International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-12 Issue-6, May 2023

RNGA based Centralized PI Controller for Multivariable Non Square Systems using Direct Synthesis Method

C.V. Nageswara Rao, Putta Vihari

Abstract: ***Design of centralized PI controllers for multivariable non square systems is proposed in the present work. The centralized controller is designed based on the direct synthesis method. The method includes approximating the inverse of the process transfer matrix with the effective transfer function matrix. The effective transfer function for each element in the process transfer function matrix is derived by using the relative normalized gain array (RNGA), and relative average residence time array (RARTA) concepts proposed by Cai et al [1]. The transfer function models used in the present work include first order processes with time delay (FOPDT). Maclaurin series is applied to reduce the resulting controllers in to standard PI forms. The design method requires a single tuning parameter (filter time constant) to adjust the performance of the controller. Simulation study is carried out for various case studies and the results show the advantage of proposed method over the literature reported methods. The control algorithms are comparatively analyzed using standard robust stability measure. The designed controllers give a good performance with lesser interaction compared to the literature methods, Davison Method [2] and Tanttu and Lieslehto's method [3].***

Keywords: First Order Plus Dead Time, Multivariable, Centralized, Maclaurin Series, Pi Controllers, Relative Normalized Gain Array, Relative Average Residence Time Array and Effective Transfer Function.

I. INTRODUCTION

Multivariable systems with an unequal number of input and output variables are called non-square systems. The systems with more outputs than inputs are generally not desirable as all of the outputs cannot be maintained at the set point since the system is undermined. Systems with more inputs than outputs are frequently encountered in process industries. Occurrence of such systems is more common in chemical process industries. Literature reveals that most commonly dealt non square systems are Shell control problem [4],[5] with three manipulated variables and two controlled variables, and mixing tank problem with three manipulated variables and two controlled variables [6].

Manuscript received on 06 April 2023 | Revised Manuscript received on 17 April 2023 | Manuscript Accepted on 15 May 2023 | Manuscript published on 30 May 2023.
*Correspondence Authors
Dr. C.V. Nageswara Rao*, Associate Professor, Department of Chemical Engineering, Gayatri Vidya Parishad College of Engineering, Madhurawada, Visakhapatnam (A.P), India. E-mail: cvnr74@gvpce.ac.in, ORCID ID: https://orcid.org/0000-0001-5308-885X
Mr. Vihari Putta, Operations Manager, Coal Gassification Plant, JSP-Angul, Odisha, India. E-mail: vihariputta@gmail.com

One of the techniques to control such systems is to square down the system and designing the decentralized multivariable controllers [7]. Literature study [2] shows that it results in poor performance because of the information neglected by its structure.

Cai et al [1] proposed a new loop pairing criterion based on a new method for interaction measurement. In their work both the steady-state and transient information of the process transfer function are investigated, and the RNGA is introduced for loop interaction measurements. They have shown the effectiveness of the method applied in design of decentralized controllers for the square systems for which the RGA based loop pairing criterion gives an inaccurate interaction assessment.

Loh and Chiu [8] have deduced that non square systems should be controlled in their original state instead of squaring down by adding or deleting the variables. Sharma and Chidambaram [9] have proposed a method to control non square systems using Davison' method [2] to design centralized controllers. They have extended the Davison's method [2] to control non square systems. Vijay et al [10] proposed centralized multivariable PI controllers for MIMO processes. Two centralized controllers (one using RGA and the other using the effective transfer function (ETF) derived from an RNGA-RARTA) are designed based on the direct synthesis method. In the present work direct synthesis method [11], [12] is used to design the centralized controller for non-square systems. In this method inverse of process transfer function matrix required for this method is estimated by using Relative Average Residence Time Array (RARTA) and Relative Normalized Gain Array (RNGA) concept proposed by Cai et al [1].

Moore-Penrose Pseudo-inverse is used to find the inverse of Non-Square multivariable systems (Non-square Matrices). The overall design method includes three steps.

1. Using the concepts of normalized gain, find (i) the relative normalized gain array (RNGA) and (ii) the relative average residence time array (RARTA) of a given transfer function matrix using pseudo inverse of matrix.
2. Use the information obtained in the first step to obtain an effective transfer function matrix for the closed-loop system.
3. Design the centralized controller by approximating the inverse of the process transfer function matrix with the transpose of the effective transfer function matrix in the direct synthesis method.

The resultant controller is not in the standard PI form. To obtain the controller in standard PI form, Maclaurin series expansion is applied on the controller matrix.

II. CONTROL SYSTEM DESIGN

Consider a m-input and n-output open loop stable multivariable system. G(s) and $G_c(s)$ are process transfer function matrix and full dimensional controller matrix with compatible dimensions, expressed by

$$G(s) = \begin{bmatrix} g_{11}(s) & g_{12}(s) & \cdots & g_{1n}(s) \\ g_{21}(s) & g_{22}(s) & \cdots & g_{2n}(s) \\ \vdots & \vdots & \ddots & \vdots \\ g_{m1}(s) & g_{m2}(s) & \cdots & g_{mn}(s) \end{bmatrix} \quad (1)$$

$$G_C(s) = \begin{bmatrix} g_{c,11}(s) & g_{c,12}(s) & \cdots & g_{c,1m}(s) \\ g_{c,21}(s) & g_{c,22}(s) & \cdots & g_{c,2m}(s) \\ \vdots & \vdots & \ddots & \vdots \\ g_{c,n1}(s) & g_{c,n2}(s) & \cdots & g_{c,nm}(s) \end{bmatrix} \quad (2)$$

Let each element of the process transfer function matrix be represented by a first order plus dead time (FOPDT) model, i.e.

$$g_{ij}(s) = \tilde{g}_{ij}(s)e^{-\theta_{ij}s} \quad , \qquad i,j = 1,2,\dots.n \quad (3)$$

We know that Controller design using direct synthesis method by

$$G_C(S) = \frac{G_{Cl}(S)}{G(S)(I+G_{Cl}(S))} \quad (4)$$

Where $G_{Cl}(S)$ is the desired closed loop transfer function. According to IMC theory (Morari and Zafiriou [13], Nageswara Rao and Padmasree [14]), the desired closed-loop transfer function $G_{Cl}(S)$ of the ith loop is chosen as

$$G_{Cl}(S) = \frac{e^{-\theta_i s}}{(\lambda_i s+1)^{r_i}} \prod_{k=1}^{q_i} \frac{z_k - s}{z_k^* + s} \quad (5)$$

After substituting Equation (5) in Equation (4) and by using Penrose Moore pseudo inverse whenever inverse of process transfer function matrix is required, we get

$$g_{c,ji}(s) = \{[G^{\dagger}(s)]^{\mathrm{T}}\} \left(\frac{e^{-\theta_i s} \prod_{k=1}^{q_i} \frac{z_k - s}{z_k^* + s}}{(\lambda_i s+1)^{r_i} - e^{-\theta_i s} \prod_{k=1}^{q_i} \frac{z_k - s}{z_k^* + s}} \right) \quad (6)$$

$G^{\dagger}(s)$ is estimated by using the concepts RNGA, RARTA and ETF proposed by Cai et al [1]. 2009. Finally the Controller for FOPDT is obtained as

$$g_{c,ji}(s) = \frac{(\hat{\tau}_{ij}s+1)}{\hat{k}_{ij}} \left(\frac{e^{(\hat{\theta}_{ij}-\theta_i)s}}{(\lambda_i+\theta_i)s} \right) \quad (7)$$

The Controller Obtained now is converted in to standard PI controller form by using Maclaurin series Expansion.

$$g_{c,ji}(s) = \frac{1}{s}\left[P_{ji}(0) + sP_{ji}{}'(0) + \cdots\right] \quad (8)$$

Comparing with standard PI controller form, the resulting controller parameters are

$$k_{I,ji} = P_{ji}(0) = \frac{1}{\hat{k}_{ij}(\lambda_i+\theta_i)} \quad (9)$$

$$k_{C,ji} = P_{ji}{}'(0) = \frac{[(\hat{\theta}_{ij}-\theta_i)+\hat{\tau}_{ij}]}{\hat{k}_{ij}(\lambda_i+\theta_i)} \quad (10)$$

Where $\hat{\theta}_{ij}$,$\hat{\tau}_{ij}$ and $\hat{k}_{ij}$ are closed loop Time delay, Time constant and gains.

The controller is expected to give better performance because in designing the controller we used dynamic interaction effects (RNGA-RARTA) along with steady state effects (RGA). The proposed controller response is compared with that of literature methods proposed by Davison [2] and Tanttu & Lieslehto [3]. Performance analysis is also carried out in terms of TV, IAE, ISE and ITAE and compared with the literature reported methods.

A. Case Study – 1: Shell control problem

The process considered is a Shell control problem [4], [5] with two controlled variables and three manipulated variables in which the two controlled variables are composition of the top product and that of side stream. The manipulated variables are top draw, side draw and the bottoms reflux. As the delay compensator is significant for delay dominant processes, here the time delays are considered as five times to the time constants of each transfer function in the process. The resulting process is given by

$$G(s) = \begin{bmatrix} \frac{4.05e^{-250s}}{50s+1} & \frac{1.77e^{-300s}}{60s+1} & \frac{5.88e^{-250s}}{50s+1} \\ \frac{5.39e^{-250s}}{50s+1} & \frac{5.72e^{-300s}}{60s+1} & \frac{6.9e^{-200s}}{40s+1} \end{bmatrix}$$

Normalized gain matrix (K_N), RGA (Λ), RNGA (ϕ), and RARTA (Γ) can be calculated as

$$K_N = \begin{bmatrix} 0.0135 & 0.0049 & 0.0196 \\ 0.0180 & 0.0159 & 0.0288 \end{bmatrix};$$

$$\Lambda = \begin{bmatrix} 0.3203 & -0.5946 & 1.2744 \\ -0.0170 & 1.5733 & -0.5563 \end{bmatrix};$$

$$\phi = \begin{bmatrix} 0.8893 & -0.7626 & 0.8734 \\ -0.5162 & 1.7346 & -0.2184 \end{bmatrix};$$

$$\Gamma = \begin{bmatrix} 2.7767 & 1.2825 & 0.6853 \\ 30.3495 & 1.1025 & 0.3926 \end{bmatrix};$$

Centralized controller matrix based on RNGA-RARTA using Equation (9) and Equation (10) is given as

$$G_{C1}(s) = \begin{bmatrix} 0.1222 + \frac{1.0e^{-3} \times 0.1647}{s} & -0.0098 + \frac{1.0e^{-3} \times -0.0053}{s} \\ -0.1252 + \frac{1.0e^{-3} \times -0.6999}{s} & 0.0360 + \frac{1.0e^{-3} \times 0.4596}{s} \\ -0.0163 + \frac{1.0e^{-3} \times 0.4515}{s} & 0.0150 + \frac{1.0e^{-3} \times -0.1347}{s} \end{bmatrix}$$

The controller is tuned by adjusting filter time constants as $\lambda_1 = 75$ and $\lambda_2 = 112$.

Controller settings using Davison's method [2] is calculated as in Equation below.

Retrieval Number: 100.1/ijitee.F95180512623
DOI: 10.35940/ijitee.F9518.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

$$G_{C2}(s)=\begin{bmatrix} 1.0e^{-3}\times0.0791+\frac{1.0e^{-3}\times0.0949}{s} & 1.0e^{-3}\times\text{-}0.0032+\frac{1.0e^{-3}\times\text{-}0.0038}{s} \\ 1.0e^{-3}\times\text{-}0.3360+\frac{1.0e^{-3}\times\text{-}0.4031}{s} & 1.0e^{-3}\times0.2751+\frac{1.0e^{-3}\times0.3301}{s} \\ 1.0e^{-3}\times0.2167+\frac{1.0e^{-3}\times0.2601}{s} & 1.0e^{-3}\times\text{-}0.0806+\frac{1.0e^{-3}\times\text{-}0.0967}{s} \end{bmatrix}$$

And by Tanttu and Lieslehto's method [3], Controller is given as

$$G_{C3}(s)=\begin{bmatrix} 00.0809+\frac{1.0e^{-3}\times0.1665}{s} & -0.0353+\frac{1.0e^{-3}\times-0.0066}{s} \\ -0.1905+\frac{1.0e^{-3}\times-0.7073}{s} & 0.1341+\frac{1.0e^{-3}\times0.5791}{s} \\ 0.0547+\frac{1.0e^{-3}\times0.4563}{s} & -0.0093+\frac{1.0e^{-3}\times-0.1697}{s} \end{bmatrix}$$

Fig.1 shows the closed loop response of the Shell control problem subject to sequential unit step changes at t =0 and t = 3000s respectively. It can be seen that the interactions are lowered in RNGA based centralized PI controller compared to the controllers proposed by Davison [2] and Tanttu & Lieslehto [3]. This is because RNGA-RARTA includes dynamic interactions effects rather than only steady state interactions. Hence the interaction effects due to changes in other outputs are comparatively lesser than any other methods. The controller performance is also checked by comparing the values of Total variation (TV), IAE, ISE, ITAE values of the controller obtained from proposed work with that of Davison's and Tanttu and Lieslehto's methods [2], [3]. Table 1 shows the comparison of values of TV, IAE, ISE and ITAE for the three methods under consideration. The Fig.2 is a graphical representation of frequency plot of spectral radius which represents stability bounds for shell control problem. The controller has been designed to have robust stability since it satisfied the small gain theorem in terms of spectral radius. The proposed controller showed an intermediate robust stability when compared to the controllers proposed by Davison and Lieslehto. Controller based on RNGA is found to be more stable than Lieslehto controller. All the three controllers show more stability at higher frequencies.

To demonstrate the robust performance of the proposed method, the simulation study was also done by inserting a perturbation uncertainty in all parameters at a time into the actual process. Nominal process controller settings are used for perturbation models. The resulting performance index for the model mismatches (perturbation in all parameters) is tabulated in Table-I. A perturbation of ±10% and ±30% in the process gain, time delay and time constant are considered, and the corresponding responses are shown in the Fig 3, 4, 5 and 6. The proposed method gives a significant improved performance when compared to literature reported methods. This shows that centralized controller gives a comparable performance when compared to literature method-based controllers even under uncertainty conditions.

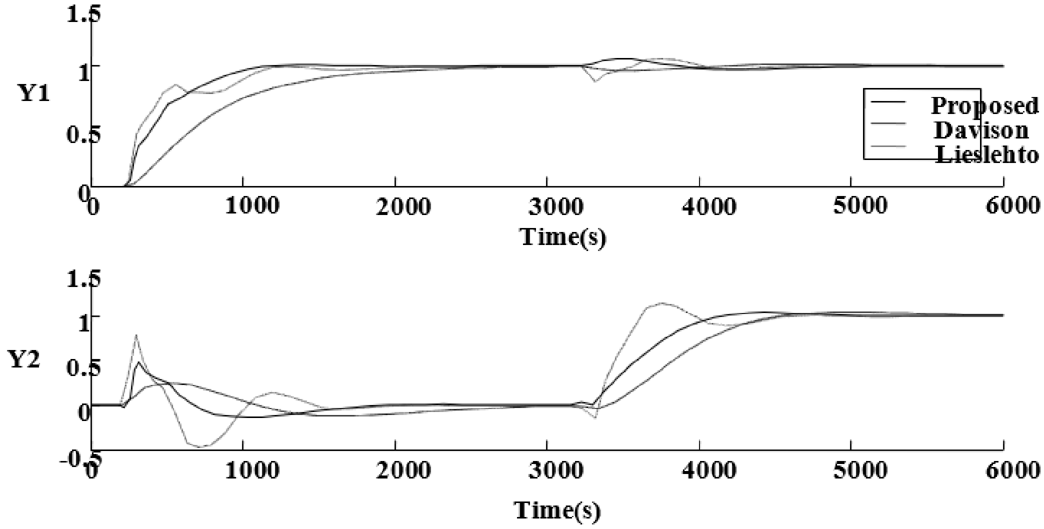

Fig. 1. Closed-loop responses to the sequential step changes in the set point for Shell Control Problem (First half of the bottom plot represents interaction when step change in Y1, second half represents response when step change in Y2)

The robust stability analysis of perturbed model with ± 10% and ± 30 % uncertainty also reveal that the proposed method is robust even under the presence of model uncertainties. Refer Table 1.

B. Case Study 2: Mixing tank problem

The process considered is a mixing tank problem with two controlled variables and three manipulated variables in which the two controlled variables are height of liquid in the tank and the exit concentration. The manipulated variables are the flow rates of the three input streams. Time delays are added intentionally to show the improvement of the delay compensator.

The resulting process is given as

$$G(s)=\begin{bmatrix} \frac{4e^{-100s}}{20s+1} & \frac{4e^{-100s}}{20s+1} & \frac{4e^{-100s}}{20s+1} \\ \frac{3e^{-50s}}{10s+1} & \frac{-3e^{-100s}}{10s+1} & \frac{5e^{-50s}}{10s+1} \end{bmatrix}$$

Normalized gain matrix (K_N), RGA (Λ), RNGA (ϕ), and RARTA (Γ) could be calculated as

$$K_N = \begin{bmatrix} 0.0333 & 0.0333 & 0.0333 \\ 0.0500 & -0.0273 & -0.0833 \end{bmatrix};$$
$$\Lambda = \begin{bmatrix} 0.2692 & 0.55577 & 0.1731 \\ 0.1154 & 0.4038 & 0.4808 \end{bmatrix};$$
$$\phi = \begin{bmatrix} 0.2529 & 0.6772 & 0.0699 \\ 0.1137 & 0.2653 & 0.6210 \end{bmatrix};$$
$$\Gamma = \begin{bmatrix} 0.9394 & 1.2143 & 0.4038 \\ 0.9857 & 0.6569 & 1.2917 \end{bmatrix};$$

Centralized controller matrix based on RNGA-RARTA using Equation (9) and Equation (10) as

$$G_{C1}(s)=\begin{bmatrix} 0.0422+\frac{1.0e^{-3}\times 0.4417}{s} & -0.0008+\frac{1.0e^{-3}\times 0.2657}{s} \\ 0.0535+\frac{1.0e^{-3}\times 0.9150}{s} & 0.0009+\frac{1.0e^{-3}\times -0.9299}{s} \\ -0.0183+\frac{1.0e^{-3}\times 0.2685}{s} & -0.0004+\frac{1.0e^{-3}\times 0.6642}{s} \end{bmatrix}$$

The controller is tuned by adjusting filter time constants as $\lambda_1 = 15$ and $\lambda_2 = 13$. Controller for this case using Davison's method [2] is calculated as

$$G_{C2}(s)=\begin{bmatrix} 0.0289+\frac{0.0007}{s} & 0.0165+\frac{0.0004}{s} \\ 0.0600+\frac{0.0014}{s} & -0.0579+\frac{-0.0013}{s} \\ 0.0186+\frac{0.0004}{s} & 0.0413+\frac{0.0010}{s} \end{bmatrix}$$

TABLE-I - Performance analysis comparison for all uncertainties for Case Study – 1

Model (nominal/uncertain)	Method	TV	IAE	ISE	ITAE
No Uncertainties	RNGA (Proposed)	1.168	1.46801×10^3	0.966×10^3	2.8237×10^5
	Davison Method	1.032	2.1612×10^3	1.443×10^3	4.3557×10^5
	Tanttu and Lieslehto method	1.322	1.4770×10^3	0.961×10^3	2.5425×10^5
+30% uncertainty	RNGA (Proposed)	0.94	1.8349×10^3	1.096×10^3	4.0246×10^5
	Davison Method	0.98	2.5247×10^3	1.686×10^3	5.5090×10^5
	Tanttu and Lieslehto method	1.162	1.6149×10^3	0.976×10^3	2.9539×10^5
-30% uncertainty	RNGA (Proposed)	2.77	2.5625×10^3	1.5158×10^3	5.8586×10^5
	Davison Method	1.36	2.0641×10^3	1.3162×10^3	4.3439×10^5
	Tanttu and Lieslehto method	2.203	1.9998×10^3	1.2264×10^3	4.0096×10^5
+10% uncertainty	RNGA (Proposed)	1.013	1.5467×10^3	992.3421	3.0803×10^5
	Davison Method	1.004	2.2701×10^3	1.5209×10^3	4.6366×10^5
	Tanttu and Lieslehto method	1.224	1.4909×10^3	958.7869	2.5746×10^5
-10% uncertainty	RNGA (Proposed)	1.45	1.5636×10^3	988.9643	3.1412×10^5
	Davison Method	1.087	2.0738×10^3	1.3736×10^3	4.1598×10^5
	Tanttu and Lieslehto method	1.46	1.5225×10^3	986.2283	2.7030×10^5

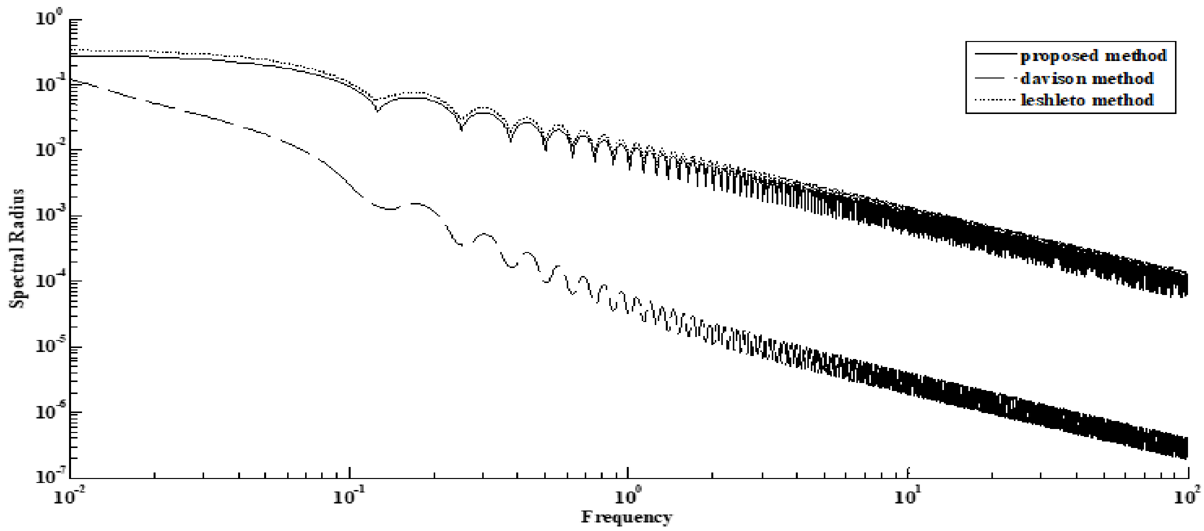

Fig. 2. Frequency plot of spectral radius with no perturbations included.

Retrieval Number: 100.1/ijitee.F95180512623
DOI: 10.35940/ijitee.F9518.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

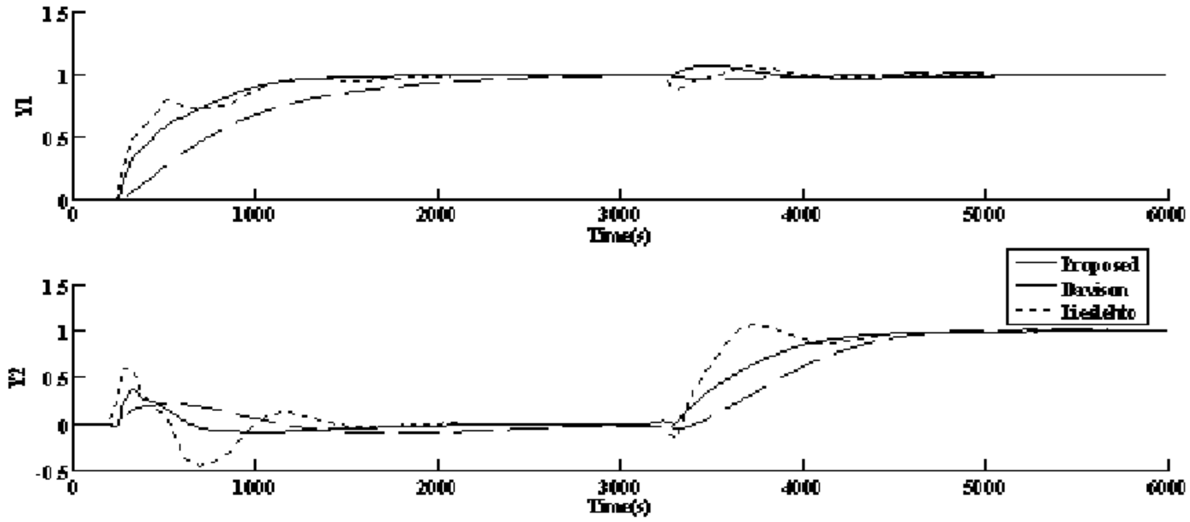

Fig.3. Response curve with +10% uncertainty in all parameters.

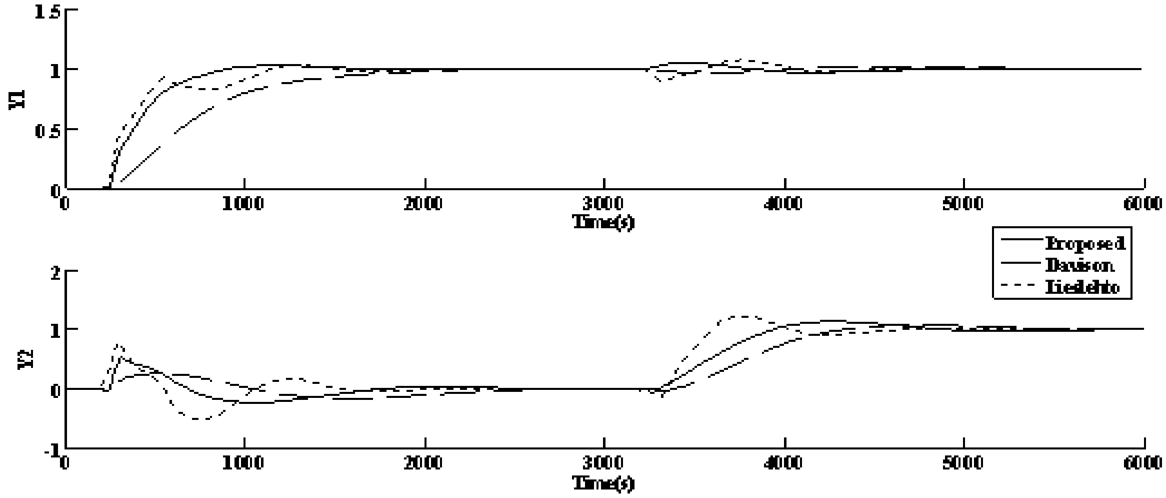

Fig.4. Response curve with -10% uncertainty in all parameters.

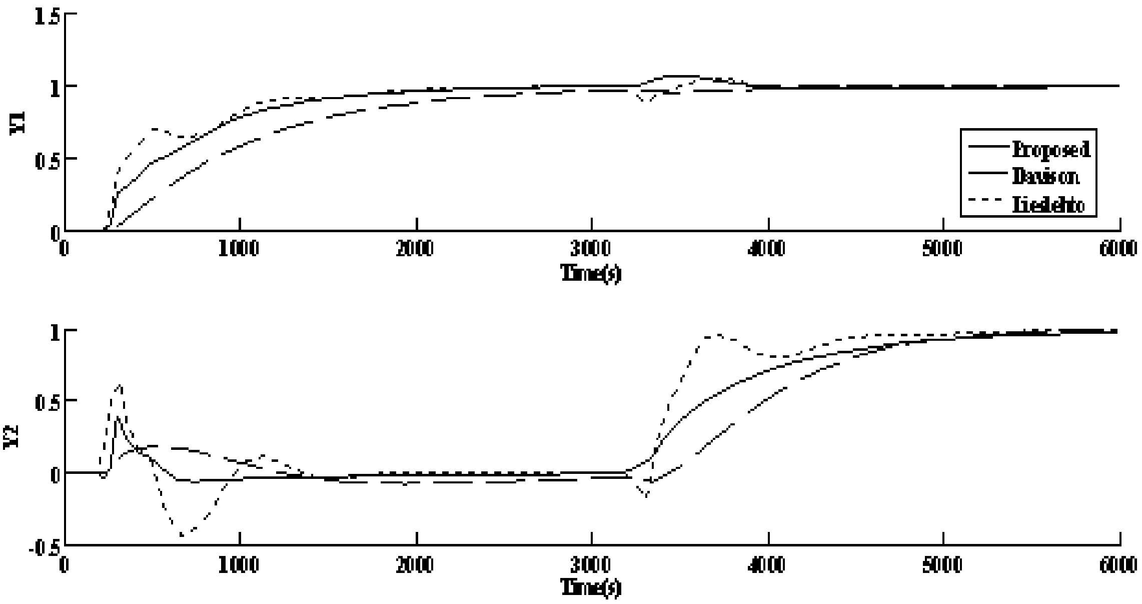

Fig.5. Response curve with +30% uncertainty in all parameters.

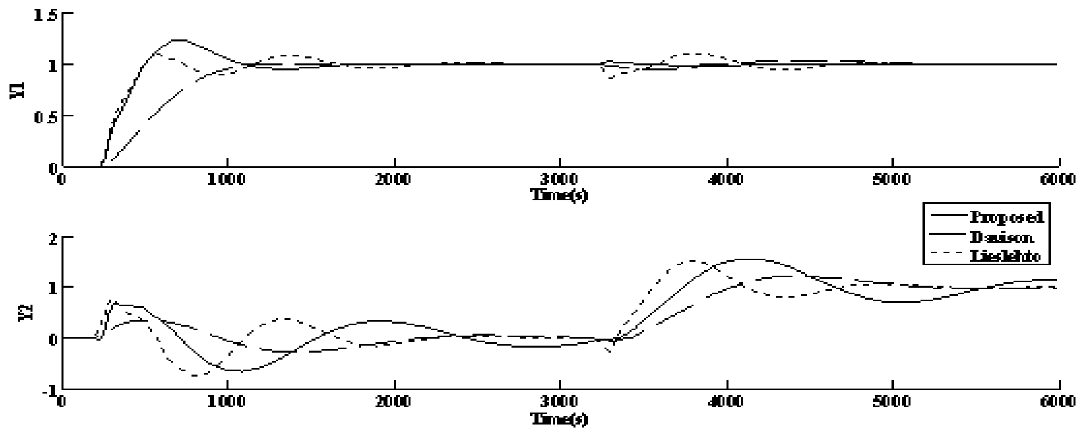

Fig.6. Response curve with -30% uncertainty in all parameters.

Controller by Tanttu and Lieslehto's method [3] as

$$G_{C3}(s) = \begin{bmatrix} 0.0306 + \frac{1.0e^{-3} \times 0.4642}{s} & 0.0092 + \frac{1.0e^{-3} \times 0.2653}{s} \\ 0.0803 + \frac{1.0e^{-3} \times 0.9615}{s} & -0.0385 + \frac{1.0e^{-3} \times -0.9284}{s} \\ 0.0097 + \frac{1.0e^{-3} \times 0.2984}{s} & 0.0293 + \frac{1.0e^{-3} \times 0.6631}{s} \end{bmatrix}$$

Fig.7 shows the closed loop response of the mixing tank problem subject to sequential unit step changes at t =0 and t = 900 respectively. It can be seen that the interactions lowered in RNGA based centralized controllers compared to the controllers proposed by Davison and Tanttu and Lieslehto. In this case also, the interaction effects due to changes in other outputs are comparatively less than any other methods.

The controller performance is also checked by comparing the values of TV, IAE, ISE and ITAE values of the controller obtained from proposed work with that of Davison's and Tanttu and Lieslehto's methods [2], [3]. Table. 2 shows the comparison of values of TV, IAE, ISE and ITAE for the three methods under consideration. This indicates that the proposed controller gives less interaction effects with a good performance. Fig.8 is a graphical representation of frequency plot of spectral radius which represents stability bounds for shell control problem. The controller has been designed to have robust stability since it satisfied the small gain theorem in terms of spectral radius. The proposed controller showed an intermediate robust stability when compared to the controllers proposed by Davison and Lieslehto. Controller based on RNGA is found to be more stable than Lieslehto controller. All the three controllers show more stability at higher frequencies. To demonstrate the robust performance of the proposed method, the simulation study was also done by inserting a perturbation uncertainty in all parameters at a time into the actual process. Nominal process controller settings are used for perturbation models.

A perturbation of ±10% and ±30% in the process gain, time delay and time constant are considered, and the corresponding closed loop responses are shown in Figures Fig. 9, Fig. 10, Fig. 11 and Fig. 12.

The resulting performance index for the model mismatches (perturbation in all parameters) is tabulated in Table-II. The proposed method gives a significant improved performance when compared to literature method-based controllers. IAE values are less affected in centralized controller scheme. This shows that centralized controller gives a comparable performance when compared to literature method-based controllers even under uncertainty conditions. The response curves show that the method proposed by Davison makes the controller unstable at -30 % uncertainties.

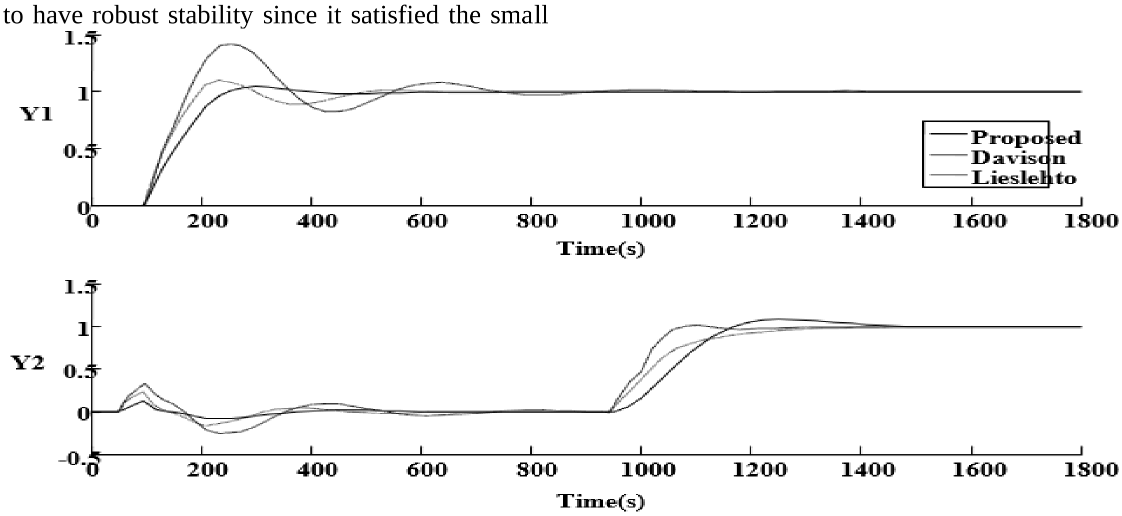

Fig.7: Closed-loop responses to the sequential step changes in the set point for Mixing Tank. (First half of the bottom plot represents interaction when step change in Y1, second half represents response when step change in Y2)

Retrieval Number: 100.1/ijitee.F95180512623
DOI: 10.35940/ijitee.F9518.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

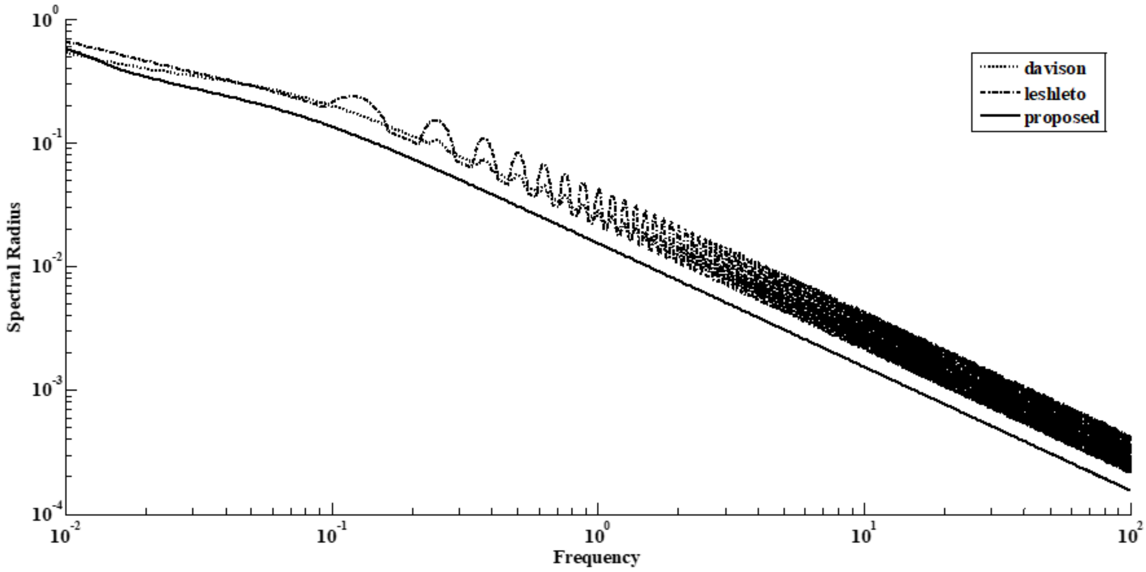

Fig. 8: Frequency plot of spectral radius with no perturbations included.

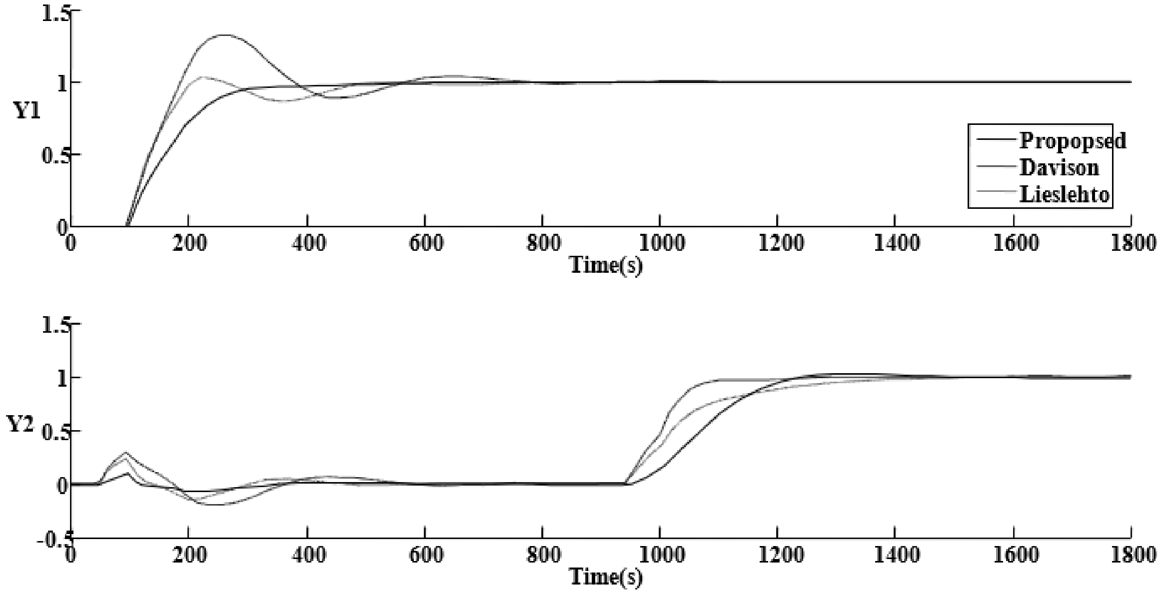

Fig.9: Response curve with +10% uncertainty in all parameters.

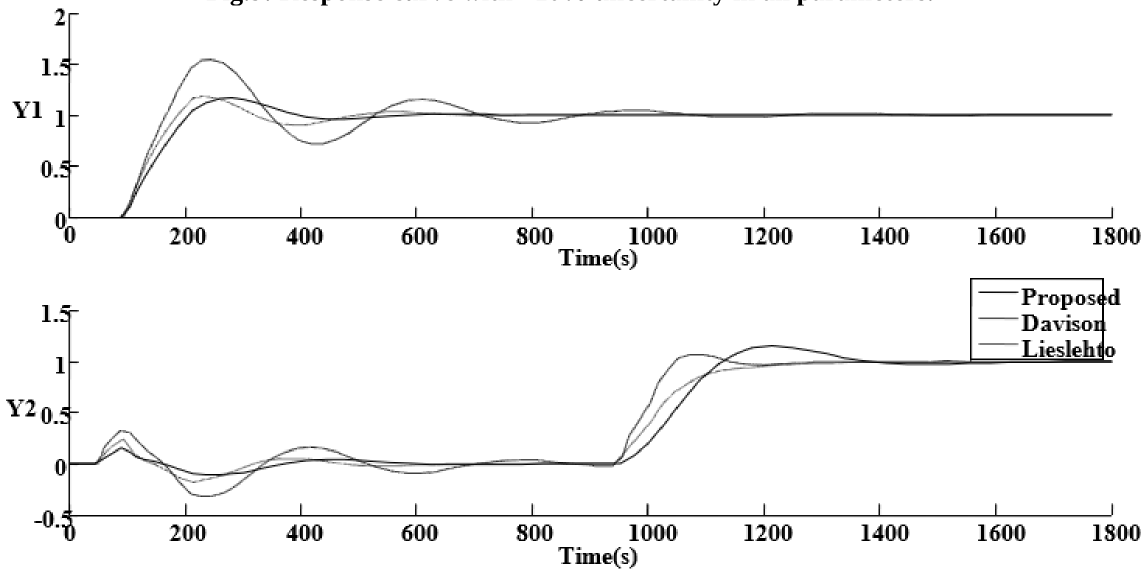

Fig.10: Response curve with -10% uncertainty in all parameters.

Retrieval Number: 100.1/ijitee.F95180512623
DOI: 10.35940/ijitee.F9518.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

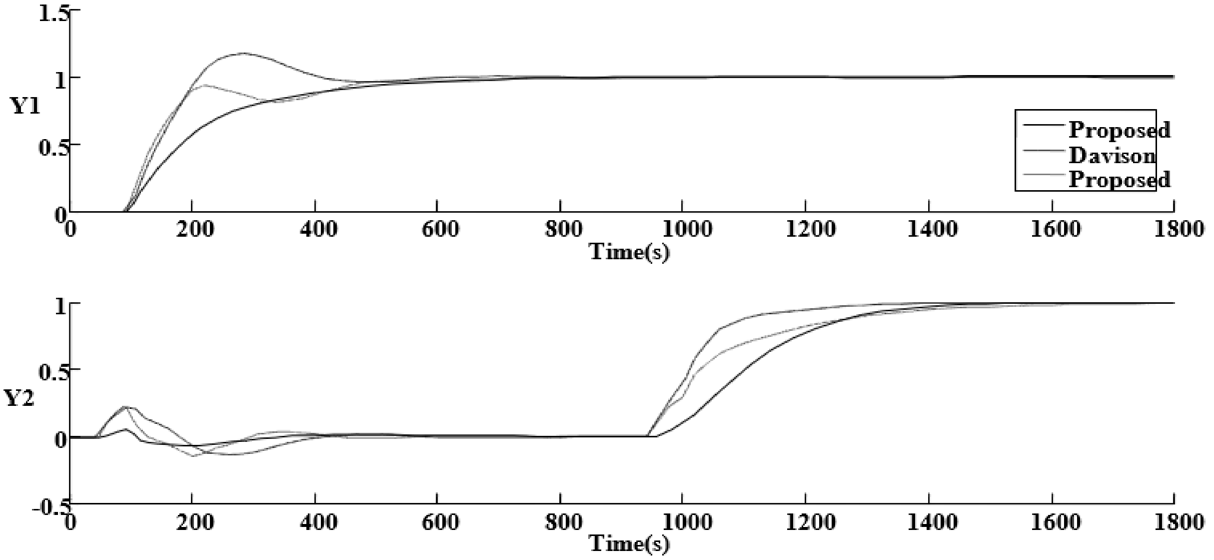

Fig. 11: Response curve with +30% uncertainty in all parameters.

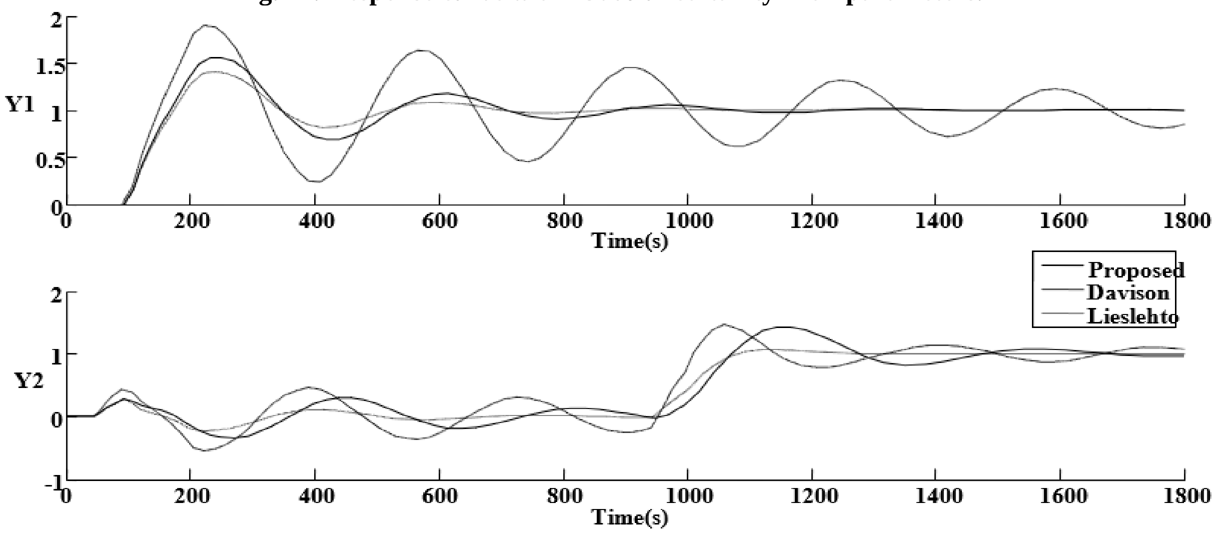

Fig.12: Response curve with -30% uncertainty in all parameters.

TABLE-II. Performance analysis comparison for nominal and model uncertainties for Case Study – 2

Model (nominal/ uncertain)	Method	TV	IAE	ISE	ITAE
No Uncertainties	RNGA (Proposed)	0.5877	380.5549	285.5328	1.9351×10^{4}
	Davison Method	0.8889	412.0307	251.2634	1.7110×10^{4}
	Tanttu and Lieslehto method	0.5778	360.5407	245.3196	1.8357×10^{4}
+30% Uncertainty	RNGA (Proposed)	0.4648	505.4479	348.9271	2.9642×10^{4}
	Davison Method	0.5703	364.5779	245.6360	1.6862×10^{4}
	Tanttu and Lieslehto method	0.5242	424.5589	263.1792	2.4575×10^{4}
-30% Uncertainty	RNGA (Proposed)	1.7781	648.0409	341.7058	3.8376×10^{4}
	Davison Method	3.4023	1.0523×10^{3}	553.3447	7.1014×10^{4}
	Tanttu and Lieslehto method	0.8949	407.2970	251.0726	1.8098×10^{4}
+10% Uncertainty	RNGA (Proposed)	0.4998	403.9143	302.9529	2.2468×10^{4}
	Davison Method	0.7210	385.1315	244.9739	1.6300×10^{4}
	Tanttu and Lieslehto method	0.5521	371.4965	248.3244	1.9934×10^{4}
-10% Uncertainty	RNGA (Proposed)	0.7416	398.1495	275.2281	2.1947×10^{4}
	Davison Method	1.1612	475.9689	268.4038	2.0533×10^{4}
	Tanttu and Lieslehto method	0.6213	357.6549	242.3320	1.6994×10^{4}

The robust stability analysis of perturbed model with 30 % uncertainty is shown by the Fig.13 and Fig.14 respectively. From these graphs it can concluded that the proposed method shows a comparable robust stability even under the presence of model uncertainties.

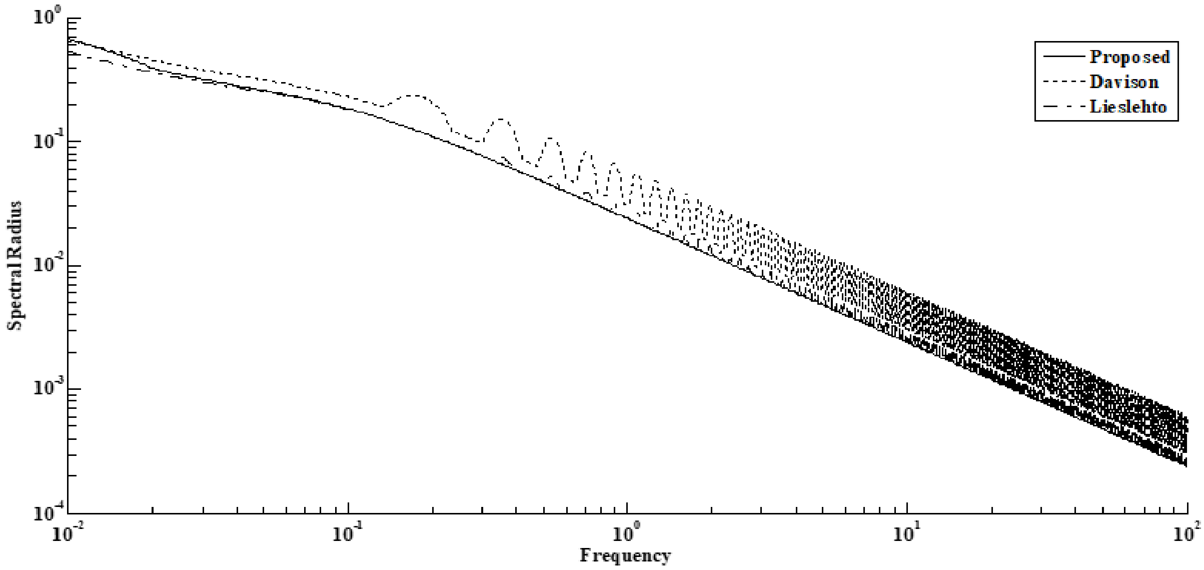

Fig.13. Frequency plot of spectral radius with -30% uncertainty in all parameters.

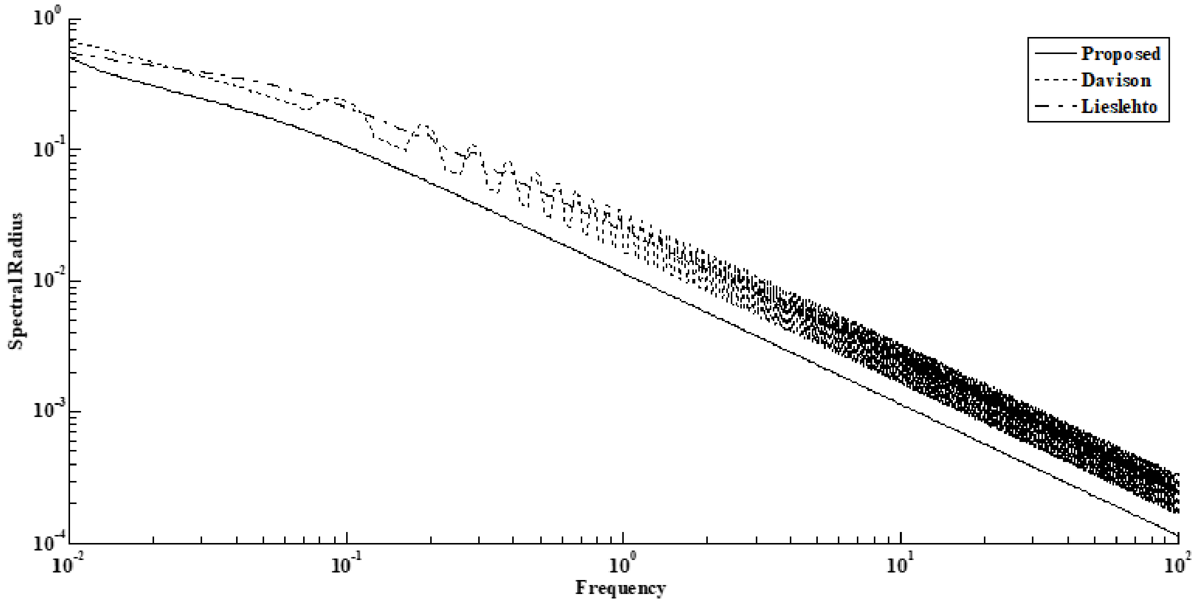

Fig.14. Frequency plot of spectral radius with +30% uncertainty in all parameters.

III. CONCLUSION

In this work, centralized multivariable PI controllers are designed for non-square multivariable systems. The proposed controller is designed based on the direct synthesis method. RNGA & RARTA are used to estimate the inverse of the process transfer function matrix in the direct synthesis method. Since inverse does not exist for non-square multi variable system, Moore-Penrose Pseudo-inverse is used in the place where inverse of a matrix is required to calculate. The resulting transfer function model of controller is converted into standard PI controller forms by using Maclaurin series expansion. The performance analysis is carried out by comparing the performance of the proposed controller with that of controllers obtained by literature methods in terms of ISE, ITAE and TV. Since, RNGA includes both steady state as well as transient information; the proposed method gives less effect of interactions than the methods proposed by Davison &Tanttu and Lieslehto when a step change is given in one of the set points. The performance parameters like ISE, ITAE and Total Variation (TV) are appreciable when compared to the conventional methods. The proposed method also showed a comparable robust stability in comparison to the literature methods.

DECLARATION

Funding/ Grants/ Financial Support	No, I did not receive.
Conflicts of Interest/ Competing Interests	No conflicts of interest to the best of our knowledge.
Ethical Approval and Consent to Participate	No, the article does not require ethical approval and consent to participate with evidence.
Availability of Data and Material/ Data Access Statement	Not relevant.

Authors Contributions	Mr. Putta Vihari has worked to obtain the data for the case study considered. Accordingly, the controller design methodology is decided upon. Second Author, Dr. C. V. Nageswara Rao took up the simulation study using a Simulation tool while training the first author. A method of RNGA based controller design is utilized based on the brainstorming discussion among the authors. As there are few research works which addressed non-square systems this methodology is adopted. Mostly PI controller would suffice maximum variables to control and hence design of PI controller.

REFERENCES

1. M.J. He, W.J. Cai, W. Ni, and L.H. Xie, "RNGA based controls system configuration for multivariable processes", *Journal of process control*, Vol. 19, 2009, 1036-1042. [CrossRef]
2. E.J. Davison, "Multivariable tuning regulators: The feed forward and robust control of general servo mechanisms", *IEEE Trans. Auto Control*, Vol. 21, 1976, 35-47. [CrossRef]
3. J.T. Tanttu, and J. Lieslehto, "A comparative study of some multivariable PI controller tuning methods", *Intelligent tuning and adaptive control*, Pergamon Press, 357-362, 1991. [CrossRef]
4. C. Valchos, D. Williams, and J.B. Gomm, "Solution to the shell control problem using generically tuned PID controllers", *Control Engg Practice*, Vol. 10, 2002, 151-163. [CrossRef]
5. I. Thirunavukkarasu, V.I. George, S. Shanmugapriya, and Yash Vardhan, "Design of PID Controller for Non Square MIMO System", *J.AIP Conference Proceedings*, Vol. 1414, 2011, 39-42. [CrossRef]
6. D.E. Reeves, and Y. Arkun, "Interaction measures for non-square decentralized control structure", *AICHE J*, Vol. 35, 1989, 603-613. [CrossRef]
7. C. Lucas, Mehrdad Fatourechi., GholamHassan Famil Khalili., Javad Abdi, and Ali Khaki-Sedigh., "Control of Multivariable Systems Based on Emotional Temporal Difference Learning Controller", *IJE Transactions A: Basics*, Vol. 17, No. 4, 2004, 363 – 376.
8. E.J. Loh, and M.S. Chiu, "Robust decentralized control of non-square systems", *Chem. Engg. Commun*, Vol. 158, 1997, 157–180. [CrossRef]
9. K.L.N. Sharma, and M. Chidambaram, "Centralized PI/PID controllers for non-square systems with RHP zeros", *J. Indian Inst. Sci.*, Vol. 85, 2005, 201–221.
10. V. Vijay Kumar, V.S.R. Rao, and M. Chidambaram, "Centralized PI controllers for interacting Multivariable process by synthesis method", *ISA transactions*, Vol. 51, 2011, 400-409. [CrossRef]
11. D.E. Seborg, T.F. Edgar, and D.A. Mellichamp, *"Process dynamics and control"*. JohnWiley & Sons. New York, 2005.
12. T.N.L. Vu, and M. Lee, "Multi-loop PI controller design based on direct synthesis method for interacting multi-time delay processes", *ISA Transactions*, Vol. 49, 2010, 79-86. [CrossRef]
13. M. Morari, and E. Zafiriou, *"Robust process control"*, Englewood Cliffs (New Jersey). Prentice Hall, 1989.
14. C.V. Nageswara Rao, and R. Padma Sree, "IMC Based Controller Design for Integrating Systems with Time Delay", *Indian Chemical Engineer*, Vol. 52, No. 3, 2010, 194-218. [CrossRef]

AUTHORS PROFILE

Dr. C.V. Nageswara Rao is Associate Professor in the Department of Chemical Engineering, Gayatri Vidya Parishad College of Engineering (Autonomous), Madhurawada, Visakhapatnam. He has 5 years of industrial experience in various Chemical Process Industries and 18 years of teaching experience in reputed Engineering Institutes. He works in the research area of Process Control, Separation of organic solvents, Modeling and Simulation and Process Safety. His PhD work focused on the advanced process control, PID Controller Design for Integrating Systems with Time Delay. He has published several papers in International and National Journals and presented papers in International Conferences. Also, the author published a book on PID Controller Design for Second Order Systems with time delay.

Mr. Vihari Putta is an operations manager in coal gassification plant at JSP-Angul. He has pursued his masters in chemical engineering from Gayatri Vidya Parsihad College of Engineering (Automomous). He has 17 years of industrial experience in refinery, petrochemicals and gassification sectors. His research areas of interest include Process Control, Gasification, Gas Sweetening and Process Optimization. He has participated and presented papers at International Conference and National Conferences organized by premier institutes. He has attended National Seminar on State Environment: Environment Protection, Management and Governance at Andhra University. Also, he has attended workshops on Advances in Separation Processes, Linear and Non-Linear Finite Element Method and MATLAB Applications in Chemical Engineering.

Retrieval Number: 100.1/ijitee.F95180512623
DOI: 10.35940/ijitee.F9518.0512623
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)