AN ABSTRACT OF THE THESIS OF

Christopher S. Brune for the degree of Master of Science in Electrical and Computer Engineering presented on August 18, 1993.

Title: Development of a Variable-Speed, Doubly-Fed Wind Power Generation System

Redacted for Privacy

Abstract approved: ______________________

René Spée

Generation of electricity from the wind is becoming increasing popular as an environmentally responsible resource. Current methods for generating electricity from the wind involve the use of fixed-speed generators. However, the use of variable-speed generators increases the amount of energy that can be extracted from the wind.

Most variable-speed technologies require processing large amounts power electronically. In large utility-scale generation systems the added cost of the power electronics may make variable-speed generation too expensive. A reduction in the size of the power electronics is achieved when using the brushless doubly-fed machine.

A proof-of-concept system has been developed to evaluate not only the advantages of variable-speed technology, but the advantages of using the brushless doubly-fed machine. The prototype system uses a two-bladed turbine with a diameter of 2.75 meters. The prototype system produces a maximum of 1500 watts in wind speeds ranging from 0 to 40 miles per hour.

Experimental data illustrates the performance of the machine over a wide range of power levels. The machine exhibits satisfactory efficiency. Experimental results

show that converter rating of the prototype system is one-fifth of that of a conventional variable-speed system.

The proof-of-concept system shows that the brushless doubly-fed machine has superior features as compared to other systems. Future research needs to evaluate its use in a utility-scale environment.

Development of a Variable-Speed, Doubly-Fed Wind Power Generation System

by

Christopher S. Brune

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed August 18, 1993

Commencement June 1994

APPROVED: Redacted for Privacy

Associate Professor of Electrical and Computer Engineering in charge of major

Redacted for Privacy

Head of Department of Electrical and Computer Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented August 18, 1993

Typed by Christopher S. Brune

ACKNOWLEDGEMENTS

I would like to acknowledge and thank my major professor, Dr. René Spée. His help and guidance has been invaluable during the time I have spent at Oregon State University. I would also like to thank the other members of the committee, Dr. Molly Shor, Dr. Alan Wallace, and Dr. Bill Warnes.

A special thanks goes to my colleague Brian Wiley, his assistance with many aspects of this thesis is greatly appreciated. I would also like to thank Chuck Meitle for his valuable assistance in developing the mechanical portion of this project.

Most of all I wish to thank Susie, my wife, for helping me to succeed at school. I would also like to thank my family for their support during my many years of school.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Development of a Variable-Speed, Doubly-Fed Wind Power Generation System

1. INTRODUCTION

In recent years, wind power has been gaining renewed interest due to an increased emphasis on environmentally sustainable resources as well as progress in wind-related technologies [1]. The Pacific Northwest is considered an attractive area for the increased usage of wind energy. Although hydroelectric power is considered a Northwest standard, several local utilities are considering wind energy conversion systems (WECS) [2]. As hydroelectric resources diminish, utility planners must look to alternative forms of energy. As the technology used in WECS is advanced, and the costs are reduced, wind energy becomes more attractive. This thesis investigates a possible method for reducing the cost of a wind energy conversion system.

Most new proposals for wind-power systems utilize advanced turbine designs as well as variable-speed generators (VSG) [3,4]. Proposed generators include systems based on induction machine technology as well as reluctance machines. While extracting more energy from the wind, most proposed variable-speed systems suffer a cost disadvantage due to the size of the required power electronic converter. This cost penalty may eventually render the additional energy capture meaningless. Consequently, reduction of the rating and thus cost of the power electronic hardware is essential for variable-speed generating systems to achieve viable and competitive

$/kWh (dollars/kilowatt-hour) ratios. Doubly-fed generators can achieve VSG operation with reduced converter requirements.

This thesis presented the development of a variable-speed, doubly-fed wind power generation system. The system is designed to be a proof-of-concept for using the brushless doubly-fed machine (BDFM) in a wind power application. The system is designed and built to produce a maximum of 1.5 kW of power. The thesis presents the theory behind development of the system, the methodology used to construct the prototype, and experimental results.

1.1 Fixed and Variable-Speed Generation

Fixed-speed generation refers to a generation system where the rotational shaft speed remains constant. In a variable-speed generation system the shaft speed is allowed to vary as needed. To date, most installed wind-generation systems are of the fixed-speed type, due to limitations of machine technology, power electronics, and cost. The following discussion compares the different aspects of fixed and variable speed systems.

Fixed-speed generation cannot extract as much energy from the wind as a variable-speed system. Figure 1 illustrates the power characteristics of the prototype wind turbine. In general, all horizontal-axis wind turbines have similar characteristics. In a fixed-speed system the generator power curve would be plotted as a vertical line on the graph. A fixed-speed system will only achieve maximum power at one wind speed. A variable-speed system, however, is able to track the maximum power point for every wind speed, thus capturing more energy from the wind.

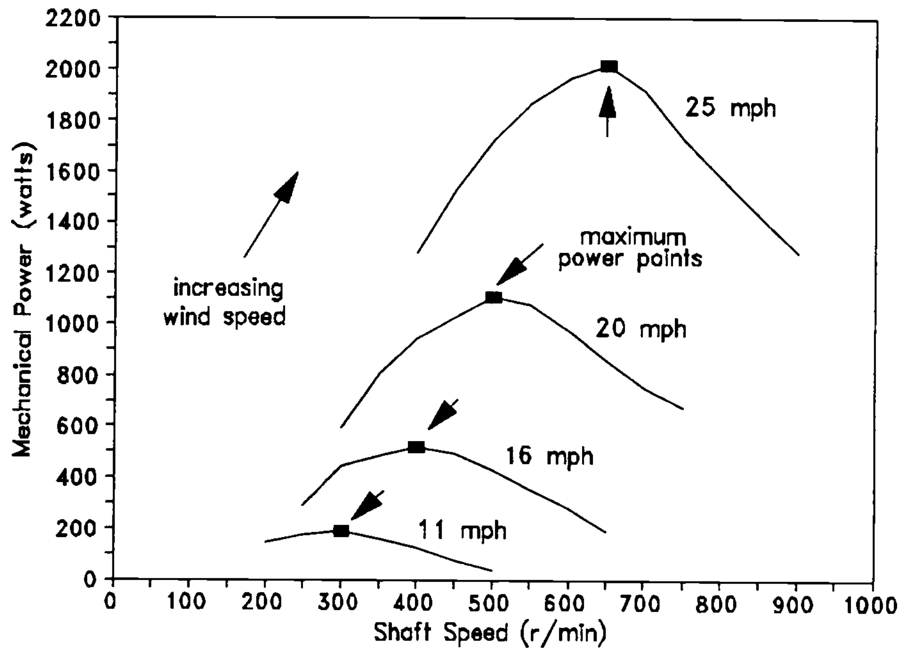


Figure 1: Prototype wind turbine output power characteristics.

Certain fixed-speed systems try to overcome the power tracking limitations by using pitch control, adjusting the angle of the turbine blades to maximize the power output of the system. Use of pitch control necessitates a complicated mechanical system connected to the rotating turbine blades. With a variable-speed system it is possible to eliminate pitch control.

Wind turbines produce a non-constant torque due to tower shadow. The supporting structure of the wind turbine (tower) reduces the speed of the wind next to the structure. This disturbance causes a reduction in torque. In a two blade system the torque ripple occurs at twice the rotational frequency.

L. Dessaint, et al have studied methods for elimination of this torque ripple by using variable-speed generation [5]. It is possible to model the disturbance in the system and design a control system to greatly reduce the effect of torque ripple in the output power.

Some large wind turbines are not self-starting or self-stopping. Tower resonances require that the wind turbine be motored up to operating speed. In a fixed-speed system this may require large soft-start mechanisms for controlling the startup characteristics of an induction machine. Since an induction machine can only run at a fixed-speed, it can not aide in the stopping of the turbine. Thus, a large mechanical braking system is needed. VSG technologies can be used to provide controlled starting and stopping. Braking energy can be captured using regenerative braking.

The supply interface of a fixed-speed system is usually controlled by the demands of the induction machine. The power generated by the machine will directly determine the power factor and harmonics at the utility interface. In a variable-speed system there is usually a power electronic interface between the generator and the electrical grid. The power conditioning unit can be used to adjust the characteristics of the power transferred to the grid. Thus, power factor and harmonics can be controlled.

1.2 Variable-Speed Generation Implementations

Several different methods of variable-speed generation have been presented in the literature. However, as a baseline, this paper will first discuss a fixed-speed induction generator set.

A fixed-speed induction generator consists of an induction machine connected directly to the electrical grid. This type of system has the advantage of reduced cost and increased reliability. The fixed-speed nature of an induction generator usually necessitates costly hardware for soft-starting capability.

The most common method for attaining VSG is to use a squirrel-cage induction machine connected to the grid through a power electronic converter. This approach is called the power conditioning approach, and is illustrated in Figure 2. The advantages of variable-speed are achieved at the expense of significantly increased cost, size and weight due to the rating of the power electronic converter at >100% of induction generator apparent power.

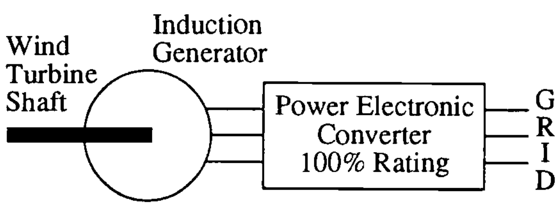


Figure 2: Power Conditioning approach.

In large-scale wind systems with ratings greater than approximately 100 kW the expense of the power converter increases significantly. It is no longer possible to use turn-off devices such as insulated gate bipolar transistors, or bipolar junction transistors. This has led to the development of WECS that use multiple power transfer shafts off of a single turbine, i.e. the power output from a single turbine is coupled to multiple induction machine/power electronic sets [6]. This can lead to an expensive and cumbersome design.

Another possible VSG system is a DC machine coupled with a power electronic converter. This type of system is restricted to low power levels. The DC machine does not offer any advantages over the induction generator set discussed above. However, it does have the disadvantage of using brushes and a commutator.

A reduction in power converter rating can be achieved by using a doubly-fed configuration such as a wound-rotor induction machine system [7]. The wound-rotor induction machine (WRIM) is an established variable-speed technology [8,9,10]. Figure 3 illustrates the use of the WRIM in a variable-speed generation system. The stator winding of the machine is connected directly to the electrical grid, and the rotor winding is connected to the grid through slip rings and a power electronic converter.

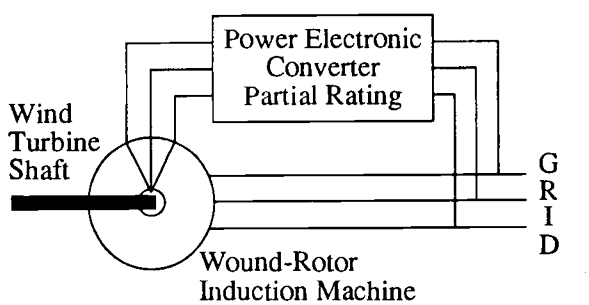


Figure 3: WRIM Doubly-Fed Approach.

In the WRIM configuration, only the rotor slip power needs to be processed, and the power electronic converter can have a reduced rating. The rating of the converter is dependent on the operational speed range of the machine.

Another possible variable-speed generation technology is the variable-reluctance generator (VRG) [11]. It has been reported that a VRG offers better efficiency and reduced cost as compared to an induction generator/converter system. However, it is important to realize that VRG systems include added components nor required for induction generators. The VRG system includes an extra inductor and capacitor in the power electronic circuit. These additional components must be rated for the maximum operating current, thus increasing converter cost. The VRG system is as yet an unproven system.

The Doubly-Excited Brushless Reluctance Machine (DEBRM) is another VSG technology [12]. The DEBRM uses a dual three-phase winding arrangement similar to the brushless doubly-fed machine. However, the DEBRM has a salient rotor. While field oriented control of the machine has been developed and simulated, the machine has not been built and tested. It is suspected that the machine may suffer from increased magnetization requirements and thus diminished power factor.

The VSG technology investigated in this thesis is the Brushless Doubly-Fed Machine (BDFM). The BDFM is a doubly-fed machine similar to both a standard induction machine and a wound-rotor induction machine. It attempts to combine the reduced converter rating of the WRIM with the robustness of the cage-rotor induction machine. The BDFM VSG system is illustrated schematically in Figure 4. As shown, the BDFM consists of two separate stator windings of different pole numbers, and a unique cage rotor structure. As in the WRIM system, only a portion of the generated power is processed through the power electronic converter.

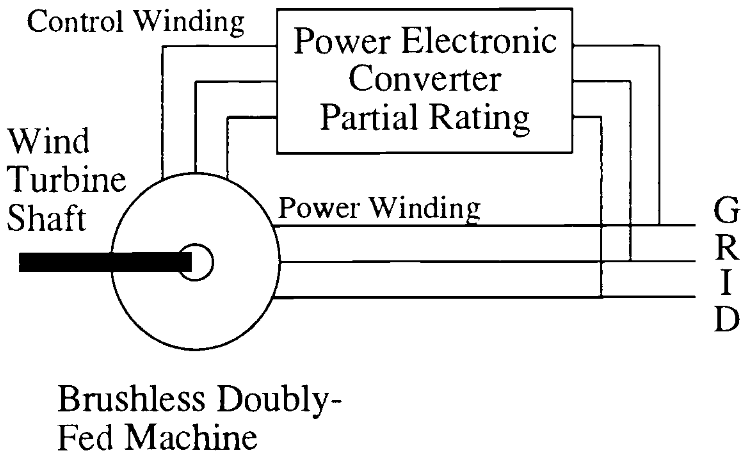


Figure 4: BDFM VSG approach.

The BDFM achieves variable-speed generation with a reduced converter rating, without the use of brushes or slip-rings. Construction techniques for the BDFM are similar to the induction machine, ensuring robust and inexpensive construction. The BDFM rotor can be die-cast, and the stator windings are wound into standard induction motor type slots.

In summary, there are several advantages to using variable-speed generation in a wind energy conversion system. These include increased energy, reduced torque ripple, elimination of pitch control, and controlled starting and stopping.

Several different methods can be used to achieve variable-speed generation. For new methods to be viable they must attempt to reduce the cost of generating electricity. The proposed BDFM system attempts to reduce cost by reducing the rating of the power electronics, while maintaining robustness and reliability.

2. WIND TURBINE CHARACTERISTICS

Wind turbines can be placed into two general categories: horizontal-axis and vertical-axis. The prototype system uses a horizontal axis wind turbine, where the shaft rotates in a horizontal plane.

A. Betz of the Institute of Gottingen established a global theory on wind turbines [13]. Betz's work develops the mechanics of an ideal wind turbine based on an incompressible flow of air. The wind turbine extracts kinetic energy from the wind by slowing it. The energy in the wind is changed into rotational energy by the wind turbine. The diagram in Figure 5 shows an "ideal" wind rotor at rest placed in a moving atmosphere. Let V_1 be the wind speed upstream of the rotor. Let V be the wind speed at the rotor, and let V_2 be the wind speed downstream.

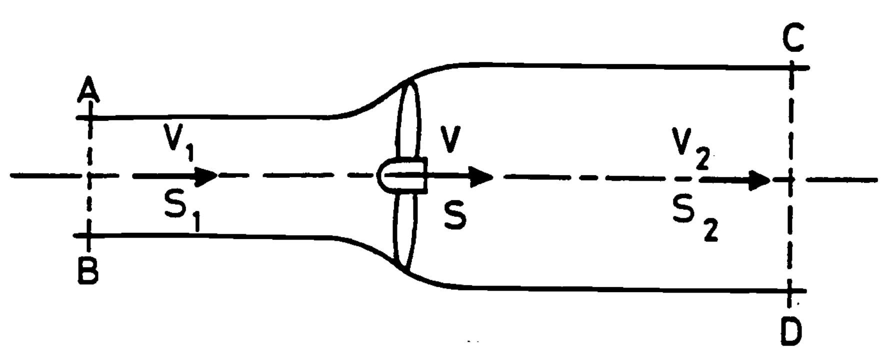


Figure 5: Ideal wind turbine.

If we assume that the air is incompressible, we can assume constant mass flow. Thus the following relationship exists:

$$S_1 V_1 = SV = S_2 V_2$$

where S is the area of the ideal wind turbine, and the force on the rotor is given by Euler's theorem and is equal to:

$$F = \rho S V (V_1 - V_2)$$

The power absorbed by the rotor, and thus convertered into mechanical power, is:

$$P = FV = \rho S V^2 (V_1 - V_2)$$

By evaluating the above relationship, and the variation of kinetic energy due to changes in wind speed, it can be found that maximum power occurs when V_2 is one-third of V_1, and V is two-thirds of V_1. Betz' formula is found by substituting these relationships into the power formula:

$$P_{max} = \frac{8}{27} \rho S V_1^3$$

where ρ is the density of air, and is equal to 1.25 kg/m3 at sea level. Betz' formula gives the maximum power available from an ideal wind turbine with area S. Thus Betz' formula is used as a benchmark to compare the efficiency of different turbine designs.

2.1 Prototype Wind Turbine

If we consider a "real" wind turbine we can expand the previous discussion. The prototype system uses a commercially available two-bladed rotor [14]. The blade is constructed out of two pieces of wood, which are joined by metal plates. The blades are coated with paint to protect them from the weather. The Rotor characteristics are given in Table I.

Table I: Prototype turbine characteristics.

Diameter	2.75 m
Optimal TSR	8.5
Maximum C_p	0.41
Maximum Power at V = 15 mph	455 W

If we define a coefficient of power (C_p) to represent the efficiency of a particular set of blades, we can expand Betz' formula to:

$$P = \frac{\pi}{8} C_p D^2 V^3$$

Where D is the diameter of the blades in meters, P is the output power in watts, and V is the upstream wind velocity in m/s. The coefficient of power can vary from 0 to 0.57 (Betz' limit), and is a function of the tip-speed ratio (TSR), and the geometry of the particular turbine blades. TSR is the ratio of the speed at the tip of blade to the upsteam wind speed. The TSR of the turbine is an operational characteristic defined as:

$$TSR = \frac{\pi DN}{V}$$

where N is the shaft speed in revolutions per second. Figure 6 shows a graph of C_p versus TSR for the prototype wind turbine. The graph indicates that there is one point of maximum power (TSR = 8.5). To extract the maximum energy from the system it is necessary operate at optimum TSR.

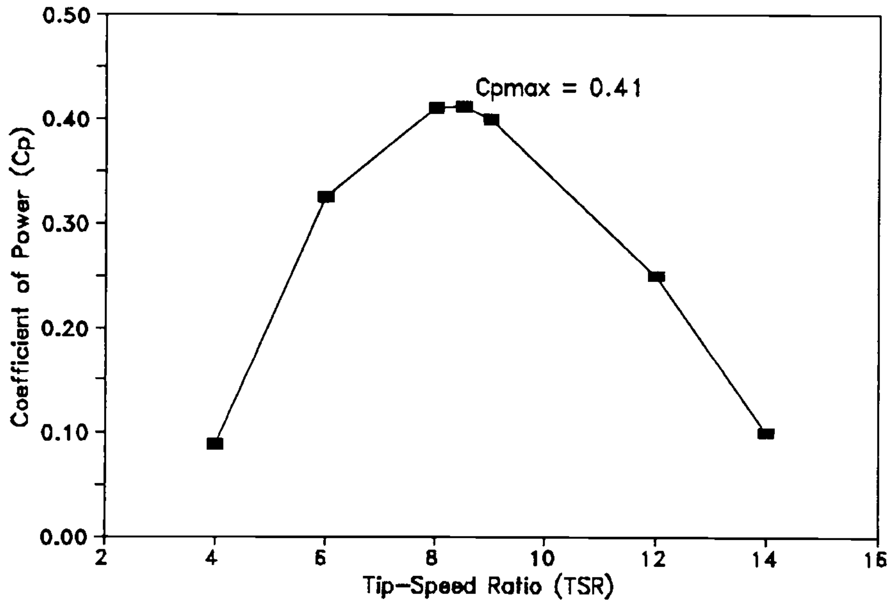


Figure 6: Graph of Cp versus TSR for the prototype turbine.

The optimal turbine shaft speed is linearly dependent on wind speed. However, accurate measurement of wind speed is impossible. An alternative method for optimizing shaft speed is to measure the output power of the turbine. The coefficient of power will be maximum when the output power is maximum. This technique is called maximum power point tracking, and requires the use of a variable-speed generator.

In a fixed speed system the TSR of the system does not remain constant, and the system usually operates at a non-optimal C_p. In general, fixed speed systems are optimized for a particular median wind speed. At this wind speed the system achieves maximum power output. However, at all other wind speeds output power is less than optimal.

2.2 Operational Considerations

The previous discussion outlines the importance of maintaining a strict relationship between shaft and wind speeds. However, the designer must impose a minimum and maximum operating wind speed. The minimum operating speed is termed the cut-in speed, and the maximum is the cut-out speed.

The minimum operating wind speed is dictated by operating losses in the system. The turbine is connected to the generator via a transmission system, which can be a gearbox, but in the case of the prototype is a belt and pulley drive. Losses in the transmission as well as in the generator must be overcome before electrical energy can be produced. There exists a minimum wind speed which will generate enough power to overcome these losses. The minimum wind speed corresponds to some particular shaft speed, which is the minimum operating shaft speed.

When using the BDFM, with a 6-pole/2-pole winding, it is necessary to keep the generator speed above 1200 r/min. Due to the nature of the BDFM, operation at precisely 1200 r/min is not possible, and operation between 900 and 1200 r/min is not desirable due to poor operational efficiency. Thus the minimum generator speed is kept at 1250 r/min.

In the prototype system, the cut-in wind speed is 10 miles-per-hour (mph). The cut-in wind speed was chosen by comparing the turbine output power and the losses of the generation system. When turbine output power exceeds the losses of the generator electricity will be produced. Since the minimum shaft speed is fixed at 1250 r/min the turbine does not operate at optimum TSR for wind speeds below 14 mph. At the cut-in speed of 10 mph, the turbine produces approximately 86 watts.

The maximum operating wind speed is determined by the mechanical strength of the system. For safety reasons, the maximum operational wind speed has been set to 40 mph. However, the generator does have a fixed maximum output power rating. In the prototype system the generator is rated for 1.5 KW. As the wind speed increases there exists a point where maximum power available is above 1.5 KW. At this point the machine must be controlled to keep the power at the maximum level, which is accomplished by reducing the rotor shaft speed and thus operating at a non-optimal C_p. Figure 7 describes this operating control strategy for the prototype system.

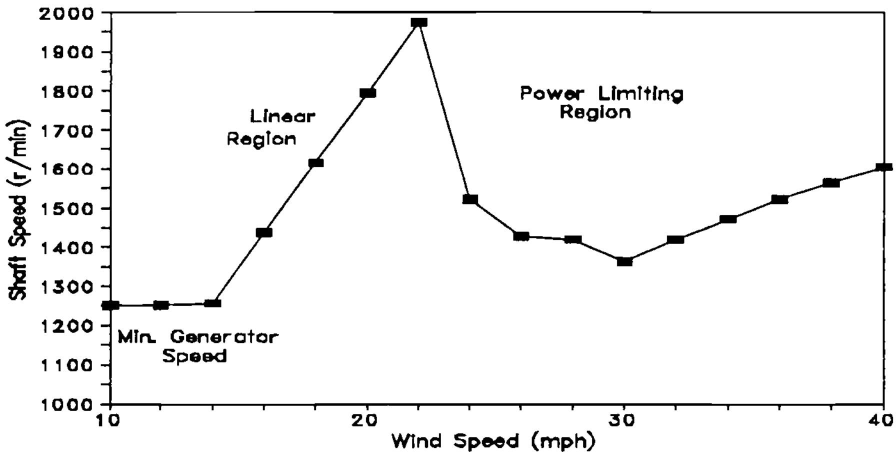


Figure 7: Shaft speed control strategy.

The prototype system uses a gear ratio of 3.4 to 1 in the belt and pulley arrangement. This gear ratio is designed to maximize the linear region while using available pulley sizes. It is possible to decrease the wind speed at which the linear region begins by increasing the gear ratio, however, this will cause the maximum shaft speed to increase.

2.3 Energy Gain

As mentioned in Chapter 1, variable-speed generation extracts more energy from the wind than fixed-speed generation. It is important to quantify the amount of additional energy that is gained using variable-speed generation. This allows evaluation of the cost benefits of variable-speed generation.

The energy gain is dependent on the particular wind characteristics for a site. As an example this thesis examines Cape Blanco, located along the southern Oregon coast. Wind data was collected approximately 76 meters above sea level [15] over period of 14 years. The site has an average wind speed of 19.3 miles per hour (mph). This site would be a good site for a WECS, and provides a good example of the advantages of VSG.

The energy gain is determined by examining the relative frequency of different wind speeds. The relative frequency is an indication of the amount of time the wind blows at each wind speed. Figure 8 shows the relative frequency of wind speeds from zero mph to 40 mph. Data is available for wind speeds from zero mph to 91 mph, and is included in Appendix A.

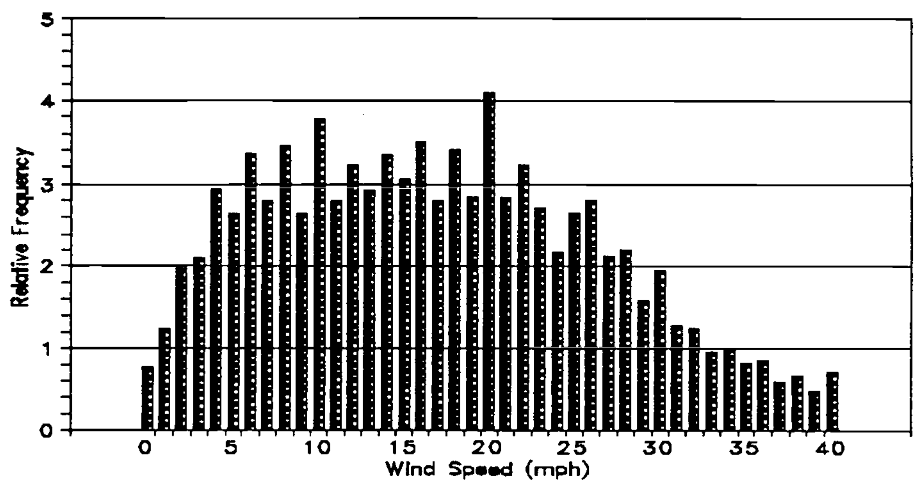


Figure 8: Relative frequency of the wind at Cape Blanco.

The power output of the prototype variable-speed system can be determined by using the shaft speed control strategy developed in Chapter 2.2. A comparable fixed-speed system can be simulated by using the concepts introduced in Chapter 2.1. Figure 9 compares the power outputs for both systems. At higher wind speeds the difference between fixed-speed and variable-speed becomes quite significant. Because the fixed speed system is optimized at a wind speed of 16 mph, the C_p of the turbine is less than the maximum at all other wind speeds. Thus the fixed-speed system produces less power than the variable-speed system.

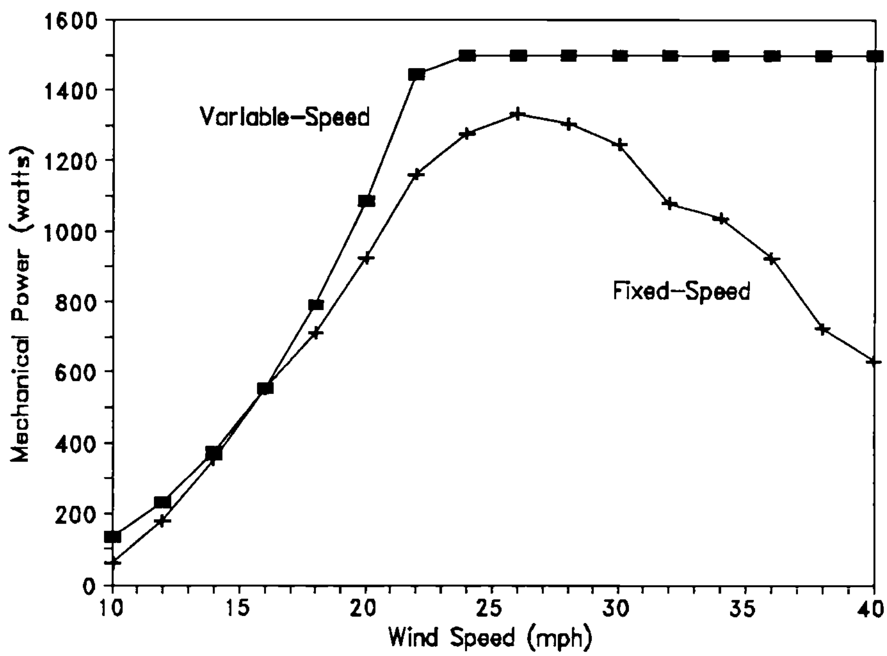


Figure 9: Power Output, fixed versus variable-speed.

For evaluation purposes the wind is considered to blow at fixed wind speeds for a certain number of hours per year. The fixed wind speeds are increments of one mile per hour. The energy generated by one wind speed is the product of the power output at that wind speed and the time spent at that wind speed. This produces a result in kilo-watt-hours (kWh). The total energy produced is the summation of the energy produced by each particular wind speed. Only wind speeds within the operational range of the system need be considered. The resulting data is given in Table II.

Table II: Energy output comparison.

Fixed-speed total energy	5006 kWh
Variable-speed total energy	5873 kWh
Increase in energy output	867 kWh
Value of added energy (@ 0.05 $/kWh)	$ 43.35
Percent increase in energy	17.3 %

The data shows that there is a substantial increase in energy output when using variable-speed generation. By comparing the cost of the VSG system to the income generated by the increase in energy, along with the value of other VSG benefits, it is possible to evaluate the usefulness of variable-speed generation. Although in small-scale systems the increased cost of VSG is not likely to offset increased income, large-scale systems should benefit from VSG.

3. PROTOTYPE SYSTEM

A prototype wind energy conversion system has been developed to evaluate the use of the BDFM. The primary goal is to show the steady-state performance of the BDFM when operated with a wind turbine. The secondary goal is to show how a control system can be developed to dynamically control the machine. The system was designed to maximize the energy captured from the wind by appropriate control of shaft speed. The system should also provide an appropriate utility interface.

3.1 General Description

A prototype system has been developed to evaluate the feasibility of using the BDFM in a wind energy conversion system. A block diagram of the system is shown in Figure 10.

At the heart of the system is the BDFM. The BDFM has one set of windings connected directly to the electrical grid, and the other connected through a power electronic converter. The wind turbine is connected to the BDFM via a belt and pulley arrangement. Power extracted from the system is measured via a transducer to determine the optimum operating point. A wind speed indicator is used to determine start-up and shut-down times.

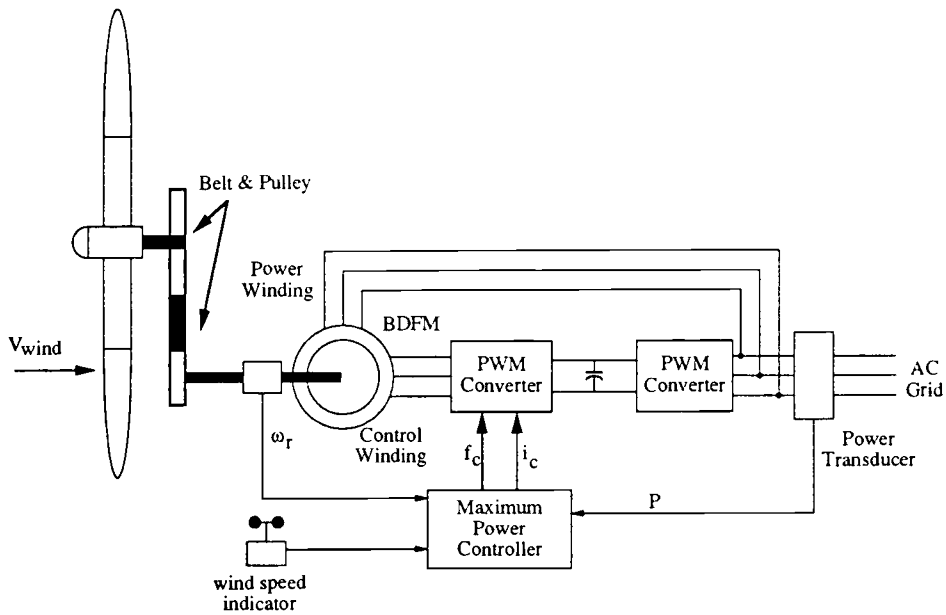


Figure 10: Block diagram of the prototype system.

The system has been installed on the roof above the third floor of Dearborn Hall at Oregon State University. The center of the shaft is approximately two meters above the roof level. A picture of the system is shown in Figure 11. The prototype system is a horizontal axis upwind turbine, i.e. the wind turbine faces into the wind, with a tail vane being used for alignment of the system with the wind. The turbine assembly has been designed for easy removal from the support structure.

Since the system was designed to conduct a feasibility study limited safety features have been implemented. The system is equipped with a small electrically actuated brake. However, this brake is not suitable for continuous operation. The system is also not tolerant of rain or snow, as the prototype BDFM is constructed in an open frame. It is possible to implement safety features and weather protection into the prototype.

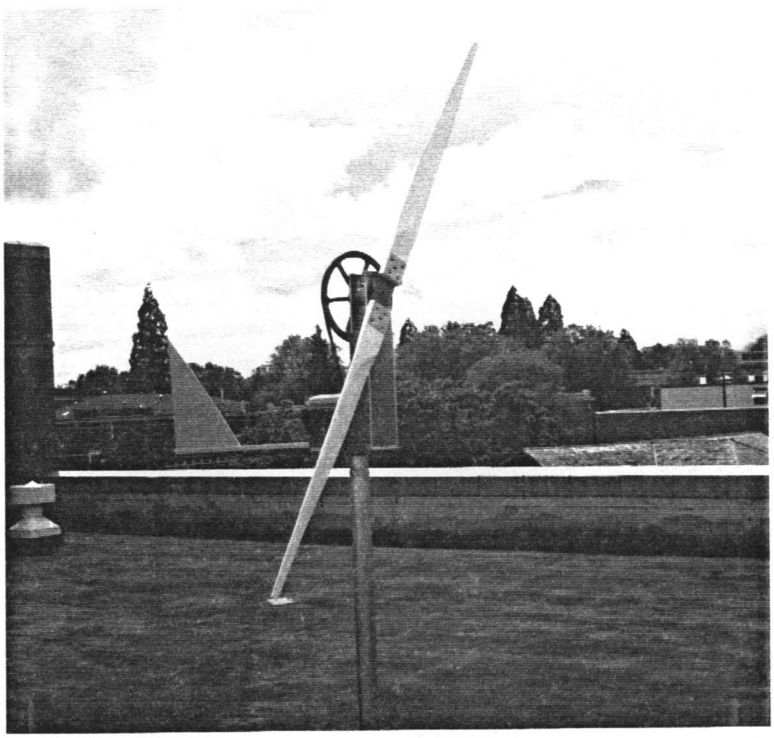


Figure 11: Picture of the prototype system.

3.2 Motor Description

The BDFM is a single frame, self-cascaded induction machine. The concept was first developed by Hunt [16] at the turn of the century. With the development of power electronics, there has been a renewed interest in the configuration. The power electronics are able to provide a variable frequency source of power. A schematic of the machine is shown in Figure 12.

The desirable aspects of the BDFM configuration are the potentially reduced converter rating and the robustness of the induction machine design. The actual rating of the converter depends on many factors, including speed range and torque rating.

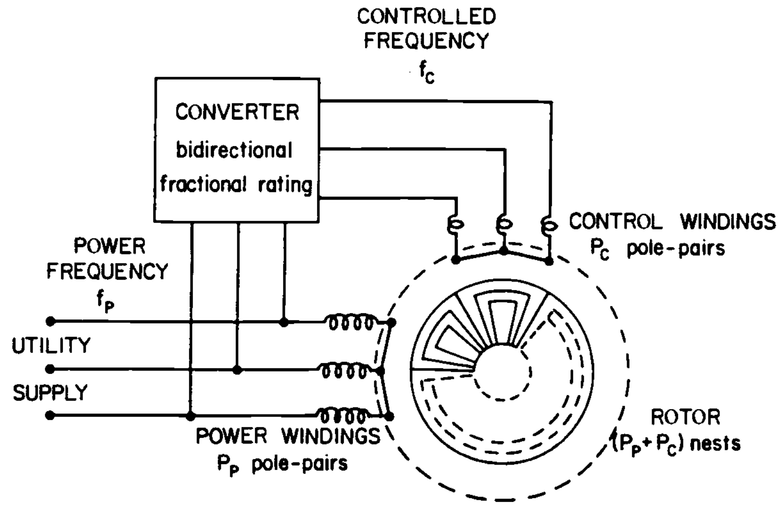


Figure 12: Schematic of BDFM.

The BDFM has two three-phase stator windings; one set of windings is called the power winding, and the other is referred to as the control winding. The power winding and control winding have different numbers of poles. In the current configuration, the power winding is wound in a six pole configuration, and the control winding is wound in a two pole configuration. As indicated in Figure 12, the control winding is connected to the electrical grid via a power electronic converter. The converter must be capable of adjusting the magnitude and frequency of the applied voltage/current.

Due to the interactions of the two stator windings with the rotor, the BDFM has several different operating modes. The desired operating mode is referred to as the "synchronous" mode. In this mode the machine exhibits a synchronous torque behavior, i.e. regardless of applied torque, the machine speed will remain constant.

To ensure that the BDFM operates in the synchronous mode the following relationship must be met:

$$N = \frac{60(f_p + f_c)}{P_p + P_c}$$

where N is the shaft speed in rev/min, f_p and f_c are the power and control winding frequencies, and P_p and P_c are the number of pole-pairs for each winding. Figure 13 shows the fundamental rotating field relationships that exist in the machine, where f_{RP} and f_{RC} refer to the rotor field due to the power and control windings.

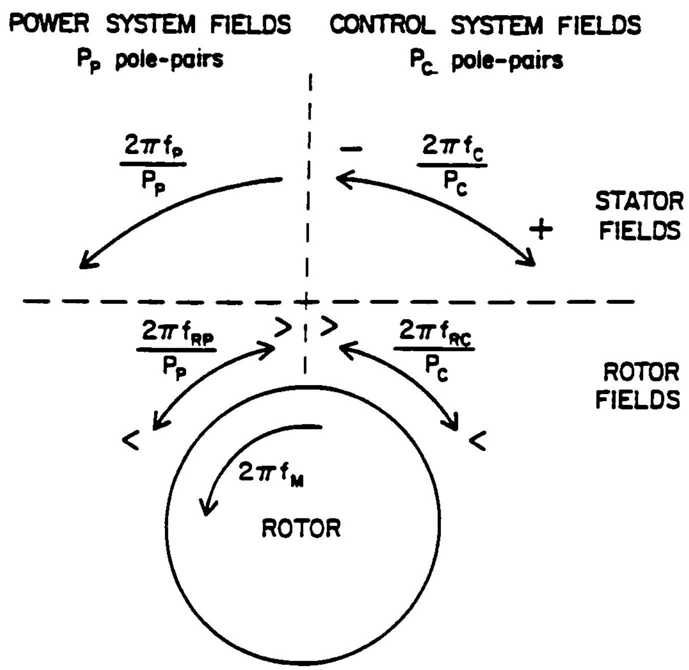


Figure 13: Relative direction of rotation of fundamental fields.

3.3 Steady-state equations of the BDFM

To help investigate the design of a BDFM it is useful to consider the steady-state equations of the BDFM. The steady-state equations are derived from the two-axis model shown in Figure 14, and represent an equivalent circuit for the machine when operating in the synchronous mode [17]. The equations use standard lumped parameters to represent the characteristics of the machine. The currents are separated into real parts (I_{Pr},I_{Cr}, and I_{Rr}) and imaginary parts (I_{Pi},I_{Ci}, and I_{Ri}), and β represents the phase angle between the power and control voltage. The solvable set of equations are:

$$r_P I_{Pr} - X_P I_{Pi} - X_{PR} I_{Ri} - V_P = 0$$
$$r_P I_{Pi} + X_P I_{Pr} + X_{PR} I_{Rr} = 0$$
$$\frac{r_C}{S} I_{Cr} - X_C I_{Ci} + I_{Ri} - \frac{1}{S} V_C \cos\beta = 0$$
$$\frac{r_C}{S} ICi - X_C I_{CR} - X_{CR} I_{Rr} + \frac{1}{S} V_C \sin\beta = 0$$
$$-X_{PR} I_{Pi} + X_{CR} I_{Ci} + \frac{r_R}{S_R} I_{Rr} - X_R I_{Ri} = 0$$
$$X_{PR} I_{Pr} + X_{CR} I_{Cr} + \frac{r_R}{S_R} I_{Ri} + X_R I_{Rr} = 0$$
$$2P_P M_{PR}(I_{Pi} I_{Rr} - I_{Pr} I_{Ri}) + 2P_C M_{CR}(I_{Ci} I_{Rr} - I_{Cr} I_{Ri}) - T_L = 0$$

A simulation program was developed to evaluate the performance for a given set of parameters [18]. The simulation allows the user to select different operating conditions, and calculate the resulting performance criteria such as efficiency and power factor.

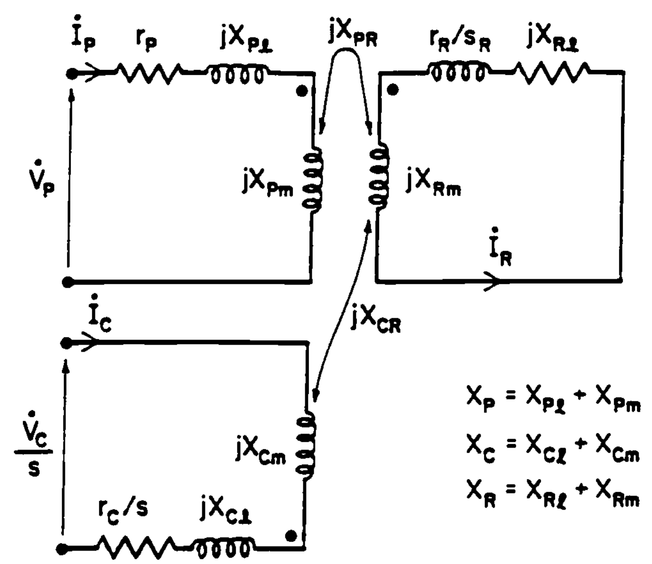


Figure 14: BDFM two-axis steady-state model.

3.4 Machine Implementation

The prototype machine is based on a standard induction motor frame. The original induction machine was a 2 horsepower machine in an NEMA 184 frame. The rotor was replaced with a BDFM type of rotor. The stator of the machine contains 36 slots.

The two windings on the stator were designed to meet the specifications outlined in Table III. The power winding was designed to interface with the available 115 Vac three-phase grid. Use of a pulse-width-modulated, voltage source inverter limits the available output voltage from 0 - 115 VAC.

The particular implementation details are shown in Table IV. The power winding is a 6-pole configuration, and the control winding is a 2-pole. Both stator

Table III: Prototype BDFM design goals.

Power Winding Voltage	115 Vrms (l-l)
Power Winding Frequency	60 Hz
Control Winding Voltage	0 - 115 Vrms (l-l)
Control Winding Frequency	0 - 80 Hz
Maximum Speed	2000 r/min
Minimum Speed	1200 r/min

windings are wound with double-layer coils. The power winding handles the majority of the power in the machine, thus it is wound with a larger diameter wire.

Table IV: Prototype winding characteristics.

Parameter	Power winding	Control winding
Winding pole pairs	3	1
Winding type	double-layer	double-layer
Winding span	5 slots	15 slots
Winding turns/coil	15 turns/coil	10 turns/coil
Wire gauge	16 AWG	19 AWG

3.5 Inverter Description

A pulse-width modulated voltage source-inverter, as illustrated in Figure 15, is used to generate the appropriate voltage and frequency for the BDFM.

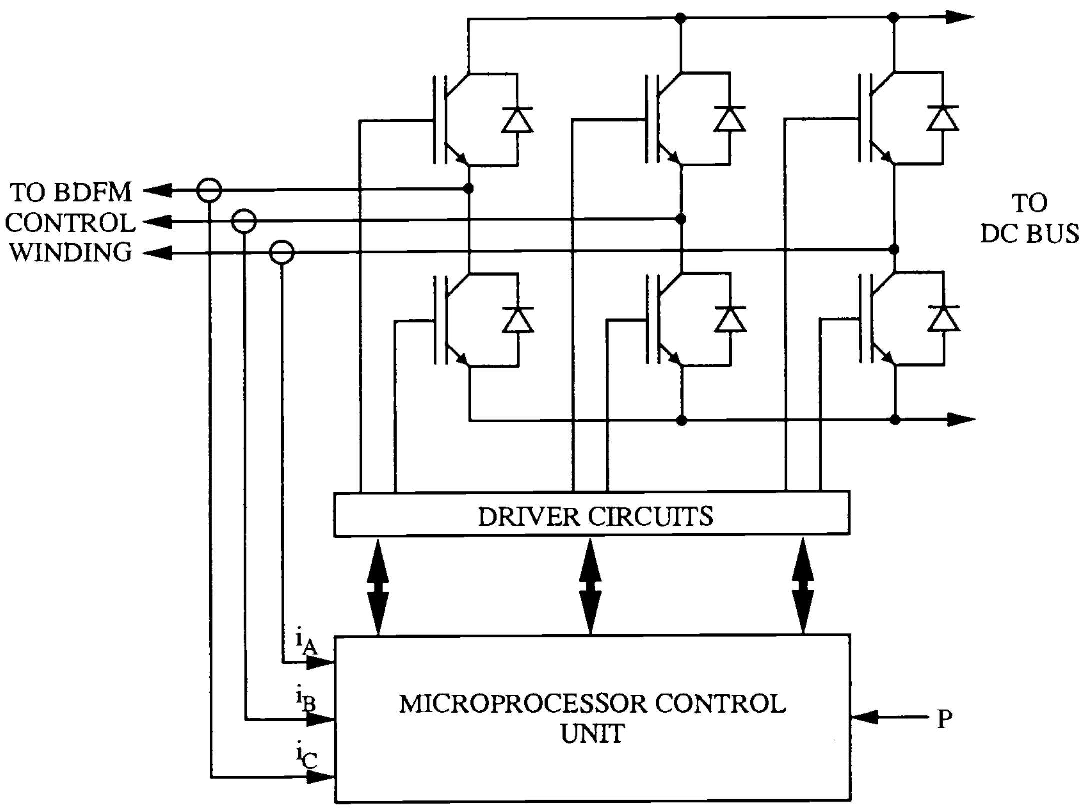


Figure 15: Schematic of the prototype inverter.

The inverter is implemented using Insulated Gate Bipolar Transistors (IGBT); in order to provide for sufficient over capacity in the prototype system, IXYS IXGH20N60U1 IGBTs with ratings of 600 V and 20 A were selected. These particular devices include an integral anti-parallel diode in the same package, thus simplifying construction. These devices are capable of switching frequencies in excess of 10 kHz.

Driver circuits are used to amplify the microprocessor control signals, and provide desaturation fault protection. An IR2121 integrated circuit is used as the low-side driver, and an IR2125 is used as the high-side driver. These two integrated circuits provide buffering between the IGBT and the logic level signals. All of the high-side drivers require a floating supply voltage due to the constantly changing voltage on the emitter of the high-side IGBT. The floating supply is provided by using a boot-strap supply, which consists of a capacitor that is recharged every time the low-side switch is used. Due to the limited size of the capacitor, the boot-strap supply provides power to the high-side for a maximum of 50 ms. The driver circuits are arranged on printed circuit boards, with one phase leg per board. Details of the driver board circuitry are provided in Appendix B.

A DC bus capacitor is used to ensure that the DC bus voltage is smooth. The DC bus capacitor ensures that any instantaneous mismatches in power flow do not lead to large transients.

The microprocessor control unit uses an Intel 80C196KC. This processor provides an on-board eight channel analog-to-digital (A/D) converter. The instantaneous values of the phase currents are used to implement a hysteresis current control algorithm. The microprocessor is capable of switching frequencies as high as 10 kHz, with current control updates occurring at 2 kHz.

Hall-effect current transducers are used to provide current feedback to the microprocessor. The transducers sense the magnetic field surrounding a wire and produce a voltage signal that is proportional to the instantaneous magnitude of the current.

3.6 Rectifier Description

Similar electronics are used in the rectifier and the inverter. The rectifier and inverter are identical accept that rectifier operates from different control inputs. Figure 16 depicts the circuitry used in the rectifier.

The synchronous rectifier is connected between the electrical grid and the DC bus, and provides for bidirectional power flow and unity power factor. Rectifier design aims at maintaining the DC bus at a particular voltage, thus ensuring equal power flow into and out of the DC bus.

If the DC bus voltage is above a nominal value, the power must flow out of the DC link and into the grid. If the DC link voltage is below the nominal value, power flow is into the DC link. Thus, the rectifier acts as a voltage regulator for the DC link.

The rectifier is controlled to provide sinusoidal currents that are in phase with the electrical grid. Zero-crossing detectors are used to detect when the AC voltage changes from positive to negative or vice versa. The microprocessor can thus control the currents to be in phase with the AC voltage.

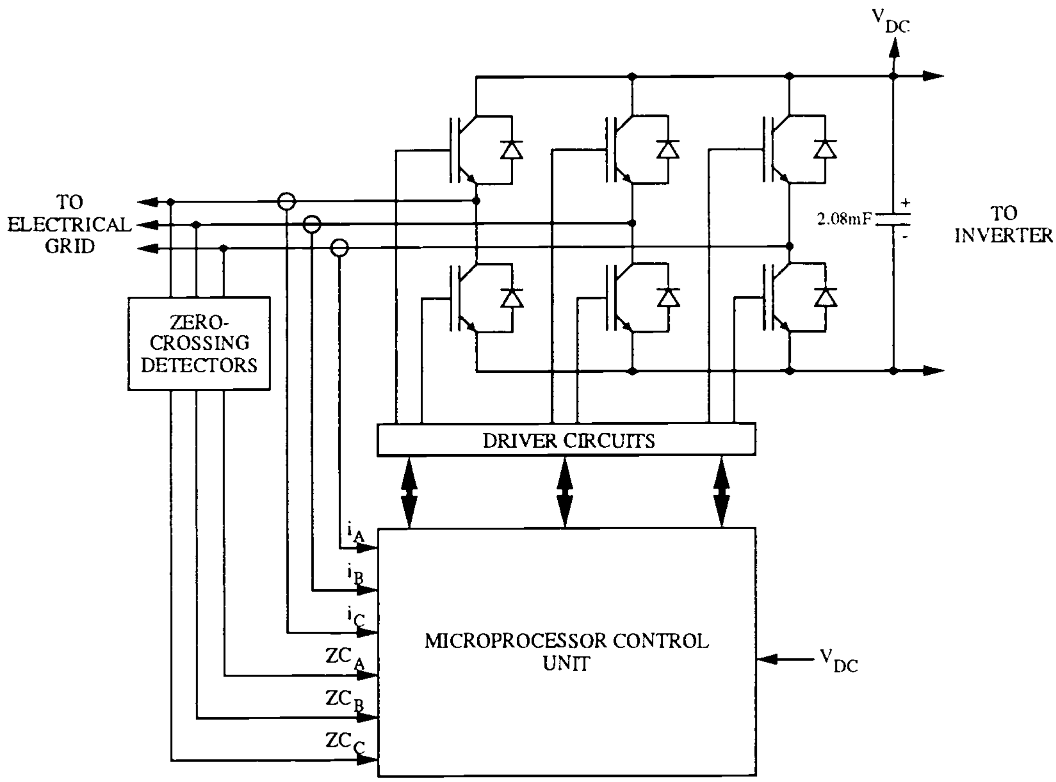


Figure 16: Rectifier schematic.

3.7 Control strategy

As described in chapter 2, the desired control strategy is termed maximum power point tracking. The inverter microprocessor implements this strategy by monitoring the instantaneous value of the system power output, and setting the inverter frequency, and thus shaft speed, to follow the derivative of the power output. If the output power increases for a given change in shaft speed, then the shaft speed is again changed in the same direction. This process continues until the output power begins to decrease, at which point the change in shaft speed reverses.

The control system must also provide for power limiting. During power limiting it is necessary to decrease the shaft speed to maintain the power output at or below the maximum point.

In order to maintain optimum performance and stability of the BDFM generation system, excitation current magnitudes are kept at the lowest possible value, depending on the current output frequency. Experimental and simulation data show that the BDFM is most efficient when the control winding current is low.

It should be noted that due to its synchronous nature, the BDFM generation system does not necessarily require a shaft speed transducer. The shaft speed feedback provided in the prototype system insures stability and allows controlled start-up, shut-down and synchronization.

The start-up time is determined by monitoring a wind speed indicator, which produces a DC voltage proportional to wind speed. The microprocessor can then determine if the generation system should start. For start-up, the power winding of the generator is connected to the electrical grid. When connected this way the BDFM acts as an induction machine and will operate near the power winding synchronous speed (1200 rev/min for the prototype). As the wind accelerates the BDFM above synchronous speed, the inverter is energized at the appropriate excitation frequency and magnitude to synchronize the machine. Once synchronized, the maximum power point controller commences operation.

4. EXPERIMENTAL SYSTEM EVALUATION

In order to examine the steady-state performance of the prototype system, laboratory testing is performed under controlled conditions. The laboratory test facility, as shown in Figure 17, uses a controlled induction machine to simulate the prime mover. A torque/speed transducer is used to measure mechanical power.

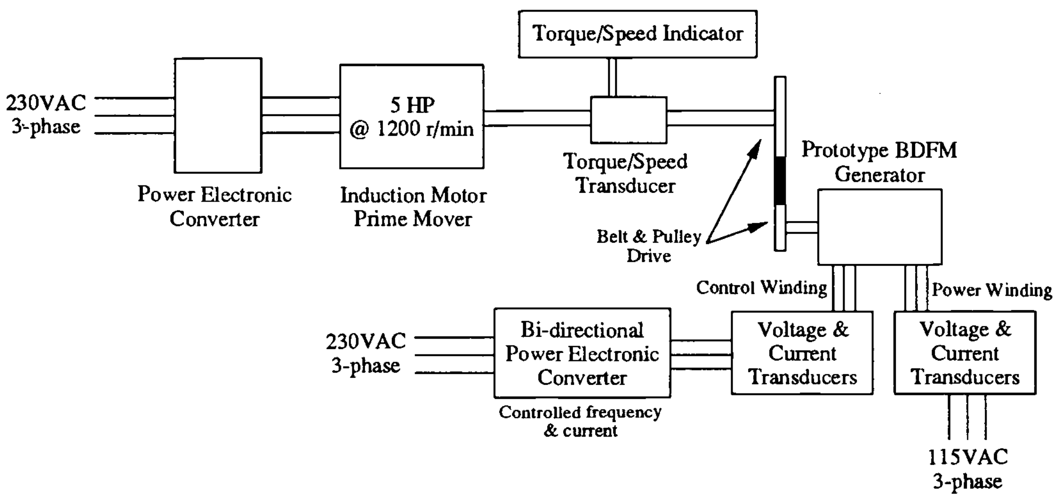


Figure 17: Laboratory facilities.

The induction machine is controlled by a power electronic converter. The converter produces an adjustable output frequency which is applied to the induction machine. Since the BDFM is a synchronous machine, an increase of the applied frequency to the induction machine, at a particular operating speed, increases the slip in the induction machine. As the slip in the induction machine rises, the applied torque to the BDFM increases. Parameters for the induction machine and the power electronic converter are listed in Table V.

Table V: Converter and induction machine description.

Induction Machine Model	Toshiba World Energy Series Model No. B0056DLF2A0H
Induction Machine Rating	5 Hp @ 1155 r/min
Converter Model	Toshiba Model No. ESP-130
Converter Rating	10 kVA

The laboratory test facility uses a belt and pulley arrangement to couple the generator to the prime mover, similar to the prototype type wind system. A Himmelstein transducer, model #66300, is used to provide torque and speed measurements [19].

To evaluate the use of the BDFM in a wind generation system it is important to consider the system efficiency. The efficiency of the BDFM system can be divided into two parts, generator efficiency and power converter efficiency. The generator efficiency is defined as follows:

$$\mathit{Efficiency} = \frac{\mathit{Power\ Winding\ Power} + \mathit{Control\ Winding\ Power}}{\mathit{Mechanical\ Input\ Power}}$$

When considering the BDFM, it is important to note that the control winding power flow can be bidirectional. Under most operating conditions the control winding power flows out of the machine. The power converter efficiency is a function of the power electronics, and is typically above 90%.

Figure 18 illustrates the resulting mechanical power profile and motor efficiency. The power profile is controlled to match that of the prototype wind turbine. As discussed earlier, it is important to note the power limiting and shaft speed reduction that occurs at higher wind speeds.

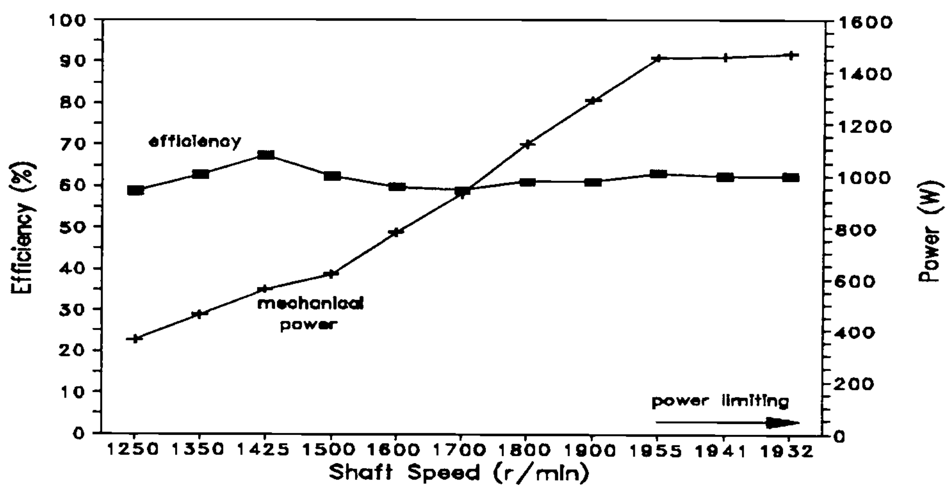


Figure 18: Measured power and efficiency of prototype.

Experimental results show that the motor efficiency is approximately 60% over the entire speed range. This efficiency level is very comparable to that of a similarly sized induction machine. It is also important to consider that a variable-speed system using an induction machine must process 100% of the power, thus the converter losses for the BDFM are significantly less. Since the prototype BDFM was built from a used induction motor frame, there are added losses in the machine due to the rewind process.

Converter losses, in a BDFM generation system, are a function of the apparent power processed by the control winding. Figure 19 shows the power distribution between the control and power windings. For simplicity, the converter losses are estimated to be the apparent power multiplied by the converter efficiency. The converter efficiency is assumed to be 90%, with resulting losses as illustrated in Figure 20.

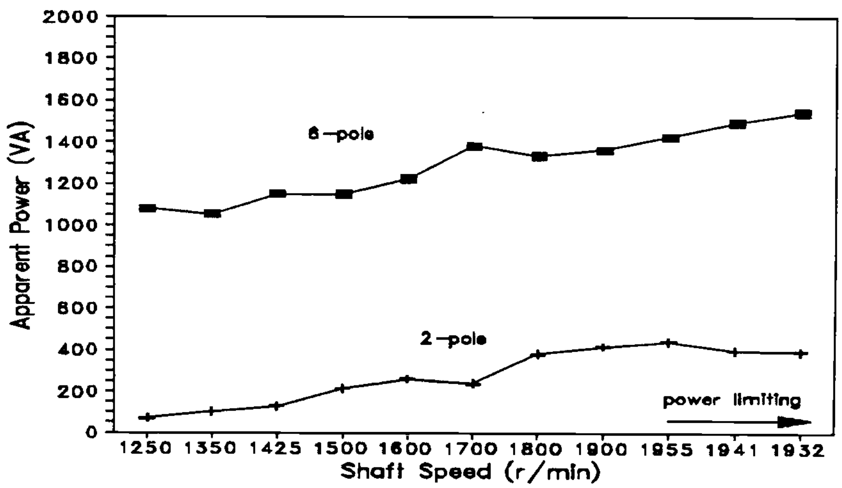


Figure 19: Apparent power distribution in the prototype.

Another important experimental quantity is converter rating. Converter rating refers to size of the converter necessary to operate the BDFM. It is usually expressed as a percentage of the rating necessary to run an induction machine of the same power rating. For comparison, the induction machine with the characteristics listed in Table VI is used to calculate the necessary converter rating. The converter rating is assumed to be the product of rated current and rated voltage.

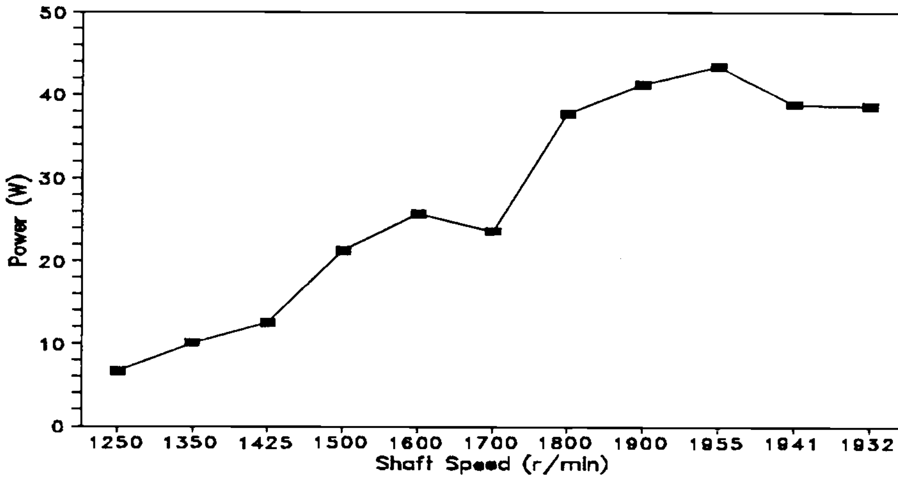


Figure 20: Converter losses in the prototype system.

Table VI: Baseline induction machine characteristics.

Motor Type	Dayton Model No 2N982-C 3 - phase induction machine
Power Rating	1500 Watts
Voltage Rating	220 VAC
Current Rating	6.2 A
Converter Rating	2363 VA

To evaluate the converter rating needed for the prototype system we can use the experimental measurements of control winding current and voltage. The voltages and currents for both stator windings are shown in Figure 21 and Figure 22. The maximum control winding voltage is 99 volts, and the maximum control winding current is 2.7 amps. This results in a converter rating of 463 VA. Compared to the

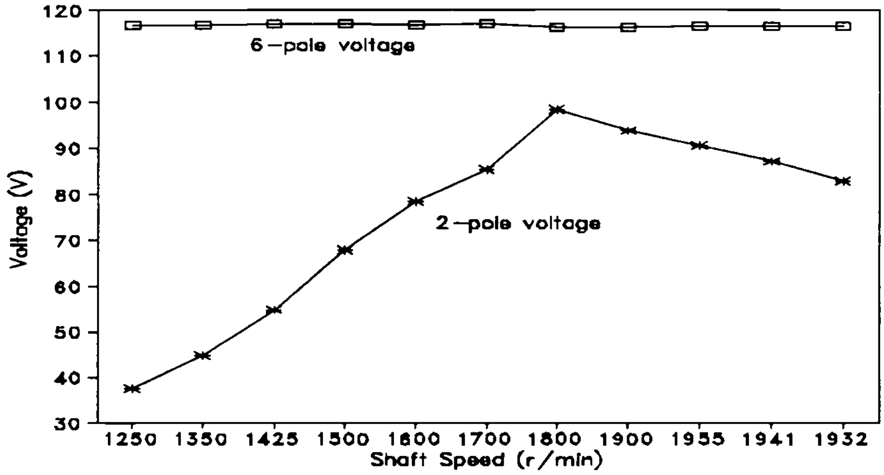


Figure 21: Measured stator voltages.

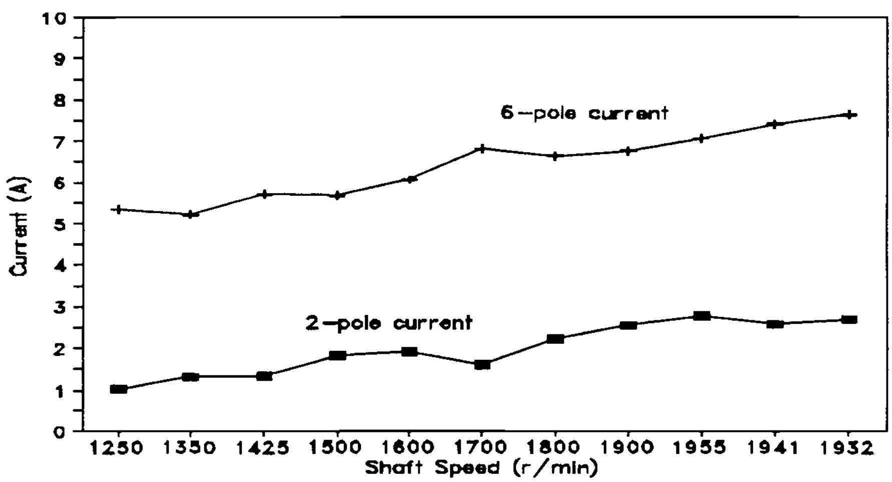


Figure 22: Measured stator currents.

rating of the base-line induction machine the prototype converter rating is reduced to 19.6 % of the base-line system. The reduction in converter rating represents significant cost savings in a utility-scale system.

As stated in Chapter 3, the control winding voltage/current significantly affects the performance of the machine. Figure 23 illustrates the effect of control winding voltage on several system parameters. The efficiency of the motor decreases as the control winding voltage increases, while the converter rating increases. Thus, optimal operation occurs at the minimum control winding voltage which ensures stable operation.

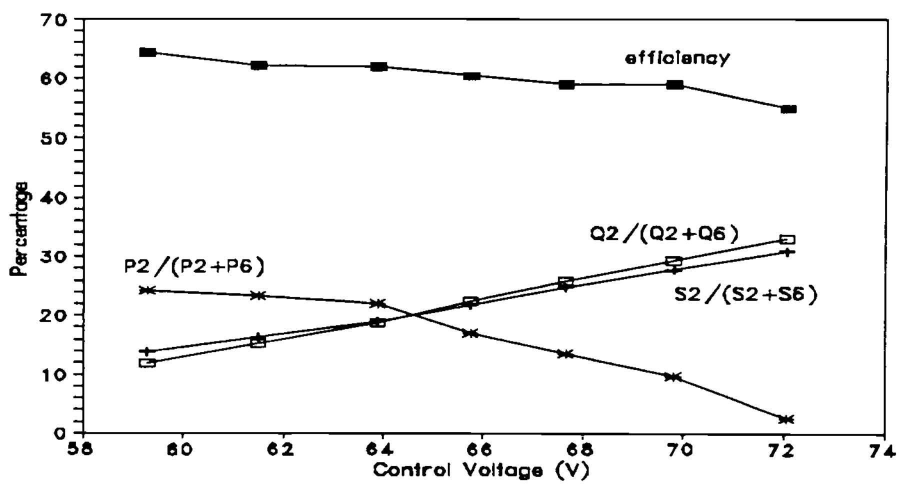


Figure 23: Effect of control winding voltage on system quantities.

It is also important to consider the harmonic distortion of currents drawn from the electrical grid by the BDFM. An oscilloscope picture of the line currents for both the control winding and the power winding is given in Figure 24. The power winding current is relatively free of harmonic distortion. Some distortion is evident as the prototype machine does not have skewed rotor bars.

The experimental results illustrate using the BDFM in a wind energy conversion system. The data shows that the BDFM has comparable efficiency to that

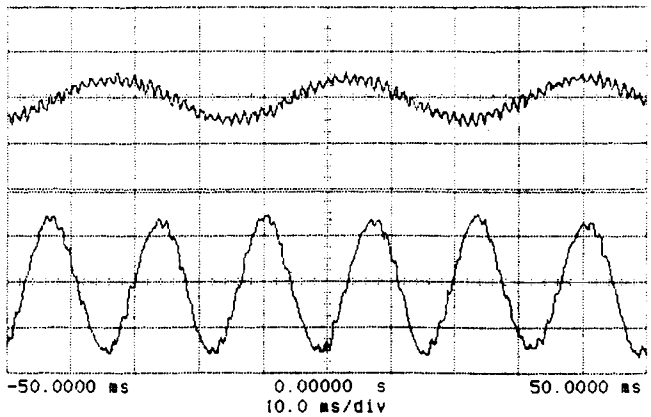


Figure 24: Measured Current Waveforms.
Upper Trace: Control winding current (2-pole), 5 A/div.
Lower Trace: Power winding current (6-pole), 5 A/div.

of an similarly sized induction machine, while the rating of the converter for the BDFM in the prototype system is significantly less than that necessary for the induction machine.

5. CONCLUSIONS & RECOMMENDATIONS

The thesis has described the development and evaluation of the BDFM in a wind energy conversion system. The system developed for this thesis is only a proof-of-concept system. There are no cost advantages to using the BDFM in a small wind system such as the prototype. However, the purpose of the research is to spark interest in developing utility-scale implementations.

By using a variable-speed system there is a notable increase in the energy captured, representing a significant increase in operating income. However, many of the variable-speed implementations examined increase the system cost significantly. In many cases the increased cost is due to the power electronic converter begin rated at maximum system power level. As stated earlier, it can be difficult to build power electronic converters with ratings above 100 kW. By using the BDFM, it is possible to build systems rated up to 500 kW with the power electronics rated at only 100 kW. In addition, reducing the size of the power electronics represents a significant reduction in system cost.

The thesis has proved the feasibility and potential of the BDFM by developing a proof-of-concept system. However, there is more research to be done before an actual implementation is attempted. First, the control strategy should be further detailed and tested. This would include evaluating the effectiveness of the maximum power point tracker, and the system's ability to track constantly varying wind speeds. Work should also be done on evaluating control strategies for the BDFM. The current control strategy implements a simple volts/hertz control; it may be necessary, however, to evaluate other methods such as direct torque control. Operational experience should be gained using the prototype system and by communication with motor drive manufacturers and wind industry representatives.

REFERENCES

[1] R. Davidson, "A New Credibility," *Windpower Monthly*, pp. 16-19, Oct. 1992.

[2] R. Colby, "Entrepreneurial Energy," *The Sunday Oregonian*, pg. J1, April 18, 1993.

[3] Y. Tang and L. Xu, "A Flexible Active and Reactive Power Control Strategy for a Variable Speed Constant Frequency Generating System," *IEEE PESC*, pp. 568-573, June 1993.

[4] H.K. Lauw, C.H. Weigand, and D. Marckx, "Variable-Speed Generation Feasibility Study: Electrical Options," Report to U.S. Department of Energy, Bonnevile Power Administration, Contract No. DE-AC79-92BP34885, Sept. 1992.

[5] L. Dessaint, H. Nakra, and D. Mukhedkar, "Propagation and Elimination of Torque Ripple in a Wind Energy Conversion System," *IEEE Trans. on Energy Conversion*, Vol. EC-1, No. 2, pp. 104-112, June 1986.

[6] R.D. Richardson and W.L. Erdman, "Variable Speed Wind Turbine," U.S. Patent No. 5,083,039, Jan. 21, 1992.

[7] J.H.R. Enslin and J.D. Van Wyk, "A Study of a Wind Power Converter with Micro-Computer Based Maximal Power Control Utilising an Over-Synchronous Electronic Scherbius Cascade," Renewable Energy, Vol. 2, No. 6, pp. 551-562, 1992.

[8] H.L. Nakra and B. Dubé, "Slip Power Recovery Induction Generators for Large Vertical Axis Wind Turbines," *IEEE Trans. on Energy Conversion*, Vol. 3, No. 4, pp. 733-737, December 1988.

[9] Z. Salameh and S. Wang, "Microprocessor Control of Double Output Induction Generator," *IEEE Trans. on Energy Conversion*, Vol. 4, No. 2, pp. 172-176, June 1989.

[10] Z.M. Salameh and L.F. Kaxda, "Analysis of the Steady State Performance of Double Output Induction Generator," *IEEE Trans. on Energy Conversion*, Vol. EC-1, pp. 26-32, No. 1, March 1986.

[11] D.A. Torrey, "Variable-Reluctance Generators in Wind Energy Systems," *IEEE PESC* pp. 561-567, June 1993.

[12] L. Xu and Y. Tang, "A Novel Wind-Power Generating System Using Field Orientation Controlled Doubly-Excited Brushless Reluctance Machine," *IEEE IAS Annual Meeting Conference Record*, pp. 408-413, 1992.

[13] D.L. Gourtérès, *Wind Power Plants*, Pergamon Press, 1982.

[14] Whisper 1000 Wind Generator available from World Power Technologies, 19 North Lake Avenue, Duluth, Minnesota 55802, 1993.

[15] S.N. Walker and P.L. Barbour, *"Historical Wind Data Summary Report: October 1991 to September 1992,"* Report to Bonneville Power Administration, Report No. BPA 92-11, Contract No. DE-BI79-91BP20838, Dec. 1992.

[16] L.J. Hunt, "A new type of induction motor," Journal IEE (London), vol. 39, pp. 648-667, 1907.

[17] R. Li, A.K. Wallace, R. Spée, and Y. Wang, "Two-axis mode development of cage-rotor, brushless doubly-fed machines," *IEEE Trans. Energy Conversion*, vol. 6(3), pp. 453-460, 1991.

[18] BDFM Steady-State Simulator Program, written by Chris Brune at Oregon State University, Spring 1993.

[19] S. Himmelstein and Company, Model 66300 users manual, 1985.

APPENDICES

APPENDIX A

Cape Blanco Wind Data

STATION - CAPE BLANCO 50'
WIND SPEED FREQUENCY DISTRIBUTION WITH NORMALIZED AVAILABLE ENERGY
DATA PERIOD OF RECORD - 1/1978 - 9/1992
NORMALIZATION PERIOD - ONE YEAR
AVERAGE WIND SPEED FOR PERIOD: 19.3 MPH
NORMALIZED AVAILABLE ENERGY: 9274.8 KWH/M**2/YEAR
TOTAL HOURS OBSERVED: 107120

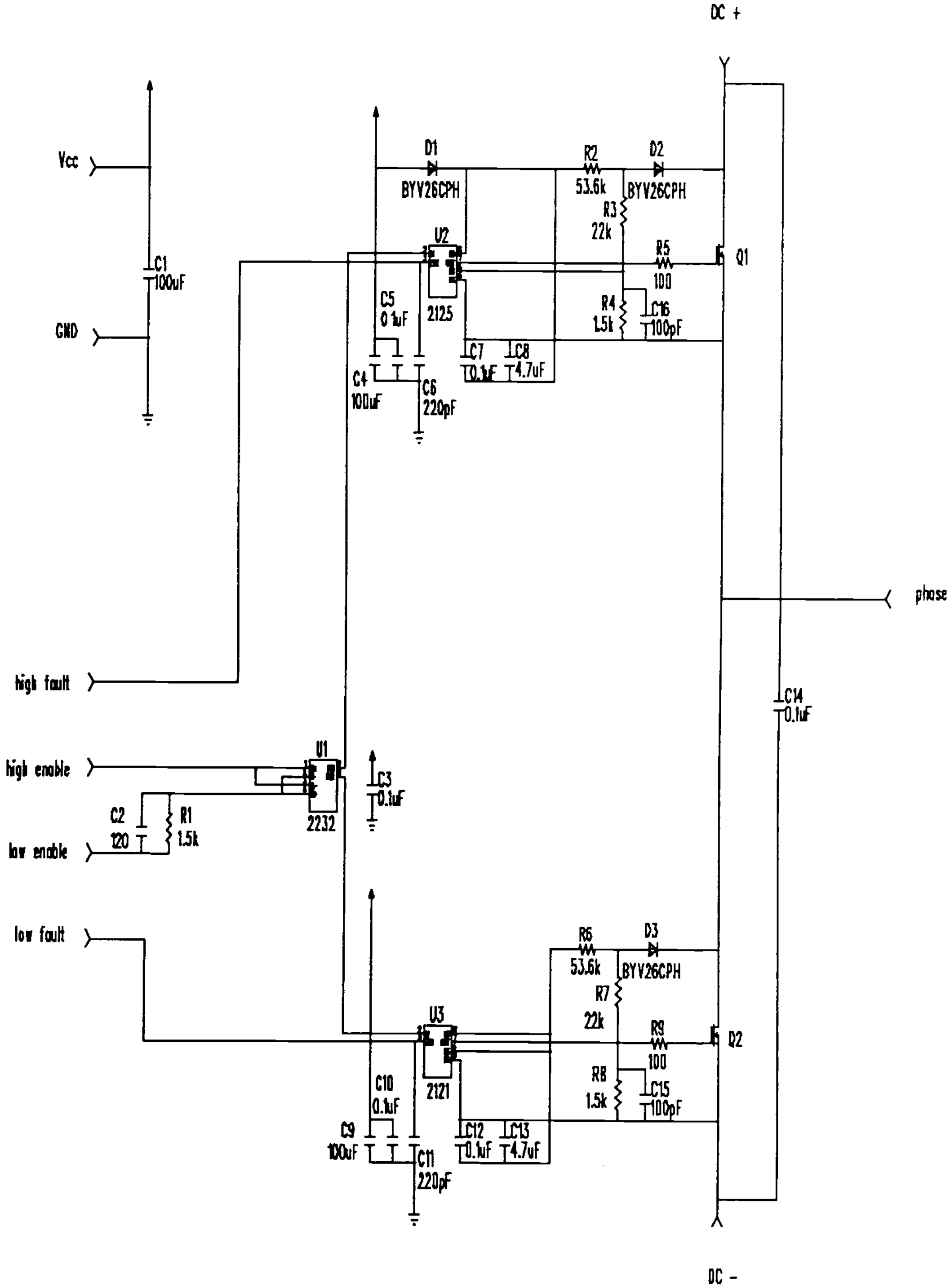
SPD MPH	HOURS/ PERIOD	RELFREQ	CUMHRS	CUMRELFREQ	NORMALIZED AVAIL. ENERGY KWH/M**2/YEAR
0	817	0.76	107120	100.00	0.0
1	1338	1.25	106303	99.24	0.0
2	2107	1.97	104965	97.99	0.1
3	2234	2.09	102858	96.02	0.3
4	3152	2.94	100624	93.94	0.9
5	2827	2.64	97472	90.99	1.6
6	3602	3.36	94645	88.35	3.5
7	3010	2.81	91043	84.99	4.6
8	3697	3.45	88033	82.18	8.4
9	2837	2.65	84336	78.73	9.2
10	4045	3.78	81499	76.08	18.0
11	2999	2.80	77454	72.31	17.8
12	3453	3.22	74455	69.51	26.5
13	3134	2.93	71002	66.28	30.6
14	3593	3.35	67868	63.36	43.8
15	3265	3.05	64275	60.00	49.0
16	3764	3.51	61010	56.95	68.6
17	3012	2.81	57246	53.44	65.8
18	3646	3.40	54234	50.63	94.6
19	3051	2.85	50588	47.23	93.1
20	4383	4.09	47537	44.38	155.9
21	3034	2.83	43154	40.29	125.0
22	3462	3.23	40120	37.45	163.9
23	2915	2.72	36658	34.22	157.7
24	3372	3.15	33743	31.50	207.3
25	2832	2.64	30371	28.35	196.8
26	2999	2.80	27539	25.71	234.4
27	2259	2.11	24540	22.91	197.7
28	2348	2.19	22281	20.80	229.2
29	1682	1.57	19933	18.61	182.4
30	2077	1.94	18251	17.04	249.4
31	1347	1.26	16174	15.10	178.5
32	1314	1.23	14827	13.84	191.5
33	1032	0.96	13513	12.61	164.9
34	1079	1.01	12481	11.65	188.6
35	870	0.81	11402	10.64	165.9
36	915	0.85	10532	9.83	189.8
37	627	0.59	9617	8.98	141.2
38	703	0.66	8990	8.39	171.5
39	515	0.48	8287	7.74	135.9
40	754	0.70	7772	7.26	214.6
41	428	0.40	7018	6.55	131.2
42	481	0.45	6590	6.15	158.5
43	395	0.37	6109	5.70	139.7
44	448	0.42	5714	5.33	169.7
45	364	0.34	5266	4.92	147.5

SPD MPH	HOURS/ PERIOD	RELFREQ	CUMHRS	CUMRELFREQ	NORMALIZED AVAIL. ENERGY KWH/M**2/YEAR
46	416	0.39	4902	4.58	180.1
47	300	0.28	4486	4.19	138.5
48	348	0.32	4186	3.91	171.1
49	239	0.22	3838	3.58	125.0
50	393	0.37	3599	3.36	218.5
51	202	0.19	3206	2.99	119.2
52	252	0.24	3004	2.80	157.6
53	190	0.18	2752	2.57	125.8
54	223	0.21	2562	2.39	156.2
55	212	0.20	2339	2.18	156.9
56	207	0.19	2127	1.99	161.7
57	154	0.14	1920	1.79	126.8
58	181	0.17	1766	1.65	157.0
59	130	0.12	1585	1.48	118.7
60	206	0.19	1455	1.36	197.9
61	122	0.11	1249	1.17	123.1
62	116	0.11	1127	1.05	122.9
63	104	0.10	1011	0.94	115.6
64	123	0.11	907	0.85	143.4
65	96	0.09	784	0.73	117.2
66	82	0.08	688	0.64	104.8
67	67	0.06	606	0.57	89.6
68	59	0.06	539	0.50	82.5
69	48	0.04	480	0.45	70.1
70	60	0.06	432	0.40	91.5
71	40	0.04	372	0.35	63.7
72	49	0.05	332	0.31	81.3
73	33	0.03	283	0.26	57.1
74	26	0.02	250	0.23	46.9
75	28	0.03	224	0.21	52.5
76	28	0.03	196	0.18	54.7
77	17	0.02	168	0.16	34.5
78	20	0.02	151	0.14	42.2
79	15	0.01	131	0.12	32.9
80	20	0.02	116	0.11	45.5
81	11	0.01	96	0.09	26.0
82	21	0.02	85	0.08	51.5
83	14	0.01	64	0.06	35.6
84	7	0.01	50	0.05	18.5
85	4	0.00	43	0.04	10.9
86	10	0.01	39	0.04	28.3
87	6	0.01	29	0.03	17.6
88	3	0.00	23	0.02	9.1
89	3	0.00	20	0.02	9.4
90	4	0.00	17	0.02	13.0
91	1	0.00	13	0.01	3.4

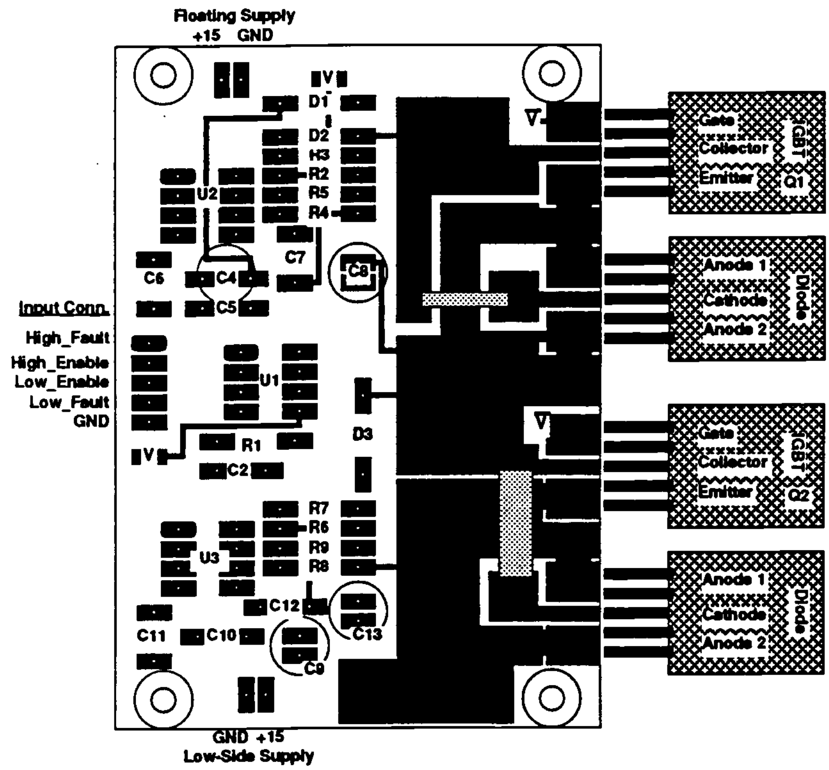
APPENDIX B

Detailed Circuit Information

Driver Circuit Board Schematic



Driver Circuit Board Layout



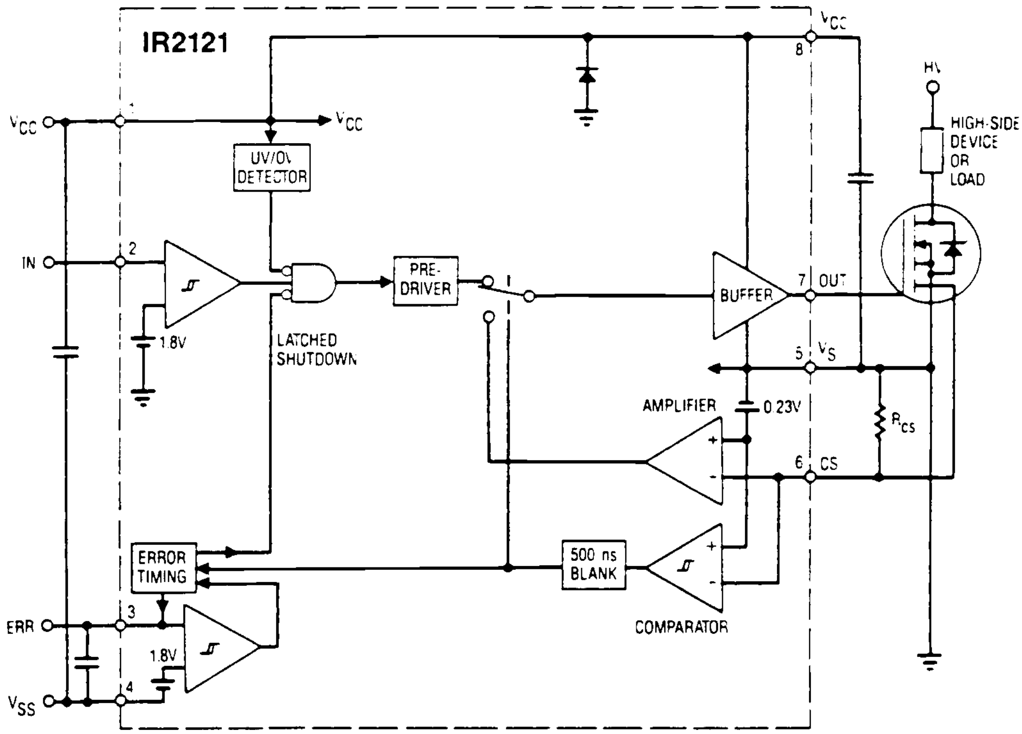
V Indicates a VIA location, top and bottom side of board must be connected together.

Indicates JUMPER, not needed if IGBT contains integral diode.

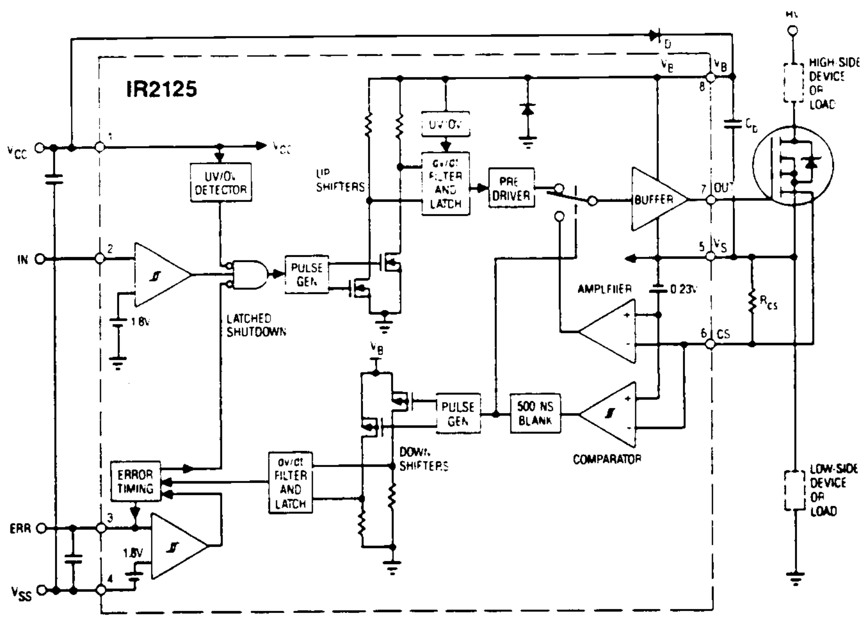
C15 and C16 are placed on top of R4 and R8.

C14 is placed on top of the board, and positioned as dictacted by packaging considerations.

IR2121 Functional Block Diagram



IR2125 Functional Block Diagram



Power Device Specifications

Manufacturer:	IXYS Corp.
Type:	IXGH20N60U1
Description:	MOSIGBT with Anti-Parallel Rectifier
Package:	TO-247AD

Characteristics:

Collector-Emitter Breakdown Voltage:	600 V
Continuous Collector Current:	20 A
Gate-Emitter Threshold Voltage:	5 V
Collector-Emitter Saturation Voltage:	2.5 V
Turn-On Delay Time:	100 ns
Current Rise Time:	200 ns
Turn-Off Delay Time:	900 ns
Current Fall Time:	530 ns
Reverse Diode Forward Voltage	1.5 V
Reverse Diode Reverse Recovery Time	35 ns