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DEVELOPMENT AND TESTING OF A 2-KILOWATT WIND TURBINE FOR WATER PUMPING

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ABSTRACT

A 3-bladed 3.3 meter diameter upwind horizontal-axis wind turbine rated at 2 kilowatts (kW) for a wind speed of 11.5 meters/second (m/s) was tested at the USDA-ARS Conservation and Production Research Laboratory from Feb. 2, 1999 to Oct. 11, 1999. The wind turbine achieved its 2 kW rating (sea level standard day conditions) at a wind speed between 11.5 and 12 m/s. Four different tails and two different yaw axis offsets were tested because the furling behavior of this wind turbine was critical to its success. Two different sets of blades with different pitch angles were also tested to determine the optimum pitch angle. The primary controller used during this testing was an ARS/AEI designed controller, but the manufacturer's controller was operated for a period of two weeks during July and performed well. Using a low head pump, a peak system efficiency of 12% was achieved at a simulated 30 m pumping depth. For a high head pump, a peak system efficiency of 8.5% was achieved at a simulated 73 m pumping depth. Both water pumping systems had a cut-in wind speed of 5 m/s.

INTRODUCTION

The USDA-Agricultural Research Service (ARS) and WTAMU-Alternative Energy Institute (AEI) have tested various systems over the past twenty years which use wind or solar energy to pump water for livestock watering, domestic purposes, or irrigation. Using small wind turbines to power off-the-shelf submersible motors and centrifugal pumps was pioneered by this renewable energy team in 1988. The demand for stand-alone (non utility intertie) wind-electric systems has mainly been in Third World countries, but a few farmers and ranchers in the U.S. are beginning to buy these systems. The Havatex* 2000 wind turbine used in this study was designed for both battery-charging and water pumping applications for low to moderate wind sites.

The goal during the testing of the Havatex 2 kW wind-electric system was to maximize performance without sacrificing reliability and at the same time keep the wind-electric system economical. Several modifications were made to the wind turbine and the Havatex controller during the testing. The wind-electric system tested consisted of: 2 kW wind turbine, 12.2 m tower, smart controller, submersible motor, and centrifugal pump. The wind turbine had a permanent magnet alternator which generated variable-frequency, variable-voltage, 3-phase AC electricity. The wind turbine blades employed airfoils of the NREL HAWT airfoil series[1]. The blades also had a mostly linear chord distribution (linear taper in chord from 12% to 97% radial location) and a near-Glauert[2] optimum twist distribution. Two controllers were used during the testing -- an ARS/AEI designed controller and the Havatex controller. The ARS/AEI controller was used during most of the testing due to its ease of adjustment, and an optimum range of settings could be determined for the Havatex controller. The Havatex controller does not allow the user to alter the settings. Both controllers added a capacitance of 50 μF/phase in parallel with the submersible motor so that an inverter would not be necessary. The submersible motors used during this testing were rated at 1.5 kW and at 1.1 kW. Both submersible motors were commercially available 3-phase, 230 V, 60 Hz motors. The centrifugal pumps used during the testing (also commercially available) were a 1.1 kW 9-stage pump and a 0.75 kW 19-stage pump.

* The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

DESCRIPTION OF WIND-ELECTRIC SYSTEM

The Havatex 2000 wind-electric system is a 3-bladed upwind, variable speed, horizontal axis wind turbine which uses horizontal furling for overspeed control. (See Figure 1). The rotor diameter is 3.3 m and uses two NREL HAWT airfoils (S822 and S823). The Havatex 2000 is rated at 2 kW for a wind speed of 11.5 m/s (sea level standard day conditions). The blades have a fairly linear chord distribution, but a non-linear twist distribution. The blades are made from epoxy prepregs with a foam core and are fixed to the hub with bolts perpendicular to the rotor axis (similar to a large utility scale wind turbine). For wind turbines below 10 kW these features (NREL airfoils, blade composition and blade attachment to hub) are unique. The wind turbine generates variable-voltage, variable-frequency, 3-phase AC electricity using a permanent magnet alternator (PMA). The Havatex PMA has 18 poles and uses rare earth magnets. The electricity generated by the PMA is conducted down the tower via a slip ring assembly and wiring harness. The total weight of the wind turbine is 82 kg (180 lb).

The Havatex 2000 was tested with two different controllers -- the Havatex 2000 controller and the ARS/AEI controller. The Havatex 2000 controller is energized from the wind turbine, so it does not require a battery. Four frequencies are used by the controller to control the operation of the wind turbine: low frequency cut-in, low frequency cut-out, high frequency cut-in, and high frequency cut-out. For a detailed explanation of the function of each of these frequency settings, see Ling, et al.[3] These frequency settings are set by the manufacturer in the microchip and can not be altered by the user. The controller uses solid state relays and incorporates three working capacitors for power factor correction which results in the pump motor running efficiently without needing an inverter. During the testing, additional solid state relays were included to allow a resistive/capacitive dump load to be added at the high frequency cut-out to reduce the wind turbine rpm in high winds. The ARS/AEI controller was mainly used during the testing to determine the optimum frequency settings for the Havatex controller, and also when modifications were being made to the Havatex controller. The ARS/AEI controller has been described by Ling, et al.[3]

The submersible motors tested were rated at 1.5 and 1.1 kW. All the motors were Franklin Electric* 3-phase, 230 V, 10 cm diameter submersible motors. The centrifugal pumps tested included a 1.1 kW, 9-stage pump and a 0.75 kW, 19-stage pump. All the pumps were Grundfos* 10 cm diameter pumps.

DESCRIPTION OF INSTRUMENTATION AND DATA ACQUISITION SYSTEM

A schematic of the test set up is shown in Figure 2. The data recorded included:

1) Julian Day
2) Time of Day (variable)
3) Wind Speed Anemometer 1 (m/s)
4) Wind Speed Anemometer 2 (m/s)
5) Flow Rate (gal/min)
6) Pressure (psig)
7) Wind Turbine Voltage (V)
8) Wind Turbine Current (A)
9) Wind Turbine Frequency (Hz)
10) Wind Turbine Power (W)
11) Wind Direction (deg).

When testing began on Feb. 3, 1999, anemometer 2 and the wind direction sensor had not been installed. On Mar. 29, 1999 anemometer 2 (Climet* wind sensor which can accurately measure wind speed every second) and a NRG* wind direction sensor were installed on the wind turbine tower -- the instruments were 10 m above ground. Anemometer 1 was a Met One* anemometer located about 40 m West South West of the wind turbine 15.5 m above the ground and can reliably measure the wind speed over a 10 second interval. The increment in time that the variables (3-11) were averaged and recorded over varied throughout the testing. From Feb. 3, 1999 until Feb. 13, 1999 the time increment was 1 minute. From Feb. 13, 1999 until Apr. 29, 1999 the time increment was 20 seconds. The change from 1 minute to 20 seconds was to determine if the power curve would change if the time interval was shortened (no significant change in power was observed due to change in time increment). From Apr. 29, 1999 to the present, the time increment was again 1 minute, but if the wind measured by anemometer 2 exceeded 10 m/s, the following data were recorded every second:

1) Time (seconds)
2) Wind Direction (deg)
3) Wind Speed Anemometer 2 (m/s)
4) Wind Turbine Frequency (Hz)
5) Wind Turbine Voltage (V) or Power (W).

This one second data was gathered in order to evaluate furling and also have data if a catastrophic failure occurred. From Apr. 29, 1999 to May 4, 1999 one-second voltage data was taken, and after May 4, 1999 we began collecting one-second wind turbine power data (again, one-second data taken when anemometer 2 wind speed is above 10 m/s). On May 5, 1999 the data collection program was edited so that one second data was recorded when the wind speed on anemometer 2 exceeded 9 m/s. On that same day the height of anemometer 2 was lowered from 10 m to 7.62 m due to the wind turbine rotor's close proximity to the anemometer (the minimum distance from the tip of the blade to the anemometer was 1.5 m). The voltage and current were measured with a Magtrol* (Model 4612b transducer). The wind turbine power was measured with a Ohio Semitronics* Model P-144X5 transducer, and the frequency was measured by a transducer designed by AEI. The water flow rate for the 0.75 kW 19 stage pump was measured with a Hersey* MVR 30 flow meter. The water flow rate for the 1.1 kW 9-stage pump was measured with a Hersey MVR 50 flow meter. The pressure measured for the 1.1 kW pump was a Data Instruments* Model EA 100. The pressure transducer used with the 0.75 kW pump was a Data Instruments Model EA 300.

The data acquisition system consisted of a Campbell Scientific* 21X data logger and the data were processed with several C++ and Quick Basic computer programs. The raw data variables were binned every 0.5 m/s with either anemometer 1 or anemometer 2 and the average and standard deviation of each binned variable was calculated. The flow rate in gal/min was converted to liters/min during processing. The pressure in psig was converted into head in meters by the following equation.

$$\text{Head (m)} = P(\text{psig}) \times 0.70 \text{ m/psig} + 1.52 \text{ m} \qquad (1)$$

The 1.52 m constant in the above equation is the change in elevation from the water outlet to the static water level of the sump. Atmospheric pressure and temperature data collected on another data acquisition system were used to correct the measured wind turbine power to power at sea level on a standard day. Furling was analyzed with a modified version of the computer program used to analyze furling on the Bergey* 1500.[4]

TESTING HISTORY OF THE HAVATEX 2000 AT BUSHLAND, TX

The Havatex 2000 wind turbine was installed on a 12.2 m 25G Rohn* tower near the hydraulic laboratory at the USDA-ARS Lab on Feb. 2, 1999. Table I describes all of the configurations tested and also when they were tested. The first month of testing Config. 1 was spent determining the power available from the wind turbine using various amounts of resistance and capacitance as a load. The optimum resistance and capacitance for maximizing the power output was found to be 40 Ω and 20 μF. Testing was begun on a 1.5 kW submersible motor and a 1.1 kW 9-stage centrifugal pump on Mar. 9, 1999. A heavier tail vane (Config 2) was installed the following day because the other tail vane (Config. 1) tended to buckle. On April 1, 1999 additional tail bumpers were added (Config. 3) to restrict how much the wind turbine furled. Furling is the aerodynamic/ mechanical ability of the wind turbine to turn out of the wind for overspeed protection. Rubber tail bumpers had already been attached on the tail root and served as spacers between the tail and the alternator casing in the unfurled position. The additional rubber tail bumpers were attached to the other side of the tail root to restrict how much the wind turbine furled. After installing the additional bumpers, the minimum frequency in the furled position increased from a few Hz to 27 Hz. Too low a frequency is a problem in moderately high winds. Without the bumpers the rotor speed will accelerate too rapidly after furling. The submersible motor can't synchronize with the wind turbine in time before the frequency exceeds the high frequency cut-out of the controller. This results in no water being pumped.

At approximately 4:00 p.m. on April 14, 1999 all three blades broke off of the wind turbine in wind speeds of 20 to 24 m/s. The tail vane that was added on Mar. 10, 1999 contributed to the catastrophic failure of the wind turbine by keeping the wind turbine from furling until a higher wind speed was reached. Besides the blade failures, the tail boom and yaw shaft were significantly bent, and the rotor bearing also failed. Havatex spent the next two weeks redesigning the wind turbine and controller and on April 27, 1999 a redesigned Havatex 2000 was installed. Modifications to the Havatex wind turbine included:

1) Increasing yaw axis offset from 25 mm (1 in) to 31 mm (1.22 in).
2) Shortening the tail boom from 182.9 cm (72 in) to 132.1 cm (52 in).
3) Use of a heavier gage steel for the tail boom.
4) Increasing the diameter of the yaw shaft from 40 to 45 mm) -- strength increased 50%.
5) Increasing grade of bolts holding the blades to hub flange (Grade 8 to Grade 9).
6) Curing the Epoxy Prepreg blades at 280° F instead of 250° F, and increasing the cure cycle time. This should increase the blades' strength 20%.

The Havatex controller was also redesigned and those changes included using:

1) a dump load (40 Ω/20 μF) at the high frequency cut-out to reduce the rpm of the machine at high wind speeds.
2) a bigger heat sink to keep the electrical components from getting too hot.
3) a bigger capacitor on the circuit board to improve the wind turbine starting capability with the submersible motor.

After a week of testing the redesigned wind turbine and controller, the water pumping performance was seen to have decreased significantly and the decision was made to do additional testing with a 40 Ω/20 μF electrical loading with no controller. After testing Tail 3 (Config. 4) and Tail 2 (Config. 5), the performance degradation was identified to be due to Tail 3. The yaw axis offset improved the furling behavior of the wind turbine enough to where it was felt that using Tail 2 would not lead to the destruction of the machine again. On May 25, 1999 water pumping was continued with the 1.5 kW motor/1.1 kW 9-stage pump and the Havatex controller. On June 4, 1999 the motor and pump were replaced with a 1.1 kW motor/0.75 kW 19-stage pump, and also the controller was switched back to the ARS/AEI controller.

The pumping depth simulated with the low head pump was 30 m and the pumping depth was increased to 73 m for the high head pump -- 73 m is the actual pumping depth for water wells in the Bushland, TX area. On July 6, 1999 a shorter 157.5 cm (62 in) but heavier, stiffer tail was installed. At the same time, blades with a different pitch angle were installed and we switched back to the Havatex controller. A significant water pumping performance degradation was recorded for this configuration (Config. 6). On July 20, 1999 we switched back to the ARS/AEI controller to see what effect the controller had on pumping performance. There was no significant difference in water pumping performance with the ARS/AEI controller. On July 29, 1999 the blades with a lower pitch setting (Config. 7) were installed. The water pumping performance came back up to the original level, so the performance degradation was due entirely to the change in pitch angle -- not to Tail 4. On Aug. 5, 1999 we switched from water pumping to the 40 Ω/20 μF electrical load (no controller) to get a good power curve for Config. 7. Future plans are to try to lower the cut-in wind speed with wind-electric system changes.

RESULTS

The majority of the changes on the Havatex 2000 (Table I) had to do with the tail, but changes were also made to the yaw axis offset and the blade pitch angle. The tail and offset changes were meant to modify the furling behavior of the wind turbine, and the blade pitch angle changes were an attempt to try to improve water pumping performance at low wind speeds. For Figures 3-6 the binned anemometer is specified. For Figures 7-10 the dependent variable is averaged for binned data of anemometer 1 and anemometer 2 -- this should approximate the hub height data.

An electrical schematic of the first part of the testing done on the Havatex 2000 is shown (Figure 3). Combinations of various values of resistance (40 to 96 Ω) and capacitance (15 to 55 μF) were tried to determine the optimal resistive/capacitive load. The highest measured wind turbine power appeared to occur with an electrical load of 40 Ω and 20 μF.

The effect on frequency of each tail/offset combination is shown in Figure 4 for a constant electrical load of 40 Ω and 20 μF. The highest frequency achieved is with Config. 3, the same configuration which resulted in the catastrophic failure on April 14, 1999. Decreasing the tail length and increasing the offset (Config. 4) dramatically reduced the output frequency of the wind turbine (i.e. decreased the furling wind speed).

The computer program used to estimate the furling wind speed determines when the frequency has decreased below a minimum frequency specified by the user when the wind speed is greater than 9 m/s. The only way the frequency can get below this minimum frequency at this high wind speed is for the wind turbine to furl. The computer program also bins data at wind speeds above 9 m/s when the wind turbine does not furl, so that the percentage of time furled can be determined as a function of wind speed. When the wind speed gets high enough, the wind turbine will furl 100% of the time. Wind direction had an affect on furling wind speed for the Havatex 2000, so only data from the prevailing wind direction was analyzed. In Figure 5 the longer tail results in the higher furling wind speed.

Figure 6 shows the effect on wind turbine power (corrected to sea level standard day conditions) of each tail/offset combination. Power is plotted against the wind speed at 15.5 m instead of the hub height (12.5 m) because the first tail configurations only had data with this wind speed measurement. Figure 4, frequency versus wind speed, shows the same trends as Figure 6. The highest power curve is achieved with Config. 3, but that again is the case when the wind turbine failure occurred. The power curves shown in Figure 7 are for the final configuration (Config. 7) tested. Power curves of an electrical loading of 40 Ω and 20 μF (solid box) and the wind turbine pumping water with a submersible motor/centrifugal pump/50 μF capacitance (plus sign) are shown. The two power curves are identical except for the low and high wind speed ends. The power for the submersible motor loading is below the power for the 40 Ω/20 μF loading at low wind speeds due to the controller not cutting the submersible motor in until a high enough frequency is reached. At the high wind speed end, the wind turbine loses synchronization with the submersible motor for the water pumping case. The power coefficient (Cp = wind turbine generated power/power in the wind) is also shown for both these two cases. A maximum Cp of 0.35 is reached at a wind speed of 5.5 m/s for the 40 Ω/20 μF loading, a maximum Cp of 0.32 is reached at a wind speed of 7 m/s for the water pumping case.

Figure 8 shows the flow rate versus wind speed for Config. 5. The controller settings for this configuration were:

1) low frequency cut-in = 40 Hz
2) low frequency cut-out = 30 Hz
3) high frequency cut-out = 75 Hz
4) high frequency cut-in = 70 Hz.

The cut-in wind speed was 5 m/s and the peak flow rate was 80 liters/min at 9.5 m/s. The flow rate could probably have been improved if the high frequency cut-out and cut-in were increased. The system efficiency (system efficiency = rate of work done on water/ Power in the wind) of this configuration was 12% at a wind speed of 8 m/s. Although Config. 5 is not the probable production version (Config. 7), the pumping performance is probably similar. In Figure 9 the flow rate for Config.'s 5 and 7 are shown for a different motor/pump/head combination. The system efficiency for these configurations are not as high(8.0% and 8.5%) as the previous motor/pump/head combination. Since the flow rates are similar, the assumption that the pumping performance for Config.'s 5 and 7 appears to be valid. The motor and pump in Figure 9 are at a lower power rating than Figure 8. The number of pump stages and pumping depth in Figure 9 are also double that shown in Figure 8. The cut-in wind speed is the same (5 m/s) for both motor/pump/head combinations, but the max flow rate in Figure 9 occurs at a higher wind speed (13 m/s) compared to the maximum flow rate wind speed (9.5 m/s) in Figure 8. The frequency settings of the controller for the 1.1 kW motor/19 stage pump/73 m head data were:

1) low frequency cut-in = 40 Hz
2) low frequency cut-out = 30 Hz
3) high frequency cut-out = 85 Hz
4) high frequency cut-in = 81 Hz

The high frequency cut-out and cut-in settings (85/81) were higher for the 1.1 kW motor/19 stage pump/73 m head data than the settings (75/70) for the 1.5 kW motor/9 stage pump/30 m head data. This is probably the reason for the difference in maximum flow rate wind speeds (13 m/s compared to 9.5 m/s).

In order to investigate whether increasing the blade pitch angle might improve the cut-in wind speed, a new set of blades were fabricated by Havatex with an increased pitch angle. The pitch angle of the blade tip with respect to the rotor plane was increased from 4.5 degrees to 6.5 degrees (i.e. angle-of-attack was decreased 2 degrees). Figure 10 shows the effect of increasing the pitch angle two degrees. Increasing the pitch angle two degrees resulted in a significant drop in flow rate and the cut-in wind speed actually increased from 5 to 5.5 m/s. Since an increase in pitch angle resulted in a decrease in water pumping performance, it is natural to wonder if a lower pitch setting would improve water pumping performance? Havatex, prior to testing at Bushland, had tested a pitch setting of 3 degrees, and although the power curve improved at most wind speeds, the cut-in wind speed increased 0.75 m/s -- not a good tradeoff.

CONCLUSIONS

Development and testing of a Havatex 2 kW wind turbine for water pumping was performed at the USDA-ARS Conservation and Production Research Laboratory from February to October of 1999. Several modifications of the Havatex wind turbine and Havatex controller were made to improve the wind-electric system's reliability and performance. During the testing all three blades broke off in high winds which resulted in a redesign which strengthened the blades, the blade mounting bolts, the yaw shaft, and the tail boom. The Havatex controller was also redesigned by adding a dump load at high wind speeds to keep the rotor rpm from getting too high. The final wind turbine configuration tested (Config. 7) reached a 2 kW rating (Sea Level Std. Day conditions) at a wind speed of 11.5 to 12 m/s. The maximum Cp (power coefficient) achieved for the optimum electrical loading with Config. 7 was 0.35 at a wind speed of 5.5 m/s. The maximum Cp reached for the water pumping data with Config. 7 was 0.32 at a wind speed of 7 m/s. The furling behavior affected the performance and reliability of this wind turbine greatly. The gentler furling behavior of Config. 7 should insure reliability without paying too much in performance. Two different motor/pump/head configurations were tested with the Havatex 2000 wind turbine. A system efficiency of 12% was reached with the 30 m low head pump. A system efficiency of 8.5% was reached with a 73 m high head pump. Both motor/pump combinations had a cut-in wind speed of 5 m/s. Although the ARS/AEI controller was used during most of the testing, the final Havatex controller configuration performed well over a two week period during July.

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HAVATEX 2000 WIND TURBINE CONFIGURATION DESCRIPTION

Configurations	Tail Used	Yaw Axis Offset	Pitch Angle	Additional Tail Bumpers	Dates Tested (1999)
Configuration 1	Tail 1	25 mm (1")	4.5 deg	No	Feb. 3 - Mar. 10
Configuration 2	Tail 2	"	"	"	Mar. 10 - Apr. 1
Configuration 3	"	"	"	Yes	Apr. 1 - Apr. 14
(Turbine down for redesign)					
Configuration 4	Tail 3	31 mm (1.22")	4.5 deg	Yes	Apr. 28 - May 18
Configuration 5	Tail 2	"	"	"	May 18 - July 6
Configuration 6	Tail 4	"	6.5 deg	"	July 6 - July 29
Configuration 7	"	"	4.5 deg	"	July 29 - Oct. 11

TAIL DESCRIPTION

Tails	Length of Tail Boom	Wt. of Tail Boom	Wt. of Tail Vane	Tail Total Tail Wt.	Tail Moment Arm C.G.	Moment Arm C/4 Tail
Tail 1	182.9 cm (72")	5.30 kg	2.71 kg	8.01 kg	109.2 cm	158 cm
Tail 2	"	"	3.48 kg	8.78 kg	115.6 cm	158 cm
Tail 3	132.1 cm (52")	6.20 kg	"	9.68 kg	80.3 cm	107 cm
Tail 4	157.5 cm (62")	7.22 kg	"	10.70 kg	86.7 cm	132 cm

Table I. Configurations Tested on Havatex 2000 Wind Turbine at Bushland, TX.

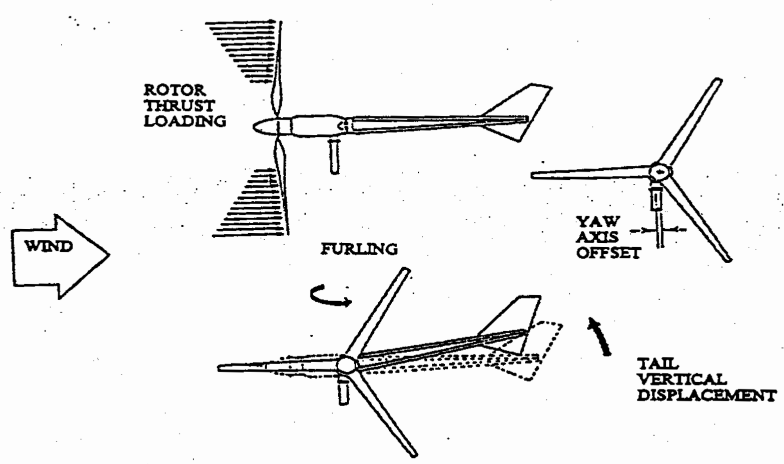

Figure 1. Horizontal Furling of a Havatex 2000 Wind Turbine.

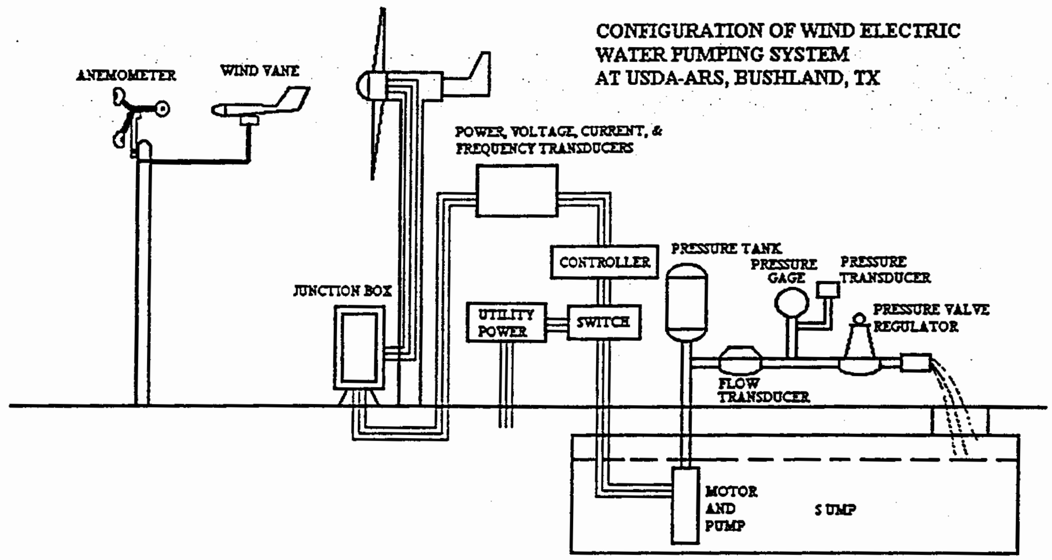

Figure 2. Schematic of Wind-Electric Water Pumping System at Bushland, TX.

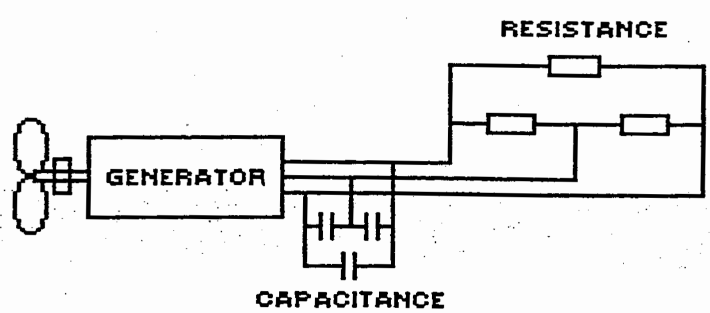

Figure 3. Schematic of Resistive and Capacitive Loading Tested on Havatex 2000.

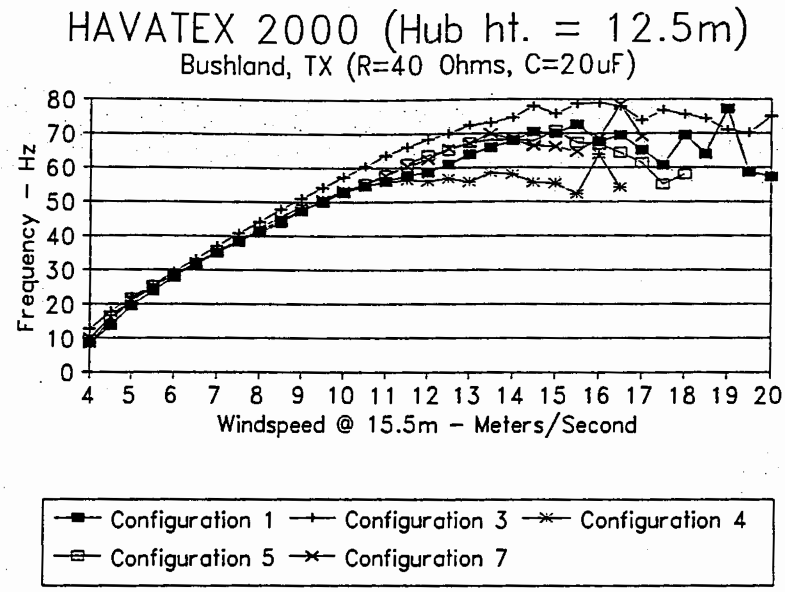

Figure 4. Effect of Various Tails and Yaw Axis Offsets on Measured Frequency.

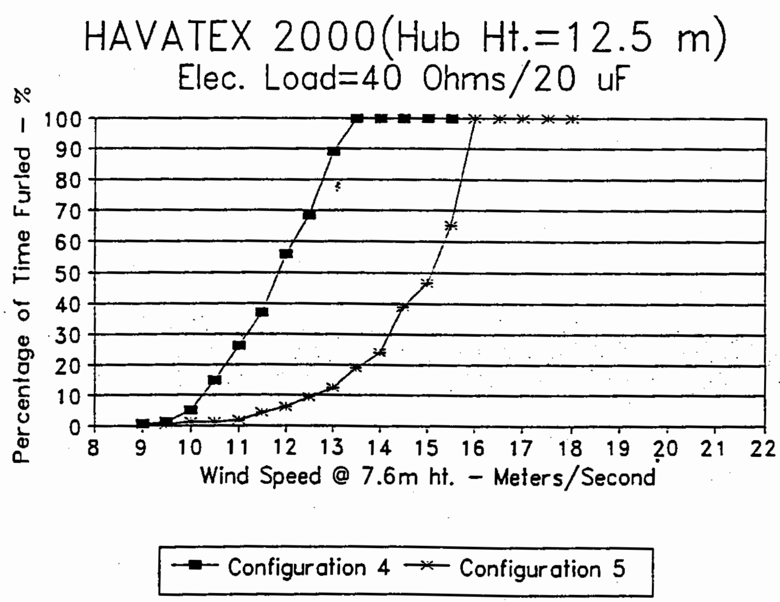

Figure 5. Change in Furling Wind Speed for Two Different Tail Configurations.

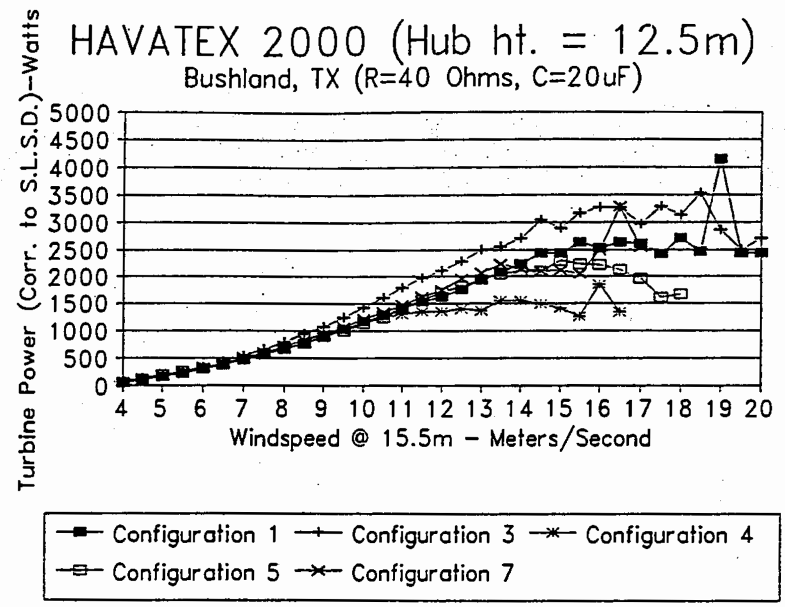

Figure 6. Effect of Different Tails and Yaw Axis Offsets on Havatex 2000 Power for a Sea Level Standard Day.

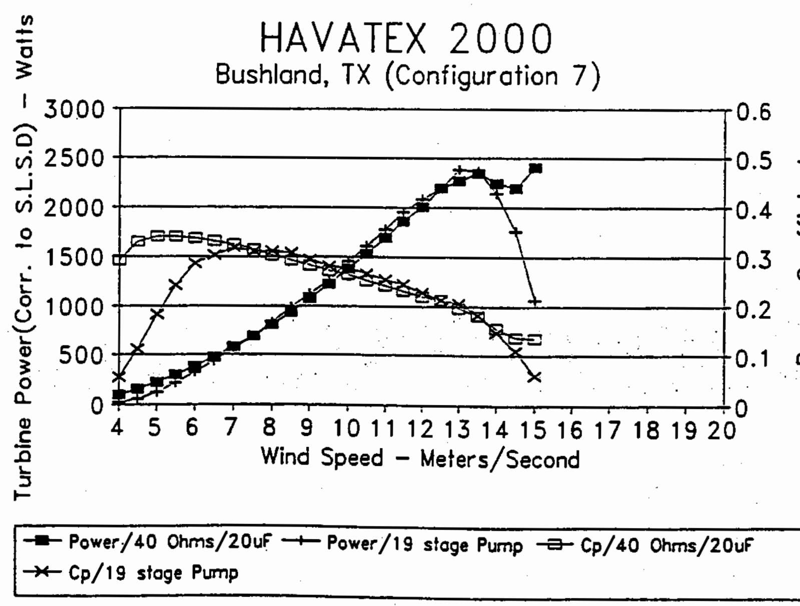

Figure 7. Power and Power Coefficient for Final Tail/Offset Configuration at Two Different Electrical Loadings.

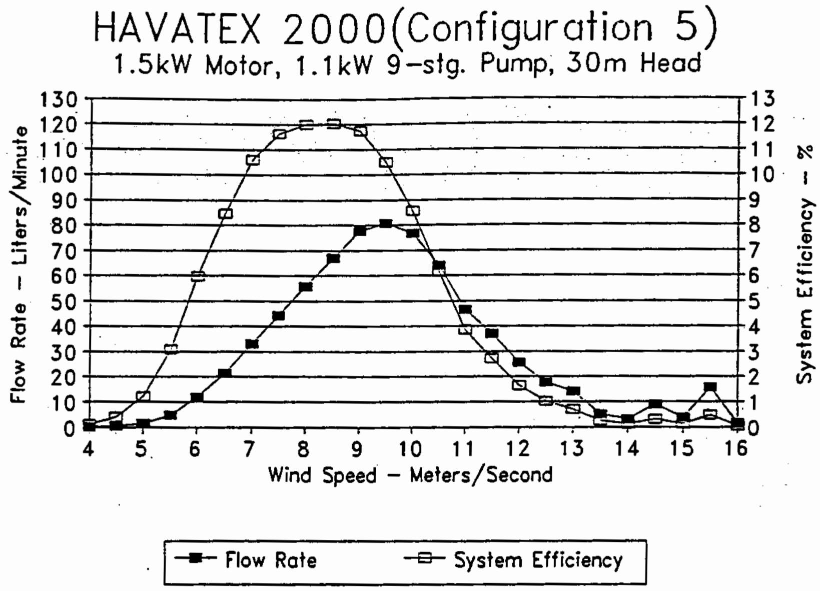

Figure 8. Flow Rate and System Efficiency of Low Stage/Low Head Pump for Configuration 5 (Frequency Settings=40,30,75,70).

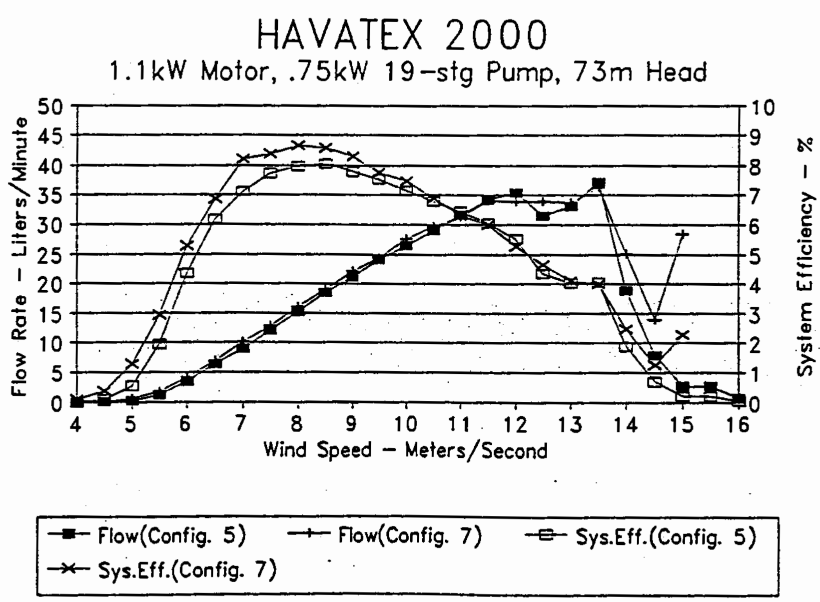

Figure 9. Flow Rate and System Efficiency of High Stage/High Head Pump for Configurations 5 and 7(Freq. Settings=40,30,85,81)

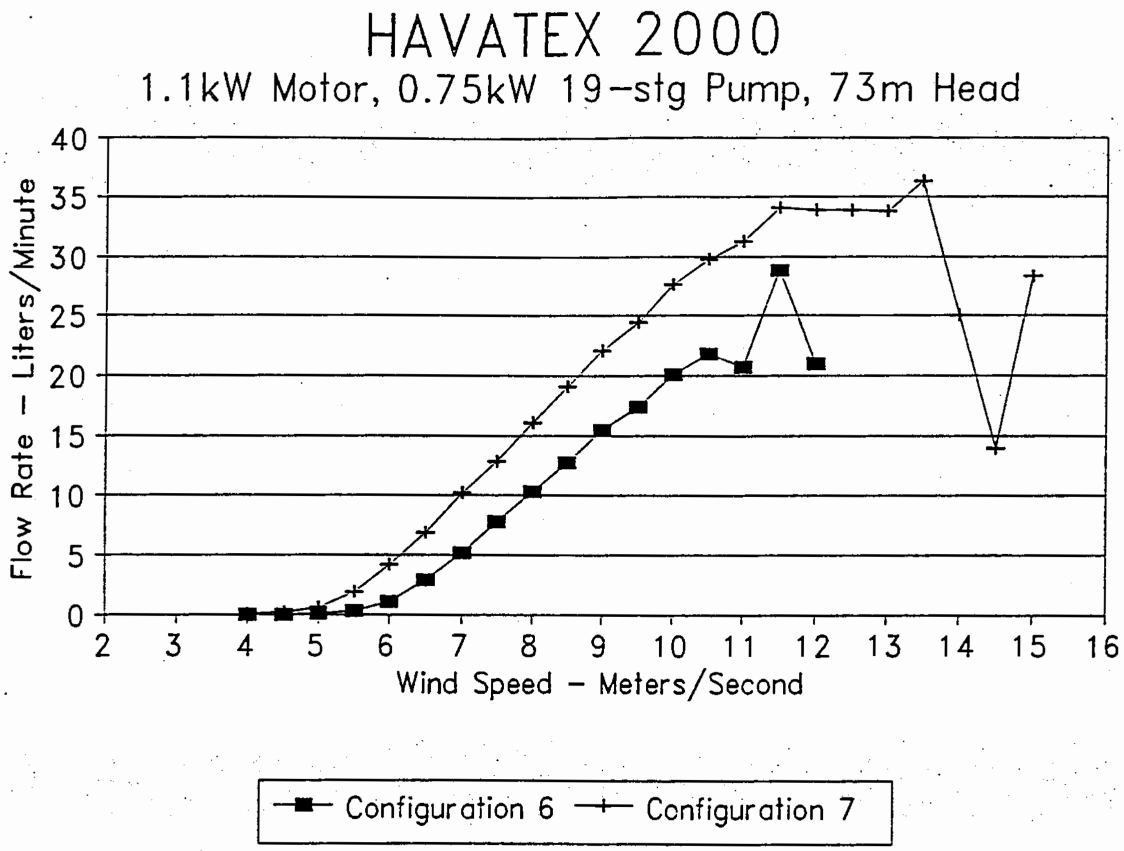

Figure 10. Effect of Blade Pitch Angle on Flow Rate for Final Tail/Offset Configuration.

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