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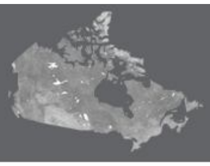

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DISTRIBUTED GENERATION ANALYSIS
CASE STUDY 4:

Dynamic Behaviour of a Distribution System with Interconnected Distributed Generation during a Grid-Connected Mode of Operation

Canada

DISTRIBUTED GENERATION ANALYSIS

Case Study 4:

Dynamic Behaviour of a Distribution System with Interconnected Distributed Generation during a Grid-Connected Mode of Operation

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DISCLAMER

ACKNOWLEDGMENT

Financial support for this research project was provided by Natural Resources Canada through the Program on Energy Research and Development. The first edition of this report was prepared by S. Soumare, F. Gao and A.S. Morched in May 2007 [1]. The second edition was prepared by G. Hernandez-Gonzalez, A. Ozeer and T.H.M. EL-Fouly.

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SUMMARY

This report details the fourth of a series of case studies which have the intent of disseminating knowledge about the impact of Distributed Generation (DG) on distribution systems planning and operation. This case study investigates the dynamic behaviour of a distribution system with interconnected DG and operating in a grid-connected mode. Disturbances such as loss of generation, loss of load and local faults are simulated for different DG technologies. In particular, the variation of frequency and voltage at different nodes in the system are obtained and compared to the permissible limits specified in the IEEE 1547 Standard. The second edition for this series of case studies is meant to update the information in the first edition, add cases involving doubly-fed induction generators (DFIG) and facilitate the study of the integration of DG into distribution systems. The simulations of this report were carried out using latest official release of CYMDIST 5.02 rev04 of the CYME software package. This case study is meant to be accompanied by the corresponding CYMDIST case study files; however, it also serves as a self-contained and informative report.

SOMMAIRE

Ce document est le quatrième d’une série d’études de cas qui ont pour but de diffuser des connaissances sur le sujet de l’impact de l’intégration de la production distribuée (PD) sur l’opération et la planification des réseaux électriques. Cette étude de cas vise à investiguer le comportement dynamique de la PD en mode parallèle avec le réseau. Différentes manœuvres (pertes de génération locales, pertes de charge, et défauts) sont effectuées pour une variété de combinaisons de technologies de PD. Entre autres, la tension et la fréquence sont obtenues et comparées à des limites établies dans la norme 1547 de l’IEEE. La deuxième édition vise à mettre à jour les études de cas de la première édition et à ajouter des études en utilisant les machines éoliennes doublement alimentés-DFIG tout en facilitant l’étude de la production décentralisée et son intégration. La dernière version officielle de CYMDIST 5.02 rev04 de CYME a été utilisée pour les simulations des cas dans le rapport. L’étude a été conçue pour servir de référence utile et informative et est aussi accompagnée des fichiers des études de cas de CYMDIST.

1 Introduction

The benefits of installing distributed generation (DG) in distribution networks have already been established and discussed in previous CYME reports commissioned for Natural Resources Canada (NRCan) [2-7].

As much as there are several positive aspects to the use of distributed generation, there are pitfalls to their application in existing distribution systems. Therefore, if the addition of these sources is not properly planned, deterioration of network reliability through voltage regulation, protection coordination and security problems could result.

The interaction between distributed resources and the distribution system in which they are embedded involves several phenomena that are worth careful investigation. Hence it is necessary to conduct thorough analyses and careful studies of the impact of different DG technologies and their implementation in distribution systems. These analyses should include the steady state behavior as well as the dynamic behaviour of the distribution system in the presence of DG.

With regards to steady state behaviour, the impact of adding DG to a distribution system on the system’s voltage profile, short circuit (SC) levels and protection coordination, has been demonstrated in previous reports [2-7].

The objective of this tutorial is to study the impact of distributed resources of different type, size and level of penetration, on the dynamic behaviour of the distribution system in which they are embedded, during a grid-connected operation.

2 Description of Assignment

In this study, the dynamic behaviour of a distribution system with interconnected DG is investigated using the dynamic modeling features of latest official release of CYMDIST5.02 rev04. The dynamic behaviour of the distribution system is analyzed, in a grid-connected mode, for the following disturbances:

Self sufficient cases:

- Loss of load.
- Loss of generation.
- Short circuit (three-phase to ground fault) at specified locations.

Over-and under-generating cases:

- Short circuit (three-phase to ground fault) at specified locations (which is considered as the worst case scenario)

Such disturbances are applied to the distribution system for the following interconnected DG technologies:

1. Small hydraulic units which drive synchronous generators with automatic voltage regulators.
2. Wind turbines connected to the system through directly coupled induction generators.
3. Wind turbines connected to the system through doubly-fed induction generators (DFIG).

The case studies of this report demonstrate the response of the system to different disturbances and the dependence of the dynamic response on the type, size and level of penetration of the involved DG technologies.

3 Distribution System Description

The distribution system selected for this tutorial is an actual 25 kV multi-grounded distribution circuit with several single-phase laterals feeding multiple loads.

The circuit is reduced to a representative equivalent circuit maintaining the main generation and load feeding points to help better analyze the impact of DG sources on the circuit. The equivalent circuit is shown in Figure 1.

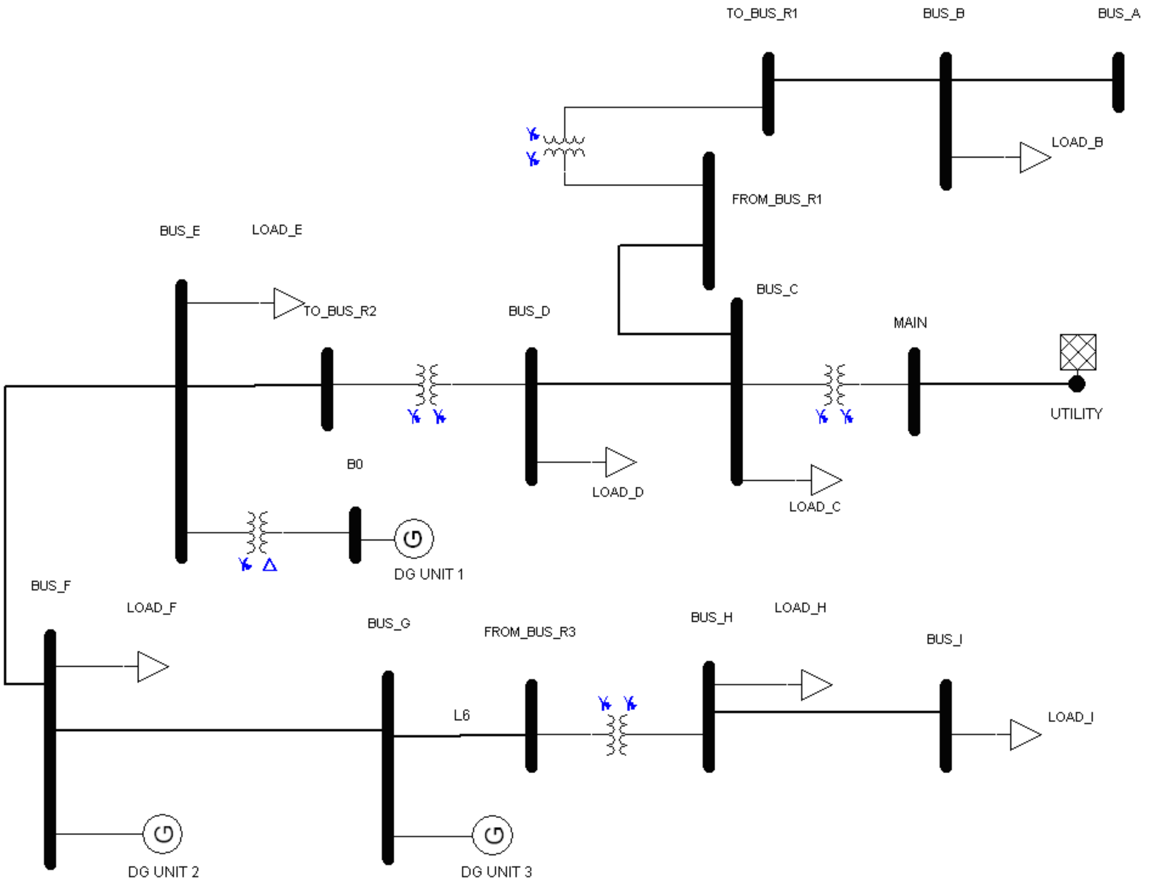


Figure 1: Investigated Distribution System

The distribution system is connected to the utility system at substation bus bar MAIN. Distributed generation units, of type and size dependent on the specific case study, are connected to bus bars B0, F and G. Spot loads are connected to bus bars B, C, D, E, F, H and I. The total load at nominal voltage is 4.622 MW + j1.308 MVAR, as given in Table 1. The largest spot load is located at bus bar D.

Table 1: System Loads at rated voltage and frequency

	MW	MVAR
Load B	0.533	0.128
Load C	0.478	0.157
Load D	1.500	0.510
Load E	0.559	0.145
Load F	0.689	0.184
Load H	0.313	0.058
Load I	0.550	0.125
Total	4.622	1.308

A number of voltage regulators are implemented in the distribution system of Figure 1. However, these voltage regulators are disabled during dynamic simulation of the system to avoid undesired interference on the investigated phenomena.

4 Dynamic models of the network components

For dynamic analysis purposes, the following models for the different system components are used throughout the simulated case studies.

4.1 Load Model

System loads are composed of static and dynamic parts with proportions that depend on the nature of the load, i.e. whether it is residential, commercial or industrial. The load composition can be expressed as a function of both system voltage and frequency, according to the following equations:

$$P = P_o \times (V_{pu})^{nP} \times [1 + Pfreq\,(F_{pu} - 1)]$$

$$Q = Q_o \times (V_{pu})^{nQ} \times [1 + Qfreq\,(F_{pu} - 1)]$$

where $\mathbf{P_o}$ and $\mathbf{Q_o}$ are the nominal active and reactive power of the load, and $\mathbf{V_{pu}}$ and $\mathbf{F_{pu}}$ are the per-unit voltage and frequency at the bus.

The dependence of the load on the system voltage is defined by parameters **nP** and **nQ** for active and reactive power, respectively, whereas its dependence on the frequency is defined by parameters ***Pfreq*** and ***Qfreq***.

Typical parameters for most common loads are

$nP = 1$, $nQ = 2$, $Pfreq = 1.5$ and $Qfreq = -1.5$.

These values are used to represent the dependence of the load on the voltage and the frequency for all the simulated case studies of this report.

4.2 Hydraulic DG units

The complete dynamic model of a hydraulic DG unit consists of

1. the synchronous generator model,
2. the excitation system model, and
3. the prime mover model.

Each of the three components of the hydraulic unit model is described in the following subsections.

4.2.1 *Salient Pole Synchronous Generator Model*

A generator model capable of modeling salient pole generators used in hydraulic units and accounting for saliency, sub-transient response and saturation effects is shown in Figure 2. This model is used throughout the study whenever hydraulic units are simulated.

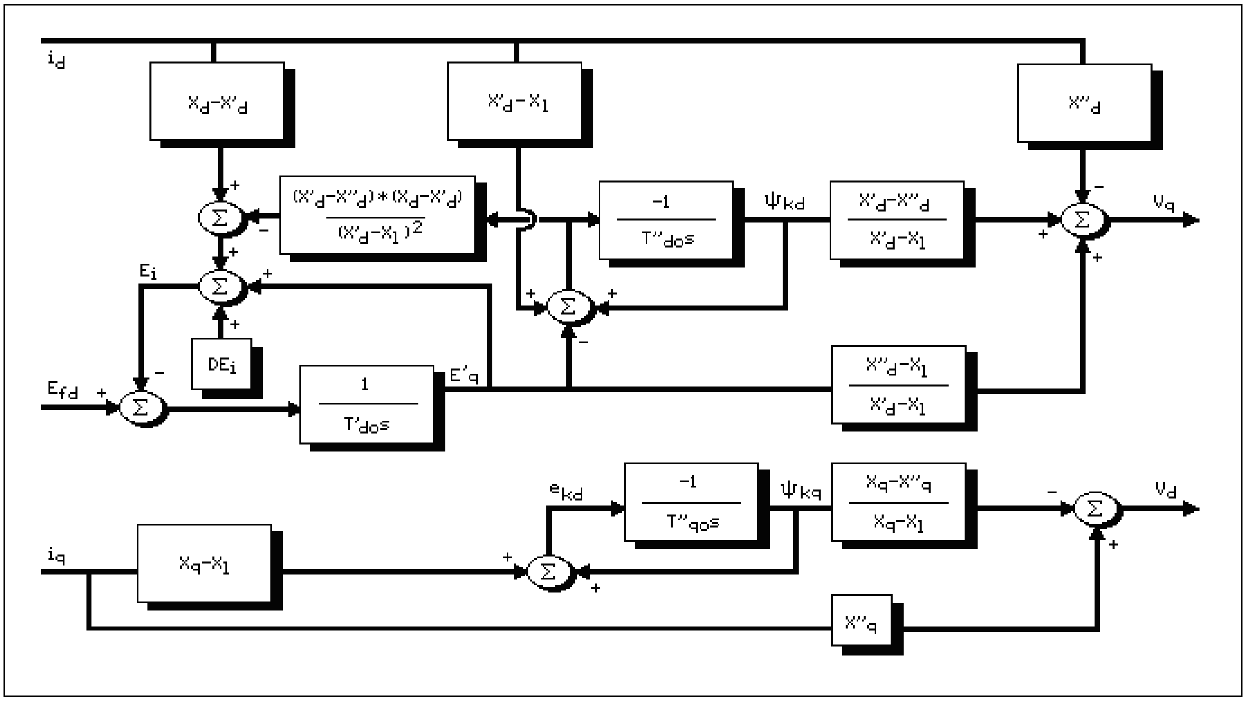


Figure 2: Salient Pole Synchronous Generator Model

The parameters of the dynamic model for the hydraulic DG units in this report are

- Synchronous Reactances:
  $X_d = 1.236$ p.u., $X_q = 0.75$ p.u., $X_l = 0.155$ p.u.

- Transient Data:
  $X'_d = 0.345$ p.u., $X'_q = 0.70$ p.u., $T'_{do} = 4.17$ sec., $T'_{qo} = 1.20$ sec.

- Subtransient Data:
  $X''_d = 0.264$ p.u., $X''_q = 0.211$ p.u., $T''_{do} = 0.03$ sec., $T''_{qo} = 0.19$ sec.

- Mechanical Data:
  H = 3.12 MW.s/MVA.

4.2.2 Excitation system model

Excitation and automatic voltage regulation systems (AVR) used for salient pole synchronous generators are modeled using the block diagram of Figure 3.

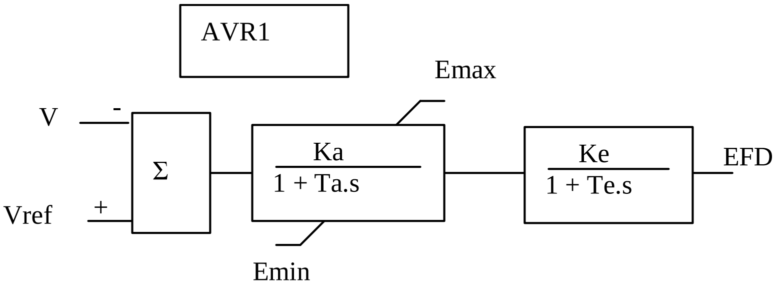


Figure 3: Excitation and Automatic Voltage Regulation Model

The parameters for the excitation AVR system model are

Ka = 10 p.u., Ta = 0.03 sec., Ke = 1 p.u., Te = 0.5 sec., Emax = 3.5 and Emin = 0.

4.2.3 Prime Mover Model

The hydraulic turbine model used in this case study reproduces water column dynamics and gate control system using a governor with permanent droop for speed control and transient droop to provide damping during transient conditions. The governor turbine model utilized for the hydraulic DG units in this report is shown in Figure 4.

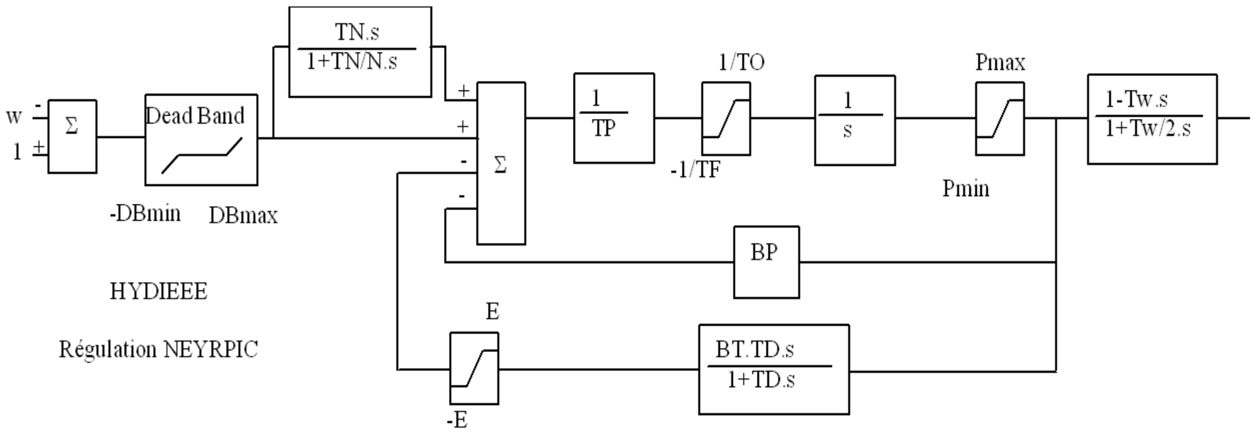


Figure 4: Hydraulic Governor and Turbine Model

The parameters of the governor/turbine model used throughout the study are given below:

BP = 0.0500 p.u., BT = 0.2500 p.u., DBmax = 0.0000, DBmin = 0.0000,
E = 1.000, N = 5.0000, Pmax = 1.000, Pmin = 0.0000,
TD = 7.0000 sec., TF = 7.3000 sec., TN = 0.3000 sec., TO = 10.0000 sec.,
TP = 0.6000 sec., Tw = 1.5000 sec., TTACHY = 0.0300 sec., Freq0 = 60 Hz, and
TBMW = 3.00 MW or 4.00 MW, depending on the case study.

4.3 Wind Energy Conversion System (wind DG units)

In this report, the selected Wind Energy Conversion System (WECS) topology consists of a directly coupled induction generator and a doubly fed induction generator driven by a wind turbine.

4.3.1 *Wind Energy Conversion System - Directly Coupled Induction Generator*

The directly coupled induction generator driven by a wind turbine is shown in Figure 5.

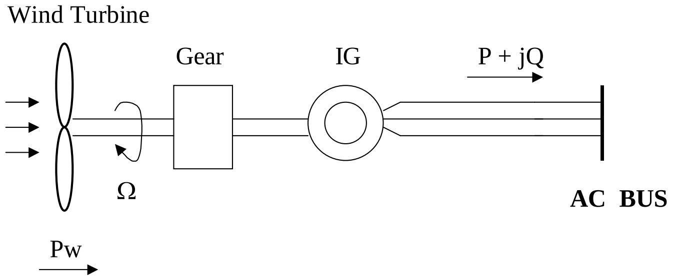


Figure 5: WECS Topology

For all the wind DG case studies, it is assumed that the wind turbine operates at constant speed and consequently, input power to the grid is determined entirely by wind speed. Figure 6 shows the operating characteristic of the wind prime mover model used throughout the simulation. At a high wind speed, the input power may reach the maximum turbine power limit. If this happens, pitch control is initiated to limit the input wind power.

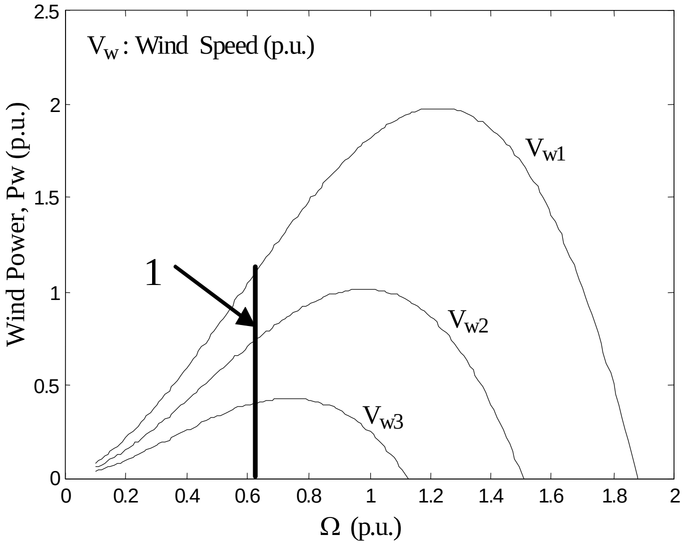


Figure 6: Operating Characteristics of the Wind Turbine

Each component of the WECS of Figure 5 is discussed in the following subsections.

4.3.1.1 WECS Drive Train Model

In this report, the WECS drive train is represented by the two-mass model shown in Figure 7:

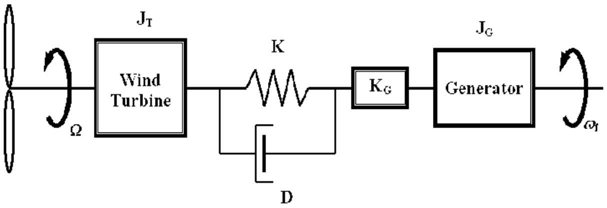


Figure 7: WECS Drive Train Model

The parameters for the WECS drive train used throughout the wind case studies are

<u>Wind turbine operating data</u>

- Rated Power = 2.6 MW
- Maximum Power = 3.00 MW
- Rated Wind Speed = 18.0 m/s
- Cut-In Wind Speed = 3.0 m/s
- Cut-Out Wind Speed = 23.0 m/s

<u>Wind turbine rotor data</u>

- Number of Blades = 3
- Rotor Radius = 50.0 m
- Rated Speed = 13.37 RPM
- Minimum Speed = 6.72 RPM
- Maximum Speed = 13.37 RPM

<u>Drive train data</u>

- Turbine Inertia = 421.877 kg.m^2
- Gear-box ratio, K_G = 134.62
- Spring constant, K = 2700.0 Nm/rad
- Damping constant, D = 0.00 Nm.s/rad

4.3.1.2 Induction Generator Model

In this report, the induction generators that are used in conjunction with wind turbines are modeled using the equivalent electrical circuit of Figure 8.

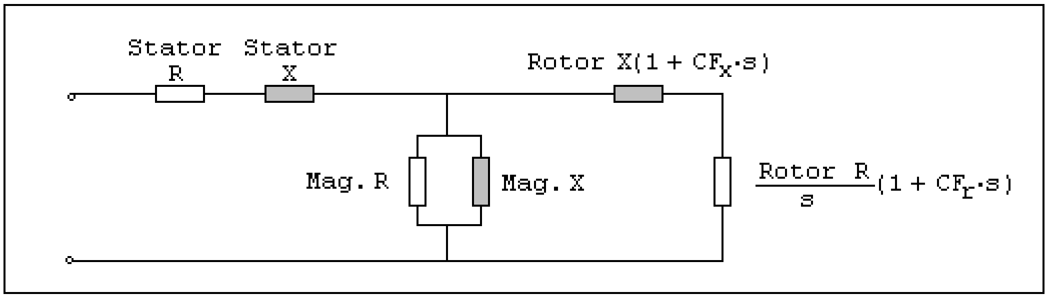


Figure 8: Induction Generator Equivalent Circuit

The parameters of the induction generator model of Figure 8 have the following values:

- Rated Capacity = 3.0 MVA
- Rated Voltage = 25 kV
- PF = 85 %
- Efficiency= 95%
- Rated Speed=1800 RPM
- Rs = 0.07 p.u., Xs = 0.067 p.u.,
- Rr = 0.04 p.u., Xr = 0.16 p.u.
- Rm = 99.99 p.u., Xm= 3.9 p.u.,
- Cage Factor CFr = 3.7439, CFx = -0.2813
- Generator Inertia = 84.375 kg.m^2

4.3.2 Wind Energy Conversion System –Doubly Fed Induction Generator

The doubly-fed induction generator driven by a wind turbine is shown in Figure 9.

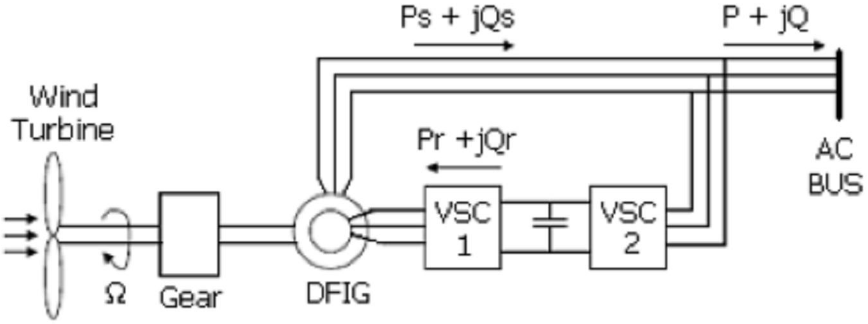
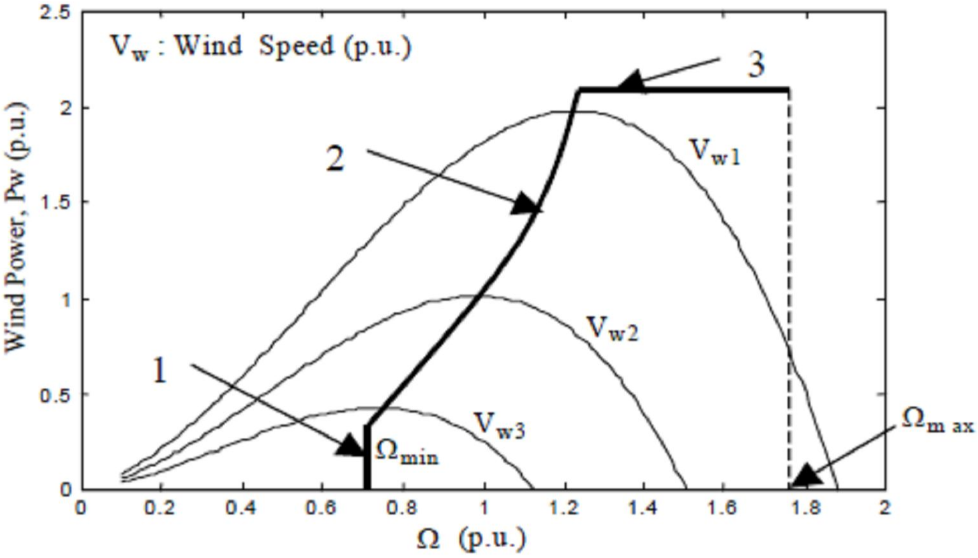


Figure 9: WECS Topology

As for the IG, in all the wind DG case studies it is assumed that the wind turbine operates at constant speed and consequently, input power to the grid is determined entirely by wind speed. Figure 10 shows the operating characteristic of the DFIG wind prime mover model used throughout the simulation. At a high wind speed, the input power may reach the maximum turbine power limit. If this happens, the pitch control is initiated to limit the input wind power.



1—Constant Speed mode; 2—Peak-Power Tracking mode; 3—Constant Power mode

Figure 10: Operating Characteristics of the Wind Turbine

Each component of the WECS of Figure 9 is discussed in the following subsections.

4.3.3 WECS Drive Train Model

In this report, the WECS drive train is represented by the two-mass model of Figure 11:

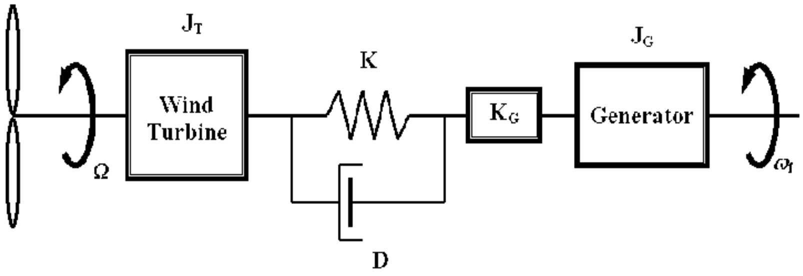


Figure 11: WECS Drive Train Model

The parameters for the WECS drive train used throughout the wind case studies are

<u>Wind turbine operating data</u>

- Rated Power = 2.6 MW
- Maximum Power = 3.00 MW
- Rated Wind Speed = 18.0 m/s
- Cut-In Wind Speed = 3.0 m/s
- Cut-Out Wind Speed = 23.0 m/s

<u>Wind turbine rotor data</u>

- Number of Blades = 3
- Rotor Radius = 50.0 m
- Rated Speed = 13.37 RPM
- Minimum Speed = 6.72 RPM
- Maximum Speed = 13.37 RPM

<u>Drive train data</u>

- Turbine Inertia = 421.877 $kg.m^2$
- Gear-box ratio, K_G = 134.62
- Spring constant, K = 2700.0 Nm/rad
- Damping constant, D = 0.00 Nm.s/rad

4.3.4 Induction Generator Model

In this report, the induction generators that are used in conjunction with wind turbines are modeled using the equivalent electrical circuit of Figure 12.

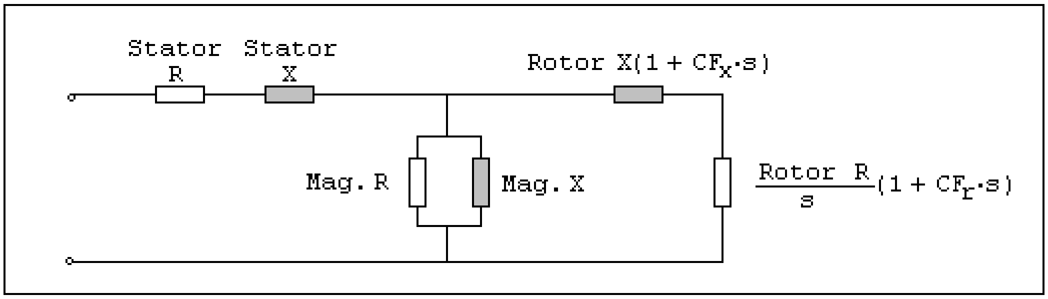


Figure 12: Induction Generator Equivalent Circuit

The parameters of the induction generator model of Figure 12 have the following values:

- Rated Capacity =3.0 MVA
- Rated Voltage = 25 kV
- PF = 85 %
- Efficiency= 95%
- Rated Speed=1800 RPM
- Rs = 0.0003 p.u., Xs = 0.1195 p.u.,
- Rr = 0.0004 p.u., Xr = 0.0597 p.u.
- Rm = 100 p.u., Xm= 100 p.u.,
- Cage Factor CFr = 3.7439, CFx = -0.2813
- Generator Inertia = 84.375 kg.m^2

5 IEEE Anti-Islanding Standards

Due to system control, protection and personnel safety concerns, the current IEEE standards do not allow part of the distribution system to operate in an islanded condition, i.e. where distributed generation is supplying part or total load of the island. The IEEE 1547-2003 Standard [8] dictates that the island condition must be detected and the DG must cease to energize the affected area within 2 seconds of the island occurrence, regardless of the islanding detection scheme. The simplest islanding detection method is based on voltage/frequency deviations outside of permissible ranges, which are also specified in the IEEE 1547-2003 Standard. However, these frequency/voltage limits can be violated due to dynamic events different from the islanded process, resulting in unnecessary DG disconnection. In this report, the ability of the distribution system to decide whether islanding has occurred or not is entirely based on the IEEE 1547-2003 Standard voltage/frequency criterion.

5.1 Voltage limits and clearing times

When the system voltage falls within the ranges given in Table 2, distributed resources (DR) shall cease to energize the affected area within the indicated clearing times, where the clearing time is defined as the time between the start of the abnormal condition and the de-energization of the affected area by the corresponding DR unit. Table 3 presents the corresponding voltage limits and clearing times according to the Canadian Standard, C22.3 No. 9-08 Interconnection of distributed resources and electricity supply systems [9].

Table 2: Interconnection System Response to Abnormal Voltages

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

[a] Base voltages are the nominal system voltages stated in ANSI C84.1-1995, Table 1.

[b] DR ≤ 30kW, Maximum Clearing Times; DR > 30kW, Default Clearing Times

Table 3: Response to Abnormal Voltage Levels

Voltage Condition at PCC (% of nominal voltage) [a]	Clearing Time[b c]
V < 50	Instantaneous – 0.16 s
50 ≤ V < 88	Instantaneous – 2 s
88 ≤ V ≤ 106	Normal operation
106 < V ≤ 110	0.5 s – 2 min [d]
110 < V ≤ 120	Instantaneous – 2 min
120 < V < 137	Instantaneous – 2 s
137 ≤ V	Instantaneous

[a] Nominal system voltage shall be in accordance with CSA CAN3-C235, Table 1 and Table 3.

[b] Specific clearing times within the ranges in this Table shall be specified by the wires owner. Other clearing times or voltage ranges may be arranged through consultation between the power producer and wires owner.

[c] lnstantaneous means no intentional delay.

[d] Required for compliance with CSA CAN3-C235.

5.2 Frequency limits and clearing times

When the system frequency falls within ranges given in Table 4, the DR shall cease to energize the affected area within the indicated clearing times. For DR less than or equal to 30 kW in peak capacity, the frequency set points and clearing times shall be either fixed or field adjustable. For DR greater than 30 kW the frequency set points shall be field adjustable. The corresponding frequency operating limits for DRs according to the Canadian Standard, C22.3 No. 9-08 are listed in Table 5.

Table 4: Interconnection System Response to Abnormal Frequencies

DR Size	Frequency Range (Hz)	Clearing Time [a] (s)
DR ≤ 30 kW	> 60.5	0.16
	<59.3	0.16
DR >30 kW	>60.5	0.16
	< {57.0 - 59.8} (adjustable setpoint)	Adjustable 0.16 to 300
	<57.0	0.16

[a] DR ≤ 30 kW, Maximum Clearing Times; DR > 30 kW, Default Clearing Times

Table 5: Frequency operating limits for DRs

DR Size	Adjustable Set Point (Hz)	Clearing Time (s) (Adjustable Set Point)
DR ≤ 30 kVA	57 - 59.3	0.1 – 2
	60.7 – 61.7	0.1 – 2
DR >30 kVA	55.5 - 59.3	0.1 – 300
	60.7 – 63.5	0.1 – 180

A fixed set point can be acceptable in some jurisdictions.
Set point should be confirmed with the wires owner.
More than one over-frequency and under-frequency set point may be required by the wires owner.

If the security concerns which resulted in the creation of the above limits could be properly dealt with, there would be major incentives for the islanded operation of DG units due to their potential ability to enhance the reliability of their host distribution system.

6 Case Study Results - System Response to Major Disturbances

This section presents the response of the distribution system to major disturbances that do not result in system disconnection from the transmission system. These disturbances include the loss of a large load or distributed generator, as well as three-phase faults at a major bus in the system followed by fault clearing. Only the short circuit fault condition, which is considered as the worst case, is carried out for the over and under generation scenarios.

6.1 Distribution System with Embedded Hydraulic Generation

6.1.1 Self Sufficient Distribution System

The load flow for this case is shown in Figure 13. Each of the three DG units connected to bus bars B0, F and G is a 3 MVA hydraulic unit which is controlled to supply 1.58 MW and to maintain its bus bar voltage at 1.03 p.u. Each hydraulic unit delivers or absorbs different amounts of reactive power depending on its location in the network. The power exchange with the transmission system is 0.004 MW and -0.046 MVAR.

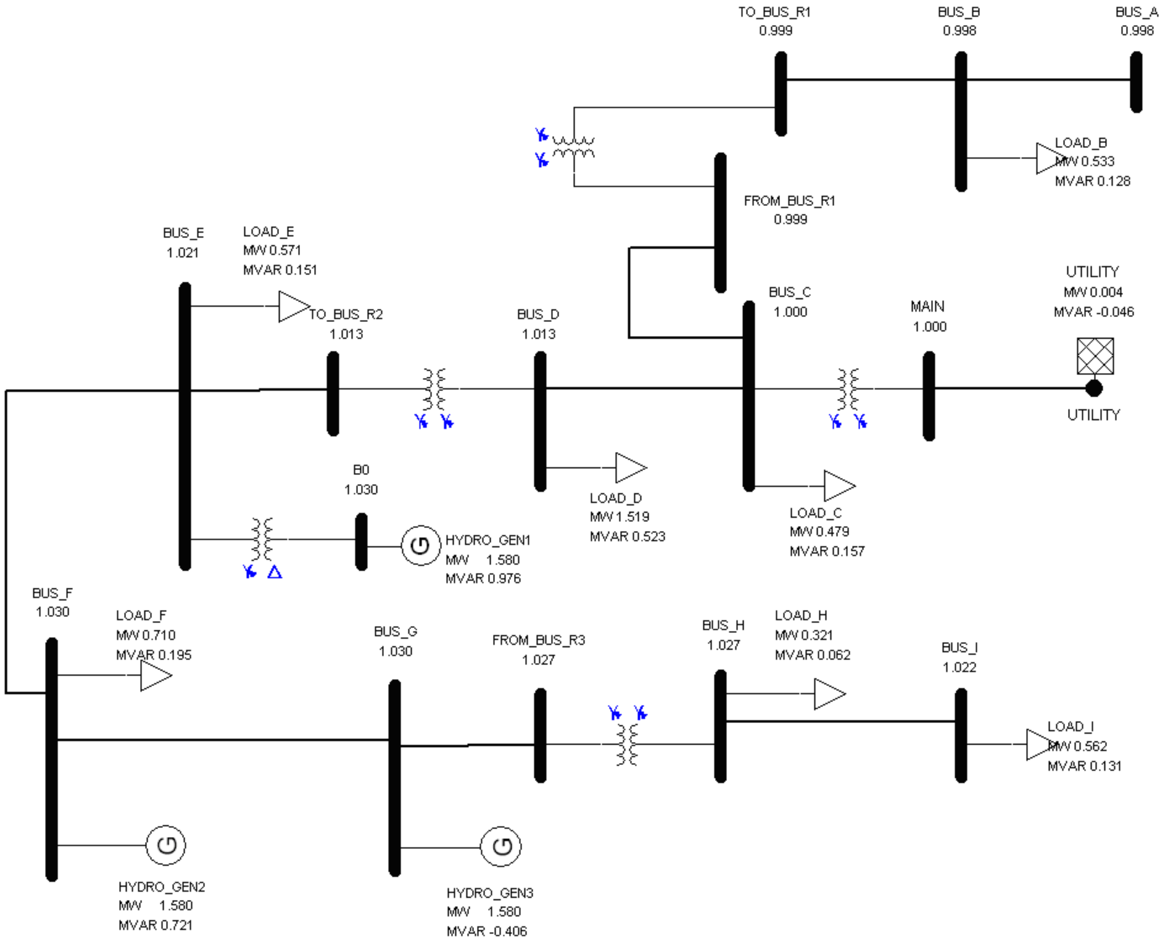


Figure 13: Self-Sufficient Distribution System – Hydraulic Units

6.1.1.1 Loss of Load Condition

This case study simulates the loss of the largest load in the distribution system (1.5 MW + j0.510 MVAR at rated voltage and frequency), which is connected to bus D. The response of the system to the loss of load at t = 2 sec. is shown in Figure 14, Figure 15 and Figure 16.

Figure 14 shows the local frequency response, at each bus, due to the loss of load at bus D. Since the distribution system operates under self-sufficient conditions and it is connected to a stronger system, the local frequency at each generator does not experience significant deviations from the nominal value of 60 Hz. The maximum frequency excursion in this case reaches 60.02 Hz. This value did not reach the IEEE limits for abnormal frequency conditions detection (or islanding detection). Since the generators frequencies return back to 60 Hz, the generators loadings return to their original values and the feeding system absorbs the excess of power created by the load loss, as observed in Figure 15 and Figure 16.

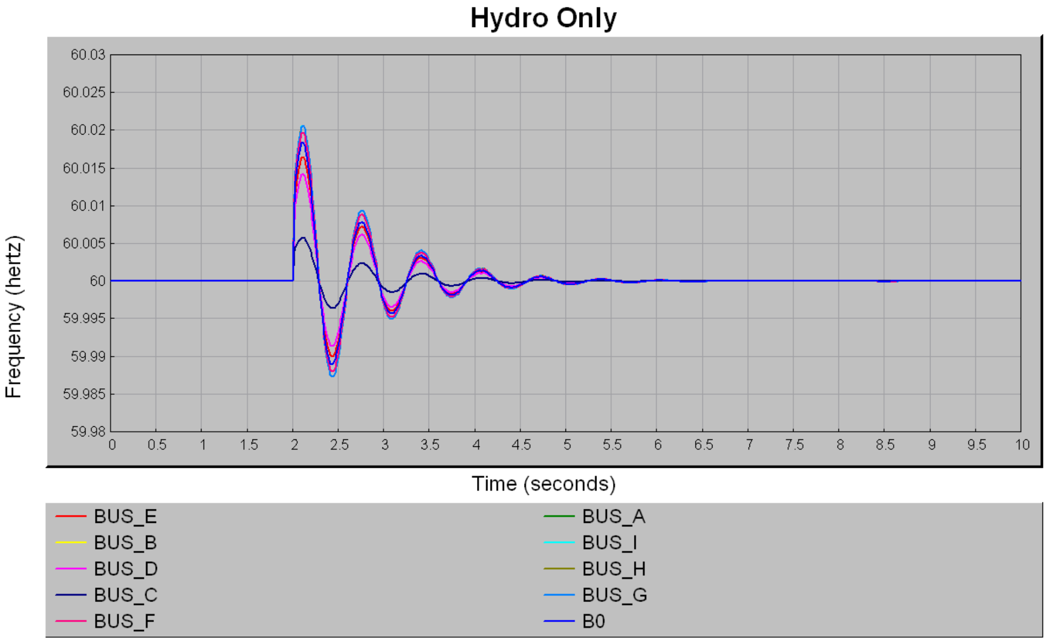


Figure 14: Frequency Response to Load Loss – Balanced Load/Generation – Hydro Units

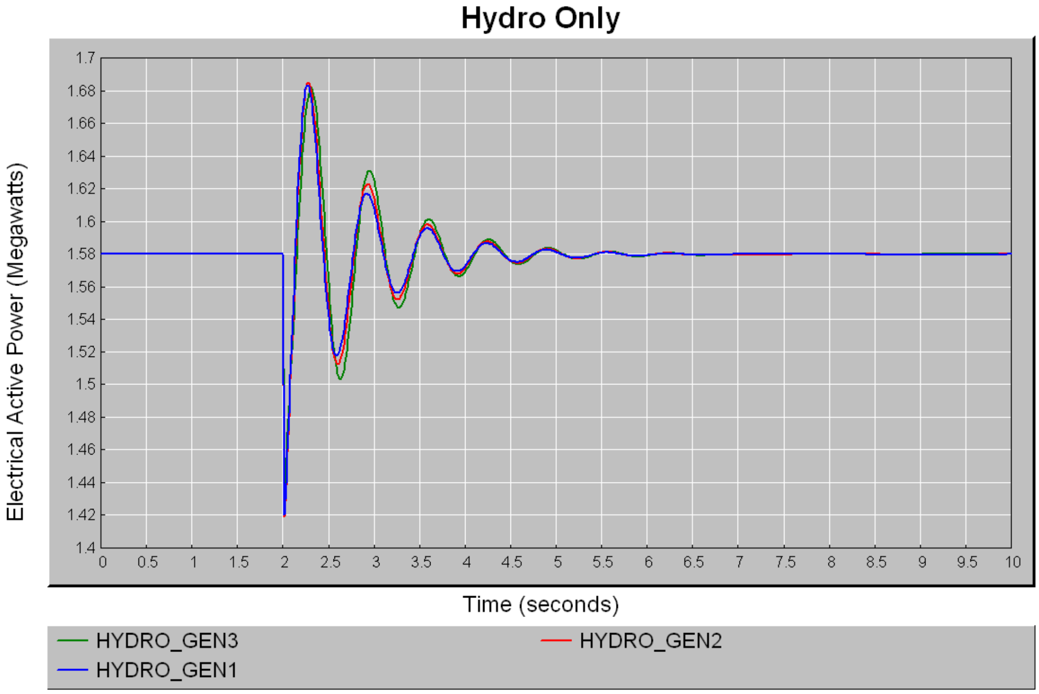


Figure 15: DG Unit Loading Response to Load Loss – Balanced Load/Generation – Hydro Units

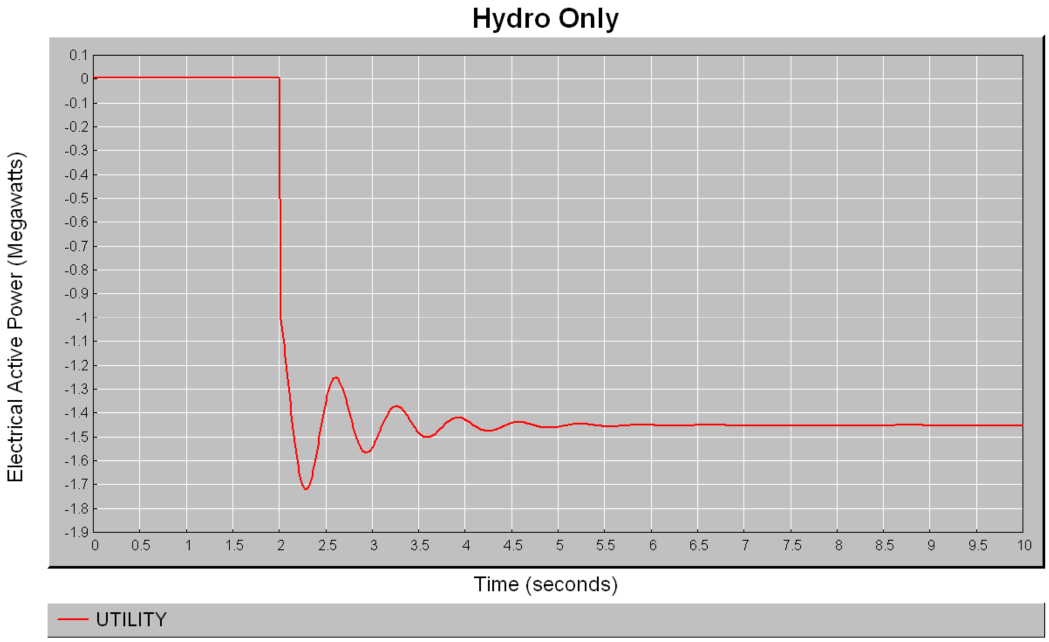


Figure 16: Transmission System Response to Load Loss – Balanced Load/Generation – Hydro Units

6.1.1.2 Loss of Generation Condition

This case study simulates the loss of the generating unit connected to bus B0, which represents a DG source of 1.58 MW and 0.976 MVAR. The response of the system to the generation loss at t = 2 sec. is shown in Figure 17, Figure 18 and Figure 19.

Figure 17 shows the local frequency response, at each bus, due to the loss of generation. Since the distribution system is connected to a stronger system, the local frequency at each generator returns back to its nominal value of 60 Hz. The maximum frequency excursion in this case does not exceed 59.98 Hz, which did not reach the IEEE limits for abnormal frequency conditions detection (or islanding detection). Since the generators frequencies return back to 60 Hz, the generators loadings return to their original values and the feeding system supplies the deficit power created by the generation loss, as observed in Figure 18 and Figure 19.

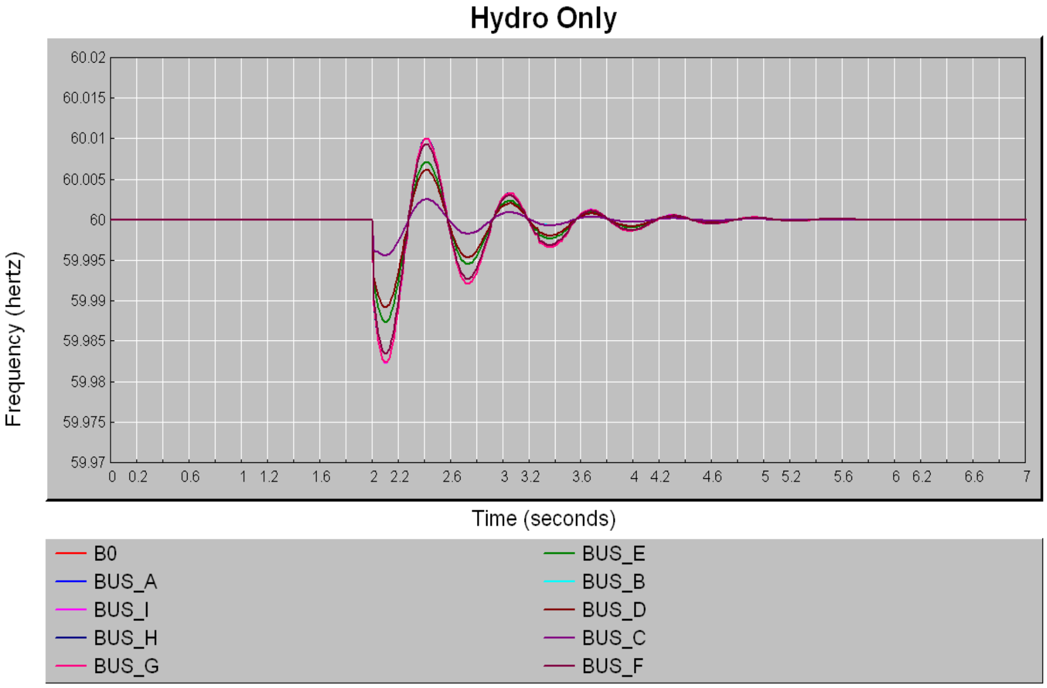


Figure 17: Frequency Response to Generation Loss – Balanced Load/Generation – Hydro Units

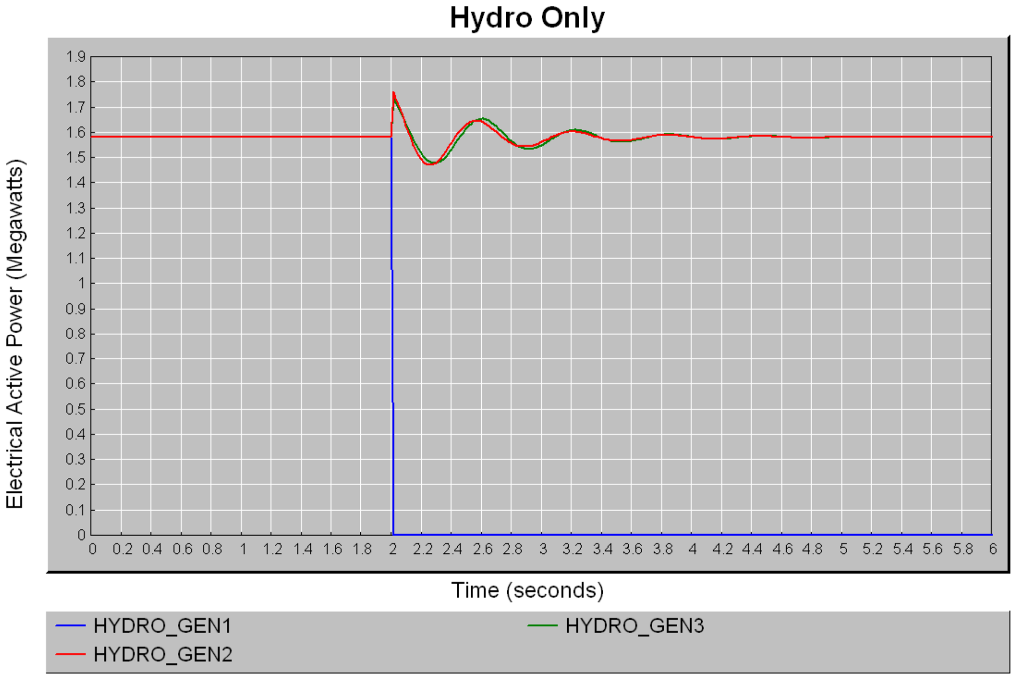


Figure 18: DG Unit Loading Response to Generation Loss – Balanced Load/Generation – Hydro Units

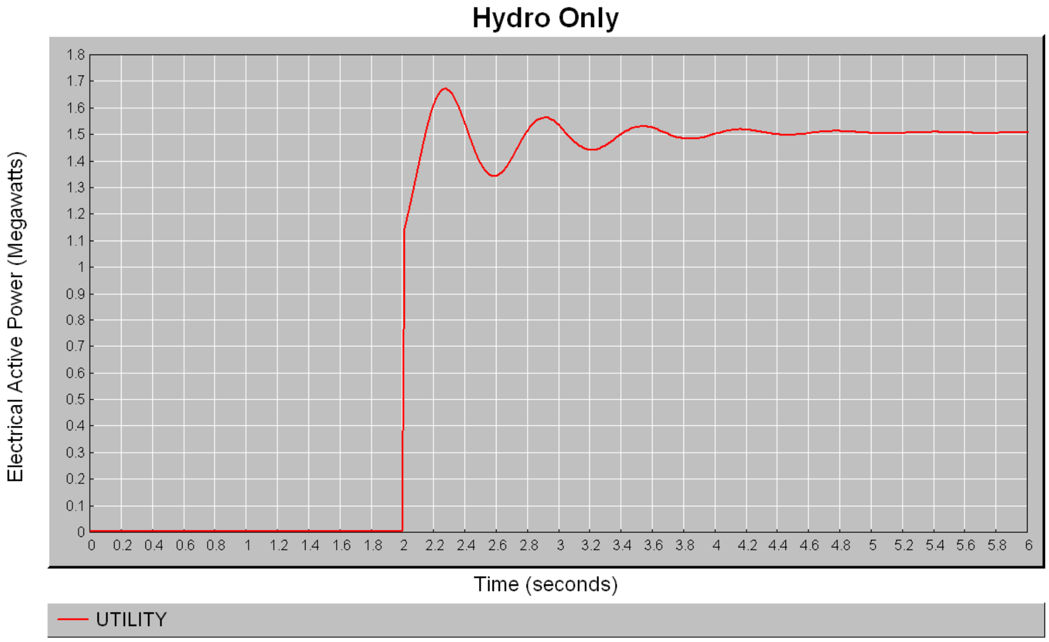


Figure 19: Transmission System Response to Generation Loss – Balanced Load/Generation – Hydro Units

6.1.1.3 Short Circuit Conditions

This case study simulates the response of the distribution system to a three-phase to ground fault applied at bus H at t = 2 sec., which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event are shown in Figure 20 and Figure 21.

Figure 20 shows the voltage dips at different buses in the distribution system. The voltage dips vary according to the electrical distances between the monitored bus and the fault location. The voltage at buses B0, F, and G, where the DG units are located, drops to 0.57 p.u., 0.33 p.u., and 0.16 p.u., respectively.

IEEE standard 1547 requires DG units to stop energizing the system within 0.16 sec. when the voltage at the point of DG connection drops below 0.5 p.u. and in 2 sec. when the voltage drops between 0.5 p.u. and 0.88 p.u. Depending on the generator breaker tripping time, an additional delay can be introduced on top as long as the time between the instant of the abnormal condition detection and the actual tripping of the generator corresponds to the IEEE specified clearing time for the detected abnormal condition. This additional delay has the purpose of allowing the system to recover from relatively short faults without any breaker tripping. However, once the additional delay runs out, even if the fault is cleared immediately after and the system re-enters into a normal condition, the tripping of the circuit breaker of the DG unit cannot be cancelled.

In this case study, for a breaker operating time of 0.05 sec., a time delay of 0.11 sec. could be implemented. Consequently, all the generating units would remain operational after the fault is cleared. However, if the breaker tripping time is longer than 0.06 sec., it would imply a shorter time delay (shorter than 100 msec. and therefore, shorter than the duration of the fault). Consequently, the DG units at buses F and G would be forced to trip, and only the DG unit at bus B0 would remain operational after the fault clearance.

Figure 21 shows the local frequency response, at each bus, due to the SC occurrence and clearance. Since the distribution system is connected to a stronger system, the local frequency at each generator returns back to its nominal value of 60 Hz. The maximum frequency excursion in this case reaches 60.12 Hz. This value did not reach the IEEE limits for abnormal frequency conditions detection (or islanding detection). Since the generators frequencies return back to 60 Hz, the generators loadings return to their original values.

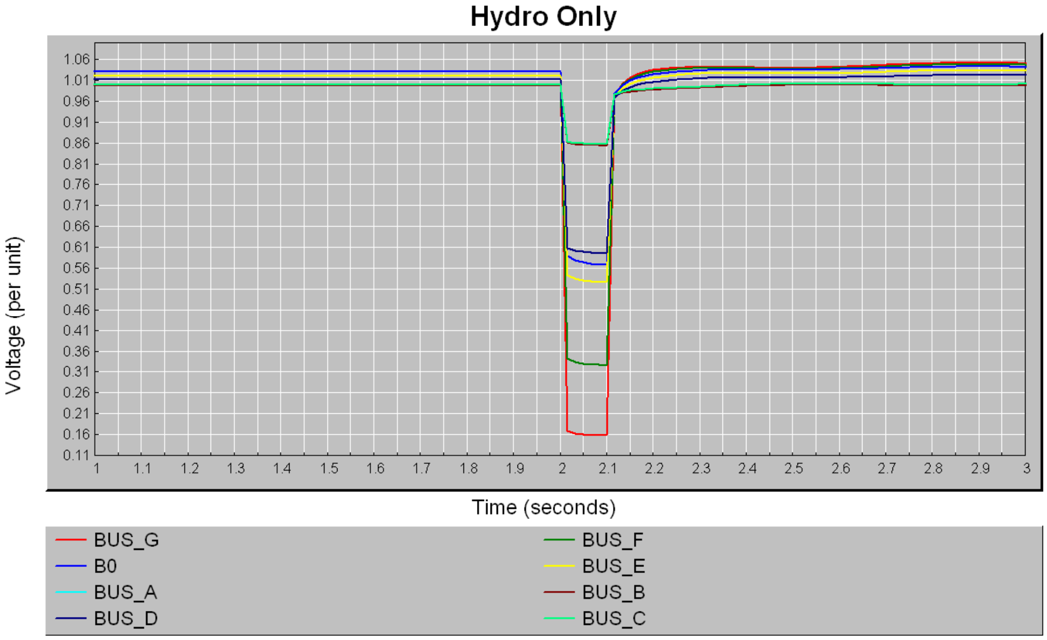


Figure 20: Voltage Response to Three-phase Fault at Bus H – Balanced Load/Generation – Hydro Units

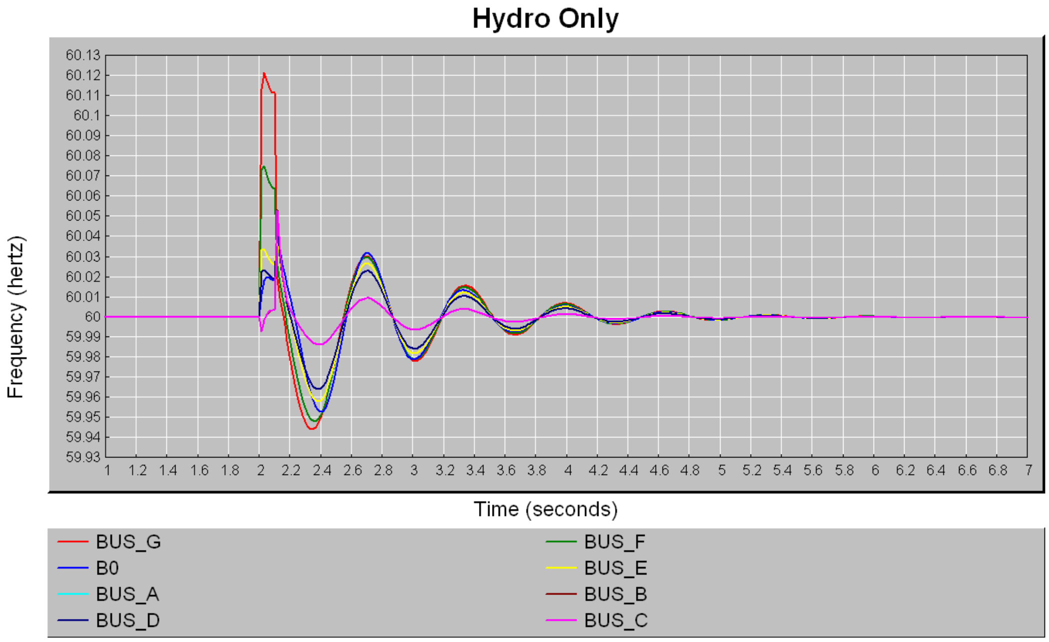


Figure 21: Frequency Response to Three-Phase S.C. at Bus H – Balanced Load/Generation – Hydro Units

6.1.2 Over-Generating Distribution System

The load flow for this case is shown in Figure 22. Each of the three DG units connected to bus bars B0, F and G is a 4 MVA hydraulic unit which is controlled to generate 3.12 MW and to maintain its bus bar voltage at 1.03 p.u. The total real power supplied by the DG units represents twice the total real power consumption of the system. Each DG unit delivers or absorbs different amounts of reactive power, depending on its location in the network. The power exchange with the transmission system is 4.076 MW exported from the distribution system and 2.792 MVAR imported into the distribution system, as observed in Figure 22.

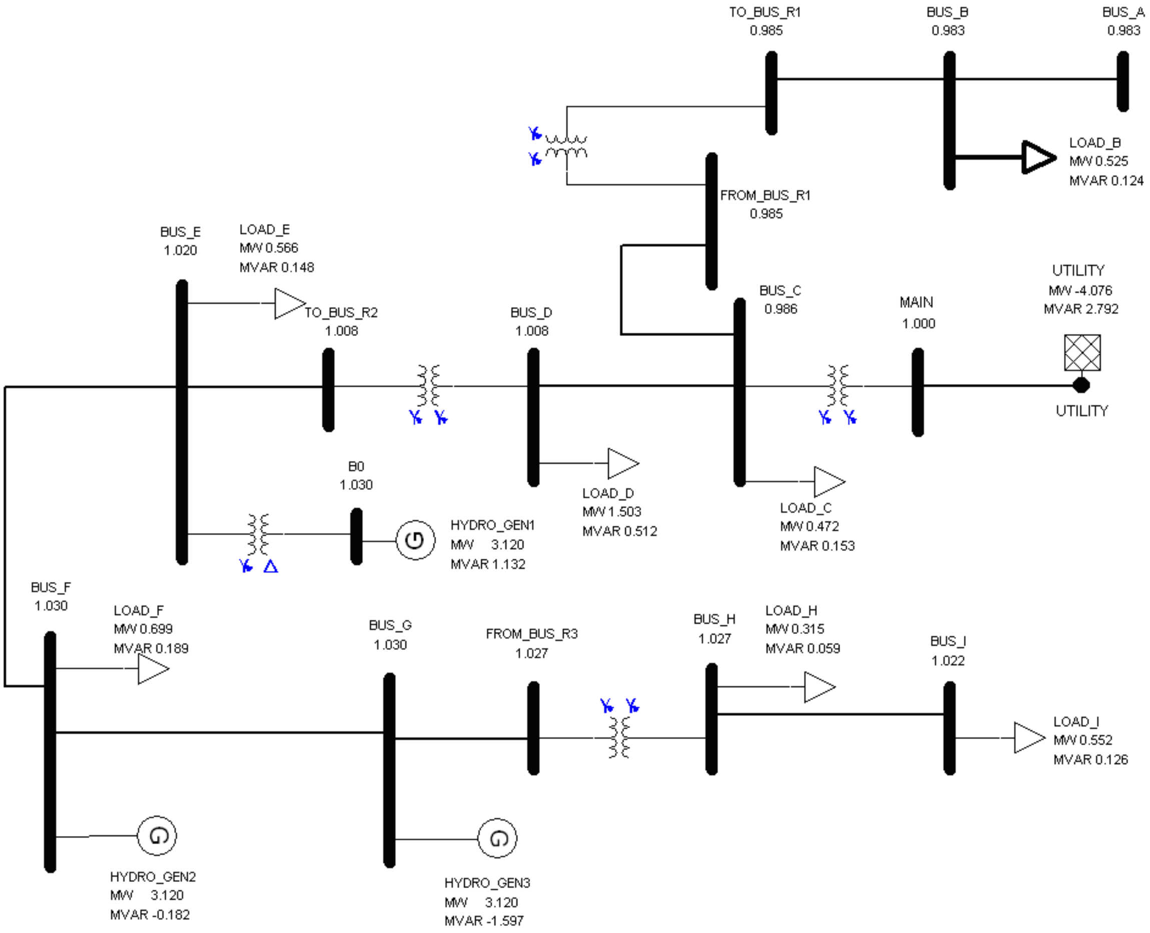


Figure 22: Over Generated Distribution System – Hydraulic Units

6.1.2.1 Short Circuit Conditions

This case study simulates the response of the distribution system to a three-phase to ground fault applied at bus H, which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event at t = 2 sec. are shown in Figure 23 and Figure 24.

Figure 23 shows the value of the voltage dip at different distribution system bus bars. The magnitude of the voltage dip varies according to the electrical distance from the fault location, and exceeds the IEEE limits for island formation at several locations. The voltage dips last for as long as the fault is present, i.e., 100 ms. This duration may or may not result in DG units shutting down, depending on their breaker operating times and any intentional added time delay before initiating breaker trip operation. Fault duration can be much longer if the fault is cleared by backup protection.

Figure 24 shows the local frequency response, at each bus, due to the SC occurrence and clearance. Since the distribution system is connected to a stronger system, the local frequency at each generator returns back to its nominal value of 60 Hz. The maximum frequency excursion in this case reaches 60.21 Hz. This value did not reach the IEEE limits for abnormal frequency conditions detection (or islanding detection). Since generator frequencies return back to 60 Hz, generator loadings return to their original values.

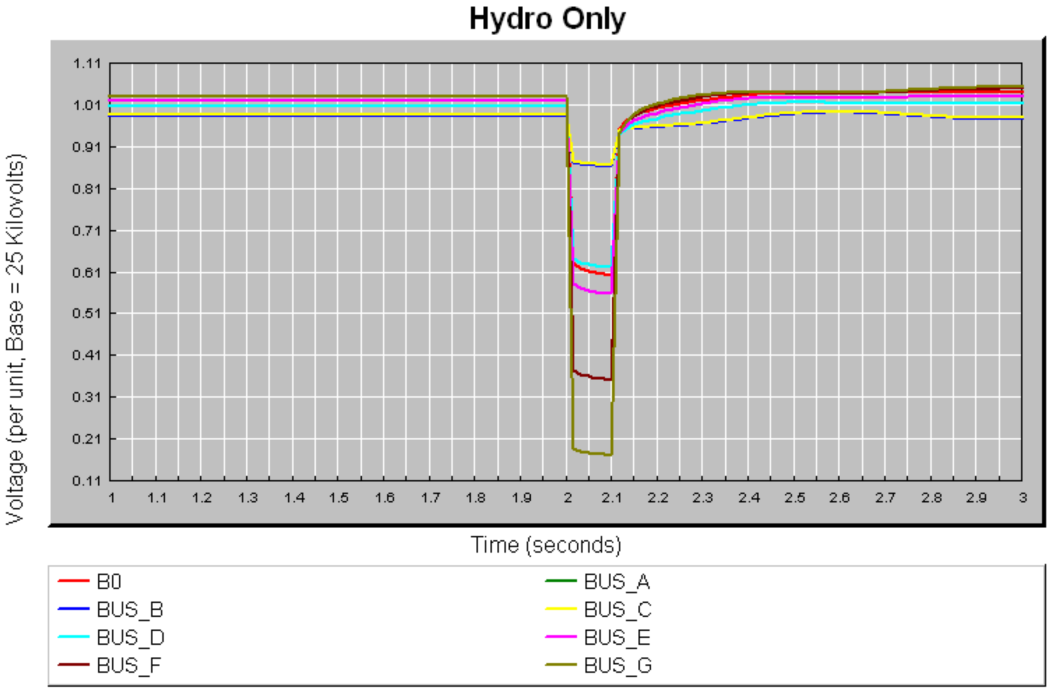


Figure 23: Voltage Response to a three-phase Fault at Bus H – Generation/Load Ratio 2/1 –Hydro Units

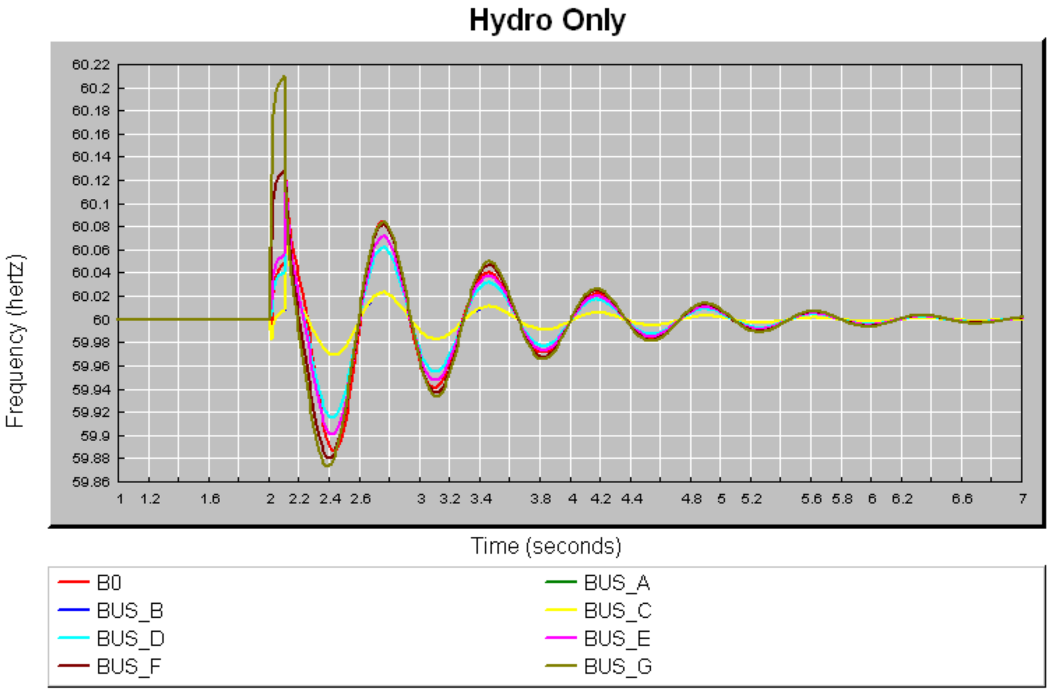


Figure 24 Frequency Response to a Three-Phase Fault at Bus H – Generation/Load Ratio 2/1 – Hydro Units

6.1.3 Under-Generating Distribution System

In this case, each of the three hydraulic DG units connected to the bus bars B0, F and G are controlled to generate 0.8 MW at 1.03 pu voltage at the respective bus. The total real power supplied by the DG units represents almost half of the total real power consumption of the system. Each DG unit delivers or absorbs different amounts of reactive power, depending on its location in the network. The power exchange with the transmission system is 2.374 MW imported into the distribution system and 1.335 MVAR exported from the later.

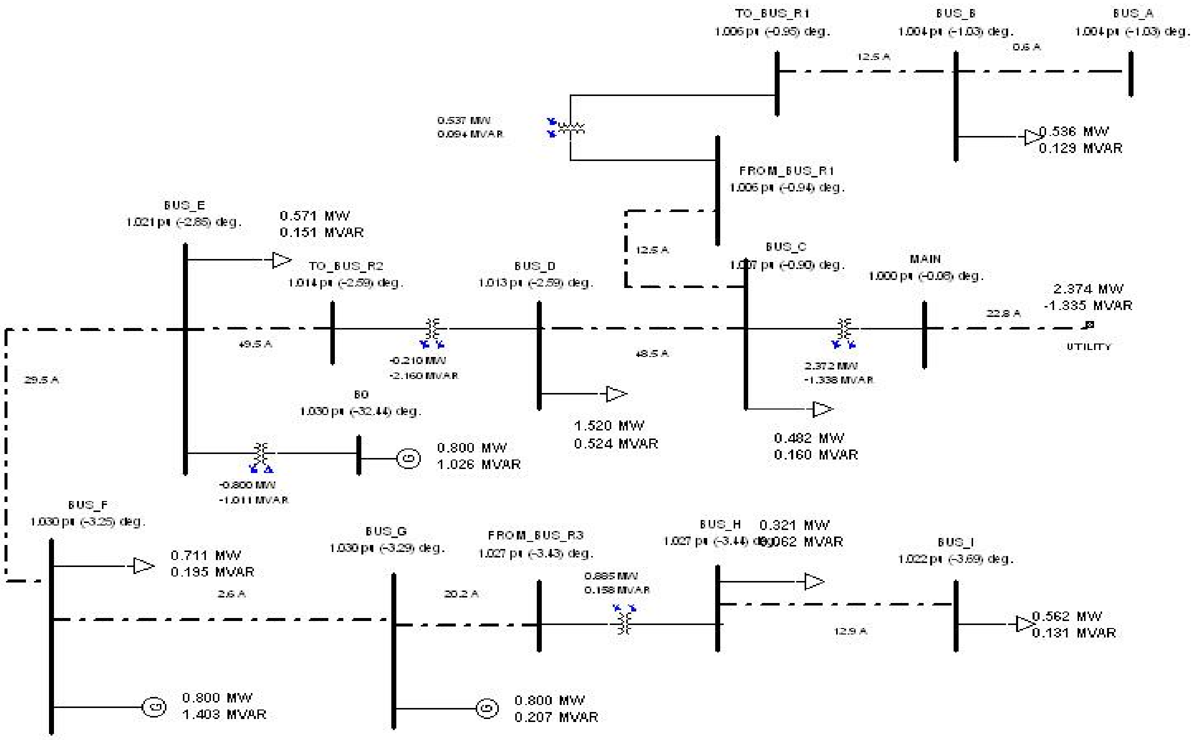


Figure 25: Under Generated Distribution System- Hydraulic Units

6.1.3.1 Short Circuit Conditions

This case study simulates the response of the distribution system to a three-phase fault applied at bus H, which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event at t = 2 sec. are shown in Figure 26 and Figure 27.

Figure 26 shows the value of the voltage dip at different distribution system bus bars. The magnitude of the voltage dip varies according to the electrical distance from the fault location, and exceeds the IEEE limits for island formation at several locations. The voltage dips last for as long as the fault is present, i.e., 100 ms. As in the previous case, this duration may or may not result in DG units shutting down, depending on their breaker operating times and any intentional added time delay before initiating breaker trip operation. Fault duration can be much longer if the fault is cleared by a backup protection.

Figure 27 shows the local frequency response, at each bus, due to the SC occurrence and clearance. Since the distribution system is connected to a stronger system, the local frequency at each generator returns back to its nominal value of 60 Hz. The maximum frequency excursion in this case reaches 60.06 Hz. Similarly to the previous case, this value did not reach the IEEE limits for abnormal frequency conditions detection (or islanding detection) and since generator frequencies return back to 60 Hz, generator loadings return to their original values.

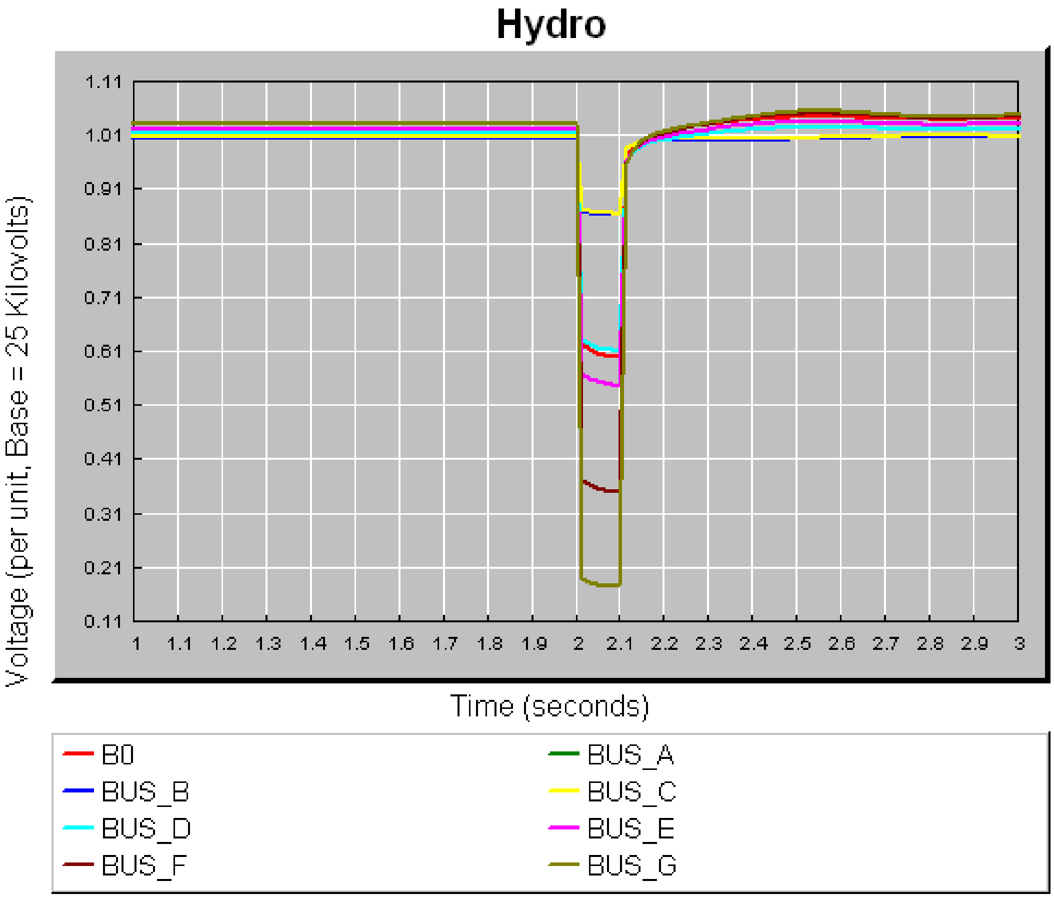


Figure 26: Voltage Response to a Three phase Fault at bus H-Generation/Load Ratio 1/2-Hydro Units

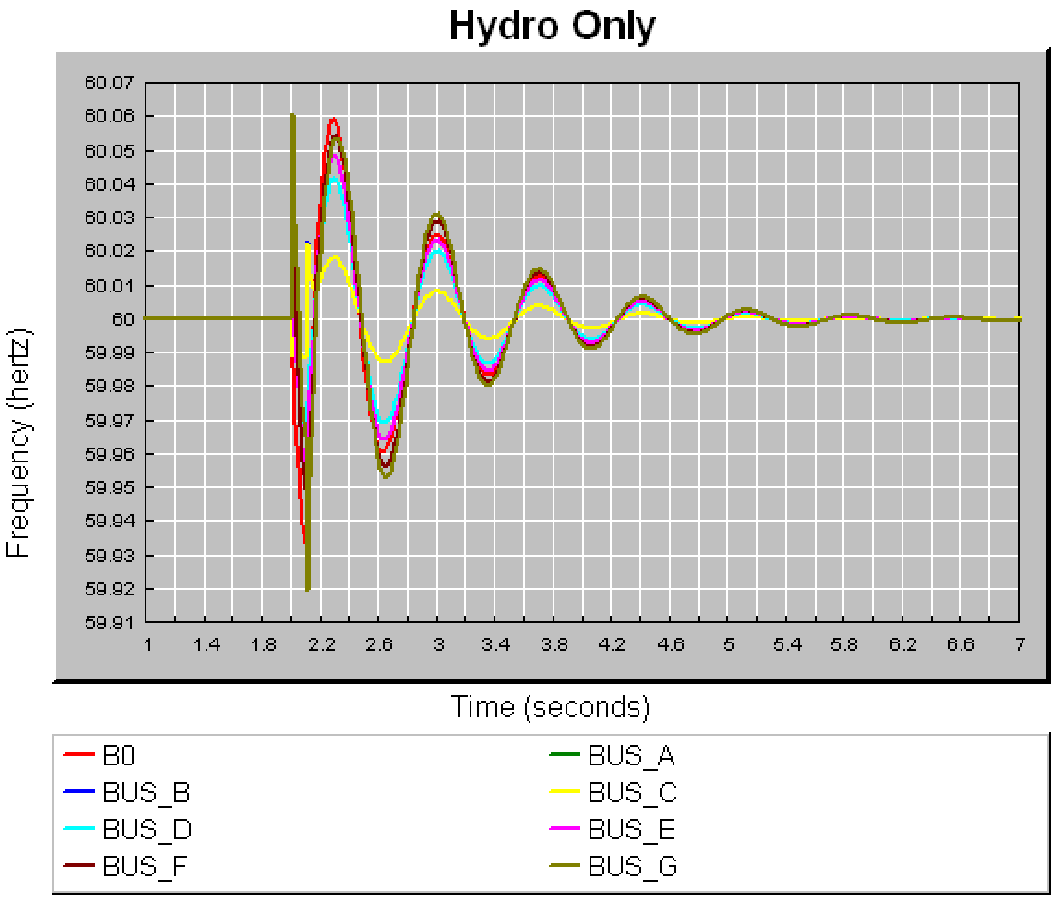


Figure 27: Frequency Response to a Three phase Fault at bus H-Generation/Load Ratio 1/2-Hydro Units

6.2 Distribution system with Embedded Wind Generation (Directly Coupled Induction Generator)

6.2.1 Self-sufficient Distribution System

The load flow for this case is shown in Figure 28. The three wind DG units connected to bus bars B0, F and G drive 3 MVA directly coupled induction generators. Each wind DG unit supplies 1.540 MW at a power factor of 84%. Additionally, a capacitor bank of 0.7 MVAR is installed at each DG bus bar, which results in an operation at an equivalent power factor of 98%. The transmission system supplies the remaining reactive power demanded by both, the induction generators and the loads, i.e., 2.218 MVAR, as indicated in Figure 28. In all cases, wind speed is maintained constant at the value computed from the load flow analysis.

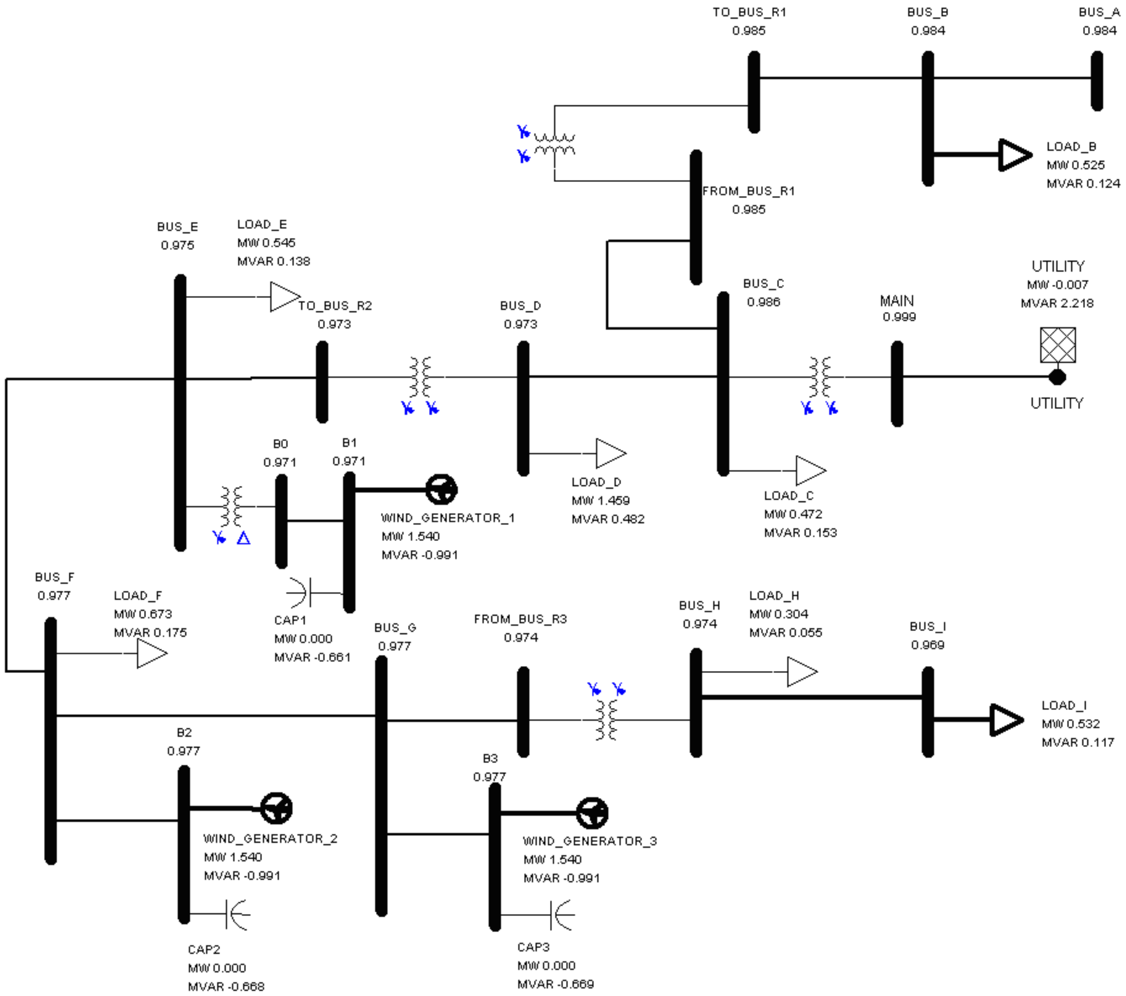


Figure 28: Self-Sufficient Distribution System - Wind Generation Units

6.2.1.1 Loss of Load Condition

This case study simulates the loss of the largest load in the distribution system which is connected to bus D. The response of the system to the loss of load at t = 4 sec. is shown in Figure 29 and Figure 30.

Figure 29 shows the local frequency response, at each bus, due to the loss of load. Since the distribution system is connected to a stronger system, the local frequency at each generator returns back to its nominal value of 60 Hz. The maximum frequency excursion in this case reaches 60.07 Hz, which did not reach the IEEE limits for abnormal frequency conditions detection. Since the wind power generation depends mostly on the wind speed, it remains practically constant, while the system delivers the deficit power created by the generation loss, as observed in Figure 30.

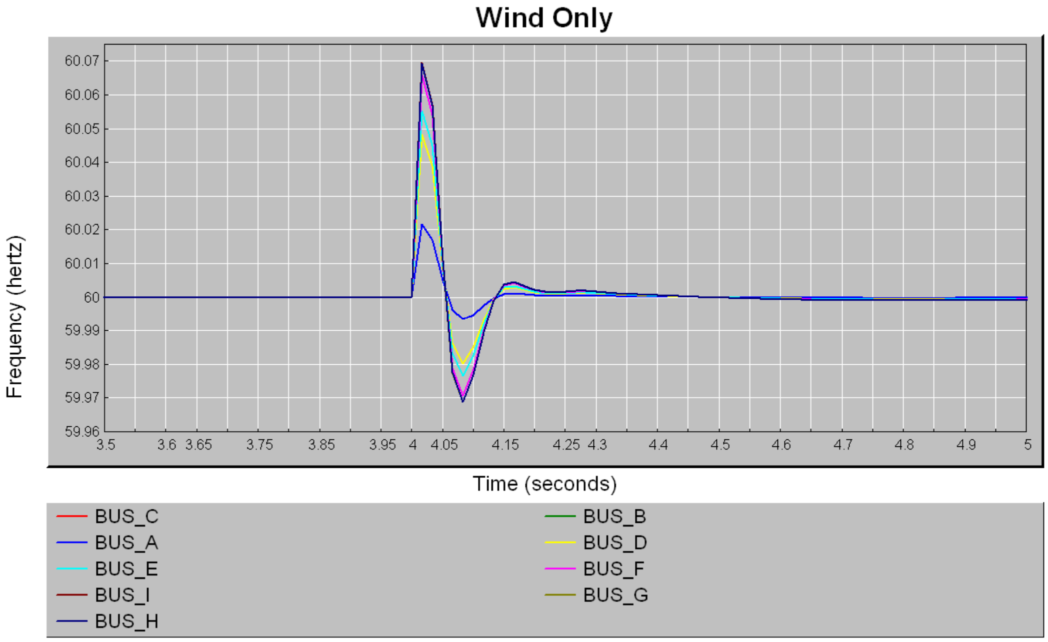


Figure 29: Frequency Response to Load Loss – Balanced Load/Generation – Wind Generation Units

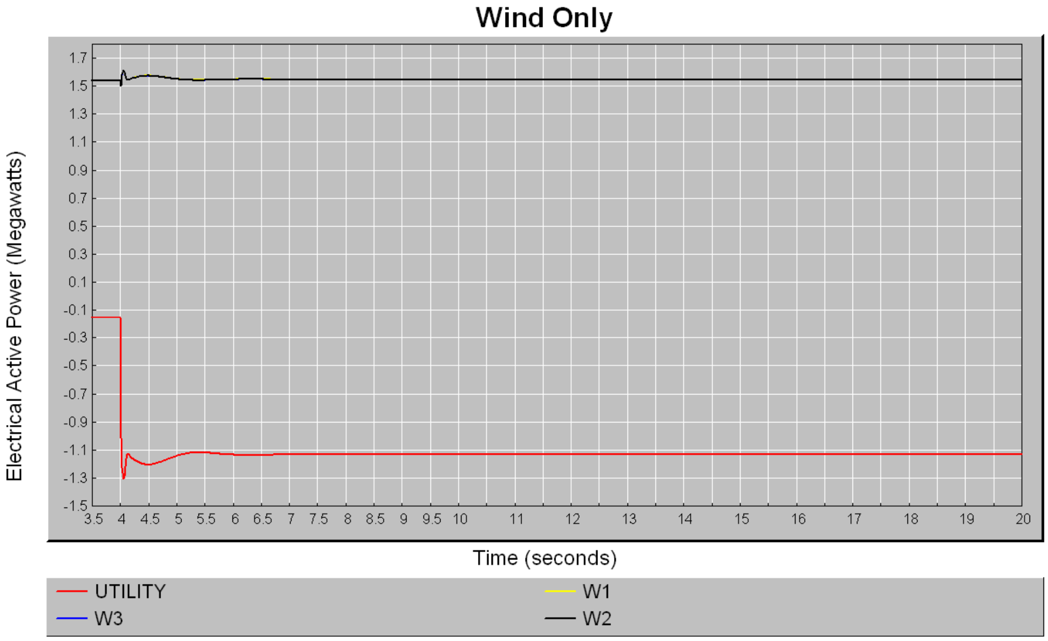


Figure 30: Generation Response to Load Loss – Balanced Load/Generation – Wind Generation Units

6.2.1.2 Loss of Generation Condition

This case study simulates the loss of the DG unit connected to bus B0, which represents a power supply of 1.540 MW – j0.991 MVAR. The response of the system to such generation loss at t = 4 sec. is shown in Figure 31 and Figure 32.

Figure 31 shows the local frequency response, at each bus, due to the loss of generation. Since the distribution system is connected to a much stronger system, the local frequency at each generator returns back to its nominal value of 60 Hz. The maximum frequency excursion in this case reaches 59.86 Hz. This value did not reach the IEEE limits for abnormal frequency conditions detection. Since the wind generation depends mostly on the wind speed, it remains practically constant while the system delivers the deficit power created by the generation loss, as illustrated in Figure 32.

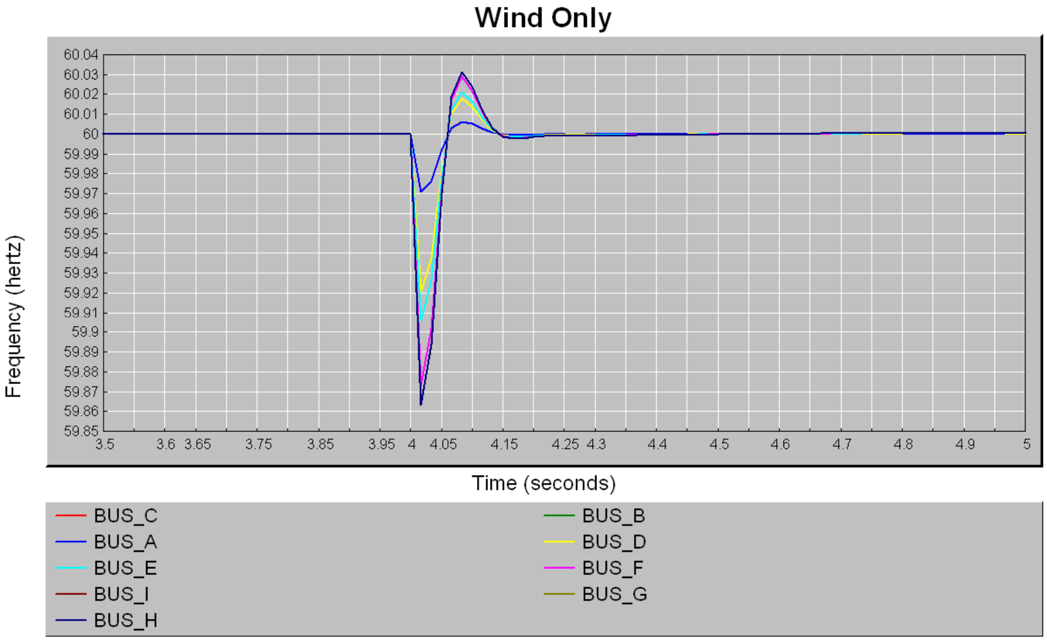


Figure 31: Frequency Response to Generation Loss – Balanced Load/Generation – Wind Generation Units

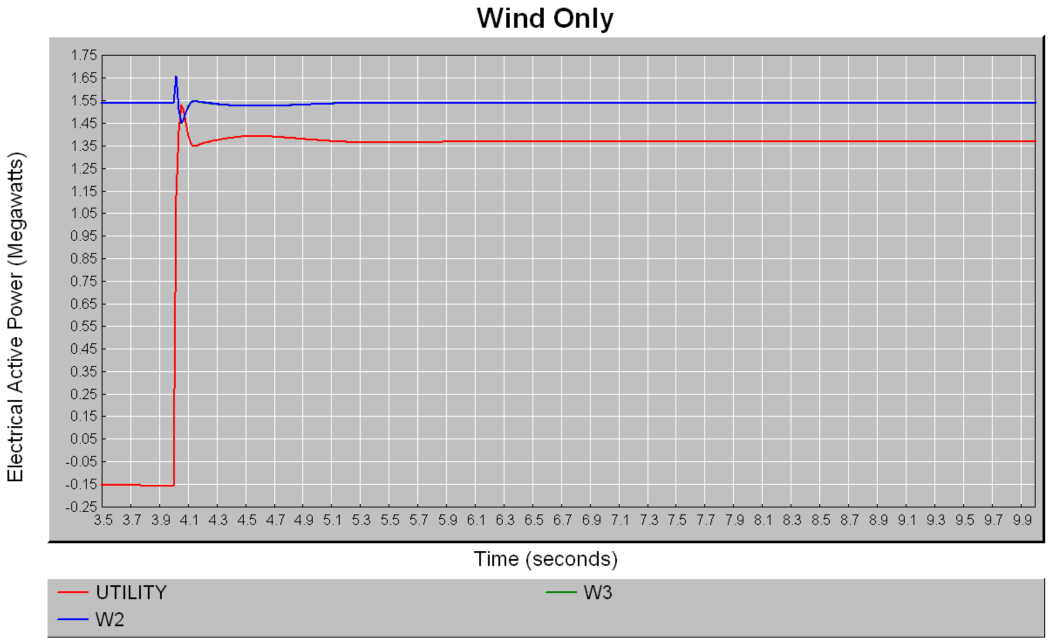


Figure 32: Generation Response to Generation Loss – Balanced Load/Generation – Wind Generation Units

6.2.1.3 Short Circuit Conditions

This case study simulates the response of the distribution system to a three-phase to ground fault applied at bus H, which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event at t = 4 sec. are shown in Figure 33 and Figure 34.

Figure 33 shows the value of the voltage dip at different distribution system bus bars. The magnitude of the voltage dip varies according to the electrical distance from the fault location, and exceeds the IEEE limits for island formation at several locations. The voltage dips last for as long as the fault is present, i.e., 100 ms. This duration may or may not result in DG units shutting down, depending on their breaker operating times and any intentional added time delay before initiating breaker trip operation. Fault duration can be much longer if the fault is cleared by a backup protection.

Figure 34 shows the local frequency response, at each bus, due to the SC event. In this case, the local frequency at each generator violates the IEEE limits for abnormal frequency conditions in two occasions (assuming a lower frequency limit of 59.3 Hz). In the first case, the frequency reaches 59.25 Hz. In the second case, the frequency reaches 61 Hz before returning back to its nominal value of 60 Hz. These frequency violations last less than 0.16 sec and therefore the DG units do not have to shut down. However, these violations might lead to unnecessary shutdown of the DG units, depending on the settings of the frequency protection relays and breaker speed.

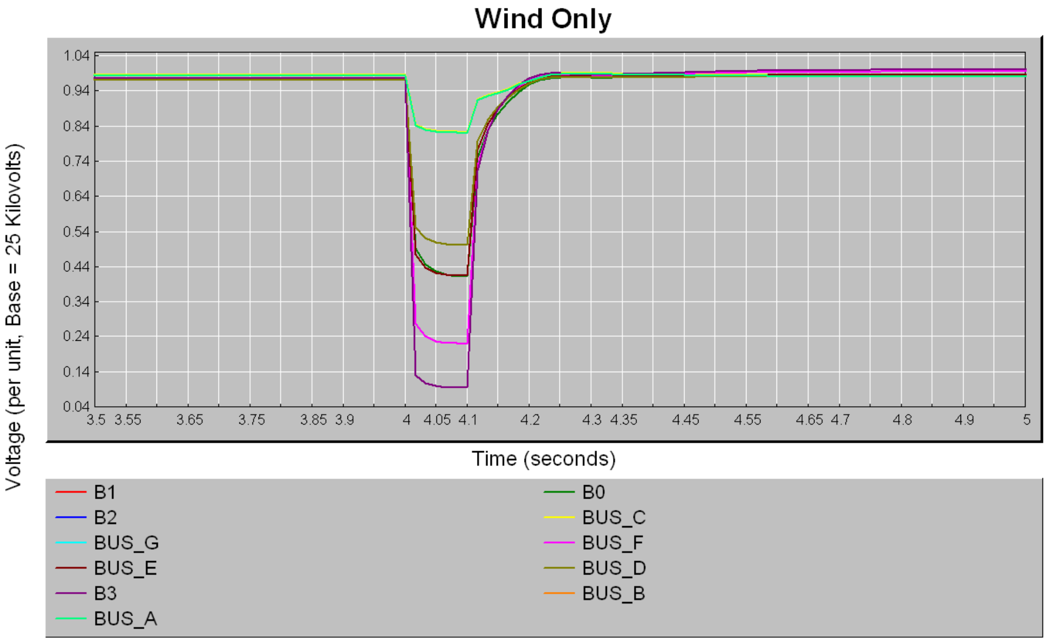

Wind Only

Figure 33: Voltage Response to a Three-phase Fault at Bus H – Balanced Load/Generation – Wind Generation Units

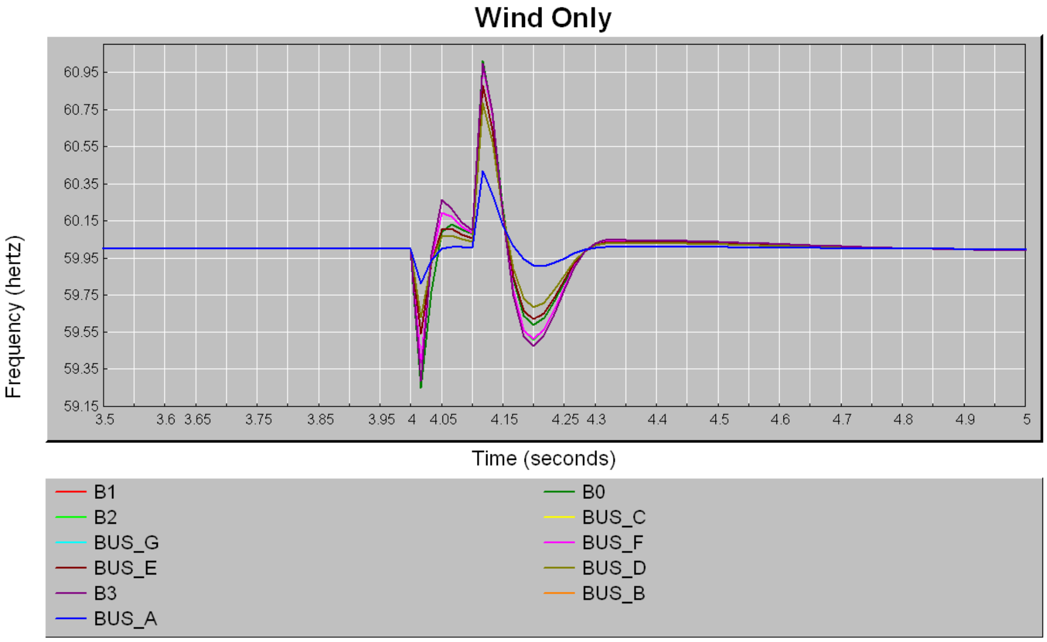

Wind Only

Figure 34: Frequency Response to a Three-phase Fault at Bus H – Balanced Load/Generation – Wind Generation Units

6.2.2 Over-Generating Distribution System

In this case, each of the three wind DG units connected to bus bars B0, F and G supplies 2.46 MW. Total wind generation is 7.38 MW, which is 1.6 times the total real power demand in the system. The transmission system absorbs the excess real power of 2.429 MW, and delivers 1.951 MVAR to both system loads and the induction generators, as depicted in Figure 35. In this case study, the wind speed is maintained constant at the value computed from the load flow analysis.

6.2.2.1 Short Circuit Conditions

This study case simulates the response of the distribution system to a three-phase to ground fault applied at bus H at t = 4 sec., which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event are shown in Figure 36 and Figure 37.

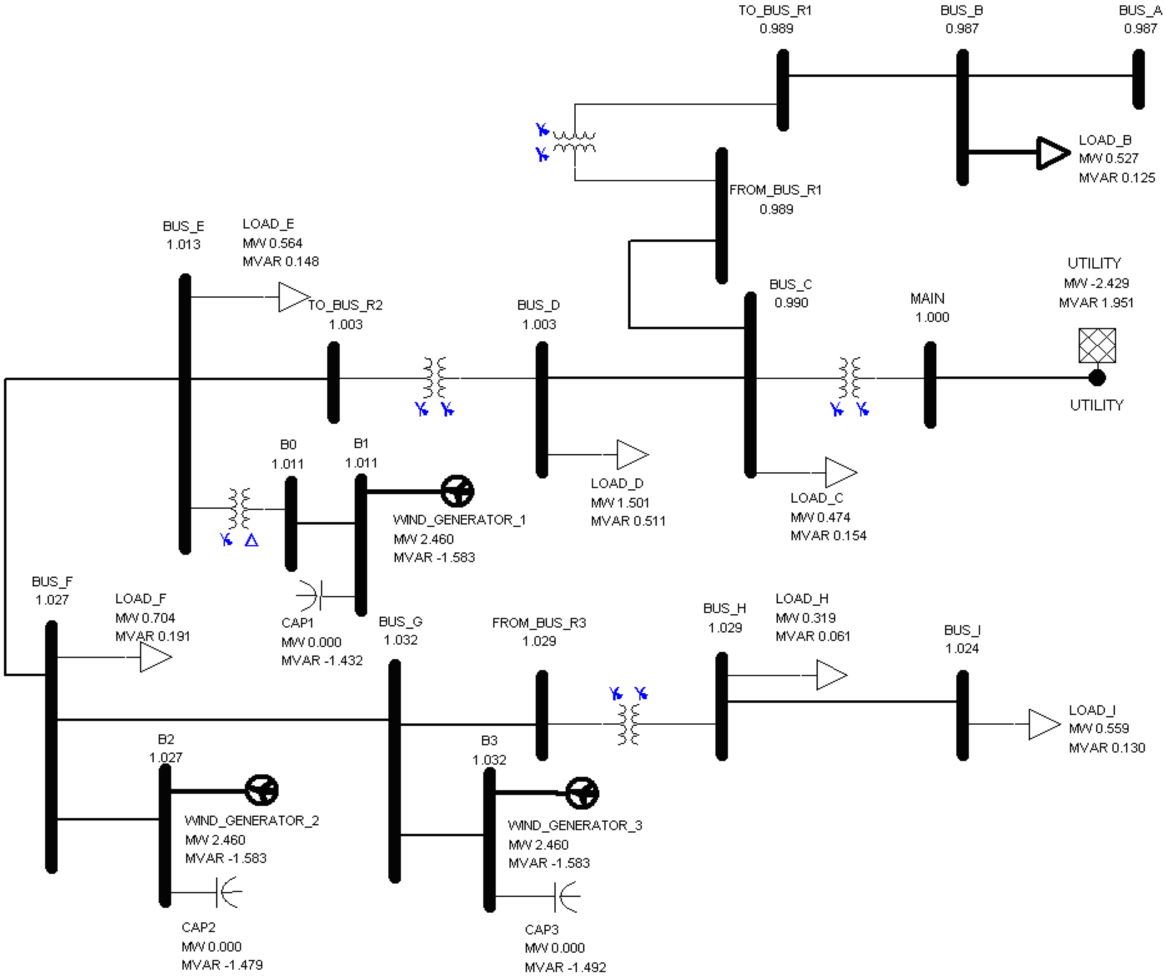


Figure 35: Over-Generating Distribution System - Wind Generation Units

Figure 36 shows the value of the voltage dip at different distribution system bus bars. The voltage dip values vary according to the electrical distance of the monitored bus bar from the fault location and exceed the IEEE limits for voltage disturbances at several locations. The voltage dips last for as long as the fault is present (100 ms). This duration may or may not result in DG units shutting down, depending on their breaker operating times and any intentional time delay before initiating breaker trip operation. Fault duration can be much longer if the fault is cleared by a backup protection.

Figure 37 shows the local frequency response, at each bus, due to SC occurrence and the subsequent clearance. In this case, the local frequency at each generator violates the IEEE limits for abnormal frequency conditions twice (assuming a lower frequency limit of 59.3 Hz). In the first case, the frequency reaches 59.2 Hz. In the second case, the frequency reaches 61.4 Hz before returning back to the nominal value of 60 Hz. These frequency violations last less than 0.16 sec. and therefore the DG units do not have to shut down. However, these violations might lead to unnecessary shutdown of the DG units, depending on the settings of the frequency protection relays and breaker speed.

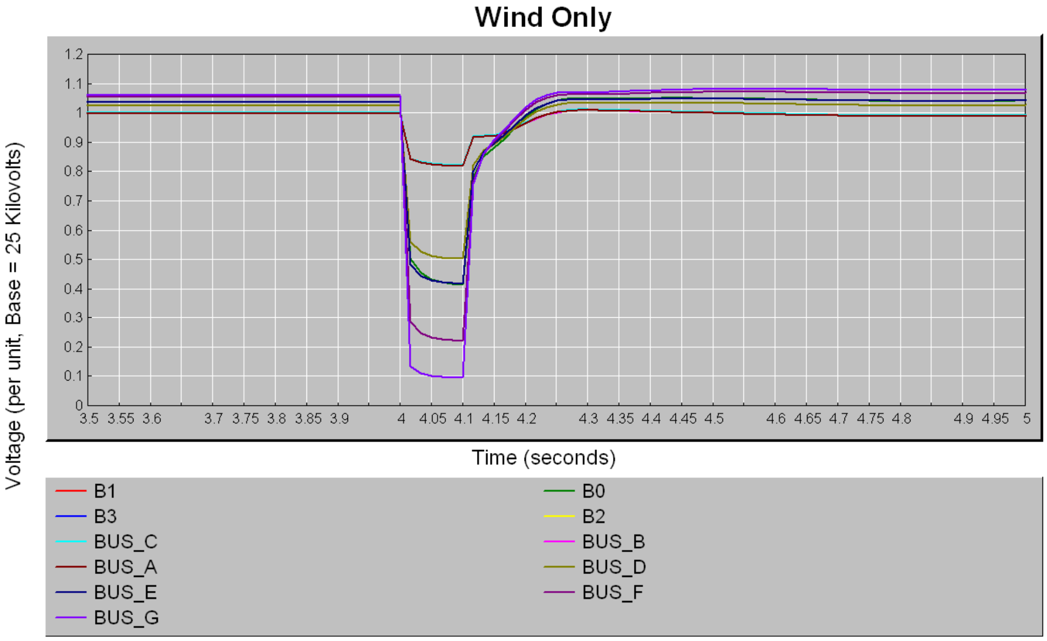


Figure 36 : Voltage Response to a Three-phase Fault at Bus H – Over-Generating system – Wind Generation Units

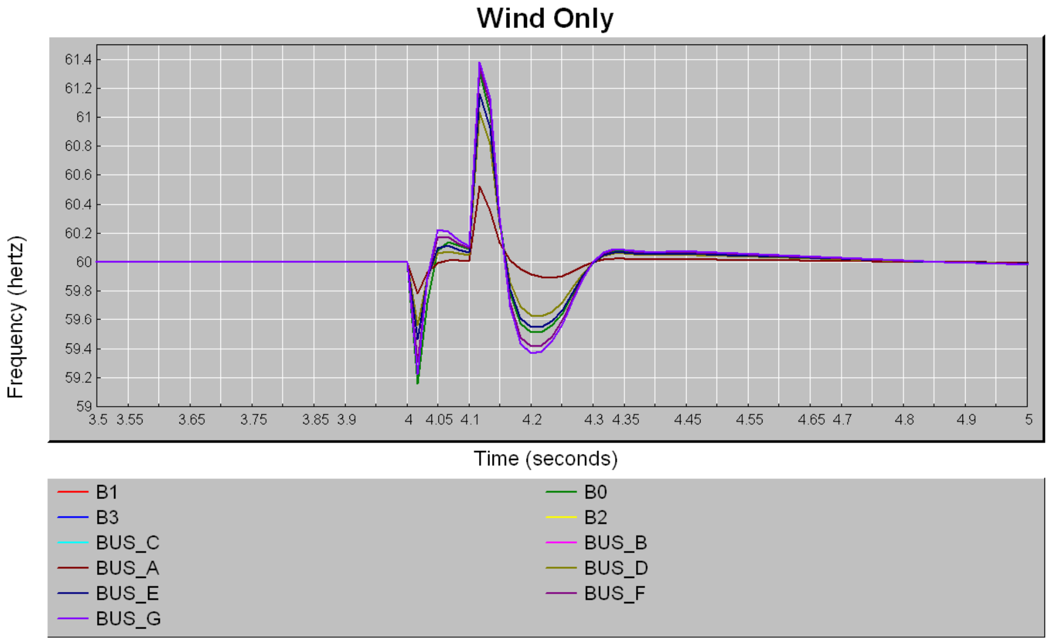


Figure 37: Frequency Response to a Three-phase Fault at Bus H – Over-Generating system – Wind Generation Units

6.2.3 Under-generating Distribution System

In this case, each of the three wind-DG units connected to bus bars B0, F and G supplies 0.96 MW. The total wind generation is 2.88 MW, which is 0.6 times the total real power demand in the system. The transmission system supplies the remaining real power requirements of 1.677 MW and also delivers 0.965 MVAR to both system loads and the induction generators, as depicted in Figure 38. In this case study, the wind speed is maintained constant at the value computed from the load flow analysis.

6.2.3.1 Short Circuit Conditions

This study case simulates the response of the distribution system to a three-phase to ground fault applied at bus bar H at t = 4 sec., which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event are shown in Figure 39 and Figure 40.

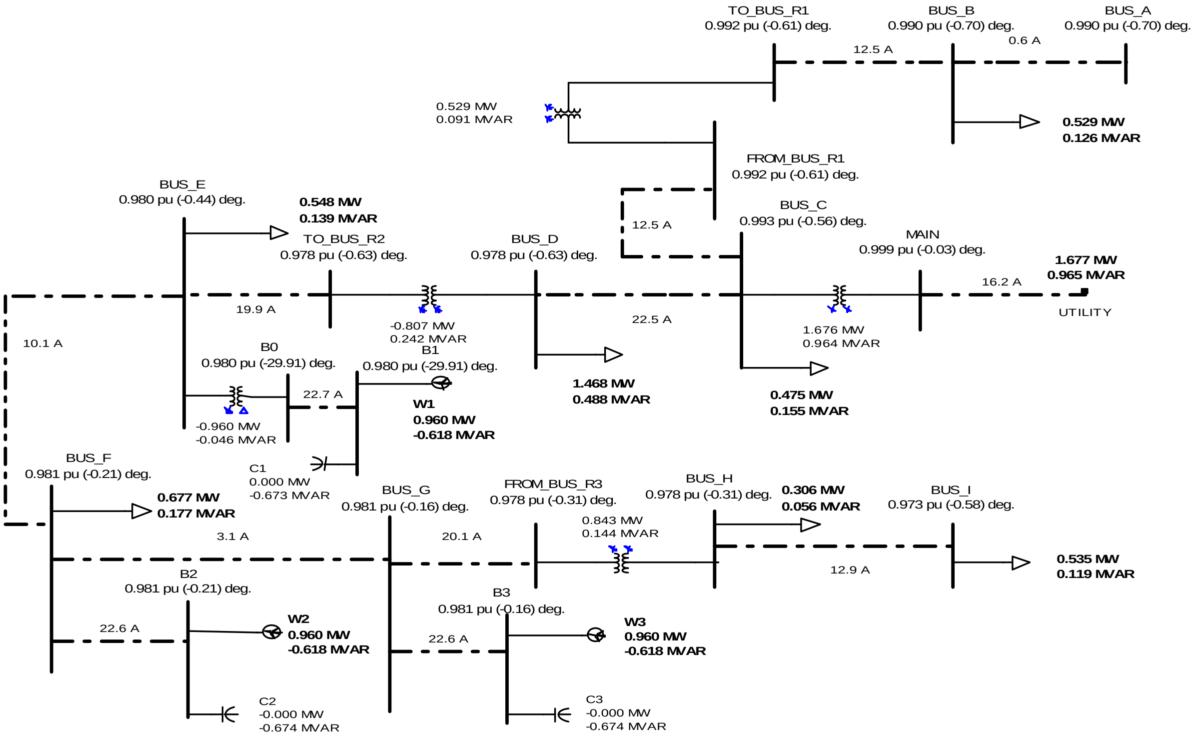


Figure 38: Under-Generating Distribution System - Wind Generation Units

Figure 39 shows the value of the voltage dip at different distribution system bus bars. The voltage dip values vary according to the electrical distance of the monitored bus bar from the fault location and exceed the IEEE limits for voltage disturbances at several locations. The voltage dips last for as long as the fault is present (100 ms). This duration may or may not result in DG units shutting down, depending on their breaker operating times and any intentional time delay before initiating breaker trip operation. Fault duration can be much longer if the fault is cleared by a backup protection.

Figure 40 shows the local frequency response, at each bus, due to SC occurrence and the subsequent clearance. In this case, the local frequency at each generator violates the IEEE limits for abnormal frequency conditions in the upper limit (assuming a lower frequency limit of 59.3 Hz).The lower frequency reaches 59.5 Hz. The higher frequency reaches 60.7 Hz before returning back to its nominal value of 60 Hz. However these frequency violations last less than 0.16 sec and therefore the DG units do not have to shut down.

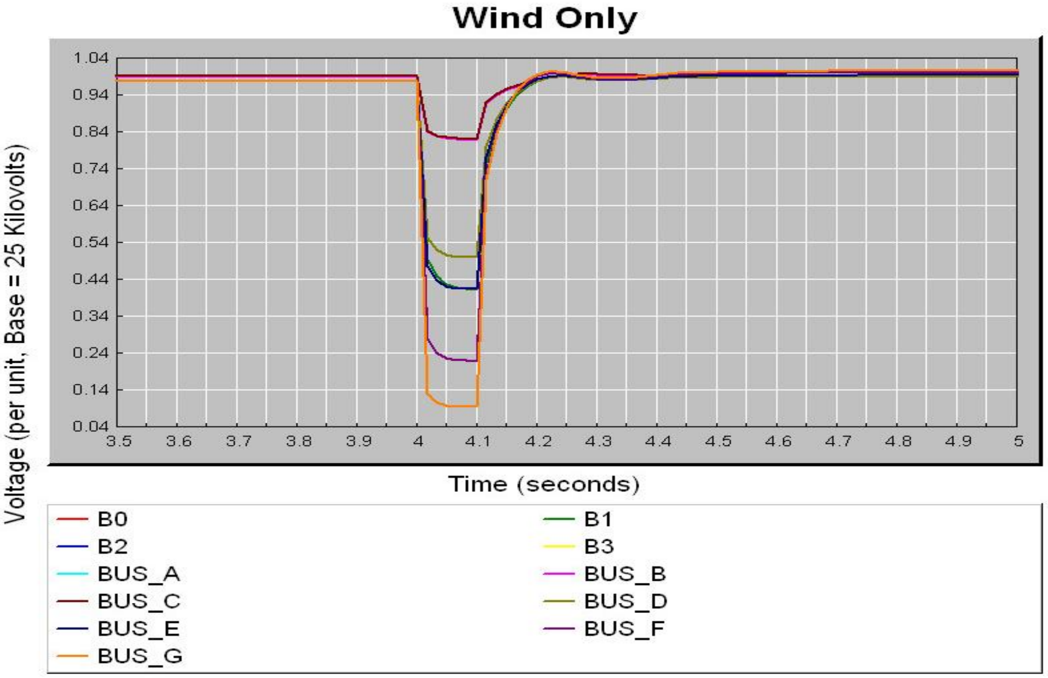


Figure 39: Voltage Response to a Three-phase Fault at Bus H- Under-Generating System-
Wind generation Units

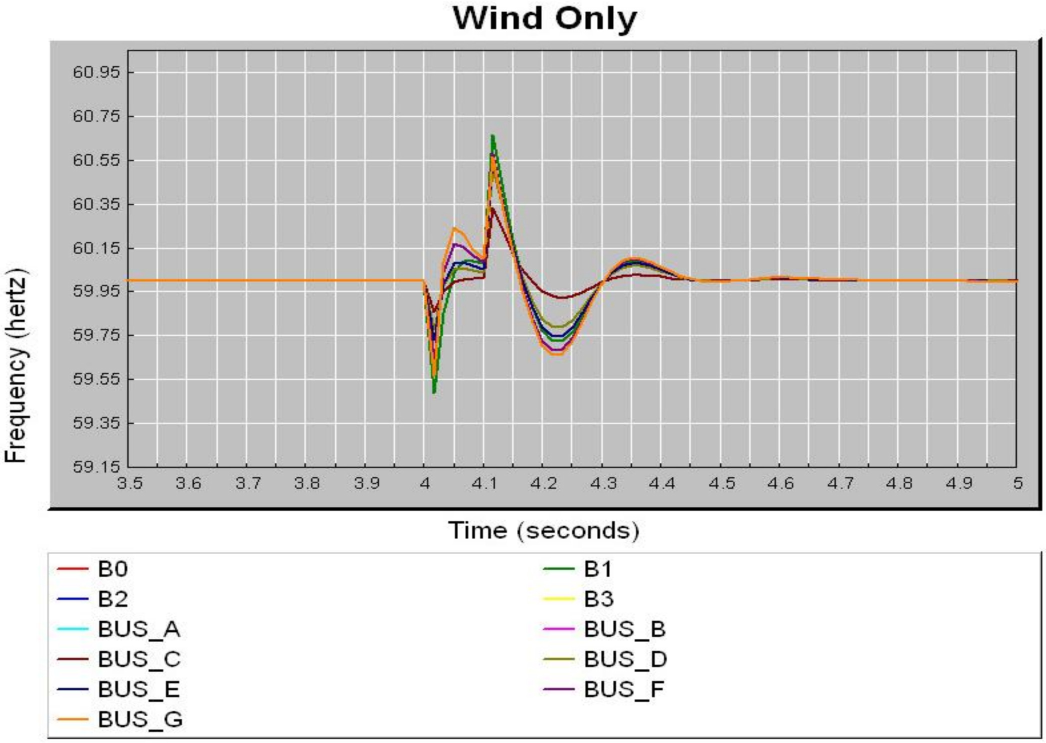


Figure 40: Frequency Response to a Three-phase Fault at Bus H –Under-Generating system-Wind generation Units

6.3 Distribution system with Embedded DFIG Wind Generation

6.3.1 Self-sufficient Distribution System

The load flow for this case is shown in Figure 41. The three wind DG units connected to bus bars B0, F and G drive 3 MVA doubly fed coupled induction generators. Each wind DG unit supplies 1.540 MW at a power factor of 100%. The transmission system supplies the remaining reactive power demanded by the loads, i.e., 1.206 MVAR, as indicated in Figure 41. In all cases, wind speed is maintained constant at the value computed from the load flow analysis.

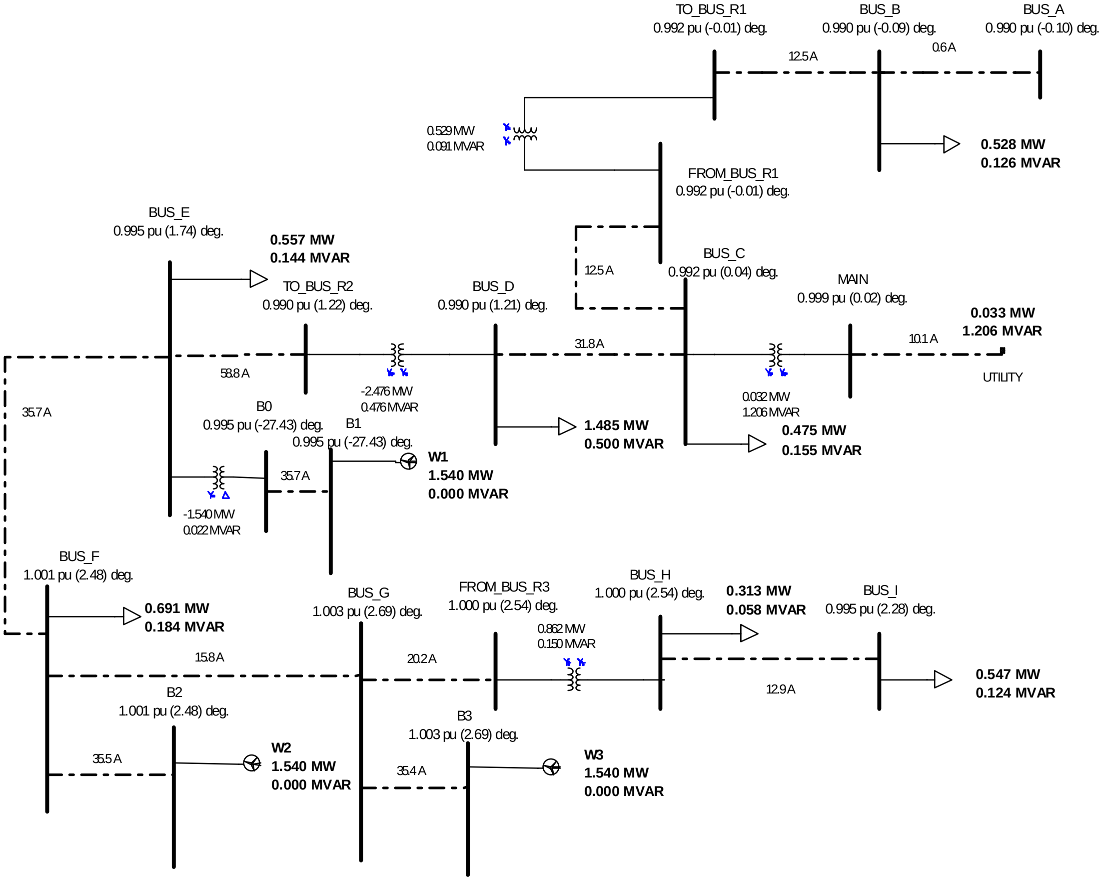


Figure 41: Self-Sufficient Distribution System – DFIG Wind Generation Units

6.3.1.1 Loss of Load Condition

This case study simulates the loss of the largest load in the distribution system which is connected to bus D. The response of the system to the loss of load at t = 4 sec. is shown in Figure 42 and Figure 43.

Figure 42 shows the local frequency response, at each bus, due to the loss of load. Since the distribution system is connected to a stronger system, the local frequency at each generator returns back to its nominal value of 60 Hz. The maximum frequency excursion in this case reaches 60.12 Hz, which did not reach the IEEE limits for abnormal frequency conditions detection. Since the wind speed is assumed constant, the wind power generation remains practically constant, while the feeding system delivers the deficit power created by the generation loss, as observed in Figure 43.

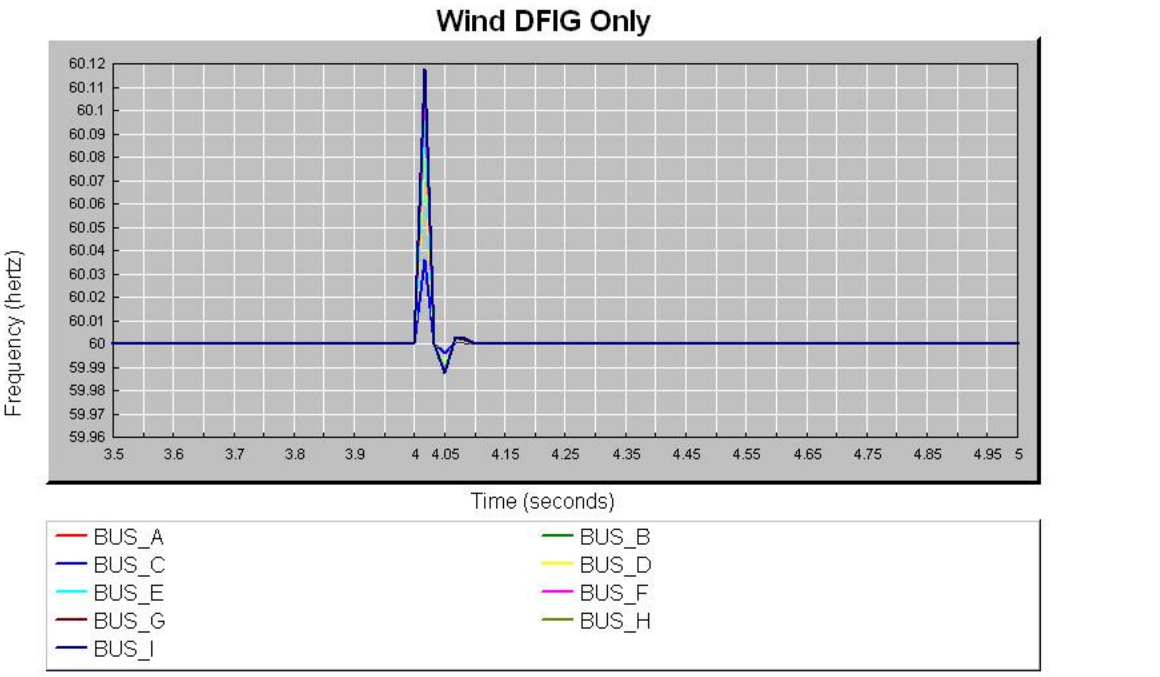


Figure 42: Frequency Response to Load Loss – Balanced Load/Generation – DFIG Wind Generation Units

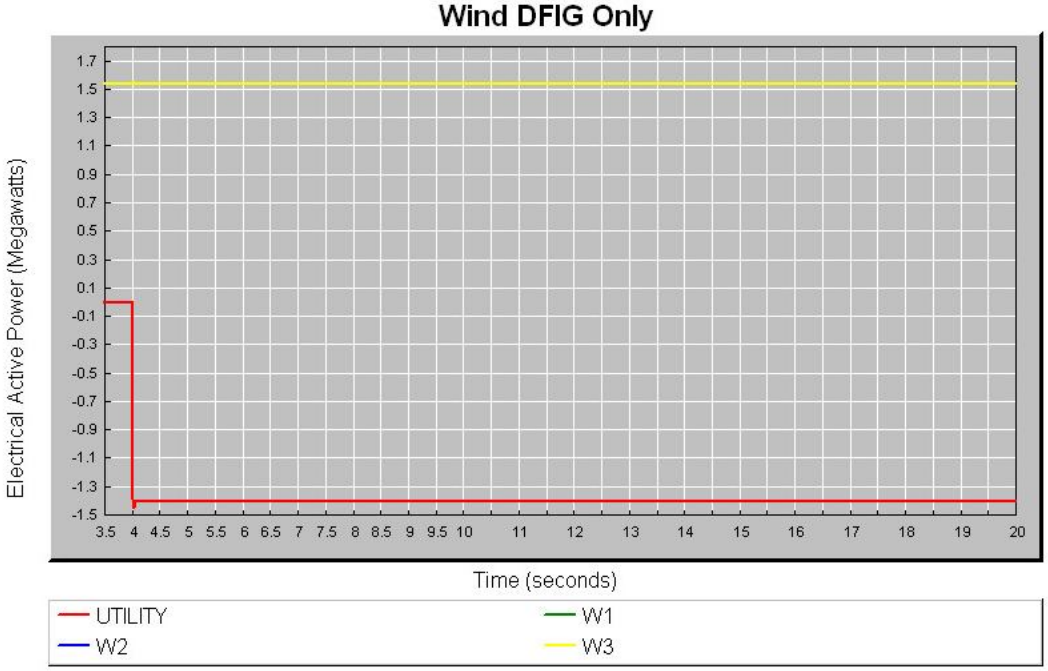


Figure 43: Generation Response to Load Loss – Balanced Load/Generation – DFIG Wind Generation Units

6.3.1.2 Loss of Generation Condition

This case study simulates the loss of the 1.54 MW DFIG unit connected to bus B0. The response of the system to such generation loss at t = 4 sec. is shown in Figure 44 and Figure 45.

Figure 44 shows the local frequency response, at each bus, due to the loss of generation that reveals that the local frequency at each generator returns back to its nominal value of 60 Hz because the distribution system is connected to a stronger system. The maximum frequency excursion in this case reaches 59.86 Hz. This value did not reach the IEEE limits for abnormal frequency conditions detection. Similar to the previous scenario, the wind power generation remains practically constant, as the wind speed is assumed constant, while the feeding system delivers the deficit power created by the generation loss, as illustrated in Figure 45.

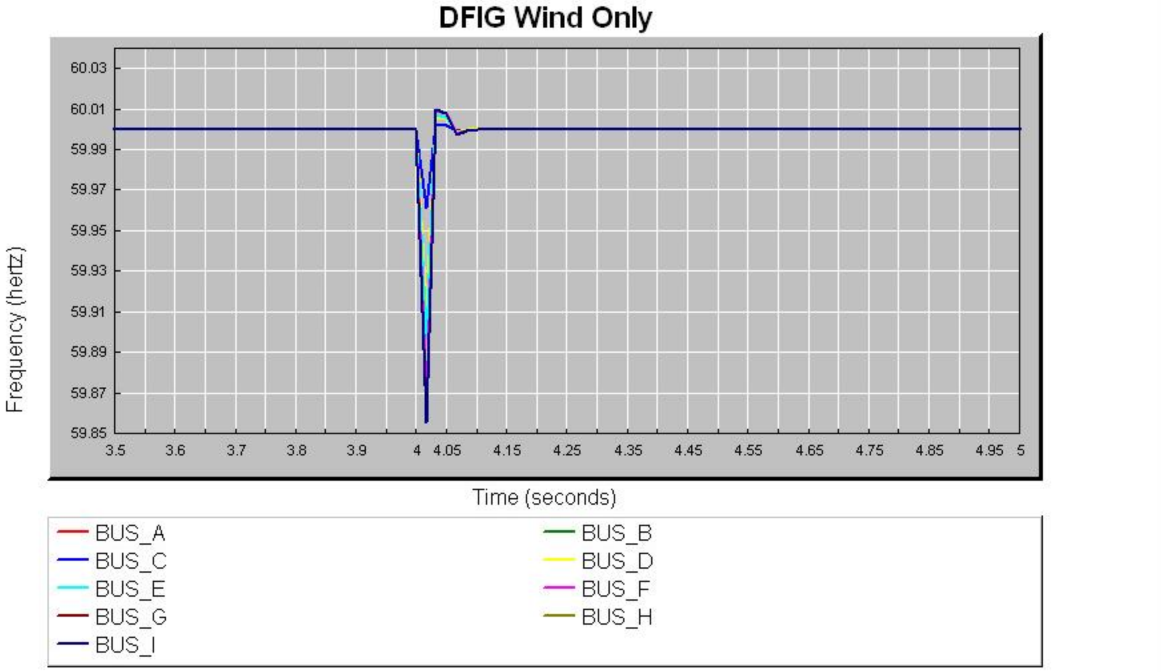


Figure 44: Frequency Response to Generation Loss – Balanced Load/Generation – DFIG Wind Generation Units

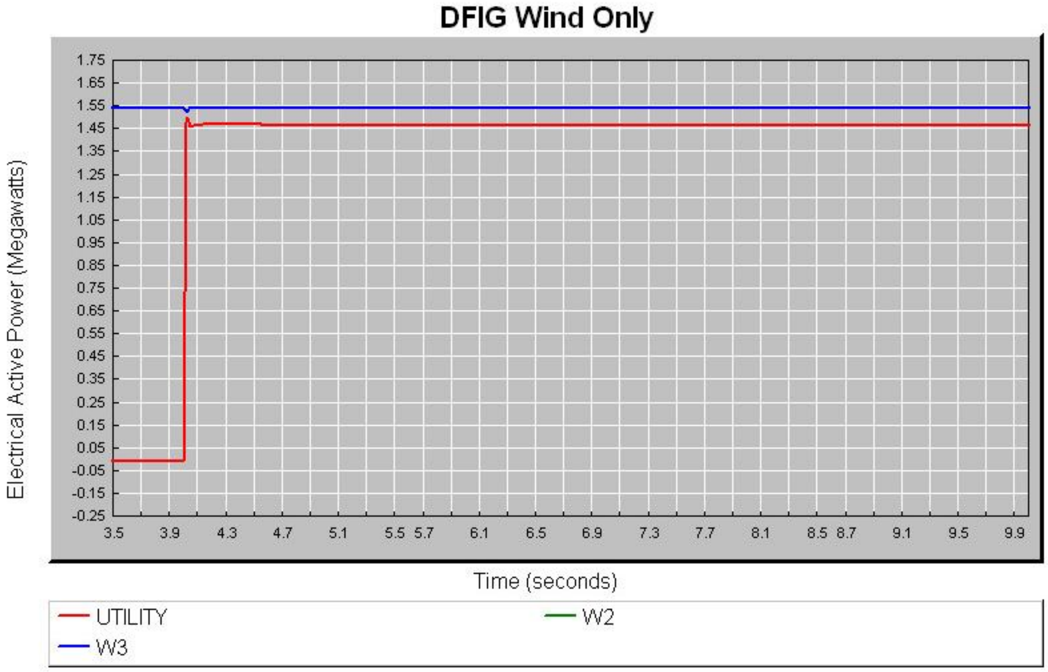


Figure 45: Generation Response to Generation Loss – Balanced Load/Generation – DFIG Wind Generation Units

6.3.1.3 Short Circuit Conditions

This case study simulates the response of the distribution system to a three-phase to ground fault applied at bus H, which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event at t = 4 sec. are shown in Figure 46 and Figure 47.

Similar to the previous scenarios, Figure 46 shows that the magnitude of the voltage dip, at different distribution system bus bars, varies according to the electrical distance from the fault location, and exceeds the IEEE limits for voltage disturbances at several locations. The voltage dips last for as long as the fault is present, i.e., 100 ms. This duration may or may not result in DG units shutting down, depending on their breaker operating times and any intentional added time delay before initiating breaker trip operation. Fault duration can as well be much longer if the fault is cleared by a backup protection.

Figure 47 shows the local frequency response, at each bus, due to the SC event. In the worst case, the local frequency of the generator at the bus G violates the IEEE limits for abnormal frequency conditions in two occasions (assuming a lower frequency limit of 59.3 Hz). In the first case, the frequency reaches 54.58 Hz. In the second case, the frequency reaches 63.2 Hz before returning back to its nominal value of 60 Hz. Since in the DFIG the rotor is connected to the grid via the converters and the stator is connected directly to the grid, the disturbance in the network is transmitted to the rotor as well and is higher than the case scenarios with the directly coupled wind induction generators. However, these frequency violations last less than 0.16 sec and therefore the DG units do not have to shut down.

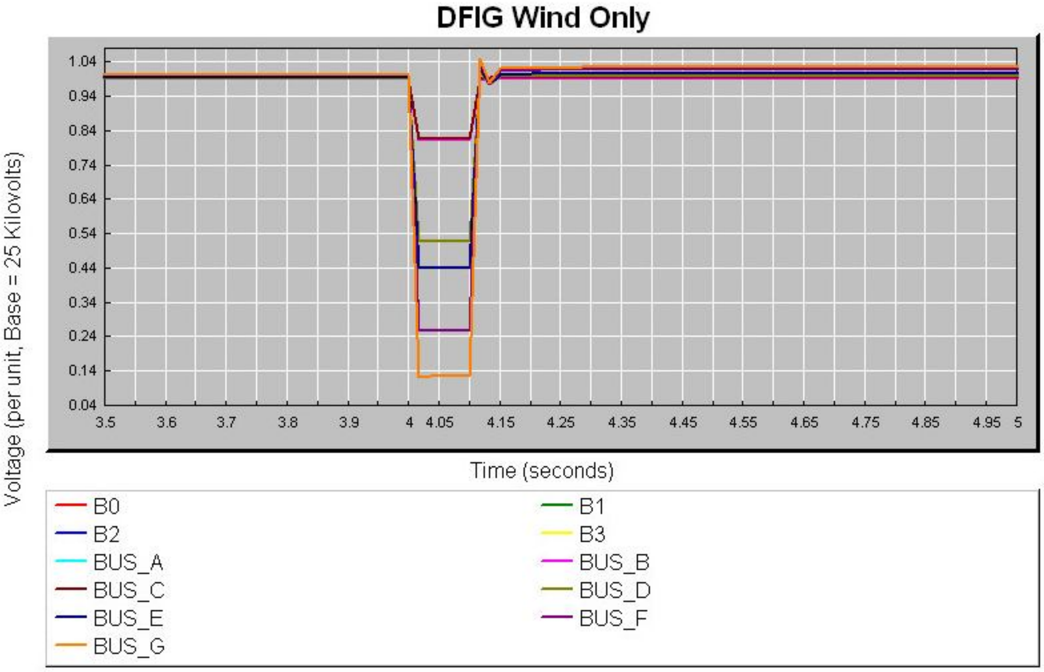


Figure 46: Voltage Response to a Three-phase Fault at Bus H – Balanced Load/Generation – DFIG Wind Generation Units

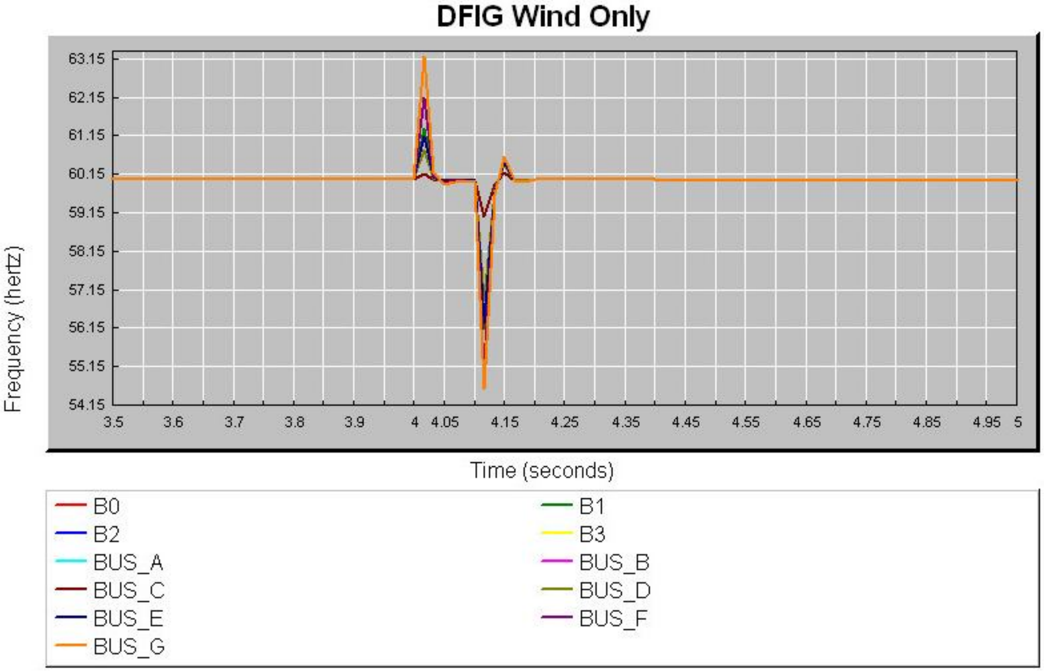


Figure 47: Frequency Response to a Three-phase Fault at Bus H – Balanced Load/Generation – DFIG Wind Generation Units

6.3.2 Over-Generating Distribution System

In this case, each of the three DFIG wind DG units connected to bus bars B0, F and G supplies 2.4 MW. Total wind generation is 7.2 MW, which is 1.6 times the total real power demand in the system. The transmission system absorbs the excess of real power of 2.263 MW, and delivers 1.556 MVAR to the system, as depicted in Figure 48. In this case study, the wind speed is maintained constant at the value computed from the load flow analysis.

6.3.2.1 Short Circuit Conditions

This study case simulates the response of the distribution system to a three-phase to ground fault applied at bus bar H at t = 4 sec., which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event at t = 4 sec. are shown in Figure 49 and Figure 50.

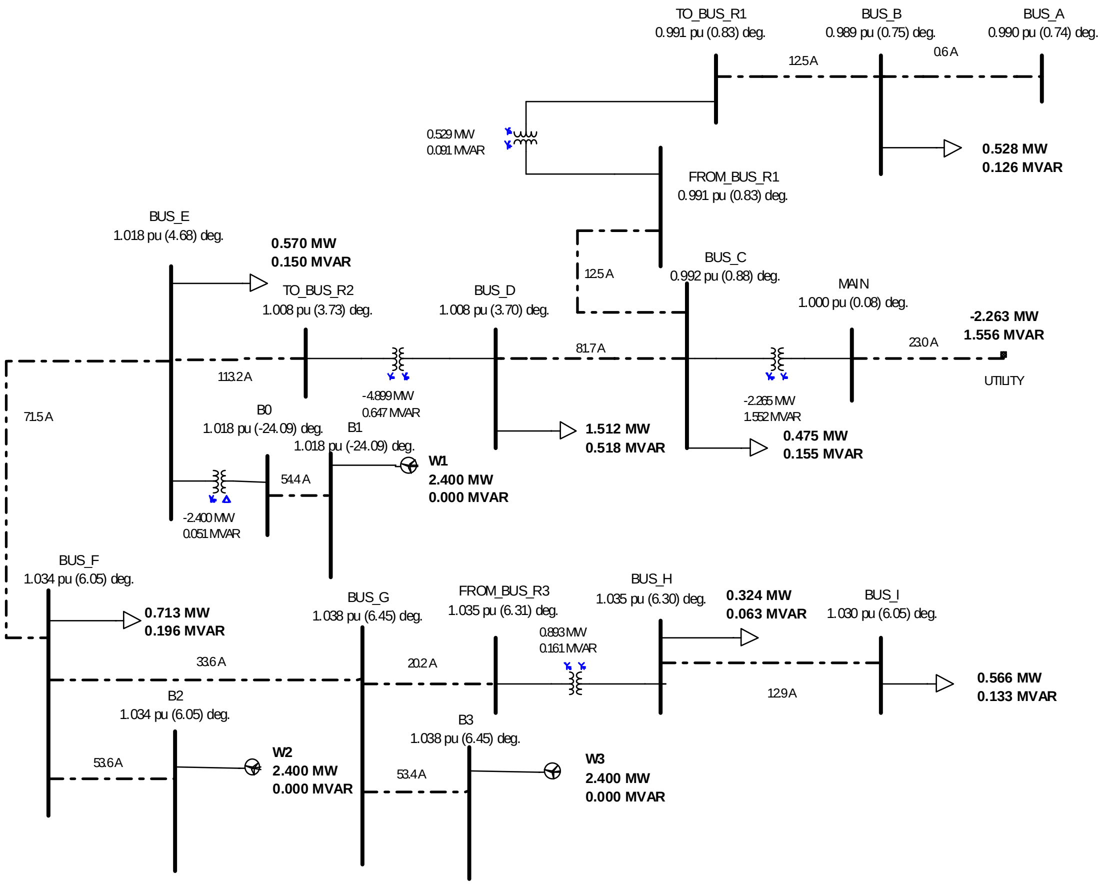


Figure 48: Over-Generating Distribution System – DFIG Wind Generation Units

Figure 49 shows that the magnitude of the voltage dip, at different distribution system bus bars, varies according to the electrical distance from the fault location, and exceeds the IEEE limits for voltage disturbances at several locations. The voltage dips last for as long as the fault is present (100 ms). This duration may or may not result in DG units shutting down, depending on the settings of the protection schemes as explained earlier.

Figure 50 shows the local frequency response, at each bus, due to SC occurrence and the subsequent clearance. In this case, the local frequency for the worst case for the generator connected to bus G violates the IEEE limits for abnormal frequency conditions two times (assuming a lower frequency limit of 59.3 Hz). At first, the frequency reaches 63.7 Hz (when the fault occurs) and then drop to 53.9 Hz (when the fault is cleared) before returning back to its nominal value of 60 Hz. Since in the DFIG the rotor is connected to the grid via the converters and the stator is connected directly to the grid, the disturbance in the network is transmitted to the rotor as well and is higher than for example in the case with directly coupled wind generator. These frequency violations last less than 0.16 sec. and therefore the DG units do not have to shut down.

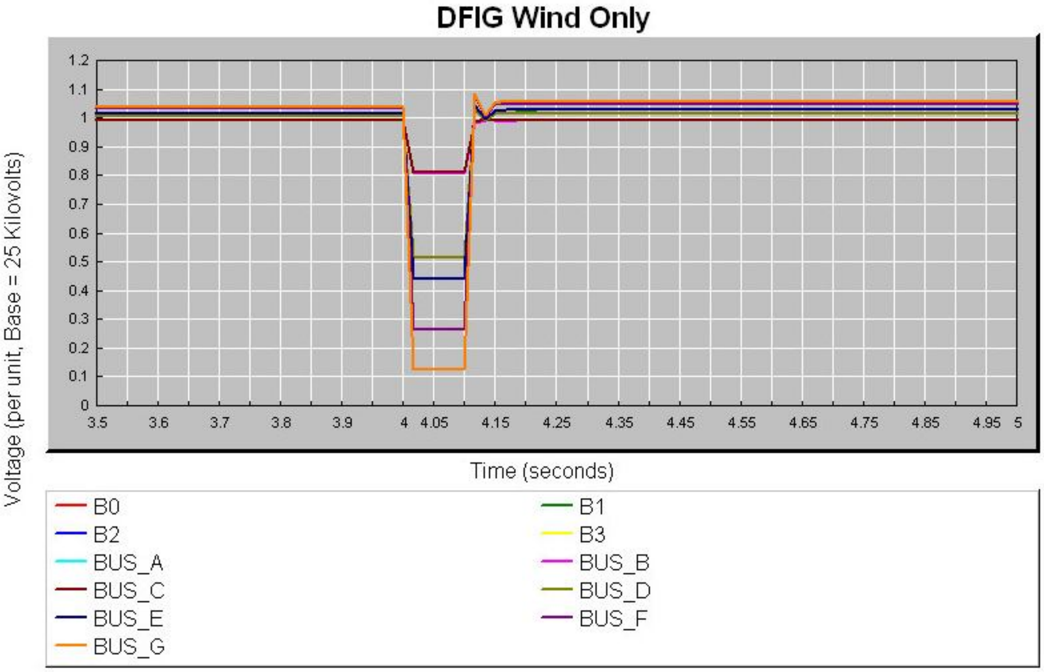


Figure 49 : Voltage Response to a Three-phase Fault at Bus H – Over-Generating system – DFIG Wind Generation Units

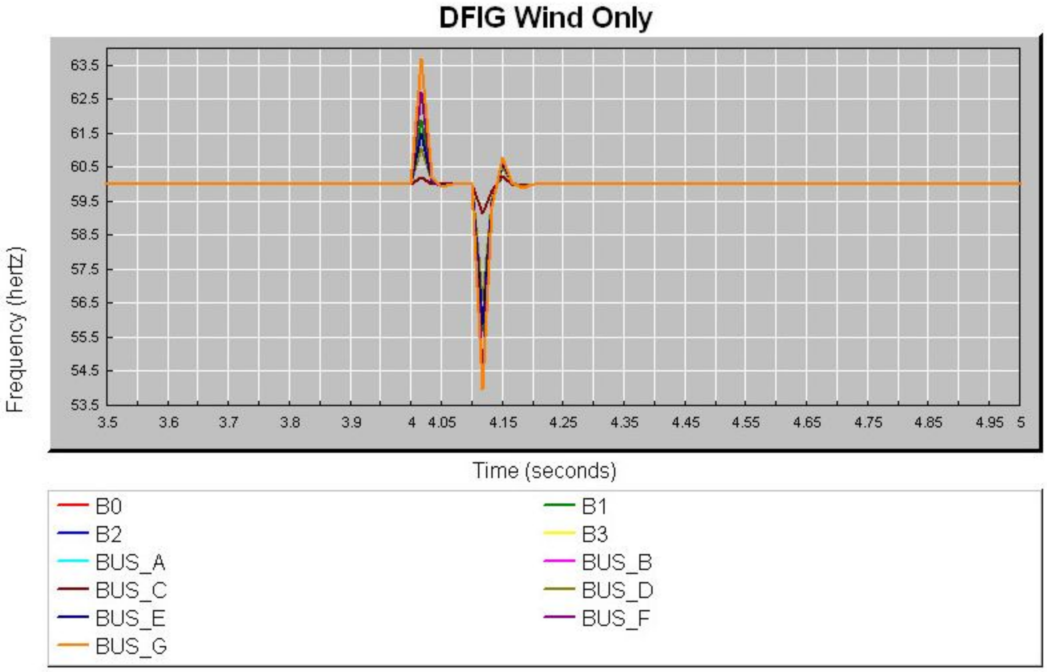


Figure 50: Frequency Response to a Three-phase Fault at Bus H – Over-Generating System – DFIG Wind Generation Units

6.3.3 Under-generating Distribution System

In this case, each of the three DFIG units connected to bus bars B0, F and G supplies 0.96MW. Total wind generation is 2.88 MW, which is 0.6 times the total real power demand in the system. The transmission system compensates the rest of the real power of 1.677MW, and also delivers 1.132MVAR to the system, as depicted in Figure 51. In this case study, the wind speed is maintained constant at the value computed from the load flow analysis.

6.3.3.1 Short Circuit Conditions

This study case simulates the response of the distribution system to a three-phase to ground fault applied at bus bar H at t = 4 sec., which is cleared after 6 cycles (100 ms) by opening line L6 (Figure 1). The responses of the distribution system to the short circuit event at t = 4 sec. are shown in Figure 52 and Figure 53.

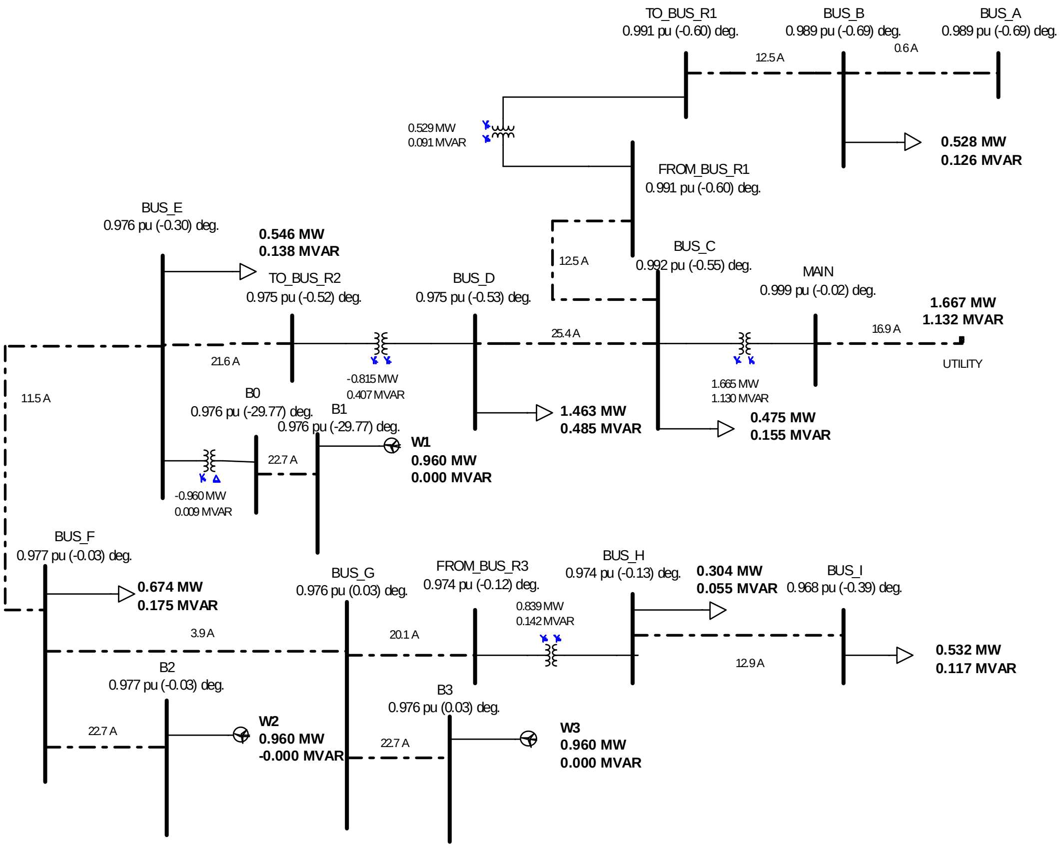


Figure 51: Under-Generating Distribution System - Wind Generation Units

Figure 52 shows that the magnitude of the voltage dip, at different distribution system bus bars, varies according to the electrical distance from the fault location, and exceeds the IEEE limits for voltage disturbances at several locations. The voltage dips last for as long as the fault is present (100 ms). This duration may or may not result in DG units shutting down, depending on the settings of the protection schemes, as explained earlier.

Figure 53 shows the local frequency response, at each bus, due to SC occurrence and the subsequent clearance. In this case, the local frequency in the worst case for the generator connected to bus G violates the IEEE limits for abnormal frequency conditions twice (assuming a lower frequency limit of 59.3 Hz). At first, the frequency reaches 63.1 Hz (when the fault occurs) and then drop to 54.8 Hz (when the fault is cleared) before returning back to its nominal value of 60 Hz after each disturbance. Since in the DFIG the rotor is connected to the grid via the converters and the stator is connected directly to the grid, the disturbance in the network is transmitted to the rotor as well and the disturbance is higher than, for example, in the case with directly coupled wind generator. However these frequency violations last less than 0.16 sec and therefore the DG units do not have to shut down.

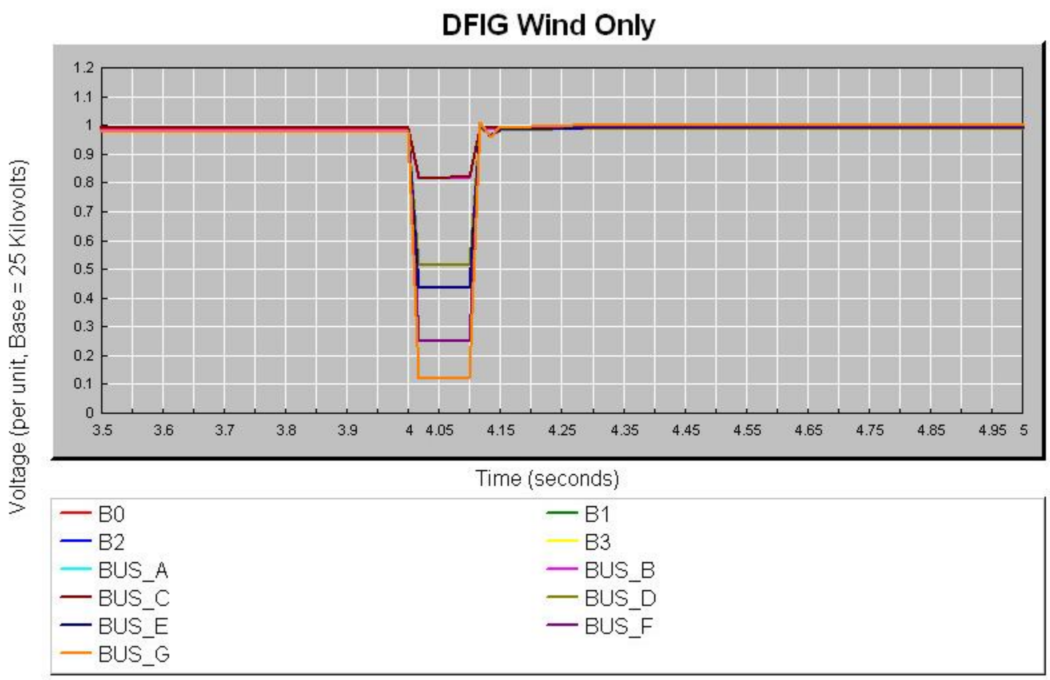


Figure 52: Voltage Response to a Three-phase Fault at Bus H- Under-Generating System- DFIG Wind generation Units

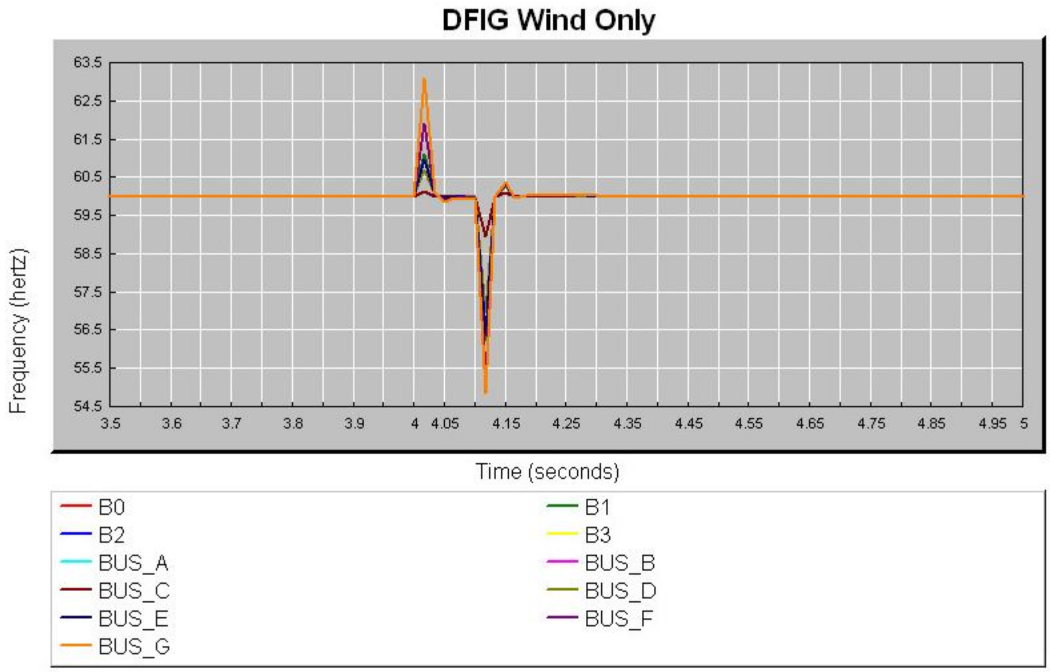


Figure 53: Frequency Response to a Three-phase Fault at Bus H –Under-Generating system - DFIG Wind generation Units

6.4 Summary of case studies

Table 6: Summary of case studies and pre-event operating conditions.
Initial load: 4.622 MW & 1.308 MVAR

Section	Reference load flow	Subsystem DG production		Interconnection Exchange		Event		Generation/load mismatch
		MW	MVAR	MW	MVAR	MW	MVAR	
6.1.1.1	Fig. 13	3 synch. hydraulic DG				Loss of load		1.03
		4.74	1.291	0.004	-0.046	1.5	0.51	
6.1.1.2	Fig. 13	3 synch. hydraulic DG				Loss of generation		1.03
		4.74	1.291	0.004	-0.046	1.58	0.976	
6.1.1.3	Fig. 13	3 synch. hydraulic DG				Short circuit		1.03
		4.74	1.291	0.004	-0.046	3 phases	6 cycles	
6.1.2.1	Fig. 22	3 synch. hydraulic DG				Short circuit		2.03
		9.36	-0.647	-4.076	2.792	3 phases	6 cycles	
6.1.3.1	Fig 25	3 synch. hydraulic DG				Short circuit		0.52
		2.4	2.636	2.374	-1.335	3 phases	6 cycles	
6.2.1.1	Fig. 28	3 induction wind DG				Loss of load		1.00
		4.62	-0.975	-0.007	2.218	1.5	0.51	
6.2.1.2	Fig. 28	3 induction wind DG				Loss of generation		1.00
		4.62	-0.975	-0.007	2.218	1.54	-0.33	
6.2.1.3	Fig. 28	3 induction wind DG				Short circuit		1.00
		4.62	-0.975	-0.007	2.218	3 phases	6 cycles	
6.2.2.1	Fig. 35	3 induction wind DG				Short circuit		1.60
		7.38	-0.346	-2.429	1.952	3 phases	6 cycles	
6.2.3.1	Fig. 38	3 induction wind DG				Short circuit		0.62
		2.88	-1.854	1.677	0.965	3 phases	6 cycles	
6.3.1.1	Fig. 41	3 induction wind DG				Loss of load		10
		4.62	0	0.033	1.206	1.5	0.51	
6.3.1.2	Fig. 41	3 induction wind DG				Loss of generation		1.0
		4.62	0	0.033	1.206	1.54	0	
6.3.1.3	Fig. 41	3 induction wind DG				Short circuit		1.0
		4.62	0	0.033	1.206	3 phases	3 phases	
6.3.2.1	Fig. 48	3 induction wind DG				Short circuit		1.56
		7.2	0	-2.263	1.556	3 phases	6 cycles	
6.3.3.1	Fig. 51	3 induction wind DG				Short circuit		0.62
		2.88	0	1.667	1.132	3 phases	6 cycles	

7 Conclusions

This study demonstrates the effect of distributed generation (DG) units on the dynamic behaviour of the host distribution system. Dynamic simulation results are provided for a series of case studies taking into account (i) different DG technologies, i.e. hydro and wind and (ii) different DG penetration levels, during a grid-connected operation.

The results of the dynamic simulations of this report indicate that

- The loss of a large load in the system does not impose frequency deviations in the system that are large enough to violate the permissible limits of the IEEE 1547 Standard, regardless of the DG technology under investigation. Besides, frequency disturbance due to islanding is not mistakenly detected due to frequency deviation for disturbances such as loss of a large load because of the presence of a strong utility system that imposes both voltage and frequency to the distribution system.

- Three-phase short-circuit disturbances are more likely to cause false islanding detection due to the large voltage dips that the system experiences under such transients. If the fault lasts long enough, islanding can mistakenly be detected based on violations to voltage limits regardless of the DG technology under investigation. In terms of frequency deviations, a three-phase short-circuit disturbance has a deeper impact on a distribution system with interconnected wind DG, and even more with doubly fed induction generators since disturbances in the network are transmitted to the rotor via the converters and also directly to the stator. However, the observed frequency deviations, although large enough to violate the permissible limits of the IEEE 1547 Standard, do not last long enough to cause a false islanding detection. Nonetheless, the DG`s line protection shall always be configured to detect such distribution system faults and would trip the generator accordingly, regardless of whether the anti-islanding DG protection is activated or not.

- The simulations of this report show that major disturbances in the system impose variations in the voltage and the frequency of the system whose magnitude depends on the type and size of the DG technology under investigation, the location of the disturbance and the measuring location.

8 References

[1] Soumare, S., Gao, F. and Morched, A.S., Distributed Generation Case Study 4 – Dynamic Behaviour during Grid Parallel Mode, report # CETC 2007-129 (TR), CANMET Energy Technology Centre – Varennes, Natural Resources Canada, May 2007, pp. 34.

[2] Kwok, C and Morched, A.S., Effect of Adding Distributed Generation to Distribution Networks Case Study 1, report # CETC 2006-099 (TR), CANMET Energy Technology Centre – Varennes, Natural Resources Canada, April 2006, 34 pp.

[3] Kwok, C. and Morched, A.S., Effects of Adding Distributed Generation to Distribution Networks Case Study 2, report # CETC 2006-100 (INT), CANMET Energy Technology Centre – Varennes, Natural Resources Canada, April 2006, 18 pp.

[4] Kwok, C. and Morched, A.S., Effects of Adding Distributed Generation to Distribution Networks Case Study 3: Protection coordination considerations with inverter and machine based DG, report # CETC 2006-147 (INT), CANMET Energy Technology Centre – Varennes, Natural Resources Canada, April 2006, 18 pp.

[5] Hernandez-Gonzalez, G. and Abbey, C., Effect of Adding Distributed Generation to Distribution Networks Case Study 1, Second edition, report # 2009-025 (RP-TEC) 411-MODSIM, CanmetENERGY, Varennes Research Centre, Natural Resources Canada, May, 2009, 34 pp.

[6] Hernandez-Gonzalez, G. and Abbey, C., Effect of Adding Distributed Generation to Distribution Networks Case Study 2, Second edition, report # 2009-116 (RP-TEC) 411-MODSIM, CanmetENERGY – Varennes, Natural Resources Canada, July, 2009, 17 pp.

[7] Hernandez-Gonzalez, G. and Abbey, C., Effect of Adding Distributed Generation to Distribution Networks Case Study 3: Protection coordination considerations with inverter and machine based DG, Second edition, report # 2009-043 (RP-TEC) 411-MODSIM, CanmetENERGY Technology Centre – Varennes, Natural Resources Canada, March 2009, 21 pp.

[8] IEEE Standards Coordinating Committee 21, IEEE_Standard for Interconnecting Distributed Resources with Electric Power Systems, 1547^{TM}-2003, July 2003.

[9] Canadian Standards Association, CSA Standard C22.3 No. 9-08 Interconnection of distributed resources and electricity supply systems, 2008.

ANNEX A
CYMEDIST file references

ANNEX A
CYMEDIST file references

The CYMDIST files corresponding to the case studies of this report are as follows and may be obtained on demand. The CYMDIST software can be obtained from www.cyme.com.

Section	CYMDIST Files
6.1.1.1,6.1.1.2,6.1.1.3 Three Synchronous Hydraulic DG units-Self-sufficient system	hydraulicDG_selfsufficient.sxst
6.1.2.1 Three Synchronous Hydraulic DG units-Over-generating system	hydraulicDG_overgen.sxst
6.1.3.1 Three Synchronous Hydraulic DG Unit – Under-generating system	hydraulicDG_undergen.sxst
6.2.1.1,6.2.1.2,6.2.1.3 Three Induction Wind DG units-Self-sufficient system	windDG_selfsufficient.sxst
6.2.2.1 Three Induction Wind DG units-Over-generating system	windDG_overgen.sxst
6.2.3.16.2.3.1 Three Induction Wind DG units-Under-generating system	windDG_undergen.sxst
6.3.1.1,6.3.1.2,6.3.1.3 Three DFIG Wind DG units-Over-generating system	windDFIG_self_sufficient.sxst
6.3.2.1 Three DFIG Wind DG units-Over-generating system	windDFIG_overgen.sxst
6.3.3.1 Three DFIG Wind DG units-Under-generating system	windDFIG_undergen.sxst