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CRONE Control Strategy for Air Pressure System

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Abstract: ***Pressure process in industry is inevitable and is considered with foremost importance in many processes like boilers, pressure vessels, reactors, closed vessels, steam drums and flash points. Pressure measurement and control is important requirements of all process, since it is related to safety of the human resources and equipment. So in this work an Air Pressure System (APS) is considered for investigation. Over the years an increasing attention made on fractional order controller and dynamic systems using fractional order calculus. Its theoretical and practical interests have been confirmed today, and its relevance to engineering society can be think carefully about as developing scientific avenue. This project discusses the design and implementation of generations of CRONE controller for APS. The Mathematical model of APS is determined from the various operating regions by using worst case modeling technique. The three generations of the strategy of CRONE control are designed based on worst case model. Simulation runs of set point tracking responses are documented. The time domain and integral error indices performances are obtained and compared on strategies of the generation CRONE controller. It is noticed that Third Generation CRONE (TGC) controller outperforms provide better performance than the other generations of CRONE controller.***

Keywords **:** ***CRONE Controller, Air Pressure System, Control System Design (CSD), FGC, SGC, TGC, Black Locus, Non Linear Optimization.***

I. INTRODUCTION

Manabe [1] initiated the idea of non integer order controller in the year 1960. Continuing his idea, Oustaloup investigated the fractional order control algorithms for the control systems. In addition he examine frequency domain on CRONE controller the year 1991. CRONE [2] is a acronym of "Commande Robuste d'Ordre Non Entier" which deals non integer order robust controller. There are three different CRONE controllers available in control environment namely First generation controller, Second generation controller and Third generation controller [3,4, 5 and 6] .

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It is contemplated to be one of the evolved approaches to design robust and fractional order controllers [8-11 and 12].In this paper worst case model is obtained for air pressure system depend on real time run parameters for different operating regions. All generations of CRONE controllers are designed based on the model. Real time servo run is carried out for the APS and the responses are recorded. The performances of all the generations of CRONE controllers are compared based on time domain criteria and integral error indices. The project is covered as follows: Section 2 presents complete information of the APS. The APS model parameters are determined in Section 3. In Section 4, Design of CRONE control strategies is depends on the worst case model. In Section 5, Implementation of CRONE controller based on CSD toolbox is discussed. The comparison of simulation outputs for the controller performances are provided in Section 6. Finally, declaring the remarks are given in Section 7.

II. DESCRIPTION OF THE PROCESS

A. Air Pressure System

Fig. 1 shows a schematic view of APS [7]. The pressure inside the process tank is to be controlled. The system consists of process tank, air filter regulator, pneumatic control valve and pressure transmitter. The air from the compressor is regulated to a certain range of pressure (0-75 psi) with the help of Air Filter Regulator (AFR) and the air is allowed to flow into the process tank. The piezoelectric transmitter is used to measure pressure in the process tank.

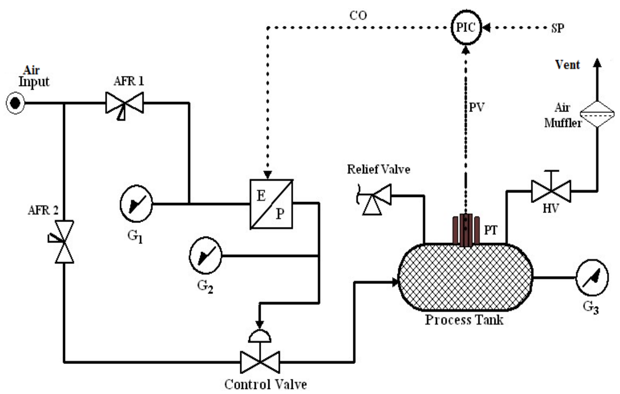


Fig. 1. Schematic view of Air Pressure System (APS)

The error deviation signal is generated by comparing the reference value with pressure in the tank. The error is processed in the controller to generate corresponding controller output (4-20 mA).

The controller output is converted into pneumatic signal (3-15 psi) using Electric to Pressure (E/P) converter. The pressure signal is used to turn on the control valve to control the flow rate of air into the process tank. Thus the pressure in the process tank is regulated.

III. PROCESS MODEL IDENTIFICATION - APS

A. Determination of Worst Case Model Parameters

In real time platform, pressure inside the tank is retained at a stable state each of various operating points of 30%, 40%, 50% and 60%. The step input of ±10% pressure value for various operating point is applied and the dissimilarity of pressure in opposition to time for every operating point is observed separately until a new stable state is achieved shown in Fig 2 and 3. The model parameter such as time constant (τ_p), time delay (t_d) and process gain (K_p) are determined and arranged in table 1 as per the recorded data.

From the Observation of table, the worst-case model parameters [9] such as smaller time constant (τ_p), larger delay (t_d) and greater process gain (K_p) are considered and these parameters are taken for design of controllers.

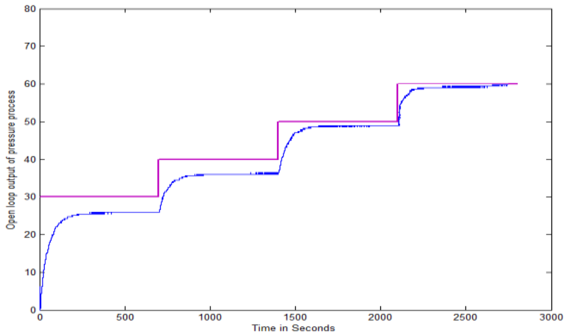


Fig. 2. Open loop responses (10% Positive step changes) – APS

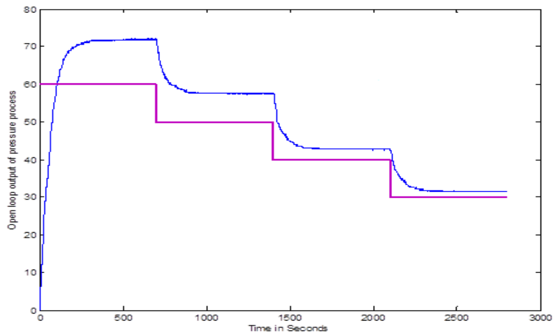


Fig. 3. Open loop responses (10% Negative step changes) - APS

Table- I: APS Worst case model parameters

Operating Region %	K_p	τ_p	t_d	$K_{p(max)}$	$\tau_{p(min)}$	$t_{d(max)}$
40 - 50	0.9	70	8	0.9	65	8
40 - 30	0.7	65	7.1			
50 - 60	1.2	64	7.3	1.2	64	7.3
50 - 40	0.7	68	7			
Model identified to a wide region of 30 - 60 %				**1.2**	**64**	**8**

The identified worst case model of APS equation is,

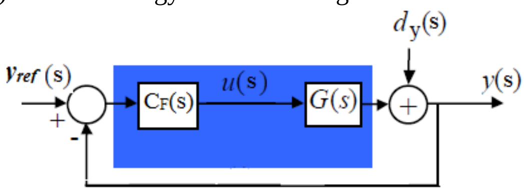
$$G(s) = \frac{1.2}{64s+1} e^{-8s} \tag{1}$$

By using the model equation, the designs of three generations of CRONE controllers are deliberated in next section.

IV. CRONE CONTROL STRATEGY

A. Design Procedure of First Generation CRONE Controller

The closed loop structure of the First Generation CRONE (FGC) control strategy is shown in Fig. 4.



y_{ref}(s) - input reference signal, **d_y(s)** – Process output disturbance, **u(s)** - controller output, **C_F(s)** – First generation CRONE controller, **G(s)** - Process transfer function, **y(s)** - plant output

Fig. 4. Closed loop structure of First generation CRONE control strategy

The FGC control strategy is particularly appropriate when the desired open-loop gain crossover frequency ω_{cg} is within a frequency range that has asymptotic response.

In this band the nominal and perturbed plant phases are constant and the plant uncertainty is gain like.

The controller $C_F(s)$ is defined within a frequency range [ω_A, ω_B] around frequency ω_{cg} from the fractional transfer function of an order '*n*' integro-differentiator:

$$C_F(s)=C_0 s^n \text{, with } n \text{ and } C_0 \in \clubsuit \tag{2}$$

In bode plot of 'n" correlates to the integro – differentiator of open loop fractional order and C0 is the gain of the FGC controller. The Bode plot of FGC controller is illustrated in Fig. 5. From the diagram it is noticed that the FGC controller confirms at a constant phase (nπ/2) around the open loop gain crossover frequency ωcg.

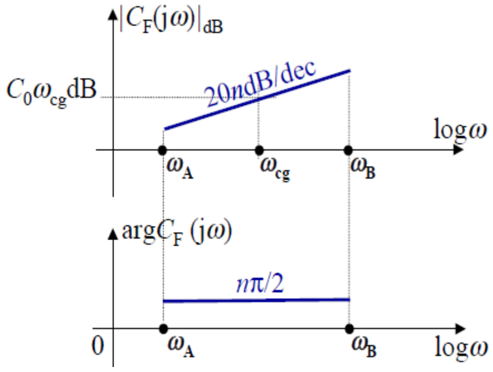


Fig. 5. Bode plot of FGC controller

The constant phase controller $C_F(s)$ does not varied even variation of plant gain or plant corner frequency, therefore need to modify the phase margin. The gain crossover frequency ω_{cg} varies within the frequency range[ω_A, ω_B]. The FGC controller $C_F(s)$ can also be defined by a band-limited transfer function on corner frequencies ω_l and ω_h as,

$$C_F(s)=C_0\left(\frac{1+s/\omega_l}{1+s/\omega_h}\right)^n, \ \omega_l<\omega_A \text{ and } \omega_h>\omega_B \quad (3)$$

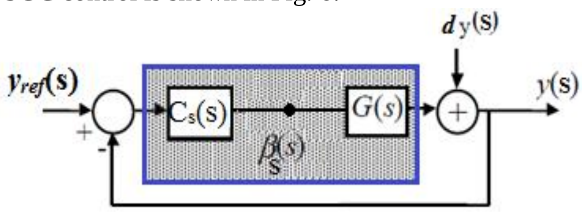
The band limited fractional order transfer function of The FGC controller is serially connected with a low pass filter of order n_F and the band limited integrator of order n_I for acquiring desired control effort and avoid steady state errors. After the computation the transfer function of fractional order FGC controller is given by,

$$C_F(s)=C_0\left(\frac{\omega_I}{s}+1\right)^{n_I}\left(\frac{1+s/\omega_l}{1+s/\omega_h}\right)^n\frac{1}{(1+s/\omega_F)^{n_F}} \quad (4)$$

Here the conditions $\omega_I<\omega_l<\omega_{cg}>\omega_h>\omega_F$ and the integer orders n_I and $n_F = 1$ .Where integrator used to reject the input disturbance and low pass filter used to avoid the amplification of the high frequency measurement noise.

B. Design Procedure of Second Generation CRONE Controller

The Second Generation CRONE (SGC) controller approach determines the transfer function of open loop $\beta_S(s)$ in the frequency limit [ω_A, ω_B] by the fractional integro-differentiator. The closed loop structure strategy of the SGC control is shown in Fig. 6.



y_{ref}(s) – reference signal, **C_S(s)** – Second generation CRONE controller,
y(s) - plant output, **β_S(s)** – SGC open loop fractional order transfer function,
d_y(s) – Plant output disturbance, **G(s)** - plant

Fig. 6. Closed loop structure of SGC control strategy

In this analysis, a SGC controller open loop fractional order transfer function $\beta_S(s)$ is represented as.

$$\beta_S(s)=C_S(s)*G(s)=\left(\frac{\omega_{cg}}{s}\right)^n, \ n\in[1,2] \quad (5)$$

The Nichols plane is plotted within the frequency range [ω_A, ω_B] as shown in Fig. 7 of open loop fractional order transfer function $\beta_S(s)$ of SGC controller. The vertical straight line $\beta_S(s)$ of Nichols locus called frequency template. The phase location is decides by order 'n' of frequency template,

where n is order of controller around the open loop gain crossover frequency ω_{cg}. the frequency template $\beta_S(s)$ vertically by registering a constant phase around the reference open loop gain crossover frequency ω_{cg} based on plant parameters such as gain and frequency. This ensures the vitality of SGC controller.

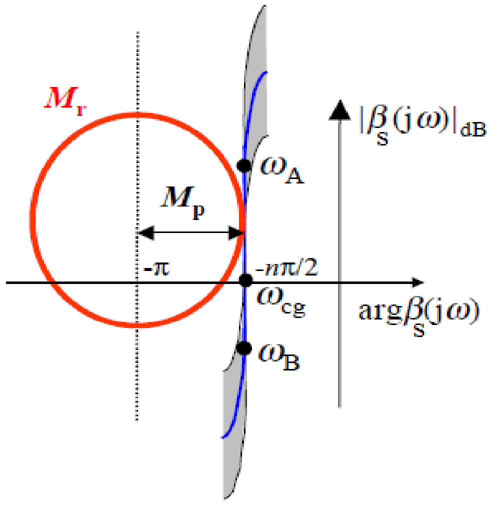


Fig. 7. Nichols locus of β_S(s) or Frequency template

The frequency template thus defined slides on its own axis as the plant parameters vary. At the time of plant perturbation (open loop gain crossover frequency ω_{cg} beyond the asymptotic frequency band), the vertical displacement of the vertical template ensures the robustness of phase margin (MP) and resonant peak (M_r) of the controller.

For the SGC controller to regulate the steady-state errors, control effort level and the open loop fractional order transfer function $\beta_S(s)$ (5) has to be band limited and made complex by incorporate integrator of order n_I and a low pass filter of order n_F.

The resultant SGC controller band limited open loop fractional order transfer function $\beta_S(s)$ is defined by,

$$\beta_S(s)=K\left(\frac{\omega_I}{s}+1\right)^{n_I}\left(\frac{1+s/\omega_h}{1+s/\omega_l}\right)^n\frac{1}{(1+s/\omega_F)^{n_F}} \quad (6)$$

Here: $\omega_I<\omega_l<\omega_{cg}<\omega_h<\omega_F$ or $(\omega_I=\omega_l)<\omega_{cg}<(\omega_F=\omega_h)$

The fractional version SGC controller $C_S(s)$ is obtained from (5) as,

$$C_S(s)=\frac{\beta_S(s)}{G(s)} \quad (7)$$

Substituting the value of $\beta_S(s)$ from (6) in (7) becomes,

$$C_S(s)=\frac{K\left(\frac{\omega_I}{s}+1\right)^{n_I}\left(\frac{1+s/\omega_h}{1+s/\omega_l}\right)^n\frac{1}{(1+s/\omega_F)^{n_F}}}{G(s)} \quad (8)$$

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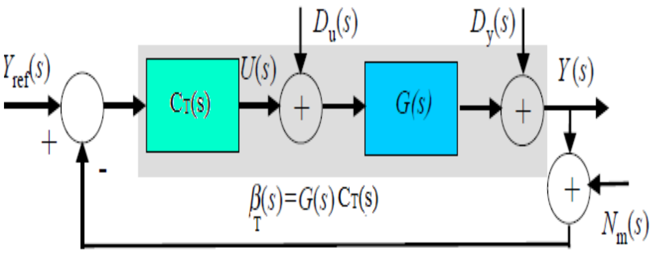
C. Design Procedure of Third Generation CRONE Controller

The structure of the strategy of TGC control is shown in Fig. 8. The TGC control design widens SGC controller by authorizing the handling of more common uncertainties.



Y_{ref}(s) – input reference signal, **C_T(s)** - CRONE controller, **G(s)** - process transfer function, **Y(s)** - plant output, **U(s)** - controller output, **D_u(s)** – i/p disturbance, **D_y(s)** – o/p disturbance, **N_m(s)** - sensor disturbance, **β_T(s)** – transfer function of open loop fractional order TGC

Fig. 8. Closed loop structure of TGC control strategy

The design strategy of TGC control classifies three stages, namely the optimal template, generalized template and open loop behavior optimization. The strategy of closed loop configuration of TGC is shown in Fig. 8. The design is depends on the elucidation of a generalized template (Fig. 9), it can be noted in every direction straight line segment over open loop ω_{cg} from the Nichols chart. The real order and imaginary order b decides phase placement and vertical angle of the template in the Nichols chart. The transfer function of complex fractional order integral is:

$$\beta_T(s)=C_T(S)G(s)=\left(\cosh\left(b\frac{\pi}{2}\right)\right)^{sign(b)}\left(\frac{\omega_{cg}}{s}\right)^{a}\left(\cos\left(b\ln\left(\frac{s}{\omega_{cg}}\right)\right)\right)^{-sign(b)} \tag{9}$$

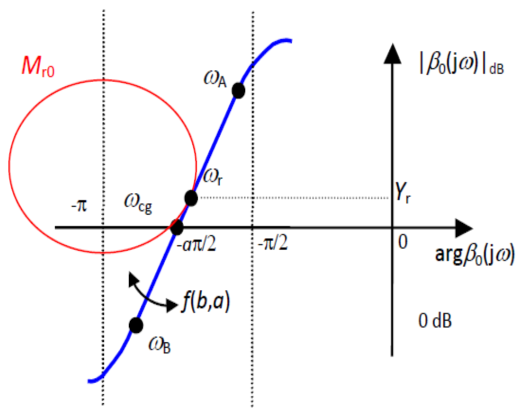


Fig. 9. Black Locus of Generalized template (Nichols plane)

The angle of the generalized template to the vertical, differentiation of the β (jω) magnitude and phase value at frequency ω_{cg} can be followed as a function of *a* and *b*:

$$\frac{d\left(|\beta_T(j\omega)|_{db}\right)}{d\left(phase\,\beta_T(j\omega)\right)}=\frac{-20\,a\,sign(b)}{ln(10)b\tanh\left(b\frac{\pi}{2}\right)} \tag{10}$$

Where the transfer function of generalized template is band-limited, then it is changed by a conventional expression.

$$\beta_T(s)=C^{sign(b)}\left(\frac{\omega_l}{s}+1\right)^{n_l}\left(\alpha_0\frac{1+s/\omega_h}{1+s/\omega_l}\right)^{a}\times\left(Re/_i\left(\alpha_0\frac{1+s/\omega_h}{1+s/\omega_l}\right)^{ib}\right)^{-q\,sign(b)}\left(\frac{1}{(1+\frac{s}{\omega_h})^{n_h}}\right) \tag{11}$$

Therefore the general equation of TGC Controller is, (11)

$$C_T(s)=\frac{\beta_T(s)}{G(s)} \tag{12}$$

It has eight high level parameters are there in open-loop complex fractional order integral transfer function β(s), they are n_l, n_h, a, b, ω_l, ω_h, ω_r and C. For which n_l and n_h are fixed by the control system designer. To obtain the tangency condition, ω_r and C are declared. The four individualistic parameters of optimal template on nonlinear optimization algorithm to minimize the J (cost function) depend on resonant peak variations and achieve a set of shaping limitation.

$$J=M_{r\,max}-M_{ro} \tag{13}$$

The primary aim of the TGC control is the optimization of three librated parameters (a tangency is obtrude) from the four high-level parameters *a*, *b*, ω_l and ω_h of template. The conventional form of TGC controller is given in (12).The equations (4), (7) and (12) are not in an implementable form, since it is having fractional order integro-differentiation terms. So it has to be converted into a rational form using recursive distribution technique. The recursive distribution of poles and zeros results in achievable rational order CRONE controller C_R(s) represented as.

$$C_R(s)=\frac{\beta_R(s)}{G(s)} \tag{14}$$

V. IMPLEMENTATION OF CRONE CONTROLLER USING CSD TOOLBOX

A. CRONE Controller parameters

The CRONE research group [5,6 & 8] is developed and managed the CRONE CSD toolbox. Which permit the user to lay down the elements such as plant parameters and its perturbations, frequency domain and time domain specifications, open loop tuned parameters and open loop fixed parameters etc. Therefore the APS plant information is set in the CRONE CSD toolbox for further analysis.

Table- II: User defined CRONE Controller Design Specifications

Required nominal open loop - ω_{cg}	3	ω_A / ω_l - ratio	10
Required nominal phase margin - P_m	54.91	ω_h / ω_B - ratio	10
Integral order - n_i	1	$\omega_{AB} / \omega_{cg}$ - ratio	1
Low-pass filter order - n_f	1	ω_{cg} / ω_i - ratio	30
Rational Approx. cell no. N	5	ω_f / ω_{cg} - ratio	30
Fractional effect width - ω_A / ω_B ratio - 0.8379			

On following the design procedures given in section IV [4] with the help of CRONE CSD toolbox one can obtain all the three generations of rational order CRONE controllers are shown in Table III.

Table- III: Rational Order CRONE Controller

Rational First Generation CRONE (FGC) controller
$C_{FR}(s) = 1.539 \times \frac{(s+0.1)(s+0.7318)(s+1.6110)(s+3.5480)}{s(s+0.5231)(s+1.152)(s+2.536)} \times \frac{(s+7.814)(s+17.210)}{(s+5.588)(s+12.3)(s+90)}$
Rational Second Generation CRONE (SGC) controller
$C_{SR}(s) = 1.88 \times \frac{(s+0.01754)(s+0.7149)(s+1.574)}{s(s+0.5534)(s+1.179)(s+2.596)} \times \frac{(s+3.467)(s+7.634)(s+16.81)}{(s+5.717)(s+12.59)(s+21.59)}$
Rational Third Generation CRONE (TGC) controller
$C_{TR}(s) = \frac{2.7229}{s} \frac{(1+\frac{s}{1.519})}{1+\frac{s}{15.31}} \frac{(1+\frac{s}{0.555})}{(1+\frac{s}{0.4779})}$

VI. RESULTS AND DISCUSSION

A. Servo Responses

The Simulation servo execution of all the three generation of crone controller are analysed and tabulated for APS. The servo response controller performances are analyzed based on error indices performance criteria viz. ISE and, IAE and the time domain performance measures viz. rise time (t_r) and settling time(t_s). The Simulation servo runs are conducted at 50% operating pressure. The set point change of ±5% and ±10% change in pressure is applied and is shown in Fig. 10, 11 &12. The error and time performances are recorded in Table IV & V.

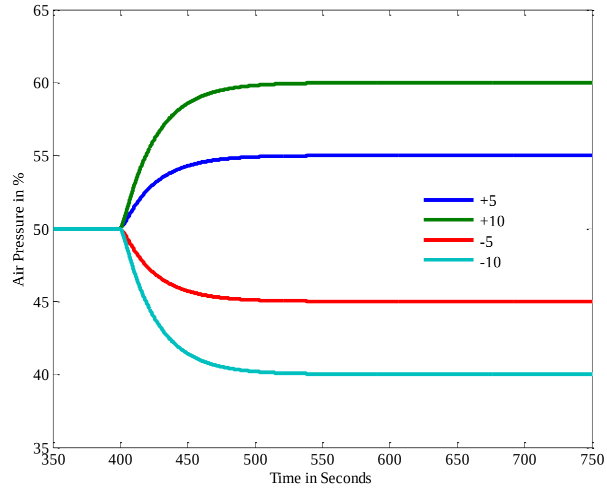


Fig. 10. Set point tracking at 50 % pressure using FGC controller

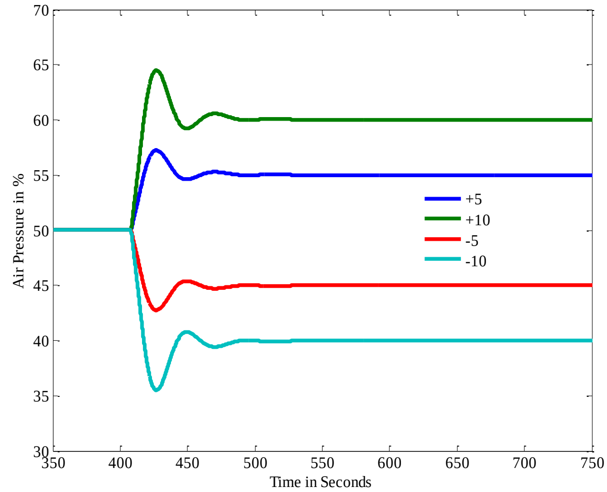


Fig. 11. Set point tracking at 50 % pressure using SGC controller

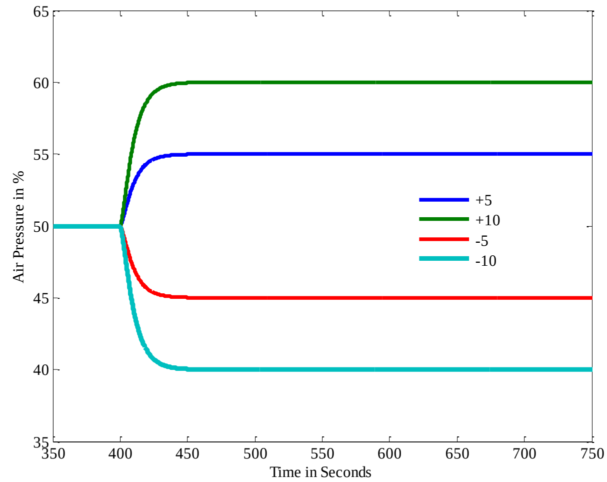


Fig. 12. Set point tracking at 50 % pressure using TGC controller

Table- IV: APS – Set point tracking –Error performances

Control System	Step Change	ISE	IAE
First Generation CRONE	+10%	1401	265
	+5%	350	132
	-5%	351.4	133
	-10%	1403	267
Second Generation CRONE	+10%	1364	215
	+5%	342	108
	-5%	343	110
	-10%	1367	216
Third Generation CRONE	+10%	601.4	106
	+5%	149	53
	-5%	151	54
	-10%	603.5	107

Table- V: APS – Set point tracking – Time domain performance

Performance measures	Step Change	Settling Time (s)	Rise Time (s)
First Generation CRONE	+10%	250	80
	+5%	200	60
	-5%	200	60
	-10%	250	80
Second Generation CRONE	+10%	150	28
	+5%	130	25
	-5%	130	25
	-10%	150	28
Third Generation CRONE	+10%	80	35
	+5%	70	32
	-5%	70	32
	-10%	80	35

It is evident from the Table IV of error performances for the operating point of 50% pressure with the step change of ±5% and ±10%. The TGC is the extraordinary performer and stand in first position. The SGC is moderate performer to that of TGC controller. The FGC stays in last position by providing lesser ISE and IAE values of other controller.

From the Table V, it is acknowledged that the case of settling time TGC performs better than FGC and SGC and similarly in the performance of rise time SGC provide superior performance than TGC and FGC. Therefore, by considering controller performance and process output taken account of ISE, IAE and settling time values only with negligible of rise time to the controller.

VII. CONCLUSION

In this paper, worst case model parameters are obtained for APS from real time open loop test at different operating regions. By using the worst case model three generation of CRONE controllers are designed. The CRONE CSD toolbox used to implement the CRONE controllers are compared based on servo response error index and time domain analysis. Simulation servo runs are conducted at 50% operating pressure. Servo responses are computed and the performance manipulates are recorded. From the analysis the TGC controller better than other two generations of CRONE controllers.

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