# Bulk Power System Oscillation Terms

Oscillation Analysis Working Group

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## 1 Introduction

Oscillations are an inherent phenomenon in power systems that can threaten grid reliability if not managed appropriately. The nature of the oscillations depends upon the operating condition of the power system. Oscillations have been the focus of significant study in the Western Electricity Coordinating Council (WECC) system for several decades. These studies have been bolstered by the widespread deployment of phasor measurement unit (PMU) networks and related software tools. As the capabilities of these tools expand and new oscillatory events are examined there is an increased need for effective communication among system operators, reliability coordinators, software vendors, and researchers. This document was developed to help facilitate this communication by explaining many of the terms used in discussing power system oscillations. Definitions for key terms are first provided in Section 2. Descriptions of system responses are provided in Section 3, followed by an overview of oscillation types in Section 4. Section 5 includes a list of terms often used by researchers to describe analysis approaches and tools. The document concludes with several real-world examples in Section 6.

## 2 Definitions

**Oscillation**: An **Oscillation** is an asynchronous periodic exchange of energy across different components of a power grid. An **Oscillation** is characterized by a set of frequency, damping, amplitude, and phase terms.

**Oscillation Shape**: An **Oscillation Shape** describes how an **Oscillation** manifests at different parts of a power grid. An **Oscillation Shape** is characterized by the amplitude and phase of a particular frequency component within an **Oscillation** at different parts of a power grid.

**Oscillatory Mode**: An **Oscillatory Mode** is a natural oscillatory property of a power system and is a function of the system's operating condition. Mathematically, these are related to the system eigenvalues of the linearized system condition about a given equilibrium. A particular **Mode** is characterized by its frequency, damping, and shape. If all **Modes** are positively damped, the system is considered small-signal stable. If one or more **Modes** are undamped or have negative damping, the system is considered small-signal unstable.

**Oscillatory Mode Shape**: Oscillatory Mode Shape describes how an oscillatory mode manifests itself at different parts of a power grid. The relative **Oscillation Shape** of a given **Mode** is characterized by the amplitude and phase of that mode at different points in the power grid. Mathematically, **Mode Shape** is characterized by the system's right eigenvector associated with the **Oscillatory Mode**. **Oscillatory Mode Shape** is an example of an **Oscillation Shape**.

## 3 System Response Types

**Ambient Response**: An **Ambient Response** is the response of the system to the small random changes within the system, such as small random changes in load, line switching, etc.

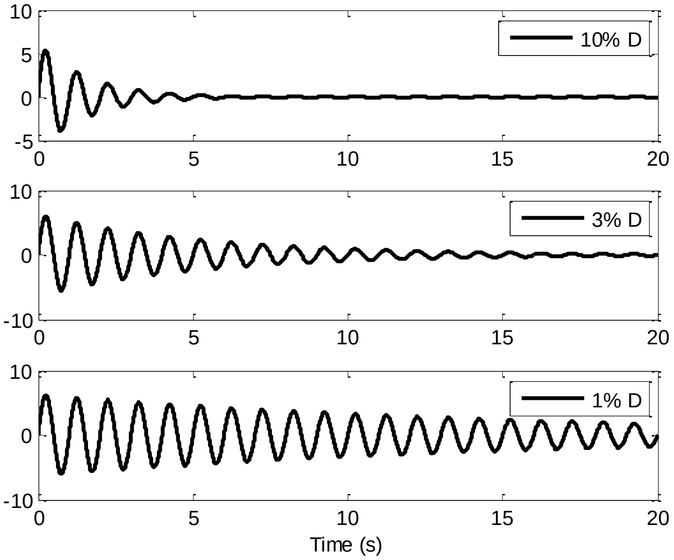
**Transient Response**: A **Transient Response** is the response of the system immediately after a sudden disturbance such as a fault, line tripping, generator trip, or load tripping. Small-scale transient responses are typically dominated by a **Natural Response**. Large-scale transient responses may include nonlinear system behavior in the initial swings of the response that will not be well represented by the natural response of a linear system. Colloquially, the term **Ringdown** is often used in reference to a **Transient Response**.

**Natural Response**: A **Natural Response** is the response of the system associated with the **Oscillatory Modes**. A **Natural Response** is often referred to as a **Natural Oscillation**.

**Forced Response**: A **Forced Response** is the response of the system associated with an external input. Examples include malfunctioning equipment such as a steam valve cycling on and off improperly, hydro turbines operating in a rough zone, unintentional behavior introduced by control systems, or normal operation of an arc furnace inducing its dynamics into the grid. A **Forced Response** is often referred to as a **Forced Oscillation**. **Forced Oscillations** may include harmonics resulting from the periodicity of the external inputs.

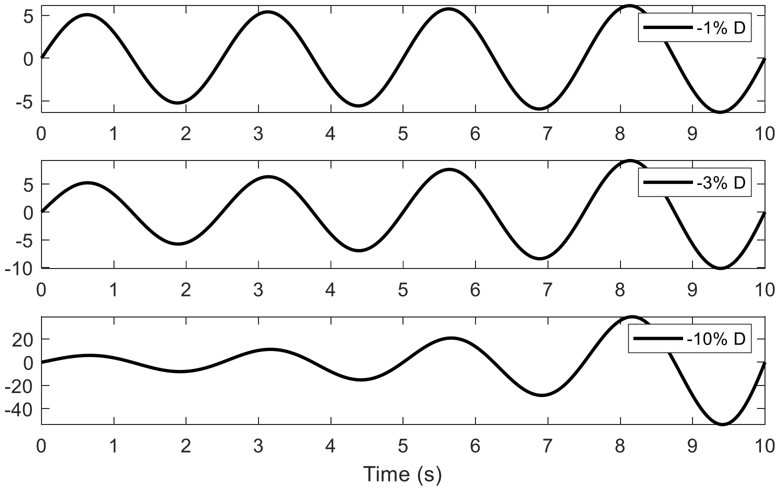
## 4 Oscillation Types

**Poorly Damped Oscillation**: A **Poorly Damped Oscillation** is a **Transient Response** of relatively long duration, that is, a **Transient Response** that requires a long time to return to **Ambient Response** conditions. A damping ratio of 3% has commonly been cited as a threshold for a poorly damped oscillation in power systems, though no specific standard threshold currently exists. Below are three single-mode simulated **Natural Oscillations** with varying damping; 10% is considered high damping while 1% is very poorly damped.



**<u>Undamped or Sustained Oscillation</u>**: An **Undamped or Sustained Oscillation** is a **Natural** or **Forced Response** that exhibits a persistent presence of **Oscillation** with zero damping. Examples include **Forced Oscillations**, as well as undamped **Natural Oscillations**, or stable limit cycles related to nonlinear dynamics. **Undamped Natural Oscillations** should not be confused with **Undamped Forced Oscillations**.

**<u>Growing Oscillations</u>**: A negatively damped oscillatory response with growing amplitude of **Oscillations**, typically caused by an unstable **Oscillatory Mode**, malfunctioning apparatus, incorrect control designs, or adverse interactions within the power system. They usually lead to tripping of components such as generators and transmission lines. As an example, **Growing Oscillations** were a contributing factor that led to the August 10, 1996 WECC blackout described in Section 6. **Growing Oscillations** over a wide area are rare but can have significant reliability implications when present. Below are three single-mode simulated **Natural Oscillations** with varying levels of negative damping.



## 5 Terms

The following “Terms” are often used by researchers to describe analysis approaches and tools. Our goal in this section is to be inclusive of many perspectives. These approaches and tools may be for real-time or non-real-time applications. For real-time applications the analysis is taking place while data is being collected such as a real-time oscillation detection. For non-real-time applications the analysis is applied to previously collect data such as for post event analysis.

**Mode Meter**: A tool used to automatically and continuously estimate a specific **Oscillatory Mode’s** frequency, damping, and shape. It operates during all system conditions – **Ambient, Transient, or Forced Responses**; or a linear combination of these.

**Oscillation Monitor**: A tool used to automatically and continuously estimate the presence and the properties of any poorly damped, undamped or negatively damped oscillation in the power grid related to natural **Oscillatory Modes** as well as from **Forced Responses**. It operates during **Ambient, Transient, or Forced Responses**; or a linear combination of these. It provides estimates of the frequency, damping, oscillatory energy level and the shape of any such oscillation in the power grid.

**Oscillation Detector**: A tool used to automatically and continuously detect oscillatory activity. An **Oscillation Detector** can provide varying degrees of quantitative information such as starting and ending times of the oscillation, frequencies in the oscillation, amplitude at a given output, and phase at a given output and frequency. An **Oscillation Detector** does not attempt to calculate damping terms of oscillations.

**Oscillation Event Analyzer:** A tool used to detect and analyze **Transient** oscillation events in order to estimate the frequencies, damping levels, shapes, and energy levels of **Oscillatory Modes** based on available measurements. The term **Ringdown Analyzer** is used colloquially to refer to these tools.

**Forced Oscillation Source Locator:** A tool capable of determining the geographic location of the apparatus injecting a **Forced Oscillation**. The tool may also indicate the underlying mechanism causing the oscillation.

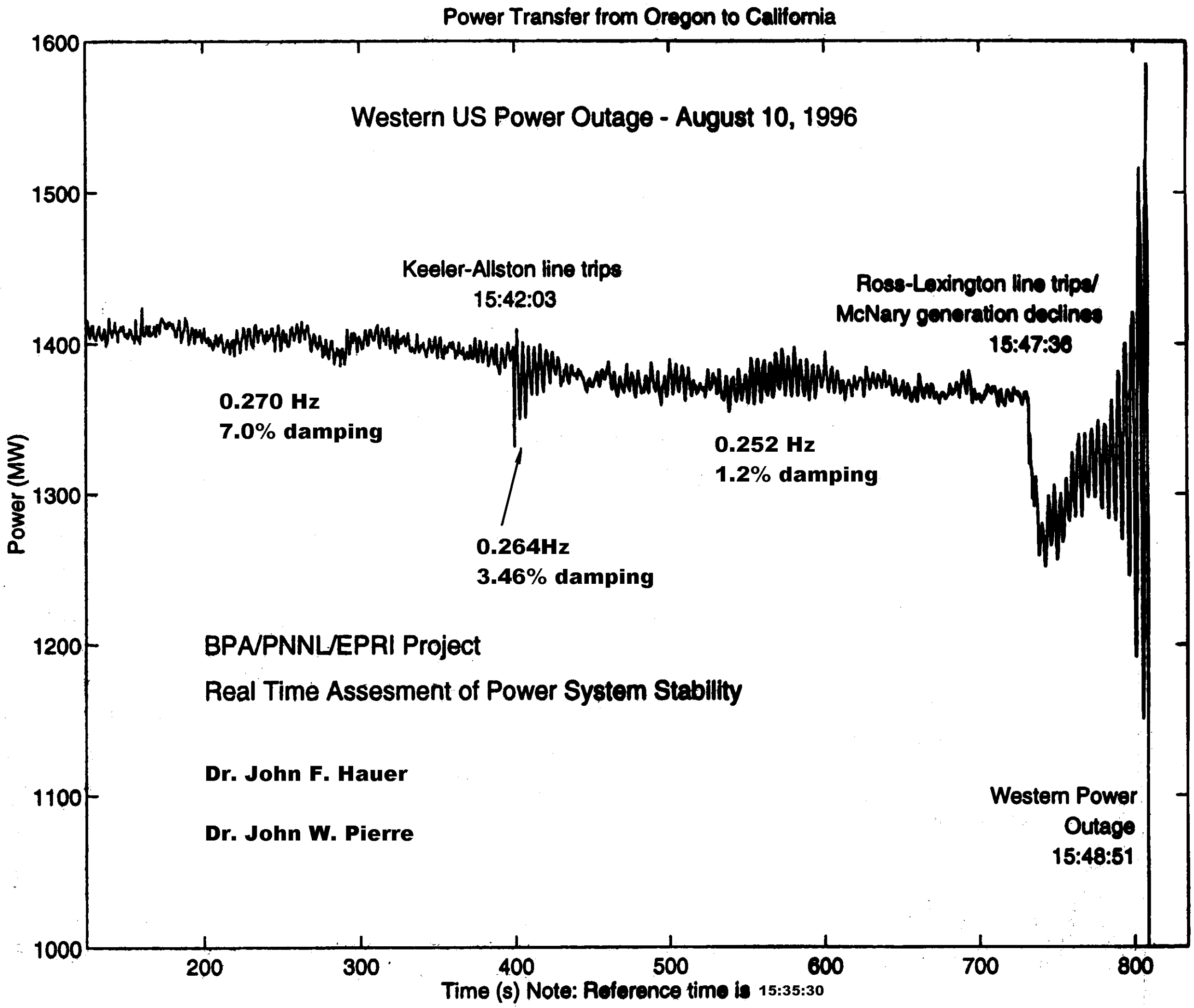
## 6 Examples

### August 10, 1996 Breakup of the Western Interconnection

The figure below depicts measurements leading up to the August 10, 1996 outage in western North America. The figure is reproduced from:

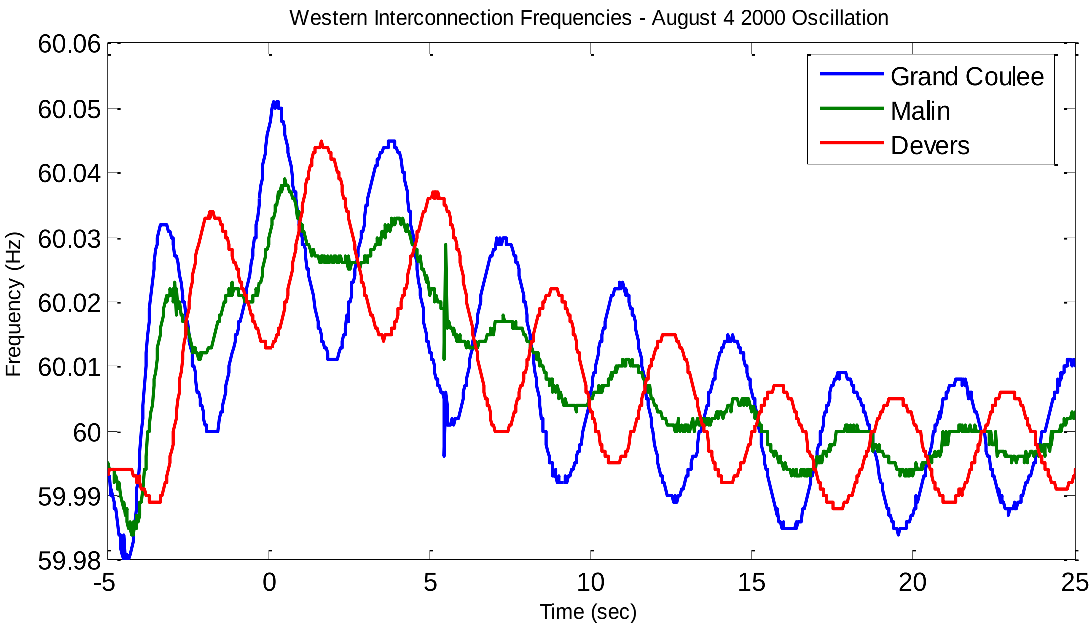
> "Model Validation for the August 10, 1996 WSCC System Outage" by Dmitry Kosterev, Carson Taylor, and William Mittelstadt published in IEEE Transactions on Power Systems, vol. 14, no. 3, pp. 967-979, Aug 1999.

**Natural Responses** are dominant throughout the plot. The system's **Ambient Response** is present until the 400 second mark when a **Transient Response** occurs. At 3.46% damping, the oscillation could be considered a **Poorly Damped Oscillation**. The system's **Ambient Response** resumes at approximately the 430 second mark and lasts until about 700 seconds. At that point a second **Transient Response** dominated by a **Growing Oscillation** occurs. The **Growing Oscillation** occurred because the damping of the **Oscillatory Mode** near 0.25 Hz became negative. The **Oscillatory Mode Shape** of the 0.25 Hz **Oscillatory Mode** involves generators in the northern part of the system swinging against those in the southern part of the system. As a result, power flows on north-south tie-lines oscillated with increasing amplitudes until system breakup occurred.

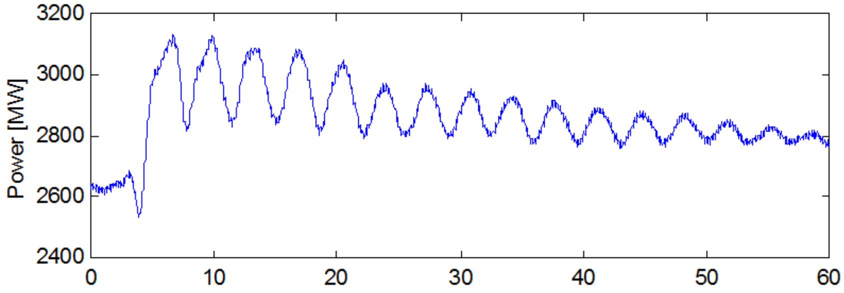


## August 4, 2000 WECC Inter-Area Natural Oscillations

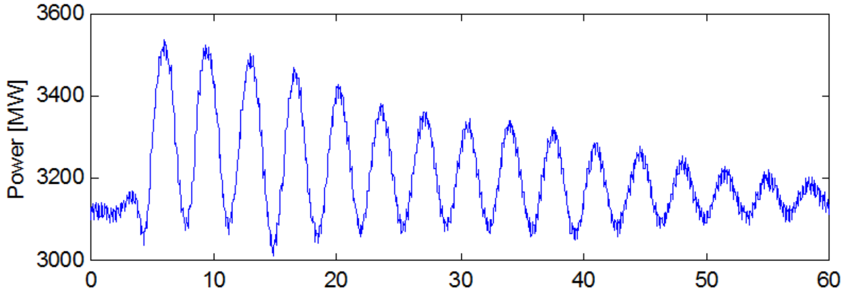
On August 4, 2000, Alberta disconnected from the rest of the western interconnection when the one 500 kV and two 230 kV ties between the Alberta and British Columbia systems were separated. The separation resulted in a **Transient Response** dominated by a **Poorly Damped Oscillation** associated with one of the newly configured system's **Oscillatory Modes**.



(a) Canada - Northwest Power

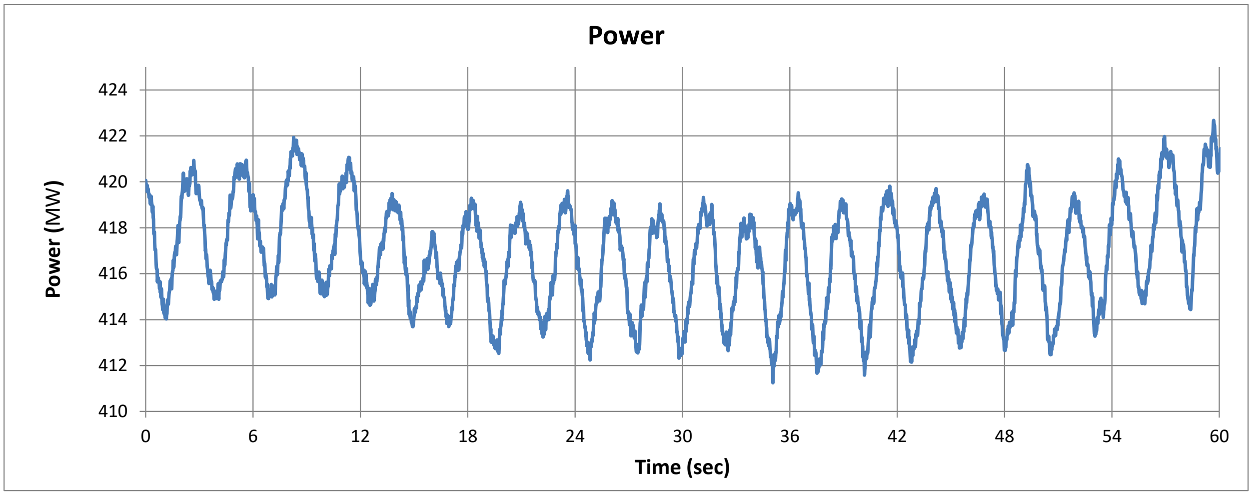


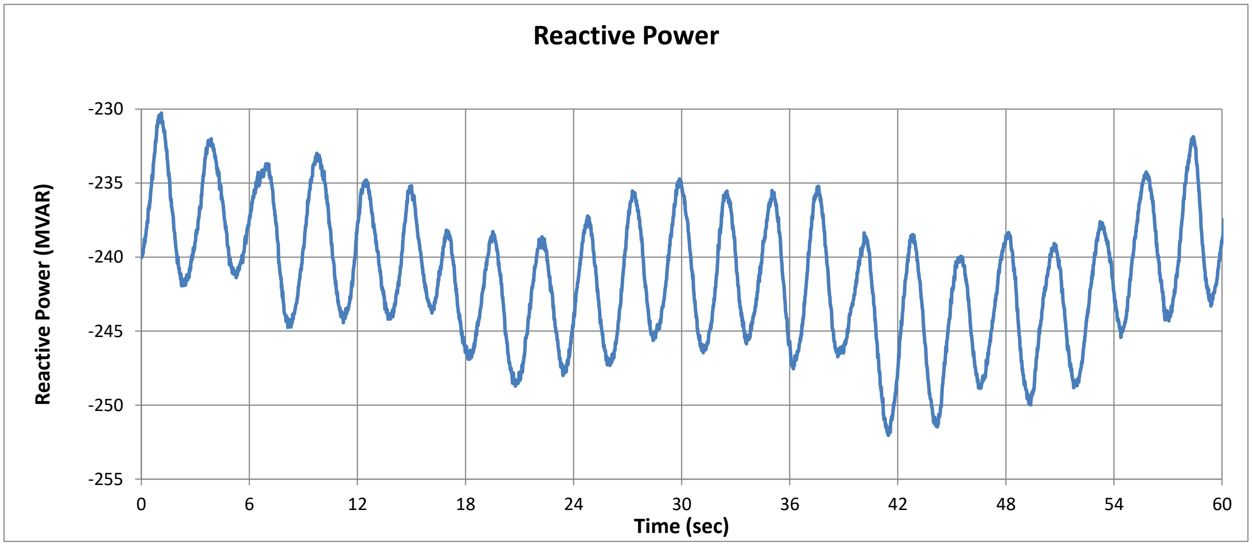
(b) California - Oregon Intertie Power



## October 2014 Hydro Rough-Zone Forced Oscillation

In October 2014, a hydro-power plant operating in its rough zone initiated a **Forced Response** in the western interconnection. Rough zone operation occurs when the generator is operated at partial load. The **Forced Response** was dominated by a **Sustained Oscillation** with a frequency of approximately 0.38 Hz. The **Sustained Oscillation** subsided when the generator was brought out of the rough zone by increasing its power.



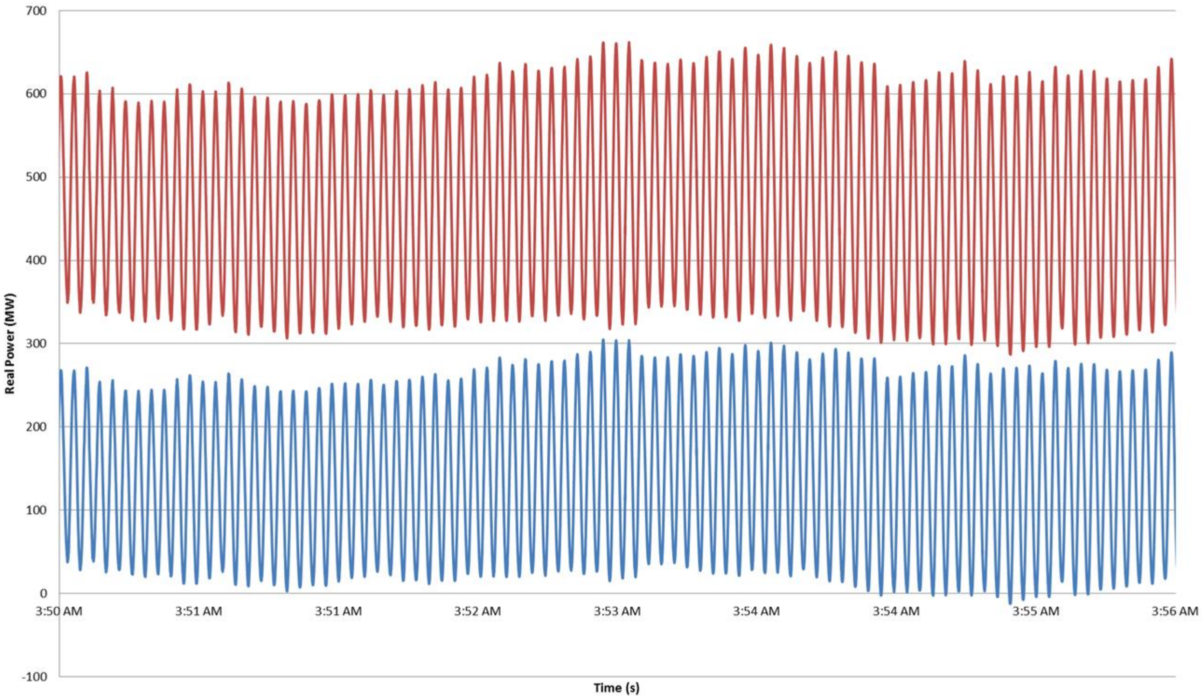


## January 11, 2019 Florida Forced Oscillation Event

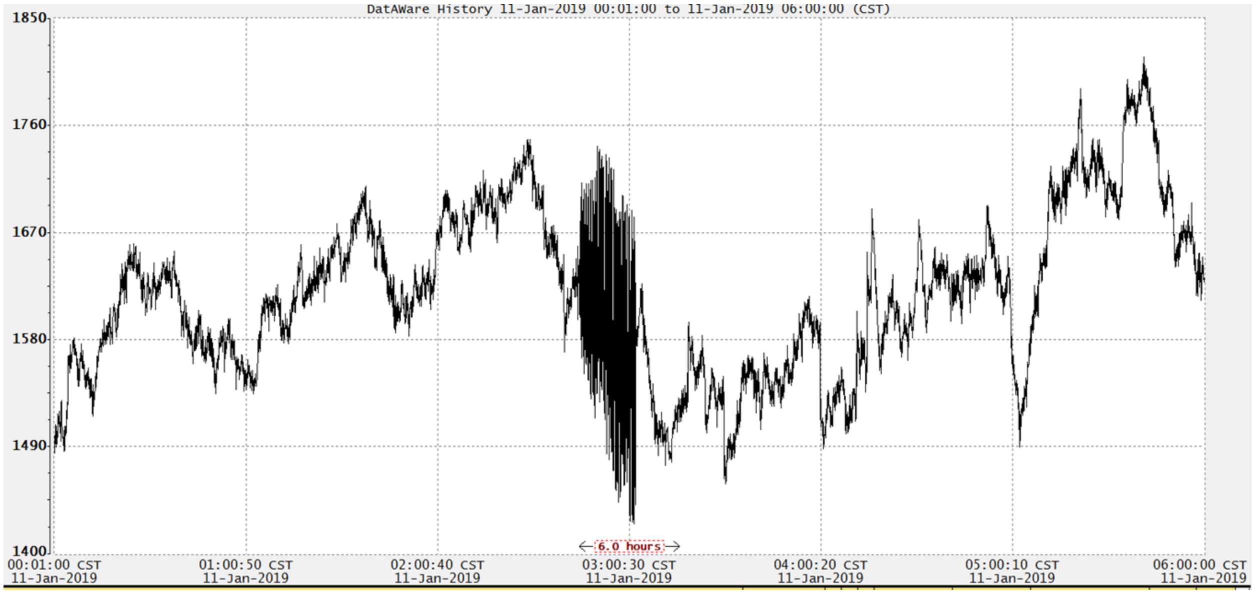
An input failure to the speed governor at a steam power plant in Florida resulted in MW oscillations being injected into the grid at 0.25 Hz and these MW oscillations resonated with the 0.24 Hz North-South inter-area **Oscillatory Mode** of the eastern interconnection. The resonant **Sustained Oscillations** were seen all over the eastern interconnection. Details on the event can be found in the NERC report:

> "Eastern Interconnection Oscillation Disturbance, January 11, 2019 Forced Oscillation Event", North American Electric Reliability Corporation, December 2019.

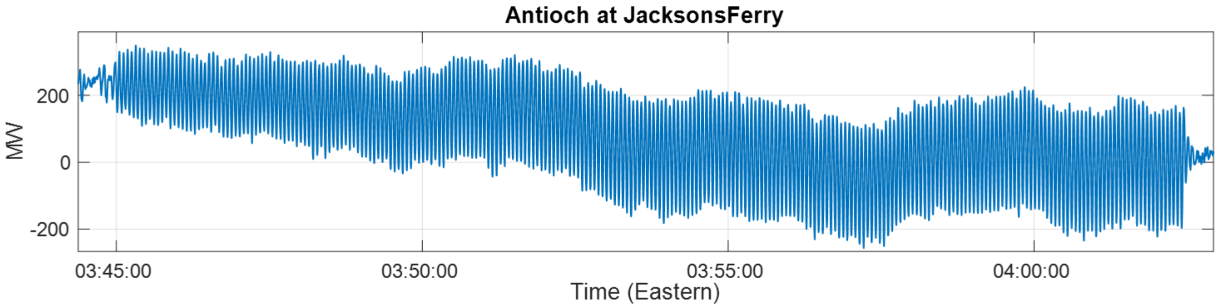
The figures below are reproduced from the report.



500 kV Line Active Power-flows in Florida [Florida Light and Power]



Line Active Power-flow in TVA Footprint



Line Active Power-flow in New England ISO footprint

# Disclaimer

## Additional Resource Information

- Model Validation for the August 10, 1996 WSCC System Outage
- Eastern Interconnection Oscillation Disturbance, January 11, 2019 Forced Oscillation Event
- Interconnection Oscillation Analysis: Reliability Assessment
- Implementation and operating experience with oscillation detection application at Bonneville Power Administration

## Version History

| Modified Date | Modified By | Description |
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