Electromechanical Wave Propagation in Large Electric Power Systems

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Doctor of Philosophy In Electrical Engineering

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Electromechanical Wave Propagation in Large Electric Power Systems

by

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Abstract

In a large and dense power network, the transmission lines, the generators and the loads are considered to be continuous functions of space. The continuum technique provides a macro-scale analytical tool to gain an insight into the mechanisms by which the disturbances initiated by faults and other random events propagate in the continuum. This dissertation presents one-dimensional and two-dimensional discrete models to illustrate the propagation of electromechanical waves in a continuum system. The more realistic simulations of the non-uniform distribution of generators and boundary conditions are also studied. Numerical simulations, based on the swing equation, demonstrate electromechanical wave propagation with some interesting properties. The coefficients of reflection, reflection-free termination, and velocity of propagation are investigated from the numerical results. Discussions related to the effects of electromechanical wave propagation on protection systems are given. In addition, the simulation results are compared with field data collected by phasor measurement units, and show that the continuum technique provides a valuable tool in reproducing electromechanical transients on modern power systems. Discussions of new protection and control functions are included. A clear understanding of these and related phenomena will lead to innovative and effective countermeasures against unwanted trips by the protection systems, which can lead to system blackouts.
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To my beloved family
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<td>ISOs</td>
<td>Independent system operators</td>
</tr>
<tr>
<td>PMUs</td>
<td>Phasor measurement units</td>
</tr>
<tr>
<td>BPA</td>
<td>Bonneville Power Administration</td>
</tr>
<tr>
<td>WSCC</td>
<td>Western Systems Coordinating Council</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier transform</td>
</tr>
<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>UTC</td>
<td>Universal time</td>
</tr>
<tr>
<td>PDC</td>
<td>Phasor data concentrator</td>
</tr>
<tr>
<td>SCE</td>
<td>Southern California Edison</td>
</tr>
<tr>
<td>WAMs</td>
<td>Wide area measurements</td>
</tr>
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<td>FACTS</td>
<td>Flexible AC transmission systems</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$y_1$</td>
<td>Generator internal admittance of the discrete system</td>
</tr>
<tr>
<td>$y_0$</td>
<td>Load connected to the bus of the discrete system</td>
</tr>
<tr>
<td>$M$</td>
<td>Rotor inertia constant</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Rotor angle of the generator</td>
</tr>
<tr>
<td>$D$</td>
<td>Mechanical damping constant</td>
</tr>
<tr>
<td>$J$</td>
<td>Rotor moment of inertia</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency of the generator rotor</td>
</tr>
<tr>
<td>$P_e$</td>
<td>Output electrical power of generator</td>
</tr>
<tr>
<td>$P_m$</td>
<td>Input mechanical power</td>
</tr>
<tr>
<td>$\delta_k$</td>
<td>Initial rotor angle of generator at node k</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity of the propagation</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Nominal system frequency</td>
</tr>
<tr>
<td>$V$</td>
<td>Magnitude of source voltage</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Phase angle of transmission line impedance</td>
</tr>
<tr>
<td>$h$</td>
<td>Inertia constant per unit length</td>
</tr>
<tr>
<td>$z$</td>
<td>Per-unit impedance per unit length</td>
</tr>
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<td>$E_{rr}$</td>
<td>Error of the simplified calculation</td>
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<tr>
<td>$K_n$</td>
<td>Reflection coefficient at the $n^{th}$ machine</td>
</tr>
</tbody>
</table>
R: Reflection coefficient for frequency
C₀: Characteristic impedance
ωₛ: Nominal system frequency
Pₑₙₐₑ: Deviation from nominal in line power flow to the terminating generator
P₀: Power flow in a loss-less line
Pₘₐₓ: Peak value of the P-δ curve
Eₛ: Sending-end voltage magnitude
Eᵣ: Receiving-end voltage magnitude
ΔPᵣ: Incremental increase in power in the direction r
f₀: Nominal system frequency
δₛ: Phase angle of the positive sequence voltage phasor at the bus
Zₓₐₛₚₙ: Apparent impedance sensed by a distance relay
Z₀: Apparent impedance sensed by the distance relay prior to the arrival of the wave
Yₘₙₜ: Equivalent admittance between nodes m and n
Tᵣᵢᵢ: Transformer impedance of the branch i
//: Parallel of impedances
+: Serial of impedances
X₂: Impedance, based on the new MVA and KV ratings
X₁: Impedance, based on the old MVA and KV ratings
V₂: Rated KV of the new system
V₁: Rated KV of the old system
S₂: MVA base of the new system
S₁: MVA base of the old system
Hᵢ: Inertia time constant of the equivalent generator of the number i group
Hᵢⱼ: Inertia time constant of the generator (i,j) within the number i group
Sᵢⱼ: Generator (i,j) MVA base of the simplified WSCC 127-bus system
Sₙₑₙ: MVA base of the non-uniform discrete ring system
Xᵢ: Internal reactance of the equivalent generator of the number i group
Xᵢⱼ: Internal reactance of the generator (i,j) within the number i group
Vᵢⱼ: Rated KV of the generator (i,j) of the simplified WSCC 127-bus system
Vₙₑₙ: New rated KV of the non-uniform discrete ring system
\( \delta_i \): Initial angle of the equivalent generator of the number i group

\( \delta_{ij} \): Initial angle of the generator \((i,j)\) of the simplified WSCC 127-bus system

\( t_{ij} \): Time that wave travels between nodes i and j in the non-uniform discrete ring system

\( z_{ij} \): Transmission line per unit impedance between nodes i and j in the non-uniform discrete ring system

\( z_{ave} \): Per-length transmission line impedance (pu) of the uniform discrete ring system.
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Chapter 1. Introduction

Power system faults and other random events cause a mismatch between the mechanical power inputs and the electrical power outputs of the generators, and this in turn moves the generator rotors with respect to the synchronous reference frame. The phenomenon of electromechanical oscillations of generator rotors imposes operational limits on the power network. The study of such transient phenomena is of significance, especially since it influences the reliable operating limits of the system.

If the protection and control systems do not function correctly in response to these oscillations, the disturbance can propagate over the network. If a sufficient number of generators lose synchronism in this fashion, a system blackout results, and very expensive, disruptive and time-consuming restoration procedures must be followed. The 1977 New York City blackout, and the December 14, 1994, July 2, 1996 and August 10, 1996 breakups of the western North American Power System are examples of multiple outages causing transient instability.

The conventional techniques for studying electromechanical transient phenomena usually involve modeling the transmission network, using a system of algebraic equations, and the generator and load dynamics, using a set of coupled differential equations [1]. The resulting set of differential algebraic equations (DAEs) is numerically integrated to obtain the time evolution of the system variables. Formulating and solving the DAEs can be time consuming for large networks, and the results are often difficult to grasp on a global scale.

Power system deregulation and the creation of large independent system operators (ISOs) have, in some cases, greatly increased the physical size of the transmission system under a unified control. Systems are larger both in terms of square miles and in the number of buses. Some effects in such large systems are not easily understood through existing models, but valuable understanding can be obtained by taking a macroscopic view of the system.

The continuum approach has been motivated by wave-like behavior observed in the power systems. Real-time tests, based on synchronized phasor measurement unit (PMU) measurements,
have shown glimpses of such electromechanical wave propagation [2] [3]. The continuum concept has been previously applied in the research of power networks (see Chapter 2).

Consider the electric power system with its transmission lines, generators, and loads to be a continuum. This is a reasonable extrapolation when the power system spans entire continents. This procedure leads to a set of coupled nonlinear partial differential equations (PDEs) with parameters that depend on spatial coordinates. One PDE describes the transmission network, and is analogous to the set of algebraic equations used in load-flow analysis. The second PDE is the continuum equivalent of the coupled set of swing equations that describe the generator dynamics in the network. The solutions of the PDE exhibit traveling wave behavior. Concepts applicable to PDEs can consequently be applied to gain further insight into the mechanisms by which these disturbances propagate through the system.

The continuum approach brings new understanding to the problem of large-system dynamics. Firstly, it takes a global view of the problem. While some of the details in the system behavior might be lost, insight into how disturbances in the system propagate through the entire network is gained. Furthermore, when the problem is cast in this fashion, techniques developed for studies of wave propagation and PDEs can be used to provide further insights.

While much research has been devoted to the continuum theory, no work has been done on applications of the continuum techniques in protection systems, and no information is available on field verifications of the continuum concept. There are few studies on how to handle either the non-uniform structure of the network or the non-uniform distribution of the generators on the network.

The objectives of the present research include the following.

- The development of discrete one- and two-dimensional models illustrate the traveling wave phenomena

- The study of the effects of electromechanical wave propagation on power system protective devices
• The use of field observations of electromechanical waves to determine whether the model is close to reality on the power system

• The proposal of new monitoring, protection and control functions to detect and suppress propagation and growth of electromechanical waves

The proposed research was part of the joint work with Cornell University. The contributions from the Cornell team include the following.

• Development of the continuum model

• The solutions of the PDEs

• Transformation of the discrete system to continuum by convolution

The major contributions of this dissertation include the following.

• The transient reactance of the generator was included in the simulations of discrete models

• The performance of the protection systems in response to the electromechanical wave phenomena was demonstrated

• A macro-scale analytical tool would be very valuable for providing solutions and introducing a new discipline to the field of electric power engineering

• Techniques are provided for the observation of electromechanical waves in actual power systems. Early-warning systems can be used to activate control actions at selected points in order to damp these electromechanical waves

• A clear understanding of these and related phenomena will lead to innovative and effective countermeasures against system blackouts
This dissertation is organized as follows. Chapter 2 reviews the literature written about the continuum theory. Chapter 3 presents one-dimensional and two-dimensional discrete models in which boundary conditions and the non-uniform structure of the network have been considered. Chapter 4 presents the effects of electromechanical wave propagation on power systems and protection systems. Chapter 5 presents the technique for obtaining a discrete model from the Western System Coordinating Council (WSCC) system. Field data from the WSCC system is used to verify the analytical solution to the problems. In Chapter 6, possible monitoring, protection, and control techniques are proposed for preventing power system blackouts. Finally, Chapter 7 offers brief concluding comments.
Chapter 2. Review of Literature

Studying dynamic phenomena in large power networks from a continuum point of view is not a new concept. Semlyen (1974) first applied the concept of the continuum to homogenous and isotropic networks with lossless transmission lines [4]. He modeled the power system as a second-order linear hyperbolic wave equation with constant coefficients.

Later, Dersin (1985) formulated the DC load flow equations into a boundary value problem [5]. He removed the homogeneity and isotropy constraints by averaging system parameters within local cells. Selecting the size of these cells was crucial. The continuum model presented by Dersin does not consider any dynamics. Therefore, the model was a second-order linear elliptic equation.

Thorp, Seyler and Phadke (1998) derived a continuum equivalent of the power network in which transmission line losses were included in the model [6]. A theoretical analysis of a continuum system with constant parameters under a constant power flow equilibrium shows that an initial disturbance that was injected into the system would propagate out. For a ring system that consists of 64 generators, the wave propagates in both directions. The wave in the direction of nominal power flow grows, while the other wave is attenuated.

Development of the Continuum Model

The continuum model by Thorp, et al. [6] modified with generator internal impedances is presented as follows. The following is a contribution of the Cornell team.

Continuum Network Equations

Consider a branch i connected to the generator at node (x,y). Each point (x,y) in the power system can be modeled by the incremental system shown in Figure 2-1. The incremental model consists of a generator and a load, connected to an arbitrary number of branches with different per-unit line impedances and orientations. The voltage magnitudes in the entire system are assumed to be constant while the generator’s internal and external phase angles are $\phi(x,y,t)$ and...
δ(x,y,t), respectively. If a branch i has a per-unit line impedance of \( R_i + jX_i \), an orientation angle of \( \theta_i \), and length \( \Delta \), then the power leaving through this incremental branch is given in equation (2.1).

\[
P_i^e = \frac{\Delta R_i |V|^2}{\Delta^2 (R_i^2 + X_i^2)} \left[ 1 - \cos(\delta(x,y,t) - \delta(x + \Delta x_i, y + \Delta y_i, t)) \right] \\
+ \frac{\Delta X_i |V|^2}{\Delta^2 (R_i^2 + X_i^2)} \left[ \sin(\delta(x,y,t) - \delta(x + \Delta x_i, y + \Delta y_i, t)) \right]
\]

(2.1)

A Taylor series expansion of \( \delta(x + \Delta x_i, y + \Delta y_i, t) \) about \( \delta(x,y,t) \) yields:

\[
\delta(x + \Delta x_i, y + \Delta y_i, t) = \delta(x,y,t) + \Delta x_i \frac{\partial \delta}{\partial x} + \Delta y_i \frac{\partial \delta}{\partial y} + \Delta x_i \Delta y_i \frac{\partial^2 \delta}{\partial x \partial y} \\
+ \frac{(\Delta x_i)^2}{2} \frac{\partial^2 \delta}{\partial x^2} + \frac{(\Delta y_i)^2}{2} \frac{\partial^2 \delta}{\partial y^2} + \text{H.O.T}
\]
Hence,

\[
\cos(\delta(x, y, t) - \delta(x + \Delta x_i, y + \Delta y_i, t)) \\
= \cos \left( -\Delta x_i \frac{\partial \delta}{\partial x} - \Delta y_i \frac{\partial \delta}{\partial y} - \Delta x_i \Delta y_i \frac{\partial^2 \delta}{\partial x \partial y} - \frac{(\Delta x_i)^2}{2} \frac{\partial^2 \delta}{\partial x^2} - \frac{(\Delta y_i)^2}{2} \frac{\partial^2 \delta}{\partial y^2} \right) \\
= 1 - \frac{1}{2} \left( -\Delta x_i \frac{\partial \delta}{\partial x} - \Delta y_i \frac{\partial \delta}{\partial y} - \Delta x_i \Delta y_i \frac{\partial^2 \delta}{\partial x \partial y} - \frac{(\Delta x_i)^2}{2} \frac{\partial^2 \delta}{\partial x^2} - \frac{(\Delta y_i)^2}{2} \frac{\partial^2 \delta}{\partial y^2} \right)^2 + \text{H.O.T} \\
= 1 - \frac{(\Delta x_i)^2}{2} \left( \frac{\partial \delta}{\partial x} \right)^2 - \frac{(\Delta y_i)^2}{2} \left( \frac{\partial \delta}{\partial y} \right)^2 - \Delta x_i \Delta y_i \frac{\partial \delta}{\partial x} \frac{\partial \delta}{\partial y} + \text{H.O.T} \tag{2.2}
\]

and

\[
\sin(\delta(x, y, t) - \delta(x + \Delta x_i, y + \Delta y_i, t)) \\
= \sin \left( -\Delta x_i \frac{\partial \delta}{\partial x} - \Delta y_i \frac{\partial \delta}{\partial y} - \Delta x_i \Delta y_i \frac{\partial^2 \delta}{\partial x \partial y} - \frac{(\Delta x_i)^2}{2} \frac{\partial^2 \delta}{\partial x^2} - \frac{(\Delta y_i)^2}{2} \frac{\partial^2 \delta}{\partial y^2} \right)^2 + \text{H.O.T} \\
= -\Delta x_i \frac{\partial \delta}{\partial x} - \Delta y_i \frac{\partial \delta}{\partial y} - \Delta x_i \Delta y_i \frac{\partial^2 \delta}{\partial x \partial y} - \frac{(\Delta x_i)^2}{2} \frac{\partial^2 \delta}{\partial x^2} - \frac{(\Delta y_i)^2}{2} \frac{\partial^2 \delta}{\partial y^2} + \text{H.O.T} \tag{2.3}
\]

From equations (2.1), (2.2) and (2.3) (ignoring higher order terms),

\[
P_i^e = \frac{\Delta R_i |V|^2}{\Delta^2 (R_i^2 + X_i^2)} \left[ \frac{(\Delta x_i)^2}{2} \left( \frac{\partial \delta}{\partial x} \right)^2 + \frac{(\Delta y_i)^2}{2} \left( \frac{\partial \delta}{\partial y} \right)^2 + \Delta x_i \Delta y_i \frac{\partial \delta}{\partial x} \frac{\partial \delta}{\partial y} \right] \\
- \frac{\Delta x_i |V|^2}{\Delta^2 (R_i^2 + X_i^2)} \left[ \Delta x_i \frac{\partial \delta}{\partial x} + \Delta y_i \frac{\partial \delta}{\partial y} + \frac{(\Delta x_i)^2}{2} \frac{\partial^2 \delta}{\partial x^2} + \frac{(\Delta y_i)^2}{2} \frac{\partial^2 \delta}{\partial y^2} + \Delta x_i \Delta y_i \frac{\partial^2 \delta}{\partial x \partial y} \right]. \tag{2.4}
\]

If N symmetric branches are connected to node (x,y), the total power leaving node (x,y) through the branches and the shunt element is as follows:
\[ \sum_{i=1}^{N} P_i^e = \sum_{i=1}^{N} \left\{ \frac{\Delta R_i |V|^2}{(R_i^2 + X_i^2)} \left[ \cos^2 \theta_i \left( \frac{\partial \delta}{\partial x} \right)^2 + \sin^2 \theta_i \left( \frac{\partial \delta}{\partial y} \right)^2 + 2 \cos \theta_i \sin \theta_i \frac{\partial \delta}{\partial x} \frac{\partial \delta}{\partial y} \right] \right\} + \Delta G |V|^2, \quad (2.5) \]

where \( \theta_i \) is the angle orientation of branch \( i \) with respect to the origin.

The electrical power delivered to the node \( (x,y) \) is:

\[ P^e = \frac{\Delta R_s |V|^2}{(R_s^2 + X_s^2)} \left[ \cos(\delta(x,y,t)-\phi(x,y,t)) - 1 \right] - \frac{\Delta X_s |V|^2}{(R_s^2 + X_s^2)} \left[ \sin(\delta(x,y,t)-\phi(x,y,t)) \right] \quad (2.6) \]

The swing equation at the node \( (x,y) \) is:

\[ \Delta m \frac{\partial^2 \phi}{\partial t^2} + \Delta d \frac{\partial \phi}{\partial t} = \Delta P^m - P^e. \quad (2.7) \]

The parameters \( m, d \) and \( P^m \) are the generator inertia, damping and mechanical power injection distributions respectively. \( P_g^e \) is the electrical power delivered by the generator and is:

\[ P_g^e = \frac{\Delta R_s |V|^2}{(R_s^2 + X_s^2)} \left[ 1 - \cos(\phi(x,y,t) - \delta(x,y,t)) \right] + \frac{\Delta X_s |V|^2}{(R_s^2 + X_s^2)} \left[ \sin(\phi(x,y,t) - \delta(x,y,t)) \right]. \quad (2.8) \]

Combining equations (2.5) and (2.6), and equations (2.7) and (2.8), we get the following set of equations.

\[ u_x \left( \frac{\partial \delta}{\partial x} \right)^2 + u_y \left( \frac{\partial \delta}{\partial y} \right)^2 + k \frac{\partial \delta}{\partial x} \frac{\partial \delta}{\partial y} - v_x \frac{\partial^2 \delta}{\partial x^2} - v_y \frac{\partial^2 \delta}{\partial y^2} - w \frac{\partial^2 \delta}{\partial x \partial y} \]

\[ = a[\cos(\delta(x,y,t)) - \phi(x,y,t) - 1] - b[\sin(\delta(x,y,t) - \phi(x,y,t))], \quad (2.9a) \]
\[
m\frac{\partial^2 \phi}{\partial t^2} + \frac{d}{dt} \frac{\partial \phi}{\partial t} = p^n - a[1 - \cos(\phi(x, y, t) - \delta(x, y, t))] - b[\sin(\phi(x, y, t) - \delta(x, y, t))], \tag{2.9b}
\]

where

\[
u_x = \sum_{i=1}^{N} R_i \frac{\sum_{i=1}^{N} |V|^2 \cos^2 \theta_i}{(R_i^2 + X_i^2)},
\]

\[
u_y = \sum_{i=1}^{N} R_i \frac{\sum_{i=1}^{N} |V|^2 \sin^2 \theta_i}{(R_i^2 + X_i^2)},
\]

\[
u_x = \sum_{i=1}^{N} X_i \frac{\sum_{i=1}^{N} |V|^2 \cos^2 \theta_i}{(R_i^2 + X_i^2)},
\]

\[
u_y = \sum_{i=1}^{N} X_i \frac{\sum_{i=1}^{N} |V|^2 \sin^2 \theta_i}{(R_i^2 + X_i^2)},
\]

\[
k = \sum_{i=1}^{N} R_i \frac{\sum_{i=1}^{N} |V|^2 2 \cos \theta_i \sin \theta_i}{(R_i^2 + X_i^2)},
\]

\[
w = \sum_{i=1}^{N} X_i \frac{\sum_{i=1}^{N} |V|^2 2 \cos \theta_i \sin \theta_i}{(R_i^2 + X_i^2)},
\]

\[
a = \frac{R_i |V|^2}{(R_i^2 + X_i^2)},
\]

\[
b = \frac{X_i |V|^2}{(R_i^2 + X_i^2)},
\]

and \( g = G|V|^2 \).
The system must satisfy the boundary condition:

\[
\begin{bmatrix}
    u_x & w/2 \\
    w/2 & u_y
\end{bmatrix} \nabla \delta \cdot \vec{n} = 0,
\]

where \( \vec{n} \) is the outward normal at the boundary.

The first partial equation (2.9a) is the continuum equivalent of the load flow equations of the power system and is a boundary value problem. The second equation (2.9b) is the continuum equivalent of the swing equations of the power system.

The techniques applied in the derivations of equations (2.9a) and (2.9b) can be used to develop a more complicated continuum model where the constant \(|V|\) and constant \(|E|\) assumptions are relaxed. The real and reactive power at a node \((x,y)\) is conserved and each of these conditions specifies a differential equation. As the assumptions are relaxed and the generator modeling gets more detailed, the complexity of the continuum model increases. One may apply the techniques used in the derivation above to develop a highly detailed continuum model of power system if one chooses to do so. However, the difficulty in solving such a system may take the model impractical.

The continuum model described by equations (2.9a) and (2.9b) is found to be appropriate in that it maintains a balance between the accuracy with which it models the power network and the computational effort required in solving the model.

**Obtaining a Continuum Model**

The parameters \(m, d, p, v_s, v_y, u_s, u_y, k, w, a, b\) and \(g\) that define the continuum system are all functions of spatial coordinates. Only idealized systems have constant parameters. At a given node \((x,y)\) these parameters depend on the generator inertia, damping, power injections, the source and shunt admittance, the number of transmission lines that intersect at the node, the per
unit length impedance of these lines and their orientations with respect to a reference axis. The network topology is therefore embedded in the continuum model.

Generator, shunt elements and loads of a power system exist at discrete locations on a spatial grid. The transmission lines exist along lines in two dimensions. We chose to model the corresponding parameter distributions \((m, d, p, a, b\text{ and } g)\) as impulsive in nature comprising of two-dimensional Dirac delta functions (either lines or points). A smooth parameter distribution with a well-behaved approximate identity function such as a two-dimensional unit norm Gaussian function \([7]\). The effect is similar to filtering a two-dimensional image with a low pass spatial filter. The network topology is consequently maintained. The lower the bandwidth of the filter, the wider the spread and smoother the overall parameter distribution. The unit norm property of the approximate identity functions ensures that the spatial integral of the smooth parameter distributions equals the spatial integral of the impulsive distributions. The power system’s overall inertia, damping, power injections, and the source and shunt admittances are thus conserved. Finally, the approximate identity functions are non-negative. The non-negative nature of the impulsive distributions is preserved in the smooth distributions.

Transmission lines form a meshed network on the spatial grid. The corresponding parameter distributions \((v_x, v_y, u_x, u_y, k\text{ and } w)\) are also impulsive in nature comprising of one-dimensional Dirac delta functions. A smooth parameter distribution that approximates the impulsive distribution can again be achieved by parameter distributions consist of one-dimensional Dirac delta functions, the spread is one-dimensional only and is perpendicular to the line. The larger the variance of the approximate identity functions, the wider identity functions ensures that the cross-sectional integral along the spread of a line equals the cross-sectional integral of the corresponding one-dimensional Dirac delta function in the impulsive distribution. The line susceptance and conductance are thus conserved. Again, the non-negative nature of the impulsive distributions is preserved in the smooth distributions.
Chapter 3. Simulation of Discretized Systems of Continuum Equations

3.1. Introduction

The continuum results provided the equations for calculating the velocity of propagation, \( v \), and the characteristic impedance, \( C_0 \) [4]. For the purpose of simulation, we discretized the continuum system in finite number of nodes. The solution to the continuum system was verified by sampling the continuum solution at the bus locations and comparing these values to those obtained from the discrete model. The two solutions were consistent with each other [6]. Therefore, from this point onward we will use the results of continuum system interchangeably with those of the discrete systems.

In this chapter, one-dimensional and two-dimensional discrete representations of continuum equations with finite machine impedances are proposed to illustrate the traveling wave phenomenon. The model presented in this chapter is different from the model previously described [6] which does not include the generator transient reactance. The simulation models include the transmission line reactances, generator transient reactances, and loads. An approximate calculation of the equivalent admittance matrix is also proposed. Numerical simulations, based on the swing equation, demonstrate electromechanical wave propagation with some interesting properties.

Boundary conditions corresponding to system terminations into open and short circuits (high inertia machines) were simulated and studied. The coefficients of reflection are calculated from the numerical results. The more realistic simulations of the non-uniform distribution of generators and transmission lines are studied. This chapter also demonstrates the applications of zero-reflection controllers at the boundaries, both in one- and two-dimensional systems.
3.2. Development of One-Dimensional Discrete Ring Systems

A one-dimensional ring system was constructed in MATLAB (see Figure 3-1) to demonstrate the traveling wave phenomenon. The system is made up of a ring of lines with admittance $y$; a generator with a finite admittance at each node $a_y$; and a shunt load $b_y$; in each of which $a$ and $b$ are parameters. The internal voltage magnitudes of all generators are assumed to be 1 per unit (pu) over the entire network.

Figure 3-2 shows the detailed structure of the ring system. This model differs from the previously published work [6], which used generators with zero internal impedance. However, as shown below, the finite generator impedances provide a mechanism by which precursors to the propagating waves are generated. This leads to a dispersive non-linear wave propagation phenomenon in the power network.
3.2.1. Equations of One-Dimensional Systems

Consider the one-dimensional system shown in Figure 3-1. A generator supplying a variable current at constant voltage is connected at each node. The generator rotor has an accelerating power $P_a$ equal to the difference between output electrical power, $P_e$, and input mechanical power, $P_m$. The motion of the rotor angle $\delta$ is governed by the swing equation:

$$M \ddot{\delta} + D \dot{\delta} = P_m - P_e = P_a,$$  \hspace{1cm} (3.1)

where $M=\omega J$, is the rotor inertia constant, $\omega$ is the angular frequency of the generator rotor and $J$ is the rotor moment of inertia. $D$ is the mechanical damping constant. The damping constant is small: A typical normalized value of $D$ is 0.01 [8]. Therefore,
\[ \dot{\delta}_k + 0.01\delta_k = P_{m,k} - P_{e,k}, \quad \text{for } k=1, \ldots, N, \quad (3.2) \]

where \( N \) is the total number of generators. The power levels, \( P_{m,k} \) are computed from the equilibrium angles \( \delta_{ek} \). The system is disturbed by a small angle impulse applied at one generator, and the propagation of the waves is observed at other nodes.

### 3.2.2. Electromechanical Waves

A 64-machine ring system was constructed by using MATLAB in order to demonstrate the electromechanical waves. The study system with the transmission line susceptance \( (y = -j10 \text{ pu}) \); generator susceptance, \( (y_1 = -j100 \text{ pu}) \); and load \( (y_0 = 0.8-j0.6 \text{ pu}) \) was simulated. The power factor lags by 0.8. The initial rotor angle \( \delta_{ek} \) of the generator at node \( k \) is \( 2\pi k/64 \), where \( k=1, \ldots, 64 \), and the initial impulse applied at the 16th machine has a peak value of 0.5 radians. The swing equations of the system are [9]:

\[ \ddot{\delta}_k + 0.01\dot{\delta}_k = P_{m,k} - P_{e,k}, \quad \text{for } k=1, \ldots, 64. \quad (3.3) \]

Figure 3-3 shows how the waves propagate around the ring system. The x axis is time and the y axis is space. The waves propagate in both directions from the source of the disturbance.
Note that Figure 3-3 shows a very significant dispersion phenomenon. The dispersion is frequency dependent, and hence for the impulsive disturbance used to generate Figure 3-3 there is strong dispersion of the wave as it propagates around the ring.

When the disturbance is a smooth function (for example, a Gaussian distribution of rotor angle displacements in a finite neighborhood of the 16th machine), very little dispersion is present. The dispersion is due to the discrete generators and is not present in the continuum simulation [6]. Figure 3-4 illustrates the electromechanical wave propagation with \( \delta_{ek} = 2\pi k/N \) and initial Gaussian disturbance centered at the 16th generator, \( \delta = 0.5e^{-0.1(s-16)^2} \), as shown in Figure 3-5, where \( s \) is the generator location. The power factor of loads is assumed to be lag by 0.8. The wave propagates in both directions. The waves in the direction of the increasing angle grow, while the waves in the reverse direction are attenuated. The estimation of wave growth is
discussed in the reference [6]. Figure 3-6 shows the wave propagation through generator number
1.

The velocity of propagation is a function of both the line susceptance (in pu length) and the
generator inertias (more details are provided in Section 3.2.4). Furthermore, if the generator
susceptance is much greater than the line susceptance, then the velocity of propagation is
independent of frequency and there would be no dispersion. However, when the ratio between
the two susceptances approaches one, the velocity of propagation is inversely proportional to
frequency, and dispersion effects would be evident. Much of the insight gained from the
theoretical analysis was visible in the simulations.

Figure 3-4. Wave propagation in the 64-machine ring system with Gaussian disturbance.
Figure 3-5. The initial Gaussian disturbance.
3.2.3. Loss of Generator

Consider the 64-machine system described in Section 3.2.2. The constant power flow equilibrium angles are \( \delta_{ek} = \frac{2\pi k}{64} \). Initially, the system is in equilibrium. The generator at the 20\(^{th}\) bus is tripped at \( t = 5 \) seconds, and is restored to the system at \( t = 10 \) seconds. When the generator at the 20\(^{th}\) bus is lost, it initiates an electromechanical disturbance in the system. Similarly, the restoration produces another disturbance. The results are shown in Figure 3-7. This case is representative of waves initiated upon loss of generation in a large-system disturbance. The wave propagates in both directions.
3.2.4. Velocity of Propagation

One of the purposes in studying the phenomena related to electromechanical wave propagation is to estimate when the wave arrives at each location. The velocity of the propagation can be calculated by the following equation [6]:

\[ v = \sqrt{\frac{\omega V^2 \sin \theta}{2h|z|}} \]  

(3.4)
where $\omega$ is the nominal system frequency, $V$ is the magnitude of source voltage, $\theta$ is the phase angle of transmission line impedance, $h$ is the inertia constant pu length, and $z$ is pu impedance per unit length. When using Equation (3.4), the generator impedance and damping constant are assumed to be 0.

To estimate the velocity, consider the 64-machine ring system presented in Section 3.2.2. Assume that $V$ is 1 pu, $\theta$ is 90°, $\frac{\omega}{2h}$ is 1 pu per length, and $|z|$ is 0.1 pu per length. We find the velocity of the propagation is 3.1623 per unit length per second.

The velocity from the simulation result can be calculated by measuring the arrival time of the disturbance between two generators. For the Gaussian disturbance centered at the 16th generator, $\delta = 0.5e^{-0.1(s-16)^2}$, as shown in Figure 3-5, where $s$ is the generator location, the results are used to estimate the velocity. Assume that the generator internal impedances and damping constants are zero. Figure 3-8 presents the wave propagation at the 30th and the 40th buses. The peak of the disturbance arrives at the 30th bus at $t=4.5419$ seconds and it arrives at the 40th bus at $t=7.7771$ seconds. Thus, the velocity of the propagation is 3.091. This is very close to the estimate derived from Equation (3.4).

Now consider the propagation phenomenon shown in Figure 3-9. Assume the generator internal impedances are $j0.01$ and damping constants are 0.01. The wave arrives at the 30th bus at $t=4.6742$ seconds, and it arrives at the 40th bus at $t=7.9834$ seconds. Figure 3-9 shows the wave propagation in the system with non-zero generator impedances and damping constants. The velocity of the propagation in this model is 3.0219. The result indicates that using Equation (3.4) to calculate the velocity of wave propagation in the system with generator impedance and damping constant produces very little error.
Figure 3-8. Wave propagation at the 30th and the 40th buses (system without generator impedance and damping constant).
Figure 3-9. Wave propagation at the 30\textsuperscript{th} and the 40\textsuperscript{th} buses (system with generator impedance and damping constant).
3.2.5. Simulation of Simplified One-Dimensional Discrete Ring Systems

One of the difficulties with the finite generator impedance case is that the electrical power calculation becomes more complex, as each of the generators contributes to the electrical output of every other generator. In the limit, this would present a problem as the coupling matrix approaches the infinite dimension. Consider the following admittance matrix formulation of the ring system:

\[
\begin{bmatrix}
I_1 \\
\cdot \\
\cdot \\
0
\end{bmatrix} =
\begin{bmatrix}
Y_{11} & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot \\
0 & \cdot & \cdot & \cdot
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_a \\
E_b
\end{bmatrix}.
\] (3.5)

Here, the generator buses are arranged to be at the beginning, and the internal nodes are arranged toward the end. Current injections exist only at the generator nodes. Let generator internal admittance \(y_1 = ay\), and load \(y_0 = by\), where \(a\) and \(b\), are constants. Partitioning the matrix along the generator axis, the admittance matrix becomes:

\[
\begin{bmatrix}
I_1 \\
I_2 \\
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
ay & 0 & \cdot & \cdot & -ay & 0 & \cdot & \cdot \\
0 & ay & \cdot & \cdot & 0 & -ay & 0 & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
-ay & 0 & \cdot & \cdot & P & -y & \cdot & -y
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_a \\
E_b
\end{bmatrix}.
\] (3.6)
where $P = y(a + b + 2)$.

The voltages and currents with numerical indices refer to generator internal nodes, and the alphabetical indices refer to generator terminal nodes. Using the network reduction formula (Kron’s formula) to eliminate external nodes,

$$
\begin{bmatrix}
I_g \\
0
\end{bmatrix} = \begin{bmatrix}
Y_{eg} & Y_{ge} \\
Y_{eg} & Y_{ee}
\end{bmatrix}
\begin{bmatrix}
E_g \\
E_e
\end{bmatrix}, \text{ and }.
$$

(3.7)

$$
I_g = Y_{eg} E_g,
$$

(3.8)

where the equivalent admittance matrix $Y_{eg}$ is given by

$$
Y_{eg} = Y_{eg} - Y_{ge} Y_{ee}^{-1} Y_{eg}.
$$

(3.9)

Note that $Y_{ge}$ and $Y_{eg}$ are dimension-changing multipliers, and $Y_{gg}$ only produces a diagonal contribution to $Y_{eg}$. Thus, the structure of $Y_{eg}$ is completely determined by $Y_{ee}^{-1}$.

To study the effect of the existence of generator internal impedance and the relationship between the transmission line admittance ($y$), the generator internal admittance ($a y$), and the load($b y$), MATLAB was used to construct ring systems of 16, 32, 64 and 128 machines with $y=-$
j10 pu, \( a=10 \), and \( b=0.06+j0.08 \). The numerical results show that \( Y^{-1}_{ee} \) has a band structure, with the size of the off-diagonal entries diminishing rapidly, thus, the terms can be assumed to be zero without affecting the accuracy of the result. It is found that the size of \( Y_i \) drops off rapidly when \( i>8 \), regardless of the number of nodes in the network. The value of \( Y_i \) have been calculated in terms of parameters \( a \) and \( b \), and it is verified that there is a symmetry in \( Y_i \) with respect to \( a \) and \( b \). Structurally, for a network that extends to infinity in both directions, the size of the entries of the matrix \( Y^{-1}_{ee} \) can be represented by Figure 3-10, where the width of the diagonal lines represents their relative size.

![Figure 3-10. The structure of \( Y^{-1}_{ee} \)](image)

This is a reasonable result in that the electric power in each machine is affected by a relatively small number of neighboring machines, regardless of the size of the network. Since the electric power of each machine affects its acceleration and the resulting angular movement, it appears that a propagating wave motion of rotor angles will have a precursor toe, much as that which exists on dispersive transmission lines.

In order to illustrate the performance by using an approximate matrix of \( Y^{-1}_{ee} \), which only has eight non-zero entries; apply the same 64-machine ring system described in Section 3.2.2 with the same initial conditions and disturbance. Figure 3-11 is the simulation result. The result
obtained from the approximation is very close to the results shown in Figure 3-4. Taking the #1 machine as an example, Figure 3-12 presents the mechanical wave propagations by using $Y_{ee}^{-1}$ and the approximation of $Y_{ee}^{-1}$.

The error of the simplified calculation can be defined as:

$$\text{Err} = \left\{ \sum_{k=1}^{n} \sum_{t=t_1}^{t_2} \left| D(k, t) - D_s(k, t) \right| / D(k, t) \right\} / (t_2 - t_1) / n,$$

where $n$ is the total number of generators, $D$ is the voltage phase angle at the bus terminal, and $D_s$ is the voltage phase angle at the bus terminal, calculated by using an approximate matrix. In Equation (3.10), the averaging is carried out over an interval from $t_1$ to $t_2$.

Use Equation (3.10) to calculate the error of Figure 3-11. It can be seen that the error of the approximate method is 0.34%. The results found in the approximation indicate that the computation of electric power can be simplified by considering only eight neighboring machines, regardless of the size of the network.
Figure 3-11. Wave propagation in the simplified 64-machine ring system.
Figure 3-12. Wave propagation of machine #1.
3.3. One-Dimensional Systems with Open Circuits at the Boundaries

The model of a one-dimensional discrete system with boundary conditions at both ends is shown in Figure 3-13. Loads and generators are connected at the buses. The detailed model of each node is shown in Figure 3-2.

Figure 3-13. One-dimensional discrete system with boundaries.

3.3.1. Equations for the One-Dimensional System with Open Circuits at Both Ends

Equations (3.8) and (3.9) can be used for the one-dimensional system with boundaries at both ends. However, Yee needs to be revised from the ring systems. Yee(1,1) and Yee(N,N) are now y(a+b+1) instead of y(a+b+2) used for the ring systems. In addition, Yee(1,N) and Yee(N,1) are 0 instead of -y.

3.3.2. Electromechanical Waves

Consider a one-dimensional system of 64 machines with open circuit at both ends. Assume there is no power flowing out of the boundaries, which are the 1st and the 64th machines. The transmission line admittance, y, is -j10 pu; the generator admittance, y1, is -j100 pu; and the load, y0, is 0.8-j0.6 pu. The power factor of loads is lags by 0.8. The initial condition is \( \delta_k = \frac{2\pi k}{64} \), where \( k = 1, \ldots, 64 \), and the initial Gaussian disturbance is centered at the 16th machine, \( \delta = 0.5e^{-10.1(s-16)^2} \), as shown in Figure 3-5.

Figure 3-14 demonstrates the electromechanical wave propagation. The wave propagates in both directions. The wave traveling in one direction increases in amplitude, while the other
decreases. When the increasing wave arrives at the boundary of the 64th machine, the wave reflects back into the system. Similarly, when the decreasing wave arrives at the boundary of the 1st machine, it also reflects back into the system.

Figure 3-14. Wave propagation of the one-dimensional system of 64 machines with boundary conditions.
3.4. Non-Uniform Distribution of Generators and Transmission Lines on the Network

The 64-machine ring system described in Section 3.2 is used in this section.

3.4.1. Ring System with Non-Uniform Distribution of Generator Inertias

To simulate the system with non-uniform distribution of generators, we increase the generator inertia constant of the 32nd machine from 1 to 100. Figure 3-15 shows the wave propagation of the non-uniform ring system.

Figure 3-15. Wave propagation of the ring system with non-uniform distribution of generators.
The increasing wave can not propagate through the 32\textsuperscript{nd} machine, and reflects through the 31\textsuperscript{st} machine back into the system. Neither can the decreasing wave propagate through the 32\textsuperscript{nd} machine, so it reflects through the 33\textsuperscript{rd} machine back into the system. The 32\textsuperscript{nd} machine with a high inertia behaves like a short circuit in the ring system.

3.4.2. Ring System with Non-Uniform Distribution of Transmission Lines

To simulate the system with non-uniform distribution of transmission lines, we increase the transmission line impedance by 100 times between machine #31 and #32, and between machines #32 and #33. Figure 3-16 shows the wave propagation of the non-uniform ring system.

![Figure 3-16. Wave propagation of the ring system with non-uniform distribution of transmission lines.](image-url)
The increasing wave can not propagate through the 32\textsuperscript{nd} machine, and reflects through the 31\textsuperscript{st} machine back into the system. Neither can the decreasing wave propagate through the 32\textsuperscript{nd} machine, so it reflects through the 33\textsuperscript{rd} machine back into the system. The transmission line connected with bus #32 with high impedance behaves as an open circuit in the ring system.

3.4.3. Effect of Generator Damping Constant

Assume the damping constant of the ring system is 0.01. To evaluate the effect of generator damping constant (D), we change the damping constant of generators #30, #31, ..., #34.

- Case I:

First, we increase the damping constant as follows:

\[ D(#30)=0.2, \ D(#31)=0.5, \ D(#32)=1, \ D(#33)=0.5, \ D(#34)=0.2. \]

The result is shown in Figure 3-17. When the increasing wave arrives at the 30\textsuperscript{th} machine, the wave reflects back into the system. However, the increasing wave is damped after passing the 30\textsuperscript{th} machine. Similarly, when the decreasing wave arrives at the 34\textsuperscript{th} machine, the wave reflects back into the system, and is also damped after passing the 34\textsuperscript{th} machine.
Figure 3-17. Wave propagation of the ring system when $D=0.01$, except $D(#30)=0.2$, $D(#31)=0.5$, $D(#32)=1$, $D(#33)=0.5$, and $D(#34)=0.2$.

Case II:

Next, we increase the damping constant as follows:

$D(#30)=2$, $D(#31)=5$, $D(#32)=10$, $D(#33)=5$, and $D(#34)=2$.

The reflected waves increase as damping constants increase, as shown in Figure 3-18.
Figure 3-18. Wave propagation of the ring system when $D=0.01$, except $D(\#30)=2$, $D(\#31)=5$, $D(\#32)=10$, $D(\#33)=5$, and $D(\#34)=2$.

- Case III:

Here, we increase the damping constant as follows:

$D(\#30)=20$, $D(\#31)=50$, $D(\#32)=100$, $D(\#33)=50$, and $D(\#34)=20$.

The traveling wave is totally reflected when it arrives at the 32nd machine. The machine with high damping constant behaves like a short circuit in the ring system.
Figure 3-19. Wave propagation of the ring system when D=0.01, except D(#30)=20, D(#31)=50, D(#32)=100, D(#33)=50, and D(#34)=20.
3.5. Wave Reflection

3.5.1. Reflection Coefficients

The reflection coefficients of the reflected waves can be found by calculating wave propagation in the ring system with and without boundaries. In order to determine the reflection coefficient, it becomes necessary to separate the reflected wave from the incident wave at each location. The incident wave in a given region can be identified as the wave that would exist in a continuous homogeneous medium. Thus, the reflected wave can be determined by subtracting from the total signal the wave corresponding to the wave in a continuous medium. The reflection coefficient $K$ can therefore be defined as follows:

$$K_n = \pm \left[ \sum_{t_1}^{t_2} d_n(t) / r_n(t) \right] / (t_2 - t_1), \quad \text{and}$$

$$d_n(t) = b_n(t) - r_n(t),$$

where $b_n(t)$ is the bus voltage phase angle of the ring system with boundaries, $r_n(t)$ is the bus voltage phase angle of the ring system without boundaries, and $n$ is the generator number. The positive and negative signs of Equation (3.11) represent the character of the reflected waves. If the shape of reflected waves is opposite to the incident waves, $K_n$ becomes negative. The reflection coefficient is computed for different points on the waveform, and then the average is taken of the reflection coefficients found at each instant of time. In Equation (3.11), the averaging is carried out over the interval from $t_1$ to $t_2$. 
3.5.2. One-Dimensional System with Open Circuit at the Boundaries

Consider a one-dimensional system of 64 machines with open circuits at both ends. Assume there is no power flowing out of the boundaries, which are the 1st and the 64th machines. The transmission line admittance, $y$, is $-j10$ pu; the generator admittance, $y_1$, is $-j100$ pu; and the load, $y_0$, is $0.8-j0.6$ pu. The power factor of the loads lag by 0.8. The initial condition is $\delta_k = 2\pi k/64$, where $k=1, \ldots, 64$, and the initial Gaussian disturbance is centered at the 16th machine, $\delta = 0.5e^{-0.4(s-16)^2}$, as shown in Figure 3-5.

Figure 3-20 shows $r_1$ and $d_1$ for the voltage at the terminal of the 1st machine. The dotted line, $r_1$, is the bus voltage phase angle of the 1st machine of a ring system (a system without boundaries) and the solid line, $d_1$, represents the bus voltage phase angle difference between the ring system and the system with boundaries. Figure 3-21 shows $r_{64}$ and $d_{64}$.

Recall that $t_1$ and $t_2$ define the interval over which the point-by-point reflection coefficient is calculated and averaged. When calculating $K_1$, $t_1$ and $t_2$ equal 4 seconds and 6 seconds, respectively. For $K_{64}$, $t_1$ and $t_2$ equal 14 second and 17 second, respectively. The average value of the reflection coefficients, $K_1$ and $K_{64}$, are found to be +1. This is in keeping with the concept of open circuits at both ends of the system.
Figure 3-20. The $r(t)$ and $d(t)$ of the 1st machine.
3.5.3 Ring System with Non-Uniform Distribution of Generator Inertias

In order to study the effect of the non-uniform distribution of generators, the rotor inertia constant of the 32nd machine was changed to 100. This led to reflected waves at the 32nd machine. The reflection coefficient, $K_{31}$ is computed between $t_1=4$ seconds and $t_2=6$ seconds; while reflection coefficient $K_{33}$ is calculated between $t_1=14$ seconds and $t_2=17$ seconds. The
results show that $K_{31}$ and $K_{33}$ are both $-1$. The concentration of inertia at the 32nd machine behaves like a short circuit on the system.

In summary, the boundaries at both ends of the open circuit system cause wave reflections where the coefficient is $+1$. Heavy generator inertia concentration (with a reflection coefficient of $-1$) at a point on the continuum behaves like a short circuit on the system.

Figure 3-22. The $r(t)$ and $d(t)$ of the 31st machine.
Figure 3-23 The r(t) and d(t) of the 33\textsuperscript{rd} machine.
3.5.4. Reflection-Free Termination

When the traveling wave hits the boundaries, it produces total reflections. If the power out of the string and the frequency at the end of the string are in constant proportion, such that \( C = \frac{\omega}{P} \), then the reflection coefficient for frequency is calculated as follows [10]:

\[
R = \frac{C - C_0}{C + C_0},
\]

(3.12)

and \( C_0 \) is the characteristic impedance, which is defined by

\[
C_0 = \sqrt{\left( \frac{\omega_s}{2h} \right) \left( \frac{1}{V^2 b} \right)},
\]

(3.13)

where \( \omega_s \) is the nominal system frequency, \( h \) is the inertia constant per unit length, \( V \) is the magnitude of source voltage, and \( b \) is the per-unit line susceptance per length.

In Section 3.5.2, \( C \to \infty \) and \( R=1 \) reflect open circuits at the boundaries. Similarly, in Section 3.5.3, \( C=0 \) and \( R=-1 \) reflect short circuits. If \( C=C_0 \), the reflections can be eliminated. A controller is designed by using the following equation (a detailed explanation can be found in other work [10]) for the generator at the end:
\[
\frac{2H}{\omega_s} \frac{d\omega}{dt} = G \left( \tilde{P}_{\text{end}} - \frac{\omega}{C_0} \right),
\]  

(3.14)

where \( \tilde{P}_{\text{end}} \) is the deviation from the nominal in the line power flow to the terminating generator, and \( G \) is a gain. If \( G \) can be chosen such that the generator dynamics are fast enough to track the incident wave, this zero-reflection controller will effectively eliminate reflections. Note that the generator internal impedance and damping constant are assumed to be zero.

We use the 64-machine string system described in Section 3.3, and let the generator impedances and damping constants be zero throughout the entire system. Place the controller on the 64th machine and choose \( G=2 \) [10]. The simulation result is shown in Figure 3-24. The controller placed on the 64th machine eliminates the reflections.

Assume the generator impedances are \( j0.01 \) and damping constants are 0.01, and then place the same controller on machine #64. The controller works well in the system that has non-zero generator impedances and damping constants as shown in Figure 3-25. The zero-reflection controllers applied in two-dimensional systems are demonstrated in Section 3.6.4.
Figure 3-24. Wave propagation in a 64-machine string system with a zero-reflection controller placed on the 64th machine.
Figure 3-25. Wave propagation in the system with non-zero generator impedances and damping constants, with a zero-reflection controller placed on the 64th machine.
3.6 Two-Dimensional Grid Systems

The one-dimensional ring system is now extended to a two-dimensional grid system in order to study wave propagation in planar systems. It is expected that the region of influence for electrical power exchange between a machine and its neighbors will extend to a finite number of machines, as is the case for the one-dimensional system. One could represent the region of influence for a machine at bus k as follows: The relative size of the entries of the matrix which defines interaction of generator k with all other generators, is indicated by the size of the square. The actual structure of the matrix will be determined in Section 3.6.2.

3.6.1. Modeling of Two-Dimensional Grid Systems

The model of an m-by-n node two-dimensional grid system is shown in Figure 3-26. Again, the system is made up of line admittances y, each node has a generator with a finite admittance, y1, ay; and a shunt load, y0, by; for each of which, a and b are parameters. The internal voltage magnitudes of all generators are assumed to be 1 per unit over the entire network.

A generator supplying a variable current at constant voltage is connected at each node. The generator rotor is accelerated by the difference between output electrical power, Pe, and input mechanical power, Pm. The motion of the rotor angle δ is governed by the swing equation (3.1).

For an m-by-n grid system, the swing equations of the system are [9]:

\[
\delta_{(i,j)} + 0.01\delta_{(i,j)} = P_{m,(i,j)} - P_{e,(i,j)} , \quad \text{for } i=1, \ldots, m \text{ and } j=1, \ldots, n. \tag{3.15}
\]

The powers, \( P_{m,(i,j)} \), are computed from equilibrium angles \( \delta_e \). The system is disturbed by a small angle impulse applied at one generator, and the propagation of the waves is observed at other nodes.
Figure 3-26. The model of the two-dimensional system.
3.6.2. Equations of Two-Dimensional Discrete Systems

Referring to the model in Figure 3-26, the generator currents are given by

\[
\begin{bmatrix}
I_{11} \\
\vdots \\
I_{1n} \\
I_{21} \\
\vdots \\
I_{2n} \\
\vdots \\
I_{n1} \\
\vdots \\
I_{nn}
\end{bmatrix}
= 
\begin{bmatrix}
Y_1 & 0 & \cdots & 0 & -Y_1 & 0 & \cdots & 0 \\
0 & Y_1 & 0 & \cdots & 0 & 0 & -Y_1 & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\
0 & \cdots & 0 & Y_1 & 0 & 0 & \cdots & 0 & -Y_1 & 0 \\
0 & \cdots & 0 & 0 & Y_1 & 0 & \cdots & 0 & \cdots & \cdots & \cdots & 0 & -Y_1
\end{bmatrix}
\begin{bmatrix}
E_{11} \\
\vdots \\
E_{1n} \\
E_{21} \\
\vdots \\
E_{2n} \\
\vdots \\
E_{n1} \\
\vdots \\
E_{nn}
\end{bmatrix}
\]

, (3.16)
where

\[ Y_1 = \begin{bmatrix}
  y_1 & 0 & \cdots & \cdots & 0 \\
  0 & y_1 & 0 & \cdots & 0 \\
  \vdots & \vdots & \ddots & \vdots & \vdots \\
  0 & \cdots & 0 & y_1 & 0 \\
  0 & \cdots & 0 & y_{1_{n \times n}} & 0 \\
\end{bmatrix}, \quad \text{and}
\]

\[ 0 = \begin{bmatrix}
  0 & 0 & \cdots & \cdots & 0 \\
  0 & 0 & \cdots & \cdots & 0 \\
  \vdots & \vdots & \ddots & \vdots & \vdots \\
  0 & \cdots & 0 & 0 & 0 \\
  0 & \cdots & 0 & 0 & 0 \\
\end{bmatrix}_{n \times n}. 
\]

Let

\[ A = \begin{bmatrix}
  Y_1 & 0 & \cdots & \cdots & 0 \\
  0 & Y_1 & 0 & \cdots & 0 \\
  \vdots & \vdots & \ddots & \vdots & \vdots \\
  0 & \cdots & 0 & Y_1 & 0 \\
  0 & \cdots & 0 & Y_{1_{n^2 \times n^2}} & 0 \\
\end{bmatrix}, \]
Then, Equation (3.16) can be written as follows:
\[
\mathbf{I}_{n^2 \times 1} = [\mathbf{A} \mid -\mathbf{A}]_{n^2 \times 2n^2} \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \end{bmatrix}_{2n^2 \times 1},
\]

(3.17)

The node equations at each bus are given by

\[
\mathbf{0}_{n^2 \times 1} = [-\mathbf{A}_{n^2 \times n^2} \mid \mathbf{B}_{n^2 \times 2n^2}]_{n^2 \times 2n^2} \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \end{bmatrix}_{2n^2 \times 1},
\]

(3.18)

where

\[
\mathbf{B} = \begin{bmatrix}
\mathbf{B}_1 & -\mathbf{Y}_1 & 0 & 0 & \ldots & \ldots & \ldots & \ldots & 0 \\
-\mathbf{Y}_1 & \mathbf{B}_2 & -\mathbf{Y}_1 & 0 & 0 & \ldots & \ldots & \ldots & 0 \\
0 & -\mathbf{Y}_1 & \mathbf{B}_2 & -\mathbf{Y}_1 & 0 & 0 & \ldots & \ldots & 0 \\
0 & 0 & -\mathbf{Y}_1 & \mathbf{B}_2 & -\mathbf{Y}_1 & 0 & 0 & \ldots & 0 \\
0 & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
\end{bmatrix}_{n^2 \times n^2},
\]
\begin{align*}
\mathbf{B}_1 &= \begin{bmatrix}
(y_1 + 2y + y_0) & -y & 0 & \cdots & \cdots & 0 \\
-\ y & (y_1 + 3y + y_0) & -y & 0 & \cdots & 0 \\
0 & -y & (y_1 + 3y + y_0) & -y & \ddots & \vdots \\
\vdots & \ddots & \ddots & \ddots & \ddots & 0 \\
0 & \cdots & 0 & -y & (y_1 + 3y + y_0) & -y \\
0 & \cdots & \cdots & 0 & -y & (y_1 + 2y + y_0)_{n \times n}
\end{bmatrix},
\end{align*}

\begin{align*}
\mathbf{B}_2 &= \begin{bmatrix}
(y_1 + 3y + y_0) & -y & 0 & \cdots & \cdots & 0 \\
-\ y & (y_1 + 4y + y_0) & -y & 0 & \cdots & 0 \\
0 & -y & (y_1 + 4y + y_0) & -y & \ddots & \vdots \\
\vdots & \ddots & \ddots & \ddots & \ddots & 0 \\
0 & \cdots & 0 & -y & (y_1 + 4y + y_0) & -y \\
0 & \cdots & \cdots & 0 & -y & (y_1 + 3y + y_0)_{n \times n}
\end{bmatrix},
\end{align*}

and

\[ \mathbf{0} = \begin{bmatrix}
0 & 0 & \cdots & \cdots & 0 \\
0 & 0 & \cdots & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & \cdots & 0 \\
0 & 0 & \cdots & \cdots & 0_{n \times n}
\end{bmatrix}. \]

From Equations (3.17) and (3.18), yield the following equation for generator current and voltage:

\[ \mathbf{I} = \mathbf{Y} \mathbf{E}_1, \]

where the equivalent admittance matrix \( \mathbf{Y} \) is given by
\[ Y = [A - (AB^{-1}A)] \]  \hspace{1cm} (3.19)

Note that coefficients A are dimension-changing multipliers, and only produces a diagonal contribution to Y. Thus, the structure of Y is completely determined by B-1.

3.6.3. Electromechanical Waves

Using MATLAB to simulate the wave propagation on a 35-by-35 grid system by giving a Gaussian distribution \( \delta = 0.5e^{-0.1((m-18)^2+(n-18)^2)} \) at t=0 seconds, the results are as shown in Figure 3-27. The transmission line admittance is –j10 pu, the generator admittance is –j100 pu, and the load is 0.8-j0.6 pu. The equilibrium angle \( \delta_e \) with \( \delta_e(i,j) = 2\pi \times j/35 \), shows an increase of \( 2\pi \) from one side to the other. Figure 3-28 illustrates the time snapshots of disturbance propagation as a function of position in a 35-by-35 grid system from t=0.5 seconds to t=30 seconds. The wave arrives at the centers of each boundary when t=5.4 seconds. The equilibrium angle has been subtracted from the results, so that only disturbance effects are shown. These results were corroborated by comparing them with the results of a continuum model simulation.
Figure 3-27. The initial Gaussian disturbance of the 35-by35 grid system.
Figure 3-28 Time snapshots of disturbance propagation as a function of position in a 35-by-35 grid system.
3.6.4. Simulation of Simplified Two-Dimensional Grid Systems

To study the effect of the existence of generator internal impedance and the relationship between the transmission line admittance($y$), the generator internal admittance($a_y$), and the load($b_y$), MATLAB was used to construct planar systems of 16, 35 and 50 machines, each of which has $y=-j10$, $a=10$, and $b=0.06+j0.08$. The numerical results show that $B^{-1}$ has a band structure, with the size of the off-diagonal entries diminishing rapidly, so that the terms can be assumed to be zero without affecting the accuracy of the results. Structurally, for a two-dimensional network that extends to infinity in four directions, the size of the entries of the matrix $B^{-1}$ can be represented by Figure 3-29, in which the widths of the diagonal lines represent their relative sizes.

The result is similar to the one-dimensional system in that the electric power in each machine is affected by the neighboring 144 machines, regardless of the size of the network. Figure 3-30 describes the neighboring machines that affect the electric power in node $(i,j)$. 

![Figure 3-29. The structure of $B^{-1}$.](image-url)
In order to illustrate the performance by using an approximate matrix of B-1, apply the same 35-by-35 system described in Section 3.6.3 with the same initial condition and disturbance. Taking machine (1,1) as an example, Figure 3-31 presents the mechanical wave propagations by using B-1 and the approximation of B-1.
Figure 3-31. Wave propagations of machine (1,1) in a 35-by-35 grid system.
The error of the simplified calculation in an m-by-n grid system can be defined as:

$$\text{Err} = \left\{ \frac{1}{(m \times n)} \sum_{i=1}^{m} \sum_{j=1}^{n} \left| D_{(i,j)}(t) - D_{(i,j)}(t) \right| / D_{(i,j)}(t) \right\} / (t_2 - t_1),$$  \hspace{1cm} (3.20)$$

where mxn is the size of the two-dimensional grid system, D is the voltage phase angle at the bus terminal, and Ds is the voltage phase angle at the bus terminal calculated by using an approximate matrix. In Equation (3.20), the averaging is carried out over an interval from t1 to t2.

Use Equation (3.20) to calculate the error of the 35-by-35 grid system described in Section 3.6.3. It can be seen that the error of the approximate method is 0.82%. The results found in the approximation indicate that the computation of electric power can be simplified by considering only 144 neighboring machines, regardless of the size of the network.

### 3.6.5. Reflection-Free Termination

The zero-reflection controller introduced in Section 3.5.4 can be used in two-dimensional systems for terminating reflections on the boundaries. The same network as in Section 3.6.3 is used to demonstrate the effect of zero-reflection controllers placed on all generators located on the edges of the network. It is assumed that the generator internal impedance and damping constants of the network are zero. A disturbance of Gaussian distribution

$$\delta = 0.5e^{-0.1((m-18)^2+(n-18)^2)}$$

is applied at t=0.

Figure 3-32 shows the time snapshots of disturbance propagation as a function of position. The waves arrive at the boundaries when t=5.4 seconds. The zero-reflection controllers absorb most of the incident waves at t=23.5 seconds. When t=30 seconds, the disturbances are eliminated. Simulation results show that the zero-reflection controllers also work very well in two-dimensional networks.
Figure 3-32. Time snapshots of disturbance propagation as a function of position in a 35-by-35 grid system with zero-reflection controllers placed on the edges of the network.

3.6.6. Reflection Coefficients

The reflection coefficient of an n-by-n network is calculated at the center of each edge. The reflection coefficients of the reflected waves can be found by calculating wave propagation in the two-dimensional system with and without boundaries. The system without boundaries can be achieved by placing the zero-reflection controllers on the edges of the system. In order to determine the reflection coefficient, it becomes necessary to separate the reflected wave from the incident wave at each location. The incident wave in a given region can be identified as the wave that would exist in a continuous homogeneous medium. Thus the reflected wave can be determined by subtracting from the total signal the wave corresponding to the wave in a continuous medium. The reflection coefficient K can therefore be defined as follows:
\[ K_{(i,j)} = \pm \left[ \sum_{n=1}^{t_2} d_{(i,j)}(t) / r_{(i,j)}(t) \right] (t_2 - t_1), \]  

(3.21)

\[ d_{(i,j)}(t) = b_{(i,j)}(t) - r_{(i,j)}(t), \]

where \( b_{(i,j)} \) is the bus voltage phase angle of the two-dimensional system with boundaries, and \( r_{(i,j)}(t) \) is the bus voltage phase angle of the two-dimensional system without boundaries. Note that \((i,j)\) is the location of the generator in the system with boundaries, and \((i\text{,}j)\) is the location of the generator in the infinite system that corresponds to \((i,j)\) of the system with boundaries. The positive and negative signs of Equation (3.21) represent the character of the reflected waves. If the shapes of reflected waves are opposite to those of the incident waves, \( K_{(i,j)} \) becomes negative. The reflection coefficient is computed for different points on the waveform, taking the average of the reflection coefficients found at each instant of time. In Equation (3.21), the averaging is carried out over an interval from \( t_1 \) to \( t_2 \).

MATLAB was used to construct 21-by-21 and 35-by-35 grid systems by giving a Gaussian distribution at the center of the systems at \( t=0 \) seconds. The transmission line admittance is \(-j10\) pu and the load is \(0.8-j0.6\) pu. The equilibrium angle is \( \delta_e = 0 \). It is assumed that the damping constant is zero over the entire systems. Zero-reflection controllers were placed on the edges of the 35-by-35 system in order to create a system without boundaries. Our purpose is to compute the reflection coefficients at the center of the edges of the 21-by-21 system.

Figure 3-33 explains \( r_{(8,18)} \) and \( d_{(1,11)} \) for the voltage at the terminal of the machine \((1,11)\) of the 21-by-21 system. The dotted line, \( r_{(8,18)} \), is the bus voltage phase angle of the machine \((8,18)\) of the 35-by-35 system (the system without boundaries) and the solid line, \( d_{(1,11)} \), represents the bus voltage phase angle difference between node \((1,11)\) of the 21-by-21 system and node \((8,18)\) of the 35-by-35 system.
Recall that $t_1$ and $t_2$ define the interval over which the point-by-point reflection coefficient is calculated and averaged. When calculating $K_{(1,11)}$, $t_1$ and $t_2$ are equal to 2 seconds and 3.5 seconds, respectively. The average value of the reflection coefficients, $K_{(1,11)}$, is found to be +1. This is in keeping with the concept of open circuits at the edges of the grid.

The system is identical and symmetric throughout the entire network. The reflection coefficients at the center of the four edges are the same. Hence, the reflection coefficients of node (1,11), node (11,1), node (11,21), and node (21,11) of the 21-by-21 system are identical.

Figure 3-33. The $r_{(8,18)}$ of the 35-by-35 grid system with controllers on the edges, and $d_{(1,11)}$ of node (1,11) of the 21-by-21 grid system.

Now consider the systems with non-zero generator impedances and damping constants. Remove the zero-reflection controller of the 35-by-35 grid system. The 21-by-21 grid system and
the 35-by-35 grid system now both have boundaries. Using Equation (3.20) to calculate the reflection coefficient of node (1,11) of the 21-by-21 grid system, $r'_{(8,18)}$ and $d'_{(1,11)}$ are shown in Figure 3-34.

When calculating $K'_{(1,11)}$, $t_1$ and $t_2$ are equal to 2 seconds and 3.5 seconds, respectively. The average value of the reflection coefficients, $K'_{(1,11)}$, is found to be +1. The result is the same as the one obtained in the previous calculation.

Figure 3-34. The $r'_{(8,18)}$ of the 35-by-35 grid system without controllers on the edges, and $d'_{(1,11)}$ of node (1,11) of the 21-by-21 grid system.
Chapter 4. Effects of Wave Propagation on Protection Systems

4.1. Introduction

The purpose of analyzing electromechanical waves is to understand whether these phenomena can harm the power network and to determine how the protection systems should respond to those disturbances.

This chapter discusses the effects of electromechanical wave propagation on power systems and power system protective devices, which include overcurrent relays, distance relays, out-of-step relays, and underfrequency load-shedding relays.

4.2. Effects on Power Systems

4.2.1. Line Loadings

The phenomena being considered in this dissertation focus on the movement of positive-sequence voltage phase angles across the network following the initiation of a disturbance. The angle deviations influence the flow of real power. Of course deviations in real power flows will affect the bus voltage magnitudes as well, but those phenomena are second-order effects, and are not considered in this work.

Deviations in angles will cause deviations in power flows which will be super-imposed on prevailing flows in the network. The angle deviations are considered to be small, hence small angle approximations of power flow are considered appropriate. The power flow in a loss-less line is given by

\[ P_0 = P_{\text{max}} \sin \delta_0. \]  

(4.1)
The angle $\delta_0$ is assumed to be small. The deviation in power flow that occurs due to an incremental increase in angle $\Delta \delta$ (also small) will be assumed to cause the power deviation given by

$$\Delta P = P_{\text{max}} \sin (\delta_0 + \Delta \delta) - P_{\text{max}} \sin \delta_0 \equiv P_{\text{max}} \Delta \delta. \quad (4.2)$$

$P_{\text{max}}$ in the above equations represents the peak of the $P-\delta$ curve, and is given by the familiar formula

$$P_{\text{max}} = \frac{E_s E_R}{X}, \quad (4.3)$$

where $E_s$ and $E_R$ are the sending and receiving end voltage magnitudes, and $X$ is the reactance of the line.

Now consider the snapshot of the angles at an instant in the network. This snapshot represents prevailing variations in phase angles across the entire network. The deviation in the angle as we travel a small distance $\Delta r$ in an arbitrary direction is given by the dot product

$$\Delta \delta = \nabla \delta \cdot \Delta r. \quad (4.4)$$
This equation can also be expressed in rectangular coordinates, as follows:

\[
\Delta \delta = \text{Re}\left\{ \frac{\partial \delta}{\partial x} + j \frac{\partial \delta}{\partial y} \right\} \left[ \cos \theta + j \sin \theta \right]^* |\Delta r|.
\]

(4.5)

This equation is illustrated in Figure 4-1, where representative equiangular contours show the disposition of the wave at an instant.

Figure 4-1. Angle change in an arbitrary direction during wave propagation.

Now consider the structure of the impedance distribution in the continuum. If the losses in the network are neglected, the impedance (reactance) of the continuum between two points infinitesimally close to each other along the vector \( r \) is given by

\[
\Delta X = \nabla X \cdot \Delta r.
\]

(4.6)
This equation also can be expressed in rectangular coordinates, as follows:

\[ \Delta X = \text{Re}\{[\partial X/\partial x + j \partial X/\partial y][\cos \theta + j \sin \theta]^*}\} |\Delta r|. \tag{4.7} \]

As a result of the gradient of the phase angle and the gradient of the impedance distribution in the network, the change in the power flow between two infinitesimally close points along direction \( r \) (assuming that the voltages are one per unit magnitude) is given by

\[ \Delta P^r = \Delta \delta / \Delta X, \tag{4.8} \]

where the superscript \( r \) represents the incremental increase in power in the direction \( r \), and the \( \Delta \delta \) and \( \Delta X \) are given by Equations (4.5) and (4.7), respectively. In the case of a uniform distribution of the system impedance in the continuum, the impedance gradient is constant in both \( x \) and \( y \) directions.

Note that \( \Delta P^r \) is not an infinitesimal quantity in the sense that it is not of the order of \( \Delta x \). The incremental increase in power flow is superimposed on the power flow at a point on the continuum.

Equation (4.8) provides a procedure by which the equi-angle contour of Figure 4-1 can be transformed into a \( P \) field whose gradient in the \( r \) direction gives the incremental increase in power flow in that direction.
\[ \Delta P_f = \nabla P \cdot r. \]  \hspace{1cm} (4.9)

The transformation is shown symbolically in Figure 4-2. Note that the angle distribution is supplemented by the impedance distribution in order to obtain the P-field. Now that the angle field is transformed into a P field, it is possible to estimate the effect of a traveling wave of angles on network loading.

![Figure 4-2. Transformation of the angle field into a power field using the impedance distribution.](image)

The \( \delta \) field can be used to anticipate the incremental change in power flow at a given location by determining both the direction of wave propagation, and the disposition of the \( \delta \) field at the remote site. This concept is illustrated in Figure 4-3.

From the present disposition of the \( \delta \)-field and the direction of wave propagation, the P-field at a remote site can be calculated in anticipation of incremental increase in load flow, which would occur in the remote site after a delay corresponding to the wave propagation delay.
Figure 4-3. Wave propagation phenomena used to determine future power flow excursions.

4.2.2. Network Frequency

The local frequency at a power system bus may be determined from the formula

\[ f = f_0 + \frac{1}{2\pi} \frac{d\delta_v}{dt}, \]  \hspace{1cm} (4.10)

where \( f_0 \) is the nominal system frequency, and \( \delta_v \) is the phase angle of the positive sequence voltage phasor at the bus. When the phase angle wave passes through a location, the local bus voltage angle will go through a time-dependent variation. Consider the disposition of the wave as shown in Figure 4-4(a). Assuming that the interest is in local frequency at an arbitrary point A, a cross-section of the wave is taken along the direction of wave propagation. As the wave passes through point A, the angular displacement will have a time dependence \( \delta(t) \) as shown in Figure
4-4(b). Knowing the function $\delta(t)$, Equation (4.10) yields the variation of local frequency at A. Indeed, the frequency wave can be directly computed from the angle wave, and the two waves can be assumed to be propagating together.

Figure 4-4. Frequency excursions accompanying the angle wave propagation.
4.3. Effects on System Protection

In many instances of catastrophic failures in power networks, some relays trip due to power swings when it is inappropriate to do so, and possibly contribute to complete system collapse. As electromechanical waves propagate through the system, it is important to study the effect of the waves on power system protection equipment.

The pickup setting of an over-current relay is set well above the maximum load current, while distance relays have a definite loadability limit [11]. The primary protection systems are dedicated to protection of individual pieces of power equipment, and consequently are almost totally immune to loading conditions. However, there are a number of back-up relay functions, system protection devices and special protection systems that will be affected by loading patterns as they evolve with time. Back-up zones of distance relays, out-of step relays and load-shedding schemes will be discussed in this section.

4.3.1 Overcurrent Relays

The pickup setting of the overcurrent relays is assumed to be twice the maximum load. As seen in Figure 3-3, the wave propagation in the system is generated by applying an impulse with a 0.5-radian peak value to the 16\textsuperscript{th} machine. The line current in each line is examined against the pick-up setting of overcurrent relays.

The results indicate that when the disturbance propagates through the ring system, several of the overcurrent relays are in danger of tripping due to the wave propagation. The relays located at the 8\textsuperscript{th} bus through the 22\textsuperscript{nd} bus will trip within 10 seconds. Others trip after 10 seconds.

Figure 4-5 illustrates the current in the relay at the 16\textsuperscript{th} bus. Figure 4-6 shows that the current in the relay located at the 36\textsuperscript{th} bus showing is likely to trip at 38.7 seconds. Figure 4-7 shows the current in the relay located at the 5\textsuperscript{th} bus, which has a trip time at 54.4 seconds. Figure 4-8 shows that the relay located at the 23\textsuperscript{rd} bus is in no danger of tripping.
Simulations show that overcurrent relays may operate when the waves pass through their locations. Since wave propagation is a transient phenomenon, it is desirable to block the tripping of these relays for the duration of the wave propagation.

Figure 4-5. Overcurrent relay pickup setting and transmission line current at the 16th bus.
Figure 4-6. Overcurrent relay pickup setting and transmission line current at the 36th bus.
Figure 4-7. Overcurrent relay pickup setting and transmission line current at the 5\textsuperscript{th} bus.
Figure 4-8. Overcurrent relay pickup setting and transmission line current at the 23rd bus.
4.3.2 Distance Relays

Distance relays are normally used for protecting transmission lines [12]. They respond to the impedance between the relay location and the fault location. The R-X diagram is a tool for describing and analyzing a distance relay characteristic. The transmission line voltages and currents are chosen to energize the distance relays [11].

Traditionally, zone-1 is set between 85% and 90% of the line length and is to be operated instantaneously. Zone-2 and zone-3 are used in back-up protection and are coordinated with a time delay to allow the primary protection to operate. Zone-2 of the distance relay is generally set at 120% to 150% of the line length. The coordination delay for zone-2 is usually of the order of 0.3 seconds. Zone-3 usually extends to 120% to 180% of the next line section. Note that zone-3 must coordinate in time and distance with zone-2 of the neighboring circuit, and the operating time of zone-3 is of the order of 1 second. Figure 4-9 shows the three zone step distance relaying that protects 100% of a line, and backs up the neighboring line.

![Figure 4-9. Three-zone step distance relaying.](image-url)
As the wave passes through the terminal of a line where the distance relay is located, the apparent impedance trajectory follows a locus, as shown in Figure 4-10. The apparent impedance seen by a distance relay is $Z_{app}$. $Z_0$ is the apparent impedance seen by the distance relay prior to the arrival of the wave. The concern is that the wave propagation would produce an incursion by the apparent impedance into one of the zones of the relays. If it does, the tripping of this relay should be blocked, since after the wave passes beyond the location of the relay, the apparent impedance should return to its previous value $Z_0$. In such cases, a trip in the line would be undesirable.

Figure 4-10. Locus of apparent impedance movement through a relay location.
In the following simulations, an impulse with peak value of 1.5 radians is applied to the 16th machine in order to generate the disturbance in the 64-generator ring system. The zone-1 setting is 90% of the line length, and zone-2 is 150% of the line length. The zone-3 of protection is extended to 150% of the next line section, where the line impedance between two buses is j0.1 per unit throughout the entire system.

From the simulation results, the zone-1 of the distance relays (located at the 15th and 16th buses) will be entered by the apparent impedance when the wave passes through. Other distance relays will not be so severely affected by the disturbance. Figures 4-11, 4-12, 4-13, and 4-14 show the loci of apparent impedance movements at the 14th, 15th, 16th and 17th buses, respectively.

The impedance locus at the 15th bus enters zone-1 at t= 0 seconds and stays for 0.2 seconds. Zone-2 and zone-3 will not operate since the coordination delays between the three zones are greater than 0.2 seconds. Similarly, the impedance locus at the 16th bus enters zone-1 at t=0 seconds and stays for 0.1 seconds. Then, it re-enters at t=0.65 seconds and stays for 0.2 seconds. Zone-2 and zone-3 will not operate because the disturbance does not stay long enough to reach the operating conditions.

Simulations show that distance relays at the 15th and 16th buses will operate when the waves pass through their locations. Since wave propagation is a transient phenomenon, it is desirable to block tripping of these relays for the duration of the wave propagation.
Figure 4-11. Partial locus of apparent impedance movement at the 14th bus.
Figure 4-12. Partial locus of apparent impedance movement at the 15th bus.
Figure 4-13. Partial locus of apparent impedance movement at the 16th bus.
Figure 4-14. Partial locus of apparent impedance movement at the 17\textsuperscript{th} bus.
4.3.3. Out of Step Relays

According to other work [11, 13], out-of-step relays are designed to detect conditions when a group of machines or a portion of the power system is about to go out of synchronism with the rest of the network. If the condition is detected, the relay should separate the affected machines from the rest of the network to avoid a catastrophic failure of the entire network. However, if the swings are stable, the out-of-step relay should block tripping even though the apparent impedance enters some relay zones.

The characteristics of out-of-step relays are shown in Figure 4-15. The inner zone is used to detect an unstable swing. The outer zone is used to start a timer. For a fault condition, the impedance locus enters the inner zone before the timer ends. For an unstable swinging condition, the inner zone is entered after the timer ends. If the inner zone is never entered after the outer zone is entered, a stable swing is stated. S1 shows an unstable swing, and S2 shows a stable swing. No tripping is permitted for a stable swing. For an unstable swing, an appropriate blocking or tripping scheme must be provided. The zone settings and various timer settings are based upon numerous simulations of transient stability events performed for assumed system conditions. It should be clear that the stability swing is a balanced phenomenon. If an unbalance occurs, the out-of-step relaying logic should be disabled.
The 64-machine ring system, as described in Section 3.2.2, is used to demonstrate the effects of wave propagations on out-of-step relays. A Gaussian disturbance with peak value of 2.5 radians is applied to the 16th machine at t=5 seconds in order to generate the disturbances. Figure 4-16 shows the wave propagation in the ring system. The inner zone of the out-of-step relay is set at j0.2 pu and the outer zone is chosen as j0.25 pu. Assume that the timer setting to determine whether a fault or an unstable swing is 0.02 seconds. If the transition between the outer and inner zones is shorter than 0.02 seconds, a fault would be indicated. Another timer setting, used to distinguish between a stable and an unstable swing, is set at 0.15 seconds. If the outer zone is entered but the inner zone is not entered after 0.15 second, a stable swing would be detected. If the outer zone is entered and then the inner zone is entered within 0.02 to 0.15 seconds after that, an unstable swing would be detected. Note that the actual zone and timer settings are based upon numerous simulations of transient stability events performed for assumed system conditions.
Figure 4-16. Wave propagation in the 64-machine ring system generated by a Gaussian disturbance with peak values of 2.5 radians, and started at t= 5 seconds.

The simulation results indicate that when the disturbance propagates through the ring system, the inner and outer zones of out-of-step relays located at the 14th bus through the 18th bus are entered, and some relays are in danger of tripping due to the wave propagation. Since wave propagation is a transient phenomenon, it is desirable to block the tripping of the out-of-step relays for the duration of the wave propagation. The results are as described follows.

Figure 4-17 shows the partial locus of apparent impedance movement at the 14th bus. The outer zone is entered when the Gaussian disturbance applied to the ring system at t=5 seconds. The direction of the swing locus path is from right to left. Thus, the swing locus does not enter the inner zone, and leaves the outer zone at t=5.26 seconds. A stable swing is declared.
Figure 4-17. Partial locus of apparent impedance movement at the 14th bus.
Figure 4-18 shows the partial locus of apparent impedance movement at the 15th bus. The swing locus enters the zones twice. First, the inner zone (on the left-hand side) is entered when the Gaussian disturbance is applied to the ring system at t=5 seconds. The locus enters the inner zone before entering the outer zone. A fault is indicated in this case.

The locus enters the outer zone again at t=5.8 seconds and leaves the outer zone (on the right-hand side) at t=5.88 seconds. The inner zone is not entered. Therefore, a stable swing is declared.

Figure 4-18. Partial locus of apparent impedance movement at the 15th bus.
Figure 4-19 shows the partial locus of apparent impedance movement at the 16\textsuperscript{th} bus. The swing locus first enters the inner zone (right-hand side) when the Gaussian disturbance is applied to the ring system at \( t=5 \) seconds, and leaves the outer zone at \( t=5.24 \) seconds. The locus stays inside the inner zone for 0.16 second and stays inside the outer zone for 0.07 seconds. According to the settings, a fault is detected.

The locus re-enters the zones (left-hand side) at \( t=5.67 \) seconds, and enters the inner zone at \( t=5.79 \) seconds. The locus stays inside the inner zone for 0.11 seconds, then enters the outer zone at \( t=5.91 \) seconds. The locus stays inside the outer zone for 0.12 seconds, then leaves the outer zone at \( t=6.03 \) seconds. An unstable swing is detected.

Figure 4-19. Partial locus of apparent impedance movement at the 16\textsuperscript{th} bus.
Figure 4-20 shows the partial locus of apparent impedance movement at the 17th bus. The outer zone is entered at \( t=6.12 \) seconds and is left at \( t=6.3 \) seconds. The inner zone is not entered. Therefore, a stable swing is declared.
Figure 4-21 shows the partial locus of apparent impedance movement at the 18th bus. The outer zone is entered at $t=6.58$ seconds and is left at $t=6.67$ seconds. The inner zone is not entered. Therefore, a stable swing is declared.

Figure 4-21. Partial locus of apparent impedance movement at the 18th bus.
4.3.4. Load Shedding

When a mismatch (caused by loss of generation, loss of load, or actions of out-of-step relays) exists between the load and generation in a power system, the generators will either speed up or slow down. If the generation is in excess, the generators will speed up, and the system frequency will be above normal. On the other hand, if the load is in excess, the generators will slow down, and the system frequency will be below normal. When the frequency is below normal, it is necessary to prevent the frequency from reaching the turbine underfrequency limits. Otherwise, the turbine blades maybe seriously damaged. The function of underfrequency load shedding relays is to detect decrease in system frequency and to shed adequate amounts of load in order to bring the system back to an operating condition [11]. This is accomplished by using underfrequency relays and timers to drop specified amounts of load at predetermined times. The load-shedding scheme must be established by studying which possible system scenarios may require load shedding. A detailed explanation can be found in other work [11].

Load-shedding relays are sensitive to local system frequency. It has been observed that during frequency swings, some load-shedding relays may operate, and indeed the operation of under frequency relays may not be uniform across the power system. It is clear that electromechanical waves are often transient in nature, and as they pass through a system it may be advantageous to anticipate the passage of the wave through a system, and to supervise the operation of the load-shedding schemes accordingly.

The 64-machine ring system, described in Section 3.2.2, will be used to demonstrate the effects of wave propagations on underfrequency load-shedding relays. A Gaussian disturbance with peak value of 2 radians is applied to the 16th machine in order to generate the disturbances. The wave propagation is shown in Figure 4-22.
Figure 4-22. Wave propagation with a Gaussian disturbance (peak value of 2 radians) applied to the 16\textsuperscript{th} machine.
We set the pickup setting at 59.8 Hertz and the time delay is 10 or more cycles. The simulation results show that frequencies detected at the 15th, 16th, and 17th buses will be below 59.8 Hertz. The results are described as follows.

Figure 4-23 shows the frequency at the 15th bus. The frequency reaches 59.8 Hertz at t=0.72 seconds and returns to 59.8 Hertz at t=1.12 seconds. The frequency stays below 59.8 Hertz for 0.4 seconds. This will meet the condition that sets the load-shedding relays. However, the tripping of load-shedding relays should be blocked, since the wave propagation is a transient phenomenon.

Figure 4-23. Frequency at the 15th bus.
Figure 4-24 shows the frequency at the 16th bus. The frequency reaches 59.8 Hertz at t=0.47 seconds and stays below 59.8 Hertz for 0.72 seconds. It reaches the setting again at t=22.31 seconds and stays below 59.8 Hertz for 0.22 seconds. The load-shedding relays will operate twice during the time period. However, both load-shedding relays trips should be blocked since the wave propagation is a transient phenomenon.
Figure 4-25 shows the frequency at the 17th bus. The frequency reaches 59.8 Hertz at t=0.72 seconds and returns to 59.8 Hertz at t=1.02 seconds. The frequency stays below 59.8 Hertz for 0.3 seconds. This meets the condition for the load-shedding relays to be set. However, the tripping of load-shedding relays should be blocked, since the wave propagation is a transient phenomenon.
4.3.5 Effects on system control

There are a number of automatic control functions on a power system that may use angle differences or frequency excursions as supplementary signals in the controllers. Examples of such controls are generator excitation control, power system stabilizers, HVDC controls, and various types of power electronic devices for active and reactive power control. As in the case for protection systems, it is advisable to also supervise the control systems, and to make them insensitive to transient electromechanical waves that may pass through the power system.
Chapter 5. Field Data on Wave Propagation Phenomena

5.1. Introduction

This chapter introduces the phasor measurement systems at the Bonneville Power Administration (BPA). Another issue of how to handle both the non-uniform structure of the network, and the non-uniform distribution of the generators on the network is settled in this chapter. The technique for obtaining a non-uniform and uniform discrete system from the WSCC 127-bus system is developed in this chapter. The non-uniform and uniform systems both consist of transmission lines, generators and loads. The methodology for obtaining the equivalent parameters is also presented. Both the non-uniform and uniform models provide analytical solutions to the problems of wave propagation in the WSCC 127-bus system.

PhasorFile is the tool used to view the data recorded at the phasor data concentrators. The phenomena of wave propagation are observed in many recorded events. Five cases were selected to verify the non-uniform and uniform models and to test the concepts proposed in this dissertation. The non-uniform model is validated on different test cases.

The simulations show that the continuum model does capture the network topology that dictates the direction and nature of wave propagation.
5.2. Study of Phasor Measurements at the BPA

Phasor measurement units (PMUs) were first developed in the Power Lab at Virginia Tech under a contract with BPA in 1986, and were installed at BPA in the WSCC system in 1988. PMUs placed at substations measure the positive sequences of phasors including voltage, current and frequency.

PMUs installed in the Western Systems Coordinating Council (WSCC) digitize three-phase power line waveforms at 720 Hz or 2880 Hz. These digital samples were computed in PMUs by using a discrete Fourier transform (DFT). The Global positioning system (GPS) satellite system is used to provide the synchronization signals. The GPS receiver provides the 1 pulse/second signal and a time tag, which contains the information of year, day, hour, minute, and second. The DFT computation is referenced to the universal time (UTC) derived from the GPS.

The sampling rate of the current PMUs in the WSCC system is 30 samples/second. The performance of PMUs was tested at BPA. Tests of steady-state accuracy, and phase, amplitude and frequency changes were included. Steady-state accuracy was within 0.5% for amplitude, 0.04 degrees for phase, and 0.001 Hz for frequency. Measurement of the rate at which frequency changes was too noisy to be useful. The dynamic tests were within 1% for phase and amplitude, and within 1 cycle for 100% response [14].

The BPA is a federal government agency whose service area included Washington, Oregon, Idaho and Western Montana. BPA is part of the western North American power grid overseen by the WSCC. Figure 5-1 shows the BPA service area and the locations of PMUs in the WSCC system [15].
Figure 5-1. WSCC system covering area and the locations of measurement points
(courtesy of Mr. Kenneth Martin at BPA).

The locations of PMU at BPA are listed as follows.

- Generation centers:
  
  – Grand Coulee (central Washington)

  – John Day (lower Columbia)

  – Colstrip (eastern Montana)
• Key transmission points:
  – Malin (California-Oregon border)
  – Big Eddy (2 PMUs in lower Columbia area)
  – Sylmar, Vincent, Devers (Los Angeles, California)

• Load centers:
  – Maple Valley, and Renton (Seattle, Washington)
  – Keeler (Portland Oregon)

    Detailed descriptions of the phasor measurement system at the BPA can be found in the reference [15].
5.3. Industry Survey to Collect Wave Propagation on Actual Systems

BPA and other utilities in the WSCC have developed a number of software packages for processing phasor data. Phasor data is recorded in files by both the phasor data concentrator (PDC) and application programs. These files are in a raw data format. A data reviewing tool, PhasorFile, is used to plot the data and convert the data to an ASCII file or a MATLAB format. The data plotting screen is shown in Figure 5-2. Available data in PhasorFile is listed in Appendix B.

We collected the data from BPA, and looked for events that show the wave propagation phenomena. The data was converted to the MATLAB format, and was used to verify the models developed in this work (see Section 5.6).

![PhasorFile - Print preview](image)

**Figure 5-2.** Data plot at Grand Coulee, using the PhasorFile program.
5.4. Obtaining a Non-Uniform Discrete Ring System from the WSCC 127-Bus System

The WSCC 127-bus system is used to demonstrate the modeling of a discrete system from an actual power system. Figure 5-3 represents the geographic layouts of the WSCC 127-bus system. Detailed data from the WSCC 127-bus system is listed in Appendix A.

The WSCC 127-bus system is divided into six groups according to the geographic locations in order to generate a discrete ring system, as shown in Figure 5-4. Table 5-1 represents the grouping information. Within each group, the generators and the load are concentrated at one location where the name of the station is chosen as the name of the node. Each node is linked with the neighboring node by an equivalent transmission line. Figure 5-5 shows the detailed structure of the non-uniform discrete ring system. The equivalent parameters of the system are described in the following sections.
Figure 5-3. Geographical layouts of the WSCC 127-bus system

(courtesy of Dr. Arun Phadke).
Figure 5-4. Discrete ring system generated from the WSCC 127-bus system.
Table 5-1. Grouping information for the WSCC 127-bus system.

<table>
<thead>
<tr>
<th>Node Number/Name</th>
<th>Bus Number Included in the Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) JOHN DAY</td>
<td>1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,24,26</td>
</tr>
<tr>
<td>(2) TEVATR2</td>
<td>21,22,23,85,86,89,90,91,92,93,94,95,96,97,98,99,100,101,102</td>
</tr>
<tr>
<td>(3) VINCENT</td>
<td>64,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,87,88,103,105,106,107,108,109,110,111,112,113,114,115,116,117,118,119,120,121,122,123,124,125,126,127</td>
</tr>
<tr>
<td>(4) ELDORADO</td>
<td>57,58,59,60,63,65,66,67,104</td>
</tr>
<tr>
<td>(5) FOURCORN</td>
<td>48,49,50,51,52,53,54,55,56,61,62</td>
</tr>
<tr>
<td>(6) BENLOMND</td>
<td>25,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47</td>
</tr>
</tbody>
</table>
5.4.1. Line Data

The equivalent admittance of the transmission line between two nodes can be calculated from the WSCC 127-bus system (see Appendix A) shown as follows.

- Equivalent admittance between (1) JOHN DAY and (2) TEVATR2:

\[ y_{12} = \frac{1}{[T_{R175} + (Z_{#65//Z_{#66}}/Z_{#67}) + (Z_{#70//Z_{#71}}) + (Z_{#132//Z_{#133}}) + (Z_{#77//Z_{#78}}) + (Z_{#79//Z_{#80}}) + T_{R179}]} \]  

(5.1)

- Equivalent admittance between (2) TEVATR2 and (3) VINCENT:

\[ y_{23} = \frac{1}{[Z_{#91} + (Z_{#135//Z_{#136}}/Z_{#137}) + (Z_{#108//Z_{#109}}) + (Z_{#141//Z_{#142}}) + T_{R179}]} \]  

(5.2)
• Equivalent admittance between (3) VINCENT and (4) ELDORADO:

\[ y_{34} = \frac{1}{[(Z_{97}//Z_{98}) + Z_{100} + TR_{188}]} \]  

(5.3)

• Equivalent admittance between (4) ELDORADO and (5) FOURCORN:

\[ y_{45} = \frac{1}{[TR_{188} + Z_{8} + Z_{11}]} \]  

(5.4)

• Equivalent admittance between (5) FOURCORN and (6) BENLOMND:

\[ y_{56} = \frac{1}{[(TR_{157}//TR_{158}) + Z_{151} + TR_{208} + Z_{120} + (Z_{123}//Z_{122}) + Z_{117}]} \]  

(5.5)

• Equivalent admittance between (6) BENLOMND and (1) JOHN DAY:

\[ y_{61} = \frac{1}{[Z_{148} + TR_{169} + Z_{72} + Z_{147} + Z_{68} + (Z_{65}//Z_{66}//Z_{67}) + TR_{175}]} \]  

(5.6)

In each of the six preceding equations:

- \( y_{mn} \) is the equivalent admittance between nodes \( m \) and \( n \),
- \( Z_{nk} \) is the impedance of the number \( k \) transmission line in pu (with new rated MVA and KV),
- \( TR_{nk} \) is the impedance of the number \( k \) transformer in pu (with new rated MVA and KV),
// is the parallel of impedances, and

+ is the serial of impedances.

Note that the impedances of the transmission lines and the transformers of the WSCC 127-bus system needed to be recalculated based on the new rated MVA and rated KV, as shown in Equation (5.7):

\[
X_2 = X_1 \times \left( \frac{V_1}{V_2} \right)^2 \times \left( \frac{S_2}{S_1} \right),
\]

(5.7)

where

\(X_2\) is the impedance base on the new MVA and KV ratings,

\(X_1\) is the impedance base on the old MVA and KV ratings,

\(V_2\) is the rated KV of the new system,

\(V_1\) is the rated KV of the old system,

\(S_2\) is the MVA base of the new system, and

\(S_1\) is the MVA base of the old system.

Assume that 1,000 MVA and 500 KV are the new rated MVA and rated KV for the non-uniform discrete ring system. The equivalent transmission line data is shown in Table 5-2, where \(R+jX\) is the equivalent line impedance between two nodes.
Table 5-2. Equivalent transmission line data.

<table>
<thead>
<tr>
<th>From Node</th>
<th>To Node</th>
<th>R+jX (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) JOHN DAY</td>
<td>(2) TEVATR2</td>
<td>0.0323+j0.3648</td>
</tr>
<tr>
<td>(2) TEVATR2</td>
<td>(3) VINCENT</td>
<td>0.0212+j0.4472</td>
</tr>
<tr>
<td>(3) VINCENT</td>
<td>(4) ELDORADO</td>
<td>0.0215+j0.4853</td>
</tr>
<tr>
<td>(4) ELDORADO</td>
<td>(5) FOURCORN</td>
<td>0.0402+j0.6344</td>
</tr>
<tr>
<td>(5) FOURCORN</td>
<td>(6) BENLOMND</td>
<td>0.0919+j1.1688</td>
</tr>
<tr>
<td>(6) BENLOMND</td>
<td>(1) JOHN DAY</td>
<td>0.0944+j0.8103</td>
</tr>
</tbody>
</table>
5.4.2. Generator Data

During electromechanical transients, the rotor angles in each group are likely to swing together. It will be convenient to define an “equivalent generator” for each group. In order to link together the generators within the same group, it is necessary to choose a new rated MVA and rated KV for the non-uniform discrete ring system. The inertia time constant of the equivalent generator is defined as follows:

\[
H_i = \sum_{j=1}^{n} [H_{ij} \times \left( \frac{S_{ij}}{S_{\text{new}}} \right)], \quad i=1, \ldots, 6,
\]  

(5.8)

where

\(H_i\) is the inertia time constant of the equivalent generator of the number i group in pu,

\(H_{ij}\) is the inertia time constant of the generator (i,j) within the number i group,

\(n\) is the total number of generators within the number i group,

\(S_{ij}\) is the generator (i,j) MVA base of the simplified WSCC 127-bus system, and

\(S_{\text{new}}\) is the MVA base of the non-uniform discrete ring system.

The transient reactance of the equivalent generator is defined as follows:
\[
X_i = \prod_{j=1}^{n} [X_{ij} \times (\frac{V_{ij}}{V_{\text{new}}}) \times (\frac{S_{\text{new}}}{S_{ij}})], \quad i=1,\ldots,6,
\] (5.9)

where

- \( P \) is the parallel,
- \( X_i \) is the transient reactance of the equivalent generator of the number \( i \) group,
- \( X_{ij} \) is the transient reactance of the generator \((i,j)\) within the number \( i \) group,
- \( V_{ij} \) is the rated KV of the generator \((i,j)\) of the simplified WSCC 127-bus system, and
- \( V_{\text{new}} \) is the new rated KV of the non-uniform discrete ring system.

Note that the transient reactance of each generator of the WSCC 127-bus system is the average of the unsaturated direct axis transient reactance \( (X_d) \) and unsaturated quadrature axis transient reactance \( (X_q) \).

The initial angle of the equivalent generator is defined to be a weighted sum of angles, as follows:

\[
\delta_i = \frac{1}{H_{\text{sum}}} \sum_{j=1}^{n} [H_{ij} \times (\frac{S_{ij}}{S_{\text{new}}}) \times \delta_{ij}], \quad i=1,\ldots,6,
\] (5.10)

where
\[ H_{\text{sum}} = \sum_{j=1}^{n} [H_{ij} \times \left( \frac{S_{ij}}{S_{\text{new}}} \right)], \]

\( \delta_i \) is the initial angle of the equivalent generator of the number i group, and

\( \delta_{ij} \) is the initial angle of the generator \((i,j)\) of the simplified WSCC 127-bus system.

Assume that 1,000 MVA and 500 KV are the new rated MVA and rated KV for the non-uniform discrete ring system, and the generator initial angle is the same as the angle of the bus voltage where the generator is connected. Table 5-3 summarizes the calculation results of the equivalent generator at each node, where

node is the unique bus where the equivalent generator is connected,

equivalent H is the equivalent inertia time constant in pu,

equivalent \( X_{\text{eq}} \) is the equivalent transient reactance in pu, and

equivalent \( \delta \) is the equivalent initial angle in degrees.
Table 5-3. Equivalent generator data.

<table>
<thead>
<tr>
<th>Node</th>
<th>Equivalent H</th>
<th>Equivalent $X_{eq}$</th>
<th>Equivalent $\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) JOHN DAY</td>
<td>122.4971</td>
<td>j1.5301×10^{-5}</td>
<td>24.7322</td>
</tr>
<tr>
<td>(2) TEVATR2</td>
<td>34.3396</td>
<td>j7.1376×10^{-5}</td>
<td>-29.2631</td>
</tr>
<tr>
<td>(3) VINCENT</td>
<td>52.8997</td>
<td>j3.3573×10^{-5}</td>
<td>-46.3987</td>
</tr>
<tr>
<td>(4) ELDORADO</td>
<td>19.9234</td>
<td>j1.8950×10^{-4}</td>
<td>-24.3394</td>
</tr>
<tr>
<td>(5) FOURCORN</td>
<td>27.7235</td>
<td>j8.8168×10^{-5}</td>
<td>-8.5199</td>
</tr>
<tr>
<td>(6) BENLOMND</td>
<td>27.7851</td>
<td>j6.7029×10^{-5}</td>
<td>14.9323</td>
</tr>
</tbody>
</table>
5.4.3. Load Data

The equivalent load of each group is the sum of the loads within the group. 1,000 MVA is chosen to be the rated MVA of the non-uniform discrete ring system. Table 5-4 shows the load data.

Table 5-4. Equivalent load data (P+jQ is the equivalent load in MW and MVAR, and P'+jQ' is the equivalent load in pu).

<table>
<thead>
<tr>
<th>Node</th>
<th>P+jQ</th>
<th>P'+Q'</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) JOHN DAY</td>
<td>27753.7+j6191.25</td>
<td>27.7537+j6.19125</td>
</tr>
<tr>
<td>(2) TEVATR2</td>
<td>7276.91+j3587.6</td>
<td>7.27691+j3.5876</td>
</tr>
<tr>
<td>(3) VINCENT</td>
<td>13960.9+j4897.6</td>
<td>13.9609+j4.8976</td>
</tr>
<tr>
<td>(4) ELDORADO</td>
<td>2612.7+j126.6</td>
<td>2.6127+j0.1266</td>
</tr>
<tr>
<td>(5) FOURCORN</td>
<td>3458.7-j13.2</td>
<td>3.4587-j0.0132</td>
</tr>
<tr>
<td>(6) BENLOMND</td>
<td>5773.5+j671.3</td>
<td>5.7735+j0.6713</td>
</tr>
</tbody>
</table>
5.4.4. Electromechanical Waves

Assume that both the resistances of the equivalent transmission lines, and the damping constants are zero. Apply an impulse with peak value of 0.5 radian at (3) VINCENT when $t=0.5$ seconds. Figure 5-6 shows that the disturbance propagates through the non-uniform discrete ring system. The waves propagate in both directions from the source of the disturbance.

Figure 5-6. Wave propagation in the non-uniform discrete ring system.
5.5. Modeling of a Uniform Discrete Ring System

A uniform ring system of six generators is derived from the discrete ring system described in Section 5.4. The uniform system has an identical transmission line, generator and load at each node. Each system parameter is obtained by taking the average of the total system parameter of six nodes. The system parameters of the uniform ring system are summarized in Table 5-5.

Table 5-5. System parameters of the uniform ring system.

<table>
<thead>
<tr>
<th>System parameters</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Line Reactance (pu)</td>
<td>j0.6518</td>
</tr>
<tr>
<td>Generator Internal Reactance (pu)</td>
<td>j0.000100442</td>
</tr>
<tr>
<td>Generator Inertia Time Constant, H (pu)</td>
<td>47.5292</td>
</tr>
<tr>
<td>Generator Initial Angle (Degrees)</td>
<td>-11.4761</td>
</tr>
<tr>
<td>Load (pu)</td>
<td>10.1394+j2.5769</td>
</tr>
</tbody>
</table>
Apply an impulse with peak value of 0.3 radians, at the 3rd bus when $t=0.5$ seconds. Figure 5-7 shows that the disturbance propagates through the uniform discrete ring system. The waves propagate in both directions from the source of the disturbance as well. Note that the results of the voltage phase angle at each bus were separated by 0.2 radians in order to show the wave propagation.

Figure 5-7. Wave propagation in the uniform discrete ring system.
Table 5-6 summarizes the arrival time (in seconds) of the disturbance at each node by observing the wave in the uniform and non-uniform discrete systems. The results show that the arrival time of the wave in the actual system may be estimated by that of the uniform discrete ring system.

Table 5-6 Arrival time of the disturbance in the uniform and non-uniform discrete systems (time in seconds).

<table>
<thead>
<tr>
<th></th>
<th>Uniform System</th>
<th>Non-Uniform System</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) JOHN DAY</td>
<td>1.63</td>
<td>2.03</td>
</tr>
<tr>
<td>(2) TEVATR2</td>
<td>1.12</td>
<td>1.00</td>
</tr>
<tr>
<td>(3) VINCENT</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>(4) ELDORADO</td>
<td>1.12</td>
<td>0.95</td>
</tr>
<tr>
<td>(5) FOURCORN</td>
<td>1.63</td>
<td>1.34</td>
</tr>
<tr>
<td>(6) BENLOMND</td>
<td>2.02</td>
<td>1.85</td>
</tr>
</tbody>
</table>
5.6. Field verification

5.6.1. Case I

Field data in Case I was recorded in a test plan. The disturbance was generated by inserting a Chief Joseph brake for 0.5 seconds. The Chief Joseph braking resistor auxiliary switch was closed at $t=54.77$ seconds, and was opened at $t=55.3$ seconds.

Figure 5-8 contains four plots from the recording at BPA that show some of the system’s reaction characteristics. Plot a shows the frequency changes at Grand Coulee. The sudden drop and rise in Grand Coulee frequency at the 54.77 and 55.3 seconds are due to the Chief Joseph dynamic brake test. Plots b, c and d show the phase angle at Grand Coulee (GC), John Day (JD) and Vincent (VC), respectively. The disturbance was propagated from north (Grand Coulee) to south (Vincent).

The phase angle in plots c and d are shown in greater detail in Figure 5-9. The first disturbance arrived at John Day and Vincent at $t=54.77$ seconds and 55.37 seconds, respectively, while the second disturbance arrived at John Day and Vincent at $t=55.57$ seconds and 57.03 seconds, respectively. The propagation time of the first disturbance was 0.6 seconds. The second disturbance took 1.46 seconds to travel from John Day to Vincent.

We apply an impulse at (1)JOHN DAY in the non-uniform system presented in Section 5.4 in order to calculate the travel time of the disturbance between (1)JOHN DAY and (3) VINCENT. Assume the initial conditions are zero. Figure 5-10 shows the simulation results. Note that the results of the voltage phase angle at each bus were separated by 0.2 radians in order to show the wave propagation. The impulse was applied at (1)JOHN DAY at $t=0.5$ seconds. The disturbance arrived at (3)VINCENT at $t=1.58$ seconds. The travel time was 1.08 seconds in the non-uniform system.

The uniform model described in Section 5.5 was also tested. Figure 5-11 shows the simulation results. The impulse starts at $t=0.5$ seconds at (1)JOHN DAY, and arrives at (3)VINCENT at $t=1.63$ seconds.
The arrival time of the disturbance at John Day and Vincent, as obtained from the field data and simulations, are summarized in Table 5-7.

Table 5-7. Summary of arrival time of the disturbance in case I (time in seconds).

<table>
<thead>
<tr>
<th></th>
<th>Field Data</th>
<th>Non-Uniform System</th>
<th>Uniform System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Initiate Disturbance</td>
<td>54.77</td>
<td>55.30</td>
<td>0.5</td>
</tr>
<tr>
<td>Disturbance Arrives at John Day</td>
<td>54.77</td>
<td>55.57</td>
<td>0.5</td>
</tr>
<tr>
<td>Disturbance Arrives at Vincent</td>
<td>55.37</td>
<td>57.03</td>
<td>1.58</td>
</tr>
<tr>
<td>Traveling Time between JD and VC</td>
<td>0.6</td>
<td>1.46</td>
<td>1.08</td>
</tr>
</tbody>
</table>

The timing study in both non-uniform and uniform discrete systems illustrates the effectiveness of the models proposed in this chapter. The simulation results indicate that the continuum approach could be used to predict the arrival time of the disturbance at other stations within an acceptable error margin.
Figure 5-8. Data plot of a dynamic brake test at Chief Joseph, using the PhasorFile program.
Figure 5-9. Detail of phase angle in case I.
Figure 5-10. Simulation of wave propagation in the non-uniform discrete system with disturbance applied at (1)JOHN DAY.
Figure 5-11. Simulation of wave propagation in the uniform discrete system with disturbance applied at (1) JOHN DAY.
5.6.2. Case II

A generator unit of 742 MW tripped at Moss Landing, California. Figure 5-12 shows the data recorded from the incident. Plots a and b illustrate the voltage phase angle at John Day and Vincent, respectively, plots c and d show their respective frequency reactions.

It is not easy to see the disturbance propagation the phase angle. However, in case II the propagation is observed from the frequency reaction. Figure 5-13 shows the detail of system frequency. The disturbance arrived at Vincent and John Day at t=52.76 seconds and 53 seconds, respectively.

For comparison, an impulse is applied at (2)TEVATR2 in the non-uniform and uniform discrete systems when t=0.5 seconds, since Moss Landing is geographically located in the group of (2)TEVATR2. Figures 5-14 and 5-15 illustrate the system reactions to this sudden change in the non-uniform and uniform discrete systems. Table 5-8 summarizes the arrival time of the disturbance at John Day and Vincent, as obtained from the field data and simulations.

Table 5-8. Summary of arrival time of the disturbance in case II (time in seconds).

<table>
<thead>
<tr>
<th>Time to Initiate Disturbance</th>
<th>Field Data</th>
<th>Non-Uniform system</th>
<th>Uniform system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbance Arrives at John Day</td>
<td>53.00</td>
<td>1.05</td>
<td>1.12</td>
</tr>
<tr>
<td>Disturbance Arrives at Vincent</td>
<td>52.76</td>
<td>0.97</td>
<td>1.12</td>
</tr>
<tr>
<td>Difference of Disturbance Arrival Time between JD and VC</td>
<td>0.24</td>
<td>0.08</td>
<td>0</td>
</tr>
</tbody>
</table>
The results indicate that the non-uniform system is a useful tool for predicting the arrival time of the disturbance. However, the uniform system can not be used in this case. The poor correlation is largely due to using lumped parameters. In the uniform system, the distances between (1)JOHN DAY and (2)TEVATR2 and between (2)TEVATR2 and (3)VINCENT are the same. In the actual system, Moss Landing is rather south in (2)TEVATR2 group. It takes some time to propagate through the group. The result would be close if the model is expanded.

Figure 5-12. Data plot of a generator trip at Moss Landing, using the PhasorFile program.
Figure 5-13. Detail of frequency in case II.
Figure 5-14. Simulation of wave propagation in the non-uniform discrete system with disturbance applied at (2)TEVATR2.
Figure 5-15. Simulation of wave propagation in the uniform discrete system with disturbance applied at (2)TEVATR2.
5.6.3. Case III

A generator unit of 645 MW tripped at Mohave. Figure 5-16 shows the data recorded from the incident. Plots a and b illustrate the voltage phase angle at John Day and Vincent, respectively, plots c and d show their respective frequency reactions.

Figure 5-17 shows the detail of change of voltage phase angle at John Day and Vincent caused by the generator trip at Mohave. The disturbance arrived at Vincent and John Day at $t=50.53$ seconds and 51.3 seconds. It took 0.77 seconds to travel from Vincent to John Day.

Mohave is located near El Dorado. The disturbance was placed at (4)ELDORADO of the non-uniform and uniform discrete systems in order to simulate the wave propagation. Figures 5-18 and 5-19 show the simulation results in the non-uniform and uniform systems, respectively.

Table 5-9 summarizes the arrival time of the disturbance at John Day and Vincent, as obtained from the field data and simulations.

<table>
<thead>
<tr>
<th></th>
<th>Field Data</th>
<th>Non-Uniform system</th>
<th>Uniform system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Initiate Disturbance</td>
<td>Unknown</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Disturbance Arrives at John Day</td>
<td>51.20</td>
<td>1.79</td>
<td>2.02</td>
</tr>
<tr>
<td>Disturbance Arrives at Vincent</td>
<td>50.53</td>
<td>0.94</td>
<td>1.14</td>
</tr>
<tr>
<td>Travel Time between JD and VC</td>
<td>0.77</td>
<td>0.85</td>
<td>0.88</td>
</tr>
</tbody>
</table>
In case III, the models of non-uniform and uniform systems work well to predict the arrival time of the disturbance.

Figure 5-16. Data plot of a generator trip at Mohave, using the PhasorFile program.
Figure 5-17. Detail of phase angle in case III.
Figure 5-18. Simulation of wave propagation in the non-uniform discrete system with disturbance applied at (4)ELDORADO.
Figure 5-19. Simulation of wave propagation in the uniform discrete system with disturbance applied at (4)ELDORADO.
5.6.4. Case IV

Field data in Case IV was recorded in a test plan. The disturbance was generated by tripping the Hoover generators with 500 MW total load at t=0 seconds. Figure 5-20 shows the data recorded from the test. Plot a and b illustrate the voltage phase angle at John Day and Vincent, respectively, plots c and d show their respective frequency reactions.

Figure 5-21 shows the detail of the change of voltage phase angle at John Day and Vincent caused by the generator trip at Hoover. Figure 5-22 shows the detail of the change in the system frequency at John Day and Vincent. It is observed in both phase angle and frequency that the disturbance arrived at Vincent at t=1.57 seconds and arrived at John Day at t=2.17 seconds.

Hoover is located near El Dorado. The disturbance was placed at (4)ELDORADO of the non-uniform and uniform discrete systems in order to simulate the wave propagation. Simulation results for case IV can be found in Figures 5-18 and 5-19. Table 5-10 summarizes the arrival time of the disturbance at John Day and Vincent, as obtained from the field data and simulations.

Table 5-10. Summary of arrival time of the disturbance in case IV (time in seconds).

<table>
<thead>
<tr>
<th></th>
<th>Field Data</th>
<th>Non-Uniform system</th>
<th>Uniform system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Initiate Disturbance</td>
<td>Unknown</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Disturbance Arrives at John Day</td>
<td>2.17</td>
<td>1.79</td>
<td>2.02</td>
</tr>
<tr>
<td>Disturbance Arrives at Vincent</td>
<td>1.57</td>
<td>0.94</td>
<td>1.14</td>
</tr>
<tr>
<td>Travel Time between JD and VC</td>
<td>0.60</td>
<td>0.85</td>
<td>0.88</td>
</tr>
</tbody>
</table>
The simulation results prove the effectiveness for the models of non-uniform and uniform systems in calculating the travel time between the two stations.

Figure 5-20. Data plot of a generator trip at Hoover, using the PhasorFile program.
Figure 5-21. Detail of phase angle in case IV.
Figure 5-22. Detail of frequency in case IV.
5.6.5. Case V

In case V, a generator unit of 740 MW tripped at Four Corners. Figure 5-23 shows the data recorded from the incident. Plots a and b illustrate the voltage phase angle at John Day and Vincent, respectively, plot c and d show their respective frequency reactions.

Figure 5-24 shows the detail of the change in voltage phase angle at John Day and Vincent caused by the generator trip at Four Corners. The disturbance arrived at Vincent and John Day at t=53.1 seconds and 53.57 seconds. It took 0.47 seconds to travel from Vincent to John Day.

Four Corners is located in the group of (5)FOURCORN in the non-uniform and uniform discrete systems. The disturbance was placed at (5)FOURCORN of the non-uniform and uniform discrete systems in order to simulate the wave propagation. Figure 5-25 and Figure 5-26 shows the simulation results in the non-uniform and uniform systems, respectively. Table 5-11 summarizes the arrival time of the disturbance at John Day and Vincent, as obtained from the field data and simulations.

Table 5-11. Summary of arrival time of the disturbance in case V (time in seconds).

<table>
<thead>
<tr>
<th></th>
<th>Field Data</th>
<th>Non-Uniform</th>
<th>Uniform system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Initiate Disturbance</td>
<td>unknown</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Disturbance Arrives at John Day</td>
<td>53.57</td>
<td>1.97</td>
<td>1.63</td>
</tr>
<tr>
<td>Disturbance Arrives at Vincent</td>
<td>53.10</td>
<td>1.32</td>
<td>1.63</td>
</tr>
<tr>
<td>Travel Time between JD and VC</td>
<td>0.47</td>
<td>0.65</td>
<td>0</td>
</tr>
</tbody>
</table>

The simulation results show that the non-uniform system is a useful tool for calculating the travel time between the two stations. However, the uniform system can not be used in this case.
In the uniform system, the distances between (1) JOHN DAY and (5) FORCORN and between (5) FOURCORN and (3) VINCENT are the same. The travel times from (5) FOURCORN to (1) JOHN DAY and to (3) VINCENT are the same. This is incorrect for presenting the incident of case V.

Figure 5-23. Data plot of a generator trip at Four Corners, using the PhasorFile program.
Figure 5-24. Detail of phase angle in case V.
Figure 5-25. Simulation of wave propagation in the non-uniform discrete system with disturbance applied at (5)FOURCORN.
Figure 5-26. Simulation of wave propagation in the uniform discrete system with disturbance applied at (5)FOURCORN.
5.7. Effect of Communication Line Delays and Data exchange on Understanding Wave Propagation

5.7.1. Communication Line Delays

The PMUs make the actual measurement and transmit the data digitally. The measurements are transmitted to PDCs through the communication lines. According to the reference [15], the time stamp of current systems is the last sample in a four-cycle window. So, an effective measurement delay of about 33 ms exists in the PMU. The PMU computes the phasor and outputs the value about 0.5 ms after the time stamp. BPA made precise measurements to benchmark the combined communications and PDC input processing delay time. Total latency with analog V.34 analog modems was typically about 90 ms. The latency decreased to 38 ms when a direct digital with fiber optic communications was used.

5.7.2. Phasor Data exchange between BPA and SCE

A PDC was developed by BPA to combine the real-time data streams from a number of PMUs into a single time-correlated system measurement. The PDC solves the problems of managing the system operation and the large quantity of data. However, it still requires a system-wide measurement obtained by combining the measurements from PMUs on the grids of different utilities.

BPA and SCE developed a PDC-to-PDC communication system to exchange the data collected from PMUs. Due to the fact that there are no common boundaries between BPA and SCE, communications between the two require a path through the Los Angeles Department of Water and Power (DWP). Figure 5-27 describes the data exchange implemented between BPA and SCE [16].
5.7.3. Data Exchange Transfer Delay

Measurement latency (delay) is the time from the instant an event occurs until the information reaches another processor in a usable state. Delay in all kinds of monitoring or control must be accounted for and managed. The delay needs to be quantified before the phasor measurements can be used by monitor or control systems.

Table 5-12 provides information on the time delay from measurement until the data is in the PDC buffer [16].

Table 5-12. Time delay from measurement (time in milliseconds).

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Coulee</td>
<td>93.39</td>
<td>2.29</td>
<td>82.72</td>
<td>113.63</td>
<td>Analog Modem</td>
</tr>
<tr>
<td>John Day</td>
<td>105.97</td>
<td>5.00</td>
<td>99.27</td>
<td>141.76</td>
<td>Analog Modem</td>
</tr>
<tr>
<td>Malin</td>
<td>94.71</td>
<td>2.81</td>
<td>81.56</td>
<td>114.07</td>
<td>Analog Modem</td>
</tr>
</tbody>
</table>
Table 5-12. Continued.

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colstrip</td>
<td>95.17</td>
<td>2.59</td>
<td>84.37</td>
<td>114.25</td>
<td>Analog Modem</td>
</tr>
<tr>
<td>Big Eddy 230KV</td>
<td>38.34</td>
<td>0.97</td>
<td>36.65</td>
<td>54.67</td>
<td>Fiber</td>
</tr>
<tr>
<td>Big Eddy 500KV</td>
<td>85.20</td>
<td>2.51</td>
<td>78.84</td>
<td>112.20</td>
<td>Analog Modem</td>
</tr>
<tr>
<td>Sylmar</td>
<td>91.94</td>
<td>4.75</td>
<td>85.00</td>
<td>222.80</td>
<td>Analog Modem</td>
</tr>
<tr>
<td>Maple Valley</td>
<td>83.38</td>
<td>3.47</td>
<td>76.01</td>
<td>183.50</td>
<td>Analog Modem</td>
</tr>
<tr>
<td>Keeler</td>
<td>90.31</td>
<td>2.50</td>
<td>80.45</td>
<td>104.72</td>
<td>Analog Modem</td>
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<td>138.19</td>
<td>190.14</td>
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</table>

The data carries a precise timetag and is relative to actual time. Data transmission does not affect this timetag and data is compared and filed by timetag. For the purpose of analysis, communication latency has no effect. In the case of this study, all PMUs are the same and the latency will be subtracted out.

The PDC provides data correlated by timetag and the data is held up by the lowest communication device. For real-time control, the latency will be determined by the longest latency PMU which may be a problem in some cases.
Chapter 6. Countermeasures

6.1. Introduction

In a number of catastrophic failures in power networks, some relays may trip due to power swings, and this can possibly lead to a complete system collapse. The sources of catastrophic failures are as follows [17].

(1) The power system is in a stressed state

(2) The operators are unaware that the system is on edge

(3) A triggering event

(4) Hidden failures in the protection system

(5) The development of electromechanical instabilities or voltage instabilities.

The developments of electromechanical instabilities or voltage instabilities may separate the power grid into islands of excess load or generation. This leads to the system collapse of a region of heavy load, resulting in a blackout.

In recent years, new techniques for monitoring, protection, and control of the power grid have been perfected in order to reduce the frequency and severity of future catastrophic failures. Bases on presented research [18], some suggestions for monitoring, protection and control systems are proposed in this chapter to prevent the false trips of relays that occur due to power swings.
6.2. GPS-Based Wide Area Measurements

The technology of synchronized phasor measurements provides effective and accurate real-time monitoring of the state of the network with millisecond latencies. These measurements, obtained in conjunction with the analytical tools provided by multi-agent systems, adaptive protection, and adaptive self-healing strategies improve the monitoring, protection, vulnerability assessment, and control of the network [17].

In the area of large-scale power systems, electromechanical instabilities may be more effectively observed and damped through the use of wide area measurements (WAMs) which can measure the bus voltage phase angle differences at widely separated points; i.e., they detect electromechanical wave propagation. The techniques involving fiber optics communication and phasor measurements are essential for implanting WAMs. By applying the GPS technology, measurements of phase and other temporal information is manageable through the use of commercially available equipment.

Because to the large-scale geographical size and the reliability of local measurements, during the inter-oscillations of a stressed electric power network, controls based on local signals are the primary actions for damping these oscillations. However, the local controllers can not optimally damp both inter-area and local plant modes. Analysis of the inter-area phenomenon shows that certain signals measured at electrical centers of the group of generators separated from the rest of the system, provide more effective control. Their signals could be measured by the GPS-based WAM system and transmitted to an optimally located flexible AC transmission systems (FACTS) controller in order to effectively damp the oscillations.
6.3. Adaptive Relaying and Self-Healing

It is recognized that primary protection systems, which are fast acting, are dedicated to protection of individual pieces of power equipment. They employ closed zones of protection and are almost totally immune to loading conditions. However, there are a number of back-up relay functions, system protection devices, and special protection system (remedial action schemes) that will be affected by loading patterns as they evolve with time.

In practice, these protection systems are vulnerable to electromechanical wave phenomena. In recent years, “adaptive relaying” was introduced in the field of power system protection. This is a concept which allows protection systems to be modified while the protection system is in service, under remote control, in order to meet the requirements of changing power system conditions. Computer relays linked to remote sites allow the application of adaptive relaying systems.

Recent research has shown that adaptive protection principles could be applied to transmission line relaying, out-of-step relaying, loss-of-field relaying, and load- and generation-tripping relaying. Adaptive relaying would diminish the likelihood of false trips during system disturbances, thus preventing catastrophic failures.

The simulation results given in Chapter 4 show that the electromechanical waves do affect the performance of some of these relays. If the effects are found to be deleterious, an early-warning of an approaching electromechanical wave is expected to enhance system security.

It would also be useful to know if one could determine meter placement strategies to effectively detect waves traveling on large networks. According to other work [17], optimum placement strategies can be achieved by the following two approaches.

(1) Development of a prioritized list of placement sites so that the area of observability and controllability will expand uniformly as more sites are included
(2) Placement of measurements so that critical dynamics of power systems will be correctly represented without complete observability. Real-time analytical methods for large systems, based on shifting coherency patterns, are needed.

Self-healing strategies [18] are control options initiated that allow the power system a more secure, less vulnerable, operating condition. When a disturbance occurs, it is necessary to determine the following.

- Whether the disturbance will affect only a portion of the system or a wide area in the system
- Whether the disturbance will damage equipment, and result in a wide spread blackout
- The expansion speed of the disturbance

The self-healing features include the abilities to reconfigure based on system vulnerability analysis, to identify appropriate restorative actions to minimize the impact of an outage or a contingency, and to perform important sampling in order to determine the weak links in a power system.
Chapter 7. Conclusions

7.1. Conclusions

This paper presents a new approach to studying electromechanical transients in large interconnected networks. By treating the power network as a continuum, important insight is gained in understanding how the disturbances spread in the network. The results obtained from the MATLAB simulations show the validity of the concept of traveling electromechanical waves on power networks following faults or other disturbances. The waves could grow in certain directions, depending upon not only the steady-state disposition of rotor angles on the network, but also other parameters, including damping coefficients, impedances of transmission lines, and generator inertia. In particular, it is shown that the disturbances do propagate at a finite velocity, and estimating the velocity for approximated conditions on a network show good correlation with observed phenomena.

In one-dimensional discrete models, both uniform homogenous systems and non-homogenous systems have been considered. Boundary conditions corresponding to system terminations into open and short circuits (high inertia machines) were simulated and studied. The boundaries at both ends of the open circuit system cause wave reflections where the coefficient is +1. Heavy generator inertia concentration (with a reflection coefficient of -1) at a point on the continuum behaves like a short circuit on the system. The results found in the approximation indicate that the computation of electric power in a large-scale network can be simplified by considering only eight neighboring machines, regardless of the size of the network.

The one-dimensional discrete model was expanded to a two-dimensional grid. Simulations on approximated models show that the generator neighborhoods, 144 neighboring machines, are defined and influence the propagation of waves. The reflection coefficient of an n-by-n network is calculated at the center of each edge. The average value of the reflection coefficients is found to be +1. This is in keeping with the concept of open circuits at the edges of the grid. The technique of reflection-free termination is tested on both one-dimensional and two-dimensional systems. The reflecting waves of traveling waves at the boundaries were successfully eliminated.
The ultimate aim of analyses of power system dynamics is to determine if the phenomena in question can do damage to the network, and if any countermeasures are available to mitigate such damage. The simulations show that over-current relays, distance relays, out-of-step relays, and load-shedding relays may operate when the waves pass through their locations. Since wave propagation is a transient phenomenon, it is desirable to block tripping of these relays for the duration of the wave propagation. In this connection, it is natural to think of an early-warning system of broadcasting the launching of these waves and their amplitudes so that appropriate relay blocking decisions could be reached in time.

The continuum model is validated on field data recorded from different cases. The simulations show that the continuum model does capture the network topology that dictates the direction and nature of wave propagation.

It is concluded that continuum approach provides a robust tool in understanding the phenomenon of electromechanical wave propagation which will lead to innovative and effective countermeasures against system blackouts.

### 7.2. Contributions

The major contributions of this work are summarized as follows.

- Observing the electro-mechanical wave propagation from a macroscopic point of view is very valuable for providing solutions on continent-wide networks

- At the intellectual level, it introduces a new discipline to the field of electric power engineering

- Machine impedance was included both in one- and two-dimensional discrete models

- Protection system performance in response to the electromechanical wave phenomena has been analyzed
• In a number of events of catastrophic failures in power systems, it has been observed that some relays may trip due to power swings, and these will compound the effect of the initial disturbance, possibly leading to a complete system collapse. Understanding the phenomenon of propagating waves helps to learn how best to observe and control these oscillations in actual power systems

7.3. Future Work

Some suggestions are given below for future work.

• Study the effects of electromechanical waves on control systems

• Handle the non-uniform structure of the two-dimensional systems

• Determine the nature of waves in smaller regions where the assumption of the continuum can no longer be supported

• Consider the effect of excitation system response in determining traveling wave phenomena

• Apply the knowledge gained from the wave propagation phenomena to develop the supervisory early-warning systems of impending transient oscillations, which would enable us to activate control actions at selected points in order to damp these electromechanical waves

• Verifications through simulations of the proposed new protection, and control functions
References


Appendices

Appendix A. WSCC 127-Bus System

The WSCC 127-Bus system was generated base on the WSCC 179-Bus system [19]. The WSCC 127-bus system consists of 127 buses, 37 generators, and 211 transmission lines. The transmission lines and buses were significantly reduced; however, the amounts of load and generation were kept essentially the same. Figure A-1 shows the one-line diagram of the WSCC 127-bus system. Detailed bus data, generator data, load data and line data are summarized in the following sections.
Figure A-1. One-line diagram of the WSCC 127-bus system (courtesy of Dr. David Elizondo).
A.1. Bus Data

Table A-1 represents the some of the bus data of the WSCC 127-bus system.

Table A-1. Bus data of the WSCC 127-bus system (bus number is the unique number used to identify the bus, bus name is the unique name used to identify the bus, \(V\) is the magnitude of bus voltage in pu, \(\theta\) is the angle of bus voltage in degree, and bus KV is the base KV of the bus).

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<th>Bus KV</th>
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<td>GLENN 200.</td>
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<td>-50.0593</td>
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<td>-49.0329</td>
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<th>Bus KV</th>
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### A.2. Generator Data

Table A-2 represents the generator data of the WSCC 127-bus system.

Table A-2. Generator data of the WSCC 127-bus system (generator bus number is the unique number used to identify the bus where the generator is connected, generator bus name is the unique name used to identify the bus where the generator is connected, $X_d'$ is the unsaturated direct axis transient reactance in pu, $X_q'$ is the unsaturated quadrature axis transient reactance in pu, $H$ is the turbine-generator inertia time constant in MW-sec/MVA, $MV_{Ab}$ is the base MVA of the generator data, and $KV_b$ is the base voltage of the generator in KV).

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<th>Generator Bus Number</th>
<th>Generator Bus Name</th>
<th>$X_d'$</th>
<th>$X_q'$</th>
<th>$H$</th>
<th>$MV_{Ab}$</th>
<th>$KV_b$</th>
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<td>Xq'</td>
<td>H</td>
<td>MVAb</td>
<td>KVb</td>
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A.3. Load Data

Table A-3 represents the load data of the WSCC 127-bus system.

Table A-3. Load data of the WSCC 127-bus system (bus number is the number of the bus where the load is connected, bus name is the name of the bus where the load is connected, P is the real parts of load components in MW, and Q is the reactive parts of load components in MVAR).

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A.4. Line Data

Table A-4 represents the line data of the WSCC 127-bus system.

Table A-4. Line data of the WSCC 127-bus system (line number is the unique number used to identify the line, from bus # is the number of the ‘From’ bus, to bus # is the number of the ‘To’ bus, R is the resistance of the branch in pu, X is the reactance of the branch in pu, KVb is the base voltage of the line in KV, MVAb is the MVA rating at nominal voltage).

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A.5. Transformer Data

Table A-5 represents the transformer data of the WSCC 127-bus system.

Table A-5. Transformer data of the WSCC 127-bus system (transformer number is the unique number used to identify the transformer, from bus # is the number of the ‘From’ bus, to bus # is the number of the ‘To’ bus, R is the resistance of the branch in pu, X is the reactance of the branch in pu, MVAb is the transformer rated MVA).

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Table A-5. Continued.

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Appendix B. Data of PhasorFile

Data available at PhasorFile is list as follows.

- **Phasor magnitude** and **Phase**:

  **Grand Coulee Bus Voltage**
  - GC50-Bank 1 Current
  - GC50-Hanford Current
  - GC50-Shultz 1 Current
  - GC50-Chief Joseph Current

  **John Day Bus Voltage**
  - John Day PH1 Current
  - John Day PH2 Current
  - John Day PH3 Current
  - John Day PH4 Current
  - JDAY-Big Eddy 1 Currents
  - JDAY-Grizzly 1 & 2 Currents
  - JDAY-Slatt 1 Currents
  - JDAY-Big Eddy 2 Currents
  - JDAY-Hanford 1 Current

  **Malin N. Bus Voltage**
  - MALIN-Round Mountain 1 Current
  - MALIN-Round Mountain 2 Current
  - MALIN-Grizzly 2 Current
  - MALIN-Captain Jack 1 Current

  **Colstrip Bus Voltage**
  - COLS-Broadview 1 Current
  - COLS-Broadview 2 Current
  - Generator 3 Current
  - Generator 4 Current

  **Big Eddy 230 Bus 3 Voltage**
  - BE23-Celilo 3 Current
BE23-Celilo 4 Current
Dalles PH 3 Current
Dalles PH 4 Current
Dalles PH 5 Current
Dalles PH 6 Current
BE23-Banks 2&5 Current
BE23-Chenowth 1 Current
BE23-Troutdale 1 Current

Big Eddy 500 Bus Voltage
BE50-John Day 2 Current
BE50-Celilo 2 Current
BE50-Celilo 1 Current
BE50-John Day 1 Current

Sylmar Bus Voltage
SYLM-Rinaldi 1 Current
SYLM-Castaic 1 Current
SYLM-Bank E Current
SYLM-East Converter Current

Maple Valley Bus Voltage
MPLV-SCL #1 (MASS) Current
MPLV-SCL #3 (EPIN) Current
MPLV-Bank #2 (ECOL) Current
MPLV-Bank #1 (ROR) Current

Keeler 500KV Voltage
KEEL-Allston Line Current
KEEL-Pearl Line Current

Keeler 230KV Bus Voltage
KEEL-SVC Bank Current

Vincent Voltage
SCE Vincent-Midway 1

Devers 500 Bus Voltage
SCE Devers-Palo Verde 500KV Line Current
• **Frequency:**
  Grand Coulee
  John Day
  Malin
  Colstrip
  Big Eddy 230
  Big Eddy 500
  Sylmar
  Maple Valley
  Keeler
  Vincent
  Devers

• **df/dt, Sample, and Status:**
  Grand Coulee
  John Day
  Malin
  Colstrip
  Big Eddy 230
  Big Eddy 500
  Sylmar
  Maple Valley
  Keeler

• **DBUF and Data Valid:**
  Grand Coulee
  John Day
  Malin
  Colstrip
  Big Eddy 230
  Big Eddy 500
  Sylmar
  Maple Valley
Keeler
PDC at SCE

- **Watts** and **Vars:**

  GC50-Bank 1
  GC50-Hanford
  GC50-Shultz 1
  GC50-Chief Joseph
  John Day PH1
  John Day PH2
  John Day PH3
  John Day PH4
  JDAY-Big Eddy 1
  JDAY-Grizzly 1 & 2
  JDAY-Slatt 1
  JDAY-Big Eddy 2
  JDAY-Hanford 1
  MALIN-Round Mountain 1
  MALIN-Round Mountain 2
  MALIN-Grizzly 2
  MALIN-Captain Jack 1
  COLS-Broadview 1
  COLS-Broadview 2
  Generator 3
  Generator 4
  BE23-Celilo 3
  BE23-Celilo 4
  Dalles PH 3
  Dalles PH 4
  Dalles PH 5
  Dalles PH 6
  BE23-Banks 2&5
  BE23-Chenowth 1
BE23-Troutdale 1
BE50-John Day 2
BE50-Celilo 2
BE50-Celilo 1
BE50-John Day 1
SYLM-Rinaldi 1
SYLM-Castaic 1
SYLM-Bank E
SYLM-East Converter
MPLV-SCL #1 (MASS)
MPLV-SCL #3 (EPIN)
MPLV-Bank #2 (ECOL)
MPLV-Bank #1 (ROR)
KEEL-Allston Line
KEEL-Pearl Line
KEEL-SVC Bank Current
SCE Vincent-Midway 1
SCE Devers-Palo Verde 500KV Line
Appendix C. MATLAB Program

% Pg64.m(#1)
% This program is simulating mechanical wave propagation on a ring system of 64 generators
% n is the number of generators; Damp is the damping constant; y is the transmission line reactance
% y1=a*y is the generator internal reactance; y0=b*y is the load
% Use B C D D1 D2 D3 D4 D5 and U to construct matrix Y
% delta is the generator internal angle
%Begin=====================================================================================================
clear all;
global n Damp Y;
n=64;
Damp=0;
Td=1/20;
Tend=30;
%system parameters
a=10;
b=0.06+0.08*i;
y=-i*10;
y1=a*y;
y0=b*y;
%Construct matrix [Y], where [Ig]=[Y][E]
B=y1*eye(n);
C=(-y1)*eye(n);
D1=ones(n);
D2=tril(D1,1);
D3=triu(D2,-1);
D4=D3*(-y);
D5=eye(n)*(y1+3*y+y0);
D=D5+D4;
D(1,n)=-y;
D(n,1)=-y;
U=inv(D);
Y=B-C*U*C;
%Find initial condition, Pm, by assuming abs(Eg0)=1 p.u. and initial Ed0(s)=2*pi*s/n
%Ig0 is the initial generator current; Eg0 is the initial generator voltage
s=1:n;
Ed0(s)=(2*pi*s./n);
Ed0=Ed0';
Eg0=cos(Ed0)+i*sin(Ed0);
Ig0=Y*Eg0;
Pm=real(Eg0.*conj(Ig0));
%Write Pm to a txt file
fid=fopen('pm64.txt','w');
for kk=1:n;
    fprintf(fid,'%f
',Pm(kk,1));
end;
close(fid);
%Solve ODEs
tspan=[0:Td:Tend];
delta0=zeros(2*n,1);
d=1:2:2*n;
s=1:n;
s=s';
delta0(d)=(2*pi*s./n)+(5*exp(-1*(s-16).^2));
delta0=delta0;
%solve differential equations
[t,delta]=ode23('pp64',tspan,delta0);
%Calculate voltage angles at bus terminals
for h=1:n
    delta_g(:,h)=delta(:,2*h-1);
end
Eg=cos(delta_g')+i*sin(delta_g');
Ig=Y*Eg;
En=Eg-Ig/(y1);
delta_n=unwrap(angle(En));
%Plot voltage phase angles at bus terminals
hold on
for q=1:n
    %plot(t,delta_n(q,:)+2*pi*q/n);
    plot(t,delta_n(q,:));
end
hold off

%pp64.m
%This program define function "deltadot" for ode23 to solve the diff. eqns.
%n is the number of total generators
%k is the generator number
%k=1:n
%Pm is mechanical power

function deltadot=pp64(t,delta)
global n Damp Y;
deltadot= zeros(2*n,1);
M=1;
load pm64.txt;
%Calculate Pe
Ed=[delta(1) delta(3) delta(5) delta(7) delta(9) delta(11)...
    delta(13) delta(15) delta(17) delta(19) delta(21) delta(23)...
    delta(25) delta(27) delta(29) delta(31) delta(33) delta(35)...
    delta(37) delta(39) delta(41) delta(43) delta(45) delta(47)...
    delta(49) delta(51) delta(53) delta(55) delta(57) delta(59)...
    delta(61) delta(63) delta(65) delta(67) delta(69) delta(71)...
    delta(73) delta(75) delta(77) delta(79) delta(81) delta(83)...
    delta(85) delta(87) delta(89) delta(91) delta(93) delta(95)...
    delta(97) delta(99) delta(101) delta(103) delta(105) delta(107)...
    delta(109) delta(111) delta(113) delta(115) delta(117) delta(119)...
    delta(121) delta(123) delta(125) delta(127)];
Ed=Ed';
Ig=Y*(cos(Ed)+i*sin(Ed));
Pe=real((cos(Ed)+i*sin(Ed)).*conj(Ig));

% Swing equations for k=1,...,n
for k=1:n
    deltax=pp64(k)=delta(2*k-1);
deltadot(2*k-1)=delta(2*k);
deltadot(2*k)=[pm64(k)-Damp*delta(2*k)-Pe(k,1)]/M;
end
%End================================(#1)==========================================
To simulate wave propagation on a two-dimensional system of $(35^2)$ machines
$n$ is the size of each dimension; i.e., there are $n^2$ machines in the system.
$y$ is the transmission line reactance.
$y_1=ay$ is the generator internal reactance.
$y_0=by$ is the load.
$\delta$ is the generator angle.

```
clear all;
global n Y;
n=35;
% system parameters
a=10;
b=0.06+0.08*i;
y=-i*10;
y1=a*y;
y0=b*y;
m2=(y1+2*y+y0);
m3=(y1+3*y+y0);
m4=(y1+4*y+y0);
% construct matrix $[Y]$, where $[I_g]=[Y][E_g]$
% A0
a1=ones(n);
a2=tril(a1,1);
a3=triu(a2,-1);
a4=-y*(a3-eye(n));
a5=m3*eye(n);
A0=a4+a5;
A0(1,1)=m2;
A0(n,n)=m2;
%A1
a44=-y*(a3-eye(n));
a55=m4*eye(n);
A1=a44+a55;
A1(1,1)=m3;
A1(n,n)=m3;
%A2
A2=(-y)*eye(n);
%A3
A3=zeros(n);
%A
```
SA=sparse(A);
U=inv(SA);
I=eye(n^2,n^2);
Y1=sparse(y1*I);
Y=Y1-(Y1*U*Y1);

%Find initial condition, Pm, by assuming abs(Eg0)=1 p.u., and initial Ed0(s)=2*pi*s/n
%Ig0 is the initial generator current; Eg0 is the initial generator voltage
for s1=0:n-1
  for s2=1:n
    Ed0(s1*n+s2)=2*pi*s2/n;
  end
end
Ed0=Ed0';
Eg0=cos(Ed0)+i*sin(Ed0);
Ig0=Y*Eg0;
Pm=real(Eg0.*conj(Ig0));

%write Pm to txt file
fid=fopen('pm2db35.txt','w');
for kk=1:n^2;
  fprintf(fid,'%f
',Pm(kk,1));
end;
fclose(fid);
tspan=[0:0.05:30];
%initial conditions
delta0=zeros(1,2*(n^2));
for dd=1:2:2*(n^2)
  delta0(1,dd)=Ed0((dd-1)/2+1);
end
%insert initial disturbance
for r1=1:35
  for r2=1:35
    delta0(2*((r1-1)*35+r2)-1)=delta0(2*((r1-1)*35+r2)-1)+0.5*exp(-0.1*((r1-18)^2+(r2-18)^2));
  end
end
%solve differential equations
[t,delta]=ode23('pp2db35',tspan,delta0);%size(delta)=601x2450
%calculate the voltage angles at bus terminals
%subtract initial condition
for hh=1:n^2
  delta_g(:,hh)=delta(:,2*hh-1);%size(delta_g)=601x1225
end
\[ [rg,cg] = \text{size}(\delta_g); \]
for \( \text{ww}=1:rg \)
  for \( \text{ii}=1:n \)
    for \( \text{jj}=1:n \)
      \( \delta_{gg}(\text{ww},(\text{ii}-1)n+\text{jj}) = \delta_g(\text{ww},(\text{ii}-1)n+\text{jj}) - (2\pi(\text{jj})/n); \)
    end
  end
end
\( \delta_{gn} = \text{unwrap}(\text{angle}(\text{En})); \)
\( \text{size}(\delta_{gn}) = 1225 \times 601 \)

\[
\text{plot} \quad \delta_{gn} \quad \text{when} \quad t=t; \\
t=1; \\
\delta_c = \delta_{gn}(:,t); \\
\text{for} \quad \text{mm}=1:n \\
  \text{for} \quad \text{ff}=1:n \\
    \delta_{nn}(\text{mm},\text{ff}) = \delta_c((\text{mm}-1)n+\text{ff}); \\
  \end{end}
end
XX = 1:n; \\
YY = 1:n; \\
\text{surf}(XX,YY,\delta_{nn})
\]

\%	exttt{pp2db35.m}
\%	ext{Define function "deltadot" for ode23 to solve the diff. eqns. in 2 dimension}
\%
\text{n}^2 \text{ is the number of generators}
\%	ext{k} is the generator number used for the diff. eqns. \#(1,2,3,......,n^2).
\%	ext{kk} = 1:1:n^2
\%	ext{Pm} is the mechanical power

\text{function} \quad \text{deltadot} = \text{pp2db35}(t,\delta)
\%	ext{global} \quad n \quad Y; \\
\text{deltadot} = \text{zeros}(2*(n^2),1); \\
\text{load} \quad \text{pm2db35.txt}; \\
\%	ext{Calculate} \quad \text{Pe}
\quad \text{Ed} = \begin{bmatrix} \delta(1) & \delta(3) & \delta(5) & \delta(7) & \delta(9) & \delta(11) & \delta(13) & \delta(15) & \delta(17) & \delta(19) & \delta(21) & \delta(23) & \delta(25) & \delta(27) & \delta(29) & \delta(31) & \delta(33) & \delta(35) & \delta(37) & \delta(39) & \delta(41) & \delta(43) & \delta(45) & \delta(47) & \delta(49) & \delta(51) & \delta(53) & \delta(55) & \delta(57) & \delta(59) & \delta(61) & \delta(63) & \delta(65) & \delta(67) & \delta(69) & \delta(71) & \delta(73) & \delta(75) & \delta(77) & \delta(79) & \delta(81) & \delta(83) & \delta(85) & \delta(87) & \delta(89) & \delta(91) & \delta(93) & \delta(95) & \delta(97) & \delta(99) & \delta(101) & \delta(103) & \delta(105) & \delta(107) & \delta(109) & \delta(111) & \delta(113) & \delta(115) & \delta(117) & \delta(119) & \delta(121) & \delta(123) & \delta(125) & \delta(127) & \delta(129) & \delta(131) & \delta(133) & \delta(135) & \delta(137) & \delta(139) & \delta(141) & \delta(143) & \delta(145) & \delta(147) & \delta(149) & \delta(151) & \delta(153) & \delta(155) & \delta(157) & \delta(159) & \delta(161) & \delta(163) & \delta(165) & \delta(167) & \delta(169) & \delta(171) & \delta(173) & \delta(175) & \delta(177) & \delta(179) \end{bmatrix} \]
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delta(2421) delta(2423) delta(2425) delta(2427) delta(2429)...
delta(2431) delta(2433) delta(2435) delta(2437) delta(2439)...
delta(2441) delta(2443) delta(2445) delta(2447) delta(2449)];
Ed=Ed';
Eg=cos(Ed)+i*sin(Ed);
Ig=Y*Eg;
Pe=real(Eg.*conj(Ig));

%These equations are for kk=1,......n^2.
for kk=1:(n^2)
    deltadot(2*kk-1)=delta(2*kk);
    deltadot(2*kk)=pm2db35(kk)-0.01*delta(2*kk)-Pe(kk,1);
end
%End==================================================(#2)============================================
% Pg64_d3relay.m(#3)
% This program is to do distance relay simulations on a ring system of 64 generators
% n is the number of generators
% y is the transmission line reactance
% y1=a*y is the generator internal reactance
% y0=b*y is the load
% B C D D1 D2 D3 D4 D5 and U are used for constructing matrix Y
% delta is the generator internal angle
%Begin=================================================================================================================
clerall;
global n Y;
 n=64;
Ts=0.05; %time step(in sec)
Tend=30; %time to end(in sec)
d1=0.09; %zone 1 setting (90% of j0.1)
d2=0.15; %zone 2 setting (150% of j0.1)
d3=0.25; %zone 3 setting (extend to 150% of the next line, j0.1)

%system parameters
a=10;
b=0.06+0.08*i;
y=-i*10;
y1=a*y;
y0=b*y;

%Construct matrix [Y], where [Ig]=[Y][E]
B=y1*eye(n);
C=(-y1)*eye(n);
D1=ones(n);
D2=tril(D1,1);
D3=triu(D2,-1);
D4=D3*(-y);
D5=eye(n)*(y1+3*y+y0);
D=D5+D4;
D(1,n)=-y;
D(n,1)=-y;
U=inv(D);
Y=B-C*U*C;

%Find initial condition, Pm, by assuming abs(Eg0)=1 p.u. and initial Ed0(s)=2*pi*s/n
% Ig0 is the initial generator current; Eg0 is the initial generator voltage
s=1:n;
Ed0(s)=(2*pi*s./n);
%Ed0(s)=0;
Ed0=Ed0';
Eg0=cos(Ed0)+i*sin(Ed0);
Ig0=Y*Eg0;
Pm=real(Eg0.*conj(Ig0));

%write Pm to txt file
fid=fopen('pm64_d3relay.txt','w');
for kk=1:n;
fprintf(fid,'%f
',Pm(kk,1));
end;
fclose(fid);
% Solve ODEs

tspan=[0:Tss:Tend];
% initial conditions
delta0=zeros(2*n,1);
d=1:2:2*n;
s=1:n;
s=s';
delta0(d)=(2*pi*s./n)+1.5*exp(-100*(s-16).^2);
delta0(31)=delta0(31)+1.5;
delta0=delta0';
[t,delta]=ode23('pp64_d3relay',tspan,delta0);

% calculate the voltage angles at bus terminals
for h=1:n
    delta_g(:,h)=delta(:,2*h-1);
end
Eg=cos(delta_g')+i*sin(delta_g');
Ig=Y*Eg;
En=Eg-Ig/(y1);

% calculate line current, follow the direction of generator numbers
for ww=1:n-1
    En_d(ww,:)=En(ww,:)-En(ww+1,:);
end
En_d(n,:)=En(n,:)-En(1,:);
I=En_d.*y;
ZZ=En./I;
[k1,k2]=size(ZZ);

% plot
hold on

% plot zone 1
xx1=((d3/2)^2-(d1-d3/2)^2)^0.5;
x1=-xx1:0.0001:xx1;
y11=plot(x1,d1,'g');

% plot zone 2
xx2=((d3/2)^2-(d2-d3/2)^2)^0.5;
x2=-xx2:0.0001:xx2;
y22=plot(x2,d2,'b');

% plot zone 3
x3=-d3/2:0.0001:d3/2;
r1=((d3/2).^2-x3.^2).^0.5+(d3/2);
r2=-(d3/2).^2-x3.^2).^0.5+(d3/2);
r3=plot(x3,r1,r',x3,r2,r');

xlabel('R')
ylabel('X')
axis([-0.25 0.25 -0.05 0.35]);

hold off
% This program defines function "deltadot" for ode23 to solve the diff. eqns.
% n is the number of generators
% k is the generator number used for the diff. eqns. #(2,3,...,n-1).
% K=2:1:(n-1)
% Pm is the mechanical power

function deltadot=pp64_d3relay(t,delta)
global n Y;
deltadot= zeros(2*n,1);
load pm64_d3relay.txt;

% Calculate Pe
Ed=[delta(1) delta(3) delta(5) delta(7) delta(9) delta(11) ... 
   delta(13) delta(15) delta(17) delta(19) delta(21) delta(23) ... 
   delta(25) delta(27) delta(29) delta(31) delta(33) delta(35) ... 
   delta(37) delta(39) delta(41) delta(43) delta(45) delta(47) ... 
   delta(49) delta(51) delta(53) delta(55) delta(57) delta(59) ... 
   delta(61) delta(63) delta(65) delta(67) delta(69) delta(71) ... 
   delta(73) delta(75) delta(77) delta(79) delta(81) delta(83) ... 
   delta(85) delta(87) delta(89) delta(91) delta(93) delta(95) ... 
   delta(97) delta(99) delta(101) delta(103) delta(105) delta(107) ... 
   delta(109) delta(111) delta(113) delta(115) delta(117) delta(119) ... 
   delta(121) delta(123) delta(125) delta(127)];
Ed=Ed';
Ig=Y*(cos(Ed)+i*sin(Ed));
Pe=real((cos(Ed)+i*sin(Ed)).*conj(Ig));

% These two equations are for K = 1,...,n
for k=1:n;
deltadot(2*k-1)=delta(2*k);
deltadot(2*k)=pm64_d3relay(k)-0.01*delta(2*k)-Pe(k,1);
end;

End================================(#3)=============================================
%% Pg64_ocrelay.m(#4)
%% This program is to do simulations of overcurrent relay on a ring system of 64 generators
%% n is the number of generators
%% y is the transmission line reactance
%% y1=a*y is the generator internal reactance
%% y0=b*y is the load
%% B C D D1 D2 D3 D4 D5 and U are used for constructing matrix Y
%% delta is the generator internal angle

%Begin================================(#4)==========================================
clear all;
global n Y;
n=64;

%system parameters
a=10;
b=0.06+0.08*i;
y=-i*10;
y1=a*y;
y0=b*y;

%Construct matrix [Y], where [Ig]=[Y][E]
B=y1*eye(n);
C=(-y1)*eye(n);
D1=ones(n);
D2=tril(D1,1);
D3=triu(D2,-1);
D4=D3*(-y);
D5=eye(n)*((y1+3*y+y0);
D=D5+D4;
D(1,n)=-y;
D(n,1)=-y;
U=inv(D);
Y=B-C*U*C;

%Find initial condition, Pm, by assuming abs(Eg0)=1 pu and initial Ed0(s)=2*pi*s/n
%Ig0 is the initial generator current; Eg0 is the initial generator voltage
s=1:n;
Ed0(s)=(2*pi*s./n);
Ed0=Ed0';
Eg0=cos(Ed0)+i*sin(Ed0);
Ig0=Y*Eg0;
Pm=real(Eg0.*conj(Ig0));

%Write Pm to a txt file
fid=fopen('pm64_ocrelay.txt','w');
for kk=1:n;
    fprintf(fid,'%f
',Pm(kk,1));
end;
close(fid);

%Solve ODEs
tspan=[0:0.05:30];
delta0=zeros(2*n,1);
d=1:2:2*n;
s=1:n;
s=s';
\[
delta_0(d) = (2\pi s./n) + (0.5*\exp(-1*(s-16)^2));
delta_0 = \delta_0';
[1,\delta_0] = \text{ode23('pp64_ocrelay',tspan,\delta_0)};
\]

% calculate the voltage angles at bus terminals
for hh=1:n
    delta_g(:,hh)=delta(:,2*hh-1);
end
E_g = \cos(delta_g') + i*\sin(delta_g');
I_g = Y*E_g;
E_n = E_g - I_g/(y1);

% calculate line current, follow the direction of generator numbers
for ww=1:n-1
    En_d(ww,:)=En(ww,:)-En(ww+1,:);
end
En_d(n,:)=En(n,:)-En(1,:);
I_line = En_d*(y);

% calculate the load current
En0 = E_g0 - I_g0*(1/y1);
for ff=1:n-1
    En0_d(ff,1)=En0(ff,1)-En0(ff+1,1);
end
En0_d(n,1)=En0(n,1)-En0(1,1);
I_ld = En0_d*(y);

[k1,k2]=size(delta_g');
for kk=1:k2
    I_load(:,kk)=I_ld(:,1);
end
oc = abs(I_line)/(2.*abs(I_load));

% plot
hold on
g=16;
plot(t,abs(2*I_load(g,:)),'r:',t,abs(I_line(g,:)),'b-')
xlabel('time')
ylabel('Current')
hold off

% pp64_ocrelay.m
% This program defines function "deltadot" for ode23 to solve the diff. equations.
% n is the number of generators
% k is the generator number used for the diff. equations. #(2,3,.....,n-1).
% K=2:1:(n-1)
% Pm is the mechanical power

function deltadot=pp64_ocrelay(t,delta)
global n Y;
deltadot= zeros(2*n,1);
load pm64_ocrelay.txt;

% Calculate Pe
Ed=[delta(1) delta(3) delta(5) delta(7) delta(9) delta(11) ...
    delta(13) delta(15) delta(17) delta(19) delta(21) delta(23) ...}
\[ \text{delta}(25) \text{ delta}(27) \text{ delta}(29) \text{ delta}(31) \text{ delta}(33) \text{ delta}(35) \ldots \]
\[ \text{delta}(37) \text{ delta}(39) \text{ delta}(41) \text{ delta}(43) \text{ delta}(45) \text{ delta}(47) \ldots \]
\[ \text{delta}(49) \text{ delta}(51) \text{ delta}(53) \text{ delta}(55) \text{ delta}(57) \text{ delta}(59) \ldots \]
\[ \text{delta}(61) \text{ delta}(63) \text{ delta}(65) \text{ delta}(67) \text{ delta}(69) \text{ delta}(71) \ldots \]
\[ \text{delta}(73) \text{ delta}(75) \text{ delta}(77) \text{ delta}(79) \text{ delta}(81) \text{ delta}(83) \ldots \]
\[ \text{delta}(85) \text{ delta}(87) \text{ delta}(89) \text{ delta}(91) \text{ delta}(93) \text{ delta}(95) \ldots \]
\[ \text{delta}(97) \text{ delta}(99) \text{ delta}(101) \text{ delta}(103) \text{ delta}(105) \text{ delta}(107) \ldots \]
\[ \text{delta}(109) \text{ delta}(111) \text{ delta}(113) \text{ delta}(115) \text{ delta}(117) \text{ delta}(119) \ldots \]
\[ \text{delta}(121) \text{ delta}(123) \text{ delta}(125) \text{ delta}(127) \];
\[ E_d = \overline{E_d}; \]
\[ I_g = Y \ast (\cos(E_d) + i \ast \sin(E_d)); \]
\[ P_e = \text{real}((\cos(E_d) + i \ast \sin(E_d)) \ast \text{conj}(I_g)); \]

for \( k = 1 : n \)
\[ \delta_{\text{d}}(2 \ast k - 1) = \delta(2 \ast k); \]
\[ \delta_{\text{d}}(2 \ast k) = \text{pm64_ocrelay}(k) - 0.01 \ast \delta(2 \ast k) - P_e(k, 1); \]
end

\%
End==================================================================(#4)==================================================================
% Pg_WSCC.m(#5)
% This program is to simulate wave propagation on WSCC system, a ring system
% n is the number of generators.
% Delta is the generator internal angle.
% y12, y23, ..., y61 are the transmission line admittance between two buses.
% y1, y2, ..., y6 are the generator internal reactance at each bus.
% L1, L2, ..., L6 are the load at each bus.
% B C D and U are use for constructing matrix Y.
%
Begin=================================================================================================
clear all;
global n Y;
n=6;
%1:JOHN DAY
%2:TEVATR2
%3:VINCENT
%4:ELDORADO
%5:FOURCORN
%6:BENLOMND
Ts=0.5;%Time to start the disturbance
Tend=2.5;%Time to end the program
Td=1/100;

%generator internal reactance
y1=(1/1.5301e-005i);
y2=(1/7.1376e-005i);
y3=(1/3.3573e-005i);
y4=(1/1.8950e-004i);
y5=(1/8.8168e-005i);
y6=(1/6.7029e-005i);

%transmission line admittance
y12=1/0.3648i;
y23=1/0.4472i;
y34=1/0.4853i;
y45=1/0.6344i;
y56=1/1.1688i;
y61=1/0.8103i;

%load
L1=27.7537-6.19125i;
L2=7.27691-3.5876i;
L3=13.9609-4.8976i;
L4=2.6127-0.1266i;
L5=3.4587+0.0132i;
L6=5.7735-0.6713i;

%Construct matrix [Y], where [Ig]=[Y][E]
B=y1*eye(n);
B(2,2)=y2;
B(3,3)=y3;
B(4,4)=y4;
B(5,5)=y5;
B(6,6)=y6;
C=-1.*B;
D=zeros(n,n);
D(1,1)=y1+y12+y61+L1;
D(1,2)=-y12;
D(1,6)=-y61;
D(2,1)=D(1,2);
D(2,2)=y2+y12+y23+L2;
D(2,3)=-y23;
D(3,2)=D(2,3);
D(3,3)=y3+y23+y34+L3;
D(3,4)=-y34;
D(4,3)=D(3,4);
D(4,4)=y4+y34+y45+L4;
D(4,5)=-y45;
D(5,4)=D(4,5);
D(5,5)=y5+y45+y56+L5;
D(5,6)=-y56;
D(6,5)=D(5,6);
D(6,6)=y6+y56+y61+L6;
D(6,1)=-y61;
U=inv(D);
Y=B-C*U*C;

%initial condition, Pm
Ed0(1,1)=(24.7322)*pi/180;
Ed0(2,1)=(-29.2631)*pi/180;
Ed0(3,1)=(-46.3987)*pi/180;
Ed0(4,1)=(-24.3394)*pi/180;
Ed0(5,1)=(-8.5199)*pi/180;
Ed0(6,1)=(14.9323)*pi/180;
Eg0=cos(Ed0)+i*sin(Ed0);
Ig0=Y*Eg0;
Pm=real(Eg0.*conj(Ig0));

%write Pm to txt file
fid=fopen('pm_WSCC.txt','w');
for kk=1:n;
    fprintf(fid,'%f
',Pm(kk,1));
end;
fclose(fid);

%Solve ODEs (1)
tspan=[0:Td:Tt-Td];
delta0=zeros(1,2*n);
for w=1:2:2*n
    delta0(w)=Ed0((w+1)/2);
end
delta0=delta0';
[t1,delta]=ode23('pp_WSCC',tspan,delta0);

calculate the voltage angles at bus terminals
for h1=1:n
    delta_g1(:,h1)=delta(:,2*h1-1);
end
Eg1=cos(delta_g1')+i*sin(delta_g1');
Ig1=Y*Eg1;
En1(1,:)=Eg1(1,:)-Ig1(1,:)/(y1);
En1(2,:)=Eg1(2,:)-Ig1(2,:)/(y2);
En1(3,:)=Eg1(3,:)-Ig1(3,:)/(y3);
En1(4,:)=Eg1(4,:)-Ig1(4,:)/(y4);
En1(5,:)=Eg1(5,:)-Ig1(5,:)/(y5);
En1(6,:)=Eg1(6,:)-Ig1(6,:)/(y6);

delta_n1=unwrap(angle(En1));

%Solve ODEs (2)
tspan=[Ts:Td:Tend];
delta0=zeros(1,2*n);
for w=1:2:2*n
    delta0(w)=Ed0((w+1)/2);
end
delta0(5)=delta0(5)+0.5;
delta0=delta0;
[t2,delta]=ode23('pp_WSCC',tspan,delta0);

%calculate the voltage angles at bus terminals
for h2=1:n
    delta_g2(:,h2)=delta(:,2*h2-1);
end

Eg2=cos(delta_g2')+i*sin(delta_g2');
Ig2=Y*Eg2;
En2(1,:)=Eg2(1,:)-Ig2(1,:)/(y1);
En2(2,:)=Eg2(2,:)-Ig2(2,:)/(y2);
En2(3,:)=Eg2(3,:)-Ig2(3,:)/(y3);
En2(4,:)=Eg2(4,:)-Ig2(4,:)/(y4);
En2(5,:)=Eg2(5,:)-Ig2(5,:)/(y5);
En2(6,:)=Eg2(6,:)-Ig2(6,:)/(y6);

delta_n2=unwrap(angle(En2));
delta_n=[delta_n1,delta_n2];
t=[t1;t2];

%plot voltage phase angles at bus terminals
hold on

%for q3=1:6
    plot(t,delta_n(1,:));
    plot(t,delta_n(2,:));
    plot(t,delta_n(3,:));
    plot(t,delta_n(4,:));
    plot(t,delta_n(5,:));
    plot(t,delta_n(6,:));
%end
hold off

% pp_WSCC.m
% This program defines function "deltadot" for ode23 to solve the diff. equations.
% n is the number of generators.
% M1, M2, ..., M6 are the generator inertia.
% Damp is the damping coefficient.
% Pm is the mechanical power.

function deltadot=pp_WSCC(t,delta)
    global n Y;
    Damp=0;
deltadot=zeros(2*n,1);
load pm_WSCC.txt;

%Calculate Pe
Ed=[delta(1) delta(3) delta(5) delta(7) delta(9) delta(11)];
Ed=Ed';
Ig=Y*(cos(Ed)+i*sin(Ed));
Pe=real((cos(Ed)+i*sin(Ed)).*conj(Ig));

%generator capacities
M1=0.6499;
M2=0.1822;
M3=0.2806;
M4=0.1057;
M5=0.1471;
M6=0.1474;

%These equations are for the diff. equations.
deltadot(1)=delta(2);
deltadot(2)=[pm_WSCC(1)-Damp*delta(2)-Pe(1,1)]/M1;
deltadot(3)=delta(4);
deltadot(4)=[pm_WSCC(2)-Damp*delta(4)-Pe(2,1)]/M2;
deltadot(5)=delta(6);
deltadot(6)=[pm_WSCC(3)-Damp*delta(6)-Pe(3,1)]/M3;
deltadot(7)=delta(8);
deltadot(8)=[pm_WSCC(4)-Damp*delta(8)-Pe(4,1)]/M4;
deltadot(9)=delta(10);
deltadot(10)=[pm_WSCC(5)-Damp*delta(10)-Pe(5,1)]/M5;
deltadot(11)=delta(12);
deltadot(12)=[pm_WSCC(6)-Damp*delta(12)-Pe(6,1)]/M6;

%End==========================================================================
Vita

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