Appendix A to FAR 00-09

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

COUNTER ROTATING WIND TURBINE SYSTEM

EISG AWARDEE

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Grant #: 51809A/00-09
Grant Funding: $74,915
Term: February 1, 2001 – April 30, 2002
PIER Subject Area: Renewable Energy Technologies

Legal Notice

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgements

The author wishes to thank Harold M. Romanowitz, President and Edward Duggan, Vice President, both of Oak Creek Energy Systems Inc. Mojave, California for providing the opportunity to use their test site facility and technical support. The author gratefully acknowledges the dedicated fabrication and integration support provided by John Flanagan of Galahad Concepts to Prototypes, and data acquisition consulting services provided by Raman Amin and Mark West.

EISG Awardee

This Project was awarded to Appa Technology Initiatives (ATI), of Orange County, CA. This is a small business entity primarily focusing on the advancement of Renewal Energy System Technologies.

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Abstract

The objective of the project was to investigate a means of enhancing wind energy conversion efficiency. Appa Technology Initiatives used the velocity compounding principle suggested by Charles Gordon Curtis to build a wind turbine configuration having contra-rotating rotors in tandem. A 6 kW prototype model was built and field-tested at Oak Creek Energy Systems facility. Wind turbine performance tests were conducted over a period of four months. Sensors and data loggers were used to record the raw data. The results of these tests indicated that a contra-rotating turbine system could extract additional 30% energy from the same wind stream or rotor swept area. The contra rotating dual rotor system was found to be more efficient at slow rotor speeds. This suggests that utility scale wind turbines that rotate in the range of 16 - 60 rpm could benefit better from the contra rotating rotor system. Further more the buffeting phenomenon that was considered to be of great concern was not observed in these tests.

To investigate the commercial aspects of the system, ATI has developed an advanced configuration that could easily be assembled and field-tested. ATI has sought the support of Oak Creek Energy Systems for grid-connected installation and computerized data collection system. Successful evaluation of the concept could lead to upgrading of existing wind farms that could promote substantially increased electrical energy production resulting in reduced cost of energy to California ratepayers.

Keywords:
Counter rotating wind turbine system, wind energy system, Hybrid Renewable Energy System

EXECUTIVE SUMMARY

Introduction

Most wind turbines in the world use a single rotor system that provides simplicity, reliability and durability. Over the years, improvements have been made to enhance energy conversion efficiency of these single rotor systems. For example, the rotor blades have much improved aerodynamic efficiency, the gears have less noise and better torque transmission efficiency, and alternators are designed for high electrical efficiency. Despite these improvements, single rotor systems are able to convert only a small fraction of wind stream energy into electrical energy.

Energy rich wind farms are rare and valuable sites. Hence these sites must very prudently be utilized by maximizing their energy production capacity. Curtis velocity compounding principle that uses multistage-rotors is seen to enhance energy conversion efficiency in excess of 75%. Based on this concept ATI built several contra-rotating wind turbines (CRWT) and demonstrated the principle with impressive results. The power coefficient of slowly spinning counter rotating wind turbine system is seen to be in excess of 70%. Although increasing rotor diameter could generate the same extra power; it is not possible to increase the farm power density (FPD) expressed in megawatts per acre (MW/acre) or MW per square kilometer, due to rotor spacing being limited to 5 to 8 diameters. Hence the contra-rotor system in tandem becomes an ideal arrangement to enhance farm power density leading to increased clean energy production and revenue from the same wind farms. In the present study, ATI built a small CRWT and demonstrated the principle in field tests. Oak Creek Energy Systems supported ATI in conducting the field tests at their facility. The preliminary test results showed increased power production by better than 40%. This concept, after maturity of commercialization technology, could lead to a huge new and retrofit business in US and worldwide. Such adaptation could result in multi-billion dollar revenue annually in the US by 2010.

Eventually after successful evaluation, a commercialization strategy will be developed to update larger single rotor systems to CRWT to achieve the stated goals of the renewable energy task force; increased clean energy production, reduced fossil fuel consumption and increased employment opportunities.

Appa Technology Initiatives (ATI) has developed several versions of the contra-rotating wind turbine systems for which two US patent, No. 6,127,739, "Jet Assisted Counter Rotating Wind Turbine," and No. 6,278,197 B1, "Contra Rotating Wind Turbine System" were granted to Kari Appa. Another US patent application on “Jet Assisted Hybrid Wind Turbine System,” is in pending.

Objectives

The objectives of the present study are:

1. To investigate performance characteristics of a contra-rotating dual rotor system as the means of enhancing wind energy conversion efficiency.
2. To assess potential design simplicity for early and economical transition in to the California wind farms to enhance electrical energy production.

Project Outcomes

A prototype contra-rotating wind turbine system was fabricated using two 3-phase alternators and two 2-bladed rotors. The rear counter-rotating rotor was designed and fabricated in house. A tail boom was used to align the system into the windward direction. The data collection unit consisted of an anemometer, an acceleration sensor, two rotor rpm sensors, two three phase power sensors and a data logger unit. Heaters were used to dissipate the electrical power. The assembled unit was installed on a 50-ft tower at the Oak Creek Energy Systems facility in Mojave, California. The tests were conducted over a period of four months. Videotaping and performance data recording were conducted. Data from both a single rotor system and a contra-rotating system were studied.

Power conversion from the dual rotor system was found to be more efficient at slower rotor speeds. At slow rotor speeds the test results showed better than 40% more energy conversion than the single rotor system. Further, the buffeting phenomenon, which happens to have been caused by windward rotor shed vortices, was not observed in these tests. The torque produced by two rotors counterbalanced each other resulting in reduced or zero net torque transmission and minimal bending stresses on the supporting tower.

Conclusions

1. The field tests demonstrated that power conversion efficiency could be increased up to 40% by means of the contra-rotating rotor system.
2. Power conversion efficiency was found to be higher at slow rotor speeds, suggesting its applicability to large-scale utility wind turbines that rotate at 16-60 rpm.
3. The buffeting phenomenon of the dual rotor system was not observed.
4. The contra-rotating system minimizes bending stress on the tower.
5. The contra rotating system could be rendered self-aligning using larger leeward rotor and having larger lever arm from the axis of rotation. It may require a light duty yaw servomotor. The directional stability could be further increased by providing about 5-degree cone angle to the rear rotor.

Benefits to California

This project is in accordance with the Public Interest Energy Research (PIER) program objectives of seeking environmentally safe and economically advantageous forms of energy production. Successful commercialization of contra-rotating wind turbine systems could reduce costs to California ratepayers, promote increased power production, and stimulate business and employment opportunities in wind turbine industries within California as well as worldwide.

Recommendations

The present study was intended to demonstrate the feasibility of a contra-rotating wind turbine system. The next step is to conduct economic performance using a utility scale grid-connected induction generators. Such field tests clearly demonstrate technological and economical advantages of the counter rotating system for commercial applications.

The president of Oak Creek Energy Systems Inc. has encouraged ATI to continue additional tests using a grid-connected unit at their test facility. Accordingly, ATI has developed a contra-rotating rotor system that could easily be assembled using refurbished components. The generated power will be supplied to the utility system and the energy data will be recorded in a logger system. ATI has discussed this task with Oak Creek Energy Systems and they have agreed to extend their cooperation.

The suggested program is as follows:

1. Select a grid-connected environment in 50 to 100 kW power rating.
2. Team with a wind power production company such as Oak Creek Power Systems Inc. to install several of high power rated units, say 250 kW.
3. Collaborate with a gear manufacturing company to design and fabricate torque-hubs, which can be coupled to two contra rotating rotors to drive a generator shaft.
4. Conduct power production performance studies with grid-connected mode for a period of one year or more.
5. Assess economics of dual rotor system versus the single rotor system using available sales data.
6. After successful completion of this study, plan to transition the technology by licensing to wind turbine manufacturers or utility providers.

1 INTRODUCTION

A wind turbine that converts wind energy into electrical energy is an environmentally safe system. Utilization of wind energy for human needs dates back to 200 B.C when Chinese used aerodynamic drag in their simple windmills to grind grains. This technology did not receive much attention until the 11th century, when the Dutch improved the mechanical aspects of the windmill and built much bigger machines. In 1890, the Danish employed aerodynamic lift, rather than drag, to improve the energy conversion efficiency and named these machines as wind turbines. In 1940, the largest wind turbine rated at 1.25 megawatt was designed and operated for electric power in the hills of Vermont in the US. It was not until the1970's oil embargo, any serious consideration was given to wind energy research and development. Now, State Energy Commissions and Federal Department of Energy support research and development (R&D) activities to reduce cost of energy to consumers to help the United States to be independent from foreign sources of energy and protect the environment from the toxic waste generated by fossil fuels.

The Federal and State Government funded R&D activities have paved the way for improved airfoil efficiency, low speed direct drive electrical generators, grid connected power distribution and automated safety mechanism in high wind environment. Lessons learnt from decades of operating wind power plants have made wind generated electric power in high wind regions affordable, although it is not yet competitive with the cost of fossil fuel-generated energy.

There are two types of wind turbines, horizontal axis and vertical axis. The horizontal axis turbines are the most preferred ones. Wind turbines can be classified as micro (less than a kilowatt), mid-sized (less than 100 kW) and large (more than 100 kW). Large diameter turbines are economical in the sense of cost of energy, however investments are very large and their installation sites are limited to above normal windy regions such as Tehachapi, San Gorgonio and Coachella valley in California. The US Department of Energy has funded and co-operated with industries to develop machines of various power rating such as; 100 kW machine MOD-0, 1.0 Mw machine MOD-1 and 2.5 Mw machine MOD-2. These experimental machines helped to resolve certain design issues related to the aerodynamic shape of airfoils, the efficiency of transmission system, the dynamic and fatigue loads. The largest wind turbine ever built under this program was the 3.2 Mw MOD-5B machine having 97.5 meter rotor, and this is operational in Oahu, Hawaii. Enron Wind Technology Inc provides customized energy solutions in 750kW to 2.0 Mw machines for on-shore and offshore sites. A patented power electronic converter is used to provide constant frequency power from a variable speed operation.

To provide uniform distribution of wind power in moderate wind zones micro and mid-sized wind turbines are becoming very popular. Paul Gipe, in his recent book, “A guide to small and micro wind systems,” discusses at length the prospects of micro and mid sized turbines and also predicts a multi-billion dollar business opportunities in the near future. There are more than 100 small wind turbine manufactures in the world. Their design skill differs in rotor blade design, assembly, direct drive generator and rotor speed control mechanism in high wind. Although it is difficult to compare their relative merits since there are no any standardized measurements, the power conversion factor of these machines varies (according to Gipe and Piggott) from 20 to 30 per cent of available power in the wind stream. This is about half of Betz's theoretical factor. In other words, 50% of the usable power is swept away in the downwind, which should not have been lost especially in low wind zones. Hence, there is a need to improve energy conversion efficiency.

In 1926, Albert Betz estimated that the maximum (or optimum) wind power conversion efficiency could be as high as 59% when the axial velocity across a rotor changes by 2/3rd (Ref.1). In 1942, Walter Just used two rotors in tandem and again considering only the axial velocity showed an efficiency of 64% (Ref.2). Both did not account for the change of moment of the tangential velocity component. Moreover, the 2/3rd velocity change criteria across a rotor can't be enforced. Early in 1896 Charles Gordon Curtis (Ref.3) had realized that it was difficult to enforce the optimality criterion (i.e. 2/3rd velocity/enthalpy change across a rotor) in a turbine operation, and hence optimal energy conversion efficiency was not possible. Therefore he used the principle of velocity compounding by means of multiple rotors in tandem on a common shaft and estimated the energy conversion efficiency to be around 75 to 85%**.** Although he did conceive the idea 13 years earlier, he had hard time selling the concept to manufacturers. Finally in 1903 General Electric funded Curtis to build and demonstrate the first American 500 kW steam turbine, which became a landmark invention in power generation. Using this principle ATI developed a counter rotating wind turbine system for which two US patents, No. 6,127,739, "Jet Assisted Counter Rotating Wind Turbine," and No. 6,278,197 B1, "Contra Rotating Wind Turbine System" were granted to Appa. Figure 1 shows the conceptual configuration of a utility scale contra rotating wind turbine system (CRWT)

Project Objectives:

The objectives of the present study are the following:

1. To investigate performance characteristics of a contra-rotating dual rotor system as a means of enhancing wind energy conversion.

2. To assess potential design simplicity of the contra-rotating dual rotor system for early and economical transition to the utility scale wind turbines.

The development described in this report is in two parts: a mathematical simulation model based on the elementary blade theory and a prototype assembly and testing.

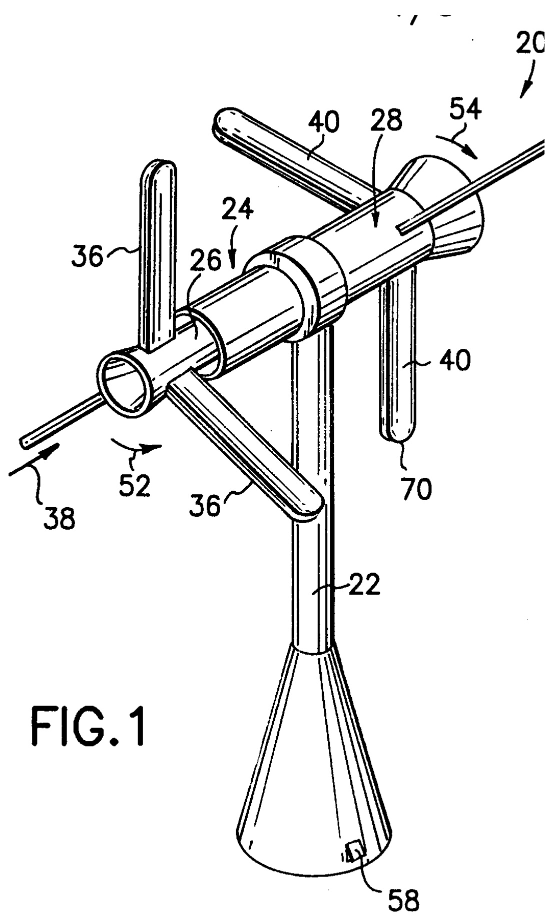


FIG. 1

Figure 1. A Conceptual Contra Rotating Wind Turbine System
(US Patent Numbers: 6,127,739, October 3, 2000, and 6,278,197 B1 August 21, 2001)

Why Industry is not investigating the proposed Concept:

This is a frequently asked question. The contra-rotating wind turbine concept has been previously considered but has not been developed beyond theory. A possible explanation is that extending the rotor diameter of single rotor turbines could achieve similar increase in power without the need for a more complex design. This argument may hold merit when considering a single turbine in an open field. However, when considering a wind farm with a finite area, it becomes necessary to factor the space required for a single turbine and the maximum number of turbines that can exist within a certain area. In a wind farm the minimum space required between turbines is about 5 to 8 rotor diameters. Thus, increasing blade diameter reduces the number of turbines per unit area (acre or km^2), which will have a diminishing effect on farm power density. Energy production and revenue depend on wind farm power density (MW/acre). Energy rich wind farms are rare commodities and hence maximum utilization of wind farms becomes a necessity. Consequently, the tandem rotor arrangement helps to increase the farm power density, and in turn increases electrical power and revenue from the same wind farms.

2 PROJECT APPROACH

The project began with the development an analytical model to compute the geometric parameters and performance characteristics. Based on this analysis, some off-the-self components were bought and some other units were fabricated with the help of the subcontractor, Galahad Concepts to Prototypes. Harold Romanowitz, president and Edward Duggan, vice president of Oak Creek Energy Systems provided the needed technical support during tests and the opportunity to use their test facility.

2.1 Mathematical Modeling

To better understand the reason for selecting the counter rotating wind turbine system, we will first review the mathematical background followed by a detailed discussion of the innovation. Let us consider two blade sections of the rotors as shown in Figure 2. The blades of these rotors are set to rotate in opposite directions. For the windward rotor 1, AB denotes the wind speed, w_1, BC is the tangential rotor speed, u_1, and AC is the relative velocity, v_1. The blade incidence is set at α_1.

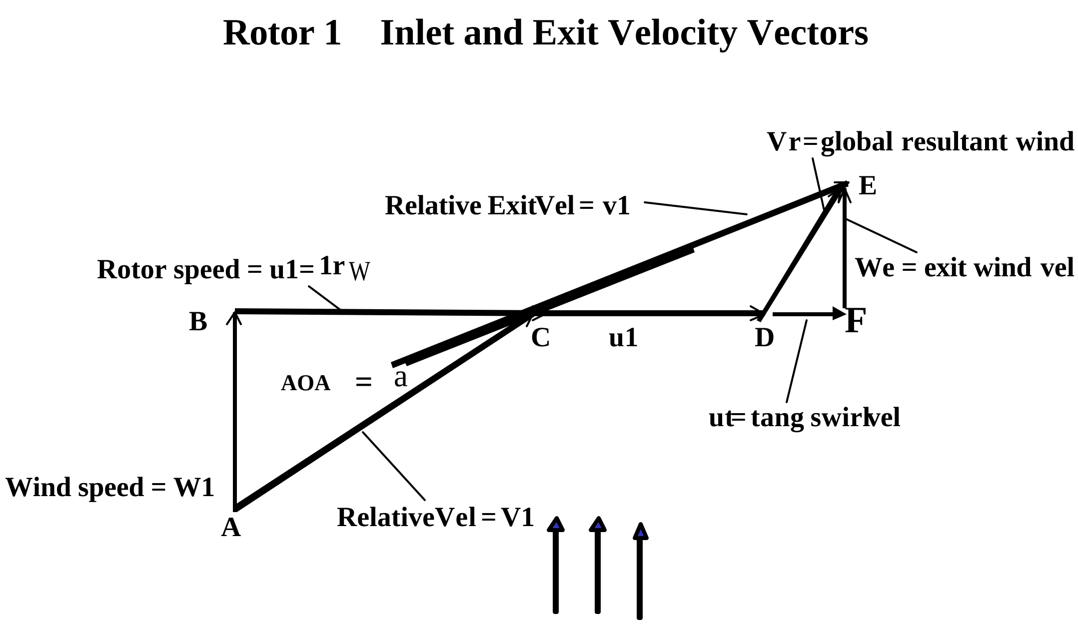


Figure 2. Windward Rotor Velocity Vector Diagram

Velocity Vector Diagram of Rotor 2

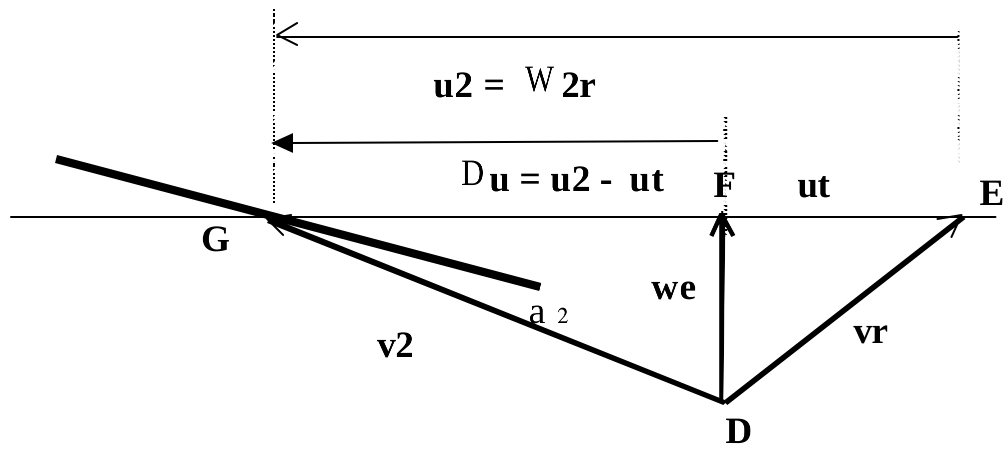


Figure 3. Leeward Rotor Velocity Vector Diagram

If the blade surface friction losses are neglected, the flow leaves the trailing edge tangentially with exit velocity v_1. However, the global exit velocity v_f is denoted by DE, having a tangential (swirl) component, u_t, and an axial exit wind velocity, w_e.

The velocity components of the leeward rotor are shown in Figure 3, in which DE denotes the on-set wind speed, v_f, EG the tangential velocity, u_2 and DG the relative velocity, v_2. It is intriguing to note that if the rotor speeds, $\Omega_2 = -\Omega_1$, the relative velocity v_2 is almost (since α_1 is small) equal to v_1, and consequently the torque of rotor 1 and rotor 2 balance each other, resulting in zero torque load on the supporting structure.

The corresponding force diagrams of two counter-rotating rotors are shown in Figure 4, in which L_1, D_1 and L_2, D_2 denote lift and drag components of rotors 1 and 2 respectively. On resolving these forces along normal and tangential directions the thrust and tangential forces for each rotor are denoted by N_1, T_1 and N_2, T_2 respectively.

The torque per unit strip dS of each rotor blade is given by

$$dt_1 = \frac{1}{2} r w^2 \sqrt{(1 + t_1^2 x^2)} [C_L - C_D t_1 x] dS r \qquad (1)$$

$$dt_2 = -\frac{1}{2} r w^2 \sqrt{(1 + (\Delta t x)^2)} [C_L - C_D \Delta t x] dS r \qquad (2)$$

Power per unit strip dS is given by

$$dP_1 = \frac{1}{2} r w^3 t_1 x \sqrt{(1 + t_1^2 x^2)} [C_L - C_D t_1 x] dS \qquad (3)$$

$$dP_2 = -\frac{1}{2} r w^3 t_2 x \sqrt{(1 + (\Delta t x)^2)} [C_L - C_D \Delta t x] dS \qquad (4)$$

in which

$dS = C_r\,dr$ is the area of the blade strip

$t_1 = \frac{\Omega_1 R}{w_1}$ rotor 1 tip speed ratio (5)

$t_2 = \frac{\Omega_2 R}{w_e}$ rotor 2 tip speed ratio (6)

$x = r / R$ (7)

$\Delta t = t_1 + t_2$ (8)

The power in the wind stream is given by

$dP_w = \frac{1}{2} r w^3 (2prdr)$ (9)

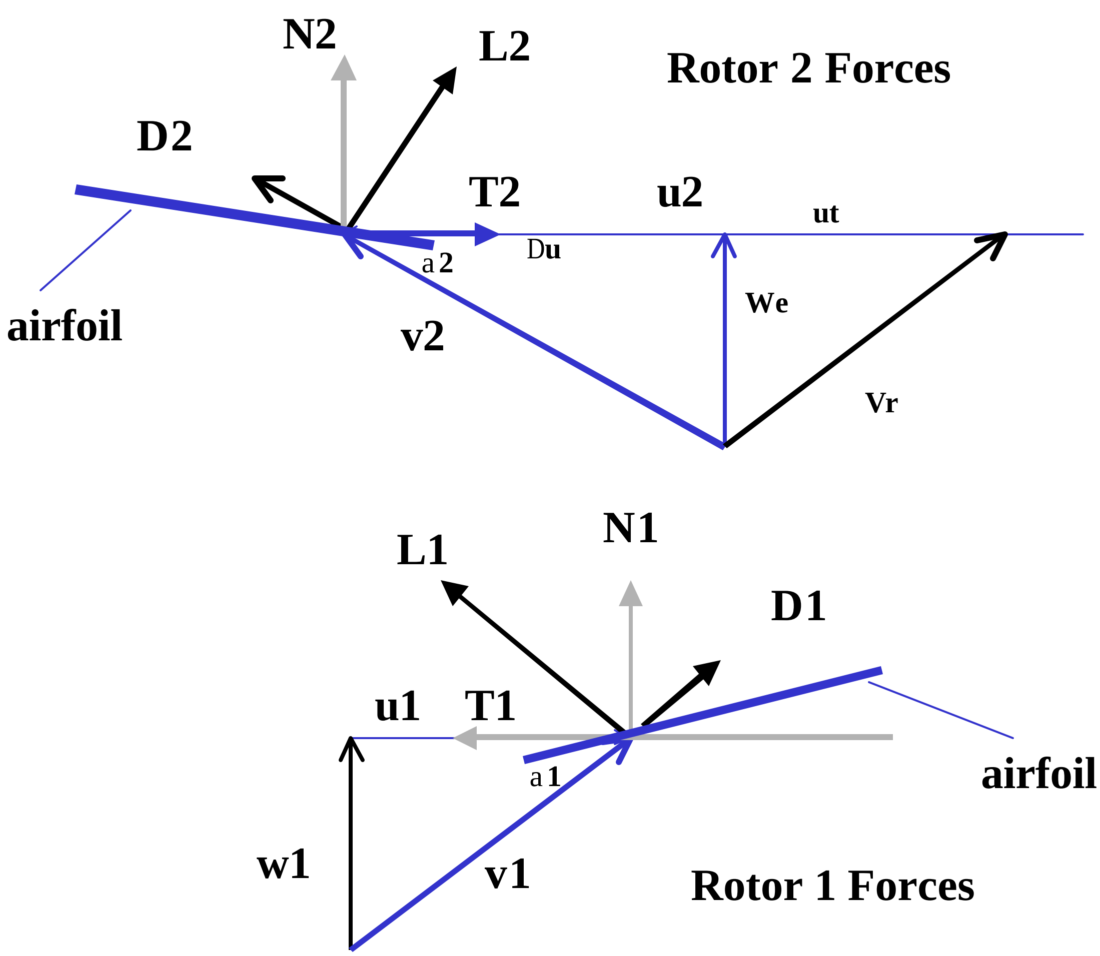


Figure 4. Force Vector Diagram in a Contra Rotating Wind Turbine System

Simple calculations were performed to demonstrate the power conversion efficiency of a contra rotating system. This example uses two bladed 4-meter diameter rotors that are set to rotate in opposite directions to each other. The tip speed ratio was selected as 6 such that the tip speed doesn't exceed 250 ft/sec at 330 rpm of the rotor speed. The computed power curves for rotors 1 and 2 are shown in Figure 5.

In this analysis a mechanical power coefficient of 0.8 was used. The available wind stream power is shown by the chain curve, while the solid line denotes the net power from both rotors. This data suggests that a counter rotating system is able to extract nearly 85% of the usable power, which is about two times more than that of a practical single rotor system. In moderately windy areas one cannot afford to loose any energy. Even if we achieve only 50% more power from the same installation it is advantageous to the ratepayers in the long run and consequently the cost of energy can be reduced by 40 to 50%. However actual benefits must be measured by a feasibility study, which includes fabrication and field testing of a prototype of a contra rotating system.

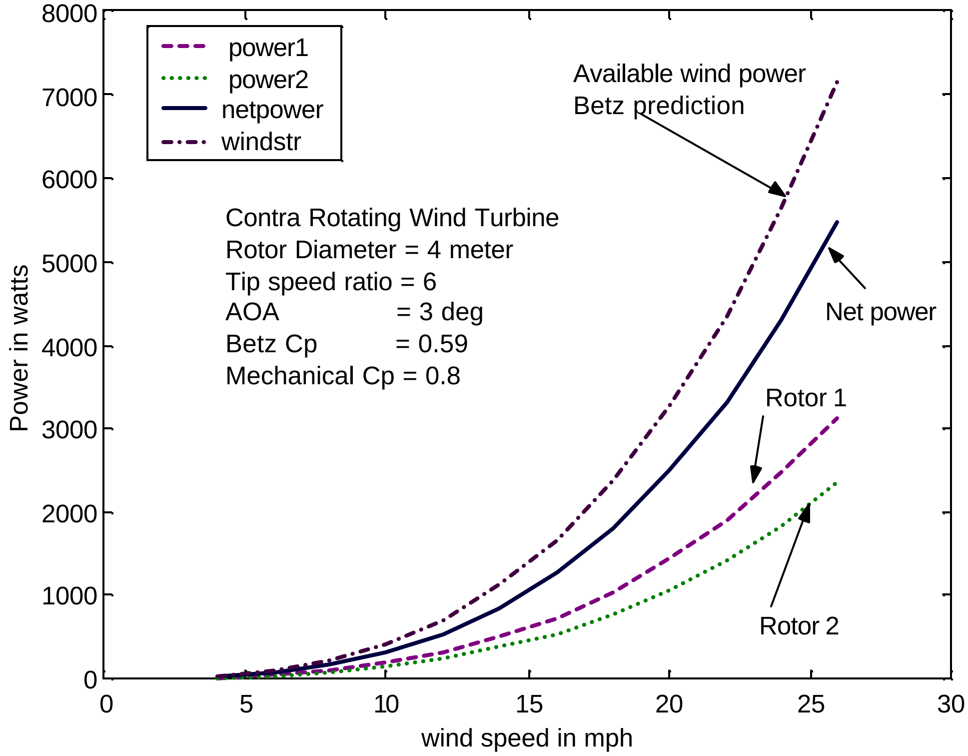


Figure 5. Power From 4-Meter Diameter Contra Rotating Rotors

2.2 Fabrication of the Contra Rotating Wind Turbine Prototype

To demonstrate the concept, a simple configuration consisting of two 3-kW rated alternators was assembled in tandem. Two 2-bladed 4-meter diameter rotors were directly attached to the magnetic drums. The leeward rotor blade angle was set to rotate in opposite direction to the windward rotor. Figure 6 shows the photograph of the magnetic drum rotor.

Figure 6. Permanent Magnet Drum Rotor

Figure 7. Laminated Stationary Armature

The drum was made out of a 267 mm diameter steel tube having 9.5 mm wall thickness. The mean flux path diameter of the drum was 223 mm. There were 16 C8 type magnets each measuring 102 mm long, 40 mm wide and 12.5 mm thick. Two bearings were used to mount the drum on to a stationary armature shaft. The armature shown in Figure 7 had 48 skewed slots and housed with 48 coils having 1.15-mm thick magnet wire. There were six groups of inductive, coils L each having eight 10-turn coils connected in series. Figure 8 shows the 3-Phase connection in Y configuration. Note that each phase had two inductive coils L in parallel. The measured impedance of the armature consisted of, resistive R=1.13 Ω and inductive L=7.5mH.

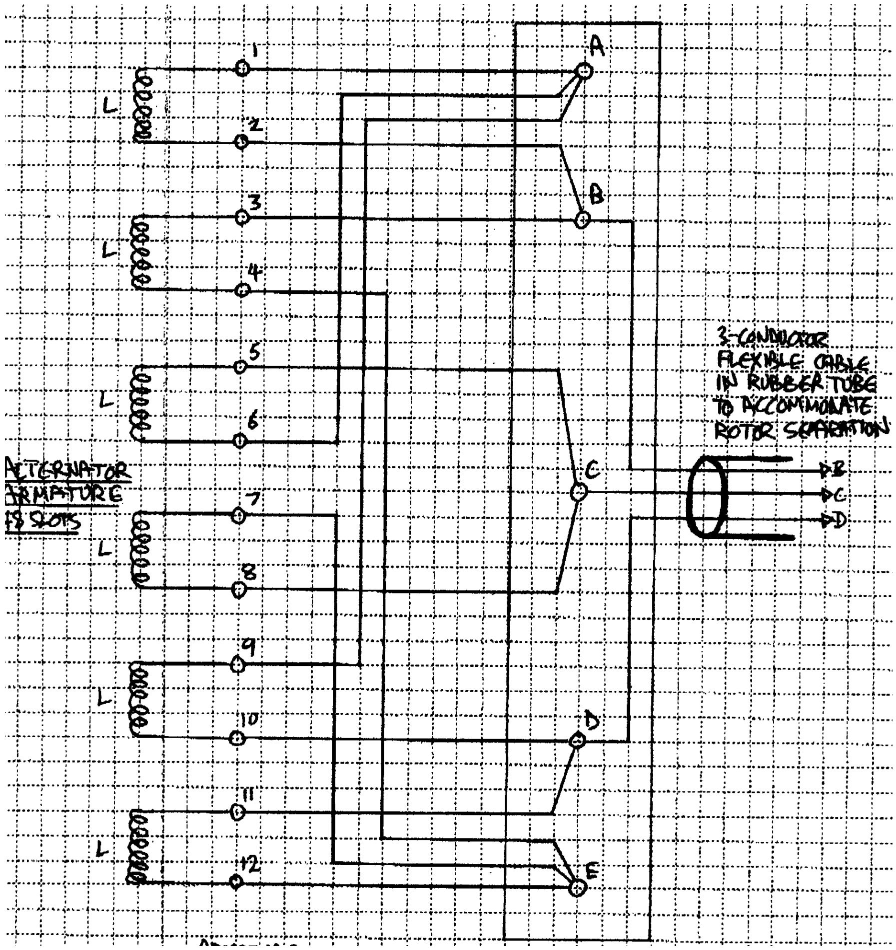


Figure 8. Three Phase Alternator Terminal Connection

Figure 9 shows other sub-components required to mount the alternator on to a support structure, while Figure 10 depicts the sequential assembly procedure.

The windward and leeward rotors consisted of two blades in each. The windward rotor blades were purchased from a commercial source. The subcontractor, Galahad Concepts to Prototypes, fabricated the leeward rotor such that it spins in opposite direction to the windward rotor. The assembled contra rotating wind turbine prototype is shown in Figure 11. A tail boom was used to turn the rotors into the wind direction. However to maintain the cost of fabrication within budget, no mechanism was provided to kill the lift in high winds. Hence no tests were conducted at wind speeds above 25 mph. Short circuiting of the armature was sufficient to set the brake at high wind speeds. Normally when the system is not in operation over a week, the tower would be brought down, and re-erected when needed.

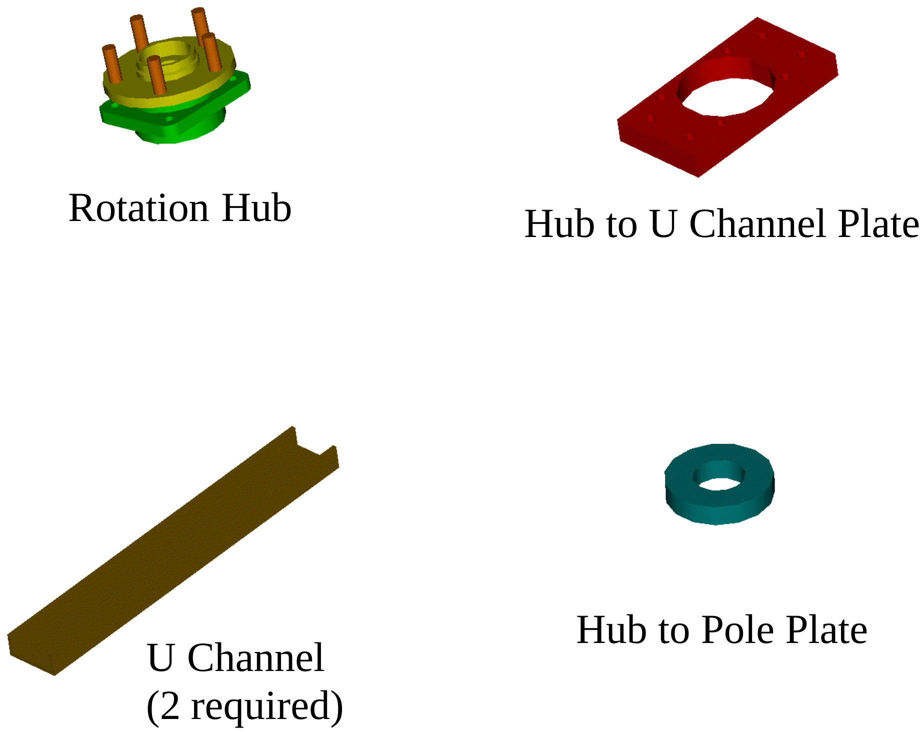


Figure 9. Subassembly components

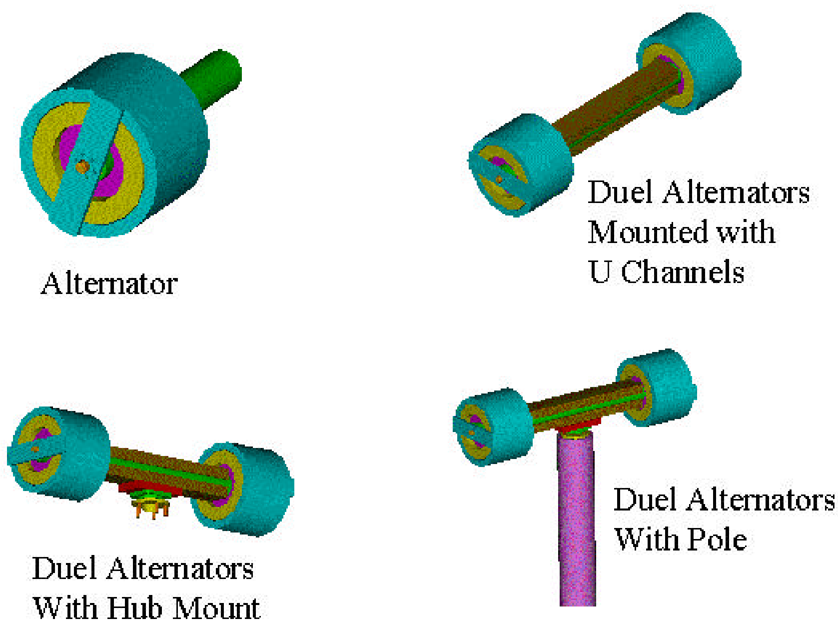


Figure 10. Sequential Assembly Process

Figure 11. Assembled Contra Rotating Wind Turbine System

2.3. Selection of Sensors

The permanent magnet (PM) wind turbine generated power varies in magnitude and frequency depending on the wind speed. That means frequency and voltage change with wind speed. Generally, the ac electrical power is first rectified to dc and stored in a bank of batteries. The stored power is then used as dc or inverted to ac at required voltage and frequency. This approach was not used in the field tests. Instead, the ac power was dissipated by means of heaters. To measure the performance characteristics of the contra rotating system the following sensors were used.

1. Two voltage sensors to measure voltage and rotor speed in rpm
2. Two watt sensors to measure 3-phase power- PH-3A by Load Controls Inc.
3. One anemometer to measure wind speed
4. one acceleration sensor to measure vibration of the system

In addition two clamp current meters and two digital multi-meters were used to monitor phase current and voltage of the units.

2.4 Calibration of Sensors

The calibration tests were conducted at West Engineering Corporation's facility. Figure 12 shows the calibration of current and voltage sensors. Figure 13 shows the instrumentation of the anemometer using a fan and a hand held wind speed meter. The NRG 9300SA data logger system is seen in Figure 13. The anemometer produces an ac voltage signal. The digital SIM boards convert the ac signals to digital data resulting in frequency. Thus the frequency will be expressed in linear relation to the input signal. In the case of the anemometer, 60 Hz equals 102 mph of wind speed. Similarly, any ac voltage signal when fed into a counter channel will be translated into frequency.

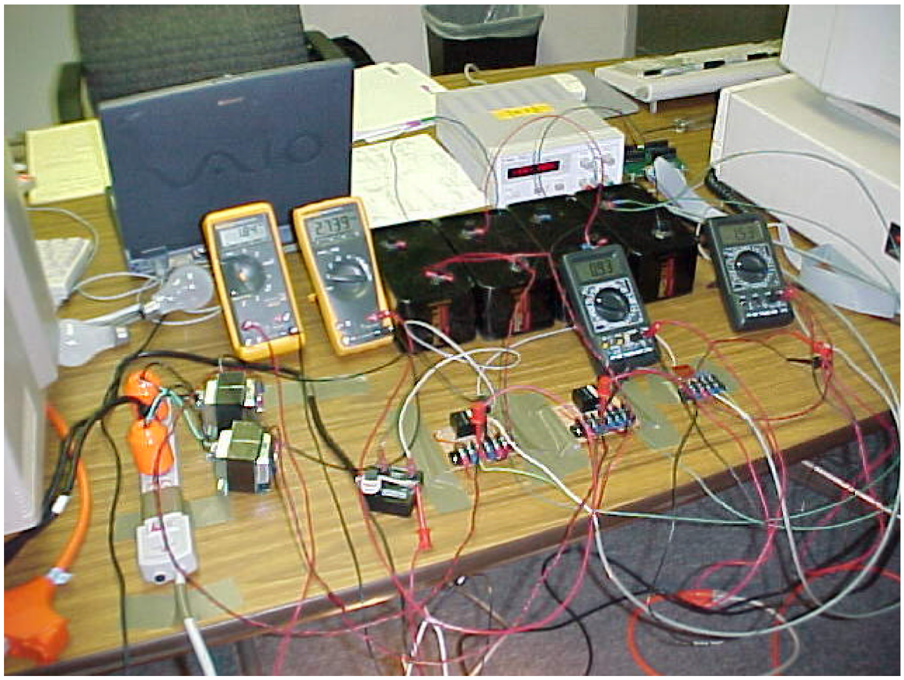


Figure 12. Calibration of Sensors

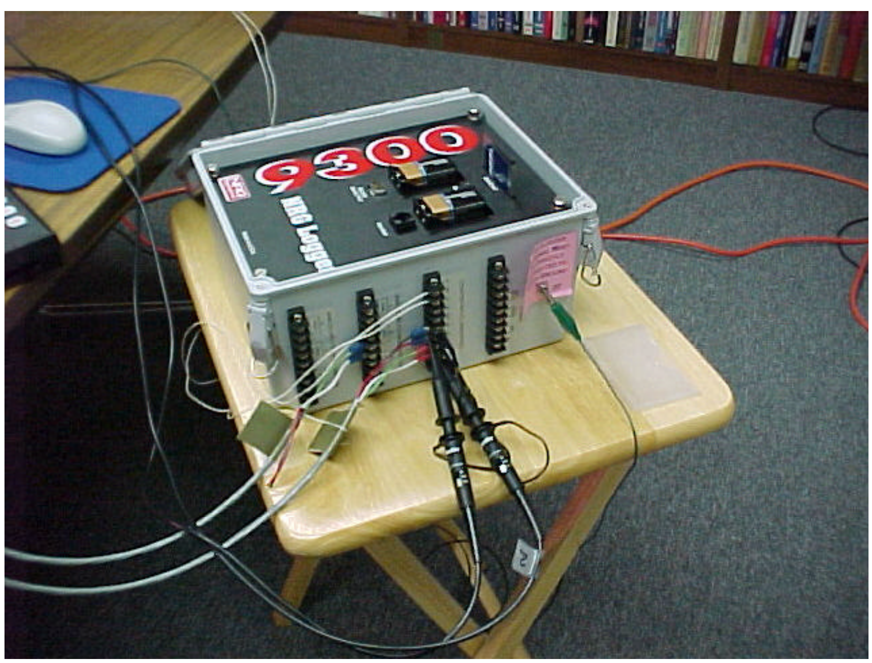


Figure 13. NRG System Instrumentation and verification

Since, there are 16 PM poles in the alternator, the rpm is given by, rpm = 120*frequency./16=7.5*frequency

The current sensors use Hall effect device in which current carrying conductor is passed through a hole. A dc supply voltage is applied perpendicular to the plane of the magnetic field generated by the current. The resulting effect is an induced voltage proportional to the current in the conductor. To increase the strength of the magnetic field several turns of the conductor can be passed through. The watt Sensor built by Load Controls Inc. is shown in Figure 14.

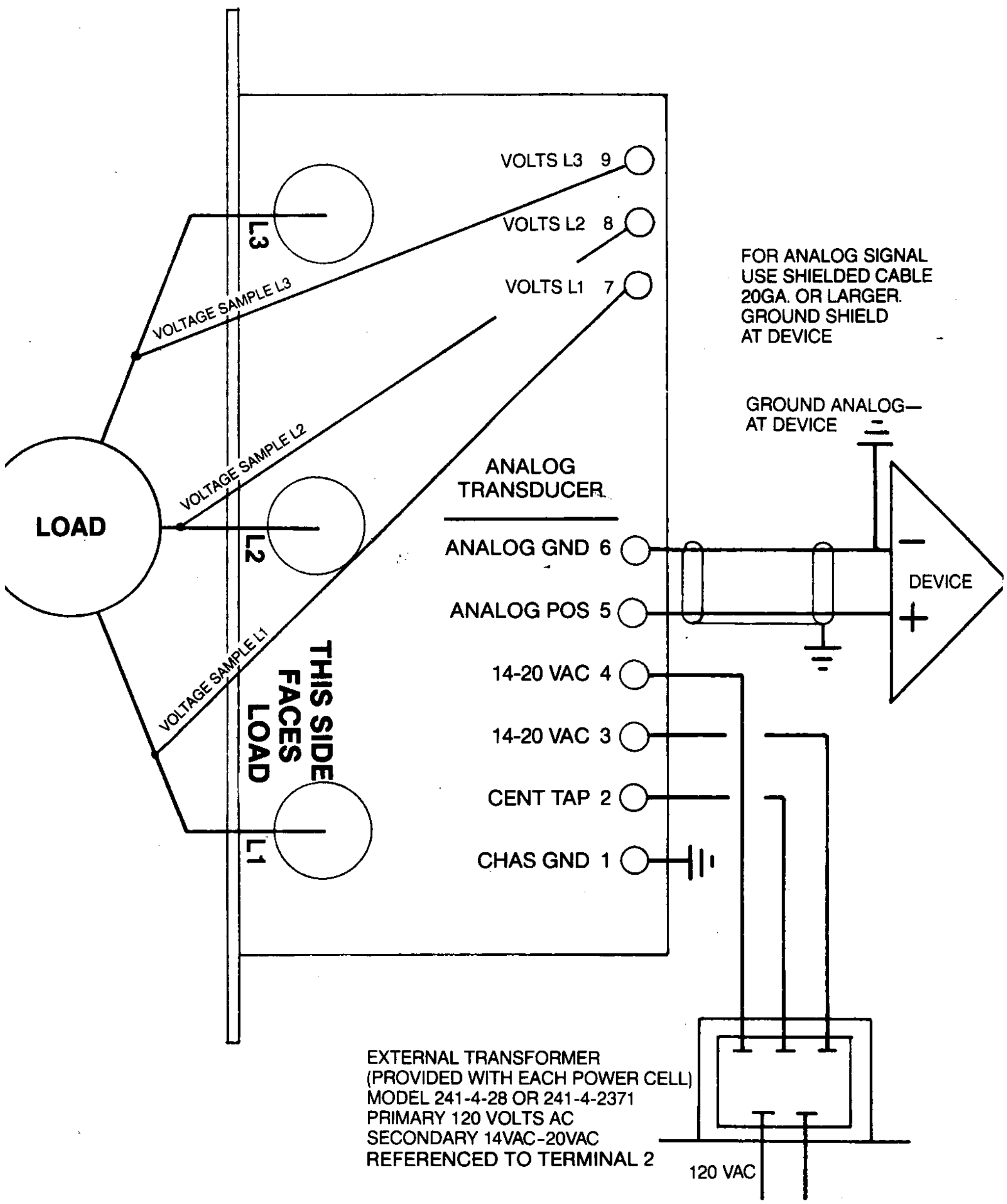


Figure 14. Three Phase Watt Sensor Manufactured by Load Controls Inc.

This can be used to record variable frequency (3 Hz to 1 kHz) power in 3 wire 3-phase or 2 wire 1-phase cases. The output is an analog signal in 0-5 V dc representing the full-scale power of 3118 watts. Each conductor may carry as much as 30 amps at 60-volt ac. After several days of field tests the NRG data logger failed to function properly. It started registering random station identification and date/time. Two other units such as HOBO-8 offered by ONSET Computer Corporation and ADC-16 manufactured by PICO Technology were selected to replace the NRG 9300SA unit

2.5 Alternator Performance Test

To calibrate the performance of the PM alternators, bench tests were conducted at Galahad's machine shop using the vertical machine tool to drive the PM rotor at various speeds. Several lamps were used as resistive load. The test setup is depicted in Figures 15 and 16. Armature voltage and current plots verses PM rotor speed are shown in Figures 17 and 18 respectively. This test shows the relation between voltage and rpm or the frequency.

Thus we have the voltage to frequency or the rpm relation;

volt =7.5*Hertz, or Volt = 0.3*rpm.

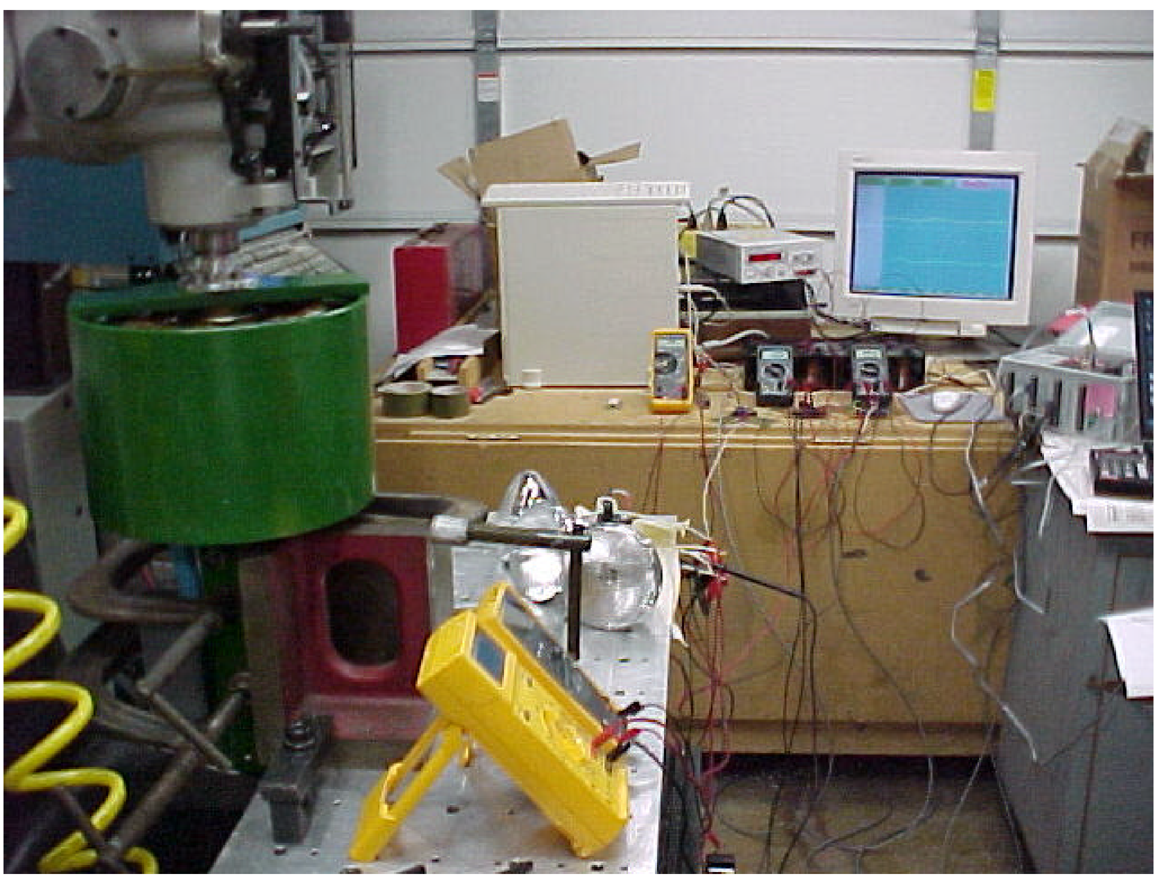


Figure 15. Alternator Performance Test

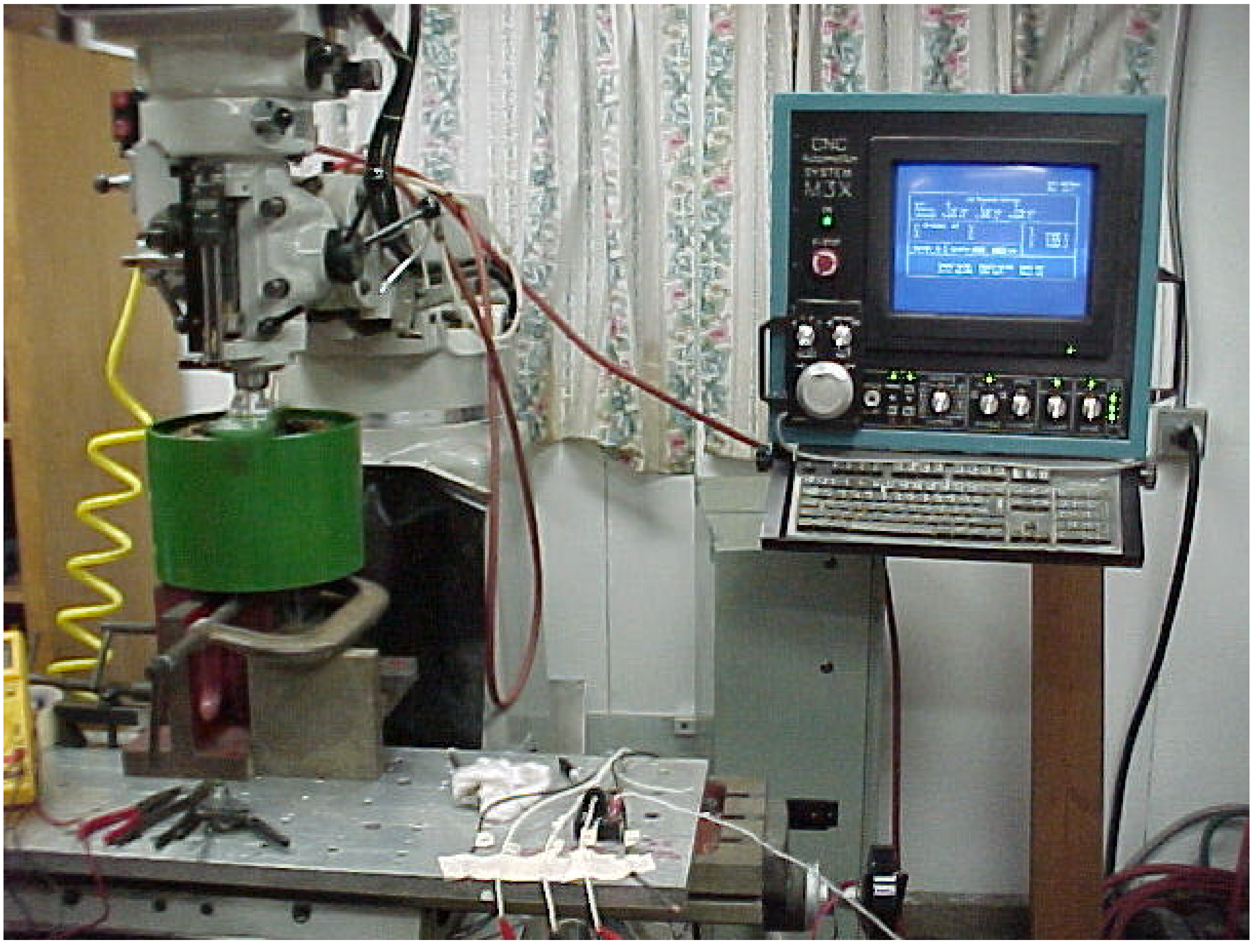


Figure 16. Alternator Performance Test

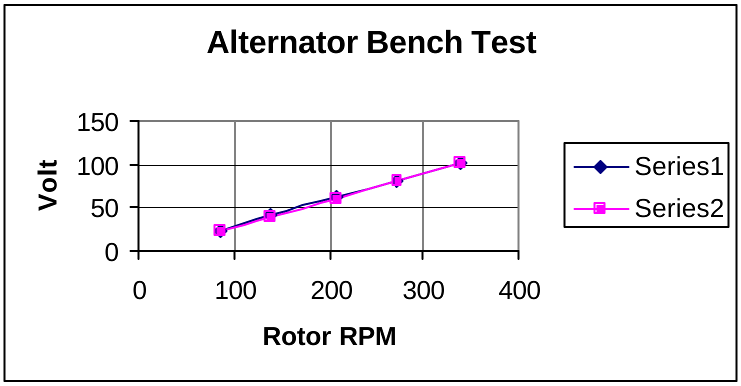


Figure 17. Armature Voltage verses Permanent Magnet Rotor RPM

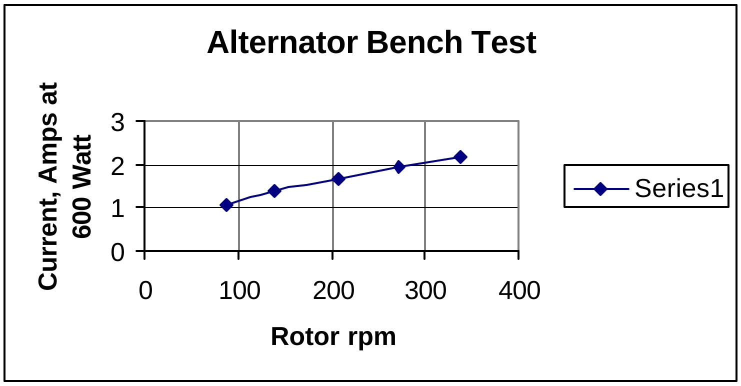


Figure 18. Armature Current verses Rotor RPM

3 PROJECT OUTCOMES

The assembled wind turbine unit was transported to the Oak Creek Energy Systems (OCES) test site. Harold Romanowitz, the president of OCES and Edward Duggan, project manager were very generous to offer onsite support. Forklift and crane were used to mount and erect the system on a 50-ft tower. Figure 19 shows the erection procedure.

As mentioned earlier the contra rotating wind turbine system was built on a limited budget just enough to demonstrate the principle. Hence, to avoid damage to the system under extreme wind conditions, the system would be laid down on the floor when not in use for an extended period of time, and lifted up when in test phase. In addition, the system is provided with a set of three position toggle switches. The short circuit position is used to hold the rotor on brake, while the no load and load positions are used to start and load the turbine. The permanent magnet machines are difficult to start on load even in high wind conditions. Therefore, first the switch will be set at no load until the armature voltage reaches 60 volts and then switch to load position. Single rotor test cases were performed with one rotor on brake (by short circuiting, i.e. magnetic brake), while the other is on load. Thus, there is no need to bring down the assembly.

It is intriguing to note that wind velocity at a point resembles the arrival of water waves. The arrival frequency of wave crests determines the operational characteristics of a non-grid connected wind turbine. In other words, if consecutive wave crests follow each other frequently then the turbine keeps generating power continuously; otherwise it stops under a constant load. Whereas in the case of a grid connected induction generator system, the load is proportion to the slip in the asynchronous speed of the rotor. Hence, so long as the wind speed is higher than the cut in speed (that required to over come friction losses) the rotor keeps spinning at constant rpm. If the wind speed is less than the cut in speed, the system works like an induction motor consuming energy from the grid. Over an extended period of low wind speed the line power will be disconnected and the rotor stays on brake. Thus, a grid-connected system permits effortless load control and continuous operation of the turbine.

Figure 19. Contra Rotating Wind Turbine On a 50 ft Tower at Oak Creek Energy Systems Test Site

Three types of data collection devices were used, namely:

1. NRG Data logging system for counter and analog signals-

   Counter channels were used to record wind speed, and rpm of the alternators.
   Note: volt = 0.3*rpm for this alternator

   Analog channels were used to record power

   (Later replaced by HOBO-8 and ADC-16)

2. Computer for acceleration and voltage collection,

3. Clamp meter and digital multi-meters to monitor current and voltage in any phase of each alternator with balanced loading in each phase.

Figure 20 shows the wind speed and power availability at the test site. Winter months are seen to be the high wind seasons. We entered the test site in December of 2001. A brief summary of the test activity is presented next.

3.1 Brief Summary of Test Activity:

ATI made five trips to the test site in a period four months to conduct field tests and collect relevant data to evaluate energy production characteristics of a contra rotating wind turbine system. The liability insurance to cover the test procedure was extended till April.

- **Test No.1, December 14-17:** Weather forecast was generally good but this year seems to error a lot. However, on Dec. 17 the wind condition was very good, video and data recording were conducted. But, the data stamping in the NRG system was defaulted to 60 minutes interval instead of a 1-minute. Hence that data became unusable.
- **Test No.2, January 24-27:** . Wind condition was supposed to be 10 to 30 mph. But never reached the expected forecast.
- **Test No.3, February 14-18:** Again forecast failed to achieve that goal for Feb. 14-16. However, on 17 and 18 the situation changed. We were able to collect data. On Feb 18 the westerly wind exceeded the design limit; hence testing was aborted, in order to avoid accidents. The monitoring multi-meters showed excessive voltage range (240 V, 5 times more than the design voltage and current well over 25 amps per conductor).
- **Test No.4, March 10-13:** Wind condition was very good on 12, but the NRG data logger started registering random numbers. It could be possible, that the previous test input signals might have exceeded the logger's limit and burnt some ICs. However video taping was made.
- ATI searched for alternate sources of data loggers and selected HOBO-8 made by ONSET Computer Systems and ADC-16 made by PICO Technology. These loggers were used in subsequent tests.
- **Test No. 5, April 2-6:** Predicted wind forecast did not prevail until April 4. Data were collected on April 4 and 5.

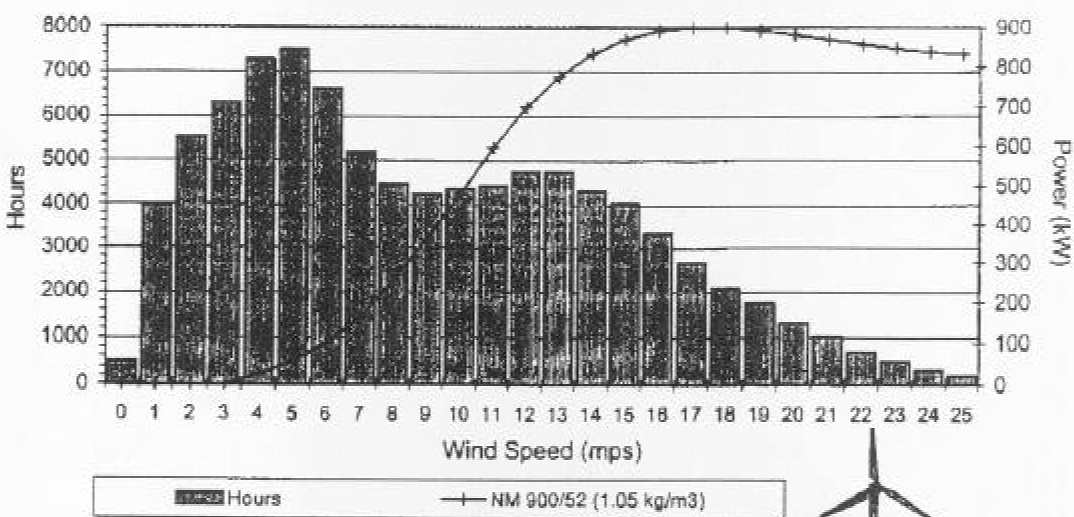
Linear Adjusted Wind Speed Distribution
Oak Creek Energy Systems, Tehachapi Pass
Site 16 64-ft, adj to hub-ht Jan 1, 1986 - Dec 31, 1999

NM 900/52 (1.05 kg/m3)

Speed (mps)	Hours	Power kW	Energy kWh
0	498	0	0
1	3986	0	0
2	5637	0	0
3	6334	0	0
4	7272	25	181,800
5	7501	55	412,555
6	6637	100	663,700
7	5179	162	838,998
8	4478	254	1,137,412
9	4249	360	1,529,640
10	4361	478	2,084,558
11	4432	595	2,637,040
12	4751	698	3,316,198
13	4754	775	3,684,350
14	4336	834	3,616,224
15	4032	871	3,511,872
16	3335	892	2,974,820
17	2681	900	2,412,900
18	2090	899	1,878,910
19	1750	892	1,561,000
20	1320	881	1,162,920
21	1038	869	902,022
22	696	857	596,472
23	505	846	427,230
24	342	837	286,254
25	207	832	172,224
26	158	0	0
27+	219	0	0
Totals:	92878	hrs	35,989,100 kWh

Adjusted (0.943) mean wind speed = 9.2 mps

92,679 hours of data, normalized to one year = 3,401,683 kWh



RON NIERENBERG
Consulting Meteorologist

January 8, 2000

Figure 20. Wind Speed Characteristics at the Test Site

3.2 Field Test Instrumentation

Figure 21 shows the conventional approach used in the operation of a non-grid connected PM wind turbine. The EZ wire unit converts the AC power into DC to charge a battery bank. If the battery is fully charged then the DC power is directed to a dump load. However we did not use this approach since additional cost is involved to setup a deep cycle battery bank. Instead we planned to dissipate the energy in a set of low cost heaters as depicted in Figure 22. The alternator phase wires were Y connected (first we thought delta connected), while the load was set in delta. Each heater is rated at 1500 watts having three steps of load control. The control panel has a provision to add three more heaters in parallel. It was necessary to do so whenever the turbines spin too fast in wind speeds above the design speed. Figure 23 shows specific details of the instrumentation used in the data collection procedure. 110 V ac supply was made available at the test site to operate the sensors and the data loggers.

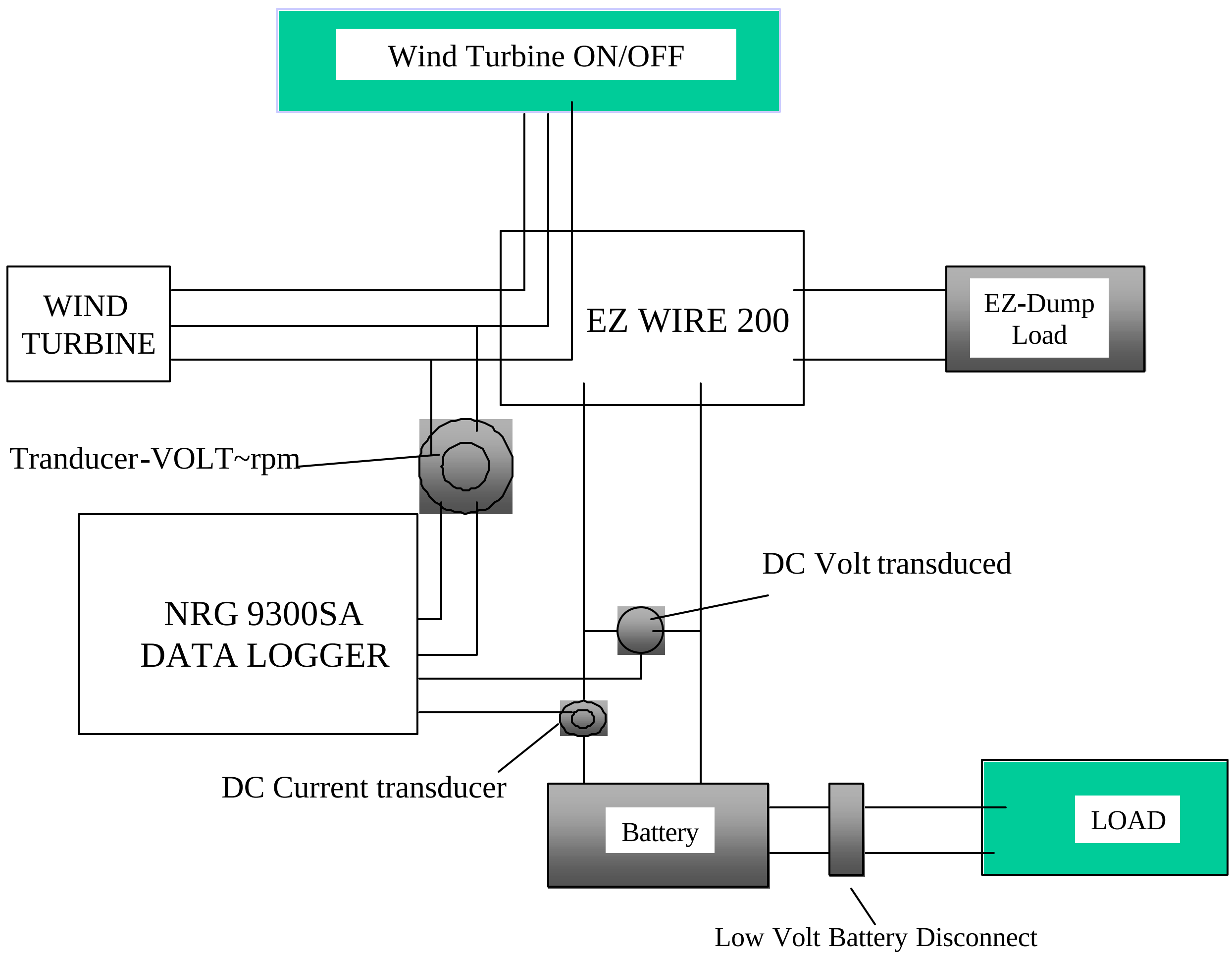


Figure 21. Conventional Operation of a Stand Alone Wind Turbine

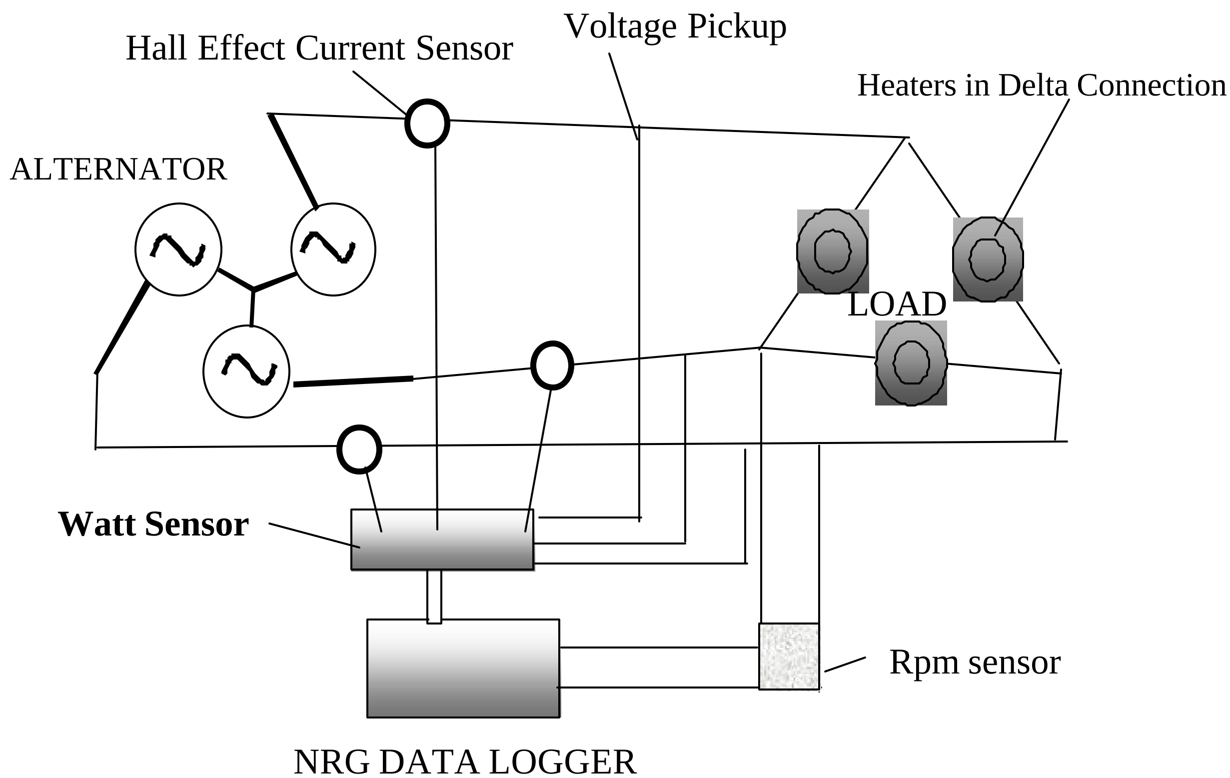


Figure 22 Load and Sensor Connection

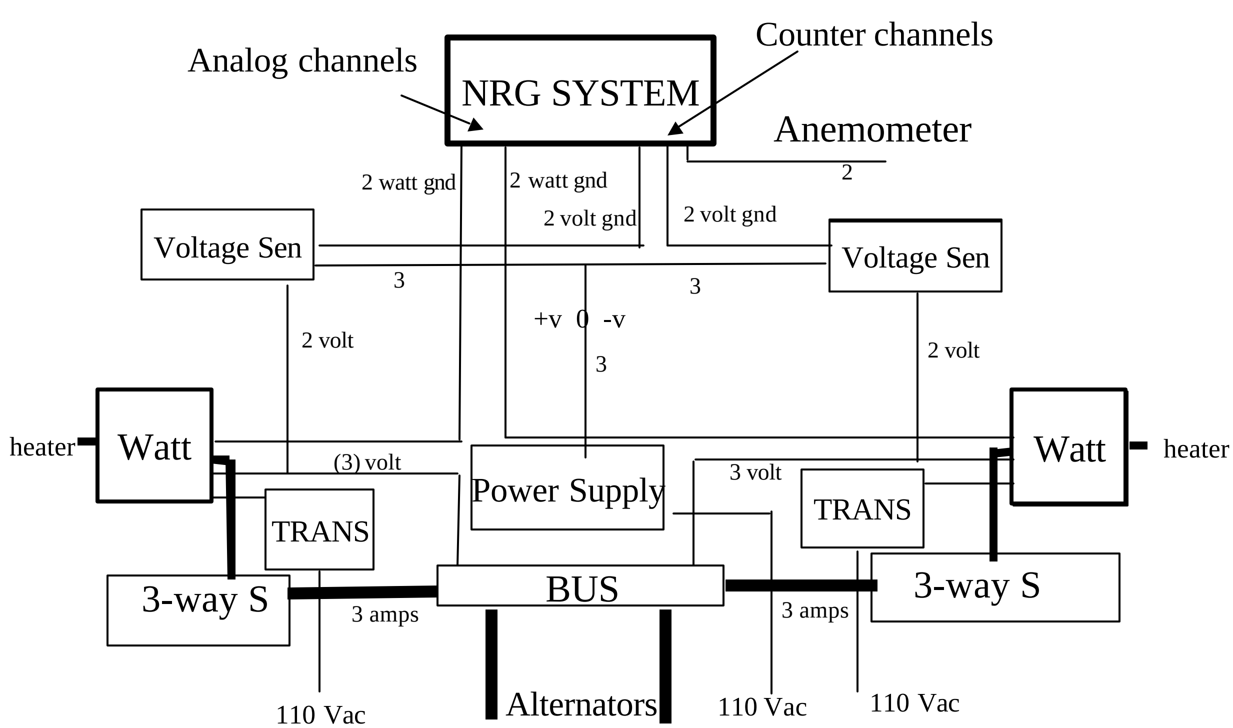


Figure 23 Field Test Instrumentation

Anemometer, and two alternator voltage sensors were connected to the three counter channels of the NRG system, while two power signals and one acceleration signal were connected to the analog channels. Nonvolatile PCMCIA card was used to store the data. After completing day's test, the PCMCIA card data was downloaded and processed using NRG provided software. Sample data strips are presented next.

3.3 Discussion of Field Test Data

Figure 24 shows the histogram of the wind speed verses time of the day. The average wind speed appears to be around 15 mph, peaking up to 25 mph and above. Wind speed at 25 mph and above both rotors spin faster than 360 rpm with current and voltage exceeding the design limit by a factor of 3 to 4 as seen in Figure 25. The armature design voltage is 60 V, but we have observed voltage exceeding 250 V. Alternator 1 voltage sensor failed to function, hence that channel was recorded on the laptop using a digital multi-meter (DMM) offered by Radio Shack. This unit was a very practical one, inexpensive and easy to use. But, it has only one channel. Figure 26 shows the rpm of alternator 2. The relationship between volt and rpm was determined in the lab test and is given as volt = 0.3*rpm or volt = 7.5*frequency in Hz.

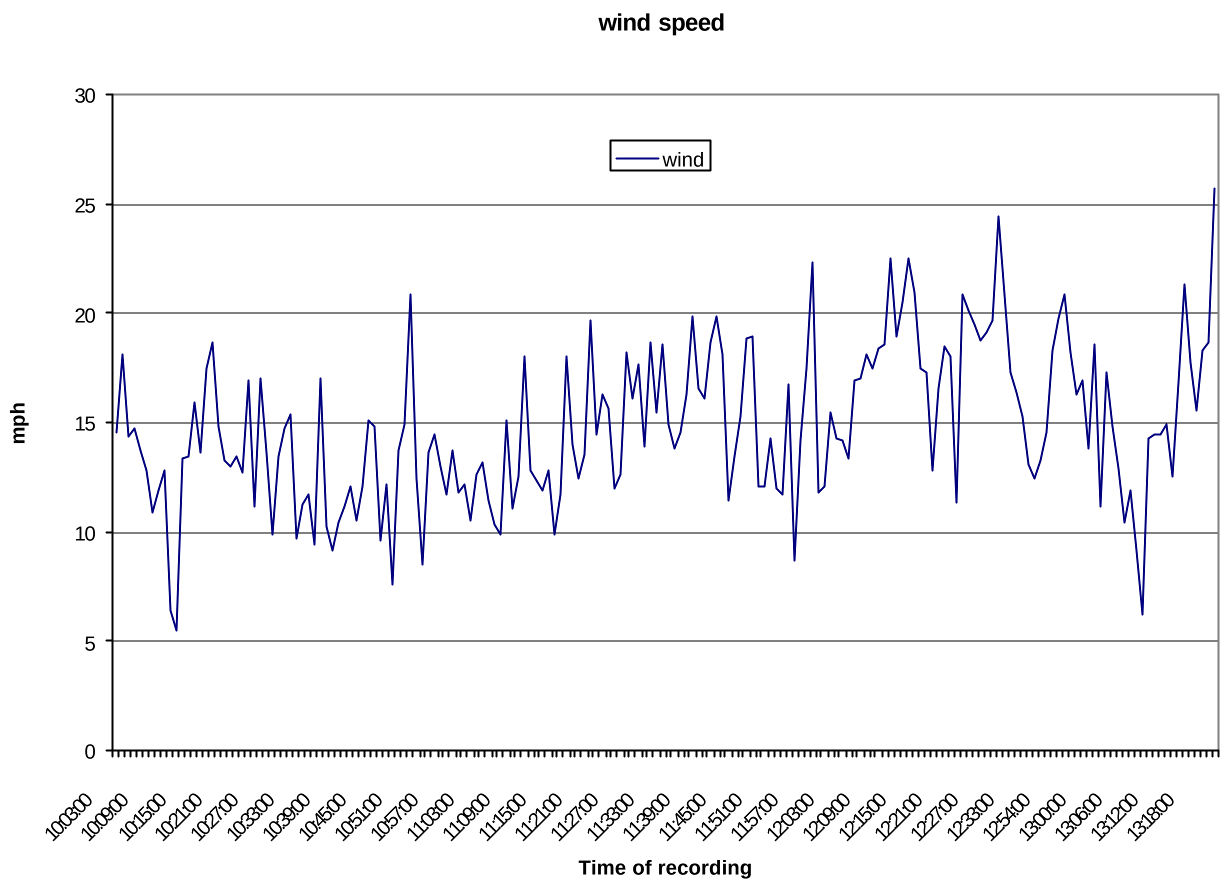


Figure 24. Histogram of Wind Speed, February 18, 2002

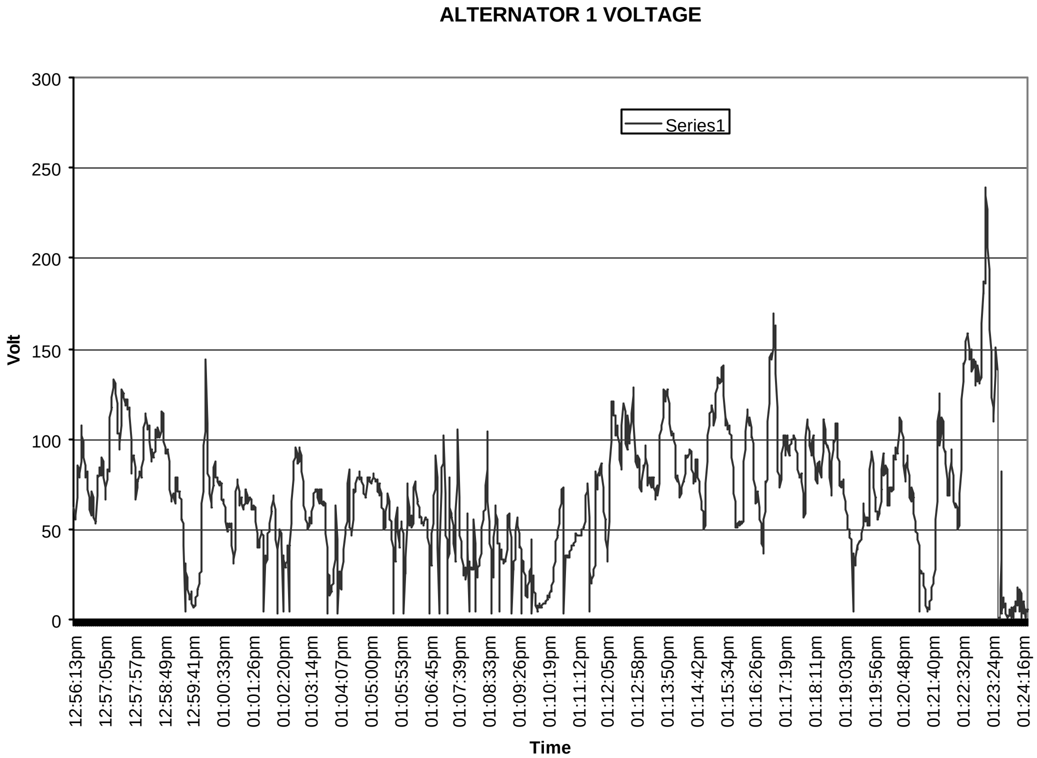


Figure 25. Voltage of Alternator No. 1

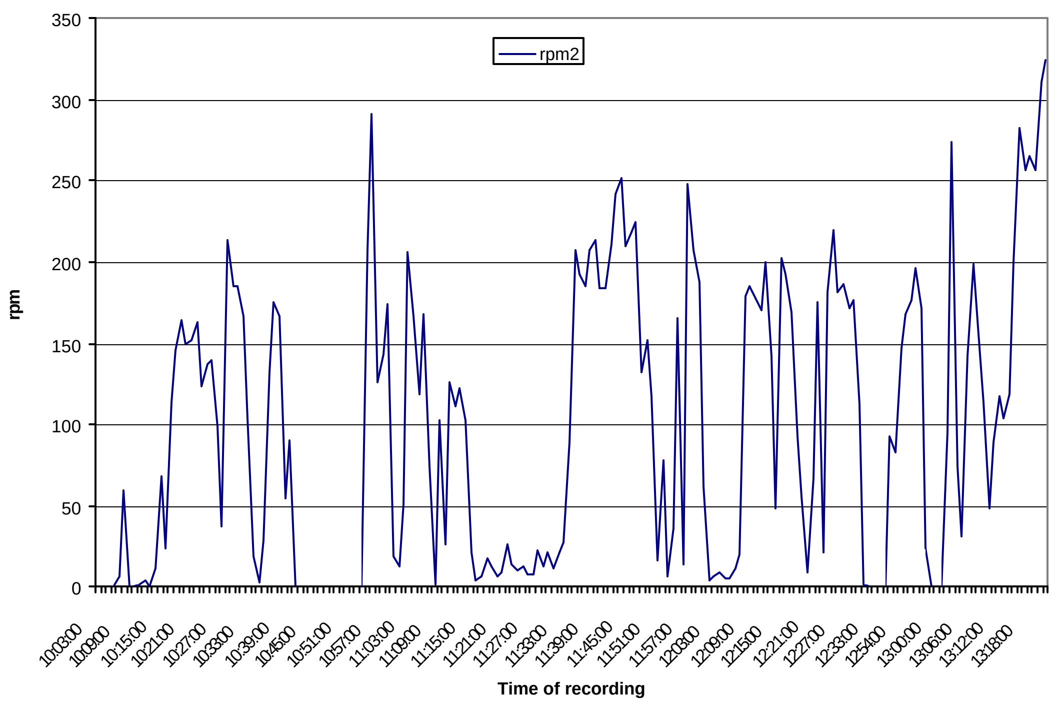


Figure 26. Alternator No. 2 Angular Speed in RPM

Volt2 = 0.3*rpm = 7.5 *frequency (Hz)

The power histogram of both alternators is shown in Figure 27. The data shown by thin line corresponds to the front rotor (alternator 1), while the data denoted by thick line corresponds to the rear rotor (alternator 2). At each burst of gust waves the power generated by the rear rotor is seen to be in the range of 35 to 50% of the front rotor. Each data point represents an average value taken in 1 minute. Similarly data recorded on different test schedules are shown in Figures 28, 29 and 30. It is interesting to note that the power conversion efficiency of leeward rotor increases with decreasing rotor speed. In Figure 28 the power ratio, which corresponds to low rotor rpm, is seen to be around 50%, whereas the higher rpm data shown in Figure 30 is seen to be around 25%. The probable reason could be that at very high rotor speeds the blade tips may stall and/or the front rotor might have a blanketing effect on the leeward rotor.

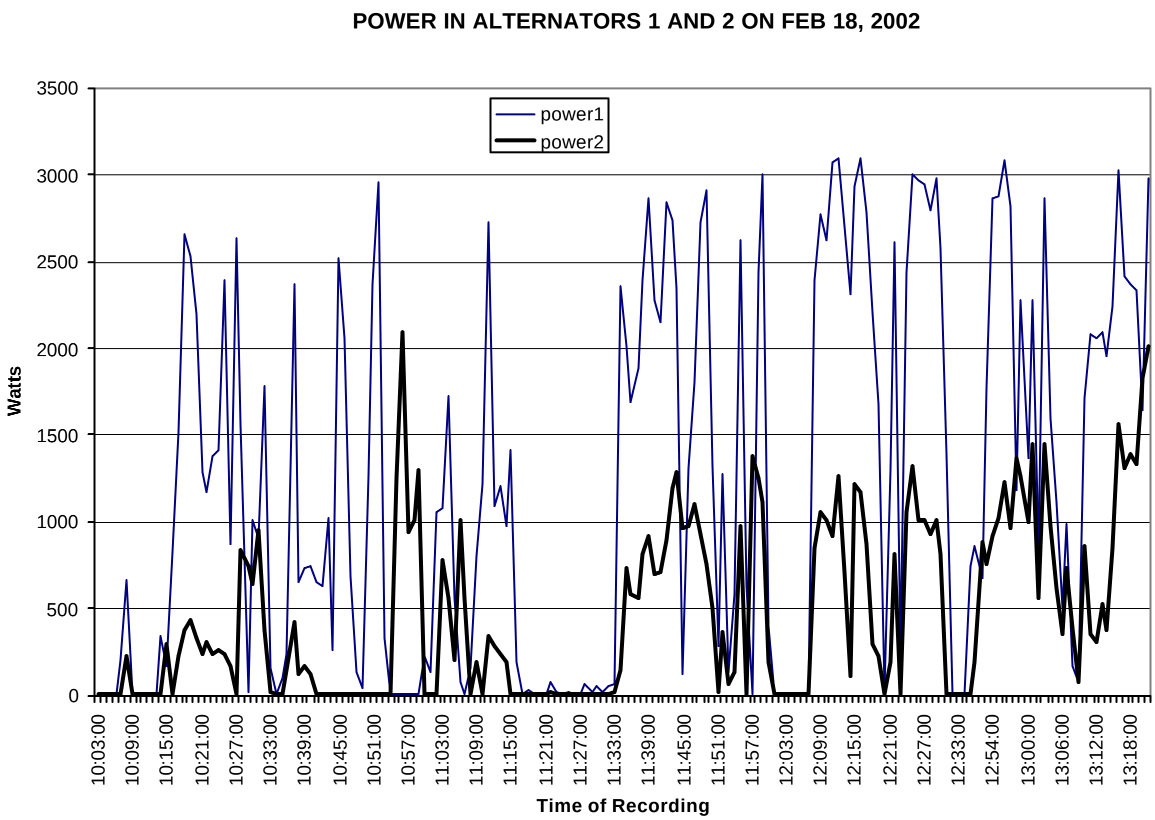


Figure 27. Power Histogram of Alternator Nos. 1 and 2

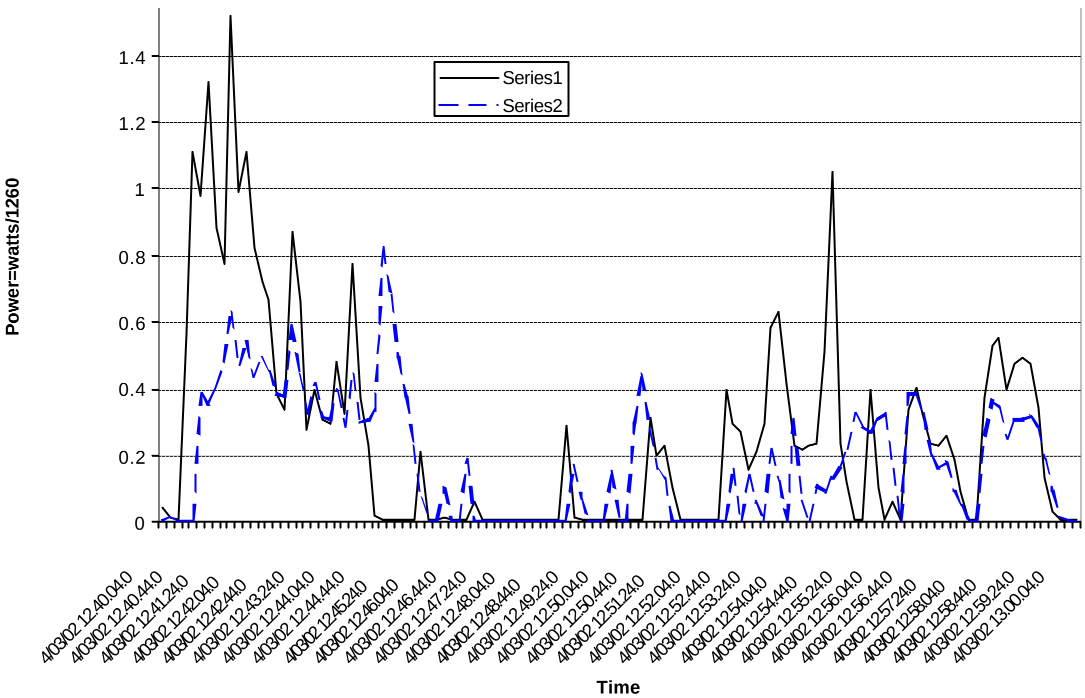


Figure 28 Comparison of Power Output in Low Rotor RPM Condition

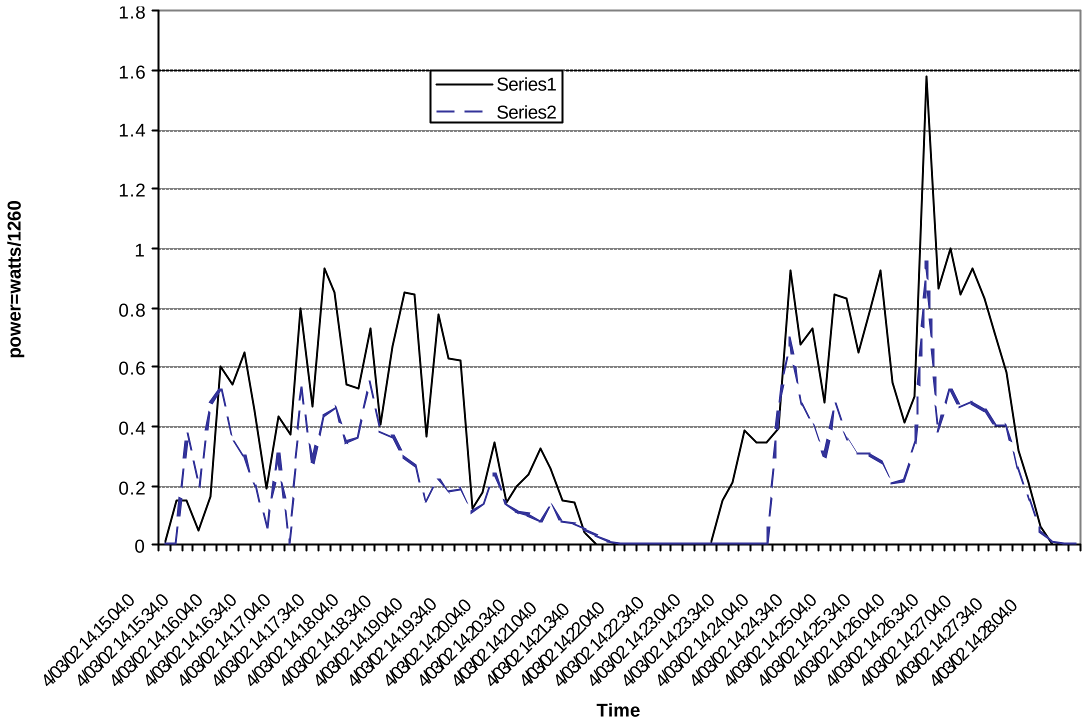


Figure 29 Comparison of Power Output in medium Rotor RPM Condition

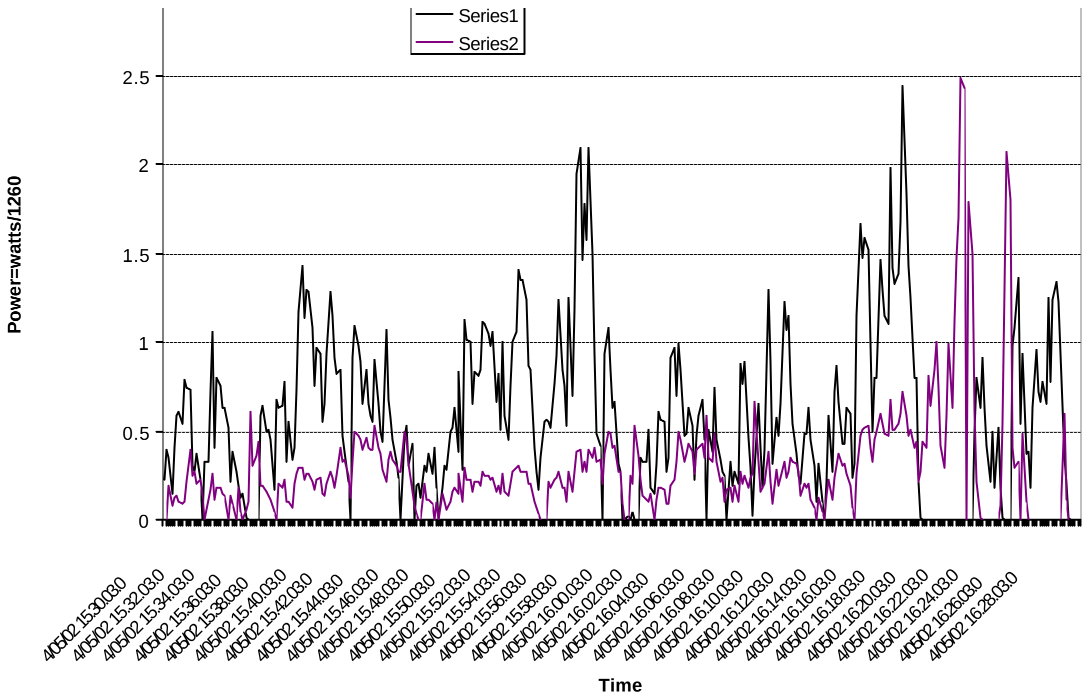


Figure 30 Comparison of Power Output in High Rotor RPM Condition

The wind turbine performance data is generally best viewed as power verses wind speed. But in the field tests such information is available as time history data. Therefore there is a need to compute the mean power at any specific wind speed. The following procedure was used to compute the mean power.

Given wind speed vs. time and power vs. time, select a velocity V_k and find n number of T_n encounters. Next find power P_i at each T_i , i=1,n. For a dual rotor configuration both power must be > 0, otherwise omit that data. Then the mean value is given by

$$p_m(k) = (\frac{1}{n}\sum_i P_i)$$

where P_i is the interpolated power data at velocity V_k , and n is the number of encounters at that velocity in a strip of data that represents the dual rotor operation. Then $p_m(k)$ vs V_k represents power vs wind speed. Thus power verses wind speed data are presented in Figures 31, 32 and 33. To evaluate the performance characteristics of the contra rotating wind turbine an analytical prediction based on the elementary blade theory was performed.

The windward rotor performance data is presented in Figure 31. There are three sets of data, the measured windward rotor power, elementary blade theory prediction and the wind stream tube power. The blade theory discussed in Section 2.1 takes into account the mechanical efficiency of 0.8 in computing electrical power output. The dotted curve represents the maximum power available in the wind stream tube that encloses the 4-meter diameter rotor. The elementary blade theory prediction is denoted by dash-dot symbol. The windward rotor test data is denoted by the diamond symbol. At low rotor speeds the test data agrees well with the analytical prediction, while at higher rotor speeds the correlation is not that good. Tip stall might have contributed to this departure.

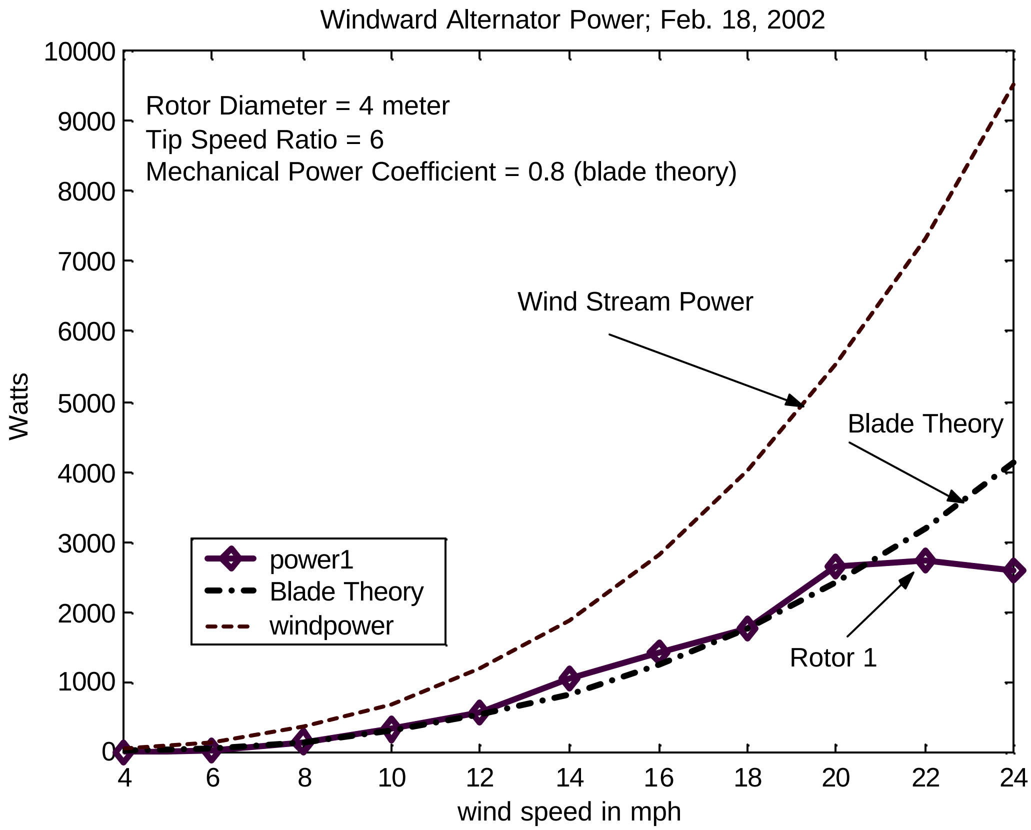


Figure 31. Rotor1 Power with Wind Speed in mph

Let us next examine the leeward rotor data shown in Figure 32. Once again at low speeds analytical prediction and test data compare well, but they depart at higher speeds. The fabricated leeward rotor blades may have some deficiency in aerodynamic performance. ATI made no attempt to conduct aerodynamic performance tests to compare with the windward rotor blade. This task was beyond the scope of this study. It would have been nice if we had identical rotors. But, in any case our objective is to test the feasibility of contra rotation and power generation

Next, we compare the net power output of the dual rotor system verses the analytical predictions. Figure 33 presents five sets of power curves. The field test data for rotors 1 (windward) and 2 (leeward) are denoted by diamond and square symbols respectively, while the net power is represented by circular symbols. The elementary blade theory prediction is shown by dash-dot curve, while the wind stream power is given by dotted curve. At low rotor speeds the net power output agrees with the blade theory. But at higher rotor speeds the departure is obvious due to two reasons, (1) blade tip stall, and (2) blanketing of the second rotor.

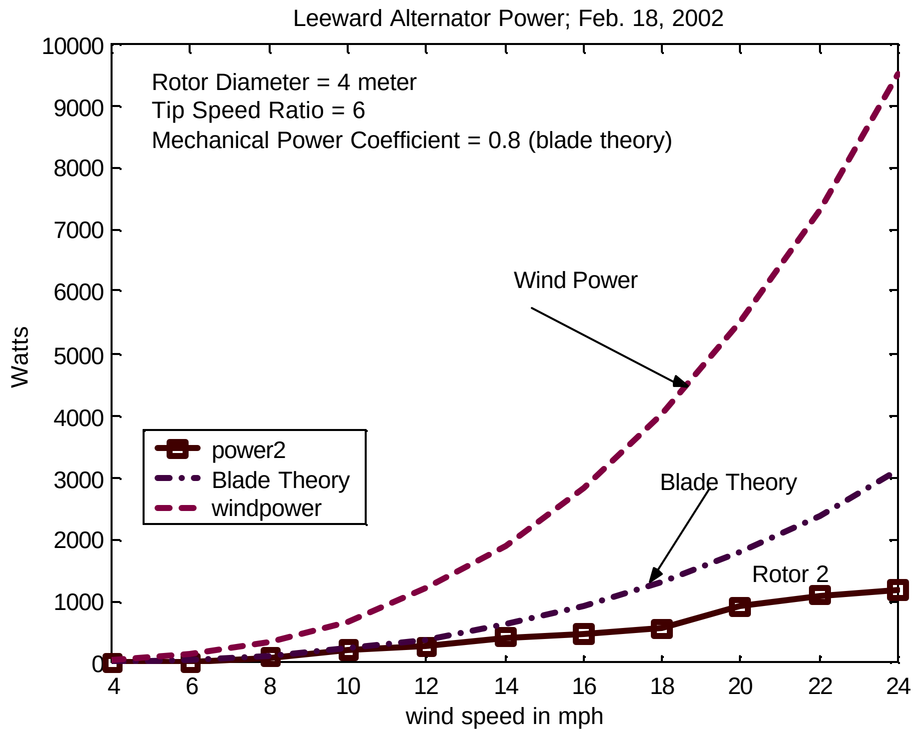


Figure 32. Rotor 2 Power with Wind Speed in mph

The performance of the contra-rotating rotor system can be better judged by comparing the power coefficients presented in Figure 34. The power coefficient is defined as the ratio of the power generated by the rotor divided by the wind stream power. According to Betz's disc theory the maximum available power coefficient is limited to 59%.

The power coefficient of rotor 1 is seen to be around 40 %, whereas the leeward rotor could produce up to 20 to 30%. However the net power coefficient is seen to be more than 60 % at low rotor speeds and levels off to 40% at high rotor speeds. The power coefficient from the blade theory is seen to be at 76%. These coefficients at low rotor speeds exceed Betz limit. This is a bit of surprising data and requires some revisiting of the field test using a grid connected contra-rotating wind turbine unit.

One possible explanation is that at low rotor speeds the two rotors might act like being independent (having less interference) working together to produce electrical power. Or possibly Curtis' velocity compounding may have some influence on the higher power production. Anyway it is too early to draw a conclusion based on a single model. For example the raw data presented in Figures 28, 29 and 30 depict higher power at slower rotor speeds. If this argument is true, then the contra-rotating dual rotor system may very well be suited for mega-watt machines, which generally operate at 15 -20 rpm.

Although the leeward rotor didn't perform aerodynamically as good as the front rotor, the net power produced in contra-rotational configuration is seen to be 20 to 30% more than a single rotor system as depicted by the solid curve in Figure 34. This means, if one were to retrofit existing wind farm machines with a contra-rotating rotor device (Sections 3.5 and 4.3) the excess revenue could pay off its expense in three to five years.

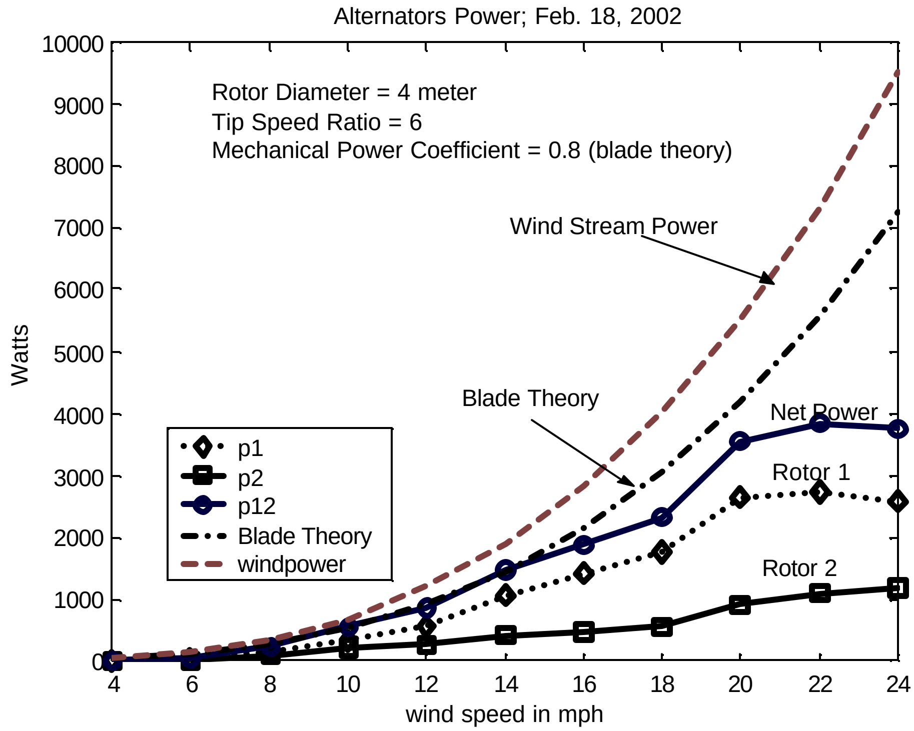


Figure 33. Net Power Generation with Wind Speed in mph

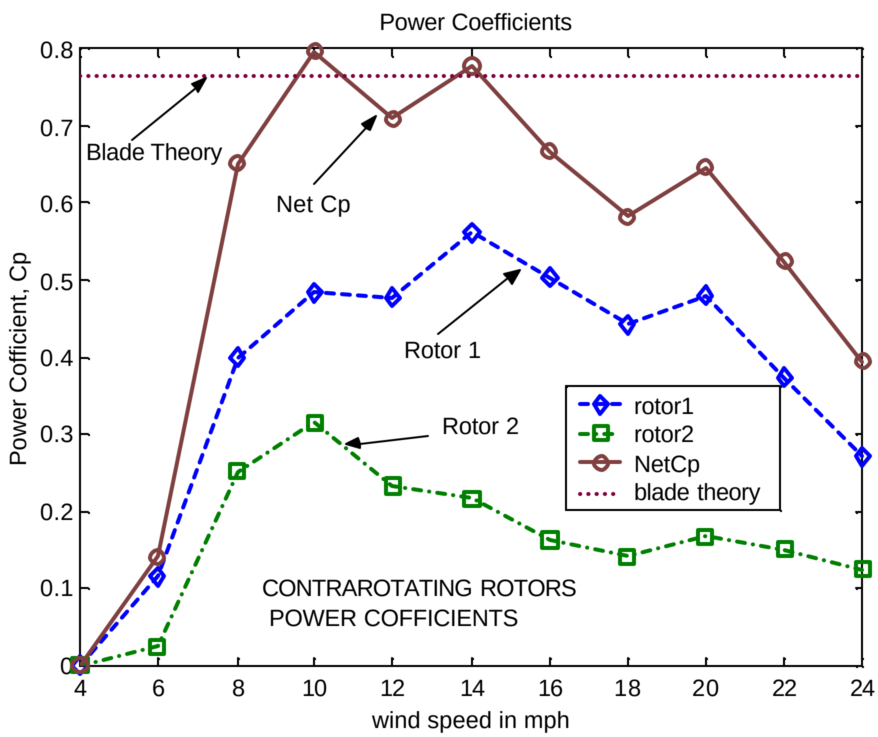


Figure 34. Power Coefficients of Contra Rotating Rotors

3.4 Buffeting

Having discussed the power conversion efficiency of the dual rotors, let us next review, the long concerned buffeting problem of the dual rotor system. An acceleration sensor was installed near the leeward alternator shaft. This sensor was made by CROSSBOW and was rated at +/- 4 g per volt of signal. From the raw data presented in Figure 35 we notice that the peak acceleration does not exceed 1/2 g even at peak load condition that prompted us to shut down the test. Such low acceleration levels might be a little bit of surprise. One possible reason could be that the passage frequency of a contra rotating system (due to relative angular velocity) is higher than that of a single rotor system. Consequently, the low frequency excitations are seen to be washed out. Thus, the contra rotation seems to be a beneficial factor that could minimize buffeting effect of wind turbine blades. Taking for granted that the acceleration sensor is faulty, we are planning to send it back to the manufacturer to examine the unit and advice us as to its accuracy.

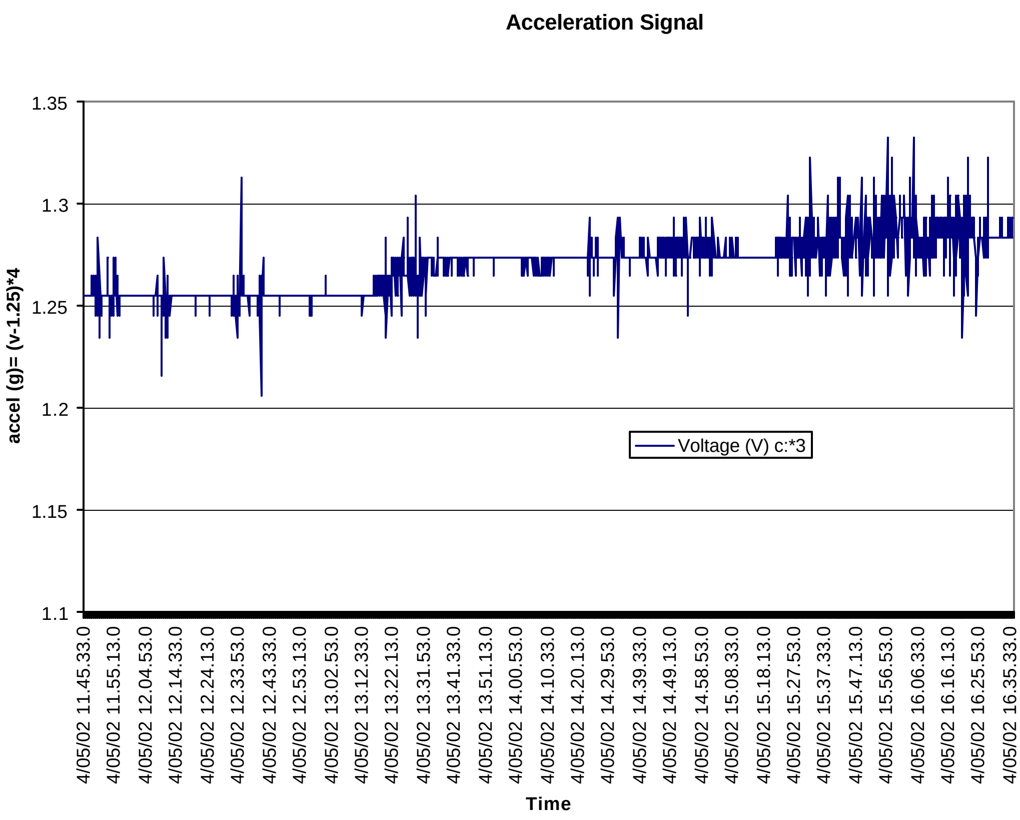


Figure 35. Acceleration of Dual Rotor assembly (Raw Data)

3.5 Retrofit Cost Analysis And Payback Period

Most utility scale generators are provided with a dual winding system that can operate efficiently at two ranges of wind speeds, say (a) the smaller unit for wind speeds less than 15 mph, and (b) the larger unit for wind speeds greater than 15 mph. Such a twin-generator unit can be programmed to operate at combined power rating in upgraded version to the contra rotating system and could produce 40% or more power. To estimate the payback period for the upgrade, first we itemize the cost elements of the upgrade and then estimate additional revenue resulting from the upgrade.

3.5.1 Cost Elements

Upgrading of an existing single rotor wind turbine system to a contra-rotating configuration can be implemented in two ways.

Approach 1: Two Generators in Back-to-Back Configuration

If the existing generator is not provided with a dual winding (twin generators) system, then it is economical to add a generator and a rotor in back to back configuration. A typical example is shown in Figure 36. Identical torque-hub used in the existing system can be adopted. The preliminary cost estimation is:

1. 1-off Torque hub for 250 kW rotor, 1:45 gear ratio	$9,000.
2. 250 kW Marathon Electric Induction Generator	$9,700.
3. 1-off 3-bladed rotor (custom fabricated), 50 ft dia, stall regulated	$15,000.?
4. New yaw Support system; assembly and grid-tie support	$10,000.?
Total	$ **43,700.**

Approach 2: Dual-Wound Single Generator

If the existing generator is provided with a twin-generator system, the same generator can be used for higher power rating as shown in Figure 37. Here, the second torque-hub will be reconfigured to change the direction of output so that both torque-hub units drive the same generator shaft. Therefore, certain amount of engineering effort and tooling is built into the unit cost. The unit cost decreases to $9500. after 100 units.

1. 1-off Torque-drive for 250 kW rotor (anti-clockwise), 1:45 ratio	$18,000.
2. 1-off 3-bladed rotor(custom fabrication), 50 ft. dia, stall regulated	$15,000.
3. New yaw Support and assembly support including grid-tie	$10,000.
Total	**$ 43,000.**

These estimates are based on few upgrade units. If similar units are produced in large quantities, the cost of fabricating blades and torque-hub units could be reduced by 50%.

3.5.2. Revenue

The amount of energy a wind turbine can generate for an installed unit depends on the site characteristics known as the power capacity. The power capacity of wind farms generally ranges from 0.2 to 0.4. If we assume an average value at 0.3, the annual wind energy generated by a 250 kW machine is given by

E1 = 0.3*250(kW)*8640(hrs)= 648,000 kWh original system

Let us now consider 40 % of power being produced by the rear rotor. Then, the new energy production is,

E2 = 1.4*648,000 = 907,200 kWh for the upgraded system
DE = E2 – E1 = 259,200 kWh excess energy

Excess revenue at 3.5 cents per kWh =$ 0.035*259,200= $9072/per year
Then the payback period is = 43000/9072= 4.7 years.
After 5 years the upgraded unit will earn additional $9k annually.

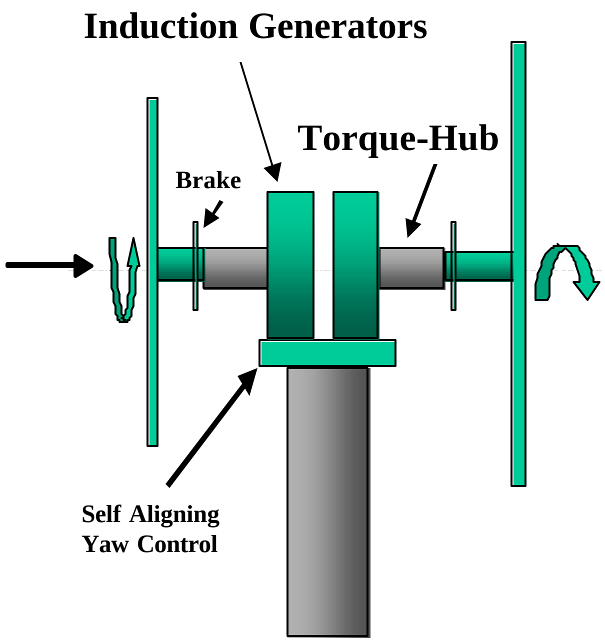


Figure 36 Dual Generators in Back to back Configuration

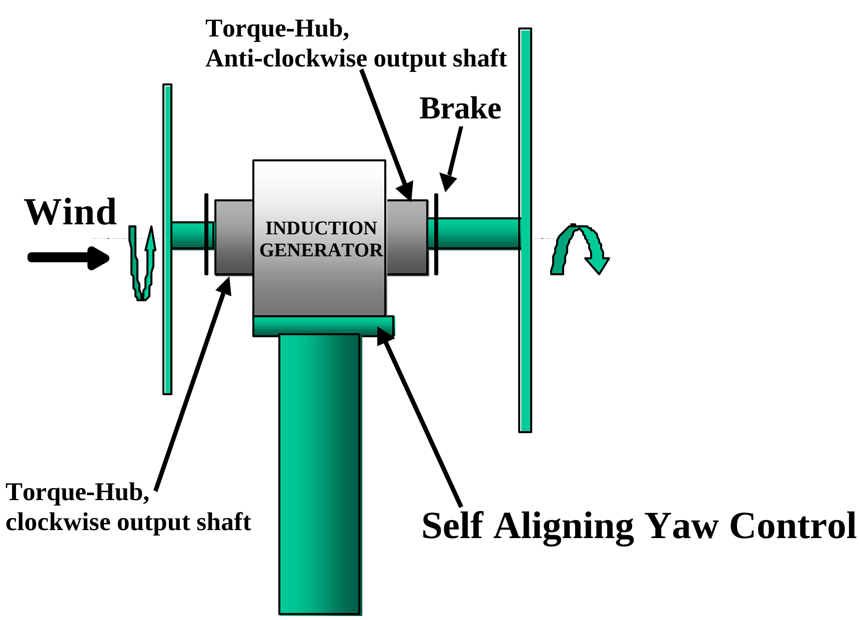


Figure 37 Grid Connected Dual Rotor Single Generator Configuration

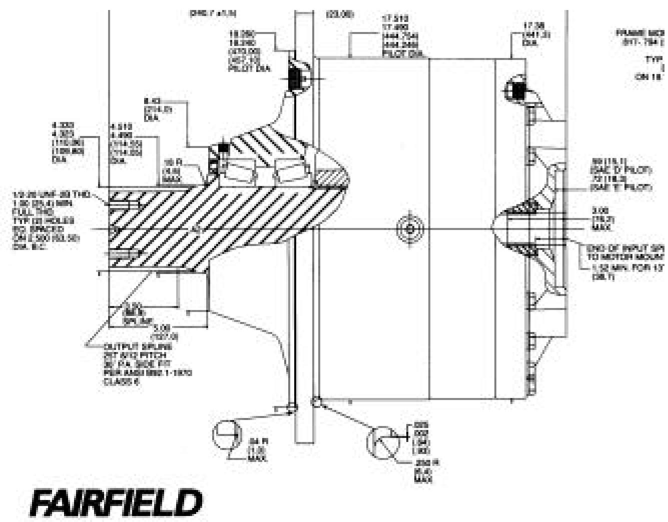


Figure 38. Torque-Hub

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The test data presented in Section 3 suggests that the leeward rotor in a contra rotating configuration could help to produce 25 to 40 per cent additional power from the same wind stream. Higher per cent power conversion efficiency is confined to lower rotor speeds. This suggests that the utility scale turbines benefit economically from the contra rotating rotors. Furthermore, the highly concerned buffeting phenomenon of dual rotors seems to be less likely.

Based on these findings, retrofitting of existing wind turbine units and manufacturing of new ones with dual rotor configuration could economically benefit California ratepayers as well as the utility service providers. Additional cost invested may be recovered in three to five years.

In summary:

1. The field tests conducted in this study demonstrated that power conversion efficiency could be increased by 25 to 40 % by means of a contra rotating rotor system.
2. At low rotor speeds the net power coefficient is seen exceed Betz limit of 59%. This might be possible since the two rotors are in different planes having velocity-compounding characteristics. Possibly the interference effect between two slowly moving rotors seems to be minimal. Therefore there is a need to revisit this test using grid-connected models
3. Moreover, the buffeting phenomenon that is believed to be resulting from the interaction of the dual rotors was not observed in these tests.
4. The second observation suggests that the contra rotation of two rotors appears to benefit large-scale wind turbines that operate at 15 to 20 rpm.

5. A simple bevel gear system could be used to transmit the net torque generated by two tandem rotors to an existing electrical power-generating unit.
6. The weight and torque of two rotors counter balance each other leading to reduced bending stress on the tower. Hence, possibly existing wind farms can be retrofitted with the new system to increase power output and reduce cost of energy to California ratepayers.
7. There are some arguments that advocate large diameter rotors to generate the same amount of energy without using a dual rotor system. But still a large percentage of wind energy is let out without being harnessed. With large diameter rotor turbines a wind farm will be limited fewer units. Thus a wind farm may not have produced more power by increasing the rotor diameter. Additionally large blades will be subjected to sever dynamic loads and frequent maintenance may be required.
8. Based on above arguments, ATI believes there is a good prospect for the contra rotating system to produce at least 30 to 50 per cent more energy from high wind speed and low wind speed farms in California. Therefore, ATI is committed to further its research and development activities seeking industrial collaboration and Government funding.

4.2 Commercialization Potential

The contra rotating wind turbine system, as discussed in Section 3, is seen to benefit large utility scale wind turbines. If a simple device such as the one discussed in Section 4.3 it may be possible to upgrade the existing wind farms retaining the same towers and rotor mechanisms. Thus worldwide commercialization potential exists for upgrading existing wind farms. In California alone there seems to be nearly 10 thousand utility scale turbines. However to capture this large market potential, a good deal of research and development in system analysis, configuration study and large scale testing is needed. Currently ATI is planning to collaborate with Oak Creek Energy Systems to study the performance of grid connected units using contra rotating rotors. This will be the first step in commercialization effort. Subsequently, expansion will be planned based on funding opportunities.

4.3 Recommendations

The follow-on development should focus on additional tests using grid connected units and system configuration study related to design of new turbines and retrofitting of existing wind farms. The next demonstration study may use the configuration depicted in Figure 37 for 50 kW and 100 kW machines. A pair of specially designed torque-hubs will be used to couple two contra rotating rotors and a generator. A typical torque-hub unit manufactured by Fairfield is depicted in Figure 38. An adapter will be employed to change the output shaft direction of the leeward rotor. The leeward rotor will be provided with slightly larger blades and also is placed offset from the center of rotation. The aerodynamic drag forces of two unequal rotors and unequal lever arm will help the system to self align into the wind direction. However, a light duty servomotor will be used to control the yaw positioning. The power output will be fed to a utility line source. Electrical energy supplied to the line may be recorded over a period of one year to assess economic benefits and payoff period. This study shall further establish whether buffeting of dual rotor system exists and power conversion efficiency observed in this study is still valid for larger machines. The approach can be stated as follows:

- Select a grid-connected environment in 50 to 100 kW power rating.
- Design a counter rotating system using a specially designed torque-hub system and stall regulated rotor blades.
- Conduct excess power production performance studies with grid connected power loading for a period of one year or more. Assess economics of contra rotating system of new as well as retrofitted configurations verses single rotor systems.
- Team with a wind power production company such as Oak Creek Power Systems Inc. to install several of high power rated units, say 250 kW.
- Develop an analytical simulation model using the characteristics of the demonstration units to predict the performance of mega-watt scale machines and economic benefits.
- After successful completion of this study, plan to transition the technology by licensing to manufacturers and utility operators.

4.4 Benefits to California

The technology described in this report were used to retrofit existing wind farms and build new innovative machines, then California may not suffer from power shortage problem and pricey energy cost. The benefits of the project results in the following forms:

4.4.1 Energy Benefits: In 2010 AWEA expects that the US-installed wind capacity will be around 30,000 MW or 105 billion kWh annually. If these wind turbines were retrofitted with dual contra-rotating rotors, 30 billion kWh of additional energy could be generated annually from the same wind farms.

4.4.2 Economic benefits: Potential economic benefits include reduced cost of energy, increased revenue to utility companies, and creation of investment and job opportunities in the US and worldwide retrofit business. At 3.5 cents/kWh, the annual revenue could be increased by 1.05 billion dollars in 2010. In addition, the overall installation cost could be lowered from $1250/kW to $800/kW in par with fossil fuel power plants. This would counter the general criticism that wind turbines are too land-intensive and expensive.

4.4.3 Environmental Benefits: Every kWh generated by wind offsets CO2 emission by 2 lb, and 0.025 lb of sulfur oxides and nitrogen oxides. AWEA estimates that by 2010, the reduction of CO2 emission would be 956,000 metric tons per billion kWh of wind energy generated. By making wind farms more efficient, contra-rotating wind turbines could help to reduce additional 33.46 MMT of CO2 in 2010 and beyond.

5.0 REFERENCES

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