Duty Cycle Control on Compressor of Split Air Conditioners Using Internet of Things Embedded in Fuzzy-PID

Husein[1,2], Maman Budiman[1], and Mitra Djamal[1]

[1]Department of Physics, Institut Teknologi Bandung, Indonesia
[2]Department of Physics, Haluoleo University Kendari, Indonesia
Huseinhsn95@yahoo.co.id

Abstract: Internet of things (IoT) makes every object have a representation in the virtual world that allows us to monitor and control them in the cyberspace. Monitoring of environmental conditions, rooms, and air conditioner controls can be used to find out and develop indoor room control strategies to be more efficient and comfortable for occupants. However, environmental conditions affect the dynamics of the system and its controller functions. This paper proposed a new approach to control room temperature through the control of the AC compressor duty cycle using IoT. Hybrid Fuzzy-PID (Proportional-Integral-Derivative) as a control algorithm that is embedded on the IoT platform. The algorithm determines optimal PID control parameters and adjusts them according to environmental conditions. Intelligent control proposed is applied to save energy and regulate the comfort of the room for residents. Finally, the Hybrid Fuzzy-PID and IoT approach allow us to achieve 50% energy savings in comfort that can be tolerated by occupants of the room.

Keywords: Internet of Things, Fuzzy-PID, Air Conditioner.

1. Introduction

Setpoint based PID control from default AC still leaves fewer savings and convenience. This is due to the PID control parameters which consist of KP, KI, and KD which have not been optimal in describing the relationship between control capacity and physical systems that work under the influence of parameters that change nonlinearly. In practice, environmental conditions can play an important role in physical processes by triggering unexpected system dynamics as in Heating, Ventilation, and Air Conditioning (HVAC) systems, changes in ambient temperature cause the heat transfer coefficient and energy balance to change [1][2][3]. To implement PID control that can adapt to changes in environmental conditions, fuzzy logic is needed to guide PID parameters to suit outdoor and indoor environmental conditions[4]. To implement a Fuzzy-PID combination, the right tools in dealing with the relationship between AC systems and very complex environmental variables to become a control decision are indispensable.

The selection of the right method to set the PID parameters is still open today due to the complex processes of the industry. Determination of key parameters (part of the usual tuning parameters of the classic PID) is still a major challenge in designing the PID controller[5]. There is no systematic way to arrange the order of PID parameter fractions due to the complexity of the PID controller. Fuzzy logic control (FLC) has been widely used in the world of control engineering[6][7][8][9][10]. Rules engine are obtained through a measured physical variable (Antecedents) fuzzification and logic mapping into the range of control parameters (Consequents)[11][12]. Nonlinear analysis has been adopted to establish FLC rules and improve control performance, especially for systems that operate under uncertain physical conditions[13][14][11][12]. In several cases, rules engine are based on experience and expert knowledge of certain system processes[15][16]. The combination of PID and FLC (Fuzzy-PID) has proven to be a smart strategy, nonlinear and reliable which can improve the performance of conventional PID through online PID gain and real-time arrangement[17]. The problem is how fuzzy-PID control is applied to the AC to control AC energy consumption and room comfort and how much the control algorithm contributes to AC energy savings and room comfort.

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There are several papers that are closely related to this research: N. Wang. et al. 2013[18] which examines AC energy consumption every setpoint thermostat. The approach method that he does is to take environmental temperature kWh data every month. However, we need a real-time history of consumption and ambient temperature in a short time step to study the default AC algorithm as the basis for designing an appropriate conservation algorithm. Meana lLorian et al. 2017 [19] has controlled the ambient temperature using IoT with the Fuzzy-Logic algorithm. AC energy savings obtained by 40%. The problem that arises in this research is that it is not synchronous between decision making and unexpected changes in environmental conditions. Wei Wang et al. 2018 [20] has controlled the Nuclear cyber-physical system using Fuzzy-PID controls to maintain chemicals that are susceptible to changes in environmental temperature. The paper is our reference in controlling AC energy consumption and the comfort of the room in this study. However, to be applied to AC systems that are associated with very complex environmental parameters, the use of IoT technology is the difference between the research and our study.

This paper proposes the implementation of Fuzzy-PID control algorithms on AC using IoT technology. IoT technology has three basic components: Instrumented, Interconnected, and analysis/intelligence. Instrumented is to measure complex environmental conditions or serves as a perception layer. Interconnected serves as a broker that interconnects all environmental variables, among sensors, sensors with the rule engine, and all components with the user. Analysis / Intelligence serves as a facility to embed fuzzy-PID for AC control. These three components can be monitored by online.

2. Fuzzy-PID design for controlling Air Conditioner (AC)

There are two very popular classic PID tuning methods: Ziegler-Nichols tuning and Cohen-Coon tuning.

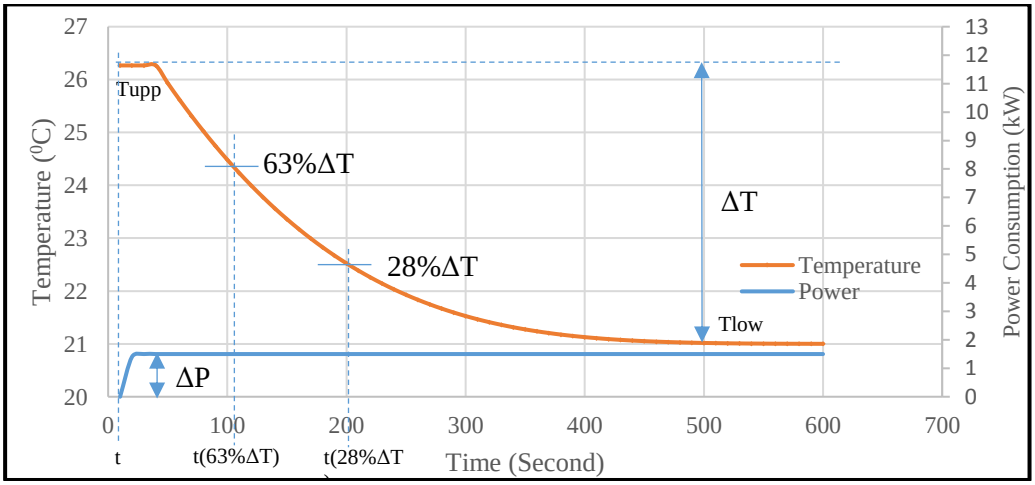

Figure 1. Cohen-Coon tuning method for the rom temperature drop

In this study, the Cohen-Coon method[21] is used to determine PID control parameters according to the pattern of changes in room temperature when the compressor is ON. AC power as input and room temperature is the response/output. However, due to the AC power consumption level cannot be adjusted so that the duration of the ON time for the compressor can replace the position ΔP in determining the value of Gain K. Based on the graph in figure 1, the parameters that must be calculated to determine the PID control parameters are as follows:

a. The differences temperature drops (ΔT)

$$\Delta T = T_{low} - T_{upp} \quad (1)$$

b. Difference in time duration ON compressor (Δt)

$$\Delta t = t_f - t_i \tag{2}$$

c. Gain K

$$K = \Delta T / \Delta t \tag{3}$$

d. 28%ΔT

$$28\%\Delta T = T_{low} + (0{,}28 * \Delta T) \tag{4}$$

e. 63%ΔT

$$63\%\Delta T = T_{low} + (0{,}63 * \Delta T) \tag{5}$$

f. t(28%ΔT) and t(63%ΔT) through data

g. Effective time constant (τ):

$$\tau = 1{,}5.(t(28\%\Delta T) - t(63\%\Delta T)) \tag{6}$$

h. Dead time (θ):

$$\theta = t(28\%\Delta T) - \tau \tag{7}$$

i. Kp constant:

$$Kp = Kc = \frac{1}{K}\frac{\tau}{\theta}((16\tau + 3\theta)/12\tau) \tag{8}$$

j. Ki constant:

$$Ki = Kc/\tau_i = Kp/\tau_i = \frac{Kp}{\theta(32 + (6\theta/\tau)/(13 + (8\theta/\tau))} \tag{9}$$

k. Kd constant:

$$Kd = Kp.\tau_D = Kp.\frac{4\theta}{(11 + (2\theta/\tau))} \tag{10}$$

The curvature of the graph in Figure 1 above will vary according to the temperature and humidity of the outdoor environment so that environmental parameters must be measured and integrated into cyber monitoring and intelligent control PID in real time. The intelligent control results are expected to guide optimal control settings for various environmental conditions and adapt themselves to changing conditions to maintain comfort and avoid waste of energy.

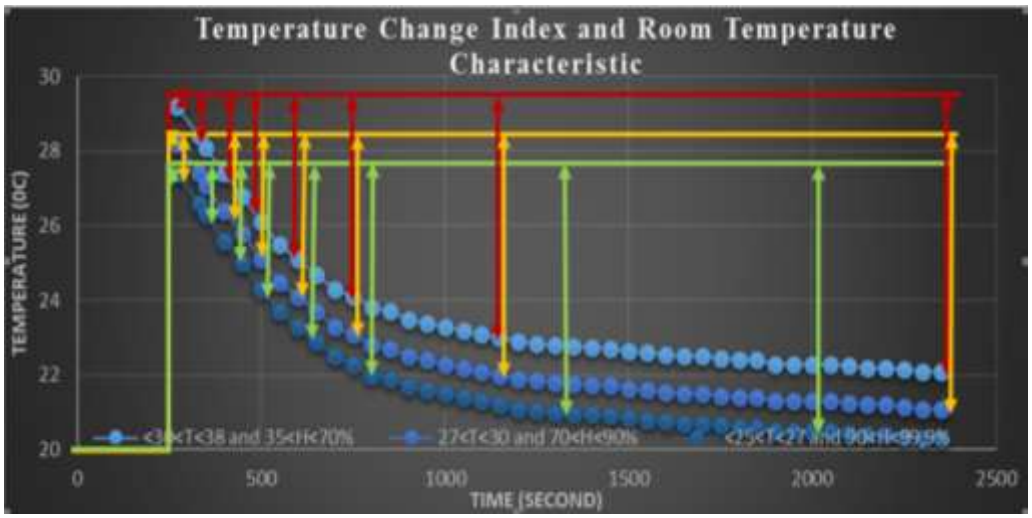

Figure 2. Graph of indoor temperature in three different outdoor conditions

Furthermore, taking PID parameters according to the portion of a certain temperature limit is more proportional compared to the overall temperature graph. Therefore, the PID parameter needs to be determined for each portion of the setpoint temperature as shown by the graph of our

experimental results in Figure 2. Figure 2 shows that the determination of the PID parameter from the temperature characteristics of the food is obtained in three outdoor conditions: 1. Outdoor temperature range ≤25 ≤T ≤27 ^{0}C with moisture ≤90 ≤H ≤99,9%. 2. Outside temperature conditions range ≤27 ≤T ≤30 ^{0}C with moisture ≤70 ≤H ≤90%. 3. External temperature conditions ≤30 ≤T ≤38 ^{0}C with moisture ≤35 ≤H ≤70%. The three conditions based on equation 1-11 above obtained 24 types of PID parameters for each condition and setpoints that can be labeled in table 1. The table can be described in the form of fuzzy rules with input variables which are outdoor temperatures, outdoor humidity, and setpoint temperature. The fuzzy inference mechanism used in this research is Fuzzy model of Tagaki Sugeno[22] because the output is firm and has been ascertained, namely three constant values: Kp, Ki, and Kd. The constant values are obtained from room temperature characteristic data in three outdoor conditions when the compressor is turned ON as shown in figure 2.

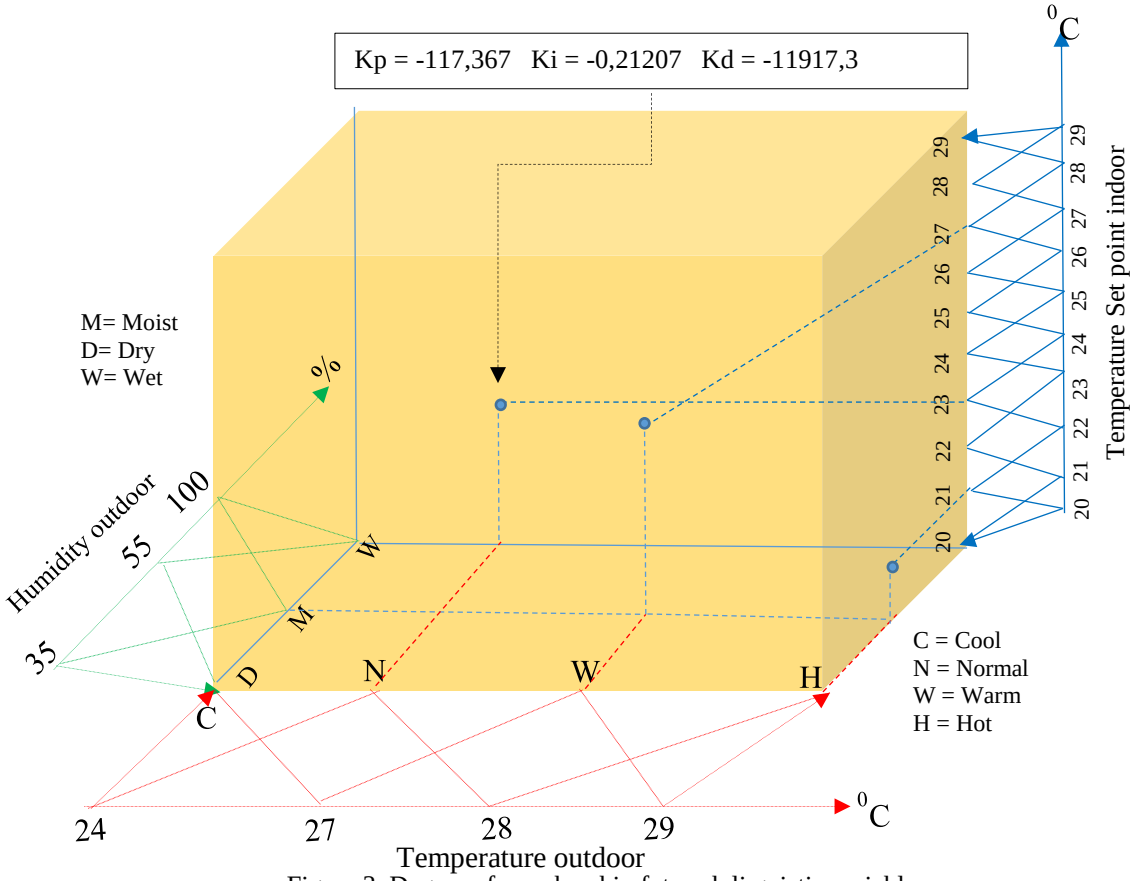

Figure 3. Degree of membership fot each li guistic variable

For outdoor temperatures, we use a triangle degree membership function consisting of four linguistic variables: Cool, Normal, Warm and Hot. Likewise, for external humidity using the triangle membership function with three linguistic variables: Dry, Moist and Wet. For setpoint temperatures, we also use the triangular membership function consisting of ten linguistic variables: 20 ºC, 21 ºC, 22 ºC., until 29 ºC. Through this function, the crisp input for outdoor temperature and humidity and indoor temperature setpoint is converted to fuzzy values by intelligent systems in the middleware. So, the degree of membership for each variable is constructed as shown in Figure 3. The inference process for fuzzy rules shown in table 2 where PID parameters are based on Graph of indoor temperature in three different outdoor conditions in Figure 2.

Table 1. PID Parameters of the room in three outside conditions and each setpoint

Category	Temperature ranges	PID Parameter Controls			Range duty cycle
		KP	KI	KD	Max. Duty Cycle
Hot (<30 <T <38 0C and <35 <H <70%)	Δ = 29,3 - 29	-34,6834	-0,1388	-2865,38	30
	Δ = 29,3 - 28	-35,1459	-0,11071	-3136,09	100
	Δ = 29,3 – 27	-45,3557	-0,11754	-4221,57	170
	Δ = 29,3 – 26	-63,6488	-0,14235	-5973,19	250
	Δ = 29,3 – 25	-77,6029	-0,15671	-7760,29	360
	Δ = 29,3 – 24	-117,367	-0,21207	-11917,3	510
	Δ = 29,3 – 23	-272,277	-0,45694	-27227,7	1030
	Δ = 29,3 – 22	-528,328	-0,85751	-52832,8	1990
Normal/Warm (<27 <T <30 0C and < 70<H <90%)		KP	KI	KD	Max. Duty Cycle
	Δ = 28,3 - 28	-32,5472	-0,13736	-2653,85	30
	Δ = 28,3 - 27	-37,9599	-0,11565	-3357,99	100
	Δ = 28,3 - 26	-45,3557	-0,11754	-4221,57	170
	Δ = 28,3 - 25	-63,6488	-0,14235	-5973,19	250
	Δ = 28,3 - 24	-77,6029	-0,15671	-7760,29	360
	Δ = 28,3 - 23	-117,367	-0,21207	-11917,3	510
	Δ = 28,3 - 22	-272,277	-0,45694	-27227,7	1030
	Δ = 28,3 - 21	-528,328	-0,85751	-52832,8	1990
Cool (<25 <T <27 0C and <90 <H <99,9%)		KP	KI	KD	Max. Duty Cycle
	Δ = 27,8 - 27	-34,375	-0,1223	-2961,54	70
	Δ = 27,8 - 26	-37,3148	-0,10633	-3444,44	130
	Δ = 27,8 - 25	-37,5864	-0,08931	-3585,16	150
	Δ = 27,8 - 24	-66,2485	-0,14019	-6573,89	300
	Δ = 27,8 - 23	-91,875	-0,17724	-9187,5	420
	Δ = 27,8 - 22	-145,65	-0,25559	-14789,1	630
	Δ = 27,8 - 21	-343,012	-0,55629	-35620,5	1420
	Δ = 27,8 – 20,5	-588,889	-0,96087	-57982,9	2120

The number of fuzzy rules obtained from the membership function of the triangle outdoor temperature, outdoor humidity, and indoor setpoint temperature is 10x4x3 = 120 which will be injected into the intelligent system in the middleware.

Tabel 2. Fuzzy rule in the form of a table of degrees of truth.

Linguistic variable of outdoor Temp/Hum		Indoor Temperature Setpoint					
		20 ^{0}C			21 ^{0}C		
		KP	KI	KD	KP	KI	KD
Cool	Dry	-588,889	-0,96087	-57982,9	-343,012	-0,55629	-35620,5
Cool	Moist	-588,889	-0,96087	-57982,9	-343,012	-0,55629	-35620,5
Cool	wet	-588,889	-0,96087	-57982,9	-343,012	-0,55629	-35620,5
Normal	Dry	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
Normal	Moist	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
Normal	wet	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
Warm	Dry	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
Warm	Moist	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
Warm	wet	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
Hot	Dry	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
Hot	Moist	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
Hot	wet	-528,328	-0,85751	-52832,8	-528,328	-0,85751	-52832,8
		22 ^{0}C			23 ^{0}C		
Cool	Dry	-145,65	-0,25559	-14789,1	-91,875	-0,17724	-9187,5
Cool	Moist	-145,65	-0,25559	-14789,1	-91,875	-0,17724	-9187,5
Cool	wet	-145,65	-0,25559	-14789,1	-91,875	-0,17724	-9187,5
Normal	Dry	-272,277	-0,45694	-27227,7	-117,367	-0,21207	-11917,3
Normal	Moist	-272,277	-0,45694	-27227,7	-117,367	-0,21207	-11917,3
Normal	wet	-272,277	-0,45694	-27227,7	-117,367	-0,21207	-11917,3
Warm	Dry	-272,277	-0,45694	-27227,7	-117,367	-0,21207	-11917,3
Warm	Moist	-272,277	-0,45694	-27227,7	-117,367	-0,21207	-11917,3
Warm	wet	-272,277	-0,45694	-27227,7	-117,367	-0,21207	-11917,3
Hot	Dry	-528,328	-0,85751	-52832,8	-272,277	-0,45694	-27227,7
Hot	Moist	-528,328	-0,85751	-52832,8	-272,277	-0,45694	-27227,7
Hot	wet	-528,328	-0,85751	-52832,8	-272,277	-0,45694	-27227,7
		24 ^{0}C			25 ^{0}C		
Cool	Dry	-66,2485	-0,14019	-6573,89	-37,5864	-0,08931	-3585,16
Cool	Moist	-66,2485	-0,08931	-6573,89	-37,5864	-0,08931	-3585,16
Cool	wet	-66,2485	-0,08931	-6573,89	-37,5864	-0,08931	-3585,16
Normal	Dry	-77,6029	-0,14235	-7760,29	-63,6488	-0,14235	-5973,19
Normal	Moist	-77,6029	-0,14235	-7760,29	-63,6488	-0,14235	-5973,19
Normal	wet	-77,6029	-0,14235	-7760,29	-63,6488	-0,14235	-5973,19
Warm	Dry	-77,6029	-0,14235	-7760,29	-63,6488	-0,14235	-5973,19
Warm	Moist	-77,6029	-0,14235	-7760,29	-63,6488	-0,14235	-5973,19
Warm	wet	-77,6029	-0,14235	-7760,29	-63,6488	-0,14235	-5973,19
Hot	Dry	-117,367	-0,21207	-11917,3	-77,6029	-0,15671	-7760,29
Hot	Moist	-117,367	-0,21207	-11917,3	-77,6029	-0,15671	-7760,29
Hot	wet	-117,367	-0,21207	-11917,3	-77,6029	-0,15671	-7760,29
		26 ^{0}C			27 ^{0}C		
Cool	Dry	-37,3148	-0,10633	-3444,44	-34,375	-0,1223	-2961,54
Cool	Moist	-37,3148	-0,10633	-3444,44	-34,375	-0,1223	-2961,54
Cool	wet	-37,3148	-0,10633	-3444,44	-34,375	-0,1223	-2961,54
Normal	Dry	-45,3557	-0,11754	-4221,57	-37,9599	-0,11565	-3357,99
Normal	Moist	-45,3557	-0,11754	-4221,57	-37,9599	-0,11565	-3357,99
Normal	wet	-45,3557	-0,11754	-4221,57	-37,9599	-0,11565	-3357,99
Warm	Dry	-45,3557	-0,11754	-4221,57	-37,9599	-0,11565	-3357,99
Warm	Moist	-45,3557	-0,11754	-4221,57	-37,9599	-0,11565	-3357,99
Warm	wet	-45,3557	-0,11754	-4221,57	-37,9599	-0,11565	-3357,99
Hot	Dry	-63,6488	-0,14235	-5973,19	-45,3557	-0,11754	-4221,57
Hot	Moist	-63,6488	-0,14235	-5973,19	-45,3557	-0,11754	-4221,57
Hot	wet	-63,6488	-0,14235	-5973,19	-45,3557	-0,11754	-4221,57
		28 ^{0}C			29 ^{0}C		
Cool	Dry	-34,375	-0,1223	-2961,54	-34,375	-0,1223	-2961,54
Cool	Moist	-34,375	-0,1223	-2961,54	-34,375	-0,1223	-2961,54
Cool	wet	-34,375	-0,1223	-2961,54	-34,375	-0,1223	-2961,54
Normal	Dry	-32,5472	-0,13736	-2653,85	-32,5472	-0,13736	-2653,85
Normal	Moist	-32,5472	-0,13736	-2653,85	-32,5472	-0,13736	-2653,85
Normal	wet	-32,5472	-0,13736	-2653,85	-32,5472	-0,13736	-2653,85

Warm	Dry	-32,5472	-0,13736	-2653,85	-32,5472	-0,13736	-2653,85
Warm	Moist	-32,5472	-0,13736	-2653,85	-32,5472	-0,13736	-2653,85
Warm	wet	-32,5472	-0,13736	-2653,85	-32,5472	-0,13736	-2653,85
Hot	Dry	-35,1459	-0,11071	-3136,09	-34,6834	-0,1388	-2865,38
Hot	Moist	-35,1459	-0,11071	-3136,09	-34,6834	-0,1388	-2865,38
Hot	wet	-35,1459	-0,11071	-3136,09	-34,6834	-0,1388	-2865,38

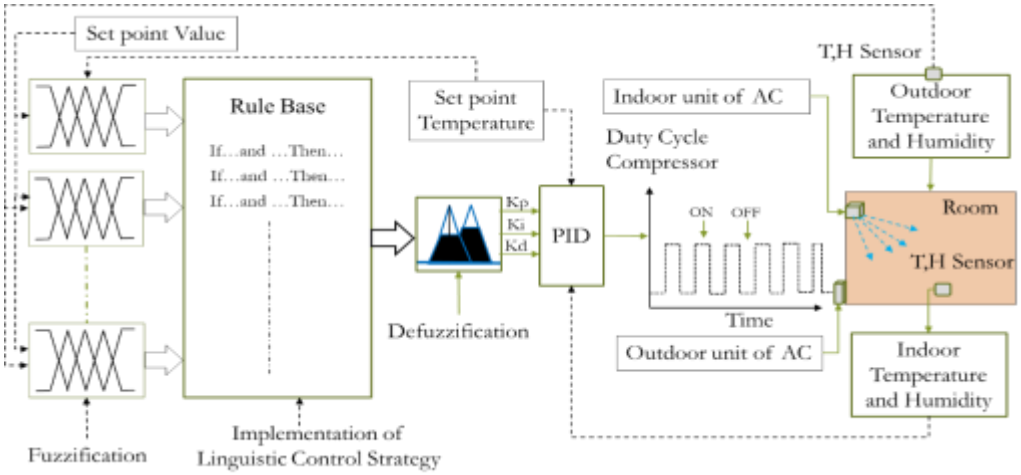

Figure 4. Architecture of Hybrid Fuzzy-PID control of compressor

3. Desain system of Internet of Things

The IoT architecture has been developed extensively with globalizing applications. The IoT architecture built in this study is in accordance with the Hybrid Fuzzy-PID control architecture in Figure 4

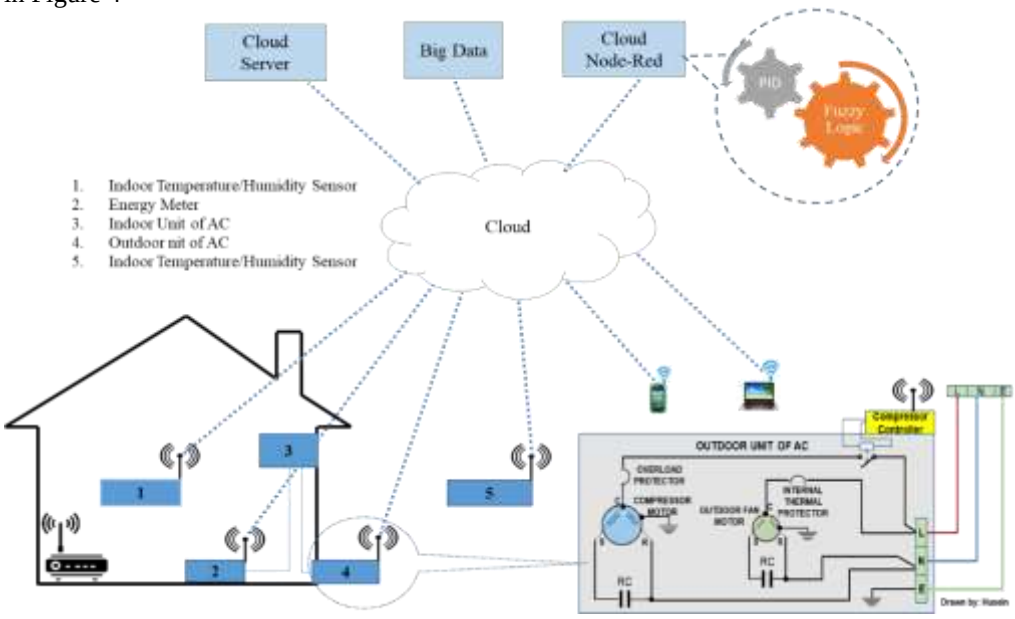

Figure 5. Simple Internet of Things (IoT) architecture for AC control

Figure 5 shows the design of the IoT system for consumption control and the comfort of a room consisting of the following elements: a) Three sensor nodes and one actuator node. b). Cloud. c). Middleware. d). Cloud server. Node I (kWh meter) will measure the power consumed

by AC. The quantity will be read by a microcontroller then they are sent by a wi-fi module (esp8266) to Cloud using the MQTT protocol. MQTT is a publish and subscribe based protocol[23]. MQTT is designed for small bandwidth and high latency. Another advantage of the MQTT feature is that it allows one data to be subscribed by many subscribers and vice versa[24]. The MQTT program will initialize the kWh meter and try to connect to the Wi-Fi network until it is successfully connected then the kWh meter data is read, processed and sent them to the cloud. Similarly, node 2 and node 3 will work in the same way as node I (kWh meter). The last node is node 4 as the compressor control actuator. This node circuit consists of a power supply, Wi-Fi module esp8266, and relay. The MQTT program will continue to try to connect with Wi-Fi networks. If it fails, the program will continue to try to connect until it is successfully connected. Then the program will subscribe to the command data from intelligent to turn on and turn off the compressor.

4. Internet of Things Platform

In this study, Node-Red is used as a middleware. Node-Red is an open-source, browser-based tool for interconnecting all things in Internet of Things. Because Node-Red covers node.js it can work on the network edge or in the cloud. Hundreds of thousands of flows and nodes are present in the current Node-Red library that allows all devices and services to be connected. All data sent by various sensor nodes to the cloud will be subscribed by the MQTT gateway node in the middleware. Then all data is processed and they are stored in the cloud server to keep the analysis needed and displayed in various graphic forms. The cloud server used in this study is Emoncms. Emoncms is an open source web application that connects various objects using standard web. This platform also offers data access control and it is suitable for processing, storing and visualizing energy and environmental data. Emoncms can be installed on the server used by the user. In this study Emoncms was used to display the consumption of electrical energy, power and other electrical parameters such as power factor and apparent power.

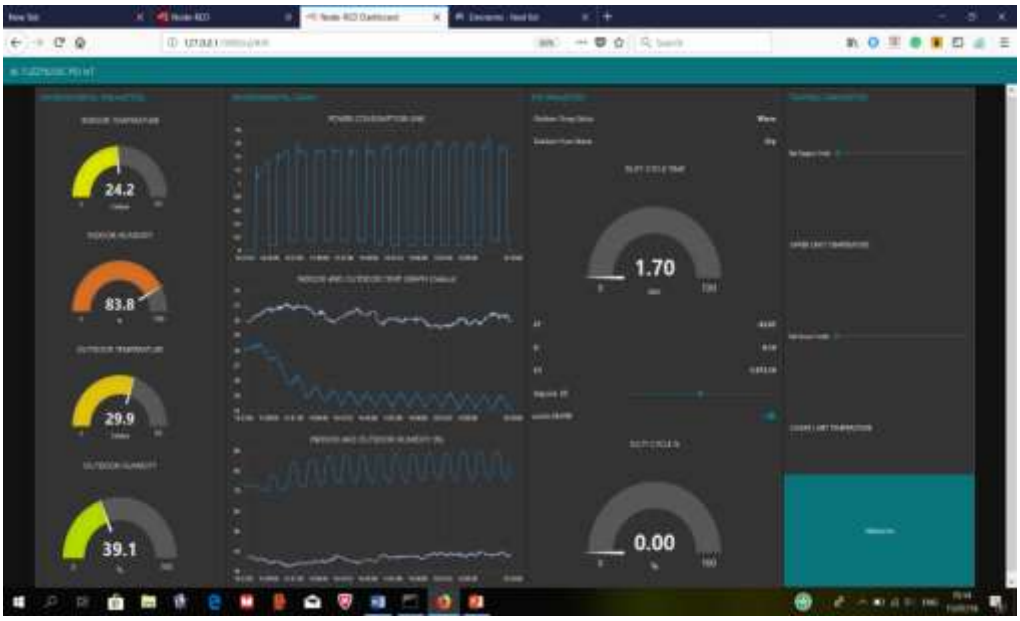

Figure 6. Fuzzy-PID control system interface in middleware

Figure 7 describes the hybrid Fuzzy-PID algorithm that is embedded in the middleware platform(Node-Red). Data published by various sensors and setpoints will be subscribed by the data input node. The node serves as the data entry gate to the middleware. The incoming data is then parsed into each independent variable. The input variable for Fuzzy Logic is the temperature

of the indoor set-point, outside temperature and humidity. While the input variable for the PID controller node is the indoor temperature, temperature setpoint and PID parameter constant which is the output of fuzzy logic.

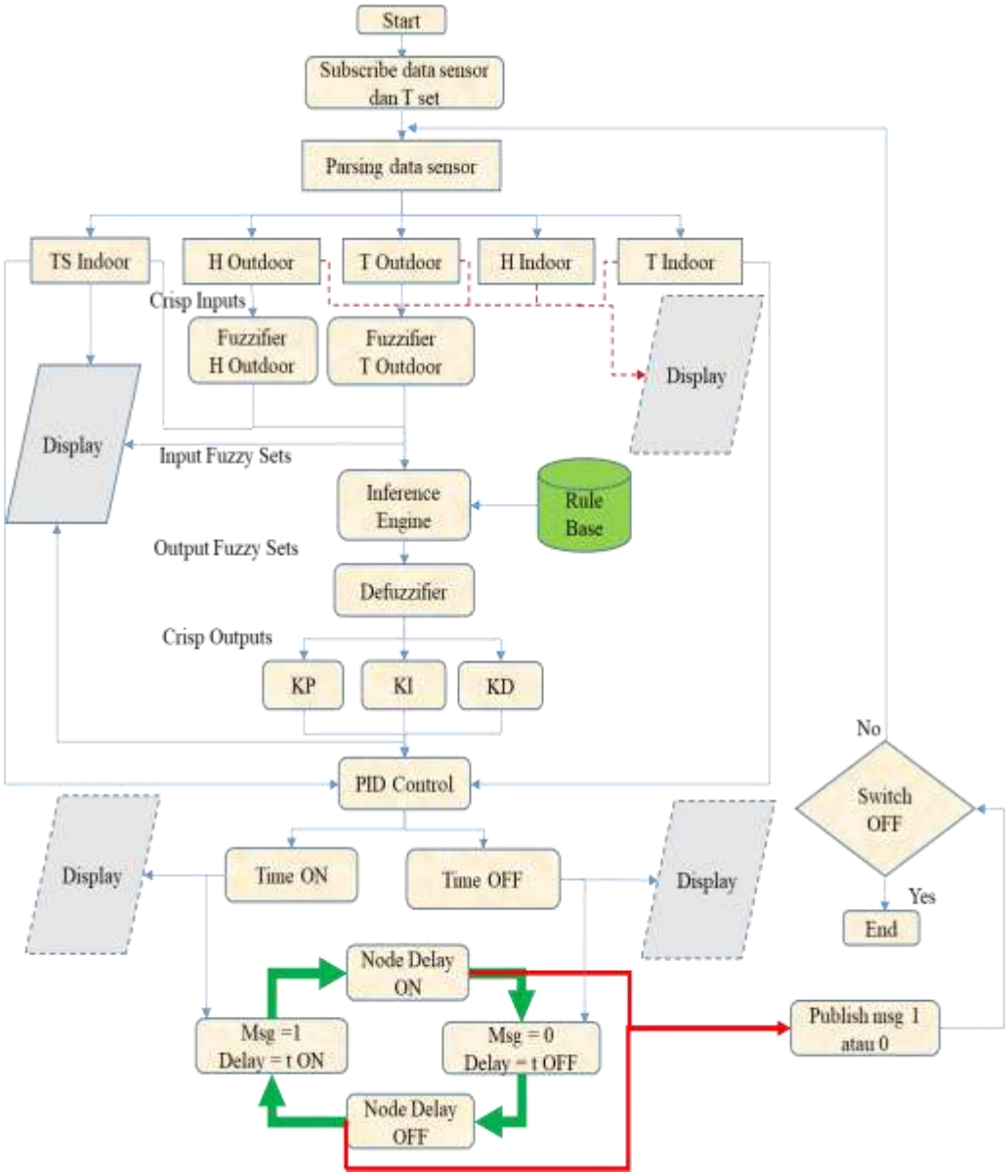

Figure 7. Hybrid Fuzzy-PID Algorithm embedded in the middleware

In fuzzy logic, three input variables are crisp values in the fuzzification process. The output of this fuzzification process is the linguistic variable which is determined as the input for the process of inference and defuzzification. Both processes are carried out using fuzzy rules shown in table 1. The output of the process is the PID constant value, namely: Kp, Ki, and Kd. The three constants together with the indoor temperature and setpoint temperature as input variables for the PID Controller. The output of the PID Controller node is the duty cycle value that is used as the duration of the compressors ON time. The duration of the OFF time is the period minus the time

duration ON. The ON/OFF time duration is a timer in a delivery cycle of commands to turn on and turn off the compressor. The interface displays in Node-Red is shown in figure 6.

5. Performance of The Air Conditioner by Using Hybrid Fuzzy-PID

The Fuzzy-PID hybrid control algorithm is to complement the shortcomings of the default AC setpoint control algorithm.

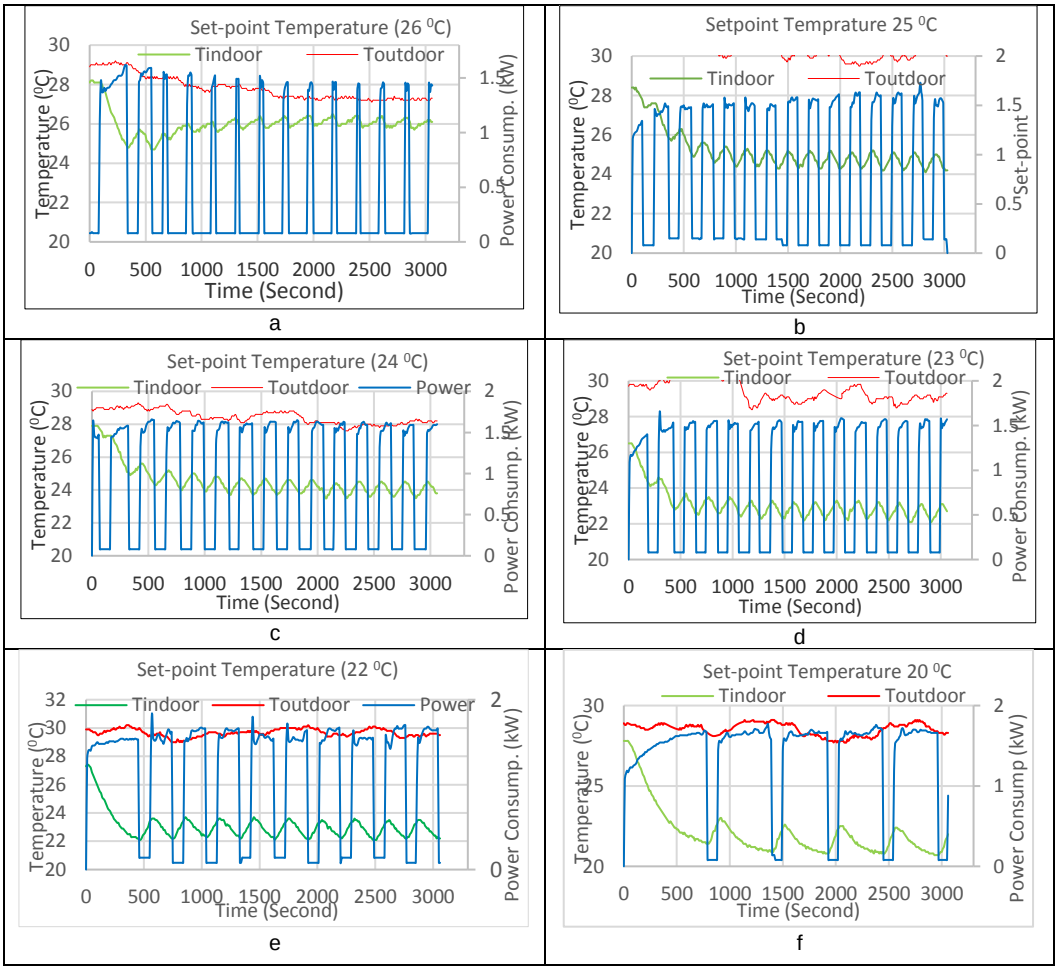

Figure 8. Room temperature performance and AC consumption due to Fuzzy-PID algorithm at each setpoint and outdoor conditions

This algorithm will search for the duty cycle value automatically so that the indoor temperature is in a fluctuating value Δ which is desired even if the outdoor conditions change. The performance superiority of this system is determined by two parameters, namely duty cycle and temperature indoor fluctuations(Δ). Intelligent control is stated to be good if both are in small value. In this study, both parameters are influenced by outdoor temperature and a temperature setpoint. Figure 8 (a, b, c, d, e, f) shows the algorithmic performance of hybrid Fuzzy-PID on AC energy consumption and room comfort. Overall, the effect of set-point temperature on the duty cycle value is inversely proportional. The higher the setpoint value, the smaller the value of the compressor duty cycle. This can be seen at setpoint 26 ºC Figure 8 (a) which shows a narrow power graph indicating the duration of the ON compressor's time is very short. This means that high set-points can be achieved in just a short time. Every 1ºC increase in set-point temperature, it will reduce AC energy consumption by 6.7 % as shown in figure 9. a. The duty cycle value is

also influenced by temperature outdoor where a high outdoor temperature will be responded by Hybrid Fuzzy-Pid control by increasing the duty cyclic value to maintain the indoor temperature at the setpoint level. Figure 9.b shows that the nature of this system when outdoor temperatures increase by 1ºC results in the hybrid fuzzy-PID to increase the duration of the ON compressor time by 28.7 seconds if the period is 700 seconds or increase energy consumption by 4.1 %.

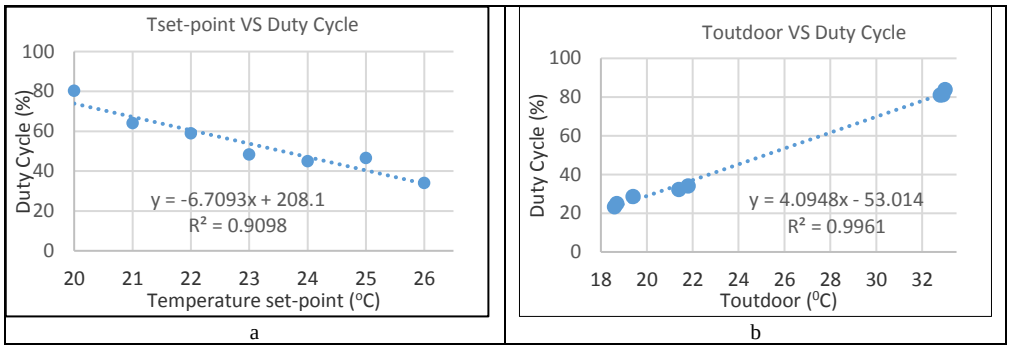

Figure 9. The effect of setpoint and outdoor temperature on duty cycle compressor

A unique thing can be found in the graph in figure 10. a where the duty cycle at 25 ºC setpoint is greater than the duty cycle at setpoint 24 ºC which should have a duty cycle at setpoint 24 ºC greater than the duty cycle at setpoint 25 ºC. The contradiction is caused by differences in the external temperature shown in figures 8.b and 8.c. Furthermore, room comfort can be seen in indoor temperature fluctuations that are influenced by outdoor temperature and a temperature setpoint. The effect of outdoor temperature on indoor temperature fluctuations is not as significant as shown in figure 10. a. This shows the reliability of this control system that is resistant to environmental changes. Indoor temperature fluctuations are influenced by temperature set points with relationships inversely proportional. In Figure 10.b shows that every 1 ºC decrease in setpoint, it will increase indoor temperature fluctuations by 0,22 ºC. This is due to the thermal potential at low temperatures being stronger to return to thermal balance (law to zero thermodynamics).

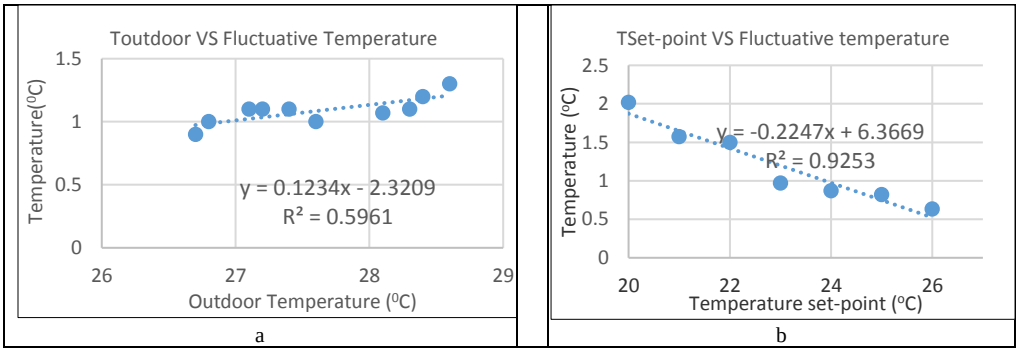

Figure 10. The effects of outdoor temperature and set-point on indoor temperature fluctuations

6. Conclusion and discussion

Hybrid Fuzzy-PID control performance in this research can overcome the disadvantages of default AC set-point control algorithms both in terms of savings and in terms of convenience. In terms of savings, hybrid Fuzzy-PID can save AC energy consumption by 50% in conditions where the default AC algorithm cannot save it. In terms of comfort, hybrid Fuzzy-PID can overcome excessive cooling and be able to pursue the desired temperature by the setpoint.

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Husein received the B.S. degree in Physics from Haluoleo University (UHO), Kendari, Indonesia, in 2002, and the M.Sc. degree in physical instrumentation systems from the Gadjah Mada University (UGM), Yogyakarta, Indonesia, in 2010. He is currently working toward the Ph.D. Program in high energy theoretical physics and Instrumentation in Bandung Institute of Technology (ITB), Bandung, Indonesia. His research interests include Smart Light, Smart Air Conditioner, Energy Management System, wireless networking sensor (WSN) and Internet of Things Infrastructure.

Maman Budiman received the B.S. degree in physical electronics instrumentation from Bandung Institute of Technology (ITB), Bandung, Indonesia, in 1990, the M.Tech. degree in electrical engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1995.and the Ph.D. Program in electrical engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1998. His research interests include Smart Light, Smart Air Conditioner, Energy Management System, wireless networking sensor (WSN) and Internet of Things (IoT) Infrastructure.

Mitra Djamal received the B.S. degree in physical electronics instrumentation from Bandung Institute of Technology (ITB), Bandung, Indonesia, in 1984, and the Ph.D. Program in electrical engineering from Munchen der Bundeswehr university, Munchen, Germany, 1992. His research interests include development of smart sensor, Design and Implementation of Online Web Based Monitoring System of a Smart Home, Development of Giant Magnetoresistance (GMR) Materials and Its Application for Sensors, Automatic Door using Voice Recognition based on Momentum Back Propagation and Cross Correlation Methods and wireless networking sensor (WSN).