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# Implementation of Hybrid Fuzzy-PID Integrated Anti-Windup Controller for Steam Distillation Process

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***Abstract*- The proper of temperature control are very important and compulsory in order to achieve high quality of desired essential oils via the process of steam distillation technique. The regulation of temperature purposely to ensure that the desired temperature value reach the setpoint without deviate which; contribute to the quality of essential oil. The well-known of PID controller is always utilized in industrial process. Unfortunately, the PID has suffer when the integral action reach at the saturation region which; the integral action unable to unwind the system. In this wind-up situation, the system exhibits high overshoot (which is deviate from the setpoint) and take more longer time to reach the settling time, which is contribute to produce bad quality of essential oil. To improve the situation the PID will be integrated with anti-windup system in effort to diminish the system overshoot and settling time. In addition, the PID plus anti-windup (PIDAW) system will be integrated with Fuzzy Logic controller in order to enhance the system performance. The Hybrid Fuzzy-PID plus Anti-Windup (HFPIDAW) controller is capable to control the time-varying of steam distillation process which; reveal the better simulation result in step test, set point tracking, load disturbance test and performance index compared to classical PID controller. Based on the simulation result, the modification of PIDAW and HFPIDAW controllers is able to contribute an ideas to industrial practitioner to design the controller in real-time process.**

***Index Terms*—Proportional-Integral-Derivatives integrated Anti-Windup (PIDAW), Hybrid Fuzzy-PID (HFPID), Hybrid Fuzzy-PID Anti-Windup (HF-PIDAW).**

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## I. INTRODUCTION

The ethereal oil or more known as essential oil have the properties like; concentrated, hydrophobic liquid that contains hundreds aromatic compounds constituents, hormones, vitamins and other natural elements [1]–[3]. The compounds can be extracted from leaves, stems, flowers, bark and roots from a botanical raw material by applying any technique of extraction. The demand is increasing due to essential oil contains highly volatile components.

Today, there has been an explosive growth of intent of essential oil usage [4], [5]. The essential oils has been widely applied, and recent studies have scientifically proved some of conventional application of the oils such as insect repellent or pesticides [6], [7], aromatic and fragrances [8], [9], food and flavors [9], and has also discovered its new applications such as anti-bacterial [8], anti-fungal [10]–[12], many applications in pharmaceutical industries [11], [13], [14] and nutraceutical (cosmetics) [8], [15].

The essential oil can be extracted through several type of extraction methods which; conventional method to modern methods with most popular and common practice method in extraction technique is by applying steam distillation method [1]. Actually, the distillation technique is pioneer in the extraction technique, which including water distillation and steam distillation [16]. Though the world demand of the essential oil is increasing and countless research efforts have been reported in improving the extraction techniques [16], and consequently to enhance the quality of essential oil is ignored.

In order to enhance the quality of essential oil, temperature regulation in production looks trivial but it is very challenging task [17]. However, the impact of the effort, also contribute to the higher production yield rate [18].

In control algorithm, PID is most selected in the solution of robotics, electronic devices, electrical system and chemical processes [19]–[21]. The basic structure PID still relevant due to its simplicity, robustness, easy to operate and wide range of capability with close to optimal performance [22]–[27]. Based on the survey by Desborough and Millers in [28] from Honeywell's reported more than 97% from 11,000 controllers for industrial processes are developed based on P, I and D algorithm. Unfortunately, the PID have three parameter but difficult to tune properly in realtime process [22]. In addition, the integral action is suffer due to actuator constraint; when an actuator reach at saturation level [29]. Although the PID controller the most selected and first choice among the researchers due to simplicity and easy to develop but yet, able to achieve satisfactory results. The drawback of PID is limited to linear operation range [30]. In addition, the wind-up phenomenon is always occur due to nature of the process itself (dead time). In wind-up situation, the elements in P, I and D controller associated to integral element ($T_i$) spike to a significantly large value and controller start to neglect the saturation occur. At this stage, the stability of the system is degraded and more longer time to unwind.

The consequences of ignoring the windup phenomenon in the process; the system running with high overshoot, long settling time and longer time to rise at setpoint; or in other word a controller is perform poorly in the present of control signal constraint [29].

In order to overcome the wind-up problem the algorithm developed in PID is integrated with tracking back-computation (anti-windup method). The advantages of back-computation technique is enequality of level of saturated and unsaturated control signal that were injected to the system by re-compute the the exact value of integral gain when controller output reach at saturated level; which allows the controller to operate within its saturation region [31]. By implementing an anti-windup system to the controller, a system performance is preserved in absence of actuator saturation.

Therefore, the research to enhance the performance of PID is continual studied which; researchers start to integrate the intelligent controller such as fuzzy logic controller, Articial Neural Network (ANN) and Model Predictive Control [30], [32], [33].

In addition, the reseachers had explored a new logic control which is fuzzy logic control where the fuzzy logic has capability on rational decision in environemnt or situation of vagueness, uncertainty, lack of information and partially decision. Today, the PID controller is always develop integrated with Fuzzy [34]–[37], Fractional Order [38], [39], Auto-Tuning [40], Adaptive Controller [41] purposely to enhance the regulation motor speed [42], [43], voltage sag or drop [17] or temperature regulation [35], [44] at the desired set-point.

## II. PID AND PID ANTI-WINDUP STRUCTURE

The PID (as shown in Fig. 1) is also known as the three elements controller. The PID is the feedback controller that consist of three elements knowns as proportional element, *P*, Integeral element, *I* and Derivative element, *D*. The PID structure is shown in Equation (1)

$$u(t) = K_p e(t) + \int_0^t K_i\, e(t)dt + K_d \frac{de(t)}{dt} \qquad (1)$$

Where the *Kp*, *Ki* and *Kd* are the proportional gain, integral gain and derivative gain repectively. Those gains is able to express as in Equation (2), (3) and (4)

$$K_p = K_p \qquad (2)$$

$$K_i = \frac{K_p}{T_i} \qquad (3)$$

$$K_d = K_p T_d \qquad (4)$$

Where the $T_i$ and $T_d$ indicates the integral time constant and derivative time constant.

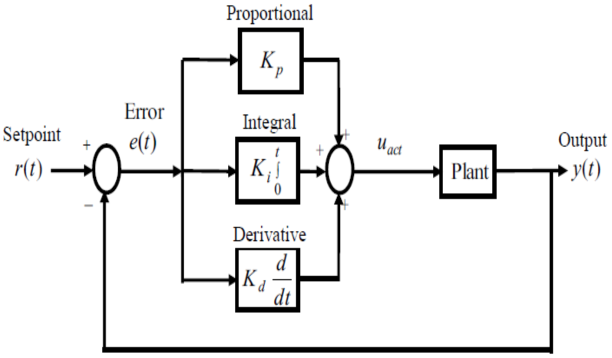

**Fig. 1.** Basic PID Controller Block Diagram

The PID is well-known and engineers still applied the controller in production floor due to easy to operate and design. Unfortunately, the PID has some limitation especially once a system is nonlinear in dynamic behavior. In addition, the limitation of actuator in order to regulate integral action at saturate region.

In this research, the basic PID structure will be integrated with additional feedback (as shown in Fig. 2); known as anti-wind up function. The functionality of additional feedback which developed in PID structure is to determine the descrepancy value produced of saturated control signal and unsaturated/actual control signal, $u_{\mathrm{act}}$.

The windup problem start to attack system dynamic once actual control input penetrate beyond the saturated region. The improvement is done by anti-windup integrated with PID controller which; an error between saturated signal and actual signal will be notified to new integrator via $1/T_a$ gain to recompute the new integral action value.

The $T_a$ value will contionously computed until the value of $T_a$ form an actual control signal and system dynamic stand at desire set point.

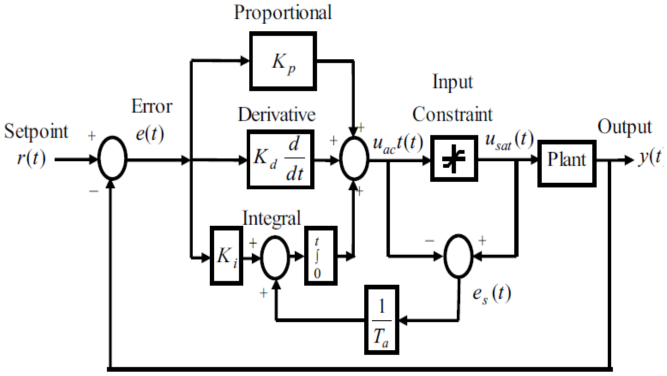

**Fig. 2.** PID Integrated Anti-Windup (PIDAW) Contoller Block Diagram.

To ensure the controller has high performance; the selection of Tracking Time Constant, $T_a$ value is important [45]. The $T_a$ value highly effect on new integrator feedback to reset faster or not and, this phenomenon indirectly effect on overall controller performance [46]. In [47] has suggested the range selection of Tracking Time Constant, $T_a$ value as in Equation (5)

$$T_i \geq T_a \geq T_d \tag{5}$$

So, referring to the Equation (5), determination of $T_a$ values as in Equation (6), (7) and (8)

$$T_a = T_d \tag{6}$$

$$T_a = T_i \tag{7}$$

$$T_a = \sqrt{T_i T_d} \tag{8}$$

The advantage of selection $T_d$ value as smallest value which is $T_a = T_d$; will contribute the fastest reset time to the integrator [29]. The values of new $T_a$ will be applied as new integrator feedback for PID Integrated Anti-Windup strategies. The compensator will be developed using Tracking Time Constant values based on Equation (6), (7) and (8). Each compensator will be evaluated using transient response and performance indexes to determine the best controller.

## III. HFPID AND HFPIDAW STRUCTURE

Today, conventional PID controller integrated with fuzzy logic is widely applied to enhance the robustness of the classical structure of PID. The integration of PID and fuzzy logic controllers, the PID gain were automatically tuned from the output of fuzzy error information. The basic configuration of the fuzzy system as described in Fig. 3.

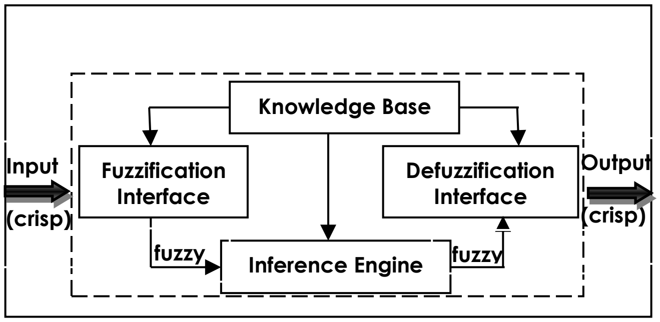

**Fig. 3.** Configuration of Fuzzy System

The function of fuzzy logic controller is supervise the PID algorithm in attempting to be tuned within the range. All the gains tuned following a set of fuzzy rules in order to achieve the optimum performance. In this study, the CHR tuning rule as a reference to build the range of PID parameters. And, the designing of Membership Function (MF) and fuzzy rules were built based on experimental experience and knowledge which is depend on the plant to be regulated.

### A. *Parameters of Hybrid Fuzzy-PID Controller*

The Mamdani inference system is applied in order to develop the HFPID and, two approaches have involved which were five and seven (Membership Function (MF). The 5MF and 7MF have couple of input variables whice are error, $e(t)$ and derivative of error, de/dt. The three elements of $Kp$, $Ki$ and $Kd$ parameters are act as the output variable of the HFPID control that then will be fed to each of the PID controller parameter.

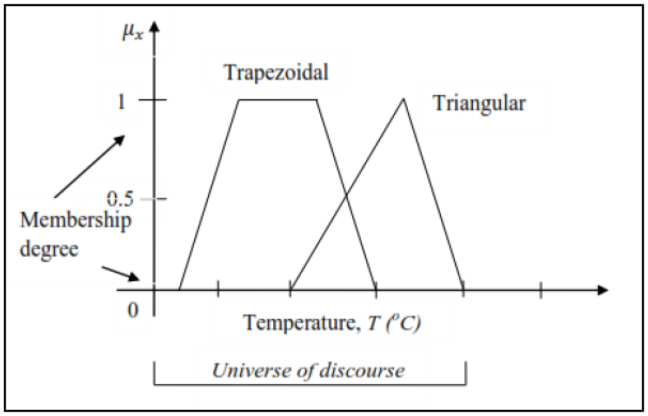

**Fig. 4.** Shape of Triangular and Trapezoidal MF

The ilustration in Fig. 4 shows the trapezoidal and triangular shape membership functions which were selected for all the linguistic variables in constructing 5MF and 7MF fuzzy systems. The challenging part to design fuzzy system is determination of MF where its play a very crucial role to represent the brain of the controller. The best arranging of MF shape will contribute the best output performance of the system. Until today, there is no method and no single best method to determine the fuzzy MF but the shape of the MF can be choosed that based on the problem domain. However, the triangular and trapezoidal patterns be the most popular in designing MF in almost application that emerged with Fuzzy Logic Controller as shown in Fig. 4. In addition, the triangular MF are preferable because of their simplicity and less computational burden.

TABLE I. FUZZY RULES MAPPING

| Derivative of Error | Error | | | | |
|---|---|---|---|---|---|
| | NB | NS | ZE | PS | PB |
| NB | NB | NB | NM | NS | ZE |
| NS | NB | NS | NS | ZE | PM |
| ZE | NM | NS | ZE | PS | PB |
| PS | NS | ZE | PS | PS | PB |
| PB | ZE | PM | PB | PB | PB |

The Fuzzy rule is developed by mapping based on the system that to be controlled. The fuzzy rules were formed according to an input-output map which; each rule consist of two antecedents (input) and one consequence (output). Therefore, there are 49 if-then rules were developed that based on input-output of the fuzzy sets as summarized in Table I.

In this research, the variable of the parameter $K_p$. $K_i$, $K_d$ are ranging in between [ *Kp min Kp max*], [*Ki min Ki max*] and [*Kd min Kd max*] respectively.

The range of PID parameter was developed referred to the simulation of PID control to ensure the feasible rule bases with high inteference efficiency. Those ranges is able to calibrate between the interval of [0 , 1] that given in Equation (9), (10) and (11)

$$K'p = \frac{K_p - K_{p\,\min}}{K_{p\,\max} - K_{p\,\min}} \tag{9}$$

$$K'i = \frac{K_i - K_{i\,\min}}{K_{i\,\max} - K_{i\,\min}} \tag{10}$$

$$K'd = \frac{K_d - K_{d\,\min}}{K_{d\,\max} - K_{d\,\min}} \tag{11}$$

## IV. THE SIMULATION OF STEAM DISTILLATION PROCESS

In order to develop simulation system to study various PID performance, the empirical input-output data form steam distillation process is needed. The input-output data is utilized to build process reaction curve for gain calculation purpose. The step input was injected to steam distillation process and the output data was collected from ambitient temperature until water saturated point. Then, the input-output data are applied to develop process reaction curve in order to obtain three main elements; process gain (*k*), dead-time or also known as time delay ($\theta$) and time constant ($\tau$). All the PID comtroller are calculated using CHR tuning rules to obtain the gain, dead time and time constant.

In addition, the transfer function to represent the whole system dynamic is needed and developed based on ARX first order model. Finally, MATLAB2019 Simulink configuration is applied to simulate controller of the steam distillation process.

TABLE II. TRACKING TIME CONSTANT, $T_a$ VALUE

| Controller Name | Tracking Time Contant, *Ta* Value |
|---|---|
| PIDAW-Td | 282 |
| PIDAW-TiTd | 674 |
| PIDAW-Ti | 1612 |

TABLE III. HFPIDAW CONTROLLER TRACKING TIME CONSTANT, $T_a$ VALUE AND MF

| Controller Name | Tracking Time Constant, $\boldsymbol{T_a}$ | $\boldsymbol{T_a}$ Value | Membership Function (MF) |
|---|---|---|---|
| HF-PIDAW - $T_i$ -5MF | $T_i$ | 1612.8 | 5 |
| HF-PIDAW- $\sqrt{T_iT_d}$ -5MF | $\sqrt{T_iT_d}$ | 396 | |
| HF-PIDAW- -$T_d$ -5MF | $T_d$ | 282 | |
| HF-PIDAW- $T_i$ -7MF | $T_i$ | 1612.8 | 7 |
| HF-PIDAW- $\sqrt{T_iT_d}$ -7MF | $\sqrt{T_iT_d}$ | 396 | |
| HF-PIDAW- $T_d$ -7MF | $T_d$ | 282 | |

In this research, the development of PIDAW will be divided to three difference value of Tracking Time Constant, $T_a$. The PIDAW were tested with three differences of Tracking Time Constants, $T_a$ values as in Table II.

While, HFPIDAW controllers are developed based on difference values of Tracking Time Constant, *Ta* where all given name with suffix are depend on *Ta* and MF applied for that controller. The name of the controllers is listed in Table III.

## V. SIMULATION RESULTS OF PID AND PIDAW CONTROLLERS

The experimental by simulation based are started with PID and PID integrated with Anti-Windup (PIDAW) which are the tracking time constant are varied from lowest gain of *Td* to highest gain of *Ti*. All the PID and PIDAW controllers in Table IV shows step test results for; percentage of overshoot, rising time and settling time. The Fig. 5 show the simulation of regulating steam temperature (step test) in steam distillation plant that were controlled by PID, PIDAW-Td, PIDAW-TiTd and PIDAW-Ti controllers.

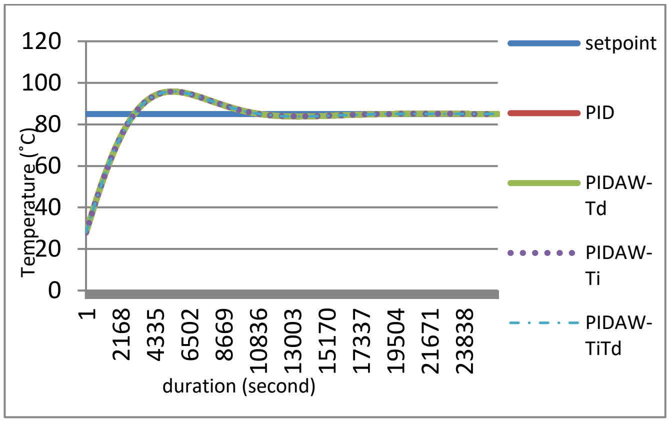

**Fig. 5.** Output Response of PID and PIDAW Controllers for Step Test.

TABLE IV: STEP TEST SIMULATION STUDIES FRO PID AND PIDAW

| **Controller** | **PID** | **PIDAW-Td** | **PIDAW-TiTd** | **PIDAW-Ti** |
|---|---|---|---|---|
| OS% | 12.7323 | 12.7113* | 12.7296 | 12.7296 |
| Tr | 2324.10* | 2324.70 | 2323.80 | 2323.80 |
| Ts | 13906 | 14003 | 13899* | 13899* |
| ITAE | 9.99E+08 | 9.99E+08 | 9.99E+08 | 9.99E+08 |
| IAE | 38400 | 38400 | 38400 | 38400 |
| ISE | 70660* | 70670 | 70670 | 70660* |

**preferred response by category*

Table IV shows the step test performance for PID and modification of PID integrated with Anti-Windup (PIDAW) controllers in step test simulation studies. The percentages of overshoot column show that the PIDAW controllers outperformed the PID controller, which the percentages of overshoot of all PIDAW controllers lower than the PID controller. The PIDAW-Td controller reveals lowest percentage of overshoot and followed by PIDAW-Ti and PIDAW-TiTd controllers. This scenario's indicate that the PIDAW controllers show good performance as a controller. For rising and settling time, the PIDAW-Ti and PIDAW-TiTd controllers show improvement which are fastest rising and settling time were recorded.

The simulation result for PID, PID-Td, PID-TiTd and PID-Ti on set point tracking are presented in Fig. 6. The Table V show the summary of set point change for PID and PIDAW controllers, which the three value of set point are being considered such as 55˚C, 70˚C and 85˚C. Then, the performance evaluation based on rise time, settling time and percentage of overshoot. The result of the study shows that the PID and PIDAW controllers were recorded the same response for the rise time criterion (55˚C) with 2323.8 seconds. For the set point of 70˚C and 85˚C shows that the PID has recorded fastest rise time with 2343.4 seconds and 2336.5 seconds respectively. As shown in the Table V that PIDAW-Ti controller has fastest settling time for the 70˚C and 85˚C with 10635 seconds and 10641 seconds respectively.

TABLE V. SET POINT CHANGE AND LOAD DISTIRBANCE TEST FOR PID AND PIDAW CONTROLLERS

| **TempStep Test** | | **PID** | **PIDAW-Td** | **PIDAW-TiTd** | **PIDAW-Ti** |
|---|---|---|---|---|---|
| 55˚C | OS% | 9.3 | 9.3 | 9.3 | 9.3 |
| | Tr | 2323.8 | 2323.8 | 2323.8 | 2323.8 |
| | Ts | 13899.0 | 13899.0 | 13899.0 | 13899.0 |
| 70˚C | OS% | 4.1 | 2.7* | 2.6 | 3.2 |
| | Tr | 2343.4* | 3357.2 | 3421.8 | 2745.2 |
| | Ts | 13800.0 | 13232.0 | 11368.0 | 10635.0* |
| 85˚C | OS% | 3.4 | 2.1* | 2.3 | 2.6 |
| | Tr | 2336.5* | 3463.0 | 3375.9 | 2779.0 |
| | Ts | 13837.0 | 12852.0 | 12106.0 | 10641.0* |
| Load Disturbance | | 3044.0 | 3000.0* | 3044.0 | 3044.0 |

**preferred response by category*

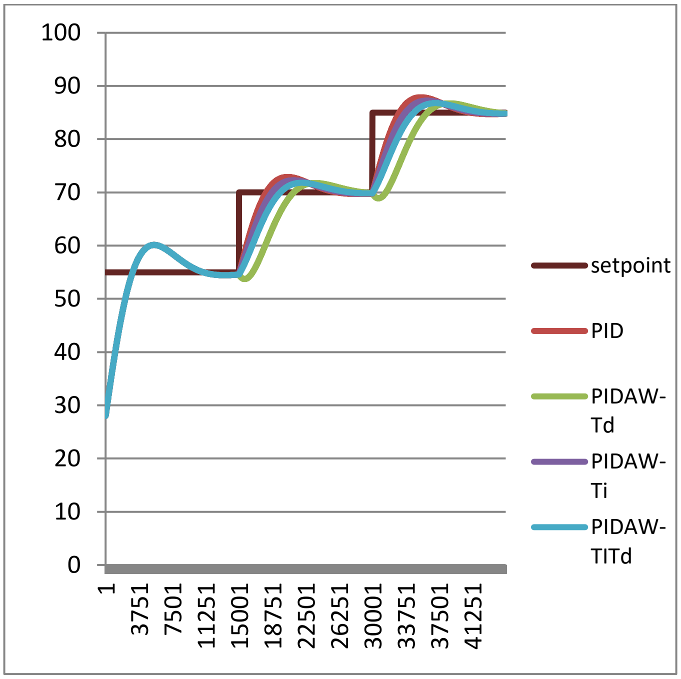

**Fig. 6**. Output Response of PID and PIDAW Controllers for Set Point Change Test.

The next criteria is percentage of overshoot showing that for the set point 70˚C and 85˚C, the PIDAW-Td has the lowest percentage of overshoot with 2.7% and 2.1% respectively. The final criteria is load disturbance test in steam distillation process. Based on the observation, the PIDAW-Td only require 3000 second to recover the set point compared to other controllers.

Based on the analysis above, following conclusion is established with PIDAW-Td has better overall performance with 3 prefered criteria in set point change criterias against PID, PIDAW-Ti and PIDAW-TiTd. In addition, the overall result shows the anti-windup system integrated in PIDAW controller reveals the improvement in step response and performance indexes. So, further investigation is to integrate the anti-windup system to intelligent controller in order to achieve better performance in steam distillation process.

## VI. SIMULATION RESULTS FOR HFPID AND HFPIDAW CONTROLLERS

The Fig. 7 show the output reponse for HFPID and and HFPIDAW for 5MF on recovering set point 85 ˚C. And, Fig. 8 show the output response for HFPID and HFPIDAW for 7MF on recovering set point 85˚C.

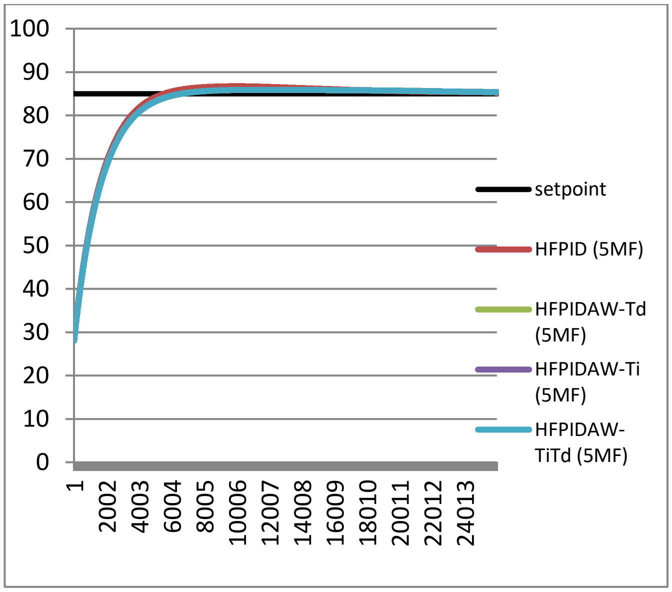

**Fig. 7.** Output Response of HFPID (5MF) and HFPIDAW (5MF) Controller for Step Test.

The step response on SISO of steam distillation process are utilized to evaluate the controller performance in terms of rise time, settling time, percentage of overshoot and performance index as numerical data are tabulated in Table VI and Table VII. The HFPIDAW are integrated with additional feedback (integral feedback) named HFPIDAW-Td, HFPIDAW-TiTd and HFPIDAW-Ti. While, the HFPID controller is developed without integral feedback. By referring to Table VI and Table VII, the controller are developed by applied the Hybrid Fuzzy with 5 MF and 7 MF respectively.

The data in Table VI shows that HFPIDAW-Td has lowest percentage of overshoot with 0.65%. In term of rising time HFPID recorded fastest rise time with 3210 seconds followed by HFPID-TiTd (3410 seconds), HFPIDAW-Ti (3410 seconds) and, and lastly HFPID-Td (3490 seconds). The settling time criteria shown that HFPIDAW-TiTd and HFPIDAW-Ti have fastest value of 5390 seconds while the HFPIDAW-Td controller recorded value 5680 seconds. Unfortunately, the HFPID took longer settling time which 15200 second. The performance index criteria are ITAE, IAE and ISE values indicates that HFPIDAW-Td, HFPIDAW-TiTd and HFPIDAW-Ti recorded the lowest value with 9.76E+08, 3.76E+04 and 6.43E+04 respectively.

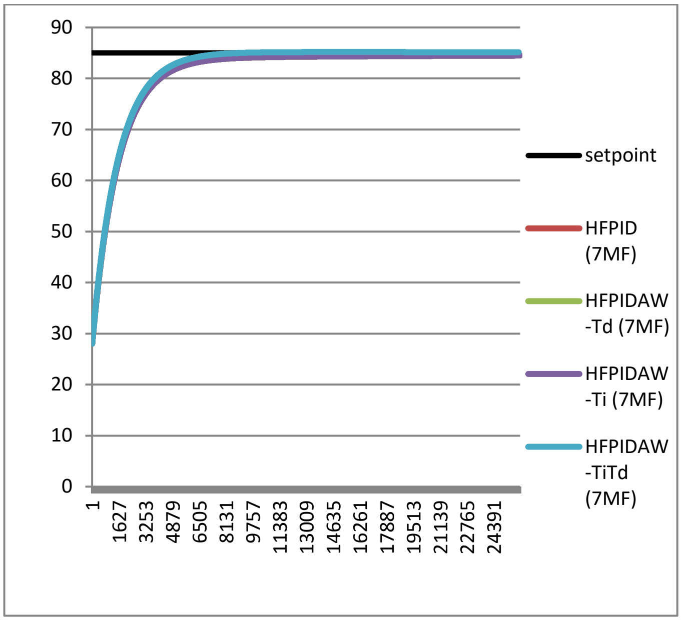

**Fig 8.** Output Response of HFPID (7MF) and HFPIDAW (7MF) Controller for Step Test.

TABLE VI. STEP TEST SIMULATION STAUDIES FOR HFPID AND HFPIDAW CONTROLLER FOR 5MF

| Controller | HFPID | HFPIDAW-Td | HFPIDAW-TiTd | HFPIDAW-Ti |
|---|---|---|---|---|
| OS% | 2.06 | 0.65* | 1.08 | 1.08 |
| Tr | 3.21E+03* | 3.49E+03 | 3.41E+03 | 3.41E+03 |
| Ts | 1.52E+04 | 5.68E+03 | 5.39E+03* | 5.39E+03* |
| ITAE | 9.82E+08 | 9.76E+08* | 9.76E+08* | 9.76E+08* |
| IAE | 3.78E+04 | 3.76E+04* | 3.76E+04* | 3.76E+04* |
| ISE | 6.56E+04 | 6.43E+04* | 6.43E+04* | 6.43E+04* |

**preferred response by category*

The data in Table VII exhibits that HFPIDAW-Td and HFPIDAW-Ti recorded the lowest percentage of overshoot with 0%. In terms of rise time, HFPID reveals the fastest rising time (3420 seconds) followed by HFPIDAW-TiTd (3460 seconds), HFPIDAW-Td (3560 seconds) and HFPIDAW-Ti (3710 seconds). The settling time criteria reveals that HFPID has fastest value of 5950 seconds while the other controller recorded value 6120 seconds (HFPIDAW-TiTd), 6680 seconds (HFPIDAW-Td) and HFPIDAW-Ti (8160 seconds). The performance index criteria are ITAE, IAE and ISE values indicates that HFPIDAW-Td recorded the lowest with 9.55E+08, 3.67E+04 and 6.20E+04 repectively.

TABLE VII: STEP TEST SIMULATION STUDIES FOR HFPID AND HFPIDAW CONTROLLERS 7MF

| Controller | HFPID | HFPIDAW-Td | HFPIDAW-TiTd | HFPIDAW-Ti |
|---|---|---|---|---|
| OS% | 0.19 | 0* | 0.03 | 0* |
| Tr | 3.42E+03* | 3.56E+03 | 3.46E+03 | 3.71E+03 |
| Ts | 5.95E+03* | 6.68E+03 | 6.12E+03 | 8.16E+03 |
| ITAE | 9.69E+08 | 9.55E+08* | 9.63E+08 | 9.55E+08* |
| IAE | 3.73E+04 | 3.67E+04* | 3.72E+04 | 3.67E+04* |
| ISE | 6.20E+04* | 6.20E+04* | 6.39E+04 | 6.20E+04* |

**preferred response by category*

Fig. 9 and Fig. 10 reveals the percentage of overshoot improvement achieve by HFPIDAW for 5MF and 7MF respectively. After carefully putting into consideration the factors mention above, clearly HFPIDAW-Td developed by 7 MF has better transient response compare to all other controller variance.

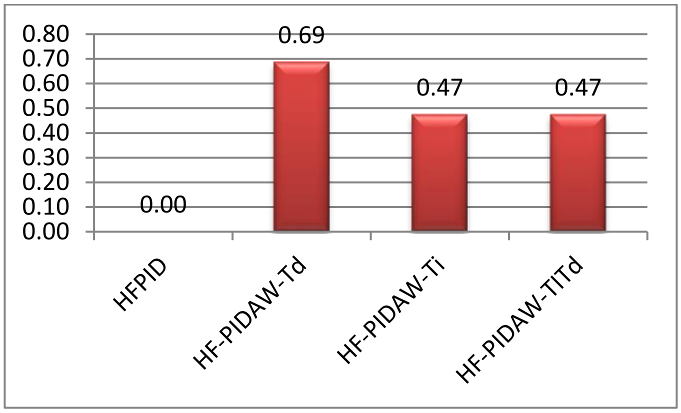

**Fig. 9.** %overshoot improvement from HFPID to HFPIDAW controllers for HFPIDAW-Td, HFPIDAW-Ti and HFPIDAW-TiTd For 5 MF.

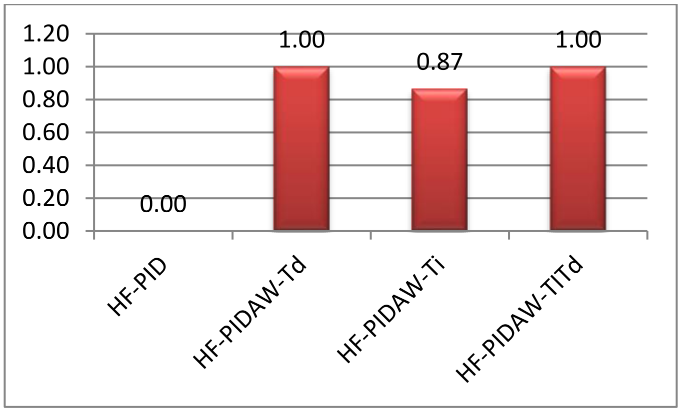

**Fig. 10.** %overshoot improvement from HFPID to HFPIDAW controllers for HFPIDAW-Td, HFPIDAW-Ti and HFPIDAW-TiTd For 7 MF.

The Table VIII presented the summary of various class of controllers. The results of the study reveals that HFPID has the fastest response towards set point change for rise time 55 ˚C, 70 ˚C and 85 ˚C with 1940 seconds, 1670 seconds and 4930 seconds. For the settling time, all the HFPID and HFPIDAW have recorded similar settling time at all level set point temperature with 15000 seconds. The last criteria for step test is percentage overshoot showing that for set pont 55 ˚C and 70 ˚C. all the HFPIDAW reveals the similar lowest overshoot with 8.63% and 1.88% respectively. Unfortunetely, set point change test at 85 ˚C exhibits all the controllers are undershoot.

Based on the load disturbance test, the HFPIDAW-Td controller only requires 1611.00 second to recover the set point compared other controller in Table VIII.

The simulation result for HFPID and and HFPIDAW for 5MF on set point tracking are presented in Fig. 11. The summary of set point change test using 5MF is presented in Table VIII. The three values of set point are being considered suh as 55 ˚C, 70 ˚C and 85 ˚C with each 15 ˚C apart between them and lastly, the performance evauation based on rising time, settling time and percentage of overshoot.

TABLE VIII. SET POINT CHANGE (SPC) SIMULATION TEST FOR HFPID AND HFPIDAW CONTROLLER FOR 5MF

| **TempStep Test** | | **HFPID** | **HFPIDAW-Td** | **HFPIDAW TiTd** | **HFPIDAW-Ti** |
|---|---|---|---|---|---|
| 55˚C | OS% | 10.62 | 8.63* | 8.63* | 8.63* |
| | Tr | 1.94E+03* | 2.09E+03 | 2.09E+03 | 2.09E+03 |
| | Ts | 1.50E+04* | 1.50E+04* | 1.50E+04* | 1.50E+04* |
| 70˚C | OS% | 3.44 | 1.88* | 1.88* | 1.88* |
| | Tr | 1.67E+03* | 2.17E+03 | 2.17E+03 | 2.17E+03 |
| | Ts | 1.50E+04* | 1.50E+04* | 1.50E+04* | 1.50E+04* |
| 85˚C | OS% | Under-shoot | Under-shoot | Under-shoot | Under-shoot |
| | Tr | 4.93E+03* | 1.50E+04 | 1.50E+04 | 1.50E+04 |
| | Ts | 1.50E+04* | 1.50E+04 * | 1.50E+04* | 1.50E+04* |
| Load Disturbance | | 1688.0 | 1611.00* | 1621.00 | 1635 |

**preferred response by category*

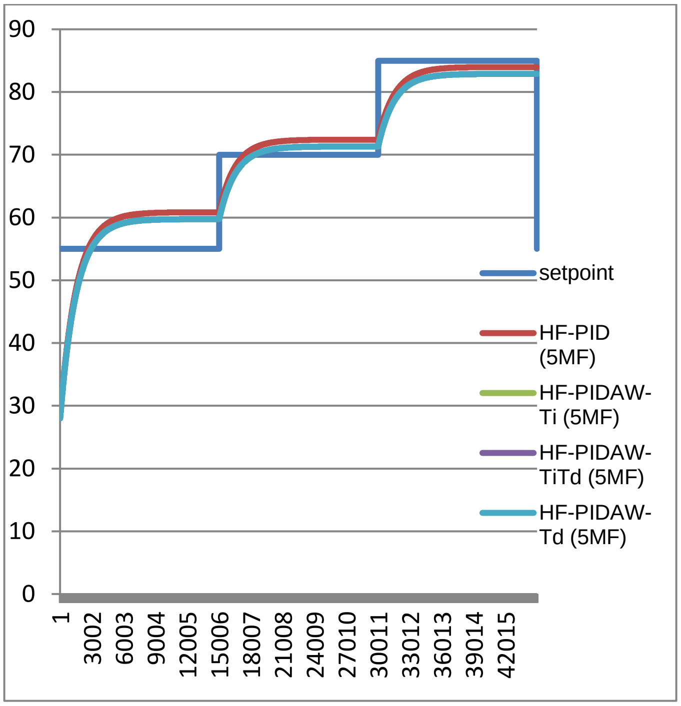

**Fig. 11.** Output Response of HFPID (5MF) and HFPIDAW (5MF) Controllers for Set Point Change Test.

The simulation result for HFPID and and HFPIDAW for 7MF on set point tracking are presented in Fig. 12. Table IX shows the set point change test and load disturbance test results for HFPID, HFPIDAW-Td, HFPIDAW-TiTd and HFPIDAW-Ti controllers for 7 MF. Based in the study suggesting that HFPIDAW-Td has the fastest response towards set point change for rising time at all temperature level with 707 second (55˚C), 505 seconds (70 ˚C) and 535 seconds (85˚C).

As shown in the Table IX that HFPIDAW-Td have the fastest settling time in all sectors of set point change with 1076.5 seconds, 858.9 seconds and 949.5 seconds. The last criteria is percentage of overshoot showing that for set ponint change 55 ˚C, 70 ˚C and 85 ˚C, the HFPIDAW-Td has the lowest overshoot with 0.1955%, 0.0172% and 0% respectively.

The load disturbance test for HFPID and HFPIDAW controllers using 7 MF, the HFPIDAW-Td controller only requires 1441 second to recover the set point compared to other controller in Table IX.

Based on the the analysis above, following conclusion is established with HFPIDAW-Td developed using 7 MF has better overall performance with 9 prefered criteria in set point change against HFPID, HFPIDAW-TiTd and HFPIDAW-Ti.

TABLE IX. SET POINT CHANGE (SPC) SIMULATION TEST FOR HFPID AND HFPIDAW CONTROLLERS FOR 7 MEMBERSHIPS

| **TempStep Test** | | **HFPID** | **HFPIDAW-Td** | **HFPIDAW-TiTd** | **HFPIDAW-Ti** |
|---|---|---|---|---|---|
| 55˚C | OS% | 10.60 | 0.1955* | 8.81 | 8.81 |
| | Tr | 1.91E+03 | 707.0006* | 2.05E+03 | 2.05E+03 |
| | Ts | 1.50E+04 | 1076.5* | 1.50E+04 | 1.50E+04 |
| 70˚C | OS% | 2.65 | 0.0172* | 1.47 | 1.47 |
| | Tr | 1.87E+03 | 505.7883* | 2.33E+03 | 2.33E+03 |
| | Ts | 1.50E+04 | 858.9302* | 1.50E+04 | 1.50E+04 |
| 85˚C | OS% | Under-shoot | 0* | Under-shoot | Under-shoot |
| | Tr | 3.63E+03 | 535.7122* | 1.49E+04 | 1.49E+04 |
| | Ts | 7.16E+03 | 949.5029* | 1.50E+04 | 1.50E+04 |
| Load Disturbance | | 1659.0 | 1441* | 1522 | 1501 |

**preferred response by category*

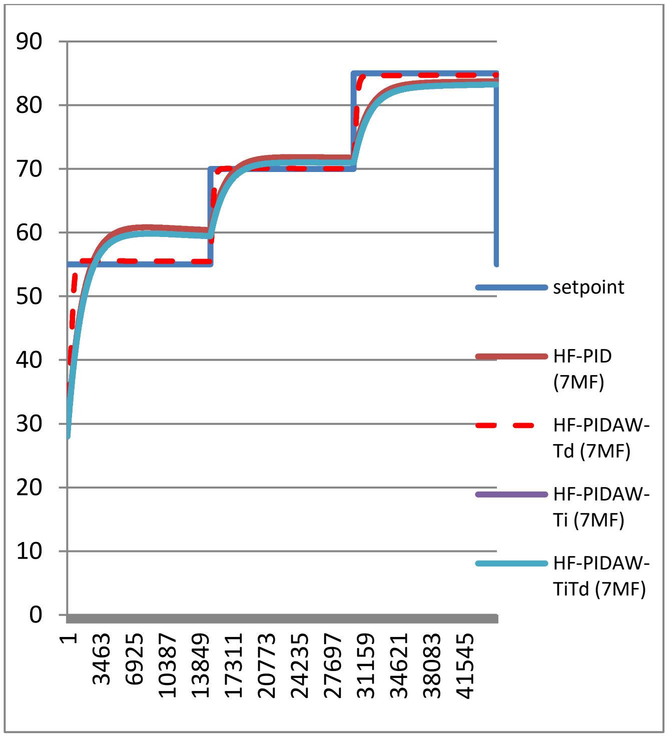

**Fig. 12.** Output Response of HFPID (7MF) and HFPIDAW (7MF) Controllers for Set Point Change Test.

## VII. CONCLUSION

In this study, the simulation of HFPID based controller in regulating the temperature of the time-varying of steam distillation process has been benchmarked with PID based controller. The result has clearly revealed that the HFPID based controller namely HF-PIDAW significantly improved the temperature regulation of steam distillation process in term of providing fast settling time, minimal overshoot and lower error in performance index as compared with the best performance of PID based controller. In general, it can be concluded that the HFPID controllers are superior as compared to the classical PID controllers in all aspects such as the step test, set point change and load disturbance tests. Overall, based on ranking, HF-PIDAW-Td-7MF is the most preferred controller in terms of producing better transient response and set point tracking, lowest error of performance index and also fastest recovery for load disturbance then, followed by others HF-PIDAW controllers consecutively.

## VIII. ACKNOWLEDGEMENT

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