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ORIGINAL CONTRIBUTION

An Optimal Robust Controller Design for Automatic Voltage Regulator System Using Coefficient Diagram Method

Surekha Bhusnur[1]

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Abstract Design of a robust controller for any control system is of paramount importance in the field of control system design. Despite parameter variations, the controller has to generate signals to enable satisfactory performance of the system. One of the recent developments of the robust controller design methods is the coefficient diagram method (CDM), which is an algebraic approach, wherein the characteristic polynomial along with the controller is simultaneously obtained from the design. A graph on semi-log axis, known as coefficient diagram, is a single tool used to analyze the key features of the system performance namely speed of response, stability and robustness. Although controller design using CDM has been used in many control applications, the method needs to be explored in the field of power system control problems. One of the crucial systems is the automatic voltage regulator (AVR) system. In this paper, a controller based on CDM has been designed for an AVR system and its robustness is analyzed in the presence of parameter variations. Also, the functioning of the system with conventional PID controller is contrasted with the performance of CDM-based controller. The results of the CDM-based controller are found to be better as compared to the former.

Keywords Coefficient diagram method · Equivalent time constant · Robustness · Stability indices · Automatic voltage regulator

✉ Surekha Bhusnur
sbhusnur@yahoo.co.in

[1] Electrical and Electronics Engineering Department, BIT, Durg, Chhattisgarh, India

Introduction

The robust controller design for an AVR system is among the significant interests of the researchers in the area of power system control. It is of paramount importance to maintain a constant voltage level to avoid equipment damage and poor voltage levels. If the voltage of a device violates the limits, the equipment may be unable to operate properly and may get damaged. The PID controller design has been one of the common methods used for controlling the AVR system. Tuning methods involving the Ziegler–Nichols method, soft computing techniques[1], optimization techniques are available in the literature [2–4]. In [5], a PID controller was tuned using particle swarm optimization for AVR system. Using a teaching and learning-based optimization algorithm, PID controller design was proposed in [6, 7] for the AVR system. A novel design method using coefficient diagram method (CDM) for controller design of an AVR system is presented in this paper. The CDM is an algebraic method which gives a robust controller so that the desired system performance is exhibited despite parameter variations [8–11]. A systematic controller design approach using CDM has been described in [12–14].

AVR Schematic

The block diagram of an AVR system [15]can be represented as shown in Fig. 1. The excitation system controls the generator terminal voltage to maintain the flow of the reactive power. The field circuit may be energized using dc generator positioned on the same rotor shaft of the synchronous machine. Advanced equipment utilize rotating rectifiers and the system is known as brush-less excitation

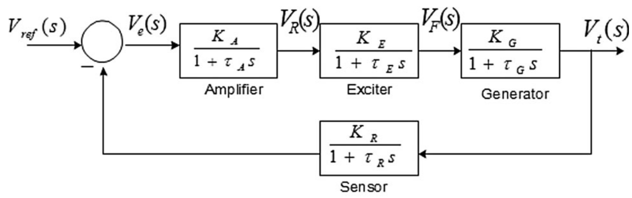

Fig. 1 Block diagram representation of automatic voltage regulator

system. The predominant means of control of reactive power is by controlling the excitation of a generator by means of AVR system. The basic operation of the AVR system is described as follows: Using a potential transformer the voltage magnitude of one phase is obtained, rectified and the disparity with the DC reference signal is assessed. The resulting error is amplified in order to regulate the field current of the exciter to further affect the exciter terminal voltage. Thus, if there is drop in the output voltage sensed by PT, the generator field current is increased that increases the generated EMF.

The transfer function for the open loop of the schematic shown in Fig. 1 is given by

$$\mathrm{AVR}_{\mathrm{openloop}}(s) = \frac{K_A K_E K_G K_R}{(1+\tau_A s)(1+\tau_G s)(1+\tau_E s)(1+\tau_R s)} \tag{1}$$

and the ratio of terminal voltage to the reference voltage is given by the transfer function

$$\frac{V_t(s)}{V_{\mathrm{ref}}(s)} = \frac{K_A K_E K_G (1+\tau_R s)}{(1+\tau_A s)(1+\tau_G s)(1+\tau_E s)(1+\tau_R s) + K_A K_E K_G K_R}. \tag{2}$$

From (2), it is clear that the transfer function is a type 0 system.

AVR System with PID Controller

One of the widely used, popular and commercially used controllers is the PID controller. The PID controller is represented by

$$G_C(s) = K_p + \frac{K_I}{s} + K_D s\,. \tag{3}$$

The transient response is improved by the zero added due to the derivative term and the integral control is used to improve or reduce steady-state error. In an example from [15] existing literature, the parameters involved in an AVR system are as given in Table 1.

The transfer function $G_{\mathrm{cl}}(s)$ of the closed-loop system is given by

$$G_{\mathrm{cl}}(s) = \frac{K_A K_E K_G (K_P s + K_I + K_D s^2)(1+\tau_R s)}{s(K_P s + K_I + K_D s^2)(1+\tau_A s)(1+\tau_E s)(1+\tau_G s)(1+\tau_R s) + K_A K_E K_G K_R}. \tag{4}$$

A Brief Overview of Coefficient Diagram Method

There are mainly three approaches of control design theories, namely classical control approach, algebraic approach and modern control approach. The mathematical expression used are the transfer function, polynomials and the state space matrices, respectively. The transfer function becomes inaccurate when pole–zero cancelations occur. The state space involves extensive machine computations. In the polynomial approach, the numerator and denominator polynomials are handled independently; hence, there is no problem of pole–zero cancelations and also preserves the rigor of state space with the polynomial expression being equivalent to controllable or observable canonical form of state space [8]. Coefficient diagram method belongs to the polynomial approach. In this method, as the controller together with transfer function for the closed-loop system is partly specified, this is known as simultaneous approach and rest of the variables are obtained by design [8, 12]. In CDM, the design parameters are equivalent time constant, stability index and stability limit represented, respectively, as

- τ
- γ_i and
- γ_i^*

In CDM, the performance specifications are rewritten in terms of stability indices γ_i and equivalent time constantτ. Thus, the target characteristic equation is represented in terms of the aforesaid quantities that satisfies stability, performance and are co-related algebraically to controller parameters. A semi-log line diagram known as coefficient diagram is plotted using which the variation in coefficients of the characteristic polynomial can be observed and modified to obtain the desired system response.

Conditions for Stability and Instability in CDM

The schematic block diagram representation for CDM [8] is described as follows:

- Reference input, r
- Plant output, y
- Control input to the plant, u
- Disturbance signal, d
- Numerator polynomial of the plant transfer function, $B_p(s)$

Table 1 Parameters of an AVR System

	Gain	Time constant
Amplifier	10	0.1
Exciter	1	0.4
Generator	1	1
Sensor	1	0.05

- Denominator polynomial of the plant transfer function, $A_p(s)$
- Reference polynomial in the numerator of the controller, $F(s)$
- Feedback polynomial in the numerator of the controller, $B_c(s)$
- Forward polynomial in the denominator of the controller, $A_c(s)$

$B_c(s)$ and $A_c(s)$ are designed to satisfy the desired transient response and $F(s)$ is used to take care of the steady-state error. The output of the whole system is

$$y = \frac{B_p(s)F(s)}{A_{\mathrm{cl}}(s)} r + \frac{A_c(s)B_p(s)}{A_{\mathrm{cl}}(s)} d \tag{5}$$

where $A_{\mathrm{cl}}(s)$ is the characteristic equation of the system and is given by

$$A_{\mathrm{cl}}(s) = A_p(s)A_c(s) + B_p(s)B_c(s) = \sum_{i=0}^{n} a_i s^i \tag{6}$$

$$\sum_{i=0}^{n} a_i s^i = a_n s^n + \cdots + a_1 s + a_0. \tag{7}$$

The definitions of τ, γ_i and γ_i^* are detailed as in[8]; the characteristic equation can be represented as [8, 12, 13]

$$A_{\mathrm{cl}}(s) = a_0 \left[\left\{ \sum_{i=2}^{n} \left(\prod_{j=1}^{i-1} \frac{1}{\gamma_{i-j}^{j}} \right) (\tau s)^i \right\} + \tau s + 1 \right]. \tag{8}$$

The conditions used in CDM for determining stability are as follows [8, 9, 16];

The stability condition for third-order and fourth-order systems is derived from Routh–Hurwitz criterion

$$\gamma_i > \gamma_i^*,\ i = 1, 2, \ldots, (n-1). \tag{9}$$

The sufficient condition of stability for higher-order systems is stated by Lipatov [9] and is given by

$$\gamma_i > 1.12\gamma_i^*, \text{ for any } i, \text{ where } i = 1, 2, \ldots, (n-1). \tag{10}$$

For instability, the sufficient condition is given by

$$(\gamma_{i+1}\gamma_i)^{0.5} < 1, \text{ for some } i, \text{ where } i = 1, 2, \ldots, (n-2)\,. \tag{11}$$

Selection of Stability Index γ_i

The selection of γ_i is very important in the design using CDM. The following properties suggested by Lipatov stability conditions [7, 9, 16] are helpful in the selection of γ_i:

- The ratio $\frac{\gamma_i}{\gamma_i^*}$ may be used as a good measure to indicate degree of stability.
- If all the γ_is are greater than 1.5, the system is stable.
- If all the γ_is are greater than 4, all the roots of characteristic equation are real, negative and distinct.
- Thus, value of stability index γ_i is usually selected in the interval of $1.5 \sim 4$.
- In actual practice, a standard form discussed in the next section is recommended for the choice of γ_i in CDM which gives sufficiently robust and stable design in most of the cases.
- The choice of stability indices can be relaxed as $\gamma_i > 1.5\ \gamma_i^*$ in order to impart more robustness by making some compromise on the stability and performance.

The standard form of CDM stated by Manabe is given by [17]

$$\gamma_1 = 2.5, \quad \gamma_{n-1} = \gamma_{n-1} = \cdots = \gamma_2 = 2. \tag{12}$$

Controller Design Using CDM

The design steps [8] are summarized as follows:

- Represent the numerator and denominator of the plant transfer function in polynomial form.
- Reframe the given performance specifications in terms of design specifications of CDM.
- Express assumed controller configuration in the polynomial form.
- Determine the unknown parameters using Diophantine equation.
- Plot coefficient diagram, cross-check the values of apposite coefficients apt to satisfy the performance specifications and make modifications in their values accordingly.

ITAE-Based Optimal Design of PID Controller

There are many performance indices used for optimal design namely ISE (Integral Square Error), IAE (Integral of Absolute Error), ITAE (Integral Time Absolute Error) and ITSE (Integral Time Square Error). It is known that ITAE has good selectivity, reduces weightage on large initial error and penalizes small errors that occur later in time response heavily [18]. Using ITAE as performance index the controller parameters of PID controller with nominal plant parameters have been obtained using MATLAB. The values obtained are

K_P	K_I	K_D
1.7789	1.9872	0.3836

ITAE-Based Optimal CDM Controller Design for AVR

For designing a CDM-based controller for AVR system, the controller structure has been chosen similar to the PID controller as

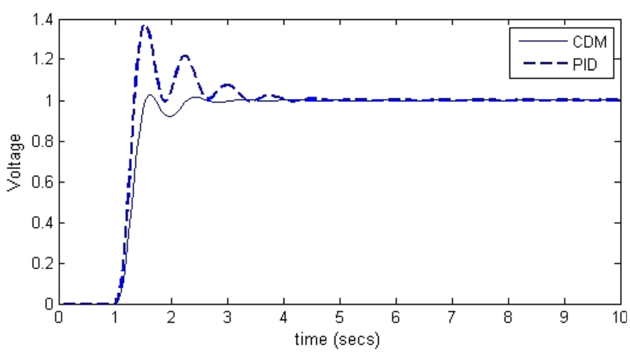

Fig. 2 Nominal plant step responses

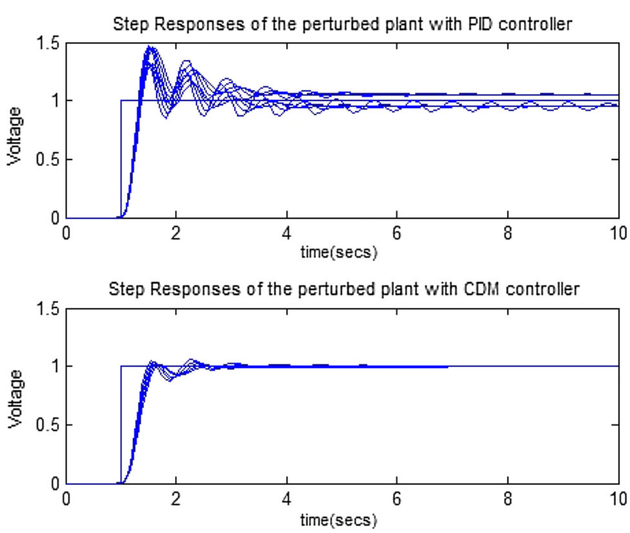

Fig. 3 Perturbed plant step responses

$$G_{\mathrm{CDM}}(s) = \frac{k_2 s^2 + k_1 s + k_0}{l_1 s}. \tag{13}$$

In CDM-based controller design, there is additional advantage that the steady-state error can be independently taken care of and settling time specification can also be incorporated to fix up τ. To get the initial values for optimization, settling time 5 secs (thus $\tau = 2$), $a_0 = 1$ have been used, using (8) and standard Manabe form the initial values were deduced. Further according to the steady-state error requirement, k_0 is evaluated as 0.1. The parameters tuned using ITAE are k_2, k_1 and l_1. Using ITAE as performance index, the controller parameters of CDM controller with nominal plant parameters have been obtained using MATLAB. The values obtained are

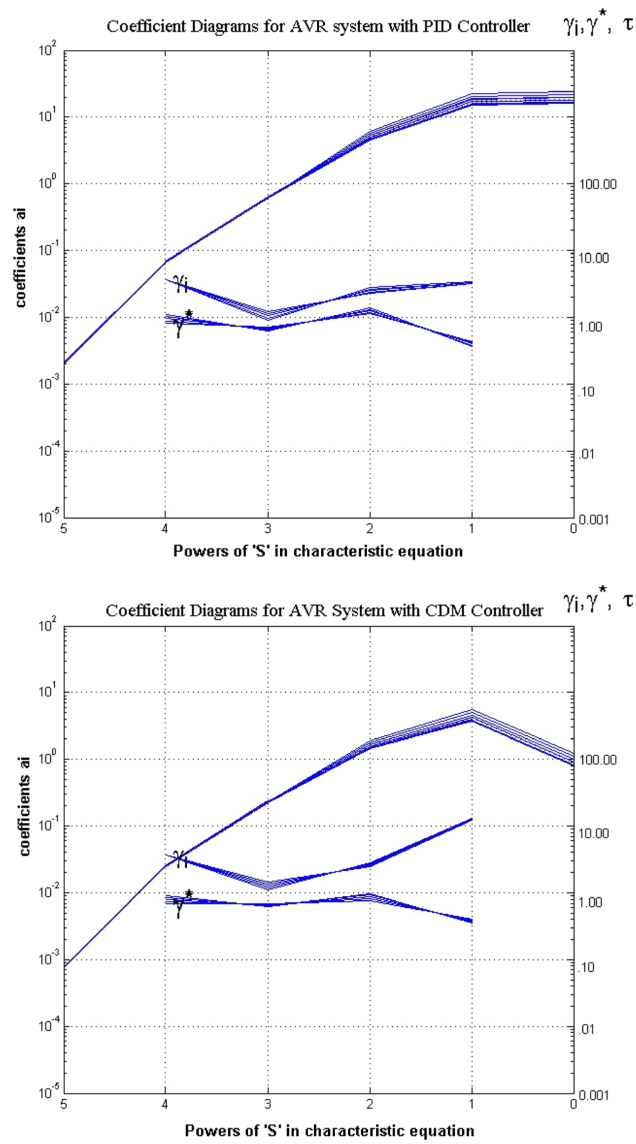

Fig. 4 Coefficient diagrams of the perturbed plant PID and CDM system

k_2	k_1	l_1
0.1088	0.4222	0.3748

The step responses of the nominal plant with PID and CDM-based controllers are shown in Fig. 2.

To investigate robustness of the two controller systems $\pm 5\%$ variation is applied to each of the plant parameters and step responses are obtained in each case. The responses of the sixteen cases of the perturbed plant are shown in Fig. 3, respectively, for PID-based and CDM-based AVR systems. The step responses depict that CDM-based system is more robust than PID system. Also, as the PID controller-based structure is devoid of pre-filter, the responses show steady-state error. However, the pre-filter of the CDM-based control structure resolves the steady-state error.

The coefficient diagrams were obtained for 16 plants only for variations ± 5 percent in the 4 gains namely K_A, K_E, K_G and K_R of the perturbed plant family in both the controller systems as shown in Fig. 4.

For comparison of stability in both the cases, the ratio of stability index and stability limit in each case can be considered (Tables 2, 3).

The comparison of the ratios of the stability index to stability limit in each case of the two systems depicts that the value of the ratios is larger for the CDM controller system than PID controlled AVR system. This indicates that the system with CDM controller is more stable as compared to the AVR system regulated by the PID controller.

Robustness Analysis Using Mikhailov's Theorem

Mikhailov's Stability Criterion

Another simple method to determine robust stability is applying Mikhailov's stability criterion to the overbounding polynomial of the uncertain system.

Mikhailov's stability criterion: A polynomial

$$P(s,q) = q_0 + q_1 s + \cdots + q_n s^n \ , \ q_n > 0$$

is said to be stable if and only if its frequency plot $P(j\omega, q)$ begins on the positive real axis, excludes and makes counterclockwise encirclement of the origin with a phase increment of $n\pi/2$ as ω varies from 0 to ∞.

The construction of overbounding polynomial that uses the monotonicity property of polynomials has been proposed by Kawamura and Shima [19]. The steps involved in determining robust stability using overbounding polynomial and Mikhailov's theorem are

1. Check the monotonicity of the coefficient of $P(s, q)$.

Table 2 Ratio of stability index and stability limit PID system

Sixteen plants of the perturbed plant and the ratio of stability index to limit in the case of PIC controller system				
	$\frac{\gamma_1}{\gamma_1^*}$	$\frac{\gamma_2}{\gamma_2^*}$	$\frac{\gamma_3}{\gamma_3^*}$	$\frac{\gamma_4}{\gamma_4^*}$
Plant1	4.4075	1.701	2.0061	7.2736
Plant2	4.1178	1.6305	2.0011	7.7375
Plant3	4.1178	1.6305	2.0011	7.7375
Plant4	3.8388	1.5623	1.9969	8.2532
Plant5	4.1178	1.6305	2.0011	7.7375
Plant6	3.8388	1.5623	1.9969	8.2532
Plant7	3.8388	1.5623	1.9969	8.2532
Plant8	3.5715	1.4962	1.9934	8.8259
Plant9	4.1178	1.6305	2.0011	7.7375
Plant10	3.8388	1.5623	1.9969	8.2532
Plant11	3.8388	1.5623	1.9969	8.2532
Plant12	3.5715	1.4962	1.9934	8.8259
Plant13	3.8388	1.5623	1.9969	8.2532
Plant14	3.5715	1.4962	1.9934	8.8259
Plant15	3.5715	1.4962	1.9934	8.8259
Plant16	3.3162	1.4321	1.9905	9.4613

2. If coefficients contribute to form monotone polynomials of q then calculate maximum value and minimum value of each coefficient.
3. Construct the overbounding polynomial.
4. Obtain Mikhailov plot, of the image set of overbounding interval polynomial and determine robust stability according to Mikhailov's stability criterion.

The characteristic polynomial in the PID controller-based AVR system is given by

$$A_{PID}(s) = s(1+\tau_A s)(1+\tau_G s)(1+\tau_E s)(1+\tau_R s) + (K_P s + K_I + K_D s^2)K_A K_E K_G K_R \tag{14}$$

and in the case of CDM controller-based AVR system, it is given by

$$A_{\mathrm{CDM}}(s) = l_1 s(1+\tau_A s)(1+\tau_G s)(1+\tau_E s)(1+\tau_R s) + (k_1 s + k_0 + k_2 s^2) K_A K_G K_E K_R. \tag{15}$$

Simplifying (14), the characteristic polynomial in the PID controller-based AVR system is represented as

$$A_{PID}(s) = [a_0^-, a_0^+] + [a_1^-, a_1^+]s + [a_2^-, a_2^+]s^2 + [a_3^-, a_3^+]s^3 + [a_4^-, a_4^+]s^4 + [a_5^-, a_5^+]s^5, \tag{16}$$

where the following definitions hold good

$$\begin{aligned}
a_0 &= 1.9872[K^- \quad K^+] \\
a_1 &= 1.7789[K^- \quad K^+] + 1 \\
a_2 &= (0.3836[K^- \quad K^+] + [\tau_A^- + \tau_G^- + \tau_R^- + \tau_E^- \quad \tau_A^+ + \tau_G^+ + \tau_R^+ + \tau_E^+]) \\
a_3 &= ([\tau_{AE}^- + \tau_{GR}^- + \tau_{AGR}^- + \tau_{EG_R}^- \quad \tau_{AE}^+ + \tau_{GR}^+ + \tau_{AGR}^+ + \tau_{EG_R}^+]) \\
a_4 &= ([\tau_{AEG_R}^- + \tau_{EGR}^- + \tau_{AGR}^- \quad \tau_{AEG_R}^+ + \tau_{EGR}^+ + \tau_{AGR}^+]) \\
a_5 &= [\tau_{AEGR}^- \quad \tau_{AEGR}^+].
\end{aligned} \tag{17}$$

The characteristic polynomial in the CDM controller-based AVR system is represented as

$$A_{\mathrm{CDM}}(s) = [b_0^-, b_0^+] + [b_1^-, b_1^+]s + [b_2^-, b_2^+]s^2 + [b_3^-, b_3^+]s^3 + [b_4^-, b_4^+]s^4 + [b_5^-, b_5^+]s^5, \tag{18}$$

where the following definitions hold good

$$\begin{aligned}
b_0 &= 0.1[K^- \quad K^+] \\
b_1 &= 0.4222[K^- \quad K^+] + 0.3748 \\
b_2 &= (0.1088[K^- \quad K^+] + 0.3748[\tau_A^- + \tau_G^- + \tau_R^- + \tau_E^- \quad \tau_A^+ + \tau_G^+ + \tau_R^+ + \tau_E^+]) \\
b_3 &= (0.3748[\tau_{AE}^- + \tau_{GR}^- + \tau_{AGR}^- + \tau_{EG_R}^- \quad \tau_{AE}^+ + \tau_{GR}^+ + \tau_{AGR}^+ + \tau_{EG_R}^+]) \\
b_4 &= (0.3748[\tau_{AEG_R}^- + \tau_{EGR}^- + \tau_{AGR}^- \quad \tau_{AEG_R}^+ + \tau_{EGR}^+ + \tau_{AGR}^+]) \\
b_5 &= 0.3748[\tau_{AEGR}^- \quad \tau_{AEGR}^+],
\end{aligned} \tag{19}$$

where the parameters have been defined as

Table 3 Ratio of stability index and stability limit CDM system

Sixteen plants of the perturbed plant and the ratio of stability index to limit in the case of CDM controller system				
	$\frac{\gamma_1}{\gamma_1^*}$	$\frac{\gamma_2}{\gamma_2^*}$	$\frac{\gamma_3}{\gamma_3^*}$	$\frac{\gamma_4}{\gamma_4^*}$
Plant1	5.2632	2.1133	3.1571	29.8015
Plant2	4.9486	2.0259	3.0924	31.3996
Plant3	4.9486	2.0259	3.0924	31.3996
Plant4	4.6419	1.9414	3.0322	33.1882
Plant5	4.9486	2.0259	3.0924	31.3996
Plant6	4.6419	1.9414	3.0322	33.1882
Plant7	4.6419	1.9414	3.0322	33.1882
Plant8	4.3443	1.8596	2.9764	35.185
Plant9	4.9486	2.0259	3.0924	31.3996
Plant10	4.6419	1.9414	3.0322	33.1882
Plant11	4.6419	1.9414	3.0322	33.1882
Plant12	4.3443	1.8596	2.9764	35.185
Plant13	4.6419	1.9414	3.0322	33.1882
Plant14	4.3443	1.8596	2.9764	35.185
Plant15	4.3443	1.8596	2.9764	35.185
Plant16	4.0568	1.7804	2.9248	37.4102

Table 4 Coefficients of overbounding characteristic polynomials

Coeff.	PID system	Coeff.	CDM system
a_0	[15.8976 23.8464]	b_0	[0.8000 1.2000]
a_1	[15.2312 22.3468]	b_1	[3.7524 5.4412]
a_2	[4.1788 6.5932]	b_2	[1.2864 2.0515]
a_3	[0.2079 0.9281]	b_3	[0.0779 0.3478]
a_4	[0.0200 0.1519]	b_4	[0.0075 0.0569]
a_5	[0.0004 0.0060]	b_5	[0.0001 0.0023]

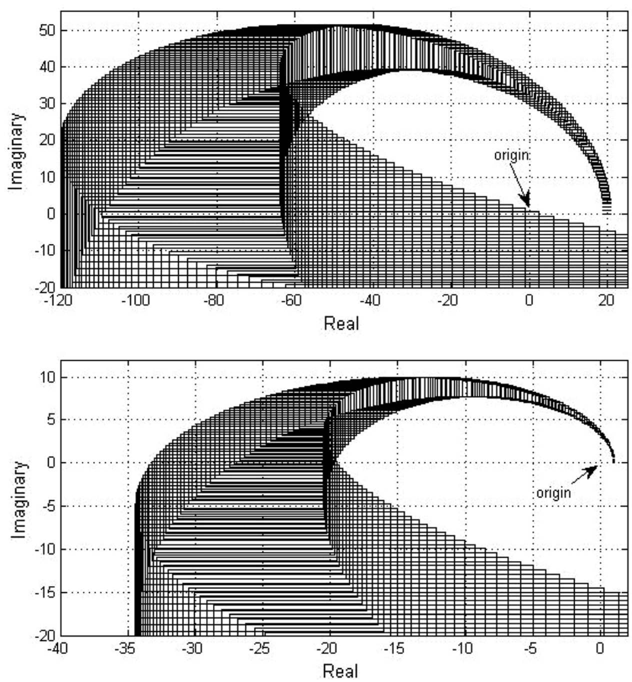

Fig. 5 Mikhailov's plot for PID controller-based and CDM controller-based AVR

$$
\begin{aligned}
K &= K_A K_E K_G K_R \\
\tau_{AEGR} &= \tau_A \tau_E \tau_G \tau_R \\
\tau_{AEG_R} &= \tau_A \tau_E (\tau_G + \tau_R) \\
\tau_{EG_R} &= \tau_E (\tau_G + \tau_R) \\
\tau_{EGR} &= \tau_E \tau_G \tau_R \\
\tau_{AGR} &= \tau_A \tau_G \tau_R \\
\tau_{AE} &= \tau_A \tau_E \\
\tau_{GR} &= \tau_G \tau_R .
\end{aligned} \tag{20}
$$

The coefficients of the overbounding characteristic polynomials in both the cases are calculated and compiled in Table 4. Also, Mikhailov's plot in each case for overbounding characteristic polynomial has been obtained to investigate robustness. The plot shown in Fig. 5 corresponds to AVR system with PID controller and CDM controller. The image set plot of PID system embraces the origin whereas for the same perturbation the CDM-based system clearly excludes the origin. It is clearly observed that CDM-based system is robustly stable as compared to PID controller-based system.

Conclusions

In this paper, a robust controller has been designed for an AVR using coefficient diagram method. The controller parameters have been obtained by minimizing ITAE. The results of AVR system controlled by the optimal CDM-based controller have been compared with the results of AVR system with a PID controller whose parameters also have been tuned using ITAE criterion. The step responses and the coefficient diagrams in both the cases have been plotted, the ratios of stability index to stability limit have been listed for each plant of the perturbed family of plants in both the cases. Also, to compare robust stability, overbounding interval polynomial has been constructed and the corresponding Mikhailov's plot of the image set of the overbounding polynomial in each case has been obtained. The results depict superior performance of CDM controller-based AVR system than the conventional PID controller system.

References

1. S. Pandaa, B.K. Sahu, P.K. Mohanty, Design and performance analysis of PID controller for an automatic voltage regulator system using simplified particle swarm optimization. J. Franklin Inst. **349**, 2609–2625 (2012)
2. C. Wong*, S. Li, H. Wang, Optimal PID controller design for AVR system. Tamkang J. Sci. Eng. **12**(3), 259–270 (2009)
3. K. Heong Ang, G. Chong, PID control system analysis, design and technology. IEEE Tran. Control Syst. Technol. **13**(4), 559–576 (2005)
4. Z.L. Gaing, A particle swarm optimization approach for optimum design of PID controller in AVR system. IEEE Trans. Energy Convers. **19**(2), 384–91 (2004)
5. S. Chatterjee, V. Mukherjee, Design of PID controller in automatic voltage regulator (AVR) system using PSO technique. IJERA **77**, 418–429 (2013)
6. V. Rajinikanth, S.C. Satapathy, Design of controller for automatic voltage regulator using teaching learning based optimization. Procedia Technol. **21**(3), 295–302 (2015)
7. S. Bhusnur, Effect of stability indices on robustness and system response in coefficient diagram method. IJRET: Int. J. Res. Eng. Technol. **4**(10), 282–287 (2015)
8. S. Manabe, Coefficient Diagram Method, in *Proc. 14th IFAC Symposium on Automatic Control in Aerospace, Seoul, Korea* (1998)
9. S. Manabe, Sufficient condition for stability and instability by Lipatov and its application to the coefficient diagram method, in

Proceedings of 9th Workshop on Astrodynamics and Flight Mechanics, Sagamihara, ISAS, July 22–23 (1999)
10. S. Bhusnur, S. Ray, Robust control of integrating systems using CDM-based two-loop control structure. Int. J. Reliab. Saf. **5**(3–4), 250–269 (2011)
11. S. Bhusnur, S. Ray, Robust performance of a stable and an unstable interval plant in the two loop model following control structure. J. Inst. Eng. (India) Ser. B **93**(2), 81–90 (2012)
12. Y. C. Kim, S. Manabe, Introduction to coefficient diagram method, in *Proceedings of the SSSC'01*, Prague (2001)
13. M. Koksal, S.E. Hamamci, A program for the design of linear time invariant control systems: CDMCAD. Wiley Periodicals, Inc. Comput. Appl. Eng. Educ. **12**, 165–174 (2004)
14. T.V. Dixit, N. Rajak, S. Bhusnur, S. Ray, CDM controller design for non-minimum unstable higher order system. Smart Innovation, Systems and Technologies, in *Proceedings of the 1st International Conference on Computational Intelligence in Data Mining, ICCIDM 2014*; Sambalpur; India; 20–21 December 2014 **33**, 417–428 (2015)
15. H. Saadat, *Power System Analysis* (Tata McGraw Hill Ltd, New Delhi, 2002)
16. S. Manabe, Brief tutorial and survey of coefficient diagram method, in *Proceedings of the 4th Asian Control Conference, Singapore* (2002)
17. S. Manabe, A solution of the ACC benchmark problem by coefficient diagram method, in *Proceedings 2nd Asian Control Conference, July 22–25, Seoul, II-135-138* (1997)
18. I.J. Nagrath, M. Gopal, *Control Systems Engineering* (New Age International Publishers, Chennai, 2000)
19. T. Kawamura, M. Shima, Robust stability analysis of characteristic polynomials whose coefficients are polynomials of interval parameters. J. Math. Estim. Control **6**(4), 1–12 (1996)