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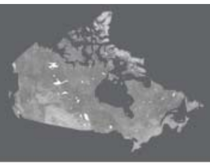

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DISTRIBUTED GENERATION ANALYSIS
CASE STUDY 5:

Investigation of Passive Anti-Islanding Detection for Rotating Machine-based DG Technologies

Canada

Distributed Generation Analysis
Case Study 5:

Investigation of Passive Anti-Islanding Detection for Rotating Machine-based DG Technologies

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DISCLAMER

ACKNOWLEDGMENT

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

SUMMARY

This report details the fifth of a series of case studies which are intended to disseminate knowledge about the impact of distributed generation (DG) on distribution systems planning and operation. This case study investigates the dynamic behaviour of rotating machine-based DG subsequent to the disconnection of the substation breaker. The passive trip settings defined in the IEEE 1547-2003 Standard are evaluated in terms of their ability to be used as anti-islanding protection for rotating machines. 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 generator 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 CYMDIST case study files; however, it also serves as a self-contained and informative report.

SOMMAIRE

Ce document est le cinquième 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 considère le comportement dynamique de la PD suite à la déconnection du disjoncteur de poste. Les plages de fréquences et tensions établies dans la norme 1547-2003 de l'IEEE sont évaluées en termes de leur capacité à servir comme protection anti-îlotage pour des machines tournantes. Cette 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, toujours avec l'intention de faciliter 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) [2-9].

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 integration of these sources is not properly planned, it could result in deterioration of network reliability through voltage regulation, protection coordination and security problems.

The interaction between distributed resources and the distribution system in which they are embedded involves several phenomena that 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 behaviour as well as the dynamic behaviour of the distribution system in the presence of DG.

The impact of adding DG to a distribution system on the system's voltage profile, short circuit levels and protection coordination has been demonstrated in previous reports [2-4], [6-8].

The objective of this report is to study the impact of rotating machine-based distributed generation of different type, size and level of penetration, on the dynamic behaviour of the distribution system in which they are embedded upon islanding occurrence. Based on the obtained dynamic response of the system, the passive trip settings defined in the IEEE 1547 Standard for islanding detection are evaluated in terms of their ability to be used as anti-islanding protection for rotating machine-based DG technologies.

2 Description of Assignment

One of the most important issues when considering the interconnection of distributed generation is anti-islanding protection. Disconnection times are cited in IEEE 1547 Standard and the Canadian Standard, C22.3 No. 9-08 or specific requirements may be imposed by the local utility. The purpose of this report is to investigate how the dynamic functionalities in CYMDIST version 5.0 can be used to study the response of distribution systems with DG following an islanding occurrence, and the ability of the system to detect islanding occurrence based on the voltage/frequency criterion defined in the IEEE 1547 Standard.

In this report, the dynamic behaviour of the distribution system upon islanding occurrence is analyzed for different DG types, sizes, levels of penetration and pre-islanding operating conditions. The rotating machine-based DG technologies under investigation are

1. Small hydraulic units, with and without governor, driving synchronous generators with automatic voltage regulators,
2. Diesel units with governors and voltage regulators,
3. Wind turbines connected to the system through directly coupled induction generators, and
4. Wind turbines connected to the system through doubly-fed induction generators.

3 Distribution System Description

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

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

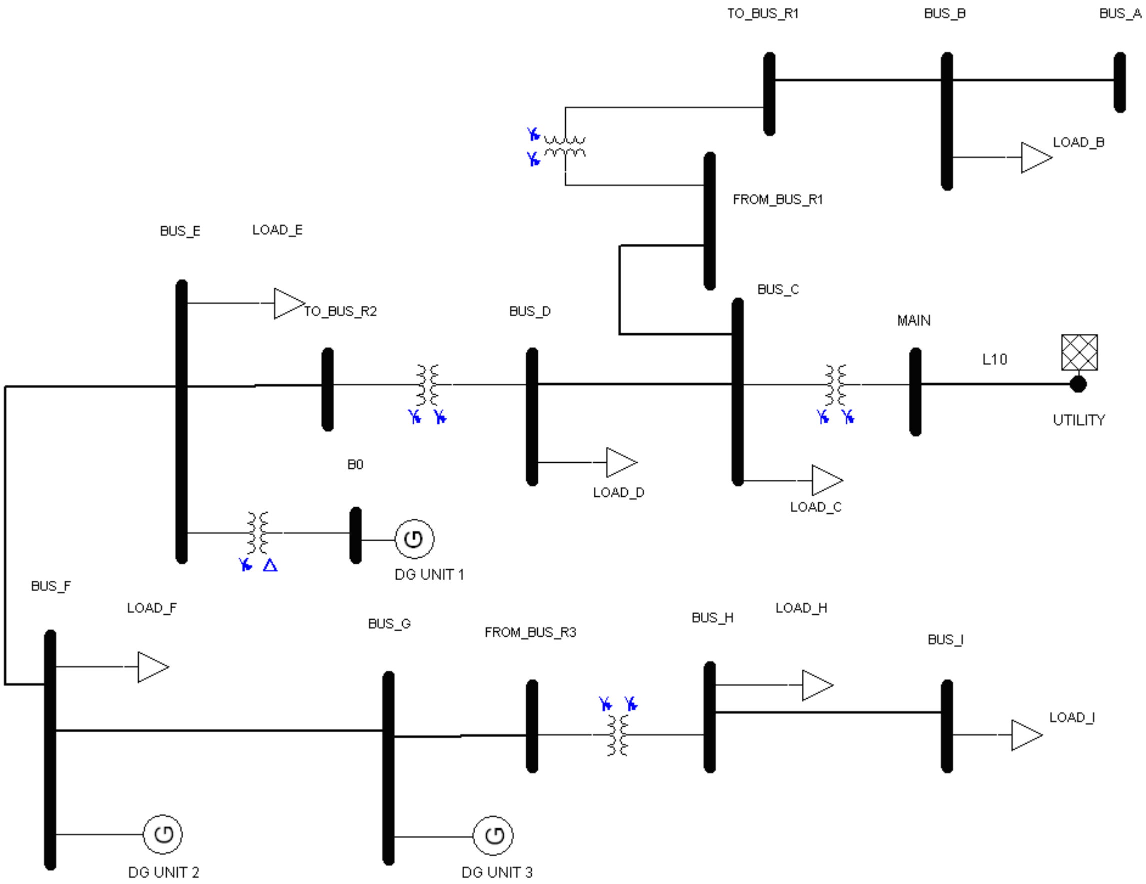

Figure 1: Distribution System Under Study [1]

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

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[1] The convention in CYMDIST for generators and the substation is to define the direction of real and reactive power as into the bus whereas loads (including shunt capacitors) are defined in the opposite direction.

load at nominal voltage is 4.622 MW +j1.308 MVAR, as shown 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 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:

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

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

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

The dependence of the load on the 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

$$nP = 1, nQ = 2, Pfreq = 1.5 \text{ and } Qfreq = -1.5$$

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 primer mover model.

Each of the three components of the hydro unit 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.

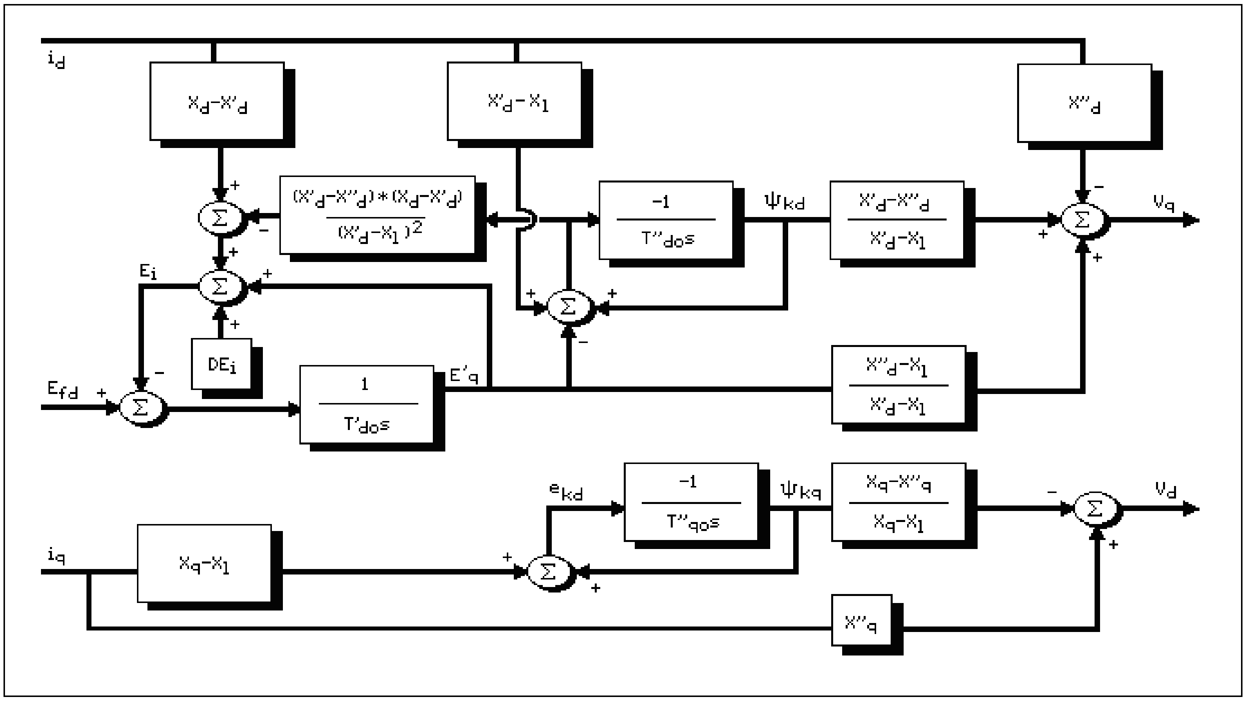


Figure 2: Salient Pole Synchronous Generator Model

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

- Synchronous Reactances:

  Xd = 1.236 p.u., Xq = 0.75 p.u., Xl = 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

The excitation and automatic voltage regulation system used for both, salient pole and round rotor synchronous generators is modeled using the block diagram of Figure 3.

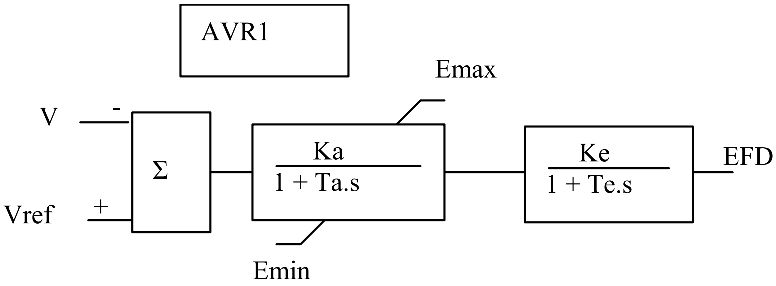


Figure 3: Excitation and Automatic Voltage Regulation Model

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, Emin = 0

4.2.3 Prime Mover Model

The hydraulic turbine model used for simulation 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.

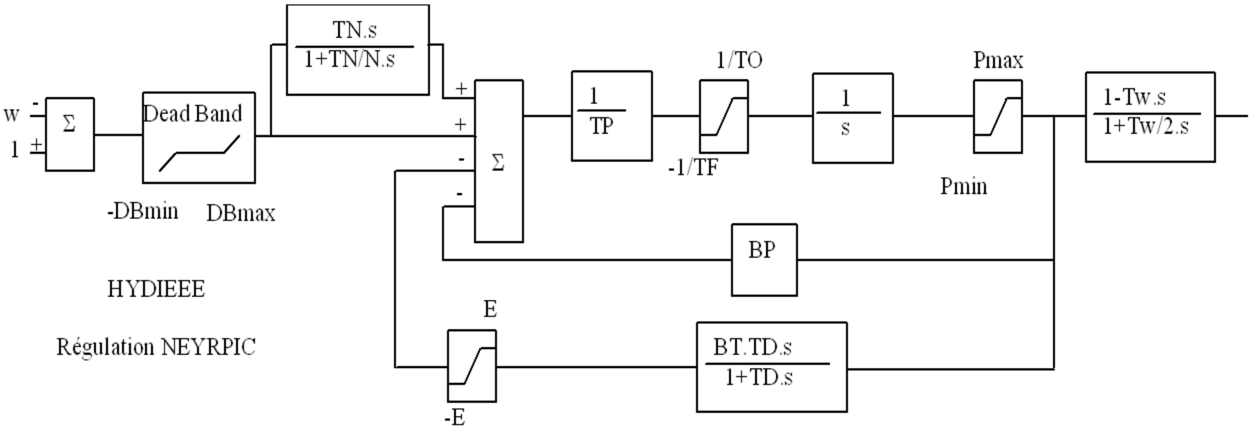


Figure 4: Hydraulic Governor and Turbine Model

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 DG unit in the case study and *TTACHY* is the time constant of a filter in the speed regulator Dead Band.

4.3 Diesel DG Units

The complete dynamic model of a diesel DG unit consists of

4. the synchronous generator model,
5. the excitation system model, and
6. the primer mover model.

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

4.3.1 Round Rotor Synchronous Generator Model

A generator model suitable for round rotor machines used in thermal units, including diesel generators and accounting for sub-transient and saturation effects is shown in Figure 5. This model is used throughout the study whenever diesel units are simulated.

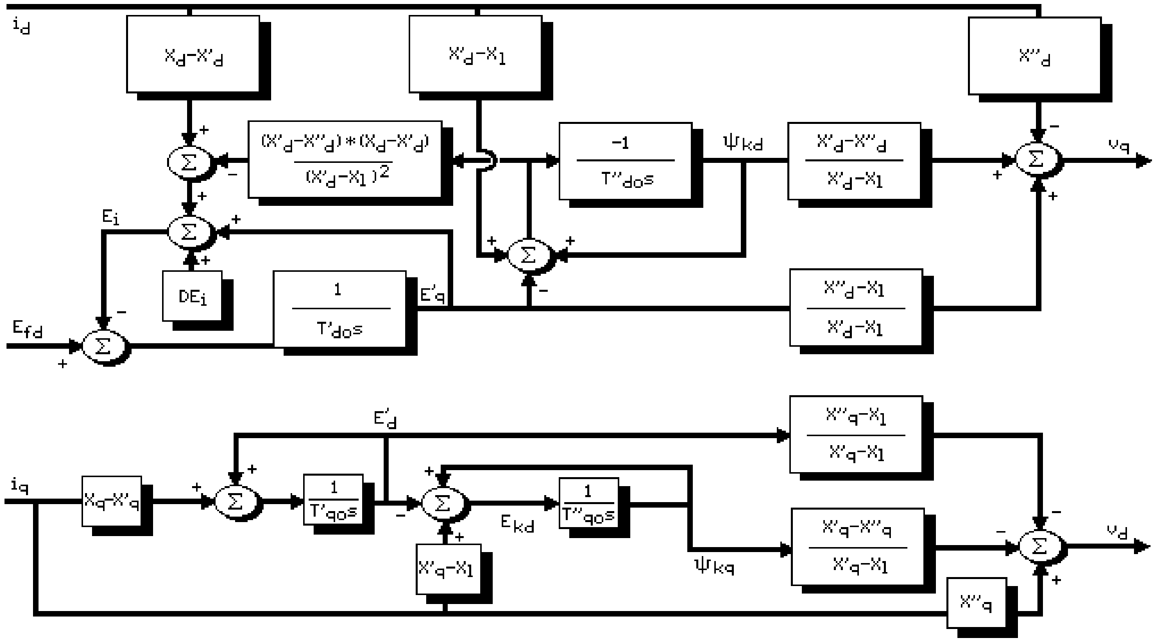


Figure 5: Round Rotor Synchronous Machine Model

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

- Synchronous Reactances:
  Xd = 1.6 p.u., *Xq = 0.95 p.u.,* *Xl = 0.105 p.u.*
- Transient Data:
  X'd = 0.33 p.u., *X'q = 0.70 p.u.,* *T'do = 4.0 sec.,* *T'qo = 1.20 sec.*
- Subtransient Data:
  X"d = 0.24 p.u., *X"q= 0.30 p.u.,* *T"do = 0.05 sec.,* *T"qo = 0.05 sec.*
- Mechanical Data:
  *H = 1.76 MW*s/MVA.*

4.3.2 Excitation System Model

The excitation and automatic voltage regulation system used for round rotor synchronous generators is identical to the one which is used for salient pole synchronous generators, i.e., that of Figure 3 in Section 4.2.2.

4.3.3 Diesel DG Units Governor

The diesel engine and governor model used for the diesel DG units is shown in Figure 6. The diesel unit governor in this case has this case has zero droop (isochronous mode), therefore it will always adjust the unit power output according to system conditions, in particular the system load, to maintain unit speed at its set point (60Hz). The response of the modeled diesel units is very fast, as can be seen from the model parameters and from the corresponding case studies.

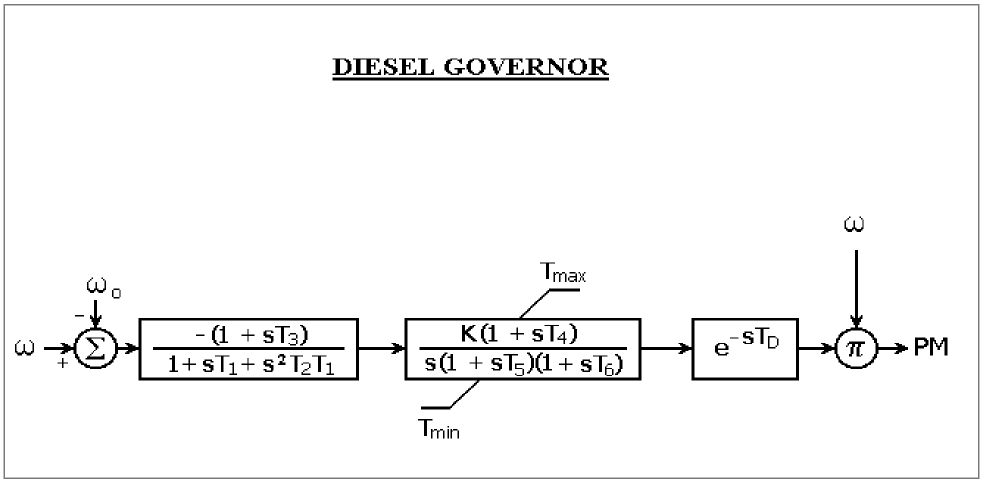


Figure 6: Governor/Turbine Model of a Diesel Engine

The parameters of the diesel unit prime mover model used throughout the simulation are:

T1 = 0.0100 sec., T2 = 0.0200 sec., T3 = 0.2000 sec.,

K = 40.0000p.u., T4 = 0.2500 sec., T5 = 0.0090 sec.,

T6 = 0.0384 sec., TD = 0.0240 sec., Tmax = 1.1000, and Tmin = 0.000,

TBMW= 3MW (in the turbine parameters).

4.4 Wind Energy Conversion System (Wind DG units)

In this report, the selected Wind Energy Conversion System (WECS) topologies consist of either a directly-coupled induction generator or a doubly-fed induction generator driven by a wind turbine.

4.4.1 Wind Energy Conversion System - Directly Coupled Induction Generator

The directly coupled induction generator driven by a wind turbine is shown in Figure 7.

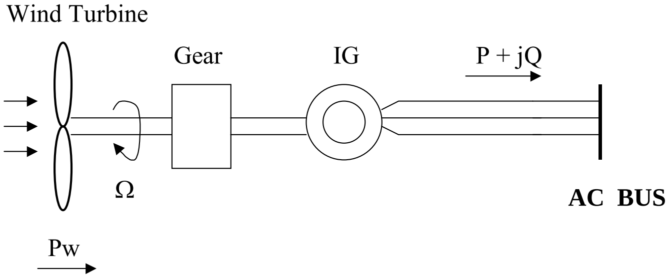


Figure 7: WECS Directly Coupled Induction Generator Topology

For all the wind DG case studies it is assumed that the wind turbine operates at constant speed (Ω) and consequently, input power to the grid is determined entirely by wind speed. Figure 8 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, the pitch control is initiated to limit the input wind power.

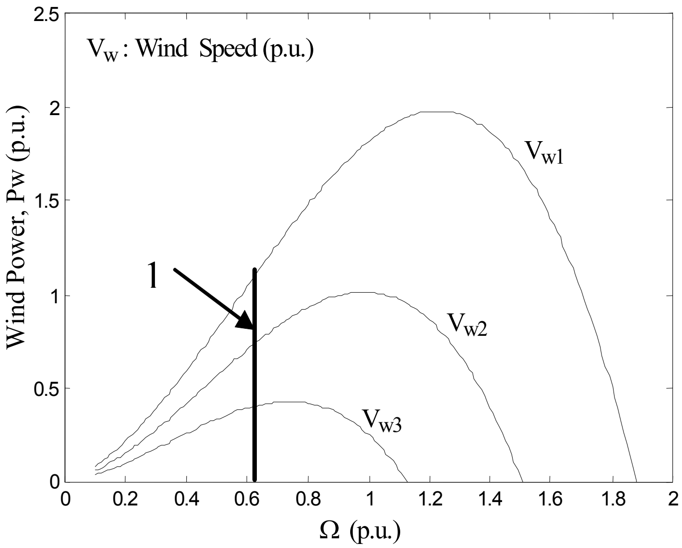


Figure 8: Operating Characteristics of the Wind Turbine – Directly Coupled Ind. Generator

Each component of the WECS of Figure 7 is discussed in the following subsections.

4.4.2 WECS Drive Train Model – Directly Coupled Induction Generator

In this report, the WECS drivetrain is represented by the two-mass model shown in Figure 9:

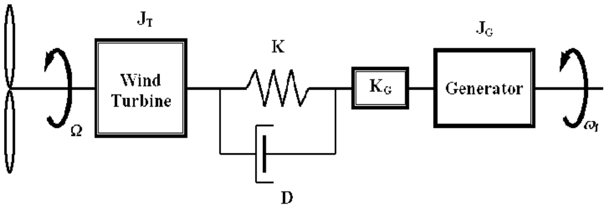


Figure 9: WECS Drivetrain Model – Directly Coupled Ind. Generator

The parameters for the WECS drivetrain used throughout the wind case studies are

Wind turbine operating data

- *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*

Wind turbine rotor data

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

Drive train data

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

4.4.3 Induction Generator Model – Directly Coupled Induction Generator

In this report, the induction generators that are used in conjunction with wind turbines are modeled using the equivalent electrical circuit of Figure 10.

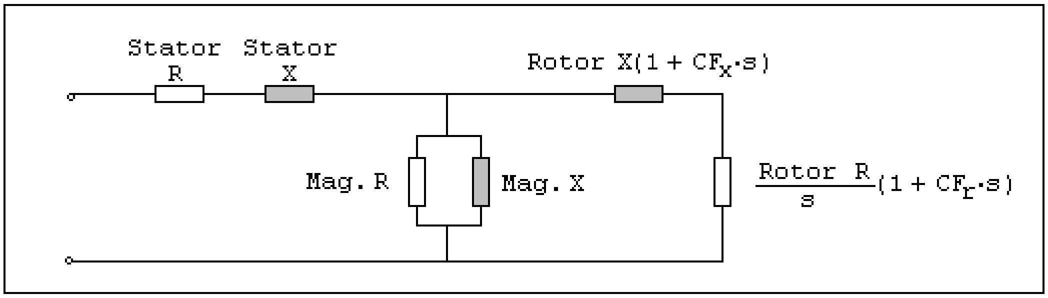


Figure 10: Induction Generator Equivalent Circuit – Directly Coupled Ind. Generator

The parameters of the induction generator model of Figure 10 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}

4.4.4 Wind Energy Conversion System – Doubly Fed Induction Generator

The doubly-fed induction generator driven by a wind turbine is shown in Figure 11.

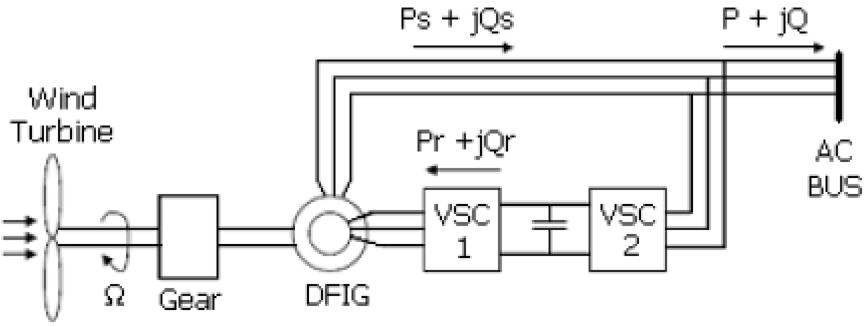
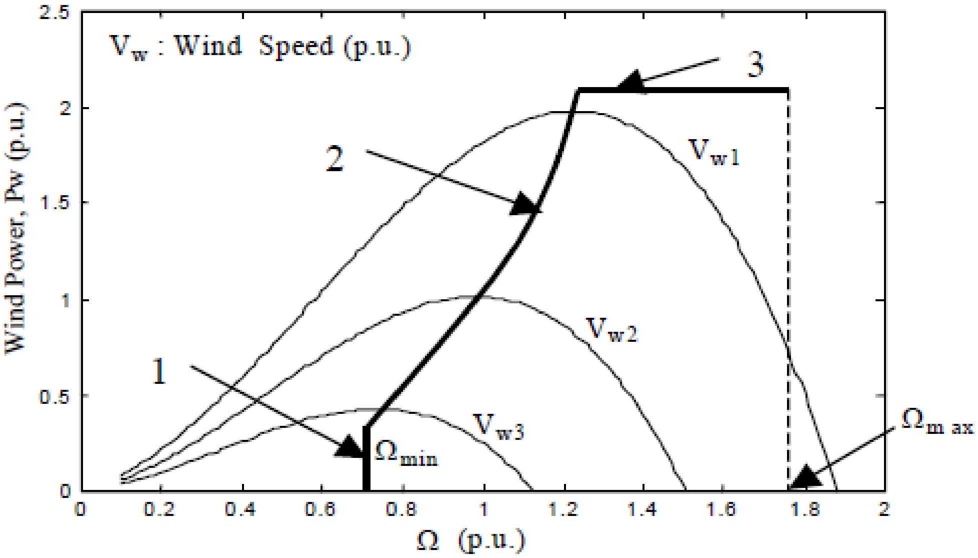


Figure 11: WECS Doubly Fed Induction Generator Topology

For the induction generator, in all the wind DG case studies, it is assumed that the wind turbine operates at constant speed and consequently, output power to the grid is determined entirely by wind speed (Ω). Figure 12 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 12: Operating Characteristics of the Wind Turbine – Doubly Fed Ind. Generator

Each component of the WECS of Figure 11 is discussed in the following subsections.

4.4.5 WECS Drivetrain Model – Doubly Fed Induction Generator

In this report, the WECS drive train is represented by the two-mass model of Figure 13:

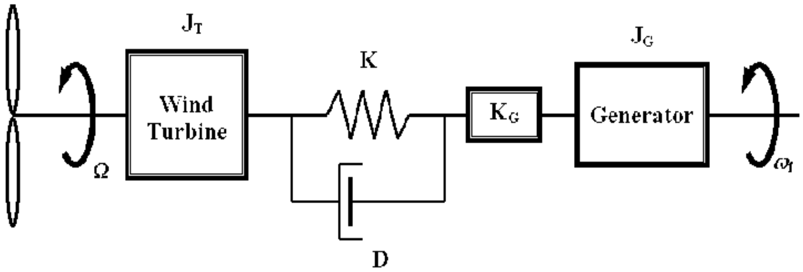


Figure 13: WECS Drivetrain Model – Doubly Fed Ind. Generator

The parameters for the WECS drivetrain used throughout the wind case studies are

Wind turbine operating data

- *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*

Wind turbine rotor data

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

Drive train data

- *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*

4.4.6 Induction Generator Model – Doubly Fed Induction Generator

In this report, the induction generators that are used in conjunction with wind turbines are modeled using the equivalent electrical circuit of Figure 14.

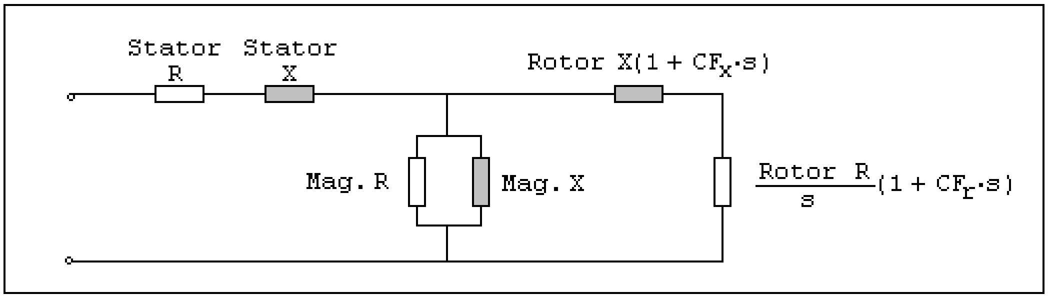


Figure 14: Induction Generator Equivalent Circuit – Doubly Fed Ind. Generator

The parameters of the induction generator model of Figure 14 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 the operation of part of the distribution system in islanded conditions, where distributed generation is supplying part or total load of the island. The IEEE 1547-2003 Standard [10] 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. 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

With respect to the IEEE 1474-2003 standard, when the system voltage falls within the ranges given in Table 2, the 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 [11].

Table 2: Interconnection System Response to Abnormal Voltages (IEEE)

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

[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 (CSA)

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] Instantaneous 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 clearing times indicated. 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 as shown in Table 4. The values in **Error! Reference source not found.** give the corresponding frequency limits and clearing times according to CSA requirements.

Table 4: Interconnection System Response to Abnormal Frequencies (IEEE)

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
	< {59.8 - 57.0} (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 (CSA)

DR Size	Adjustable Set Point (Hz)	Clearing Time (s) (Adjustable Set Point)
DR ≤ 30 kVA	59.3 – 57	0.1 – 2
	60.7 – 61.7	0.1 – 2
DR >30 kVA	59.3 – 55.5	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 and safety concerns which resulted in the creation of the above standards 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 the distribution system.

6 Case Study Results: Disconnection of the Distribution System – Island Detection

The case study results of this report illustrate the dynamic response of system variables upon islanding occurrence, i.e., when the distribution system is disconnected from the main power system. Also, the ability of the distribution system to detect the islanding phenomenon is examined. The islanding detection criterion is entirely based on the voltage and frequency permissible values of Tables 2 and 4.

In this section, different combinations of load and generation, as well as different DG technologies within the distribution system, are simulated. Different scenarios are carried out in the first case study with hydraulic generation. Afterwards, only the under-generating scenario is carried out for the rest of the case studies.

6.1 Distribution System with Embedded Hydraulic Generation

6.1.1 Self-Sufficient Condition

The load flow under this condition is shown in Figure 15. Each of the three hydraulic DG units connected to buses B0, F, and G has a capacity of 3 MVA, and is controlled to supply 1.58 MW and to maintain its bus bar voltage at 1.03 p.u. Each DG unit delivers or absorbs different amounts of reactive power depending on its location in the network. The power exchange with the main power system is very small (0.004 MW-j0.046 MVAR). At t = 2 sec., the distribution system is disconnected from the main power system by disconnecting cable L10 (between the utility and bus Main, labelled in Figure 1). The system frequency response due to the islanding event is shown in Figure 16. It indicates that the variation in the frequency is insignificant subsequent to the islanding event due to the balanced power condition of the separated distribution system. In this case, island formation cannot be detected based on the frequency ranges in the IEEE 1547 Standard. All the generating units would remain connected and the distribution system would operate autonomously unless islanding conditions are detected by other methods [12]. The slight frequency variation in this case is attributed to the change of the loads' real power due to voltage changes at the loads' feeding bus bars.

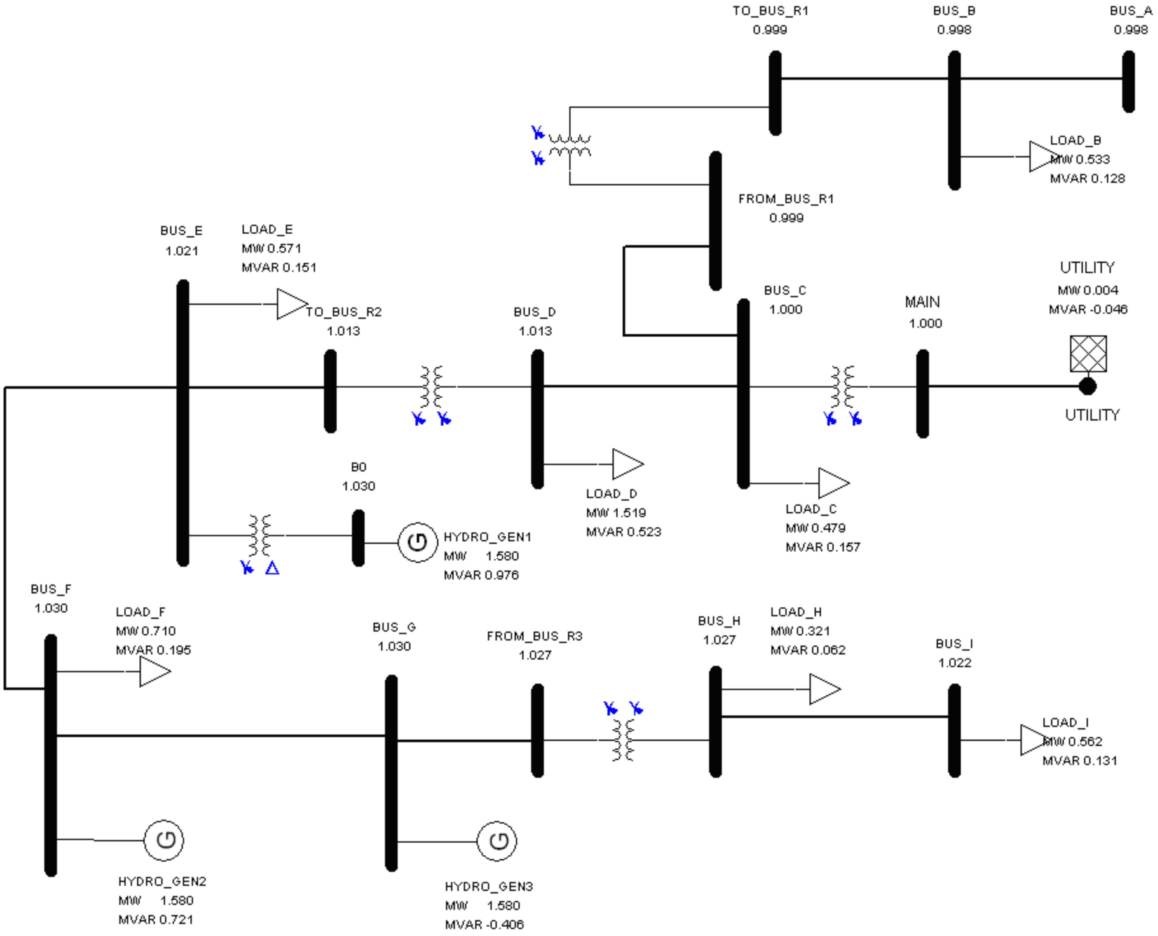


Figure 15: Investigated Distribution System - Self-Sufficient conditions

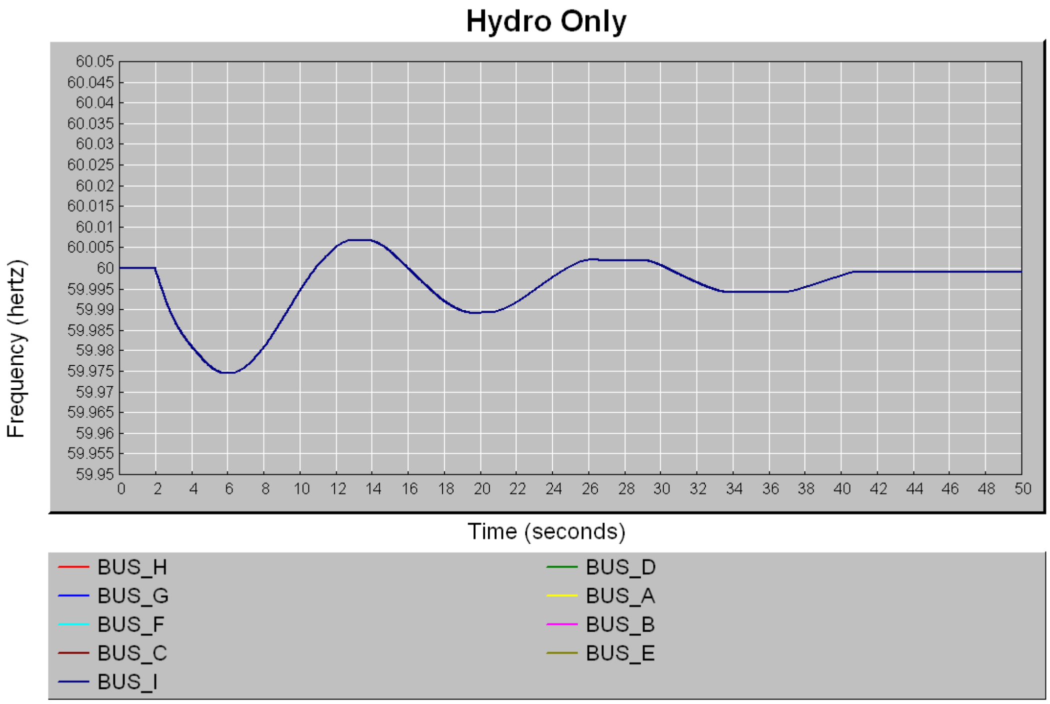


Figure 16: Frequency Response to an Islanding Event (Self-Sufficient Condition, Hydro Units Only)

6.1.2 Over-Generating Condition

The load flow of the distribution system under this operational condition is shown in Figure 17. Each of the three DG units is a 4 MVA hydraulic unit which is controlled to supply 3.12 MW and to maintain its bus bar voltage at 1.03 p.u. Each DG unit delivers or absorbs different amounts of reactive power depending on its location in the network. The total generation represents as much as twice the total load in the distribution system. The power exchange with the main power system is 4.076 MW exported out of the distribution system and 2.792 MVAR imported into the distribution system. At t = 2 sec., the distribution system is isolated from the main power system by disconnecting cable L10, Figure 1.

Figure 18 shows the transient frequency response of the distribution system due to the islanding event. Due to the power imbalance in the distribution system, the islanding event results in a large variation in the frequency, with a maximum value of 71.7 Hz and a minimum value of 55.5 Hz. Island formation can be easily detected according to IEEE 1547 Standard as the frequency exceeds the 60.5 Hz limit after 0.12 s. and lasts for 9.65 s subsequent to the islanding event. All generating units will be tripped in 0.16 s after the (start of the) violation has been detected. It is worth mentioning that the simulation results don’t show the effect of tripping the generating units.

Figure 19 shows the voltage variation at bus D subsequent to the islanding event on the network. The loss of power in the distributed generators, immediately after the islanding event, causes the voltage to dip close to 0.976 pu. The voltages at the terminals of the distributed generators are then corrected towards their final value by the action of the automatic voltage regulator and, in the process, undergo some oscillations. The same voltage pattern is transmitted throughout all the buses of the islanded system as shown by the voltage at bus D.

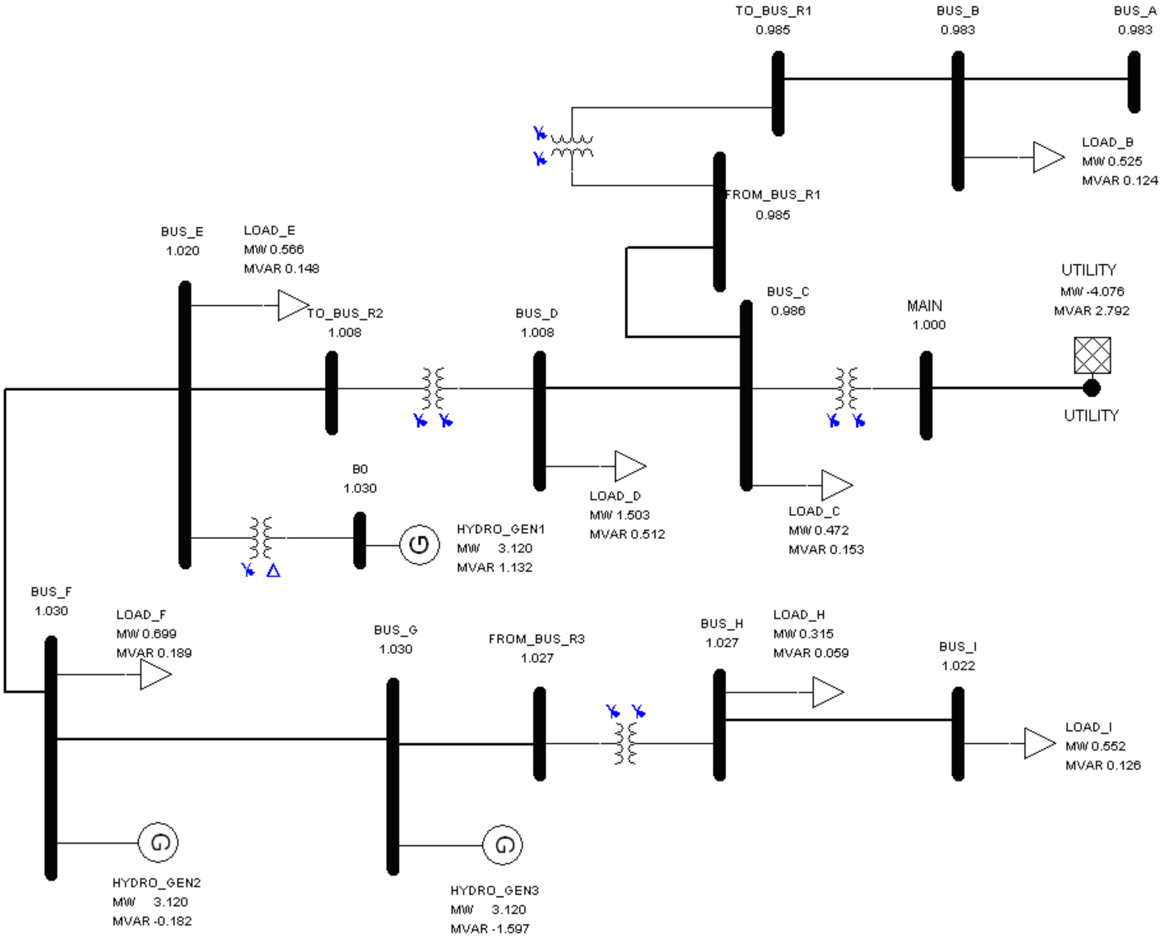


Figure 17: Over Generated Distribution System – Hydraulic Units

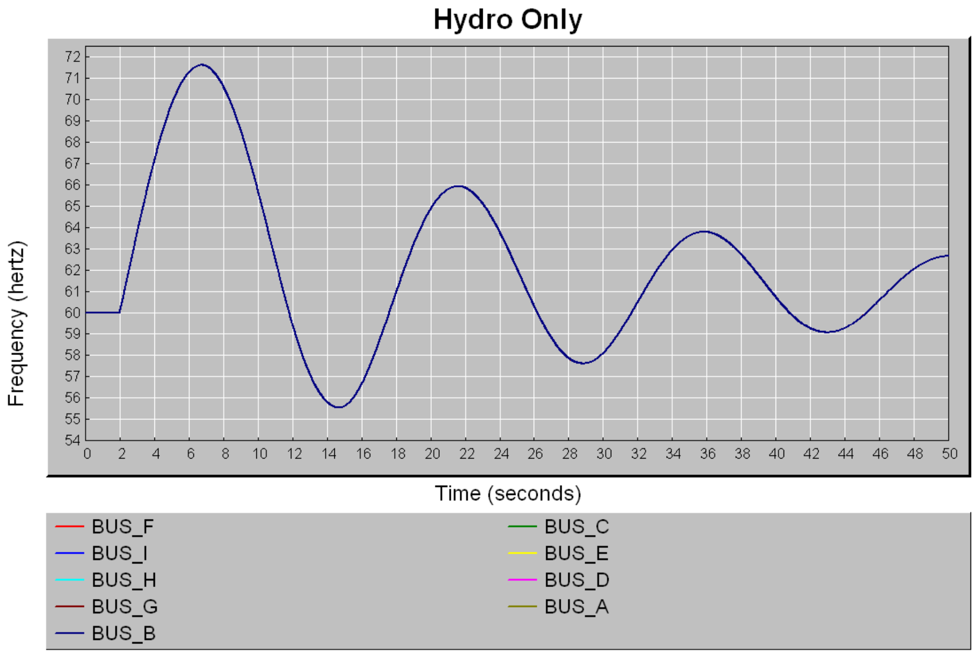


Figure 18: Frequency Response due to an Islanding Event (Over-Generating Condition with Generation/Load Ratio Equal to 2, Hydro Units Only)

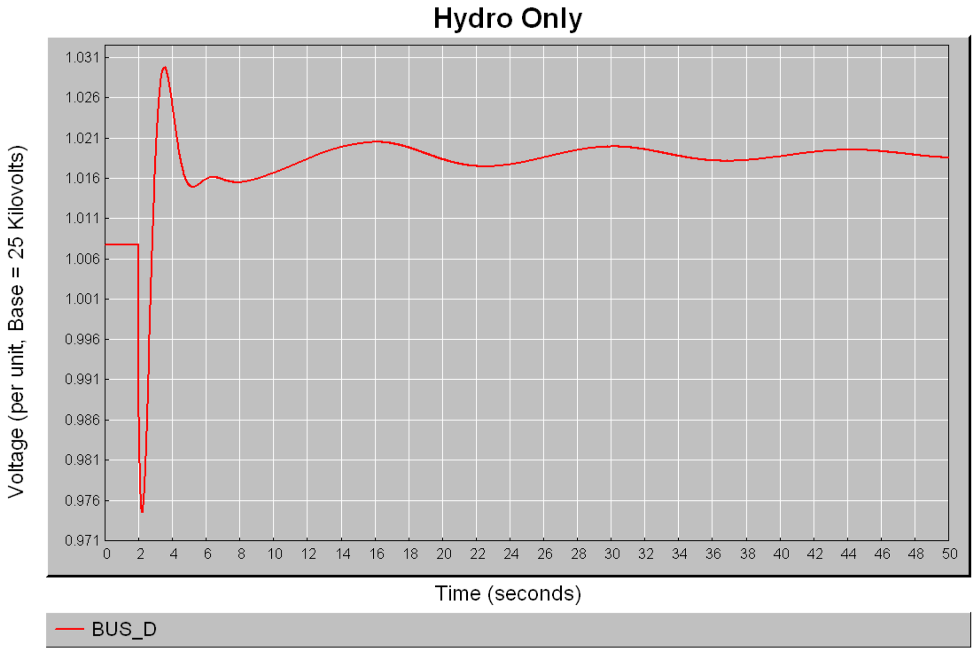


Figure 19: Voltage Response at Bus D due to an Islanding Event (Over-Generating Condition with Generation/Load Ratio Equal to 2, Hydro Units Only).

6.1.3 *Under-Generating Condition*

Figure 20 shows the load flow of the distribution system when only two hydro units operate in this system. The two hydro units have 3 MVA of capacity, and are controlled to supply 1.58 MW and to maintain their bus voltage at 1.03 p.u., which results in a power generation of 1.58 MW + j1.17 MVAR from the hydro unit at bus B0, and 1.58 MW + j0.934 MVAR from the hydro unit at bus bar G. The main power system supplies 1.57 MW to the distribution system, indicating an under-generating condition within the distribution system. The generation/load ratio for the system is approximately 2/3.

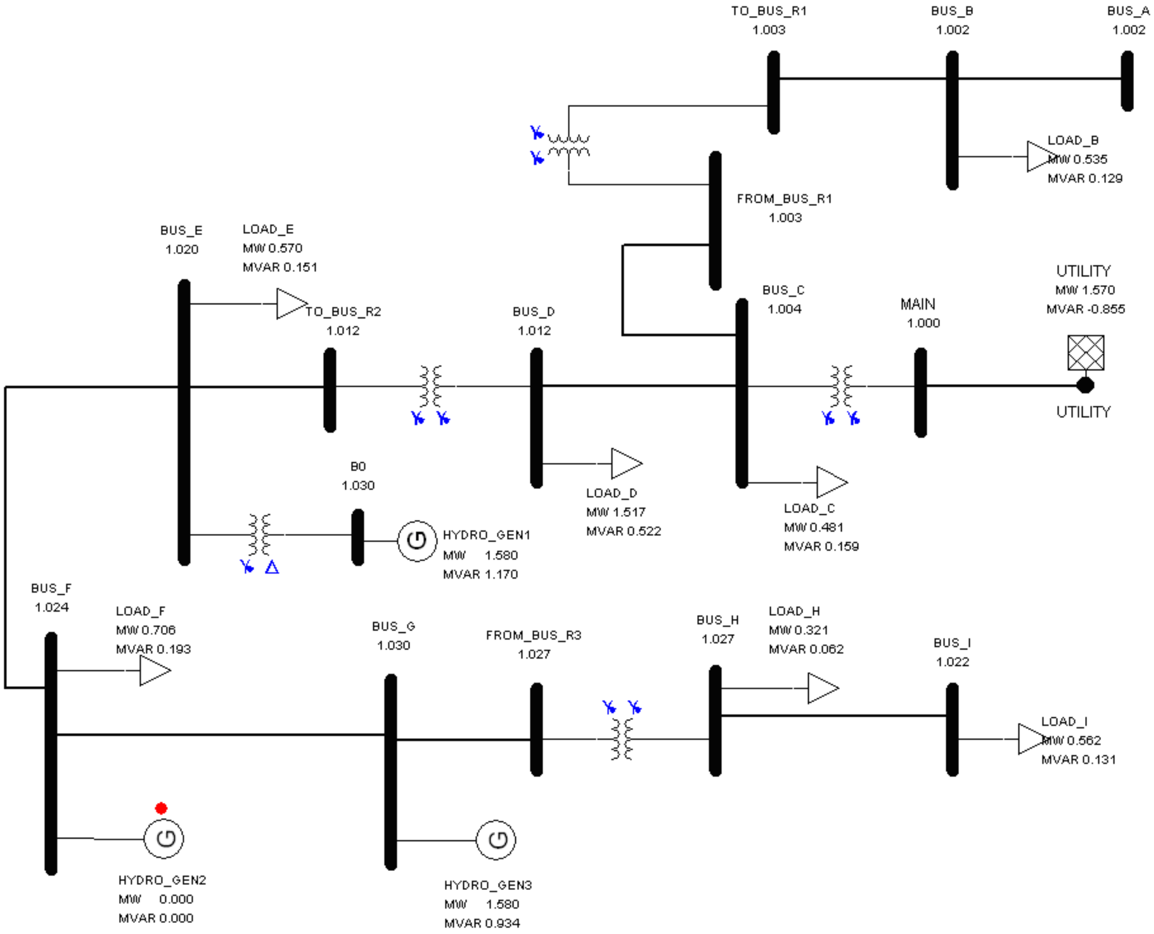


Figure 20: Load Flow Diagram of the Distribution System (Under-Generating Condition with Generation/Load Ratio Equal to 2/3, Hydro Units Only)

Figure 21 shows the frequency response of the distribution system for the under-generating condition when the system is disconnected after 2 seconds from the main system. Due to the lack of generation in the distribution system, the frequency drops significantly to 52.7 Hz. Island formation can be easily detected according to IEEE standard 1547 as the frequency decreases below the 57.0 Hz limit at 1.2 sec. and lasts for 6.1 seconds subsequent to the islanding event. All generating units will be tripped in 0.16 s after the start of the frequency violation has been detected.

Figure 22 shows the voltage variation at bus D subsequent to the islanding event on the network. The boost of power in the distributed generators, immediately after the islanding event, causes the voltage to rise close to 1.05 pu. The voltages at the terminals of the distributed generators are then corrected towards their final value by the action of the automatic voltage regulator and, in the process, undergo some oscillations. The same voltage pattern, as shown by the voltage at bus D, is transmitted throughout all the buses of the islanded system

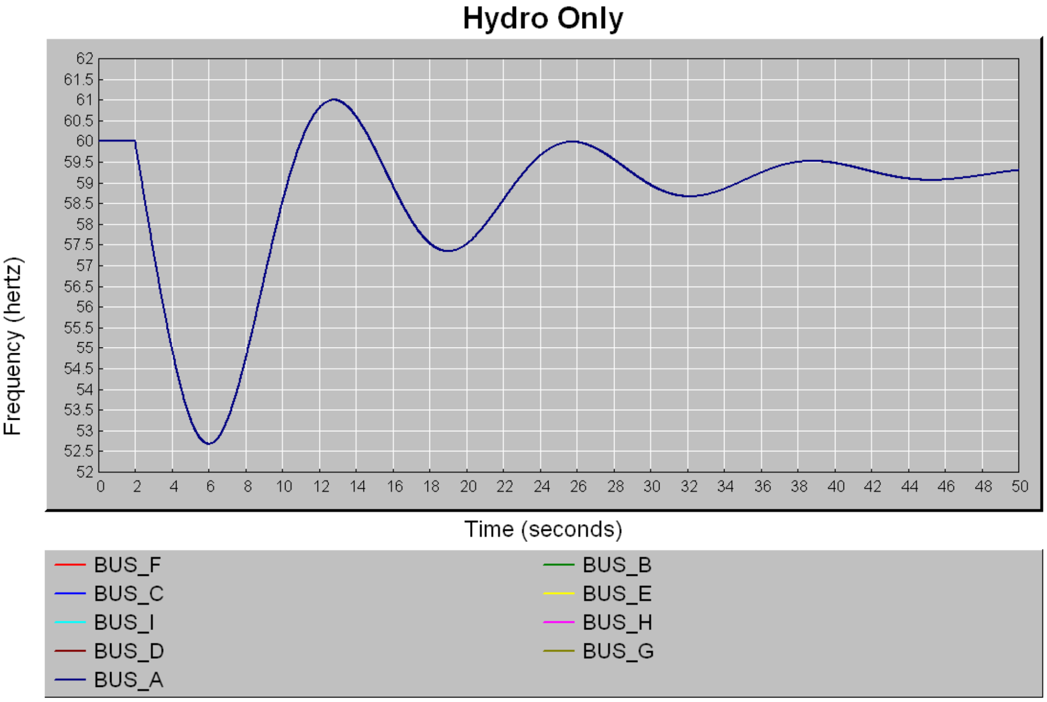


Figure 21: Frequency Response to an Islanding Event (Under-Generating Condition with Generation/Load Ratio Equal to 2/3, Hydro Units Only)

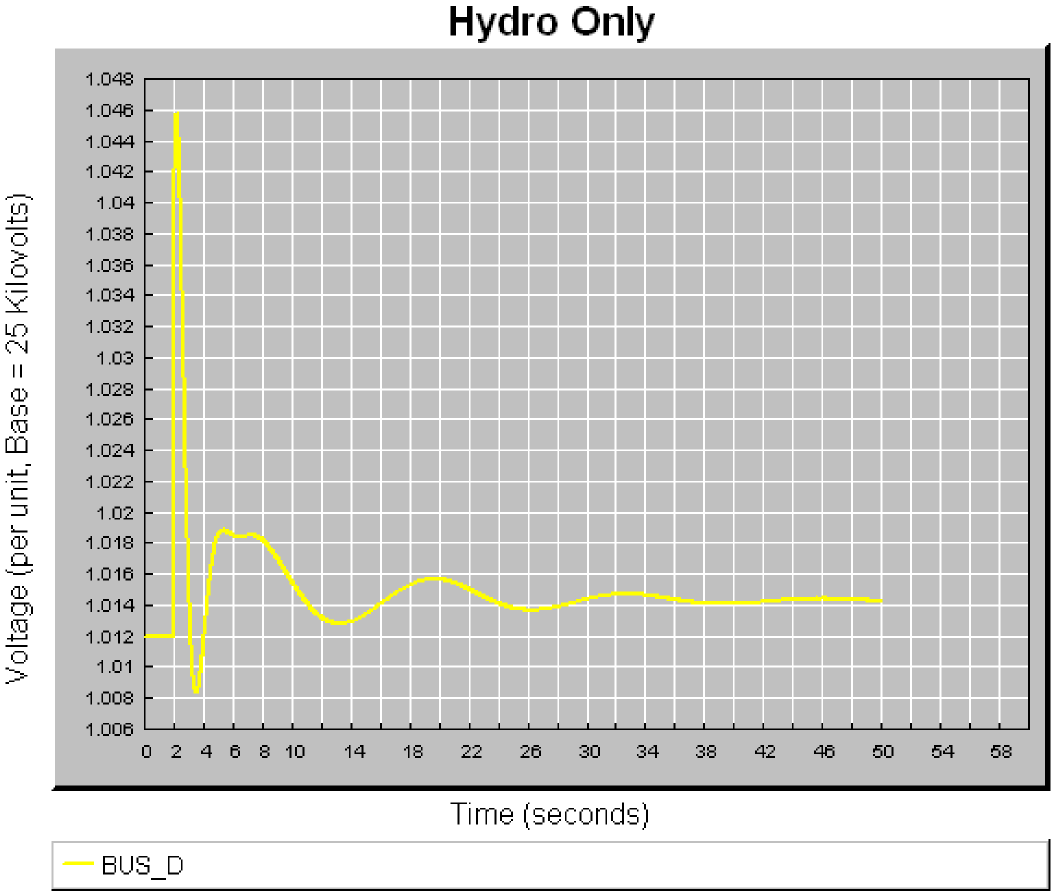


Figure 22: Voltage Response at Bus D due to an Islanding Event (Under-Generating Condition with Generation/Load Ratio Equal to 2/3, Hydro Units Only).

6.1.4 Under-Generating Condition – governor disabled

Figure 23 shows the frequency response of the distribution system for the under-generating condition when the system is subject to a disconnection, after 2 seconds, from the main power system at bus MAIN. The frequency response corresponds to the case when the governor systems of the two generating units are disabled prior to the islanding event. Without the governor systems, the system frequency decreases monotonically and drops quickly to values exceeding the IEEE limits for island formation detection. The frequency value drops to 57.0 Hz in about 1.25 s and stays below 57 Hz subsequent to the islanding event. Thus, all the generating units will be tripped about 1.41 s after island formation, according to IEEE 1547 Standard.

If all the generating units were to remain operational, the system frequency would finally settle down at around 46.5 Hz, as shown in Figure 23. However, that frequency value is much lower than any acceptable standards operating frequency. Consequently, equipment protection would trip to avoid equipment damage.

The load generation balance is established in this case as the real power supply from each DG units returns to its pre-islanding value in the absence of the governor. The load frequency dependence reduces the load as the frequency decreases until balance is achieved, as can be seen from Figure 24.

Figure 25 shows the voltage variation at bus D subsequent to the islanding event on the network. The boost of power in the distributed generators, immediately after the islanding event, causes the voltage to rise close to 1.05 pu. The voltages at the terminals of the distributed generators are then corrected towards their final value by the action of the automatic voltage regulator and, in the process, undergo some oscillations. The same voltage pattern, as shown by the voltage at bus D, is transmitted throughout all the buses of the islanded system.

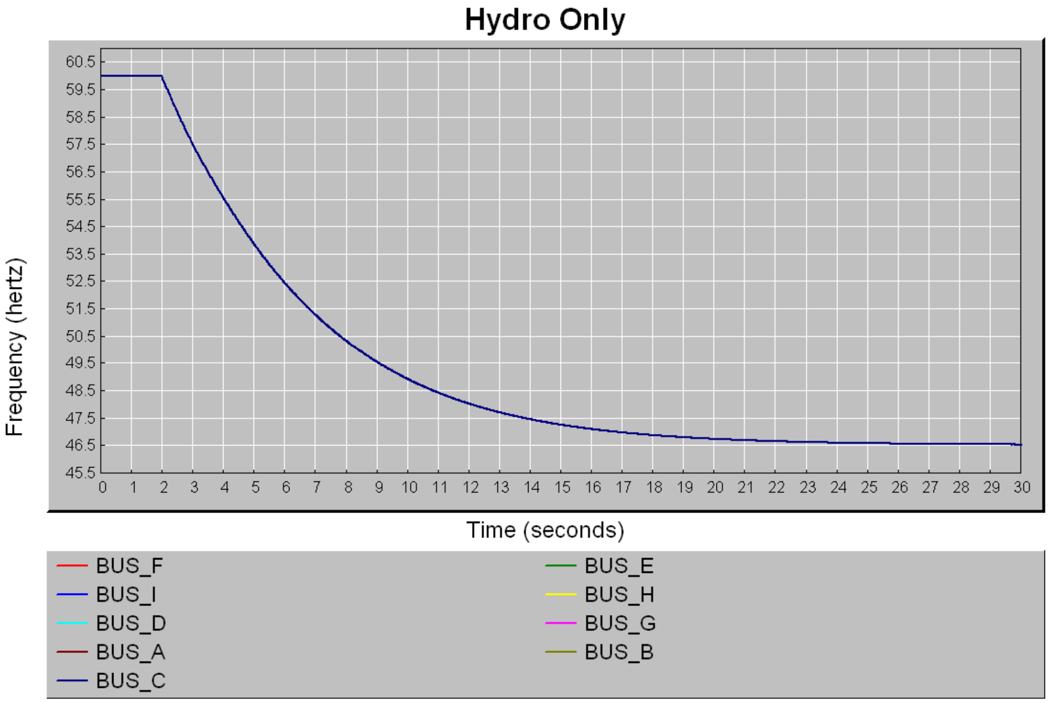


Figure 23: Frequency Response of Distribution System to an Islanding Event with Governor System Disabled (Under-Generating Condition with Generation/Load Ratio Equal to 2/3, Hydro Units Only)

It is observed that for over and under generating conditions, passive anti-islanding detection techniques based on monitoring the voltage and frequency variations can detect island conditions and disconnect all the generating units. The worst scenario is the self sufficient conditions (or when the power mismatch level is very low), where frequency and/or voltage variations wasn't able to detect island formation [13].

In light of this we will consider only the under generating scenario in the next sections in order to carry out cases with other types of distribution generation since as we already know a self-sufficient case will lead to no detection and the under-generating case is representative enough for the dynamics involved in both the other cases.

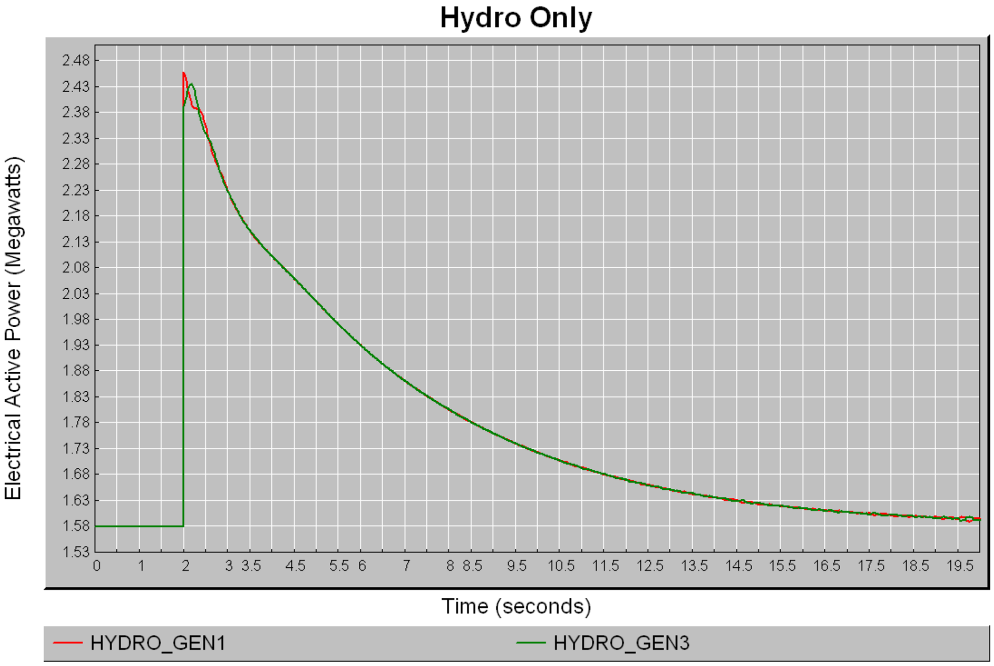


Figure 24: Real Power Response of Generating Units with Governor System Disabled to an Islanding Event (Under-Generating Condition with Generation/Load Ratio Equal to 2/3, Hydro Unit Only)

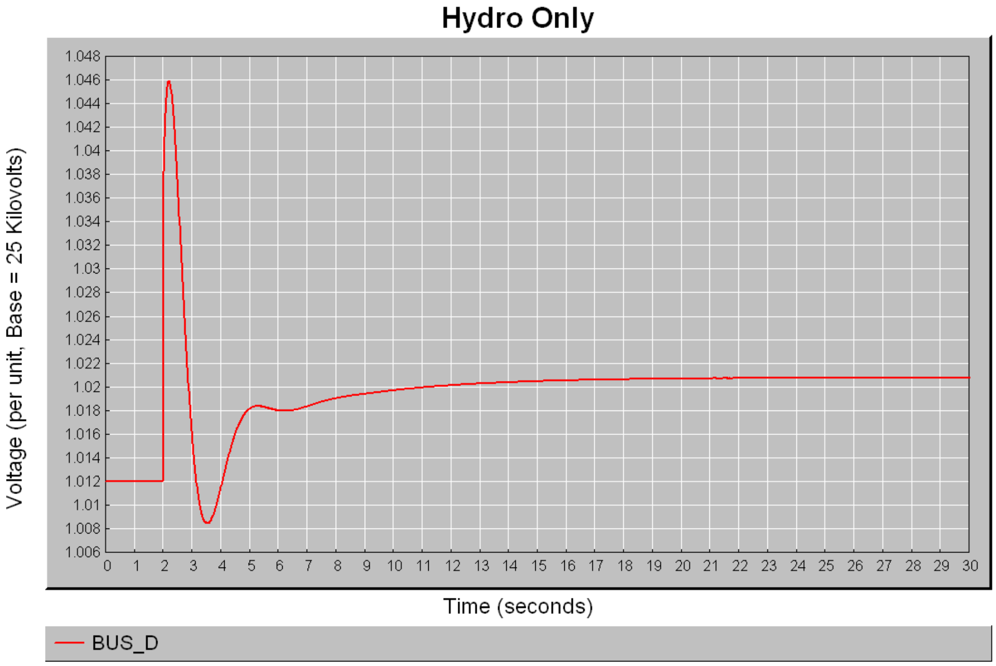


Figure 25: Voltage of Load at Bus D for no Governor Case (Under-Generating Condition with Generation/Load Ratio Equal to 2/3, Hydro Unit Only)

6.2 Distribution System with Embedded Diesel DG Units

6.2.1 *Under-Generating Condition*

Figure 26 shows the load flow of the distribution system with three embedded diesel generating units. Each diesel unit is controlled to supply 0.85 MW and to maintain its bus bar voltage at 1.03 p.u. Consequently, the units at buses B0, F, and G supply 1.02 MVAR, 1.355 MVAR, and 0.168 MVAR, respectively. The three diesel DG units have 3 MVA of capacity. The main power system supplies 2.216 MW to the distribution system and absorbs 1.257 MVAR. The ratio of generation to load for this system is approximately ½.

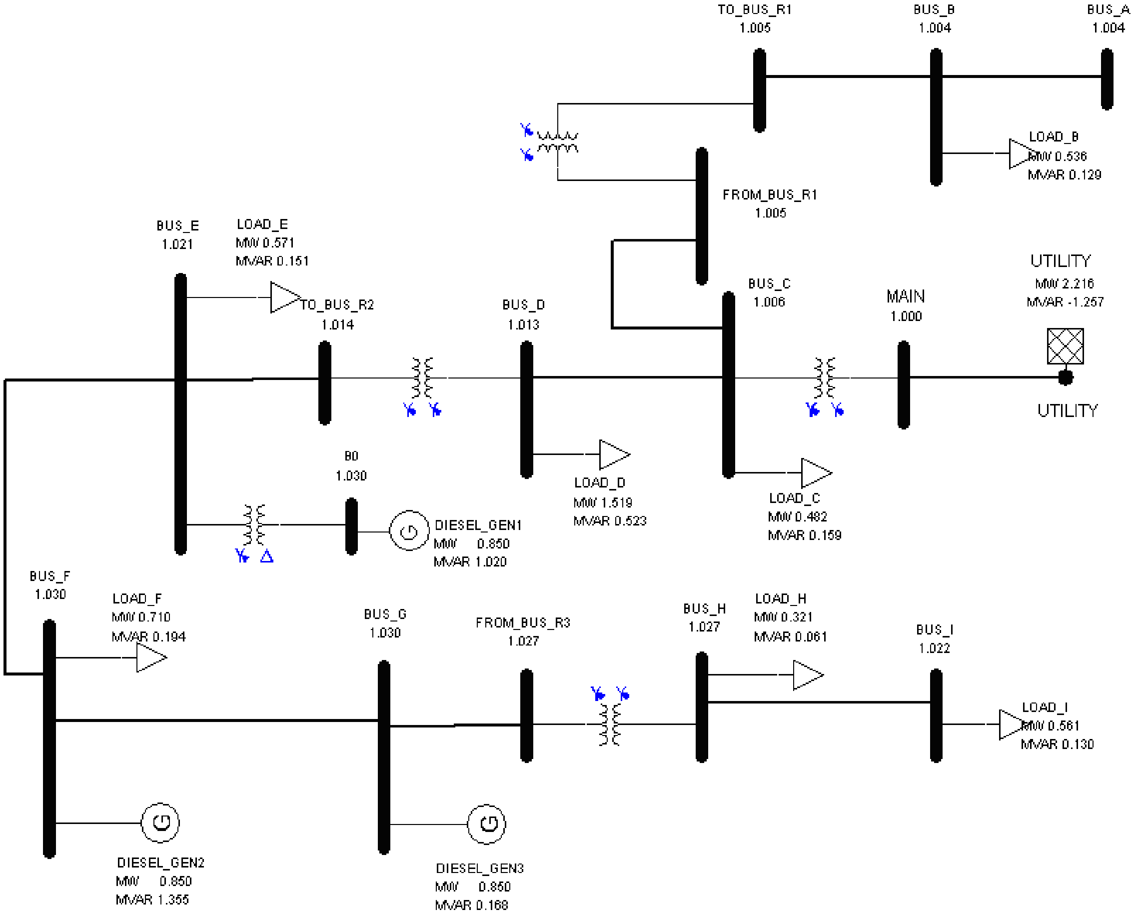


Figure 26: Load Flow Diagram of the Distribution System (Under-Generating Condition with Generation/Load Ratio Equal to 1/2, Diesel Units Only)

At t = 2.0 s, the distribution system is disconnected from the main power system at bus MAIN. The system response due to the islanding event is shown in Figure 27 and Figure 28. Figure 27 shows that, subsequent to the disconnection, the lack of generation in the distribution system results in a frequency drop with a minimum value of 59.39 Hz. The frequency excursion is much smaller than that seen in Figure 21, even though the generation deficiency for the case of Figure 21, is larger than the generation deficiency in this case. This decrease in the frequency change is due to the faster response of the diesel units. The frequency value is within the IEEE limits for island formation detection. Thus, no generating units will be tripped and the separated distribution system will remain operational.

Since the generating units have sufficient capacity, their governors systems quickly adjust the real power outputs to match the system load and the system frequency returns to its nominal value of 60 Hz in about 5 sec. after the island formation. It should be noted that there is no steady state frequency deviation from the nominal value after the islanded system settles down since the governor systems of the diesel generating units do not apply a droop control. This would also be the result if diesel unit governors have droop characteristics as long as one unit is left without droop to maintain the island frequency at 60 Hz. However, under these conditions the units with droop characteristics will return to their set point generation while the unit without droop will look after the balance of power.

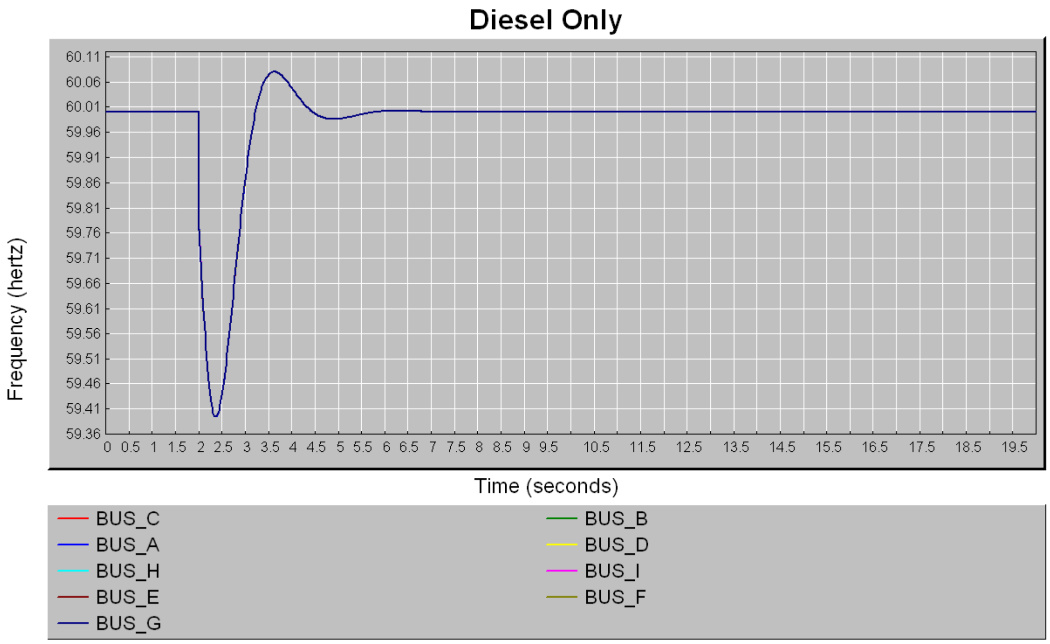


Figure 27: Frequency Response to an Islanding Event (Under-Generating Condition with Generation/Load Ratio Equal to 1/2, Diesel Units Only)

Figure 28 shows the real power response of the generating units due to the islanding event. Immediately after the islanding event, the real power outputs of the DG units increase abruptly to share the load deficiency caused by the loss of the main power system. Through the fast control action of the governor systems, the real power outputs quickly settle down to a new operating point which corresponds to the total real power demand within the islanded system. The dynamic response of all three diesel units is similar due to the identical values of their control parameters.

Figure 29 shows the voltage variation at bus D subsequent to the islanding event on the network. The boost of power in the distributed generators, immediately after the islanding event, causes the voltage to rise close to 1.06 pu. The voltages at the terminals of the distributed generators are then corrected towards their final value by the action of the automatic voltage regulator and, in the process, undergo some oscillations. The same voltage pattern, as shown by the voltage at bus D, is transmitted throughout all the buses of the islanded system

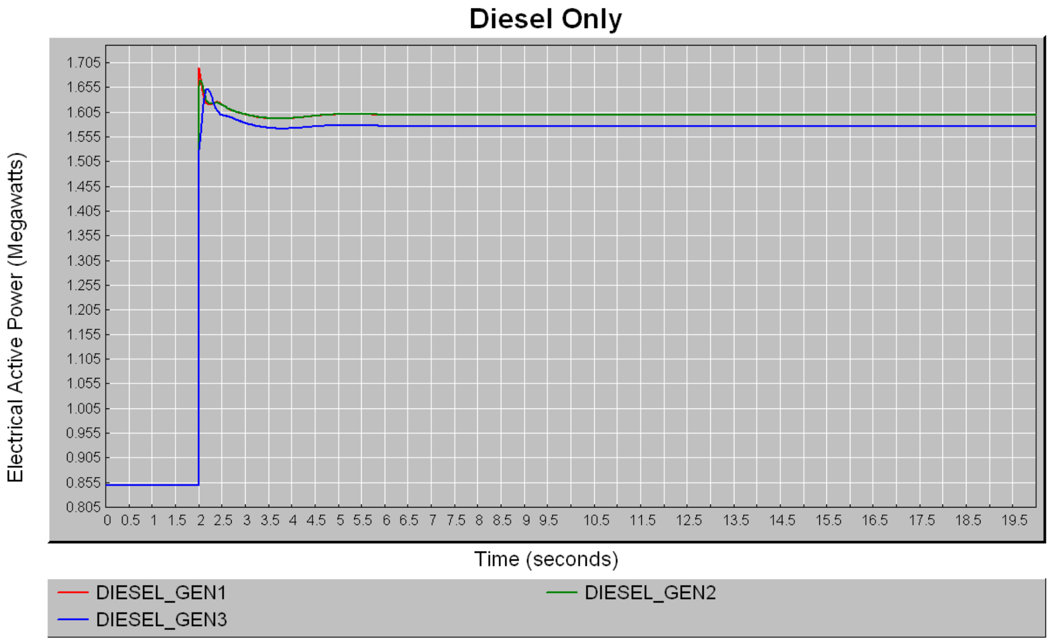


Figure 28: Real Power Response of Generating Units to an Islanding Event (Under-Generating Condition with Generation/Load Ratio Equal to 1/2, Diesel Units Only)

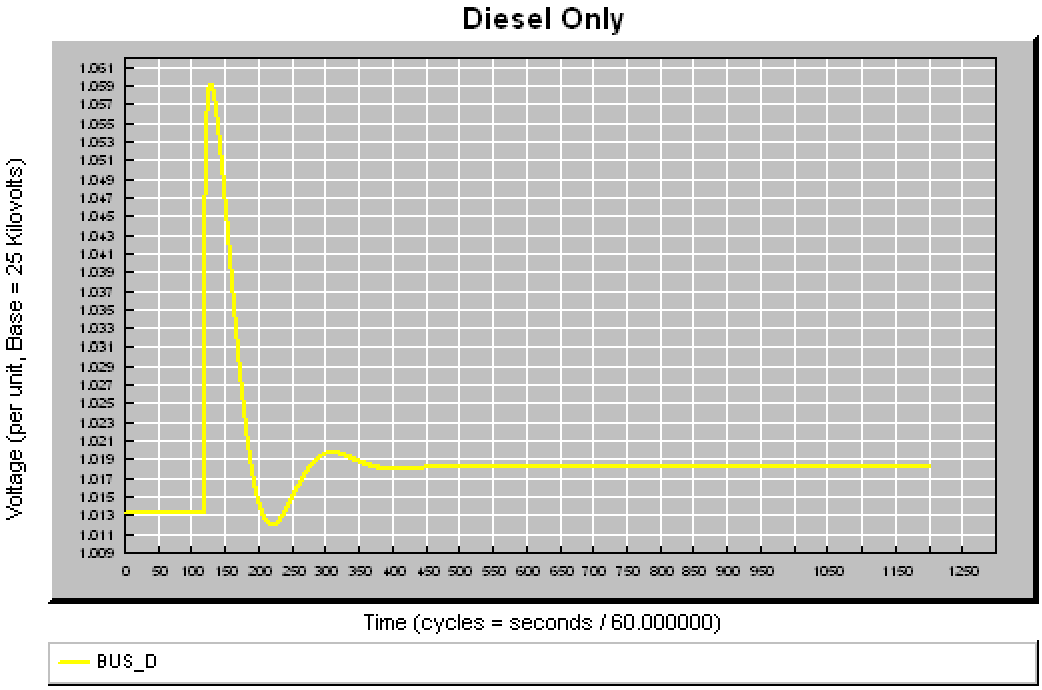


Figure 29: Voltage of Load at Bus D due to an Islanding Event (Under-Generating Condition with Generation/Load Ratio Equal to 1/2, Diesel Unit Only)

6.3 Distribution System with Embedded Wind DG Units

6.3.1 Under-Generated Condition

The load flow of the distribution system under this condition is shown in Figure 30. There are three embedded wind DG units connected at buses B1, B2, and B3. Each of the generating units is controlled to supply 0.85 MW at a power factor of 84.1%. A capacitor bank is connected at each wind unit bus to compensate the reactive power consumed by the induction generator. Each bank provides 0.13 MVAR, which results in an improved power factor of the corresponding generating unit to 98%. The distribution system still absorbs 1.712 MVAR from the main power system to meet the reactive power requirements of the DG units and the system loads. The real power exchange with the main power system corresponds to an import of 1.954 MW. In this case study, the wind speed is assumed constant at the value computed from the load flow analysis.

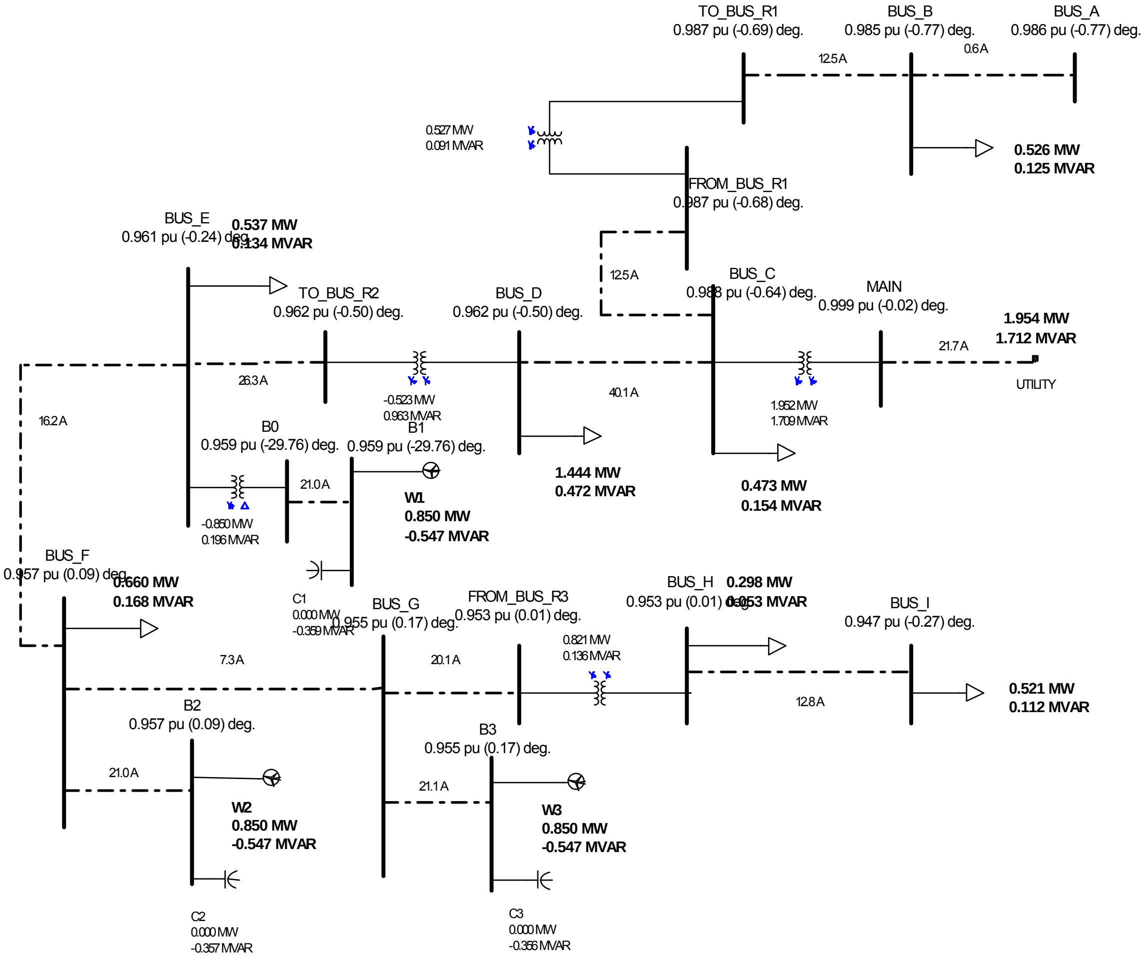


Figure 30: Load Flow Diagram of the Distribution System (Under-Generating Condition, Wind Units Only)

At t = 2.0 sec., the distribution system is disconnected from the main power system at bus MAIN. The system response to this islanding event is shown in Figure 31, Figure 32 and Figure 33.

Figure 31 illustrates the voltage response of the distribution system due to the islanding event. Due to the lack of reactive power in the separated distribution system, the bus voltages decrease monotonically and drop to almost zero within 2 s. The voltage values exceed the IEEE limits for island formation detection. Figure 31 shows that the voltages drop to 0.5 p.u. in about 0.15 s subsequent to the islanding event, thus all the generating units will be tripped in about 0.31 s after the island formation, according to the IEEE 1547 Standard.

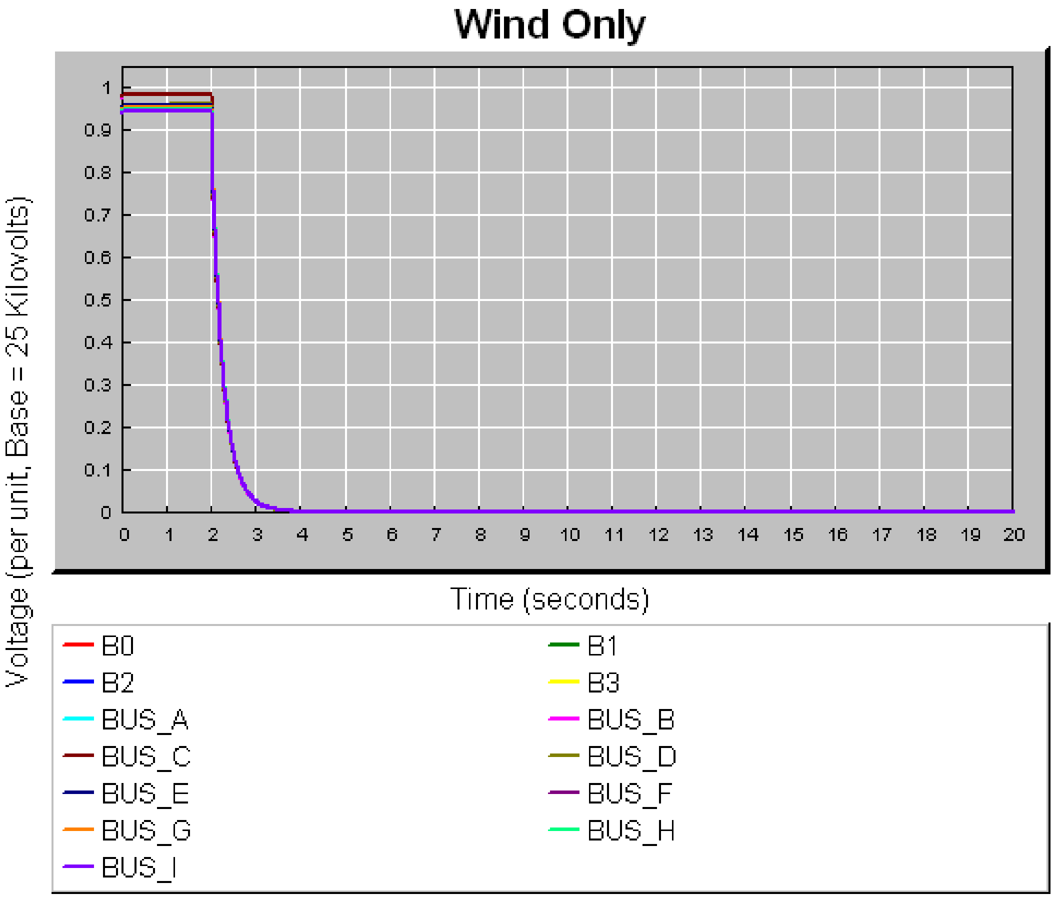


Figure 31: Voltage Response due to an Islanding Event (Under-Generating Condition, Wind Units Only)

Figure 32 shows the real power response of the wind generating units. As the connected bus voltage of each generating unit drops to zero within 2 sec., the real power output of the generating unit also drops to zero. Since the input mechanical power to the wind turbine almost remains constant, depending mostly on the wind speed, zero real power output of the unit results in acceleration of the generator rotor, consequently increasing the system frequency monotonically, as shown in Figure 33. This condition is obviously unsustainable and protection systems will disconnect the wind turbines.

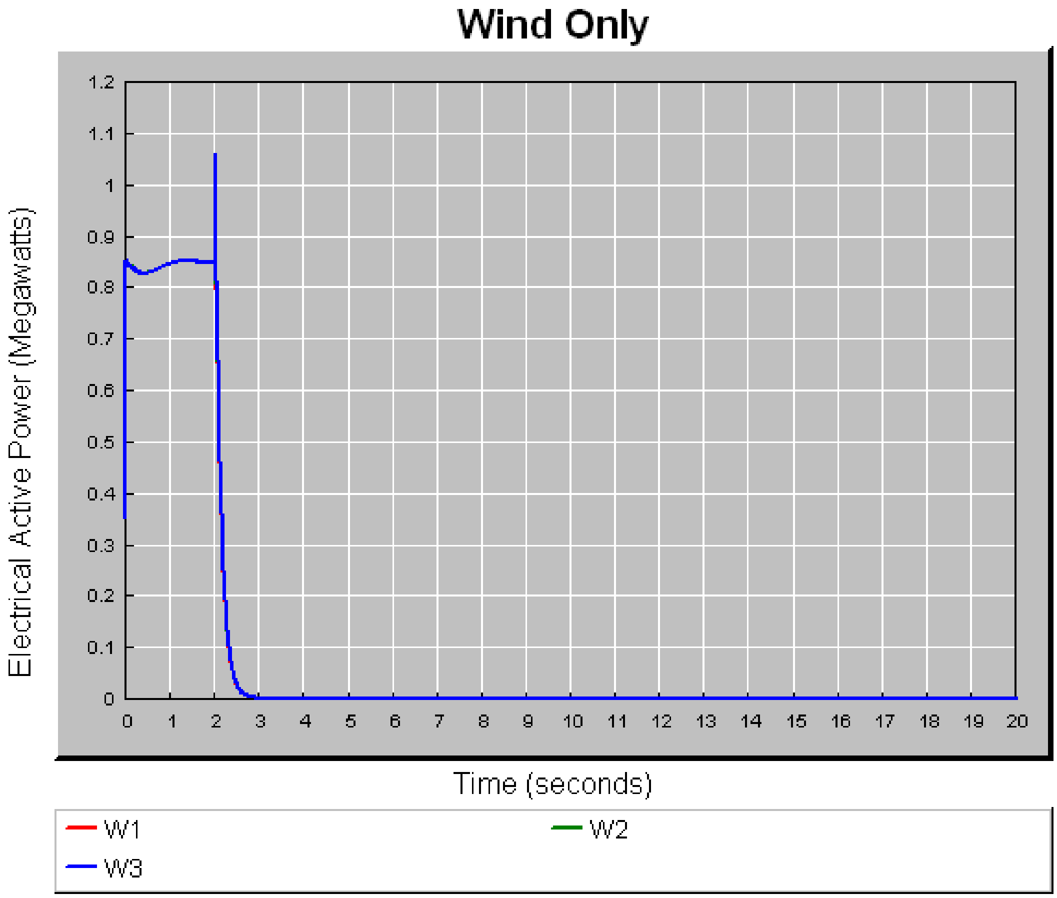


Figure 32: Real Power Response of the Generating Units to an Islanding Event (Under-Generating Condition, Wind Units Only)

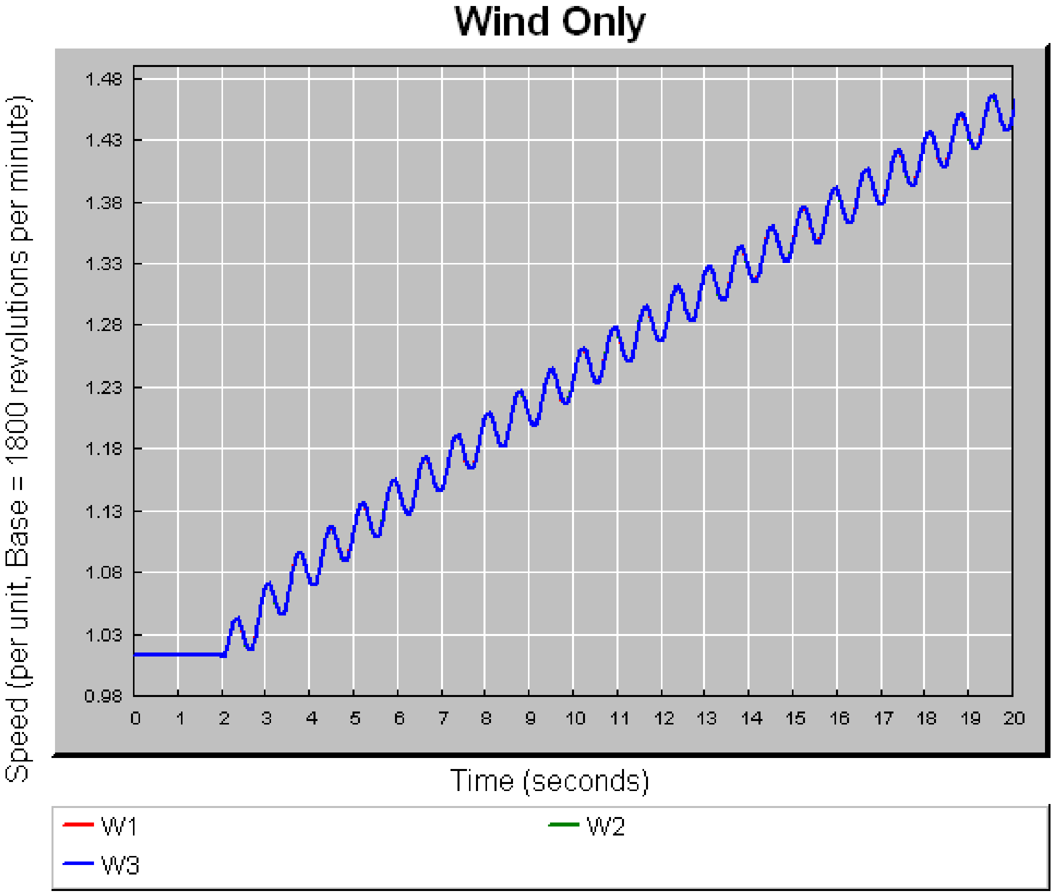


Figure 33: Speed Response to an Islanding Event (Under-Generating Condition, Wind Units Only)

6.4 Distribution System with Embedded Wind DFIG Units

6.4.1 Under-Generating Condition

The load flow of the distribution system under this condition is shown in Figure 34. There are three embedded wind DG units connected at buses B1, B2, and B3. Each of the generating units is controlled to supply 0.85 MW at a power factor of 100%. The distribution system still absorbs 1.134 MVAR from the main power system to meet the reactive power requirements of the system loads. The real power exchange with the main power system corresponds to an import of 1.985 MW. In this case study, the wind speed is assumed constant at the value computed from the load flow analysis.

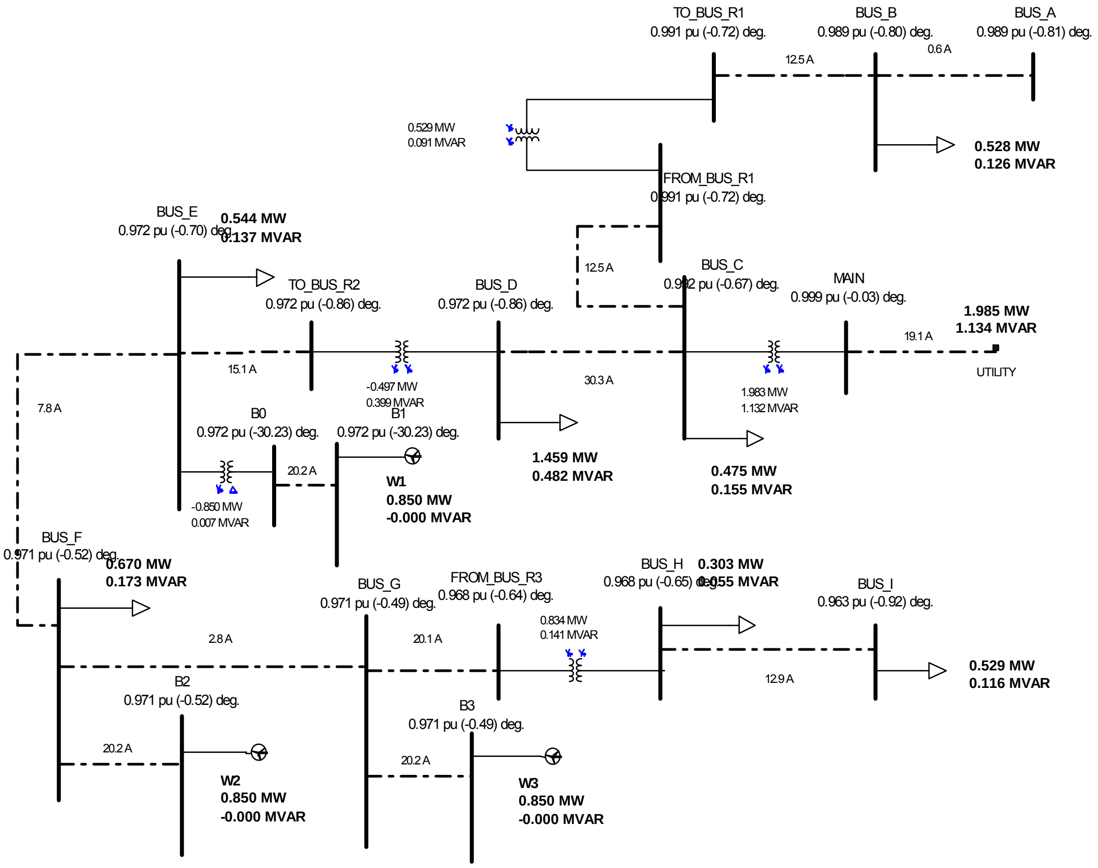


Figure 34: Load Flow Diagram of the Distribution System (Under-Generating Condition, DFIG Wind Units Only)

At t = 2.0 sec., the distribution system is disconnected from the main power system at bus MAIN. The system response to this islanding event is shown in Figure 35, Figure 36 and Figure 37.

Figure 35 illustrates the voltage response of the distribution system due to the islanding event. The voltage values exceed the IEEE limits for island formation detection. Figure 35 shows that the voltages drop to 0.5 p.u. in about 0.02 s subsequent to the islanding event, thus all the generating units will be tripped in about 0.18 s after the island formation, according to the IEEE 1547 Standard.

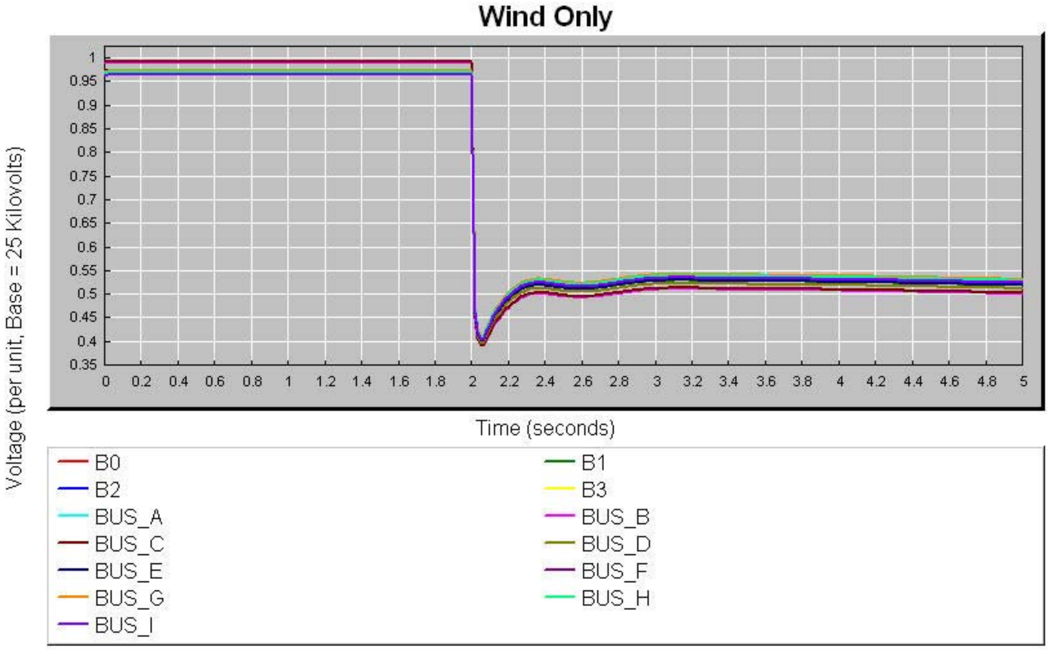


Figure 35: Voltage Response due to an Islanding Event (Under-Generating Condition, Wind Units Only)

Figure 36 shows the real power response of the wind generating units. As the connected bus voltage of each generating unit drops, the real power output of the generating unit also drops. Since the input mechanical power to the wind turbine almost remains constant, depending mostly on the wind speed, reduced real power output of the unit results in acceleration of the generator rotor, consequently increasing the system frequency beyond nominal values, as shown in Figure 37. Left to itself the system will eventually settle to this new regime. However this condition will eventually cause the overfrequency protection systems to disconnect the wind turbines.

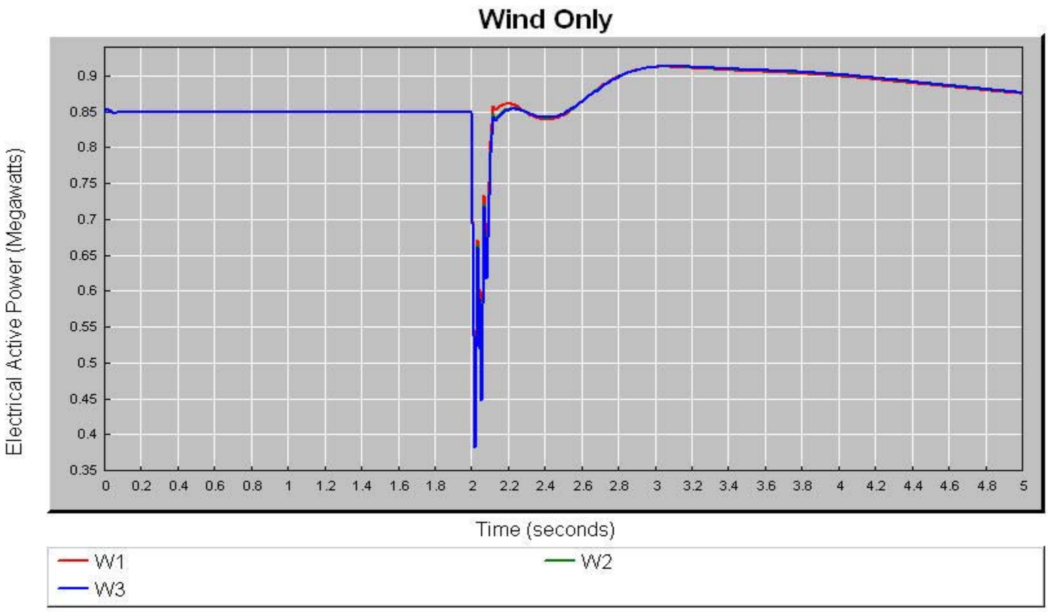


Figure 36: Real Power Response of the Generating Units to an Islanding Event (Under-Generating Condition, Wind Units Only)

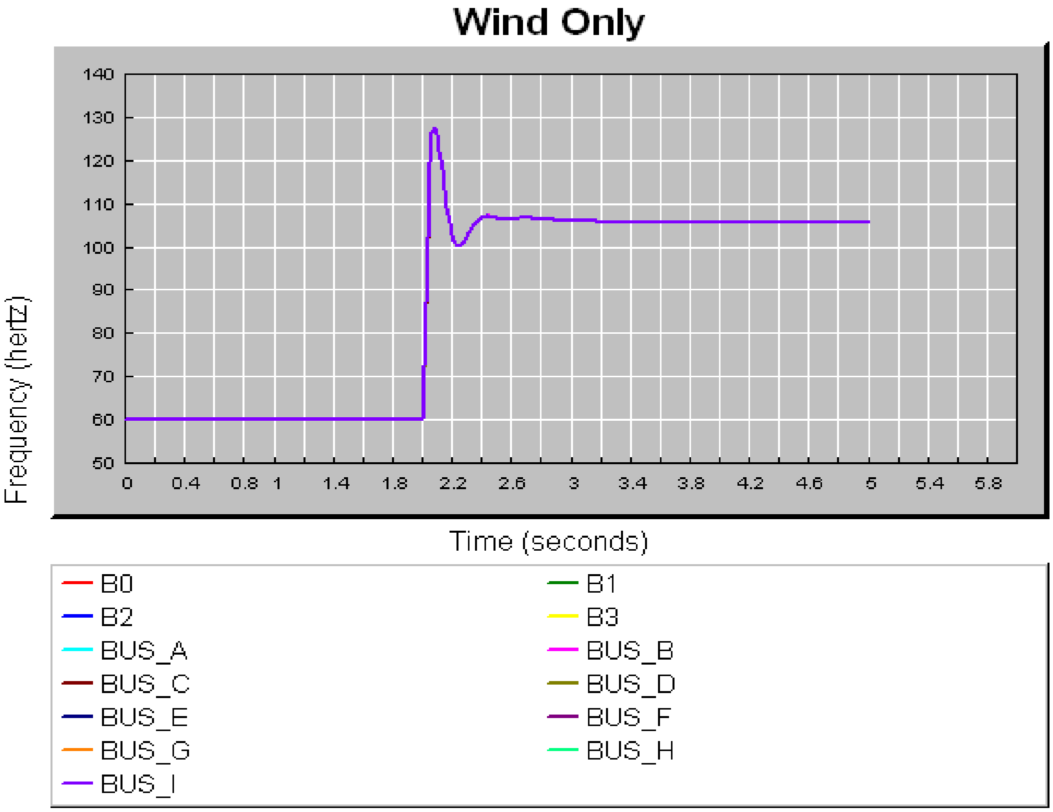


Figure 37: Frequency Response to an Islanding Event (Under-Generating Condition, Wind Units Only)

6.5 Summary of Results

Table 6 : Summary of Cases Considered and Pre-Islanding Operating Conditions.
Initial load: 4.627 MW & 1.313 MVAR

Section	Reference load flow	Subsystem DG production		Interconnection Exchange		Event		Generation/load mismatch
		MW	MVAR	MW	MVAR	MW	MVAR	
6.1.1	Figure 15	3 synch. hydraulic DG				Islanding		1.03
		4.74	1.291	0.004	-0.046	self sufficient syst.		
6.1.2	Figure 17	3 synch. hydraulic DG				Islanding		2.03
		9.36	-0.647	-4.076	-2.792	over generating system		
6.1.3	Figure 20	2 synch. hydraulic DG				Islanding		0.68
		3.16	2.104	1.57	-0.855	under generating system		
6.1.4	Figure 20	2 synch. hydraulic DG				Islanding		0.68
		3.16	2.104	1.57	-0.855	under generating system		
6.2.1	Figure 26	3 synch. diesel DG				Islanding		0.55
		2.55	2.543	2.216	-1.257	under generating system		
6.3.1	Figure 30	3 induction wind DG				Islanding		0.55
		2.55	-1.941	1.954	1.712	under generating system		
6.4.1	Figure 34	3 ind..DFIG wind DG				Islanding		0.55
		2.55	0	1.985	1.134	under generating system		

7 Conclusions

This study demonstrates the dynamic behaviour of a system with distributed generation units following islanding 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, diesel, and wind, and (ii) different DG sizes and penetration levels.

The simulations of this report show that a major disturbance in the system, in the form of an islanding occurrence, imposes variations in the voltage and the frequency of the system, whose magnitude depends mainly on the type, size and control configuration of the DG technology under investigation.

The results of the conducted dynamic simulations indicate that the following:

- Hydro DG units with enabled governors are capable of maintaining the frequency of the isolated system at permissible levels once the system has reached a new steady state, if the pre-islanding operation of the distribution system is a self-sufficient (or close) condition. However, if the pre-islanding operation is different from a self-sufficient condition, the transient frequency excursions might be large enough and long enough to violate the IEEE 1547 Standard limits. Consequently, islanding would be detected and the DG units would be forced to shut down. Hydro units with disabled governor can not maintain the frequency of the islanded system at permissible levels and therefore the DG units would be forced to shut down.

- The simulation involving diesel DG units, Section 6.2.1, is a good example of the impact of prime mover characteristics on the system response due to islanding conditions. Even though the ratio of real power generation to consumption is approximately 2/3, the ability of the governor and its associated control to provide quick changes in power allows a fast recovery of the frequency upon islanding. Thus the IEEE 1547 limits are not violated and the system remains operational, which is an unacceptable condition under current regulations. As such, an additional means of detecting the island condition other than voltage and frequency limits would need to be employed. There are a number of reliable, low cost islanding detection options using measurement of local signals

- Distribution systems with wind DG units embedded, and operating with under generated real power conditions, can not maintain voltage/frequency of the isolated system within permissible limits. Therefore islanding is detected and the wind DG units must be shut down.

- The ability of the distribution system to detect islanding formation solely based on the voltage/frequency criterion of IEEE 1547 Standard depends on the DG technology and the associated control scheme, and the pre-islanding operating condition. Thus, additional islanding strategies should be implemented for reliable islanding detection.

- Detailed dynamic simulation is essential for planning and operation studies of systems with distributed generation. Predicting dynamic system behaviour based on rules of thumb and/or common engineering wisdom may have its place in providing a reasonable estimation of the expected outcome but can, in many cases, produce misleading results.

- Dynamic models of the different components in the system, including load modeling, will impact the dynamic behaviour upon islanding occurrence. Appropriate dynamic models are required in order to ensure an accurate representation of the system's dynamic behaviour.

8 References

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

[12] M. Ropp, and W. Bower, "Evaluation of islanding detection methods for photovoltaic utility interactive power systems," International Energy Agency Implementing agreement on Photovoltaic Power Systems, Tech. Rep. IEA PVPS T5-09, March 2002.

[13] T.H.M. EL-Fouly and C. Abbey, “Commercial Relays Field Tests for Passive Anti-Islanding Protection Schemes of Synchronous Generator Based DGs”, CIGRE Canada Conference on Power Systems, Toronto, Canada. (October 4 – 6, 2009). Available at http://198.103.48.154/eng/renewables/integration_der/publications.html?2009-181

ANNEX A
CYME file references

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CYME file references

The CYMDIST software and the CYMDIST files corresponding to the case studies of this report can be obtained from CYME International (www.cyme.com). Interested users should contact CYME International directly.

Section	CYMDIST Files
6.1.1 Three Synchronous Hydraulic DG units-Self-sufficient system	hydraulicDGselfsufficient_islanding.sxst
6.1.2 Three Synchronous Hydraulic DG units-Over-generating system	hydraulicDGovergen_islanding.sxst
6.1.3 Two Synchronous Hydraulic DG units-Under-generating system	hydraulicDGundergen_islanding.sxst
6.1.4 Two Synchronous Hydraulic DG units-Under-generating system, no governor	hydraulicDGundergen_islanding_nogov.sxst
6.2.1 Three Synchronous Diesel DG units-Under-generating system	dieselDGundercomp_islanding.sxst
6.3.1 Three Induction Wind DG units-Under-generating system	windDGundergen_islanding.sxst
6.4.1 Three Induction Wind DG units-Under-generating system	windDGDFIGundergen_islanding.sxst