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Distribution system operation and planning in the presence of distributed generation technology

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DISTRIBUTION SYSTEM OPERATION AND PLANNING IN THE PRESENCE OF DISTRIBUTED GENERATION TECHNOLOGY

by

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Approved by

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ABSTRACT

Distributed generation (DG) is becoming an increasingly attractive power generation paradigm in the field of power engineering as economic and environmental factors drive new technologies to be more efficient and less polluting than their earlier counterparts. Although the concept of DG is not new, little research has been done on the topic and even fewer field tests have been performed. This lack of research, along with other factors, has somewhat slowed the acceptance of DG into markets, other than industrial or commercial co-generation for heat and power. This thesis attempts to examine and compare three types of DG: diesel generators, microturbines, and small wind turbines within the structure of a distribution system. The DG types are compared in both steady-state and transient operation to determine which type is suitable for a particular application. Steady-state operation is examined under heavy loading conditions and each DG type is compared on the basis of the voltage profile improvement and power loss reduction. Transient operation is examined during islanding conditions, as well as lesser and more common system events like a single-phase fault, relay operation, and a short-term load increases. The results indicate improvement in the steady-state conditions of a system from DG, but also indicate some significant problems during relatively minor transient events.

ACKNOWLEDGMENTS

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1. INTRODUCTION

1.1 DEFINITION

Distributed generation (DG) is generally regarded as small generators, both in terms of power output and physical size, connected to the existing power distribution grid. The difference between distributed generation and power plants operating in the modern transmission system is at least partly semantic. Although both types of generators operate in an interconnected system, power plants on transmission systems are generally located far from the loads they serve and are operated by utilities, whereas distributed generators are typically located on-site close to the loads they serve and could be operated independently by a customer or independent power producer instead of a utility company. Customers are, however, limited in the amount of control they can exert on their own generators. However, the technology offers several benefits to both consumers and producers of electrical power and has resulted in increased research and usage of DG technologies.

1.2 BACKGROUND

The origins of distributed generation arguably go back as far as Thomas Edison's invention of the electric light bulb, which helped to create a widespread need for electrical power. The original light bulb was powered by direct current (DC), which became Edison's preferred method of transmitting power. Until recently, power transmitted by direct current had to be sent to a load at the load voltage, resulting in high currents and high losses due to line resistance, which created drops in voltage. Therefore, in order to keep voltage high enough for a load to operate; DC generators had to be located near every load, thus making all power produced

This need soon evaporated after Nikola Tesla's discovery of alternating current (AC) for transmitting power and William Stanley's invention of the first practical AC transformer in 1886 [1]. Alternating current became the preferred method of power transmission due in large part to the transformer. This is because transformers can reduce the amount of current sent over power lines (and the line losses that result) by "stepping up" voltages with very few losses in the process. This allowed for much greater distances between the generally large, noisy, and polluting power plants of the time and utility customers. Thus, the modern power grid model of a few large power plants sending power long distances at high voltages to lower voltage distribution systems was created, while independent power production was only utilized when the grid could not easily be accessed.

Distributed generation technology is now being rediscovered due to several recent trends. The most widely cited are [2]:

- Advancements in the technologies associated with DG
- Concerns of environmental pollution and emission of greenhouse gases resulting from the burning of fossil fuels along with an interest in more environmentally friendly technologies
- An increase in the cost of fossil fuels
- A greater demand for power quality, especially from industry
- The deregulation of the power industry

- The laws, codes, and popular sentiment against building new transmission lines along with the desire of utility companies to reduce costs by building transmission lines.

The technology and concept is also being revisited because of the benefits it can provide. The use of DG can improve power quality for utilities in several ways, although each depends on the location and type of DG used. The use of DG can strengthen the system voltage profile [3] and can reduce both real and reactive power system losses when located near loads at the end of lossy lines. The units that can operate in stand-alone mode can provide power quality benefits to customers by supplying sections of the power system grid when there are outages on other sections of the distribution system [4]. Some have even speculated that both permanent and temporary outages could be virtually eliminated if the technology were developed further and used independently of the power grid.

Distributed generation has many benefits for both consumers and producers of power, but it also has many drawbacks. One of the biggest drawbacks to DG use is economics. Most alternatives to coal and fossil fuels, such as sunlight and wind, require the purchase of technology that is still high in initial cost despite recent advancements. Also, while many states in the U.S. have allowed for net metering, which allows utility customers to be paid the retail price for excess power produced by DG, nine states still have no such laws in place, creating little economic incentive for independent power producers to invest in the technology. Easy access to reliable power from the grid in most industrialized nations also reduces the demand for small scale generators, which further decreases the incentive to invest. Another drawback to DG usage is that many methods of converting alternative fuels into electric power are simply inefficient when used solely for power. As an example, wind turbines do not exceed 40% mechanical efficiency at most wind speeds [6] and microturbines achieve electrical efficiencies of only 30% when used solely for power [7]. Along with the economic and efficiency problems posed by DG technology, power quality and the coordination of protective devices can become significant problems as even minor system events can lead to false tripping and outages.

1.3 OBJECTIVES

Whereas the limitations of technology were what drove the need for distributed generation after the discovery of electricity, the newfound capabilities of technology is what drives a return to the concept. Advances in power electronics have allowed many sources of energy like wind, the sun, and several others to become viable options. As with many developing technologies, there is a lack of knowledge about the applicability and impact of DG, which is one of the larger factors in its slowness to develop. The objective of this thesis is to examine the pros and cons about three types of distributed generation technology: diesel generators, microturbines, and wind turbines through the simulation of the underlying technologies on a realistic distribution system in realistic steady-state and transient events all modeled using DIgSILENT [12].

1.4 SOFTWARE USED

There are currently a wide variety of software applications that can model DG systems, including PSCAD [8], SKM PowerTools [9], Matlab/Simulink [10], ETAP [11], and DIgSILENT [12]. DIgSILENT was chosen as the software application to be used for the simulation of doubly-fed induction generators (DFIGs) and synchronous generators. These two models were important as DFIGs are becoming the standard generator type in wind turbines and synchronous generators are the standard in both diesel generators and microturbines.

DIgSILENT was chosen because of economic limitations and because of its ease of use, as it contains blocks to model most common power system components along with the capability of simulating the components in a steady-state and during transient events.

1.5 OVERVIEW

This thesis is focused on the three types of technology typically used in commercially available DG and the benefits and drawbacks that each offers to a typical distribution system under steady-state and transient conditions. It is divided into five sections. Section 2 will focus on the impact of DG on the power system and a review of the studies performed on DG's impact. Section 3 will discuss microturbines and diesel generators, two technologies that utilize synchronous generators for power production. Section 3 will also examine wind turbines and, more specifically, doubly-fed induction generators. Section 4 will discuss the procedure, results, and analysis of the DIgSILENT studies performed. Section 5 will discuss the conclusions that can be drawn as well as future work to be done in the field.

2. IMPACT OF DG ON SYSTEM BEHAVIOR

2.1 OVERVIEW

This section of the thesis will examine the impact of distributed generation on the voltage profile, system losses, and system reliability. Then the technical issues, including islanding, transients, and coordination of protective devices associated with DG will be examined. These investigations of each benefit and drawback examined will also include a review of the literature available.

2.2 VOLTAGE PROFILE

The popular saying “the customer is always right,” still carries a lot of truth, especially in the utility industry. As industry has advanced from manufacturing largely by hand to producing precision parts and equipment with machines, the importance of having high-quality and consistent power has grown along with it, which makes power quality an issue for both the utility customer and the utility itself. Since voltage quality is directly associated with power quality and all distribution systems contain at least some voltage drop somewhere in the system, voltage profile and measures to improve it are both important. The generally accepted steady-state range for bus voltages on any power system is 0.95-1.05 per unit (p.u.), meaning that the voltage at the bus is between 95-105% of the nominal voltage of the bus.

Distributed generators are used less frequently to address voltage profile deficiencies than voltage regulators and capacitors, but there have been several recent studies on DG’s possibilities of improving the profile. Distributed generation generally offers the best voltage regulation and voltage profile improvement when operated as a voltage-controlled generator, but most forms of DG are operated as a power factor-controlled generator to maximize the power output as most generators operate are most efficient at peak power outputs. However, this maximization of output and efficiency can come at the cost of creating overvoltages at the point of common coupling (PCC) and surrounding buses.

One case study [3] examines the use of a probabilistic approach and a non-probabilistic approach to maximize the voltage profile of a system with wind turbines as acting as distributed generators. The study used both approaches to optimize the location, size, and power factor for the wind turbines. The probabilistic approach was slightly more accurate but significantly more complicated although both methods showed that the voltage profile improved as the generator size was increased and as it was moved closer to the load. The study showed load voltage improved by 0.005 p.u. when the distance from the load was adjusted from 80% to 0%. The study also showed that the load voltage improved by 0.01 p.u. when the wind turbine's power output was increased from 0.08 p.u. to 0.32 p.u..

A comparative analysis similar to the one performed in this thesis compared the voltage profile of a system using a synchronous generator acting as a DG against the same system with an induction generator as a DG [13]. The system was tested under several loading conditions and with varied control conditions for the synchronous generator. This study found that a constant voltage synchronous generator provided the best voltage regulation for the system under both minimum and maximum load demand, but also required six generators to do so and had the greatest variation in voltage when a generator was disconnected from the system.

The studies relating DG and voltage profile use different methods, but do indicate several common relationships between the two:

- Voltage profile was improved in each case by locating the distributed generator close to the load
- Voltage profile is improved by increasing the size of the distributed generator, but the sizing needs to be limited through careful study of the system or through the generator regulating itself as overvoltages can occur for oversized generators.

The relationships described above are often considerations followed when placing and sizing capacitors on distribution systems and many who have studied distributed generation recommend following the same practices when placing distributed generators as when placing capacitors for an improved voltage profile.

2.3 SYSTEM LOSSES

Although system losses are not directly a power quality issue, the losses in a system are usually related to the voltage profile of the system. One study found that active power losses are reduced under heavy loading conditions, but losses are actually increased under light loading conditions [14]. This was possible because the distributed generator removed congestion on lines during heavy loading periods, but during lighter loading conditions the DG reversed power flow rather than reduce line loading. An increase in system losses is especially noticeable with voltage-controlled synchronous generators as this type of generator will begin to “motor” and absorb reactive power produced on the system to regulate voltage [14]. Another study found that the location of the distributed generation is important in reducing system losses and that increasing the sizing of distributed generation generally results in fewer losses, but the gains slowly diminish [15]. An additional study confirmed the results of the sizing study and also found that increasing penetration and power output of DG can result in increased system losses [16].

2.4 RELIABILITY AND ISLANDING

Distributed generation has the ability to reduce both temporary and permanent outages on distribution systems, but this generally requires what is called intentional islanding, although it is possible to switch a section with distributed generation onto a separate feeder without creating an island.

Islanding usually occurs when a section of the distribution system supported by DG is disconnected from the main substation during a transient. Islands are not inherently harmful to distribution systems, although most utilities utilize some form of anti-islanding protection due to problems associated with islanding.

One of the major problems with islanding is that it is often caused by faults that occur between the DG and the substation, which often results in relays opening at different times to remove fault current and results in a loss of phase and voltage synchronization. The loss of synchronization can result in large transients when a recloser operates to reconnect the island and can then result in false tripping.

A further problem with islanding is that, even if synchronization is not lost during the relay operation, synchronism can be lost after the island is created because the generator may not be capable of supporting the island and this may result in damage to the generator as it speeds up to attempt to meet the load demand.

The Standards Coordinating Committee of the IEEE devised a set of recommendations for utilities to follow for interconnection between distribution systems and DG and these became the IEEE 1547-2003 Standard. The standard recommends anti-islanding protection operate within two seconds of detecting an islanding condition [17], while also putting forth recommendations for disconnecting during under/overvoltages and under/overfrequency events, although these types of events are often an indication that islanding has already occurred.

Studies have been conducted examining both improvements in reliability from DG and methods for preventing islanding, with mixed results. One study of a simple distribution system with DG on a lateral found that the hours of power unavailability for customers could be reduced by 100 for each additional section of the feeder that could be supported by DG, although the study found that the number of interruptions per year increased slightly [18]. Another study of automatic sectionalizing switching devices (ASSDs) used in intentional islanding schemes could reduce system interruptions by up to 90% and the duration of interruptions by up to 82% for one test system [19]. An additional study found distributed generators had very little effect on the number of outages per year, but could have a significant effect on the duration [20]. The use of anti-islanding devices has only recently started. Most types, including rate-of-change-of-frequency (ROCOF) relays, which detect islanding conditions through sudden changes in frequency, and vector surge relays, which detect islanding conditions through phase differences in a generator’s internal voltage and the terminal voltage, are found to be difficult to coordinate with existing protection measures or trip incorrectly [21].

2.5 TRANSIENTS AND FAULT PROTECTION COORDINATION

Transients are a two-sided issue for users of distributed generation as the protective devices used in systems with distributed generators must be capable of picking up transients in the system without operating incorrectly and should also avoid creating system transients. This is made more difficult by the fact that faults on systems with DG require protective devices to remove multiple sources of fault current rather than only one. Distributed generation also creates a problem for protective device coordination by reducing not only steady-state current from the main substation, but also fault current [22]. This requires protective devices at the substation to have more sensitive settings to pick up fault conditions [23]. Temporary faults can also create problems for systems with DG, as sections that may be experiencing a temporary fault are acted upon by a relay to extinguish the arcing current, the protective devices acting for a distributed generator may not see the fault and thus allow the fault current to continue flowing while turning a temporary fault into a permanent one [24].

Several studies of the effect of DG on transient stability have been performed with mixed results, depending on the system and cause of the transient. One such study found that asynchronous generators had very little effect on transient stability while synchronous generators stabilize the frequency of large scale generators, but caused the duration of transients to increase [25]. Another study showed that DG can reduce the magnitude of voltage dips through series compensation and through the temporary creation of an island using static transfer switches [26].

In general, research indicates that the best coordination schemes will only be possible through extensive examination of protection coordination and communication between protective devices. Some studies have shown that DG can improve transient stability in distribution systems through careful selection of technology and location [27].

3. DISTRIBUTED GENERATION TECHNOLOGY

a. OVERVIEW

This section of the thesis will examine the operation of diesel generators, microturbines, and wind turbines, three technologies commonly used or being developed for usage in DG applications. Diesel generators and microturbines commonly use synchronous generators for producing power, while wind turbines commonly utilize DFIGs for power production, although there are a few exceptions.

3.2 DIESEL GENERATOR

Diesel generators are commonly used by residential consumers, businesses, and important services like the police and hospitals as they are both a cheap and reliable source of power. Many diesel generators available to consumers are rated for 10,000 hours of operation or more and generators with power ratings of up to 2.5 MVA. Diesel generators also offer high power density and an installation cost below $500/kW, which, combined with its other benefits, has made it the most commonly used generator type for backup power.

Diesel generators have several drawbacks to their use as a distributed generator. Diesel generators rely on a fossil fuel that has seen its retail price increase over 200% in the last five years [28]. Diesel generators are generally noisier and emit more pollutants than technologies relying on renewable resources, although both of these negative characteristics have improved-since 1980, diesel engines have reduced emissions of NO_x and particulate matter by 90 % [29]. Diesel generators also need to be operated approximately once per month if used as stand-by power, although in the context of distributed generation discussed in this thesis, this is not a large concern. Fuel stocks for diesel generators also require heating in colder environments as diesel fuel will become a gel at sufficiently low temperatures.

Diesel generators consist of two basic parts: a diesel engine and a synchronous generator. Figure 3.1 [30] shows a block diagram design of a diesel generator.

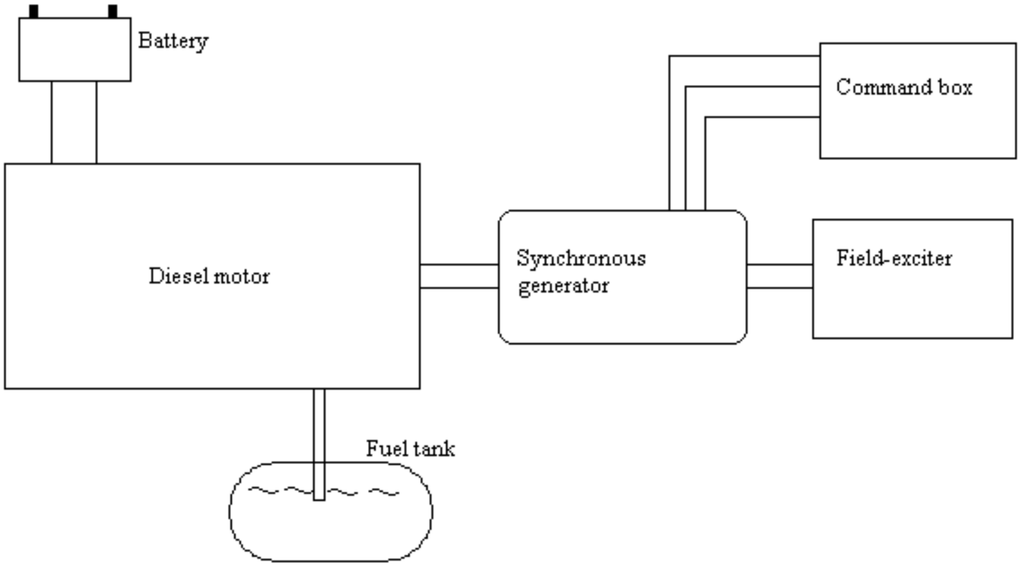

Figure 3.1 Block diagram of a diesel generator set [30]

3.2.1 Diesel Engine. The diesel engine operates similarly to most internal combustion engines in that it produces energy from a combustible fuel igniting within its cylinders and has both air intake and fuel intake valves and a fuel injector, with a crankshaft to transfer energy. However, the major difference between gasoline and diesel engines is the thermodynamic process known as the Diesel cycle, named for its inventor, Rudolph Diesel, which is shown in Figure 3.2 [31].

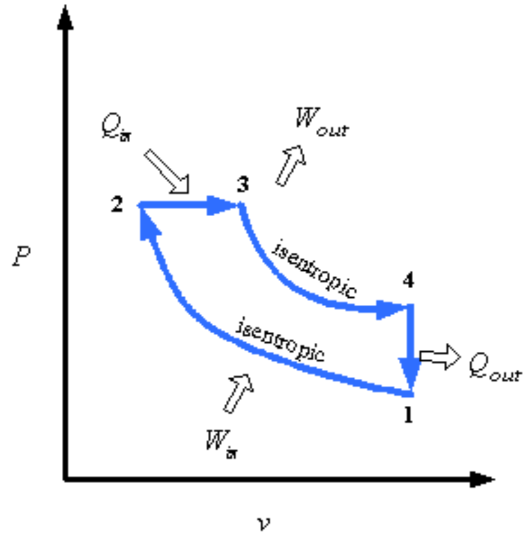

Figure 3.2 Pressure-volume plot of Diesel cycle [31]

The input work necessary to operate a diesel engine, which occurs during the first stroke of a four-stroke diesel engine, is the area under curve 1-2 in Figure 3.2. The work obtained from a diesel engine, which occurs during the third stroke of a four-stroke diesel engine is shown as the area under curve 3-4 in Figure 3.2. As the area under curve 3-4 is greater than the area under curve 1-2, the net work obtained from a diesel engine is positive.

The diesel cycle is possible because of the way diesel fuel is ignited within the cylinder of the engine. Diesel engines rely on compression ratios of between 14:1 and 20:1 [30] to produce high enough temperatures within the piston cylinder to cause ignition when diesel fuel is injected. The compression rate is defined in Equation 1 [30].

$$\rho_c = \frac{v_a + v_e}{v_e} \tag{1}$$

Where:

v_a - total volume of the piston cylinder

v_e - volume of the compression chamber

This high compression ratio differs from gasoline engines, which use a lower compression ratio of between 4:1 and 10:1, and a spark plug for ignition within the piston. The greater compression ratio within diesel engine pistons allows diesel engines to obtain more energy per unit volume of fuel than other internal combustion engines. Most modern diesel engines utilize a turbocharger to further compress incoming air by acting as a large fan to force more air into the piston cylinder.

Most diesel engines operate using a four-stroke process in the piston. A typical diesel engine piston and cylinder is shown in Figure 3.3 [29]. The initial stroke is considered the intake stroke, which is the initial downstroke. This downstroke reduces the air pressure in the cylinder, allowing air to be drawn in. The second stroke is compression, which occurs when the crankshaft forces the piston upward to increase the air pressure while decreasing the volume. This increases the temperature within the cylinder as demonstrated by the ideal gas law shown in Equation 2.

The third stroke is fuel injection, where the diesel fuel is injected into the compressed, hot air and ignites, which increases the volume of the gas in the cylinder while counteracting the pressure placed on the gas by the piston to drive the piston downward to rotate the crankshaft and pass the rotational energy to the synchronous generator. The amount of fuel injected during the third stroke is controlled by a governor, which keeps the motor from overspeeding through a mechanical system of weights or an electrical system with controllers, depending on the motor.

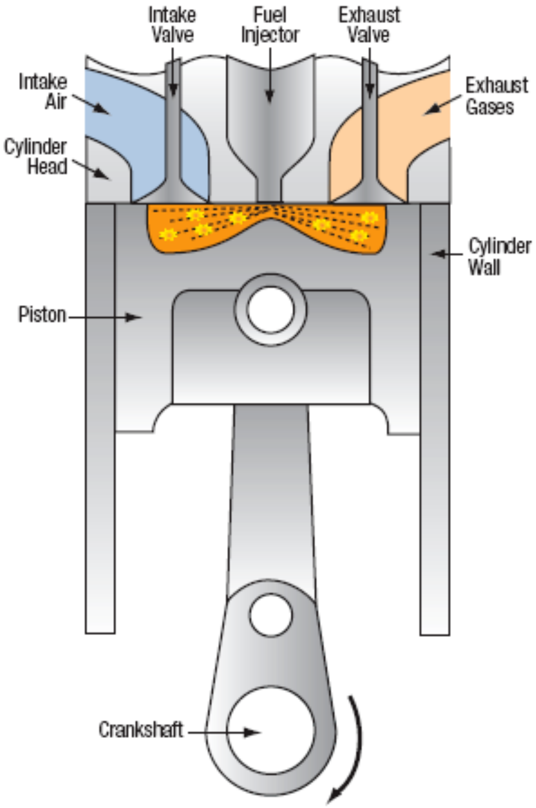

Figure 3.3 Diagram of diesel engine piston and cylinder [29]

$$pV=nRT \tag{2}$$

Where:

p – pressure

V - volume

n – molar amount

R – gas constant

T – temperature

The fourth and final stroke is an upstroke, which forces the exhaust to exit through the exhaust valve and starts the process over.

3.2.2 Synchronous Generator. The synchronous generator is made of two main components: the rotor and stator. The rotor contains the field windings, which act as a magnet. When the rotor rotates within the stator, the magnetic flux created by the armature windings interacts with the field windings of the rotor, to induce a current at the system frequency that is then sent to the load. The equivalent circuit diagram of the field and armature windings of a single phase can be seen in Figure 3.4 [39].

The output power of a synchronous generator in terms of the voltage and current of the armature windings is given in Equation 3 [39].

$$P = 3V_a I_a \cos(\theta) \tag{3}$$

The synchronous generator of a diesel generator is typically unable to produce reactive power as the field current of a generator, which controls reactive power output, is maintained at a constant level by the exciter such that generator voltage, represented by E_{af} in Figure 3.4, is always equal to the terminal voltage, represented by V_a.

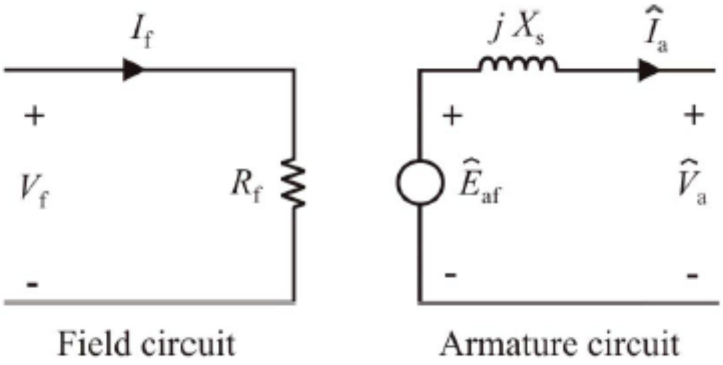

Figure 3.4 Circuit diagram of field and
armature windings for a synchronous generator [39]

This means constant power output also allows diesel generators to operate as power factor-controlled synchronous machines. Power factor control is demonstrated by Equation 5.

$$pf = \cos(\tan^{-1}(\frac{Q}{P})) \tag{5}$$

3.3 MICROTURBINE

Microturbines are a very recent development in the field of distributed generation as most manufacturers of microturbines have only been producing the technology for 10-

15 years. The technology offers several important benefits over other sources of distributed generation, perhaps the most important of which is that microturbines can operate using most combustible fuels, including liquid fuels like diesel and gasoline, and gaseous fuels like digester gas from landfills and natural gas. However, there are limits to this, as many types of microturbines are not rated for the use of multiple fuel types. Figure 3.5 shows a set of microturbines operating in parallel.

Figure 3.5 Three Capstone microturbines in operation [40]

Microturbines also offer high power densities, generally from 3-4 kW/sq. ft. Installation costs of microturbines are significantly higher than those of diesel generators and are generally \$1000-\$1500/kW installed [32]. Microturbines are generally inefficient when used solely for power, as the peak electrical efficiency of a microturbine is approximately 30% [33] and this occurs when running at maximum output. Microturbines are frequently used for combined heating and power (CHP), which can increase the electrical efficiency up to 70% and the total efficiency to 75%, making them a viable option for both office buildings and industry. Most microturbines currently produced are capable of only about 300 kW, although multiple microturbines can be placed in parallel to produce a greater combined output. Some microturbines are capable of only grid-parallel operation, although most manufacturers produce models capable of both stand-alone and grid-parallel operation. Microturbines are generally used for peak-shaving and base load operation due to their high cost and efficiency limitations.

A microturbine is composed of two parts: a high-speed gas turbine and a permanent magnet synchronous generator [34]. A block diagram of a typical microturbine is shown in Figure 3.6 [30].

The gas turbine is generally made up of a compressor, a combustion chamber, a turbine and a recuperator. Although a recuperator is not required for operation, it can improve the efficiency of the microturbine by 5-10% and allows for CHP applications [35]. A gas turbine model can be seen in Figure 3.7 [41]. The gas turbine operates produces power through the use of the Brayton cycle, shown in Figure 3.8 [42].

The initial step of the Brayton cycle is when air is allowed to enter the compressor and this can be seen as curve A-B in Figure 3.7. The compressor then increases the air pressure while simultaneously decreasing the volume of the air within the compressor. This can be seen as curve B-C in Figure 3.7.

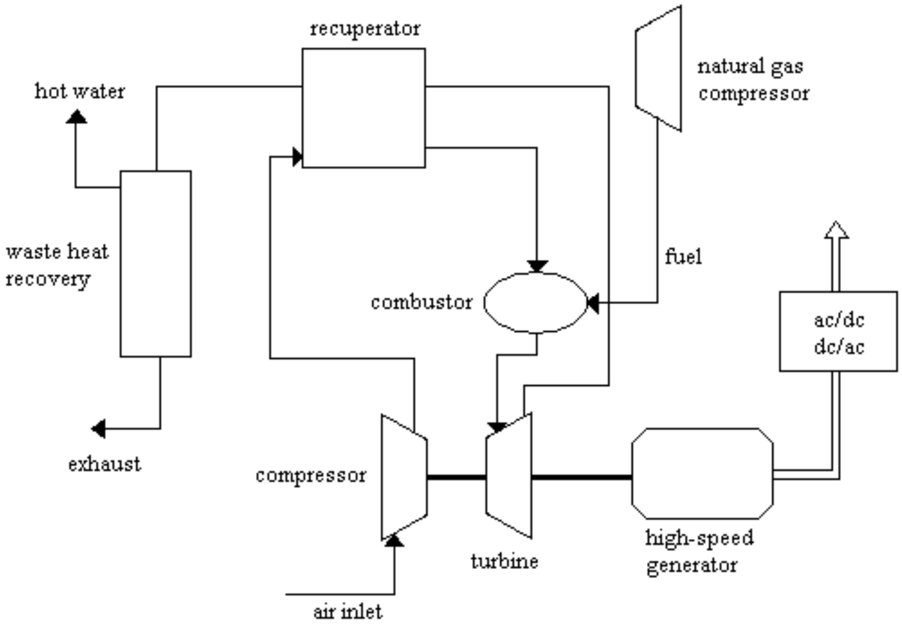

Figure 3.6 Block diagram of a single-shaft microturbine [30]

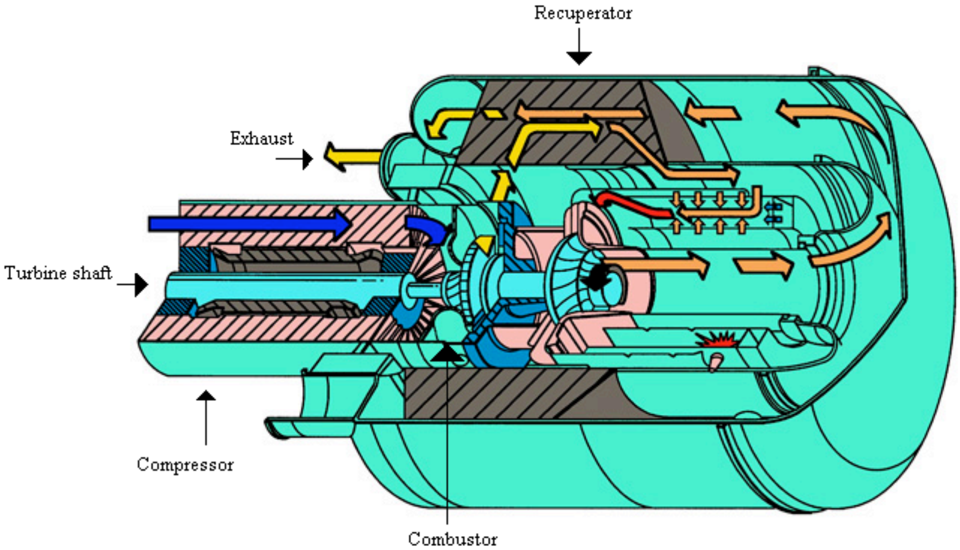

Figure 3.7 Cross-section of gas turbine [41]

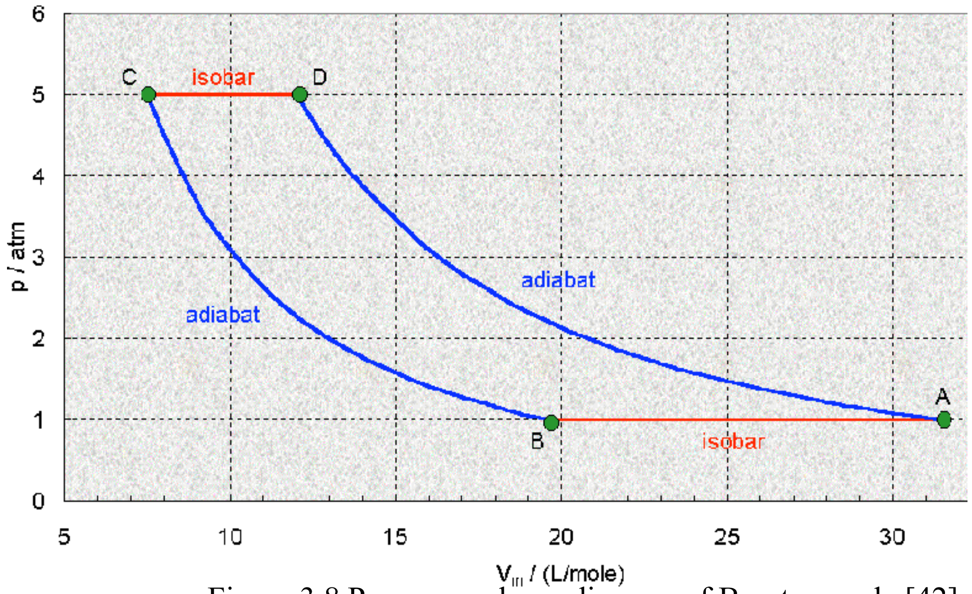

Figure 3.8 Pressure-volume diagram of Brayton cycle [42]

The compressed air then enters the combustion chamber or combustor, where it is mixed with fuel and ignites and drastically increases in volume while simultaneously dropping in pressure, as shown in Figure 3.7 as curve C-D. The air expelled from the combustion of the gas turbine then flows over aerodynamic blades to rotate the turbine shaft. This rotation allows the turbine to operate at approximately 100,000 RPM [30]. This rotation is then fed to either a high-speed permanent magnet synchronous generator or a gear reducer, depending on whether the microturbine is single-shaft or split-shaft design, respectively [30].

For a single-shaft design, unidirectional power electronic devices are typically connected to the synchronous generator, as these are cheaper to construct and significantly less complex than bidirectional power electronics, although both can be used. The unidirectional power electronics consist of a rectifier to convert incoming, high-speed AC power into DC, and an inverter to change the DC power into a 60 Hz output. The split-shaft design uses a gear reducer connected to an additional shaft to reduce the rotational speed seen by the generator and thus the electrical frequency being produced by the generator [30].

The synchronous generator of a microturbine can act to control power factor or voltage, although for the purposes of this thesis, voltage-controlled operation will be examined. Voltage control is accomplished essentially by comparing the generated voltage of a generator or line to the terminal voltage that the generator or line is connected to. Equation 6 [43] describes this relationship.

$$P_{out} = \frac{E_g V_t}{X_s} \sin\delta \tag{6}$$

Where:

P_{out} - Real power output

E_g - generator voltage

V_t - terminal voltage

X_s - stator reactance

δ - generator power angle

Equation 6 demonstrates that as the terminal voltage decreases, the generator voltage increases along with the real power output of the generator. The generator power angle, which is the phase difference between the generator voltage and terminal voltage can also be increased to control voltage, although there is a limit to this as generators also have limits on field and armature currents. These limits to the power angle can be seen in the capability curves of synchronous generators. A typical capability curve of a synchronous generator can be seen in Figure 3.9 [44]. The field limit on the amount of power output can be seen as the green curve in the figure while the armature limit on power output is represented by the blue curve.

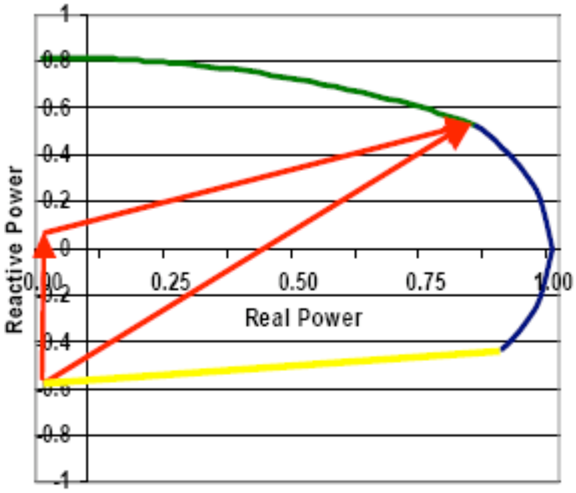

Figure 3.9 Capability curve for a synchronous generator [44]

3.4 WIND TURBINE

The use of wind to perform work has been around for well over a thousand years, but it has only been in the last seventy years that it has become commonly used for electricity production and the last thirty years that the wind has been used for large scale production. The large scale use of wind power in the U.S. originated because of oil shortages in the early 1970s and an increase in oil prices in the last decade has driven a return to the technology in the U.S. Denmark has used wind turbines for more than 20% of their power production for almost two decades.

Wind turbines have several advantages over other generator types. The fuel source is free, limitless, and does not require storage or transportation. Also, wind turbines do not produce emissions like fossil fuel-consuming generators. Recent advancements in power electronics and controls have allowed technologies like DFIGs, active stall controllers, and variable slip controllers have increased the efficiency of wind turbines. These advancements have also greatly extended the range of wind speeds and locations that wind turbines can be used at. Several types of turbine design also allow for stand-alone operation, which allows for operation independent of the power grid.

While wind power offers many advantages over more conventional sources of energy, wind turbines also have several important drawbacks. Perhaps the largest drawback to wind turbines is that, just as the wind is inconsistent in its speed, wind turbines cannot produce a constant power output. Another significant drawback to wind turbine usage is that the technology offers low power density and requires large areas of land to produce a significant power output. The location of wind turbines is also an important factor despite the advances in power electronics and controls described earlier. Also, many load centers, like cities and industrial parks are often not ideal locations for wind turbines due to the limited availability and cost of land along with relatively low wind speeds. This lack of optimal locations near load centers can mean that power lines are necessary for access to the power, thus eliminating one typical advantage of distributed generation. The map of U.S. wind speeds shown in Figure 3.10 [45] shows that rural areas, like the mountain and plains states have the highest average wind speeds.

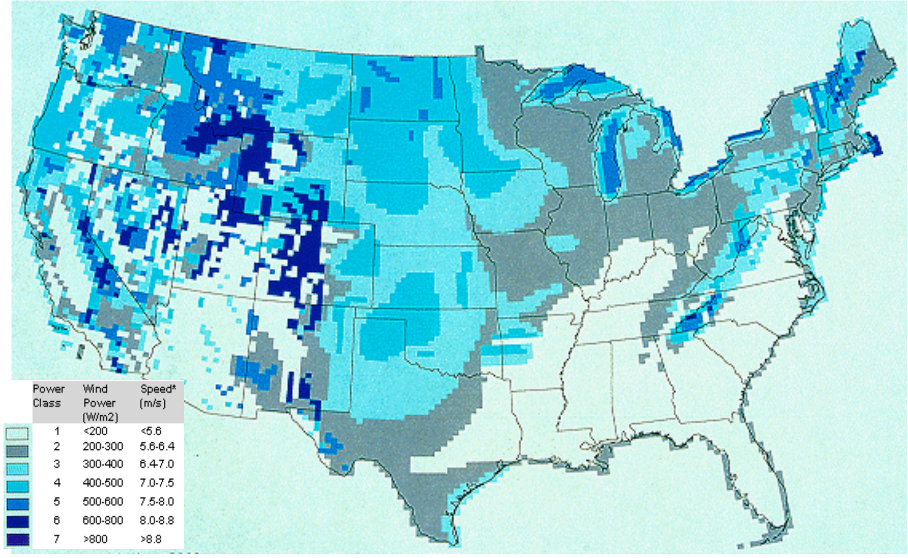

Figure 3.10 Map of average U.S. wind speeds [45]

The amount of energy that can be obtained from the wind is limited by several factors. Equation 7 [36] shows the maximum amount of kinetic energy, P_{WIND}, that flows incident over the rotor blades of a wind turbine. Obviously, a wind turbine will be incapable of converting all kinetic energy incident upon its rotor blades, as this would require zero wind speed on the downwind side of the rotor blades.

$$P_{WIND} = \frac{1}{2}\rho_{AIR}\pi R^2 V_{WIND}{}^3 \qquad (7)$$

Where:

ρ_{AIR} - air density

R - rotor radius

V_{WIND} - wind speed

This kinetic energy must then be limited by another factor. energy, P_{MECH} by the rotor blades, This limiting factor is Betz's law shown in Equation 8 [36], which states that the amount of mechanical energy, P_{MECH}, is limited by a conversion factor, C_P. This conversion factor is limited to 59% or 16/27.

$$P_{MECH} = C_P P_{WIND} \tag{8}$$

The values of C_P can be maximized by designing the rotor tips to spin at roughly 8 to 9 times the speed of the incoming wind [36]. As rotor blades are designed to have the greatest rotational speed for wind incident upon the top rotor blade, this means that the angle between the direction of the wind speed and the rotor tip, φ, is quite large. This angle of incidence, φ, is calculated by Equation 9 [36].

$$\varphi = \arctan(\frac{V_{WIND}}{\omega_{turb} R}) \tag{9}$$

Where:

ω_{turb} = turbine rotational speed

These equations allow us an understanding of the mechanics of the rotor blades, but now the next step in power production will be examined. As has been discussed, wind incident on the rotor blades produces rotation. This rotation is transferred to a gear box with a variable slip control, which allows the rotational speed sent from the turbine itself to the rotor shaft to maintain a relatively constant speed over a variety of wind speeds. The rotor shaft from the gearbox is sent into a DFIG, which can be seen in Figure 3.11 [36].

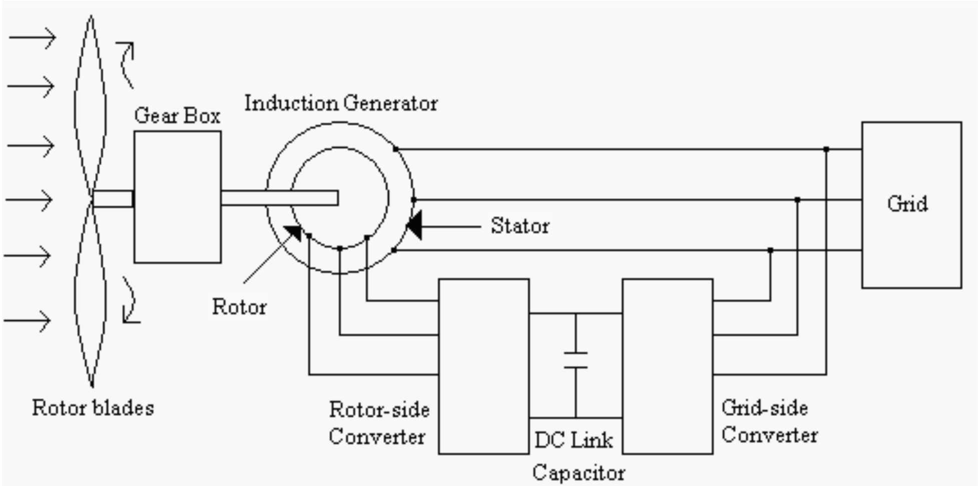

Figure 3.11 Block diagram of wind turbine and DFIG [36]

The DFIG utilizes an induction generator, which is quite similar to a synchronous generator except for two main differences:

- The rotor of an induction generator can operate at greater than synchronous speed
- The rotor of an induction generator is magnetized separately from the grid

Although the DFIG utilizes an induction generator for power production, it also has some important differences from other induction generators. The largest difference is that the rotor voltage of a DFIG is applied from a power converter, while the stator voltage is applied from the grid itself-this ‘feeding’ of two separate sources for rotor and stator voltages is how the DFIG became known as ‘doubly-fed’. The other important difference between the DFIG and an induction generator is that a DFIG actually can be magnetized from the rotor circuit, as opposed to from the grid [36].

The advantage that DFIGs have over other types of generators is that the slip of the generator, which is the difference between synchronous rotor speed and maximum rotor speed, is quite small. This allows the DFIG to produce power over a wide variety of wind speeds. The other important advantage DFIGs have is that the power converter can feed into or out of the rotor depending on the rotor speed. This allows power to be fed into the rotor when the rotor is above synchronous speed and out of the rotor when the rotor speed is subsynchronous. In either rotor speed situation, the stator feeds electricity into the system [36].

The real and reactive power output of a DFIG can be shown as a function of the rotor and stator voltages and currents in the q-d reference frame as observed in Equations 10 and 11 [46].

$$P = v_{ds} i_{ds} + v_{qs} i_{qs} + v_{dr} i_{dr} + v_{qr} i_{qr} \tag{10}$$

$$Q = v_{qs} i_{ds} - v_{ds} i_{qs} + v_{qr} i_{dr} - v_{dr} i_{qr} \tag{11}$$

Where:

v_{ds} – d-axis stator voltage

i_{ds} – d-axis stator current

v_{qs} – q-axis stator voltage

i_{qs} – q-axis stator current

v_{dr} – d-axis rotor voltage

i_{dr} – d-axis rotor current

v_{qr} – q-axis rotor voltage

i_{qr} – q-axis rotor current

These equations demonstrate that a DFIG can produce both real and reactive power and can operate to absorb reactive power from the system when necessary.

4. SYSTEM STUDIES

4.1 OVERVIEW

This section will examine the system used as well as outline the procedures and tests performed on the system. This section will also present the results obtained and attempt to analyze and compare the results.

4.2 SYSTEM

The IEEE 34-bus system shown in Appendix A.1 was created in DIgSILENT using specifications from IEEE [37] with line data shown in Appendix table B.1 and line model parameters in Appendix table B.2. Equation 1 [38] is used to calculate the sequence impedances for the distribution lines.

$$[(R+jX)_{012}] = [A_s]^{-1} * [(R+jX)_{abc}] * [A_s] \tag{1}$$

Where:

$[(R+jX)_{012}]$ - sequence impedance matrix

$[A_s]$ - $\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$

a - $1\angle 120$

$[(R+jX)_{abc}]$ -phase impedance matrix

The distributed loads shown in Appendix B.3 were modeled as split loads with half on each bus. The system was then verified using an unbalanced loadflow study in DIgSILENT with reactive power limits and automatic tap adjustment to ensure the system was modeled correctly. The loads throughout the system were then increased by 50% to model heavy loading conditions.

4.3 VOLTAGE PROFILE AND LOSS STUDY

The microturbine and diesel generator were modeled as voltage- and power factor-controlled synchronous generators, respectively, while the small wind turbine was modeled as a DFIG. These models were created to output 10% of the base case power output of the main generator on the system. The base case had an average bus voltage was 0.915 p.u. and system losses totaling 1.179 MW. Loadflow studies were performed to determine which locations provided the largest system-wide improvement in voltage profile and the greatest reduction in losses. Figure 4.1 shows the average bus voltage in the system when the specific DG type was moved from bus to bus. Figure 4.2 shows a comparison of the line losses for each type of DG and each location.

The small wind turbine and the microturbine provided approximately the same improvement in the voltage profile at locations close to the substation, although a significant and consistent difference appeared between the average voltages for both types at bus 832 and beyond. This was likely due to the wind turbine producing at full power while the microturbine was limited in its VAR output due to voltage-controlled operation. The diesel generator model did show an increase to the voltage profile of the system, although its impact was limited due to its inability to provide reactive power support to the system. Each DG type showed significant improvement to the voltage profile at bus 890 and maintains a relatively constant improvement to the voltage profile at locations further from the substation. This is because power flow from the DG and main generator does not drastically change for these locations and there is no additional redundancy due to voltage regulators.

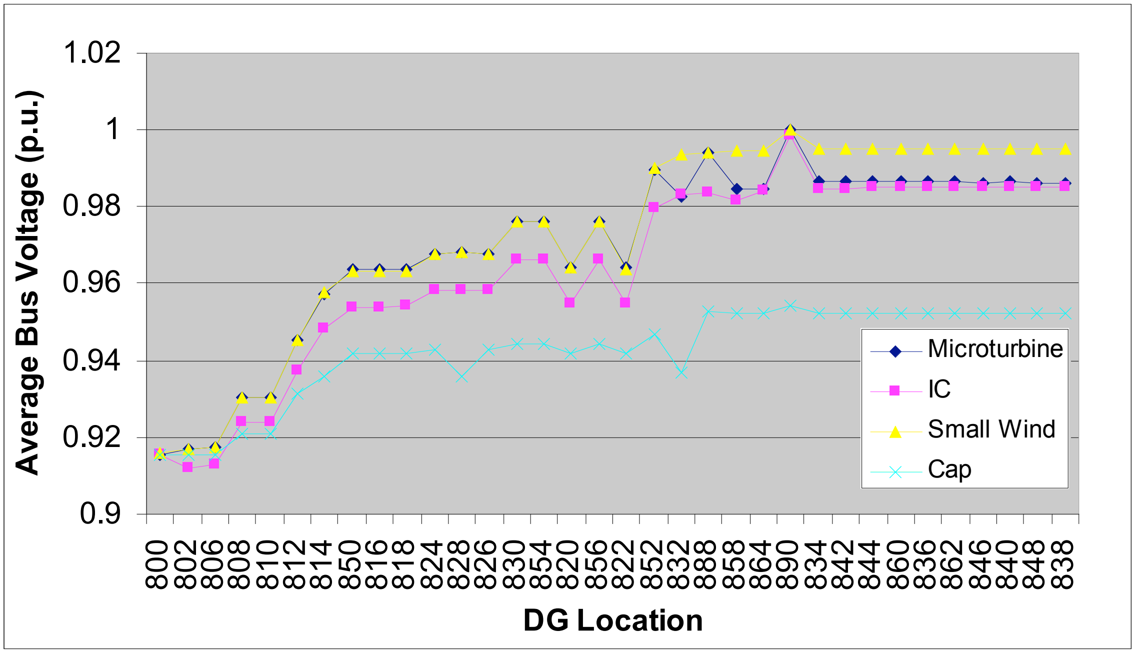

Figure 4.1 Plot of average bus voltage as
DG is moved farther from main generator

The loss study indicates similar overall line loss improvement as the voltage profile study. Bus 890 is the optimal location for DG and buses located at bus 832 and beyond all provide approximately the same reduction to system losses. This is again an indirect result of the location of the DG in relation to the voltage regulators.

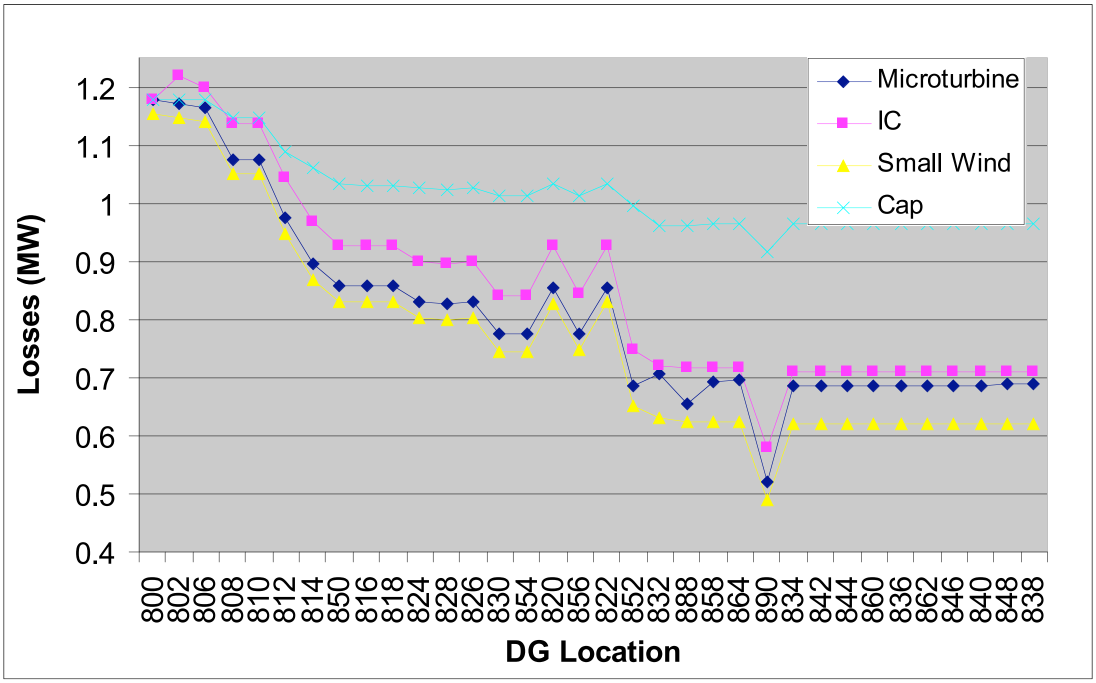

Figure 4.2 Plot of line losses as
DG is moved farther from main generator

Three buses, 890, 862, and 848, were then identified as possible ideal locations for DG based on the voltage profile and loss studies, as these buses showed the greatest improvement on the average system voltage and the greatest reduction in line losses. Additional voltage profile studies were then performed at each bus location and each type of DG was increased in steps of 5% to observe the effect of location and sizing of DG on the voltage profile. Figure 4.3 demonstrates the results of the voltage profile studies.

Each set of three voltage profiles shown was for an isometric power output as the distance from the main generator was increased, while every third voltage profile shown was for an isometric location and varied output. The figure indicates that the system voltage profile is more strongly related to the sizing than the location of the DG, although a system can reach a point where the voltage profile is adequate and any additional DG power output results in only minimal improvement in the best case and reverse power flow into the main generator in the worst case.

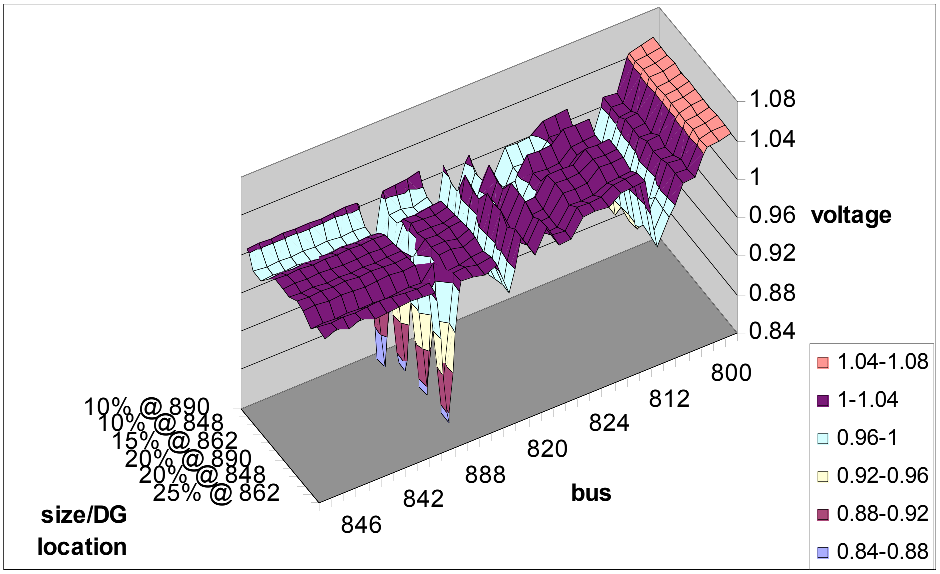

Figure 4.3 3-D voltage profiles with varying diesel generator size and location

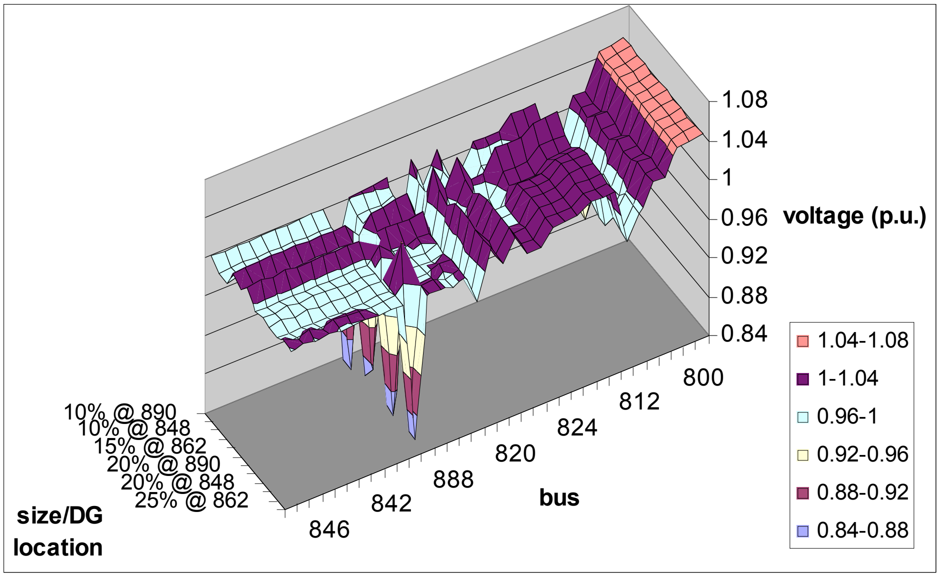

Figure 4.4 3-D voltage profiles with varying microturbine size and location

The voltage profile study was then repeated in the same fashion for both the microturbine and small wind generator models, as seen in Figures 4.4-4.5. Interestingly, both studies indicate that voltage profile improvement may be tied to a specific sizing or set range of sizing than to maximizing output or optimizing location. It would appear that the optimal location is bus 890 with approximately 25% power output from a microturbine. This location, power output and DG type would allow the minimum system voltage to be 0.978 p.u., which is easily above the minimum allowable bus voltage.

The system losses for each of the three locations tested and each level of output can be seen in Figures 4.6-4.8.

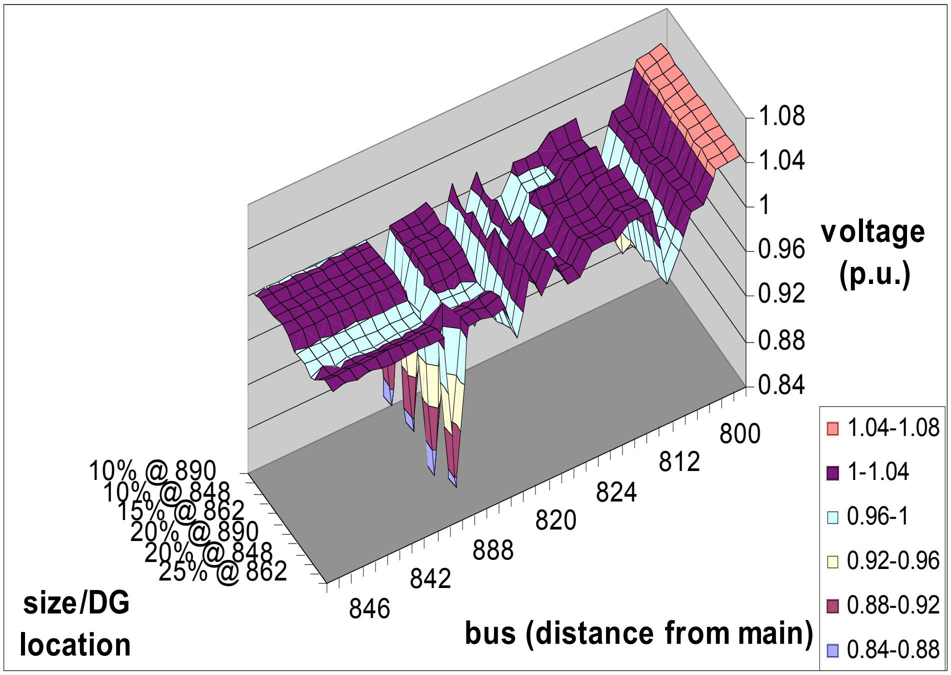

Figure 4.5 3-D voltage profiles with varying small wind turbine size and location

The system loss plots indicate that bus 890 is the ideal location for DG to reduce system losses as well as increase the voltage profile. The plots also show a sharp decrease in system losses as output was increased for both the diesel generator and microturbine. The wind turbine demonstrates a significantly different pattern as system losses decrease much more sharply as output power is increased to 20% from 15% than it does from 10% to 15%.

4.4 ISLANDING STUDIES

The diesel generator and microturbine models were tested under islanding conditions to observe their performance. The small wind turbine was excluded from this study, as the model is incapable of operating separately from the grid.

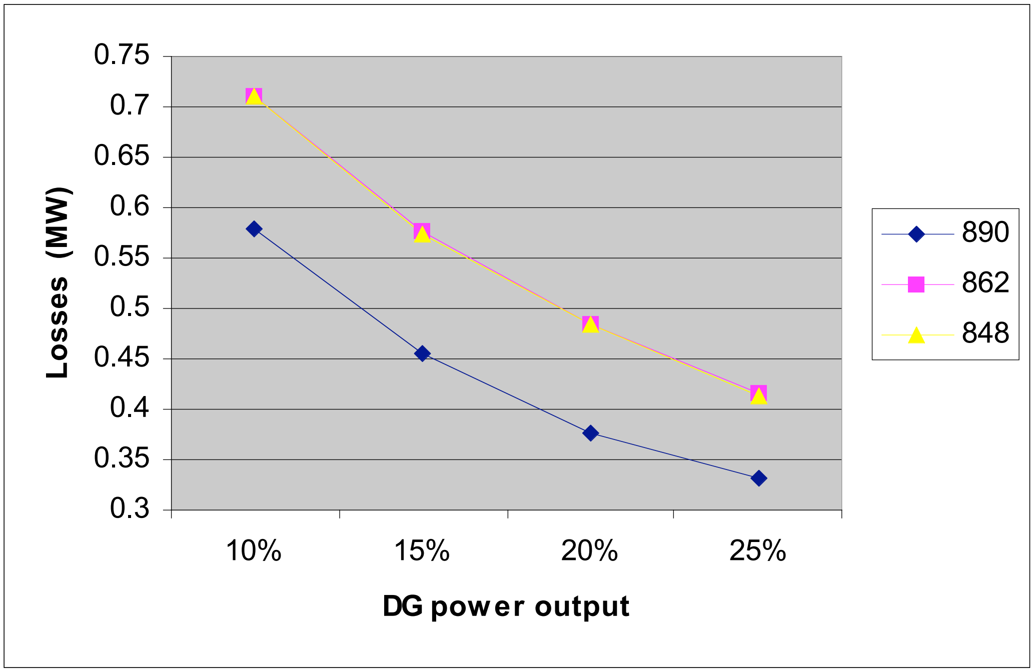

Figure 4.6 Plot of system losses with diesel generator at three locations

The microturbine and diesel generator models were placed at bus 890 and were first operated at a real and reactive power output equal to that of the load at bus 890. This was done because the minimum DG power output that caused no undervoltages on the system would be unable to sustain an island and would not be designed for intentional islanding by a utility. Three-phase faults were than programmed to occur at 1 second of simulation time at bus 890. The frequency and line-line voltage plots can be seen in Figures 4.9-4.12.

The graphs show that the diesel generator model experienced some significant speeding and voltage variations, but did stabilize upon being islanded. The diesel generator was capable of reclosing onto the grid with only a small transient, but required a recloser delay of approximately one minute to allow the generator frequency to stabilize. The microturbine model shows generator speeding, something typically associated with too much power generation. The microturbine also demonstrates some ability to stabilize its voltage upon being islanded, but generator speeding observed after each relay operation kept the model from being reconnected. The cause for the generator speeding was caused by a failure of the voltage-control system to recognize that the generator was not operating at the voltage set point. The generator can also be observed to be slow to increase the bus voltage after it had reached a stable, but low condition.

The reactive power output of the diesel generator model was then reduced to zero and the MVA power output was increased to 25% to determine whether the diesel generator or microturbine are capable of operating as a stable island when not specifically dispatched and limited to a power output equal to that of the islanded load. The results can be observed in Figures 4.13-4.16.

These studies again indicate that neither the microturbine nor the diesel generator can stabilize during islanded operation and since both experience generator speeding, neither type is suitable for intentional islanding in this study.

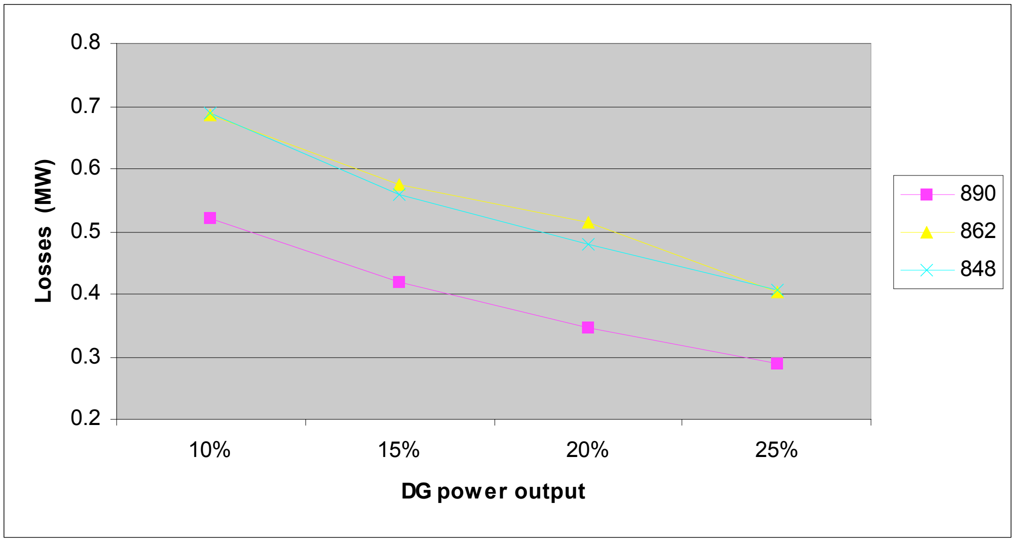

Figure 4.7 Plot of system losses with microturbine at three locations

4.5 TRANSIENT STUDIES

The system was then tested under a variety of smaller transient events to observe how each DG type can handle typical system events.

4.5.1 Single-Phase Fault Study. The first study performed was for a 1-phase fault at bus 890 at 1.0 seconds of simulation time that was cleared at 1.25 seconds of simulation time. The DG was set to 15% power output in each case. The results can be observed in Figures 4.17-4.22.

The plots show that the diesel generator and microturbine models experienced greater oscillation in voltage and frequency than the wind turbine. This was likely due to the wind turbine model requiring excitation from the grid. The fault condition removed part of the wind turbine's connection to the grid and thus partially removed a source of fault current.

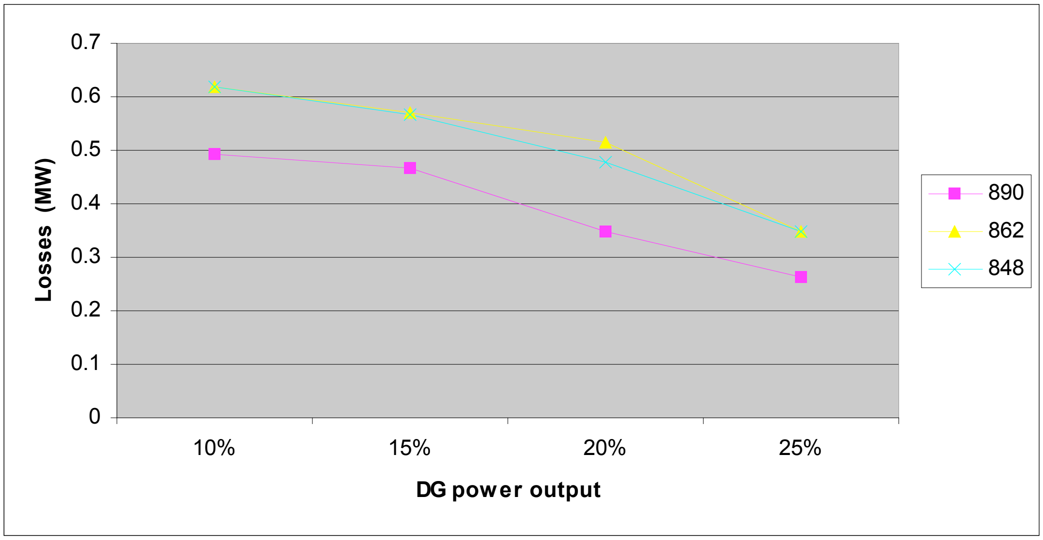

Figure 4.8 Plot of system losses with small wind turbine at three locations

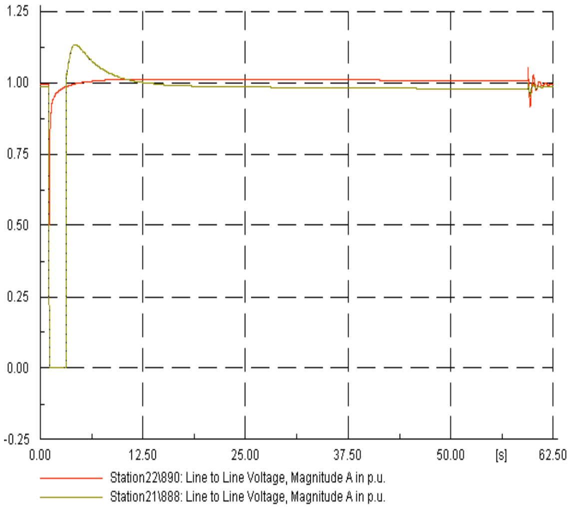

Figure 4.9 Bus voltages for islanding study islanding study with diesel DG

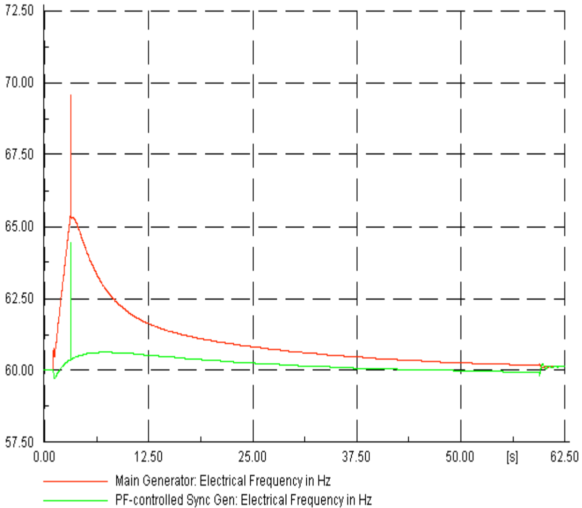

Figure 4.10 Generator frequencies for islanding study with diesel DG

The microturbine was shown to be more stable during the fault than the diesel generator model, but this was likely due the lack of reactive power production from the diesel generator and the load at the DG bus. As the diesel generator was producing only real power and the load required a large amount of reactive power, more current was required from the main generator to supply the load than with the microturbine, which was capable of reactive power production. This additional current from the main generator caused the single-phase fault to have a more significant effect on the faulted bus's voltage. The study does indicate that the system approaches steady-state operation for each DG type, despite the transient event.

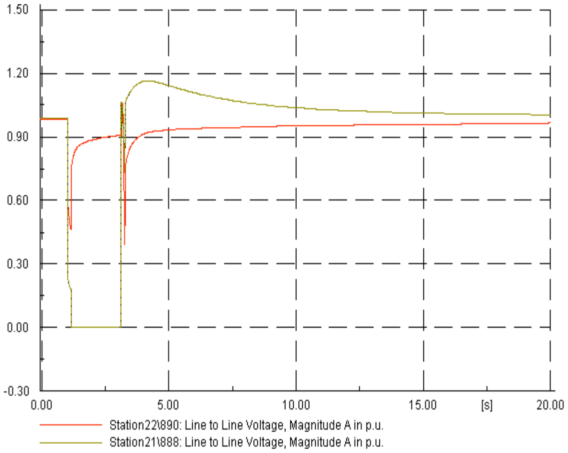

Figure 4.11 Bus voltages for islanding study with microturbine DG

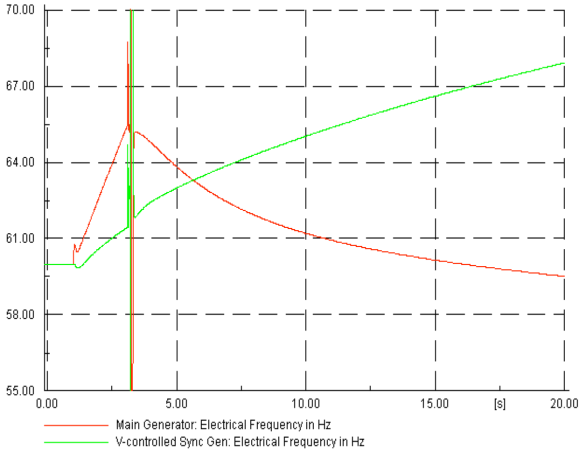

Figure 4.12 Generator frequencies for islanding study with microturbine DG

4.5.2 Load Shedding Study. The next transient study performed was a temporary load shedding on the system. The lateral containing buses 842, 844, 846, and 848 was disconnected from the system at 1.0 seconds of simulation time and reconnected at 3.25 seconds. This was to simulate a false relay trip and reconnection. The results can be observed in Figures 4.23-4.28.

The load shedding study indicates that, although the wind turbine model maintains frequency stability much more than the diesel generator or microturbine models, it also causes a significant overvoltage. The wind turbine study also indicates a subsynchronous frequency after the voltage has been restored to normal levels. This was likely a response to the torque placed on the main generator due to a sudden load increase from re-connection.

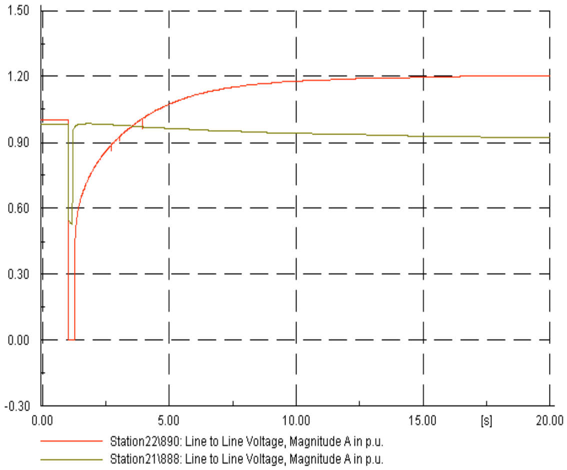

Figure 4.13 Bus voltages for islanding study with 25% diesel DG

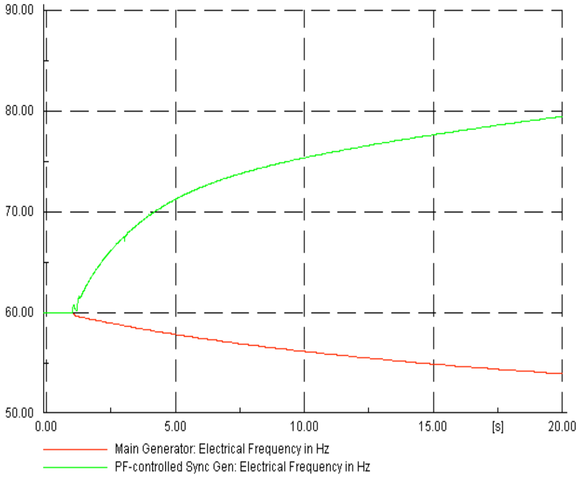

Figure 4.14 Generator frequencies for islanding study with 25% diesel DG

A large increase in both real and reactive power output of the main generator can be observed in Figure 4.29. It can also be noted that the wind turbine draws reactive power from the grid for several tenths of a second after the load was shed. The minimum point of reactive power absorption corresponds roughly to the reactive power setpoint of

–0.3 MVAR of the PWM converter used in the model. This absorption may represent an attempt to stabilize the bus voltage.

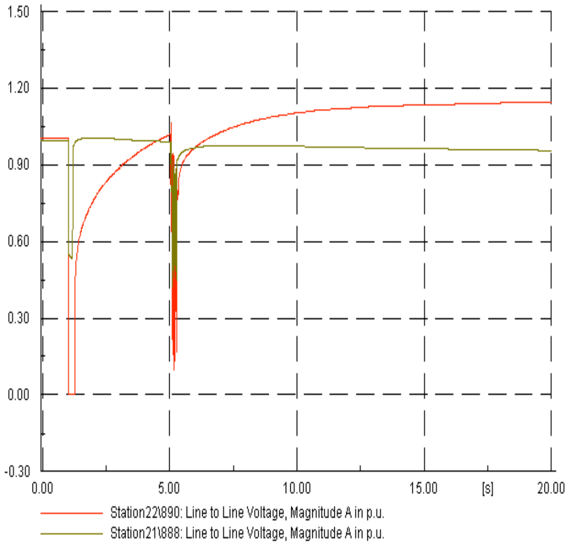

Figure 4.15 Bus voltages for islanding study with 25% microturbine DG

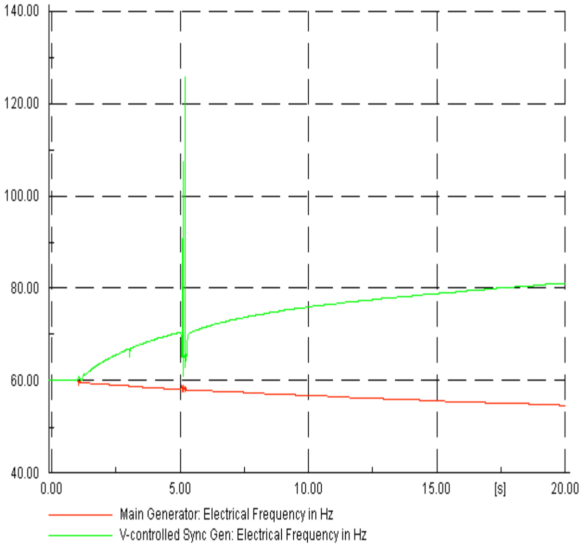

Figure 4.16 Generator frequencies for islanding study with 25% microturbine DG

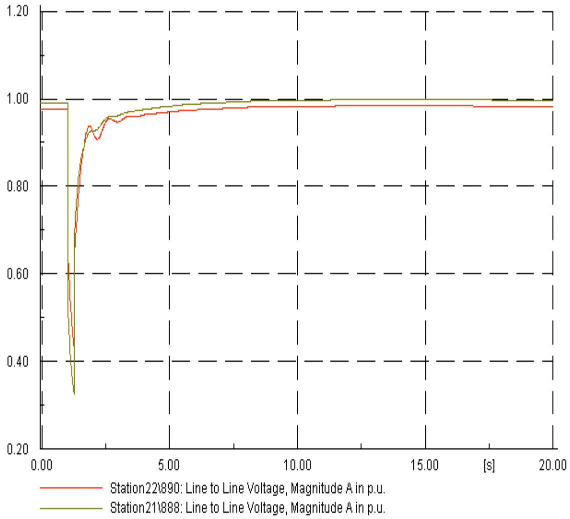

Figure 4.17 Bus voltages for 1-phase fault study with diesel DG

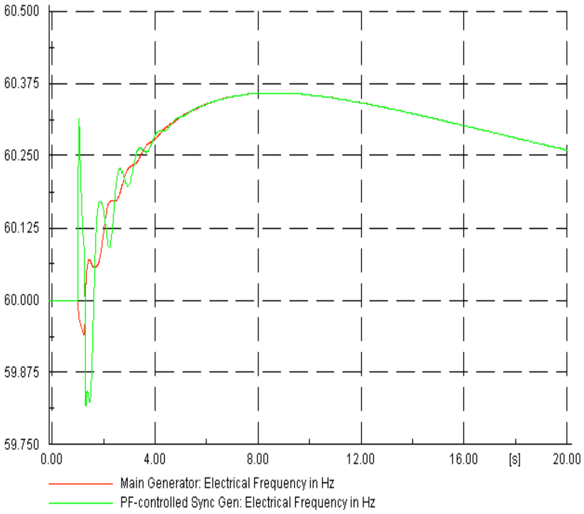

Figure 4.18 Generator frequencies for 1-phase fault study with diesel DG

The load shedding study demonstrates that the system returns to steady-state operation for each DG type used.

4.5.3. Load Increase Study. The final transient study was performed for a sudden load increase on the system. This was simulated by increasing the load at bus 890 by 25% at 1.0 seconds of simulation time and then decreasing the load to its previous value at 1.2 seconds of simulation time. The results can be seen in Figures 4.30-4.35.

The load increase study shows the wind turbine model experiences very fast frequency oscillations immediately after the load increases, but steadies very quickly to follow the main generator frequency. The diesel generator and microturbine models show a greater oscillation in frequency and bus voltage, although it appears the voltage oscillation stabilizes before the wind turbine's oscillations. The system approaches steady-state operation after the load increase for each DG type, indicating that DG does not significantly affect system stability for this type of event.

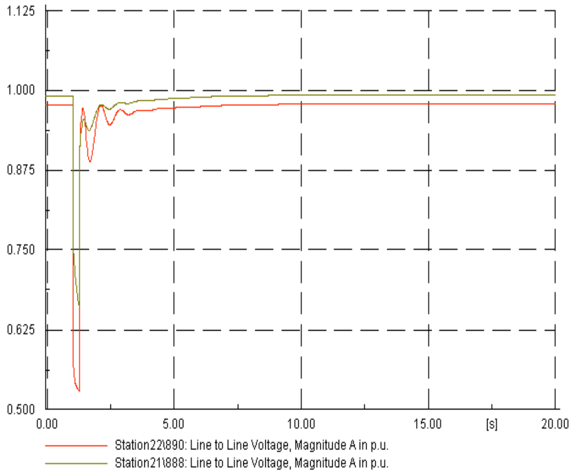

Figure 4.19 Bus voltages for 1-phase fault study with microturbine DG

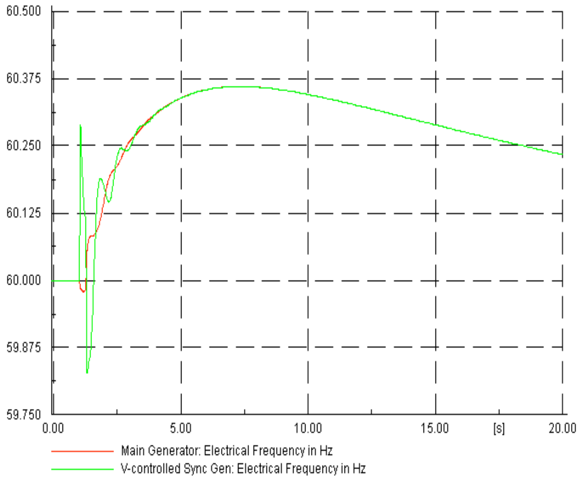

Figure 4.20 Generator frequencies for 1-phase fault study with microturbine DG

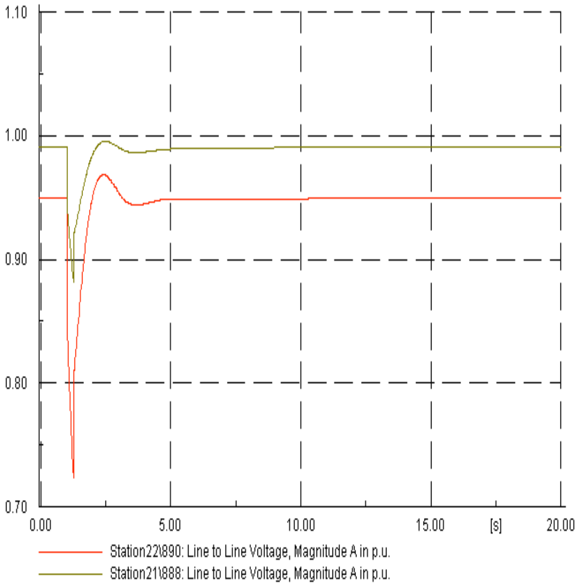

Figure 4.21 Bus voltages for 1-phase fault study with small wind turbine DG

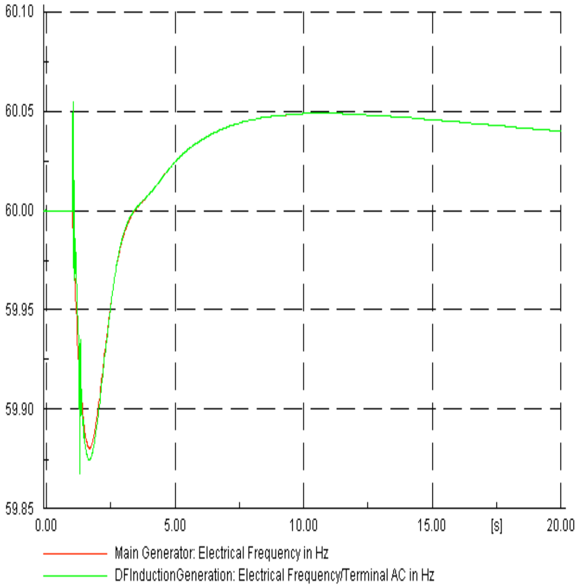

Figure 4.22 Generator frequencies for 1-phase fault study with small wind turbine DG

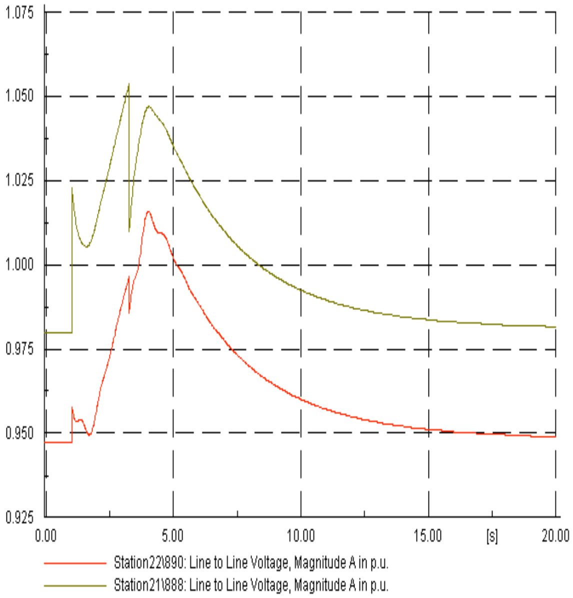

Figure 4.23 Bus voltages for load shedding study with diesel DG

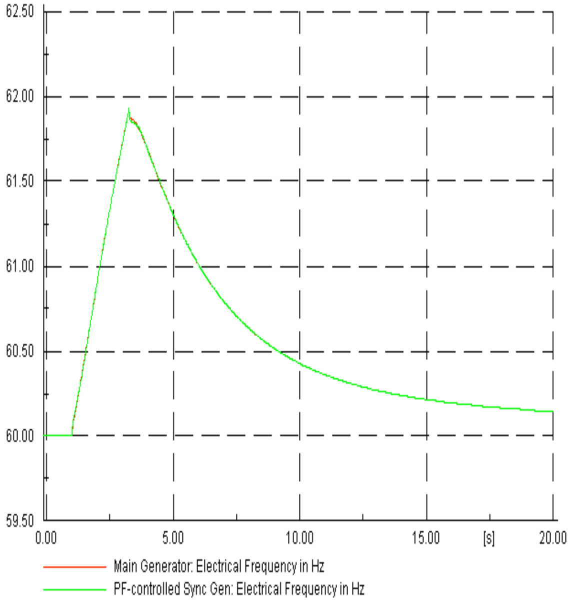

Figure 4.24 Generator frequencies for load shedding study with diesel DG

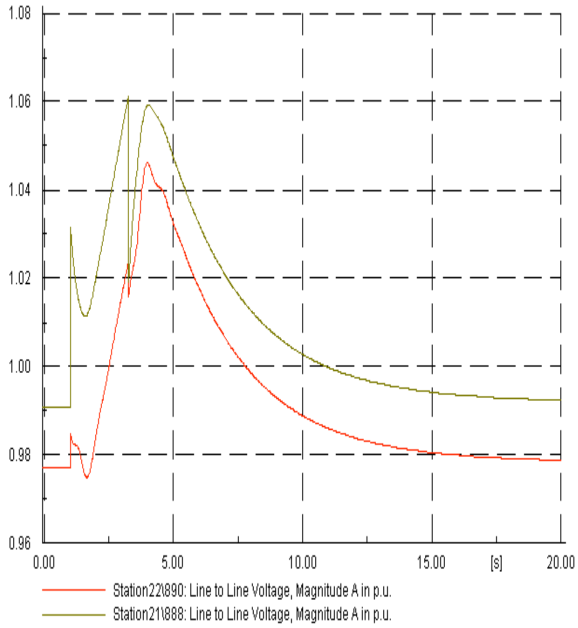

Figure 4.25 Bus voltages for load shedding study with microturbine DG

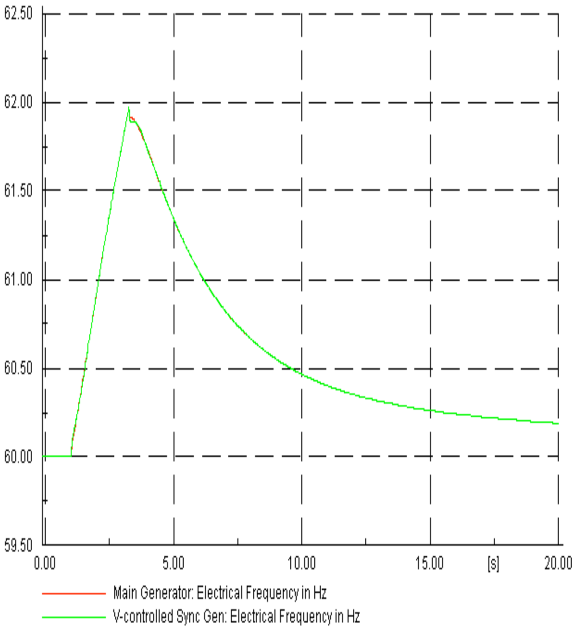

Figure 4.26 Generator frequencies for load shedding study with microturbine DG

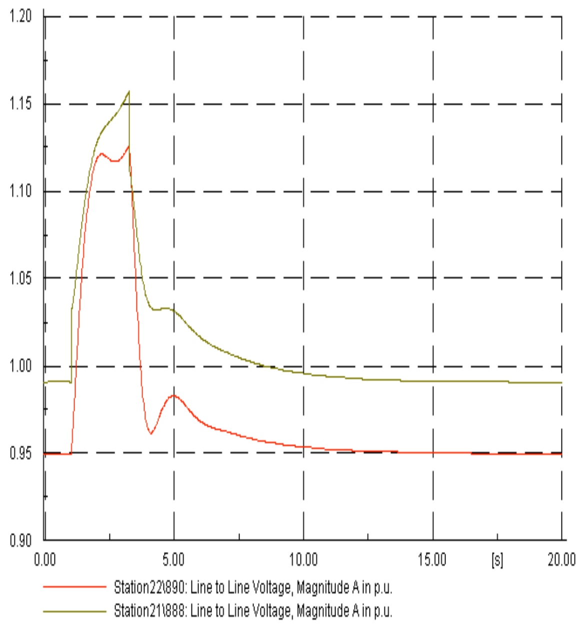

Figure 4.27 Bus voltages for load Shedding study with small wind turbine DG

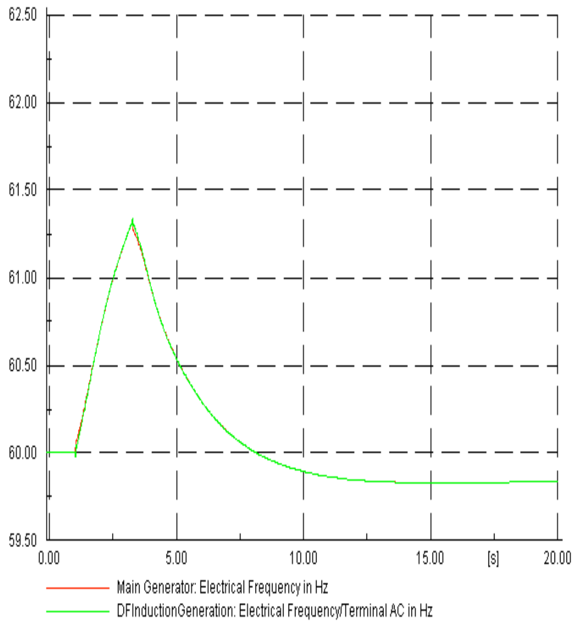

Figure 4.28 Generator frequencies for load shedding study with small wind turbine DG

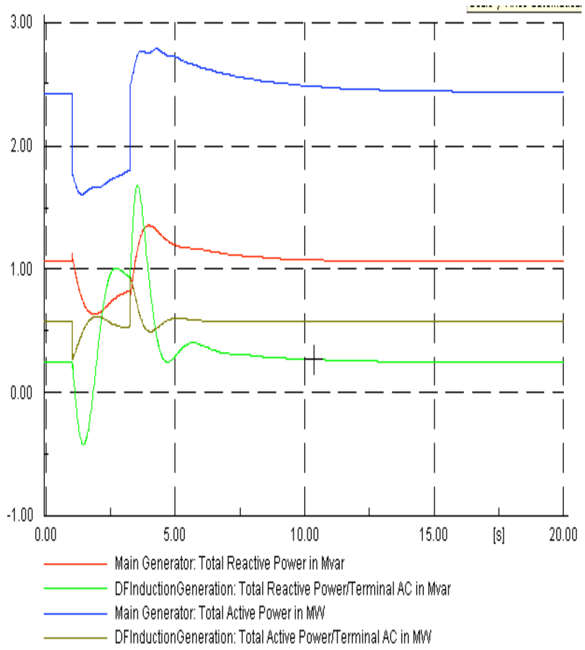

Figure 4.29 Generator power outputs for load shedding study with small wind turbine DG

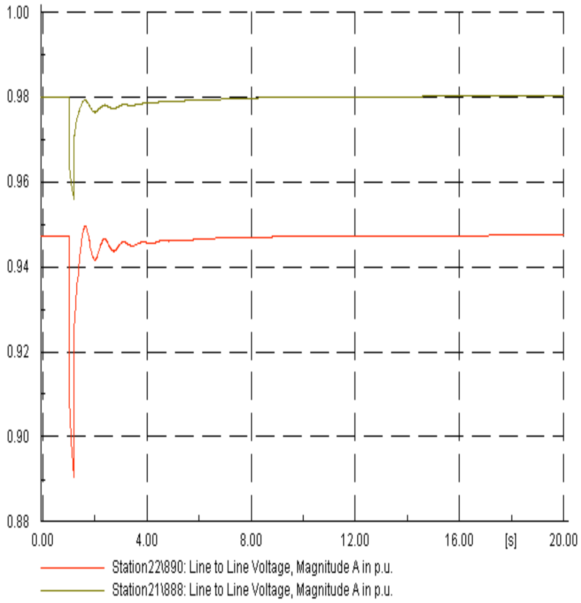

Figure 4.30 Bus voltages for load increase study with diesel DG

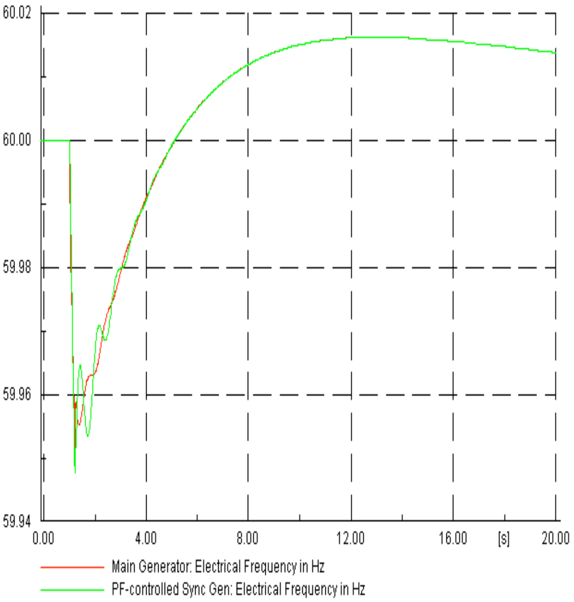

Figure 4.31 Generator frequencies for load increase study with diesel DG

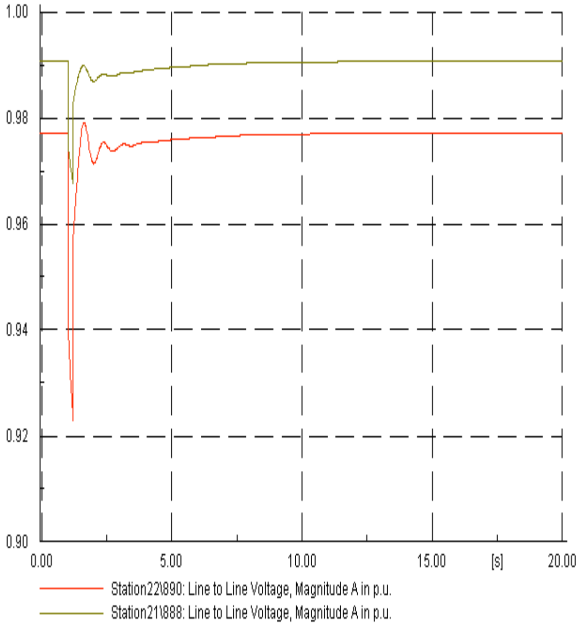

Figure 4.32 Bus voltages for load increase study with microturbine DG

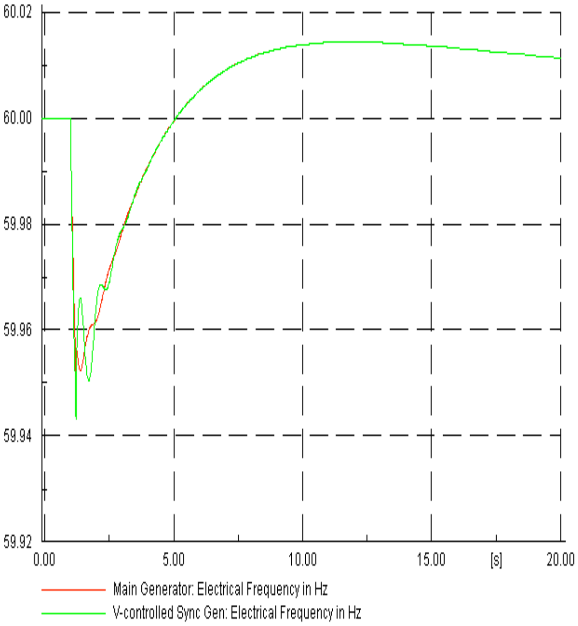

Figure 4.33 Generator frequencies for load increase study with microturbine DG

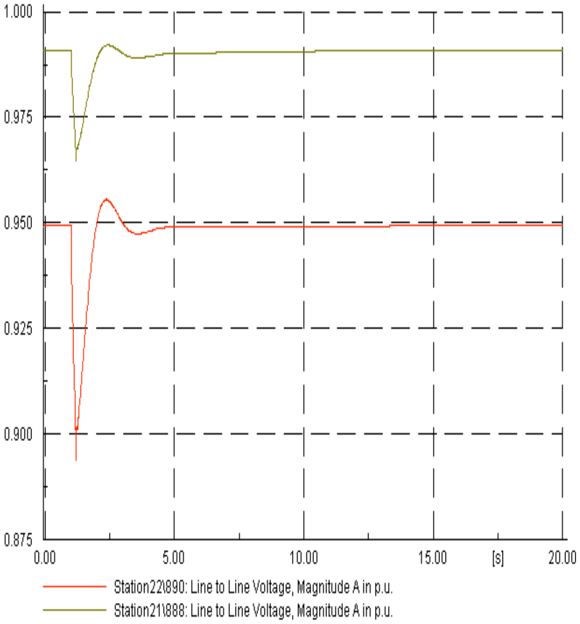

Figure 4.34 Bus voltages for load increase study with small wind turbine DG

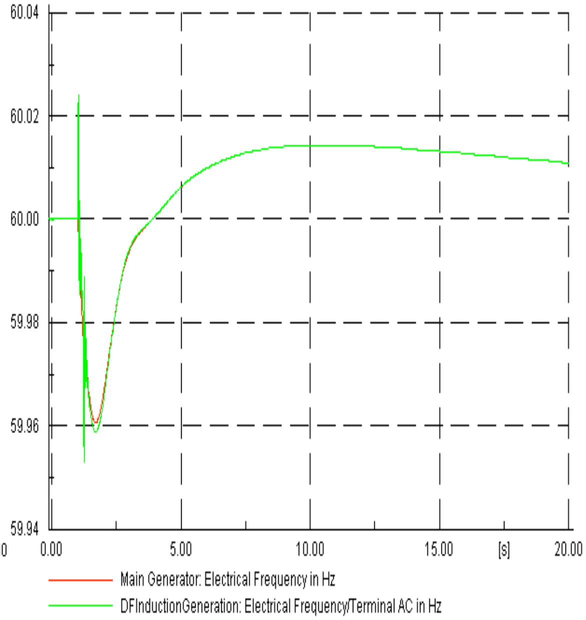

Figure 4.35 Generator frequencies for load increase study with small wind turbine DG

5. CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

This thesis has examined three types of DG: diesel generators, microturbines, and wind turbines. This thesis has also examined the technology behind these types of DG in a realistic system during steady-state and transient conditions to evaluate their strengths and weaknesses. The voltage profile and loss studies confirmed that a small level of DG can provide a significant improvement to the voltage profile of the system. The voltage profile and loss studies also demonstrated the importance of location and sizing, while demonstrating that increased DG power output does not necessarily correlate to an improved voltage profile. The voltage profile and loss studies indicated the wind turbine model was slightly more effective than the microturbine model.

The islanding studies performed demonstrated that the two most important factors in being able to support a load during an islanding condition are having the power output necessary to sustain the load and having the correct control settings. This was demonstrated by the 15% power diesel generator and microturbine models which were unable to maintain a 1.00 p.u. voltage or a constant frequency, due to being underpowered. The 25% power diesel generator and microturbine models demonstrated that, although each had a high enough MVA rating to sustain an island, neither was operating in the correct control setting to do so.

The transient studies indicated that each type of DG studied produced significant oscillations for system transients and each experienced significant frequency instability. The wind turbine had the highest frequency oscillations in both the single-phase fault study and load increase study and this may have been due to both transient events occurring at the bus that the DFIG model was connected to. The transient studies involving the diesel generator and microturbine models showed largely the same characteristics, although this is likely because both were modeled as a synchronous generator. The microturbine showed slightly better transient characteristics, although this may have been due to its reactive power support capacity.

The load shedding studies demonstrated the largest frequency variations, although this was likely due to the system event lasting roughly nine times as long as other system events studied. The removal of the load likely reduced the electrical torque observed by the generators and caused each DG type to temporarily speed up. The recloser operation may have then drastically increased the torque seen by each type of DG, especially the small wind turbine, which caused some overcompensation. It is likely that had such an event occurred on a real system, the DG would have been disconnected by a frequency or voltage relay.

This thesis has compared three different types of DG and found that each has its own advantages and disadvantages. The voltage profile and loss studies and several of the transient studies indicated the wind turbine has the most ideal characteristics for use in this system, but many other factors should be considered before using DG. Economics, reliability, relay coordination, and physical size were just a few of the factors not investigated in the simulations performed in this thesis that should be considered before any utility, independent power producer, or residential customer decides to put power back onto the distribution system.

5.2 FUTURE WORK

Future work should focus on creating a unified model using a larger distribution system model with models of anti-islanding protection, overcurrent protection, and other protective devices to study how these devices coordinate during faults and other transients. The distributed generation technology should be studied dynamically to determine which types are best suited to support an islanded section without losing synchronization. Further research should also be performed in synchronizing relay operations and methods of control for distributed generation to maintain synchronization during islanded conditions.

The most important work to be done in the field of distributed generation is in utilizing the technology and studying its benefits in real-world environments. Much has been studied in the field in terms of simulations, but there are very few case studies of the technology actually in use on distribution systems. Several possible technologies for distributed generation will require research to improve efficiency, durability, and reduce costs. The research into distributed generation is sure to expand over the coming years, as non-renewable fuel prices increase and because the use of distributed generation provides a variety of benefits that cannot be obtained from other sources.

APPENDIX A

DIgSILENT MODELS

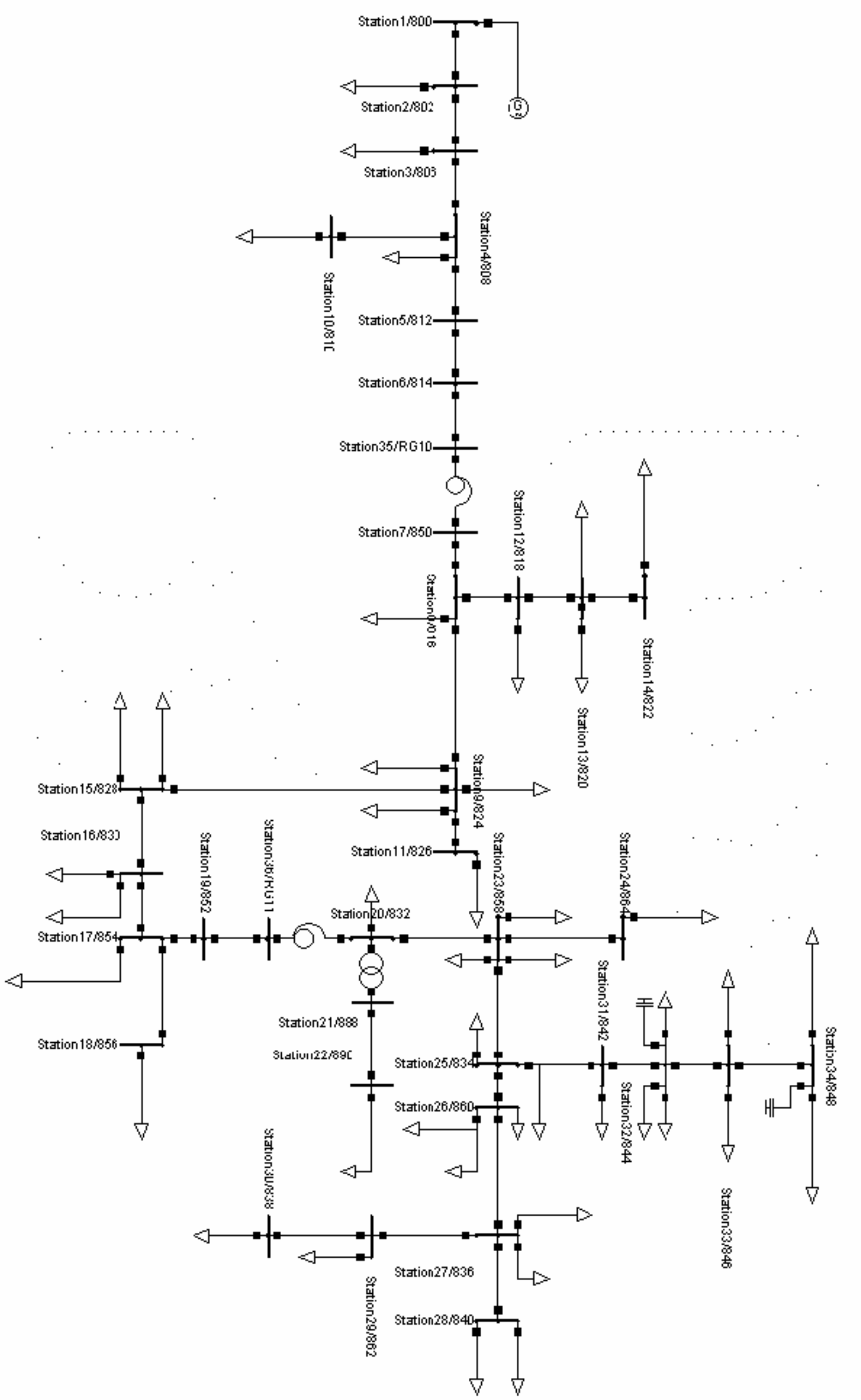

Figure A.1 DIgSILENT model of 34-bus system

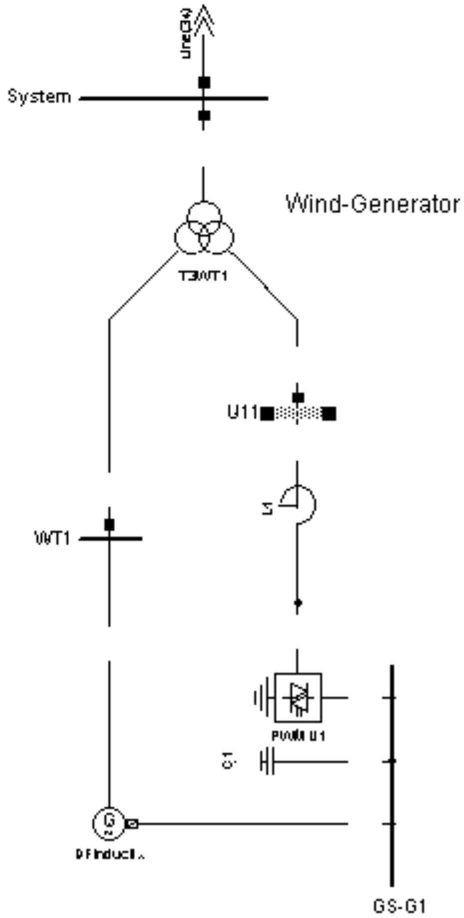

Figure A.2 DIgSILENT model of DFIG/wind turbine

APPENDIX B

DIgSILENT MODEL PARAMETERS

Table B.1 Line data

Line		Model	Distance (km)	Voltage (kV)	Frequency (Hz)
800	802	300	0.7862	24.9	60
802	806	300	0.5272	24.9	60
806	808	300	9.8216	24.9	60
808	810	303	1.7687	24.9	60
808	812	300	11.4276	24.9	60
812	814	300	9.0598	24.9	60
814	RG10	301	0.003	24.9	60
850	816	301	0.0945	24.9	60
816	818	302	0.5211	24.9	60
818	820	302	14.673	24.9	60
820	822	302	4.1871	24.9	60
816	824	301	3.1113	24.9	60
824	828	303	0.9233	24.9	60
824	826	301	0.256	24.9	60
828	830	301	6.2288	24.9	60
830	854	301	0.1585	24.9	60
854	856	303	7.1095	24.9	60
854	852	301	11.2234	24.9	60
852	RG11	301	0.003	24.9	60
888	890	300	3.218	4.16	60
832	858	301	1.4932	24.9	60
858	864	303	0.4937	24.9	60
858	834	303	1.7766	24.9	60
834	842	301	0.0853	24.9	60
842	844	301	0.4114	24.9	60
844	846	301	1.1092	24.9	60
846	848	301	0.1004	24.9	60
834	860	301	0.6156	24.9	60
860	836	301	0.8167	24.9	60
836	840	301	0.2621	24.9	60
836	862	301	0.0853	24.9	60
862	838	304	1.481	24.9	60
890	System	Short	0.0001	4.16	60

Table B.2 Line model parameters

Model	Type	Rated Current (kA)	Phases/ Neutral	R_0+jX_0 (Ω/km)	$R_{12}+jX_{12}$ (Ω/km)	B_0 (μS/km)	B_{12} (μS/km)
300	Overhead	1	3/1	1.0875 + j1.4741	.6961 + j0.5179	1.8702	3.8259
301	Overhead	1	3/1	1.4838 + j1.6024	1.0504 + j0.5228	3.6696	1.8227
302	Overhead	1	3/1	0.58 + j0.3077	0.58 + j0.3077	0.8753	0.8753
303	Overhead	1	3/1	0.58 + j0.3077	0.58 + j0.3077	0.8753	0.8753
304	Overhead	1	3/1	0.3981 + j0.2944	0.3981 + j0.2944	0.904	0.904
Short	Overhead	1	3/1	0.0001 + j0.0001	0.0001 + j0.0001	0.0001	0.0001

Table B.3 Load data

Location	Model	Phase a (MW + jMVAR)	Phase b (MW + jMVAR)	Phase c (MW + jMVAR)
802	2 PH-N	0.0225+j0.01125	0.01875+j0.0105	
806	3 PH-N	0.0225+j0.01126	0.01875+j0.0106	
808	1 PH-N	0.012+j0.006		
810	2 PH-N	0.012+j0.007		
816	1 PH-N	0.00375+j0.0015		
818	1 PH-N	0.0255+j0.0255		
820	1 PH-N	0.0255+j0.0256		
820	1 PH-N	0.10125+j0.0525		
822	1 PH-N	0.10125+j0.0525		
824	1 PH-N	0.003+j0.0015		
824	ABC-YN	0.01+j0.005	0.01+j0.005	0.01+j0.005
824	1 PH-N	0.00375+j0.0015		
826	1 PH-N	0.003+j0.0015		
828	ABC-YN	0.00175+j0.001	0.00175+j0.001	0.00175+j0.001
828	1 PH-N	0.003+j0.0015		
830	ABC-D	0.015+j0.0075	0.015+j0.0075	0.0375+j0.015
830	ABC-YN	0.00175+j0.001	0.00175+j0.001	0.00175+j0.001
854	1 PH-N	0.003+j0.0015		
856	1 PH-N	0.003+j0.0015		
832	ABC-D	0.00525+j0.00225	0.0015+j0.0015	0.009+j0.0045
858	ABC-D	0.00525+j0.00225	0.0015+j0.0015	0.009+j0.0045
858	ABC-D	0.003+j0.0015	0.01125+j0.006	0.00975+j0.00525
858	1 PH-N	0.0015+j0.00075		
864	1 PH-N	0.0015+j0.00075		
834	ABC-D	0.003+j0.003	0.01125+j0.006	0.00975+j0.00525
834	ABC-D	0.012+j0.006	0.015+j0.0075	0.0825+j0.04125
842	1 PH-N	0.00675+j0.00375		
844	2 PH-N	0.01875+j0.009	0.015+j0.00825	
844	1 PH-N	0.00675+j0.00375		
844	1 PH-N	0.00675+j0.00375		
846	1 PH-N	0.01725+j0.00825		
846	2 PH-N	0.01875+j0.009	0.015+j0.00825	
848	1 PH-N	0.01725+j0.00825		
848	ABC-D	0.03+j0.024	0.03+j0.024	0.03+j0.024
860	ABC-D	0.0225+j0.01125	0.0075+j0.0045	0.0315+j0.0165
860	ABC-D	0.012+j0.006	0.015+j0.0075	0.0825+j0.04125
860	ABC-YN	0.03+j0.024	0.03+j0.024	0.03+j0.024
836	2 PH-N	0.0135+j0.00675	0.0165+j0.00825	
836	ABC-D	0.0225+j0.01125	0.0075+j0.0045	0.0315+j0.0165

Table B.3 Load data (cont.)

Location	Model	Phase a (MW + jMVAR)	Phase b (MW + jMVAR)	Phase c (MW + jMVAR)
840	2 PH-N	0.0135+j0.00675	0.0165+j0.00825	
840	ABC-YN	0.0135+j0.0105	0.0135+j0.0105	0.0135+j0.0105
862	1 PH-N	0.021+j0.0105		
838	1 PH-N	0.021+j0.0105		
890	ABC-D	0.225+j0.1125	0.225+j0.1125	0.225+j0.1125

Table B.4 Capacitor data

Location	Technology	Power (MVAR)	Nominal Voltage (kV)
844	ABC-Y (AC)	0.3	24.9
848	ABC-Y (AC)	0.45	24.9
GS-G1	DC	2	1.15

Table B.5 Voltage regulator 1 data

Regulator 1 (RG10-850)	
Rated Power:	5 MVA
Nominal Frequency:	60 Hz
HV-Side:	24.9 kV Y-N (850)
LV-Side:	24.9 kV Y-N (RG10)
Short Circuit Voltage uk:	3%
X/R:	0.5926001
Phase Shift	0
Tap Changer:	HV
Voltage per Tap	0.625%
Neutral Position:	0
Minimum Position	-16
Maximum Position	16
No Load Current	0%
No Load Losses	0 kW
Mag. Reac. / uk0	100
Tap Changer:	Discrete
Controlled Node:	HV
Phase:	Pos. Seq.
Control Mode:	V
Voltage Setpoint	1.00 p.u.
Lower Voltage Bound	0.97 p.u.
Upper Voltage Bound	1.02 p.u.
LDC:	Internal
CT Ratio:	100 A
VT Ratio:	120
Rset:	2.7 V
Xset:	1.6 V

Table B.6 Voltage regulator 2 data

Regulator 2 (RG11-832)	
Rated Power:	5 MVA
Nominal Frequency:	60 Hz
HV-Side:	24.9 kV Y-N (832)
LV-Side:	24.9 kV Y-N (RG11)
Short Circuit Voltage uk:	3%
X/R:	0.6000007
Phase Shift	0
Tap Changer:	HV
Voltage per Tap	0.625%
Neutral Position:	0
Minimum Position	-16
Maximum Position	16
No Load Current	0%
No Load Losses	0 kW
Mag. Reac. / uk0	100
Tap Changer:	Discrete
Controlled Node:	HV
Phase:	Pos. Seq.
Control Mode:	V
Voltage Setpoint	1.00 p.u.
Lower Voltage Bound	0.97
Upper Voltage Bound	1.04
LDC:	Internal
CT Ratio:	120 A
VT Ratio:	100
Rset:	2.5 V
Xset:	1.5 V

Table B.7 Transformer 1 data

Transformer 1 (832-888)	
Rated Power:	5 MVA
Nominal Frequency:	60 Hz
HV-Side:	24.9 kV Y-N
LV-Side:	4.16 kV Y-N
Short Circuit Voltage uk:	3%
X/R:	2.1474
HV Side Star Point:	Grounded
HV Grd. Z (Re + jXe):	(0+j0) Ω
LV Side Star Point:	Grounded
LV Grd. Z (Re + jXe):	(0+j0) Ω

Table B.8 Three-winding transformer data

DFIG 3-Winding Transformer			
HV-Side Power:	5.6 MVA	MV-Side Star Point:	Grounded
MV-Side Power:	5 MVA	MV Grd. Z (Re + jXe):	(0+j0) Ω
LV-Side Power:	0.6 MVA	LV Side Star Point:	Grounded
HV-Side Voltage:	4.16 kV	LV Grd. Z (Re + jXe):	(0+j0) Ω
MV-Side Voltage:	3.3 kV	Phase Shift:	0
LV-Side Voltage:	0.69 kV	Phase Shift:	150°
HV-Side Connection:	D (System)	Phase Shift:	150°
MV-Side Connection:	YN (WT1)		
LV-Side Connection:	YN (U11)		
Pos. Sequence Short Circuit Voltage		Copper Losses	
HV-MV:	5.3571430%	HV-MV:	13.1537 kW
MV-LV:	0.4285715%	MV-LV:	0.1894133 kW
LV-HV:	0.4285715%	LV-HV:	0.06887756 kW
Zero Sequence Short Circuit Voltage		Magnetizing Reactance	
HV-MV:	2.6785710%	Position:	Star Point
MV-LV:	0.3214286%	No Load Current:	0.70%
LV-HV:	0.3214286%	No Load Losses:	3.9 kW

Table B.9 Main generator data

Main Generator-Reference Machine (800)			
Nominal Apparent Power:	5 MVA	Synchronous Reactance	
Nominal Voltage:	24.9 kV	xd:	2 p.u.
Power Factor:	1	xq:	2 p.u.
Connection:	YN	Zero Sequence Data	
Voltage-Controlled		Reactance x0:	0.1 p.u.
Active Power Dispatch:	2.5 MW	Resistance r0:	0 p.u.
Reactive Power Dispatch:	1 MVAR	Negative Sequence Data	
Voltage:	1.05 p.u.	Reactance x2:	0.2 p.u.
Angle:	0	Resistance r2:	0 p.u.
Prim. Frequency Bias:	0 MW/Hz	Subtransient Reactance	
Reactive Power Limits		saturated value xd'' sat:	0.2 p.u.
Minimum:	-5 MVAR	Stator Resistance	
Maximum:	5 MVAR	rstr:	0 p.u.
Active Power Limits		Reciprocal of short-circuit ratio:	1.2 p.u.
Minimum:	0 MW	Salient Pole Series 1	
Maximum:	5 MW	xd':	0.3 p.u.
Ground Impedance			
Star Point:	Grounded		
Rearth+jXearth:	(0+j0) Ω		

Table B.10 Diesel generator synchronous generator data

Distributed Generator-Diesel (890)			
Nominal Apparent Power:	5 MVA	Synchronous Reactance	
Nominal Voltage:	4.16 kV	xd:	2 p.u.
Power Factor:	1	xq:	2 p.u.
Connection:	YN	Zero Sequence Data	
Power Factor Controlled		Reactance x0:	0.1 p.u.
Active Power Dispatch:	.6230 MW	Resistance r0:	0 p.u.
Reactive Power Dispatch:	0 MVAR	Negative Sequence Data	
Voltage:	1.0 p.u.	Reactance x2:	0.2 p.u.
Angle:	0	Resistance r2:	0 p.u.
Prim. Frequency Bias:	0 MW/Hz	Subtransient Reactance	
Reactive Power Limits		saturated value xd'' sat:	0.2 p.u.
Minimum:	0 MVAR	Stator Resistance	
Maximum:	0 MVAR	rstr:	0 p.u.
Active Power Limits		Reciprocal of short-circuit ratio:	1.2 p.u.
Minimum:	0 MW	Salient Pole Series 1	
Maximum:	.6230 MW	xd':	0.3 p.u.

Table B.11 Microturbine generator synchronous generator data

Distributed Generator-Microturbine (890)			
Nominal Apparent Power:	5 MVA	Synchronous Reactance	
Nominal Voltage:	4.16 kV	xd:	2 p.u.
Power Factor:	1	xq:	2 p.u.
Connection:	YN	Zero Sequence Data	
Voltage Controlled		Reactance x0:	0.1 p.u.
Active Power Dispatch:	.5736 MW	Resistance r0:	0 p.u.
Reactive Power Dispatch:	.243 MVAR	Negative Sequence Data	
Voltage:	1.02 p.u.	Reactance x2:	0.2 p.u.
Angle:	0	Resistance r2:	0 p.u.
Prim. Frequency Bias:	0 MW/Hz	Subtransient Reactance	
Reactive Power Limits		saturated value xd" sat:	0.2 p.u.
Minimum:	0 MVAR	Stator Resistance	
Maximum:	.243 MVAR	rstr:	0 p.u.
Active Power Limits		Reciprocal of short-circuit ratio:	1.2 p.u.
Minimum:	0 MW	Salient Pole Series 1	
Maximum:	.5736 MW	xd':	0.3 p.u.

Table B.12 Small wind turbine DFIG data

Distributed Generation-Small Wind Turbine (890)	
Use Integrated PWM Converter	
Active Power:	0.5736 MW
Reactive Power:	0.243 MVAR
Slip:	8%
Rated Slip Ring Voltage:	1939 V
Rated Voltage:	3.3 kV
Rated Mechanical Power:	5000 kW
Nominal Frequency:	60 Hz
Pole Pairs:	2
Connection:	Y
Single Cage Rotor	
Stator Resistance Rs:	0.00298989 p.u.
Mag. Reactance Xm:	2.5 p.u.
Stator Reactance Xs:	0.125 p.u.
Rotor Resistance RrA:	0.004 p.u.
Rotor Reactance XrA:	0.05 p.u.
Locked Rotor Current:	7 p.u.
R/X Locked Rotor:	0.4288744
Inertia:	101.7156 kgm^2

Table B.13 and Table B.14 PWM converter and series reactor data

PWM Converter (U12-GS-G1)	
AC-Voltage:	0.7042283 kV
Rated Power	2 MVA
No-Load Losses:	0 kW
Short Circuit Impedance	0%
Copper Losses	0 kW
Sinusoidal PWM Modulation	
Control Mode:	Vdc-Q
DC Voltage Setpoint:	1.15 p.u.
Controlled Node (DC):	GS-G1
Reactive Power Setpoint	-0.3 MVAR
Controlled Flow:	WT1H-G
Model:	Const. V

Series Reactor (U11-U12)	
Rated Voltage:	0.69 kV
Rated Power:	2 MVA
System Type:	AC
Phases:	3
Short-circuit Voltage uk:	31.80%
Copper Losses:	20.99996 kW

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