Relay Auto Tuning Of Parallel Cascade Controller

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Abstract

The present work is concerned with relay auto tuning of parallel cascade controllers. The method proposed by Srinivasan and Chidambaram [10] to analyze the conventional on-off relay oscillations for a single loop feedback controller is extended to the relay tuning of parallel cascade controllers. Using the ultimate gain and ultimate cross over frequency of the two loops, the inner loop (PI) and outer loop (PID) controllers are designed by Ziegler-Nichols tuning method. The performances of the controllers are compared with the results based on conventional relay analysis. The improved method of analyzing biased auto tune method proposed for single feedback controller by Srinivasan and Chidambaram [11] is also applied to relay auto tune of parallel cascade controllers. The proposed methods give an improved performance over that of the conventional on-off relay tune method.

Key words: Parallel cascade, relay, PI controllers, asymmetric relay

Introduction

Åström and Hägglund [1] have suggested the use of an ideal (on-off) relay to generate sustained closed loop oscillations. The ultimate gain can be found using $k_u=4h/(\pi a_0)$ [where h is the relay height and 'a_0' is the amplitude of the closed loop oscillation]. PID controllers can then be designed by using Ziegler-Nichols method. Luyben (1987) has employed the relay feedback method to identify a first order plus time delay transfer function (FOPTD) model. Once, k_u and ω_u are known, then the amplitude criterion and phase angle condition can be written down. To get the three parameters of FOPTD model, knowledge of the process gain or delay should be known. Luyben noted the delay form the initial portion of the relay oscillation. In deriving the relation k_u , an assumption made in the conventional relay oscillation is that all higher order harmonics (of the relay output) are filtered by the system. Li et al. [7] have pointed out that error of –18% to +27% is obtained in the calculation of k_u by this method. An excellent review on the relay feedback method is given by Yu [13]. Srinivasan and Chidambaram [10] have improved the conventional relay auto tune method by proposing a method to calculate the value of k_u by using appropriate value of number of harmonics coming out of the system output. This method gives an accurate value of k_u.

Shen et al.[9] have used a biased relay for getting the model parameters of a FOPTD model. In the method the process gain is calculated from $k_p = \int e(t)\ d(\omega t) / \int y(t)\ d(\omega t)$, the limits of integration are from 0 to 2π. Since the value of k_u is calculated form $k_u = 4h/(\pi a_0)$, the method also does not give good results. Recently Srinivasan and Chidambaram [11] have proposed an improved analysis of the biased relay auto tune method.

Parallel cascade control scheme utilizes two control loops: the secondary (or 'slave') or inner loop receives its set point from the primary (or 'master') or outer loop. In parallel cascade control manipulated variable affects both variables directly [6]. Due to two control loops present, there are two controllers to be tuned. Hang et al.[3] have proposed a relay auto tuning of series cascade control loops. They have used conventional on-off relay testing and using the value of k_u from $4h/(\pi a_0)$ and using Ziegler-Nichols tuning formulae, the controllers are tuned. With the inner loop under PI control action, the relay test is repeated for the outer loop. Vivek and Chidambaram [8] extended Srinivasan and Chidambaram [10] method to tune series cascade controllers to get an improved performance. In the present work, the methods of Srinivasan and Chidambaram [10],[11] are applied to tune parallel cascade controllers. The improved performance of the proposed parallel controller is compared with that of the conventional relay analysis.

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1. Propose method-1

The parallel cascade control scheme is considered here. First the conventional on-off relay is considered. The relay is used in the inner loop and the outer loop is kept under manual mode. The relay oscillations are noted. For simulation study, the process mode is assumed are $(k_pG_p)_2=k_{p2}\exp(-4.0)/(s+1)$ and $(k_pG_p)_1=k_{p1}\exp(-6.0)/(s+1)$. Where $kp_1=1.0$ and $kp_2=1.0$. Using a symmetric relay height of 1, the oscillation in the inner loop output variable y_2 is noted. The amplitude and frequency of oscillations are noted as 0.98 and 0.67 respectively. Using the relation $k_u = 4h/(\pi a_0)$, the value of k_u is obtained as 1.29. Based on the transfer function model, the exact value of k_u is calculated as 1.18. Thus significant error is obtained in k_u by the conventional relay analysis. Using the results of relay testing, the PI settings are calculated by using Ziegler and Nichols continuous cycling tuning method as $k_c = 0.57$ and $\tau_I = 7.8$.

Using these PI settings in the inner loop (instead of the relay) and introducing a relay in the outer loop, the oscillation in the outer loop is noted with amplitude of 1.12 and frequency of 0.48. The value of $k_u = 1.13$ is obtained from $4h/(\pi a_0)$. Based on the relay test results, the outer loop PID controller is designed by using Ziegler-Nichols method as $k_c=0.68$, $\tau_I = 6.49$ and $\tau_D = 1.63$. The closed loop servo response is evaluated for a unit step change in the set point and the response is shown in Fig. 1. An oscillatory response is obtained. Similar response is obtained for a regulatory problem also [with $(k_LG_L)_2 = 1$] as shown in Fig. 2.

The method of Srinivasan and Chidambaram [10] is applied now. Srinivasan and Chidambaram [10] have given a method to find out the value of k_u by considering the higher order harmonics. The initial portion of the relay output gives an indication of how many higher order harmonics present in the relay output. A value of 5 higher order harmonics (N=5) is recommended. Let us use their method for analyzing the parallel cascade auto tuning.

For the system under study, the value of k_u in the inner loop is obtained as 1.17 for the inner loop and frequency of oscillations $\omega_u=0.67$. Once PI controller is designed based on these values, the inner loop is kept under PI and then the relay is kept in the outer loop. From the relay oscillation, the value of $k_u=1.13$ is obtained by conventional method. Srinivasan and Chidambaram [10] method gives k_u as 1.09 and $\omega_u=0.47$. A PID controller is designed based on this value. The details of the results are given in Table I. The servo response is evaluated for a step change in the set point. The response by the conventional analysis using single harmonics gives oscillatory response. Whereas, using the method of Srinivasan and Chidambaram [10] gives an excellent response. The IAE values for servo and regulatory performance are given in Table II.

2. Proposed method –2

In this section, the biased relay auto tune is applied with a relay height of +2 and –1. In literature for single loop asymmetric relay tuning method, the value of $\gamma = 2$ is used. Therefore, the relay height of +2 and –1 is used in the present study also. However, simulations studies are carried out with different relay heights of γ=2, 2.5, 3 and 4. The results are summarized in Table 3. It is observed that the resulted PI controller settings are not changed significantly.

The method proposed by Srinivasan and Chidambaram [11] is extended here to parallel cascade systems. The value of k_u for the inner loop based on the identified FOPTD model ($k_P=0.99, \tau=0.97, \tau_D = 4.01$) obtained by the relay method is 1.20 and frequency of oscillation $\omega=0.66$. PI controller is designed by Ziegler-Nichols method. The inner loop is kept under PI and the asymmetric relay is then used in the outer loop. Based on the oscillation obtained in y_1 and hence based on the identified FOPTD model ($k_P = 1.0$, $\tau=0.99$, $\tau_D = 6.0$), the value of k_u is obtained for the outer loop as 1.1 with $\omega=0.47$. PID controller is designed for the outer loop based on the values of k_u and ω_u. The results of the relay test are given in Table I. The servo response in y_1 for a unit step change in the set point is shown in Fig. 4. The performance is as good as the proposed method-1. In the proposed method-1, the value of order (N) of higher order harmonics is to be selected. Whereas in the asymmetric method of Srinivasan and Chidambaram [11], there is no such value of N required. In the asymmetric method, the model is to be identified and then the controller settings are calculated. In the symmetrical method, the controller settings are calculated based on the ultimate values obtained from the relay test. Fig. 2 shows the regulatory response for step a change in the inner loop disturbance.

For a single loop system, it is known that Ziegler-Nichols tuning formulae give an oscillatory response. An attempt is made here to use the tuning formulas other than Ziegler-Nichols tuning formulae. For a single loop control system, Tyreus and Luyben [12] and Luyben [6] have suggested improved tuning formulas. Basically Tyreus-Luyben method detunes the proportional gain and increases integral time. The performance of the Tyreus-Luyben tuning formula for the cascade control system has not been reported so far. An attempt is made here to compare the performance of the Tyreus-Luyben tuning formulas for a parallel cascade control system. In the present work, Tyreus-Luyben tuning formulae are applied to design the controller settings for the inner loop and outer loop. Since the relay test for the outer loop depends on the settings for the inner loop, the relay tuning for the outer loop has to be repeated. As stated earlier, using a symmetric relay height of ±1, the oscillation in the inner loop output variable y_2 is recorded. The amplitude and frequency of oscillations are noted as 0.98 and 0.67 respectively. Based on the principle harmonics, the value of k_u is obtained as 1.29. The PI settings are calculated using Tyreus-Luyben tuning formula as k_c = 0.4 and τ_I = 20.59. Using the PI settings in the inner loop and introducing a relay in the outer loop, the oscillation in the outer loop is noted with a amplitude of 0.55 and frequency of 0.49. The value of k_u =2.3 is obtained from $4h/(\pi a_0)$. Based on the relay test results, the outer loop PID controller settings are designed as k_c=1.04, τ_I =27.9 and τ_D =2.0

Srinivasan and Chidambaram method (proposed method-1) for the improved auto tuning is applied now. For the inner loop, considering higher order harmonics (N=5) k_u and ω_u are obtained as 1.17 and 0.67. Using Tyreus-Luyben settings, the PI settings are calculated as k_c = 0.36 and τ_I = 20.59. Using this PI setting in the secondary loop and a relay in the outer loop, an oscillations in the outer loop are noted with amplitude of 0.51 and ω_u = 0.48 respectively. By using the proposed method-1 with N=9, the value of k_u is calculated as 2.0. By using Tyreus-Luyben tuning formulas, the PID settings are calculated as k_c = 0.91, τ_I = 28.67 and τ_D =2.068. Table V shows the details of controller settings for conventional and proposed method-1. The servo response in y_1 for a unit step change in the set point is shown in Fig. 6. Fig. 7 shows the regulatory response for step a change in the inner loop disturbance. The performances are found to be sluggish.

The sluggish response observed because of detuning the proportional gain and increasing integral time for secondary loop. In cascade control system the response of the secondary loop should be faster so as to take quick action on disturbance entering in the secondary loop before its effect is felt by main control variable. If Fig. 4 and Fig. 6 are compared then, the response (rise time and settling time) using Ziegler-Nichols tuning formulae, is faster than the response using Tyreus-Luyben tuning formulae. In this view, the performance analyzed using Ziegler-Nichols tuning formulae is preferred.

Conclusions

The modified analysis of relay auto tuning proposed for single feedback system by Srinivasan and Chidambaram [10] and modified analysis of asymmetric auto tuning by Srinivasan and Chidambaram [11] are extended to tune parallel cascade controllers. Both the methods effectively take care of higher order harmonics. The performances of the PI-PID controllers are compared with the conventional relay analysis (principle harmonic analysis). The present methods give a better performance than that of the conventional analysis. The controller settings using the Tyreus-Luyben tuning formulae proposed for a single loop system gives a sluggish response when applied to the parallel cascade control systems.

Table I Controller setting comparisons using Ziegler-Nichols settings

Loop	Controller settings	Symmetric relay		Asymmetric Relay
		N=1	N=5	
Inner	k_c	0.5837	0.5294	0.54
	τ_I	7.8000	7.8000	7.9
		N=1	N=9	
Outer	k_c	0.6818	0.6568	0.664
	τ_I	6.4915	6.5660	6.6097
	τ_D	1.6229	1.6415	1.6524

Table II. Performance Comparison of proposed methods and conventional method for $(\tau_d/\tau)_{\text{inner-loop}}= 4.0$, $(\tau_d/\tau)_{\text{outer-loop}}= 6.0$

Comparison parameters	Symetric Relay				Asy. Relay	
	Con.		PM-1		PM-2	
Overshoot	0.214		0.1196		0.1314	
Settling time	98		68		74	
	Servo	Regu.	Servo	Regu.	Servo	Regu.
IAE	16.98	15.18	15.0	11.6	15.07	11.89

Con.: Conventional PM-1: Proposed method-1
PM-2: Proposed method-2

Table III. Effect of change in relay height (asymmetric relay testing) on PI settings

Asymmetric relay		PI controller		
H	γ	k_u	k_c	τ_I
0.5	4.0	1.1859	0.5336	0.2050
1.0	2.0	1.1972	0.5387	0.1975
1.0	2.5	1.1902	0.5356	0.2000
1.0	3.0	1.1837	0.5327	0.2008

Table IV. Controller setting comparisons using Tyreus-Luyben settings

Loop	Controller settings	Conventional method	Proposed method-1
		N=1	N=5
Inner	k_c	0.4054	0.3676
	τ_I	20.592	20.592
		N=1	N=9
Outer	k_c	1.0548	0.91
	τ_I	27.984	28.67
	τ_D	2.019	2.068

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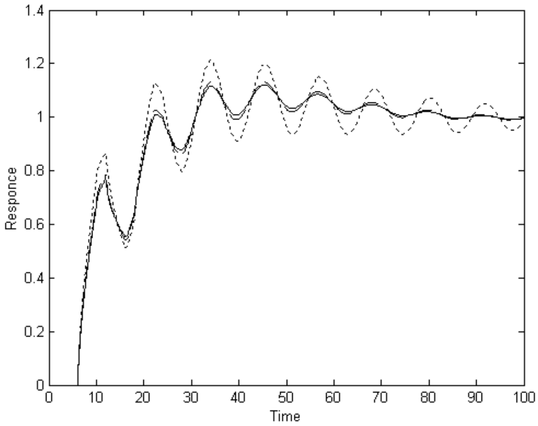

Fig. 1 Servo response in y_1 using Ziegler-Nichols settings
Outer oscillatory response – Conventional analysis
Inner solid – Proposed method -1
Inner dash – Proposed method -2

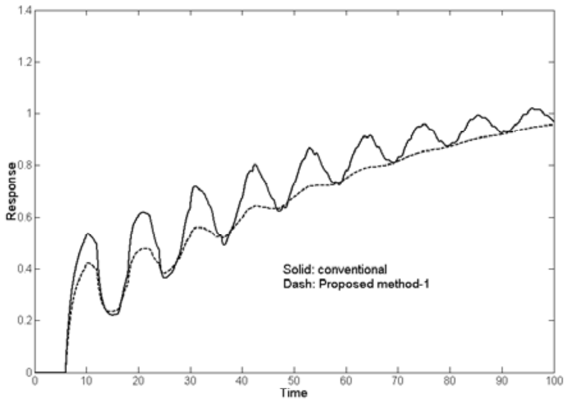

Fig. 3 Servo response in y_1 using Tyreus-Luyben settings
Legends:
Solid – Conventional analysis
Inner dash – Proposed method -1

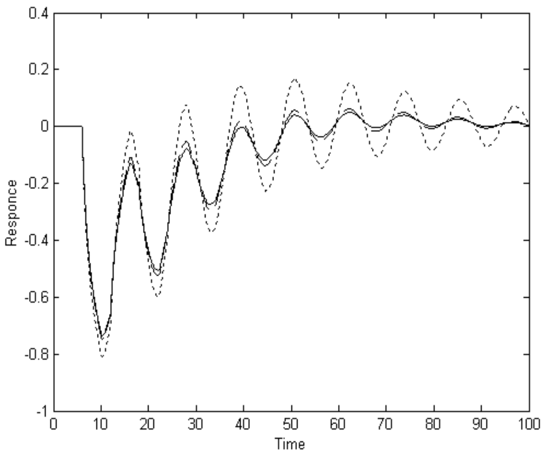

Fig. 2 Regulatory response in y_1 for a disturbance in inner loop using Ziegler-Nichols settings PID controller for outer loop and PI for inner loop (Legends: as in Fig. 1.)

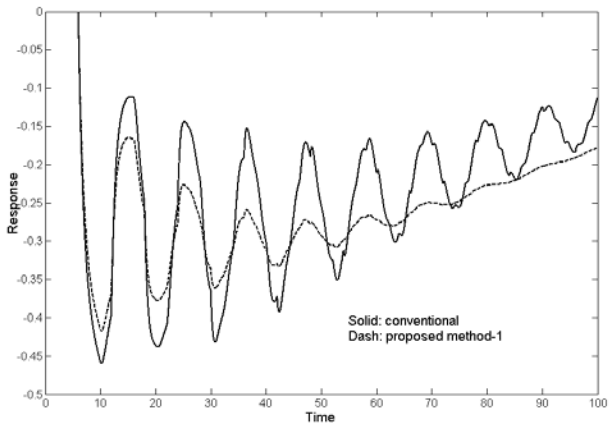

Fig. 4 Regulatory response in y_1 for a disturbance in inner loop using Tyreus-Luyben settings
PID controller for outer loop and PI for inner loop (Legends: as in Fig. 3)