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INTER-AREA OSCILLATION DAMPING IN LARGE-SCALE POWER SYSTEMS USING DECENTRALIZED CONTROL

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ABSTRACT

Inter-area oscillation is one of the main concerns in power system small signal stability. It involves wide area in power system, therefore identifying the causes and damping these oscillations are challenging. Undamped inter-area oscillations may cause severe problems in power systems including large-scale blackouts. Designing a proper controller for power systems also is a challenging problem due to the complexity of the system. Moreover, for a large-scale system it is impractical to collect all system information in one location to design a centralized controller. Decentralized controller will be more desirable for large scale systems to minimize the inter area oscillations by using local information. In this paper, we consider a large-scale power system consisting of three areas. After decomposing the system into three subsystems, each subsystem is modeled with a lower order system. Finally, a decentralized controller is designed for each subsystem to maintain the large-scale system frequency at the desired level even in the presence of disturbances.

INTRODUCTION

Electromechanical oscillatory behavior is an inherent characteristic of weakly interconnected synchronous machines, where the operating conditions, excitation system, and load model can intensify it. As a result, any stress such as disturbances, heavy power transmission through tie lines or system component outages can result in unstable oscillations for power systems. To prevent power systems from potential damages and crisis, damping inter-area oscillations is a significantly important subject to electric power systems. In addition, with the growth in size of power exchange demand among utilities, this problem becomes even more challenging.

Identification of the oscillation modes and damping the inter area oscillations are widely investigated. A distributed algorithmic approach has been studied to estimate the electro-mechanical oscillation modes of power system network by using real-time synchrophasor measurements of phase angles and frequencies [1]. In another study, in specified procedures of identifying critical oscillation modes are proposed based on the oscillation contribution factor, where the oscillation contribution factor for each generator is defined based on synthesizing parameters like amplitude, damping ratio and attenuation obtained by Prony algorithm [2]. Tao Jiang et.al, [3] used a stochastic subspace identification (Data-SSI) algorithm to identify the system state space model, and proposed a new approach to estimate the dominant modes for monitoring inter-area oscillation in the China Southern power grid (CSG) by the use of phasor measurement units (PMUs) under both ring down and ambient conditions. Several techniques and approaches have been proposed to damp inter-area oscillations in power systems. Stabilization of the oscillation modes via excitation systems has been extensively investigated [4]. In [5], the authors proposed a fault-tolerant wide-area damping controller using modal-based control allocation to coordinate a group of actuators to optimally contribute to the damping of inter-area oscillations. Several modern control approaches such as model predictive control (MPC) [6], adaptive control [7], and fault tolerant control [8] have been investigated to damp inter-area oscillations. Decentralized control approaches [9] and robust control approaches [10] have also been proposed for wide-area damping control systems. It has been shown that energy storage systems like batteries can improve system response and damp inter area oscillations in power systems. An energy storage system based on Ultra Capacitor technology is proposed for damping control via real power modulation in [12].

As decentralized control approaches is more practical in large scale systems, due to their advantages, they have been widely used in power systems [13, 14]. To design each individual controller, no exchange of information among

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different areas is necessary which makes the control design easier to implement in large power systems. Also decentralized control design of lower dimensional subsystems increases system robustness with respect to a wide variety of structured and unstructured perturbations in the interconnections [15]. For this purpose, a large-scale system is decomposed into smaller subsystems without losing any information. These subsystems will have smaller dimensions compared to the large-scale system so that the control design problem will be more tractable to solve.

In the majority of the existing literature on inter-area oscillation damping based on system dynamics, a two area power system connected through a tie line is considered as the case study [4, 11, 12]. However, in power grids a loop shape connection is more common and realistic. In this paper, we consider a loop shape power system consisting of three different interconnected areas. The objective of this paper is to find a systematic solution to design decentralized controller for a large scale system that uses a simplified model structure. This approach consists first in augmenting the system by overlapping decomposition [16, 17] and then identify a reduced order model for each subsystem with a specific structure that guarantees the existence of the solution for decentralized servomechanism problem as from [18]. After the decentralized controllers have been derived, the performance results based on the original interconnected system are represented in section VI. The remainder of the paper is organized as follows: Section II describes modeling of the large scale power grid. In Section III, system decomposition is discussed. Section IV discusses system identification, and Section V covers the design of decentralized state feedback controllers based on reduced order subsystems to perform disturbance rejection in the original large scale system.

SYSTEM DESCRIPTION

In this paper, a large-scale power grid consisting of three areas interconnected through tie lines which form a loop shape power grid has been studied (see Fig 1.). In the following each of these three areas are explained in details.

A. First Area

The first area is a subsystem composed of two parts. The first part contains a wind generator, a diesel generator for long term backup for wind turbine, and a battery energy storage as a short-term backup for wind generation. In rural and remote areas, electricity demand for systems is typically supplied by diesel generator systems. Now in presence of renewables and due to high operating cost, fuel transportation problems and environmental issues comparing to the clean energy, a new hybrid power system supply has been introduced. Usually hybrid Remote Area Power Supply (RAPS) systems consist of one or more renewable energy technologies like wind turbine, and/or batteries with conventional generation schemes such as diesel. This integration is crucial for reliability of the power system due to uncertainties associated with renewable sources [19]. Conceptual model of wind turbine coupling to a diesel generator is shown in Fig. 2 [20].

The dynamic model of the first part in Laplace domain is shown in Fig. 2. The second part of the first area is a micro hydro generation unit connected to the first part through a tie line. Figure 3 shows the dynamic model of the second part.

Battery as an energy storage device, has several advantages in power system. Energy storage devices have very fast response times and can provide both power injection and absorption (discharge and charge, respectively). This can allow the energy storage system to participate in both a power and energy application simultaneously, thus increasing the value proposition of the device [21]. Batteries in power systems are accompanied by DC/AC inverters. Figure 4 shows the dynamic model of the battery and inverter [22].

The first area has overall three inputs and three outputs, and it defines by a 16×16 state matrix.
The state variables defining this area are:

$$x_1 = [\Delta f_{1-1}, \Delta P_{GD}, \Delta X_{ED1}, \Delta X_{ED2}, \Delta F_T, \Delta X_{PC1}, \Delta X_{PC2}, \Delta X_{PC3}, \Delta P_{BES}, \Delta P_{BESdroop}, \Delta P_{tie}, \Delta f_{1-2}, \Delta P_{GH}, \Delta P_{RH}, \Delta X_{EH}, \Delta P_{refH}]$$

where is Δf_{1-1} frequency variation of the first part (hybrid system), and Δf_{1-2} is frequency variation of the second part (micro hydro unit). More details are given in [20,22]. $\Delta P_{BES}, \Delta P_{BESdroop}$ are representing battery dynamics. And ΔP_L models the effect of loads' variation connecting to the system.

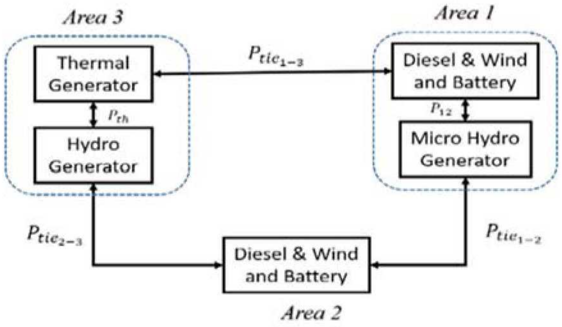


Fig. 1. Large scale power system case study model

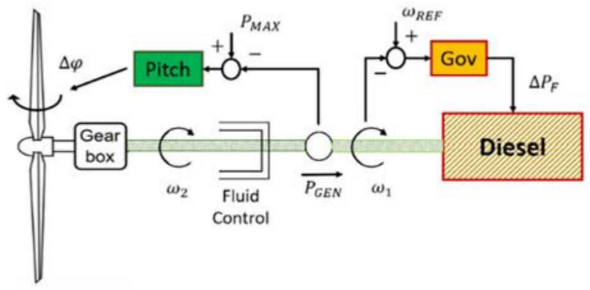


Fig. 2. Conceptual model of wind turbine coupling to a diesel [20]

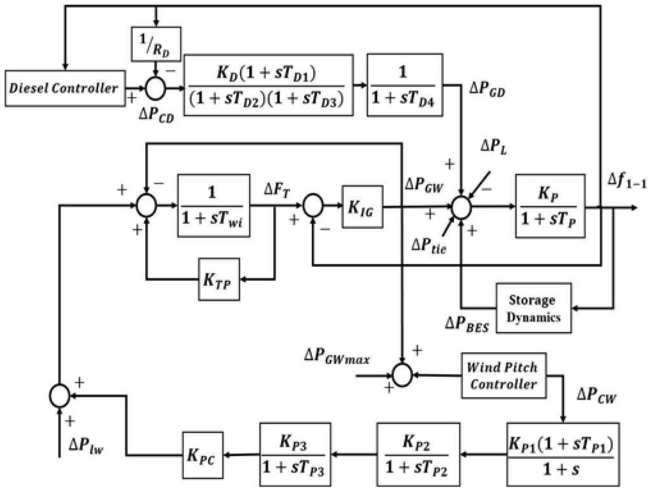


Fig. 3. Dynamic model of wind generator, diesel generator, and battery as a backup (first part of the first area) [22]

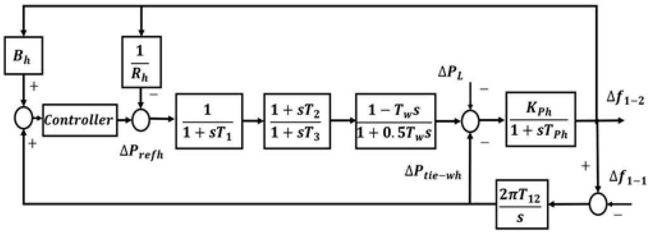


Fig. 4. Dynamic model of micro hydro generator (second part of the first area) [22]

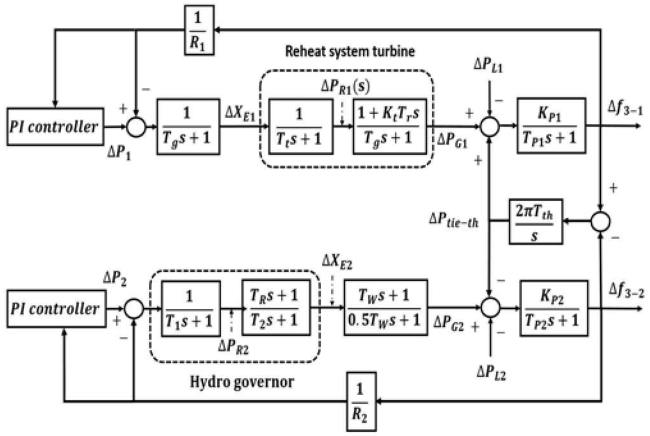


Fig. 5. Dynamic model of a hydro generator and a reheat thermal generator connecting through a tie line [23]

B. Second Area

The second area, which is the same as the first part of the first area, is shown in Fig. 3. This area consists of a wind generator, a diesel generator, a battery as a short-term backup for wind generation. This subsystem has been modeled with a 10×10 state matrix with two inputs and two outputs.

C. Third Area

The third area contains of a reheat-thermal generator unit and a hydro generator. These generators are connected together through a tie line as shown in Fig. 5. This system also is a two inputs- two outputs system modeled via a 11×11 state matrix.

The state variables defining the third area are:

$x_3 = [\Delta X_{E1}, \Delta P_{G1}, \Delta P_{R1}, \Delta f_{3-1}, \Delta Y_1, \Delta X_{E2}, \Delta P_{G2}, \Delta P_{R2}, \Delta f_{3-2}, \Delta P_{th}, \Delta Y_2]$, Δf_{3-1} is frequency variation of the thermal unit, and Δf_{3-2} is the hydro unit frequency variation [23].

The original large scale power system will be simulated by a 40×40 state matrix containing three aforementioned subsystems and three tie lines' dynamics. Simulated system has seven inputs and outputs in total.

SYSTEM DECOMPOSITION

There exist several examples of large scale and hybrid systems that their complexity make them almost impossible to control. These large-scale systems have various examples in different fields, such as economic systems, electric power systems, and mechanical structures. Decomposition for such systems with overlapping structure is an important approach to ease their control design. The methodology of the decomposition is based on expanding the system's state space equations; so that, the overlapping subsystems appear as disjoint subsystems.

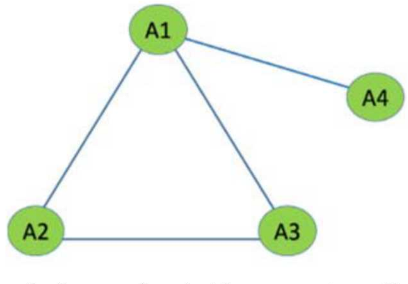
Each disjoint subsystem includes all necessary information from the rest of the system that gives the decomposed subsystem the opportunity of working independently. So, a decentralized controller can be designed for each subsystem to guarantee the desired performance of the system [17].

There are three important particular structures to define interconnected systems: longitudinal (chain), connection of A_2 to A_4, through A_1; radial (star), connection of A_1, to A_2, A_3, and A_4 and loop (circle), connection of A_1, A_2, and A_3 (see Fig.6) [17]. All real systems can be defined as a combination of these structures. In this project, our case study system is in the loop shape structure connected to each other through tie lines. The schematic of the system is shown in Fig. 7.

In this schematic X_1, X_3, and X_5 are first, second, and third area's state variables respectively; and X_2, X_4, and X_6 as the common dynamics between the areas, are the tie lines dynamics.

The states variables of the whole power network with the loop configuration shown in Fig. 7 are

$$X = [X_1, X_2, X_3, X_4, X_5, X_6]^T$$



Fig, 6. Schematic diagram of an electric power system with four areas in different connections

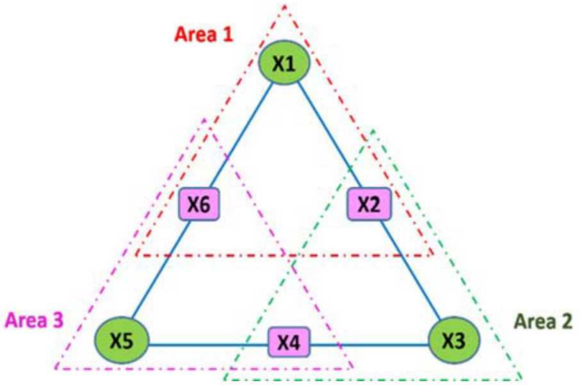


Fig. 7. Overlapping decomposition schematic for Loop structure

To decompose a large-scale system in any of the aforementioned structures, there is possibility to have some common part (dynamics) between two pairs such as X_2, X_4, and X_6 in Fig.7. In this case, we define the overlapped (common) dynamics as a subsystem that is a part of the pairs of other subsystems. To decompose such structure, we need to apply extended version of overlapping decomposition, multi-overlapping decomposition theory [17].

If we write the general state matrix for our loop shape connection as below:

$$A = \begin{bmatrix} A_{11} & A_{12} & 0 & & A_{1N} \\ A_{21} & A_{22} & A_{23} & \cdots & 0 \\ 0 & A_{32} & A_{33} & & 0 \\ & \vdots & & \ddots & \vdots \\ A_{N1} & 0 & 0 & \cdots & A_{NN} \end{bmatrix}$$

and consider the expanded system as

$$\begin{cases} \dot{\tilde{x}} = \tilde{A}\tilde{x} + \tilde{B}\tilde{u} \\ y = \tilde{C}\tilde{x} \end{cases} \tag{1}$$

where $\tilde{x}\epsilon R^{\tilde{n}}$, $\tilde{u}\epsilon R^{\tilde{m}}$ and $\tilde{y}\epsilon R^{\tilde{l}}$ are the state, input, and output vectors for expanded space and $\tilde{A}$, $\tilde{B}$, and $\tilde{C}$ are matrices with appropriate dimensions such that

$$\tilde{A} = VAU + M_A,\ \tilde{B} = VBQ + M_B,$$

$$and\ \tilde{C} = TCU + M_C \tag{2}$$

M_A, M_B, and M_C are complementary matrices, and V, U, R, Q, T, and S are full rank matrices with dimensions of $\tilde{n} \times n$, $n \times \tilde{n}$, $\tilde{m} \times m$, $m \times \tilde{m}$, $\tilde{l} \times l$, and $l \times \tilde{l}$ respectively such that $UV = I_n, QR = I_m$, and $ST = I_l$.

To decompose a multi-overlapping system, we need to:

1-Use a full rank transformation matrix to map the overlapping blocks for the sufficient times (depending on the number of pair-wise subsystems that share those blocks) and eliminate the interconnection parts by using appropriate complementary matrices.

2-Apply suitable permutation transformations to achieve the desired structure.

By using overlapping decomposition theory, expanded state matrix for loop structured system will be as follows:

$$\tilde{A} = \begin{bmatrix} A_{11} & 0 & A_{12} & 0 & \cdots & 0 & A_{1N} \\ 0 & A_{11} & A_{12} & 0 & \cdots & 0 & A_{1N} \\ 0 & A_{21} & A_{22} & 0 & \cdots & 0 & 0 \\ 0 & A_{21} & 0 & A_{22} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ A_{N1} & 0 & 0 & 0 & \cdots & A_{NN} & 0 \\ A_{N1} & 0 & 0 & 0 & \cdots & 0 & A_{NN} \end{bmatrix}$$

and after applying permutation matrix, the resulting state matrix will be:

$$\tilde{A}_P = P_A^{-1}\tilde{A}P_A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1N} & 0 \\ A_{21} & A_{22} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & A_{NN} & A_{N1} \\ 0 & A_{12} & \cdots & A_{1N} & A_{11} \end{bmatrix}$$

In the studied system, with $X = [X_1, X_2, X_3, X_4, X_5, X_6]^T$ by using the overlapping decomposition methodology, each decomposed subsystems will be represented as:

First decomposed area:

$$\begin{cases} \dot{\bar{X}}_1 = \bar{A}_1\bar{X}_1 + \bar{B}_1\bar{U}_1 \\ \bar{Y}_1 = \bar{C}_1\bar{X}_1 \end{cases} \tag{3}$$

where the first subsystem given in (3) has three inputs and three outputs, and 18 states. These states are $\bar{X}_1 = [X_6, X_1, X_2]^T$ and the state matrix, input and output matrix are

$$\bar{A}_1 = \begin{bmatrix} A_{66} & A_{61} & A_{62} \\ A_{16} & A_{11} & A_{12} \\ A_{26} & A_{21} & A_{22} \end{bmatrix},\ \bar{B}_1 = \begin{bmatrix} B_{13} & B_{11} & B_{12} \\ B_{23} & B_{21} & B_{22} \\ B_{33} & B_{31} & B_{32} \end{bmatrix}$$

$\bar{C}_1$ is block diagonal $\{C_{66}, C_{11}, C_{22}\}$, and

$\bar{X}_1 \in R^{18}, \bar{U}_1 \in R^3, \bar{Y}_1 \in R^3$, $\bar{A}_1: R^{18} \times R^{18}$, $\bar{B}_1: R^{18} \times R^3$, and $\bar{C}_1: R^3 \times R^{18}$.

Second decomposed area:

The second subsystem has two inputs and outputs. The subsystem in (4) has 12 states which are defined as

$$\bar{X}_2 = [X_2, X_3, X_4]^T$$

$$\begin{cases} \dot{\bar{X}}_2 = \bar{A}_2\bar{X}_2 + \bar{B}_2\bar{U}_2 \\ \bar{Y}_2 = \bar{C}_2\bar{X}_2 \end{cases} \tag{4}$$

The state, input and output matrices for the second subsystem are

$$\overline{A}_2 = \begin{bmatrix} A_{22} & A_{23} & A_{24} \\ A_{32} & A_{33} & A_{34} \\ A_{42} & A_{43} & A_{44} \end{bmatrix}, \overline{B}_2 = \begin{bmatrix} B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \\ B_{41} & B_{42} & B_{43} \end{bmatrix}$$

and $\overline{C}_2$ is block diagonal $\{C_{22}, C_{33}, C_{44}\}$ where

$\overline{X}_2 \in R^{12}$, $\overline{U}_2 \in R^2, \overline{Y}_2 \in R^2$, $\overline{A}_2 : R^{12} \times R^{12}$, $\overline{B}_2 : R^{12} \times R^2$, and $\overline{C}_2 : R^2 \times R^{12}$.

Third decomposed area:

Finally, the third decomposed subsystem is defined as in (5). It has two inputs and two outputs, with 15 states.

$$\begin{cases} \dot{\bar{X}}_3 = \bar{A}_3\bar{X}_3 + \bar{B}_3\bar{U}_3 \\ \bar{Y}_3 = \bar{C}_3\bar{X}_3 \end{cases} \tag{5}$$

These states are $\overline{X}_3 = [X_4, X_5, X_6]^T$ and the state, input and output matrices are

$$\overline{A}_3 = \begin{bmatrix} A_{44} & A_{45} & A_{46} \\ A_{54} & A_{55} & A_{56} \\ A_{64} & A_{65} & A_{66} \end{bmatrix}, \overline{B}_3 = \begin{bmatrix} B_{42} & B_{43} & B_{41} \\ B_{52} & B_{53} & B_{51} \\ B_{62} & B_{63} & B_{61} \end{bmatrix}$$

and $\overline{C}_3$ is block diagonal $\{C_{44}, C_{55}, C_{66}\}$ such that

$\overline{X}_3 \in R^{13}$, $U \in R^2$, $Y \in R^2$ and $\overline{A}_3 : R^{13} \times R^{13}$, $\overline{B}_3 : R^{13} \times R^2$, $\overline{C}_3 : R^2 \times R^{13}$.

After decomposing the large-scale system, still it can be too complicated to deal with decomposed subsystems due to their high order equations. Therefore, approximation procedures based on physical considerations or mathematical approaches is used to identify the original complicated models with lower order models, for purpose of controller design.

SYSTEM IDENTIFICATION

System identification tries to estimate a black or grey model of a dynamic system based on the observation of input-output experimental data. System identification can be done in time domain or frequency domain. In time domain identification, measured data are used directly to estimate model parameters. In frequency domain identification, the data are transformed to the frequency domain by using discrete Fourier transform (DFT), then, model parameters are estimated in the frequency domain. In this paper, we use time domain system identification to identify each subsystem in specific form as (6). This specific form of systems modeling guarantee the existence of the answer to design desired controller for the system in certain conditions [18]. Hence, we should reduce the order of the system according to the number of inputs, and given structure in (6). System identification provides a reduced order model approximation of the high order system which is required for the proposed approach in [18]. For this purpose, using the input/output data of original decomposed subsystem, and a nonlinear optimization algorithm, a linear system in the form of (6) is identified for each individual decomposed subsystem. This identified model mimics its original system with acceptable accuracy.

It has been shown if we identify each decentralized subsystem as (6)

$$\ddot{Y} = P\dot{Y} + QY + RU \tag{6}$$

By defining $Y = X_1$, and $\dot{Y} = X_2$ we can rewrite the system as

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & I \\ P & Q \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ R \end{bmatrix} U \tag{7}$$

$$Y = \begin{bmatrix} I & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$$

where both Y(t) and U(t) are n-dimensional vectors. P, R, and Q are real with compatible dimension matrices.

For system given in (7), we can apply following theorem in control design.

Theorem [18]:

A necessary and sufficient condition for the existence of a solution to decentralized servomechanism for given system in (7) such that $y(t) \rightarrow y_{ref}(t)$ or $e(t) \rightarrow 0$ as $t \rightarrow \infty$ in presence of specific class of disturbances described in [24] and the stability of closed loop system is that matrix R be full rank.

The full rank matrix *R* guarantees the existence of the solution for the given system. If we model each subsystem as given structure in (7) such that R matrix be full rank, the existence of a decentralized controller will be guaranteed. Next we will design decentralized controller for each rescued order identified subsystem based on given structure in (7).

STATE FEEDBACK DISTURBANCE REJECTION

After identifying system in given structure that guarantees the existence of the solution for system, we need to design the controller. Various controller design' approaches have been proposed based on disturbance nature. In this paper we assume that we have bounded disturbance affecting our system.

If we rewrite system (7) with given disturbances as

$$\begin{cases} \dot{x} = Ax + Bu + \omega \\ y = Cx \end{cases} \tag{8}$$

where $A = \begin{bmatrix} 0 & I \\ P & Q \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ R \end{bmatrix}$, and $C = \begin{bmatrix} I & 0 \end{bmatrix}$

the state of the system x is a n vector, and the output, y, is a r-vector ($r \leq n$), and $\omega(t)$ is a n-vector unknown, unmeasurable impulse or step-function type, and bounded disturbance. The necessary and sufficient conditions to find a linear time invariant differential feedback controller to $y(t) \rightarrow y_{ref}(t)$ or $e(t) \rightarrow 0$ as $t \rightarrow \infty$ are:

i) (A, B) be controllable

ii) $\text{rank}\begin{pmatrix} A & B \\ C & 0 \end{pmatrix} = n + r$

and, the minimum order feedback control will be defined as

$$u = k_1 x + k_2 \int_0^t y(t) dT + \eta_0 \tag{9}$$

where η_0 is unspecified and is arbitrary and it can be lumped in with the disturbance [25]. k_1 and k_2 will be found such that the eigenvalues of the matrix (10) are negative and equal to the desired values.

$$\begin{pmatrix} A + Bk_1 & Bk_2 \\ C & 0 \end{pmatrix} \tag{10}$$

To design the state disturbance rejection controller based on (10), we need to identify the new subsystems' states. A Luenberger observer is designed to have a good state estimation of the reduced order model states.

Choosing Luenburger observer with given structure in

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y}) \\ \hat{y} = C\hat{x} \end{cases} \tag{11}$$

with appropriate observer gain L, such that eigenvalues of A-LC are on the left half plan, the estimation error in (13), will tend asymptotically to zero. The eigenvalues of A-LC determine how fast the estimated values of $x, \dot{x}$ converge to it.

$$\dot{\tilde{x}} = \dot{x} - \dot{\hat{x}} = (A - LC)(x - \hat{x}) = (A - LC) \tag{12}$$

We first design the observer on the identified model of each subsystem. Next, having a good estimation over the states of the subsystems, we can design proper state feedback controller for each subsystem. Based on (9), the system is formulated as (13).

$$\frac{d}{dt}\begin{bmatrix} x \\ q \end{bmatrix} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix} \cdot \begin{bmatrix} x \\ q \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} \begin{bmatrix} k_1 & k_2 \end{bmatrix} \begin{bmatrix} x \\ q \end{bmatrix} + \begin{bmatrix} 0 \\ -I \end{bmatrix} y_{ref} \tag{13}$$

$$\rightarrow \frac{d}{dt}\begin{bmatrix} x \\ q \end{bmatrix} = \begin{bmatrix} A + Bk_1 & k_2 \\ C & 0 \end{bmatrix} \cdot \begin{bmatrix} x \\ q \end{bmatrix} + \begin{bmatrix} 0 \\ -I \end{bmatrix} y_{ref} \tag{14}$$

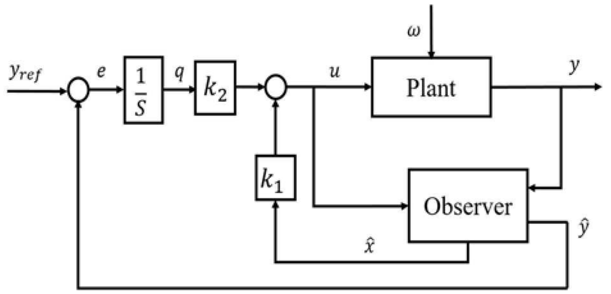


Fig. 8. Observer and State feedback controller

where $q = \int(\hat{y} - y_{ref})dt$ is defined as integrator of the tracking error. The block diagram of the observer and state feedback controller design for disturbance rejection is shown in Fig. 8.

Remark: It is worth mentioning that the designed controller works for any bounded disturbances, which may occur in the plant or in feedback matrices as long as the new close loop system remains stable [24].

The remark is very important for two reasons: First, we use an observer to estimate the identified system states. Second, we design the controller based upon the identified reduced model of the subsystems and next we apply the controller to the original system. The difference between the original system and identified system generates disturbances that can make the closed loop system unstable [25,26]. Hence, we need to design the gains of the controller such that the new closed loop system (16) is stable.

$$\begin{pmatrix} \overline{A_\iota} + \overline{B_\iota} k_1 & \overline{B} k_2 \\ \overline{C_\iota} & 0 \end{pmatrix} \quad \text{for } i\text{=1,2.3} \tag{65}$$

where $\overline{A_\iota}$, $\overline{B_\iota}$, and $\overline{C_\iota}$ are decomposed system matrices. Finding the k_1 and k_2 such that the given matrix in (10), and (15) are stable is the most challenging part in control designing which depends on accuracy of the system identification.

In our case study k_1 and k_2 for second and third area are found based on predefined eigenvalues for (10). The designed controllers work for the original systems properly which means that the matrix (15) is stable with given k_1 and k_2. For the first area finding the k_1 and k_2 was more challenging due the system identification error. k_1 and k_2 for each subsystem is given in (16), (17), and (18) respectively.

k_{1-i} is k_1 for area i=*1,2.3*

k_{2-i} is k_2 for area i=*1,2.3*

$$k_{1-1} = \begin{bmatrix} 8.24 & -0.14 & -6.05 & -2.36 & -40.1 & -2.8 \\ 8.23 & 14.7 & -7.45 & 20.4 & 34.2 & -14.2 \\ 41.7 & 8.95 & -15.4 & -4.7 & -227 & 2.59 \end{bmatrix}$$

$$k_{2-1} = \begin{bmatrix} 0.01 & -0.12 & 0.03 \\ -0.07 & 0.73 & -0.15 \\ 0.01 & -0.15 & 0.03 \end{bmatrix} \tag{76}$$

$$k_{1-2} = \begin{bmatrix} 191 & 27.7 & 5.9 & 1546 \\ 187 & -1230 & 273.5 & -1854 \end{bmatrix},$$

$$k_{2-2} = \begin{bmatrix} -0.2 & 3 \\ 8.1 & -152.3 \end{bmatrix} \tag{87}$$

$$k_{1-3} = \begin{bmatrix} 2.1 & -1.63 & -2.68 & -14.48 \\ -5.5 & -28.7 & 89.2 & -267.9 \end{bmatrix},$$

$$k_{2-3} = \begin{bmatrix} 0.01 & 0.01 \\ -0.52 & -0.68 \end{bmatrix} \tag{18}$$

DISCUSSION AND RESULTS

To analyze the effect of the controller on inter-area oscillation damping, a step disturbance with magnitude of 0.01 pu is applied to the system in tie line between first and second areas at t=5 *s*. Results before and after applying the controller to the system in each area is shown in Fig. 9, Fig10, and Fig.11. It has been shown that the oscillations in frequency of each area has been well damped in presence of the controller.

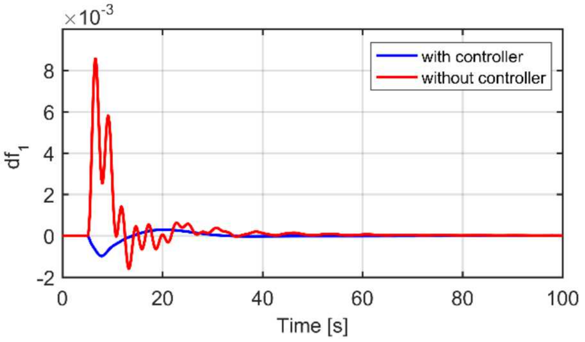


Fig. 9. Frequency deviation in first area due to fault in tie line

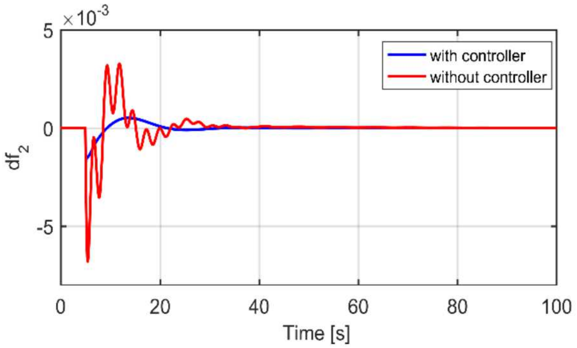


Fig. 10. Frequency deviation in second area due to fault in tie line

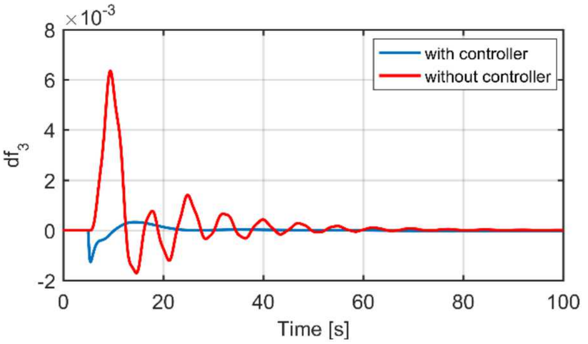


Fig. 11. Frequency deviation in third area due to fault in tie line

CONCLUSION

For a given loop shape large scale power system, after decomposing the system to three subsystems, the order of each subsystem is reduced based on their inputs number in the given structure. A disturbance rejection state feedback controller has been designed for each identified subsystem and has been applied to the original system. Due to some error between the original system and the identified system, it is shown that design of a desired controller for the system is challenging. A successfully designed control system should be able to maintain the stability and performance level of the system in spite of uncertainties up to a certain degree. To enhance the controller design in this system, we can take three approaches: *i)* improving the system identification to decrease the identification error, *ii)* defining the disturbances affecting the system accurately, and *iii)* employing more robust control approach in the system such as robust controller or robust servomechanism controller approaches.

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