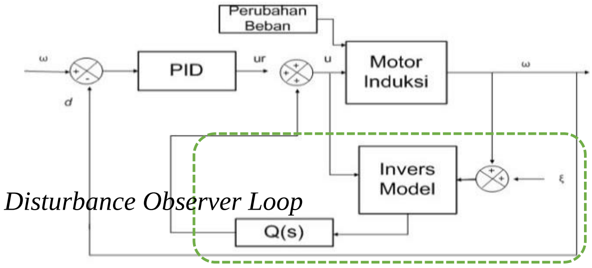

Fig. 5. Simulink Diagram Control Motor Speed Conduction

Computers with Labview are used as control processes and as HMIs for operators to monitor motor rotation speed. The PID + Disturbance Observer controller is designed using Labview 2014 software with and output control signal transmitted via DAQ Advantech USB-4716 analog output, DAQ signal output is analogue signal with range between 0 - 10 VDC. The DAQ output signal is used to provide input to the inverter, then the inverter converts it into a frequency change so that the induction motor rotation becomes manageable. Rotary encoder sensor functions to detect the speed of motor (rpm) by converting the number of pulses that produced by rotary encoder by DAQ.

B. System Identification

An identification method is needed to find the model response closest to the plant response. Identification on the induction motor is done on an open loop system using dynamic identification. Dynamic identification is done by giving random or random signals. This signal is commonly referred to as PRBS signal (Pseudo-Random Binary Sequence). For the given setpoint is 700 - 800 rpm and added the loading of a magnetic brake. For its configuration can be seen in figure 6. In this research identification is done using toolbox identification in Matlab software. From the input and output signals can be formed to the function transfer equation through process identification (P2D) on the Matlab toolbox. After obtaining the mathematical model from the plant, then validate the error with MSE to model the result of identification close to the original model.

C. Overview of Data Retrieval System

In this research, 3 phase induction motor is given load of electromagnetic brake. This load illustrates the conditions in a process on the conveyor used to transport the wet material driven by a 3-phase induction motor. The loading is done with 3 different values, ie minimum load, nominal and max. The Voltage values that enter into the electromagnetic brake can be seen in Table 1. As for the results can be seen in Table 2.

TABLE I. Method of Loading System.

Loading Method	Value
Minimum	0 Volt
Nominal	60 Volt
Maximum	120 Volt

TABLE II. INDENTIFICATION RESULT FOR EACH LOADING CONDITION

No	Loading Method	Matematic Model
1.	Minimum Load	$\frac{101.3}{s^2+1.430s+0.7580}$
2.	Nominal Load	$\frac{115.6}{s^2+1.620s+0.8775}$
3.	Maximum Load	$\frac{127.8}{s^2+1.731s+0.9891}$

The response output from the mathematical model approach to each loading condition is shown in Figure 6.

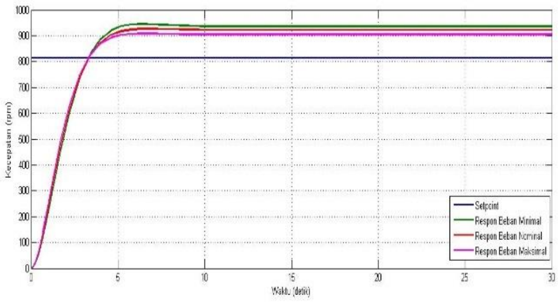

Fig. 6. Response Result in each loading condition

D. Design of PID Controller + Disturbance Observer Controller

Design of PID Controller + Disturbance Observer is a merger between PID controller and Disturbance Observer method. It is hoped that with the integration of both PID controllers can improve system performance while the Disturbance Observer method can maintain steady state value when various load values are given.

1) PID Controller Parameters

To obtain the objectives achieved, it is necessary to design the PID controller applied to the induction motor speed control system, designing the controller in question is a conventional PID controller in the loop in the system. The design of the conventional PID controller is done to control the speed of the induction motor according to the design requirements. Here are the steps to get PID controller parameters from Induction Motor by manual tuning:

a) Gain a value of proportional gain Kp with initial value 1. Gain Kp used to get the output response value close to the desired, while the value of Ki and Kd parameters made zero. Then tuning the parameters Kp according to the needs of design.

b) Gives Ki integral gain value with value 1. Gain Ki is used to speed up the transient response and to eliminate steady state error, while the value of Kd is made zero. Then tuning on Ki parameters according to the needs of design.

c) Gives a derived derivative value of Kd with a value of 1. The Kd Gain is used to slow the response on the transient and reduce the overshoot on the output response.

From the steps of obtaining the parameter values Kp, Ki, Kd on the PID controller, the parameter values of the PID controller on the induction motor with the nominal load and the 700 rpm input are obtained. Table 3.1 shows the parameters of the PID controller obtained.

TABLE III. PARAMETERS OF PID CONTROLLER

Parameter	**Value**
Kp	0.093
Ki	0.0056
Kd	0.002

2) Disturbance Observer Method

The method used to adjust the speed of the induction motor in this study is DOB. This method is used for a robust system to load changes. There are several stages done in this design such as finding the inverse model of the nominal plant mathematical model and looking for inverse models such as Equation (12) and Q-filter design. Then it will be transformed into discrete to get the inverse model as in Equation (13).

$$\frac{y(z)}{u(z)} = \frac{b0+b1z^{-1}+b2z^{-2}}{a0+a1z^{-1}+a2z^{-2}} \qquad (12)$$

Equation (13) is a discrete transformation of Equation (12) into the Tustin form.

$$a0y(z) + a1y(z)z^{-1} + a2y(z)z^{-2} = b0u(z) + b1u(z)z^{-1} + b2u(z)z^{-2} \qquad (13)$$

From Equation (13) we obtain Equation (14)

$$a0y(k) + a1y(k-1) + a2y(k-2) = b0u(k) + b1u(k-1) + b2u(k-2) \qquad (14)$$

To estimate the control signal on the plant when the load changes, the equation is in the equation

$$u(k) = \frac{1}{b0}(-b1u(k-1) - b2u(k-2) + a0y(k) + a1y(k-1) + a2y(k-2) \qquad (15)$$

With value

a0 = 1;	b0 = 7.1958e-04
a1 = -1.9919;	b1 = 0.0014
a2 = 0.9919;	b2 = 7.1958e-04

In the DOB design, it is important to select the appropriate Q (s) filter. Generally the designed Q - filter is the Low Pass Filter (LPF). Control system in this research using first order LPF. By entering the value of N = 1 and r = 1 in Eq. (10), we obtain Equation (16) which shows first order LPF.

$$Q(s) = \frac{1}{\tau_f(s)+1} \qquad (16)$$

With,

$$\tau_f \leq \frac{1}{3}\tau_p$$

Where,

τ_f : *time constant filter*

τ_p : *time constant plant*

IV. Testing and Analysis

A. Magnetic Brake Testing

This test is used to determine the speed reduction caused by magnetic brakes. Imposition is divided into three parts, the no-load, nominal load and maximum load. The magnitude of the load is set by giving Voltage of the Variac onto the magnetic brake. Variac for maximum load Voltage is 120 Volts, nominal load Variac Voltage is 60 Volts, while the no-load Voltage is 0 Volts Variac. Figure 7 shows a decrease in the speed of three phase induction motor.

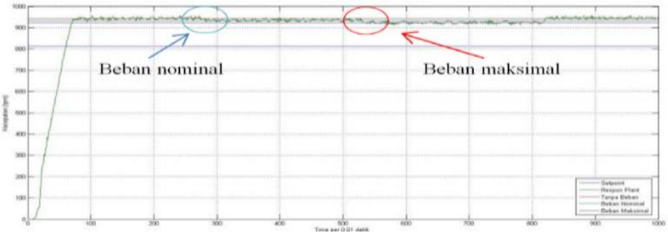

Fig. 7. Decrement graph of the speed of three phase induction motor

The test results obtained from the decreased speed data of three-phase induction motors as shown in Table 4.

TABLE IV. The Test Results of Magnetic Brakes

Load	Speed (rpm)
Setpoint	812
No Load	935
Nominal	922
Maximum Load	904

B. Overall System Simulation

This phase was conducted to determine and test the working process of the controller that has been designed. The test was performed using Matlab software. In this research, the tests were conducted for the PID controller and PID + Disturbance Observer. The block diagram is shown in Figure 8.

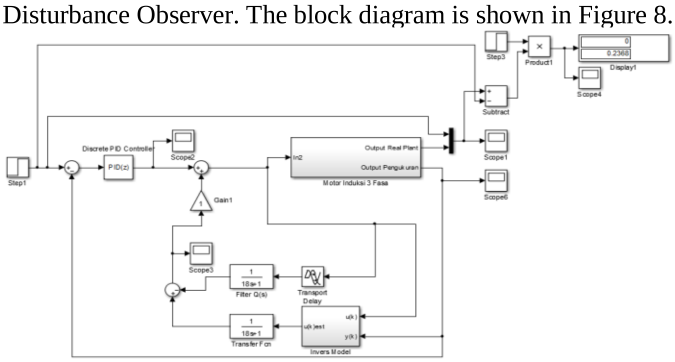

Fig. 8. Simulink block diagram of the whole PID + DOB system

C. Invers Model of Plant with Nominal Load

At this stage, the inverse model of the plant at nominal load will be generated. It is expected that with the inverse models gained, the control signal can be estimated, the purpose is for when the load changes or noise measurements are entered into the system. Later inverse model with the help of filters will keep the system stay in nominal models.

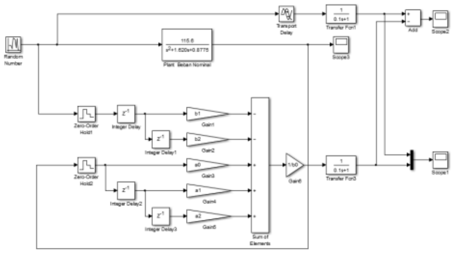

Fig. 9. Simulink Diagram of Invers Model of the Plant

D. Simulation test of PID controller

At this stage, the PID controller that has been designed will be simulated. This test is performed by giving an input step in all load ranges from minimum load to maximum load. After that the response will be analyzed to find the value of rise time, settling time, overshoot, and steady state error.

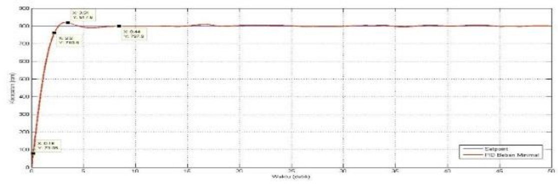

Fig. 10. The response of the simulation test of PID with minimum load

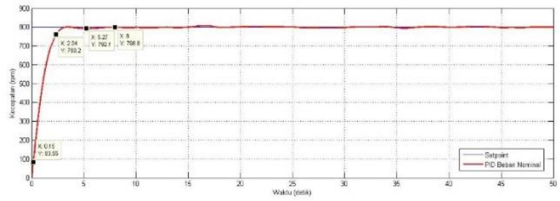

Fig. 11. The response of the simulation test of PID with nominal load

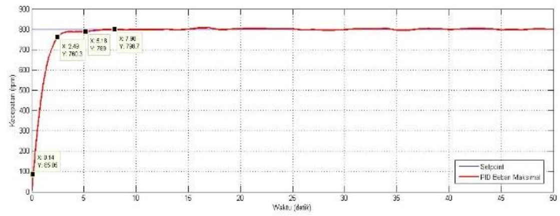

Fig. 12. The response of the simulation test of PID with maximum load

Specifications response of the system after being given a PID controller on the condition of minimum load, nominal load and the maximum load can be seen in Table 5.

TABLE V. Internal Factors Evaluation Matrix

Specification	Loading condition		
	Minimum	Nominal	Maximum
t_s (5%)	8.4 seconds	8 seconds	8.1 seconds
t_r (5% - 95%)	2.33 seconds	2.49 seconds	2.65 seconds
Overshoot or *Undershoot*	2.875 %	1.525 %	1.95 %
Error Steady State	1 %	1.25 %	2.10 %

E. Simulation test of PID + DOB

PID controller + DOB testing aims to determine the response plant whether it is able to eliminate the noise measurement better than PID controller. Then it is analyzed to find the value of rise time, settling time, overshoot, and steady state error.

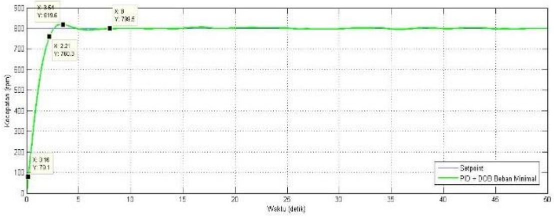

Fig. 13. Simulation response of PID controller with minimum load

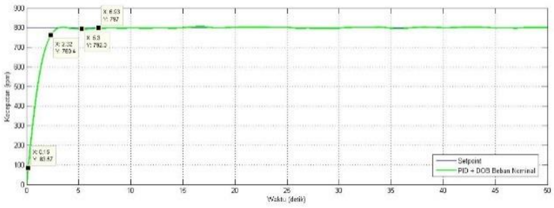

Fig. 14. Simulation response of PID controller with nominal load

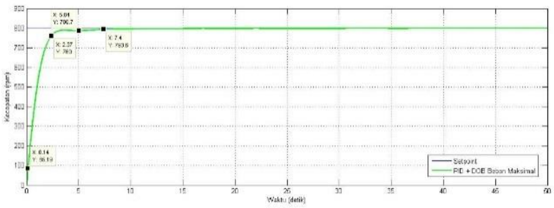

Fig. 15. Simulation response of PID controller with maximum load

Specifications response of the system after being given a PID controller + DOB at minimum load conditions, the nominal load and the maximum load can be seen in Table 6.

TABLE VI. RESPONSE ANALYSIS OF PID CONTROLLER + DISTURBANCE OBSERVER

Specification	Loading Condition		
	Minimum	Nominal	Maximum
t_s (5%)	8 seconds	6.93 seconds	7.4 seconds
t_r (5% - 95%)	2.3 seconds	2.2 seconds	2.60 seconds
Overshoot or *Undershoot*	2.3 %	1.3 %	0.91 %
Error Steady State	0.5 %	0.1 %	0.3 %

F. Analysis

The test results showed that the error steady state of PID controller is greater than the steady state error of PID controller + DOB with the same noise. Settling time of the PID controller + DOB is also superior then PID controller in the transient response specifications.

V. CONCLUSION

Based on the test results and analysis on simulation control of three-phase induction motor speed by using PID + Disturbance Observer we can conclude that:

1) The decrement of the speed from the minimum load to the total nominal load is 13 rpm, while the maximum load speed is 31 rpm.
2) The response of the plant using PID controllers can follow the pre-determined setpoint value with 1.3% error, and overshoot or undershoot of 1.8% time settling (ts) 5% for 8 seconds, and time rises (tr) for 2.4 seconds
3) The response plant using PID controller + DOB can follow the pre-determined setpoint value with 0.1 % of error, and overshoot or undershoot of 1.5%, time settling (ts) 5% for 7.1 seconds, and time rises (tr) for 2.2 seconds

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