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**Salik Ram Dewangan, P.D.Dewangan, V.P.Singh**

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# An Approximation of Higher-Order Interconnected Power System Model Using Direct Truncation Approach

Salik Ram Dewangan [1], P.D.Dewangan [1], V.P.Singh [2]

[1]Department of Electrical Engineering, National Institute of Technology, Raipur,Chhattisgarh, India
[2]Department of Electrical Engineering, Malaviya National Institute of Technology, Jaipur,Rajasthan, India

**ABSTRACT**

The higher-order single-area interconnected power system model is reduced to a comparatively lower order in this article. The model of interconnected power system with hydro, thermal and gas electric power plant is constructing the overall 11$^{th}$ order higher-order system(HOS) by integrating all the system dynamics. This HOS is reduced to 2$^{nd}$ ,3$^{rd}$,4$^{th}$ , and 5$^{th}$ –order models in this article. These models are proposed by employing truncation-based order reduction method. To demonstrate the suitability of the proposed reduced order models (ROMs), a comparative analysis between HOS and ROM is also done. The stability analysis is presented by tabular representation of time specifications and indices of error. The stability analysis is also shown for the same by Bode plot. MATLAB/Simulink is used of obtain responses.

**KEYWORDS**
Approximation, Direct truncation, Reduced-order modelling, Stability

## 1. INTRODUCTION

The power system is made up of three distinct components: distribution, transmission, and generation, each with its own set of auxiliary components. The order of the system is increased by combining thermal and gas electric power plants with renewable energy sources (wind, hydro, PV arrays, etc.). The complexity of the power system is further increased by this integration. For the synthesis, analysis, and modelling of higher order systems (HOS), a reduced order model (ROM) is advised rather than a higher order system (HOS) due to the complexity of HOSs. Most of the attributes of HOS can be kept by proposing a lower-order model using an order reduction technique [1]. Model order reduction (MOR) aims to replace a complex system description with a more straightforward approximation model that faithfully captures the core components of the original system [2].

The literature has introduced a number of MOR methods for higher-order power system models. The direct Routh approximation method is used by Khokhar et al. in [3] to reduce an eight-order autonomous microgrid (MG) model to a third-order model. In [4], Chaniotis et al. employ a balanced truncation strategy with an expanded Krylov subspace approach to decrease the order of a large-scale power systems model.Bashir et al. In [5] use frequency-weighted MOR approach to lower the order of the variable-speed wind turbine-based power system model. A massive power system model's order is reduced using a dynamic clustering-based technique by Ranjbar et al. in [6]. In [7], Yadav et al. investigated the approximation of a higher-order 19$^{th}$-order power system model of multi-input multi-output based on Sylvester. Parameters of Time-moments and Markov are utilised for finding lower order model from higher order system. Additionally, there are a different mixed approaches in the literature [8-24]. Additionally, order reduction has also been accomplished using optimisation approaches including the genetic algorithm, particle swarm optimisation, and grey wolf optimisation, big bang big crunch optimization, sine cosine algorithm and Cuckoo Search algorithm [25–34].

This study examines a 11th-order single area power system model. The governor, reheat turbine, and thermal turbine are the parts of the thermal system. A hydro governor, droop controller, and hydro turbine are included in a hydro system. The position of valve, gas governor, fuel system, and system of compressor discharge are also components of the gas-electric system. The transfer functions for each model component serve as a representation [35].In this work, the direct truncation approach is employed to generate a ROM for a high-order power system model.

This article is structured as follows: In Section II, the problem description is presented after considerations of the direct truncation method for lower order modelling. The higher-order linked power system concept is represented in Section III. Section IV then demonstrates how to employ a straightforward truncation approach to lower the provided 11th-order. The findings and comments on them are presented in Section V. The work that has been completed is summarized in section VI.

## 2. PROBLEM DESCRIPTION

### 2.1 Demonstration of Higher-Order System and its Reduced Order Model:

Consider the following for the higher-order system's (HOS) transfer function:

$T_n(s) = a(s)/h(s)$

$$= \frac{a_0 + a_1s + a_2s^2 + \cdot\cdot\cdot + a_{n-1}s^{n-1}}{h_0 + h_1s + h_2s^2 + \cdot\cdot\cdot + h_ns^n} \quad (1)$$

where the numerator's coefficients $a_i$ for i = 0, 1, 2,..., (n -1) are defined.

Coefficients $h_i$ for i = 0, 1, 2,..., n also displays HOS denominator coefficients.

It is desired to reduce the system of order n shown in (1) to a model of order r. Order in this concept of lower order is such that r > n.

Consider the following $r^{th}$ order model:

$T_r(s) = b(s)/l(s)$

$$\frac{b_0 + b_1s + b_2s^2 + \cdot\cdot\cdot + b_{r-1}s^{r-1}}{l_0 + l_1s + l_2s^2 + \cdot\cdot\cdot + l_rs^r} \quad (2)$$

Coefficients $l_i$ for i = 0,1,2,...,r show denominator coefficient of the model as given in (2), and coefficients $b_i$ are defined for i = 0, 1, 2,.., (r -1) for the numerator.

A suitable lower order modelling method can be used to determine the r order model as stated in (2). In this study, a truncation-based reduction strategy is used to achieve the $r^{th}$ order model. The next part describes in detail how to obtain a $r^{th}$ order model for an $n^{th}$ order system.

### 2.2 : Direct Truncation based reduction approach:

One of the simplest approaches for reducing HOSs to comparatively lower order models is the direct truncation-based reduction strategy. This truncation method reduces the order of the HOS by removing the higher-order terms from the numerator and denominator without changing any of the reported HOS's coefficients [20].

As seen in (1), the transfer function of higher order system of order n is rewritten as

$T_n(s) = a(s)/h(s)$

$$= \frac{a_0 + a_1s + a_2s^2 + \cdot\cdot\cdot + a_{n-1}s^{n-1}}{h_0 + h_1s + h_2s^2 + \cdot\cdot\cdot + h_ns^n} \quad (3)$$

The desired $r^{th}$ order model for (1) is obtained by truncating the higher-order terms of (1) such that the terms higher than $r^{th}$ order are eliminated. After elimination $r^{th}$ order model for (1) will become

$T_r(s) = b(s)/l(s)$

$$= \frac{b_0 + b_1s + b_2s^2 + \cdot\cdot\cdot + b_{r-1}s^{r-1}}{l_0 + l_1s + l_2s^2 + \cdot\cdot\cdot + l_rs^r} \quad (4)$$

The $5^{th}$ order model is obtained by applying truncation approach as

$T_5(s) = b(s)/l(s)$

$$= \frac{b_0 + b_1s + b_2s^2 + b_3s^3 + b_4s^4}{l_0 + l_1s + l_2s^2 + l_3s^3 + l_4s^4 + l_5s^5} \quad (5)$$

Similarly, $4^{th}$, $3^{rd}$ , and $2^{nd}$ order ROMs for HOS become

$T_4(s) = b(s)/l(s)$

$$= \frac{b_0 + b_1s + b_2s^2 + b_3s^3}{l_0 + l_1s + l_2s^2 + l_3s^3 + l_4s^4} \quad (6)$$

$T_3(s) = b(s)/l(s)$

$$= \frac{b_0 + b_1s + b_2s^2}{l_0 + l_1s + l_2s^2 + l_3s^3} \quad (7)$$

$T_2(s) = b(s)/l(s)$

$$= \frac{b_0 + b_1s}{l_0 + l_1s + l_2s^2} \quad (8)$$

## 3. HIGHER-ORDER INTERCONNECTED POWER SYSTEM REPRESENTATION

This section presents a mathematical model of a single region power system. thermal, hydro and gas turbine units are all included in the construction of this model of an interconnected power system. The $11^{th}$-order transfer function of the system is produced from these generating units. Fig. 1 illustrates the auxiliary of thermal, hydro, and gas electric plant. The eleventh-order system is produced using the

numerical values shown in Table 1. (9), which depicts this system of $11^{th}$ order.

$$T_{11}(s) = \frac{(-6s^{10} - 319.9s^9 - 6604s^8 - 6.965 \times 10^{04}s^7 - 4.166 \times 10^{05}s^6 - 1.461 \times 10^{06}s^5 - 2.947 \times 10^{06}s^4 - 3.159 \times 10^{06}s^3 - 1.472 \times 10^{06}s^2 - 1.562 \times 10^{05}s - 3783)}{}$$

$$(s^{11} + 53.37s^{10} + 1099s^{9} + 1.149 \times 10^{04}s^{8} + 6.852 \times 10^{04}s^{7} + 2.542 \times 10^{05}s^{6} + 6.471 \times 10^{05}s^{5} + 1.212 \times 10^{06}s^{4} + 1.519 \times 10^{06}s^{3} + 9.387 \times 10^{05}s^{2} + 1.438 \times 10^{05}s + 4746) \quad (9)$$

In the next section, the obtained 11th- order system is reduced in to comparatively lower order by applying direct truncation based reduced order modelling.

**Table. 1** Numerical values

| Sno: | **Numerical values** |
|---|---|
| 1. | $\Delta P_{T\,1}$ : Thermal power plant's Governor output in pu MW. |
| 2. | $\Delta P_{T\,2}$ : Thermal power plant's Reservoir output power in pu MW. |
| 3. | $\Delta P_{T\,3}$ : Thermal power plant's Turbine output power in pu MW. |
| 4. | $\tau_{g\,T}$ : Time constant of Generator.= 0.08sec |
| 5. | $\tau_{r\,T}$ : Time constant of Reheat = 10sec. |
| 6. | Kr T : Reheat steam turbine's coefficient = 0.3 |
| 7. | $\tau_{t\,T}$ : Time constant of Turbine = 0.3sec |
| 8. | $f_T$ : regulation of speed governor = 2.4Hz/puMW . |
| 9. | $\Delta P_{H\,1}$ : Hydropower plant's Governor output in pu MW. |
| 10. | $\Delta P_{H\,2}$ : hydro power plant's Reservoir output power in pu MW. |
| 11. | $\Delta P_{H\,3}$ : hydro power plant's Turbine output power in pu MW. |
| 12. | $\tau_{r\,H}$ : time constant of main servo. = 0.2sec. |
| 13. | $\tau_{g\,H}$ : Rest time of Speed governor = 0.5sec. |
| 14. | $\tau_{t\,H}$ : Time constant of water = 1sec. |
| 15. | $f_H$ : regulation of speed governor = 2.4Hz/pu MW . |
| 16. | $\Delta P_{G\,1}$ : Gas power plant's valve position in pu MW. |
| 17. | $\Delta P_{G\,2}$ : gas power plant's governor output in pu MW. |
| 18. | $\Delta P_{G\,3}$ : gas power plant's fuel system output power in pu MW. |
| 19. | $v_1$ : constant of valve position = 1.0 |
| 20. | $v_2$ : constant of valve position = 0.05sec. |
| 21. | $\tau_{g\,1}$ : Speed governor's lead time constant = 0.6sec |
| 22. | $\tau_{g\,2}$ : Speed governor's lag time constant = 0.6sec |
| 23. | $\tau_{f\,G}$ : Time constant of fuel = 0.23sec. |
| 24. | $\tau_{r\,G}$ : Time delay of Combustion reaction = 0.01sec. |
| 25. | $\tau_{c\,G}$ : Compressor discharge volume time constant = 0.2Sec. |
| 26. | $f_G$ : Regulation of Speed governor= 2.4Hz/pu MW |
| 27. | $K_p$ : Gain of power system = 120Hz/puMW |
| 28. | $\tau_p$ : power system's time constant = 20sec. |

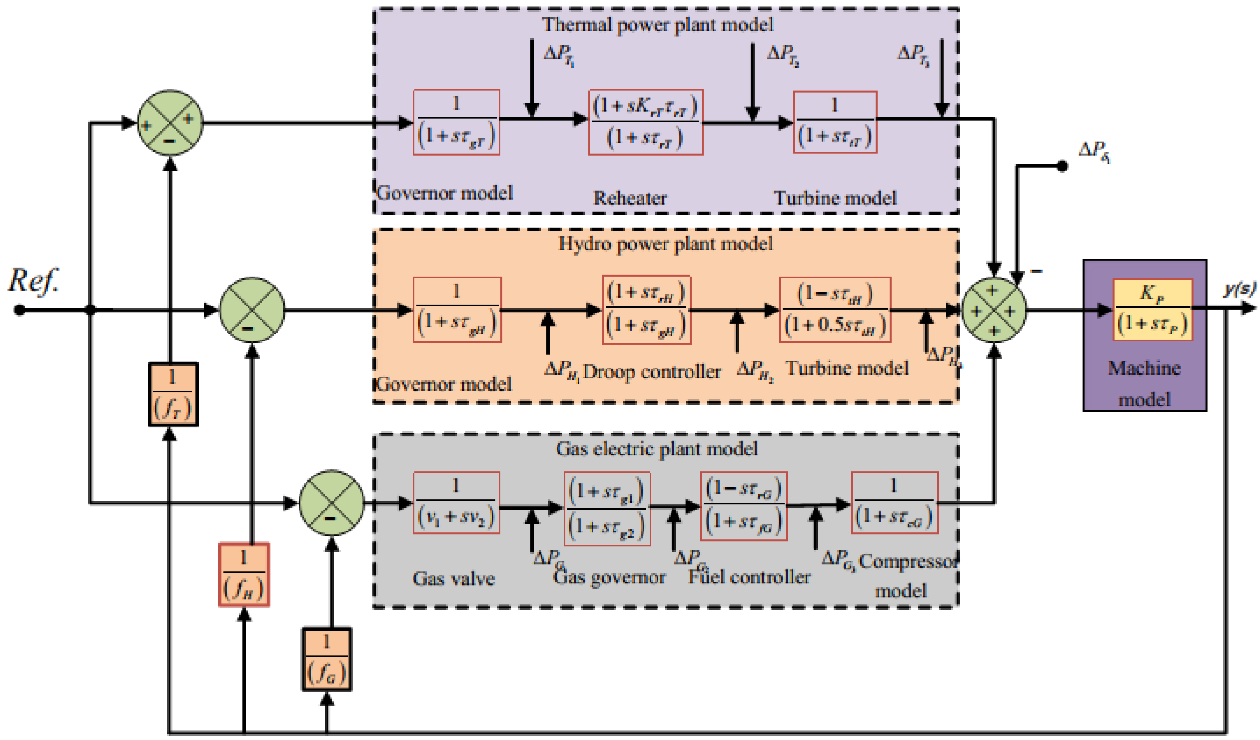


**Fig. 1** Single area power system model

## 4. REDUCTION OF 11TH ORDER INTER-CONNECTED POWER SYSTEM MODEL USING TRUNCTION BASED APPROACH

The truncation of n$^{th}$ order transfer function shown in (1) is incorporated for determining the 5$^{th}$ , 4$^{th}$ , 3$^{rd}$ r and 2$^{nd}$ order, reduced order models (ROMs) provided in (5), (6), (7) and (8), respectively. Similar, approach is employed for determination of 5$^{th}$ , 4$^{th}$ , 3$^{rd}$ and 2$^{nd}$ order models for 11$^{th}$-order system depicted in (9).

The truncated 5$^{th}$ - order model for (9) can be given as

$$T_5(s) = \frac{(-2.947 \times 10^{06}s^4 - 3.159 \times 10^{06}s^3 - 1.472 \times 10^{06}s^2 - 1.562 \times 10^{05}s - 3783)}{(6.471 \times 10^{05}s^5 + 1.212 \times 10^{06}s^4 + 1.519 \times 10^{06}s^3 + 9.387 \times 10^{05}s^2 + 1.438 \times 10^{05}s + 4746)} \quad (10)$$

Similarly, by employing truncation approach 4$^{th}$ - order, 3$^{rd}$ - order and 2$^{nd}$ -order ROMs are obtained as

$$T_4(s) = \frac{(-3.159 \times 10^{06}s^3 - 1.472 \times 10^{06}s^2 - 1.562 \times 10^{05}s - 3783)}{(1.212 \times 10^{06}s^4 + 1.519 \times 10^{06}s^3 + 9.387 \times 10^{05}s^2 + 1.438 \times 10^{05}s + 4746)} \quad (11)$$

$$T_3(s) = \frac{(-1.472 \times 10^{06}s^2 - 1.562 \times 10^{05}s - 3783)}{(1.519 \times 10^{06}s^3 + 9.387 \times 10^{05}s^2 + 1.438 \times 10^{05}s + 4746)} \quad (12)$$

$$T_2(s) = \frac{(-1.562 \times 10^{05}s - 3783)}{(9.387 \times 10^{05}s^2 + 1.438 \times 10^{05}s + 4746)} \quad (13)$$

In (10),(11), (12) and (13), the four different models of different orders are presented. In the support of these proposed truncated models, plots and tabular comparative analysis are exhibited in the next section.

## 5. RESULTS & DISCUSSION

Figs. 2 and 3 display the step and impulse responses respectively. The Bode plots, as depicted in Fig. 4, shows how stable the system is. Table 2 and 3 presents the comparative analysis of time specification data, and Table 4 displays performance error indices. The rise time, settling time, overshoot, undershoot, peak, and peak time are all displayed as comparison data in Table 2 and 3. The performance errors are displayed in Table 4 .The data of table 4 shown the performance errors for the 5th-order model are comparably lower, it can be shown from this tabular comparison that the smaller truncated model retains the majority of the HOS- characteristics. Thus, 5th-order ROM response is better in comparison with other lower order ROMs.

**Table. 2** Comparision of time domain specification

| Time specification | $11^{th}$ order model (9) | $5^{th}$ order model (10) | $4^{th}$ order model (11) | $3^{rd}$ order model (12) | $2^{nd}$ order model (13) |
|---|---|---|---|---|---|
| Rise time (s) | 0.1059 | 0.1525 | 0.2814 | 0.851 | 5.925 |
| Settlingtime (s) | 28.523 | 35.073 | 43.2742 | 41.38 | 93.59 |
| Overshoot | 385.23 | 249.97 | 167.622 | 91.81 | 35.22 |
| Undershoot | 54.648 | 0 | 0 | 0 | 0 |
| Peak | 3.8678 | 2.7896 | 2.1332 | 1.528 | 1.077 |
| Peak time (s) | 0.8963 | 1.2781 | 2.098 | 4.815 | 21.03 |

**Table. 3** Comparision of time domain specification

| Time specifi-cation | Rise Time (s) | Settling Time (s) | Overshoot | Under shoot | Peak | Peak time (s) |
|---|---|---|---|---|---|---|
| $11^{th}$ order model(9) | 0.105 | 28.523 | 385.23 | 54.64 | 3.86 | 0.89 |
| $5^{th}$ order Model(R. S. Sengar et al[35]) | 0.103 | 28.344 | 361.50 | 3.561 | 3.67 | 0.85 |
| $5^{th}$ order model (proposed model) | 0.152 | 35.073 | 249.97 | 0 | 2.78 | 1.27 |

**Table. 4** Comparision of error indices

| ith respect to system HOM(9) | Error indices | | |
|---|---|---|---|
| | IAE | ISE | ITAE |
| $2^{nd}$ order Model(13) | 9.371 | 18.4 | 38.03 |
| 3rd order Model(12) | 8.511 | 13.47 | 35.5 |
| 4th order Model(11) | 7.981 | 11.42 | 34.01 |
| 5th order Model(10) | 7.552 | 10.11 | 34.3 |

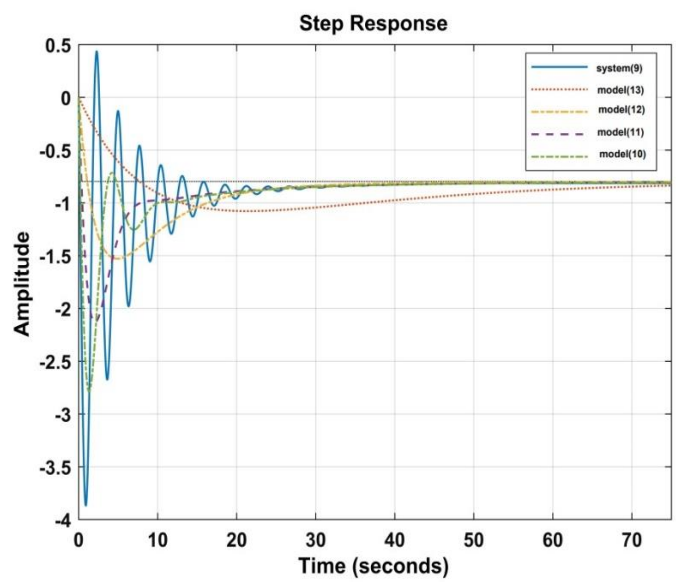


**Fig. 2** Step-responses of system and ROMs

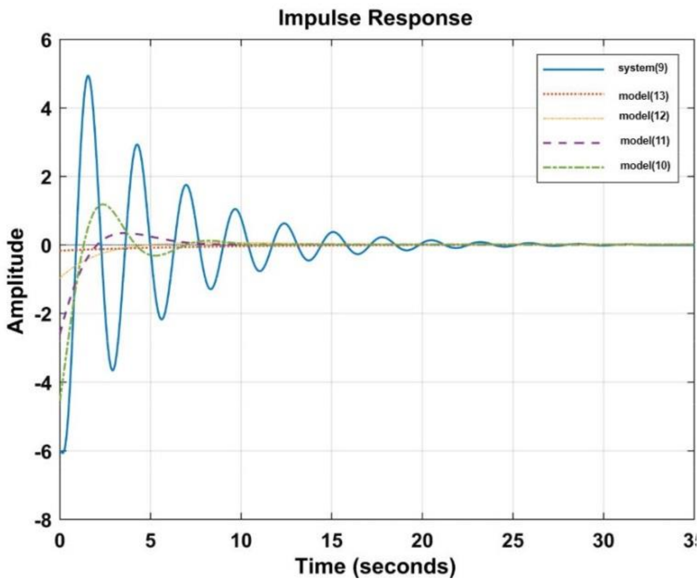


**Fig. 3** Impulse-responses of system and ROMs

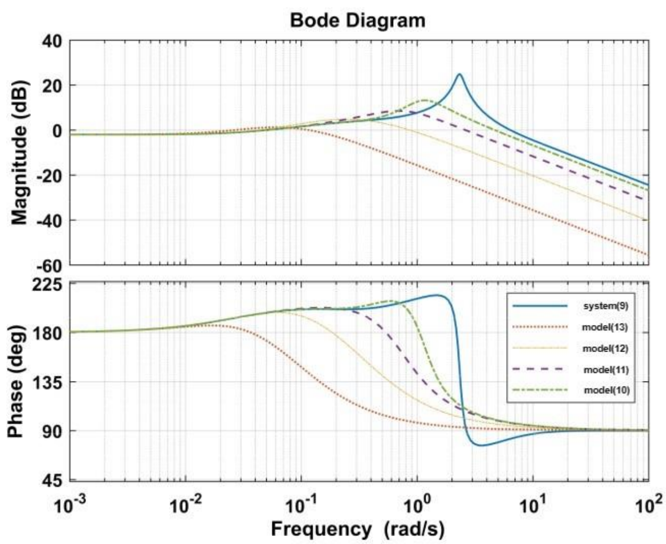


**Fig. 4.** Bode-responses of system and ROMs

## 6. CONCLUSION

The direct truncation technique is used in this article to create the reduced-order models (ROMs).This method is simple and easy to apply. This frequency approach method is first time applied to considered 11$^{th}$ order power system model that is the novelty of this paper. The model for the 2$^{nd}$,3$^{rd}$, 4$^{th}$, and 5$^{th}$ -order is found in this paper. To assess their performance, the step and impulse responses of the new approach are contrasted with those of the old system. The obtained ROMs' Bode plot is also provided. This shows that the system ROMs that were received are reliable. For the 2$^{nd}$,3$^{rd}$, 4$^{th}$, and 5$^{th}$ –order models, the integral square error (ISE), integral absolute error (IAE), and the integral time absolute errors (ITAE) are also tabulated. These errors are considerable. In the future, ROMs for fixed coefficient single input single output and multi input multi output systems can be determined using mixed approaches.

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## AUTHORS BIOGRAPHY

**Salik Ram Dewangan** received his BE degree in Electrical Engineering from Pt.R.S.U., Raipur, India in 2006 and M.Tech degree in Electrical Engineering from C.S.V.T.U. Bhilai , India in 2011. He is currently pursuing PhD at the Department of Electrical Engineering, National Institute of Technology Raipur, India. His areas of interest are Model order reduction, Renewable energy and controller design.

Email: srdewangan.phd2022.ee@nitrr.ac.in

P.D.Dewangan is graduated from GEC/ National Institute of Technology, Raipur, India in 1990. He received M.Tech. Degree in Electrical Engg from VNIT Nagpur in 2000 and Ph.D. Degree in Electrical engineering from National Institute of Technology, Raipur, India in 2021. Currently, he is working as Associate Professor at National Institute of Technology, Raipur, India. His areas of interest are Model order reduction, Control Systems, Power Systems and Optimization.

Email: pddewangan.ele@nitrr.ac.in

V. P. Singh is graduated from UPTU, Lucknow, India in 2007. He received M.Tech. Degree in Control and Instrumentation and Ph.D. Degree in Electrical engineering in 2009 and 2013, respectively, from Motilal Nehru National Institute of Technology, Allahabad, India. Currently, he is working as Associate Professor and Associate Dean (P&D) at Malaviya National Institute of Technology, Jaipur, India. His areas of interest are Control Systems, Optimization, Artificial Intelligence and Power Systems.

Corresponding author's Email: vinay.ee@nit.ac.in