ISSN (Print) : 0974-6846
Indian Journal of Science and Technology, Vol 9(44), 10.17485/ijst/2016/v9i44/102985, November 2016 ISSN (Online) : 0974-5645

Analysis and Design of a Controller for an SMIB Power System via Time Domain Approach

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Abstract

Background/Objectives: Designing a large interconnected system and to guarantee the system stability at a minimum cost is of very challenging task. From control theory point of view, a power system is a higher order multivariable process which operates constantly in a changing environment. Hence, it is necessary to perform the order reduction, for such a complex system. **Methods/Statistical Analysis:** In this paper order reduction techniques i.e. Modal Analysis Approach and Aggregation methods have been used to diminish the stable higher order system to a stable demoted order model. **Findings:** During approximation, the uniqueness of the original system are conserved in its demoted order model. **Application/Improvements:** The response of the demoted order model has been improved by designing a controller using pole placement technique.

Keywords: Aggregation Method, SMIB Power System, Design of Controller, Modal Analysis Approach, Order Reduction

1. Introduction

Forecasting and process of modern power systems have become difficult due to a large number of interconnections involved in the system. When a system is subjected to a disturbance, the behavior of the system related to stability is considered. Generally depending on the input the stability of a nonlinear system is known, whereas for the linear system it is self determining[1]. The stability of a nonlinear system is classified as follows.

- Local stability (or) stability in small
- Finite stability
- Global stability (or) stability in large

The performance related to stability is considered as case study in this paper when a single machineis connected to a large system through transmission lines. Generally, during normal operation small signal stability refers to the system dynamics. The ability of a system to maintain synchronism even when subjected to small disturbances is said to be as Power System Stability. The insufficient damping of system oscillations is treated as one of the small signal stability problems in power system. In the design of power system, small signal analysis using linear techniques provides a valuable information about the inherent dynamic characteristics. This paper reveals the order reduction techniques in time domain approach applied to power systems and also designing of a controller to improve the performance of the system.

There are two types of order reduction methods i.e. classical approach and Modern approach. If a system is in the form of frequency domain (or) transfer function it comes under classical approach. Similarly, if it is in the form of Time domain (or) state space, then it comes

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under Modern Approach. The difference between two approaches is that by using Modern approach the interior of the system can be known at any instant.

The outline of this section includes four sections. Problem Statement will be discussed in Section 2. Different Model reduction techniques are discussed in Section 3. Design of a controller via Pole Placement technique is described in Section 4. The SMIB Power System has been represented in state space for which the reduction procedure is applied in Section 5. In the last section, i.e. Section 6 conclusion is stated.

2. Problem Statement

Most of the model reduction methods focus on linear time invariant and discrete time systems. Here in this paper Linear time invariant systems are described by the following equations.

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (1)$$
$$y(t) = Cx(t) + Du(t)$$

Here $x(t)$ is state vector of $n\times 1$ dimension
$u(t)$ is input vector of m inputs
$y(t)$ is output vector of p outputs
A is known as state or plant matrix of order $n\times n$
B is known as control or input matrix of order $n\times m$
C is known as output matrix of order $p\times n$
D is known as Transmission matrix of order $p\times m$

Its corresponding reduced model state equations is represented as

$$\dot{x}_r(t) = A_r x_r(t) + B_r u(t) \qquad (2)$$
$$y_r(t) = C_r x_r(t) + D_r u(t)$$

The task of reduction process is to determine a stable reduced model of order $r, (r < n)$ where it should retain the properties of original system.

3. Different Model Reduction Methdologies

Most of the model reduction methods focus on linear systems, which in many cases provide accurate descriptions of the physical systems[2–3]. There are two methods which are used in this paper to reduce the order of the system.

A Modal Analysis Approach
B Aggregation Method

Modal Analysis Approach

Modal reduction methods based on modal analysis approach identify and preserve the important properties of original system. The objective of this method is to eliminate the eigen values, which are far away from the origin and retain only the dominant eigenvalues[4–5]. This method can even be applied to uncertain systems[6]. There are few applications of Modal analysis approach i.e to overcome the vibration problem in ship mast using participation factor[7] and to know the performance parameters of PZT based impulse hammer[8].

The algorithm of the proposed method is given below:

Step I: Find the Eigen values of the original system using Eqn. (1).

Step II: The Eigen vectors can be known using Step I.

Step III: The Eigen vectors which are obtained from Step II are arranged to form a modal matrix (M) and arrange them into sub matrices as shown below.

$$M = \begin{bmatrix} M_1 & M_2 \\ M_3 & M_4 \end{bmatrix} \qquad (3)$$

Where dimension of M_1 is $(r \times r)$
dimension of M_4 is $(n-r)\times(n-r)$
Here 'n' is the order of original system
'r' is the order of demoted model

Step IV: Partition the matrices A, B, C into sub matrices as shown below

$$A = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \qquad (4)$$

$$B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \qquad (5)$$

$$C = \begin{bmatrix} C_1 & C_2 \end{bmatrix} \qquad (6)$$

Where dimension of A_1 is $(r \times r)$
dimension of A_4 is $(n-r)\times(n-r)$
dimension of B_1 is $(r \times 1)$
dimension of B_2 is $(n-r)\times 1$
dimension of C_1 is $(1 \times r)$
dimension of C_2 is $1\times(n-r)$

Step V: The reduced order state matrix 'A_r' can be calculated using Equations (3) and (4) as

$$A_r = A_1 + A_2 M_3 M_1^{-1} \qquad (7)$$

Step VI: The reduced order input matrix 'B_r' can be obtained from Equation (5) as

$$B_r = B_1 \qquad (8)$$

Step VII: The reduced order output matrix 'C_r' can be calculated by using Equation (6) as

$$C_r = C_1 \qquad (9)$$

Step VIII: The reduced order state model as shown in Equation (2) can be represented from the above data.

Aggregation Method

This method focuses on preserving the important property of the original system such as stability in the demoted order model with less computational effort[9–11].

The algorithm of the Aggregation method is shown below.

Step A: Repeat Steps I to III.

Step B: Calculate the inverse of modal matrix (M) which is represented by

$$N = \begin{bmatrix} N_1 & N_2 \\ N_3 & N_4 \end{bmatrix} \tag{10}$$

Where $N_1 = (r \times r)$

$N_4 = (n-r) \times (n-r)$

Step C: Calculate the regular arbitrary matrix (M_0) using the equation as shown below

$$M_0 = [I_r \;\vdots\; 0_{(r \times n-r)}] \tag{11}$$

Step D: Compute the aggregation matrix 'K' using the equation

$$K = M_1 M_0 N \tag{12}$$

Step E: The demoted order matrices are represented as

$$A_r = KAK^T[K[K^T]]^{-1} \tag{13}$$

$$B_r = KB \tag{14}$$

$$C_r = CK^T[K[K^T]]^{-1} \tag{15}$$

Step F: The state model matrices of reduced order as known through Equation (2) can be formed from the above information.

4. Design of a Controller via Pole Placement Technique

The performance of the demoted (or) reduced model can be improved by designing a controller using pole placement technique. Pole placement method is a devise approach of locating the closed loop poles at desired location on s-plane[12].

The sufficient conditions that has to be satisfied before designing controller.

- The system should be completely state controllable.
- The state variables are measurable and available for feedback.
- Control input is unconstrained.

During design of controller the choice of closed loop poles should satisfy the following

- Not only the dominant poles, but all the poles are forced to lie at desired locations.
- The poles which we choose should be close to the open loop poles.

The Block Diagram representation of state variable feedback system is shown in Figure 1

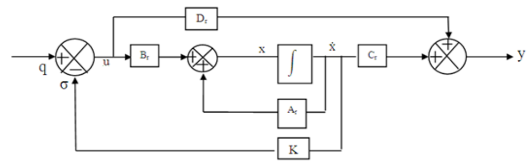

Figure 1. Block Diagram of state variable feedbacksystem.

The state model of a system without using state feedback is given by Equation 1

From the block diagram

q = system input when state variable feedback is employed

σ = Feedback signals obtained from state variables

u = Scalar control vector

The feedback signal σ is obtained from state variables and it is given by $\sigma = Kx$

Where K is the feedback gain matrix of order $1 \times r$ and it is given as $K = [K_1 \;\; K_2 \;\; \cdots \;\; K_r]$

If the system employing state variable feedback then,

$$u = q - \sigma \quad \text{(Or)} \quad q - Kx \tag{16}$$

The state equations of the compensated model is obtained by substituting Equation (16) in Equation (1) as

$$\begin{aligned} \dot{x}(t) &= (A - BK)x(t) + Bq(t) \\ y(t) &= (C - DK)x(t) + Dq(t) \end{aligned} \tag{17}$$

Steps to Design the controller using Pole Placement technique

Step A: Check controllability of the system by using

$$Q_c = [B \;\; AB \;\; A^2B \;\; \cdots \;\; A^{r-1}B]$$

Step B: Consider the desired poles $\mu_1 \mu_2 \cdots \mu_r$ at which the system is to be placed

Step C: By using Step B, we obtain the desired characteristic polynomial as

$$(s-\mu_1)\ldots(s-\mu_r) = s^2 + a_1 s^{r-1} + a_2 s^{r-2} + \ldots + a_r$$

Step D: By using state variable feedback, the characteristic polynomial of the system is given by

$$|sI - A + BK| = s^r + b_1 s^{r-1} + b_2 s^{r-2} + \cdots + b_r$$

Where $K = [K_1 \;\; K_2 \;\; \cdots \;\; K_r]$

Step E: Equate Steps C and D to know the values of K

Step F: The state equations using feedback is obtained from Equation (17)

5. Case Study

Analyze the Small Signal Stability of a Single Machine Infinite Bus (SMIB) power system consisting of four thermal generating stations of 555MVA, 24KV at 60Hz. The Schematic diagram of SMIB system is shown in

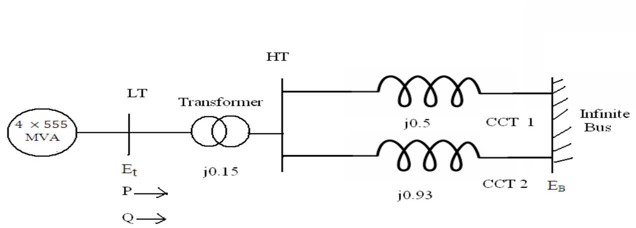

Figure 2. Schematic diagram of SMIB system.

The network reactance is taken in p.u and the resistances are to be neglected. Here the transmission circuit 2 is out of service, P= 0.9, Q=0.3(Over excited), $E_t = 1.0\angle 36^0$, $E_B = 0.995\angle 0^0$. The p.u fundamental parameters of the equivalent generator are $L_{adu} = 1.65$, $L_{aqu} = 1.60$, $R_{fd} = 0.0006$, $R_a = 0.003$ $L_{fd} = 0.153$.

The Block Diagram representation of Figure 2 is represented in

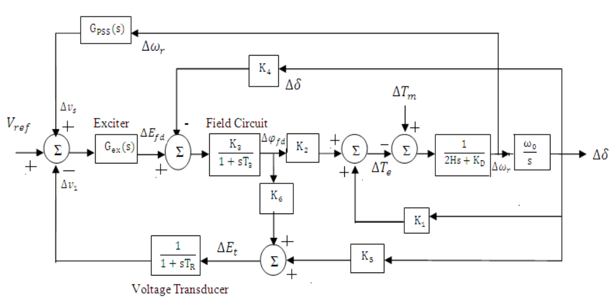

Figure 3. Block Diagram representation of Figure 2.

The state space form of Figure 3 is represented as

$$\begin{bmatrix} \Delta\dot{\omega}_r \\ \Delta\dot{\delta} \\ \Delta\dot{\varphi}_{fd} \\ \Delta\dot{v}_1 \\ \Delta\dot{v}_2 \\ \Delta\dot{v}_s \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 \\ a_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} & 0 & a_{36} \\ 0 & a_{42} & a_{43} & a_{44} & 0 & 0 \\ a_{51} & a_{52} & a_{53} & 0 & a_{55} & 0 \\ a_{61} & a_{62} & a_{63} & 0 & a_{65} & a_{66} \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\varphi_{fd} \\ \Delta v_1 \\ \Delta v_2 \\ \Delta v_s \end{bmatrix} + \begin{bmatrix} b_{11} \\ b_{21} \\ b_{31} \\ b_{41} \\ b_{51} \\ b_{61} \end{bmatrix} [\Delta T_m]$$

Or $\dot{x} = Ax + Bu$

$$\Delta v_s = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\varphi_{fd} \\ \Delta v_1 \\ \Delta v_2 \\ \Delta v_s \end{bmatrix}$$

Or $y = Cx + Du$

The Elements of Matrix "A" can be known by using shown in Table 1

The Gain and Time constants of the system can be known by using shown in Table 2

Table 1. Elements of Matrix 'A'

$a_{11} = \frac{-K_D}{2H}$	$a_{12} = \frac{-K_1}{2H}$
$a_{13} = \frac{-K_2}{2H}$	$a_{21} = \omega_0 = 2\pi f_0$
$a_{32} = \frac{-\omega_0 R_{fd}}{L_{fd}} m_1 L'_{ads}$	$a_{33} = (-\omega_0 R_{fd})/L_{fd}\,[1 - (L_{ads}'')/L_{fd} + m_2 L_{ads}'']$
$a_{34} = -b_{32}K_A = \frac{-\omega_0 R_{fd}}{L_{adu}} K_A$	$a_{36} = \frac{-\omega_0 R_{fd}}{L_{adu}} K_A$
$a_{42} = \frac{K_5}{T_R}$	$a_{43} = \frac{K_6}{T_R}$
$a_{44} = \frac{-1}{T_R}$	$a_{51} = K_{STAB} a_{11}$
$a_{52} = K_{STAB} a_{12}$	$a_{53} = K_{STAB} a_{13}$
$a_{55} = \frac{-1}{T_\omega}$	$a_{61} = \frac{T_1}{T_2} a_{51}$
$a_{62} = \frac{T_1}{T_2} a_{52}$	$a_{63} = \frac{T_1}{T_2} a_{53}$
$a_{65} = \frac{T_1}{T_2} a_{55} + \frac{-1}{T_2}$	$a_{66} = \frac{-1}{T_2}$

Table 2. Gain and Time constants of the system

Gain Constants
$K_1 = 0.7643$ $K_2 = 0.8649$ $K_3 = 0.3230$ $K_4 = 1.4187$ $K_5 = -0.1463$ $K_6 = 0.4168$ $K_{STAB} = 9.5$ $K_A = 200$
Time Constants
$T_1 = 0.154$ (s) $T_2 = 0.033$ (s) $T_3 = 2.365$ (s) $T_\omega = 1.4$ (s) $T_R = 0.02$ (s)
H=3.5(MW.s/MVA), $K_D = 0$

Modal Analysis Approach

The matrices from the above equations are

$$A = \begin{bmatrix} 0 & -0.1092 & -0.1236 & 0 & 0 & 0 \\ 376.99 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.1938 & -0.4229 & -27.3172 & 0 & 27.3172 \\ 0 & -7.3125 & 20.8391 & -50 & 0 & 0 \\ 0 & -1.0372 & -1.1738 & 0 & -0.7143 & 0 \\ 0 & -4.8404 & -5.4777 & 0 & 26.9697 & -30.303 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.1428 \\ 0 \\ 0 \\ 0 \\ 16.625 \\ 77.5833 \end{bmatrix} C = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} D = [0]$$

The matrix "A" has Eigen values as follows -39.0967, 19.7970±j12.8224, -1.0055±j6.6073, -0.7385

The Modal matrix consists the elements of Eigen vectors which is obtained from Eigen values as shown below

$$M = \begin{bmatrix} 0.0014 & -0.0024+0.0160i & -0.0024-0.0160i & -0.0012 & 0.0036+0.0020i & 0.0036-0.0020i \\ -0.0133 & 0.9145 & 0.9145 & 0.6138 & -0.0311-0.0587i & -0.0311+0.0587i \\ 0.4474 & 0.0290+0.2608i & 0.0290-0.2608i & -0.5495 & 0.8193 & 0.8193 \\ 0.8639 & -0.1072+0.1254i & -0.1072-0.1254i & -0.3236 & 0.4905-0.1940i & 0.4905+0.1940i \\ 0.0133 & -0.0397+0.1505i & -0.0397-0.1505i & -0.3444 & -0.0350+0.0203i & -0.0350-0.0203i \\ 0.2305 & -0.1645+0.1268i & -0.1645-0.1268i & -0.3129 & -0.0908+0.1902i & -0.0908-0.1902i \end{bmatrix}$$

From Equation 3

$$M_1 = \begin{bmatrix} 0.0014 & -0.0024+0.0160i \\ -0.0133 & 0.9145 \end{bmatrix}$$

$$M_4 = \begin{bmatrix} 0.4474 & 0.0290+0.2608i \\ 0.8639 & -0.1072+0.1254i \\ 0.0133 & -0.0397+0.1505i \\ 0.2305 & -0.1645+0.1268i \end{bmatrix}$$

Similarly from Equation's (4), (5) and (6) the demoted order model is represented as

$$A_r = \begin{bmatrix} -39.97 & -255.98 \\ 1 & 0 \end{bmatrix}$$

$$B_r = \begin{bmatrix} 0.1428 \\ 0 \end{bmatrix} C_r = \begin{bmatrix} 0 & 1 \end{bmatrix} D_r = [0]$$

Under steady state conditions s $\rightarrow$ 0, then

$$A_r = \begin{bmatrix} -39.97 & -255.98 \\ 1 & 0 \end{bmatrix} B_r = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C_r = \begin{bmatrix} 0 & -10253 \end{bmatrix} D_r = [0]$$

The Step response of Original (6th) order and reduced (2nd) order system using Modal Analysis Approach method is shown in Figure 4

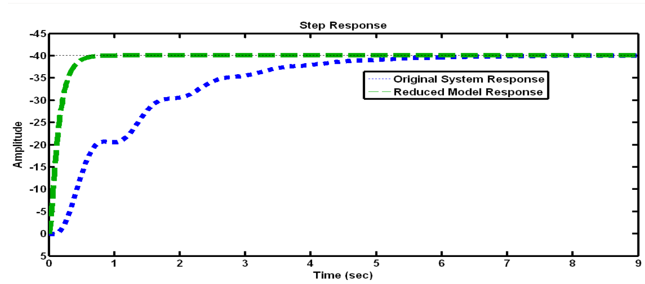

Figure 4. Step response of Original (6th) order and reduced (2nd) order system using Modal Analysis Approach method.

Design of a Controller

From Steps A and B the system is state controllable and the desired poles are -8.0256, -10.0562

The desired characteristic polynomial from Step C is $(s^2 + 18.1098s + 80.98861)$

By using state variable feedback, the characteristic polynomial of the system is given by $(s^2 + (39.97 + K_1)s + (255.98 + K_2))$

The gain values K_1 and K_2 is obtained from Steps C and D as $K = [-21.8602 \quad -174.9913]$

The compensated state equations are obtained from Equation 17 as

$$A_{rc} = \begin{bmatrix} -18.1098 & -80.9887 \\ 1 & 0 \end{bmatrix} B_{rc} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C_{rc} = \begin{bmatrix} 0 & -10253 \end{bmatrix} D_{rc} = [0]$$

Under Steady State Conditions s→0, then

$$A_{rc} = \begin{bmatrix} -18.1098 & -80.9887 \\ 1 & 0 \end{bmatrix} B_{rc} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C_{rc} = \begin{bmatrix} 0 & -3237.3 \end{bmatrix} D_{rc} = [0]$$

The Step response of Compensated (2nd) order model using Modal Analysis Approach method is shown in Figure 5

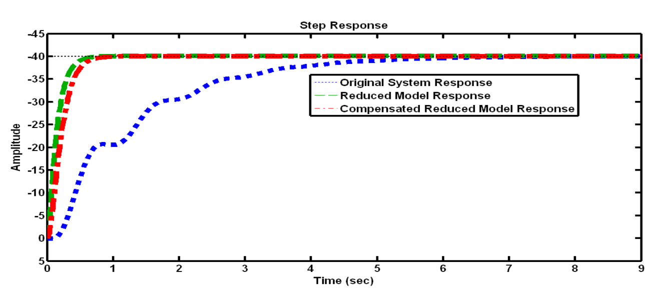

Figure 5. Step response of Compensated (2nd) order model using Modal Analysis Approach method.

Aggregation Method

Consider the same original system of 6^{th} order, by using the aggregation method algorithm the matrix "A" and "M" is known.

The inverse of modal matrix can be obtained by using Equation (10) as

$$N=\begin{bmatrix} -3.1133 & 0.3229 & -0.4195 & 1.0511 & -0.9157 & 1.3032 \\ -9.9586-31.0231i & 0.5703-0.0918i & 0.0805+0.2649i & -0.0636-0.1391i & 0.8696-0.5461i & 0.1244+0.2189i \\ -9.9586+31.0231i & 0.5703+0.0918i & 0.0805-0.2649i & -0.0636+0.1391i & 0.8696+0.5461i & 0.1244-0.2189i \\ 29.1631 & -0.0571 & 0.0030 & -0.0017 & -3.1129 & 0.0028 \\ 1.1080+2.8966i & -0.1567-0.1144i & 0.8073-0.8886i & -0.3295+0.9436i & -0.9985+2.0950i & -0.2896-1.9571i \\ 1.1080-2.8966i & -0.1567+0.1144i & 0.8073+0.8886i & -0.3295-0.9436i & -0.9985-2.0950i & -0.2896+1.9571i \end{bmatrix}$$

The regular arbitrary matrix using Equation (11)

$$M_0=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The aggregation matrix using Equation (12)

$$K=\begin{bmatrix} 0.5159-0.0849i & 0.0006+0.0093i & -0.0050+0.0007i & 0.0038-0.0007i & 0.0054+0.0152i & -0.0020+0.0015i \\ -9.0658-28.3706i & 0.5172-0.0839i & 0.0792+0.2422i & -0.0722-0.1272i & 0.8074-0.4994i & 0.0964+0.2002i \end{bmatrix}$$

Similarly from Equation's (13), (14) and (15) the demoted order model can be obtained as

$$A_r=\begin{bmatrix} -40.6395 & -259.6297 \\ 1 & 0 \end{bmatrix} B_r=\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C_r=[6.9781 \quad 45.6059] D_r=[0]$$

Under steady state conditions s $\rightarrow$ 0, then

$$A_r=\begin{bmatrix} -40.6395 & -259.6297 \\ 1 & 0 \end{bmatrix} B_r=\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C_r=[-1586 \quad -10366] D_r=[0]$$

The Step response of Original (6^{th}) order and reduced (2^{nd}) order system using Aggregation method is shown in Figure 6

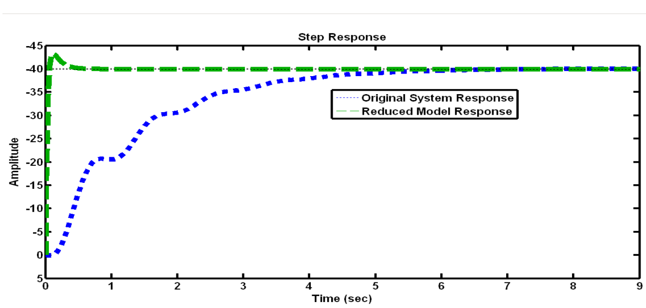

Figure 6. Step response of Original (6^{th}) order and reduced (2^{nd}) order system using Aggregation method.

Design of a Controller

From Steps A and B the system is state controllable and the desired poles are -9.854, -7.689

The desired characteristic polynomial from Step C is $(s^2+17.543s+75.7674)$

By using state variable feedback, the characteristic polynomial of the system is given by ($s^2+(40.6395+K_1)s+(259.6297+K_2)$)

The gain values K_1 and K_2 is obtained from Steps C and D as $K=[-23.0965 \quad -183.8623]$

The compensated state equations are obtained from Equation 17 as

$$A_{rc}=\begin{bmatrix} -17.543 & -75.7674 \\ 1 & 0 \end{bmatrix} B_{rc}=\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C_{rc}=[-1586 \quad -10366] D_{rc}=[0]$$

Under Steady State Conditions s→0, then

$$A_{rc}=\begin{bmatrix} -17.543 & -75.7674 \\ 1 & 0 \end{bmatrix} B_{rc}=\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C_{rc}=[-461.9 \quad -3018.6] D_{rc}=[0]$$

The Step response of Compensated (2^{nd}) order Model using Aggregation method is shown in Figure 7

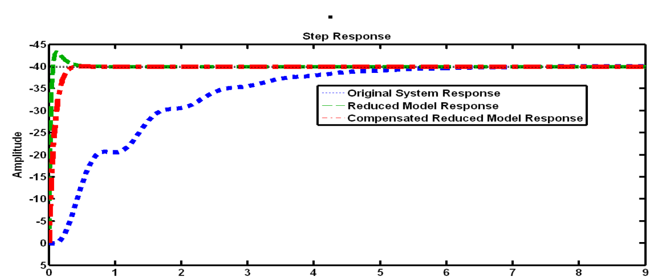

Figure 7. Step response of Compensated 2^{nd} order Model using Aggregation method.

6. Summary and Conclusion

The increase in power system dimensions posses higher order transfer function. Behaviour of such systems makes it difficult to analyze. In the past, many methods have been developed to approximate the large order system to lowest order. In this paper, modal analysis approach and aggregation methods areused to reduce the system to its lowest order. The performance of the demoted order model has been improved by designing a controller using pole placement technique. The simulation results of both the methods are presented in this paper.

7. References

1. Kundur K. TATA McGraw-Hill Edition: Power system stability and control. 2006; p. 699-822.
2. Obinata G, Anderson, Brian DO. Modern reduction for control system design. 2012.
3. Aoki M. Control of large-scale dynamic systems by aggregation. IEEE Transactions on Automatic Control. 1968; 13(3):246-53.
4. Zhao P, Rozsa G, Sinha NK. On the selection of the Eigen values to be retained in a reduced-order model. Proceedings 19th Annual Allerton, Conference on Control, Communication and Computing Monticello. 1981; 111:163-73.
5. Elrazaz Z, Sinha N. A review of some model reduction techniques. Electrical Engineering Journal Canadian. 1981; 6(1):34-40.
6. Gayatri B, Kumar KK, Lakshmi AVS. Uncertain Systems Order Reduction by Modal Analysis Approach. Indian Journal of Science and Technology. 2016 Oct; 9(38):1-9.
7. Ahmad MS, Jamil M, Iqbal J, Khan MN, Malik MH, Butt SI. Modal Analysis of Ship's Mast Structure using Effective Mass Participation Factor. Indian Journal of Science and Technology. 2016 Jun; 9(21):1-5.
8. Kandagal SB. Piezoceramic (PZT) Patch in Impulse Hammer for Modal Analysis. Indian Journal of Science and Technology. 2009 Mar; 2(3):1-4.
9. Fortuna G, Nunnari A, Gallo G. Model order reduction techniques with Applications in Electrical Engineering. 2012.
10. P.R.G.J, Sinha NK. On the selection of states to be retained in a reduced-order model. IEEE Proceedings D (Control Theory and Applications). 1984.
11. Mitra D. On the reduction of complexity of linear dynamic models. United Kingdom Atomic Energy Authority, Win frith, Report AEEW-R520. 1967.
12. Ogata K. PHI Pvt. Ltd.: Modern Control Engineering, 2nd Edition. 2004.