Simulation Tools to Study Distribution Systems Including Distributed Generation and Practical Case Studies in Canada

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Overview

- Introduction
- CYME-NRCan Collaboration
- Utility Survey and Current Status
- CYMDIST Enhancements
- Case Studies – Demonstration/Tutoring
- Conclusions

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Introduction

- The benefits of installing DGs in distribution networks have already been established
- There are several pitfalls to their application to existing distribution systems
- Interaction between DGs and the distribution system involves several phenomena that need thorough investigation
- There is a need for enhanced analysis tools for distribution systems as well as the development of engineering skills in using them

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NRCan – CYME collaboration




CYME/NRCan DG software approach

1. Industry survey
   - Identify gaps
2. CYMDIST software enhancements
   - Add DG models
   - Add dynamic functionalities
   - Add planned islanded network option
3. Knowledge transfer
   - Case studies for training/tutorial material
   - Educate – DG issues, relevant standards, new modeling features

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Utility Survey and Current Status

- **A survey of 30 distribution utilities representing 9 provinces and 2 territories serving over 7million customers was conducted by CYME on behalf of NRCan**

- **The main objectives of the survey were to:**
  - **Establish distribution engineers experience and adequacy of analytical tools at their deposal for conduction of DG integration studies**
  - **Provide insight into the direction distribution planning is heading and its effect on the need for special skills and enhanced tools.**

Utility Survey and Current Status (Cont.)

The survey results indicated that:

- **Major enhancement of current analytical tools is necessary for handling emerging technology in distribution systems**
- **Increasing distribution engineers familiarity with and ability to handle state of the art is essential**
- **CYMDIST is the most widely used distribution analysis tool among Canadian engineers**

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CYME - NRCan Collaboration Plan

- A collaboration plan between CYME and NRCan Was developed

- The primary objectives of the project are:

  - To add feature to CYMDIST to simplify the use of the program for DG interface studies

  - To implement the most common DG models in CYMDIST and provide adequate means to investigate the impact of DG on distribution networks

- The plan is being implemented in three phases

Phase I – Steady State Analysis

- Create a library of typical data for DG units in the form of look-up tables or estimation functions
- Provide the ability to simulate isolated distribution systems with embedded generation
- Provide the capability of automated network reduction for easier evaluation of DG integration studies
- Create Test Cases of typical systems involving DG for testing different steady state phenomena

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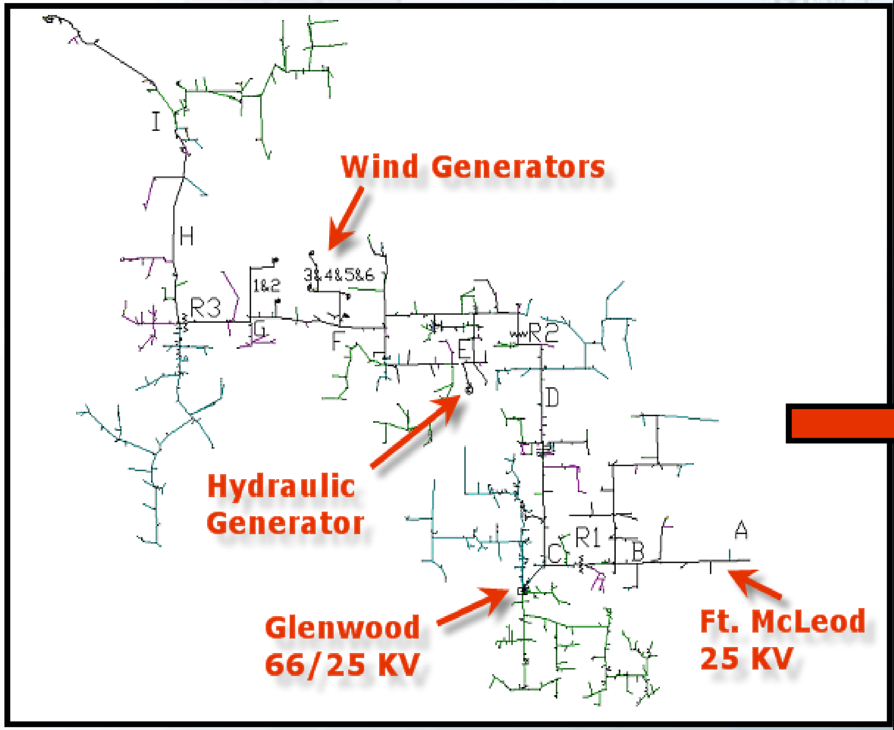
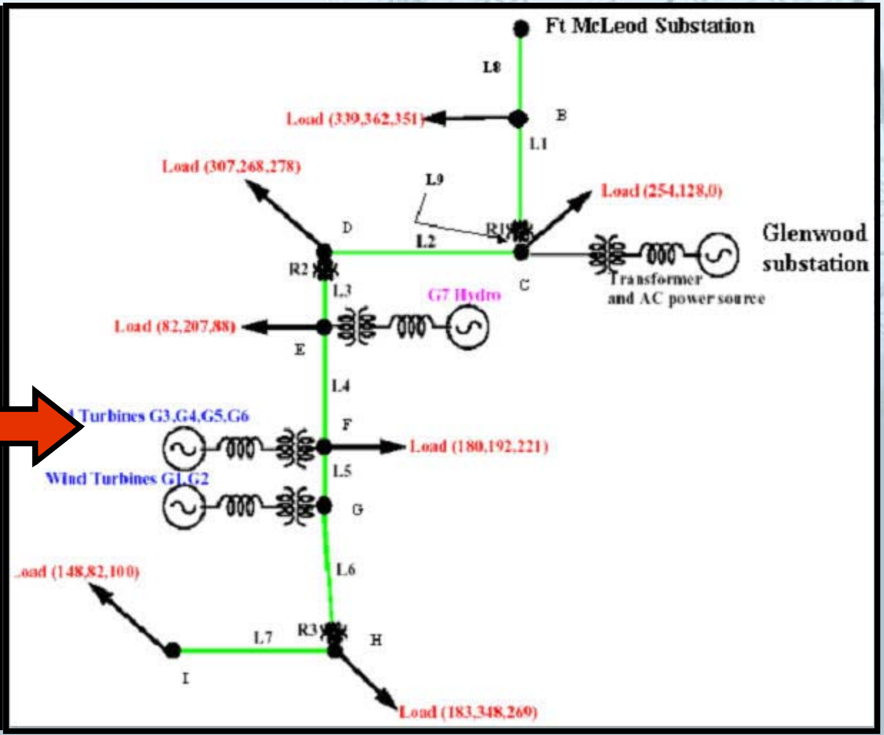
The System Reduction Concept

- **System reduction concept is demonstrated in the following figure**





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Phase II – Dynamic Analysis

- Implement, in CYMDIST, dynamic models of system components involved in transient stability and frequency behavior studies
- Provide ability to simulate events such as faults, load and generation rejection, component tripping, etc.
- Provide the ability to report and monitor different variables during the dynamic simulation
- Create Test Cases of typical systems to be used for testing dynamic behavior of DS systems

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Phase III – Additional DG Models

- **Add models of electronically-interfaced DGs:**
  - **Micro-turbine generation systems**
  - **Variable-speed wind energy systems:**
    - **Direct drive synchronous generator**
    - **Direct drive permanent magnet generator**
    - **Doubly-fed induction generator**
  - **Photovoltaic systems**
  - **Fuel cell systems**
  - **Battery energy storage systems**

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Phase III – Additional DG Models (Cont.)

- Develop dynamic models of small DG units of conventional technologies:
  - Combined cycle units
  - Kaplan turbine hydraulic units
- Implement protective functions relevant to distribution systems with embedded DG resources.
- Develop typical distribution system with DG units and set up test cases to illustrate system / unit dynamic interaction

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Case studies - objectives

- To demonstrate the effect of distributed resources on steady-state and dynamic behavior of distribution systems
- Education and dissemination of information
- The study cases demonstrate the response of the system to disturbances and the effect of:
  - Type of embedded generation
  - Operating conditions
  - Degree of penetration of the DG resources

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Distribution system modeled

- Actual 25 kV multi-grounded distribution circuit with several laterals feeding multiple loads.
- The distribution system is connected to the main power system at bus bar B1.
- DG units, of varying types and sizes are connected to bus bars B0, F and G. Loads are connected to bus bars B, C, D, E, F, H and I.
- Total load is 4.627 MW +1.313 MVAR, the largest is 1.5 MW +0.51 MVAR connected to bus bar B.

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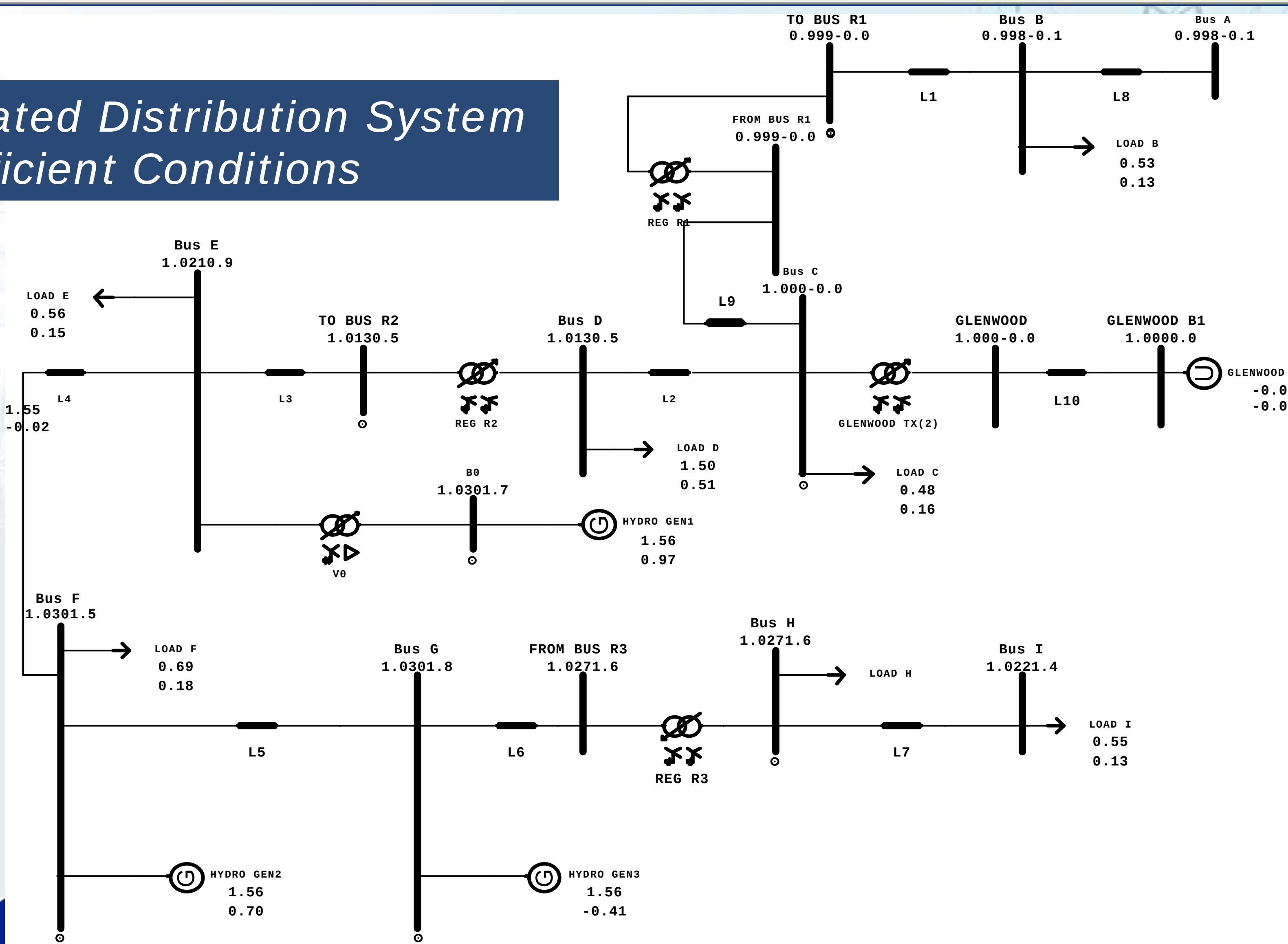
Distribution System Modeled (cont.)

Investigated Distribution System Self-Sufficient Conditions



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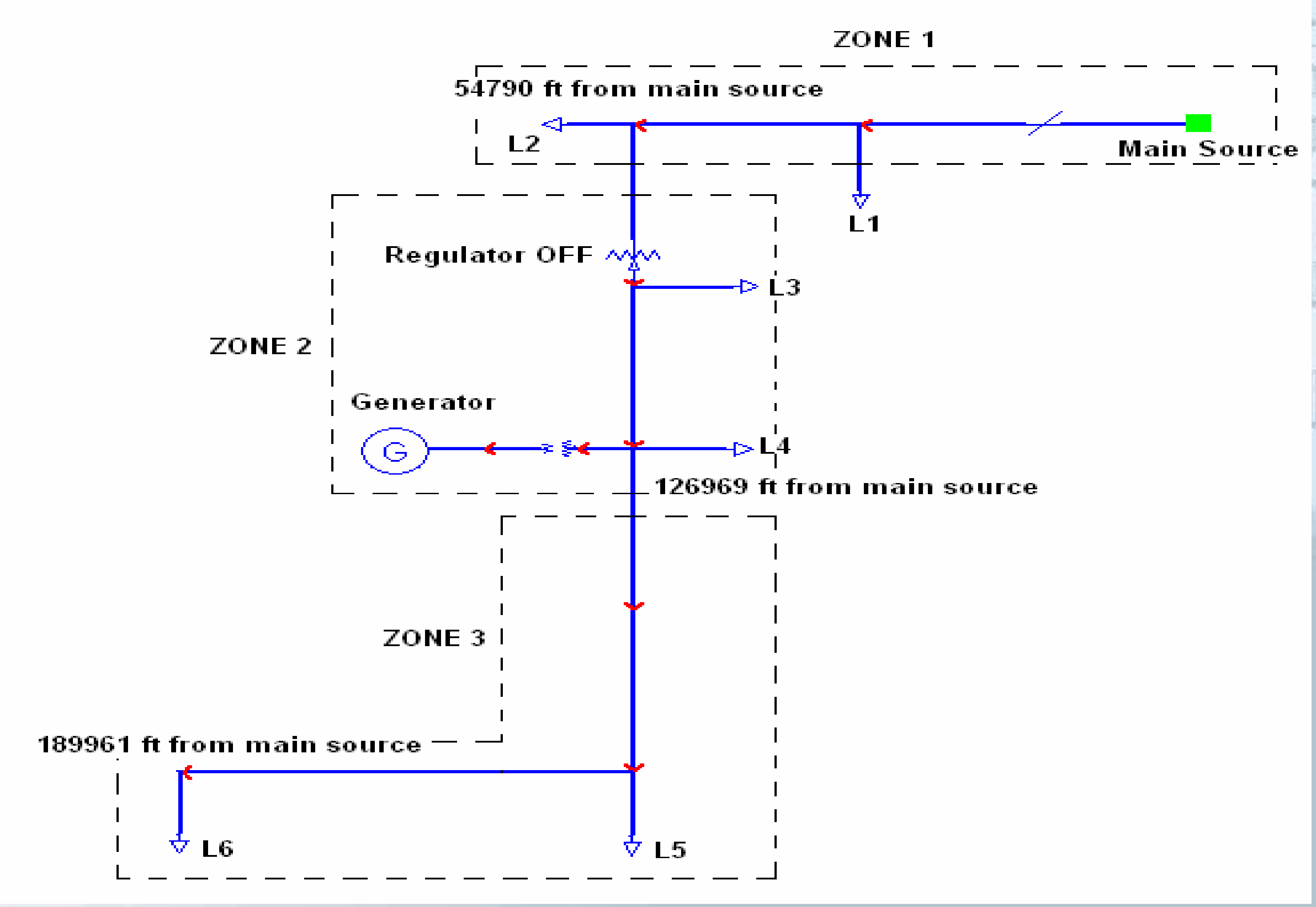
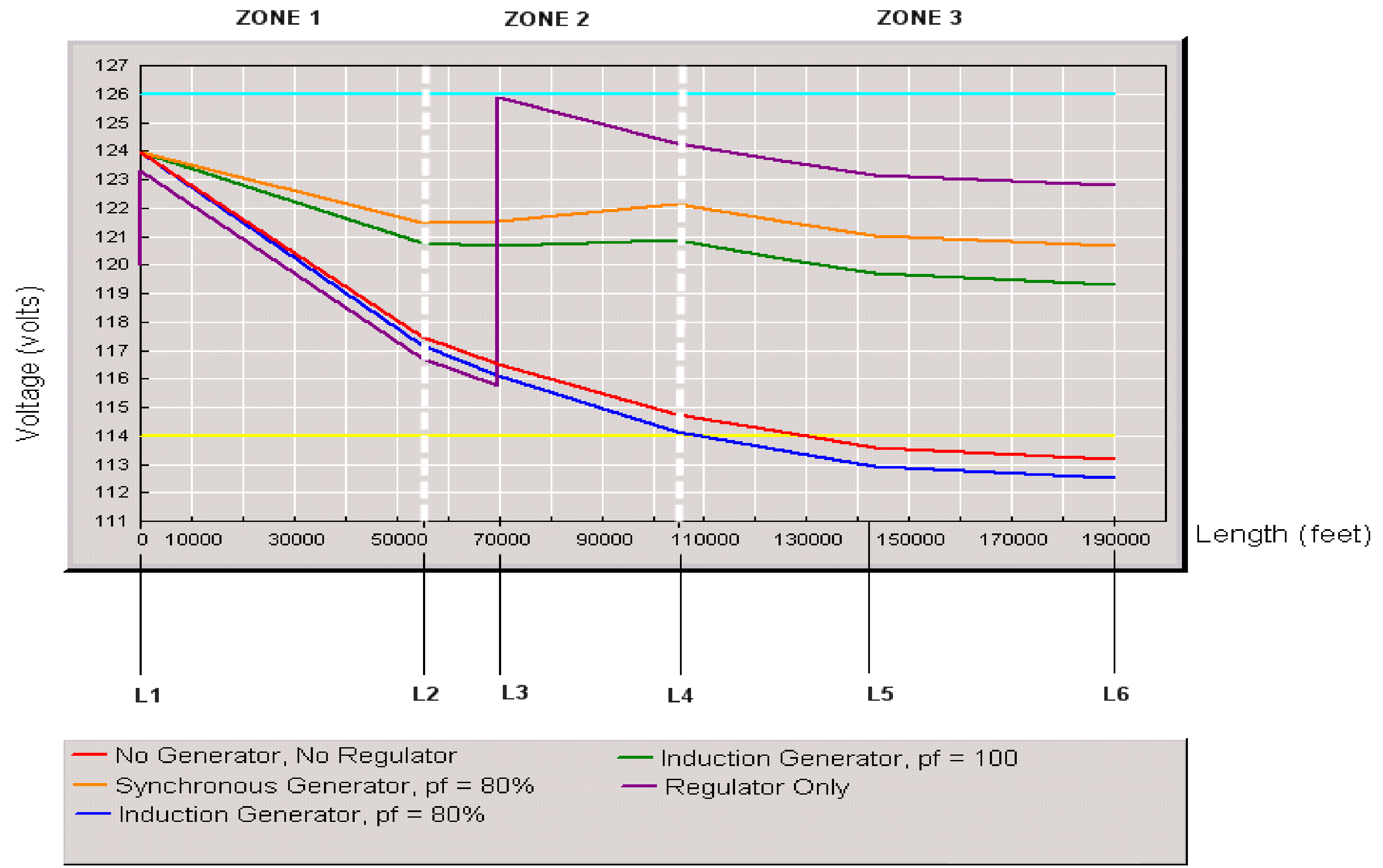
Phase I - Voltage profile analysis



Phase I - Voltage profile analysis (Cont.)



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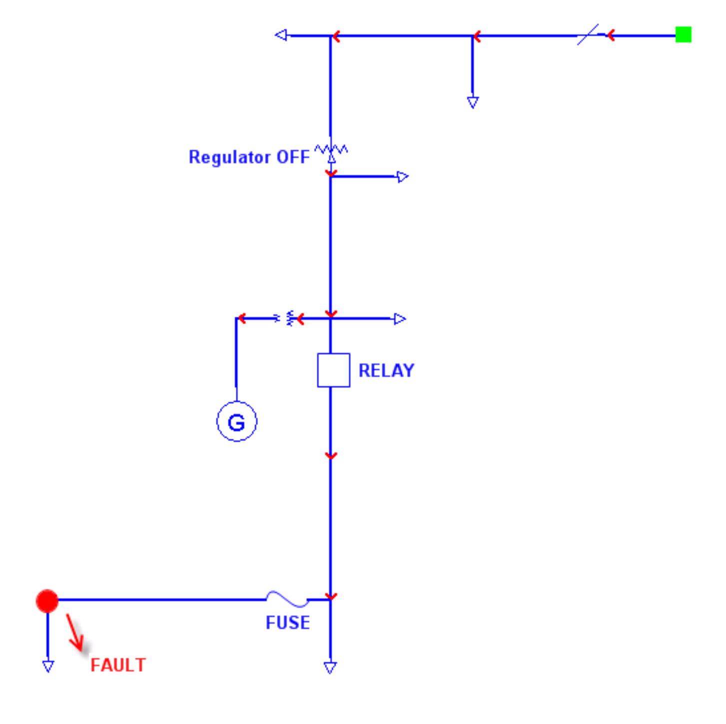
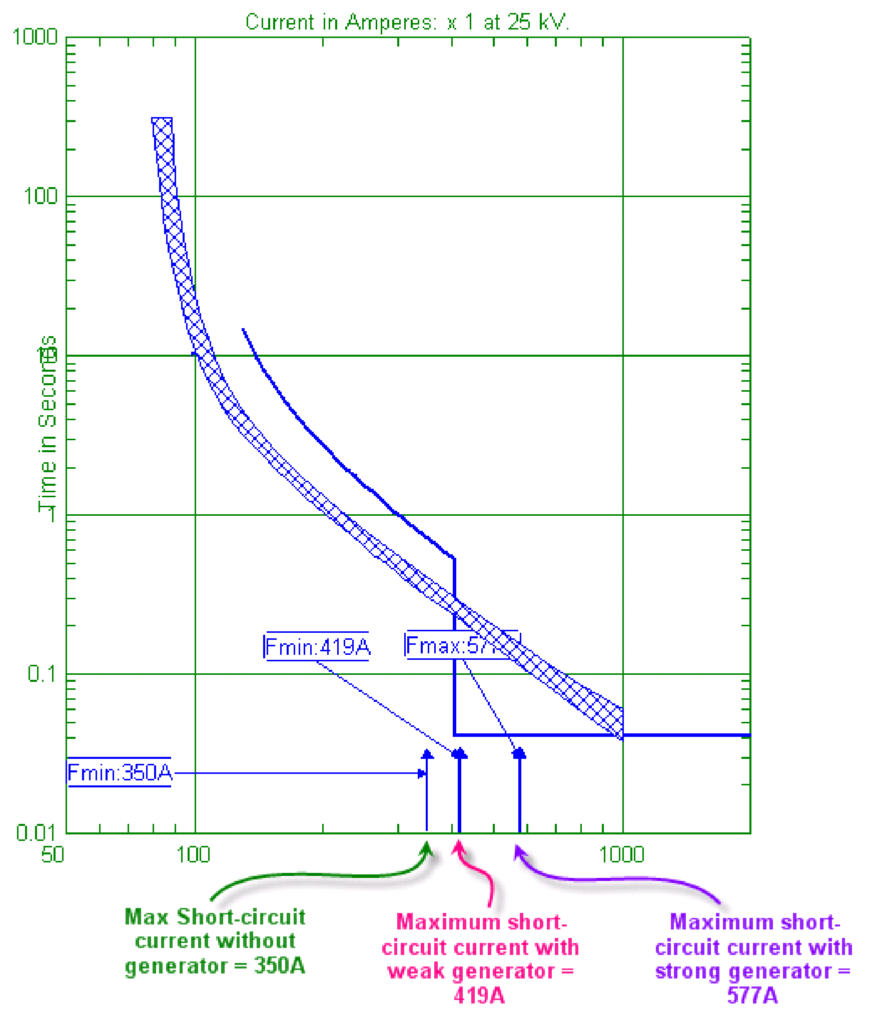
Phase I - Protection coordination study





Phase II - Dynamic Models of Component

- The following components models were used:
  - Load model
  - Generator models
  - Excitation system model
  - Prime mover models
  - Wind turbine model
  - IEEE Anti-Islanding Standards

Load Model

- **Load composition is reflected in its dependence on system voltage and frequency:**

$$P = Po \times (Vpu)^{nP} \times [1 + \mathit{Pfreq}\,(Fpu - 1)]$$

$$Q = Qo \times (Vpu)^{nQ} \times [1 + \mathit{Qfreq}\,(Fpu - 1)]$$

- **Voltage dependence reflected in nP and nQ**
- **Frequency dependence reflected in Pfreq and Qfreq.**

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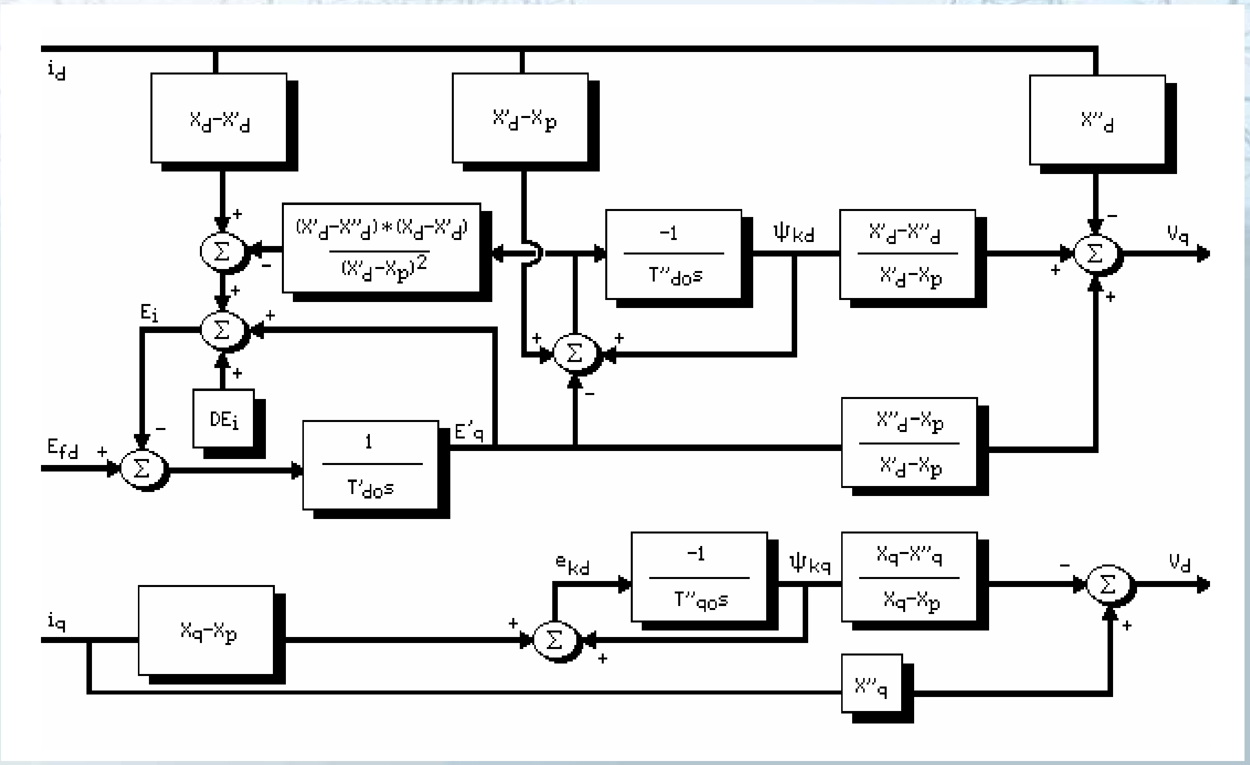
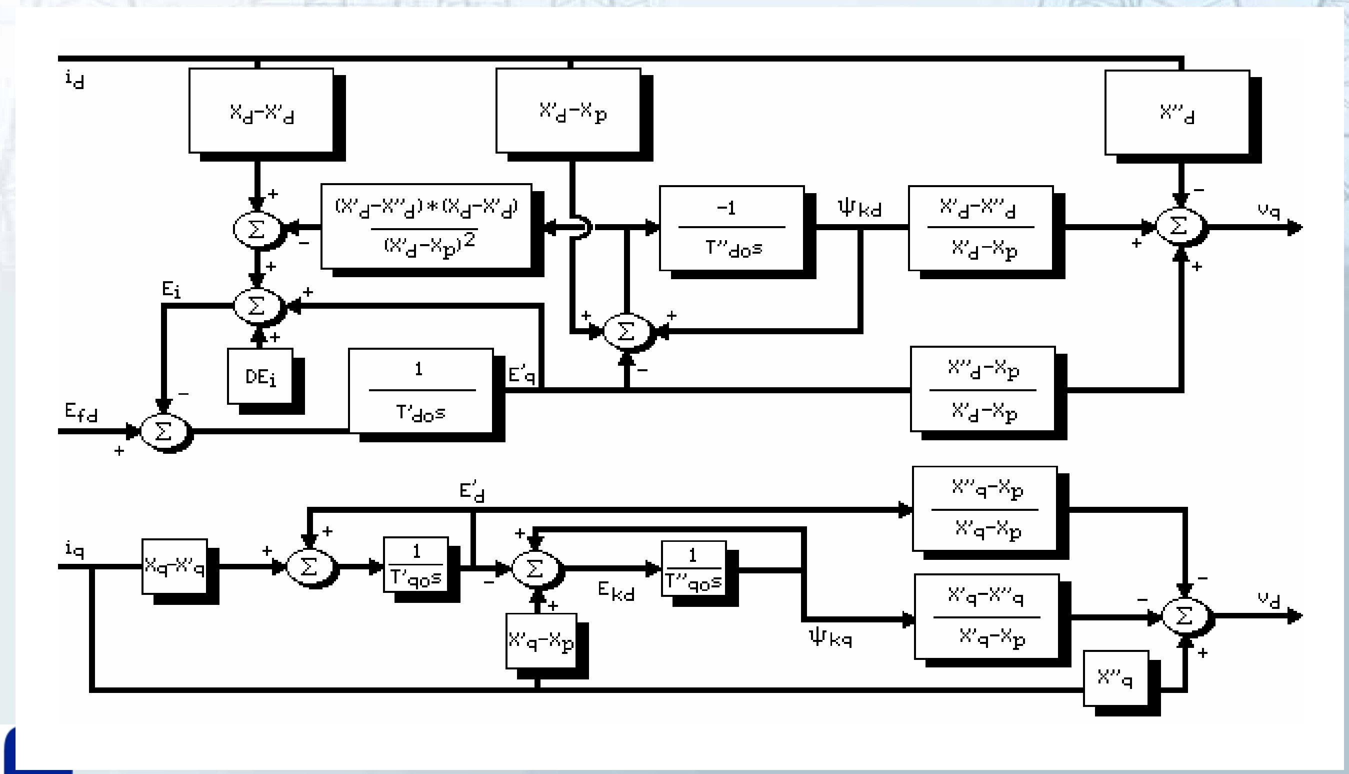
Generator Models

- **Salient pole synchronous generators**
  - Used in hydraulic units. Model accounts for saliency, sub-transient response and saturation effects.



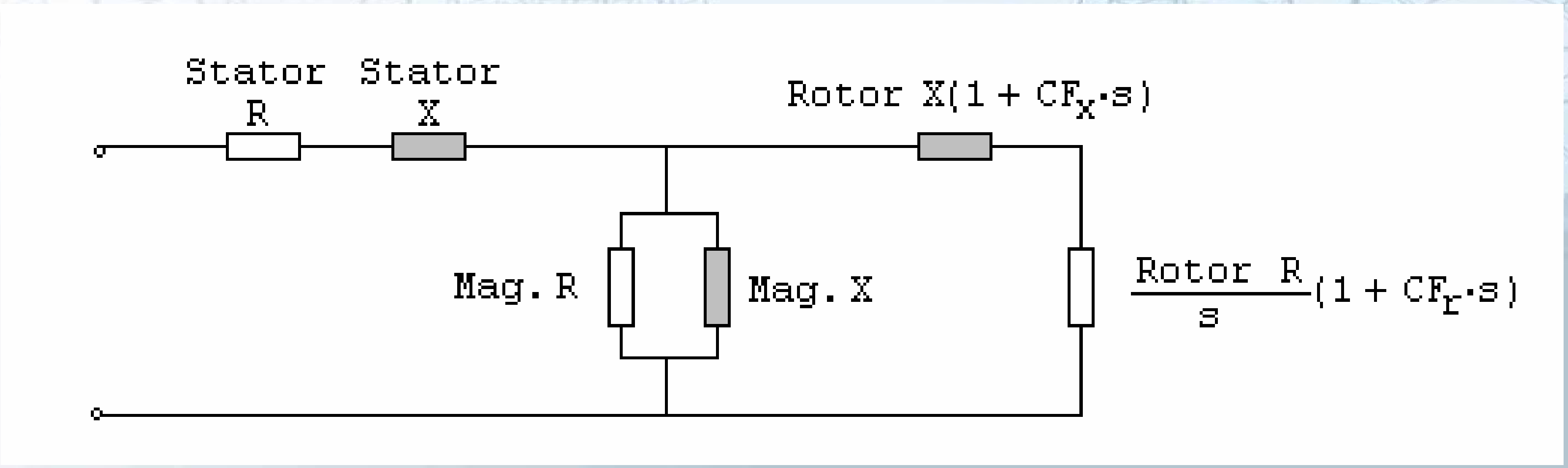
Generator Models (cont.)

- **Round rotor synchronous machines**
  - Used for thermal units. Model accounts for sub-transient and saturation effects.



Generator Models (cont'd)

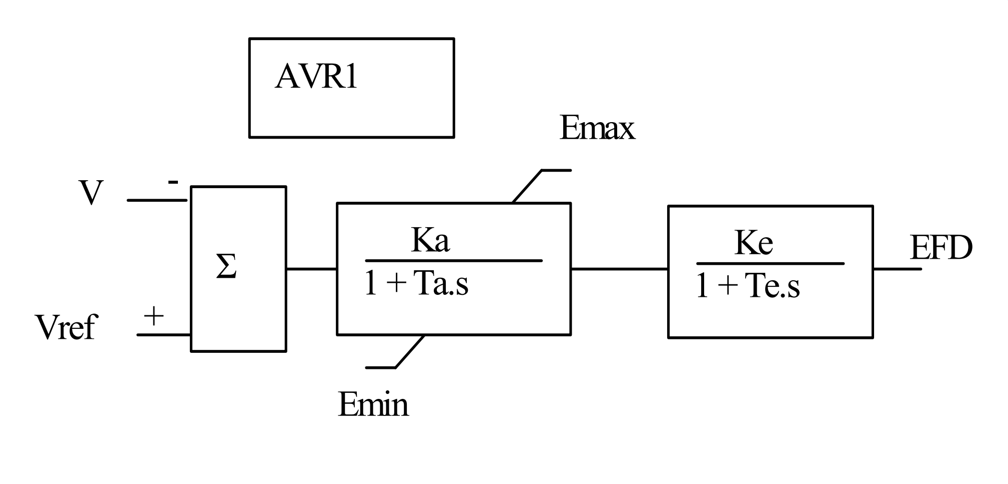
- **Induction generator model**
  - Modeled using equivalent electrical circuit



Induction Generator Equivalent Circuit

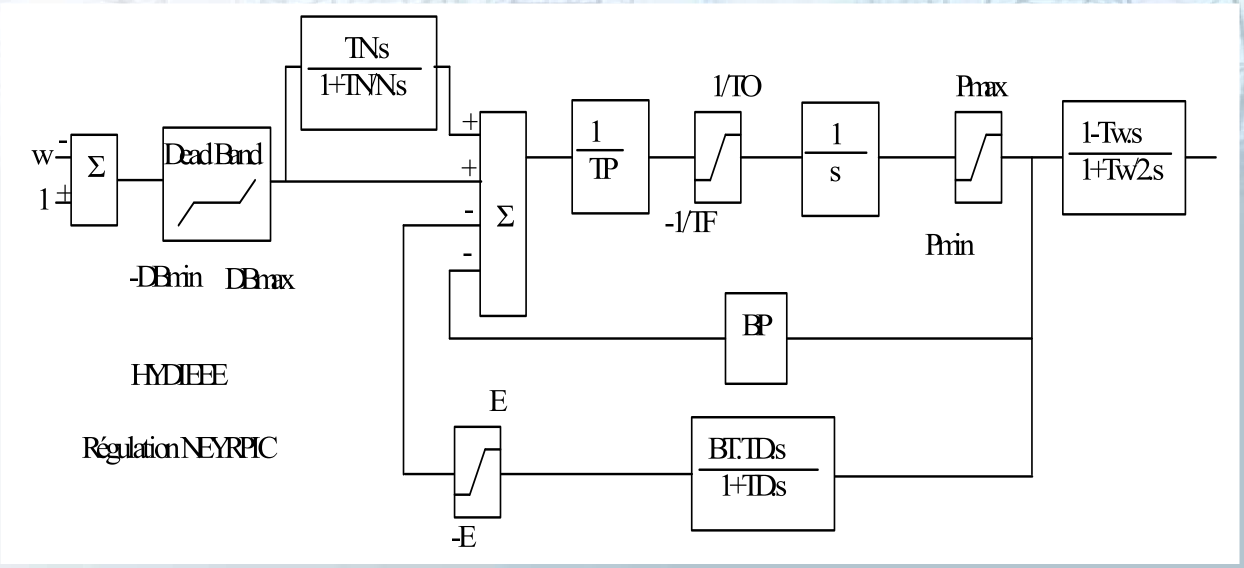
Excitation System Model

- **Excitation and automatic voltage regulator model**
  - Used for salient pole and round rotor synchronous generators



Prime Mover Models

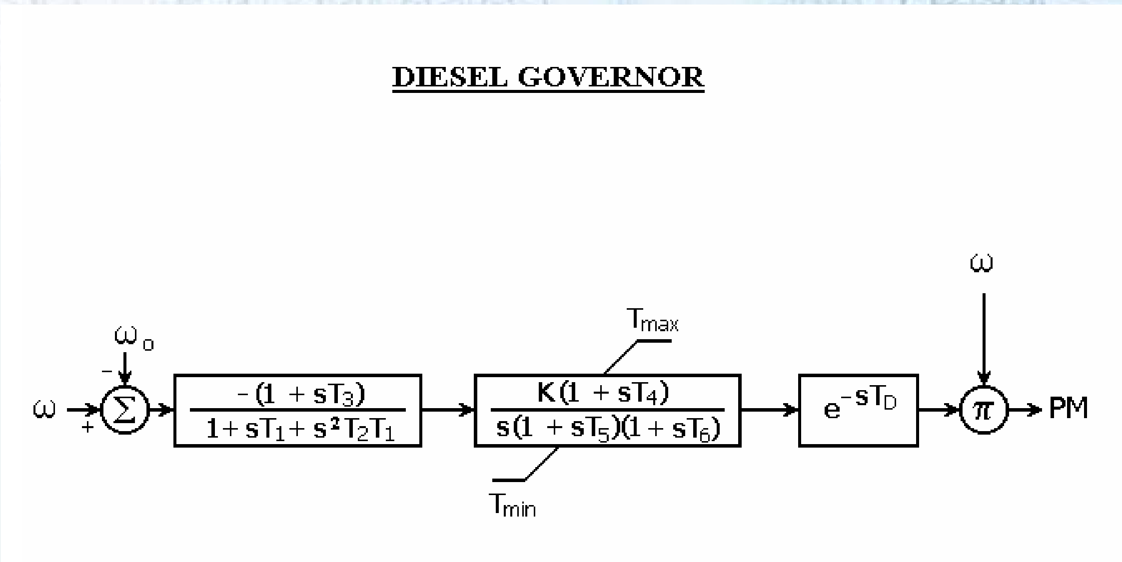
- **Hydraulic units**
  - Hydraulic turbine model reproduces water column dynamics and gate control
  - Governor model includes permanent and transient droops



Hydraulic Governor and Turbine Model

Prime Mover Models (cont.)

- **Diesel units**
  - Diesel unit governor - fast response - no permanent droop.
  - Adjusts unit speed to its set point (60Hz) irrespective of load.

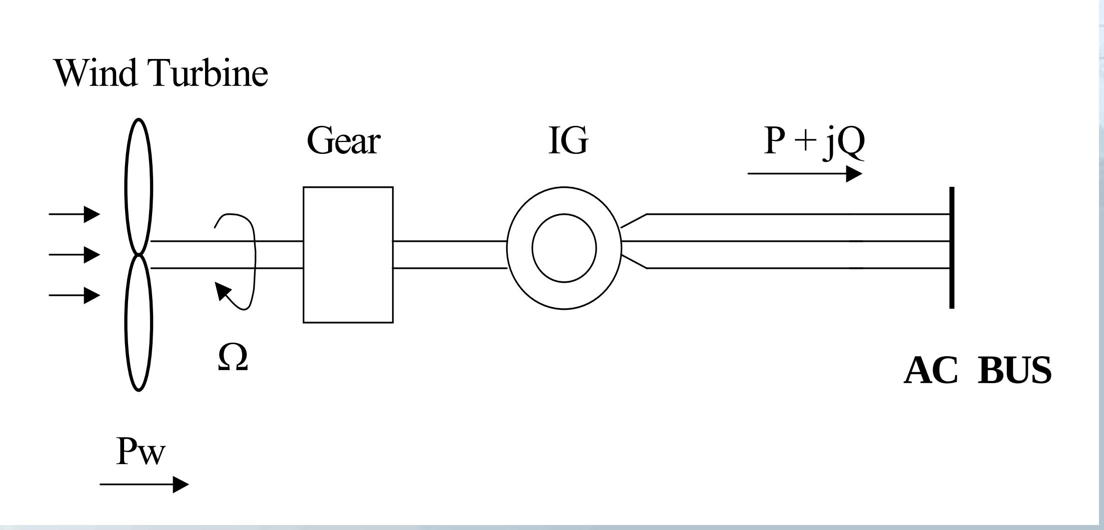


Governor/Turbine Model of a Diesel Engine

Prime Mover Models (cont.)

Wind turbine model

- Directly coupled induction generators driven by wind turbine.



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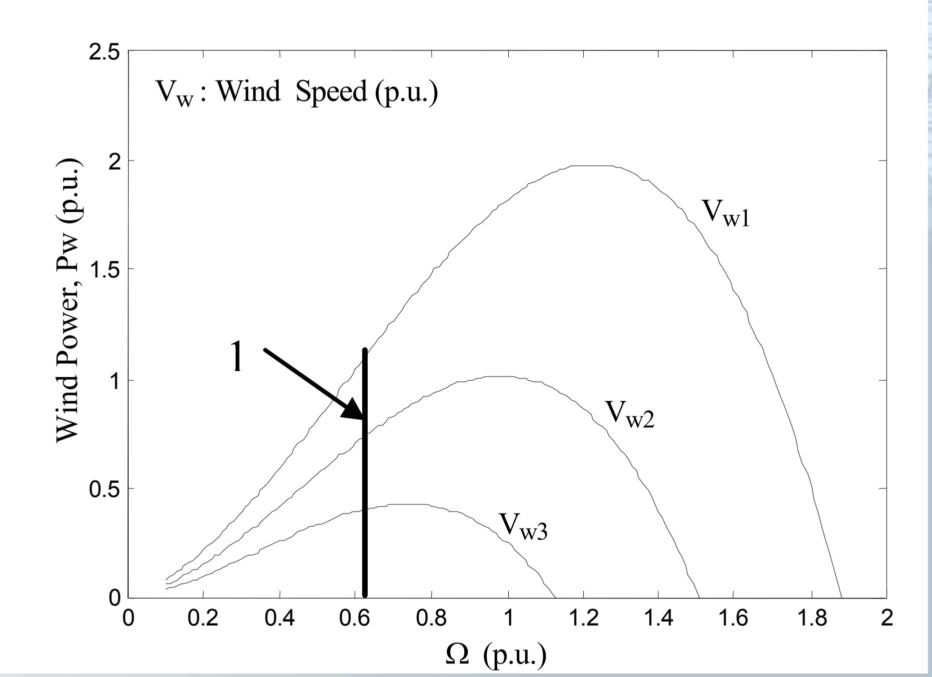
Prime Mover Models (cont.)

- **Wind turbine model**
  - Operates at roughly constant speed.
  - Input wind power is determined entirely by wind speed.



IEEE Anti Islanding Standards

Current IEEE Standards do not allow island operation of distribution systems

- **Voltage limits and clearing times**
  - When voltage is in specified range, DR disconnects within the clearing times indicated.

Voltage Range (% of base voltage[a])	Clearing Time[b] (s)
V< 50	0.16
50 ≤V<88	2
110<V<120	1
V ≥ 120	0.16

Notes.

(a) Base voltages are the nominal system voltages.

(b) DR ≤ 30kW, Maximum Clearing Times; DR > 30kW, Default Clearing Times

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IEEE Anti Islanding Standards (cont.)

- **Frequency limits and clearing times**
  - When frequency is in specified range, DR shall disconnect within the clearing times as indicated.

<table>
<tr><th>DR SIZE</th><th>Frequency Range (Hz)</th><th>Clearing Time[a] (s)</th></tr>
<tr><td>≤30 kW</td><td>> 60.5</td><td>0.16</td></tr>
<tr><td colspan="2"><59.3</td><td>0.16</td></tr>
<tr><td>>30 kW</td><td>>60.5</td><td>0.16</td></tr>
<tr><td colspan="2">< {59.8 - 57.0} (adjustable set-point)</td><td>Adjustable 0.16 to 300</td></tr>
<tr><td colspan="2"><57.0</td><td>0.16</td></tr>
<tr><td colspan="3">Note. (a) DR ≤ 30 kW, Maximum Clearing Times; DR > 30 kW, Default Clearing Times</td></tr>
</table>

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Phase II - Study Cases

- System response to:

  1. Major disturbances - load or generation rejection – short circuits
  2. Detection of island formation
  3. System operation in island mode

- Study cases are repeated for different DG types, mixes and penetration levels.

Response to Major Disturbances – Case 1

- Response to disturbances not resulting in system separation - load or generation rejection – Sever SCs
- Investigated system conditions:

A. Distribution system with hydraulic generation
- A.1 Self-sufficient distribution system
- A.2 Over generating distribution system

B. Distribution system with wind generation
- B.1 Self-sufficient distribution system
- B.2 Over generating distribution system

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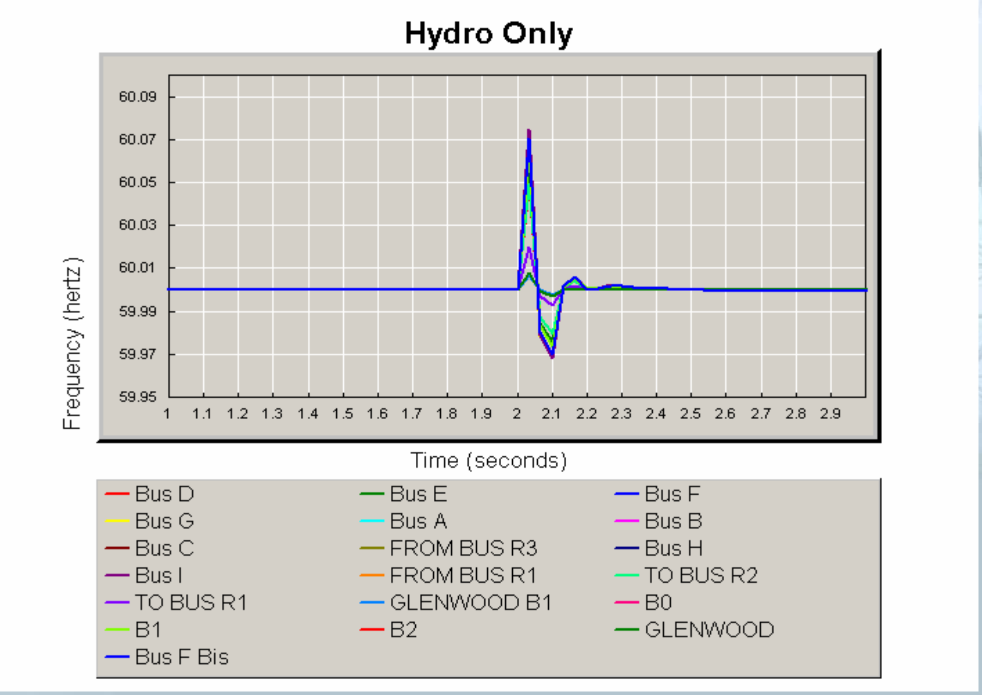
A. Distribution System with Hydraulic Units

A.1.1 - Loss of load condition

Frequency Response to Load Loss
Balanced Load/Generation
Hydro Units



- Frequency returns to its nominal value (60Hz)
- Maximum frequency excursion (60.07 Hz) within IEEE limits

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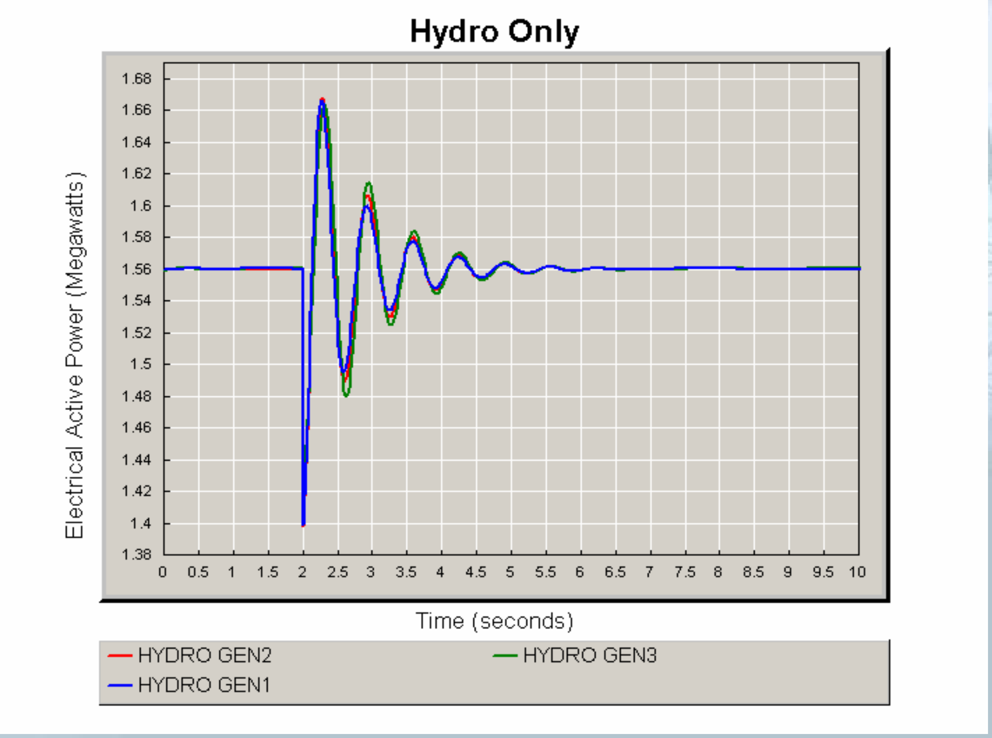
A. Distribution System with Hydraulic Units (cont.)

A.1.1 - Loss of load condition

Unit Load Response to Load Loss

Balanced Load/Generation

Hydro Units



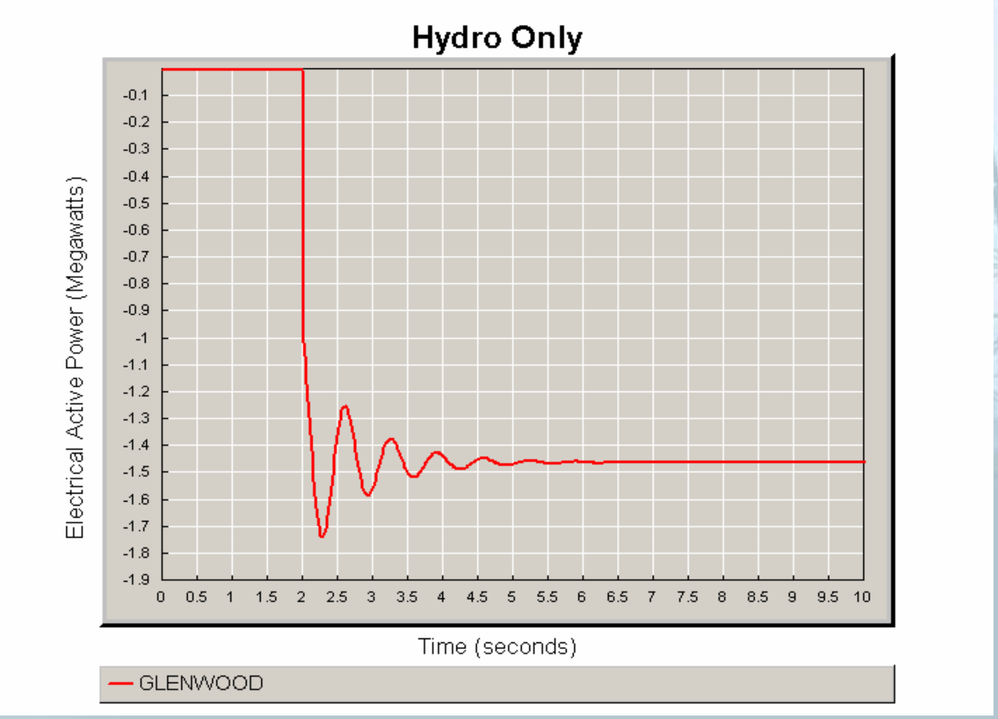
- **Generator loads return to their original values**

A.1.1 - Loss of load condition

Transmission System Response to Load Loss

Balanced Load/Generation

Hydro Units



- **Feeding system absorbs the excess power**

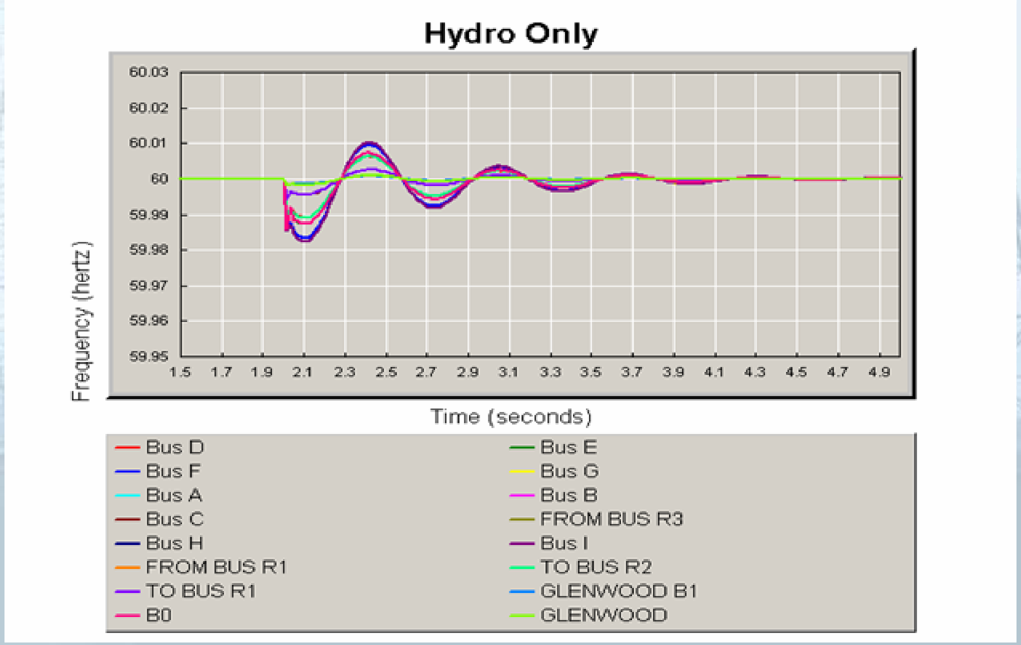
A. Distribution System with Hydraulic Units (cont.)

A.1.2 - Loss of generation condition

Frequency Response to Generation Loss

Balanced Load/Generation

Hydro Units

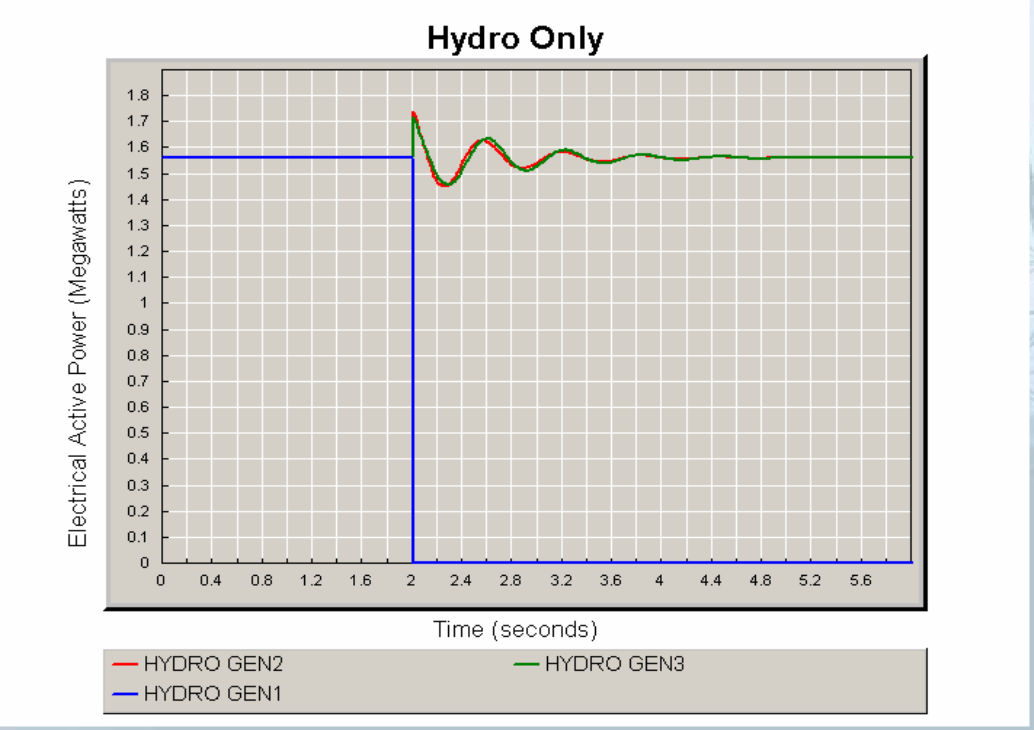


- **Frequency returns to its nominal value (60Hz)**
- **Maximum frequency excursion (59.98 Hz) within IEEE limits**

A. Distribution System with Hydraulic Units (cont.)

A.1.2 - Loss of generation condition

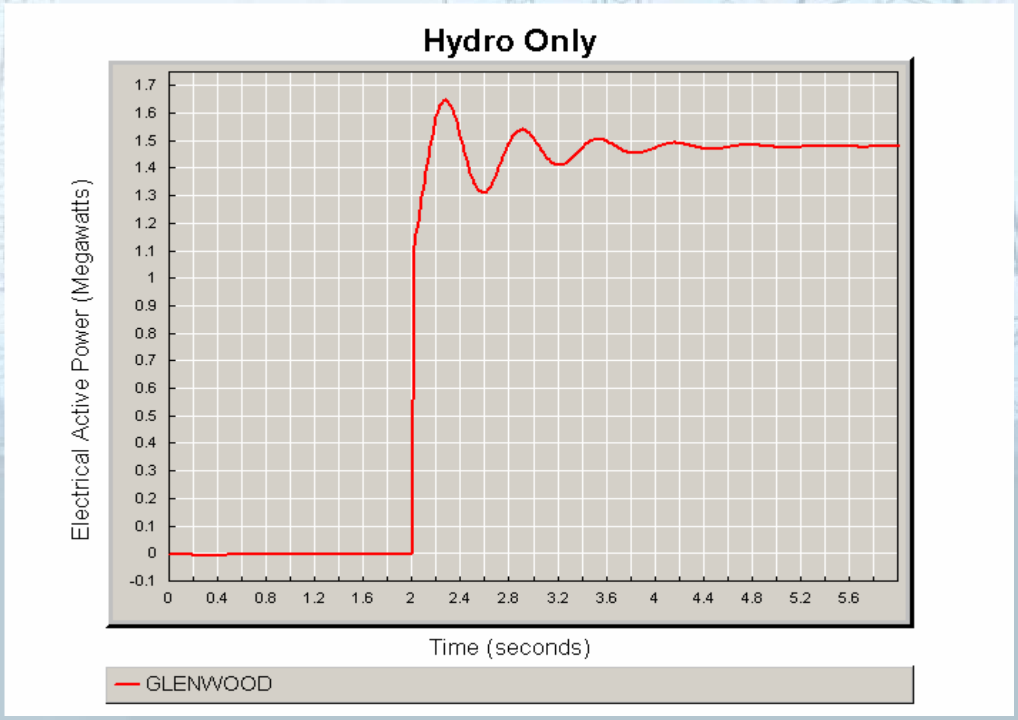
Unit Load Response to Generation Loss
Balanced Load/Generation
Hydro Units



- **Generator loads return to their original values**

A.1.2 - Loss of generation condition

Transmission System Response to Generation Loss
Balanced Load/Generation
Hydro Units



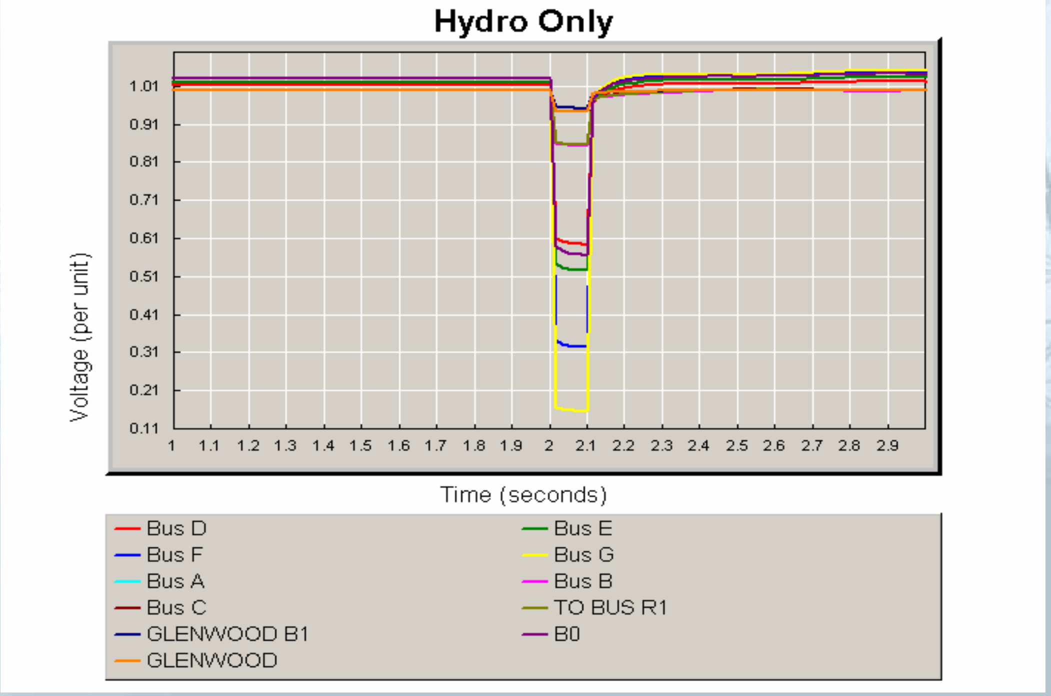
- **Feeding system supplies the deficit power**

A.1.3 - Short circuit conditions

Voltage Response to three Phase S.C. at Bus H

Balanced Load/Generation

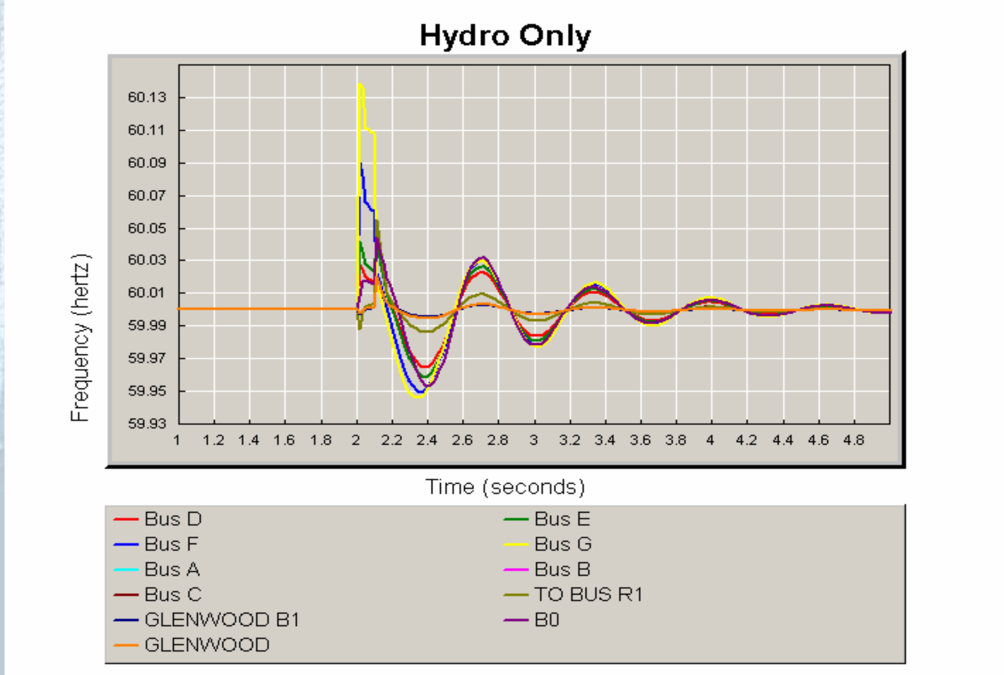
Hydro Units



- **The voltage dips vary with distance from fault**
- **The voltages at buses B0, F, and G drop to 0.56 pu, 0.32 pu, and 0.15 pu**

A.1.3 - Short circuit conditions

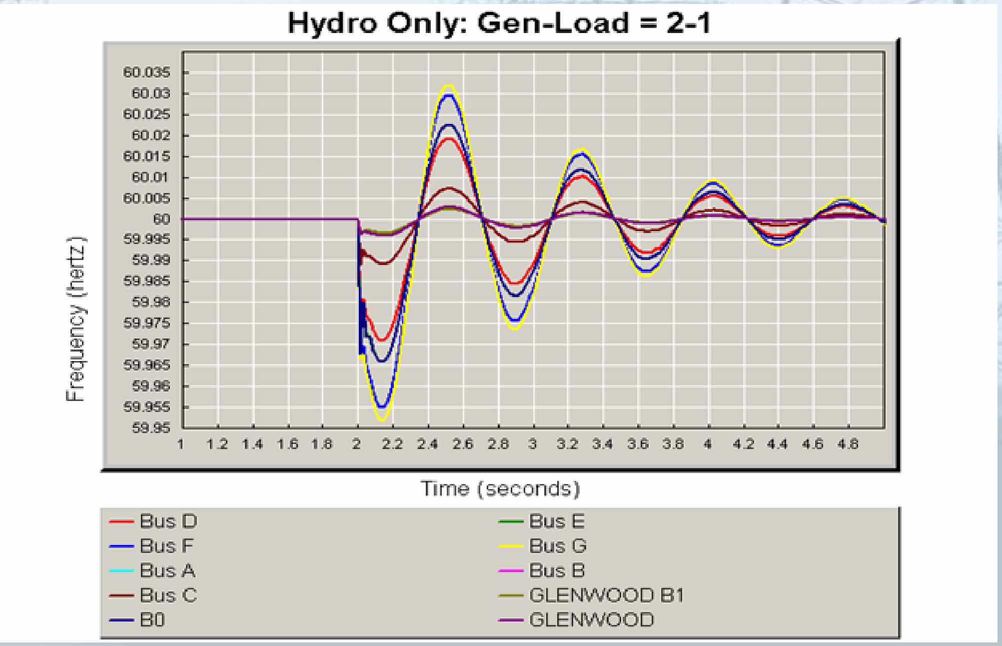
Frequency Response to three-Phase S.C. at Bus H
Balanced Load/Generation
Hydro Units



- **Frequency returns to its nominal value (60Hz)**
- **Maximum frequency excursion (60.14 Hz) within IEEE limits**

A.2.1 - Loss of generation condition

Frequency Response to Generation Loss
Generation/Load Ratio 2/1
Hydro Units

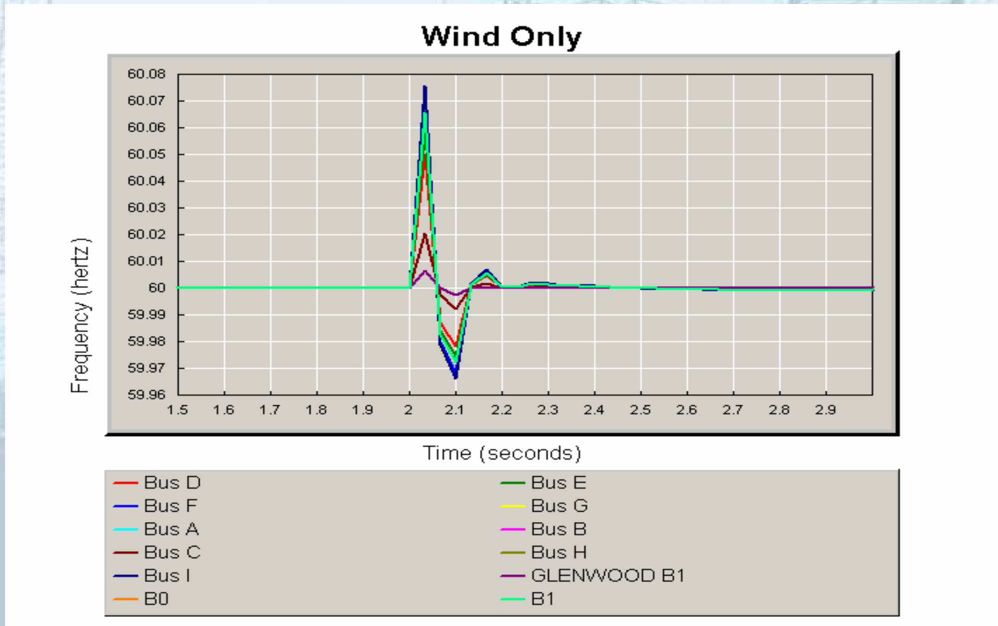


- **Frequency returns to its nominal value (60Hz)**
- Maximum Frequency excursion (59.95 Hz) within IEEE limits.

B. Distribution System with Wind Units

B.1.1 - Loss of load condition

Frequency Response to Load Loss
Balanced Load/Generation
Wind Units

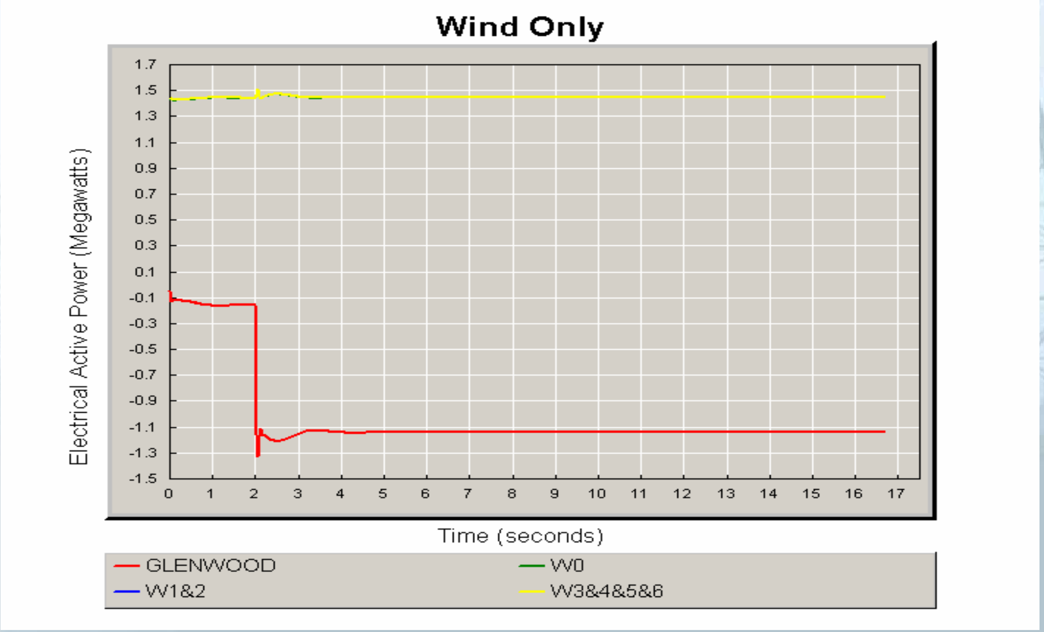


- **Frequency returns to its nominal value (60Hz)**
- **Maximum frequency excursion (60.08 Hz) within IEEE limits**

B.1.1 - Loss of load condition

Generation Response to Load Loss

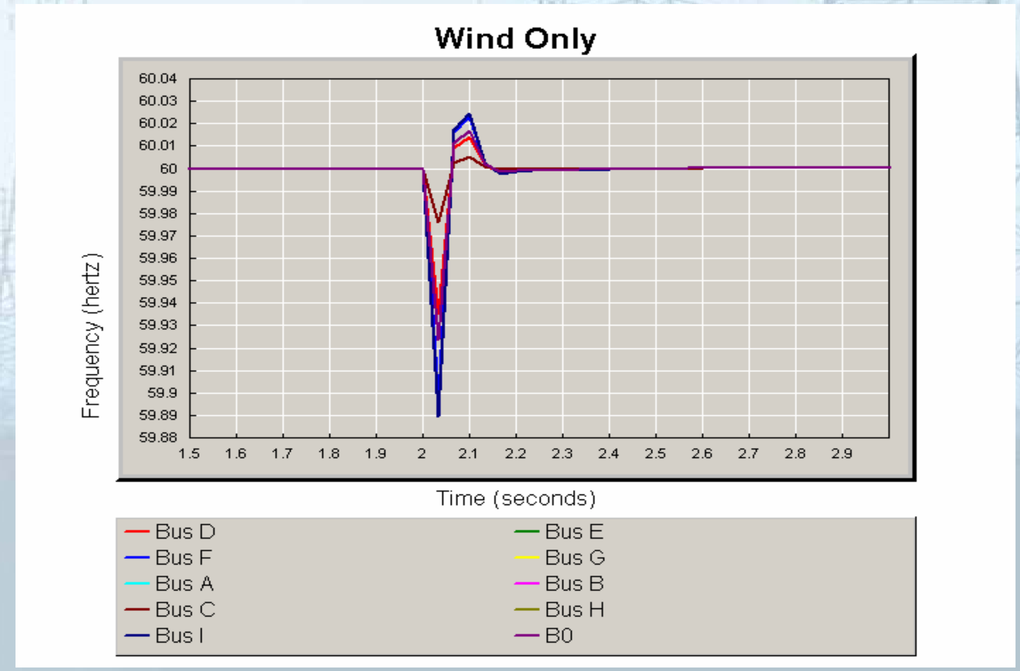
Balanced Load/Generation
Wind Units



- **Wind generation remains constant**
- **Main system absorbs the excess power**

B.1.2 - Loss of generation condition

Frequency Response to Generation Loss
Balanced Load/Generation
Wind Units

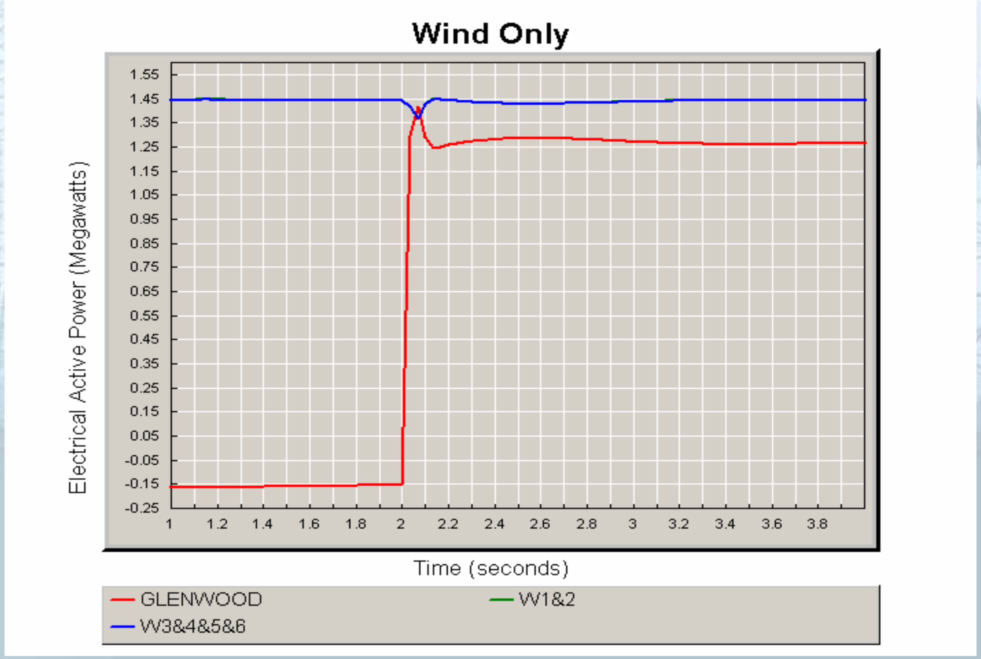


- **Frequency returns to its nominal value (60Hz)**
- **Maximum frequency excursion (59.89 Hz) within IEEE limits**

B. Distribution System with Wind Units (cont.)

B.1.2 - Loss of generation condition

Generation Response to Generation Loss
Balanced Load/Generation
Wind Units



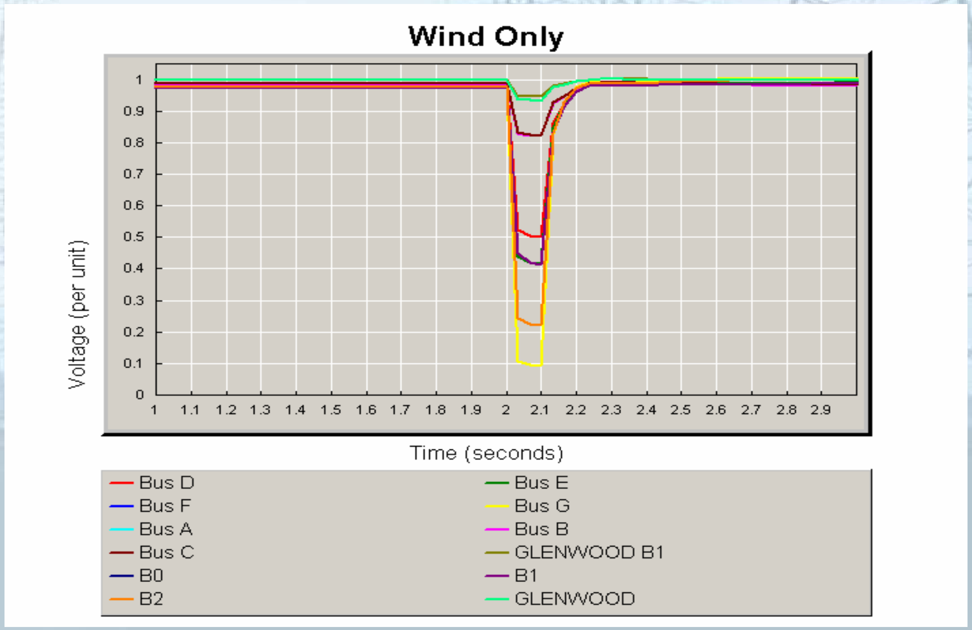
- **Wind generation remains constant**
- **Main system supplies the power deficit**

B.1.3 – Short-circuit condition

Voltage Response to three-phase S.C. at Bus H

Balanced Load/Generation

Wind Generation Units



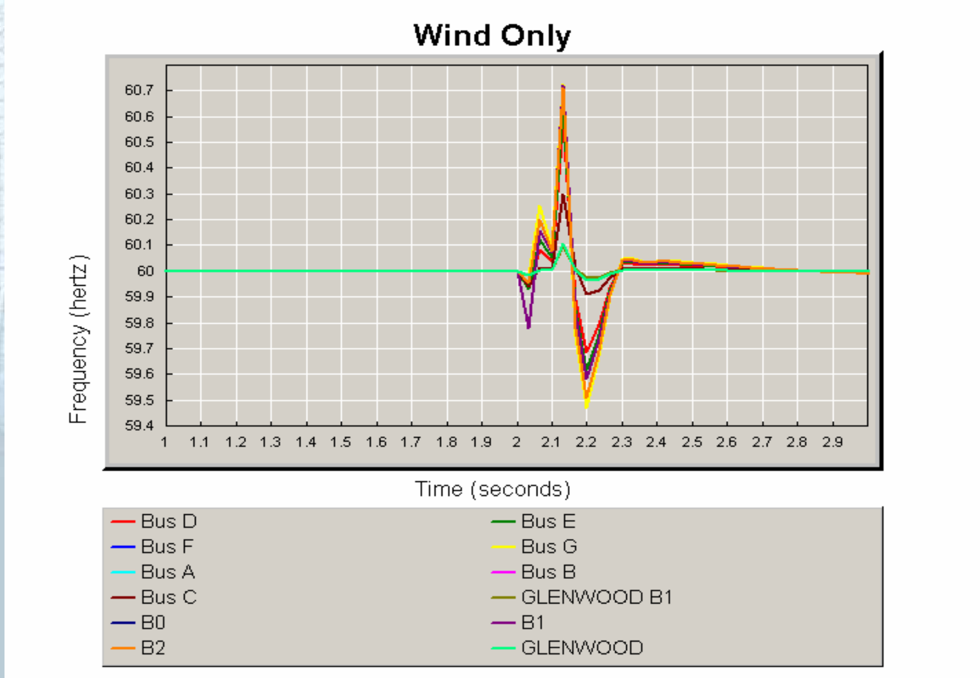
- **The voltage dip vary with distance from fault**
- **The voltages at buses B0, F, and G drop to 0.42 pu, 0.42 pu, and 0.1 pu**

B.1.3 – Short-circuit condition

Frequency Response to three-phase S.C. at Bus H

Balanced Load/Generation

Wind Generation Units



- **Frequency returns to its nominal value (60Hz)**
- **Maximum Frequency excursion (60.7 Hz) exceeding IEEE limits**

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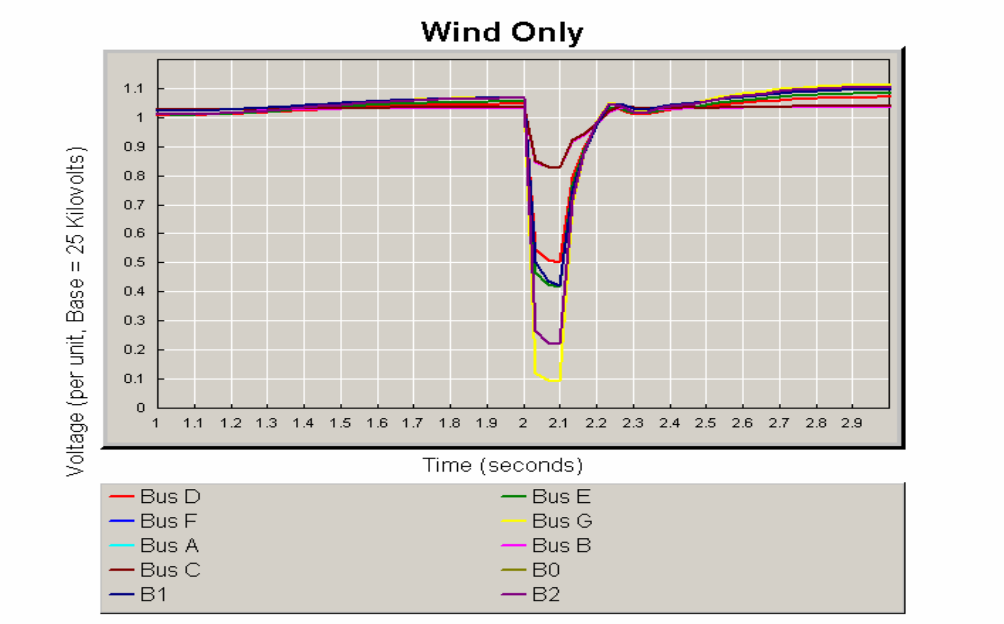
B. Distribution System with Wind Units (cont.)

B.2.1 – Short-circuit condition

Voltage Response to three-phase S.C. at Bus H

Generation to load ratio

2/1 Wind Generation Units



- **The voltage dip varies with distance from fault**
- **The voltages at buses B0, F, and G drop to 0.42 pu, 0.42 pu, and 0.1 pu**

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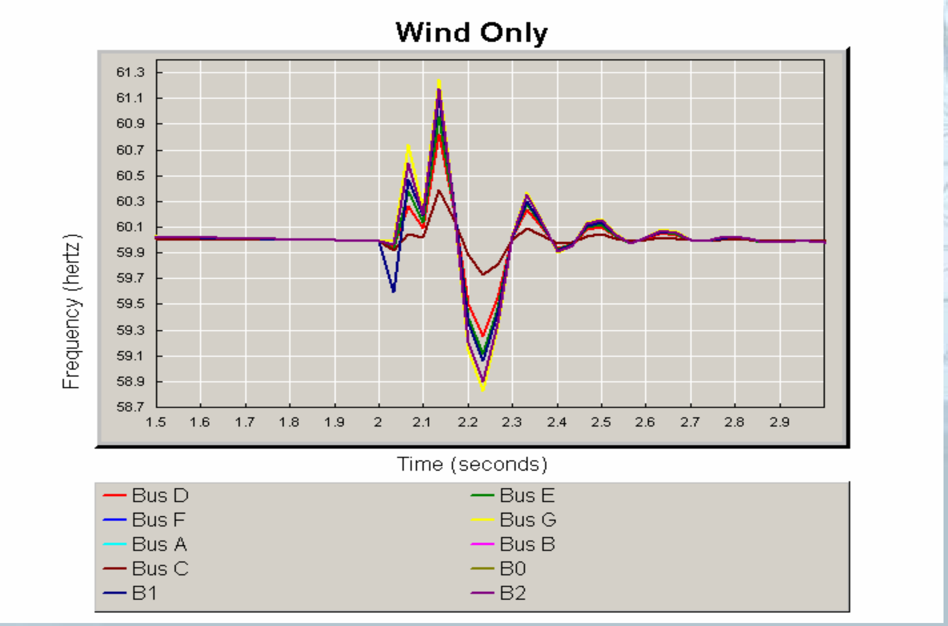
B. Distribution System with Wind Units (cont.)

B.2.1 – Short-circuit condition

Frequency Response to Three-phase S.C. at Bus H

Generation to load ratio ½



- **Frequency returns to its nominal value (60Hz)**
- **Maximum frequency excursions (61.2 and 58.9 Hz) exceed the IEEE limits**

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Detection of Island Formation

- **Distribution system response after separation**
- **DG types, operating conditions and penetration levels:**

A. Distribution System with Hydraulic Units:

A.1 Self-Sufficient Condition

A.2 Under-Generating Condition

B. Distribution System with Diesel Units:

B.1 Under-Generating Condition

C. Distribution System with Wind Units:

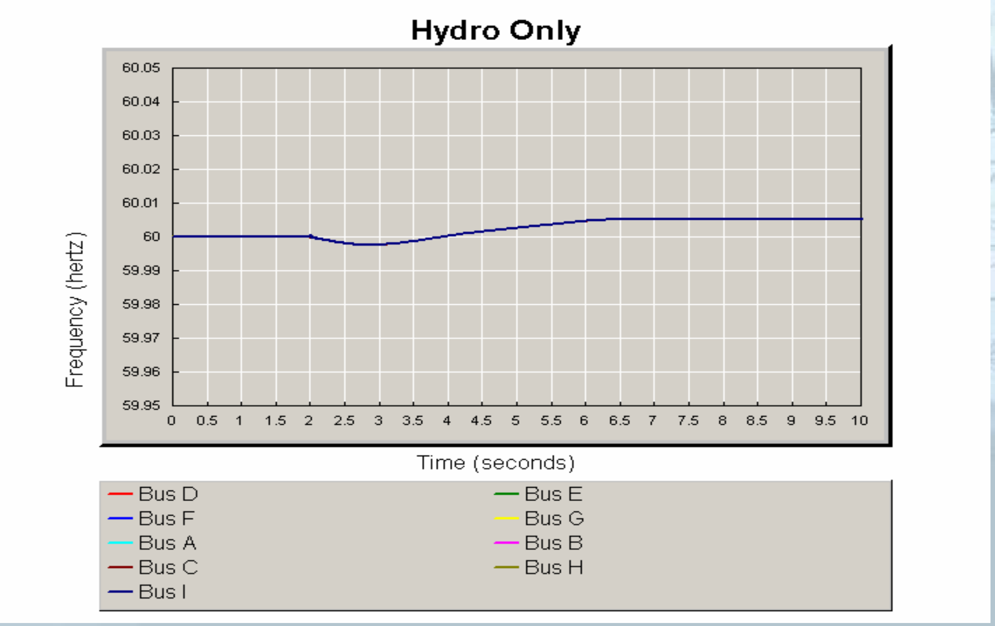
C.1 Under-Compensated Condition

C.2 Over-Compensated Condition

A. Distribution System with Hydraulic Units

A.1 Self-sufficient condition

Frequency Response to Islanding
Self-Sufficient Condition
Hydro Units Only



- **Frequency variation is insignificant**
- **Island formation cannot be detected based on the frequency value**

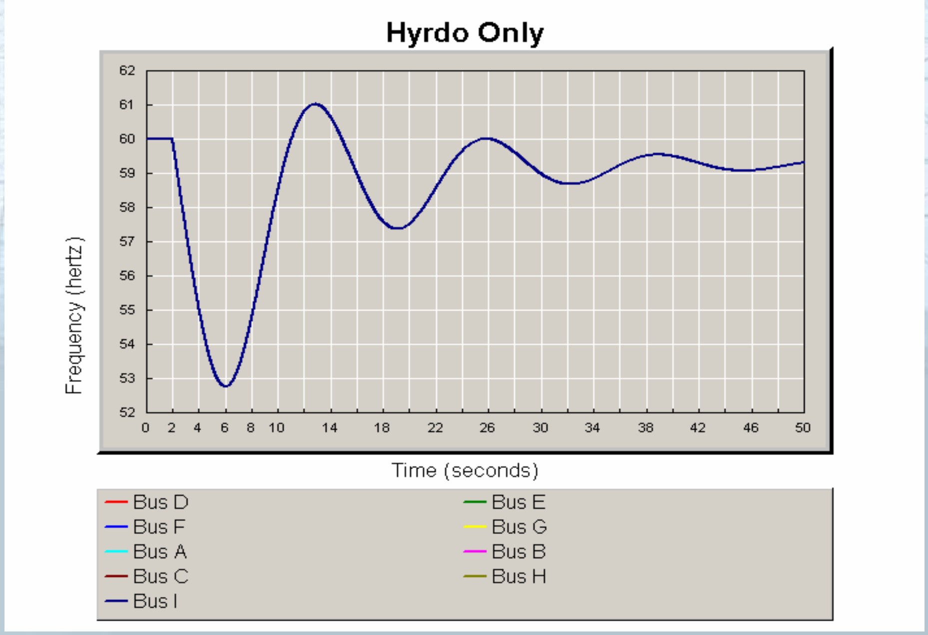
A. Distribution System with Hydraulic Units (cont.)

A.2 Under-generating condition

Two generators each producing 1.56 MW

Frequency Response to Islanding

Generation/Load Ratio 2/3



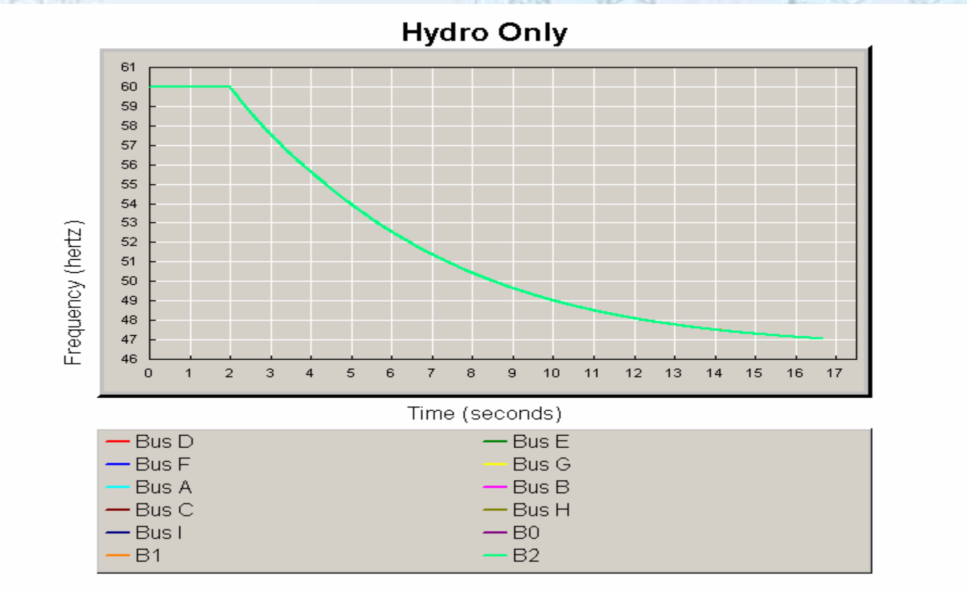
- **Large variation in the frequency of 55.6 Hz, Island can be detected**

A. Distribution System with Hydraulic Units (cont.)

A.2 Under-generating condition with disabled governor

Frequency Response to Islanding - No Governor

Generation/Load Ratio 2/3

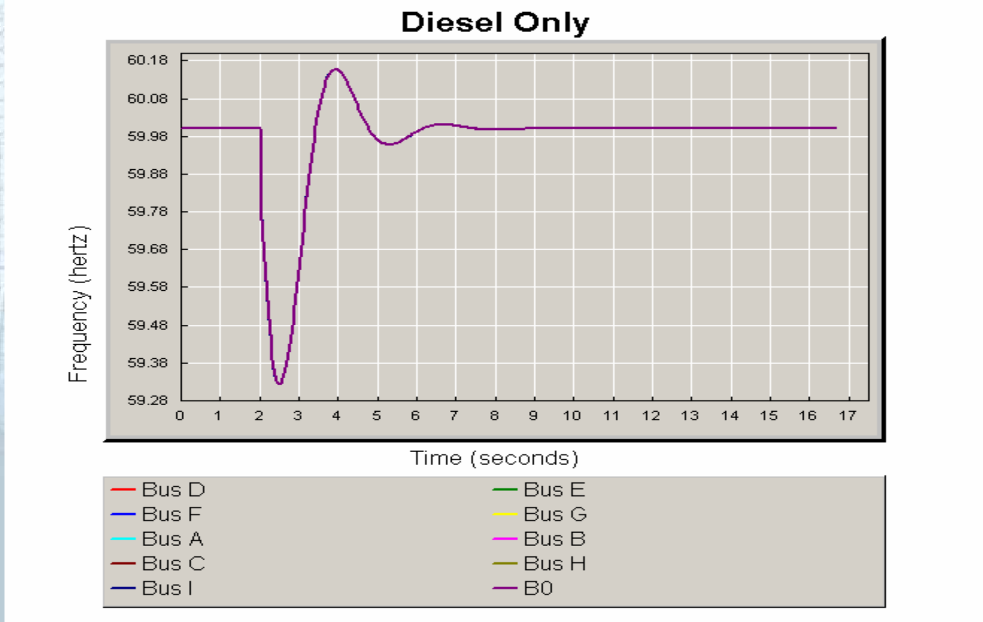


- **Frequency decreases monotonically**
- **The frequency deviation exceeds the IEEE limits**

B. Distribution System with Diesel Units

B.1 Under-generating condition

Frequency Response to Islanding
Generation/Load Ratio ½
Diesel Units Only



- **Small variation in the frequency (59.32 Hz) Island cannot be detected.**
- **Frequency returns to nominal value of 60 Hz**

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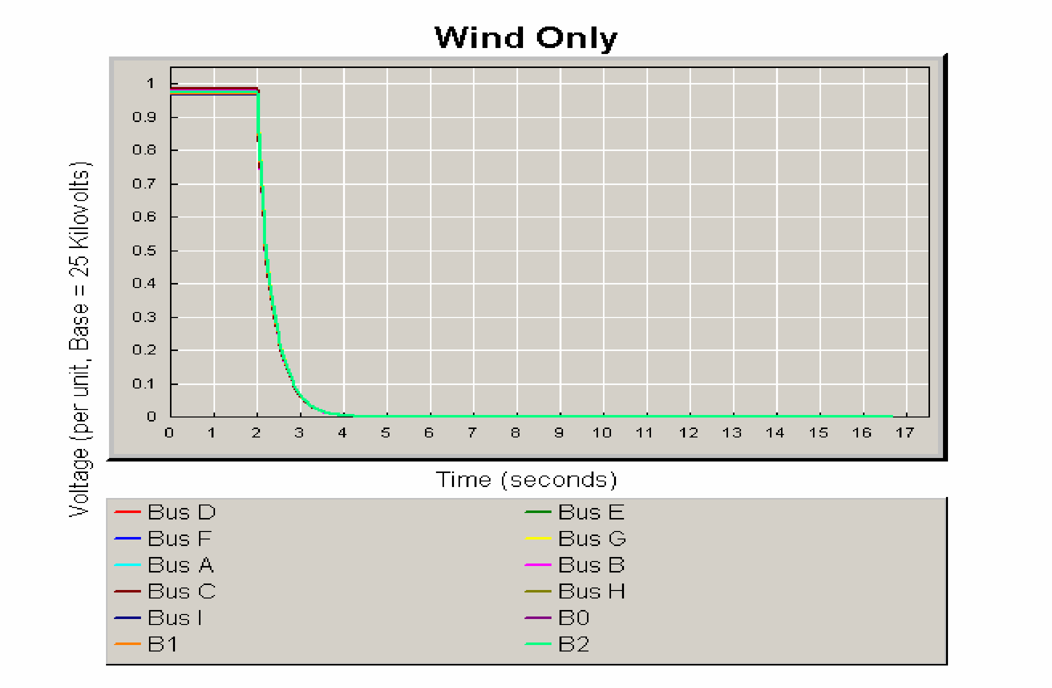
C. Distribution System with Wind Generating Units

C.1 Under-compensated condition

Voltage Response to Islanding
Balanced Condition
Wind Units Only



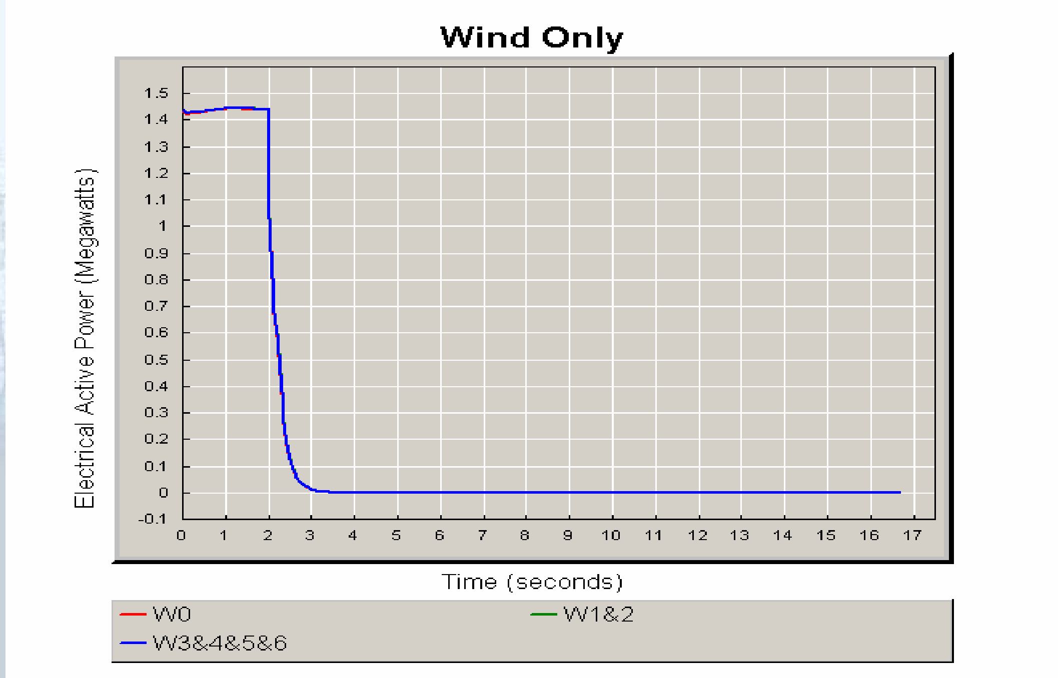
- **Voltages decrease monotonically to zero**
- **The voltage exceeds IEEE limits for island formation**

C. Distribution System with Wind Units (cont.)

C.1 Under-compensated condition

Real-Power Unit Response to Islanding

Balanced Condition

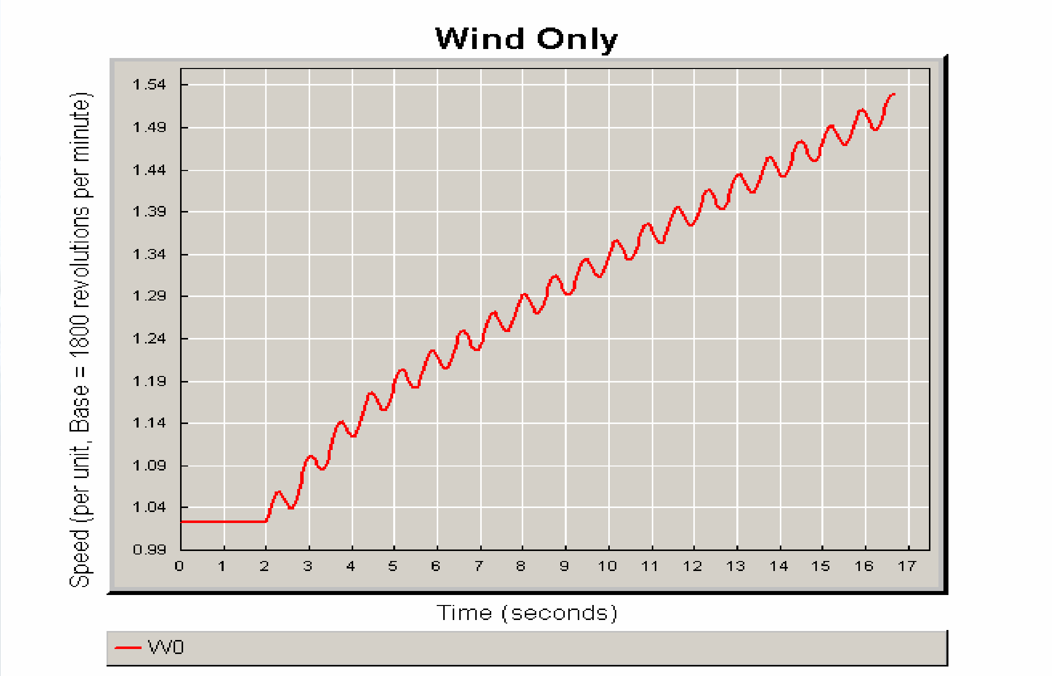


- **System voltage drops to zero and generator outputs also drop to zero**

C. Distribution System with Wind Units (cont.)

C.1 Under-compensated condition

Frequency Response to Islanding
Balanced Condition



- **Constant wind, mechanical power remains constant**
- **System frequency (speed) increases monotonically**

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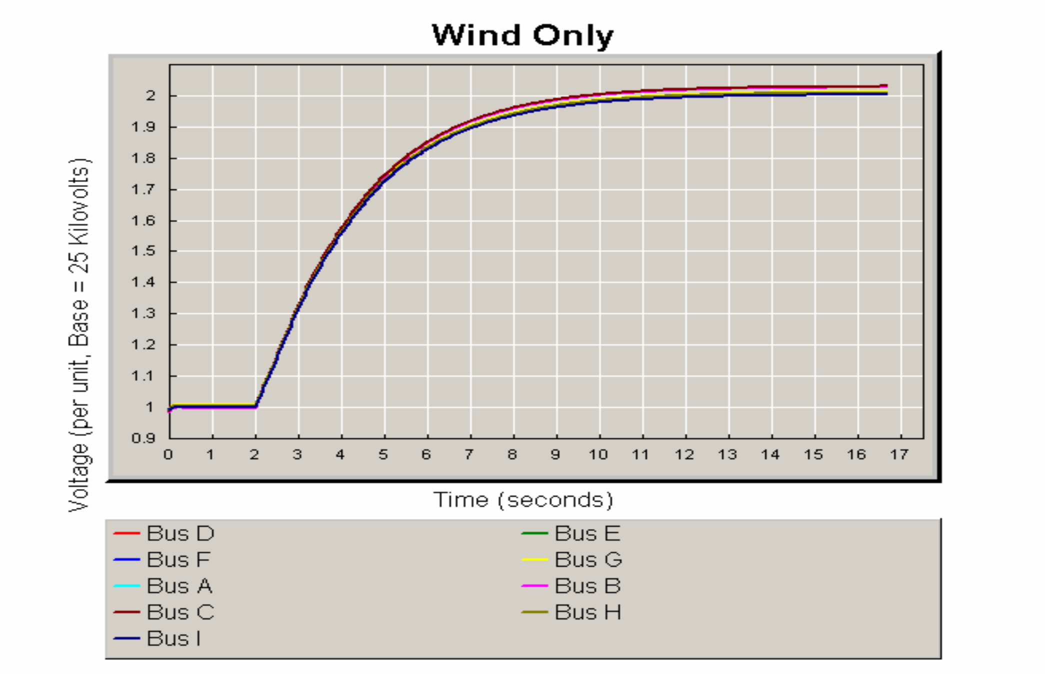
C.2 Over-compensated condition

Voltage Response to Islanding

Over-Compensated Condition – 0.43 MVAR



- **Bus voltages increase monotonically**
- **Voltages exceed the limits for island detection**

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System Operation in Island Mode – Case 3

- **Feasibility of Island Mode Operation:**

  A. Distribution System with Hydraulic Units:

  A.1 Over-Generating Condition with Under-Damped Governor

  A.2 Over-Generating Condition with Generation/Load 10 MW/4.6 MW

  A.3 Under-Generating Condition with Generation/Load 1.5 MW/4.6 MW

System Operation in Island Mode – Case 3 (cont.)

B. Distribution System with Diesel Units:

- B.1 Over-Generating Condition with Generation/Load 10 MW/ 4.6 MW
- B.2 Under-Generating Condition with Generation/Load 1.5 MW/4.6 MW

C. Distribution System with Hydro and Wind Units

D. Distribution System with Diesel and Wind Units

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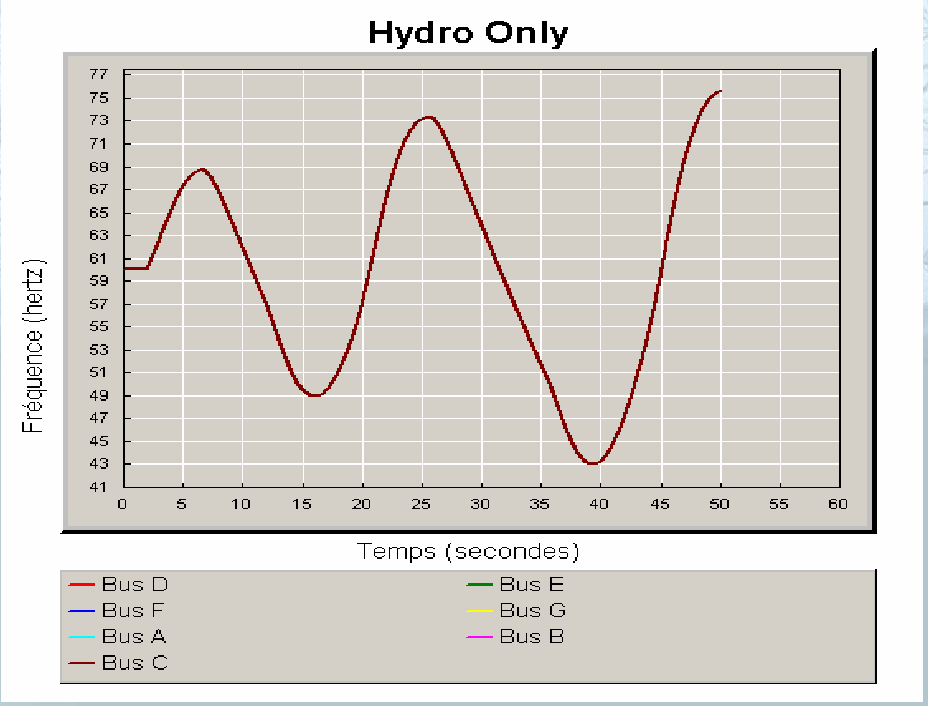
A. Distribution System with Hydraulic Units

A.1 Over-generating condition with under-damped governor

Frequency Response to Islanding
Generation/Load Ratio 2/1

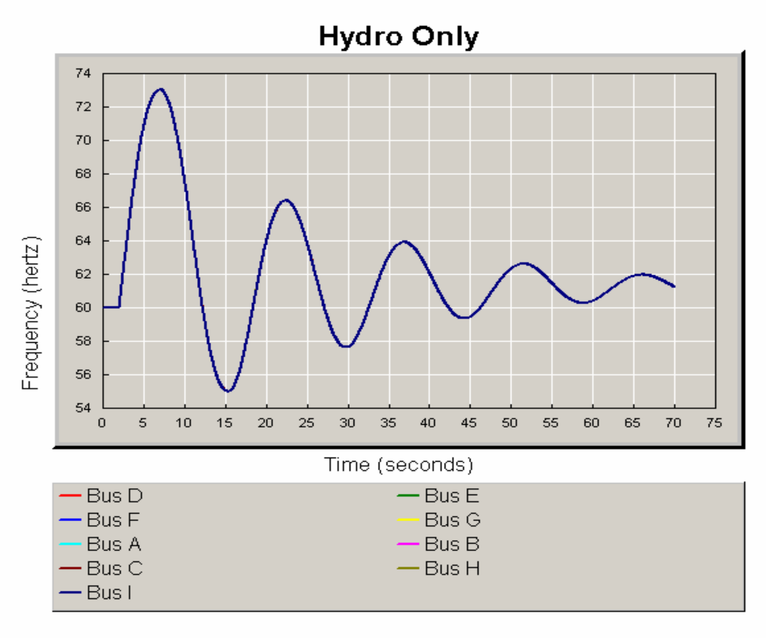


- **Unstable island**

A. Distribution System with Hydraulic Units (cont.)

A.2 Over-generating condition with generation/load 10 MW/4.6 MW

Frequency Response to Islanding
Generation/Load 10 MW/4.6 MW

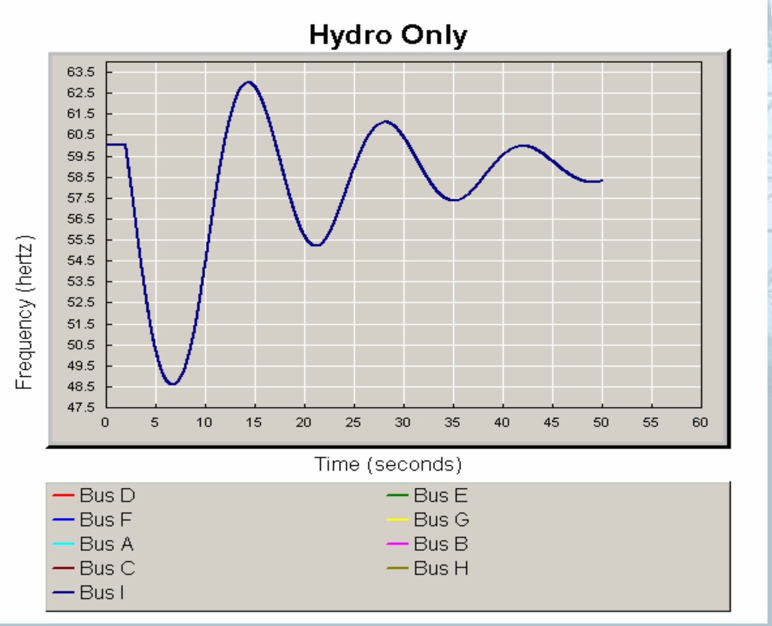


- **The frequency excursion reaches 73 Hz**
- **The generators trip on over-speed protection of the turbine set at 72 Hz**

A. Distribution System with Hydraulic Units (cont.)

A.3 Under-generating condition with generation / load 1.5 MW / 4.6 MW

Frequency Response to Islanding
Generation/Load 1.5 MW/4.6 MW



- **The frequency excursion reaches 48.5 Hz**
- **Frequency is very close to the under-speed protection set at 48 Hz**

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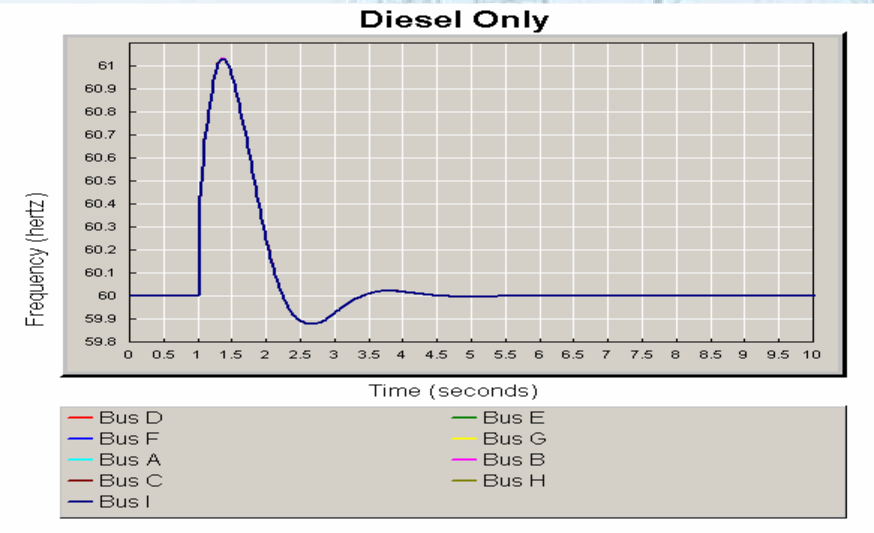
B. Distribution System with Diesel Units

B.1 Over-generating condition with generation / load 10 MW / 4.6 MW

Frequency Response to Islanding

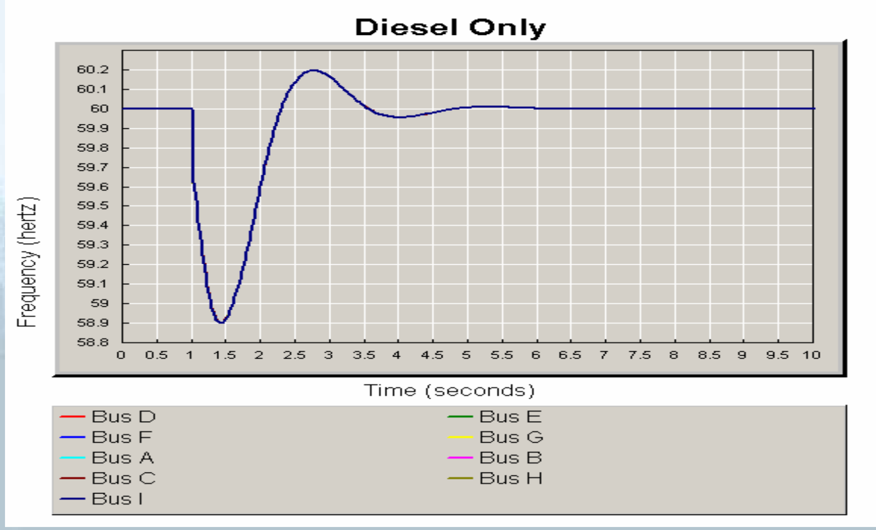
Generation/Load
10 MW/4.6 MW



- **Maximum frequency 61.04 Hz**
- **Not large enough to trigger over-speed protection**
- **System frequency returns to 60 Hz**

B.2 Under-Generating Condition with Generation/Load 1.5 MW/4.6 MW

Frequency Response to Islanding
Generation/Load 1.5 MW/4.6 MW



- **Maximum frequency 58.9 Hz**
- **Not large enough to trigger over-speed protection**
- **System frequency returns to 60 Hz**

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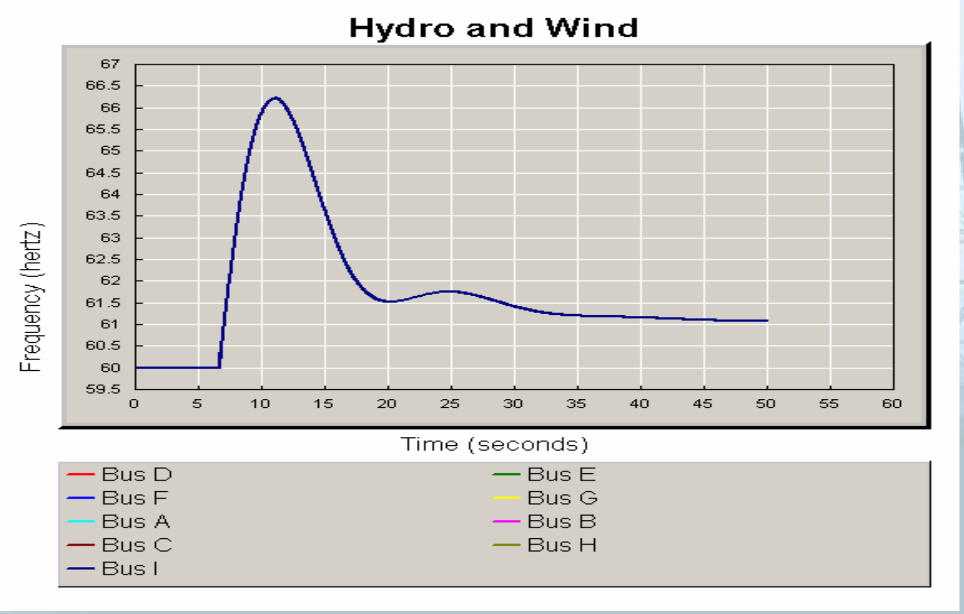
C. Distribution System with Hydro and Wind Units

C. Over-Generating Condition with Generation / Load 5.9 MW / 4.6 MW

Frequency Response to Islanding

Hydro Units 3 MW, Wind Units 2.9 MW



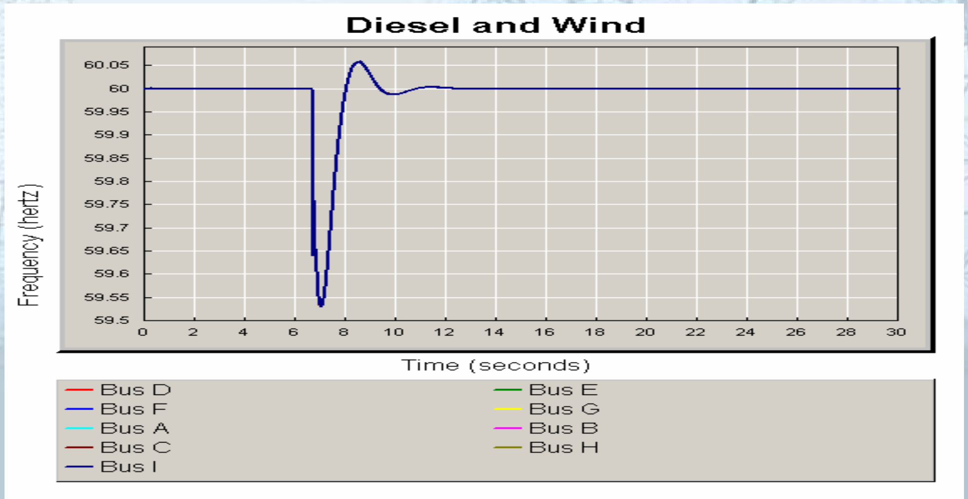
- **Maximum 66.3 Hz**
- **Not high enough to trigger protection**
- **Steady-state frequency 61 Hz**

D. Distribution System with Diesel and Wind Units

D. Under-Generating Condition with Generation / Load 3.9 MW / 4.6 MW

Frequency Response To Islanding

Diesel Units 1 MW, Wind Units 2.9 MW



- **Maximum frequency variation 59.53 Hz**
- **Not low enough to trigger protection**
- **The system frequency returns to 60 Hz**

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Conclusions

- Implementing distributed generation changes the way distribution systems are planned and operated

- Enhanced analytical tools capable of meeting the emerging requirements need to evolve

- CYME – NRCan collaboration
  - Tool enhancement
  - Case studies

- Ongoing activities
  - Expanded DG model library
  - More case studies for illustation / education

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