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DISTRIBUTED GENERATION ANALYSIS
CASE STUDY 6:

Investigation of
Planned Islanding Performance
of Rotating Machine-based DG Technologies

Canada

DISTRIBUTED GENERATION ANALYSIS
Case Study 6
–
Investigation of Planned Islanding Performance of Rotating Machine-based DG Technologies

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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]. This 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 sixth 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 planned islanding performance of a system with various rotating machine-based DG technologies. The frequency and voltage of the system, as well as the real power of the generators, are analyzed during the transition from the grid-connected state to the islanded state. This second edition of 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 the 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 sixième 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 l'îlotage d'un réseau de distribution pour différentes technologies de génération. La fréquence ainsi que la tension et la puissance réelle de la génératrice et les charges sont analysées pour la transition au mode isolé. 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. 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 has already been established and discussed in previous CYME reports commissioned for Natural Resources Canada (NRCan) [2-11].

As much as there are several positive aspects to the use of distributed generation, there are also pitfalls to their application in existing distribution systems. Therefore, if the addition 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 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 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], [7-9]

The object of this report is to study the impact of rotating machine-based distributed resources, 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 observed dynamic response of the system, it can be determined whether the distribution system under study is allowed to operate in the islanded mode.

2 Description of Assignment

While DG will normally be required to disconnect when the main supply is disconnected, there is an emerging trend to operate a distribution system in a planned islanding mode under certain circumstances. The IEEE 1547.4 application guide [12] addresses this mode of operation, which can be applied at the discretion of the local utility. In addition to demonstrate the performance of a system while transitioning between grid-connected and islanded states, the purpose of this report is to demonstrate the dynamic functionalities of CYMDIST, version 5.0, under such conditions.

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

1. Hydraulic units which drive 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.

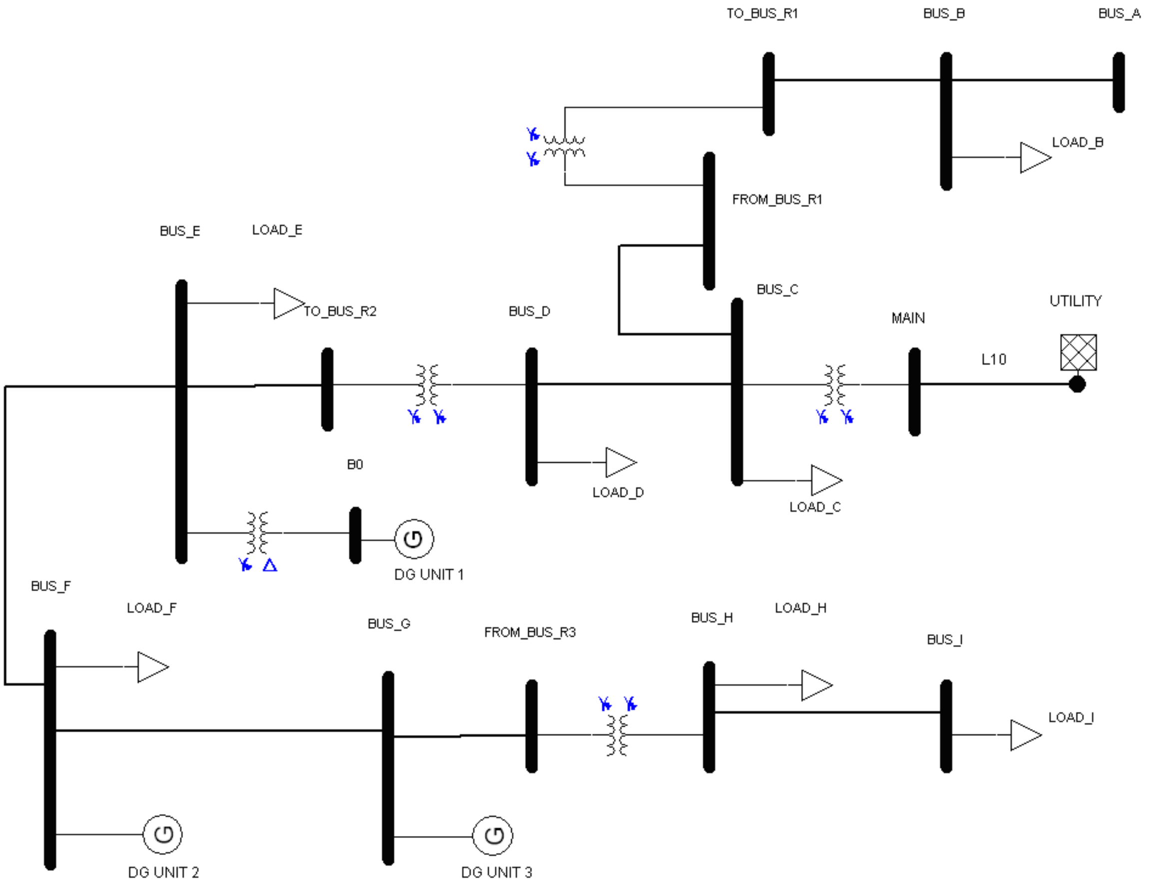

Figure 1: Distribution System Under Study [1]

The distribution system is connected to the main power 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 $\boldsymbol{P_o}$ and $\boldsymbol{Q_o}$ are the nominal active and reactive power of the load, and $\boldsymbol{V_{pu}}$ and $\boldsymbol{F_{pu}}$ 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.

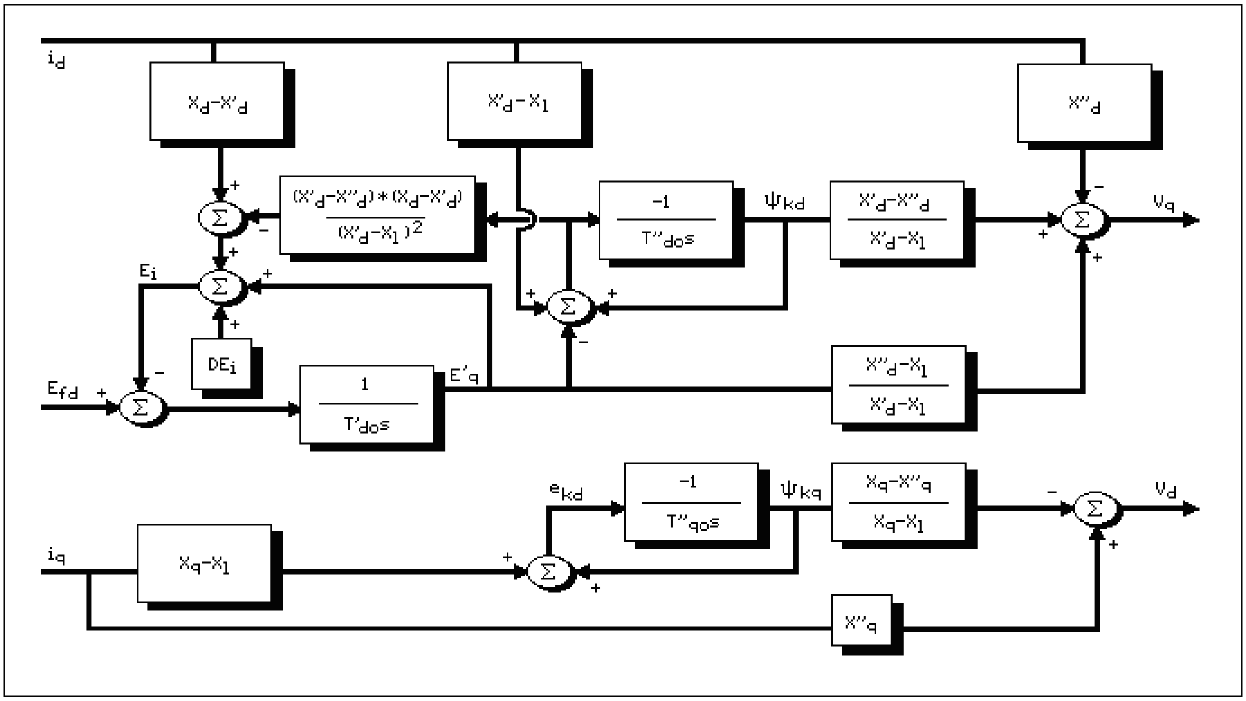


Figure 2: Salient Pole Synchronous Generator Model

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

- Synchronous Reactances:

  $X_d = 1.236$ 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

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.

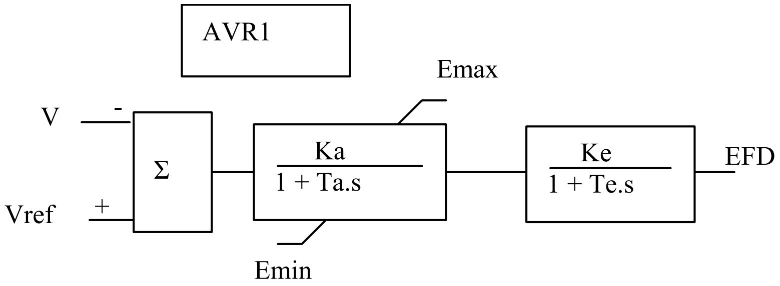


Figure 3: Excitation and Automatic Voltage Regulation Model

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.

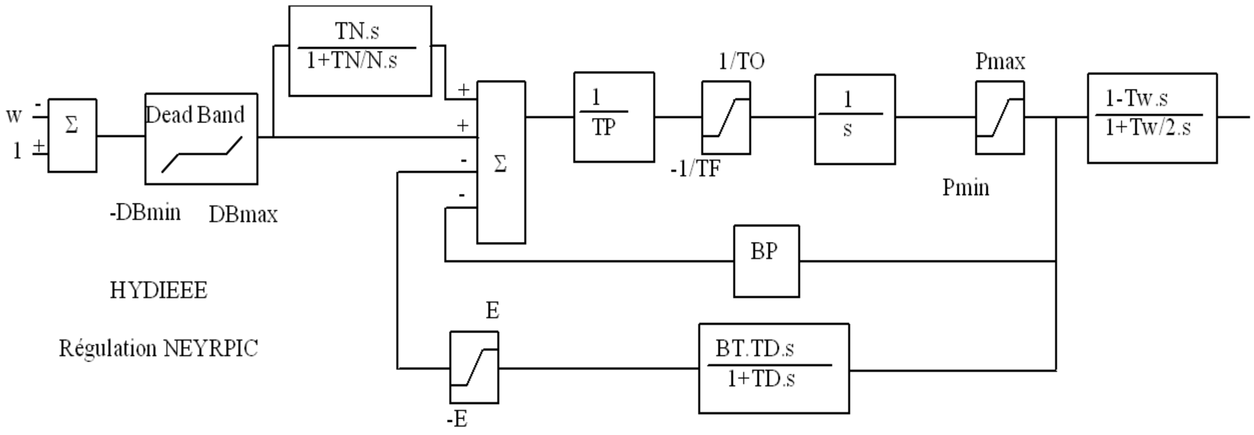


Figure 4: Hydraulic Governor and Turbine Model

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 is variable, depending on the capacity of the DG unit, 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

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

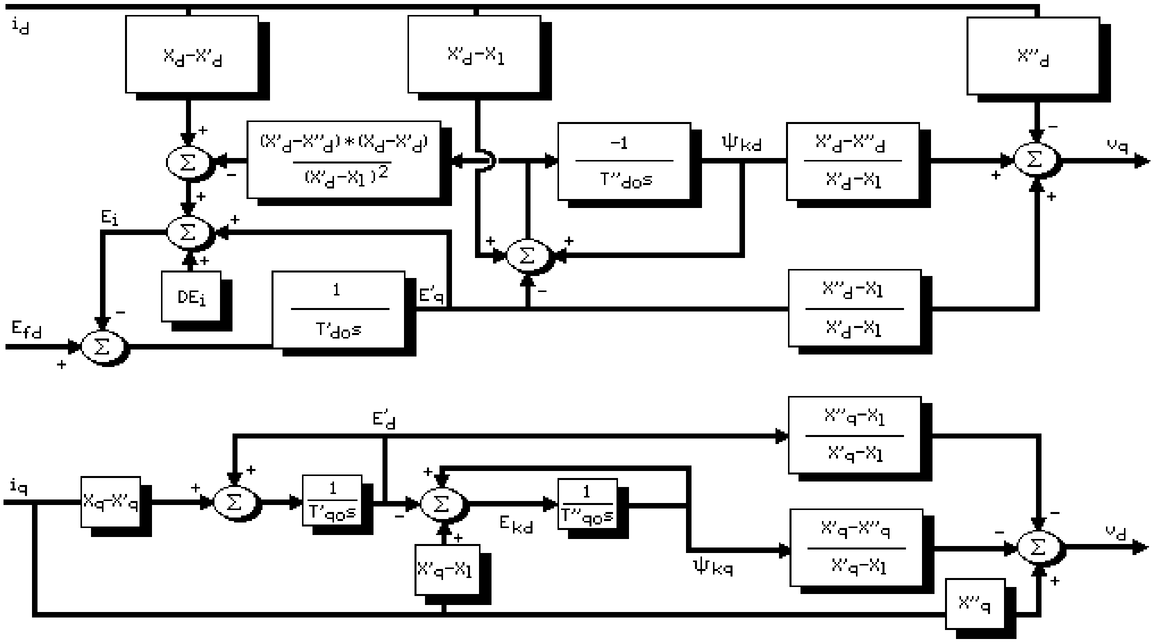


Figure 5: Round Rotor Synchronous Machine Model

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

- Synchronous Reactances:

  $X_d = 1.6$ *p.u.,* $X_q = 0.95$ *p.u.,* $X_l = 0.105$ *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 zero droop (isochronous mode), therefore it will always adjusts 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.

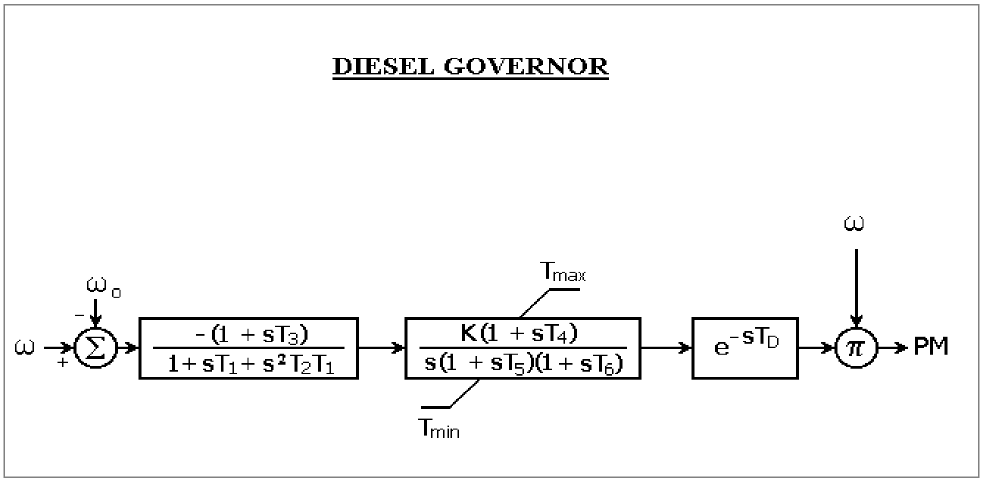


Figure 6: Governor/Turbine Model of a Diesel Engine

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 in the turbine parameters, is variable, depending on the case study.

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.

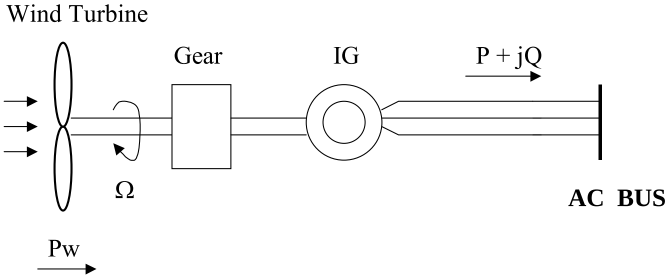


Figure 7: WECS Directly Coupled Induction Generator Topology

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.

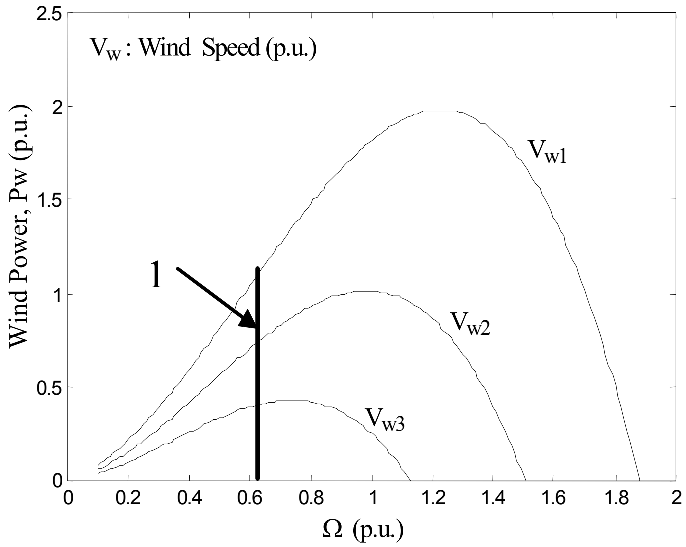


Figure 8: Operating Characteristics of the Wind Turbine – Directly Coupled Ind. Generator

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

4.4.2 WECS Drivetrain Model – Directly Coupled Induction Generator

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

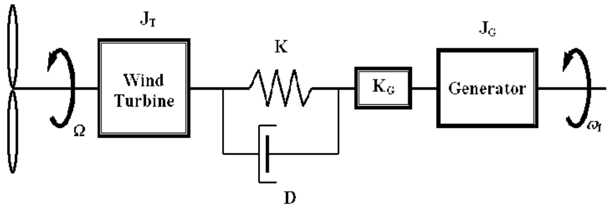


Figure 9: WECS Drivetrain Model – Directly Coupled Ind. Generator

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*

Drivetrain 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 shown in Figure 10.

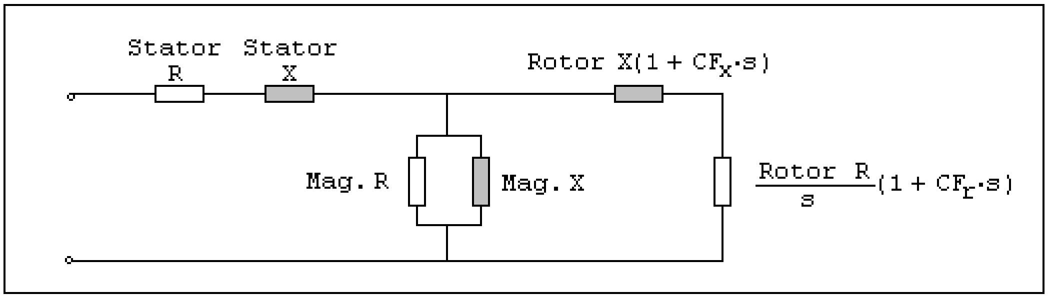


Figure 10: Induction Generator Equivalent Circuit – Directly Coupled Ind. Generator

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.

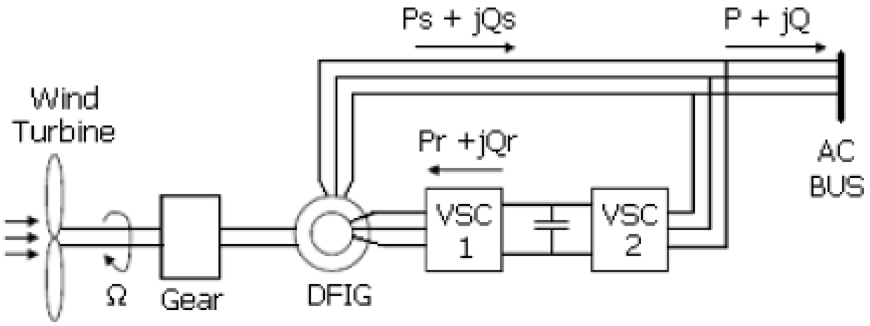
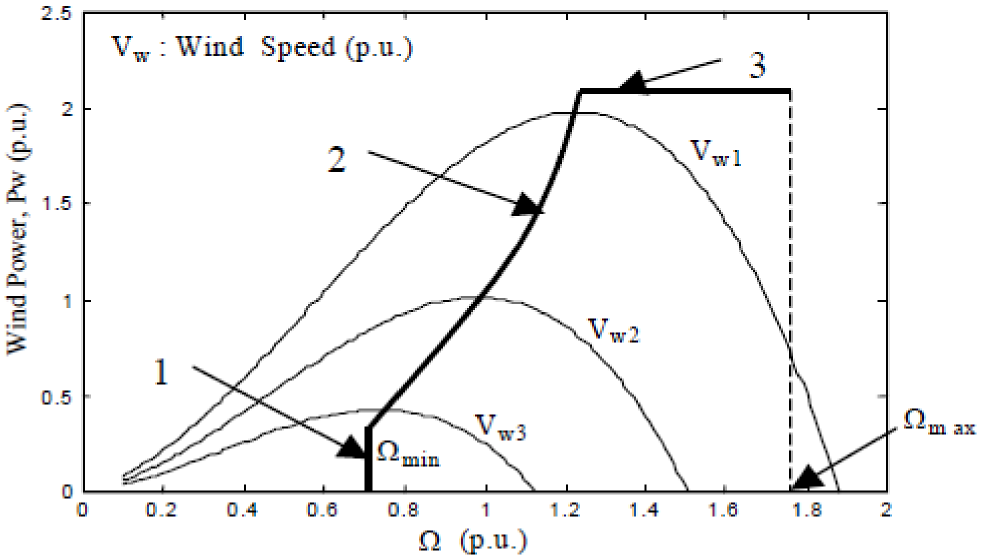


Figure 11: WECS Doubly Fed Induction Generator Topology

For the induction generator, in all the wind DG case studies, it is assumed that the wind turbine operates at constant speed and consequently, input 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 drivetrain is represented by the two-mass model of Figure 13:

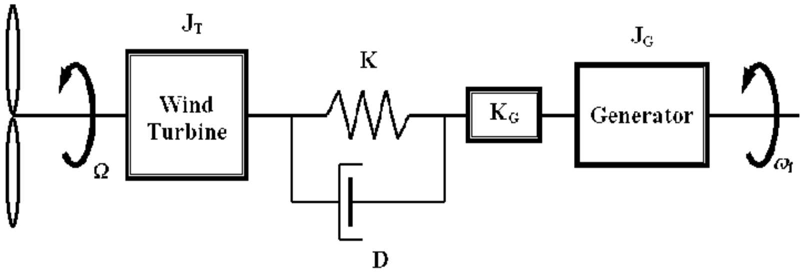


Figure 13: WECS Drivetrain Model – Doubly Fed Ind. Generator

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*

Drivetrain 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.

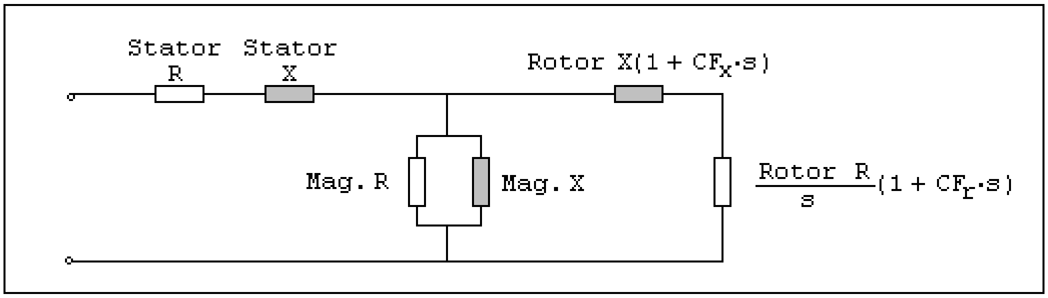


Figure 14: Induction Generator Equivalent Circuit – Doubly Fed Ind. Generator

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 [13] 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, as specified also in the IEEE 1547-2003 Standard. For a planned islanding operation, these voltage/frequency limits may need to be relaxed.

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 [14].

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

Voltage Range (% of base voltage[a])	Clearing Time[b] (s)
$V < 50$	0.16
$50 \le V < 88$	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 (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 . The values in Table 5 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 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. However, a distribution network with embedded distributed generation implies a greater level of complexity in terms of operation and planning. If islanded operation of a distribution system is permitted in the future, dynamic studies would be required to predict the system behaviour during (i) the transition from the grid-connected mode to the islanded mode, and (ii) the islanded operation once disconnected from the utility system. In this report, the frequency limits of Table 4 and Table 5 are adjusted in order to facilitate the islanded operation of the system. The over/under frequency limits for the three different DG technologies of this report are summarized in Table 6.

Table 6: Adjusted Frequency Limits for Islanded Operation

DG Technology	Frequency Threshold (Hz)		Delay
Hydro DG unit	Under frequency	48.0	Instantaneous
	Over frequency	72.0	Instantaneous
Diesel DG unit	Under frequency	58.2	Instantaneous
	Over frequency	61.8	Instantaneous
Wind DG unit	Under frequency	Not specified*	Not specified*
	Over frequency	Not specified*	Not specified*

* No under- and over-frequency limit is set on the wind turbines in order for it to stay operational.

6 Case Study Results: Islanding Operation of the Distribution System

Results of the case study presented in this report will illustrate the dynamic response of system components upon islanding occurrence, i.e. when the distribution system is isolated from the main power system. The objective of the case studies is to examine whether the operation of the distribution system in an islanded configuration is possible.

In this report, the feasibility of the formed islanded system is determined by the frequency limits for the embedded generating units presented in Table 6. Local utilities will ultimately decide whether or not the frequency and the voltage limits can be relaxed for the islanded mode of operation.

6.1 Distribution System with Embedded Hydraulic Generating Units

6.1.1 Generation/Load Ratio of 10 MW/4.6 MW (117 % power mismatch)

In this case study, three hydraulic units are connected at buses B0, F and G, as shown in Figure 15. The hydraulic unit connected at bus B0 (DG1) has a capacity of 6 MVA, while the hydraulic units at buses F and G (DG2 and DG3) have a capacity of 3 MVA each. DG1 is controlled to supply 5 MW, whereas DG2 and DG3 are controlled to supply 2.5 MW each. The three units are controlled to maintain their terminal voltage at 1.05 p.u.. Figure 15 shows the pre-islanding load flow of the distribution system corresponding to this case study where the total system load is about 4.6 MW. At t = 2.0 s, the distribution system is disconnected from the main power system at bus MAIN. The system response to this islanding event is shown in Figure 16 and Figure 17.

Figure 16 shows the frequency response of the distribution system subsequent to the island formation. As the power imbalance is large, the islanding event also results in a large variation in the frequency, with a maximum value of 72.86 Hz and a minimum value of 55 Hz. The frequency value exceeds the limits of a hydro generating unit of Table 6. Thus, in terms of frequency, all the generating units will be tripped. Figure 16 shows that the frequency increases to 72 Hz in about 4 sec. after the island event. At this moment the generating units will instantaneously tripped by their over-speed protection. It is worth mentioning that the presented results did not simulate the tripping action. It is also worth mentioning that if the power mismatch is less than the presented case, it could result in continuous operation of the DG units without tripping.

Figure 17 shows that the real power of the generating units decreases significantly right after the islanding event to match the system load. Through the control action of the governor systems, the real power outputs of DG2 and DG3 (2.5 MW) and of DG1 (5 MW) reach new steady-state values about 1.25 MW (x2) and 2.5 MW, respectively.

The voltages at the terminals of DG1 here goes permanently beyond the limit of 1.06 pu of

Table 3 whereas the voltages at the terminals of DG2 and DG3 goes beyond the limit of 1.06 pu for about 1 second and may result in their tripping off the network depending on the protection setting of the network operator.

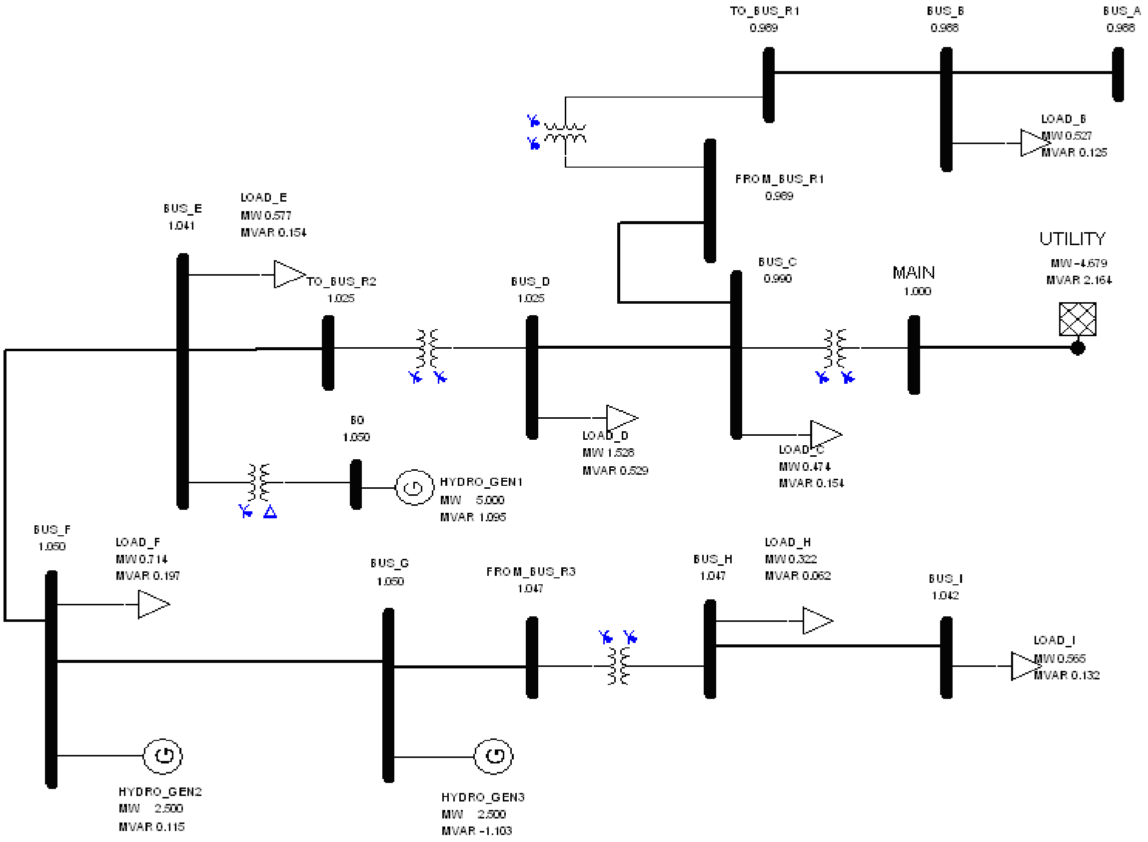


Figure 15: Load Flow Diagram of the Distribution System
(Over-Generating Condition with Generation/Load ratio of 10MW/4.6MW, Three Hydro Units)

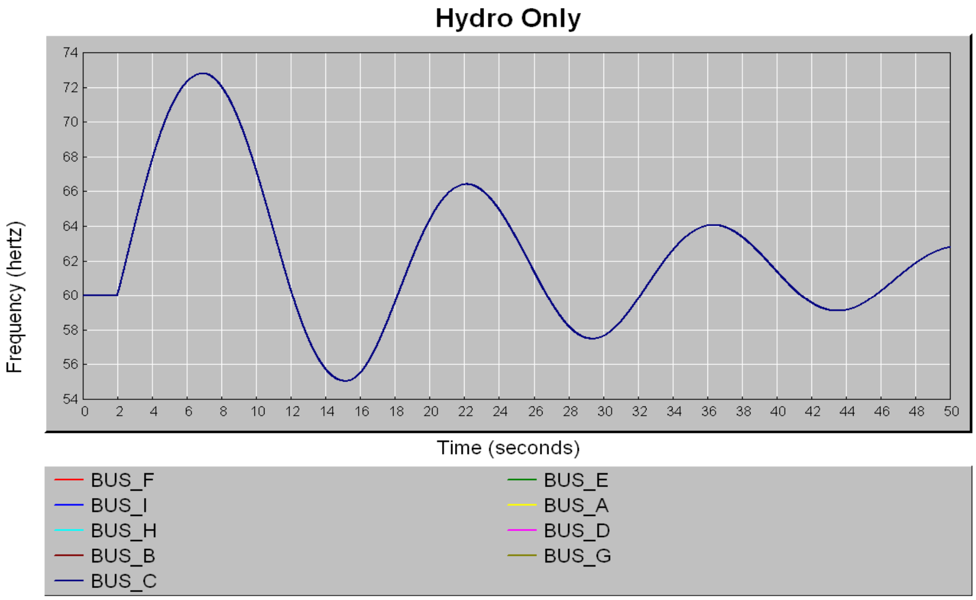


Figure 16: Frequency Response due to an Islanding Event
(Over-Generating Condition with Generation/Load ratio of 10 MW/4.6 MW, Hydro Units Only)

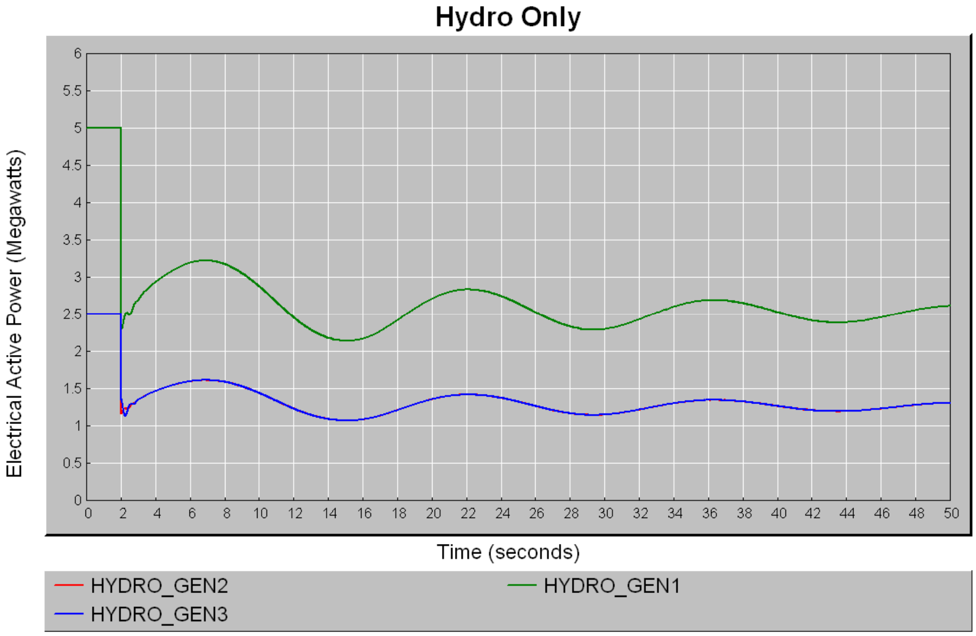


Figure 17: Real Power Response of Generating Units to an Islanding Event
(Over-Generating Condition with Generation/Load ratio of 10 MW/4.6 MW, Hydro Units Only)

6.1.2 Generation/Load ratio of 1.5 MW/4.6 MW (67% power mismatch)

In this case study, each of the three hydraulic generating units in the distribution system has a capacity of 3 MVA and it is controlled to supply 0.5 MW and to maintain its terminal voltage at 1.03 p.u. The load-flow for this operating point is illustrated in Figure 18 with a total system load of about 4.6 MW. 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 19 and Figure 20.

Figure 19 shows the frequency response of the distribution system subsequent to the islanding event. Due to the power imbalance, the islanding event results in a variation in the frequency lower than that of section 6.1.1, with a maximum value of 63.25 Hz and a minimum value of 48.07 Hz. The variation in the system frequency is close to the under frequency protection of the hydraulic unit, i.e., 48 Hz (Table 6). In this case, in terms of frequency, the generating units remain operational, while the system frequency settles down at a new steady-state point through the control action of the governor systems of the generating units. The new steady-state frequency is below the nominal value of 60 Hz due to the droop characteristics of the governor systems. The voltages at the terminals of the two wind turbines however goes beyond the limit of 1.06 pu of

Table 3 for about 0.9 seconds and may result in their tripping off the network depending on the protection setting of the network operator.

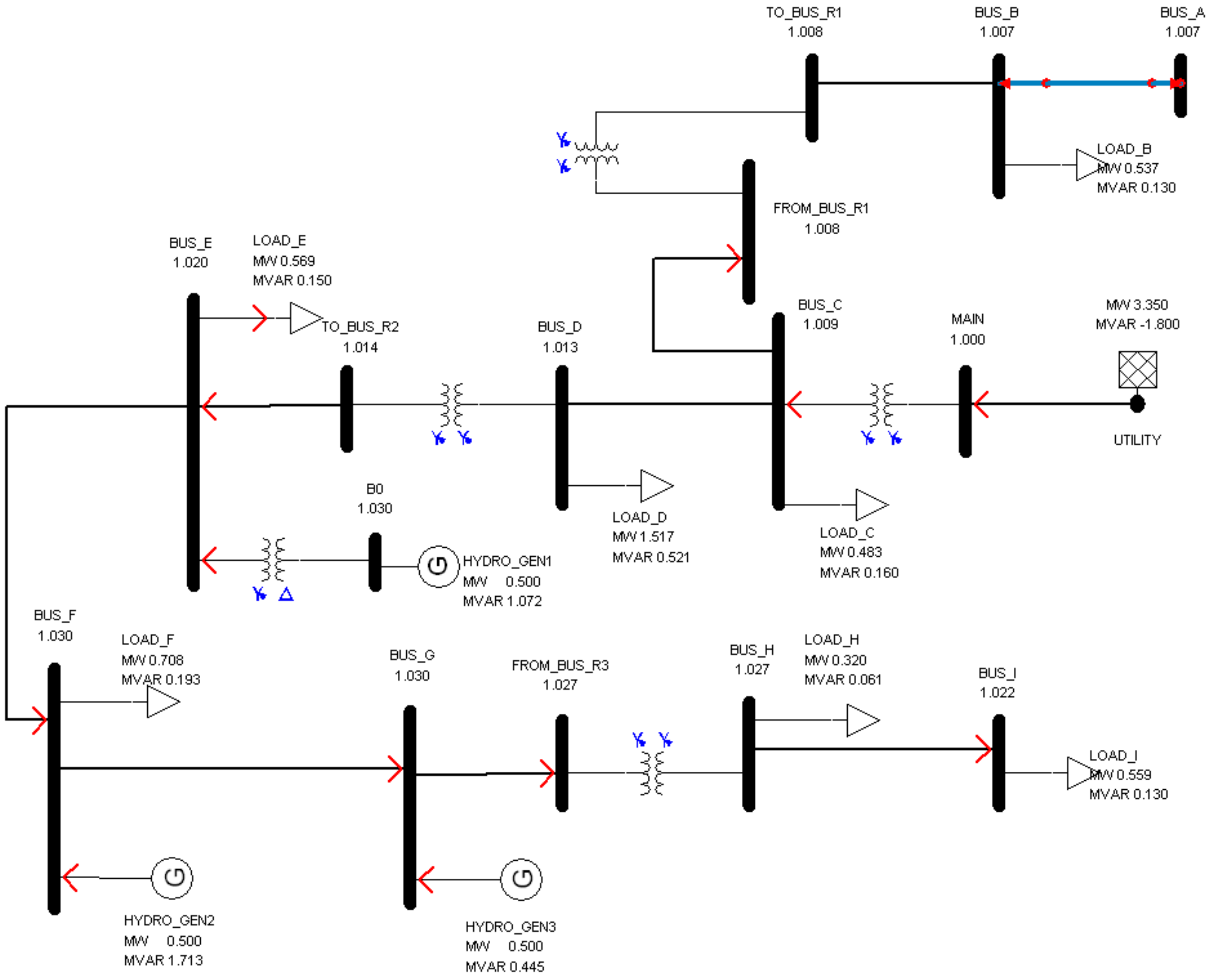


Figure 18: Load Flow Diagram of the Distribution System (Under-Generating Condition with Generation/Load ratio of 1.5 MW/4.6 MW, Three Hydro Units)

Figure 20 shows that the real power outputs of the generating units increase significantly right after the islanding event to match the system load. Through the control action of the governor systems, the real power of each generating unit reaches a new steady-state value around 1.55 MW.

Figure 21 shows that due to the significant increase of the power from the generating units the voltage also increases significantly before settling to a new higher steady state value of around 1.03 pu with the action of the exciter.

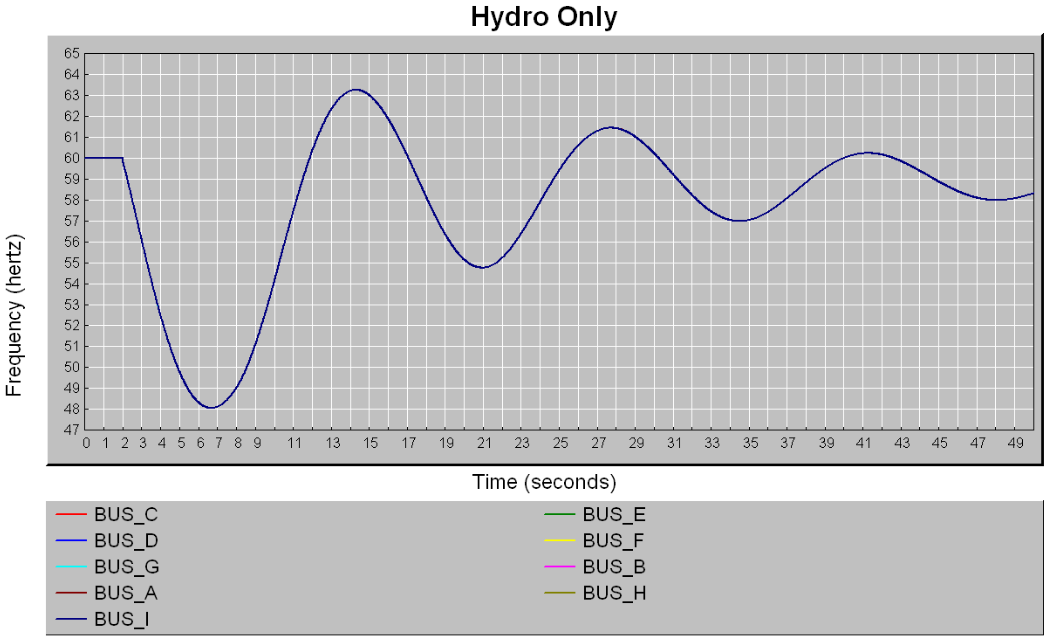


Figure 19: Frequency Response to an Islanding Event (Under-Generating Condition with Generation/Load ratio of 1.5 MW/4.6 MW, Hydro Units Only)

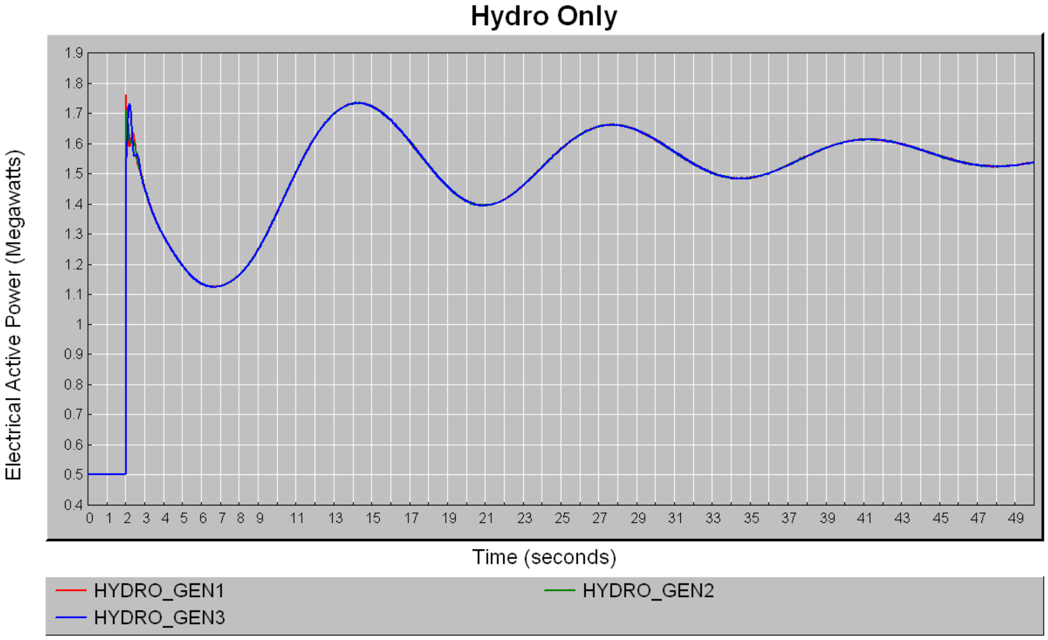


Figure 20: Real Power Response of Generating Units to an Islanding Event (Under-Generating Condition with Generation/Load ratio of 1.5 MW/4.6 MW, Hydro Units Only)

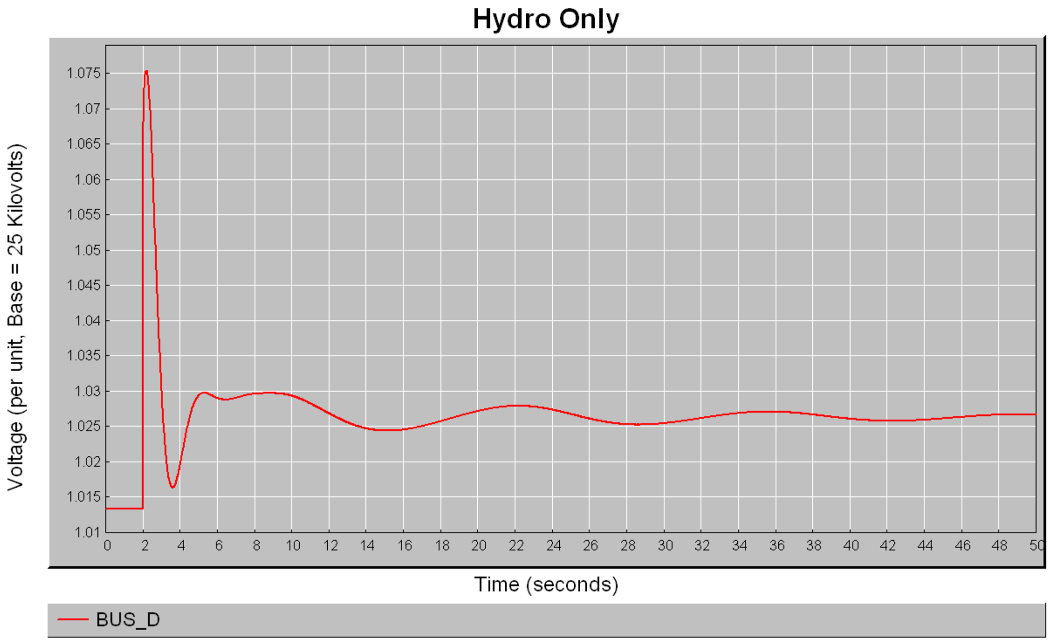


Figure 21: Voltage at Load at Bus D due to an Islanding Event (Under-Generating Condition with Generation/Load Equal to 1.5 MW/4.6 MW, Hydro Units Only)

6.2 Distribution System with Embedded Diesel Generating Units

6.2.1 Generation/Load Equal to 10 MW/ 4.6 MW

In this case study, there are three diesel generating units connected to the distribution system. The diesel unit connected at Bus B0 (DIESEL_GEN1) has a capacity of 6MVA, while the other two diesel units (DIESEL_GEN2 and DIESEL_GEN3) have a capacity of 3 MVA each. The three diesel units are controlled to supply a pre-determined amount of real power to the distribution system and to maintain their terminal voltage at 1.05 p.u.. As depicted in Figure 22, diesel unit DIESEL_GEN1 supplies 5 MW, and units DIESEL_GEN2 and DIESEL_GEN3 supply 2.5 MW each.

The total system load is about 4.6 MW. At t = 1.0 s, the distribution system is disconnected from the main power system at bus MAIN. The system response to this islanding event is shown in Figure 23 and Figure 24.

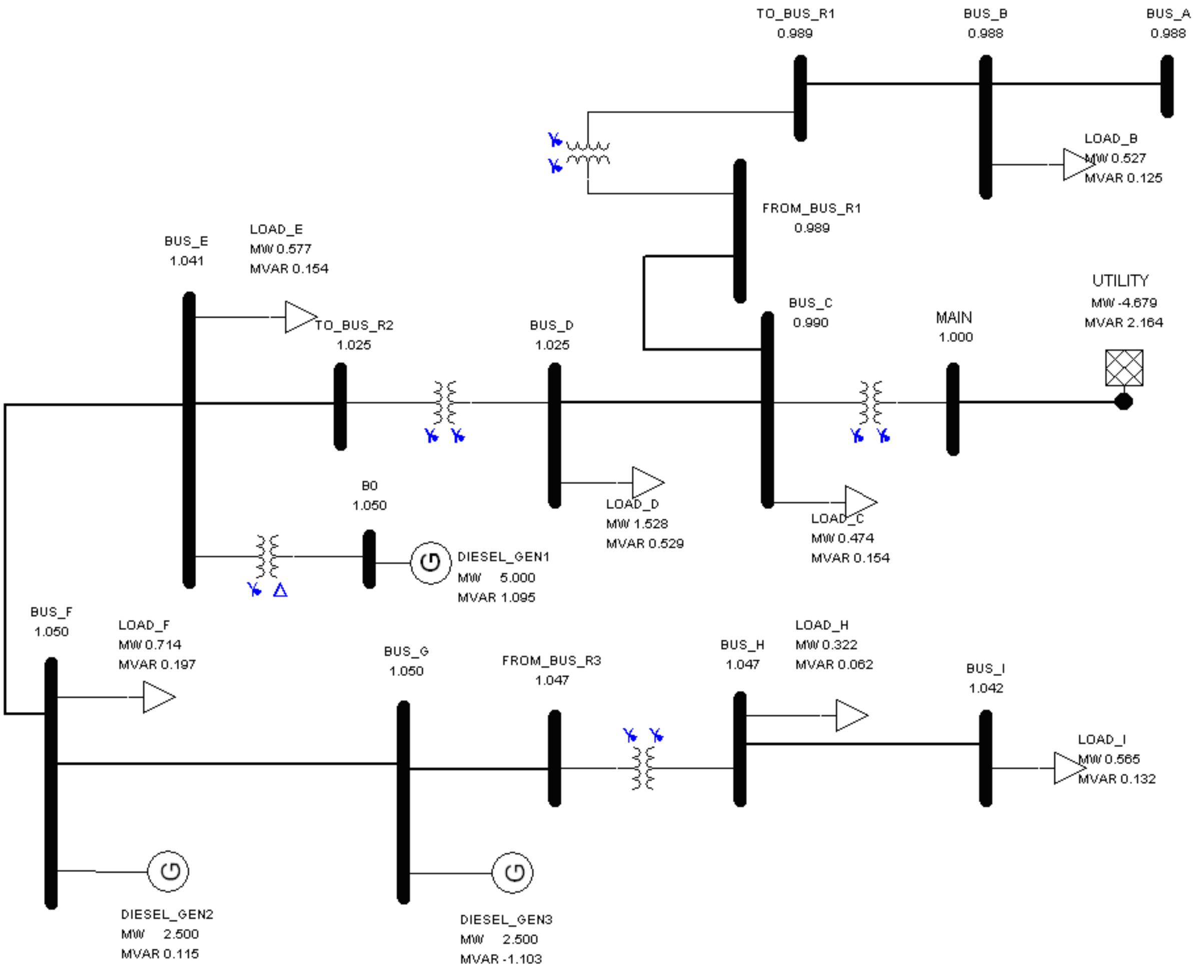


Figure 22: Load Flow Diagram of the Distribution System
(Over-Generating Condition with Generation/Load ratio of 10 MW/4.6MW, Three Diesel Units)

Figure 23 shows the frequency response of the distribution system subsequent to the islanding event. Due to the power imbalance, the islanding event results in a variation in the frequency, with a maximum value of 61.01 Hz and a minimum value of 59.88 Hz. The frequency variation is much smaller as compared to the case of Figure 16 due to the fast response nature of the governor system of diesel units. The frequency value is within the limits of the diesel generating units in terms of frequency protection, presented in Table 6. In terms of frequency the generating units, remain operational while the system frequency returns to the nominal value of 60 Hz since the governor system of the diesel units does not apply droop control.

Figure 24 shows that the real power outputs of the generating units decrease significantly right after the islanding event to match the system load. Through the control action of the governor systems, the real power of each generating unit reaches a new steady-state value in around 0.5 s depending on the corresponding DG capacity.

The voltages at the terminals of the three generators, however, goes permanently beyond the limit of 1.06 pu of

Table 3 and will result in their tripping off the network according to the protection setting of this table.

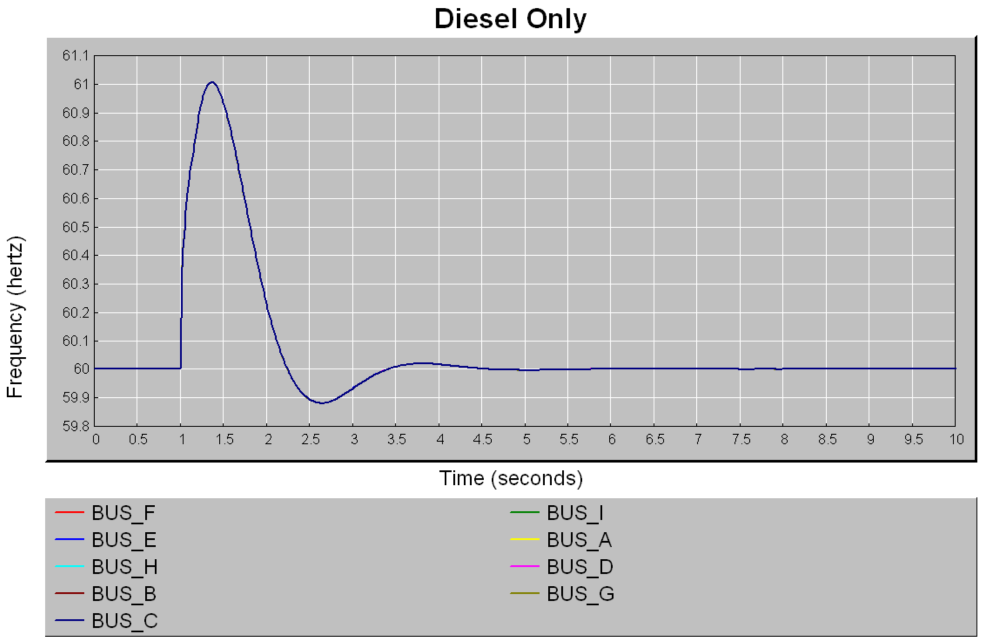


Figure 23: Frequency Response to an Islanding Event
(Over-Generating Condition with Generation/Load ratio of 10 MW/4.6 MW, Diesel Units Only)

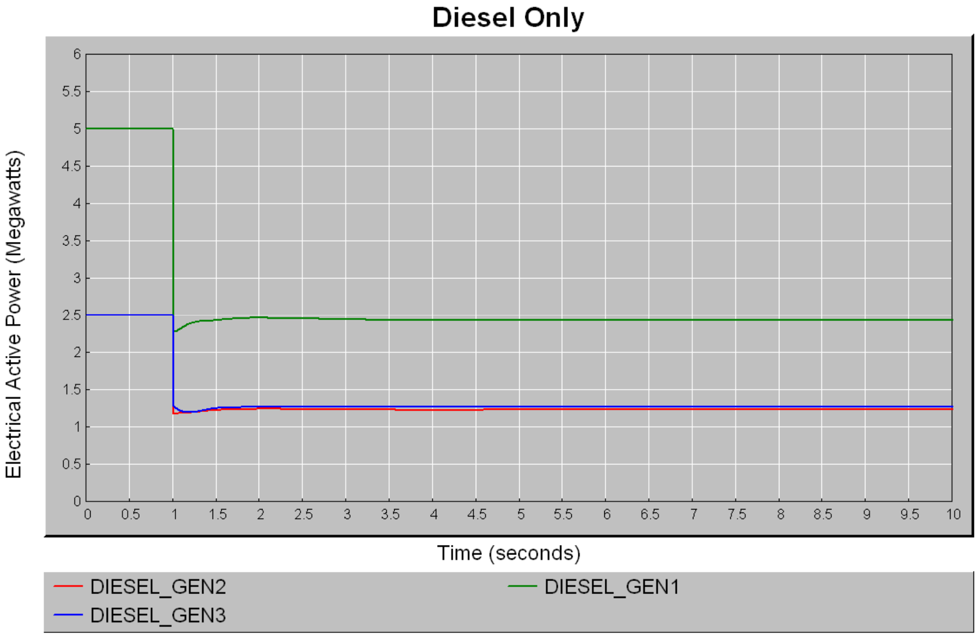


Figure 24: Real Power Response of Generating Units to an Islanding Event (Over-Generating Condition with Generation/Load ratio of 10 MW/4.6 MW, Diesel Units Only)

6.2.2 Generation/Load Equal to 1.5 MW/4.6 MW

In this case study, the three diesel unit DIESEL_GEN1 has a capacity of 3 MVA, unit. The three diesel units are controlled to supply 0.5 MW each and to maintain their terminal voltage at 1.03 p.u., as illustrated in Figure 25. In this case study, the parameter TBMW in the DG unit's governor, Section 4.3.3, corresponds to the capacity of the unit, i.e., TBMW1= 3 MW.

The total system load is about 4.6 MW. At t = 1.0 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 26 and Figure 27.

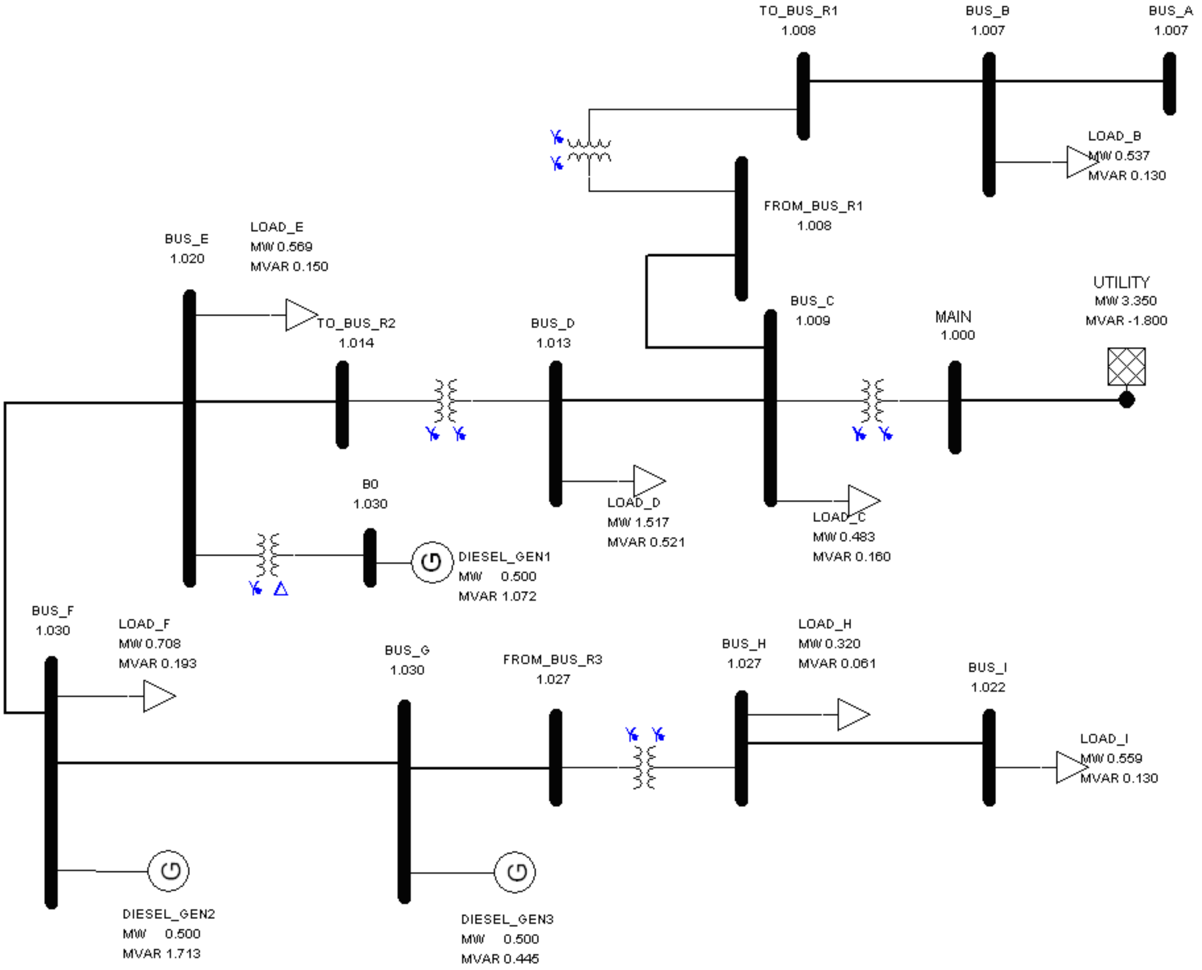


Figure 25: Load Flow Diagram of the Distribution System
(Over-Generating Condition with Generation/Load ratio of 1.5 MW/4.6 MW, Three Diesel Units)

Figure 26 shows the frequency response of the distribution system subsequent to the islanding event. Due to the power imbalance, the islanding event results in a variation in the frequency, with a maximum value of 60.11 Hz and a minimum value of 59.13 Hz. The variation is much smaller as compared with the hydro generation case of Figure 19. The frequency value is within the limits of diesel generating units in terms of frequency protection of Table 6. In terms of frequency, the generating units remain operational while the system frequency returns to the nominal value of 60 Hz since the governor system of diesel units does not apply droop control.

Figure 27 shows the real power outputs of the diesel units after the islanding event. The load sharing between units, Figure 27, is very close to each other as the capacity of the DG units are similar and settles with respect to the new configuration of the network.

The voltages at the terminals of the two wind turbines here goes beyond the limit of 1.06 pu of

Table 3 for about 1 seconds and may result in their tripping off the network depending on the protection setting of the network operator.

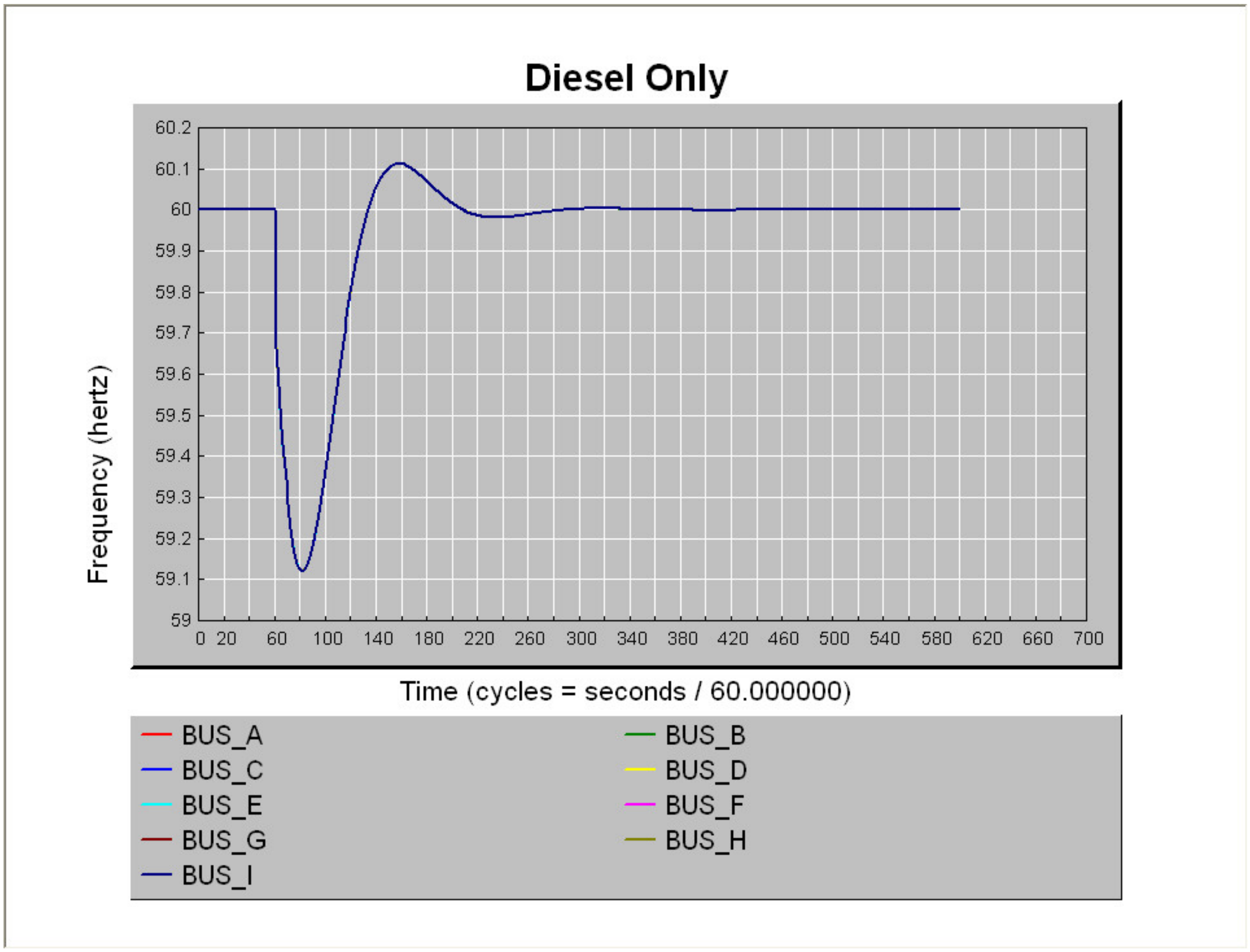


Figure 26: Frequency Response to an Islanding Event
(Under-Generating Condition with Generation/Load ratio of 1.5 MW/4.6 MW, Diesel Units Only)

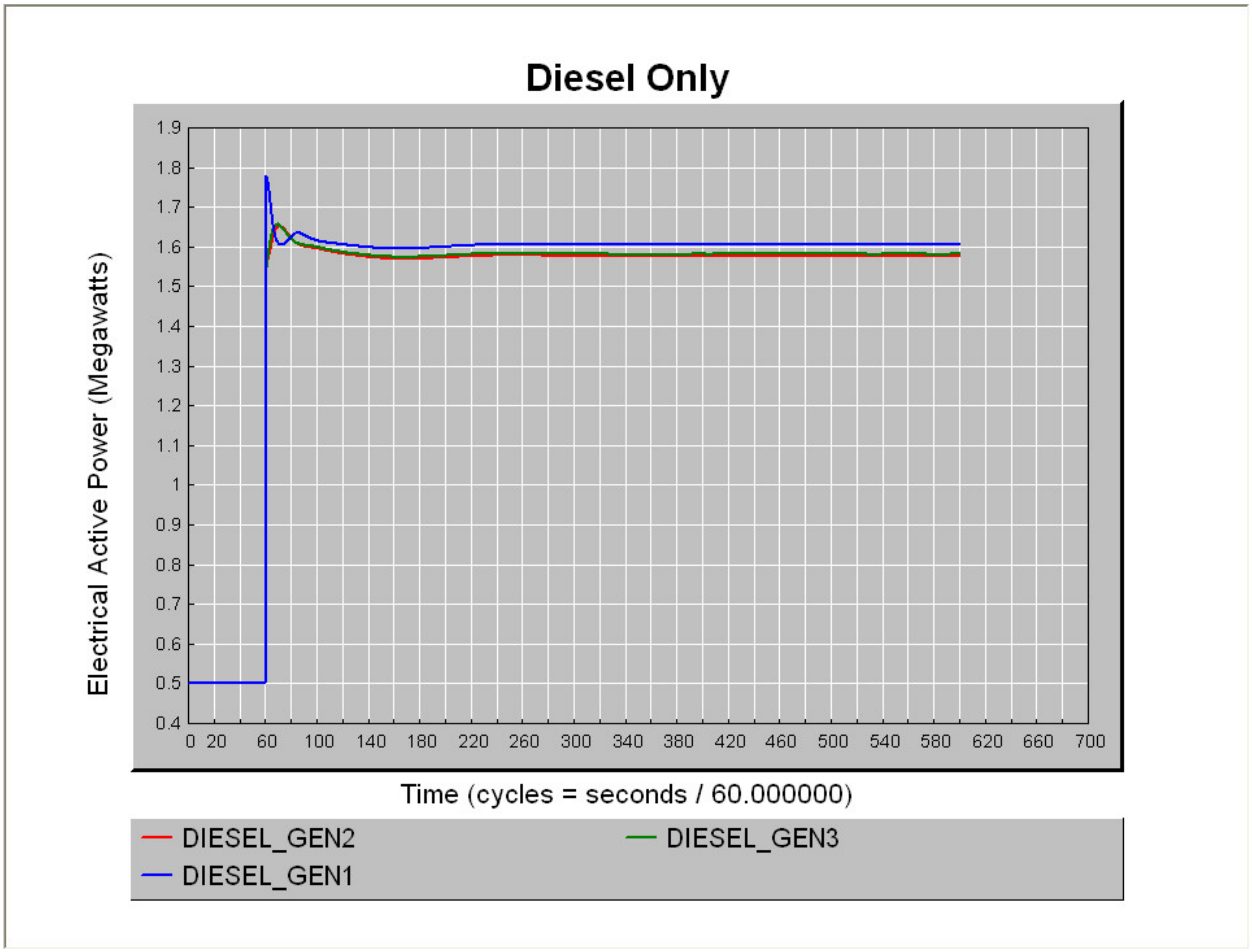


Figure 27: Real Power Response of Generating due to an Islanding Event (Under-Generating Condition with Generation/Load ratio of 1.5 MW/4.6 MW, Diesel Units Only)

6.3 Distribution System with Combined DG Technologies-Directly Coupled Wind

6.3.1 Distribution System with Hydro and directly coupled Wind Generating Units

Figure 28 shows the load flow of the distribution system when both hydro and wind generating units are installed in this system. One hydraulic generating unit of 4 MVA is connected to bus B0, and it is controlled to supply 3 MW and to maintain its terminal voltage at 1.037 p.u. Two wind units are connected to the distribution system at bus F and bus G. Both wind units are controlled to supply 1.46 MW each at a power factor of -81.7 % (consuming MVAR). Each wind unit is compensated by a bank of capacitors at its corresponding bus, which provides 0.736 MVAR to the system. The total system load is about 4.6 MW. Under the steady-state condition, the distribution system exports 1.131 MW to the main power system. However, in terms of reactive power, the distribution system is under-compensated and absorbs 0.51 MVAR from the main power system. In this case study, the wind speed is maintained constant at the value computed from the load flow analysis.

At t = 7.0 s, the distribution system is disconnected from the main power system at bus MAIN. The system response to the islanding event is shown in Figure 29 and Figure 30.

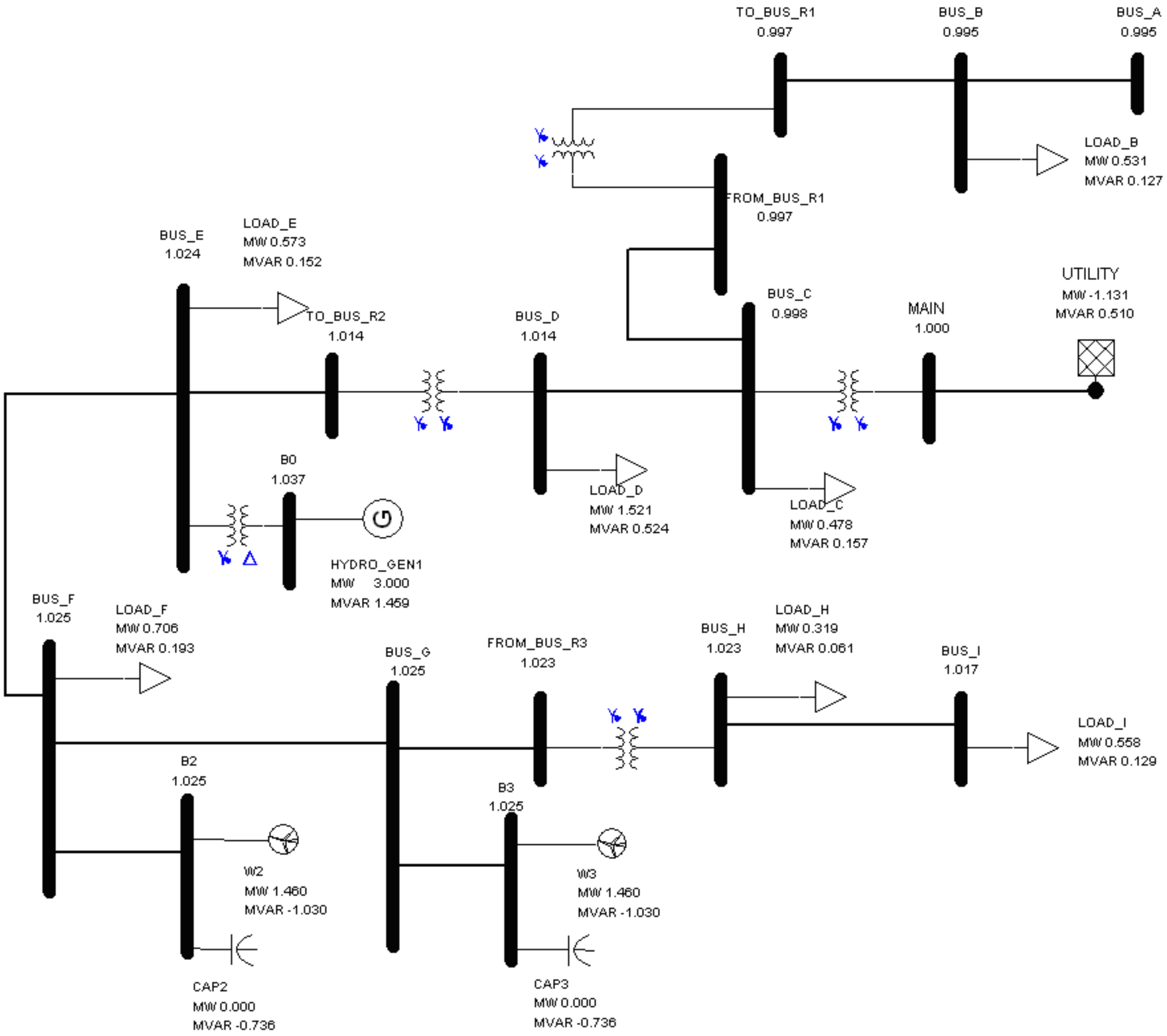


Figure 28: Load Flow Diagram of the Distribution System (Over-Generating Condition, Hydro Unit 3 MW, Wind Units 2.92 MW)

Figure 29 shows the frequency response subsequent to the islanding event. Due to the power imbalance, the islanding event results in an increase in the frequency, with a maximum value of 62.7 Hz. The frequency value is within the limits of a hydro generating unit in terms of frequency protection, as presented in Table 6. It should be noted that it is assumed that there is no frequency limits for the wind generating units. Thus, all the generating units remain operational while the system frequency settles down at a new steady-state point through the control action of the governor system of the hydro unit. The new steady-state frequency is above the nominal value of 60 Hz due to the droop characteristics of the hydro governor system.

Figure 30 shows that the real power of the hydro generating unit decreases significantly right after the islanding event to match the system load, while the real power output of the wind units shows small variations. Through the control action of the hydro governor system, the real power of the hydro generating unit reaches a new steady state value of about 2.1 MW. Figure 30 indicates that the hydro unit in the system picks up the load imbalance after the loss of the main power system, and determines the system frequency through its governor system.

Figure 31 shows the voltage response at the bus terminals of the three generators. The dip in power also causes the voltages to dip and settle back to a new steady state value with respect to the new configuration of the network with the action of the exciters of the generators.

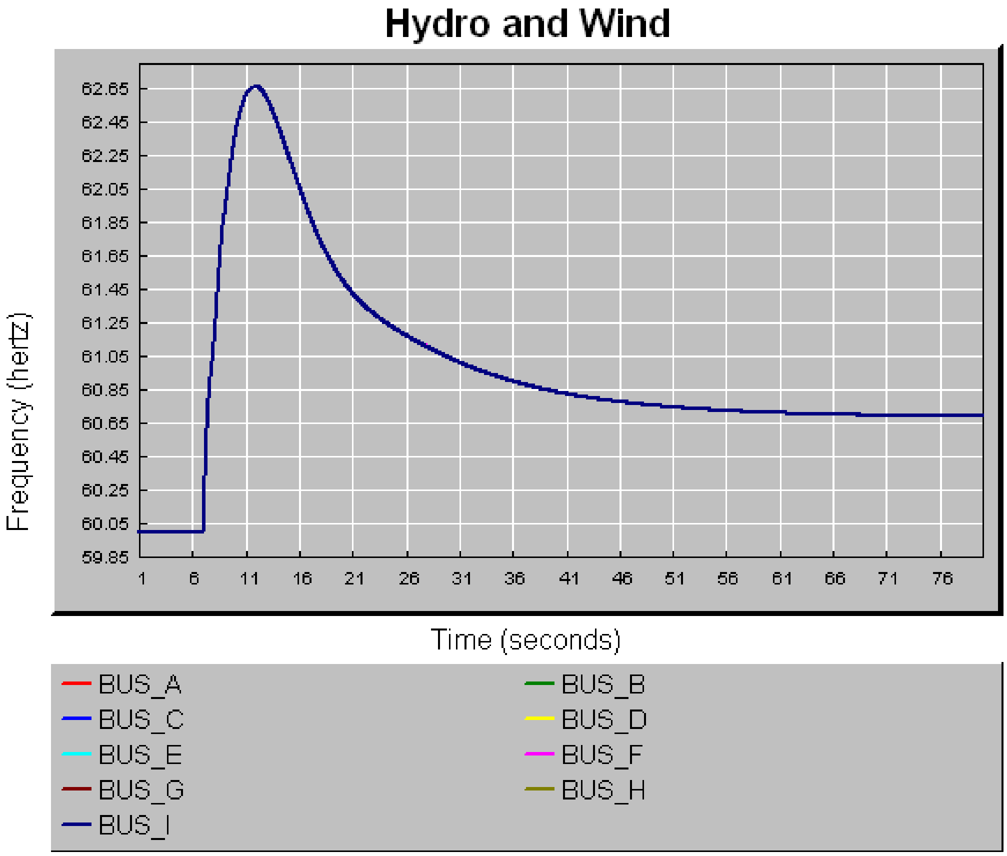


Figure 29: Frequency Response to an Islanding Event (Over-Generating Condition, Hydro Unit 3 MW, Wind Units 2.92 MW)

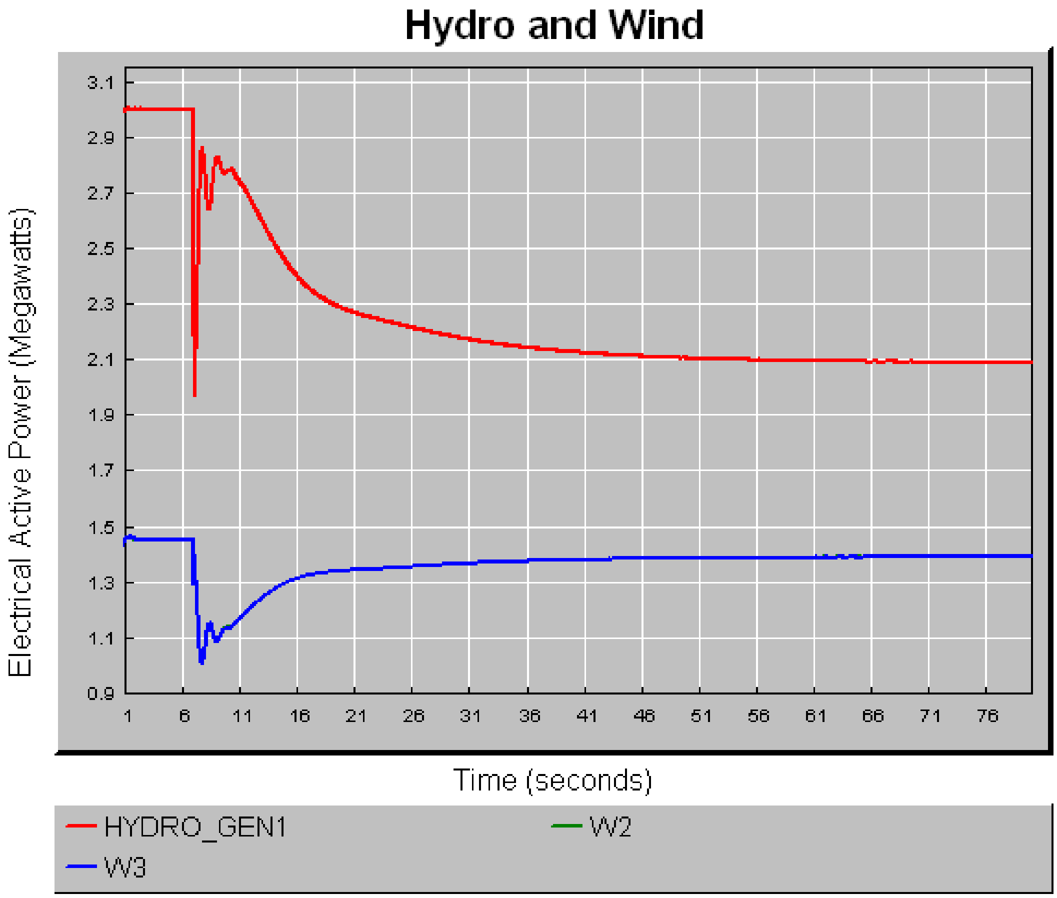


Figure 30: Real Power Response of Generating Units to an Islanding Event (Over-Generating Condition, Hydro Units 3 MW, Wind Units 2.92 MW)

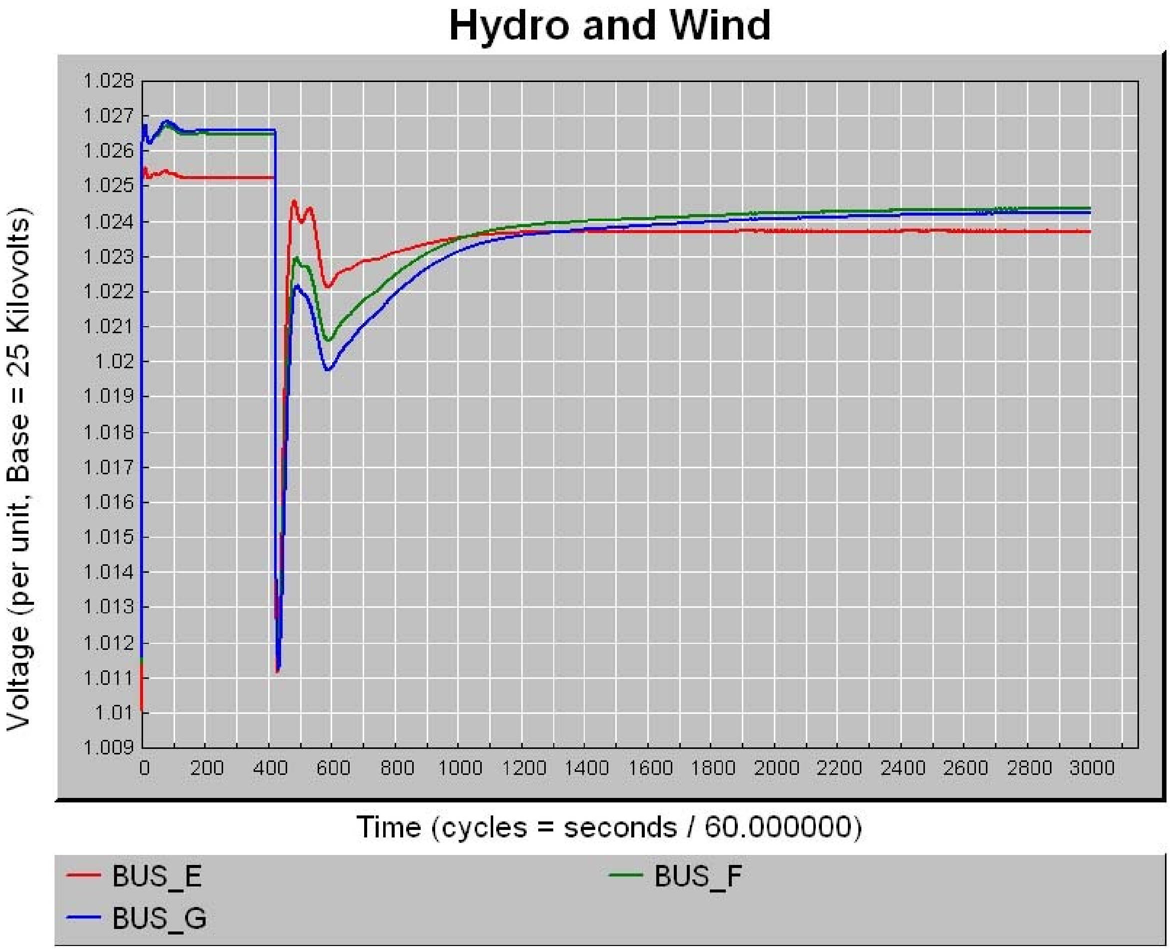


Figure 31: Voltage Response of Generating Units to an Islanding Event (Over-Generating Condition, Hydro Units 3 MW, Wind Units 2.92 MW)

6.3.2 Distribution System with Diesel and directly coupled Wind Generating Units

Figure 32 shows the load flow of the distribution system when both diesel and wind units are installed in the system. One diesel unit of 3 MVA of capacity is connected at bus B0. This diesel unit is controlled to supply 1 MW and to maintain its terminal voltage at 1.037 p.u. There are two wind units in the system, one connected at bus F and one connected at bus G. Each wind unit is controlled to supply 1.46 MW at a power factor of -81.7% (consuming MVAR). Each wind unit is compensated by a bank of capacitors at its corresponding bus, which provides 0.727 MVAR to the system. The total load in the system is about 4.6 MW. In this case study, the wind speed is maintained constant at the value computed from the load flow analysis.

At t = 6.5 s, the distribution system is disconnected from the main power system at bus MAIN. The system response to the islanding event is shown in Figure 33 and Figure 34.

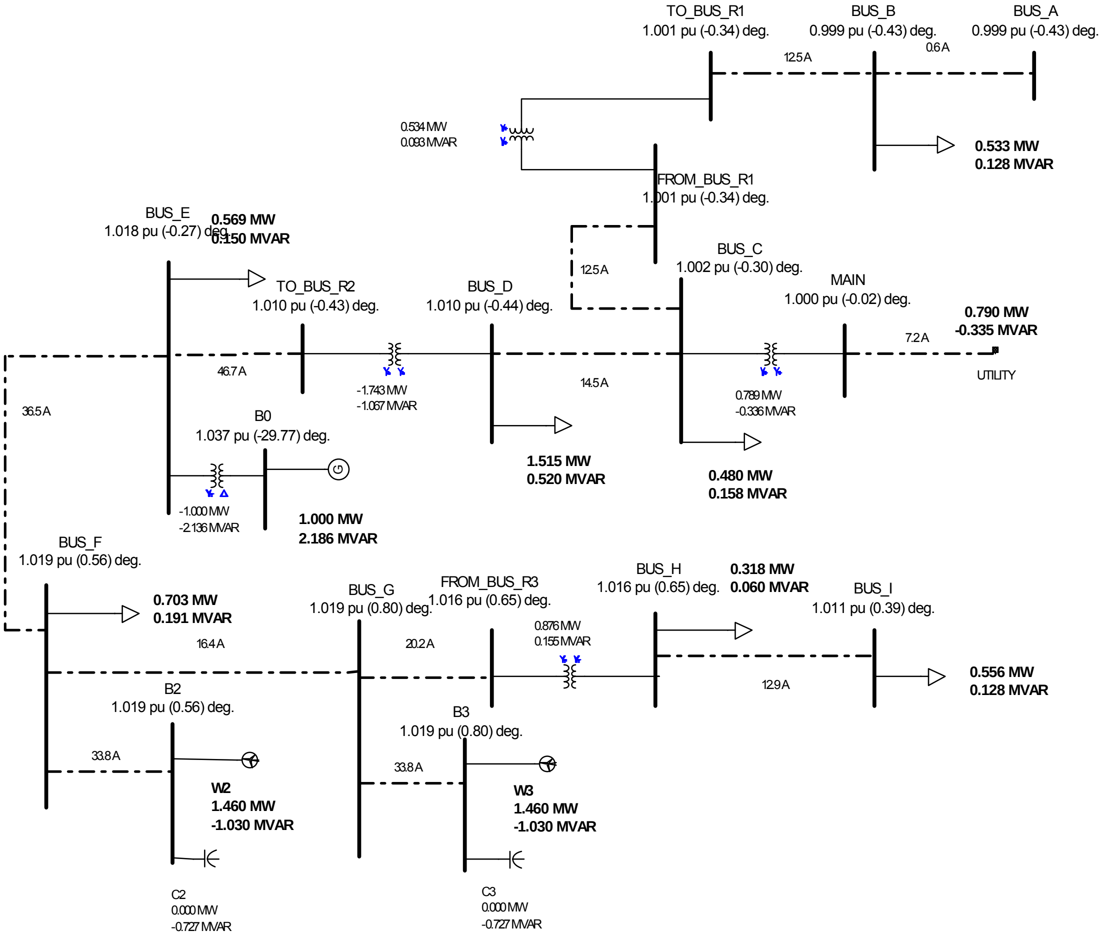


Figure 32: Load Flow Diagram of the Distribution System (Slight Under-Generating Condition, Two Wind Turbines and Diesel Units)

Figure 33 shows the frequency response subsequent to the islanding event. Due to the power imbalance, the islanding event results in a variation in the frequency, with a maximum value of 60.07 Hz and a minimum value of 59.59 Hz. The frequency value is within the limits of a diesel-generating unit in terms of frequency protection. Since it as assumed that there is no frequency limits for the wind generating units, all the generating units remain operational while the system frequency returns to the nominal value of 60 Hz through the control action of the governor system of the diesel unit.

Figure 34 shows that the real power of the diesel generating unit increases significantly right after the islanding event to match the system load, while the real power outputs of the wind generating units show small variations. Through the control action of the diesel governor system, the real power of the diesel generating unit reaches a new steady state value about 1.87 MW. The real power outputs of the wind generating units return to their original values prior to the island formation. Figure 34 indicates that the diesel unit in the system picks up all load disturbances after the loss of the main power system, and determines the system frequency through its governor system.

Figure 35 shows the voltage response at the bus terminals of the three generators. The spike in power also causes the voltages to rise and settle back to a new steady state value with respect to the new configuration of the network with the action of the exciters of the generators. The higher voltage at the diesel unit terminal confirms the dominance of the diesel unit, suggested above, in picking up the load disturbance in the network.

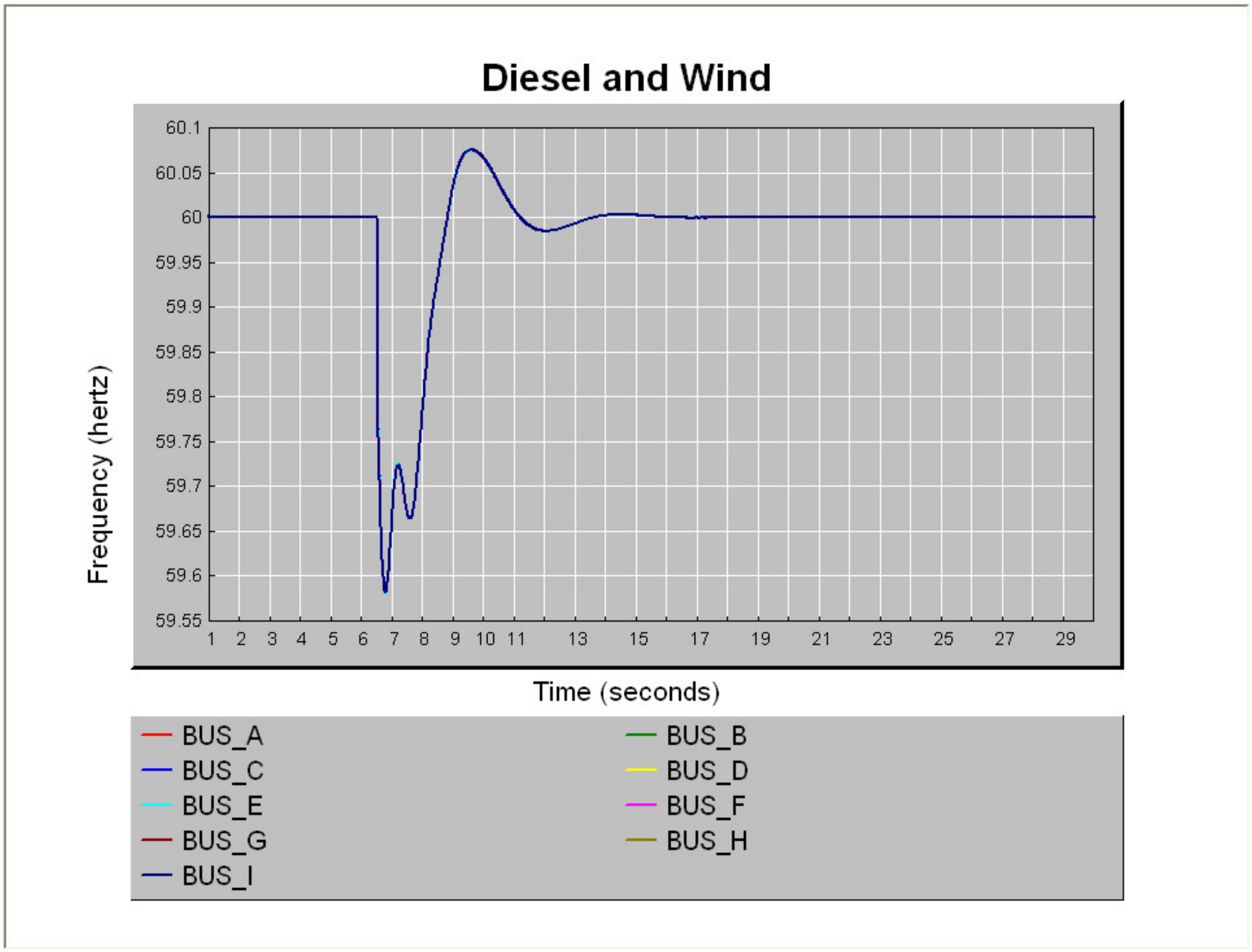


Figure 33: Frequency Response to an Islanding Event (Under-Generating Condition, Diesel Units 1 MW, Wind Units 2.92 MW)

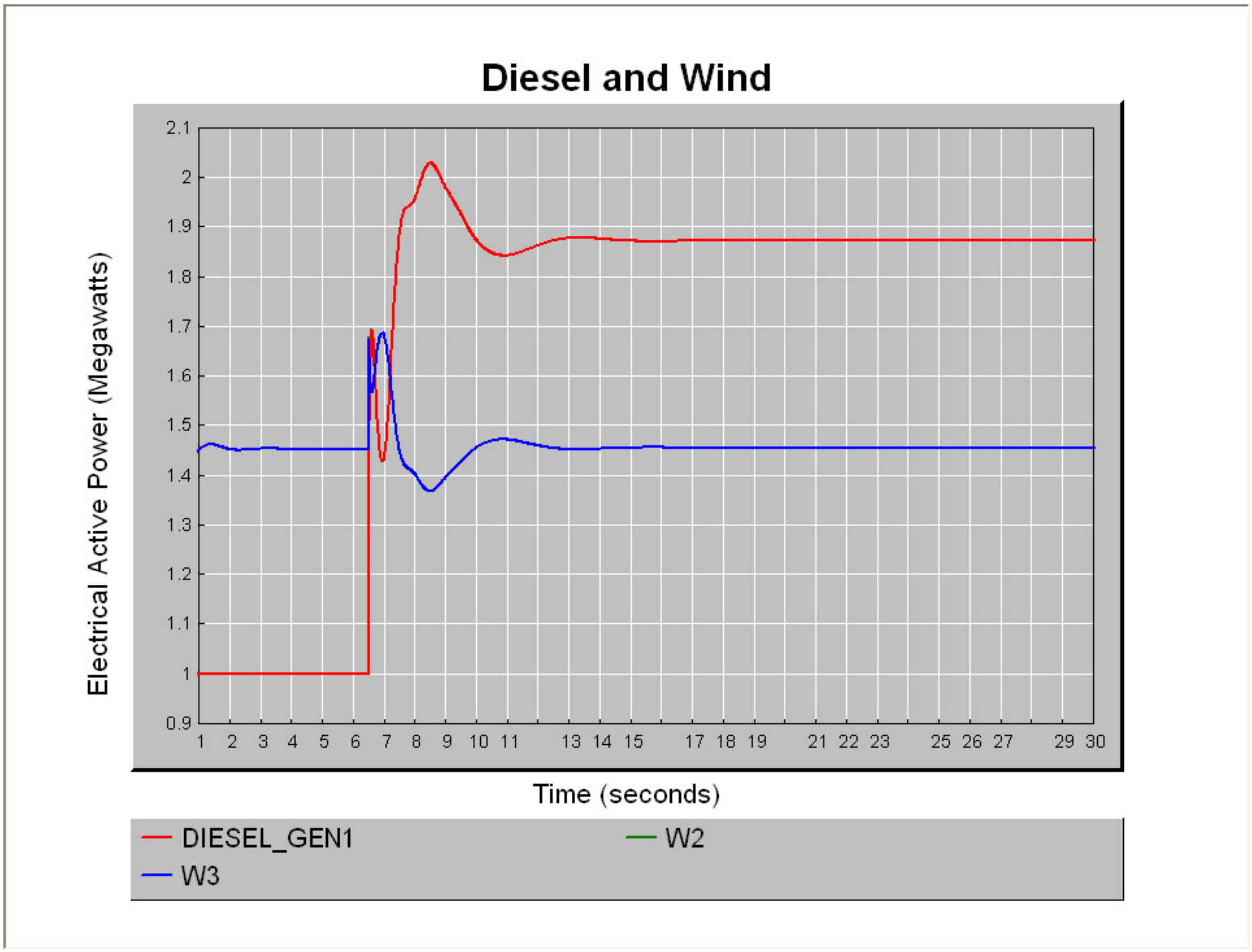


Figure 34: Real power Response of Generating Units to an Islanding Event (Under-Generating Condition, Diesel Units 1 MW, Wind Units 2.92 MW)

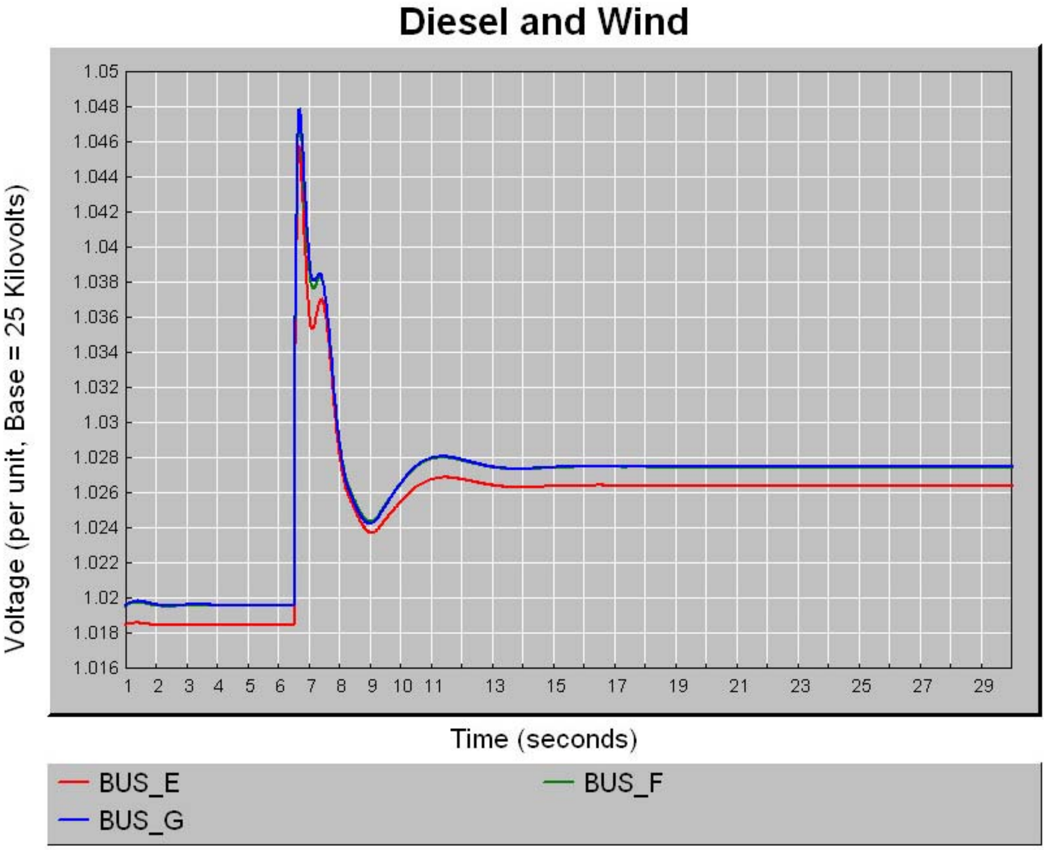


Figure 35: Voltage Response of Generating Units to an Islanding Event (Under-Generating Condition, Diesel Units 1 MW, Wind Units 2.92 MW)

6.4 Distribution System with Combined DG Technologies-DFIG Wind

6.4.1 Distribution System with Hydro and DFIG Wind Generating Units

Figure 36 shows the load flow of the distribution system when both hydro and wind generating units are installed in this system. One hydraulic generating unit of 4 MVA is connected to bus B0, and it is controlled to supply 3 MW and to maintain its terminal voltage at 1.037 p.u. Two DFIG wind units are connected to the distribution system at bus F and bus G. Each wind unit is controlled to supply 1.46 MW at unity power factor. The total system load is about 4.6 MW. Under the steady-state condition, the distribution system exports 1.12 MW to the main power system. However, in terms of reactive power, the distribution system is under-compensated and absorbs 0.32 MVAR from the main power system. In this case study, the wind speed is maintained constant at the value computed from the load flow analysis.

At t = 7.0 s, the distribution system is disconnected from the main power system at bus MAIN. The system response to the islanding event is shown in Figure 37 and Figure 38.

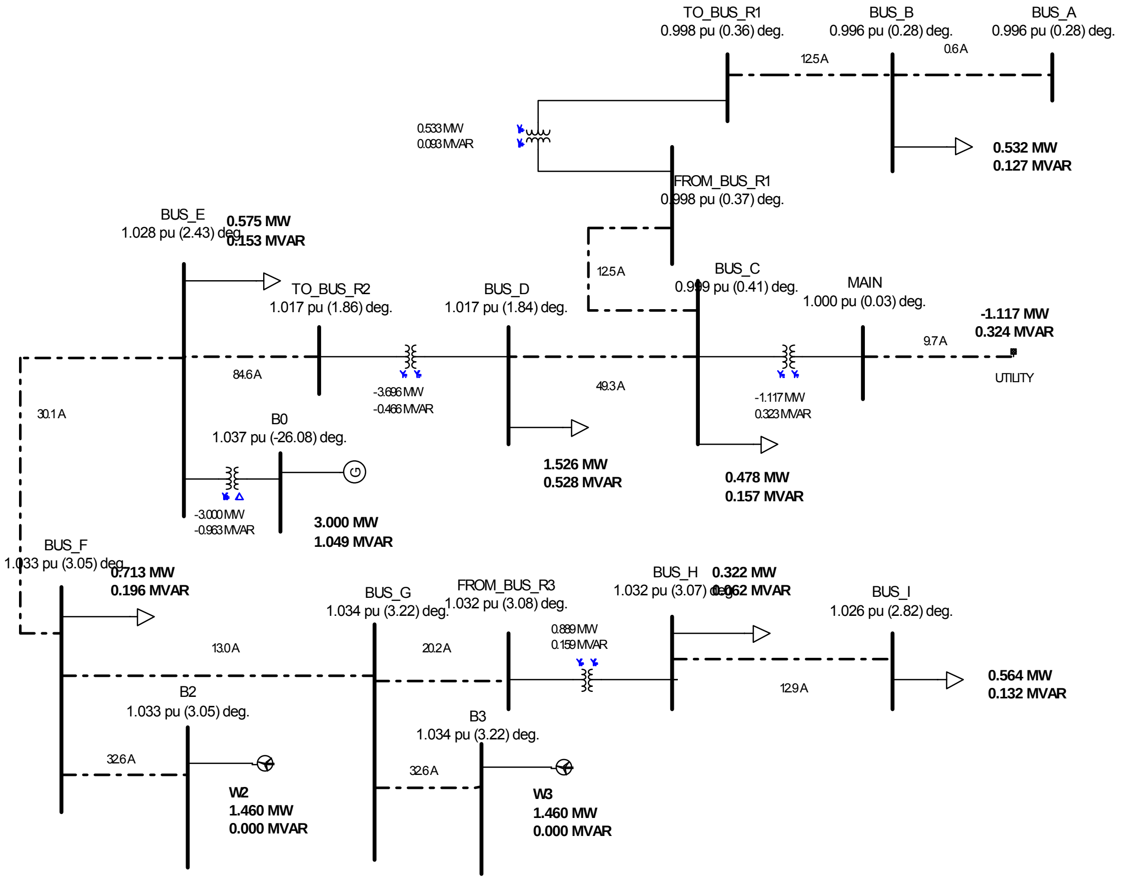


Figure 36: Load Flow Diagram of the Distribution System (Over-Generating Condition, Hydro Unit 3 MW, Wind Units 2.92 MW)

Figure 37 shows the frequency response subsequent to the islanding event. Due to the power imbalance, the islanding event results in a large variation in the frequency, with a maximum value of 66 Hz. The frequency value is within the limits of a hydro generating unit in terms of frequency protection, Table 6. It should be noted that it is assumed that there is no frequency limits for the DFIG units. Thus, all the generating units remain operational while the system frequency settles down at a new steady-state point through the control action of the governor system of the hydro unit. The new steady-state frequency is above the nominal value of 60 Hz due to the droop characteristics of the hydro governor system.

Figure 38 shows that the real power of the hydro generating unit decreases significantly right after the islanding event in an attempt to match the system load, while the real power output of the wind units shows small variations. Through the control action of the hydro governor system, the real power of the hydro generating unit reaches a new steady state value about 2.0 MW. Figure 38 indicates that the hydro unit in the system picks up the load imbalance after the loss of the main power system, and determines the system frequency through its governor system.

Figure 39 shows the voltage response at the bus terminals of the three generators. The dip in power also causes the voltages to dip and settle back to a new steady state value with respect to the new configuration of the network with the action of the exciters of the generators. The higher voltage at the diesel unit terminal confirms the dominance of the diesel unit, suggested above, in picking up the load disturbance in the network.

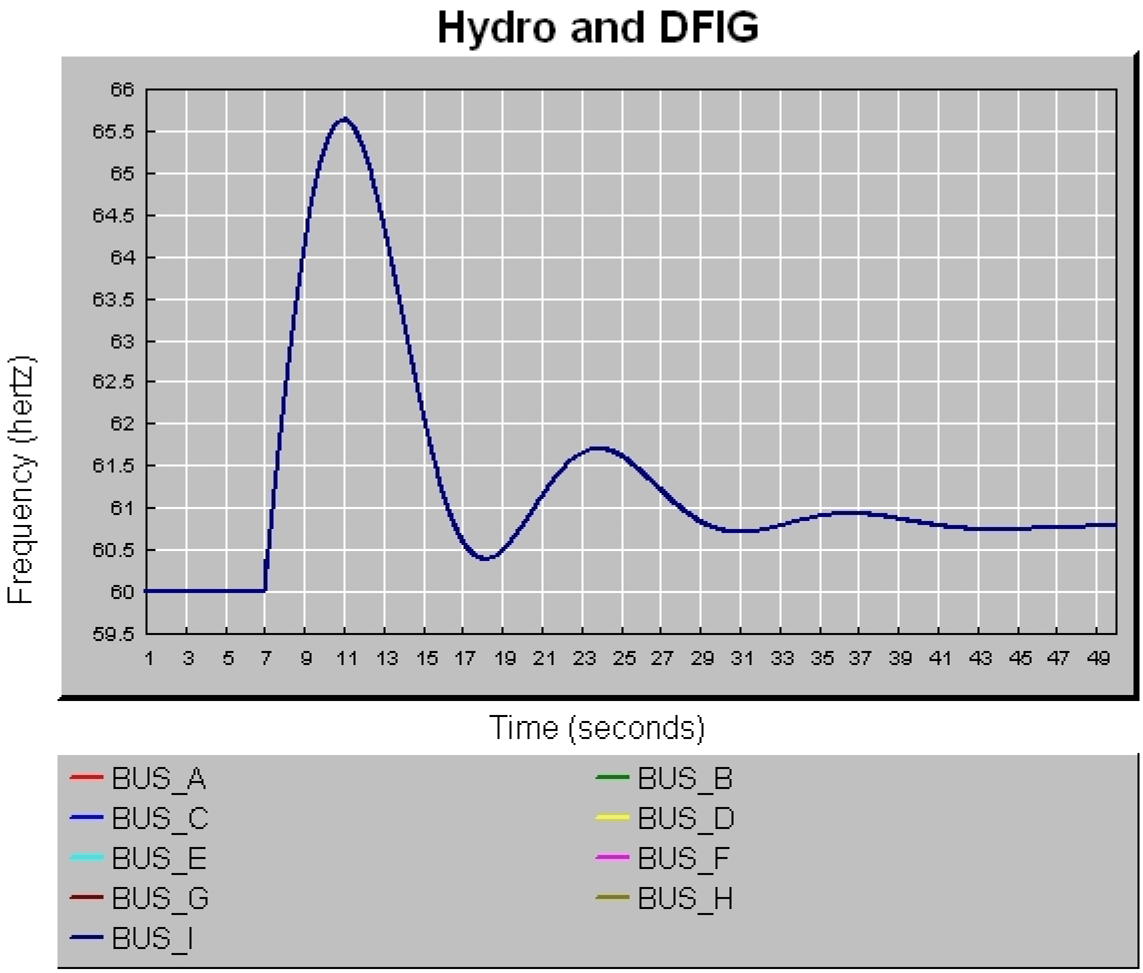


Figure 37: Frequency Response to an Islanding Event (Over-Generating Condition, Hydro Unit 3 MW, Wind Units 2.92 MW)

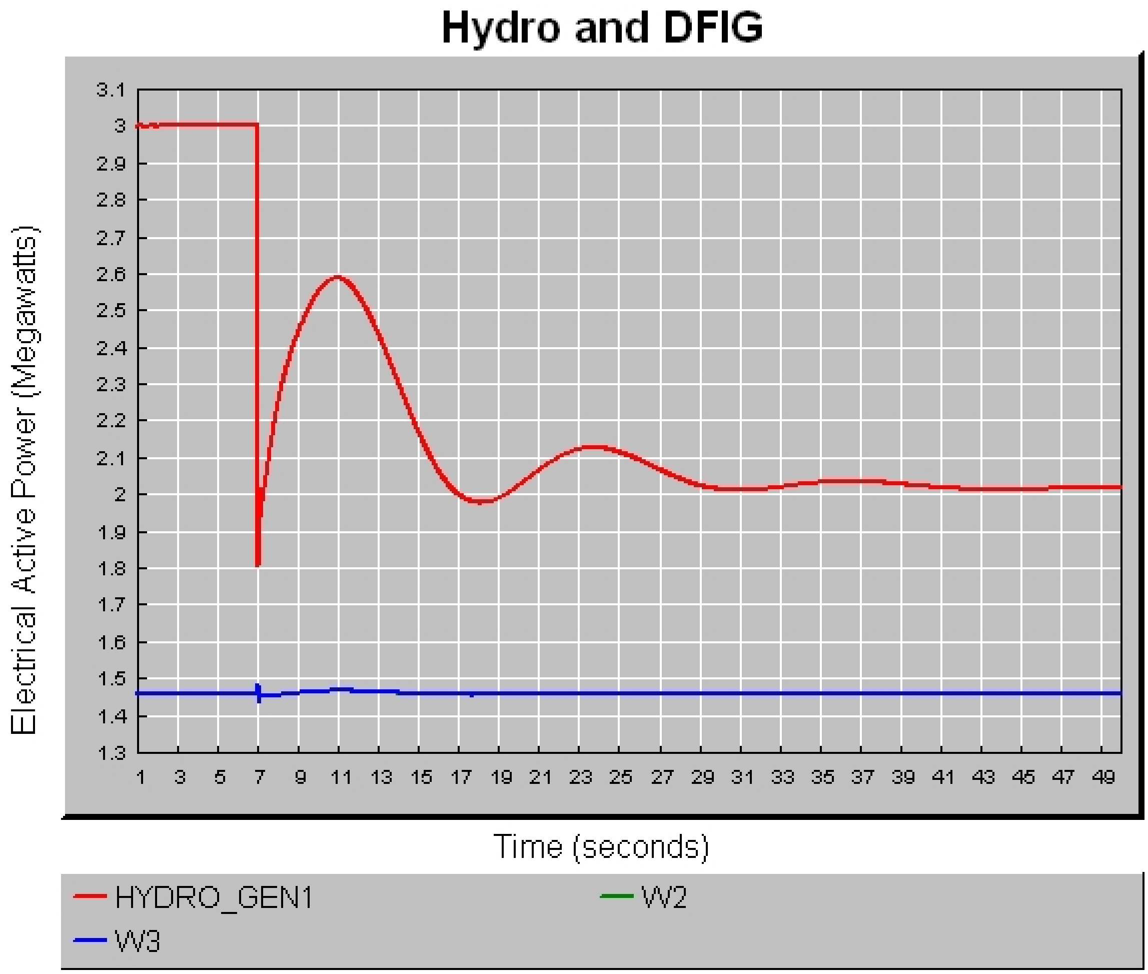


Figure 38: Real Power Response of Generating Units to an Islanding Event (Over-Generating Condition, Hydro Units 3 MW, Wind Units 2.92 MW)

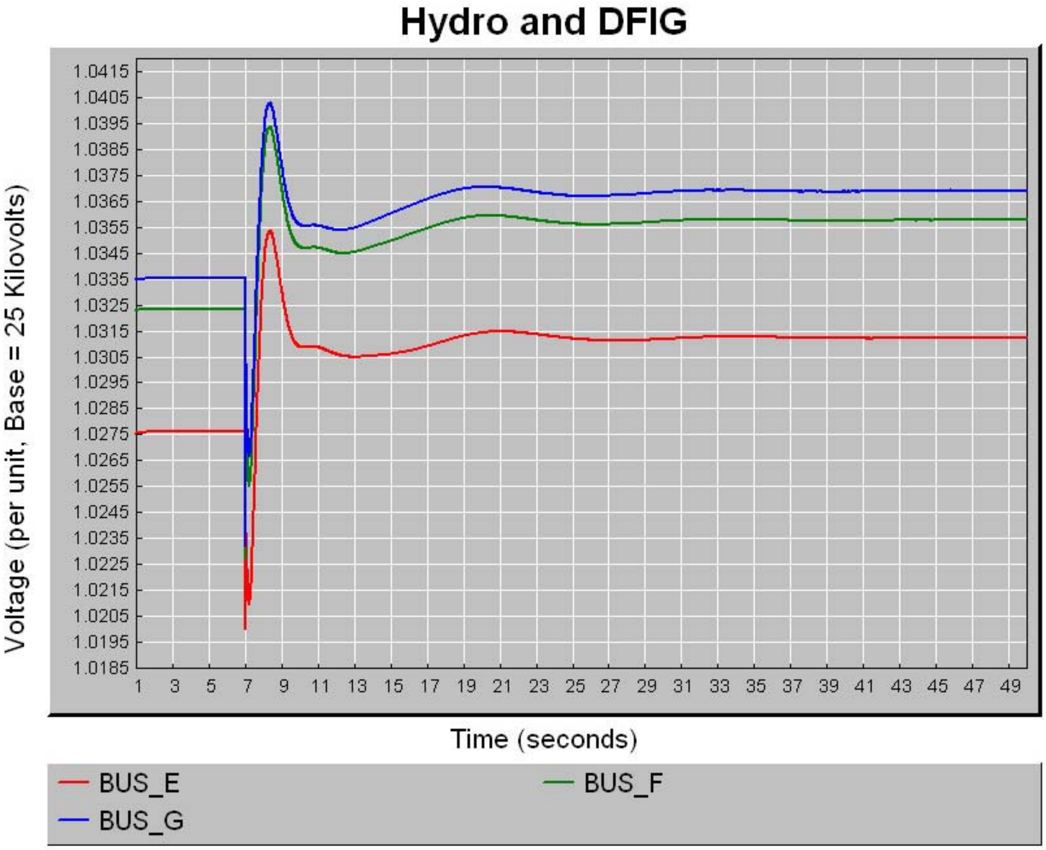


Figure 39: Voltage Response of Generating Units to an Islanding Event (Over-Generating Condition, Hydro Units 3 MW, Wind Units 2.92 MW)

6.4.2 Distribution System with Diesel and DFIG Wind Generating Units

Figure 40 shows the load flows of the distribution system when both diesel and DFIG wind units are installed in the system. One diesel unit of 3 MVA of capacity is connected at bus B0. This diesel unit is controlled to supply 1 MW and to maintain its terminal voltage at 1.037 p.u. There are two DFIG wind units in the system, one connected at bus F and the other one connected at bus G. Both wind units are controlled to supply 1.46 MW at 100% power factor. The total load in the system is about 4.6 MW. In this case study, the wind speed is maintained constant at the value computed from the load flow analysis.

At t = 6.5 s, the distribution system is disconnected from the main power system at bus MAIN. The system response to the islanding event is shown in Figure 41 and Figure 42.

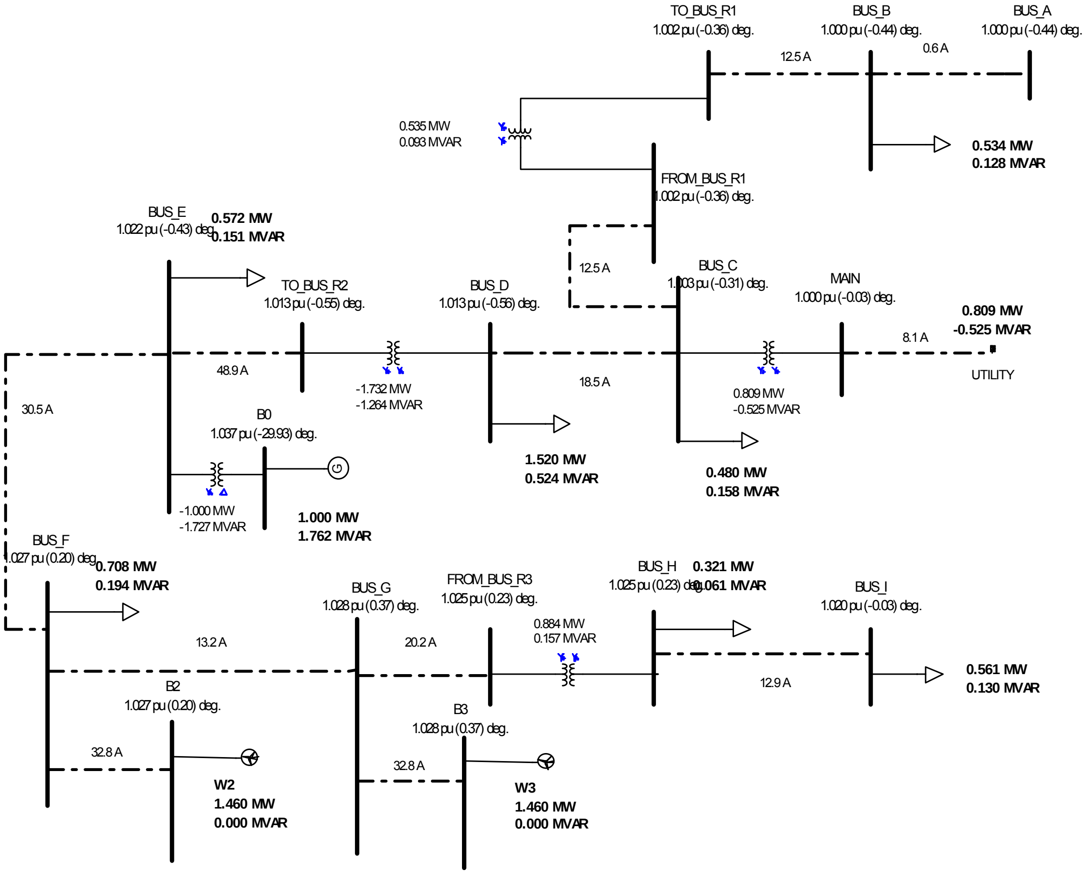


Figure 40: Load Flow Diagram of the Distribution System
(Slight Under-Generating Condition, Two Wind Turbines and Diesel Units)

Figure 41 shows the frequency response subsequent to the islanding event. Due to the power imbalance, the islanding event results in a variation in the frequency, with a maximum value of 60.1 Hz and a minimum value of 59.25 Hz. The frequency value is within the limits of a diesel-generating unit in terms of frequency protection. Since it is assumed that there is no frequency limits for the wind generating units, all the generating units remain operational while the system frequency returns to the nominal value of 60 Hz through the control action of the governor system of the diesel unit.

Figure 42 shows that the real power of the diesel generating unit increases significantly right after the islanding event to match the system load, while the real power outputs of the wind generating units show small variations. Through the control action of the diesel governor system, the real power of the diesel generating unit reaches a new steady state value about 1.92 MW. The real power outputs of the wind generating units return to their original values prior to the island formation. Figure 42 indicates that the diesel unit in the system picks up all load disturbances after the loss of the main power system and determines the system frequency through its governor system.

Figure 43 shows the voltage response at the bus terminals of the three generators. The spike in power also causes the voltages to spike and settle back to a new steady state value with respect to the new configuration of the network with the action of the exciters of the generators. The higher voltage at the diesel unit terminal confirms the dominance of the diesel unit, suggested above, in picking up the load disturbance in the network. The voltages at the terminals of the two wind turbines here goes beyond the limit of 1.06 pu of

Table 3 for about 0.6 seconds and may result in their tripping off the network depending on the protection setting of the network operator.

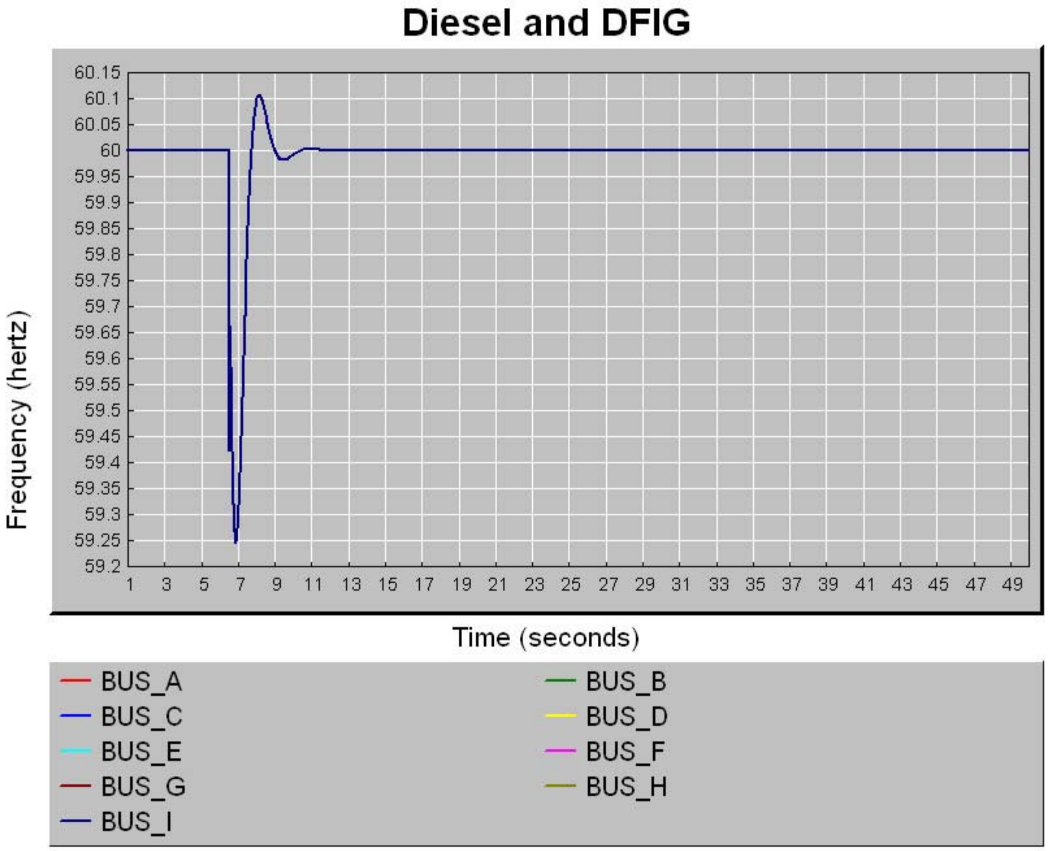


Figure 41: Frequency Response to an Islanding Event (Under-Generating Condition, Diesel Units 1 MW, Wind Units 2.92 MW)

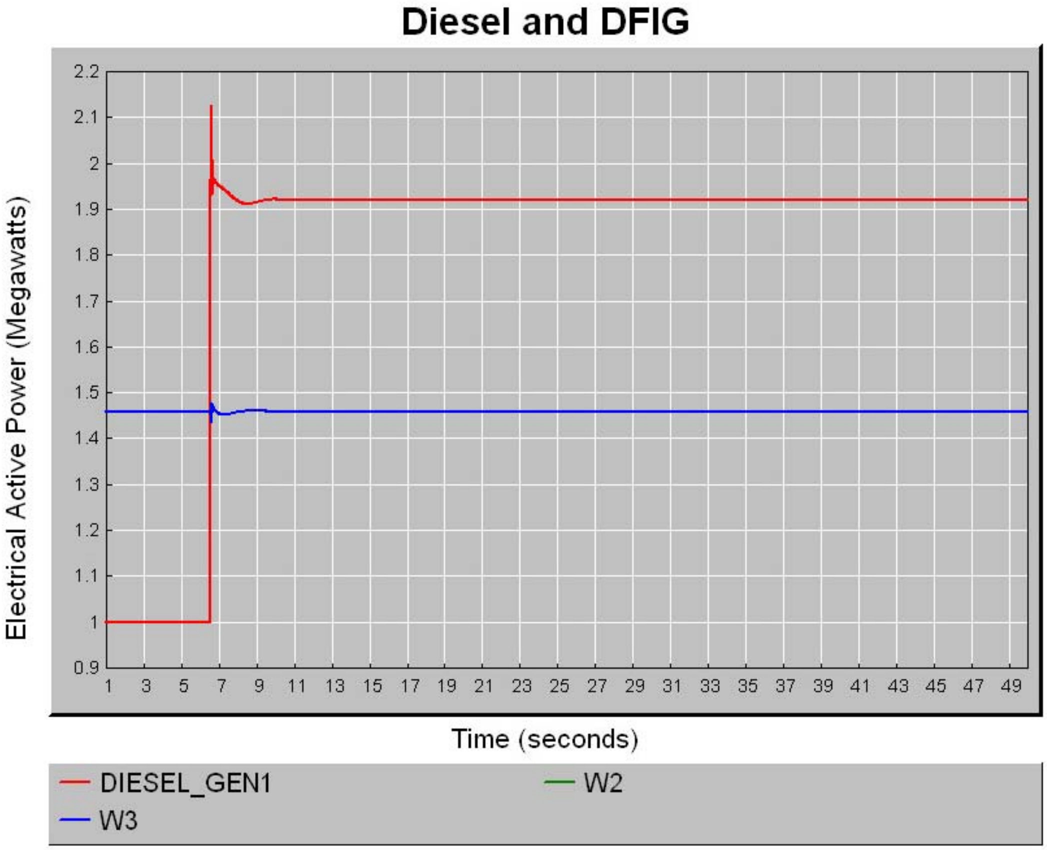


Figure 42: Real Power Response of Generating Units to an Islanding Event (Under-Generating Condition, Diesel Units 1 MW, Wind Units 2.92 MW)

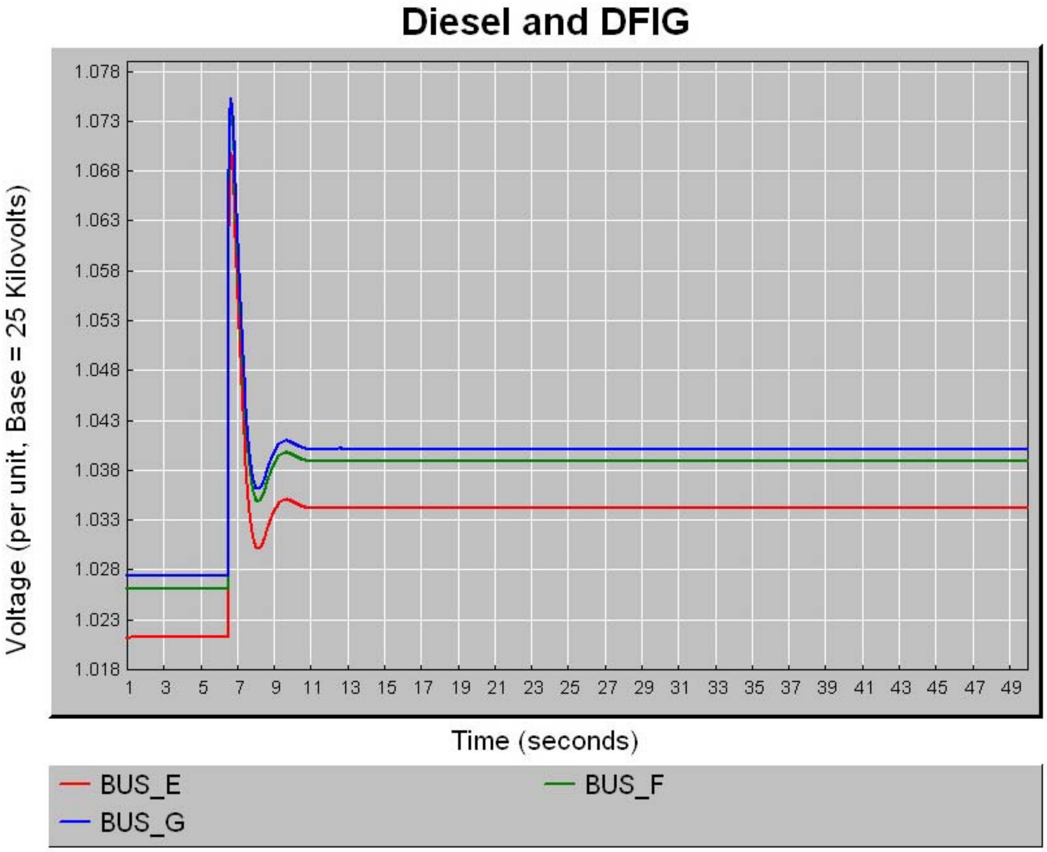


Figure 43: Voltage Response of Generating Units to an Islanding Event (Under-Generating Condition, Diesel Units 1 MW, Wind Units 2.92 MW)

6.5 Summary of Results

Table 7: Summary of Cases Considered and Pre-Islanding Operating Conditions. Initial conditions 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	Figure 15	3 synch. hydraulic DG				Islanding	2.16
		10	0.107	-4.679	-2.164	over generating system	
6.1.2	Figure 18	3 synch. hydraulic DG				Islanding	0.32
		1.5	-3.22	3.348	-1.791	under generating system	
6.2.1	Figure 22	3 synch. diesel DG				Islanding	2.16
		10	0.107	-4.679	2.164	over generating system	
6.2.2	Figure 25	3 synch. diesel DG				Islanding	0.32
		1.5	-3.23	3.35	-1.8	under generating system	
6.3.1	Figure 28	1 hydro, 2 wind DG				Islanding	1.28
		5.92	0.871	-1.31	0.51	over generating system	
6.3.2	Figure 32	1 diesel, 2 wind DG				Islanding	0.84
		3.9	1.587	0.790	-0.335	under generating system	
6.4.1	Figure 36	1 hydro, 2 wind DFIG				Islanding	1.28
		5.92	1.049	-1.117	0.324	over generating system	
6.4.2	Figure 40	1 Diesel, 2 wind DFIG				Islanding	0.84
		3.9	1.770	0.808	-0.525	under generating system	

7 Conclusions

This study demonstrates the dynamic behaviour of a system with distributed generation units following planned 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 pre-islanding operating conditions.

The results of the dynamic simulations of this report indicate that:

1. There is a need for dynamic simulation of distribution systems with embedded generation in order to predict their behaviour under new modes of operation, such as the islanded mode.

2. Voltage and frequency limits such as those indicated in the IEEE 1547 Standard might need to be adjusted in order to facilitate the transition between the grid-connected mode and the islanded mode.

3. The magnitude of these frequency oscillations is a function of (i) pre-islanding operating point and (ii) types of DG. It has been noticed that the largest frequency variations were observed in distribution systems with embedded hydro DG. Further analysis should be conducted in order to study the impact of different DG type combinations on the dynamic response of the system during the transition from the grid-connected to the islanded mode.

4. 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 as seen from the conducted studies.

5. Different types of distributed generation will behave differently and even within the same DG technology, the behaviour might as well vary between different manufacturers. Appropriate models for generators and loads need to be used in order to ensure an accurate representation of the system's dynamic behaviour.

8 References

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

ANNEX A
CYME file references

ANNEX A
CYME 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 Three Synchronous Hydraulic DG units- Generation/Load ratio of 10MW/4.6MW	hydroDGislanding-ratio2_16.sxst
6.1.2 Three Synchronous Hydraulic DG units- Generation/Load ratio of 1.5MW/4.6MW	hydroDGislanding-ratio0_32.sxst
6.2.1 Three Synchronous Diesel DG units- Generation/Load ratio of 10MW/4.6MW	dieselDGislanding-ratio2_16.sxst
6.2.2 Three Synchronous Diesel DG units- Generation/Load ratio of 1.5MW/4.6MW	dieselDGislanding-ratio0_32.sxst
6.3.1 One Synchronous Hydro DG unit , Two Wind DG units- Generation/Load ratio of 5.9MW/4.6MW	hydrowindDGislanding-ratio1_28.sxst
6.3.2 One Synchronous Diesel DG unit , Two Wind DG units- Generation/Load ratio of 3.9MW/4.6MW	dieselwindDGislanding-ratio0_84.sxst
6.4.1 One Synchronous Hydro DG unit , Two DFIG Wind DG units- Gen./Load ratio of 5.9MW/4.6MW	hydrowindDFIG_DGislanding-ratio1_28.sxst
6.4.2 One Synchronous Diesel DG unit , Two DFIG Wind DG units- Gen./Load ratio of 3.9MW/4.6MW	dieselwindDFIG_DGislanding-ratio0_84.sxst