Speed Control of Three Phase 1.5 kW Induction Motor using VSD LS SV015IG5A-2 with Proportional Integral Anti-Windup Method

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***Abstract*—The industrial world in Indonesia is experiencing increasing development. In general, most of the tools in the industrial world use electric motors as the main drive. Induction motors are alternate current (AC) electric motors that are most widely used to support performance in the industrial world. Factors that make induction motors commonly used in the industrial world are due to high efficiency and performance, a size that is not too large, easier maintenance, and does not cost much. The drawback of the induction motor is that controlling the speed of the induction motor is not easy and includes a non-linear motor. Therefore, the right technology is needed to regulate the speed of the induction motor to remain stable when given a change in load. The research conducted is the speed regulation of a 220-volt 1.5 kW 3-phase induction motor by adjusting the frequency using Variable Speed Drive LS SV015IG5A-2 with Arduino-based PI Anti-windup control. This control aims to get a constant 3-phase induction motor speed with a speed of 1200 Rpm when given a loading of 1-8 Nm with a maximum speed error value of ±6%, maximum rise time of 10s, and maximum settling time of 10s. PI Anti-windup will reduce the integral calculation so that the PI value does not exceed the maximum limit and is less than the minimum limit of control saturation to maintain a better system response and responsiveness to changes in actual values triggered by varying load changes. Based on the test results of the induction motor speed regulation system using the PI Anti-windup method with a value of $K_p = 4$; $K_i = 0.967$; $K_a = 0.884$ which results in an average rise time of 2.12s, settling time of 4.882s, and steady-state error of 0.606.**

Keywords*—Induction Motor; PI Anti-windup; Variable Speed Drive; Arduino

I. INTRODUCTION

Industry in Indonesia has experienced increasing progress. Most industrial equipment uses electric power as the main driver, one of the main drivers is the induction motor is one of the most widely used electrical machines in the industrial world. The working principle of an induction motor is based on electromagnetic induction, the supply voltage is given to the stator coil, which can make the iron core in the stator into a magnetic field, then induces the magnetic field to the rotor [1]. Induction motors are widely used because of their excellent performance, small size, low maintenance requirements, and low cost. Induction motor rotation control has various ways, namely by changing the number of poles on the motor, adjusting the voltage, or adjusting the input frequency. By changing the frequency of the voltage, the change in rotation or speed can be done more smoothly or linearly according to the change in frequency [2]. However, the speed regulation of the induction motor is not easy. Therefore, the right technology is needed to be able to regulate the rotation of the induction motor to remain stable. Today's developing technology has created a variety of renewable innovations in the field of control. Proportional Integral Derivative (PID) control is a conventional control. Proportional Integral Derivative (PID) control is one of the controls that is widely used in regulating the speed of induction motors automatically by using feedback. A PID method whose use continues to this day [3]. In PID or PI control, windup makes the integral part larger. To overcome this, the system must add an anti-windup system in order to avoid the undesirable impact of the effect on closed-loop performance [4]. Research conducted by Q. Ariyansyah, et al, is controlling motor speed using the PID method, with the results of the PID controller response when the DC motor is given a load affecting the resulting rotation response, the speed of the DC motor is decreasing so it is necessary to change the parameters [5]. Saturation will make the performance of the control system not maximized or worse [6]. In addition, induction motors have shortcomings in high starting currents and experience overshoot. To overcome this, an experimental analysis was carried out by A. Kurniawan [7] by using PWM switching using the fuzzy method and getting the results of controlling the speed of a three-phase induction motor with a rise time of 0.2s and a steady speed of 0.3s. In addition, experiments were carried out by S. Yahya, et al [8]. The experiments carried out were the design and implementation of controlling the speed of a three-phase induction motor with the same PLC-based method with a setpoint of 1400 rpm with inconstant load changes. The test results when given fuzzy logic control and loaded up to 6 Nm, the speed is 1375 rpm. There is still an error of 1.78%.

In addition to using fuzzy methods, S. Sariman, et al. [9] conducted research to compare commonly used controls namely PI, PD, and PID with the help of Supervisory Control and Data Acquisition (SCADA). The result on the PI controller is that no overshoot occurs but a long settling time in reaching the specified setpoint is 10.5 seconds. The PD controller has a very large overshoot which is above

765 RPM and is unable to return to setpoint. Meanwhile, the PID controller can reduce the steady state error even though there is a very small overshoot and a stable speed response. Then PID control is able to return to setpoint despite the disturbance, and the results of this test are compared with SCADA readings for reading validation and there is a deviation of 0.1%. The research by H. Hartono, *et al.* [10] which uses a similar method, namely controlling a three-phase induction motor using PID and adding a Universal Bridge is able to produce a better steady speed of 0.2 seconds than without a controller that can reach a steady speed of 0.9 seconds. One of the weaknesses of the PID controller is the difficulty of handling non-linear systems because its performance will decrease while the induction motor is a non-linear system. This weakness can be overcome by re-tuning or tuning up every time there is a change in conditions to stay optimized. One of the methods used is the automatic tuning algorithm. The result is better dynamic speed performance characteristics than the use of the trial & error method with performance benchmarks in the form of rise time less than 20ms, steady state error, overshoot, and undershoot which are each worth a maximum of ±2% [11]. Then, research was also conducted by R. W. Ramdani, et al, namely controlling the speed of a three-phase induction motor with a variable speed drive with the PID method successfully achieving maximum overshoot below 15% and steady-state error below 10% when loaded and unloaded [12].

In addition to using conventional methods, there is research that combines two methods, namely Fuzzy PID. FPID consumes more energy by 4.5% with better performance in no-load testing. As for testing with load, it also has better performance with less energy by 1.03% compared to PID [13]. The use of the Indirect Field Oriented Control (IFOC) method with a Fuzzy Proportional Integrator and Derivative (FPID) controller is chosen to be able to regulate the speed of the three-phase induction motor. The simulation results in this study prove that using an FPID controller is better than a PID controller. The result of the overshoot response for the FPID controller is 0% while the PID controller is 0.23%. Similarly, the undershoot response for FPID control is 2.88% while the PID controller is 6.78%. For the rise time response, the settling time is almost the same, and steady-state error is better for FPID [14]. F. Wang, *et al.* conducted research with Field Oriented Control (FOC) and Direct Torque Control (DTC) methods which resulted in slower FOC dynamics, inversely proportional to DTC which produces high dynamics [15]. In addition, the Fuzzy PID-based FOC method obtained overshoot results that were greater than previous research using IFOC, with the results using Fuzzy PID, overshoot of 100.07%, settling time of 12s, and overshoot on PID of 118%, and settling time of 15s [16]. Other studies using similar FPID methods were conducted, adding PID limits to produce good system performance when the PID limits are close to the nominal starting torque or without limiting it [17]. In addition, S. Yahya, et al. conducted research on induction motor speed control using the Adaptive Fuzzy-PID (AFPID) method based on the Omron CP1H PLC. The research was carried out with a loading scenario of 1-9 Nm, with an average rise time of 6.78s, settling time of 21.00s, maximum undershoot of 2.43%, and steady-state error of 0.51% [18]. In another study conducted by Maghfiroh et al using the Fuzzy PI method, the result is that Fuzzy PI control is better than the PI method, Fuzzy PI is superior in terms of settling time, overshoot, undershoot, and IAE. It has lower IAE in both speed tracking and loaded conditions by 44.98% and 4.47%, respectively [19].

Proportional Integral Anti-windup is a variation of PID control designed to address saturation issues. The main difference between PID and PI Anti-windup is in the handling of saturation. In conventional PID, when the output reaches the maximum or minimum limit, the controller can no longer provide the necessary changes to achieve the desired setpoint. This can cause the system to not reach the setpoint accurately or the system response to be slow. When the output reaches the limit, the Anti-windup PI will reduce the integral contribution thus avoiding excessive accumulation and maintaining a better system response. In research conducted by N. R. Mulyawan, *et al.* [20], Proportional Integral Anti-windup control was modeled on MATLAB Simulink by comparing Linear PI, Saturated PI, and PI Anti-windup controls. The results of the simulation show that Proportional Integral Anti-windup has the best response in the control signal by not exceeding the plant working setpoint of 220V and a speed response that does not exceed the plant setpoint of 146.40 rad/s, no voltage drop occurs, 2.15% overshoot of its speed response, with a rise time of 2.6 seconds even though the settling time response results are more 1 second than the PI Linear response. PI Anti-windup is able to produce the best response for three-phase induction motor speed control with a control signal that does not exceed the limit. Research conducted by F. Hamada, *et al.* [21] which combines the PI Anti-windup method with Sensorless Vector Control has the same results as the research by B. Aichi and K. Kendouci [22] using the PI Anti-windup method with Sliding Control, the results of both studies can eliminate overshoot, settling time, and fast system dynamic response.

This study aims to control the speed of a 1.5 kW/220 Volt three-phase induction motor using a variable speed drive with an Arduino UNO-based PI Anti-windup method, with the aim of this research expected to obtain a maximum value of steady-state error of ±6%, maximum rise time of 10 seconds, maximum settling time of 10 seconds.

II. RESEARCH METHOD

A. PI Anti-Windup Control System

The block diagram of the speed control of a three-phase induction motor using VSD LS SV015IG5A-2 with PI Anti-windup control can be seen in Fig. 1. Fig. 1 is a block diagram of the entire system from plant to control. Close loop control system, where the output value is always measured and fed back to the input part [23]. Arduino is used as a controller by processing the setpoint value of 1200 RPM and receiving feedback when the motor speed decreases when given a load. The loading is a 3-phase induction motor coupled with a generator as a motor load. The Arduino control signal in the form of PWM will enter the PWM to analog converter to convert the PWM signal into an analog voltage of 0-10 VDC which enters the VSD to change the frequency value to regulate the induction motor speed to stay at the setpoint of 1200 RPM. Then the motor speed will be measured by a tacho generator with an analog output value of 0-15 VAC and then converted by the Autonics terminal into a 4-20mA current. To be processed by Arduino, the current from Autonics is converted into a voltage of 0-5 VDC which will be received by Arduino as a feedback value.

In Fig. 2. namely the control circuit on the Arduino which requires a 12 Volt DC voltage obtained from the power supply. Arduino functions to control the Variable Speed Drive to run and adjust the motor speed by sending an analog voltage to the Variable Speed Drive which will change the frequency in the Variable Speed Drive. For the output of the VSD on the U, V, W terminals connected to the U, V, W terminals on the three-phase induction motor using a delta connection due to adjusting the output of the Variable Speed Drive which is 220 Volts AC three phases and adjusting the specifications of the induction motor and for the P1 and CM inverter terminals which function to run the VSD with forward rotation, for the V1 and CM pins to adjust the frequency using an analog voltage whose input is obtained from the PWM arduino.

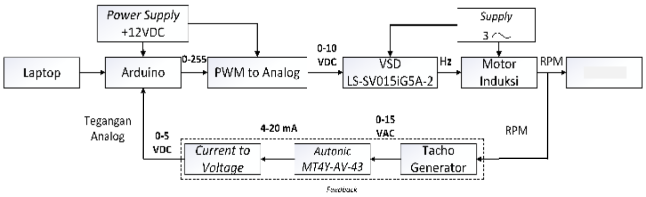

Fig. 1. Three Phase Induction Motor Speed Control System Block Diagram

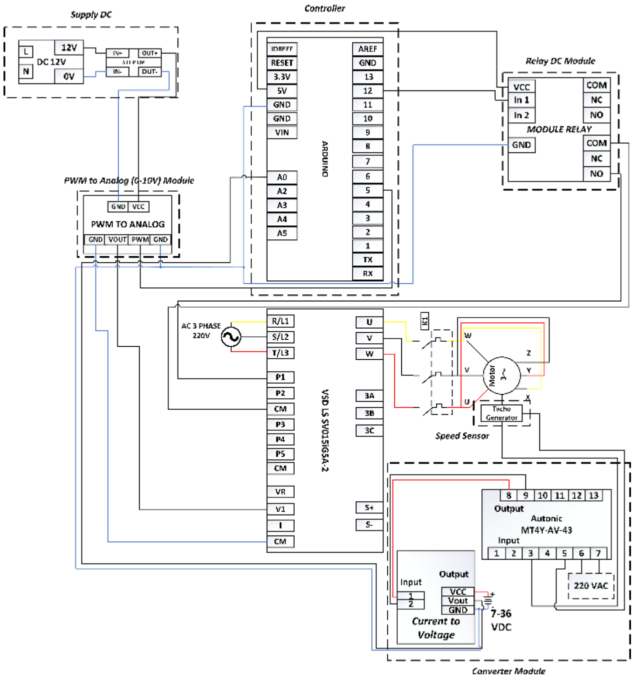

Fig. 2. Wiring DC Control

In Fig. 3 This circuit will be used to test the characteristics of a 220-volt 1.5 kW 3-phase induction motor with 1-8 Nm loading which includes the lower limit of speed when given the maximum load range and the frequency required for the motor to maintain its speed when given loading.

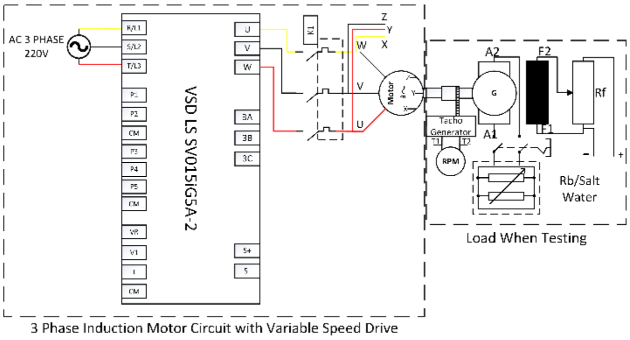

Fig. 3. Three Phase 220 Volt 1.5 Kw Induction Motor Circuit

B. PI Anti-windup Design

In the case of PID controllers, the integral term can become very large, which may cause the control signal to be outside the operating region for a long time, causing a large overshoot and high settling time [24].

In this design, the control used to control the stability of motor rotation is PI AW, following the design of PI AW control. In the PI AW control design, it is necessary to first determine the PI parameters used by using PI tuning optimization with the Ziegler Nichols 1 method. In tunning, it starts by looking for the initial response graph analysis of the open-loop control system. In the 6th experiment, the parameters *Kp*, *Ki*, and *Ka* values were obtained as follows.

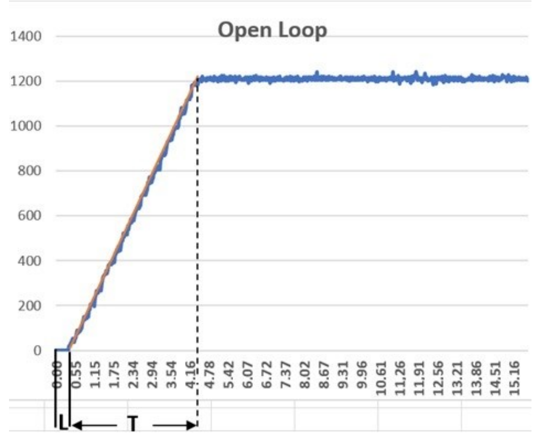

Fig. 4. Reaction Curve of Open Loop Plant System

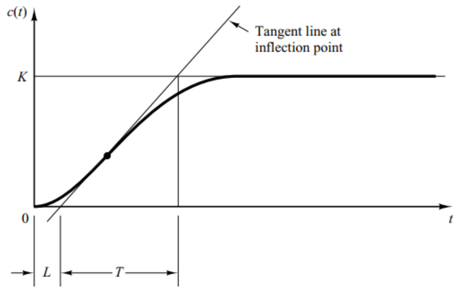

Fig. 5. Open Loop Response Curve [25]

Fig. 4 is a curve of the open loop response of the system without control, and Fig. 5 is an example of an ideal S curve. From the graph, the calculation is obtained with the results L = 0.34s T = 4.13s. After knowing the values of L and T, then find the values of Kp, Ti.

$$Kp = 0.9 \times (\frac{T}{L}) \tag{1}$$

$$Ti = \frac{L}{0.3} \tag{2}$$

From equation 1, the Kp value is 10.93. And from equation 2, the value of Ti is 1.13. Then next look for the Ki value from the equation (3)

$$Ki = (\frac{Kp}{Ti}) \tag{3}$$

From equation 3, a Ki value of 9.67 is obtained. Finally, determine the Anti-windup Constant Value (Ka).

$$Ka = (\frac{Ki}{Kp}) / (\frac{1}{Ti}) \tag{4}$$

From the equation, the anti-windup constant value of 0.884 is obtained. This Anti-windup Constant (Ka) is the value of 1/Ti which is used as the feedback constant value of the Anti-windup system.

Anti-windup PI control equation is as follows:

$$u = Kp \cdot e + \frac{Ki}{s} \cdot e - \frac{1}{T_i}(u - u_{sat}) \tag{5}$$

Fig. 6 is a block diagram of a closed-loop system with AW PI control. The block diagram design above is a close loop PI Anti-windup control design with feedback in the form of speed from an induction motor generated by a tacho generator. Anti-windup design in the program as follows:

$$If\ (PI \geq 255), I = I - (Ka \cdot (PI - 255),$$
$$PI = 255$$

$$If\ (PI \leq 0), I = I - (Ka \cdot PI), PI = 0$$

In the application of the anti-windup control design in the Arduino program above, it can be explained that when the PI control value exceeds the maximum saturation limit (255), the Integral control (I) will experience a reduction in value calculation as follows: $I = I - (Ka \cdot (PI - 255)$, and the PI control output value becomes the maximum saturation limit value, which is PI = 255. If the PI control value is below the minimum saturation limit (0), the Integral control (I) will experience a reduction in the calculated value as follows: $I = I - (Ka \cdot PI)$, and the PI control output value becomes the minimum saturation limit value, which is PI = 0.

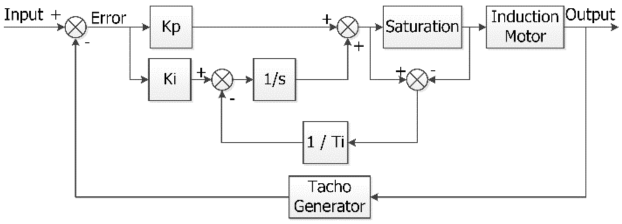

Fig. 6. Block Diagram of Close Loop System with PI AW

C. System Realization

The following is a picture of the realization of the controller hardware system as shown in Fig. 7.

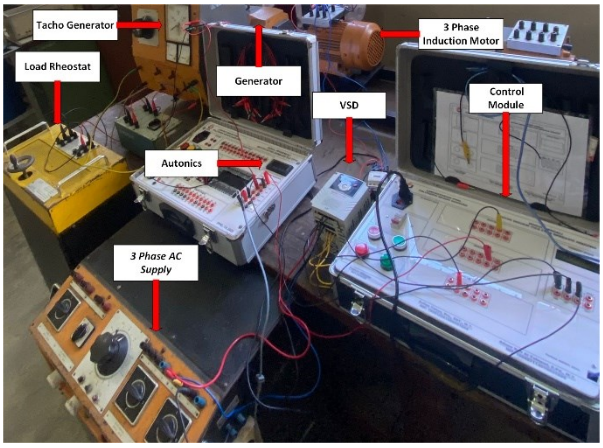

Fig. 7. System Realization

Fig. 7 can be seen to consist of various tools and components used. Consists of a 3-phase 220 Volt AC supply, a 3-phase 220 Volt 1.5 Kw induction motor as the main speed-controlled plant, a tacho generator as a speed sensor that converts the rotation value (RPM) 0-2000 RPM into an AC electrical signal with a range of 0-20V, a separate amplifier generator coupled to the induction motor rotor shaft as a load from the motor, load rheostat or load resistor which functions to adjust the amount of current in a separate amplifier generator which will increase the rotation of the generator which is coupled to the rotor shaft of the induction motor as a load, variable speed drive as a tool that functions to change the amount of frequency received by the induction motor as a regulator of motor rotation speed, and finally the control module which consists of components contained in the circuit in Fig. 2.

D. Integral Absolute Error (IAE)

Integral Absolute Error (IAE) is a performance value in control systems that calculates the total error or absolute error of the system response over a period of time. The absolute error is the absolute value of the difference between the setpoint value and the actual value of the system output. This Integral Absolute Error (IAE) is a performance index criterion that is often used to design control systems in a system [26]. Integral Absolute Error includes Integral Error Performance Criteria based on the calculation of the error signal or error between the input reference signal and the system output [27].

$$IAE = \int_{Tmin}^{Tmax} |e| dt \tag{6}$$

III. RESULT AND DISCUSSION

This test is carried out by experimental means on a three-phase induction motor plant using a loading scheme using a generator coupled to the induction motor shaft by giving a load of 1-8 Nm.

A. Proportional Integral (PI) Control

The performance test results of the three-phase induction motor speed control system with a setpoint of 1200 RPM using PI control are shown in Table 1. Fig. 8 shows a control response with PI control. The induction motor is in a no-load test, and the control response starts at a steady state at 11.3 seconds. Fig. 9 is a control response with PI control, where the induction motor is in a load test, whereas in the control test, it is disturbed by increasing the motor load.

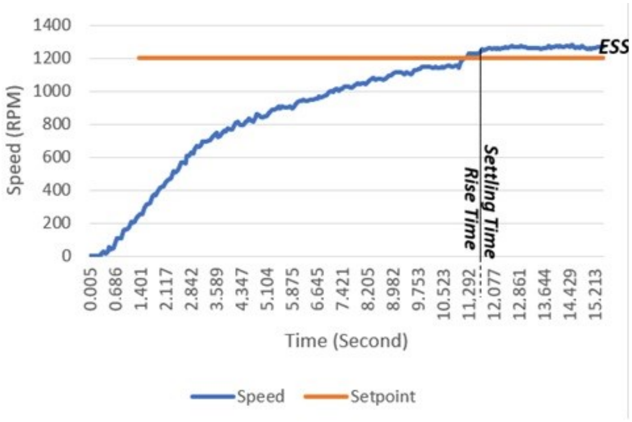

Fig. 8. System Response when No Load with PI Control

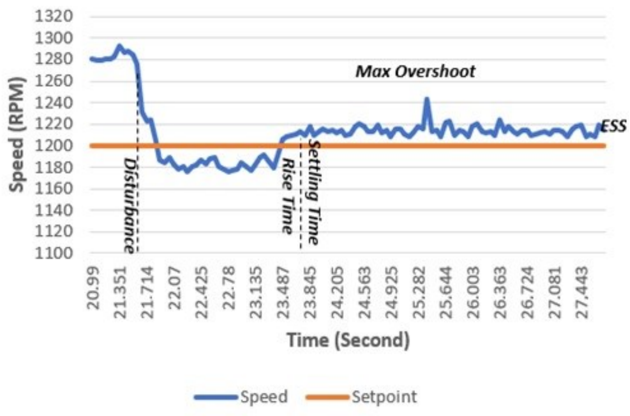

Fig. 9. System Response when given a Load of 8 Nm with PI Control

Table 1. System Performance Results with PI Control

Load (Nm)	*Rise Time (s)*	*Settling Time (s)*	*Max Overshoot (%)*	*Max Undershoot (%)*	*Error Steady State (%)*
1	11.72	11.720	6.901	N/A	5.450
2	7.480	7.480	7.063	N/A	6.231
3	10.49	10.495	5.792	N/A	4.680
4	1.388	1.388	6.533	N/A	4.804
5	1.749	1.749	5.051	N/A	3.338
6	3.318	3.318	5.157	N/A	3.230
7	3.039	3.039	3.886	1.515	2.157
8	2.253	2.253	3.568	2.045	1.204
Average	**5.180**	**5.180**	**5.494**	**N/A**	**3.887**

Table 1 is the performance result with PI control. Testing the system with PI control, there is a maximum undershoot parameter that cannot be observed or Not Applicable (N/A) because the initial steady system response exceeds the setpoint and cannot reach the specified setpoint. Except for the 7 Nm and 8 Nm load tests, the response graphs of both experiments have undershot conditions. In testing using the PI control system, the average steady-state error is 3.923%.

B. Proportional Integral Anti-windup (PI AW) Control

The performance test results of the three-phase induction motor speed control system with a setpoint of 1200 RPM using PI AW control are shown in Table 2. Fig. 10. shows a control response with PI AW control. The induction motor is in a no-load test, and the control response starts at a steady state at 5.18 seconds. Fig. 11 shows a control response with PI control. The induction motor is in a load test, and the control test is disturbed by increasing the motor load. The response can return to setpoint with minimal steady-state error.

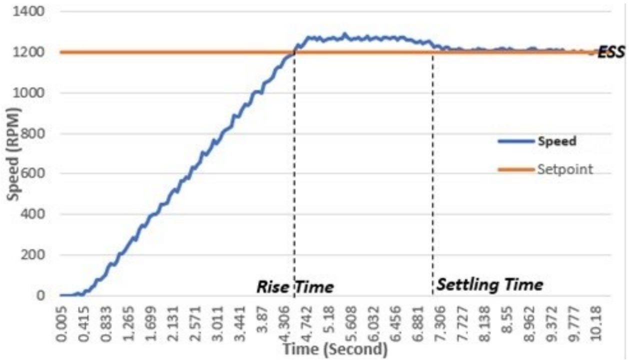

Fig. 10. System Response when No Load with PI AW Control

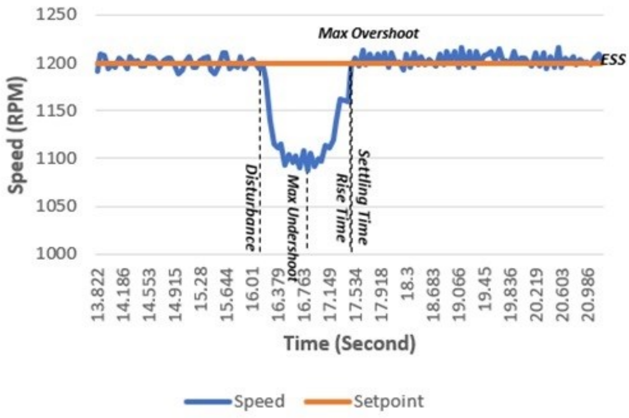

Fig. 11. System Response when given a Load of 8 Nm with PI AW Control

Table 2. System Performance Results with PI AW Control

Load (Nm)	*Rise Time (s)*	*Settling Time (s)*	*Max Overshoot (%)*	*Max Undershoot (%)*	*Error Steady State (%)*
1	0.914	0.966	1.132	1.091	0.419
2	4.636	7.538	6.427	2.256	0.485
3	3.728	6.786	7.91	2.468	0.6
4	2.062	5.118	7.75	3.950	0.544
5	1.634	7.01	6.639	4.798	0.883
6	1.314	5.379	4.945	6.386	0.811
7	1.365	4.951	2.932	7.869	0.657
8	1.312	1.312	1.873	9.35	0.449
Average	**2.120**	**4.882**	**4.951**	**4.771**	**0.606**

Table 2 is the performance result with PI AW control. In system testing with PI Anti-windup control all parameters can be observed because the system response before and after being given a load is able to reach the setpoint value well with an average steady-state error of 0.606%.

C. Integral Absolute Error (IAE)

To determine the performance of the control used, the IAE value is sought at the time of steady state after being given a load of 1-8 Nm by sampling the last 65 data in the response. Table 3 is the Integral Absolute Error (IAE) result for PI control, and Table 4 is the IAE result for PI AW control. IAE results have been obtained from both controls. In the test results, the IAE results on the PI Anti-windup control have an average value of 450.107. While in PI control, it has an average value of 2996.82. The smaller the IAE value, the better the performance of the control system. Anti-windup PI control shows that the system is closer to the desired value within the measured time range and is better than PI control.

Table 3. Results of Integral Absolute Error of PI Control

ESS PI Control	
Load (Nm)	**IAE**
1	3752.62
2	4860.69
3	3744.96
4	3737.48
5	2714.39
6	2542.78
7	1682.46
8	939.18
Average	**2996.82**

Table 4. Results of Integral Absolute Error of PI AW Control

ESS PI AW Control	
Load (Nm)	**IAE**
1	308.11
2	383.93
3	471.34
4	284.27
5	669.19
6	643.32
7	494.12
8	346.58
Average	**450.107**

IV. CONCLUSION

Based on the results of tests that have been carried out on the speed control system of a 3-phase 220 volt 1.5 kW induction motor with Variable Speed Drive as a whole, it can be concluded that the addition of Anti-windup to PI control is proven to be able to make the system response become more stable and responsive, The test results show that the Anti-windup PI control is able to maintain the speed of the induction motor with an average steady-state error of 0.606% at a setpoint of 1200 RPM with a load range of 1-8 Nm, and from the parameters that can be compared, the Anti-windup PI control is better with the results of the average value of rise time 2.120 seconds, settling time 4.882 seconds, and maximum overshoot 4.951%.

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REFERENCES

[1] W. Liu, G. Nair, Y. Li, D. Nesic, B. Vucetic and H. V. Poor, "On the Latency, Rate, and Reliability Tradeoff in Wireless Networked Control Systems for IIoT," in *IEEE Internet of Things Journal*, vol. 8, no. 2, pp. 723-733, 2021, https://doi.org/10.1109/JIOT.2020.3007070.

[2] M. M. Zirkohi, "Fast terminal sliding mode control design for position control of induction motors using adaptive quantum neural networks," *Applied Soft Computing*, vol. 115, p. 108268, 2022, https://doi.org/10.1016/j.asoc.2021.108268.

[3] M. J. Lencwe, S. D. Chowdhury, S. Mahlangu, M. Sibanyoni, and L. Ngoma, "An Efficient HVAC Network Control for Safety Enhancement of a Typical Uninterrupted Power Supply Battery Storage Room," *energies*, vol. 14, no. 16, p. 5155, 2021, https://doi.org/10.3390/en14165155.

[4] L. R. da Silva, R. C. Flesch, and J. E. Normey-Rico, "Analysis of anti-windup techniques in PID control of processes with measurement noise," *IFAC-PapersOnLine*, vol. 51, no. 4, pp. 948-953, 2018, https://doi.org/10.1016/j.ifacol.2018.06.100.

[5] Q. Ariyansyah and A. Ma'arif, "DC Motor Speed Control with Proportional Integral Derivative (PID) Control on the Prototype of a Mini-Submarine," *J. Fuzzy Syst. Control*, vol. 1, no. 1, pp. 18–24, 2023, https://doi.org/10.59247/jfsc.v1i1.26.

[6] S. C. Pratama, E. Susanto and A. S. Wibowo, "Design and implementation of water level control using gain scheduling PID back calculation integrator Anti Windup," *2016 International Conference on Control, Electronics, Renewable Energy and Communications (ICCEREC)*, pp. 101-104, 2016, https://doi.org/10.1109/ICCEREC.2016.7814981.

[7] N. Farah *et al.*, "A Novel Self-Tuning Fuzzy Logic Controller Based Induction Motor Drive System: An Experimental Approach," in *IEEE Access*, vol. 7, pp. 68172-68184, 2019, https://doi.org/10.1109/ACCESS.2019.2916087.

[8] F. Rossi, J. P. Sembiring, A. Jayadi, N. U. Putri and P. Nugroho, "Implementation of Fuzzy Logic in PLC for Three- Story Elevator Control System," *2021 International Conference on Computer Science, Information Technology, and Electrical Engineering (ICOMITEE)*, pp. 179-185, 2021, https://doi.org/10.1109/ICOMITEE53461.2021.9650221.

[9] T. Nosheen *et al.*, "A fractional order controller for sensorless speed control of an induction motor," *Energies*, vol. 16, no. 4, p. 1901, 2023, https://doi.org/10.3390/en16041901.

[10] H. Hartono, R. I. Sudjoko, and P. Iswahyudi, "Speed control of three phase induction motor using universal bridge and pid controller," In *Journal of Physics: Conference Series*, vol. 1381, no. 1, p. 012053, 2019, https://doi.org/10.1088/1742-6596/1381/1/012053.

[11] G. A. Olarinoye, C. Akinropo, G. J. Atuman and Z. M. Abdullahi, "Speed Control of a Three Phase Induction Motor using a PI Controller," *2019 2nd International Conference of the IEEE Nigeria Computer Chapter (NigeriaComputConf)*, pp. 1-7, 2019, https://doi.org/10.1109/NigeriaComputConf45974.2019.8949624.

[12] B. -F. Wu and C. -H. Lin, "Adaptive Neural Predictive Control for Permanent Magnet Synchronous Motor Systems with Long Delay Time," in *IEEE Access*, vol. 7, pp. 108061-108069, 2019, https://doi.org/10.1109/ACCESS.2019.2932746.

[13] H. Maghfiroh, J. S. Saputro, F. Adriyanto, A. Sujono, and R. L. Lambang, "Performance Evaluation of Fuzzy-PID in Speed Control of Three Phase Induction Motor," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1096, no. 1, p. 012071, 2021, https://doi.org/10.1088/1757-899X/1096/1/012071.

[14] I. Ferdiansyah, M. R. Rusli, B. Praharsena, H. Toar, Ridwan and E. Purwanto, "Speed Control of Three Phase Induction Motor Using Indirect Field Oriented Control Based on Real-Time Control System," *2018 10th International Conference on Information*

Technology and Electrical Engineering (ICITEE), pp. 438-442, 2018, https://doi.org/10.1109/ICITEED.2018.8534864.

[15] M. A. Hannan, J. A. Ali, A. Mohamed, and A. Hussain, “Optimization techniques to enhance the performance of induction motor drives: A review,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1611-1626, 2018, https://doi.org/10.1016/j.rser.2017.05.240.

[16] I. M. Mehedi, N. Saad, M. A. Magzoub, U. M. Al-Saggaf and A. H. Milyani, "Simulation Analysis and Experimental Evaluation of Improved Field-Oriented Controlled Induction Motors Incorporating Intelligent Controllers," in *IEEE Access*, vol. 10, pp. 18380-18394, 2022, https://doi.org/10.1109/ACCESS.2022.3150360.

[17] A. N. Mohammed and G. A.-R. Ghoneim, “Fuzzy-PID Speed Controller Model-Based Indirect Field Oriented Control for Induction Motor,” in *2020 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE)*, pp. 1–6, 2021, https://doi.org/10.1109/ICCCEEE49695.2021.9429623.

[18] Ahmed, A. H., Yahya, A. S., & Ali, A. J. (2024). Speed Control for Linear Induction Motor Based on Intelligent PI-Fuzzy Logic. *Journal of Robotics and Control (JRC)*, *5*(5), 1470-1478, 2024, https://doi.org/10.18196/jrc.v5i5.22203.

[19] H. Maghfiroh, J. Slamet Saputro, F. Fahmizal, and M. Ahmad Baballe, “Adaptive Fuzzy-PI for Induction Motor Speed Control,” *Journal of Fuzzy Systems and Control,* vol. 1, no. 1, pp. 1–5, 2023, https://doi.org/10.59247/jfsc.v1i1.24.

[20] D. Zakaria, H. Hindersah, A. Syaichu-Rohman and A. G. Abdullah, "PI and PI Antiwindup Speed Control of Switched Reluctance Motor (SRM)," *2021 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, Surabaya, Indonesia, 2021, pp. 46-51, 2021, https://doi.org/10.1109/ISITIA52817.2021.9502255.

[21] F. Hamada, F. Husnayain, and F. Yusivar, “Speed Sensorless Vector Control of Parallel Connected Induction Motor with Anti-windup Integral-Proportional Speed Controller,” in *2019 IEEE 2nd International Conference on Power and Energy Applications (ICPEA)*, pp. 89–93, 2019, https://doi.org/10.1109/ICPEA.2019.8818527.

[22] B. Aichi, M. Bourahla and K. Kendouci, "Real-Time Hybrid Control of Induction Motor Using Sliding Mode and PI Anti-Windup," *2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM)*, pp. 1-6, 2018, https://doi.org/10.1109/CISTEM.2018.8613320.

[23] J. P. de Moura, J. V. d. F. Neto and P. H. M. Rêgo, "A Neuro-Fuzzy Model for Online Optimal Tuning of PID Controllers in Industrial System Applications to the Mining Sector," in *IEEE Transactions on Fuzzy Systems*, vol. 28, no. 8, pp. 1864-1877, 2020, https://doi.org/10.1109/TFUZZ.2019.2923963.

[24] F. R. Rahman, A. S. Rohman, I. Munawar and S. Sereyvatha, "Speed Control System of BLDC Motor using PI Anti – Windup Controller on an Autonomous Vehicle Prototype (AVP)," *2018 IEEE 8th International Conference on System Engineering and Technology (ICSET)*, pp. 51-56, 2018, https://doi.org/10.1109/ICSEngT.2018.8606398.

[25] M. D. M. Shah, N. N. Mohammad and N. Hambali, "Nonlinear Modelling for Time-Varying Water Temperature PID Control," *2021 IEEE 17th International Colloquium on Signal Processing & Its Applications (CSPA)*, Langkawi, Malaysia, 2021, pp. 177-182, 2021, https://doi.org/10.1109/CSPA52141.2021.9377296.

[26] R. Aisuwarya and Y. Hidayati, “Implementation of Ziegler-Nichols PID Tuning Method on Stabilizing Temperature of Hot-water Dispenser,” in *2019 16th International Conference on Quality in Research (QIR): International Symposium on Electrical and Computer Engineering*, pp. 1–5, 2019, https://doi.org/10.1109/QIR.2019.8898259.

[27] C. Zhang, T. Peng, C. Li, W. Fu, X. Xia, and X. Xue, “Multiobjective optimization of a fractional-order pid controller for pumped turbine governing system using an improved nsga-Iii algorithm under multiworking conditions,” *Complexity*, vol. 2019, no. 1, p. 5826873, 2019, https://doi.org/10.1155/2019/5826873.