PUMP CONTROLLER TESTING ON WIND TURBINES USED IN WATER PUMPING

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ABSTRACT

Pump controllers for wind-electric water pumping systems were tested on several different size wind turbines at the USDA - Agricultural Research Service, Bushland, Texas. All the wind turbines tested used permanent magnet alternators which generated 3-phase, AC electricity. The wind turbines tested varied in rated power from 1 kW to 10 kW at a wind speed of about 12 m/s. The 3-phase submersible motors tested were all rated at 230 V and the rated power varied from 0.38 kW to 5.6 kW. The pump controllers tested ranged from simple (on/off at certain frequency) to moderately sophisticated (low/high cut-in/cut-out frequency selection with thermal protection for submersible motors). No inverters were used on any of the pumping systems in order to reduce the cost and increase the efficiency of the pumping systems. An inverter isn't necessary for off-the-shelf AC motors and pumps if the voltage to frequency ratio is maintained between 3 and 4. A voltage to frequency ratio of 3 to 4 was obtained on all the pump controllers tested from the cut-in wind speed to a 13 m/s wind speed by adding the proper capacitance on all three phases. Capacitance was varied on all of the pump controllers tested and it was discovered that optimal capacitance for maximum water pumping performance varied with windspeed. Problems which occurred during the testing which could have been prevented with a modification of the controller were: no water pumping when sufficient winds were available, inability to stop the wind turbine in high winds, blade failures, burned up motors.

INTRODUCTION

Mechanical windmills have been used to pump water for people and livestock in the Great Plains for the past 120 years. Mechanical windmills (possibly numbering in the hundreds of thousands) are still being used to pump water in the Great Plains. However, many of these windmills are close to 50 years old, and are becoming too costly to maintain. Some farmers and ranchers are turning to solar and/or wind-electric water pumping systems to supply their water needs. It has been reported that over 30% of the world population doesn't have a safe drinking water supply, and many locations do not have access to electrical power from a utility, so an attractive alternative is a stand-alone wind-electric water pumping system.

Stand-alone wind-electric water pumping systems have been tested at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Tx. for over a decade. A description of the experimental setup at the USDA-ARS at Bushland was given by Clark and Vick (1994). In order to improve the performance and affordability of the wind-electric water pumping systems, several areas have been researched over the past year. The selection of the proper pump size for a wind-electric water pumping system was discussed by Clark and Vick (1994). The selection of the proper motor size for two different size wind-electric water pumping systems was discussed by Clark and Vick (1995). This paper discusses the advantages and disadvantages of pump controllers on three different size wind-electric systems tested at the USDA-ARS Laboratory in Bushland.

WHISPER 1000 PUMP CONTROLLER

The World Power Technologies[1] Whisper 1000 wind turbine is rated at 1 kW at a windspeed of 11 m/s (25 mph), and overspeed protection is accomplished by furling vertically. The Whisper 1000 uses a permanent magnet alternator which generates 3 phase, AC electricity. The voltage and frequency of the generated electricity varies with rotor rpm. One has the option of buying a rotor with two or three blades, and those blades can be made out of wood or fiberglass. The rotor speed at rated power is 850 rpm, and the rotor diameter is 2.7m (9 ft.). Only a 2 blade rotor has been tested so far at the USDA-ARS, but both wooden and fiberglass blades have been tested.

The Whisper 1000 controller works by switching the wind turbine electricity to the submersible motor at about 35 Hz as the winds increase. As the winds are decreasing the electricity is switched from the motor when a frequency of about 20 Hz is reached. This pump controller contains only four components which are:

1) A rectifier circuit which at certain frequency will engage the motor relay.
2) Motor relay which switches wind turbine electricity to a submersible motor.
3) Capacitors in parallel with motor. The main reason being to reduce the phase angle between the voltage and current which increases the motor/pump efficiency at high wind speeds. For further discussion on this topic, see Muljaki, et al (1995).
4) Manual brake switch which can brake the wind turbine in windspeeds less than 10 m/s.

The major benefits of having a simple controller like the Whisper 1000 are:

1) Less maintenance because of fewer parts.
2) Less expensive.
3) No additional power supply for the controller is needed (the wind turbine acts as a power supply).

The main disadvantage is the risk of damaging the alternator, motor, and pump since there is no high frequency cut-out or thermal circuit breaker. A disadvantage with the brake switch is it doesn't stop the wind turbine in high winds. If an attempt is made to brake the wind turbine in high winds, the alternator can be damaged. Despite these disadvantages during eight months of testing at the USDA - no alternators, pumps or motors have been damaged.

There have been wooden blade failures, but we believe these were probably caused by improper balance of the blades. The out of balance wooden blades could probably have been saved if an additional dump load had been applied to keep the rotor speed from getting too high. When the unbalanced wooden blades reached a certain rotor speed, then a flutter would occur which eventually would cause a blade failure due to fatigue. The last wooden blade failures occurred because of golf ball size hail striking the blades on October 4, 1994, and no changes to the controller would have prevented these blade failures. During the same golf ball size hail storm -- none of the fiberglass blades on the other wind turbines were damaged from the hail. Since Jan. 27, 1995 the Whisper 1000 has been tested with fiberglass blades.

During July 1994 various amounts of capacitance were tested on the Whisper 1000 with a 0.38 kW (0.5 hp) motor and a 0.56 kW (0.75 hp) 9-stage pump to determine the effect on pumping performance. Figure 1 shows the effect on flow rate of varying the capacitance when the pumping depth was constant (25 m). Although only three hours of data were gathered for the 20 μF capacitance, there did appear to be a slight improvement in flow rate at low to moderate wind speeds for using 20 μF instead of 50 μF. Three hours of data were gathered at a capacitance of 20 μF

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

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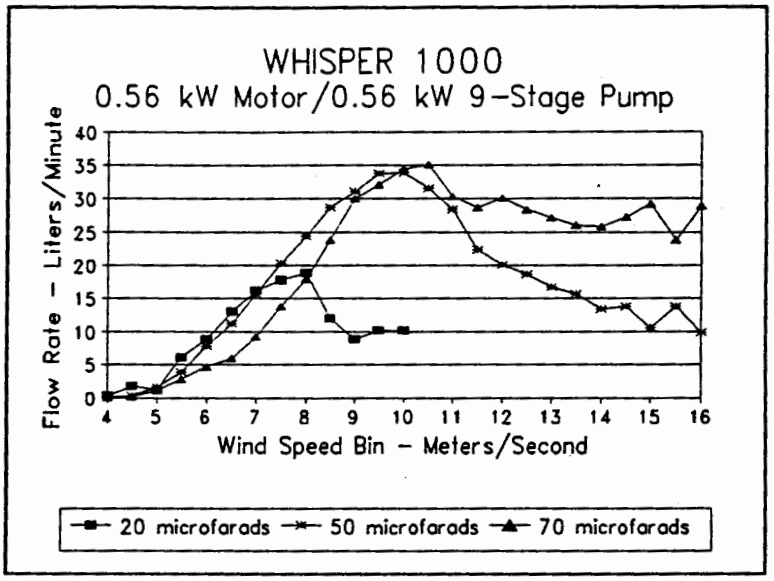

Figure 1. Effect of Capacitance on Flow Rate of Whisper 1000

because of concern that the unloading of the wind turbine could lead to damage of the wooden blades because of the high rotor rpm at high wind speeds. There was an even larger improvement at moderate wind speeds for using a 50 μF capacitance compared to a 70 μF capacitance. However, at high wind speeds the 70 μF capacitance had a higher flow rate than the 50 μF capacitance. This implies that the optimum capacitance changes with windspeed. The capacitors were connected between the controller and the motor on the Whisper 1000. Therefore, the decreased flow rate for the higher capacitance at low to moderate windspeeds could be caused by the charging of the capacitors when the controller switches the electricity from the wind turbine to the motor. Since Jan. 27, 1995 the capacitors have been installed between the wind turbine and the controller. Locating the capacitors between the wind turbine and the controller should decrease the wear on the motor relay.

Another way of improving the water pumping performance would be to apply a dump load at higher windspeeds in order to keep the frequency from exceeding 70 Hertz. Figure 2 shows how the water pumping performance of the Whisper 1000 with a 0.75 kW motor and 0.38 kW 9-stage pump was improved at higher windspeeds when the pumping depth was increased from a 30m to 45m. The frequency and current were also reduced by increasing the pumping depth. The lower current means less heating of the alternator, motor, and pump and therefore longer life.

BERGEY 1500 PUMP CONTROLLER

The Bergey Windpower[1] 1500 wind turbine is rated at 1.5 kW at a windspeed of 12.5 m/s (28 mph), and overspeed protection is accomplished by the wind turbine furling horizontally. The Bergey 1500 has a permanent magnet alternator which generates 3-phase, AC electricity, and the voltage and frequency of the electricity vary with rotor speed and the rotor speed varies with wind speed. The rated rotor speed varies between 0 and 500 rpm. The rotor has three fiberglass blades, and the rotor diameter is 3.05m (10 ft.). The fiberglass blades can be either standard or extra stiff -- all the testing at the USDA-ARS in Bushland has been with the standard fiberglass blades.

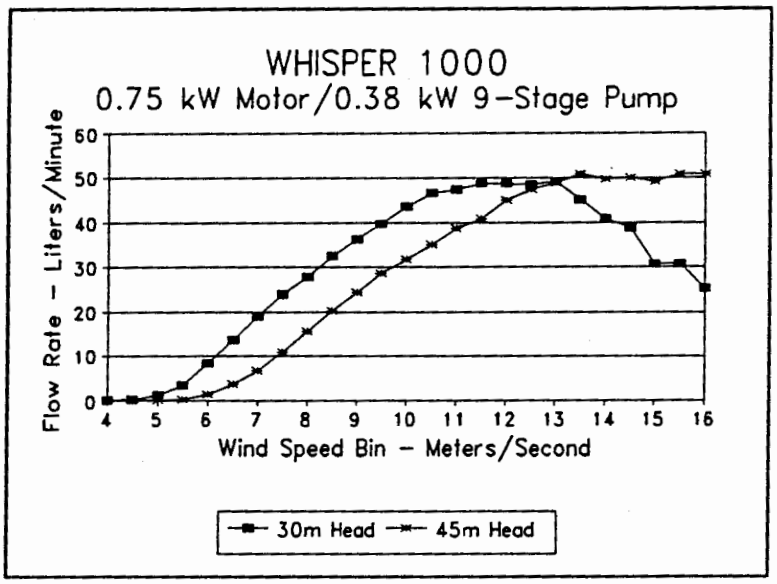

Figure 2. Effect of Increasing the Pumping Depth on the Whisper 1000.

The Bergey 1500 pump controller is a moderately sophisticated pump controller. This controller monitors the frequency and has four different frequency switches which are adjustable. The frequency switches are:

1) Low Speed Cut-in Frequency
2) Low Speed Cut-out Frequency (Should be less than low speed cut-in frequency)
3) High Speed Cut-out Frequency
4) High Speed Cut-in Frequency (Should be less than high speed cut-out frequency)

All of the above frequency switches have a range from 0 to 99 Hz. There are also six channels available for connecting external sensors -- three of the channels respond when the circuit is open and three channels respond when the circuit is closed. Some possible sensor types are pressure, float, flow, and water level. For instance, if the water level of the well drops below a certain depth, then in order to keep the motor and pump from pumping the well dry, the controller would cut off the electricity from the wind turbine to the motor. There is also a time reset switch which will switch the motor back on after a certain amount of time has elapsed (i.e. to give the well time to replenish itself). The range in time for the time reset switch is 0 to 990 minutes.

In addition to the frequency and external sensor switches discussed above, there is also an adjustable thermal disconnect where the electricity will be disconnected from the motor when the current goes above a certain amount for about 10 seconds. The range in maximum current is 5.5 to 8 amps. Once the thermal switch is tripped, it can be automaticly or manually reset -- depends on the setting specified by the user. Most of the motors used with this wind turbine have a current range of 5 to 8 amps, and the maximum current was set to 8 amps. At this setting the high frequency cut-out was set to 90 Hz from Sept. 1992 to Apr. 1993. During the high winds of Mar. 1993 the thermal switch was tripped several times which caused a considerable amount of downtime. In Apr. 1993 the high frequency cut-out was set to 75 Hz, and this corrected the problem.

Another cause of downtime was when the 12 volt rechargeable battery (which is the power supply for this controller) discharges to a low voltage. Low battery voltage can result if:

1) Several days occur with: no wind, ice on the blades, or furled wind turbine.
2) An inoperative chip keeping the controller from going into a sleeper mode below 20 Hz.

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Another cause of downtime was when the motor relay switch becomes worn. After about two years of use the metal contacts of the motor relay switch will be worn and a new motor relay switch will be needed. One should suspect a problem with the motor relay switch when during sustained winds the pump quits pumping water, but the thermal switch has not tripped. The motor relay wear is mainly caused by the Bergey unit cutting in and out at high frequencies and high current results in arcing on the contacts.

Capacitance on the Bergey 1500, as with the Whisper 1000, should be added in parallel to the submersible motor. The capacitance needs to be added on the load or the motor side rather than the wind turbine side. If the capacitors are on the wind turbine side they would interfere with the charging of the battery on low wind days and would result in low battery voltage and increased downtime. Figure 3 shows the effect on the flow rate if the capacitance is doubled on the Bergey 1500 with a 1.1 kW (motor) and a 0.75 kW (1.0 hp) 15-stage pump. While on the Whisper 1000, less capacitance improved the flow rate at lower wind speeds, the Bergey 1500 showed little change in flow rate for wind speeds below 10 m/s for both a 30 μF and 60 μF capacitance. Above a wind speed of 10 m/s there was a dramatic improvement in flow rate. When the true wind turbine power was compared for the two values of capacitance (Figure 4) the improvement in true power for the higher capacitance at higher windspeeds demonstrates the reason for the higher flow rate.

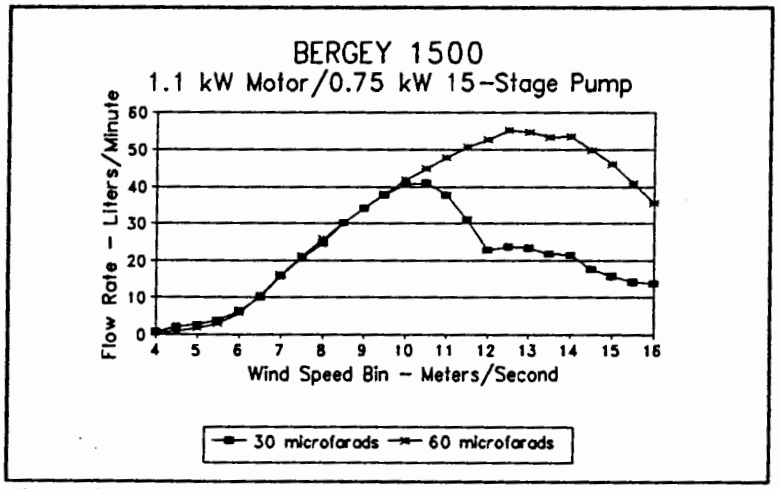

Figure 3. Effect of Capacitance on Flow Rate of Bergey 1500.

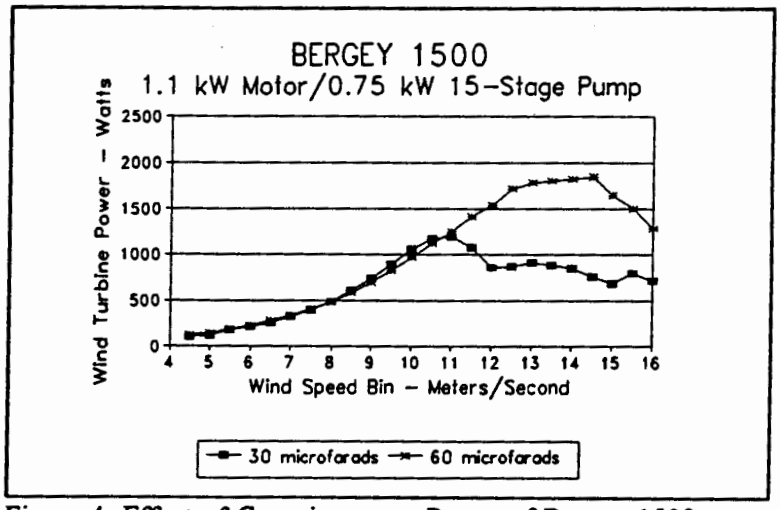

Figure 4. Effect of Capacitance on Power of Bergey 1500.

Of course the higher flow rate at higher windspeeds for the 60 µF capacitance was not gained without a price. Figure 5 shows how the current was increased by adding additional capacitors which means the wind turbine alternator and the submersible motor will be exposed to more heating. However, the 60 µF capacitance has been used now for a year and no apparent decrease in performance has been measured.

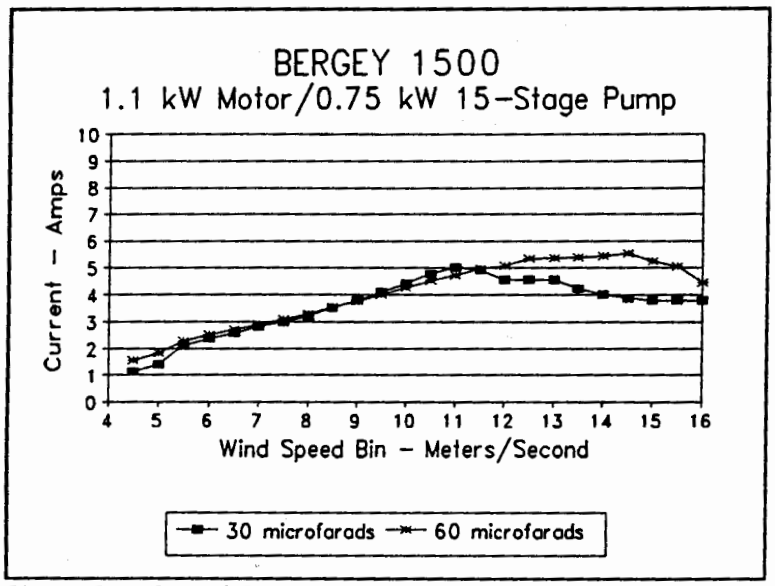

Figure 5. Effect of Capacitance on Current of Bergey 1500.

BERGEY EXCEL-PD PUMP CONTROLLER

The Bergey Windpower[1] Excel-PD wind turbine is rated at 10 kW at a windspeed of 12.1 m/s (27 mph) and overspeed protection is accomplished by the wind turbine furling horizontally. The Bergey Excel-PD has a permanent magnet alternator which generates 3-phase, AC electricity, and the voltage and frequency vary with wind speed. The rated rotor speed varies between 0 and 360 rpm. The rotor has three fiberglass blades and the rotor diameter is 7m (23 ft). One has the option of buying either standard or extra stiff fiberglass blades -- at the USDA-ARS in Bushland both types have been tested.

The Bergey Excel-PD (10 kW) pump controller is very similar to the Bergey 1500 (1.5 kW) pump controller. Because of the higher currents and voltages experienced on the 10 kW controller, some of the electrical components on the Bergey Excel-PD controller are different. The discussion on the frequency switches, thermal switch, and motor relay for the Bergey 1500 is equally valid for the Bergey Excel-PD. The maximum current range on the thermal switch is 23 to 32 amps. Most of the motors tested on the Bergey Excel-PD were rated between 15 and 24 amps, and the maximum current was set to 23 amps.

Because the Bergey Excel-PD current is higher than on the Bergey 1500 and Whisper 1000, the wires connecting the capacitors will sometimes be burned up. Since the high wind speed performance can be degraded dramaticly when the capacitance is altered, burning up the capacitor wires can be a problem. The wires that have been burned up have ranged in size from 10 to 16 AWG. Since the high heat occurs where the wires clip on to the capacitor cans, it may help to solder the wire to the capacitor connection or increase the number of wires connecting the capacitors. Increasing the size of the wires used may also cure the problem.

Another problem that has occurred has been that the controller will try to switch the electricity from the wind turbine to the motor at a very high frequency. The reason this happens is because the controller only has a range in frequency from 0 to 99 Hz, and the Bergey Excel-PD furls unloaded in a windspeed range of 16 to 18 m/s. At this high windspeed the wind turbine can reach a frequency of 140 Hz. During 1995 the low speed cut-in frequency was set to 35 Hz and the low speed cut-out frequency was set to 20 Hz. On March 22, 1995 the frequency reached 135 Hz, and the controller saw this frequency as 35 Hz and switched the electricity to a 5.6 kW motor (7.5 hp), but since this motor will not synchronize with the wind turbine at high frequency then no water was pumped although high current (35 amps) went to the motor. The load slowed the wind turbine frequency to 120 Hz, and the controller saw this frequency as 20 Hz and therefore cut-off the electricity to the motor. Unloaded, the frequency went to 135 Hz, and the motor came on again. This operation of the wind turbine will keep the wind turbine from ever furling. A prototype Excel-PD controller used in earlier tests did not have this problem since it had a frequency range of 0 to 999 Hz. This problem has never occurred on the Bergey 1500 because of the lower furling wind speed of 13.5 m/s. Bergey Windpower has identified this problem as a CPU software error, and the error is being corrected.

The prototype Excel-PD controller did not have a thermal disconnect and this resulted in the burning up of two 3.8 kW motors in July '94. If the high frequency cut-out on the prototype controller had been set to 90 Hz instead of 120 Hz, then the 3.8 kW motors would not have burned up. The reason the 5.6 kW motor will never burn up with a high frequency cut-out setting of 120 Hz is because the motor will lose synchronization with the wind turbine at 90 Hz with 150 μF of capacitance. Since the same capacitance (150 μF) is used with the 3.8 kW motor and the 3.8 kW motor produces less inductance, the 3.8 kW motor stalls at a much higher frequency. From the above discussion it is evident that using a 5.6 kW motor with 150 μF of capacitance is the most logical choice.

The effect of capacitance on the flow rate of the Bergey Excel-PD with a 5.6 kW (7.5 hp) motor and a 3.8 kW (5 hp) 5-stage pump is shown in Figure 7. Similar to the Bergey 1500, the effect of increased capacitance on the Bergey Excel-PD was an improvement in the flow rate at high wind speeds and no improvement at low wind speeds. Figures 7, 8, and 9 show the effect of additional capacitance on voltage, frequency and voltage/frequency ratio. It is interesting to note that a dropoff in flow rate is accompanied by a dropoff in the voltage to frequency ratio.

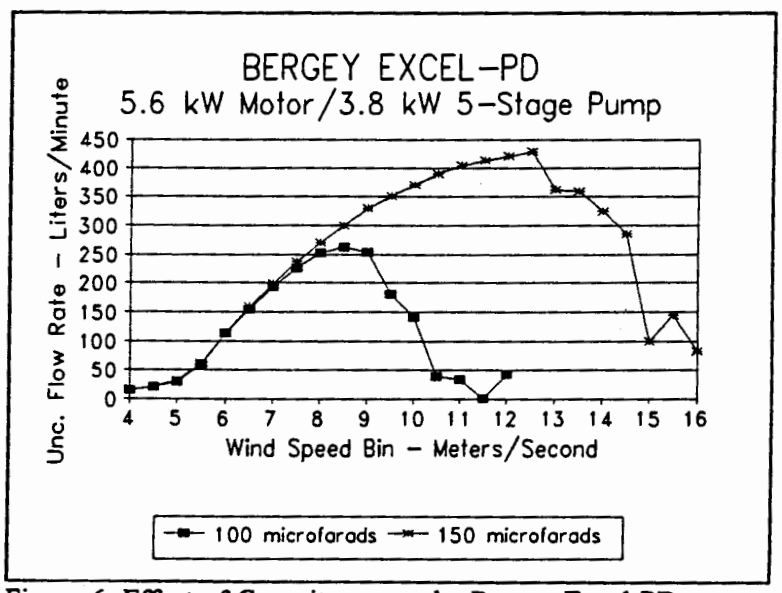

Figure 6. Effect of Capacitance on the Bergey Excel-PD.

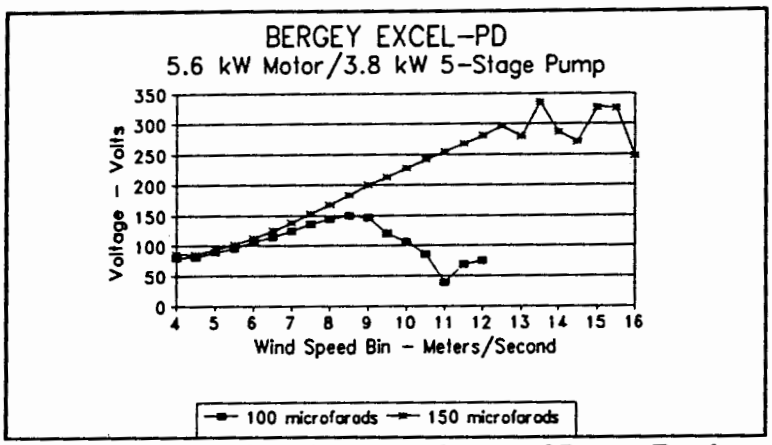

Figure 7. Effect of Capacitance on Voltage of Bergey Excel.

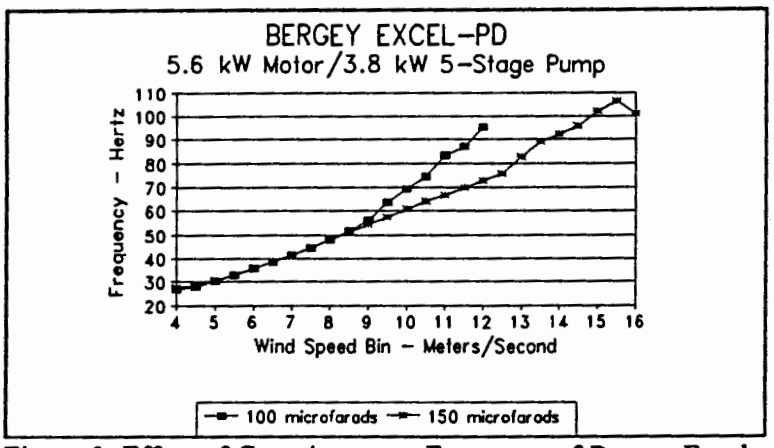

Figure 8. Effect of Capacitance on Frequency of Bergey Excel.

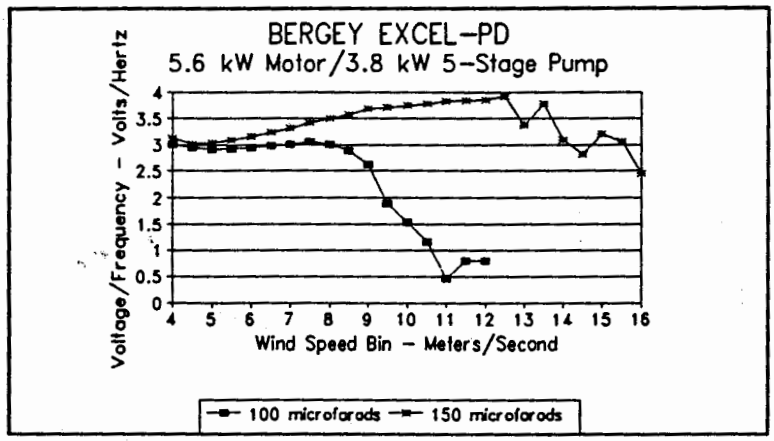

Figure 9. Effect of Capacitance on Voltage to Frequency Ratio of Bergey Excel.

Figure 10 shows the ratio of "ON" to "ON + OFF" data samples which indicates the percentage of time water is being pumped. One can see that increasing the amount of capacitance helped in improving the percentage of time that the wind turbine would pump water at high windspeeds. However, it is also evident that considerable improvement is still possible at higher windspeeds. The best way for improving the percentage of "ON" time at higher wind speeds is to decrease the furling windspeed from 16 - 18 m/s to 13 - 14 m/s. The most sure way of decreasing the furling windspeed is to increase the offset distance from the tail centerline to the rotor centerline. Another way of increasing the "ON" time at higher windspeeds is to have the controller switch to a dump load at a certain frequency. As the windspeed decreases and the frequency gets lower, then at a lower frequency the controller could switch the electricity from the dump load.

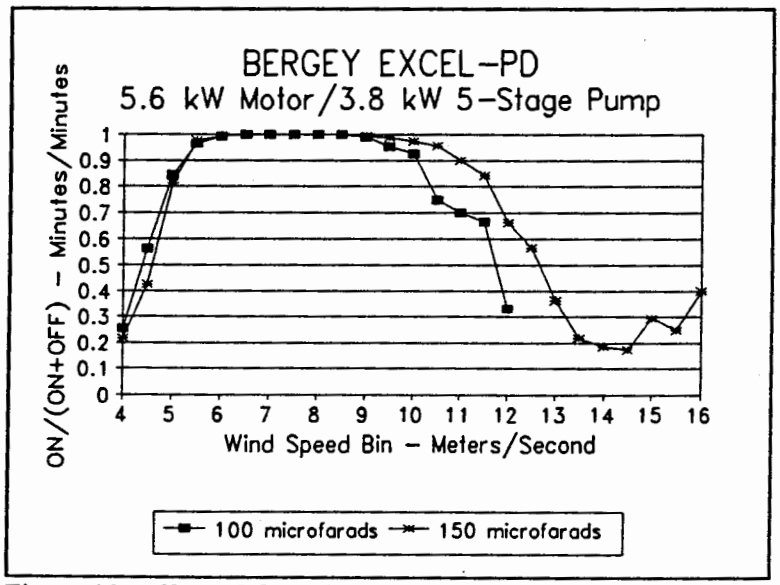

Figure 10. Effect of Capacitance on the Amount of Time the Bergey Excel-PD is Pumping Water.

CONCLUSIONS

Three different wind-electric water pumping systems were tested and the performance of the pump controllers on each pumping system was analyzed. The Whisper 1000 pump controller was the least expensive and had the least amount of downtime of any of the pump controllers. There were however some disadvantages with the Whisper 1000 pump controller which were: the wind turbine can't be braked in high winds, there is no thermal circuit breaker to protect the motor or alternator if high current occurs. The current Bergey Excel-PD controller does have a thermal circuit breaker, but the frequency range on the pump controller is 0 to 99 Hz. Because of the high furling windspeed on the Bergey Excel-PD the frequency will reach 135 Hz which the controller will see as 35 Hz and try to cut the motor in (this problem is being corrected by Bergey Windpower). Both the Bergey Excel-PD and Bergey 1500 pump controllers can experience downtime if the pump controller battery voltage gets low or the motor relay switch begins to wear out.

Substantial improvements in pumping performance were obtained when capacitance was added to the wind-electric water pumping systems. The data gathered on the Whisper 1000 pumping system implies the amount of capacitance should increase as the windspeed increases. The Bergey 1500 and Excel-PD showed an improved flow rate only at high wind speeds when capacitance was increased.

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