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Research Article

Comparative Study of PID and FPD+I Controller of PVC Moisture-Free Temperature

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Abstract

The insulated wire manufacturing process goes through variety of processes. Quality of wire is primarily determined by the quality formation of PVC paste. For good quality PVC paste formation one of the parameters of concern is the moisture contents in raw PVC and it is necessary to remove complete moisture. For this purpose in Industries an Electrical Oven (EO) is used in which raw PVC filled trays are placed. The paper explicates the design of PID controller and FPD+I controller of PVC moisture-free temperature control. Also simulation based comparative study on the performance of PID controller and FPD+I controller for control of moisture-free PVC temperature is reported. In respect to the performance parameters the FPD+I controller shows better performance than PID controller.

Keywords: *Wire coating, Moisture-free PVC temperature, PID controller, Fuzzy logic, FPD+I controller.*

1. Introduction

There are varieties of processes to outcome a product insulation coated wire viz. removal of moisture from raw PVC material, creation of PVC paste, passing it towards spindle, drawing the bare wire through molten Polyvinyl Chloride (PVC) etc. In the insulated wire manufacturing industries paste of insulating PVC is passed towards the die through which bare wire is drown. Quality of wire is primarily determined by the quality formation of PVC paste. For good quality PVC paste formation, one of the parameters concerned is the moisture contents in raw PVC and it is necessary to remove complete moisture (Harold F. Giles, et al, 2005; Precise Cables, Shirgaon MIDC, Kolhapur). For making the PVC moisture free the small scale Industries depend on the Electrical Oven (EO). The temperature required to make PVC free from moisture is a function of the grade of PVC material. In the small scale Industries the experienced Operator takes the decision about setting the temperature value so as to make PVC free completely from moisture contents (Precise Cables, Kolhapur). Moisture freed PVC is then inserted in the hopper of Extruder Machine (EM) to form the PVC melt.

1.1 Conventional Process

The EO has built-in tray arrangement in which raw PVC is placed. Master-Batch is mixed with PVC in these trays for desirable color. When EO is switched ON the temperature in EO gradually increases, so is the PVC temperature. This temperature is observed manually on the thermometer. When temperature of PVC reaches to moisture free set temperature (sT) value in between 700C to 900C decided by Operator depending on PVC grade (G) and Operator's judgment, the PVC is supposed to be moisture free and liable to insert in hopper of EM (Precise Cables, Shirgaon MIDC, Kolhapur). In this process the sT value to make PVC moisture-free is decided by Machine Operator. If the Operator is not an Expert to take decision of moisture-free PVC temperature for the given grade of PVC, then temperature decided by him may not be close to the optimum value of desirable temperature. If this temperature exceeds an optimum value the current consumed by EO for the excess temperature results unnecessarily in to the loss of power. On other hand if it is less than optimal there is an extra load on EM and may affect the quality of PVC paste. Manual decision of optimal temperature to make PVC moisture-free suffers from following drawbacks:

1. This leads to loss of power besides quantity of PVC.
2. Diminish the quality of molten PVC.

The PID and Fuzzy-PID strategies were applied to control the PVC temperature. The results of both controllers were compared pertaining to the different parameters.

1.2 PVC Temperature TF Model

In the past work (S. S. Nirmale et al, 2011) reported design of Fuzzy Decision Support System (FDSS) to determine sT value of raw PVC material kept in the Oven from grade of PVC to make it moisture-free aiming to circumvent the drawbacks of existing manual techniques.

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To represent behavior of PVC temperature in EO a transfer function (TF) was estimated. The estimation of first order Transfer Function (TF) with dead time for the PVC placed in the tray of Electric Oven (EO) is described in past work (S. S. Nirmale et al, 2013). The TF is estimated using the real time measured response of PVC temperature in EO for the applied step change in power to EO and with the help of MATLAB. The estimated TF given in Eq. (1) was verified by making simulation model for it in MATLAB and comparing the simulated result with measured data.

$$G(s) = \frac{14.01}{9000s+1} e^{-2400s} \quad (1)$$

The time domain response of estimated TF shows closely represents the real time behavior of PVC temperature in EO. The verified TF is used as process model in the design of PID controller and Fuzzy PD + Conventional I (FPD+I) controller of moisture-free PVC temperature.

2. PID based PVC temperature control

Over the years in the Industries the control of processes and systems are customarily handled by the Experts with the aid of the conventional PID control techniques. This is due to its simplicity, low cost design and robust performance in a wide range of operating conditions (Astrom K. J., Hagglund T., 1995). PID control strategy emulated to control the EO temperature aimed to make the PVC moisture free. The block diagram of PID control with process model is shown in Fig.1.

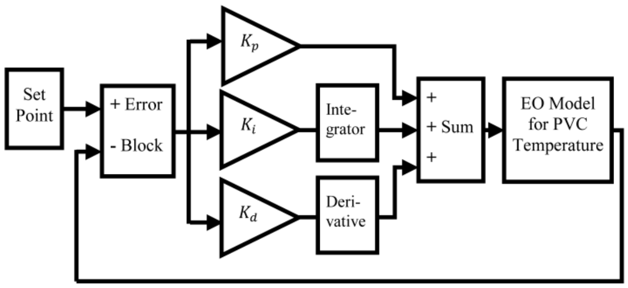


Fig.1 Block diagram of PID controller with temperature of PVC placed in EO process model

The ideal version of the PID controller is given mathematically by Eq. (2) (Astrom K. J., Hagglund T., 1995; J. G. Ziegler, N. B. Nichols, 1942).

$$u = K_p \left(e + \frac{1}{T_i} * \int edt + T_d * \frac{de}{dt} \right) \quad (2)$$

Where, u is the manipulated control signal, e is the error between set point value and current value of controlled variable, K_p is the proportional gain, $K_i$is the integration gain and $K_d$is the derivative gain. T_i is known as integral action time and T_d is the derivative action time.

To obtain the initial gain values of PID the Ziegler-Nichols (ZN) method was used. The ZN tuning rules were the first tuning rules employed with the PID controller and they are widely used even today. ZN describes two methods for tuning the parameters of P, PI and PID Controllers (J. G. Ziegler, N. B. Nichols, (1942). First is the ZN's open loop method and second is the ZN's closed loop method. ZN's closed loop method being more useful is applied in the process of PID parameter tuning method anticipated for PVC moisture free temperature control.

This method is simple and straight forward. Initially the controller is set only to P mode by setting the integral gain Ki and derivative gain Kd to Zero (J. G. Ziegler, N. B. Nichols, 1942). Next a set point of 800C is given and the proportional gain of the controller is set to a small value of 0.1, and the response of the PVC temperature is being observed. As gain is low, response tends to be sluggish. The value of Kp is then increased by 0.1 and again the corresponding response was observed. The controller's response was under damped oscillatory up to Kp = 0.4 and over damped oscillatory for Kp = 0.5. The process of adjusting the value of Kp followed in smaller steps for sustained oscillatory response shown in Fig. 2. It happened at an ultimate gain (Ku) value of 0.467. From the sustained oscillatory response the period of the oscillations called ultimate period (Pu) was noted down as 8750Sec.

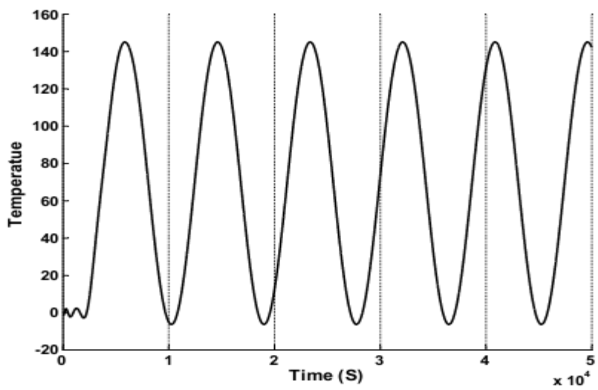


Fig.2 Oscillatory response of temperature model of PVC placed in Electric Oven

Once the values of Ku and Pu achieved for the sustained oscillatory response, the initial gains of PID controller using the ZN tuning rules were calculated. The relations of PID parameters suggested by ZN for closed loop method are given in the Table I.

2.1 Determination of values of PID controller parameters

Using available values of K_u, P_u the values of parameters K_p, T_i and T_d can be obtained from the Table I (J. G. Ziegler, N. B. Nichols, (1942).

Table 1 The Ziegler-Nichols rules of PID for closed loop method

	K_p	T_i	T_d
PID	$K_u/1.7$	$P_u/2$	$P_u/8$

From these PID controller's parameter values for Ki and Kd can be easily calculated as follows-

$K_p = K_u/1.7 = 0.467/1.7 = 0.2747$,

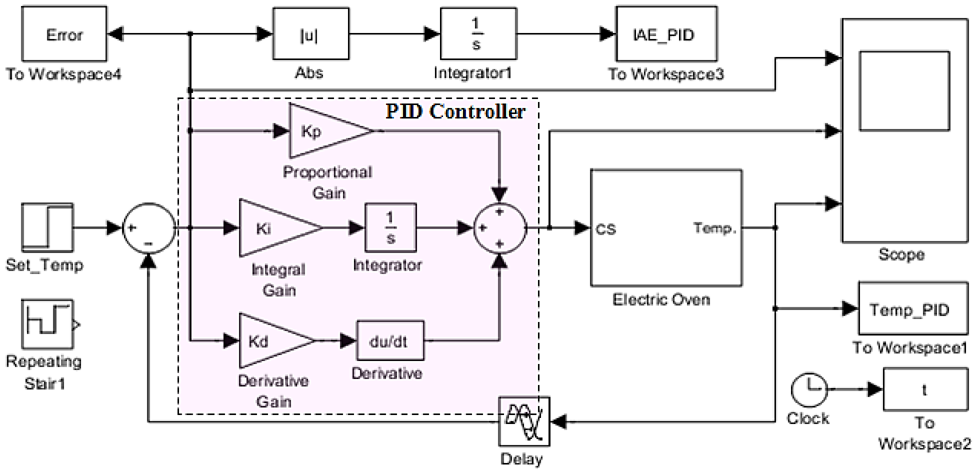


Fig.3 Simulink model of PID controller of PVC temperature

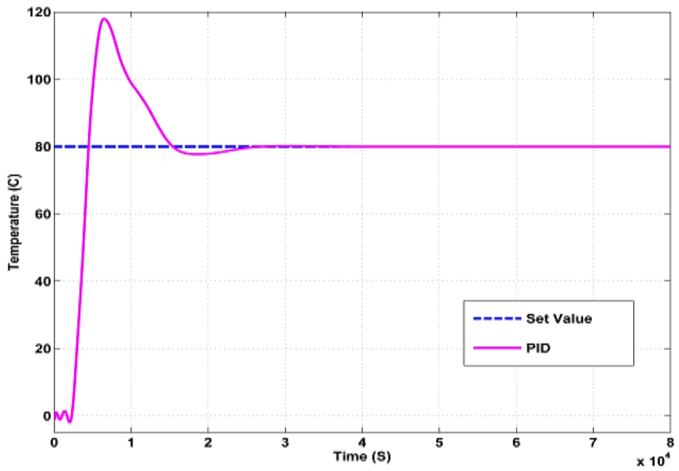


Fig.4 Response of PID controlled PVC temperature with ZN's tuning parameters

$T_i = P_u/2 = 8750/2 = 4375$,
$T_d = P_u/8 = 8750/8 = 1093.75$,
$K_i = K_p/T_i = 0.2747/4375 = 6.2789*10^{-5}$ and
$K_d = K_p*T_d = 0.2747*1093.75 = 300.4531$.

For the purpose of study, the response of PID controller pertaining to the control the PVC temperature a Simulink model using the MATLAB (Arun Rajagopalan, Gregory Washington, 2002; SIMULINK for MATLAB, 1996) has been developed as shown in Fig. 3.

In the Simulink model the computed controller parameter values for the K_p, K_i and K_d are assigned. Based on the estimated TF model of EO for PVC temperature given by Eq. (1) with the PVC placed in EO system is implemented by Simulink model. During simulation runs the response of PID controller for the PVC temperature was observed, its response is shown in Fig. 4.

The PVC temperature gets steady after a large overshoot followed by smaller undershoot.

3. Fuzzy PD + Conventional I (FPD+I) Controller

Although the PID controllers have gained wide spread usage across technological industries, the unnecessary of mathematical rigorousness, preciseness and accuracy involved with the design of the controllers turns out to be the major drawback. This has made it difficult for Designers, Engineers and Technology Experts to design intelligent complex, nonlinear and higher order systems with dead time. However, the knowledge-based approaches such as Fuzzy Logic have gained a promising scope intending to overcome the drawbacks of PID Controller design (Abdullah I. Al-Odienat et al, 2008; C. C. Lee, 1990; T. Takagi, M. Sugeno, 1985). There are various strategies to build a Fuzzy-PID (FPID) controller viz. individual FP-FI-FD controller, hybrid FPID, Single input or three inputs FPID, gain scheduled FPID etc (Birkan Akbıyık et al, 2005; Vineet Kumar, 2008; Leehter Yao, Chin-Chin Lin, 2005).

To build three inputs FPID, the rule base becomes rather big and defining the rules for integral action tends to be troublesome. Therefore it is common to separate the integral action. The simple Fuzzy PD + Conventional I (FPD+I) Controller introduced by the Jan Jantzen practiced, Because of the initial values for the scaling factor can be determined using the formulae suggested by him (Jan Jantzen, 1998). It can be achieved by connecting a Fuzzy PD Controller in parallel with the Conventional Integral controller. The Simulink model of Jantzen FPD+I controller with the process model of PVC temperature placed in EO is shown in Fig. 5. It depicts clearly the structure of the FPD+I Controller

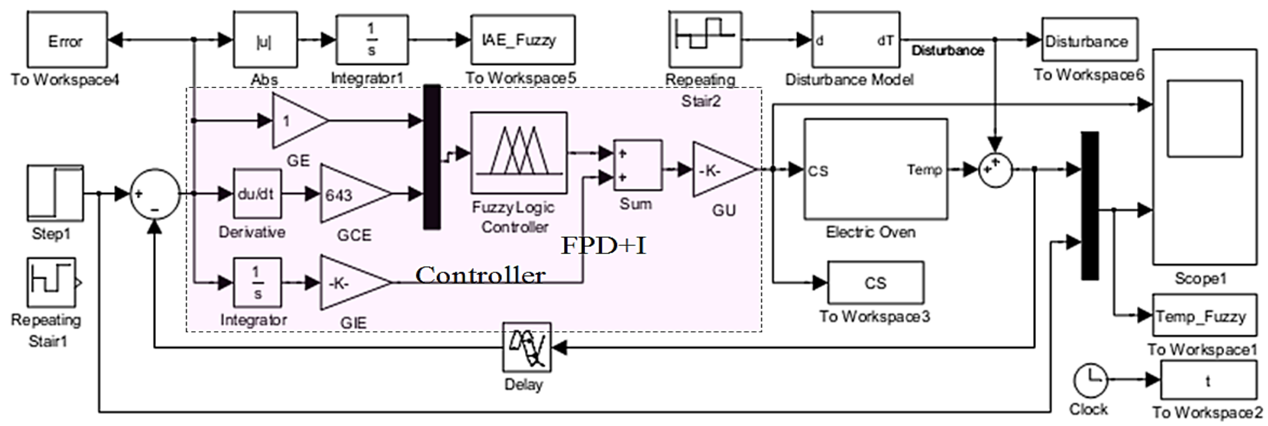


Fig.5 Simulink model for moisture-free PVC temperature control with FPD+I controller

3.1 Fuzzy PD Controller

From the proposed FPD+I controller for the FPD controller the FIS was designed as shown in Fig. 6. FPD controller FIS has two inputs: one is the error 'E' and another is the rate of change of error 'CE' and single output control signal 'CS'.

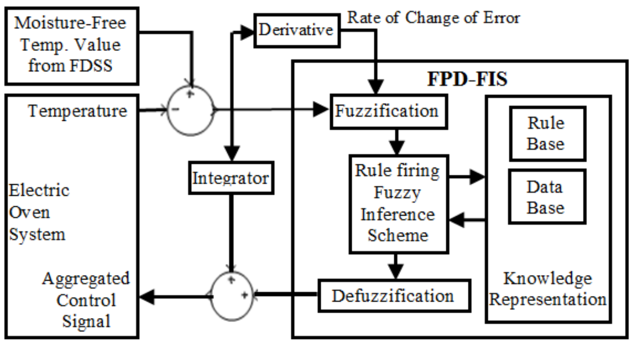


Fig.6 Block diagram of FIS module for FPD+I controller

It has thus a structure of two inputs-single output Fuzzy Controller. For the two input FIS the number of MFs could be 3, 5, 7, 9 or 11 for both the inputs. In the proposed FPD controller structure three fuzzy membership functions for the inputs 'E' and 'CE' as shown in Fig. 7 have been utilized, which are triangular shaped. The membership labels N, Z and P stands for Negative, Zero and Positive respectively.

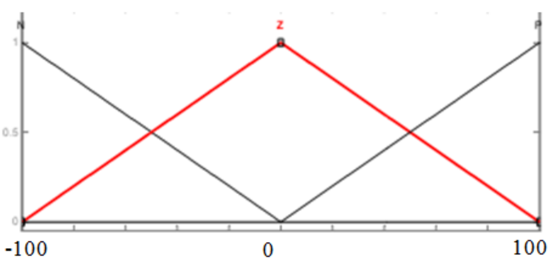


Fig.7 Membership functions for inputs variable E and CE of FPD FIS

These three MFs cover all possible situations leading to small sized rule base. The universes of discourse must be large enough for the inputs such that they don't get saturated. As the possible maximum temperature value for the PVC moisture free temperature is 90^0C, the range for both the input variables from -100 to 100 was assigned. The triangular fuzzy sets of input variables are such that they cross their neighboring sets at the membership value μ=0.5 i.e. the overlapping of 50%, so that any input value will be a member of two fuzzy sets.

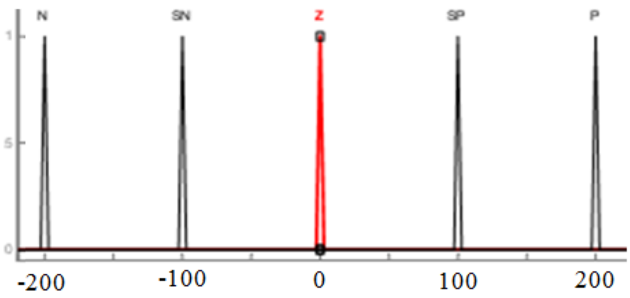


Fig.8 Membership functions for output variable CS of FPD FIS

For the output variable 'CS' the five fuzzy membership functions are defined which are singleton type MFs as shown in Fig. 8.

The labels N, SN, Z, SP and P stands for Negative, Small Negative, Zero, Small Positive and Positive respectively.

Since in the proposed FPD+I controller the output of FPD-FIS is equivalent to the summation of the two inputs (Jan Jantzen, 1998), the range for the output variable 'CS' has been assigned from -200 to 200. The shape of MFs selected to be singletons, because this can make defuzzification simpler. For the FPD-FIS Centroid Defuzzification method was employed.

The control strategy to make a decision about CS pertaining to the input conditions was formulated in terms of if-then rules. The rules have been formulated for the two input conditions so that PVC temperature remains maintained at reference value. The number of MFs in each input variable determines the number of rules, they must be interlaced by AND combination of all terms to ensure completeness. The system response can be divided into three phases: first is the system output is below the set point, second the system output is about the set point and third the system output is above the set point.

In the FPD FIS there are two input variables and each input has three MFs. So depending upon response of PVC temperature in all nine (3x3) rules have been derived. Nine rules are easily manageable hence often used in practice to implement control policies (Vineet Kumar et al, 2008; Jan Jantzen, 1998). The PVC temperature control strategy presented in the form of fuzzy IF-THEN rules for FPD-FIS is shown in Table 2.

Table 2 Rule base of the FPD FIS

CS		CE		
		N	Z	P
E	N	**N**	**SN**	**Z**
	Z	**SN**	**Z**	**SP**
	P	**Z**	**SP**	**P**

For FPD FIS Centroid Defuzzification method was employed. From the surface view of designed FIS it can be observed that the output CS value is actually equivalent to a summation of the two inputs. Since the surface is equivalent to a summation, the Controller designed is equivalent to a PD Controller in performance (Jan Jantzen, 1998).

3.2 Determination of Scaling Factors of FPD+I Controller

Jantzen provided the design procedure to transfer the PID gains into the Linear Fuzzy Controller. According to him the relations between the PID controller gains and the Proposed FPD+I controller gains are given by the Eqs. (3), (4) and (5) (Jan Jantzen, 1998).

$$GE + GU = K_p \quad (3)$$

$$\frac{GCE}{GE} = T_d \quad (4)$$

$$\frac{GIE}{GE} = \frac{1}{T_i} \quad (5)$$

In the process of PVC temperature control the maximum error reached could be 100 and accordingly the universe of discourse for the fuzzy input error (E) is fixed as (−100, 100) and the value of GE=1 was chosen which automatically avoids the saturation condition. By using the above relations and values of K_p, T_i, T_d the values of parameters of FPD+I Controller were determined. The values so obtained are as follows-

GE = 1,

GCE = GE*Td = 1*1093.75 = 1093.75,

GIE = GE/Ti = 1/4375 = 2.2857*10-4

GU = Kp/GE = 0.2747/1 = 0.2747.

4. Simulation of PVC Temperature Controllers

The response of PVC temperature for the controllers designed has been studied based on the system model shown in Fig. 3 for the PID controller and Fig. 5 for the FPD+I controller, which have simulated for the similar input conditions. The parameter values obtained for the PID controller by ZN method and for the FPD+I controller by the Jantzen suggested by relations (3), (4) and (5) were inserted in the Simulink models before their simulation run. The response of the PVC temperature for these non-tuned parameter values is shown in Fig. 9. It reveals that FPD+I controller set point tracking almost follows the response of the PID controller.

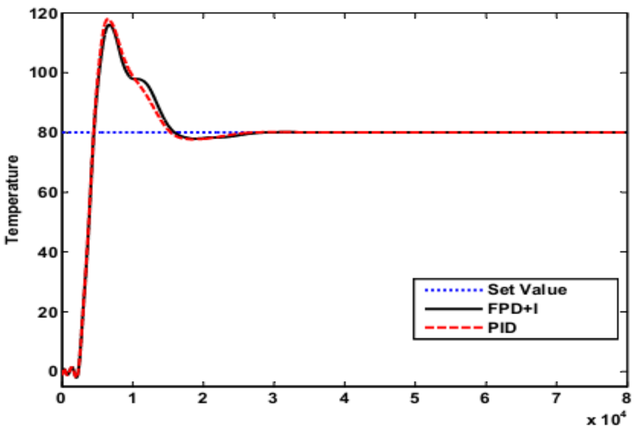


Fig.9 Response of PID and FPD+I controller before tuning

To achieve the better and desired response of both the controllers of PVC temperature hand-tuning process being adopted. This is based on rules of thumb as given in Table 3 (Astrom K. J., Hagglund T., 1995; J. G. Ziegler, N. B. Nichols, 1942). The tuning is aimed at the compromise between fast reaction and good stability.

Table 3 Rules of thumb for tuning PID controller

Action	**Rise Time**	**Overshoot**	**Stability**
Increase Kp	Faster	Increases	Gets Worse
Increase Td	Slower	Decreases	Improves
Increase 1/Ti	Faster	Increases	Gets Worse

For the reference input of 80^0C following the rules of thumb the PID parameters values were tuned. After the fine tuning for the desired response the parameters value comes out to be as follows-

Kp = 0.161
Ki = $1.51*10^{-5}$
Kd = 98

Similarly fine-tuning of the GU, GCE and GIE parameters of FPD+I controller was done to achieve best performance using rules of thumb suggested by Jantzen and by observing the response of PVC temperature. The Jantzen's rules of thumb for FPD+I controller are as follows (Jan Jantzen, 1998),

1. Adjust GE according to step size and universe to exploit the range of the universe fully.

2. Remove integral action and derivative action by setting GCE=GIE=0 and tune GU to give the desired response, ignoring any final value offset.
3. Increase the proportional gain by means of GU, and adjust the derivative gain by means of GCE to dampen the overshoot.
4. Adjust the integral gain by means of GIE to remove any final value offset.
5. Repeat the whole procedure until the desired response is achieved.

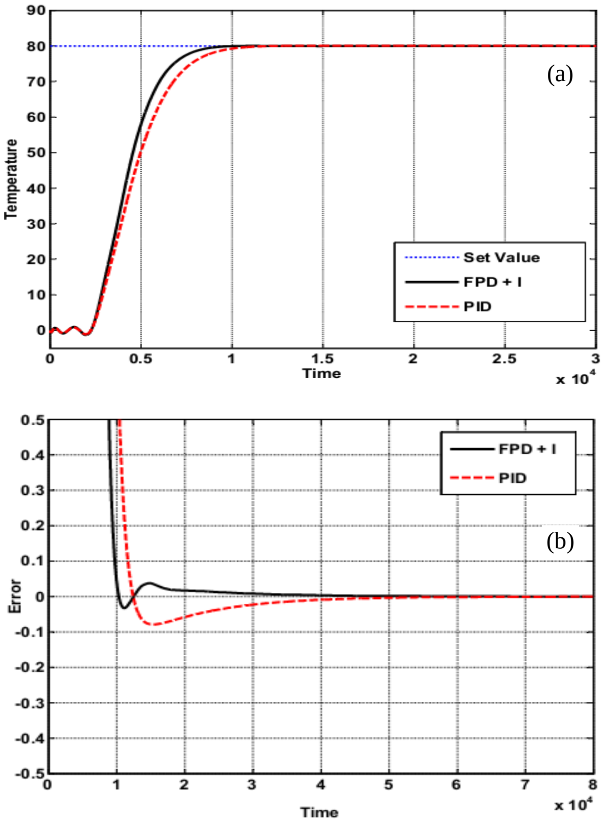
The values optimized after fine hand tuning for these parameters by adopting five rules are as follows-

GE = 1
GCE = 643
GIE = $8.565*10^{-5}$
GU = 0.1915

4.1 System performance of tuned moisture-free PVC temperature controllers

The step response of PVC temperature for both the tuned controllers is shown in Fig. 10(a) and the zoomed view of error between set temperature and present temperature in Fig. 10(b).

It is observed that the FPD+I controller gives better response than the PID controller. The overshoot, rise time and settling time in case of FPD+I controller is low. Fig. 10(c) shows the corresponding control signal intending for tracking the set point. The system performance with PID Controller and FPD+I Controller was studied in respect of parameters Overshoot, Rise time, Settling time and Steady state error. The values for these parameters before and after tuning are summarized in Table 4.



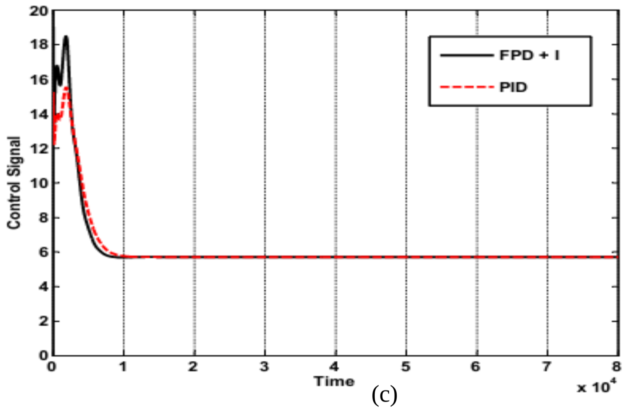


Fig.10 Response of PID and FPD+I controller after tuning, a) PVC moisture-free temperature responses b) Error, c) Corresponding control signal

Table 4 System performance of PID and FPD+I controllers for PVC temperature

Performance Parameter	Design Method			
	ZN's PID	Tuned PID	Jantzen's FPD+I	Tuned FPD+I
Kp / GU	0.2747	0.161	0.2747	0.1915
Ki / GIE	$6.28*10^{-5}$	$1.51*10^{-5}$	$2.28*10^{-4}$	$8.56*10^{-5}$
Kd / GCE	300.45	98	1093.75	643
Overshoot M (^{0}C)	38.01	0.08	36.02	0.033
Rise Time (Min.)	74.55	206.866	75.016	171.9
Setting Time(Min.)	535.45	245	578.316	96.316
IAE	$4.97*10^5$	$3.81*10^5$	$5.00*10^5$	$3.48*10^5$

(For the temperature set point 80^{0}C and simulation time 500 Minutes)

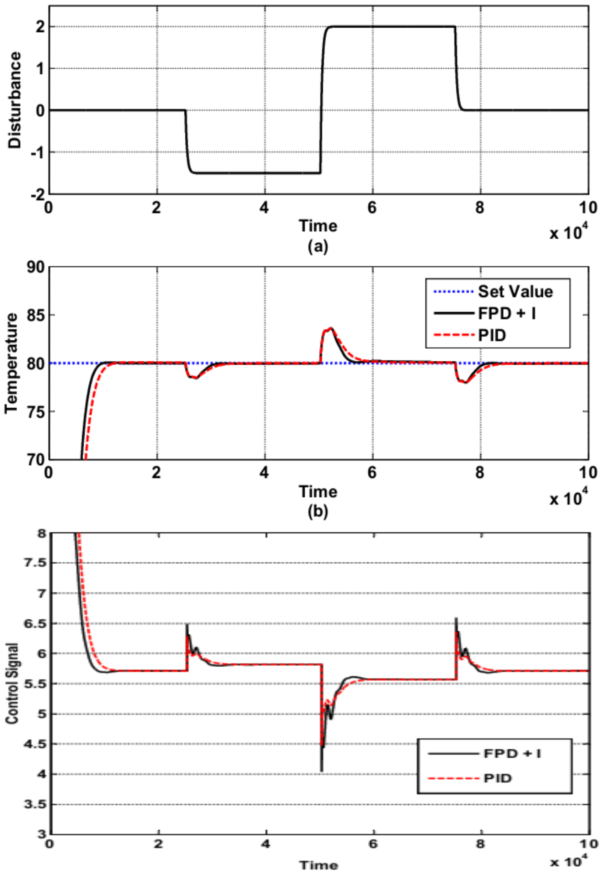
The parameter Integrated Absolute Error (IAE) is measured for the simulation time 30,000 Seconds. The value of IAE for FPD+I controller is less than that for the conventional PID controller.

The disturbance is also injected in the temperature of PVC and the responses of disturbance rejection of both the controllers were observed. The negative disturbances of magnitude 1.5^{0}C and 2^{0}C at 25000 Sec and 75000 Sec respectively and a large-magnitude of 3.5^{0}C positive disturbance at 50000 Sec as shown in Fig. 11(a) were created. The effect of disturbance on the PVC temperature is shown in the Fig. 11(b).

To reject the disturbance and achieve the reference value of PVC temperature, the control signal CS generated by the system is shown in Fig. 11(c). It is seen that the system response under the FPD+I Controller is quick and smooth enough to achieve set temperature value even under extreme conditions of disturbance than the PID controller.

To investigate the system performance for the input set point variations the repeating stair-case signal at reference signal was applied. Initially the value of 80^{0}C for reference temperature was applied. When both the Controller response went tracking the set point of 80^{0}C it was decreased to the value 70^{0}C at 30000 Sec. Same way the set temperature value was increased to 90^{0}C at 60000 Sec.

Fig. 12(a) demonstrates the response of PVC temperature of both the Controllers for the set point tracking.



(c)

Fig.11 PVC temperature response under disturbance, a) Disturbance, b) Change in Temperature, c) Corresponding change in control signal

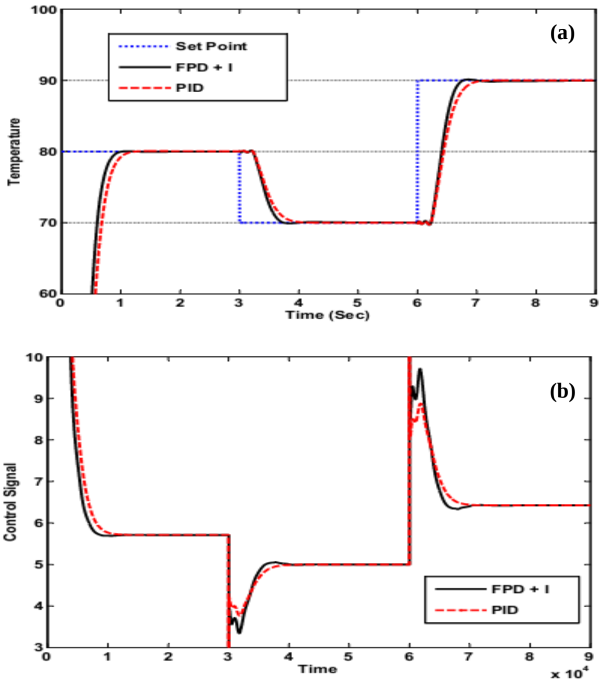


Fig.12 a) Response of controllers for Set-Point tracking, b) Corresponding change in control signal

To achieve the change in reference level the corresponding control signal generated (CS) is shown in Fig. 12(b). The response of FPD+I Controller reached earlier to the new set value than the PID counterpart. In both the cases of disturbance rejection and set point tracking, at the start the FPD+I controller applies the high value of control signal than the PID controller as per the error and becomes smaller quite earlier than the PID control signal when error reaches near to zero.

Conclusion

PID and FPD+I controllers of moisture-free temperature of PVC placed in EO has been proposed in this paper. The FPD+I controller has achieved and maintained moisture-free PVC temperature with very small overshoot and lower rise and settling time. The performance of FPD+I controller shows better performance than the PID controller under disturbance and set-point tracking. Moisture-free PVC temperature does not exceed its reference value. Therefore unnecessarily loss of power for excess temperature is avoided. The estimated TF has been used to design and develop virtually PID. This has helped to design a Fuzzy Controller to control the PVC temperature that can be explored in the real process parameter controller design. Thus the time and also the power required for iteratively doing the real experiment during design of controller can be saved. Maintaining PVC temperature at an optimal moisture-free temperature removes an extra load on EM to make PVC moisture-free and helps to get good quality PVC paste, in turns a good quality insulated wire product.

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