# Comparative analysis of Cohen-Coon and Ziegler-Nichols tuning methods for three-phase induction motor with speed sensorless control

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**ABSTRACT**

The use of speed sensors in the speed controller of three-phase induction motors affects the reliability of the induction motors. In addition, the drive engine that is often used in industry is a three-phase induction motor. So, speed sensorless control is needed for induction motors to achieve the best performance. This study uses a discrete disturbance observer (D0) as feedback on the speed sensorless control. The controller used in this method is a discrete PI with the Cohen-Coon (CC) and Ziegler-Nichols (ZN) tuning method. The purpose of this study is to obtain a comparative analysis of the CC and ziegler nichols tuning method using a discrete PI on the speed sensorless control scheme with torque load variation. This study was carried out experimentally using an Alliance AY3A-90L4 induction motor. The results show that the CC tuning method is better under parameter efficiency and robustness against disturbance and ZN is better under parameter reliability.



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## 1. INTRODUCTION

The closed-loop control method on induction motors requires precise and accurate information about the rotary speed of the induction motor. The use of direct speed sensors, such as encoders, can reduce the reliability of the motor and require extra maintenance costs due to the vibration generated by the induction motor [1], [2]. This problem is overcome by designing a discrete disturbance observer (DO) as a substitute for a direct speed sensor by estimating the rotary speed value of the induction motor based on current sensor information. Discrete DO is a system that can estimate the variables of a plant expressed in the form of state space [3], [4]. The condition for the use of observers is that the system controlled must be proven observable [5]. The closed-loop control method using discrete DO is usually called speed sensorless control [6].

Various innovations have been made in the field of induction motor speed sensorless control, such as supply frequency control, direct torque control, and field-oriented control [7]-[9]. However, the overall control method is not economical, requiring additional devices, high computing loads, difficulty in controlling torque and flux, and varying switching frequencies [8], [10]. In previous works, discrete PI controller shows simple implementation, low cost, stability at slow dynamics, and low computational load [11]. PI discrete is becoming more suitable for use on various industrial scales [12], [13].

Two tuning methods are commonly used in discrete PI controllers, namely Ziegler-Nichols (ZN) and Cohen-Coon (CC). Recent research shows ZN is more widely used due to its simplicity in the tuning process based on the system's oscillation response [14] and has been used in various processes because of its simplicity and ease of implementation [15], [16]. Other research aiming to show CC tuning methods tend to be used for systems with well-identifiable mathematical models, especially for plants that exhibit dead time properties [17]-[19]. An optimal tuning method is required in discrete PI controllers based on the controlled plant. Inconsistency of tuning methods will cause the control system to have poor performance and poor adaptability to operating conditions [20], [21]. A better controller performance will give better efficiency, robustness of disturbance, and good reliability of the induction motor [22]-[25]. Moreover, a comparative analysis of CC and ZN tuning methods on induction motors is needed to determine the most optimal performance of the control system for induction motors in specific parameters, which are the efficiency, robustness, and reliability of the induction motor.

However, there has been no in-depth research on the quantitative identification of CC and ZN tuning methods for discrete PI controllers in dealing with complex induction motor dynamics. Based on this finding, this study proposes a comprehensive quantitative analysis of the ZN and CC tuning methods on discrete PI controllers for induction motors. This study will compare the two methods in two operational conditions, namely no load and with load. Pada studi ini, sistem kontrol akan diintegrasikan dengan discrete DO. This gap is an opportunity in this study to see how both methods work in speed sensorless schemes using discrete DO and various situations, such as transient response, steady-state errors, and sensitivity to load changes. This is in contrast to previous studies that focused more on the application of one tuning method. This research provides new insights into the advantages and limitations of each tuning method. Therefore, this research is expected to provide more accurate and useful guidance for academics and industry practitioners in choosing the best tuning method for speed sensorless control on induction motors in various conditions.

This study aims to obtain a comparative analysis of the CC and ZN tuning method using a discrete PI on the speed sensorless control scheme without torque load and with torque load variation through experiment. The discrete DO will be used to replace the role of the encoder as the speed informant in real-time. The test was carried out in three schemes, namely without load, with a 170 Watts load and 200 Watts load. The analysis was carried out to determine the optimal performance of the tuning method between CC and ZN in terms of energy efficiency, robustness to disturbance, and reliability of the induction motors.

## 2. METHOD

### 2.1. System description

In this study, the software used was MATLAB and Simulink. Meanwhile, the hardware used is a Data Acquisition National Instrument (DAQ NI USB-6001), Toshiba VF-nC3 Inverter, infrared velocity measurement module (IR HW-201), SCT-013 current measurement module, Arduino, and a three-phase induction motor Alliance AY3A-90L4. Table 1 shows the specification of Alliance AY3A-90L4

Figure 1 shows the set-up of the three-phase induction motor system in this study. Data Acquisition is used as an interface between the computer and hardware with an output signal produced in the form of a voltage of 0–10 VDC. The microcontroller used is an Arduino which functions as a speed validator by reading the speed sensor module through revolution time in digital signal produced by IR HW-201. The inverter is used as a one-phase AC voltage converter to a three-phase AC voltage with an output that can be adjusted to the frequency value in the range of 0–50 Hz. DC generators are varied as a variable disturbance in the system. The control carried out by MATLAB and Simulink is included in the controller.

The induction motor system is equipped with a JKEXER DC generator. The DC generator functions to generate DC current when rotated by the rotor of the induction motor. The faster the induction motor rotates, the greater the DC current produced. A series of DC lamps arranged in series and parallel are connected with DC generators as fixed loads of 170 and 200 Watts.

Table 1. Specification of plant

| Parameter | Value |
|---|---|
| Pole (P) | 4 |
| Power | 1.5 kW, 2 HP |
| Max Frequency | 50 Hz |
| Max Speed | 1440 RPM |
| Efficiency | 78.5% |
| Power Factor | 0.78 |
| Rotor Inertia | 0.031 $kgm^2$ |

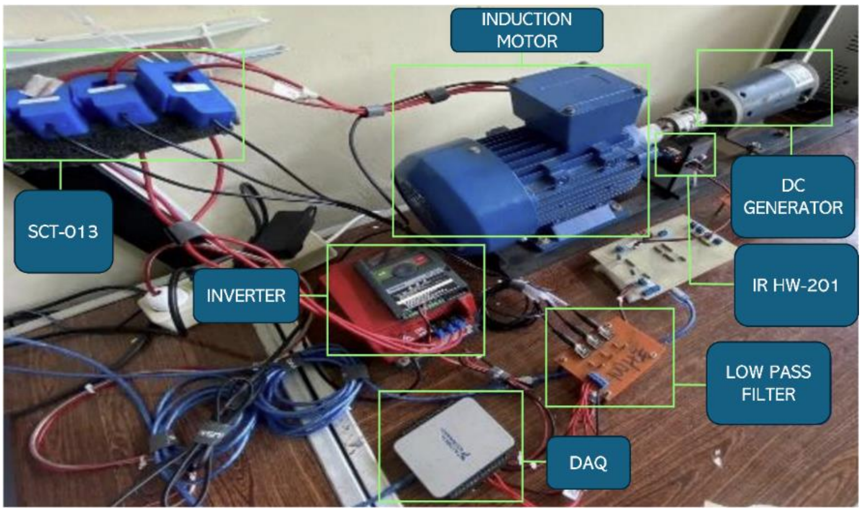


Figure 1. Three-phase induction motor system set-up

The following is a mathematical model of a 3-phase induction motor in the state space equation [26].

$$\begin{bmatrix} \dot{i}_{\alpha s} \\ \dot{i}_{\beta s} \\ \dot{\varphi}_{\alpha r} \\ \dot{\varphi}_{\beta r} \end{bmatrix} = \begin{bmatrix} -A_1 & 0 & A_2 & 0 \\ 0 & -A_1 & 0 & A_2 \\ A_4 & 0 & -A_5 & 0 \\ 0 & A_4 & 0 & -A_5 \end{bmatrix} \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \\ \varphi_{\alpha r} \\ \varphi_{\beta r} \end{bmatrix} + \begin{bmatrix} A_3 & 0 \\ 0 & -A_3 \\ -\frac{P}{2} & 0 \\ 0 & \frac{P}{2} \end{bmatrix} \begin{bmatrix} d_\alpha \\ d_\beta \end{bmatrix} + \begin{bmatrix} B_1 & 0 \\ 0 & B_1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{\alpha s} \\ v_{\beta s} \end{bmatrix} \quad (1)$$

the above equation can also be written as (2):

$$\dot{x} = Ax + Bu + D_d d \quad (2)$$

The disturbance ($d$) of the system can be written as (3) and (4):

$$d_\alpha = \omega_r \varphi_{\beta r} \quad (3)$$

$$d_\beta = \omega_r \varphi_{\alpha r} \quad (4)$$

where, $A_1 = \frac{L_m^2 R_r + L_r^2 R_s}{\sigma L_r^2 L_s}$, $A_2 = \frac{L_m R_r}{\sigma L_r^2 L_s}$, $A_3 = \frac{P\, L_m}{2\sigma L_r L_s}$, $A_4 = \frac{L_m R_r}{L_r}$, $A_5 = \frac{R_r}{L_r}$, and $B_1 = \frac{1}{\sigma L_s}$. The values of electrical and mechanical parameters are shown in Table 2. The value of electrical and mechanical parameters in is obtained based on the condition of the plant used.

Table 2. Electrical and mechanical parameter of induction motor

| Parameters | Symbols | Value |
|---|---|---|
| Pole | $P$ | 4 |
| Motor Inductance | $L_m$ | 9.249 H |
| Stator Resistance | $R_s$ | 4.85 Ω |
| Rotor Resistance | $R_r$ | 7.805 Ω |
| Stator Inductance | $L_s$ | 0.274 H |
| Rotor Inductance | $L_r$ | 4.274 H |
| Rotor Inertia | $J$ | 0.031 $kgm^2$ |

### 2.2. Implementing discrete disturbance observer

In this study, the induction motor rotation speed estimator is designed based on the dynamic model of the plant. The modeling of the induction motor plant was changed to obtain the discrete DO equation. DO is a modified form of Luenberger Observer with the addition of state vector d which is called disturbance [26]. The discrete DO implementation method in this study is carried out by referring to the algorithm that has been developed [27].

$$\dot{\widehat{x_a}}(k+1) = A_d\widehat{x_a}(k) + B_d u(k) + L\left(i_s(k) - \widehat{i_s}(k)\right) \quad (5)$$

$$\hat{y} = C_a x_a(k) \quad (6)$$

where, $k$ is the time index on the discrete and $L$ is the observer gain obtained through LQR. The values of the parameters $x_a$, $A_d$, and $B_d$ are as (7)-(9):

$$x_a = \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \\ \varphi_{\alpha r} \\ \varphi_{\beta r} \\ d_\alpha \\ d_\beta \end{bmatrix} \quad (7)$$

$$A_d = I + \begin{bmatrix} A & D_d \\ 0 & \varepsilon I \end{bmatrix} T_s \quad (8)$$

$$B_d = \begin{bmatrix} B \\ 0 \end{bmatrix} \quad (9)$$

Discrete DO implementations require stator current and stator voltage information in phase $\alpha$ and $\beta$. The current information is provided through the SCT-013 sensor installed on the three phases U, V, and W.

### 2.3. Designing speed sensorless control using discrete PI

The design of the PI discrete is carried out by looking for the proportional and integral parameters of the system. Tuning of PI parameters is performed in open loop conditions. The goal of the control is to increase rise time and reduce steady state errors to below 5%. The design was carried out by 2 methods, namely the CC and ZN methods with tuning tables as in Tables 3 and 4.

Table 3. Tuning table CC [28]

| Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | $\frac{\tau_m}{Kt_d}\left(1+\frac{t_d}{3\tau_m}\right)$ | - | - |
| PI | $\frac{\tau_m}{Kt_d}\left(0.9+\frac{t_d}{12\tau_m}\right)$ | $t_d\left(\frac{30+\frac{3t_d}{\tau_m}}{9+\frac{20t_d}{\tau_m}}\right)$ | - |
| PID | $\frac{\tau_m}{Kt_d}\left(1+\frac{t_d}{3\tau_m}\right)$ | $t_d\left(\frac{32+\frac{6t_d}{\tau_m}}{13+\frac{8t_d}{\tau_m}}\right)$ | $t_d\left(\frac{4}{11+\frac{2t_d}{\tau_m}}\right)$ |

Table 4. Tuning table ZN [29]

| Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | $\frac{T}{L}$ | - | - |
| PI | $0.9\frac{T}{L}$ | $\frac{L}{0.3}$ | - |
| PID | $1.2\frac{T}{L}$ | $2L$ | $0.5L$ |

where, $\tau_m$ is the effective time constant from the first-order response, $t_d$ is dead time, and $K$ is the result of dividing the steady state output with the input step. These parameters are searched using the (10)-(12):

$$K = \frac{\Delta Output}{\Delta Input} \quad (10)$$

$$\tau_m = 1.5(t63\% - t28\%) \quad (11)$$

$$t_d = t63\% - \tau_m \tag{12}$$

where, $T$ is the time constant and $L$ is the delay time. These parameters are searched using the (13) and (14):

$$T = 1.5(t63\% - t28\%) \tag{13}$$

$$L = t63\% - T \tag{14}$$

Controller gain retrieval was carried out at 2-speed variations, namely 0 RPM to 800 RPM and 0 RPM to 1200 RPM. Data collection was carried out on an open-loop scheme. Speed information is obtained by the IR HW-201 speed measurement module. Data collection was carried out for 30 seconds with a sampling time of 0.01 seconds. Table 5 shows the results of the calculation of the tuning parameters of CC and ZN at both speed variations.

Table 5. Tuning parameter discrete PI

| RPM tracking | K | $t28\%$ | $t63\%$ | $\tau_m$ (s) | $t_d$ (s) | T (s) | L (s) |
|---|---|---|---|---|---|---|---|
| 0-800 | 1 | 4.329 | 8.711 | 6.573 | 2.138 | 6.573 | 2.138 |
| 0-1200 | 1 | 5.28 | 10.543 | 7.895 | 2.648 | 7.895 | 2.648 |

The controller that has been obtained is then analyzed on the speed sensorless scheme using discrete DO with a block diagram as shown in Figure 2. In Figure 2, the transmission of information from Software and Hardware is carried out through DAQ. The signal obtained from DAQ to the software (Personal Computer) will be sampled to convert the continuous to discrete with a sampling time of 0.01 s.

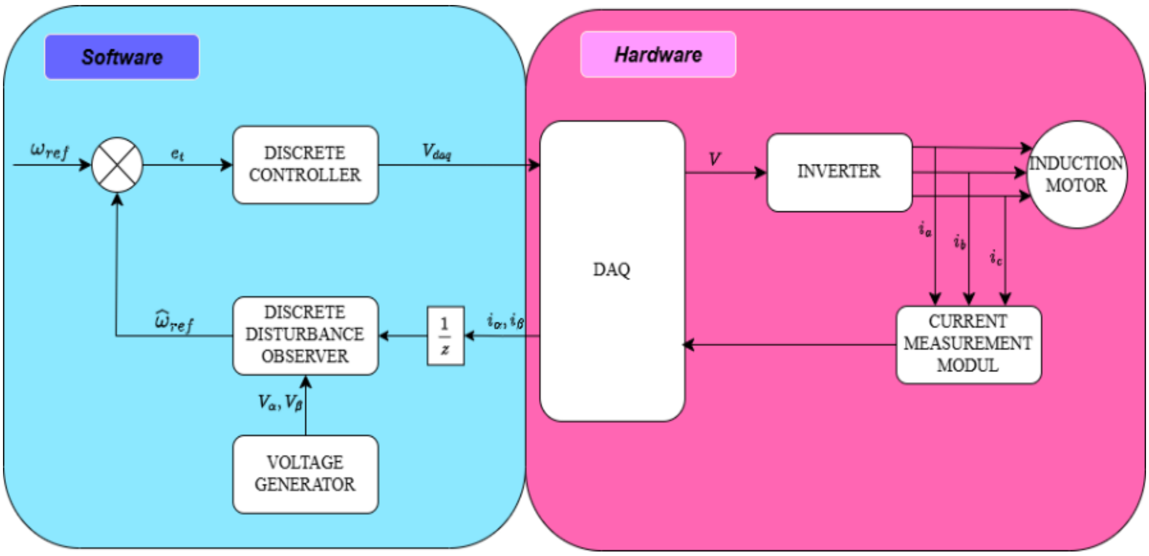


Figure 2. Block diagram of speed sensorless PI control

## 3. RESULTS AND DISCUSSION

The calculation of proportional and integral gain using the CC and ZN methods is carried out based on equations obtained from Tables 3 and 4. Table 6 demonstrates that the values $K_p$ and $K_i$ are obtained in the CC and ZN tuning methods are different. The value of $K_i$ on the CC method is greater than on the ZN method. The magnitude of the value is predicted to affect the rise time and overshoot value of the control system response. The integral gain character tends to accelerate the system's response which makes the system overshoot or undershoot [30]. Control is carried out through Simulink MATLAB utilizing the discrete PID. The values of K_p and K_i in the discrete block parameters of PID are obtained from the information in Table 6.

Table 6. PI gain value

| RPM tracking | Method | $K_p$ | $T_i$ | $K_i$ |
|---|---|---|---|---|
| 0-800 | Cohen-Coon | 2.849 | 4.269 | 0.667 |
| 0-1200 | | 2.766 | 5.224 | 0.529 |
| 0-800 | Ziegler-Nichols | 2.766 | 7.126 | 0.388 |
| 0-1200 | | 2.683 | 8.826 | 0.303 |

Figures 3 and 4 show the control system's response to no-load conditions. Figures 5 and 6 shows the response of the control system under conditions with load variations of 170 and 200 Watts at speeds of 800 RPM, while Figures 7 and 8 show the response of the control system at load conditions of variation of 170 and 200 Watts at speeds of 1200 RPM. In each figure of the response test result, there is a ripple that arises from the reading of the IR HW-201 speed sensor. This ripple arises due to the reading of the IR-HW201 sensor based on the revolution time of the digital signal changes (1 and 0) sent by Arduino via DAQ to Simulink MATLAB. This ripple value is also affected by its sensitivity to light from the sensing element on the sensor. Ripple will not affect the results of the control system, because the speed sensorless control-based control system will not be affected by the results of the speed sensor.

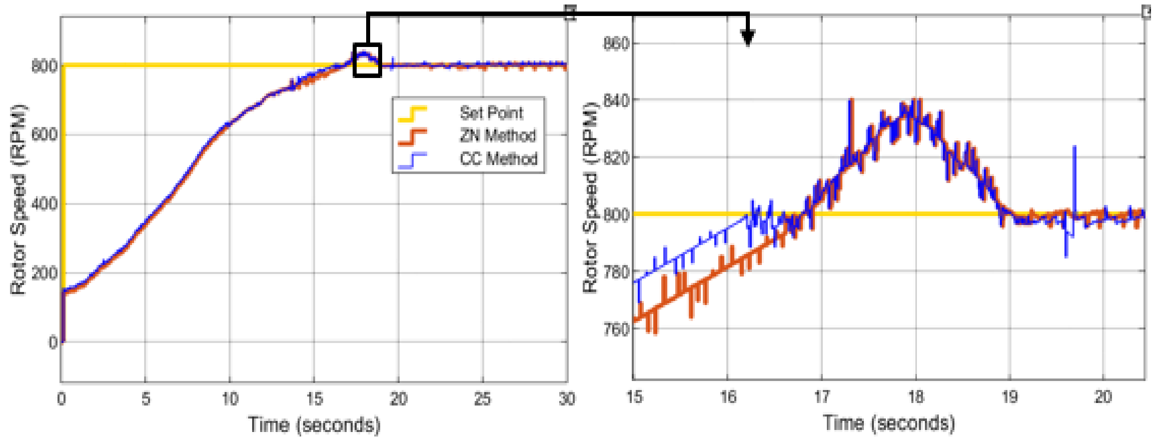


Figure 3. Testing at 800 RPM

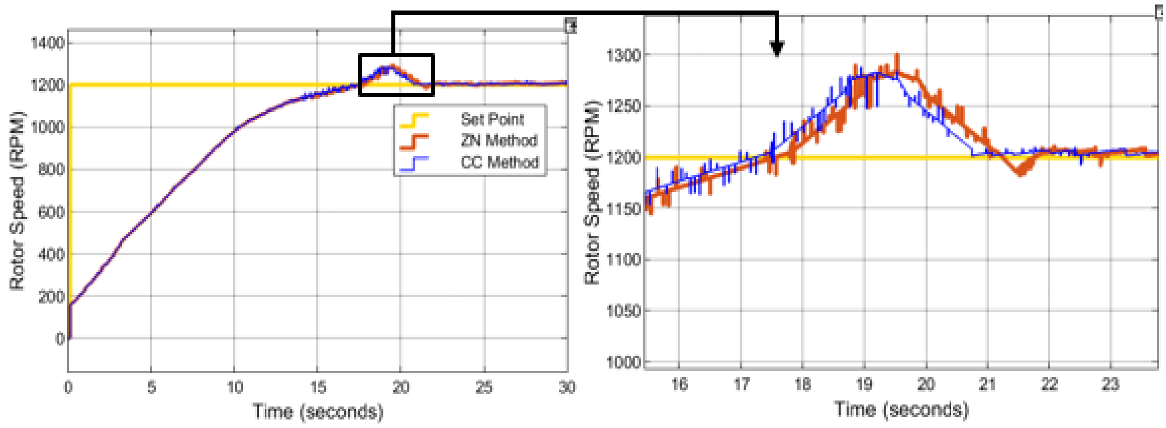


Figure 4. Testing at 1200 RPM

The analysis of the control system response in Figures 3 and 4 is shown in Table 7, while Figures 5 to 8 are shown in Table 8. It is found that in all variations in speed and load conditions as well as without load, the CC tuning method has a better rise time value. The result corresponds to the magnitude of the integral gain value of the CC tuning method is greater than that of ZN. This result is in accordance with the theory where the integral gain value tends to accelerate the system response in achieving a steady state value with the impact having an overshoot [30]. This impact is also shown in the increase in overshoot along with the increase in the rotation speed of the induction motor at 1200 RPM compared to 800 RPM.

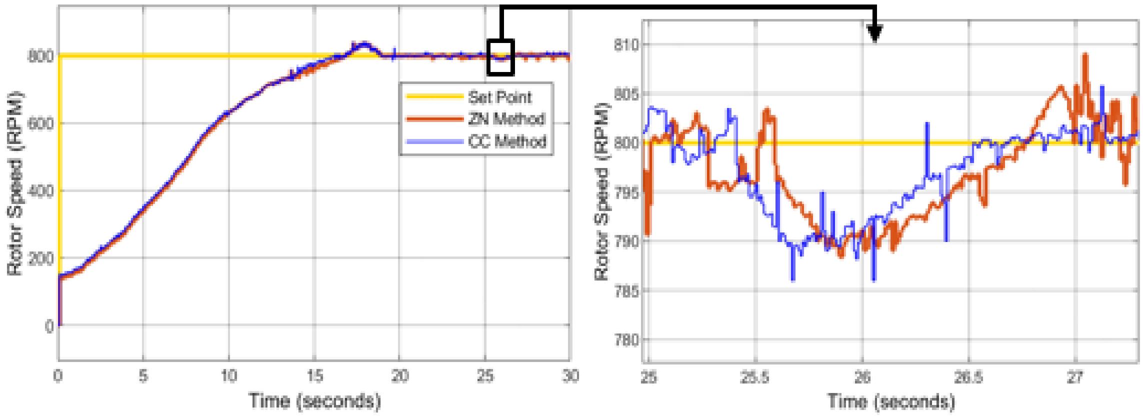


Figure 5. Testing at 800 RPM with 170 Watt load

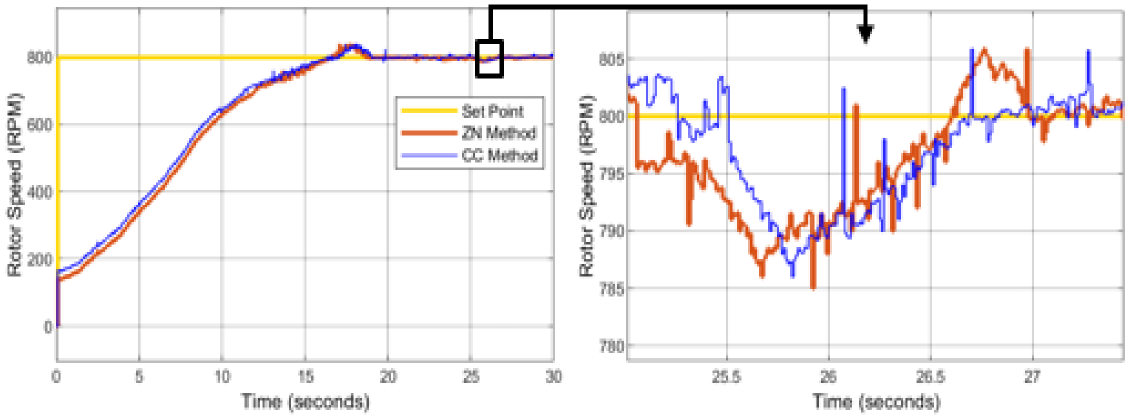


Figure 6. Testing at 800 RPM with 200 Watt load

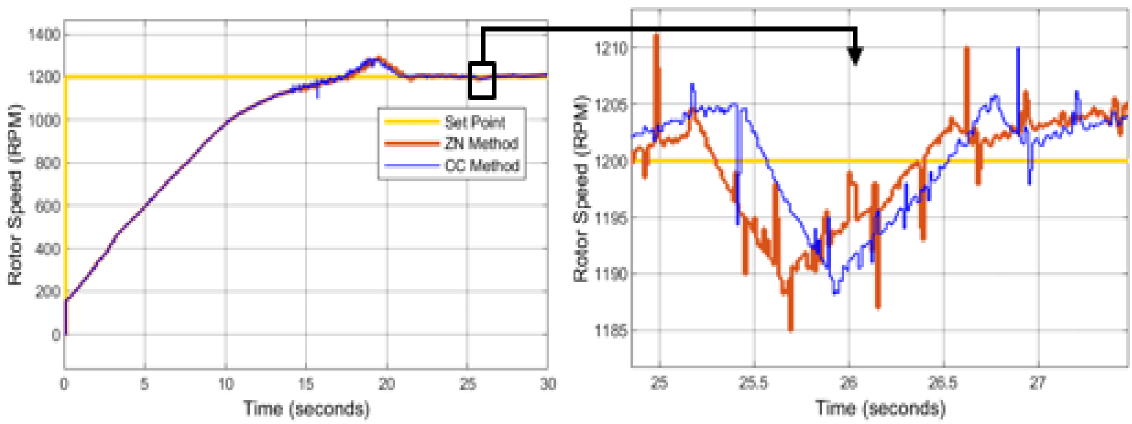


Figure 7. Testing at 1200 RPM with 170 Watt load

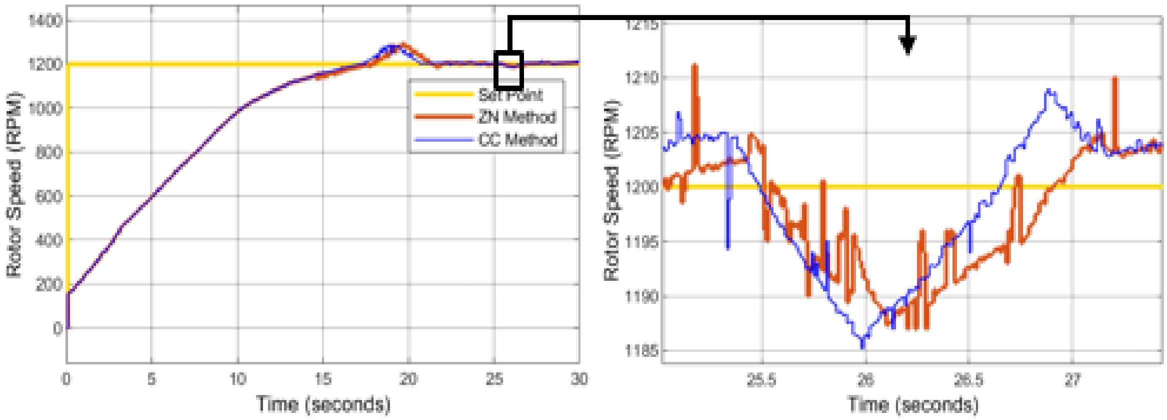


Figure 8. Testing at 1200 RPM with 200 Watt load

Table 7. No-load discrete PI test results

| Tuning method | RPM tracking | Rise time (s) | Settling time (s) | Overshoot (%) | Steady state error (%) |
|---|---|---|---|---|---|
| | 0-1200 | 16.956 | 20.544 | 6.92 | 0.37 |
| Cohen-Coon | 0-800 | 12.232 | 16.255 | 6.26 | 0.45 |
| | | Average Steady State Error (%) | | | 0.41 |
| | 0-1200 | 17.188 | 21.489 | 6.86 | 0.79 |
| Ziegler-Nichols | 0-800 | 12.897 | 17.288 | 6.25 | 0.43 |
| | | Average Steady State Error (%) | | | 0.46 |

Table 8. With load discrete PI test results

| Speed (RPM) | Method | Load (Watt) | Rise time (s) | Settling time (s) | Overshoot (%) | Steady state error (%) |
|---|---|---|---|---|---|---|
| 800 | Ziegler-Nichols | 170 | 27.12 | 27.31 | 0.62 | 0.37 |
| | | 200 | 27.29 | 27.66 | 0.65 | 0.32 |
| 1200 | | 170 | 27.21 | 27.39 | 0.33 | 0.33 |
| | | 200 | 27.33 | 27.42 | 0.41 | 0.44 |
| | Average | | 27.24 | 27.45 | 0.50 | 0.37 |
| 800 | Cohen-Coon | 170 | 26.78 | 27.14 | 0 | 0.38 |
| | | 200 | 26.99 | 27.20 | 0.60 | 0.31 |
| 1200 | | 170 | 26.91 | 27.18 | 0.43 | 0.47 |
| | | 200 | 27.01 | 27.35 | 0.74 | 0.12 |
| | Average | | 26.92 | 27.22 | 0.44 | 0.32 |

From the analysis of four control system response parameters, namely rise time, overshoot, settling time, and steady-state error, it shows that CC has a better parameter value than ZN, except for the overshoot parameter as the price of the high integral gain value is owned by CC. The analysis of the impact of the controller on the induction motor is carried out by assessing three aspects, namely efficiency, robustness, and reliability of the system.

The efficiency of the control system weighs the power usage used by the induction motor through the inverter. This value is represented by the system's ability to achieve a steady state quickly. In the transient response, the induction motor experiences a suboptimal parameter change, causing unstable current and torque [31]. The instability of current and torque values in transient conditions will cause the induction motor to suffer power losses. To improve the efficiency of the PI control system, the determination of tuning methods that can shorten transient response times or have low settling and rise times will have an effect. In this condition, the CC tuning method has a better average response value of 0.989 seconds, and a better rise time of 0.449 seconds compared to ZN in a no-load scenario. In loading, CC also had a better average settling time response of 0.23 seconds and a better rise time of 0.32 seconds compared to ZN. The results showed that CC was 5.1% better in the settling time aspect and 2.98% in the rise time aspect compared to ZN.

The robustness of the control system can be seen from its performance in overcoming external disturbances. The robustness of a control system can be analyzed based on its ability to compensate the external disturbance [32]. In this study, the variation in DC load acts as an external disturbance. The information from Figures 5 to 8 shows that the control system response to both tuning methods can overcome disturbances in the form of changes in torque load. The analysis was carried out to determine better performance against external interference. The results showed that in the parameters of settling time, rise time, and steady-state error, the CC tuning method had better performance. The ZN tuning method has a better value for the overshoot parameters. These results show that the performance of CC control is better in overcoming disturbances at a slightly higher price than the ZN tuning method.

Reliability is an important parameter in induction motors. Induction motors with rapidly declining reliability will be detrimental to the industry in terms of economy and system performance efficiency. One way to ensure the reliability of an electric motor is the magnetic vibration that occurs in the system [33]. The relationship of the closed-loop control system to the vibration generated in the motor is closely related to the resulting overshoot. Induction motor systems that have overshoot, especially at high speeds will produce higher vibrations. Therefore, the analysis of the control system's performance on the reliability of the system is reviewed based on the resulting overshoot value. The ZN tuning method has an average overshoot of 0.035% better than CC under no load. The loading scenario also showed that the ZN tuning method had an average overshoot of 0.06% better than CC. The results showed that the ZN tuning method was 12% more efficient in the overshoot parameter with load and 0.532% better in the no-load condition. These results show that the ZN tuning method has a better influence on the reliability of the induction motor which is judged by the magnetic vibrations generated due to overshoot.

In the system response graph, it is found that the controller after responding to an overshoot will respond to return to the desired set point. Where, in each variation, there was no second overshoot or undershoot response. This indicates that the system does not experience excessive oscillation after an overshoot. The speed at which the system achieves a steady in steady-state error tolerance below 5% is called settling time. The settling time required by a speed of 800 rpm tends to be faster because the rotor of the induction motor will be faster to go to a steady state at lower speeds. As for the comparison of tuning methods, it was found that CC had a better settling time response.

Table 9 shows a summary of the findings of this study. Both tuning methods have their advantages and uniqueness. The selection of the right tuning method depends on the conditions and needs of the plant that has a better response. The selection and implementation of CC and ZN tuning methods will have a good response depending on their needs. The CC method is suitable for systems that require efficiency, electrical power savings, and robustness against disturbances, such as changes in torque loads. The ZN method is more suitable for induction motor systems that operate at high speeds and are susceptible to vibration anomalies and sensitive to overshoot or undershoot.

Table 9. Major findings in this study

| Comparative parameters | Tuning method | |
|---|---|---|
| | Ziegler-Nichols | Cohen-Coon |
| Energy Efficiency | | V |
| Robustness against Disturbance | | V |
| Reliability | V | |

## 4. CONCLUSION

This study compares CC and ZN tuning methods on the efficiency, robustness, and reliability parameters of the induction motor plant. The analysis was carried out on four closed-loop response parameters, namely rise time, settling time, overshoot, and steady-state error with a variety of torque loads, namely no-load, 170 watts, and 200 Watts. Comparative analysis of CC and ZN was carried out by looking at the performance of the control system on the efficiency, robustness, and reliability of the induction motor plant. The results showed that the CC tuning method was better on the parameters of energy efficiency and robustness against interference. While the ZN method has smaller overshoot characteristics, it is a better choice to consider the reliability conditions of the induction motor. The selection and implementation of CC and ZN tuning methods will have a good response depending on their needs. This study provides consideration to academics and practitioners in choosing tuning methods for discrete PI controllers, especially in speed sensorless control schemes with discrete DO.

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