The Anti Windup PID Controller ISE Tuning Based for Small-Scale Steam Distillation System

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Abstract- Proportional-Integral-Derivative (PID)controller are easy to develop and tuned, efficient and reliable in any control system areas. The main problem of PID controller when a system facing unwanted windup phenomena due to existence of input saturation. This phenomenonis occur due to failure of controller to unwind the control input signal. The objective of this paper is to develop the Proportional-Integral-Derivative integrated Anti-Windup (PIDAW) controllers in order to diminish windup phenomenon using the tracking calculation tuning by Integral Square Error (ISE). The simulation results show that the proposed PIDAW controller is capable to reduce the overshoot and faster settling time. It is proven that PIDAW controller has better performance compared to the conventional PID controller.

Index Terms—Proportional (P), Integral (I), Derivative (D), Integral Absolute Error (IAE), Integral Square Error (ISE) and Integral Time Absolute Error (ITAE), PID integrated Anti Windup (PIDAW).

I. INTRODUCTION

Since 1930, PID controllers are widely utilized in industrial processes due to easy to develop and tuned, efficient and reliable in any control system areas[1], [2]. Until today, more than 500 tuning methods have been derived to tune the PID controllers in order to achieve best performance[3]. However, no general claim that signifies which method would produce the best tuning.

The problem of conventional PID controllers whena system exhibit nonlinearities in their dynamic and windup phenomenon will occur. In addition, the limitation of controller capability to unwind the presence of the phenomenonand control signal will fluctuate beyond the upper or limit of actuator operation level.

The windup phenomenon occur when the integral action from controller reach at maximum level and controller feedback does not affect anymore. The output of controller start to increase; where an integral action non-stop accumulate without realize it's already produce some error to the system. The value of integrator increase and undesired error controller signal is produced which are ouside the operating region of the actuator operation[4].

The situationcan cause actuator saturation level broken the fedback loop function[5]; feedback loop not function anymore and causing high overshoot, longer settling time and instability dynamic[5]–[7]. The problem of windup occur in a control system must be considered when designing a controller to reach best performance of close-loop system [4].

In other word, this phenomenon occurs due to failure of controller to unwind the control input signal[8]. Input saturation situation is common nonlinearities phenomenon in control system. The phenomenon occur when actuator operation is achieved the saturation point level and input of a plant will be different from the controller output[9]. Consequently,an integrator start to integrate an error and wind up start to occur..

In steam distillation process, PID controller utilized widely to control the whole process[10]–[14]. Unfortunately, only few number of research tune a PID controller and consider the windup phenomenon problem in steam distillation system[15]–[17].Until today, almost all works related to control the steam of distillation column only focusing on development of PID without consider unwanted windup phenomena[6], [17].

The basic PID structure suffers to control windup phenomenon due to the presence of the most encountered nonlinearities on the system caused by control input constraint[6]. The problem is associated with the integral action on the PID controller itself. The integral action is continuously integrate an error and start to produce too large controller signals which are beyond the upper or lower limit of the actuator operation; known as windup phenomenon[18], [19]. The phenomenon will cause actuator saturation level broken the system feedback loop function. The windup problem will effect the efficiency of a system; where produce undesired close-loop performance which produced by the PID controller such as high overshoot, steady state error and instability dynamic[6], [20], [21].

The unwanted windup problem could be solved by implementation of PID integrated Anti Windup (PIDAW) controller. This paper propose the solution to overcome windup phenomenonproblem using PID integrated Anti-Windup (PIDAW) controller tuned by Integral Square Error (ISE) method. The function of anti-windup action integrated in classical PID structure is to minimizebad effect of control input nonlinearities in close loop system performance [22].

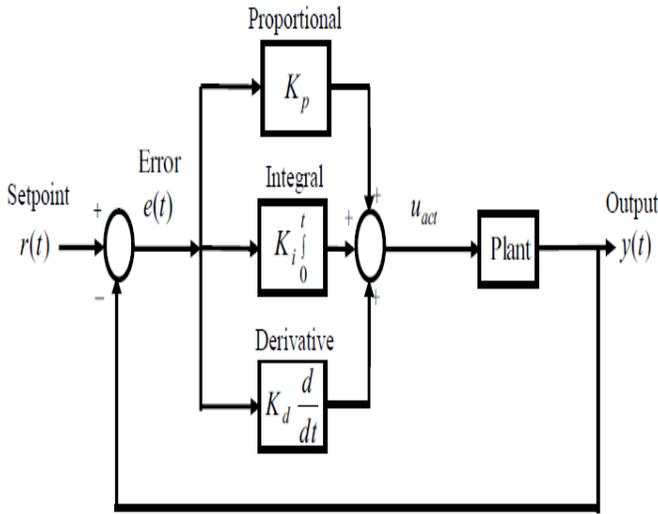## II. BASIC PID STRUCTURE AND PID INTEGRATEDANTI-WINDUP STRUCTURE

Fig. 1: Basic PID Controller Block Diagram

Fig. 1 shows the basic PID controller block diagram.The PID or so called "three terms" controller because it is a combination of a three modes which *P* (Proportional mode), *I* (Integral mode), and *D* (Derivative mode) [14]. The principle of PID controller is monitor an error occur between a measured process variable and a desired set point. Based on value of error, a corrective signal will be computed and eventually feed back to the input to improve a process accordingly.

The general PID control structure is expressed in equation (1)

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}\right)$$ (1)

where$u(t)$ is the input control signal and $e(t)$ is the error signal where the $e(t)=Y(s) - X(s)$. The development of PID controller is tuning by ISE method. Proportional gain is calculated by equation (2)

$$K_p = \frac{1.473(}{k}\left(\frac{\theta}{\tau}\right)^{-0.970}$$ (2)

And, Integral Time Contsant is computed by equation (3)

$$T_i = \frac{\tau}{1.115}\left(\frac{\theta}{\tau}\right)^{0.753}$$ (3)

Then, Derivative Time Constant is expressed by equation (4)

$$T_d = 0.550\tau\left(\frac{\theta}{\tau}\right)^{0.9480}$$ (4)

The PID controlleris able to control a system response at a desired set point so that there is no error between output signal and desired set point. The PID parameter's have their own function where the proportional gain gives output which is proportional to current error, *e(t)*. It compares between reference signalversus output value and; resulting error is multiplied with proportional constant to obtain the output signal. Due to limitation of proportional gain, the integral action is neededto improve the steady state error. The integral action will improve the steady state error so that the output is close to desired set point. Meanwhile, derivative action is to improve the system response by anticipating future behavior of the error.
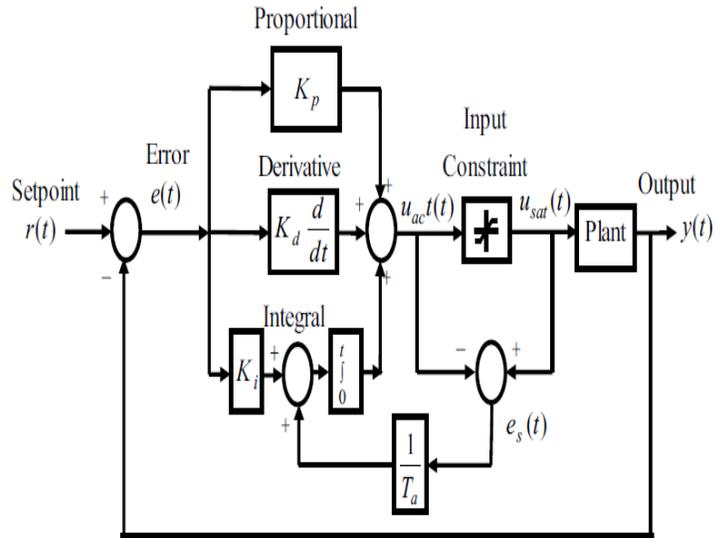

Fig. 2: PID integrated Anti Windup (PIDAW) Controller Block Diagram

Fig. 2 shows the PID Integrated Anti Windup (PIDAW) controller block diagram. The basic PID controller as compared to PID Integrated Anti-Windup (PIDAW) strategies can be expressed based on additional feedback $(1/T_a)$ integrated in PIDAW.The function of additional feedback is to compute the different value of saturated control signal, u_{sat} and unsaturated/actual control signal, u_{act}.

Once the u_{act} goes beyond the saturated level, the residual value of u_{sat} and u_{act}will befeed backto integrator via $1/T_a$ gain to recalculate the new integral action term.The process is continuously occur until the value of integral term $1/T_a$to form $u_{act}(t)$ lies on the saturation limit of the system.

The successful of PIDAW controller using tracking calculation is highly depending on selection of Tracking Time Constant, T_a value[6].The determination of T_a value will influent the how fast an integral term rate is being reset and this phenomenon indirectly effect on overall controller performance[23]. Ioannou*et. al*[24] suggest that theT_a value is within the range shown in equation (2)

$$T_i \gtrsim T_a \geq T_d$$ (2)

And, Astrom*et al.*[25]are proposed the determination of T_a value shown in (3)

$$T_a = \sqrt{(T_iT_d)}$$ (3)

Referring to equation (3) proposed by Astrom*et. al* [25],the value of $T_a$is within the range of equation (2); which proposed byIoannou*et. al*[24].Hence, to study the performance integrator feedback; three selected Tracking Time Constant, T_a will be manipulated in the range of equation (2). The proposed of T_a values can be expressed by equation (4)-(6)

$$T_a = T_i \tag{4}$$

$$T_a = T_d \tag{5}$$

$$T_a = \sqrt{(T_i T_d)} \tag{6}$$

The equation (4)-(6) will be applied for new integral action term in PIDAW controllers. The selected T_a value will be analysed to determine which controller is able to achieve good performance index.

III. CONTROLLER PERFORMANCE INDEX

In order to evaluate the performance of controller, three performance index are utilized: ISE, IAE and ITAE based on the numerical method.

The ISE performance index integrates the square of errorfrom a system via a period of time. The performance index scale will penalized larger errors occur compared to the smaller one since the square of large error will be much bigger. The ISE is given by

$$ISE\ performance\ index = \int \varepsilon^2\ dt \tag{7}$$

The IAE performace index integrates the absolute of error occur in a system over a period of time. The IAE performance index do not accumulate weight to any of the error that occur in a system reponse. The IAE is given by

$$IAE\ performance\ index = \int |\varepsilon|\ dt \tag{8}$$

The ITAE performance index integrates an absolute error from a system multiplied by the time over a period of time. The ITAE will penalized the error occur heavily compared to initial response of a system. The ITAE is given by

$$ITAE\ performance\ index = \int t|\varepsilon|\ dt \tag{9}$$

IV. THE SIMULATION OF STEAM DISTILLATION SYSTEM

The MATLAB2018 software is applied to develop simulation system for steam distillation process. The transfer function for steam distillation system is developed from process reaction curve; which is obtained from actual process of small-scale steam distillation system. The process reaction curve is able to reveal an actual dynamic of a system where

three main components will be obtained; gain (k), dead time (θ) and time constant (τ).

The steam distillation experiment was conducted at Distributed Control System (DCS) Laboratory in Faculty of Electrical Engineering, UiTM Shah Alam.

The small-scale steam distillation plant as in Fig. 4 was designed to extract and produce essential oilsby applied the steam distillation technique. The small-scale steam distillation systemis built by several components such as stainless steel distillation tank with diameter 30cm, water-cooled copper condenser, two resistive-temperature detector (RTD) assensoring element's to measure steam and water temperatures, control panel and data acquisition compartment. The stainless steel distillation column for the plant have the maximum capacity of 25 liters. During the extraction of essential oils process, the raw material is placed inside the distillation column.

In initial stage of development of controller to control steam temperature of distillation process, only water is placed in the distillation tank. The water will be heated by heater placed at bottom of distillation tank. The step signal was injected to the plant with maximum voltage 5V to study the actual behavior of the system. The dynamic of steam distillation system will be recorded and calculated using First Order Plus Dead Time (FOPDT) method. Thepocess reaction curve in Fig. 3 revealed the behavior of the system and three main parameters; gain, time constant and dead time will be calculated. The parameterscalculation of process are shown in Equation (10)-(21).
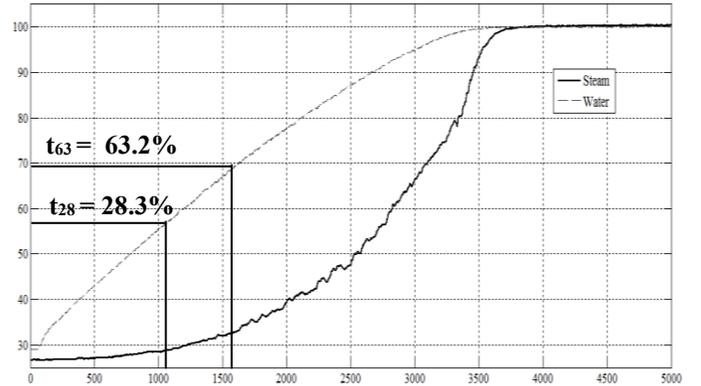

Fig. 3: Process Reaction Curve By Step Input Signal

$$Gain, K = \frac{\Delta y}{\Delta u}; 0V \tag{10}$$

$$K = \frac{100-25}{5V-0V} \tag{11}$$

$$K = 15 \tag{12}$$

$$Time\ Constant,\ \tau = 1.5\ (t_{63}- t_{28}) \tag{13}$$

$$Where\ t_{63}=1562\ and,\ t_{28}=1031 \tag{14}$$

$$Time\ constant, \tau = 1.5\ (1562 - 1031) \qquad (15)$$

$$Time\ constant, \tau = 796.5 \qquad (16)$$

$$Dead\ Time, \theta = t_{63} - \tau \qquad (17)$$

$$Dead\ Time, \theta = 1562 - 796.5 \qquad (18)$$

$$Dead\ Time, \theta = 765.5 \qquad (19)$$

From the three main parameters; Gain, Time Constant and Dead Time are utilized to develop FOPDT model and represent the actual behavior of the process dynamic. The Equation (20) and (21) illustrates the FOPDT model for the Small-scale Steam Distillation plant.

$$\frac{Y(s)}{X(s)} = \frac{Ke^{-\theta s}}{\tau s + 1} \qquad (20)$$

$$\frac{Y(s)}{X(s)} = \frac{15e^{-765.5s}}{796.5s + 1} \qquad (21)$$

The FOPDT model is applied in simulation process in order to study the performance of developed controllers. The PID controllers are tuned based on ISE method. It also integrated with anti windup scheme using the difference Tracking Time Constant values.
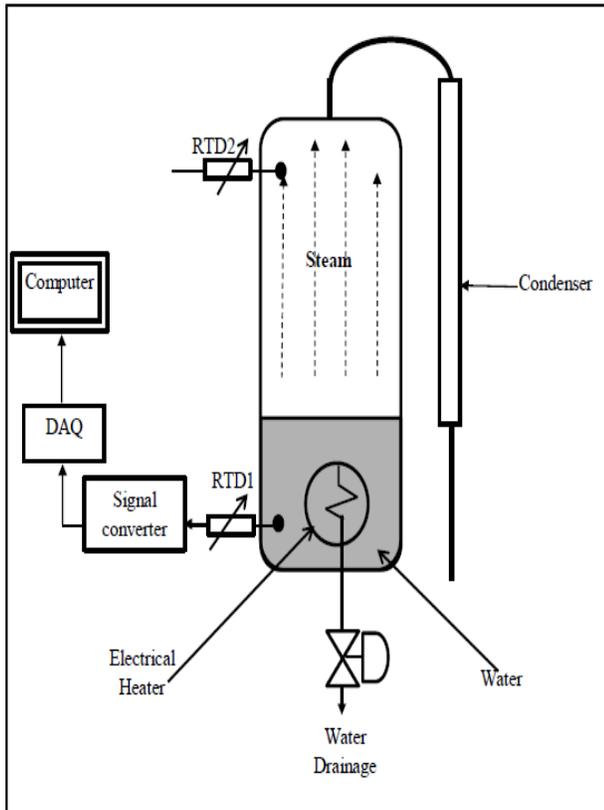

Fig. 4: The layout of Small-scale Steam Distillation System

V. SIMULATION RESULTS

Table 1 shows the summary data for ISE-PID and enhancement of all ISE-PIDAW performances in step test simulation studies and also transient response illustrated in Fig. 5. The enhancement of all ISE-PIDAW controllers show significant inprovement in overshoot percentage. The settling time also, show significant improvement are achieved by all ISE-PIDAW controllers compared to the ISE-PID. The IAE, ISE and ITAE performances index also indicate less error computed for ISE-PIDAW controllers compared to the ISE-PID.

Fig. 6 shows the percentage improvement of overshoot from ISE-PID controller to all ISE-PIDAW controllers for ISE-PIDAW-√(TiTd), ISE-PIDAW-Ti and ISE-PIDAW-Td. By rank, the best improvement is obtained from ISE-PIDAW-Td controller, which achieved at 62.16% and, followed by the ISE-PIDAW-√(TiTd) controller is improved at 60.29%. And, third is ISE-PIDAW-Ti which achieved 57.56%. In general, the improvement achived by all ISE-PIDAW controllers over the ISE-PID controller are significant. Overall, the scenario is showed that the ISE-PIDAW controllers have outperformed the ISE-PID controller.

TABLE 1
SUMMARY DATA FOR VARIOUS CONTROLLER PERFORMANCE IN STEP TEST
SIMULATION STUDIES

| Performance Index	ISE-PID	ISE-PIDAW-√(TiTd)	ISE-PIDAW-Ti	ISE-PIDAW-Td#
OS%	36.17%	14.36%	15.35%	*13.69%
Ts	1.2692 X10⁴	0.86090 X10⁴	0.86553 X10⁴	*0.85814 X10⁴
Tr	*2.3529 X10³	2.3530 X10³	*2.3529 X10⁴	2.3548 X10⁴
IAE	5.6760 X10⁴	5.6020 X10⁴	5.6050 X10⁴	*5.6000 X10⁴
ISE	1.7550 X10⁴	1.5340 X10⁴	1.5430 X10⁴	*1.5270 X10⁴
ITAE	1.4700 X10⁹	*1.4510 X10⁹	1.4520 X10⁴	*1.4510 X10⁴

*preferred response by category/#the best controller
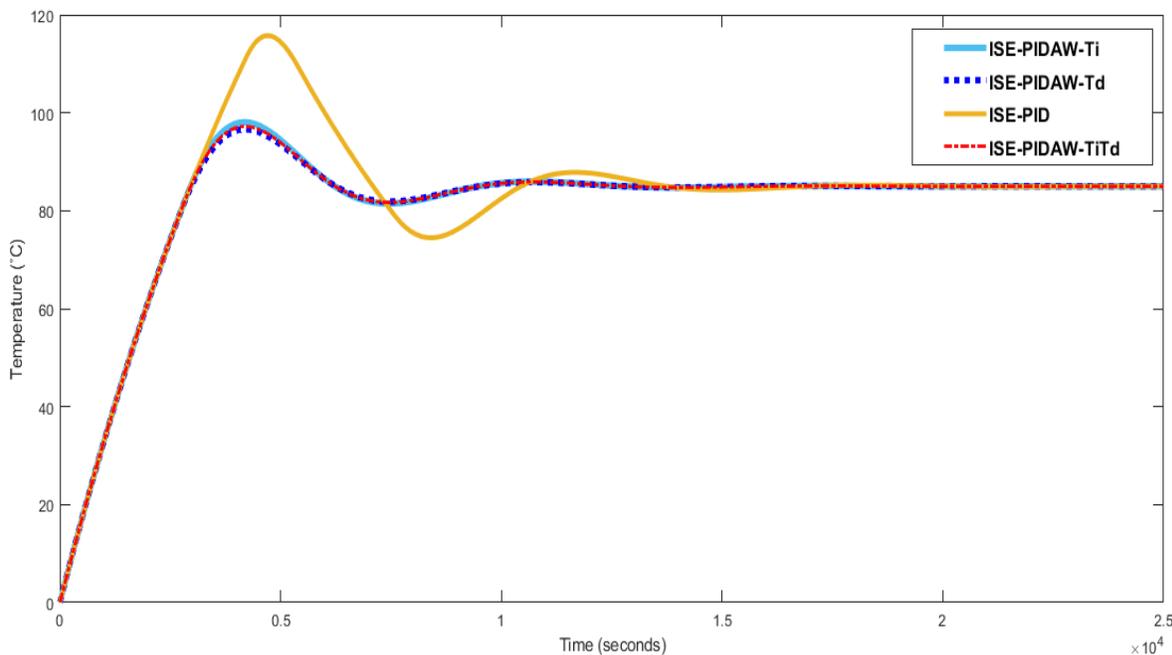
Fig. 5: Output for ISE-PID, ISE-PIDAW-Ti, ISE-PIDAW-Td and ISE-PIDAW-$\sqrt{(T_i T_d)}$ Controllers in Step Test Simulation.
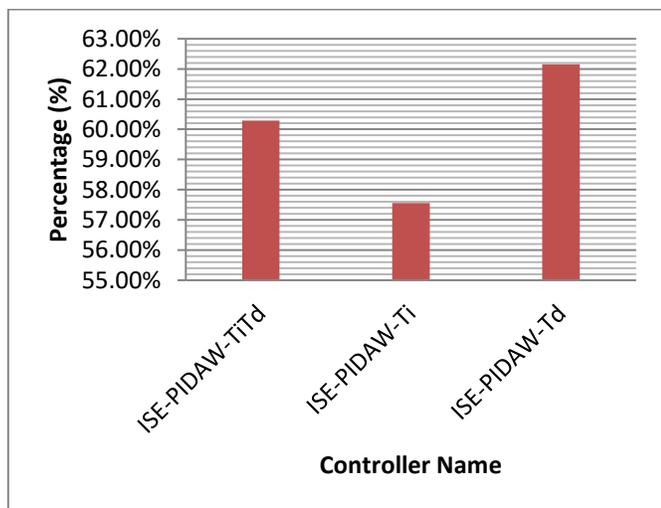

Fig. 6: Percentage overshoot improvement from ISE-PID to ISE-PIDAW controllers for ISE-PIDAW-Ti, ISE-PIDAW-Td and ISE-PIDAW-$\sqrt{(TiTd)}$.
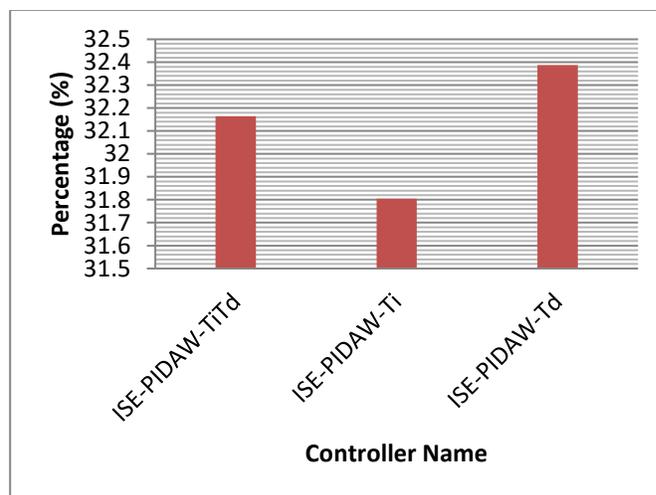

Fig. 7: Percentage improvement of Settling time from ISE-PID to ISE-PIDAW controller for ISE-PIDAW-Ti, ISE-PIDAW-Td and ISE-PIDAW-$\sqrt{(TiTd)}$.

The simulation result for ISE-PID and ISE-PIDAW controllers on recovering the set point 85˚C are shown in Fig. 7. The qualitative result indicate that all the ISE-PIDAW controllers are able to return to the set point faster than ISE-PID controller. The best improvement is obtained from ISE-PIDAW-Td controller, which achieved 32.3%. ThenISE-PIDAW-$\sqrt{(TiTd)}$ controller is improved at 32.1%, and the ISE-PIDAW-Tiis 31.8% recorded. In general, the improvement achived by all ISE-PIDAW controllers over the ISE-PID controller are significant. Overall, the scenario is showed that theISE-PIDAW controllers have outperformed the ISE-PID controller.

VI. CONCLUSION

Based on the simulation results, all the ISE-PIDAW controllerstuning based on Integral Square Error using tracking calculation shows improvement in all performance index. The proposed of Tracking Time Constant,T_a values are capable to reduce the windup phenomenon occurred in simulation of small-scale steam distillation system. Based on ranking, thebest controller ISE-PIDAW-Td show lowest percentage of overshoot and 62.16% improvement of overshoot compared to the ISE-PID. And, the second best controller is the ISE-PIDAW-$\sqrt{(TiTd)}$ show 60.29% improvement of overshoot compared to the ISE-PID. From the

overall comparison between the ISE-PID and ISE-PIDAW controllers, all theISE-PIDAW controllers have shown to be advantageous in all aspects. In this study,all theISE-PIDAW controllershave successfully improved the overshoot and settling time of the system over 30%.

VII. REFERENCES

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