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# Relay Protection For Small Wind-Driven Turbine-Generators With Interconnections To A Utility Power System.

Kenneth W. Schuette

# Relay Protection For Small Wind-Driven Turbine-Generators With Interconnections To A Utility Power System

By

Kenneth W. Schuette

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Professor in Charge

Chairman of Department

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## Abstract

An increased search for alternative energy sources has stimulated a new research effort directed at the installation of wind-driven turbine-generators. To date, most of the existing wind turbine-generators have been installed to serve isolated loads not supplied from public utility networks; however, the wind turbine's capacity for cheap, non-polluting power is prompting trial interconnections with utility systems by farsighted customers.

This addition of wind turbines has the potential to degrade the power system reliability and pose threats to the public safety if the protective relay systems of both the wind turbine-generators and the utility systems are not designed and coordinated to insure that reliability and safety are not sacrificed.

This paper examines the design philosophy and the equipment necessary to adequately protect small wind-driven turbine-generators installed by an individual homeowner or a small business, and interconnections to a utility power system.

Development of adequate protection packages requires close examination of the physical and electrical characteristics of the equipment, and an understanding of the operating procedures of both the generator and the utility. Standard relays can be combined in schemes to provide adequate protection for these systems.

Recommended protection schemes for the small wind turbine generators consist of overvoltage-undervoltage protection, overheating protection, overspeed protection, vibration protection, d.c. bus and battery protection, rectifier fuses and inverter fuses. Operation of the relay schemes requires a circuit breaker at the generator output terminals. Protection for the utility facilities and the interconnection requires a set of three fuses mounted at the step-up transformer high voltage terminals.

Recommended protection schemes for the large wind turbine generators consist of voltage-controlled overcurrent protection, overcurrent ground fault protection, overheating protection, overspeed protection, vibration protection, generator motoring protection, generator differential protection (optional) and negative sequence protection (optional). Operation of these relay schemes requires a circuit breaker at the generator output terminals. Protection for the utility facilities and the interconnection requires a circuit breaker with directional overcurrent phase and non-directional overcurrent ground relays, plus overvoltage-undervoltage protection.

The installed cost of these recommended schemes represents a small fraction of the total value of the wind turbine generator system; only one operation of the protection schemes could justify the additional cost.

Concerns about generator lightning protection and auxiliary circuit protection are not covered in this thesis, but are suggested as topics for future research.

Chapter I

## Introduction

Presently, much of the nation's attention is focused on the intensive research aimed at establishing alternate energy sources, such as wind energy. Recent application of small wind turbine generators by government agencies has prompted private individuals to install machines and interconnect them with the electric utilities' supply lines. These interconnections must be properly relayed in order to provide protection and control of both the wind turbine generator, and the utility distribution system.

The requirements for additional energy sources can be appreciated by considering the magnitude of the national energy demands - approximately 2.5 trillion kilowatt-hours per year.[6] Although a combination of public conservation and energy-management techniques have helped to reduce the yearly increase in energy consumption - only 1.8 percent increase in 1978, down from 2.5 percent in 1977 and 5.3 percent in 1976,[4] annual United States energy demands in the year 2000 could easily reach 3.8 trillion kilowatt-hours (assuming 1.8 percent growth) or 4.5 trillion kilowatt-hours (assuming 2.5 percent growth). Current sources of U.S. energy include:

Oil - approximately 40% of the total

Natural gas - approximately 33% of the total

Coal - approximately 20% of the total

Hydropower - approximately 4% of the total

Nuclear - approximately 2% of the total[6]

The remaining one percent is supplied by synthetic fuels, oil shale, geothermal energy, solar energy and wind energy. The last three items of this list are all renewable energy resources, which will not be depleted by increasing use.

Historically, most wind turbine generators have been relatively small units, ranging up to 10 kilowatts in capacity. These machines were used mainly for isolated loads, where the cost of supplying power through transmission lines would have been prohibitive. Much larger machines are required for economical generation and integration with modern power systems. An understanding of the economics of increasing scale can be appreciated by considering the amount of power which can be extracted from a moving volume of air which is expressed by equation 1-1 below:

$$P = 0.2325\ D^2\ \rho\ V^3\ P_c \qquad (1\text{-}1)$$

where:

$P$ = actual usable power from air stream

$D$ = blade diameter in feet

$\rho$ = mass density of air

$V$ = velocity of air in feet per second

$P_c$ = power coefficient, the actual power removed from the air compared to the total usable power available.[21]

Note that the power extracted from the air stream increases as the square of the rotor diameter, and as the cube of the wind speed. This is the reason designers are trying to take advantage of the largest technically feasible rotor diameter and the highest wind speed normally available.

How much of a contribution wind power can make to overall energy requirements is subject to many factors, such as:

1. Rate at which energy extracted from the winds at the earth's surface can be replenished by winds from higher levels.

2. Limitations on available land which can be devoted to wind generation.

3. Economical and technical constraints on the equipment stresses, size, rated capabity and capacity factors.

Accounting for all of the above factors, it is estimated that a maximum of 1 to 2 trillion kilowatt-hours per year could be extracted from winds over the U.S., excluding offshore regions,[23] or 25 to 50% of our minimum year 2000 needs.

Several government-sponsored wind turbine generator programs are currently under way to provide the necessary research to develop large and small units. Current government wind turbine generator projects are designated:

- MOD 0 - 125 foot rotor diameter, 100 KW output
- MOD OA - 125 foot rotor diameter, 200 KW output
- MOD 1 - 200 foot rotor diameter, 1.5 - 2.0 MW output
- MOD 2 - 300 foot rotor diameter, 2.5 - 3.0 MW output

The Department of Energy is also sponsoring programs to evaluate and commercialize improved machines in the one, eight and forty kilowatt sizes. Federal budgets for wind energy research has increased to match the interest in this technology from $0.2 million in 1973 to a proposed $40 million in 1979.[5]

Such increased interest in both small and large capacity wind turbine generators requires that utility companies make provisions to integrate them into the power transmission system. In the future, more private wind turbine generators will be installed, but most will require backup capacity from the local utilities. As the economics of wind generation become more favorable, the utilities may find it advantageous to install wind turbines for their own generation. In either case, the generators must be properly interfaced with the utility distribution or sub-transmission system.

Properly designed and coordinated protective relays must promptly isolate any element of an electrical system when it suffers a fault or operates in an abnormal manner which could damage or interfer with normal operations. A secondary function of the relays is to provide indication of the location and type of failure when one occurs.[15] Large central station power plants are extensively protected and monitored; the investment is justified by the value of the plant and the energy which is produced. A wind turbine generator has less investment at stake and a smaller generating capability, but it is necessary to evaluate the cost and degree of protection afforded by a particular protection system with the risk encountered if no or minimal protection would be provided for a particular hazard.[2]

This paper will discuss the protection that is required for a wind turbine generator installed and interconnected with a utility distribution network. (The test utility used in the discussion of system facilities and operating procedures is Pennsylvania Power and Light Company, of Allentown, Pennsylvania.)

## Chapter II

## Description of Major Electrical Equipment Components and System Characteristics

When designing the protection for wind turbine generators, it is necessary to consider the electrical characteristics of the generator system and the utility system to which it is connected. In this paper, two generator systems will be examined, a small wind turbine generator producing only enough power for a single family house or a small business, and a larger generator which would be sized to cover the power requirements of a small industrial customer. Each of the wind turbine generators will be of a different type, in order to evaluate the two most common systems installed to date. Both will be assumed to be driven by a horizontal-axis rotor.

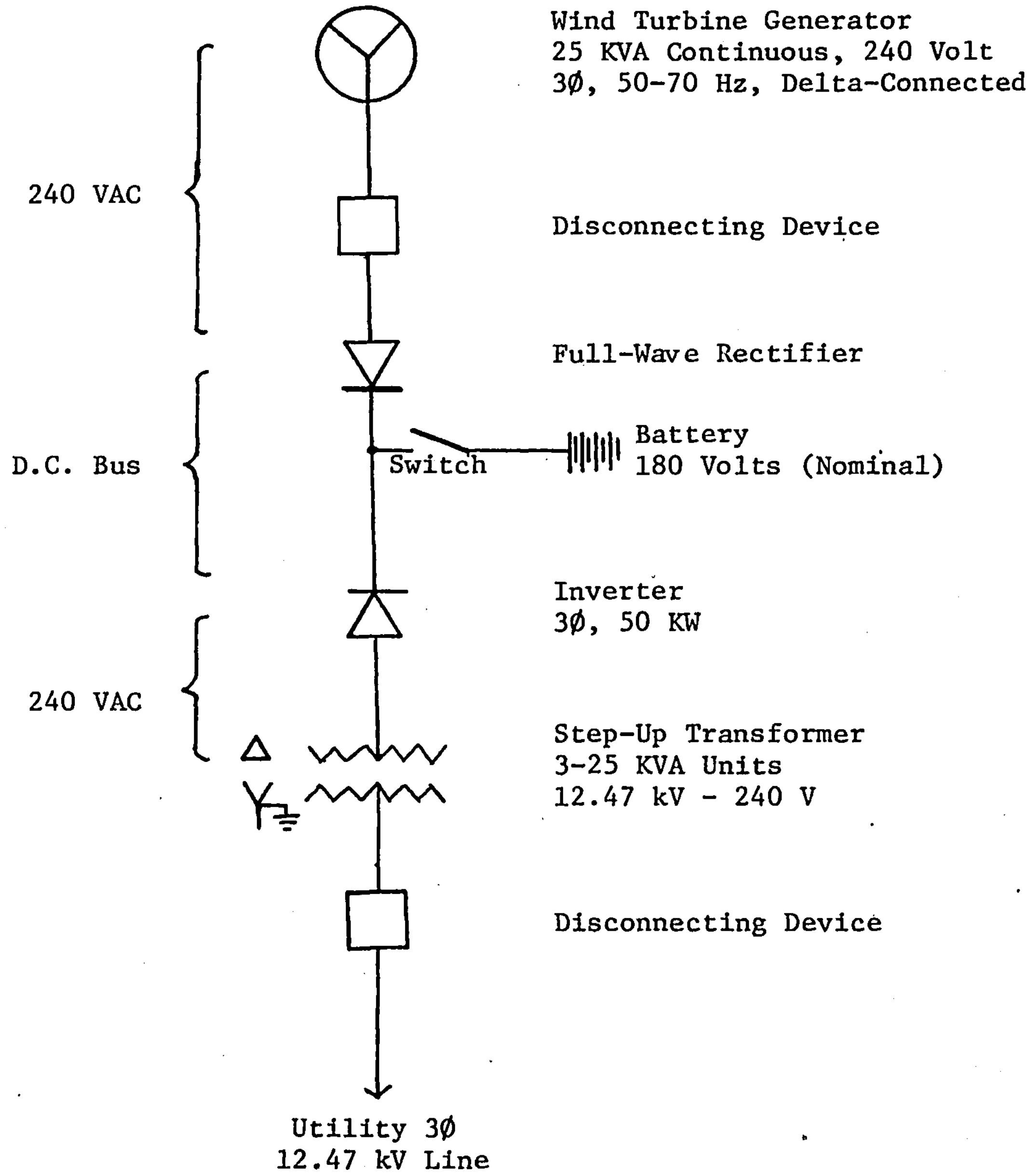
The smaller of the two systems is sized for private residential use and generates 25 KVA continuously, with about 45 KVA peak capability (similar generators with 250 KVA capacity have been installed). The rotor drives a variable frequency, variable voltage, three phase alternator; the output varies with the input. The power output of the generator is rectified to direct current, which is then supplied to a synchronous inverter. Utility line voltage is used to fire the inverter, which applies a pulse of current to the utility system each cycle.

Larger wind turbine generators, which are designed in the range of 100 to 2000 KVA, are suitable for utility commercial or industrial customers, or for installation by the utility. These systems employ synchronous generators to produce power at a fixed frequency (generally 60 Hz) and at a fixed voltage. Since the wind speed varies, the rotor blades have an adjustable pitch mechanism to allow the rotor to turn at a constant rate of rotation over a range of wind speed. No other power conditioning devices are required between the generator and the utility system.

Each system is discussed in detail below.

## Small Wind Turbine Generator

The major electrical components of this system are: the generator, rectifier, direct current (d.c.) bus, synchronous inverter, step-up transformer and disconnecting devices. Such a system is shown in Figure 1, page 12 and is based on a system recently installed by the test utility.




Small Wind Turbine Generator System

Figure 1

The generators used in these systems are fairly simple machines. The one considered in this case is a three phase generator. It has a variable frequency and variable ouput voltage, which depends on the type of prime mover. The generator has four poles, and a revolving armature. It also has static excitation and regulation systems. The power factor of the alternator is 0.8. In this case, the machine is a general purpose alternator designed for low maintenance and high reliability.

The rectifier is a three phase, full wave bridge which converts the sinusoidal three phase voltage produced by the generator into d.c. voltage. Voltage output of the rectifier consists of six pulses of the same polarity with the magnitude depending on the wind speed. A set of batteries may be connected to the d.c. bus to smooth the voltage ripple effect.

Synchronizing or matching the wind turbine generator voltage with the utility system is performed by a synchronous inverter interposed between the d.c. bus and the low voltage side of the step-up transformer. Six semiconductor controlled rectifiers (SCR's) are used in a three phase bridge arrangement to transfer short bursts of power into the a.c. lines on both positive and negative half-cycles. Control of the power inversion is accomplished by sensing a.c. line voltage, d.c. bus voltage and direct current and by using regulators to adjust the switching action of the SCR's. The SCR's act as a reversing switch to change the relative polarities of the a.c. voltage as seen by the d.c. source. Each half cycle will appear as the same polarity to the d.c. source, since the a.c. line polarities are reversed. Power can only be delivered to the a.c. circuit for the portion of the cycle where both the d.c. voltage and current are greater than zero, a very small portion of the cycle. When the instantaneous a.c. voltage exceeds the d.c. voltage level, the control circuit directs the SCR's to disconnect the two devices. When no power is flowing from the d.c. sources, the utility a.c. lines provide power to any connected load.

The switching action of the inverter SCR's is synchronized to the a.c. line, so there is no tendency to upset frequency. Voltage harmonics are produced by the inverter, but distortion of the waveform is limited to switching transients and it has not been considered detrimental. A reactor is used between the d.c. source and the inverter to limit the current flow during periods of SCR conduction. Maximum inverter current occurs when the system voltage crosses zero, the time when the line voltage is not subtracting from the d.c. source voltage. Therefore, voltage and current are largely out of phase, causing a relatively large reactive power flow into the inverter.

To prevent backfeeding into the utility lines from the wind turbine generator system when the utility lines are deenergized, safety features are typically designed into this type of synchronous inverter. First, the inverters are designed with disconnecting contactors on both the a.c. and d.c. sides; the contactors are energized from the a.c. line so that the inverter is completely deenergized on both sides in the event of a deenergized utility line. Simultaneous failure of both sets of contactors would be required to allow power to flow into the a.c. line. Secondly, fusing on both sides of the inverter protects against overload of the a.c. connections to the step-up transformer, the inverter and the d.c. supply.

Batteries are practical energy storage devices which are fairly simple to add on this type of a wind turbine generator system since a d.c. link is available. The bank of batteries is connected to the d.c. bus between the rectifier and the inverter. Output of the storage battery can be supplied to the synchronous inverter as desired to supply energy to the a.c. line. With the battery connected to the d.c. bus, it helps to regulate the d.c. voltage supplied to the synchronous inverter, smoothing out some of the voltage fluctuations due to the varying wind velocities. The battery also levels the load supplied by the wind turbine generator, accepting excess power from the generator when available and providing power when the load increases suddenly; the a.c. line also has this power smoothing capacity.

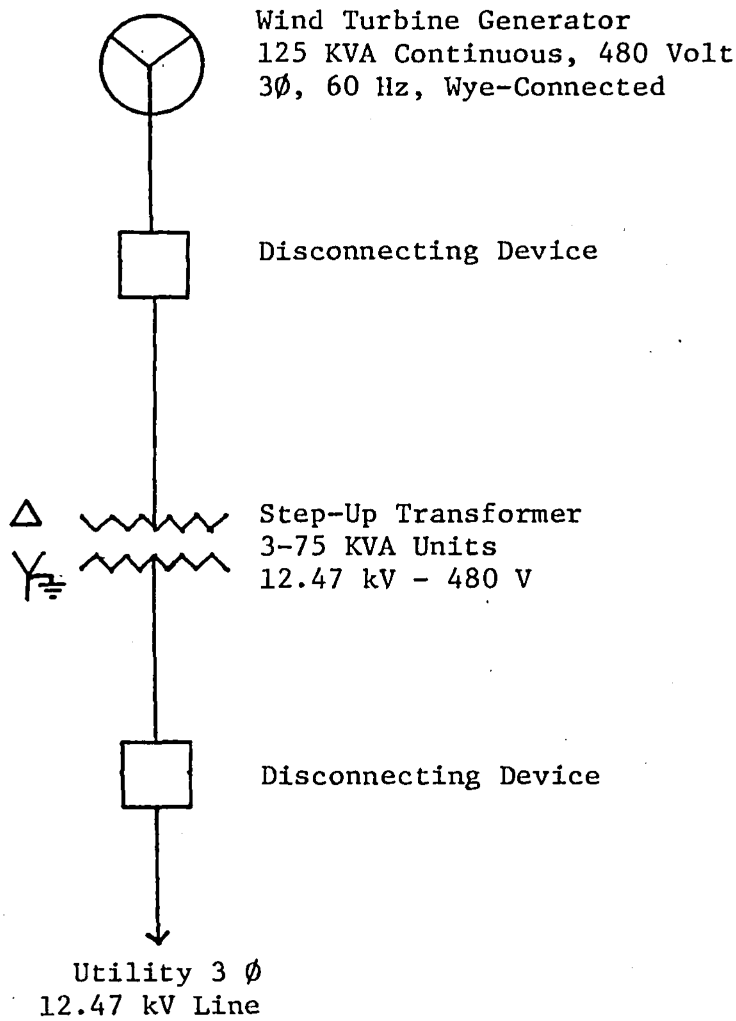
Step-up transformers and disconnecting devices, which will be similar for both small and large wind turbine generators, will be discussed later.

Large Wind Turbine Generators

Whereas the small wind turbine generator discussed previously was a variable-frequency, variable-voltage alternator, the typical larger machines are synchronous generators which produce a power output at 60 Hz compatible with the utility system. Synchronous generators producing power at the utility frequency are usually chosen at higher machine ratings since this type of machine has much better stability under variable or gusting wind conditions, and can supply reactive power to the lines if necessary. Major components of the large wind turbine generators are the variable pitch hub, generator step-up transformer and disconnecting devices. Such a system is shown in Figure 2, page 18.

In order to provide a constant frequency power output, the synchronous generator requires a fairly constant speed prime mover. This is accomplished by a hub with variable pitch controls for the blades. By variation of the blade pitch, excess wind energy can be spilled and the torque transmitted to the generator can be varied to compensate for varying wind intensities.

These generators are usually commercially available synchronous machines with four poles and designed to operate at 1800 rpm. The unit under consideration here is rated 125 KVA, 60 Hz, has a power factor of 0.8 and three phase output voltage of 480 volts a.c. (measured phase-to-phase). The generator winding is connected in a grounded wye configuration. A shaft mounted, brushless exciter controlled by a solid state regulator and power stabilizer will provide voltage control. The regulator supplied with the generator is capable of maintaining the output voltage within plus or minus two percent of the rated value from no load to full load at 0.8 power factor.[10]




Large Wind Turbine Generator System

Figure 2

A synchronizer is required for the large wind turbine generator employing a synchronous machine to match the wind power with that produced by the utility. There are several types on the market, but perhaps the simplest is a solid state automatic synchronizer, plus a synchronizing relay. This synchronizing scheme must be used with a fairly fast closing breaker (eight cycles or less on a 60 Hz base). The synchronizer senses the generator and utility voltages beating against each other. When the generator and utility voltages are matched, the difference in the two voltages will be zero, and the breaker will be closed to connect the two systems. A bandwidth of both voltage and frequency is allowable, since the synchronous generator will "lock into" the utility frequency.

Since the large wind turbine generator supplies 60 Hz power directly to the distribution system, it does not need a storage system. The a.c. distribution lines serve as storage, accepting excess power from the wind turbine generator when available, but supplying additional a.c. power from the utility to the local load when power is insufficient or unavailable from the wind.

Interconnection Equipment

Interconnection of a wind turbine generator with a utility system is normally done at the distribution voltage level, not at transmission or even subtransmission voltages. The systems under consideration here, and even the largest wind turbine generators currently designed by the Department of Energy/NASA are of much less capacity than the normal load carrying capability of a typical 12.47 kV distribution line. At this voltage level, the maximum fault levels are low enough to greatly reduce the cost of step-up transformers and disconnect devices such as circuit breakers, automatic reclosers, fuses, motor operated disconnects, etc. Interconnection at transmission level voltages would require:

a. A higher class of insulation on all interconnection equipment,

b. Greater interrupting capability of the disconnecting devices, due to the greater available fault current, and

c. A greater degree of sophistication to interface with the relays and protection schemes used at higher voltage levels.

For example, a power circuit breaker rated at 66 kV and 27,000 amperes interrupting capability would cost approximately $27,000 installed. In comparison, a breaker rated at 12.47 kV and 20,000 amperes interrupting capability would have an installed cost of approximately $11,900, less than half the cost of the larger breaker. These costs do not include any of the control or protection costs which would be required.

Both large and small wind turbine generator systems will require step-up transformers to raise the voltage of the output power to match that of the utility. These transformers may consist of a single three phase unit or three single phase units, typically connected wye on the distribution line side and delta on the generator side. No zero sequence fault current contribution from the generator is allowed for single phase to ground faults on the 12.47 kV system since the delta connection on the transformer effectively blocks zero sequence current. The transformer is typically an oil-insulated, self-cooled distribution unit, sized to match the capacity of the wind turbine generator output. In the examples shown in Figures 1 and 2, pages 12 and 18, the transformers are 240 - 12470 volt and 480-12470 volt respectively, measuring line-to-line voltages.

Disconnecting devices must be provided to isolate the wind turbine generator from the utility system. The devices considered here offer manual and automatic disconnecting capability (automatic disconnecting may require additional relays and equipment):

1. Power circuit breakers
2. Automatic circuit reclosers
3. Fused disconnects.

Power circuit breakers are the most expensive but the most versatile disconnecting devices to be considered. Circuit breakers are three pole, single throw switches with varying load and fault current interrupting capability. Arc extinguishing takes place in a special medium such as air, gas, oil or vacuum; the breakers are generally classified according to the interrupting medium. Protective relays are required to sense line quantities (through current and potential transformers) and provide a tripping signal to the breaker operating mechanism. A reclosing relay may be provided to automatically reclose the breaker to test the equipment after a fault. In addition to automatic operation, local manual and remote supervisory control may also be provided for the breaker. An external a.c. and/or d.c. power supply is required for the breaker operation, and a d.c. power supply is required for the protective relay circuits.

Automatic circuit reclosers are three phase disconnecting devices which have self-contained overcurrent units to sense equipment failures and open the recloser. After the fault is cleared, the recloser can automatically reclose to test the equipment, according to a preprogrammed operating sequence. While automatic operation is available as described, manual control is not possible. All relays, instrument transformers and operating units are contained within the circuit recloser; operating power is taken from the distribution line. Circuit reclosers have less interrupting capacity than the circuit breakers; the largest recloser used by the test utility is rated to interrupt 10,000 amperes, (RMS) symmetrical.

Fused disconnects provide the cheapest means of disconnecting the wind turbine generator from the distribution line. Automatic clearing of faults is accomplished by using the fault current to heat and melt the fuse; but reclosing can only be accomplished by manually replacing the fuse link; local manual opening and closing of the disconnect is possible, but no remote supervisory control is available. No external devices or power supplies are required. Limitations on the use of fuses in multiphase circuits is caused by clearing only the faulted phase; the unopened phases remain energized, which could cause damage to the protected equipment.

The utility system to which the wind turbine generator is connected, consists of a network of transmission and distribution lines. Using the test utility system as a typical model, the wind turbine generators will be connected to the distribution system which operates at 12,470 volts, measured line-to-line, three phase.

The 12.47 kV system is supplied by small power transformers, rated from 10 to 34 MVA, tapped off the 66 or 138 kV lines. These transformers are located in substations, and may be used singly or in pairs, to supply power to 12.47 kV buses. Distribution lines are then tapped off the 12.47 kV bus through power circuit breakers. Most of the lines are operated radially, that is, they have only one source of supply, with no closed ties to other 12.47 kV sources. This operating mode simplifies protection of these lines considerably, since power will flow in only one direction on the line, from the source to the load. Automatic circuit reclosers and tap fuses are used to sectionalize the line for faults either on the line or on customer equipment; ideally a minimum amount of the line will be taken out of service, depending on the fault location and type.

The 12.47 kV system has a multi-grounded neutral. The neutral is maintained as close to ground potential as possible by the following means:

1. One grounded neutral conductor is established for each line.

2. The 66-12.47 kV or 138-12.47 kV transformers are operated with a delta connection on the high voltage side and a directly grounded neutral wye connection on the low voltage side.

3. All 12.47 kV - 240 volt transformers are also operated with a grounded neutral wye connection.

4. The grounded neutral conductor is used for all additional facilities that require grounding, such as lightning arrestors, breaker tanks, reclosers, etc.

# Chapter III

## Fault Characteristics

In order to determine the type of protection required for wind turbine generators and the utility interconnection, it is necessary to have values of the expected fault currents which could occur on the system. While calculations for all types of faults at numerous locations on the system would be needed to coordinate and set the relays, fewer calculations are needed to enable one to design the general protection schemes.

This chapter is devoted to the fault studies which are necessary for both of the selected configurations - the small (25 KVA) and the large (125 KVA) wind turbine generators. The objective is to determine the maximum interrupting duty for three-phase and single-phase short circuits located at critical points in the networks. Fault current contributions from each source will be required: the wind turbine generator and the utility 12 kV system.

Standard fault study procedures were followed, which involved these calculations:

1. Determine the backup impedances (for the 66 kV system).

2. Determine the impedances of the wind turbine generators.

3. Develop schematic equivalent diagrams of the interconnections and assign all circuit values.

4. Calculate current magnitudes for faults at selected points in the systems.

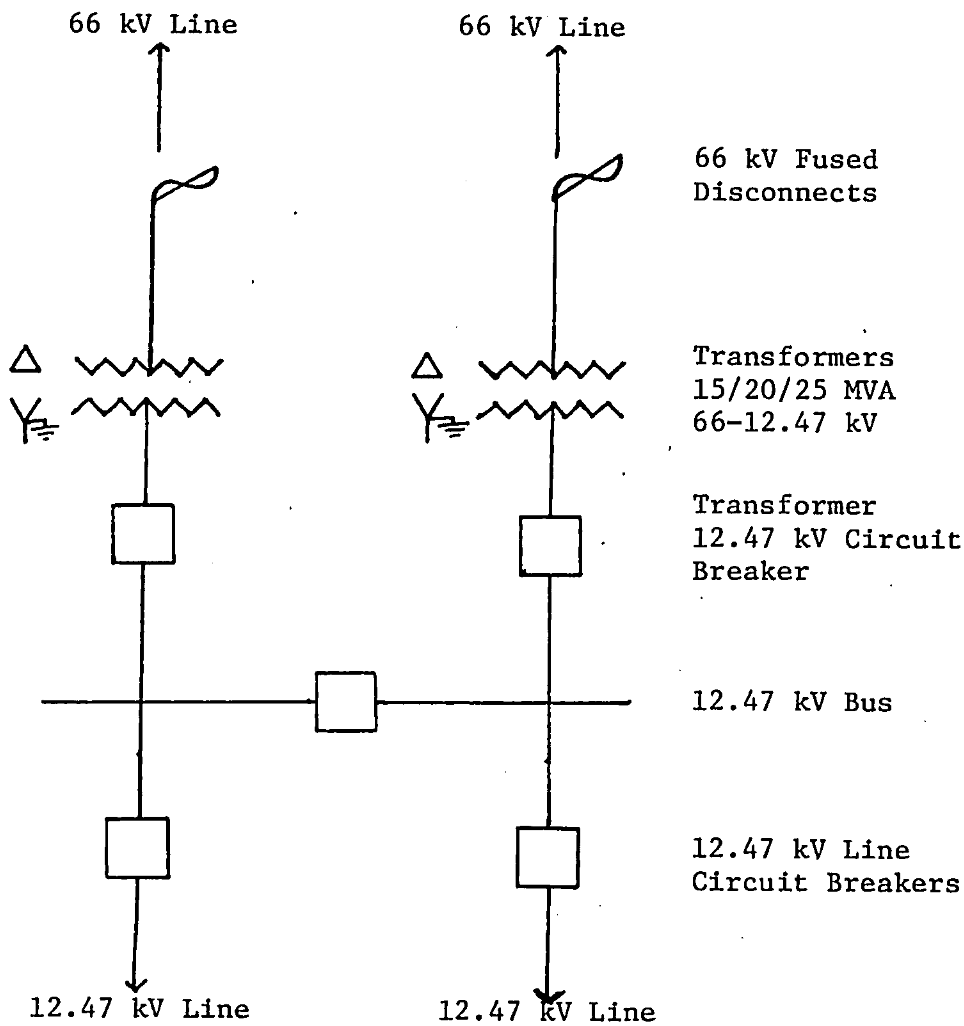
The first step is to examine the maximum fault contribution from the utility system. Typical values of line and transformer impedances will be assumed, in order to calculate the equivalent impedance of the system supplying the 12.47 kV bus. All equipment impedance values will be based on those of the test utility's subtransmission and distribution systems.

Design philosophy at the test utility requires that the maximum 12.47 kV bus fault be limited to 20,000 amperes or less, in order to maintain reasonable costs for 12.47 kV interrupting devices. Maximum fault current levels may be found at a typical large standard substation, consisting of two 66 kV lines, each supplying a triple rated 15/20/25 MVA, 66-12.47 kV transformer. The low voltage sides of the transformers are connected in parallel at a 12.47 kV bus. See Figure 3, page 30 for a diagram of a typical substation.

Backup impedances of the 66 kV system are available in tables of the utility system constants. Typical values are:

$$Z_1 = Z_2 \cong j\ 0.04 \text{ per unit (100 MVA, 66 kV base)}$$

This is based on approximately 0.02 per unit impedance for the system behind the 66 kV bus and 0.02 per unit impedance for one mile of 66 kV transmission line. It will be shown later that this figure is negligible compared to the 66-12.47 kV transformer impedances and the 12.47 kV line impedances. Resistance is normally neglected in these calculations at higher voltage levels since it contributes less than ten percent of the total impedance.




Typical Utility 66-12.47 kV Substation

Figure 3

In order to meet the requirement of 20,000 amperes maximum for a 12.47 kV bus fault, the 66-12.47 kV transformers are normally specified to have a seven percent internal impedance on their own self-cooled, 15 MVA base.

$$Z_{T1} = Z_{T2} = Z_{T0} = j\ 7.0\% = j\ 0.07 \text{ per unit}$$

$$\text{(15 MVA, 66 or 12.47 kV base)}$$

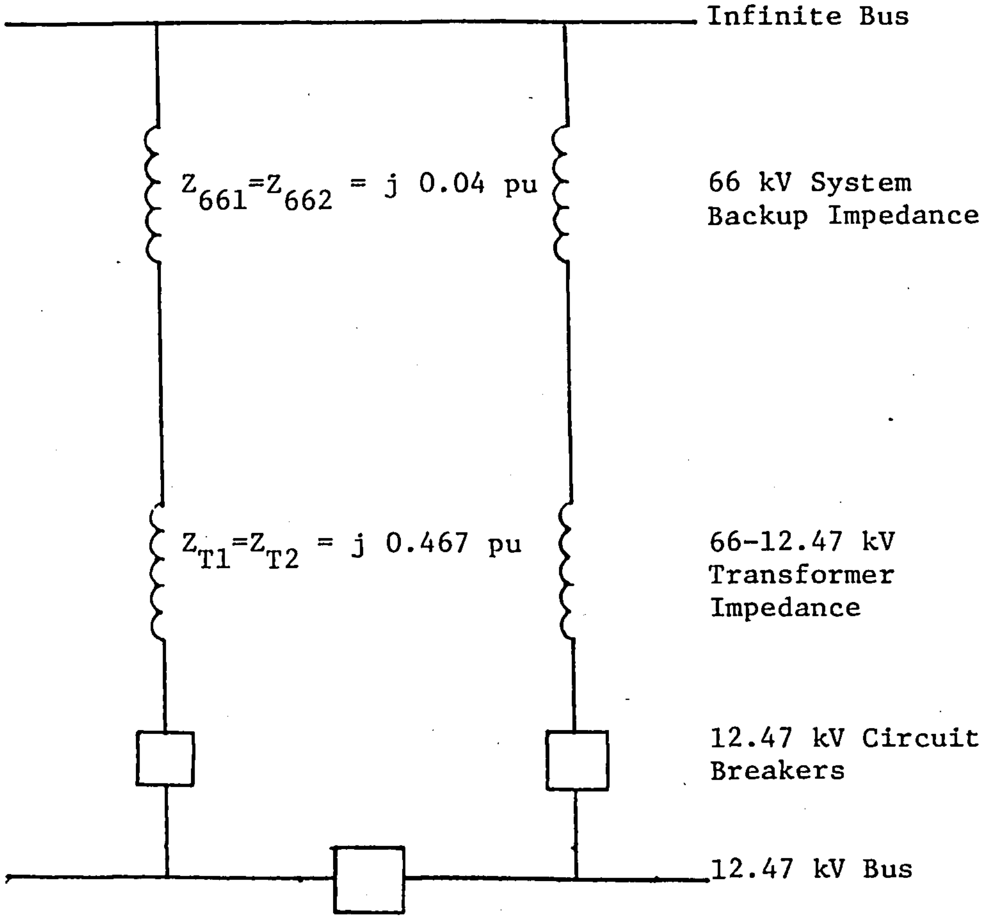
For these types of fault calculations, resistance is neglected in large power transformers, since it is negligible compared to the total impedance. Converting the transformer impedance to the 100 MVA base used to specify the 66 kV line impedance:

$$Z_{new} = Z_{old}\ \frac{\text{new base MVA}}{\text{old base MVA}} \qquad (3\text{-}1)$$

$$Z_{T1} = Z_{T2} = Z_{T0} = j\ 0.07\ \frac{\text{new base MVA}}{\text{old base MVA}} = j\ 0.07\ \frac{100 \text{ MVA}}{15 \text{ MVA}}$$

$$= j\ 0.467 \text{ per unit}$$

The positive and negative sequence components of the 66 kV line and 66-12.47 kV transformer impedances will add and combine as parallel circuits shown in Figure 4, page 32. A single equivalent impedance may now be calculated.




66 and 12.47 kV
Positive and Negative Sequence
Impedances

Figure 4

$$Z_{BU1} = Z_{BU2} = (Z_{661} + Z_{T1}) || (Z_{661} + Z_{T1}) =$$

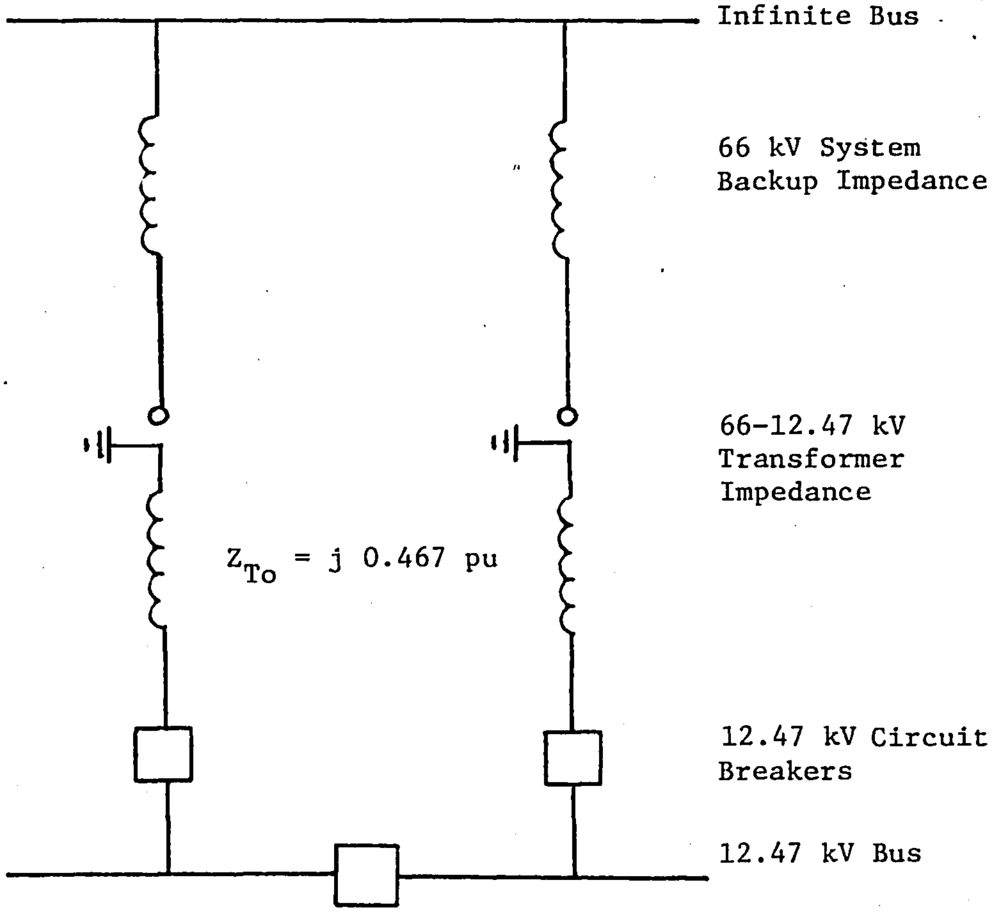
$$= (j\ 0.04 + j\ 0.467) || (j\ 0.04 + j\ 0.467) = j\ 0.253 \text{ per unit}$$

The zero sequence impedance diagram shown in Figure 5, page 34, reveals that the delta-wye connection of the 66-12.47 kV transformer provides a discontinuity in the zero sequence circuit, and does not allow the 66 kV system to contribute to a zero sequence fault on the 12.47 kV system. The back-up zero sequence impedance is just the parallel combination of the zero sequence impedances of the two transformers.

$$Z_{BU0} = Z_{T0} || Z_{T0} = j\ 0.467 || j\ 0.467 = j\ 0.233 \text{ per unit}$$

When working on the 12.47 kV system, a 10 MVA base is generally more convenient and will be used here. Changing bases according to equation 3-1, page 31:

$$Z_{BU1} = Z_{BU2} = j0.252 \frac{\text{new MVA base}}{\text{old MVA base}} = j0.253 \frac{10 \text{ MVA}}{100 \text{ MVA}} = j0.0253 \text{ per unit}$$




66 and 12.47 kV
Zero Sequence Impedance

Figure 5

$$Z_{BU0} = j\ 0.233\ \frac{10\ MVA}{100\ MVA} = j\ 0.0233 \text{ per unit}$$

These impedances are the values of the equivalent impedance of the utility system supplying the 12.47 kV bus; they are used when calculating faults on the distribution system. Obviously, smaller transformers would yield a higher impedance, as would a single transformer. The factor with the most influence on the fault current contributed by the utility 12.47 kV distribution system is the length of line between the 12.47 kV bus and the wind turbine generator. Typically, the test utility distribution lines may run from three to ten miles. For 336.4 MCM aluminum cable (61% aluminum, hard drawn), the per unit impedances are:

$$Z_{L1} = Z_{L2} = 0.0197 + j\ 0.0418 \text{ per unit per mile}$$

$$Z_{L0} = 0.0503 + j\ 0.0903 \text{ per unit per mile (10 MVA, 12.47 kV base)}$$

Obviously, for any appreciable length of line, the line impedances will be the determining factor in the amount of fault current available.

Similarly, the step-up transformer banks at the wind turbine generators will also have impedances which will effect the available fault current. For these wind turbine generator installations, three single phase distribution transformers will be used, each rated 138 - 7200 volts, or 277 - 7200 volts, connected delta - wye for line-to-line voltage ratios of 240 - 12470 volts or 480 - 12470 volts.

The small wind turbine generator which will be considered is rated continuously for an output of 25 KVA, and has a peak rating of 45 KVA. Accordingly, three 25 KVA single phase transformers, rated 240 - 12470 volts will be used to match voltages between the wind turbine generator and the 12.47 kV distribution line. The lowest impedance available on these transformers (which would result in the maximum fault current) is:

$$Z_{T1} = Z_{T2} = Z_{T0} = 0.0125 + j\ 0.01 \text{ per unit (at transformer KVA rating)}$$

Converting these transformer impedances to a 10 MVA base to match the bases chosen previously, according to equation 3-1, page 31:

$$Z_{T1} = Z_{T2} = Z_{T0} = (0.0125 + j\ 0.01)\ \frac{10\ \text{MVA}}{75\ \text{KVA}} = 1.67 + j\ 1.33 \text{ per unit} =$$

$$= 2.13\ \underline{/38.66^\circ} \text{ per unit}$$

The large wind turbine generator will require a larger step-up transformer bank. Since the generator is rated 125 KVA, three 75 KVA single phase transformers, 480 - 12470 volts, will be used. The lowest impedance available on these transformers (which would result in the maximum fault current is:

$$Z_{T1}=Z_{T2}=Z_{T0}=0.0103+j\ 0.0123 \text{ per unit (at transformer KVA rating)}$$

Converting these impedances to a 10 MVA base, according to equation 3-1, page 31:

$$Z_{T1}=Z_{T2}=Z_{T0}=(0.0103+j\ 0.0123)\ \frac{10\ \text{MVA}}{225\ \text{KVA}}=0.458+j\ 0.547 \text{ per unit}$$

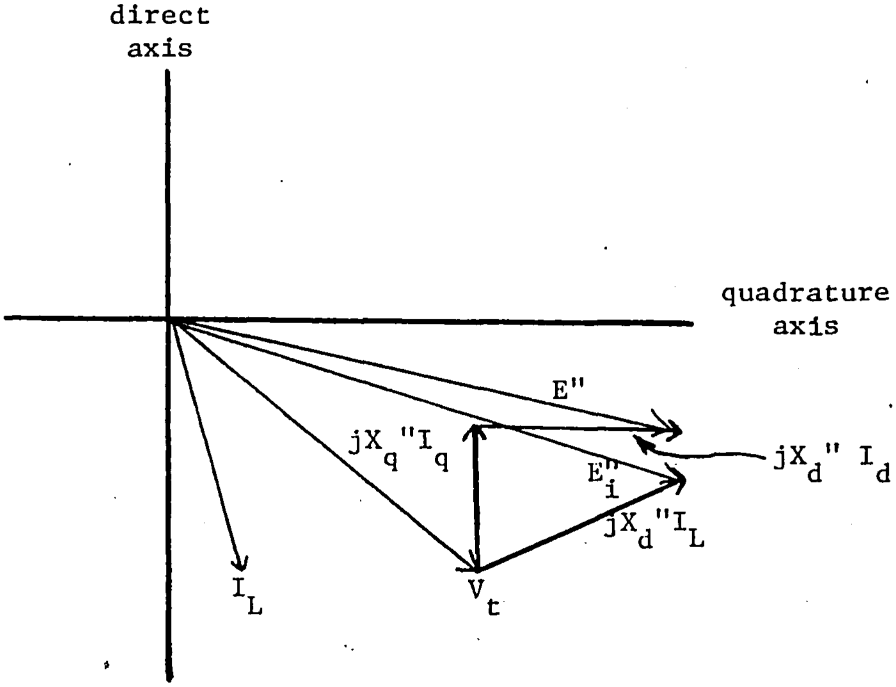
$$=0.713\ \underline{/50.06^\circ} \text{ per unit}$$

The standard procedure to calculate fault currents for the generators is to determine the subtransient reactance for each synchronous machine, calculate the voltage behind the subtransient reactance, and then calculate the fault current.

If the generator is unloaded when the short circuit occurs, the machine may be represented by the no-load voltage to neutral in series with the proper reactance; in this case, the subtransient reactance. Use of the subtransient reactance will yield the initial current flowing in the machine due to a fault. This current is very short-lived, but for a fairly high-speed protective system, this will be the current sensed by the relays and interrupted by the appropriate disconnect device. Generally, the machine armature resistance may be neglected, since the resistance is much less than the machine reactance. Load current supplied by the generator prior to the fault will have the effect of increasing the magnitude of the machine voltage behind the subtransient reactance. Therefore, the maximum generator fault currents will occur when the generator is operating at full load prior to the fault occurrence. The effects of load current on the generator internal voltage can be seen from the diagram in Figure 6, page 39.

The approximation to the voltage behind the subtransient reactance E" is:

$$E_i'' = V_t + j\, X_d''\, I_L \qquad (3\text{-}2)$$




$V_t$ = Generator Terminal Voltage

E" = Voltage Behind the Subtransient Reactance

$E_i$" = Approximation to E"

$I_L$ = Load Current Prior to Fault

$jX_d$"= Direct Axis Component of Subtransient Reactance

$jX_q$"= Quadrature Axis Component of Subtransient Reactance

Generator Phasor Diagram

Figure 6

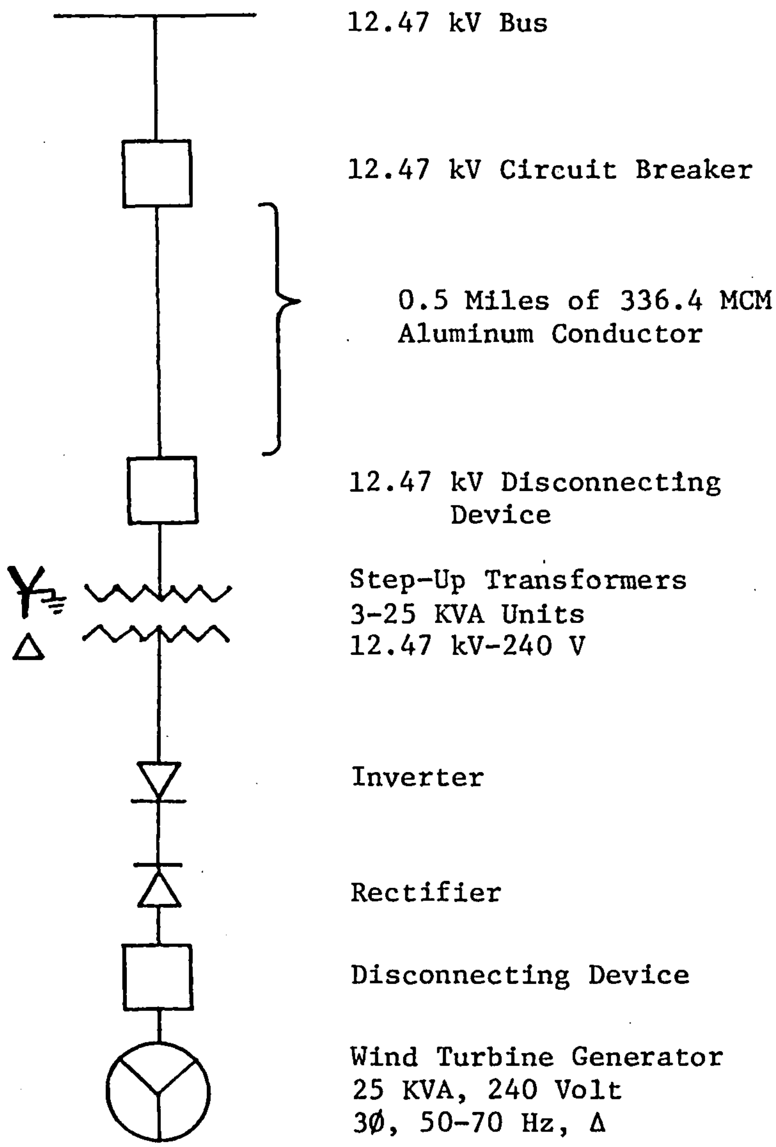
For conventional synchronous machines, it may be assumed with small error that the magnitude of $E_i''$ is equal to the magnitude of $E''$.[16]

The following calculations are made for both the small and large wind turbine generators for the worst case (maximum voltage) $E_i''$ with the generators operating at full load at the time of fault.

Small Wind Turbine Generator-Rated 25 KVA

The small wind turbine generator is assumed to be installed to provide power for a home or small business. Therefore, it is unlikely that the generator would be connected directly to the utility 12.47 kV bus, but rather at a location on the 12.47 kV distribution line. The closer the generator is to the bus, the higher the available fault current from the utility system; for these calculations, a relatively short line length of 0.5 miles of 336.4 MCM aluminum conductor is assumed. The system diagram would appear as shown in Figure 7, page 41.

The rectifier and the inverter may be considered to have zero impedance when they are conducting, and infinite impedance when




Small Wind Turbine Generator System

Figure 7

they are switched off. Actual values of generator impedances were not available, but typical values for a 25 KVA machine may be assumed to be:

$X_d'' = 0.17$ per unit (240 v, 25 KVA base)

$X_o = 0.14$ per unit (240 v, 25 KVA base)

Converting to the 10 MVA base, according to equation 3-1, page 31:

$$X_d'' + 0.17 \frac{10 \text{ MVA}}{25 \text{ KVA}} = 68.0 \text{ per unit}$$

$$X_o = 0.14 \frac{10 \text{ MVA}}{25 \text{ KVA}} = 56.0 \text{ per unit}$$

Considering the 12.47 kV bus voltage as fairly constant, and solving for $E_i''$ as defined previously,

$$E_i'' = V_t + I_L \, (j \, X_d'' + Z_T + Z_1) \qquad (3\text{-}3)$$

where:

$V_t = 1.0$ per unit (12.47 kV bus voltage)

$$I_L = \frac{\text{generator VA}}{\sqrt{3}(\text{generator voltage})} = \qquad (3\text{-}4)$$

$$= \frac{25 \times 10^3 \text{ VA}}{\sqrt{3} \ (240 \text{ V})} = 60.14 \text{ amperes}$$

on a 10 MVA, 240 volt base

$$I_{base} = \frac{VA\ base}{\sqrt{3}\ V_{base}} \tag{3-5}$$

$$= \frac{10 \times 10^6\ VA}{\sqrt{3}\ (240\ V)} = 24056 \text{ amperes}$$

$$I_L = \frac{60.14 \text{ amperes}}{I_B} = \frac{60.14}{24056} = 0.0025 \text{ per unit}$$

Assuming the machine is operated at 0.8 power factor, lagging:

$$I_L = 0.0025\ \underline{/-36.86°} \text{ per unit}$$

Previously determined positive sequence impedance values of $Z_{L1}$ and $Z_{T1}$ may be used (from pages 35 and 36)

$$Z_{T1} = 1.67 + j\ 1.33 \text{ per unit}$$

$$Z_{L1} = 0.0197 + j\ 0.0418 \text{ per unit per mile}$$

Substituting these values into the formula for $E_i''$ given in equation 3-3, page 42:

$$E_i''=1.0+0.0025\underline{/-36.86°}[j\ 68.0+(1.67+j\ 1.33)+.5(0.0197+j\ 0.0418)]$$

$$=1.107 + j\ 0.136 \text{ per unit} = 1.12\ \underline{/7.0°} \text{ per unit}$$

Three-Phase Fault Calculations

To calculate three-phase faults on the small wind turbine generator system, a positive sequence network may be drawn as shown in Figure 8, page 45.

For a three-phase fault at the generator terminals, the fault current will be:

$$I_F = \frac{E_i''}{j\, X_d''} + \frac{E}{Z_T + Z_L + Z_{Bu}} \qquad (3\text{-}6)$$

$$= \frac{1.12\angle 7.0^\circ}{j\ 68.0} + \frac{1.0\angle 0^\circ}{(1.67 + j\ 1.33) + (0.01 + j\ 0.0209) + j\ 0.0253}$$

$$= 0.0165\angle -83.0^\circ + 0.46\angle -39.4^\circ = 0.472\angle 40.8^\circ \text{ per unit}$$

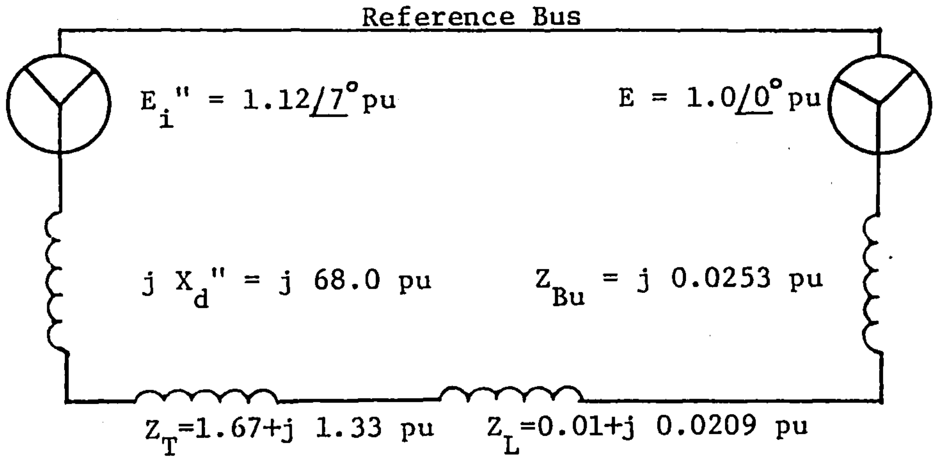
Since $I_b$ = 24056 amperes on the 240 volt side of the transformer, according to equation 3-5, page 43:

$$I_F = 0.472\angle 40.8^\circ (I_b) = (0.472\angle 40.8^\circ)24056 = 11,347\angle 40.8^\circ \text{amperes}$$

The fault current contributions from the wind turbine generator and from the utility can be calculated as:

$$I_{F\ WTG} = 0.0165\angle -83.0^\circ (24056) = 397\angle -83.0^\circ \text{ amperes}$$

$$I_{FU} = 0.46\angle -39.4^\circ (24056) = 11,066\angle -39.4^\circ \text{ amperes}$$




Positive Sequence Network
for Small Wind Turbine Generator

Figure 8

To calculate the current supplied by the utility, on the 12.47 kV base, according to equation 3-5, page 43:

$$I_b = \frac{10 \times 10^6 VA}{\sqrt{3}\ (12.47 \times 10^3 V)} = 463 \text{ amperes}$$

$$I_{FU} = 0.46(463) = 213 \text{ amperes}$$

For a three-phase fault at the high voltage terminals of the step-up transformer:

$$I_F = \frac{Ei''}{j\ X_d'' + Z_T} + \frac{E}{Z_L + Z_{Bu}} \tag{3-7}$$

$$= \frac{1.12\underline{/7.0^\circ}}{j\ 68.0 + (1.67 + j\ 1.33)} + \frac{1.0\underline{/0^\circ}}{(0.01 + j\ 0.0209) + j\ 0.0253}$$

$$= 0.01615\underline{/-81.62^\circ} + 21.28\underline{/-77.79^\circ} = 21.30\underline{/77.8^\circ} \text{ per unit}$$

On the 12.47 kV base:

$$I_F = 21.30(I_b) = 21.30(463) = 9860 \text{ amperes}$$

$I_{F\ WTG} = 0.01615\ (463) = 7.48$ amperes

$I_{FU} = 21.28(463) = 9852$ amperes

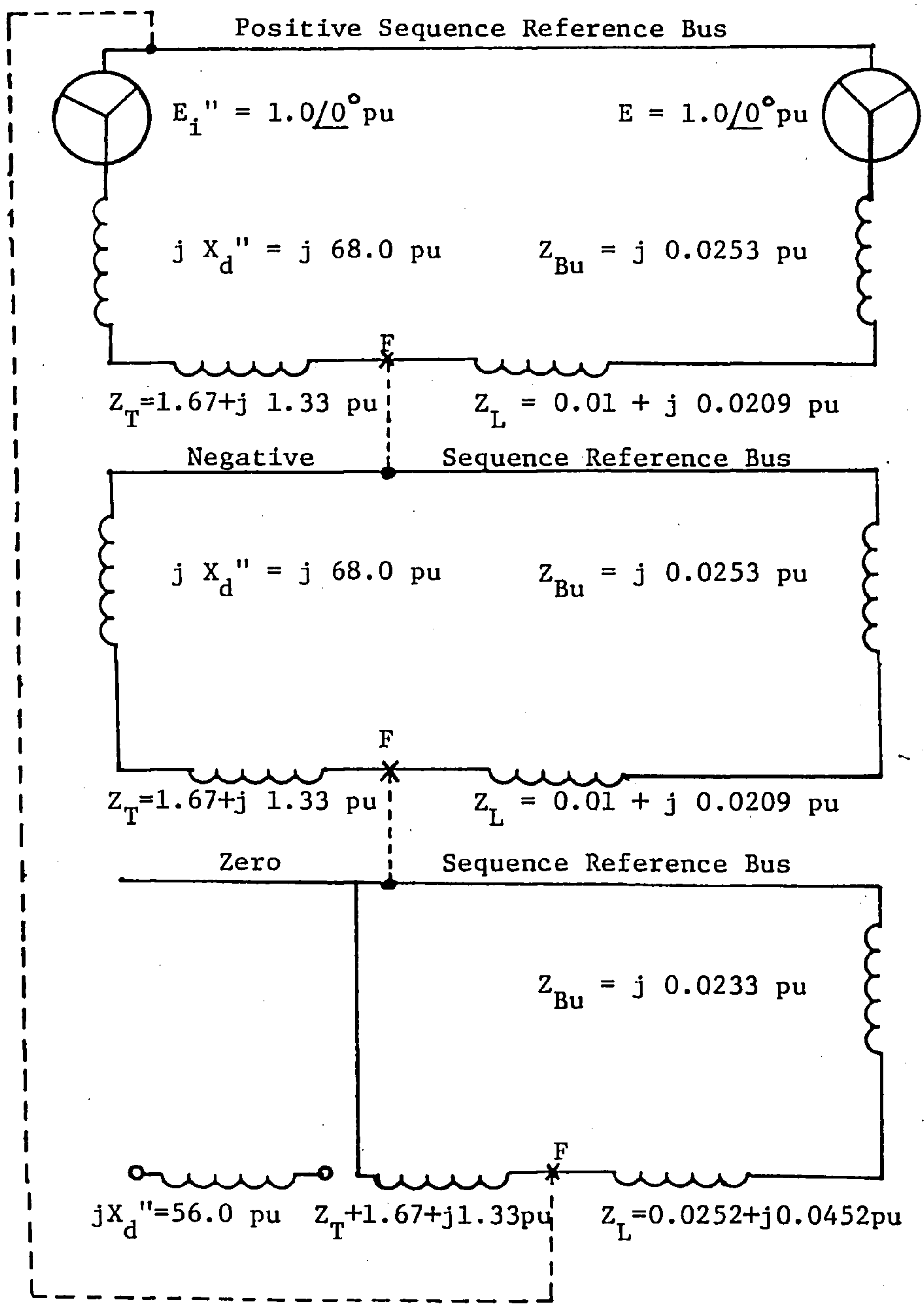
On a 240 volt base:

$I_{F\ WTG} = 0.01615(24056) = 388.5$ amperes

Single-Phase-to-Ground Fault Calculations

In order to calculate single-phase-to-ground faults on the small wind turbine generator system, the positive, negative and zero sequence networks may be drawn as shown in Figure 9, page 48.

As is evident from viewing the network shown in Figure 9, no fault current can flow for single-phase-to-ground faults between the generator terminals and the low voltage bushings of the step-up transformer. Generator contributions are blocked by the delta winding used in the generator, and utility contributions are blocked by the delta-wye winding of the step-up transformer. Phase-to-ground faults in this area of the system will result in no fault current, just a shifting of the system neutral. The faulted phase will then be at ground potential, and the other two phases will retain the same phase-to-phase voltages and angles.




Positive, Negative and Zero Sequence Networks
Small Wind Turbine Generator

Figure 9

Phase-to-ground voltages for the unfaulted phases will be the same as the phase-to-phase values.

Single-phase-to-ground faults at the step-up transformer 12.47 kV bushings will result in fault currents, with zero phase sequence current supplied by the grounded neutral of the step-up transformer. The fault is indicated as "F" and the sequence networks are connected as shown in dashed lines on Figure 9, page 48.

Calculating the resulting fault currents requires equivalent positive, negative and zero sequence impedances:

$$Z_1 = (j\, X_d'' + Z_t) \,||\, (Z_L + Z_{BU})$$
$$= (j\, 68.0 + 1.67 + j\, 1.33) \,||\, (0.01 + j\, 0.0209 + j\, 0.0253)$$
$$= 0.0473 \;\underline{/77.75^\circ} \text{ per unit}$$
$$Z_2 = Z_1$$
$$Z_o = (Z_T) \,||\, (Z_L + Z_{BU})$$
$$= (1.67 + j\, 1.33) \,||\, (0.0252 + j\, 0.0452 + j\, 0.0233)$$
$$= .0705 \;\underline{/68.8^\circ} \text{ per unit}$$

The fault current will be calculated by the formula:

$$I_1 = I_2 = I_0 = \frac{E}{Z_1 + Z_2 + Z_0} \tag{3-8}$$

In this calculation, $E_i''$ is approximated by $E_i''=1.0\underline{/0^\circ}$ per unit. This approximation greatly simplifies the calculations and provides results accurate within 0.08 percent of the more rigorous solution.

$$I_1=I_2=I_0=\frac{1.0\angle 0^\circ}{0.0473\angle 77.75^\circ+0.0473\angle 77.75^\circ+0.0705\angle 68.8^\circ}$$

$= 6.077\angle -73.91^\circ$ per unit

Phase currents at the fault (assuming phase A is faulted) are calculated as follows:

$$I_A = 3\ I_1 = 3\ I_2 = 3\ I_0 \qquad (3\text{-}9)$$

$$= 3(6.077\angle -73.91^\circ) = 18.231\angle -73.91^\circ \text{ per unit}$$

$$I_B = 0$$

$$I_C = 0$$

In order to find the contributions of each source to the above fault currents, the distribution factors for the positive, negative and zero sequence currents will be calculated to determine the current splits. The phase currents from each source will then be calculated. $I_{SUT}$ will be used to designate the current contributions on the 12.47 kV system from the step-up transformer, and $I_U$ will be used to designate the current contributions from the utility system.

$$I_{SUT\ 1}=(\text{distribution factor})I_1=\frac{0.0473\angle 77.79^\circ}{69.40\angle 88.61^\circ}6.077\angle -73.91^\circ$$

$$= 0.00414\angle -84.73^\circ \text{ per unit}$$

$$I_{SUT\ 2} = I_{SUT\ 1}$$

$$I_{SUT\ 0}=(\text{distribution factor})I_0=\frac{0.0730\angle 69.80^\circ}{2.20\angle 39.53^\circ}6.077\angle -73.91^\circ$$

$$= 0.225\angle -43.64^\circ \text{ per unit}$$

$I_{SUT\ A} = I_{SUT\ 1} + I_{SUT\ 2} + I_{SUT\ 0} = 0.231\underline{/-44.87}°$per unit

$I_{SUT\ B} = a^2 I_{SUT\ 1} + aI_{SUT\ 2} + I_{SUT\ 0}=0.219\underline{/-42.17}°$per unit

$I_{SUT\ C} = aI_{SUT\ 1}+a^2 I_{SUT\ 2}+I_{SUT\ 0}=0.219\underline{/-42.17}°$ per unit

$I_{U1}=(\text{distribution factor})I_1=\frac{69.35\underline{/88.62}°}{69.40\underline{/88.61}°}6.077\underline{/-73.91}°=$

$= 6.073\underline{/-73.9}°$ per unit

$I_{U2} = I_{U1}$

$I_{U0} =(\text{distribution factor})I_0=\frac{2.13\underline{/38.53}°}{2.20\underline{/39.53}°}6.077\underline{/-73.91}°=$

$= 5.884\underline{/-74.91}°$ per unit

$I_{UA} = I_{U1} + I_{U2} + I_{U0} = 18.03\underline{/-74.23}°$ per unit

$I_{UB} = a^2 I_{U1} + a\ I_{U2} + I_{U0} = 0.217\underline{/134.44}°$ per unit

$I_{UC} = aI_{U1} + a^2\ I_{U2} + I_{U0} = 0.217\underline{/134.44}°$ per unit

The actual fault currents can be calculated using the base current of the 12.47 kV system, per equation 3-5, page 43:

$I_{base} = 463$ amperes

$I_A = I_{base}\ (I_A)= 463(18.231\underline{/-73.91}°)=8441\underline{/-73.91}°$amperes

$I_B = 0$

$I_C = 0$

$I_{SUT\ A}= 107\underline{/-44.87}°$ amperes

$I_{SUT\ B}= 101.4\underline{/-42.17}°$ amperes

$I_{SUT\ C}= 101.4\underline{/-42.17}°$ amperes

$I_{UA} = 8348\underline{/-74.23^\circ}$ amperes

$I_{UB} = 100.5\underline{/134.44^\circ}$ amperes

$I_{UC} = 100.5\underline{/134.44^\circ}$ amperes

In order to obtain the values of the fault current contribution on the 240 volt base of the generator, the positive and negative sequence currents must be calculated on the low voltage side of the step-up transformer. According to convention, the high voltage positive sequence currents must lead the low voltage positive sequence currents by 30°, and the high voltage negative sequence currents must lag the low voltage negative sequence currents by 30°. Since zero sequence current can not flow from the delta winding, there will be no transformation. Therefore:

$I_{WTG1} = I_{SUT1}\ \underline{/-30^\circ} = 0.00414\underline{/-114.73^\circ}$ per unit

$I_{WTG2} = I_{SUT\ 2}\ \underline{/+30^\circ} = 0.00414\underline{/-54.73^\circ}$ per unit

$I_{WTG0} = 0$

$I_{WTG\ A} = I_{WTG\ 1} + I_{WTG\ 2} + I_{WTG\ 0} = 0.00717\underline{/-84.72^\circ}$ per unit

$I_{WTG\ B} = a^2\ I_{WTG\ 1} + a\ I_{WTG\ 2} + I_{WTG\ 0} = 0.00717\underline{/95.27^\circ}$ per unit

$I_{WTG\ C} = a\ I_{WTG\ 1} + a^2\ I_{WTG\ 2} + I_{WTG\ 0} = 0$

The actual fault currents can be calculated using the base current of the 240 volt system, and equation 3-5, page 43:

$I_{base} = 24056$ amperes

$I_{WTG\ A} = I_{base}(I_{WTG\ A}) = 24056(0.00717\underline{/-84.72°}) = 172.5\underline{/-84.72°}$

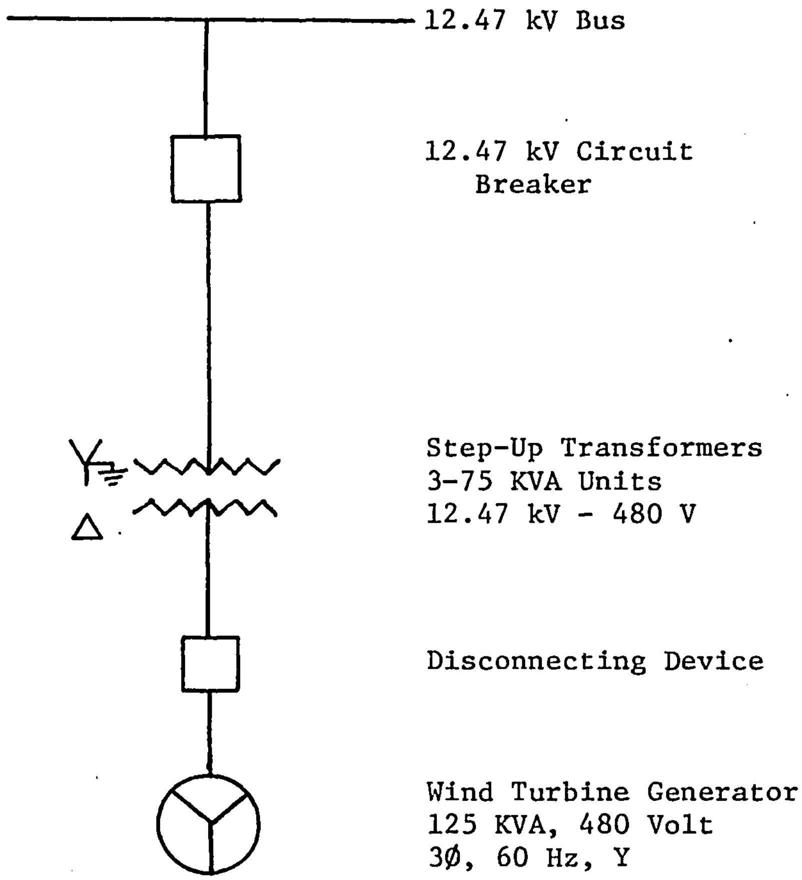
$I_{WTG\ B} = 172.5\underline{/95.27°}$ amperes

$I_{WTG\ C} = 0$

Large Wind Turbine Generator - Rated 125 KVA

The large wind turbine generator is assumed to be installed by an industrial customer, or even by a utility to provide additional power to the system. As such, it is possible that the generator would be connected to a substation 12.47 kV bus, or at some point on the distribution line. The worst case faults would occur with the generator installed at a substation 12.47 kV bus, since the 12.47 kV line impedance would be deleted from the circuit. The system diagram will appear as shown in Figure 10, page 54.

Data for the 125 KVA wind turbine generator is available, based on the MOD-0 unit installed by the Department of Energy and the National Aeronautics and Space Administration.




Large Wind Turbine Generator System

Figure 10

$X_d'' = 0.128$ per unit

$X_o = 0.0058$ per unit

Converting to the 10 MVA base, according to equation 3-1, page 31:

$$X_d'' = 0.128 \frac{10 \times 10^6 VA}{125 \times 10^3 VA} = 10.24 \text{ per unit}$$

$$X_o = 0.0058 \frac{10 \times 10^6 VA}{125 \times 10^3 VA} = 0.464 \text{ per unit}$$

Considering the 12.47 kV bus voltage is fairly constant, and solving for $E_i''$ as defined previously,

$$E_i'' = V_t + I_L (j X_d'' + Z_T) \tag{3-10}$$

where:

$V_t = 1.0\underline{/0°}$ per unit

$$I_L = \frac{125 \text{ KVA}}{\sqrt{3}\ 480 \text{ V}} = 150.35 \text{ amperes,}$$

as defined previously in equation 3-4, page 42.

On the 10 MVA base, according to equation 3-5, page 43:

$$I_{base} = \frac{10 \times 10^6 \text{ VA}}{\sqrt{3}\ 480 \text{ V}} = 12028 \text{ amperes}$$

$$I_L = \frac{150.35}{I_b} = \frac{150.35}{12028a} = 0.0125 \text{ per unit}$$

If the machine is operating at a 0.8 power factor, lagging,

$$I_L = 0.0125 \ \underline{/-36.87°} \text{ per unit}$$

Previously determined positive sequence valves of $Z_T$ may be used (see page 37):

$$Z_T = 0.458 + j\ 0.547 \text{ per unit}$$

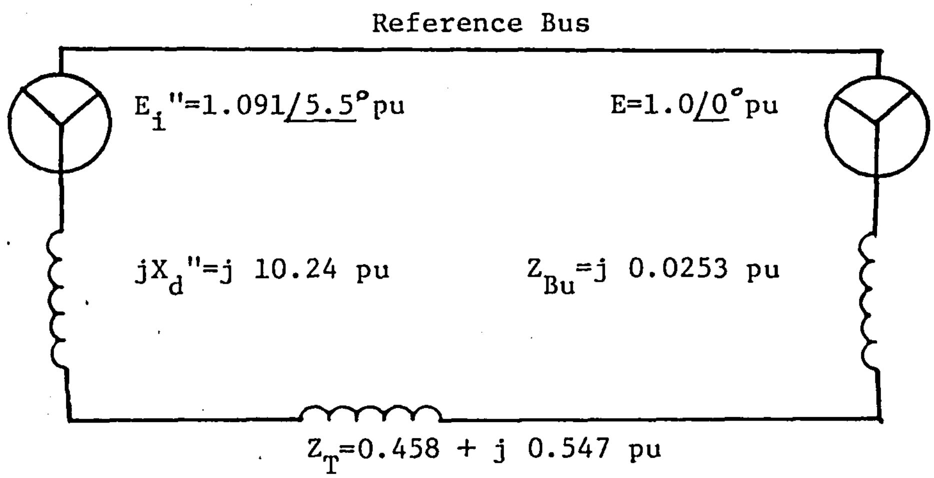
Substituting these values into the formula for $E_i''$(equation 3-10, page 55)

$$E_i'' = 1.0 + 0.0125\underline{/-36.87°}[j\ 10.24+(0.458+j\ 0.547)]$$

$$= 1.0855 + j\ 0.104 = 1.091\underline{/5.5°} \text{per unit}$$

Three-Phase Fault Calculations

To calculate three-phase faults on the large wind turbine generator system, a positive sequence network may be drawn as shown in Figure 11, page 57.




Positive Sequence Network for
Large Wind Turbine Generators

Figure 11

For a three-phase fault on the generator terminals, the fault current will be:

$$I_F = \frac{E_i''}{j X_d''} + \frac{E}{Z_T + Z_{Bu}} = \frac{1.091\underline{/5.5^\circ}}{j\ 10.24} + \frac{1.0\underline{/0^\circ}}{(0.458 + j\ 0.547) + j\ 0.0253}$$

$$= 0.1065\underline{/-84.5^\circ} + 1.364\underline{/-51.33^\circ} = 1.454\underline{/-53.6^\circ} \text{ per unit.}$$

Since $I_d$ = 12028 amperes on the 480 volt side of the step-up transformer, according to equation 3-5, page 43:

$$I_F = 1.454(I_b) = 1.454(12028) = 17489 \text{ amperes}$$

$$I_{F\ WTG} = 0.1065(12028) = 1280 \text{ amperes}$$

$$I_{FU} = 1.364(12028) = 16406 \text{ amperes}$$

To calculate the current supplied by the utility, on the 12.47 kV base, according to equation 3-5, page 43:

$$I_b = 463 \text{ amperes}$$

$$I_{FU} = 1.364(I_b) = 1.364(463) = 632 \text{ amperes}$$

For a three-phase fault at the high voltage terminals of the step-up transformer:

$$I_F = \frac{E_i''}{j\,X_d'' + Z_T} + \frac{E}{Z_{BU}} = \frac{1.091\underline{/5.5^\circ}}{j\,10.24 + (0.458 + j\,0.547)} + \frac{1.0\underline{/0^\circ}}{j\,0.0253} =$$

$$= 0.101\underline{/-82.07^\circ} + 39.53\underline{/-90^\circ} = 39.63\underline{/-89.97^\circ} \text{ per unit}$$

On the 12.47 kV base:

$$I_F = 39.63(I_b) = 39.63(463) = 18348 \text{ amperes}$$

$$I_{F\ WTG} = 0.101(463) = 46.8 \text{ amperes}$$

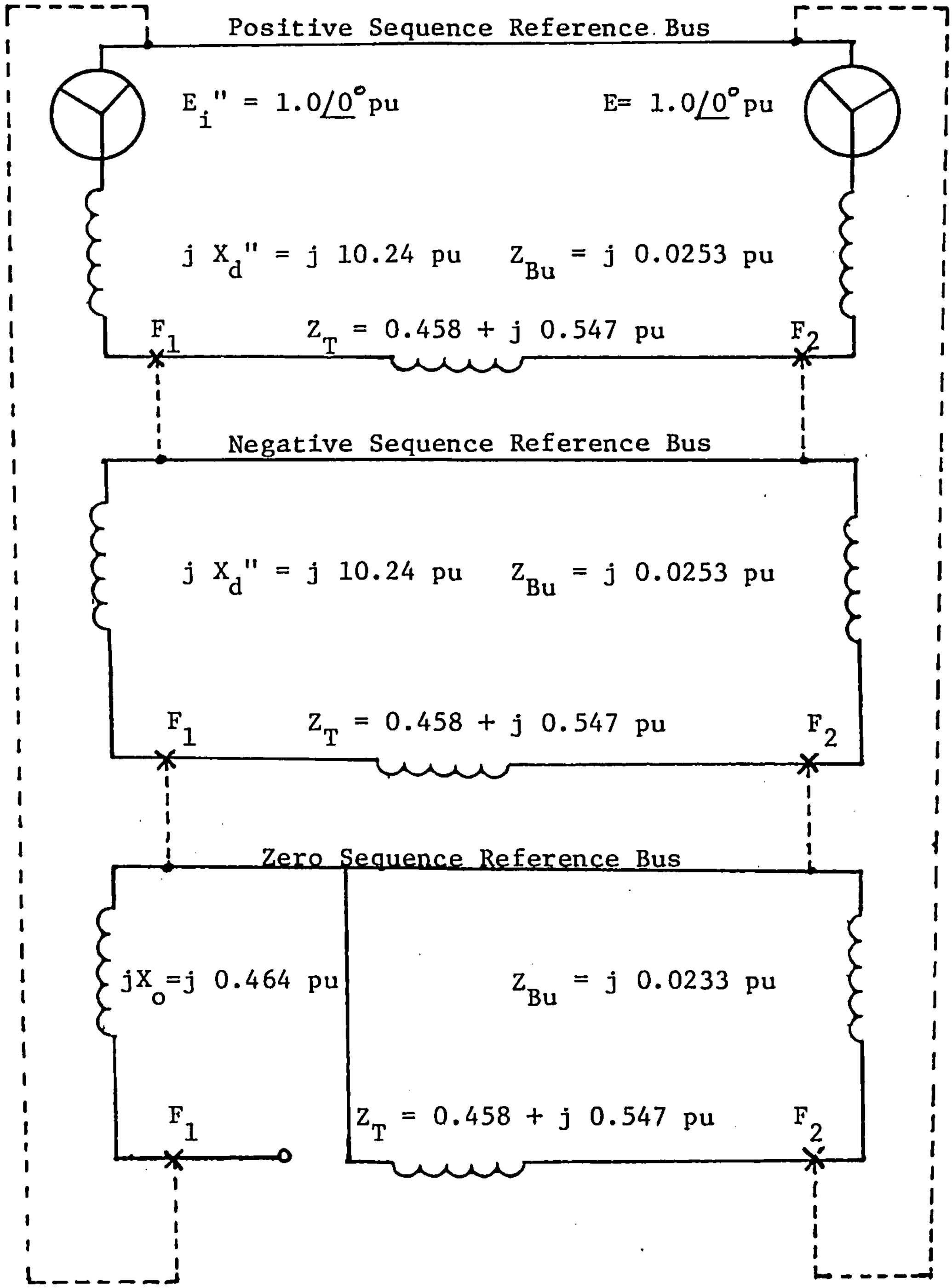
$$I_{FU} = 39.53(463) = 18301 \text{ amperes}$$

On the 480 volt base:

$$I_{F\ WTG} = 0.101(I_b) = 0.101(12028) = 1215 \text{ amperes}$$

Single-Phase-to-Ground Fault Calculations

In order to calculate the single-phase-to-ground faults on the large wind turbine generator system, the positive, negative and zero sequence networks may be drawn as shown in Figure 12, page 60.




Positive, Negative and Zero Sequence Networks
for Large Wind Turbine Generators

Figure 12

Since this generator is assumed to be connected wye-grounded, the generator will supply zero sequence currents for single phase to ground faults on the 480 volt side of the step-up transformer. Since the transformer is connected delta-wye, it appears as an open circuit to zero sequence currents. Single phase to ground faults on the 480 volt system are indicated as "F", on Figure 12, page 60.

Equivalent values of positive, negative and zero sequence impedances are calculated for the fault indicated as $F_1$.

$$Z_1=(j\ X_d'')||(Z_T+ Z_{Bu})=(j\ 10.24)||(0.458+j\ 0.547+j\ 0.0253)=$$
$$=0.694\underline{/53.75^\circ}\ \text{per unit}$$

$$Z_2=Z_1$$

$$Z_o=j\ X_o = j\ 0.464\ \text{per unit}$$

The sequence fault currents may be calculated by the equation 3-8; page 49. As on page 49, $E_i''$ is approximated by $E_i''=1.0\underline{/0^\circ}$ per unit. This approximation provides results accurate within 1.6 percent of the more rigorous solution.

$$I_1= I_2= I_0= \frac{E}{Z_1+ Z_2+ Z_0} = \frac{1.0\underline{/0^\circ}}{0.694\underline{/53.75^\circ}+0.694\underline{/53.75^\circ}+j\ 0.464}$$
$$= 0.547\underline{/-59.96^\circ}\ \text{per unit}$$

Phase currents at the fault (assuming phase A is faulted) are calculated from equation 3-9, page 50, as follows:

$I_A=3I_1=3I_2=3I_0=3(0.547\underline{/-59.96°})=1.641\underline{/-59.96°}$ per unit

$I_B=0$

$I_C=0$

In order to find the contributions of each source to the above fault currents, the distribution factors for the positive, negative and zero sequence currents are calculated to determine the current splits. The phase currents from each source are calculated. $I_{WTG}$ is used to designate the current contributions from the generator, and $I_{SUT}$ is used to designate the current contributions from the step-up transformer.

$$I_{WTG\ 1}=(\text{distribution factor})I_1=\frac{0.733\underline{/51.32°}}{10.82\underline{/87.57°}}(0.547\underline{/-59.96°})$$
$$=0.0371\underline{/-96.21°} \text{ per unit}$$

$$I_{WTG\ 2}=I_{WTG\ 1}$$

$$I_{WTG\ 0}=I_0 = 0.547\underline{/-59.96°} \text{per unit}$$

$$I_{WTG\ A}=I_{WTG\ 1} + I_{WTG\ 2} + I_{WTG\ 0} = 0.609\underline{/-64.10°} \text{per unit}$$

$$I_{WTG\ B}=a^2\ I_{WTG\ 1} + a\ I_{WTG\ 2} + I_{WTG\ 0}=0.518\underline{/-57.54°} \text{per unit}$$

$$I_{WTG\ C}=a\ I_{WTG\ 1} + a^2\ I_{WTG\ 2} + I_{WTG\ 0}=0.518\underline{/-57.54°} \text{per unit}$$

$$I_{SUT\ 1}=(\text{distribution factor})I_1= \frac{10.24\underline{/90°}}{10.82\underline{/87.57°}}0.547\underline{/-59.96°}=$$

$$=0.518\underline{/-57.53°} \text{per unit}$$

$I_{SUT2} = I_{SUT\ 1}$

$I_{SUT\ 0} = 0$

$I_{SUT\ A} = I_{SUT\ 1} + I_{SUT\ 2} = I_{SUT\ 0} = 1.039\underline{/-57.53}°$ per unit

$I_{SUT\ B} = a^2\ I_{SUT\ 1} + aI_{SUT\ 2} + I_{SUT\ 0} = 0.518\underline{/122.47}°$ per unit

$I_{SUT\ C} = aI_{SUT\ 1} + a^2 I_{SUT\ 2} + I_{SUT\ 0} = 0.518\underline{/122.47}°$ per unit

The actual fault currents can be calculated using the base current values of the 480 volt system, according to equation 3-5; page 43:

$I_{base} = 12028$ amperes

$I_A = I_{base}\ (I_A) = 12028(1.641\underline{/-59.96}°) = 19738\underline{/-59.96}°$ amperes

$I_B = 0$

$I_C = 0$

$I_{WTG\ A} = 7325\underline{/-64.10}°$ amperes

$I_{WTG\ B} = 6231\underline{/-57.54}°$ amperes

$I_{WTG\ C} = 6231\underline{/-57.54}°$ amperes

$I_{SUT\ A} = 12497\underline{/-57.53}°$ amperes

$I_{SUT\ B} = 6231\underline{/122.47}°$ amperes

$I_{SUT\ C} = 6231\underline{/122.47}°$ amperes

In order to obtain the values of the fault current contribution on the 12.47 kV base of the distribution system, the positive and negative sequence currents must be calculated on the high voltage side of the step-up transformer, following the rules as specified on page 52.

$$I_{U1} = I_{SUT\ 1}\underline{/+30^\circ} = 0.518\underline{/-27.53^\circ} \text{ per unit}$$

$$I_{U2} = I_{SUT\ 2}\underline{/-30^\circ} = 0.518\underline{/-87.53^\circ} \text{ per unit}$$

$$I_{U0} = 0$$

$$I_{UA} = I_{U1} + I_{U2} + I_{U0} = 0.897\underline{/-57.53^\circ} \text{ per unit}$$

$$I_{UB} = a^2 I_{U1} + aI_{U2} + I_{U0} = 0$$

$$I_{UC} = aI_{U1} + a^2 I_{U2} + I_{U0} = 0.897\underline{/122.47^\circ} \text{ per unit}$$

The actual fault currents can be calculated using the base current of the 12.47 kV system, according to equation 3-5; page 43:

$$I_{base} = 463 \text{ amperes}$$

$$I_{UA} = I_{base}\ (I_{UA}) = 463(0.897\underline{/-57.53^\circ}) = 415\underline{/-57.53^\circ} \text{ amperes}$$

$$I_{UB} = 0 \text{ amperes}$$

$$I_{UC} = 415\underline{/122.47^\circ} \text{ amperes}$$

Single-phase-to-ground faults between the high voltage bushings of the step-up transformer and the 12.47 kV bus will not include any zero sequence current contribution from the wind turbine generator, since the delta-wye transformer connection will act as an open circuit to zero sequence currents from the generator. The 12.47 kV wye side of the transformer has a grounded neutral and will provide a ground path for zero sequence currents to circulate. This fault is indicated as $F_2$ on the sequence network diagrams in Figure 12, page 60.

Equivalent values of positive, negative and zero sequence impedances are calculated for this single-phase-to-ground fault.

$$Z_1=(j\ X_d''+Z_T)||(Z_{BU})=(j\ 10.24 + 0.458 + j\ 0.547)||(j\ 0.0253)$$

$$=j\ 0.0253 \text{ per unit}$$

$$Z_2=Z_1$$

$$Z_0=(Z_T)||(Z_{BU}) = (0.458 + j\ 0.547)||(j\ 0.0233)$$

$$= 0.0227\underline{/88.83^\circ} \text{ per unit}$$

The sequence fault currents may be calculated from equation 3-8; page 49. As on page 49, $E_i''$ is approximated by $E_i''=1.0\underline{/0^\circ}$ per unit. This approximation provides results accurate within 0.15 percent of the more rigorous solution.

$$I_1=I_2=I_0=\frac{E}{Z_1 + Z_2 + Z_0}=\frac{1.0\underline{/0^\circ}}{j\ 0.0253 + j\ 0.0253 + j\ 0.0227}$$

$$= 13.64\underline{/-90^\circ} \text{ per unit}$$

Phase currents at the fault (assuming phase A is faulted) are calculated according to equation 3-9; page 50:

$$I_A = 3I_1 = 3I_2 = 3I_0 = 3(13.64\angle{-90^\circ}) = 40.92\angle{-90^\circ} \text{ per unit}$$

$$I_B = 0$$

$$I_C = 0$$

In order to find the contributions of each source to the above fault currents, the distribution factors for the positive, negative and zero sequence currents are calculated. $I_{SUT}$ is used to designate the current contributions from the step-up transformer, and $I_U$ is used to designate current contributions from the utility system.

$$I_{SUT\ 1} = (\text{distribution factor})I_1 = \frac{0.0253\angle{90^\circ}}{10.82\angle{87.57^\circ}} 13.64\angle{-90^\circ} =$$

$$= 0.0319\angle{-87.57^\circ} \text{ per unit}$$

$$I_{SUT\ 2} = I_{SUT\ 1}$$

$$I_{SUT\ 0} = (\text{distribution factor})I_0 = \frac{0.0233\angle{90^\circ}}{0.731\angle{51.23^\circ}} 13.64\angle{-90^\circ}$$

$$= 0.435\angle{-51.23^\circ} \text{ per unit}$$

$I_{SUT\ A} = I_{SUT\ 1} + I_{SUT\ 2} + I_{SUT\ 0} = 0.488\underline{/55.67^\circ}$ per unit

$I_{SUT\ B} = a^2 I_{SUT\ 1} + aI_{SUT\ 2} + I_{SUT\ 0} = 0.410\underline{/-48.57^\circ}$ per unit

$I_{SUT\ C} = aI_{SUT\ 1} + a^2 I_{SUT\ 2} + I_{SUT\ 0} = 0.410\underline{/-48.57^\circ}$ per unit

$$I_{U1} = (\text{distribution factor})I_1 = \frac{10.80\underline{/87.57^\circ}}{10.82\underline{/87.57^\circ}} 13.64\underline{/-90^\circ}$$

$= 13.61\underline{/-90^\circ}$ per unit

$I_{U2} = I_{U1}$

$$I_{U0} = (\text{distribution factor})I_0 = \frac{0.713\underline{/50.06^\circ}}{0.731\underline{/51.23^\circ}} I_0$$

$= 13.30\underline{/-91.17^\circ}$ per unit

$I_{UA} = I_{U1} + I_{U2} + I_{U0} = 40.518\underline{/-90.39^\circ}$ per unit

$I_{UB} = a^2 I_{U1} + aI_{U2} + I_{U0} = 13.93\underline{/91.12^\circ}$ per unit

$I_{UC} = aI_{U1} + a^2 I_{U2} + I_{U0} = 13.93\underline{/91.12^\circ}$ per unit

The actual fault currents can now be calculated using the base current for the 12.47 kV system, according to equation 3-5; page 43:

$I_{base}$ = 463 amperes

$I_A = I_{base}\ I_A$ = $(463)40.92\underline{/-90^\circ} = 18946\underline{/-90^\circ}$ amperes

$I_B = 0$

$I_C = 0$

$I_{SUT\ A} = 226\underline{/55.67^\circ}$ amperes

$I_{SUT\ B} = 190\underline{/-48.57^\circ}$ amperes

$I_{SUT\ C} = 190\underline{/-48.57^\circ}$ amperes

$I_{UA} = 18760\underline{/90.34^\circ}$ amperes

$I_{UB} = 6450\underline{/91.12^\circ}$ amperes

$I_{UC} = 6450\underline{/91.12^\circ}$ amperes

In order to obtain the values of the fault current contribution on the 480 volt base of the generator system, the positive and negative sequence currents must be calculated on the low voltage side of the step-up transformer. Following the rules as specified on page 52:

$$I_{WTG\ 1} = I_{SUT\ 1}\underline{/-30°} = 0.0319\underline{/-117.57°} \text{ per unit}$$

$$I_{WTG\ 2} = I_{SUT\ 2}\underline{/+30°} = 0.0319\underline{/-57.57°} \text{ per unit}$$

$$I_{WTG\ 0} = 0$$

$$I_{WTG\ A} = I_{WTG\ 1}+I_{WTG\ 2}+I_{WTG\ 0}=0.0553\underline{/-87.57°} \text{ per unit}$$

$$I_{WTG\ B} = a^2I_{WTG\ 1}+aI_{WTG\ 2}+I_{WTG\ 0}=0.0553\underline{/92.43°}\text{per unit}$$

$$I_{WTG\ C} = aI_{WTG\ 1}+a^2I_{WTG\ 2}+I_{WTG\ 0} = 0$$

The actual fault currents can be calculated using the base current of the 480 volt system, according to equation 3-5, page 43:

$$I_{base} = 12028 \text{ amperes}$$

$$I_{WTG\ A}= I_{base}(I_{WTG\ A})=(12028)(0.0553\underline{/-87.57°})=665\underline{/-87.53°} \text{ amperes}$$

$$I_{WTG\ B}= 665\underline{/92.43°} \text{ amperes}$$

$$I_{WTG\ C}= 0$$

In summary, fault currents for both three-phase and single-phase-to-ground faults were calculated for both the small and large wind turbine generators, interconnected to the utility system. Results of these calculations are presented in Tables 1 and 2, pages 71 & 72, which show fault currents for the small and the large wind turbine generators, respectively. This information will be used later in Chapter IV to determine the types of protection and interrupting devices required for the wind turbine generators and utility interconnections.

| | Total Fault Current (At Fault) | WTG Fault Contribution (240 v Base) | Utility Fault Contribution (12.47 kV Base) |
|---|---|---|---|
| 3Ø Fault at Generator Terminal | 11,347 | 397 | 213 |
| 3Ø Fault on Transformer 12.47 kV Terminal | 9,860 | 389 | 9852 |
| 1Ø Fault on Generator Terminal | 0 | 0 | 0 |
| 1Ø Fault on Transformer 12.47 kV Terminal | | | |
| AØ | 8,441 | 173 | 8348 |
| BØ | 0 | 173 | 101 |
| CØ | 0 | 0 | 101 |

All of the above values are given in amperes

Single-Phase-to-Ground and Three-Phase
Fault Current Values for
the Small Wind Turbine Generator

Table 1

| | Total Fault Current (At Fault) | WTG Fault Contribution (480 v Base) | Utility Fault Contribution (12.47 kV Base) |
|---|---|---|---|
| 3Ø Fault at Generator Terminal | 17,489 | 1280 | 632 |
| 3Ø Fault on Transformer 12.47 kV Terminal | 18,348 | 1215 | 18,301 |
| 1Ø Fault on Generator Terminal | | | |
| AØ | 19,738 | 7,325 | 415 * |
| BØ | 0 | 6,231 | 0 |
| CØ | 0 | 6,231 | 415 * |
| 1Ø Fault on Transformer 12.47 kV Terminal | | | |
| AØ | 18,946 | 665 | 18,760 |
| BØ | 0 | 665 | 6,450 |
| CØ | 0 | 0 | 6,450 |

* Fault current values prior to operation of generator 480 volt circuit breaker.

All of the above values are given in amperes

Single-Phase-to-Ground and Three-Phase
Fault Current Values for
the Large Wind Turbine Generator

Table 2

## Chapter IV

## General Protective Relay Schemes

Numerous relay schemes for the protection of large generators have been developed and successfully applied; the purpose of this chapter is to present and evaluate the protection which will be required for the wind turbine generator systems under consideration. Generally, the main objectives of generator protection should include these items:

1. Minimize damage to generator components for internal faults,

2. Minimize the adverse effects of generator internal faults on the rest of the power system, and

3. Protect the generator from adverse conditions imposed by the power system.

The most important stresses to which a generator is subjected are: electrical voltages which may stress the insulation, mechanical forces which affect various parts of the machine, and temperature rises. A well designed machine must be able to withstand normal operating conditions over its expected lifetime, as well as certain excesses, provided that they do not occur too frequently. To protect against operating conditions beyond the design limits, properly designed protection must be applied. Since the wind turbine generators are connected to a utility system, the generator protection must also interface with the utility system's protection.

To a large extent, the amount of protection which will be provided is inversely proportional to the amount of risk which can be accepted. The higher the level of protection, the higher the sophistication and cost, but risk of major damage due to a fault is decreased. This point must be considered throughout the discussion: what may constitute an unacceptable risk to one person may be accepted by another, depending on the costs involved.

The major types of generator relay schemes which are applicable to the wind turbine generators are:

1. Differential protection
2. Ground fault protection
3. Overcurrent protection
4. Overheating protection
5. Overvoltage (overspeed) protection
6. Loss of excitation protection
7. Negative sequence protection
8. Vibration protection
9. Generator motoring protection
10. Field ground fault protection

A short discussion of each of the above types of generator protection is presented in order to highlight the application of and protection provided by each scheme.

In most of the following schemes, it is specified that operation of the protective scheme should trip the generator circuit breaker, and halt the generator. Wind turbine generators, unlike most other machines, are equipped with mechanical and/or electrical brakes which are capable of slowing the rotor to a stop. This is required to lock the wind rotor in case of excessive wind velocities, but can also be initiated by the operation of other protective schemes to minimize generator damage.

1. Differential Protection

It is standard practice for manufacturers to recommend differential protection for low voltage generators rated 1000 KVA or higher and medium voltage generators rated 500 KVA or higher. Generators below these ratings are considered "small", and are rarely supplied with the sophisticated protection provided by differential relays. However, it is not the size of a generator that determines how complex the protection should be; rather it is the effect on the rest of the system for a prolonged fault in the generator, and how great the hardship would be if the generator was badly damaged by a fault and out of service for an extended time to effect major repairs.

In differential protection, the currents in each phase on either side of the machine are compared in a differential circuit. Any unbalance in the currents results in a differential current which operates the relay. For normal operation or for faults outside the relay's zone of protection, the current entering the machine equals the current leaving in all phases (neglecting internal losses). The differential current is very small, and the relay is set above the maximum current value expected during full load conditions. Internal faults result in large differential currents which quickly operate the relay, trip the generator circuit breaker, and halt the generator.

Since the current transformers on each side of the generator are not perfect, they will not yield exactly the same secondary currents for the same values of primary currents. The differences are caused by variations in the manufacturing processes, unequal lengths of leads to the relays, and unequal burdens of devices connected in the secondaries of one or both current transformers. While normally very small, this differential error can be quite large during external fault conditions. Percentage differential relays utilize restraining coils to measure the total secondary fault current and desensitize the relay operation for high fault currents when the current transformer error is greatest. The amount of current required to operate the differential relay increases as the magnitude of the external fault current increases. The effect of the restraint windings is negligible during internal fault conditions, since the operating coil has more ampere-turns and it receives the total secondary current.

Use of differential generator protection requires that access is provided to the leads at both ends of each winding so that current transformers can be fitted. Since this is an additional expense, most small units do not have both leads accessible from the exterior of the machine - normally access is only provided for the output leads. Without leads from both sides of each winding, differential protection can not be provided.

2. Ground Fault Protection

Generator ground fault protection is highly desirable, since faults inside the generator generally occur as a ground in one of the phase windings and may spread to involve other phases. Grounding of the generator neutral is widely practiced where possible, since it has the following benefits:

a. Mechanical stress on the generator windings is limited, since the maximum phase-to-ground fault current in any winding must be equal to, or less than, the maximum three-phase fault current.

b. Selective relaying is made easier for phase-to-ground faults.

c. Transient overvoltages are limited to safe values during phase-to-ground faults.

d. Damage at the fault is minimized. [13]

The most practical method of providing ground fault protection for small wye-connected generators is to ground the generator neutral through a resistor. A current transformer is placed in the neutral lead to measure the ground current and provide an input signal to a time-delayed overcurrent relay. Operation of the relay should isolate the generator by opening the main power circuit breaker, and bring the generator to a stop.

The actual value of the resistor has two major effects on the operation of the protective systems:

a. The higher the value of the resistor, the less damage as done to the generator, since the fault current is limited by three times the value of the resistance. (The total fault current is equal to the system voltage divided by the total resistance. Since $I_F = 3I_o$ and all of the sequence currents are assumed to be equal and in series, the resistances between the neutral point and ground for any device may be replaced by three times its value if the resistance is shown only in the zero sequence diagram. The calculated fault currents would be too large if only the actual resistance value was used.

b. The higher the value of the resistor, the greater the relay sensitivity, since more of the available voltage is consumed by the zero sequence impedance, and less in the positive and negative sequence impedances.

The resistor cannot be made too large, since this will limit the sensitivity of transformer differential relays, and will increase the sensitivity of the ground fault relay to transient overvoltages. Time delay on tripping is desirable in order to provide selectivity with other protective devices for single-phase-to-ground faults on the system and in potential transformer secondary circuits.

### 3. Overcurrent Protection

If only the generator output leads are available for the addition of current transformers, protection must be limited to the use of overcurrent relays instead of differential relays. In this case, the overcurrent relays can provide protection for generator internal faults only if sufficient fault current is supplied by the rest of the system. Protection for internal faults is not provided if the main power circuit breaker is open, or if the system has no other supply source. If protection is desired only for generator internal faults, directional overcurrent relays must be used; otherwise, non-directional voltage-restrained overcurrent relays will provide protection for both internal and external faults. Operation of this scheme should trip the generator circuit breaker and bring the generator to a stop.

4. Overheating Protection

Overheating protection for generator overload conditions is desirable and fairly easy to provide. Small generators, rated under 30 MVA, are generally provided with replica-type temperature relays.[18] This relay is energized directly by the current passing through one of the machine phase windings, or from a secondary of one of the phase current transformers. Heating and heat storage devices in the relay heat and cool at nearly the same rate as the machine, in response to the current variations. A thermostat element operates to provide a machine shut-down signal at a preselected temperature.

Another type of overheating relay which is available operates from the signals of temperature-detecting devices imbedded in the machine windings. This system would respond both to overload conditions and to failure of the generator's cooling system. Normally, this type of relay is provided only on large generators. Operation of either type of protective device should trip the main power circuit breaker, but allow the generator to rotate in order to cool the unit. Only in case of cooling system failure should the generator be stopped.

5. Overvoltage Protection (Overspeed)

Overvoltage protection is generally provided on all generators which are susceptable to overspeed or overvoltage on sudden loss of load. This type of protection can be provided by the voltage regulating unit, but it may be provided by a separate time and instantaneous overvoltage relay connected to a potential transformer on the stator output leads. The time-delay overvoltage unit is normally set to operate at 110 percent of rated voltage, and the instantaneous unit is set at 130 to 150 percent. Operation of this scheme should trip the generator main circuit breaker and initiate generator shutdown.

Overspeed protection is provided by a mechanical or equivalent electrical device which measures the speed of rotation of the generator main shaft. The overspeed detector is connected to operate at three to five percent above the generator's rated speed. Protective action should include opening the main circuit breaker and halting the prime mover.

Generally, only overvoltage <u>or</u> overspeed protection is applied, since they provide essentially the same protection, but by different means.

## 6. Loss of Excitation Protection

Loss of excitation protection is required to prevent damage to the generator or loss of system stability. When a synchronous generator loses excitation, it operates as an induction generator at a speed above the synchronous speed. Round rotor generators do not have amortisseur windings to carry induced rotor currents which result from this type of operation. Consequently, the rotor will overheat, particularly at the ends, in as little as two minutes. Stator currents can reach as high as two to four times the rated values, resulting in overheating of the stator.

Large generators may cause system instability upon loss of excitation, since a reactive load of two to four times the machine's rated load must be supplied from the system. Unless this reactive demand can be met, system voltage will drop and instability may result. For small generators, the reactive demands placed on the system for loss of excitation will not present a problem.

Undercurrent relays may be placed in the field circuit to detect loss of excitation, but the most sensitive protection is provided by a directional distance relay, set to "see" into the generator. When excitation is lost, the equivalent generator impedance moves from the first quadrant into the fourth quadrant of the impedance diagram, a condition easily detected by the directional distance relay. Operation of loss of excitation protection should trip the main and field circuit breakers and, if the problem can be corrected, the generator can be returned to service without shutdown.

## 7. Unbalanced Three Phase Stator Currents

Unbalanced three phase stator currents will cause currents of twice the system frequency to be induced in the rotor. If allowed to continue, these currents may cause severe machine vibration and overheating of the rotor. The length of time that a generator can withstand unbalanced rotor currents is given by the formula:

$$\int_0^t i_2^{\ 2} \, dt = K \qquad (4\text{-}1)$$

where $i_2$ = instantenous negative sequence component of stator currents as a function of time

$t$ = time

$K$ = generator constant (assumed to be about 40 for small generators)

If the integrated value of equation 4-1 is between K and twice the value of K, the generator may suffer varying degrees of damage. But, if the integrated value of equation 4-1, is greater than twice the value of K, severe damage to the generator will occur.

Recommended protection consists of an inverse time overcurrent relay operating from the negative sequence currents in the stator. Proper coordination with the system relaying is required, since remote relays may respond to unbalanced phase currents in the generator. Operation of the scheme should trip the main circuit breaker.

8. Vibration Protection

Protection for vibration should be provided for all generators to minimize exposure to vibration. A variety of conditions can cause severe vibration, including unbalanced stator currents or ground faults in the field. Generally, vibration protection is provided by mechanical devices, such as a spring-mounted detector or a simple paddle switch. Operation of the relay should trip the main circuit breaker and halt the generator, although care must be taken to avoid severe vibrations which may increase as the machine slows down.

9. Generator Motoring Protection

Protection for generator motoring benefits the prime mover, not the generator. In situations where the power supplied to the generator from the prime mover is lost, the generator will operate as a motor, requiring power from the system. Depending on the prime mover, damage may result due to overheating in the turbine or engine used to drive the generator.

Sensitive power directional relays may be used to detect reverse power to the generator. Required settings for the relays vary from 0.5 to 15 percent of the generator rated power, depending on the type of prime mover. Operation of the scheme should trip the main circuit breaker.

## 10. Field Ground Fault Protection

Field ground fault protection is used to detect ground faults in the normally ungrounded field circuit of a generator. A single ground fault will not damage the generator or affect the generator operation in any way, but it does increase the stress on the insulation at other points in the field wiring. The probability of a second ground fault is increased; this second fault will short out a part of the field winding so the current through the remaining portion will increase. The air-gap fluxes will be unbalanced, which will unbalance the magnetic fluxes on the rotor, causing severe vibration and eccentricity of the rotor shaft.

Protection consists of either detecting the ground fault or using vibration detectors to monitor the resulting vibration.

Operation of either type of relay should trip the main circuit and field breakers, but allow the generator to continue rotating, since the rotor may return to its original shape. Stopping the generator for a field ground fault may result in a permanent "set" to the rotor shaft or even more severe vibration as the generator slows, due to resonance.

## System and Interconnection Protection

Protective philosophy of the test utility, as applied to customer-owned equipment, is to apply protective relays which will operate for any faults or abnormal conditions at the point of customer ownership and up to the first customer-owned disconnecting device at the interconnection. Invariably, protection is provided for some of the customer's equipment as well, although the test utility will not accept responsibility for providing protection for any of the customer's equipment. Nor will the test utility delete any of its own relays, even if the customer's protection package provides coverage for part of the utility's system.

Transformer protection for large transformers generally consists of differential and sudden pressure relays, with additional oil level and high temperature relays. However, small distribution transformers of the size considered here can be adequately protected by the use of overcurrent devices such as fuses or overcurrent relays. The characteristic of the protective device must be matched to the withstand time of the transformer for through faults. Placement of the overcurrent devices must be carefully considered, since single phase to ground faults on the delta-connected side of the transformer will not be detected from the wye-connected side, once the fault is isolated by the delta side relaying. In addition, most distribution transformers are supplied with a pressure relief device to vent the tank pressure caused by internal faults.

On the test utility's distribution system, each 12.47 kV line is protected with time and instantaneous overcurrent relays supplied from current transformers in power circuit breaker bushings. One breaker is provided for each line connected to a substation 12.47 kV bus. Overcurrent relays monitor each phase and the neutral of each line.

The instantaneous relay provides protection for close-in faults on the main portion of the distribution line; it is set to cover as much of the 12.47 kV line as is possible without causing the line to trip unnecessarily for faults on distribution transformer secondaries or for faults beyond protective devices located on the line. Length of line protection is a function of the line impedance and is generally available for five miles of line measured from the substation circuit breaker. Instantaneous overcurrent protection clears faults on the main portion of the line in a minimum amount of time and limits equipment and conductor damage. Test data indicates that 90 percent of faults are transient, requiring no repairs following interruption of the fault. Instantaneous clearing of transient faults allows the circuit breaker to be reclosed within one-half second.

If the first trip and reclose operation of the circuit breaker is unsuccessful, further operation of the instantaneous overcurrent relay is blocked to allow selective coordination of the time overcurrent relays with other automatic sectionalizing devices located on the distribution line. Permanent faults which are beyond the line sectionalizing devices should be cleared in such a manner to remove the least amount of line from service. The time-overcurrent relays must clear faults on the main portion of the distribution line, but must not operate before line protective devices, which may be able to isolate the fault.

Usually, three attempts are allowed to reclose the line circuit breaker: an instantaneous reclosure, a time-delayed reclosure at 15 seconds, and a final reclosure attempt at 145 seconds. If the circuit breaker trips after the third reclosure, then automatic reclosing is blocked. Further attempts to reenergize the line must be performed manually or by remote control, after the fault is located and isolated.

The above sequence of operation applies to a distribution line which is operated radially, that is, fault current can flow in one direction only, from the substation bus out to the line. No other sources of power are available on the 12.47 kV line to supply a fault.

However, for lines which have a substantial amount of generation capacity located at some point on the distribution line, the effect of the line contribution to a fault on the bus or adjacent lines must be considered. The instantaneous and time overcurrent relays are not directional, hence they will operate for any fault current magnitude above the relay set point, regardless of the direction of the power flow. Bus faults or close-in faults on adjacent lines may cause reversal of the current flow in an unfaulted line which has generation, and may lead to incorrect tripping. Directional relays, properly applied, use a polarizing current, voltage or combination of both to determine if the fault is internal or external to the protected line. Tripping is permitted only for internal faults, and is not initiated for external faults.

Determination of the need for directional overcurrent relays must be evaluated for each individual location. Unless the amount of generation located on a line is quite large compared to the total load supplied by the line, the generators will not be able to maintain their terminal voltage and supply current to the fault. For small generators, the generator protective devices would trip the units before any appreciable amount of power could be detected by the substation circuit breaker protective devices.

The preceding discussion has attempted to provide a brief summary of the standard types of protective schemes which are available for generators, transformers and distribution lines. In the case of the wind turbine generators considered in this paper, the individual unit size is much smaller than those normally installed by a utility. The smaller capacity of these machines and their unique operating characteristics suggest that some of the standard relay schemes may not be applicable, but that specialized schemes may be required. Protection schemes for both the small and large wind turbine generator systems will be evaluated and developed in the next chapter.

Chapter V

# Protection of the Small and Large Wind Turbine Systems

Before discussing the protection which is required for each of the wind turbine generators, an assumption must be made concerning whether the generators will be operated as attended or unattended stations. The following protective systems will be specified for unattended operation of the generators. Considering the small capacity of the generators and their purpose, it is impractical to assume that an operator will always be on duty, although the owner would be available at least periodically. Completely automatic relaying will be specified-all protective relay operations will isolate the faulted equipment, not just alarm the condition as might be appropriate for a manned installation.

## Small Wind Turbine Generator System

The small wind turbine generator is a very unique system, since the a.c.-d.c.-a.c. power transformation effectively blocks any current flow from the utility system to the generator for generator internal faults. While this characteristic will simplify the protective system, it may also limit the protection that can be provided for certain generator faults.

Since the small wind turbine generator is supplied as a delta-connected machine, without access to the internal phase connections, generator differential protection cannot be applied.

Similarly, since no generator ground connection is available and the generator output is connected to a static rectifier, the neutral grounding protection as previously described is not applicable. If a phase-to-ground fault occurs in either the generator windings or on the leads to the rectifier, no fault current will flow, as shown in the fault current calculations of Chapter III. The only result of a phase-to-ground fault is that the phase voltages will shift with respect to ground potential. The faulted phase will be at or near ground potential and the other two unfaulted phases will have phase-to-ground potentials equal to the unfaulted phase-to-phase potentials. All three phases will maintain their phase-to-phase voltage magnitudes and phase relationships. The fault should be detected and cleared since the phase-to-ground insulation on the two unfaulted phases will be overstressed and may result in a second fault, with large fault currents.

The best solution to recognizing the fault is to monitor the phase-to-ground voltage of one phase with an overvoltage - undervoltage relay. It is not necessary to monitor all three phases since the faulted phase voltage will approach zero, and the unfaulted phase-to-ground voltages will increase by a factor of 1.7. Operation of the relay should deenergize the generator and halt the rotor, as well as provide an alarm or target to identify the fault. No major damage to the generator will occur, but the chance of a more severe double-phase-to-ground fault must be prevented.

Overcurrent protection, in the form of either overcurrent relays or fuses, should be applied at the generator terminals. Neither the relays nor the fuses will recognize internal faults, since there is no other source of fault current, but protection will be provided for external faults, such as faults on the generator leads or failure of the rectifier. Protection will also be provided for generator overload conditions, or for faults elsewhere in the system. Voltage-controlled overcurrent relays will not be required, since faults on the generator leads or in the rectifier will draw more fault current than the generator full load current, as seen in the calculations of Chapter III. Operation of the relay should deenergize the generator and halt the rotor, as well as provide an alarm or target to identify the fault.

Overheating protection is recommended for this generator, especially since protection by normal relay schemes is rather limited due to the lack of fault contributions from the utility system. It is doubtful if temperature detectors would be embedded in the windings of such a small machine, but the replica-type overtemperature relay will suffice. Overheating protection will provide slow but eventual clearing for some generator internal faults or unbalanced conditions. Operation of the relay should deenergize the generator, halt the rotor and provide an alarm or target.

Overspeed protection is mandatory for any wind turbine generator, since a sudden loss of load or gusting winds can cause a very rapid buildup in rotor speed. In the case of wind turbine generators, the greatest concern is for the rotor blades, which must withstand substantial forces at the blade tips. Blade tip speeds are a limiting factor to the largest technically feasible blade diameter as well as the maximum allowable wind velocity. The most reliable indicator of rotor speed is a mechanical device which monitors the angular velocity and operates at a preset limit. Operation of the scheme should deenergize the generator, halt the rotor and provide a target or alarm.

Protection for loss of excitation in small generators such as this is generally not feasible, unless it is part of a package in the field circuit. Loss of excitation can cause voltage disturbances on the system, rotor overheating and loss of synchronism only if a synchronous tie is maintained with the utility system. Since the small wind turbine generator is electrically isolated from the system and it is of such small capacity compared to the system, loss of excitation protection has no value and is not recommended.

Protection against unbalanced faults or open phases is not required for the small wind turbine generator since the utility cannot provide negative sequence currents to the generator. Unbalanced faults on the generator leads or in the generator windings will be detected by the overcurrent protection or the overvoltage-undervoltage relay. Excessive heating of the generator windings caused by unbalanced currents will operate the overheating protection.

Motoring of the generator is not possible due to the rectifier and inverter between the generator output and the utility system. No current can flow from the utility to supply the generator if input from the wind rotor is lost, therefore this protection is not required.

Vibration protection is especially important for wind turbine generators, since the possibility of blade breakage, icing or loss of excitation could cause major vibration damage to the generator and its bearings. In addition, pulsating forces on the blade caused by wind shear effects or tower shadow may at times match the natural frequency of the tower. All of these vibration sources underscore the requirement for reliable mechanical devices to detect excessive machine vibration, trip the generator circuit breaker and halt the generator, plus initiate an alarm or target.

Protection from ground faults in the field circuit is generally not supplied for small generators, unless the static excitation package includes this protection. Since a single ground fault in the field circuit will not damage the generator, and a second ground fault is detectable by the vibration relays, it is not necessary to provide a separate protection scheme. The vibration protection will be considered as adequate coverage for this size of generator.

Protection of the direct current system and the battery, if applied, should consist of overvoltage-undervoltage protection and ground fault detectors. Use of a battery connected to the d.c. bus is advisable since it permits some storage of energy so the system can tolerate a period of no wind energy, and more importantly, it helps to smooth the ripples of the d.c. bus voltage. Overvoltage - undervoltage protection should be applied to the bus to detect if the generator is not charging the battery properly, or coming up to speed too quickly and increasing the d.c. voltage beyond the equipment limits. Excessive d.c. bus voltage can damage the inverter and create a three-phase fault across the generator terminals. Undervoltage protection is required to protect the battery from being discharged to the point of damage, a possibility if the wind energy is very low or non-existent over a period of time.

Ground fault protection is required on the d.c. system since the bus is not grounded, but is allowed to float with respect to ground potential. As in the generator excitation system, a single ground fault would not result in any fault current, but a second ground fault could cause great damage due to the high currents. Ground detection consists of connecting a center-tapped resistor between the positive and negative d.c. buses, with the resistor tap grounded. By monitoring the voltage across the two resistances, the presence of a single ground will cause one voltage to approach zero and the other voltage will double. Operation of this scheme should trip the generator main circuit breaker, any breakers on the a.c. side of the inverter and provide a target or alarm.

Protection of both the rectifier and the inverter can best be accomplished by the use of fuses, matched to the thermal characteristics of each device. Faults on the d.c. bus or the a.c. voltage side of the inverter could damage the semiconductor controlled rectifiers (SCR's) used in both the rectifier and the inverter. Damage to one of the SCR's could also be detected and cleared by the fuses. In addition, the inverter has a.c. voltage-operated contactors on both the input and output leads, which deenergize the inverter for loss of a.c. line potential. This is a safety feature to prevent a deenergized line from being energized by the wind turbine generator through the inverter.

A decision can now be made in the choice of disconnecting devices used for the small wind turbine generator system. Although adequate overcurrent protection for the generator can be supplied by the 240 volt fuses, the additional relay protection schemes require a circuit breaker to deenergize the generator. Overcurrent protection alone, as provided by fuses, will not be adequate protection for the generator. Automatic or remote reclosing control will probably not be advisable, since the generator should be inspected to determine the cause of the malfunction before being returned to service. Synchronizing logic will not be required, since the a.c.-d.c.-a.c. transformation provides electrical isolation between the generator and the utility line.

The utility system can supply multi-phase fault currents for faults only as far as the inverter; beyond that point, the SCR's will block a.c. current flow. Therefore, the utility protection requirements may be fulfilled by installation of fused disconnect switches on the 12.47 kV side of the transformer. If the transformer is owned by the utility, normal practice is to size the fuses to clear for fault current at twice the transformer's rated current. This will allow adequate margin for temporary overloads, but will clear even a fault on the transformer low-voltage terminals. Faults on the 12.47 kV distribution line need not be cleared by the transformer fuses, since the utility's line circuit breaker at the substation will clear the fault and deenergize the line. Without a.c. voltage on the distribution line, the inverter will not be able to transmit power from the d.c. bus to the a.c. line.

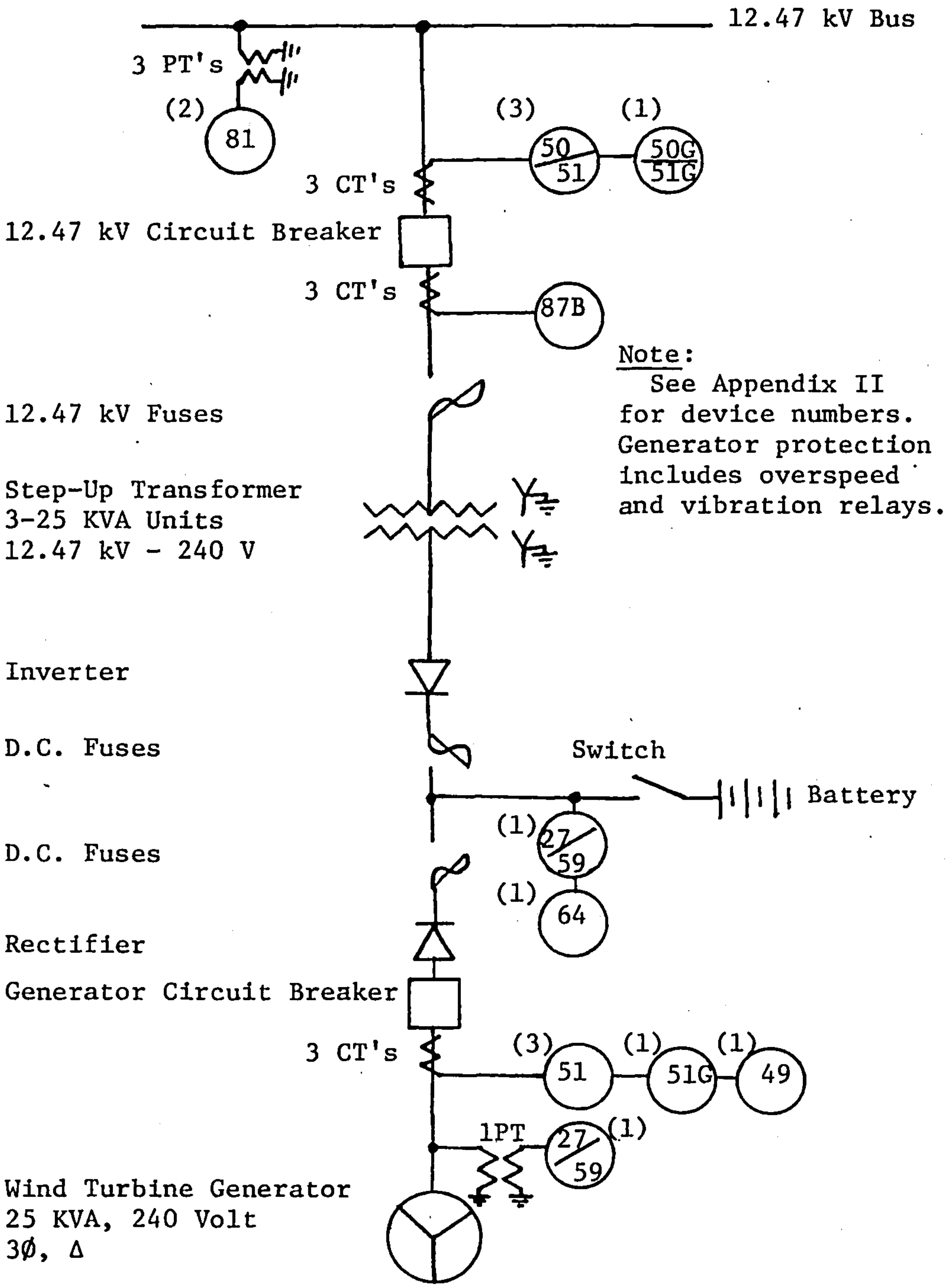
Single-phase-to-ground faults on the 240 volt side of the step-up transformer can not be detected by the 12.47 kV fuses, since no fault current will flow from the utility system through the delta-wye connected transformer, after the generator breaker opens. Since the overcurrent relays at the generator terminals will probably detect the fault and trip the generator breaker faster than the 12.47 kV fuses can melt, the fault will not be isolated from the utility system. This can be corrected by one of two possible solutions: install a 12.47 kV breaker with overvoltage-undervoltage relays to detect the ground fault or replace the delta-wye transformer with a grounded wye-wye unit (this will allow single-phase-to-ground fault currents to pass through the transformer). The best solution is to use a grounded wye-wye transformer; installation of a 12.47 kV breaker and relaying would be very expensive. Since the generator is delta connected, no zero sequence currents can flow from the generator for utility system faults, and the rectifier-inverter combination blocks zero sequence current flow from the utility for generator faults. The delta-wye transformer connection is unnecessary; use of a grounded wye-wye unit will not result in increased generator ground fault current magnitudes.

The standard complement of time and instantaneous overcurrent relays at the utility's 12.47 kV line breaker will suffice for phase and ground fault protection. Fault current contribution from the wind turbine generator for faults on the 12.47 kV bus or an adjacent line will be less than seven amperes (the value calculated in Chapter III for a three phase fault on the step-up transformer 12.47 kV bushings). This is insignificant to the utility relays, and will not require voltage control of the overcurrent relays to prevent false tripping of the 12.47 kV line breaker at the substation.

A one line diagram of the small wind turbine generator system and utility 12.47 kV line is shown in Figure 13, page 107. All of the recommended protection schemes have been indicated, along with interrupting devices and instrument transformers.

## Large Wind Turbine Generator System

The large wind turbine generator system is more of a standard generation system and easier to protect, than the small




One Line Diagram - Recommended
Protection for Small Wind Turbine Generators

Figure 13

wind turbine generator, for two reasons:

1. The large wind turbine generator has wye-connected stator windings, and both terminals of each winding are accessible for protection purposes.

2. The generator operates at synchronous speed; therefore it is directly connected to the utility system through a step-up transformer and a circuit breaker.

Minimum protection for generator internal faults, generator overload conditions and system phase faults can best be provided by the use of three voltage-controlled overcurrent relays, one per phase, monitoring the current in the generator output leads. Since the machine synchronous impedance, line impedance and arc resistance may limit the sustained available fault current, voltage-controlled overcurrent units have the advantage of not operating unless the voltage is below a predetermined value. The overcurrent units can be set below the rated load level but will not operate unless a fault is present to reduce the voltage. Internal machine faults may be detected by the overcurrent relays, since the utility system is capable of supplying significant amounts of fault current. Operation of this scheme should trip the generator circuit breaker, halt the generator and provide an alarm or target.

Since the generator neutral connection is accessible, it is recommended that it be grounded through a suitable resistor, for the reasons discussed in Chapter IV. Ground fault protection is then required, and should consist of a time-delayed overcurrent relay supplied by a current transformer monitoring the current in the generator neutral lead. Operation of the overcurrent relay should trip the generator circuit breaker, halt the generator and provide a target or alarm. The practice of the test utility is to size the neutral resistor to limit the phase-to-ground fault current from five to fifteen amperes, in order to limit damage and allow for greatest relay selectivity. The resistor must have a sufficient rated wattage to withstand the fault current for the amount of time required to deenergize the generator.

Since time-delayed operation of the phase overcurrent relays is required to coordinate with other protective devices on the distribution system, generator protection for internal faults must be compromised. Similarly, the time-delayed setting for the ground fault relay will not operate for all generator internal faults. In addition, if the utility's 12.47 kV circuit breaker is opened and the wind turbine generator is supplying the connected load, no protection is supplied for generator multi-phase internal faults since the utility system cannot supply fault current to operate the overcurrent relays.

Therefore, generator differential relays are desirable although not absolutely required, since they provide instantaneous, sensitive detection of generator internal faults. Differential relays provide generator protection for single-phase-to-ground as well as multi-phase faults, with or without fault current contributions from the utility system. The drawback to differential relays is in the relatively high cost--not only are three differential relays required, but also six high-accuracy current transformers are needed. Preferably, no other relays or meters are wired to these current transformers; they should be dedicated to differential protection. Many small generators of the size considered here do not have the separate phase leads available on the neutral side of the windings; usually the neutral connection is made internally in the generator, so only the neutral lead is accessible. In this case, differential relays can not be applied. If the generator leads are available and the owner is willing to make the investment (which is small in comparison to the value of the wind turbine generator), differential relays, especially percentage differential relays, are a highly recommended protection package. Operation of the relays should trip the generator circuit breaker, halt the generator and provide an alarm or target.

Overheating protection is recommended for this generator, especially to provide protection for unbalanced conditions on the system. Single-phase-to-ground faults or an open phase on the utility system can cause negative sequence currents to circulate in the generator, causing high internal temperatures. Overheating protection, either by the embedded temperature detectors or by the replica-type overtemperature relay, will provide protection for these unbalanced conditions, as well as backup protection for internal faults or generator overload conditions. Operation of this scheme should trip the generator circuit breaker, halt the generator, and provide a target or alarm.

Overspeed protection is required for the large wind turbine generator, for identical reasons as those discussed for the small wind turbine generator. Operation of overspeed protection should trip the generator circuit breaker, halt the generator and provide a target or alarm. An overvoltage relay, used in this instance for overspeed detection, would be relatively insensitive, since the synchronous connection to the utility system would tend to maintain a fixed voltage. Mechanical overspeed detectors are the preferred devices for this type of protection.

Synchronous generators can not tolerate an external unbalanced fault nearly as well as they can withstand three-phase faults. Negative sequence currents flow during the unbalanced fault or for open phase conditions, and will induce 120 Hz currents in the reverse direction in the generator rotor. If sustained, these negative sequence currents can overheat the rotor and cause extensive damage. Protection is already provided by several other schemes; overheating protection, overcurrent protection and the generator ground fault protection. The combination of these schemes will provide adequate protection, but a time delay is imposed before clearing by any scheme; so the generator will heat up considerably before being deenergized. Better protection for unbalanced conditions can be provided by installing a negative sequence overcurrent relay to detect the negative sequence currents, trip the generator circuit breaker, halt the generator and provide an alarm or target. This protection is especially advisable if fuses are used anywhere between the utility source and the generator. Opening one fuse for a single-phase-to-ground fault is possible and is not easily detected by the overcurrent or ground fault relays.

Vibration protection is as important for the large wind turbine generator as for the small unit, since the same hazards are present. A mechanical device should be provided to detect excessive machine vibrations, trip the generator circuit breaker, halt the generator and provide an alarm or target.

Generator motoring protection is a requirement for wind turbine generators operated in synchronism with the utility system. Loss of wind power will result in the generator being connected to the utility line with no power input to the machine. The generator will operate as a synchronous motor, driving the blades. Wind turbine generators are generally provided with control schemes to feather the blades and lock the rotor for wind speeds above or below the recommended range. This scheme can also be used to open the generator breaker instead of applying sensitive power directional relays as is normally done for conventional generators.

Protection for ground faults in the generator field circuit is not necessary, following the same discussions as presented for the small wind turbine generator. Vibration protection will be adequate for detecting ground faults in the field circuit.

Disconnecting devices used in the large wind turbine generator system should be power circuit breakers. One circuit breaker should be supplied on the 480 volt system to disconnect the generator, and one 12.47 kV circuit breaker should be located at the utility bus. This arrangement will allow power to be supplied by the utility to the customer's equipment, even if the generator is out of service. (If the wind turbine generator is installed by the utility and is connected to the substation bus through a step-up transformer, only a 12.47 kV circuit breaker is required.) Although adequate overcurrent protection for the generator could be supplied by a set of 480 volt fuses, a circuit breaker is required to permit the additional protection schemes to disconnect the generator. Synchronizing the generator to the utility system should be accomplished through the generator breaker; this can not be performed by fuses or automatic circuit reclosers. Automatic or remote operation of the breakers may be desirable, particularly if the wind turbine generator is owned by the utility. Automatic reclosing of the breaker following a generator fault is not advisable, since the generator should be inspected for possible damage before being returned to service.

Directional time and instantaneous overcurrent relays should be applied on each phase of the utility's 12.47 kV circuit breaker; a non-directional time and instantaneous overcurrent relay can be applied to the neutral. The directional supervision of the phase relays is required to prevent the utility breaker from tripping incorrectly for faults on the 12.47 kV bus or on adjacent lines. Normal full load current supplied by the generator to the 12.47 kV system is almost six amperes, but the generator can supply 47 amperes for a three-phase fault on the utility's 12.47 kV bus, as shown in the calculations of Chapter III. This amount of fault current can cause non-directional phase overcurrent relays to misoperate, particularly if the utility supplied little normal load through the 12.47 kV breaker so that the overcurrent relay settings were low. Directional supervision of the ground overcurrent relays is not required since the wind turbine generator will not be able to supply zero sequence fault current to the 12.47 kV system due to the delta-wye step-up transformer connection.

Protection of the step-up transformer will be accomplished by the overcurrent relays installed at the generator and at the utility's 12.47 kV breaker. Faults between these two sets of relays, including the transformer, will operate the time or instantaneous overcurrent phase and ground relays at the utility's installation, and the time overcurrent phase relays or time overcurrent ground fault relay at the generator.

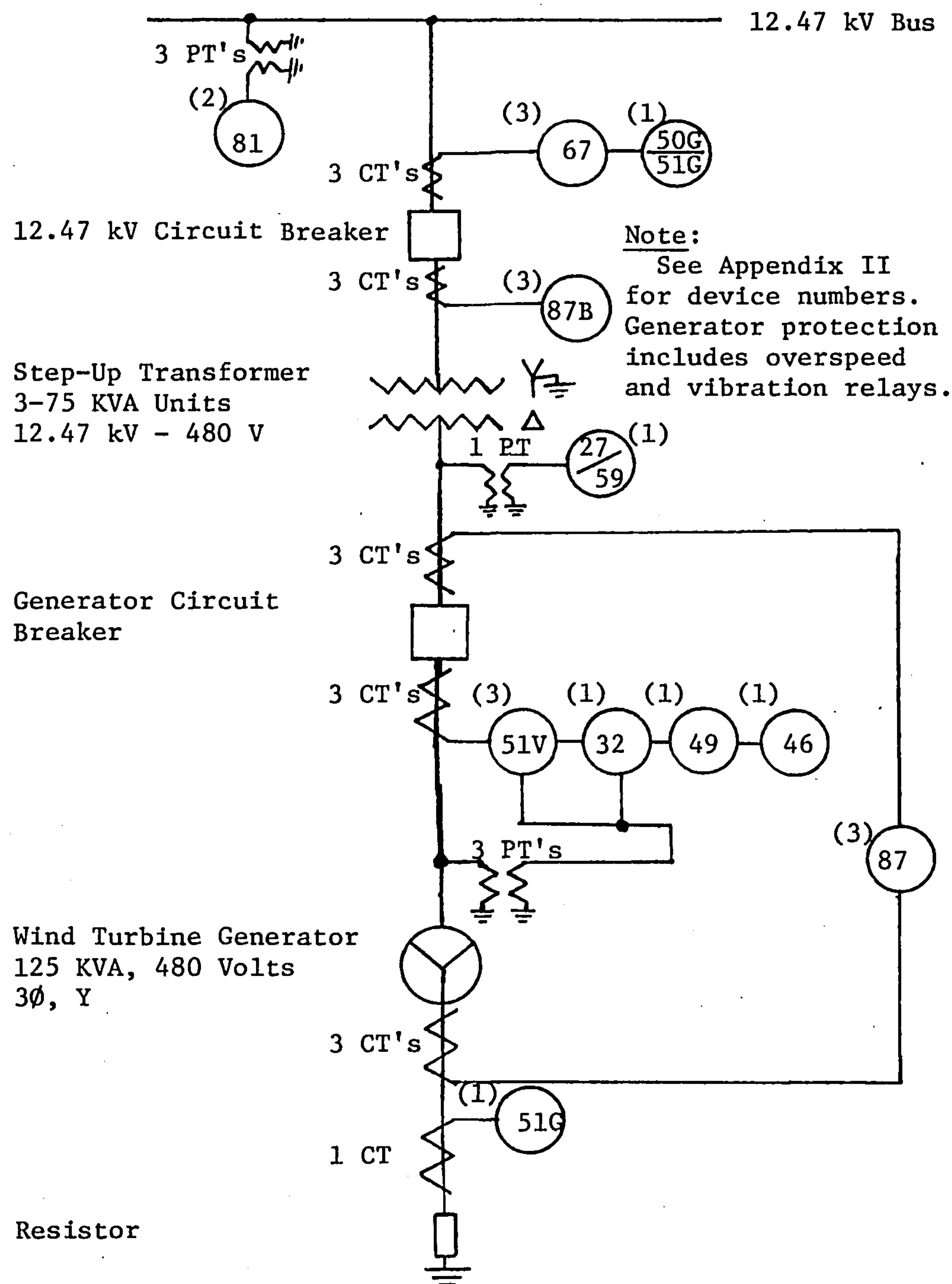
Single-phase-to-ground faults on the 480 volt side of the step-up transformer may not be recognized by the utility's overcurrent relays, since zero sequence fault current is blocked by the delta-wye transformer connection. To insure that the fault is deenergized, two options are available: the utility breaker may be tripped upon operation of the generator ground fault protection, or an overvoltage-undervoltage relay can be used to monitor one phase of the 480 volt system. After the fault is cleared by the generator circuit breaker, no fault current would flow, but the 480 volt system would remain energized through the transformer. The phase voltages would all be shifted with respect to ground potential, similar to the situation for ground faults on the small wind turbine generator system. An indication of overvoltage or undervoltage would operate the relay and trip the utility circuit breaker, plus provide a target or alarm.

Of the two schemes, tripping the utility circuit breaker for operation of the generator ground fault protection is the simplest and cheapest solution. In the case of the test utility, the installation of the separate overvoltage-undervoltage relay would probably be required, in order to conform with the utility's guidelines not to rely on customer-owned relays to clear the utility breakers.

The utility must also install underfrequency relays to trip the 12.47 kV breaker for any underfrequency conditions which could lead to damage to the generator. For underfrequency conditions, the utility would normally shed load in preselected steps in an effort to stabilize the system. Since wind turbine generators of this size cannot make an appreciable contribution to the utility to maintain voltage and frequency, it is best to trip the utility's breaker. The customer could then operate separately from the utility and use the output of the wind turbine generator to meet his own load. Failure to trip the utility's breaker on underfrequency conditions could damage the generator; it should trip upon operation of its own protective relays.

A one line diagram of the large wind turbine generator system and the utility 12.47 kV line is shown in Figure 14, page 119. All of the recommended schemes have been indicated along with the circuit breakers and instrument transformers.

Costs for each of the proposed generator protection packages will be calculated in the next chapter. If economically justified, these protection schemes will be recommended for application.




One Line Diagram - Recommended
Protection for Large Wind Turbine Generators

Figure 14

# Chapter VI

## Costs of Proposed Protection Schemes

In the previous chapter, the general types of protective relaying for small and large wind turbine generators were presented and discussed. A proposed package of protective schemes was evaluated for each wind turbine generator system under consideration, but before a final recommendation is made, the economics of these protective packages must be considered, especially in comparison with the cost for each system installation. Obviously, each additional protective scheme improves the system reliability but the cost for relaying must be justified.

First, estimates of the basic cost of the wind turbine generator installations have been calculated. Then the cost for each type of proposed relaying was estimated, to allow pricing of the total protective package. Based on these costs, the final recommended levels of protection for each wind turbine generator are presented in Chapter VII.

## Small Wind Turbine Generator Installation

### Installed Cost Estimate

The test utility installed a wind turbine generator at its Harwood Substation, identical to the small unit discussed in this paper. Costs to install the wind turbine generator and interconnect it with the utility's 12.47 kV distribution system are well documented and will be the basis of the estimated costs.

The final installed cost of the test utility's wind turbine generator amounted to approximately $230,000.* Much of this cost was due to the extra instrumentation and test procedures specified for this facility; it was treated as a research project by the utility and cannot be considered a typical installation. In addition to the basic equipment and installation costs, many "extras" were included which the average homeowner would not consider. Some of the added costs were for fencing, site preparation and stoning of the yard; construction of an access road; fence and building ground system; three-phase transformer and utility interconnection;

* All dollar figures quoted in this thesis are 1979 dollars.

single-phase electric service for on-site facilities; prefabricated building and foundation to house utility equipment, including heating, ventilation and air conditioning; requirements to meet the National Electrical Code standards; requirements to comply with OSHA regulations; telephone service, local and remote alarming; stock of spare parts; permanent project drawings according to the test utility's specifications; interest for allowance for funds used during construction and other overhead costs.[11]

A similar wind turbine generator installation using the same major components was contracted for a private homeowner at a cost of $30,000.[11] However, this price did not include these required items:

| | |
|---|---|
| Power metering-equipment and installation | $2,000 |
| Step-up transformer and associated distribution line work | $6,000 |
| Labor and material required by an electrical contractor ($500 of material, $2,500 labor) | $3,000 |

| | |
|---|---|
| Utility-type control cubicle to house equipment | $9,200 |
| Administrative and organizational time (100 hours @ $20.00) | $2,000 |
| Permanent drawings (80 hours @ $20.00) | $1,600 |
| Fencing | $2,000 |
| Local alarms | $3,000 |
| | $28,800 |

Adding the additional costs to the initial wind turbine generator price of $30,000, the complete system installed cost could easily approach $58,800. Even this figure does not include the cost of interest, the costs to meet any local electrical codes, nor the costs of the protection package.

## Cost for Proposed Protection Package

Costs for the proposed protection packages are estimated in detail in Appendix 1, page 142. A compilation of these costs for the small wind turbine generator indicates the following:

| | |
|---|---|
| 240 volt, three phase power circuit breaker including long and short time overcurrent protection | $2,240 |
| Overvoltage-Undervoltage protection | $1,310 |
| Overheating protection | $1,000 |
| *Overspeed protection (mechanical) | 0 |
| Vibration protection | $ 250 |
| D.C. bus and battery protection | $1,670 |
| *Rectifier fuses | 0 |
| *Inverter fuses | 0 |
| D.C. supply for protection schemes includes 24 VDC battery, charger and protection | $2,310 |
| Equipment cabinet | $ 340 |
| | $9,120 |

* These items are included in the price of the wind turbine generator, rectifier or inverter. The manufacturer normally supplies this type of protection as standard.

The total price for the protection package of $9,120 amounts to about 13 percent of the total installed price (based on installed price of $67,920, obtained by adding the protection costs to the previous installed cost of $58,800.) While this represents a sizeable amount to spend on "insurance", the equipment repair or replacement costs plus the energy replacement costs can easily surpass these relaying costs. One single operation of the protection scheme for faults on the a.c. distribution line, inverter, d.c. bus, rectifier or generator could justify the expenditure required for this recommended level of protection.

It should be noted that the estimated price of the protection schemes includes the cost of the generator breaker and the 24 volt battery and charger, items which could be required even if the protection package was not installed. Some type of generator disconnect device would be required, if a circuit breaker was not provided. A fused disconnect switch would have an installed cost of about $800, and would be the simplest device permitted under most electrical codes. However, the fused disconnect switch would not allow the application of other protective schemes, since there is no provision for operation by other devices. Similarly, the 24 volt battery system could be used not only for control of the protection schemes, but also for the manufacturer's turbine generator control circuitry, remote telemetering, local alarms and other various functions.

Protection costs incurred by the electric utility would be limited to installation of a set of three 12.47 kV fused disconnect switches to provide protection for the 12.47 kV line and transformer from faults on the customer's system or the transformer itself. Installed cost for these fuses is estimated at $1,000, as listed in Appendix I.

## Large Wind Turbine Generator Installation Installed Cost Estimate

A 125 KVA wind turbine generator was installed by the Energy Research and Development Administration at the National Aeronautical Space Administration's Plum Brook Station near Sandusky, Ohio. While this first installation was reported to cost in excess of several million dollars, much of this cost was associated with the research and development phase and ongoing testing of the pilot project. A more realistic estimate for similar wind turbine generators constructed under the Federal programs is about $1,220,000, exclusive of protection scheme costs.[19] Unlike the estimate for the small wind turbine generator installation, this figure is complete and does not require the addition of any other costs.

Cost for Proposed Protection Package

The following costs are estimated for the required minimum protection package recommended for the large wind turbine generator. Detailed pricing data is provided in Appendix I.

| | |
|---|---|
| 480 volt, three-phase power circuit breaker (includes long and short time overcurrent protection) | $3,070 |
| Voltage-controlled overcurrent relays | $4,270 |
| Overcurrent ground fault protection | $ 920 |
| Overheating protection | $1,000 |
| *Overspeed protection (mechanical) | 0 |
| Vibration protection | $ 250 |
| *Gencrator motoring protection | 0 |

| | |
|---|---|
| D.C. supply for protection schemes includes 24 VDC battery, charger and protection | $2,310 |
| Equipment cabinet | $ 340 |
| | $12,160 |

* These items are included in the price of the generator. The manufacturer normally supplies this type of protection as standard.

The total price for this protection package amounts to $12,160 or slightly less than one percent of the total installed price (based on installed price of $1,232,000, obtained by adding the protection costs to the previous installed cost of $1,220,000.) As noted in the previous discussion for the small wind turbine generator, the 480 volt circuit breaker could be required for other functions, and as automatic synchronization of the generator with the utility system, remote supervisory control and the variety of protection schemes. The 24 volt d.c. supply system would probably be required for the manufacturer's generator control schemes, remote telemetering and local alarms, as well as operation of the protective relay schemes.

In addition to the minimum protective package described above, two optional relay schemes will be very desirable for the large wind turbine generator. These schemes will provide enhanced protection of the generator:

| | |
|---|---|
| Generator differential protection | $4,230 |
| Generator negative sequence protection | $2,490 |
| | $6,720 |

The total protection package for the large wind turbine generator, including the differential and negative sequence protection, will cost $18,880. This represents about 1.5 percent of the total installed cost of $1,239,000 and is relatively inexpensive protection for the value of the equipment which is involved.

In addition, the utility will require protection on the

12.47 kV side of the step-up transformer, consisting of:

| | |
|---|---|
| 12.47 kV power circuit breaker, complete with directional overcurrent phase and non-directional overcurrent ground relays, automatic reclosing and provisions for remote supervisory control | $15,000 |
| 480 volt system overvoltage - undervoltage protection | $ 1,310 |
| | $16,310 |

This cost of $16,130 represents the additional cost to the utility for protection of the interconnection. Underfrequency protection and 12.47 kV bus differential protection are both provided by the test utility as standard protection for most larger 66-12.47 kV substations; no additional costs would be incurred for these schemes.

If the large wind turbine generator was installed on a 12.47 kV distribution line but at a location removed from the 66-12.47 kV substation, the same protective packages for the generator and for the utility system will be required. Costs for the protection installed by the utility are likely to be much higher, since the substation facilities would not be available. Separate a.c. and d.c. supplies, potential transformers, and other items would have to be supplied, at greater cost.

## Chapter VII

## Recommendations and Conclusions

The electric utility industry must explore and be receptive to all potential sources of energy, in order to meet the rising demand for electricity at reasonable costs. With shortages of traditional fuels, public skepticism of nuclear energy and increasingly restrictive laws with regard to the levels of environmental pollutants, wind power is receiving much interest. As more wind turbine generators are installed and interconnected with the electric utility's power system, consideration must be given to the protection of this new equipment, while maintaining the reliability of the existing utility system.

Protection of the wind turbine generators requires close examination of the physical and electrical characteristics of the equipment, and an understanding of the operating procedures of both the generator and the utility. It has been shown that standard relay schemes, with some special provisions, can be combined to provide adequate protection for these systems. Only the relay schemes are specified in this paper; coordination is best considered for each individual installation. Even slight alteration of the equipment impedances, cable sizes, line length or even the utility's protective philosophy could greatly change the relay settings required for proper coordination and protection.

Recommended protection schemes for each of the wind turbine generators and the utility interconnection, are summarized as:

Recommended Protection for Small Wind Turbine Generator

Overvoltage - undervoltage protection

Overheating protection

Overspeed protection

Vibration protection

D.C. bus and battery protection

Rectifier fuses

Inverter fuses

Operation of these protective schemes requires a 240 volt circuit breaker at the generator output terminals. The breaker must be provided with automatic tripping and manual reclosing facilities. A separate 24 volt battery and charger is required for operation of the breaker and relays.

Utility protection requires a set of three 12.47 kV fuses sized to provide protection of the step-up transformer and the 240 volt connection from the transformer to the synchronous inverter. The step-up transformer should be connected grounded wye-wye in order to allow the fuses to protect for single-phase-to-ground faults on the transformer low voltage side, up to the inverter terminals. The utility will not be effected by faults internal to the generator, rectifier, d.c. bus or inverter, since the inverter blocks all current flow from the utility system to the generator system.

<u>Recommended Protection for Large Wind Turbine Generators</u>

Voltage-controlled overcurrent protection

Overcurrent ground fault protection

Overheating protection

Overspeed protection

Vibration protection

Generator motoring protection

Generator differential protection (optional)

Negative sequence protection (optional)

Operation of these protective schemes requires a 480 volt circuit breaker at the generator terminals, with automatic tripping and reclosing facilities. Synchronization of the generator with the utility system will be performed by closing the generator breaker. As in the small wind turbine generator system, a separate 24 volt battery and charger will be required.

Minimum recommended generator protection is provided by the first six schemes listed above, and enhanced protection is provided by the addition of the two schemes indicated as optional. Generator differential and negative sequence schemes offer much more sensitive protection in case of generator internal faults or for system unbalanced conditions, respectively. Both of these conditions can be highly damaging to synchronous generators, so the fastest possible clearing is desired in order to minimize damage.

Utility protection for the large wind turbine generator system must consist of a 12.47 kV circuit breaker with directional overcurrent phase and non-directional overcurrent ground relays. Additional protection for single-phase-to-ground faults on the transformer 480 volt side and the customer's equipment should include an overvoltage-undervoltage relay, monitoring the phase-to-ground voltage on one phase of the 480 volt system.

Installation of these recommended protection schemes will increase the cost of the wind turbine generator, but no protection would pose an unacceptable risk to the reliability of the utility's system, in addition to the potential for damage to the generator. Even one operation of the protection schemes could easily save an amount equal to or greater than the cost of installation of the protective equipment. Based on a projected thirty year operating life of the wind turbine generators, this expenditure represents cheap insurance to minimize equipment damage and lost generator capacity.

This thesis has made no recommendations on the subjects of lightning protection, protection or control of auxiliary circuits, control of the generators insofar as yaw, speed, start-up or shut-down, supervisory control, telemetering or other considerations. The sole purpose was to investigate the protection requirements of the generator and utility equipment for abnormal or fault conditions; these other concerns would be excellent topics for future research.

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## Appendix I

Estimated installed costs (in 1979 dollars) for individual protection schemes as recommended for both the small and large wind turbine generator systems are calculated in detail. These costs are used in Chapter VI to determine total costs for protection of each type of generator system.

### Control Cubicle

| | | |
|---|---|---|
| Material | \$1,800 | |
| Labor (200 manhours @ \$11.25) | \$2,250 | |
| Labor expense (87%) | \$1,960 | |
| Subtotal | | \$6,010 |
| Overheads (19%) | \$1,140 | |
| Subtotal | | \$7,150 |
| Foundation installed cost | \$2,000 | |
| Total | | \$9,150 |

24 Volt Battery and D.C. Charger

| | | |
|---|---|---|
| Battery | $ 550 | |
| Charger (including protection) | $ 700 | |
| Labor (33 manhours @ $11.25) | $ 370 | |
| Labor expense (87%) | $ 320 | |
| Subtotal | | $1,940 |
| Overheads (19%) | $ 370 | |
| Total | | $2,310 |

240 or 480 Volt Power Circuit Breaker

| | Manual Reclosing | Electric Reclosing |
|---|---|---|
| Breaker, indoor three-pole 225 amperes continuous, 15000 amperes interrupting capability | $1,360 | $2,060 |
| Labor (25 manhours @ $11.25) | $ 280 | $ 280 |
| Labor expense (87%) | $ 240 | $ 240 |
| Subtotal | $1,880 | $2,580 |
| Overheads (19%) | $ 360 | $ 490 |
| Total | $2,240 | $3,070 |

240 or 480 Volt Fuses

| | | |
|---|---|---|
| Fuses, including enclosure | $ 200 | |
| Labor (8 manhours @ $11.25) | $ 90 | |
| Labor expense (87%) | $ 80 | |
| Subtotal | | $ 370 |
| Overheads (19%) | $ 70 | |
| Total | | $ 440 |

12.47 kV Fuses

| | | |
|---|---|---|
| Three fuses and holders | $ 600 | |
| Labor (12 manhours @ $11.25) | $ 140 | |
| Labor expense (87%) | $ 120 | |
| Subtotal | | $ 860 |
| Overheads (19%) | $ 160 | |
| Total | | $1,020 |

Generator Overcurrent Phase Relays

| | | |
|---|---|---|
| 3 current transformers on generator | $ 240 | |
| 3 time overcurrent relays | $ 490 | |
| Miscellaneous | $ 110 | |
| Labor (30 manhours at $11.25) | $ 340 | |
| Test (8 manhours at $12.65) | $ 100 | |
| Labor expense (87%) | $ 380 | |
| Subtotal | | $1,660 |
| Overheads (39%) | $ 650 | |
| Total | | $2,310 |

Overvoltage-Undervoltage Protection

| | | |
|---|---|---|
| 1 potential transformer | $ 100 | |
| 1 over-under voltage relay | $ 340 | |
| Miscellaneous | $ 70 | |
| Labor (16 manhours at $11.25) | $ 180 | |
| Test (4 manhours at $12.65) | $ 50 | |
| Labor expense (87%) | $ 220 | |
| Subtotal | | $ 940 |
| Overheads (39%) | $ 370 | |
| Total | | $1,310 |

Equipment Cabinet

| | | |
|---|---|---|
| 1 cabinet | $ 200 | |
| Labor (4 manhours at $11.25) | $ 50 | |
| Labor expense (87%) | $ 40 | |
| Subtotal | | $ 290 |
| Overheads (19%) | $ 50 | |
| Total | | $ 340 |

Generator Overheating Protection

| | | |
|---|---|---|
| Use existing CTs | $ 0 | |
| 1 overtemperature relay | $ 400 | |
| Miscellaneous | $ 60 | |
| Labor (8 manhours at $11.25) | $ 90 | |
| Test (4 manhours at $12.65) | $ 50 | |
| Labor expense (87%) | $ 120 | |
| Subtotal | | $ 720 |
| Overheads (39%) | $ 280 | |
| Total | | $1,000 |

Overcurrent Ground Fault

| | | |
|---|---|---|
| Resistor in generator neutral | $ 100 | |
| Time overcurrent relay | $ 250 | |
| Miscellaneous | $ 50 | |
| Labor (8 manhours $11.25) | $ 90 | |
| Test (4 manhours at $12.65) | $ 50 | |
| Labor expense (87%) | $ 120 | |
| Subtotal | | $ 660 |
| Overheads (39%) | $ 260 | |
| Total | | $ 920 |

Vibration Protection

| | | |
|---|---|---|
| Paddle switch and trip contact | $ 50 | |
| Labor (4 manhours at $11.25) | $ 50 | |
| Test (2 manhours at $12.65) | $ 20 | |
| Labor expense (87%) | $ 60 | |
| Subtotal | | $ 180 |
| Overheads (39%) | $ 70 | |
| Total | | $ 250 |

Battery System Protection

| | | |
|---|---|---|
| Resistor, center-tapped | $ 50 | |
| Two auxiliary relays | $ 200 | |
| Overvoltage-Undervoltage relay | $ 340 | |
| Miscellaneous | $ 90 | |
| Labor (8 manhours @ $11.25) | $ 180 | |
| Test (8 manhours @ $12.65) | $ 100 | |
| Labor expense (87%) | $ 240 | |
| Subtotal | | $1,200 |
| Overheads (39%) | $ 470 | |
| Total | | $1,670 |

Voltage-Controlled Overcurrent Relays

| | | |
|---|---|---|
| 3 current transformers | $ 240 | |
| 3 480 volt potential transformers | $ 300 | |
| 3 voltage-controlled overcurrent relays | 1,070 | |
| Miscellaneous | $ 240 | |
| Labor (40 manhours @ $11.25) | $ 450 | |
| Test (16 manhours @ $12.65) | $ 200 | |
| Labor expense (87%) | $ 570 | |
| Subtotal | | $3,070 |
| Overheads (39%) | $1,200 | |
| Total | | $4,270 |

Generator Differential Relays

| | | |
|---|---|---|
| 6 current transformers on generator | \$ 480 | |
| 3 generator differential relays | \$1,100 | |
| Miscellaneous | \$ 240 | |
| Labor (40 hours at \$11.25) | \$ 450 | |
| Test (16 manhours at \$12.65) | \$ 200 | |
| Labor expense (87%) | \$ 570 | |
| Subtotal | | \$3,040 |
| Overheads (39%) | \$1,190 | |
| Total | | \$4,230 |

Negative Sequence Overcurrent Relays

| | | |
|---|---|---|
| Use existing current transformers | \$ 0 | |
| 1 negative sequence relay | \$ 860 | |
| Miscellaneous | \$ 130 | |
| Labor (20 manhours at \$11.25) | \$ 230 | |
| Test (16 manhours at \$12.65) | \$ 200 | |
| Labor expense (87%) | \$ 370 | |
| Subtotal | | \$1,790 |
| Overheads (39%) | \$ 700 | |
| Total | | \$2,490 |

## Appendix II

The following numbers with appropriate suffix letters are used in Figures 13 and 14, pages 107 and 119, respectively. These numbers identify the types and functions of the protective relays used in the recommended protection schemes for wind turbine generator protection.

| Device Number | Function |
|---|---|
| 27/59 | Undervoltage - Overvoltage |
| 32 | Anti-motoring (reverse power flow) |
| 46 | Negative Sequence |
| 49 | Machine Thermal |
| 50 | Instantaneous Overcurrent |
| 50G | Instantaneous Ground Overcurrent |
| 51 | Time Overcurrent |
| 51G | Ground Time Overcurrent |
| 51V | Time Overcurrent, Voltage-Controlled |
| 64 | Ground Detection |
| 67 | Directional Overcurrent |
| 81 | Underfrequency |
| 87 | Generator Differential |
| 87B | Bus Differential |

# Vita

The author was born to Mr. and Mrs. Lawrence H. Schuette on September 20, 1951 in Alexandria, Virginia. He graduated from Fort Hunt High School, Alexandria in June 1969 and was admitted to Virginia Polytechnic Institute and State University, Blacksburg, Virginia, in the Electrical Engineering curriculum in September of that same year. During this time, the author was accepted as a member of Eta Kappa Nu, Tau Beta Phi and Phi Kappa Phi (honorary societies).

Upon graduating "with distinction" from V.P.I. & S.U. in 1973, he accepted a position with the Pennsylvania Power and Light Company as an engineer in the Relay and Control Section of the System Power and Engineering Department. From August 1977 to date, the author has been employed as a Project Engineer in the same Section.

The author is a registered Professional Engineer in the State of Pennsylvania by examination, since June 1977. He has been a member of the Institute of Electrical and Electronic Engineers since 1973.

The author presently resides in Wescosville, Pennsylvania with his wife, Lorraine and daughter, Alexis.