IMPROVING INTER-AREA OSCILLATIONS DAMPING OF POWER SYSTEMS THROUGH COOPERATIVE ACTIVE POWER CONTROL OF DISTRIBUTED ENERGY RESOURCES

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ABSTRACT

The remarkable growth of power electronics-interfaced renewable generations in the electric power grid has the potential to pronounce the effect of frequency disturbances such as inter-area oscillations. These low-frequency disturbances reduce transmission lines capacity, and at worst even damage the power grid infrastructures. In this paper, we propose a novel control algorithm to eliminate inter-area oscillations modes based on local measurements of frequency and the system’s global average frequency. The performance of the proposed solution is investigated on different multi-machine test systems with classic and detailed electromechanical dynamic models through modal analysis and time-domain simulations. The modal analysis results indicate that all the inter-area modes are damped for all test cases. Time-domain simulations also demonstrate that the proposed control not only takes the system to near-zero inter-area oscillations but also improves other power system stability measures such as transient stability and frequency nadir.
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CHAPTER 1

INTRODUCTION

1.1 General Background

The massive deployment of distributed energy resources (DERs) is set to profoundly transform the twenty-first-century power systems. The high penetration of DERs has made the modern grids susceptible to frequency instabilities. The growth of intermittent renewable energy resources has pronounced the effect of frequency disturbance such as inter-area oscillations. This necessitates new control laws to improve the damping of oscillations in power systems for the secure and reliable operation of the grids. Below is a brief description on the terms that have been frequently used in the thesis.

*Inter–Area Oscillations* are undesirable oscillations resulting from small disturbances in the power grid with weakly connected tie lines; the group of generators in one side of tie line oscillate against the group of generators in the other side of the tie lines.

*Distributed Energy Resources* (DER) are the spatially distributed resources in the physical structure of the grid, which are predominantly renewable in nature.

*Distributed Control System* is a system of geographically distributed control elements with no dedicated central controller.
1.2 Statement of Problems

Low frequency oscillations compromise the power transfer capability of transmission lines, and have the potential to damage the power grid infrastructure. This work investigates the control laws to improve inter-area oscillation damping through the control of DERs.

• **Inter-Area Oscillation Damping through Active Power Control of DERs:** Power System Stabilizers have been fundamental to damp the low frequency oscillations. However, recent literature [1] have proposed methods to damp the oscillations using the existing loads in the system. However, to the best of my knowledge, there is a gap in the literature in the active power control of DERs to damp the low frequency oscillations.

• **Distributed Inter-Area Oscillation Damping through Active Power Control of DERs:** In recent literature, distributed control approaches in damping the low frequency oscillations have been proposed [1–3]. None of the authors, however, propose distributed control of DERs based on the local frequency deviation from the estimate of the average frequency of the network.

1.3 Contributions

This thesis proposes novel control solutions to achieve near-zero inter-area oscillations. The control design exploits local frequency measurements from phasor measurement units (PMUs) combined with a communication network and local energy storage systems (ESS) in order to damp inter-area modes. The proposed control adjusts the power output of a local energy storage system
(ESS) based on the difference between the local frequencies values and system average frequency.

The contribution of this thesis are as follows:

- **Inter-Area Oscillation Damping through Active Power Control of DERs:** First, a control solution is proposed in chapter 3, with a straight-forward control loop to adjust the power output for each participating agent. In this platform, all network buses (or generation buses) communicate their local frequencies with each other and calculate the system average frequency at their end. The mismatch between local frequencies and the average frequency through some proportional gains defines how much each generator must increase or decrease its power output to contribute to inter-area oscillation damping. For the minimal impact on the power network’s operation, the control is designed to tackle only the inter-area oscillations modes, without affecting the other dynamic modes.

- **Distributed Inter-Area Oscillation Damping through Active Power Control of DERs:** Chapter 5 expands the framework in chapter 4 and proposes distributed control framework to mitigate inter-area oscillations. In this platform, which is called *distributed frequency deviation control (DFDC)* hereafter, each bus defines how much power to absorb or inject in response to its own frequency deviation from average frequency to contribute in the inter-area oscillation damping process. To avoid the need for a central communication platform, DFDC employs a distributed average consensus process based on [4, 5] to let each bus have a meaningful estimate about average frequency. As the objective of DFDC is to force local frequencies to converge at any time to mitigate the inter-area oscillations, it increases (or decreases) the power injection at any bus if the local frequency is lower (or greater) than the
average frequency. The other feature of DFDC is that it can be designed to address inter-area oscillations only—without affecting the other dynamic modes of the system.

1.4 Thesis Outline

The rest of the thesis is organized as follows. Chapter 3 introduces some background on graph theory, and small signal analysis. Chapter 4 presents the proposed control architecture for a complete connected network, where all the agents (or generator) share information about their local frequency. Chapter 5 expands the algorithm to work in a distributed fashion, based on the dynamic average consensus. Chapter 6 concludes with directions ahead for future research.
CHAPTER 2
LITERATURE REVIEW

Electric power grids experience oscillations or power swings between disperse geographical areas, which is a result of synchronous machines in one area oscillating against other generators in farther regions connected by weak tie lines. These frequency excursions are known for reducing the transmission lines power transfer capabilities [6] and, when not damped, can cause serious stability issues. High power transfers and weak interconnections between distant regions are the main causes of such oscillations [7]. Currently, as traditional synchronous machines are being slowly replaced by inverter-based energy resources, the electrical grid loses inertia and traditional sources of oscillation damping, which can intensify low frequency modes. For example, authors in [8] found that as "photovoltaic (PV) generation increases, the damping of the dominant oscillation mode decreases monotonically," which suggests that inter-area oscillations escalate as PV generation grows. Furthermore, because of the intermittent nature of distributed energy resources (DER), recurring mismatches between the generation and load are expected to happen, disrupting the angles between machines, and consequently enhancing inter-area oscillations.

The rapid increase in penetration of DER—especially variable renewable energy (VRE) systems including solar and wind—has caused some adverse impacts on power system operation such as voltage [9], protection relay settings [10], and frequency [11]. Consequently, reliable operation of power systems becomes a major concern for distribution and transmission system operators (DSO,
TSO) [12]. After the recent advancement in addressing the adverse impacts of inherent intermittency of DER on distribution system voltage profiles through smart inverters [13] and distribution system control devices [14, 15], their impacts on frequency rise has been the next concern for TSO. These concerns are not only due to the intermittent nature of DER but also because of the loss of the inertia in power systems as synchronous generators are gradually replaced by inertia-less power electronic converters.

Historically, power system stabilizers (PSS) have been the most important component to improve the damping of low-frequency oscillatory modes. They provide a stabilizing signal to the exciter based on local measurements of frequency and/or power mismatch to produce an electrical torque in phase with the rotor speed deviations to eliminate regional oscillatory modes. However, PSS signals may intrinsically counteract with the voltage signals from automatic voltage regulators (AVR) and deteriorate transient stability in case of sudden disturbances.

The recent advancements on wide-area measurement systems (WAMS) and smart grid capabilities in power systems, has equipped Transmission System Operators (TSO) with enhanced power system monitoring capabilities through instantaneous communication between distant areas, which has allowed new real-time control approaches to surge [16, 17]. These capabilities may be utilized to develop cooperative solutions for frequency control including inter-area oscillation damping.

Currently power system stabilizers (PSS), FACT devices [3], and energy storage systems (ESS) [18] constitute the main actors of control architectures to damp low-frequency oscillations. Some recent works on the literature [19–23] propose to use phasor measurement units (PMU) information to fine-tune PSS devices to damp inter-area modes. In [21], for instance, PSS is adjusted to
create a trade-offs between power system transients and small-signal responses. Other author such as [1] propose to use PMU information as a decision parameter to curtail the load in specific clusters of the network, in order to damp the inter-area oscillations. A similar approach is proposed in [2] where wind turbine generation and the load aggregators are coordinated in a distributed fashion to provide supplementary damping to the low frequency oscillation modes. For this, they adapt their active power generations and consumption to support inter-area oscillation damping. Furthermore, other works on the literature propose to coordinate FACT devices [3] and energy storage systems (ESS) [18] to damp the low-frequency modes.

The high share of distributed energy resources (DER) that are unpredictable and variable necessitates a real-time approach for PSS tuning. However, as central PSS-based centralized control architectures require fast and often expensive communication channels to exchange data, they are not practical and reliable. Distributed solutions are one of the ways to address this concern. So far, several methods based on distributed control are proposed to damp low-frequency oscillations [1–3]. A distributed approach is proposed in [2] to coordinate wind-turbine generation and load aggregators to provide supplementary damping of the low-frequency oscillation modes. As the deployment of DER increases, a plethora of articles have investigated the pertinence and efficacy of distributed algorithms in control and optimization of power systems. A distributed algorithm is implemented to optimize generators’ output in [24], and DC optimal power flow is realized in distributed fashion in [25]. Apart from addressing the computational complexity, the ability of distributed algorithms to control and optimize with the limited information from the connected neighbor helps to preserve privacy of information. Further, a distributed approach extends in control applications such as optimal frequency control of multi-area systems in [26], and a time-varying
state-of-charge parameter is defined using a dynamic average consensus algorithm to implement frequency control in [27]. Some distributed frequency control algorithms are also reported in literature where the main focus is on operating the power network at its optimal operation condition and where local frequencies are used as a proxy for global power mismatch [28, 29].
CHAPTER 3
FUNDAMENTAL CONCEPTS

This chapter introduces fundamental concepts on graph theory, consensus algorithms, and small-signal stability, which together build the foundation for the coming chapters.

3.1 Distributed Consensus Algorithms

3.1.1 Graph Theory

Network Notation: Let $\mathcal{G}$ denote a graph with the set of vertices $\mathcal{V} = \{1, \cdots, n\}$ and the edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$; $\mathcal{G}$ is restricted to simple, undirected graph without multi-edges and self-edges. The cardinality of node, $|\mathcal{V}|$ is $n$ and that of edge, $|\mathcal{E}|$ is $m$. We define $\mathcal{N}_i = \{ j \in \mathcal{V} | (j, i) \in \mathcal{E} \text{ and } j \neq i \}$ as the set of all the neighbors of the agent $i$ excluding itself; the cardinality of the set $|\mathcal{N}_i|$ is $d_i$, called the degree of the node $i$. The set of all real numbers is denoted by $\mathbb{R}$, $\mathbb{R}^*_+$ as the set of positive real numbers, and $n$ as the number of agents of the network. $\mathbf{I}_{n \times n} \in \mathbb{R}^{n \times n}$ is an identity matrix, and $\mathbf{1}_n \in \mathbb{R}^n$ is a unit vector.

Spectral Graph theory is the study of eigenvalues and eigenvectors to understand the graph network. Let $\mathbf{A}$ be the adjacency matrix of graph $\mathcal{G}$, and $\mathbf{D}$ be the degree matrix with the vertex degree along its diagonal. Then, the graph Laplacian $\mathbf{L} \in \mathbb{R}^{N \times N}$ can be expressed in matrix form.
as:

\[ L = D - A \]  \hspace{1cm} (3.1)

In full form:

\[
l_{ij} := \begin{cases} 
    d_i & i = j, \\
    -1 & i \neq j \text{ and there is an edge } (i,j) \\
    0 & \text{otherwise}
\end{cases}
\] \hspace{1cm} (3.2)

The Laplacian consensus dynamics is given by the equation

\[ \dot{x} = -Lx \] \hspace{1cm} (3.3)

where \( x \in \mathbb{R}^N \) is the values of corresponding vertices of the network. The spectral analysis on the Laplacian graph shows that

\[ 0 = \lambda_1(L) \leq \lambda_2(L) \leq \cdots \leq \lambda_N(L) \] \hspace{1cm} (3.4)

where \( \lambda_i \) denotes eigenvalue.

Note that \( L \) is a symmetric positive semi-definite matrix, and the connectivity is revealed by the algebraic connectivity \( \lambda_2(L) \).

Following lemmas on graph network are listed below, which would be employed in later chapters.
Lemma 1 Communication topology between all the agents $A(t)$ is connected at all times $t \geq 0$.

i.e., $\lambda_2(L) \geq 0$

Lemma 2 Any bus $i$ can exchange information only with its neighboring agents i.e. $N_i = \{j \in V | (j, i) \in E \text{ and } j \neq i\}$. The coloring scheme of the network is available.

Lemma 3 Laplacian Matrix $L$ is positive semidefinite, $\sum_j L_{ij} = 0$, and $\lambda_2(L)$ is the algebraic connectivity of the network. The speed of convergence to reach the consensus in the iterative process is governed by $\lambda_2(L)$ for it represents the convergence rate of the slowest mode [30].

3.1.2 Completed Graph

The communication network is modeled as a complete graph in which each pair of distinct vertices is connected by an edge. Let $x_j$ be a signal at node $j$, and $\bar{x}$ be the average of the network, then,

$$\bar{x}_i = \frac{1}{n} \sum_{j=1}^{n} x_j, \quad \forall i \in V$$

In matrix format,

$$\bar{x} = \frac{1_n 1_n^T}{n} x = W x$$

3.1.3 Decentralized and Distributed Algorithms

Consensus algorithms are iterative process of searching for the consensus on some parameters. Based on their architectural framework, they are categorized in three types: centralized,
decentralized, and distributed. Figure 3.1 [31] shows three different design architectures of algorithms

In a centralized framework, one central entity calculates the average, and communicates back to the agents. This algorithm has been employed for a long time, and still extensively used. While it is often characterized by its simplicity, the computation and communication challenges are quite serious. In decentralized algorithms, all agent can individually run the consensus process in the presence of a master node(s) for tight coordination. This coordinator are often called by the name of aggregators. While the large problem is divided among agents, but this is still vulnerable to single point failure, and the concern for the confidentiality of data still alarms the participating agents.

In distributed algorithms, each agent finds consensus based on its and neighbor’s information. Some of the characterizing features of distributed algorithms are worth listing here [32].
• **Scalibility**: The size of optimization problem doesn’t grow with the network size as compared to centralized framework.

• **Robustness**: Most of the distributed algorithms can be modeled to handle communication delays, packet drop, plug-and-play etc.

• **Data Privacy**: Distributed algorithms do not need to trust a single entity to collect data, and facilitate the optimization process.

### 3.1.4 Dynamic Average Consensus

Let \( x^0 \in \mathbb{R}^n \) be the initial value at each node of \( G \), where \( x^0 = \{x^0_1, \ldots, x^0_i, \ldots, x^0_n\} \). In a fully distributed algorithm, any agent \( i = \{1, \ldots, n\} \) has to calculate the average of the network, \( \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x^0_i \), from the information of its own and that of neighbors’. Let us consider **distributed linear iteration** of the form

\[
 x_{i}^{k+1} = w_{ii}x_{i}^{k} + \sum_{j \in \mathcal{N}_i} w_{ij}x_{j}^{k}, \quad i = 1, \ldots, N
\]  

(3.7)

where \( k = 0, 1, 2, \ldots \) and \( w_{ij} \) is the weight on \( x_j \) at node \( i \), and \( \mathcal{N}_i \) denotes the set of all neighbors of agent \( i \). Setting \( w_{ij} = 0 \) for \( j \notin \mathcal{N}_i \), this iteration can be written as

\[
 x^{k+1} = Wx^k
\]

(3.8)
or equivalently as

\[ x_{i}^{k+1} = W_{i}^{T}x_{k} \] (3.9)

where \( W = [w_{ij}] = [W_{1}, \ldots, W_{N}] \in \mathbb{R}^{N \times N} \) with \( W_{i} \in \mathbb{R}^{N \times 1} \). According to [33], the constraint on the sparsity pattern of the matrix \( W \) can be expressed as \( W \in \mathcal{S} \), where

\[ \mathcal{S} = \{ W \in \mathbb{R}^{N \times N} | W_{ij} = 0 \text{ if } \{i, j\} \notin \mathcal{E} \text{ and } i \neq j \} \] (3.10)

and (3.8) can be written as

\[ x^{k} = W^{k}x^{0}, \quad k = 0, 1, 2, \ldots \] (3.11)

This brings to a matrix \( W \) such that

\[ \lim_{k \to \infty} W^{k} = \frac{11^{T}}{N} \quad \text{as} \] (3.12)

This brings to state the following Lemma on weight matrix \( W \).
Lemma 4. The following conditions are necessary to guarantee the convergence [33]

\[
\begin{cases}
1^T W = 1^T \\
W 1 = 1 \\
\zeta(W - 1 1^T / N) < 1
\end{cases}
\]  

(3.13)

where \(\zeta(\cdot)\) is the spectral radius of the matrix, \(1 = [1, \cdots, 1]^T\) is the eigenvector associated with weight matrix \(W\), and \(1^T\) is the transpose of \(1\).

The coefficients of matrix \(W\) determines the speed of the convergence. Constant edge weight and local degree weight matrices are discussed in [33]. The local degree weight matrix \(W\) with coefficients depending only on the degree of the incident node is

\[
w_{ij} = \begin{cases}
\frac{1}{\max\{d_i, d_j\}} & \{i, j\} \in \mathcal{E} \\
1 - \sum_{j \in \mathcal{E}} \frac{1}{\max\{d_i, d_j\}} & i = j \\
0 & \text{otherwise}
\end{cases}
\]  

(3.14)

This method is implied from the Metropolis-Hastings algorithm and often called Metropolis method.

The improved Metropolis called Mean Metropolis is proposed in [34] where

\[
w_{ij} = \begin{cases}
\frac{2}{\{d_i + d_j + \epsilon\}} & \{i, j\} \in \mathcal{E} \\
1 - \sum_{j \in \mathcal{E}} \frac{2}{\{d_i + d_j + \epsilon\}} & i = j \\
0 & \text{otherwise}
\end{cases}
\]  

(3.15)
where $\epsilon$ is a very small number. The average consensus described by (3.8) can be extended to on a consensus on general time varying signal [5].

**Dynamic Average Consensus:** Let $\Delta z$ be the input bias applied to average consensus system. We can claim that the following modification to (3.8) makes the dynamic consensus algorithm track the time-varying average consensus:

$$x^{k+1} = Ax^k + \Delta z \quad (3.16)$$

where the bias $\Delta z$ is equal to $z^{k+1} - z^k$. See the authors’ previous paper [24] for more details on convergence of average consensus and dynamic average consensus. Figure 3.2 shows an example of communication network for IEEE bus.

![Communication Network for IEEE 39-bus](image)

**Figure 3.2** Communication Network for IEEE 39-bus; the value in each node can be thought as changing over time and each node estimates the average of the network in a distributed fashion.
3.2 Small Signal Stability

Small signal stability analysis is characterized by the ability of the power system to keep its synchronism while subjected to small disturbances. This analysis is applied into the linearized system models under a given balanced condition and provides useful information on the level of safety in which the system is operating [35].

Small disturbances, like the normal small fluctuations in the system loads or small changes of the set values of some parameters, are always present in a power system. They normally result in power (or electromechanical) oscillations that are stable; in other words, the oscillations are positively damped and decay with time. On the other hand, these spontaneous oscillations may occasionally grow in amplitude with time, because of insufficient damping. This leads to sustained low frequency oscillations that cause loss of synchronism. The low frequency oscillations of the inter-area mode of the system are investigated in depth, since their interaction with forced oscillation can lead to resonance phenomena. For that purpose, modal analysis and linearization techniques are of great importance, as they set the basis of the low frequency oscillations. The purpose of this section is to describe the theoretical background of these concepts.

3.2.1 State-Space Representation

The dynamical behavior of a nonlinear system may be described as a set of $n$ first order nonlinear ordinary differential equations of the following form:

$$\dot{x}_i = f_i(x_1, x_2, \ldots, x_n; u_1, u_2, \ldots, u_r, t)$$ (3.17)

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Assuming that the derivatives of the state variables are not time dependent, we can rewrite (3.17) in the vector form as

\[ \dot{x} = f(x, u) \]  

(3.18)

where \( x \) is a column vector referred as the state vector, and its entries as state variables. The column vector \( u \) is a vector of inputs that are applied to the system, which influence its dynamics. We are often interested in output variables which can be observed on the system. These maybe expressed in terms of the state variables and the input variables in the following form:

\[ y = g(x, u) \]  

(3.19)

Where \( y \) is a column vector of outputs, and \( g \) is a vector of nonlinear functions associating the states and inputs to the output variables.

### 3.2.2 Eigenproperties of the state matrix

#### 3.2.2.1 Eigenvalues

The eigenvalues of a matrix are given by the values of the scalar parameter \( \lambda \) for which there exist non-trivial solutions to the equation

\[ A \phi = \lambda \phi \]  

(3.20)
where $A$ is a $n \times n$ matrix and $\phi$ is an $n \times 1$. In order to determine the eigenvalues, $\lambda$, (3.20) can be rewritten as the following

$$A\phi - \lambda \phi = 0$$  \hspace{1cm} (3.21)

For a non-trivial solution

$$det(A - \lambda I) = 0$$  \hspace{1cm} (3.22)

The development of the determinant on (3.21) results in the characteristic equation of $A$ and its roots, $\lambda = \lambda_1, \lambda_2, \ldots, \lambda_n$, are refereed as eigenvalues, which can be either real or complex. Another characteristic of it is that similar matrices or conjugated matrices will always have the same eigenvalues. Those can be also refereed as the modes of a system they carry out important information about the oscillatory modes of the system it represents. The equation (3.23) displays the components of the eigenvalues the real part of the refereed as $\sigma_i$ shows represents the damping of the $i^{th}$ mode the imaginary component , $\omega_i$, gives the oscillation frequency of the $i^{th}$ mode.

$$\lambda_i = \sigma_i \pm j\omega_i$$  \hspace{1cm} (3.23)

The oscillation in hertz can be obtained by the equation (3.24) and the damping ratio of the oscillatory mode can be calculated by (3.25).

$$f_i = \frac{\omega_i}{2\pi}$$  \hspace{1cm} (3.24)
\[ \zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \] (3.25)

Oscillatory modes will diminish for negative values of \( \sigma_i \), and those constitute stable modes. On the other hand, negative values of \( \sigma_i \) represent a exponential growth in the amplitude of these modes, in which case the system will be unstable.

### 3.2.2.2 Eigenvectors

For any \( \lambda_i \) the column vector \( \phi_i \) that satisfies the equation (3.20) is refereed as right eigenvector of \( A \) associated with the eigenvalue \( \lambda_i \). Therefore, we have

\[ A\phi_i = \lambda_i\phi_i \] (3.26)

The left eigenvector of \( A \) corresponding to the eigenvalue \( \lambda_i \) must satisfy the equation (3.27)

\[ \psi_i^T A = \lambda_i\psi_i^T \] (3.27)

Where \( \psi_i^T \) is a row vector \( 1 \times n \). The left and the right eigenvectors corresponding to different eigenvalues are orthogonal. Therefore for \( \lambda_i \) and \( \lambda_j \) the product of the left eigenvector with the right eigenvector must be equal to zero as it is shown in equation (3.28).

\[ \psi_i\phi_j = 0 \] (3.28)
On the other hand, for the same eigenvalues the product should result in a scalar as expressed in equation (3.29).

\[ \psi_i \phi_i = C_i \]  

(3.29)

Where \( C_i \) is a non-zero constant, for this reason it is a common practice to normalize the vectors so then the results of (3.29) equals to 1.

### 3.2.3 Modal Matrices

In order to express the aforementioned properties in a convenient way we introduce the modal matrices notation.

\[ \Phi = [\phi_1, \phi_2, \ldots, \phi_n] \]

(3.30)

\[ \Psi = [\psi_1^T, \psi_2^T, \ldots, \psi_n^T]^T \]

In addition to that, we introduce notation of the diagonal matrix \( \Lambda \) containing all the eigenvalues of a system as

\[ \Lambda = \begin{bmatrix}
\lambda_1 & 0 & \ldots & 0 \\
0 & \lambda_2 & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & \lambda_n
\end{bmatrix} \]

(3.31)

Each of these matrices is \( n \times n \) and the equations can be expanded as follows.

\[ A \Psi = \Phi \Lambda \]  

(3.32)
\[ \Psi \Phi = I \quad \Psi = \Phi^{-1} \]  \hspace{1cm} (3.33)

\[ \Psi A \Phi = \Lambda \]  \hspace{1cm} (3.34)

### 3.2.4 Linearization of the system

The stability of a linear system is fully independent of the system’s input, and initial states, i.e.: the states of a stable system with zero input will always retreat to the origin of the state space, independently of the magnitude of its finite initial [35]. On the other hand, the stability of a nonlinear system is bounded to its initial state and input magnitudes. Therefore, one of the ways to understand the stability of such systems under different conditions is to use linearization techniques. Those can provide the means for engineers to have a good understanding of the stability of the non-linear system.

Let \( x_0 \) be the vector containing all the initial values of each state variable being modeled in our system, and let \( u_0 \) be the vector containing all initial input magnitudes. We are assuming that at \( t = 0 \) the system is at rest and therefore:

\[ \dot{x}(t) = f(x_0, u_0) = 0 \]  \hspace{1cm} (3.35)

By applying a small perturbation at the states and inputs we have the following:

\[ x = x_0 + \Delta x \quad , \quad u = u_0 + \Delta u \]  \hspace{1cm} (3.36)
Where \( \Delta \) denotes a small deviation on the parameter it precedes. In this new condition the equation (3.18) will still hold true, and we can develop it as

\[
\dot{x} = \dot{x}_0 + \Delta \dot{x}
\]

\( = f[(x_0 + \Delta x), (u_0 + \Delta u)] \) (3.37)

Since the perturbations are considered to be small, the nonlinear function \( f(x, u) \) can be expressed in terms of Taylor’s series expansion. With terms above second order being neglected we may write for each individual state \( x_i \)

\[
\dot{x}_i = \dot{x}_{i0} + \Delta \dot{x}_{i0}
\]

\( = f_i[(x_0 + \Delta x), (u_0 + \Delta u)] \)

\( = f_i(x_0, u_0) + \frac{\partial f_i}{\partial x_i} \Delta x_1 + \ldots + \frac{\partial f_i}{\partial x_n} \Delta x_n + \frac{\partial f_i}{\partial u_i} \Delta u_1 + \ldots + \frac{\partial f_i}{\partial u_r} \Delta u_r \) (3.38)

Since \( \dot{x}_{i0} = f(x_0, u_0) \) we obtain

\[
\Delta x_i = \frac{\partial f_i}{\partial x_1} \Delta x_1 + \ldots + \frac{\partial f_i}{\partial x_n} \Delta x_n + \frac{\partial f_i}{\partial u_1} \Delta u_1 + \ldots + \frac{\partial f_i}{\partial u_r} \Delta u_r
\]

(3.39)

with \( i = 1, 2, \ldots, n \). The same process can be applied in equation (3.19) leading to with \( j = 1, 2, \ldots, m \).

\[
\Delta y_j = \frac{\partial g_j}{\partial x_1} \Delta x_1 + \ldots + \frac{\partial g_j}{\partial x_n} \Delta x_n + \frac{\partial g_j}{\partial u_1} \Delta u_1 + \ldots + \frac{\partial g_j}{\partial u_r} \Delta u_r
\]

(3.40)
Therefore, the linearized form of equations (3.18) and (3.19) are

\[ \Delta \dot{x} = A \Delta x + B \Delta u \]  
(3.41)

\[ \Delta y = C \Delta x + D \Delta u \]  
(3.42)

where

\[
A = \begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\
\vdots & \ddots & \vdots \\
\frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
\frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_r} \\
\vdots & \ddots & \vdots \\
\frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r}
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
\frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\
\vdots & \ddots & \vdots \\
\frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_n}
\end{bmatrix}
\]

\[
D = \begin{bmatrix}
\frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_r} \\
\vdots & \ddots & \vdots \\
\frac{\partial g_m}{\partial u_1} & \cdots & \frac{\partial g_m}{\partial u_r}
\end{bmatrix}
\]

The aforementioned partial derivatives are calculated at the equilibrium point about which the small perturbation is being analyzed.

- \( \Delta x \) is the state vector of dimension \( n \)

- \( \Delta y \) is the output vector of dimension \( m \)

- \( \Delta u \) is the input vector of dimension \( r \)

- \( A \) is the state matrix or plant matrix of dimension \( n \times n \)
• **B** is the control or *input* matrix of dimension $n \times r$

• **C** is the output matrix of dimension $m \times n$

• **D** is the matrix that characterizes the portion of input which appears on the output, its dimension is $m \times r$

By applying the Laplace transform on the above differential equations, we obtain the following state equations in the frequency domain:

\[
s\Delta \mathbf{x}(s) - \Delta \mathbf{x}_0 = A\Delta \mathbf{x}(s) + B\Delta \mathbf{u}(s)
\]  

(3.43)

\[
\Delta \mathbf{y}(s) = C\Delta \mathbf{x}(s) + D\Delta \mathbf{u}(s)
\]  

(3.44)

Solving for $\Delta \mathbf{y}(s)$, leads to

\[
\Delta \mathbf{y}(s) = C \frac{\text{adj}(sI - A)}{\det(sI - A)} [\Delta \mathbf{x}_0 + B\Delta \mathbf{u}(s)] + D\Delta \mathbf{u}(s)
\]  

(3.45)

The Laplace transform of $\Delta \mathbf{y}(s)$ has two components, one dependent on the initial conditions and the other on the inputs. These are the Laplace transforms of the *free* and *zero-state components* of the output vectors. The poles of $\Delta \mathbf{y}(s)$ are the roots of the equation

\[
\det(sI - A) = 0
\]  

(3.46)
The values which satisfy (3.46) are known as eigenvalues of matrix $A$, and the equation is refereed as characteristic equation of matrix $A$. The small signal stability of a non-linear system is dictated by the values the eigenvalues assume which can fall under the following categories.

Let $\lambda_1, \cdots, \lambda_m \ m \leq n$ be the eigenvalues of $A$

- asymptotically stable iff $|\lambda_i| < 1, \forall i = \{1, \cdots, m\}$
- stable if $|\lambda_i| \leq 1, \forall i = \{1, \cdots, m\}$
- unstable if $\exists i$ such that $|\lambda_i| > 1$

3.2.5 Dynamic Modes of a System

If we consider no input values at equation (3.41), we will obtain the Free Motion equation of the system (3.47).

$$\dot{x} = Ax \quad (3.47)$$

This equation states that the rate of change of each state variable, is a linear combination of all state variables. For this reason it is difficult to isolate the parameters that have the most impact on the motion. In order to eliminate the cross-coupling between the state variables, the system in transformed to an linear time invariant (LTI) system whose state matrix is diagonalized based on the modal matrices.

$$z(t) = \Psi x(t) = \Phi^{-1} x(t) \quad (3.48)$$
consequently

\[ x(t) = \Phi z(t) \quad (3.49) \]

Applying this (3.49) in (3.47) we obtain the following

\[ \Phi \dot{z}(t) = A \Phi z(t) \]

\[ \dot{z}(t) = \Phi^{-1} A \Phi z(t) \quad (3.50) \]

\[ \dot{z}(t) = \Lambda z(t) \]

Thus the dynamic system (3.50) represents \( n \) uncoupled first order differential equations of the general form.

\[ \dot{z}_i = \lambda_i z_i \quad (3.51) \]

Which has the solution with respect to time \( t \) is given by

\[ \dot{z}_i(t) = z_i(0)e^{\lambda_i t} \quad (3.52) \]

where \( z_i(0) \) is the initial of \( z_i \), which can be determined from (3.48)

\[ z_i(0) = \psi_i x(0) \quad (3.53) \]

which is a scalar and will be denoted by \( c_i \). Furthermore, \( x(0) \) is a \( n \)-row vector containing the initial values of the system states. Through (3.48), (3.51) and (3.53) the solution of the dynamical system can be defined as below.
\[ x(t) = \sum_{i=1}^{n} \phi_i c_i e^{\lambda_i t} \]  

(3.54)

Or if we write in terms of the time response of the \(i^{th}\) state variable

\[ x_i(t) = \phi_{i1} c_1 e^{\lambda_1 t} + \phi_{i2} c_2 e^{\lambda_2 t} + \ldots + \phi_{in} c_n e^{\lambda_n t} \]  

(3.55)

Thus, the free response of a linear system is given by a linear combination of its \(n\) dynamic modes corresponding to the \(n\) eigenvalues of the state matrix \(A\). The equation (3.54) suggests that the right eigenvector dictates the distribution of each dynamic mode among the state variables \(x_i\). And equation (3.53) expresses that the left eigenvector weights the initial condition \(x(0)\) contribution into the \(i^{th}\) mode.
CHAPTER 4
FREQUENCY DEVIATION CONTROLLER

This chapter introduces the proposed control method, and displays the time domain results of its implementations in the eleven bus area system from [35]. Moreover, the stability of the proposed algorithm is also validated through small signal analysis of the system IEEE 39 bus case.

4.1 Coordinated Inter-Area Oscillation Damping Control

4.1.1 Proposed Modifications in Synchronous Machine Control Systems

Consider a power grid composed by a graph with nodes (buses) $\mathcal{V} := \{1, \ldots, n\}$ and edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ (transmission lines). We consider a small-signal version of a network [6, 37] where the passive loads are eliminated via Kron reduction [38], and the active $i$ buses present a linearized dynamics.

$$m_i \dot{\omega}_i + d_i \omega_i = p_{in,i} - p_{e,i}, \quad i \in \{1, \ldots, n\} \tag{4.1}$$

to represent its frequency dynamics.

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This chapter was published in Innovative Smart Grid Technologies 2021 (ISGT) [36]. Permission is included in Appendix A.
Where $p_{in,i}$ and $p_{e,i}$ are the initial mechanical power output and electrical power output at bus $i$, respectively. To mitigate the inter-area oscillations of this power system, we propose a novel feedback control, which is called frequency deviation control (FDC) hereafter, which generates an additional control signal $p_{c,i}$, defined as

$$p_{c,i} = k(\omega_i - \overline{\omega}).$$  \hfill (4.2)

where $k$ is the gain for the proposed coordinated controller, $\omega_i$ and $\overline{\omega}$ represent the local frequencies in bus $i$ and the grid average frequency respectively. For any generation bus $i$, $p_{c,i}$ is a electrical power exchange between the machine at bus $i$ and a local ESS located at the same bus, where power exchange value is given by (4.2). Adding the control contribution into (4.1) we obtain the following.

$$m_i\ddot{\omega}_i + d_i\dot{\omega}_i = (p_{in,i} - p_{c,i}) - p_{e,i}, \quad i \in \{1, \ldots, n\}$$  \hfill (4.3)

as the updated swing equation of bus $i$. The control signal $p_{c,i}$ is designed to decrease the power generation on any bus $i$ when $\omega_i > \overline{\omega}$ and vice versa. Therefore, the control is expected to drive the local frequencies to converge to average frequency $\overline{\omega}$ at each moment and eliminate the inter-area oscillation modes.
Fig. 4.1 depicts the frequency control structure of an n-bus power system with FDC highlighted in red. As illustrated, controllers on all buses include some control systems and are connected to a power grid to exchange power and to a communication layer to exchange data with the other controllers. They continuously communicate their local frequency measurements with the other buses, so every bus has access to the instantaneous value of the system average frequency. FDC then adjusts power input requirements by computing the difference between local frequency deviation ($\omega_i$) and global average frequency deviation ($\overline{\omega}$) on the grid, and multiplying it by a gain $k$.

Remark 1: For DER buses where the generation is provided from inverter-based energy resources e.g. energy storage and photovoltaic systems, $p_{c,i}$ is applied to the net power generated.
by these resources. For any DER bus \( i \), the corresponding swing equation follows the same equation and platform as (4.3) and Fig. 4.1 where \( P_{m,i} \) denotes the total power output of DER, \( m_i \) accounts for the total virtual inertia emulated by power electronic control devices, and \( d_i \) denotes the total droop control coefficients [39, 40].

**Remark 2:** It is intended to design the solution to target inter-area oscillations only with minimal impact on the other dynamic modes of the system. That is, it must not affect the current operation of the power system from stability point of view. While the values of coefficients \( k \) could be different at different buses, selecting one value for all the controllers ensures that the total power adjustment on the network is equal to zero at any moment, i.e.

\[
\sum_{i=1}^{n} p_{c,i} = k \sum_{i=1}^{n} (\omega_i - \bar{\omega}) = 0.
\]  

(4.4)

Thus, synchronous generators must coordinate with each other to agree on applying the same coefficients in their inter-area oscillation control loops to ensure the total power injection to the grid as a result of FDC is zero at any time. As a result, FDC does not change the total damping and inertia of the network and just targets the inter-area oscillation modes with no impact on other dynamic modes.

**Remark 3:** Moreover, it was assumed that the communication network connecting the agents is reliable and stable, allowing them to share their information with its neighbors in close to real time. Based on all the aforementioned assumptions the model’s formulation is expressed in equation (4.2).
4.1.2 Classic Electromechanical Dynamic Model

We are interested in modeling the machine control system as a linear dynamic system. Here, we discuss the impacts of FDC on classical state-space representation for power system dynamics where the dynamic model of each bus is represented by its total inertia and damping and transmission lines are assumed to be purely inductive. With the state equation \( \dot{\delta} = \Omega_b \omega \) for rotor angle \( \delta \in \mathbb{R}^{n \times 1} \) and the definition of \( p_{c,i} \) from (4.2), the swing equation (4.3) can be written in vector format as

\[
M \dot{\omega} + D \omega = P_{in} - k(\omega - \bar{\omega}) - P_e
\]  

(4.5)

with \( \omega = [\omega_1, \cdots, \omega_n]^T \), \( \bar{\omega} = \bar{\omega} \mathbf{1}_n \), \( M = \text{diag}\{m_i\} \), and \( D = \text{diag}\{d_i\} \).

Replacing \( \bar{\omega} \) with the definition of average from (3.6) leads (4.5) to

\[
M \dot{\omega} + D \omega = P_{in} - k(I_{n \times n} - W)\omega - P_e
\]  

(4.6)

With definition of the Laplacian matrix \( L \) for the network as \( L = (I_{n \times n} - W) \), (4.6) is simplified to

\[
M \dot{\omega} + (D + kL)\omega = P_{in} - P_e
\]  

(4.7)
Assuming that transmission lines are purely inductive, electrical power output at each bus \( i \) can be

\[
p_{e,i} = \sum_{j=1}^{n} b_{ij} (\delta_i - \delta_j), \quad i \in \{1, \ldots, n\}
\]

(4.8)

where \( b_{ij} \in \mathbb{R}_+^* \) is the susceptance between the buses \( \{i, j\} \in \mathcal{E} \) [35]. Let us introduce the matrix for our network \( B = B^T \in \mathbb{R}^{n \times n} \) such that the elements \( B_{ij} = -b_{ij} \) for off-diagonal elements and \( B_{ii} = \sum_{j=0, j \neq i}^{n} b_{ij} \) for diagonal values. If no lines exist between any bus \( i \) and \( j \), the parameter \( B_{ij} \) is equal to zero. Consequently,

\[
P_e = B \delta
\]

(4.9)

and the state equation for the state variable \( \omega \) is equal to

\[
\dot{\omega} = M^{-1} (P_{in} - B \delta - (D + kL)\omega)
\]

(4.10)

Using (4.9) and (4.10), the linear dynamic system of the power system with FDC is expressed as

\[
\begin{bmatrix}
\dot{\delta} \\
\dot{\omega}
\end{bmatrix} =
\begin{bmatrix}
0_{n \times n} & \Omega_0 I_{n \times n} \\
-M^{-1}B & (-M^{-1}D - kM^{-1}L)
\end{bmatrix}
\begin{bmatrix}
\delta \\
\omega
\end{bmatrix} +
\begin{bmatrix}
0_{n \times n} \\
M^{-1}
\end{bmatrix} P_{in}
\]

(4.11)
Note that (4.11) represents the classic electromechanical dynamic model of the power network, which neglects the inherent electromechanical dynamics of synchronous machines and its controllers such as governor, automatic voltage control (AVR) and PSS.

### 4.1.3 Detailed Electromechanical Dynamic Models

As the classical electromechanical model (4.11) neglects the electromagnetic dynamics of synchronous machines, its adoption on modal analysis may lead to inaccurate results. For this reason, a detailed dynamic model was obtained, for various test cases, using PSAT [16]. Afterwards, the proposed control was added into the linearized system matrix as it is shown in (4.14).

Let (4.12) represent the detailed linearized dynamic model of a network obtained from PSAT as

\[
\dot{x} = Ax + Bu \tag{4.12}
\]

for state vector \( x \) and control input vector \( u \), we discuss here how it is modified by FDC in this chapter.

Let us divide the state vector \( x \in \mathbb{R}^N \) into three partitions: the angular deviation vector \( \delta \in \mathbb{R}^n \) in rad/sec, the electrical speed deviation \( \omega \in \mathbb{R}^n \) in p.u., and a state vector \( y \in \mathbb{R}^{N-2n} \) containing all other states including the subtransient dynamics states [11]. Therefore, (4.12) is
written as

\[
\begin{bmatrix}
\dot{\delta} \\
\dot{\omega} \\
\dot{y}
\end{bmatrix}
= \begin{bmatrix}
0_{n \times n} & \Omega_\delta & 0_{n \times n} \\
A_{\omega \delta} & A_{\omega \omega} & A_{\omega y} \\
A_{\gamma \delta} & A_{\gamma \omega} & A_{\gamma y}
\end{bmatrix}
\begin{bmatrix}
\delta \\
\omega \\
y
\end{bmatrix}
+ \begin{bmatrix}
0 \\
B_\omega \\
B_y
\end{bmatrix}
+ \begin{bmatrix}
0 \\
B_\omega \\
B_y
\end{bmatrix} u
\] (4.13)

Similar to (4.11), FDC just modifies the rows corresponding to \( \dot{\omega} \) in (4.13) by subtracting the term \( kM^{-1}L_\omega \) from its current value. Thus, the only modification required is to replace \( A_{\omega \omega} \) with \( A_{\omega \omega} - (kM^{-1}L) \) in (4.13), \( i.e. \) the modified electromechanical dynamic model can be written as

\[
\begin{bmatrix}
\dot{\delta} \\
\dot{\omega} \\
\dot{y}
\end{bmatrix}
= \begin{bmatrix}
0_{n \times n} & \Omega_\delta & 0_{n \times n} \\
A_{\omega \delta} & A_{\omega \omega} - (kM^{-1}L) & A_{\omega y} \\
A_{\gamma \delta} & A_{\gamma \omega} & A_{\gamma y}
\end{bmatrix}
\begin{bmatrix}
\delta \\
\omega \\
y
\end{bmatrix}
+ \begin{bmatrix}
0 \\
B_\omega \\
B_y
\end{bmatrix} u
\] (4.14)

4.2 Simulation Results and Discussion

This section presents the modal analysis simulations results, for both aforementioned models. The state-space models were built for IEEE 14-bus case and the two-area system test case is from [35]. This section also includes time domain simulation, when a small disturbance is applied on the system with the control and without the control.
4.2.1 Modal Analysis

The proposed control modal analysis is firstly studied on the classic electromechanical dynamic models of IEEE 14-bus test system. Afterwards, the analysis is expanded to the detailed electromechanical dynamic models of the Kundur’s two-area multi-machine test system adopted from [35] and IEEE 14-bus test system.

4.2.1.1 Classic Electromechanical Dynamic Models

To investigate the impacts that FDC has on inter-area oscillations, (4.11) has been setup with different values of $k$ for IEEE 14-bus test system. The results, illustrated on Fig. 4.2, shows the eigenvalues for this test system for various gains of $k$.

Figure 4.2 Dynamic modes of IEEE 14-bus test systems based on the classic electromechanical dynamic model of synchronous generators, without and with FDC with variable control gain $k \in (0, 100]$
Initially, with no gain, most modes damping ratio falls below 1\%, meaning that those modes are poorly damped and its oscillatory behavior lasts for many seconds after a disturbance. On the other hand, when the control is applied, it is evident that, as the gain $k$ increases, the initially poorly damped, modes move towards higher damping ranges, confirming a more stable behavior of the system.

The subplot within Fig. 4.2 shows two modes which are not affected by the FDC. One of these modes lies on the origin, representing the rotor angles part of the state variables. The other mode is a non-oscillatory mode, \textit{i.e.} lying on the x-axis, at $\lambda = -(\sum_i d_i)/(\sum_i m_i)$, equals to the single dynamic mode of the lumped model of the test system. The same roots also appear if the impacts of transmission lines are neglected–\textit{i.e.} $B = 0_{n \times n}$. This also confirms that applying FDC with sufficiently high gain diminishes the oscillatory modes completely, removes the impact of the transmission lines on the dynamic model of the power systems, and leads the dynamic model of the power system to that of the corresponding lumped model. This is equivalent to one single frequency waveform for all buses and zero (or near-zero) inter-area oscillations in the system.

4.2.1.2 \textit{Detailed Electromechanical Dynamic Models}

While a classic electromechanical dynamic model is a handy, straight-forward model to quickly capture the performance of FDC, it is not a reliable model to comprehensively analyze a real power system where electromagnetic dynamics of synchronous machines and other controllers on the grid matter. One must take these dynamic systems into account for a thorough modal analysis. Here, the detailed dynamic models of Kundur’s two-area multi-machine test system and IEEE
14-bus test system are generated using the method explained in 4.1.3. Using (4.14), these dynamic models are modified to include FDC with a variable gain \( k \), with the results being shown in Fig.4.3. Where Fig.4.3(a) illustrates all the existing eigenvalues for Kundur’s test system. The

![Figure 4.3 Dynamic modes of two test systems based on the detailed electromechanical dynamic model of synchronous generators, without and with FDC with variable control gain \( k \): (a)-(b) Kundur’s test system \( k \in (0, 500] \); (c)-(d) IEEE 14-bus test system \( k \in (0, 100] \)](image)

low-frequency modes, demarcated by the blue rectangle, is shown in details in Fig.4.3(b). Notice that the damping of those modes increases as the gain \( k \) is incrementated, confirming the assumption that the system performance is improved for higher gains of \( k \). Investigation on the critical value and the choice of optimum gain parameter \( k \) are beyond the scope of this work.
Similarly, inter-area oscillation modes of the IEEE 14-bus, depicted in Fig. 4.3(c), has initially most of its eigenvalues within 20% of damping ratio and has the gain $k$ increases up to 100 those modes move towards higher damping areas.

Note that the impacts of FDC on the other dynamic modes other than the ones corresponding to inter-area oscillation are trivial, which clearly shows that the FDC gain $k$ can increase for even better inter-area oscillation damping without significant effect on other dynamic models of the system.

4.2.2 Time-Domain Analysis

As the final analysis, a time domain analysis is performed on Kundur’s test system [35] to investigate local frequency waveforms when FDC is applied. These models are built in MATLAB Simulink with four different PSS setups, which are: i) no PSS, ii) multi-band PSS (MB-PSS), iii) conventional PSS with frequency mismatch as input signal ($\Delta \omega$ Kundur PSS), and iv) conventional $\Delta P_n$ PSS

Figure 4.4 Time-domain frequency response of Kundur’s test system in response to a 12-cycle, 5% voltage increase on generator 1 with and without FDC for different PSS configura-tions: (a),(e) No PSS; (b),(f) multi-band PSS; (c),(g) $\Delta \omega$ Kundur PSS; (d),(h) $\Delta P_n$ PSS

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PSS with power disturbance as input signal ($\Delta P_a$ PSS). All the models are tested against a 12-cycle increase in voltage of generator 1 by 5% at $t = 1s$.

Fig. 4.4 depicts the frequency waveforms of all the buses for different PSS setups (columns) with and without FDC (rows) when the disturbance scenario occurs. The control gain $k$ is set to 1000 in all cases. Comparing Figs. 4.4(a) and 4.4(e) suggests that the FDC not only removes the inter-area oscillations, but it also supports the frequency stabilization after the disturbance. For the cases where MB-PSS and $\Delta \omega$ Kundur PSS are utilized—i.e. Figs. 4.4(b), 4.4(c), 4.4(f) and 4.4(g)—two significant improvements are identified. First, FDC enhances the inter-area oscillations damping significantly, as all frequency waveforms travel together where it is employed. Secondly, it reduces the frequency nadir from 0.48 Hz (MB-PSS) and 0.72 Hz ($\Delta \omega$ Kundur PSS) to around 0.015 Hz in both cases.

Figs. 4.4(d) and 4.4(h) also illustrate that when $\Delta P_a$ PSS is employed, FDC reduces frequency nadir and enhances the inter-area oscillation damping by forcing all the local frequencies to be equal to each other at any time. The improvement can be seen in the first 10 seconds after the disturbance happens, the oscillation that remains afterwards, is purely result of the PSS that is being used. If we compare the other implementations with the $\Delta P_a$ PSS, it can be notice the former is the only case where the oscillatory dynamics persists after the disruption happens. Moreover, it is also important to point out that this oscillation does not represents a inter-area mode since all the four frequencies are traveling together in this case.

Besides, in all the stable cases, it can be seen that the final value of frequencies with and without FDC are the same, i.e. employment of FDC does not change the steady-state frequency deviation. As discussed in Remark 2 in Section 4.1, the underlying reason is that the same gain $k$
applied to all synchronous machines, and thence other dynamic modes remain unchanged if FDC
is applied.

4.3 Summary

In this chapter, we introduced the Frequency Deviation Control algorithm, which solely
based on the local frequency measurements was able to enhance inter-area oscillation in post-
disturbance scenarios. The control implementations requires a completed connected network, full
cooperation between the existing agents, and allocation of local ESS close to the generation buses.
The efficacy of the proposed method was demonstrated through modal analyses and time domain
simulations for IEEE 14 bus system and Kundur two area system [35].
CHAPTER 5
DISTRIBUTED INTER-AREA OSCILLATION DAMPING CONTROL

In this chapter, we expand the algorithm presented in Chapter 4 into a new platform, called *Distributed Frequency Deviation Control (DFDC)*. This algorithm employs a distributed average consensus process \([4, 5]\) to let each agent to have a meaningful estimate about average frequency, based on its direct neighbors information, in a incomplete network graph. This iterative process allows each bus to define its power absorption or injection in response to the frequency information its has from its neighbors. This implementations avoids the need for a central communication platform, or a complete communication network bridging the generation units. The results show that this method also contributes with the inter-area oscillation damping process.

5.1 Power System Model

Let's simplify the power system as an equivalent synchronous machine to in order to study its dynamics. Let \(\omega_s\) be the per unit angular rotor speed, \(p_{in}\) and \(p_e\) are the mechanical per unit power input and electrical power output respectively, then the mechanics of motion of a synchronous

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machine is best represented in differential equations as [35]:

\[ 2H \frac{\partial \omega_s}{\partial t} = p_{in} - p_e - D\omega_s \] (5.1)

where \( H \) is inertia constant, \( D \) is the damping torque.

In order to study the frequency dynamics, we express \( \Delta \omega \), defined as \( \Delta \omega = \omega_s - 1 \), as the per unit deviation of frequency from its nominal value. Also, let us define \( \Delta \delta \) as the angular position of the rotor in electrical radians with respect to a synchronously rotating reference and \( \Omega_b \) as the reference base frequency in rad/s. Based on (5.1), the mechanics of motion of a synchronous machine in response to any mechanical and electrical power disturbances—denoted by \( \Delta p_m \) and \( \Delta p_e \)—can be expressed as

\[ \Delta \dot{\delta} = \Omega_b \Delta \omega \] (5.2)

\[ \Delta \dot{\omega} = \frac{1}{M} (\Delta p_{in} - \Delta p_e - D\Delta \omega) \] (5.3)

where \( M = 2H \) is the starting time of the machine. (5.3) is referred to as _swing equation_ as it represents the swings in rotor triggered by the disturbances. For convenience, the symbol \( \Delta \) is removed from the equations appearing hereafter, letting \( \delta, \omega, p_m, \) and \( p_e \) denote the disturbances instead of the actual parameter values.
5.2 Proposed Model

5.2.1 Distributed Frequency Deviation Control Unit

Consider a connected power systems network modeled as a graph network with nodes (buses) \( V := \{1, \ldots, n\} \) and edges (transmission lines) \( E \subseteq V \times V \). Let \( G_p \subset V \) be the set of buses with the generating unit. For \( i \in G_p \), the small-signal version of the power system model, (5.3) can be written as [6]

\[
m_i \dot{\omega}_i + d_i \omega_i = p_{in,i} - p_{e,i}, \quad \forall i \in G_p
\]  

(5.4)

to represent its frequency dynamics. We propose a communication based distributed control called *distributed frequency deviation control (DFDC)* to mitigate the inter-area oscillations of the power system, where every bus \( i \in G_p \) in the grid estimates the average frequency of the network by communicating with only its directly connected neighbors. Based on the deviation of local frequency \( \omega_i \) from the estimated average frequency \( \gamma_i \), a control signal \( p_{c,i} \) is generated. This signal is equivalent to the amount of electrical power to be injected or drained from the power grid by a local ESS on bus \( i \in G_p \). Thus,

\[
p_{c,i} = K(\omega_i - \gamma_i), \quad \forall i \in G_p
\]  

(5.5)

where \( K \) is the gain for the proposed DFDC. In practical applications, this gain is constrained by the physical limits of the local ESS, i.e., the higher the ESS’s power rating the higher values of \( K \).
are possible. Adjusting (5.5) into (5.4) leads to

\[ m_i \dot{\omega}_i + d_i \omega_i = p_{in,i} - p_{c,i} - p_{e,i}, \quad \forall i \in G_p \]  \hspace{1cm} (5.6)

as the updated swing equation of bus \( i \). When \( \omega_i \) is higher than \( \gamma_i \), the control signal \( p_{c,i} \) is positive signaling the local ESS to absorb power, which drives the local frequencies to converge to the estimate of the average frequencies \( \gamma_i \) thus eliminating the inter-area oscillation modes.

The proposed DFDC is depicted in dashed-red in Fig. 5.1. As illustrated in the control architecture, the proposed control continuously adjusts power input requirements by computing the difference between local frequency deviation \( \omega_i \) and the estimation of the average frequency deviation \( \gamma_i \) on the grid multiplied by a gain \( K \).

**Remark 1:** For the buses where the generation is provided from inverter-based DER e.g. energy storage and photovoltaic systems, \( p_{c,i} \) is applied to the net power generated by these resources and it follows the corresponding swing equation as (5.6). In Fig. 5.1, \( P_{in,i} \) denotes the power output of DER, \( m_i \) and \( d_i \) account for the total virtual inertia of bus \( i \) emulated by power electronic control devices and the total droop control coefficients respectively [39, 40].

**Remark 2:** The values of coefficients \( K \) could be different at different buses but the selection of one value for all the controllers ensures that the total power adjustment on the network is equal to zero, i.e.

\[ \lim_{k \to \infty} \sum_{i \in G_p} p_{c,i}^k = \lim_{k \to \infty} K \sum_{i \in G_p} (\omega_i^k - \gamma_i^k) = 0. \]  \hspace{1cm} (5.7)
The fixed gain $K$ ensures that the DFDC doesn’t change the total damping and inertia of the network. That is, it just targets the inter-area oscillation modes with no impact on other dynamic modes.

Remark 3: In the distributed platform employed for dynamic average consensus, each bus just relies on its local measurements and its neighbors’. Thus, the distributed feature of the algorithm is achieved and local communication channels are sufficient. Also, in this chapter, the communication channels are assumed stable and reliable, which allows agents to share their information with its own neighbors in real-time with no delay or data loss.
5.2.2 Small-Signal Stability Analysis of Wide-Area Power Systems

Let $\gamma \in \mathbb{R}^{n \times 1}$ be the estimate of the average frequency by all the agents, where $\gamma = [\gamma_1, \cdots, \gamma_i, \cdots, \gamma_n]^T$. According to (3.16), the estimate of the average frequency of the network by the bus (agent) $i$ is:

$$\gamma_{i}^{k+1} = A_i^T \gamma^k + \omega_i^{k+1} - \omega_i^k$$  \hspace{1cm} (5.8)

where $A = A^T = [A_1, \cdots, A_n] \in \mathbb{R}^{n \times n}$ is derived from Mean Metropolis on, (3.15) $A_i \in \mathbb{R}^{n \times 1}$. For the entire network, (5.8) can be written in a matrix form as:

$$\gamma^{k+1} = A \gamma^k + \omega^{k+1} - \omega^k$$ \hspace{1cm} (5.9)

Subtracting $\gamma^k$ on both the sides of (5.9) and dividing by $\Delta t$, leads to:

$$\frac{\gamma^{k+1} - \gamma^k}{\Delta t} = \frac{A - I_{n \times n}}{\Delta t} \gamma^k + \frac{(\omega^{k+1} - \omega^k)}{\Delta t}$$  \hspace{1cm} (5.10)

The iterative process of calculating $\gamma$ and sharing information can be translated into real time assuming that each iteration $k$ happens in a tiny fraction of time $\Delta t$ such that $\Delta t \rightarrow 0$. Thus.

$$\dot{\gamma} = L \gamma + \dot{\omega}$$ \hspace{1cm} (5.11)
where $L = \frac{A - I}{\Delta t}$. Defining an auxiliary parameter $\beta = \omega - \gamma$ which is differentiated and substituted in (5.11) giving:

$$\dot{\beta} = -L\gamma \quad (5.12)$$

Consequently,

$$\dot{\beta} = L\beta - L\omega \quad (5.13)$$

The state equation for rotor angle $\delta \in \mathbb{R}^{n \times 1}$ is:

$$\dot{\delta} = \Omega_\delta \omega \quad (5.14)$$

Substituting $p_{c,i}$ in (5.6), we get:

$$M\dot{\omega} + D\omega + K\beta = P_{in} - P_e \quad (5.15)$$

where $M = diag\{m_i\}$ and $D = diag\{d_i\}$ are diagonal matrices containing the values of inertia and damping.
In order to expand $P_e$ to write in state equations, we assume no line losses, i.e. purely inductive lines. Thus, the electrical power output at each bus can be described by [35]

$$p_{e,i} = \sum_{j=1}^{n} b_{ij} (\delta_i - \delta_j), \quad i \in \mathcal{V} \quad (5.16)$$

where $b_{ij} \in \mathbb{R}_+^*$ is the susceptance of the line $\{i, j\} \in \mathcal{E}$ between the buses $i$ and $j$. We introduce the matrix for our network $B = B^T \in \mathbb{R}^{n \times n}$ such that the elements $B_{ij} = -b_{ij}$ for $i \neq j$, the elements $B_{ij} = \sum_{j=0,j \neq i}^{n} b_{ij}$ for diagonal values, and $B_{ij} = 0$ for $ij \notin \mathcal{E}$. Consequently,

$$P_e = B\delta \quad (5.17)$$

and the state equation for the state variable $\omega$ is,

$$\dot{\omega} = M^{-1}(P_{in} - B\delta - D\omega - K\beta) \quad (5.18)$$

With (5.14), (5.18), (5.18), the linear dynamic system of the power system with DFDC unit is expressed as:

$$\begin{bmatrix}
\dot{\delta} \\
\dot{\omega} \\
\dot{\beta}
\end{bmatrix} = \begin{bmatrix}
0_{n \times n} & \Omega_0 I_{n \times n} & 0_{n \times n} \\
-M^{-1}B & -M^{-1}D & -M^{-1}K \\
0_{n \times n} & -L & L
\end{bmatrix} \begin{bmatrix}
\delta \\
\omega \\
\beta
\end{bmatrix} + \begin{bmatrix}
0_{n \times n} \\
M^{-1}P_{in}
\end{bmatrix} \quad (5.19)$$

This model is used in our simulations for both modal analysis and time-domain simulations.
5.3 Case Study

In this section, the effects of the DFDC are evaluated on two IEEE test systems (57-bus and 118-bus) through modal analysis and time-domain simulations. In our simulation for IEEE 57-bus, total inertia of 50.3 and a total damping of 5.9 are distributed between buses proportional to the total capacity of generation installed on each bus. For IEEE 118-bus, same allocation rule is used to distribute total inertia of 253 and total damping of 11.8 among the system buses.

5.3.1 Modal Analysis

The modal analysis, (5.19) was setup for various values of gain $K$, varying equally from 0 to 10. For each case the eigenvalues or dynamic modes where calculated, and are displayed in the figures Fig.5.2 and Fig.5.3 for IEEE 57-bus and IEEE 118-bus, respectively.

In Figs. 5.2(a) and 5.3(a), all the dynamic modes of each simulation setup are shown, whereas the other graphs focus on more dominant modes–closer to the y-axis and therefore with slower damping–to clearly exhibit the impacts of DFDC. All the results, suggest that the oscillatory modes shift towards the left hand side as the gain $K$ increases, which means that these modes will damp faster as $K$ grows.

Fig. 5.2(d) illustrate that the most dominant dynamic mode of the IEEE 57-bus test case has an oscillation frequency of $17.12/2\pi = 2.77$ Hz and a damping ratio of 0.00073694 Neper when DFDC is not applied. When DFDC is applied the damping ratio of this mode increases to 0.125 Neper for $K = 10$, resulting in damping of this mode 47-times higher. Other dominant mode has a frequency $473.1/2\pi = 75.3Hz$ with a damping of 0.0014631 with no DFDC and 0.074867 with
DFDC with a gain $K=10$. That is, applying the control damps this mode 51 times faster. For the IEEE 118-bus test system, Fig. 5.3(d) illustrates that all the low-frequency modes are significantly damped. The most dominant mode after DFDC is applied has a frequency of $\frac{6.267}{2\pi} = 0.997 \text{Hz}$, and its real value is shifted from $-0.073294$ without DFDC to $-0.52$ when DFDC with $K = 10$ is applied. This shows that this mode is 20 times more damped with DFDC.

Figure 5.2 Modal analysis results of IEEE 118-bus test case for different values of DFDC gains $K$: all graphs show the same curves with different zooms to capture mode details.

Figure 5.3 Modal analysis results of IEEE 118-bus test case for different values of DFDC gains $K$: all graphs show the same curves with different zooms to capture mode details.

Note that the dynamic model of both system show two modes which are not affected by DFDC. They can be identified on Figs. 5.3(d) and 5.5(d) where cyan and red triangles coincide.
One of these modes lies on the origin because rotor angles are included within the state variables, and their derivatives (rotor speed deviation) are not necessarily equal to zero at the steady state. The other dynamic mode is a non-oscillatory mode at \( \lambda = -\frac{(\sum_i d_i)}{(\sum_i m_i)} \), which is exactly equal to the single dynamic mode of the lumped model of the test system. These modes also appear in (5.18) if transmission lines are neglected—i.e. \( \mathbf{B} = 0_{n \times n} \). This mode does not change with DFDC since local and average frequencies are exactly the same in a lumped system and DFDC control signal is always zero. It proves the point that applying DFDC with sufficiently high gain i) mitigates the oscillatory modes completely, ii) eliminates the effects of the transmission lines on the dynamic model of the power systems, and iii) leads the dynamic model of the power system to be equivalent to its lumped model. Thus, the frequency response of the network with DFDC with sufficiently high gain is a single waveform for buses’ frequencies and zero inter-area oscillations in the system.

Fig. 5.4 illustrates a histogram of all the dynamic modes binned based on their corresponding damping ratio for both cases. It is seen that when DFDC gain \( K \) increases, the modes are moved from bins of low-damping ratios to those of higher-damping ratios. This explains clearly that DFDC contributed effectively in damping the inter-area oscillation modes. Moreover, the dynamic modes associated with the dynamic average consensus process—which comprises 1/3 of the total eigenvalues—are always binned in the bin with highest damping ratio and DFDC does not affect them. This observation proves these dynamic modes are damped perfectly and the averaging process does not adversely affect the proposed control platform.
5.3.2 Time Domain Analysis

In this section, the time domain simulations results for both IEEE test cases are presented and discussed. A time-domain simulation based on (5.19) is built in MATLAB Simulink for this study, and the results for IEEE 57-bus and 118-bus test systems are shown in Figs. 5.5 and 5.6, respectively.

Figs. 5.5(a) and 5.6(a) depict the disturbances applied. Initially, the system rests at equilibrium with zero disturbance, but they experience two sets of uniformly distributed random disturbances between $(-0.1, 0.1)$ p.u. occurring on any bus with non-zero inertia. The sum of the individual disturbances are depicted as a blue-dashed line. In Figs. 5.5(b) and 5.6(b), the dynamic
response of the lumped model of the power system is presented, where all the inertia and damping factors are lumped in one single bus. Since a perfect inter-area oscillation damping control results in the dynamic response of the lumped model of the power system studied, we benchmark the frequency response of DFDC against that of the lumped system. In Figs. 5.5(c) and 5.6(c), it is shown that both systems without DFDC suffer from a severe inter-area oscillations. In both cases, especially in IEEE 118-bus test system, there are some oscillatory modes which cause significant frequency oscillations on all buses of the system. Figs. 5.5(d) and 5.6(d) illustrate the dynamic response of both systems when DFDC with a gain $K$ is employed. Comparing these graphs with the ones without DFDC clearly shows remarkable damping of inter-area oscillations. Also, these graphs show identical behaviors compared to the one associated with the lumped models shown in Figs. 5.5(b) and 5.6(b). This proves the fact that DFDC not only mitigates the inter-area oscillations significantly, as it also does not affect the other dynamic modes of the system, which is the mode associated with the lumped model in our test cases.
Figure 5.5  Time-domain case study for IEEE 57-bus test system: (a) power disturbance of individual buses and total disturbance of the system, (b) dynamic response of lumped model of the network, (c) dynamic response of the network without DFDC (d) dynamic response of the network with DFDC $K = 10$

Figure 5.6  Time-domain case study for IEEE 118-bus test system: (a) power disturbance of individual buses and total disturbance of the system, (b) dynamic response of lumped model of the network, (c) dynamic response of the network without DFDC (d) dynamic response of the network with DFDC $K = 10$
5.4 Summary

In this chapter, we introduced the Distributed Frequency Deviation Control (DFDC) algorithm, which works based on the cooperation between each agent and its direct neighbors, in a incomplete network. Using solely local frequency measurements it was able to enhance inter-area oscillation in post-disturbance scenarios. Different from the proposed solution in chapter 4, the control implementations doesn’t require a completed connected network but only allocation of local ESS close to the generation buses and complete cooperation among the agents that area connected. The efficacy of the proposed method was demonstrated through modal analyses and time domain simulations for IEEE 57 bus and IEEE 118 bus system.
CHAPTER 6
CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

In this thesis, two inter-area oscillation damping solutions are proposed. The first one, proposed in Chapter 4, works in a complete graph network, and the second in Chapter 5 in a connected graph. Both algorithms employ the mismatch between local frequencies and system average frequency to mitigate inter-area oscillations by adjusting the power exchange of local ESS with the power system.

The results demonstrate that the proposed control significantly damps the inter-area modes for either a complete or partially connected network, without affecting the other dynamic modes of the system. The time-domain simulation results also demonstrates the efficacy of the proposed control that not only mitigated the inter-area modes but also improved the transient stability and frequency response of the test systems.

For both network configurations presented in Chapter 4 and 5, the time domain simulations suggest that the damping of inter-area modes improves as the agents are more connected with each other. Which means that a complete network, where all agents share information with each other, provides the best performance of the proposed algorithm. As the agents lose communication the algorithm will still perform, as far as the communication network is still a unique connected graph. The later framework is presented in Chapter 5 and serves as a more accurate representation of a
real network, where most the agents are communicating only with a few neighbors. Moreover, the small signal analysis performed in both cases suggests that a higher gain of the feedback loop will enhance the damping of the inter-area mode for all cases.

6.2 Future Directions

With the power grid going through an unprecedented transformation of its energy sources there is an imminent need to design new control laws to make up for the inherent stability features that will be lost as conventional synchronous generations are replaced by DER. We propose in this thesis a robust control that has the potential to help the power grid to transition into cleaner energy without comprising the system stability and security. There are ample research directions to pursue within the framework we proposed in this thesis. Some of these open research areas are listed below.

- The impact of measurement and communication delays in the damping of the existing oscillatory modes must be considered for a full analysis. These delays are expected to adversely affect the oscillatory modes, so the proposed solution needs to be modified accordingly to address them.

- Investigate the trade-off between the gain ($K$) of the proposed control the ESS requirements and cost. We have noticed that higher $K$ requires higher sizes of ESS, and thence higher implementation cost. An optimization process will be needed to optimize the inter-oscillation damping and ESS cost simultaneously.
• Apply the distributed algorithm framework in other existing devices known to help mitigating inter-area modes such as PSS’s or FACTs devices. For instance, one idea is to feed PSS with the mismatch between the local and network average frequencies and investigate the impacts.
REFERENCES


APPENDIX A

REUSE PERMISSIONS FOR CONTEND IN CHAPTER 4
Figure A.1  Reuse permission for [36]
APPENDIX B

REUSE PERMISSIONS FOR CONTEND IN CHAPTER 5
Figure B.1  Reuse permission for [41].
VITA

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