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A Hybrid Approach for Model Order Reduction of A MIMO System

[1]Naman Ku Sanger, [2]Monika Mittal
Dept. of Electrical Engineering
National Institute of Technology Kurukshetra, India
[1]naman_32114114@nitkkr.ac.in, 2monika_mittal@nitkkr.ac.in

Abstract-In this paper, a hybrid model order reduction strategy is proposed to obtain the reduced order model of a multiple input multiple outputs (MIMO) power system. . The proposed hybrid technique involves the use of Routh approximation and factor division approach for the denominator and numerator polynomials, respectively. The proposed technique preserves pivotal parameters such as stability & initial time moments of the higher-order model after reduction. The effectiveness of the proposed method is compared with the existing methods using Integral square error (ISE). Also, reduction in computational time is achieved by the proposed approach as observed from the MATLAB profiler.

1. INTRODUCTION

Engineering solution of a problem usually entails its mathematical modeling at the first stage. Systems in electrical, electronics, and mechanical, are increasingly becoming complicated nowadays that result in their higher order mathematical models such as differential equations or transfer functions. These higher-order models involve significantly higher computations, time and cost during their analysis, design, simulation and implementation. Therefore, there is a need of reducing these orders to reduce the overall costs incurring on account of higher computations and time while retaining the fundamental characteristics of the original system. Reduced order modeling has emerged as a crucial technique in the thriving engineering disciplines of fluid dynamics, power systems, and control systems. The following requirement are essential to generate a good reduced order model of a large-scale system:

(i) Preservation of fundamental characteristics such as stability of higher order systems.
(ii) Good approximation of higher order system to ensure less error.
(iii) Reduction algorithm should be computationally easy and efficient.

Numerous researchers have reported various strategies for model reduction that can be generally divided into two categories: classical reduction methods and stability preservation methods.

Mathematical approximation is the foundation of the classical reduction approach. Some of the most prominent of them are Pade approximation[1], moment matching[2], and factor division[3]. These are suitable for matching initial time moments of the reduced order model with that of the original model. But these approaches more often than not result in the derived reduced order models that are unstable in spite of the stable original systems [4].

Stability preservation methods thus came into picture. Some of the most of them are are Routh stability [5], Routh approximation [6], Pole clustering method[7]. Minimum and non-minimum higher order systems complexity can be reduced using the pole clustering approach but with certain drawbacks, such as the necessity for gain and tuning factors to match the static and dynamic behavior of the reduced and original systems, respectively. The Routh stability approach is appropriate for matching the diminished model's Markov characteristics with the original system resulting in matching of their transient responses but this becomes ineffective when pole-zero cancellation takes place [8]. Hutton and Friedland [6] and Papadopoulos and Bandekas [9] suggested a technique called Routh approximation for SISO and MIMO systems, respectively. In this approach, two tables (α-table, β-table) must be created with the Routh Hurwitz table utilized for α-table. However, formulation of β-table is complex. Big disadvantage of these methods is that they lack accuracy in approximating the higher order systems.

The above shortcomings of both Stability Preservation and Classical reduction methods can be overcome by using Hybrid reduction methods. Here, the techniques that can ensure stability are used to determine the denominator polynomial and those from the classical approach are used to determine the numerator polynomial. Thus, the stability of the reduced order model is ensured while keeping the approximation error less [10], [11], [12].

Power systems are a good example of a higher order MIMO system that involves multivariate processes running continuously in dynamic environments. Analysis of such large interlinked MIMO system is very time-consuming and computationally -intensive that may even surpass the storage capacity of contemporary, fast computers. Also, complexity of the such a system makes it challenging to get in-depth knowledge of its behaviour. These challenges can be overcome by reducing the order of such systems.

Therefore, in this paper, a hybrid model reduction strategy is proposed to obtain the reduced model of the MIMO power system model. In the proposed approach, the denominator polynomial of the reduced order model is computed by Routh approximation and its numerator polynomial is determined by using factor division. Hence, this method ensures stability of the reduced order model for the stable higher order system as guaranteed by Routh approximation method. Additionally, the initial time moments of actual model are preserved in the diminished model as guaranteed by the factor division method resulting in matching of both their transient & steady-state responses. [13]. Thus, respective benefits of both the methods are harnessed in the proposed approach. Also, the proposed approach is less complex than the Routh approximation approach as it needs only straightforward Routh table in place of the beta table. The resulting Integral square error (ISE) is also less [14] leading to close match between their responses.

This paper is organized as; MIMO power system model is described in section 2 in detail. Fundamental steps of the proposed approach are discussed in section 3. In section 4, the original and its reduced versions are analyzed followed by conclusions in section 5.

2. PROBLEM FORMULATION

Consider an electric power system with a salient-pole synchronous generator connected to an infinite bus bar as given in [17], [15]. There, a very accurate non-linear state-space mathematical model was developed using the well-known transmission line & synchronous machine performance equations. From the q-d equivalent circuit, A set of winding currents was selected as state variables of the electrical section of the synchronous machine using its q-d equivalent circuit. The 7th order state vector of the original system consists of field current i_{fd}, damping currents i_{kq}, i_{kd}, stator currents i_d, i_q, and associated mechanical quantities viz. δ, ω.

The input vector includes two parameters viz. the mechanical torque T_m and the voltage V_f. The machine terminal voltage, power angle, and speed parameters have been selected as output variables as mentioned below.

Input 1: ΔT_m which represents changes in mechanical torque

Input 2: ΔV_f which represent the changes in field voltage

Output 1: ΔV_t which represents changes in terminal voltage

Output 2: $\Delta\delta$ which represents change in power angle

Output 3: $\Delta\omega$ which represent change in speed

Ramamoorty and Arumugan [18] developed a linear model by taking into account minor deviations (Δ) near the operating point in the steady state. Corresponding state-space representation of the linearized model S(A, B, C) is

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -52.08 & -23.54 & 9.415 & -23.54 & -99.2 & 27.8 \\ -541.2 & 0.6953 & -2.216 & -36.23 & 24.15 & 664.2 & -362.3 \\ -1136 & 1.46 & -0.664 & -76.08 & -12.08 & 1395 & -760.8 \\ -541.2 & 0.6953 & -2.216 & -36.23 & 24.15 & 664.2 & -362.3 \\ 398 & 3.403 & 879.1 & -1346 & 897.1 & -53.83 & -29.91 \\ 298.5 & 2.552 & 672.9 & -1009 & 672.9 & -40.37 & -35.89 \end{bmatrix}$$
(1)

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 52.08 \\ 2.121 & 0 \\ 0.6642 & 0 \\ -1.328 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -0.17 & 0 & 0 & 0.3018 & 0 & -0.0375 & 0 \end{bmatrix}$$

MIMO transfer function of state space representation is

$$G(s) = \frac{1}{D(s)} \begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \\ N_{31} & N_{32} \end{bmatrix}$$
(2)

where,

$$D(s) = s^7 + 258.64s^6 + 430959s^5 + 48281341s^4 + 1844291625s^3 + 2.50 \times 10^{10}s^2 + 5.46 \times 10^{10}s + 1.18 \times 10^{10}$$

$$N_{11}(s) = -12.41377s^4 + 12124.7928s^3 - 2881410.04s^2 - 336887170.06s - 6506657015.653$$

$$N_{12}(s) = 52.08s^5 + 10758.478s^4 + 21869382.1s^3 + 1373714674.95s^2 + 21862117031.65s + 16563848167.052$$

$$N_{21}(s) = 12.41377s^5 + 12124.7928s^4 - 2881410.04s^3 - 336887170.06s^2 - 6506657015.653s$$

$$N_{22}(s) = 52.08s^6 + 10758.478s^5 + 21869382.1s^4 + 1373714674.95s^3 + 21862117031.65s^2 + 16563848167.052s$$

$$N_{31}(s) = 0.2004556s^6 + 47.86274s^5 + 39267.896s^4 + 5153949.74s^3 + 231384193.179s^2 + 3482982404s + 5467885491.0124$$

$$N_{32}(s) = 7.453455s^5 + 27013.4259s^4 + 868109.387s^3 - 16222929.178s^2 - 632247763.066s - 8357195607.8251$$

The order of the MIMO transfer function in (2) is 7 and hence, its analysis is quite difficult. Consequently, a model reduction technique is required to obtain its reduced order model. The proposed hybrid model order reduction technique is described in the next section.

3. PROPOSED HYBRID MODEL ORDER REDUCTION TECHNIQUE

The proposed hybrid model order reduction technique consists of two steps for determining .

(i) denominator polynomial using Routh approximation method.

(ii) numerator polynomial using factor division method.

The details are described in next subsections.

3.1 Computation of denominator polynomial of the r^th^ Order Reduced Model

Routh approximation approach is proposed to be used for determining the denominator polynomial as described next.

(i) Obtain reciprocal of the denominator polynomial of the original system as

$$\widetilde{D}(s) = s^n \, D\left(\frac{1}{s}\right)$$
(3)

(ii) Coefficients of $\widetilde{D}(s)$ are used to then develop the alpha table to find $\alpha_1, \alpha_2 \ldots\ldots \alpha_r$ parameters as shown in Table 1

Assuming $\widetilde{D}(s) = c_0 + c_1 s + c_2 s^2 + \text{--------} + c_n s^n$ (4)

The alpha table can be formulated as

	$c_0^0 = c_0$	$c_2^0 = c_2$	$c_4^0 = c_4$	$c_6^0 = c_6$	----
	$c_0^1 = c_1$	$c_2^1 = c_3$	$c_4^1 = c_5$	----	
$\alpha_1 = \frac{c_0^0}{c_0^1}$	$c_0^2 = c_2^0 - \alpha_1 c_2^1$	$c_2^2 = c_4^0 - \alpha_1 c_4^1$	$c_4^2 = c_6^0 - \alpha_1 c_6^1$	----	
$\alpha_2 = \frac{c_0^1}{c_0^2}$	$c_0^3 = c_2^1 - \alpha_2 c_2^2$	$c_2^3 = c_4^1 - \alpha_2 c_4^2$	----		
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Table 1: alpha table

(iii) r^{th} order polynomial is then obtained using

$$\tilde{P}_r(s) = \alpha_r s \tilde{P}_{r-1}(s) + \tilde{P}_{r-2}(s), \qquad r = 1, 2, \dots \quad (5)$$

With $\tilde{P}_0(s) = \tilde{P}_{-1}(s) = 1$

(iv) denominator polynomial $P_r(s)$ of the reduced order model is obtained using reciprocal of $\tilde{P}_r(s)$ in (5) as

$$P_r(s) = s^r \tilde{P}_r\left(\frac{1}{s}\right) \quad (6)$$

Next the procedure for determining the numerator polynomial of the reduced order model is described.

3.2 Computation of the r^th Order Reduced Model's Numerator Polynomial

Factor division approach is utilized to calculate the numerator of the reduced model. Before that, comparison of the reduced system's transfer function with original system's transfer function must be done as explained below.

Original transfer function: $G(s) = \frac{N(s)}{D(s)}$ (7)

Reduced transfer function: $R(s) = \frac{Q_r(s)}{P_r(s)}$ (8)

After comparison of Eqn. 7 and Eqn. 8

$$Q_r(s) = \frac{N(s)}{D(s)} \times P_r(s) \quad (9)$$

$$Q_r(s) = \frac{b_0 + b_1 s + b_2 s^2 + \dots + b_{r-1} s^{r-1} + \dots + b_{n+r-1} s^{n+r-1}}{c_0 + c_1 s + c_2 s^2 + \dots + c_{n-1} s^{n-1} + c_n s^n} \quad (10)$$

Reduced numerator $Q_r(s)$ is power series expansion of $\frac{N(s)}{D(s)} \times P_r(s)$ about s = 0 and for calculation of this moment generating algorithm given in [19] can be used. This algorithm makes sure that the initial "r" time moments of the actual model are preserved in the diminished structure and it is shown in Eqn. 11.

$$q_0 = \frac{b_0}{c_0} \begin{cases} b_0 & b_1 & b_2 & \dots & b_{r-1} \\ c_0 & c_1 & c_2 & \dots & c_{r-1} \end{cases}$$

$$q_1 = \frac{w_0}{c_0} \begin{cases} w_0 & w_1 & w_2 & \dots & w_{r-2} \\ c_0 & c_1 & c_2 & \dots & c_{r-2} \end{cases}$$

$$q_2 = \frac{x_0}{c_0} \begin{cases} x_0 & x_1 & x_2 & \dots & x_{r-3} \\ c_0 & c_1 & c_2 & \dots & c_{r-3} \end{cases} \quad (11)$$

$\vdots$

$$q_{r-2} = \frac{y_0}{c_0} \begin{cases} y_0 & y_1 \\ c_0 & c_1 \end{cases}$$

$$q_{r-1} = \frac{z_0}{c_0} \begin{cases} z_0 \\ c_0 \end{cases}$$

where,

$$w_i = b_{i+1} - q_0 c_{i+1}, \qquad i = 0, 1, \dots\dots, r-2$$

$$x_i = w_{i+1} - q_1 c_{i+1}, \qquad i = 0, 1, \dots\dots, r-3$$

:

$$z_0 = y_1 - q_{r-2} c_1,$$

Thus, numerator of reduced model is

$$Q_r(s) = q_0 + q_1 s + q_2 s^2 + \dots\dots + q_{r-1} s^{r-1} \quad (12)$$

Reduced model numerator polynomial can be evaluated by utilizing the above mention approach.

Hence, hybrid reduced model can be computed in which denominator polynomial is computed by approach given in section 3.1 and its numerator polynomial is computed by approach given in section 3.2.

3.3 Development Of 2nd Order Reduced Model For 7th Order MIMO Power System Model

Now by using the model reduction technique discussed in this section, 7^{th} order MIMO power system model is diminished into 2^{nd} order MIMO model as depicted in Eqn. 13.

$$R(s) = \frac{1}{P_r(s)}\begin{bmatrix} Q_{r11} & Q_{r12} \\ Q_{r21} & Q_{r22} \\ Q_{r31} & Q_{r32} \end{bmatrix} \quad (13)$$

Where,

$P_r(s) = s^2 + 2.21938437s + 0.4796472$

$Q_{r11} = -0.013693813s - 0.264483019$

$Q_{r12} = 0.888652765s + 0.673288382$

$Q_{r21} = -0.264483019s$

$Q_{r22} = 0.673288382s$

$Q_{r31} = 0.141576497s + 0.222258966$

$Q_{r32} = -0.02569965s - 0.339703833$

After the development of reduced order model, in the next section its performance is analyzed with the original higher order model.

4. RESULT AND DISCUSSION

In this section analysis of higher order model and its reduced model is performed.

Considering the transfer function of $G_{11}(s) = \frac{N_{11}}{D(s)}$ and $R_{11}(s) = \frac{Q_{r11}}{P_r(s)}$

$$G_{11}(s) = \frac{-12.41377s^4 + 12124.7928s^3 - 2881410.04s^2 - 336887170.06s - 6506657015.653}{s^7 + 258.64s^6 + 430959s^5 + 48281341s^4 + 1844291625s^3 + 2.50\times10^{10}s^2 + 5.46\times10^{10}s + 1.18\times10^{10}}$$

$$= -0.5514 + 2.522897s - 10.505743s^2 + \cdots\cdots \quad (14)$$

$$R_{11}(s) = \frac{-0.013693813s - 0.264483019}{s^2 + 2.21938437s + 0.479647171} \quad (15)$$

$$= -0.5514 + 2.5228972s - 10.52413s^2 + \cdots\cdots \quad (16)$$

From Eqn. 15, it is concluded that $R_{11}(s)$ is stable, so key feature of the Routh approximation, to conserve stability is maintained in this technique.

The initial time moments of the diminished model must be matched with the original system in order to correctly match the steady state responses & transient responses of the original & its diminished model, as mentioned in [13]. Eqn. 14 and Eqn. 16 represent the time moments of actual system & reduced system respectively. From Eqn. 14 & 16, it's observed that initial two-time moments of the actual system are retained in its diminished model. As a result, the factor division technique's property of retaining time moments is maintained.

In Fig. 1 to Fig. 6 step responses of actual & its reduced model are plotted and comparison based on time domain parameter is enlisted in Table 2. From Step response Fig. 1 to Fig. 6 and time domain parameters data Table 2, it is found that the responses of actual & diminished systems are quite comparable.

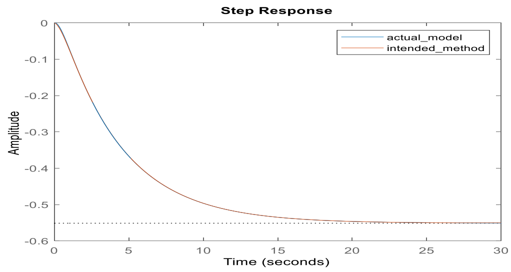

Fig. 1: Step response plot of original $G_{11}(s)$ & its diminished model $R_{11}(s)$

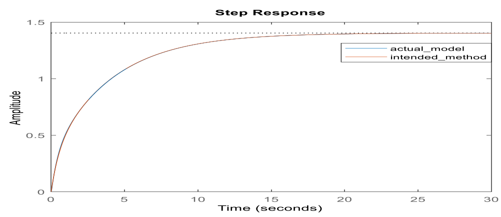

Fig. 2: Step response plot of original $G_{12}(s)$ & its diminished model $R_{12}(s)$

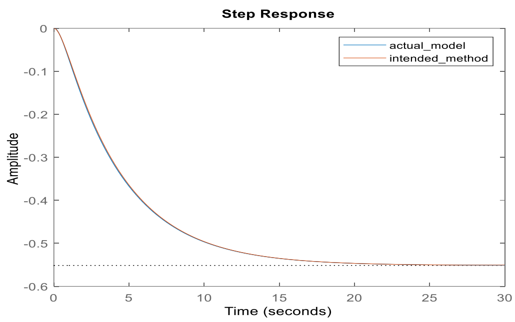

Fig. 3: Step response plot of original $G_{21}(s)$ & its diminished model $R_{21}(s)$

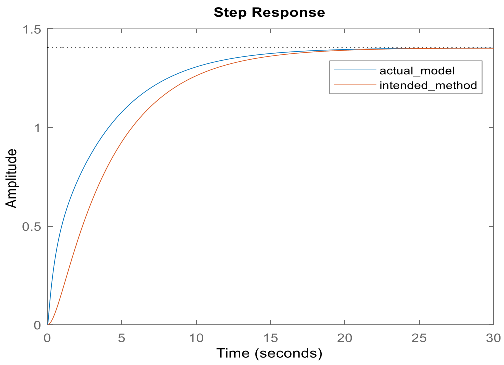

Fig. 4: Step response plot of original $G_{22}(s)$ & its diminished model $R_{22}(s)$

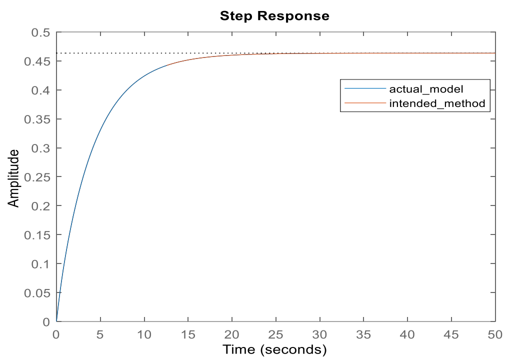

Fig. 5: Step response plot of original $G_{31}(s)$ & its diminished model $R_{31}(s)$

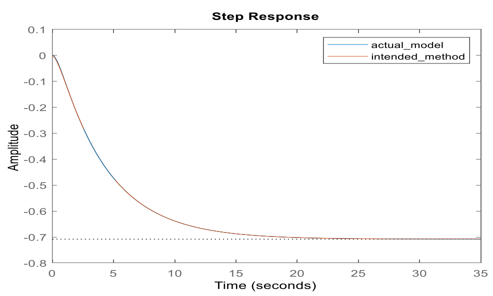

Fig. 6: Step response plot of original $G_{32}(s)$ & its diminished model $R_{32}(s)$

	Rise time	**Peak value**	**Peak time**	**Settling time**
$G_{11}(s)$	9.1347	0.5511	31.7375	16.6028
$R_{11}(s)$	9.1705	0.5505	26.9777	16.6101
$G_{12}(s)$	8.2806	1.4028	29.4124	15.0933
$R_{12}(s)$	8.2591	1.4013	25.1140	15.0712
$G_{21}(s)$	9.1347	0.5511	31.7375	16.6028
$R_{21}(s)$	9.1712	0.5505	26.9777	16.6622
$G_{22}(s)$	8.2806	1.4028	29.4124	15.0933
$R_{22}(s)$	9.1712	1.4014	26.9777	16.6622
$G_{31}(s)$	8.9787	0.4634	52.9652	15.9754
$R_{31}(s)$	8.9736	0.4634	52.9514	15.9707
$G_{32}(s)$	9.1348	0.7082	37.9377	16.5789
$R_{32}(s)$	9.1696	0.7071	26.9777	16.5858

Table 2: Comparison of original & its reduced model based on time domain parameters

To assess the usefulness and efficiency of the intended reduction approach with other model reduction methods, ISE between actual model & its diminished model is evaluated using Eqn. 16.

$$ISE = \int_0^{\infty} [y(t) - y_r(t)]^2 dt \quad (16)$$

where y(t) and $y_r(t)$ represent step responses of actual & diminished system respectively.

Table 3 compares the intended reduction method & other model reduction strategies in terms of ISE. Table 3 clearly shows that the intended method has lower ISE value, and lower values of ISE indicate that the time response of the diminished model accurately resembles the response of the actual system.

Table 3: ISE comparison between intended and other reduction techniques.

	Integral Square Error (ISE)					
	G_{11}	G_{12}	G_{21}	G_{22}	G_{31}	G_{32}
A. K. Prajapati and R. Prasad[12]	3.422×10^{-5}	0.003759	1.166×10^{-4}	0.3425	2.839×10^{-5}	5.672×10^{-5}
Sambariya[15]	1.05×10^{-5}	0.003455	9.752×10^{-5}	0.3708	2.264×10^{-5}	0.00381
Intended method	1.055×10^{-5}	0.001401	8.492×10^{-5}	0.3686	4.338×10^{-7}	1.581×10^{-5}

The actual MIMO system $G(s)$ is of 7th order and the order of its reduced system $R(s)$ is 2. It is clearly evident from Fig. 1-6 and Table 2 that performance of $G(s)$ and $R(s)$ is quite identical but computational time is more in the former as demonstrated in Fig.7 by using MATLAB Profiler. Therefore, the use of 2nd order $R(s)$ is preferred over $G(s)$ to reduce the computational time significantly as shown in Fig.7.

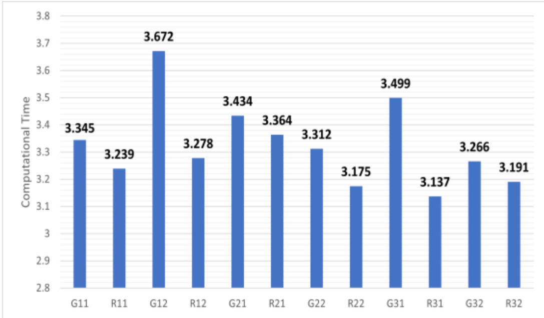

Fig. 7: Computational time comparison between original higher-order model & its diminished model.

5. CONCLUSION

In this paper, a hybrid approach for model order reduction is proposed to obtain reduced model of MIMO power system model. Here, Routh approximation & factor division algorithms have been successfully utilized to obtain denominator and numerator polynomials of the reduced order model, respectively. The order of the reduced model is 2 as against 7 of that of the original complex model. A close match of the step responses of both reduced and original systems has been observed. Also the time response parameters for both are summarized in Table 2. It can be clearly observed that these values are in close agreement demonstrating that the reduced order model accurately represents the original system. Additionally, the lesser values of ISE given in Table 3 establishes effectiveness of the proposed approach. The advantage of the proposed approach in terms of reduction of the computational time is clearly demonstrated in Fig.7.

Some excellent features of given hybrid techniques are

I. Preservation of higher order system's stability.
II. Preservation of initial "r" time moments in rth order reduced model to ensure perfect matching of responses of higher and it's reduced model.
III. Overcoming the complexity of Routh approximation method by not calculating β-table.

Further this hybrid method can be readily used for controller design for higher order processes using their reduced order models.

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