SED-Vol. 16, Wind Energy – 1995
ASME 1995

# DETERMINING THE PROPER MOTOR SIZE FOR TWO WIND TURBINES USED IN WATER PUMPING

**R. Nolan Clark and Brian Vick**
Agricultural Research Service
U.S. Department of Agriculture
Bushland, Texas

## ABSTRACT

Two different size wind turbines were tested for pumping water at the USDA - Agricultural Research Service, Bushland, Texas. One was a three-bladed 7.0-m diameter wind turbine which was rated at 10 kW at a 12.1 m/s wind speed. The other was a two-bladed 2.75-m diameter wind turbine which was rated at one kW at a 11.0 m/s wind speed. Both wind turbines used a permanent magnet alternator to provide electrical power to a motor which powered a submersible pump. The one kW wind turbine can be used for watering livestock or providing water for a family of four. The 10-kW wind turbine can be used for small scale irrigation or providing water for a small village. During the testing of both wind turbine/motor/pump systems, two different motors were tested. The 5.6 kW motor had a 10 percent advantage in system efficiency over the 3.8 kW motor for the 10-kW wind turbine. For the one kW wind turbine the maximum system efficiency was the same for both the 0.38 kW and 0.56 kW motors, but occurred at different wind speeds.

## INTRODUCTION

The purpose of this paper was to investigate the selection of the proper motor size in wind-electric water pumping. While mechanical windmills continue to be used extensively around the world, wind-electric water pumping is beginning to compete with mechanical windmills (Clark and Mulh, 1992) depending on the wind regime. For a theoretical background on wind-electric water pumping, see (Clark, 1988), (Wyatt, 1988) and (Vosper and Clark, 1985). Wind-electric water pumping with permanent magnet alternators has been researched at the USDA-ARS since 1988. Various size wind turbines, motors, and pumps have been tested to determine their ability to pump water for different applications at different well depths. This paper will cover testing performance on two of those wind turbines (a one kW and a 10 kW) and the results of using two different size motors on both wind turbines. It is felt by the authors that optimizing a wind turbine/motor/pump system starts with matching the correct motor with the particular wind turbine.

## TESTING APPARATUS AND INSTRUMENTATION

The water pumping testing was performed at the Conservation and Production Research Laboratory, Bushland, Tx. which is located about 10 miles west of Amarillo. The average windspeed during the year for this site is 6.25 m/s at a height of 10 meters. This is a typical windspeed for much of the Great Plains. A drawing of the test setup for both wind turbines is shown in Figure 1. The wires from the wind turbine generator to the wind laboratory building are buried underground in 2.54 cm conduit pipe. Before the wires from the wind turbine go into the pump controller, they are routed through a double throw switch. This switch allows the submersible motor to be powered by the utility or the wind turbine. It is important for the submersible motor to be powered by the utility in order to:

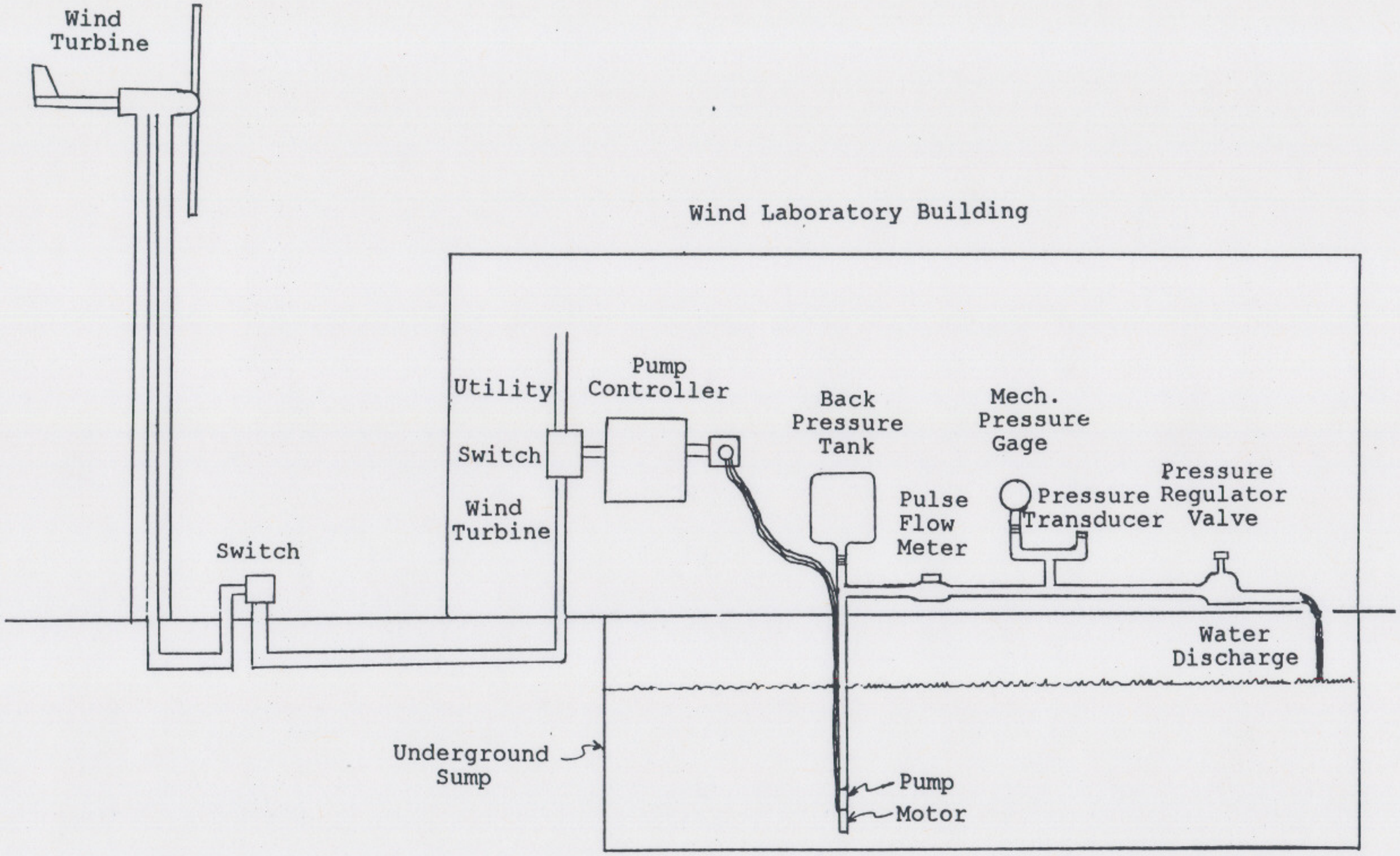


Figure 1. Drawing of Water Pumping Performance Testing at the USDA-ARS, Bushland, Texas

1) Generate a pump curve (flow head versus flow rate) to compare to the manufacturer's pump curve and determine if the motor/pump performance has decreased.
2) Calibrate the flow meter.
3) Set the pressure with the pressure regulator valve in order to simulate different water well depths.
4) Perform troubleshooting on the motor,pump,controller, and wind turbine.

The pump controller for the 10 kW wind turbine is more complicated than the one kW wind turbine, but both have low cut-in frequency of about 35 Hz. The frequency the motor/pump actually begins pumping water at depends on the pumping depth and the voltage/frequency ratio. Both wind turbine controllers also sense whether the frequency is too low, and if so, then the load (motor/pump) is disconnected from the wind turbine. The low cut-out frequencies for the one kW and the 10 kW wind turbine controllers were 35 and 20 Hz, respectively. The 10 kW controller also had a high frequency cut-out of 120 Hz and a high frequency cut-in of 75 Hz. The voltage and frequency vary with the wind speed for both wind turbines since they both use permanent magnet alternators. Since the motors were designed to operate at 240 V and 60 Hz, the voltage to frequency ratio should be approximately 240V/60Hz = 4.0. This ratio can be approximated if some capacitance is included in the controller. Both pump controllers contain some operating compacitors (as opposed to start-up capacitors) in order to keep the voltage to frequency ratio close to 4.0.

The other equipment used in the testing included a pressure regulator valve, a back pressure tank, and devices for measuring and recording the pertinent flow and electrical variables. The purpose of the back pressure valve and tank is to help keep the pressure steady. This is done by pressurizing the back pressure tank above the pressure that is being maintained with the pressure regulator valve. By varying the pressure with the pressure regulator valve then different well depths could be simulated. The flow meters for measuring the flow rate for both wind turbines were selected according to the flow rate expected for each. The pulse flow meters used for the 10 kW and the one kW wind turbine water pumping systems were Hersey[1] R-38 MVR 160 and MVR 30 respectively. The pressure transducers used for both wind turbine pumping systems were Data Instruments[1] Model EA. A mechanical pressure gage was used to determine the approximate pressure without having to look at the data logger. The wind speeds were measured with Met One[1] anemometers which were located at the hub height of both wind turbines. The anemometer for the one kW wind turbine was located 35 meters northwest of the wind turbine and the anemometer for the 10 kW wind turbine was located 45 meters due east of the wind turbine. The data loggers used for both wind turbines were Campbell Scientific[1] Model CR21X. The data recorded on each was:

1) Date (Julian Day)
2) Standard time(hours-minutes-seconds)
3) Frequency (Hz)
4) Wind Speed (m/s)
5) Pressure (kPa)
6) Flow rate (Liters/Min)
7) Voltage (Volts)
8) Current (Amps)

The sampling rate for (3) through (8) above was 1 Hz, and the average value over each minute was recorded. The voltage, current, and frequency were measured between the pump controller and the motor. The voltage on the 10 kW wind turbine was measured with a Rochester Instruments[1] transducer. The voltage and current on the one kW wind turbine were measured with a Magtrol[1] Power Analyzer Model 4612B. The frequency was measured by transducers built by Mike Bayless (Instrumentation Specialist) at USDA-ARS, Bushland.

## WPT WHISPER 1000 MOTOR COMPARISON

Data were collected during June, July, and August, 1994 on the water pumping performance of the World Power Technologies[1] (WPT) Whisper 1000 with a 0.56 kW(3/4 hp) pump with nine stages (McDonald[1] 21075P). Two different motors were tested and they were Franklin Electric[1] 3 phase 230 V motors rated at 0.38 kW(1/2 hp) and 0.56 kW(3/4 hp). The WPT Whisper 1000 tested had two blades made of aspen wood. The hub height of the wind turbine was located ten meters above the ground and therefore was subjected to more turbulent air than if it had been located higher. There also were some structures (building and telephone poles) located about 10 rotor diameters from the wind turbine which could have resulted in reduced performance. This wind turbine will begin furling vertically at a wind speed of about 10 m/s. The average density of the air during the test period was 1.02 kg/m$^3$.

[1]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.

Figure 2 shows the calculated total dynamic head. The calculated head was determined by the following equation:

Head(meters)=4.854*Pressure(kPa)+1.524

The constant on the end of the equation represents the vertical distance from the surface of the water in the underground sump to the point of water discharge. The kinetic energy of the water at discharge was negligible and therefore was not included in the calculation. A pressure which simulates a total dynamic head of 25 m was not reached until a wind speed of 8 m/s was reached. Therefore, the flow rate and system efficiency for this wind turbine is too high for wind speeds below 8 m/s. The difference in pressure is within 13.79 kPa(2.0 psi) at all wind speeds for the 0.38 kW and the 0.56 kW motors, and so the comparison between the two motors will be valid.

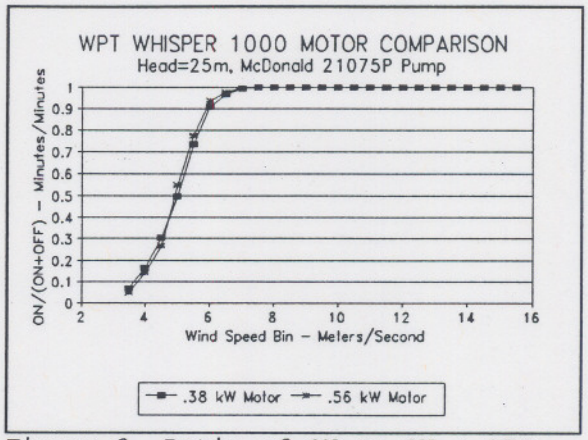


Figure 3. Ratio of ON to ON + OFF Samples (0 = OFF, 1 = ON).

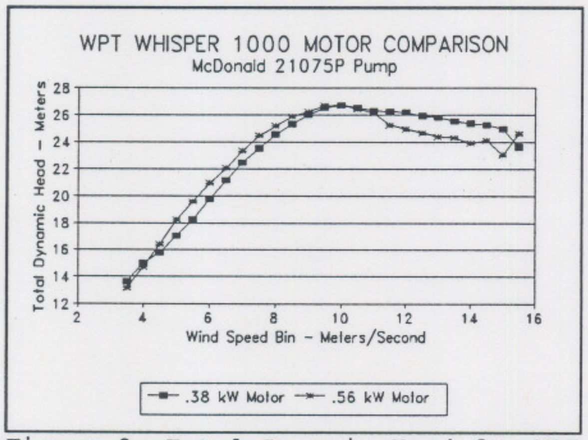


Figure 2. Total Dynamic Head for WPT Whisper 1000.

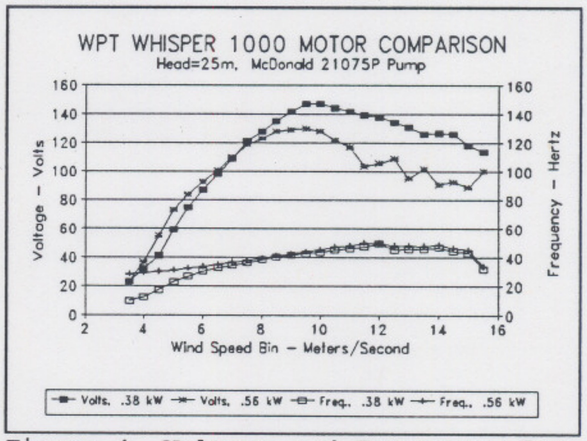


Figure 4. Voltage and Frequency for WPT Whisper 1000.

Figure 3 shows how often each of the two motors is pumping water at each wind speed. This ratio of ON to ON + OFF samples is important since it is needed to correct the flow rate and system efficiency. If the flow rate is not corrected by the percentage of ON samples then higher water volumes will be predicted. Since the ratio of ON to ON + OFF samples is about the same for both motors then neither shows an advantage for an earlier cut-in windspeed.

Figure 4 shows the measured voltage and frequency for the two motors. The measured voltage is lower for the 0.38 kW motor at lower windspeeds and higher at higher wind speeds compared to the 0.56 kW motor.

The frequency of the 0.56 kW motor is slightly higher than that of the 0.38 kW motor at wind speeds above 6 m/s. The voltage to frequency ratio is better (closer to 4) for the 0.38 kW motor than the 0.56 kW motor for all windspeeds (Figure 5).

Figure 6 shows the flow rate and the system efficiency for both motors. As was discussed previously, the flow rate was corrected by multiplying the flow rate by the ratio of ON to ON + OFF samples. Also, the flow rate below 8 m/s is optimistic for a 25 meter head since the pressure wasn't maintained. Despite these inconveniences, one can see that the 0.38 kW motor will pump more water than the 0.56 kW motor for wind speeds above 8.5 m/s and less water for wind speeds below 8.5 m/s.

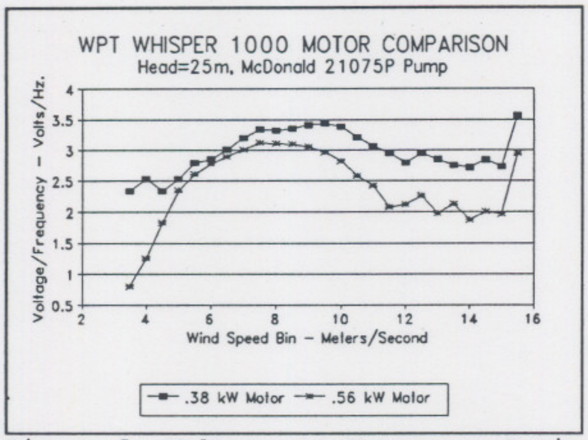


Figure 5. Voltage to Frequency Ratio for WPT Whisper 1000.

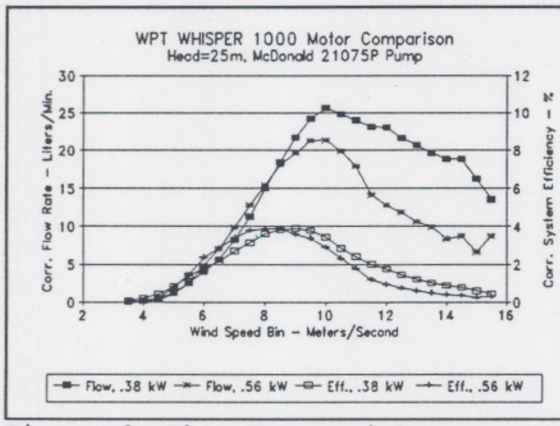


Figure 6. Flow Rate and System Efficiency for WPT Whisper

The maximum system efficiency is the same for both motors (4%), however, the system efficiency occurs at a slightly lower windspeed for the 0.56 kW motor.

Figure 7 shows the average daily volume of water pumped for both the 0.38 kW and 0.56 kW motors. The wind distribution data used to produce Figure 7 was gathered in Bushland, Tx. with a Met One anemometer at a 20 meter height and was averaged every minute from April 1, 1993 to March 31, 1994. The flow rates for the two motors shown in Figure 6 were used to determine the volume shown in Figure 7. Figure 7 shows the 0.38 kW motor pumped more water than the 0.56 kW motor during every month. However, if the windspeeds had been lower due to a lower wind site or at a lower hub height, then the 0.56 kW motor would have pumped more water than the 0.38 kW motor. During the entire year, the average daily water pumped by the 0.38 kW motor was 12,600 L/day. The lowest average daily water pumped for the 0.38 kW motor was during August and was 9500 L/day. This amount of water could easily water a herd of 100 beef cattle.

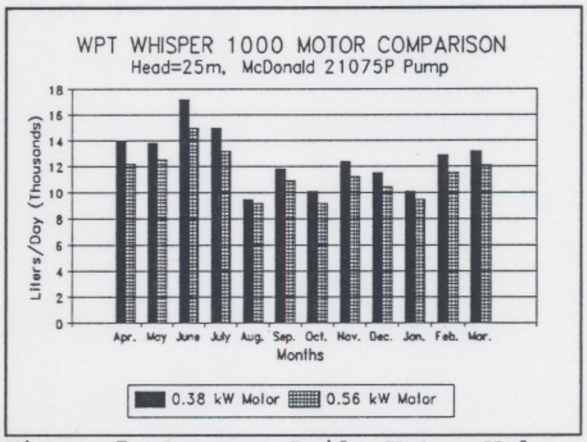


Figure 7. Average Daily Water Volume for WPT Whisper 1000.

**BWC EXCEL-PD MOTOR COMPARISON**

Water pumping performance data for the Bergey Windpower Corp.[1](BWC) Excel-PD shown in this paper was collected from March, 1994 to July, 1994. The pump that was used during the testing was a 3.8 kW Grunfos[1] 80S50-5 pump with 5 stages. The hub height for the BWC Excel-PD was 20 meters and this unit had three extra stiff fiberglass blades. Two motors were tested and they were Franklin Electric 3 phase 230 volt motors rated at 3.8 kW(5 hp) and 5.6 kW(7.5 hp). The average air densities were 1.05 kg/m$^3$ for the 5.6 kW motor test and 1.015 kg/m$^3$ for the 3.8 kW motor test. The pump controller used was developed by the USDA-ARS in 1989 and it did not have a thermal control on it like the newer BWC pump controller. Having no thermal control resulted in the 3.8 kW motor being burned up on July 1, 1994. Enough data, however, had been gathered on the 3.8 kW motor to make a comparison between it and the 5.6 kW motor.

Two different pressure ranges were gathered for both the 3.8 and the 5.6 kW motors. Using the equation discussed previously, the pressure data were used to calculate the total dynamic head data shown in Figure 8. From the calculated total dynamic head data shown in Figure 8, it was possible to interpolate between the two sets of data and get a comparison of the 3.8 and 5.6 kW motors at a constant 35 m total dynamic head. This was not possible for the WPT Whisper 1000 pumping performance since the data were only gathered at one pressure for each wind speed bin.

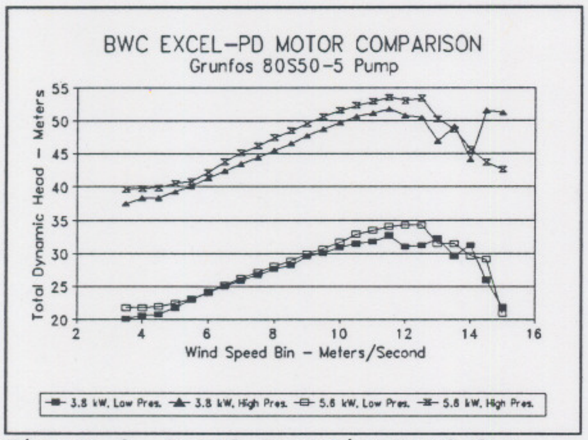


Figure 8. Total Dynamic Head for BWC Excel-PD.

Figure 9 shows how often water is being pumped at each wind speed for both the 3.8 and 5.6 kW motors. At low wind speeds (3.5 to 6.5 m/s) both motor/pump systems pump water about the same amount of time. At

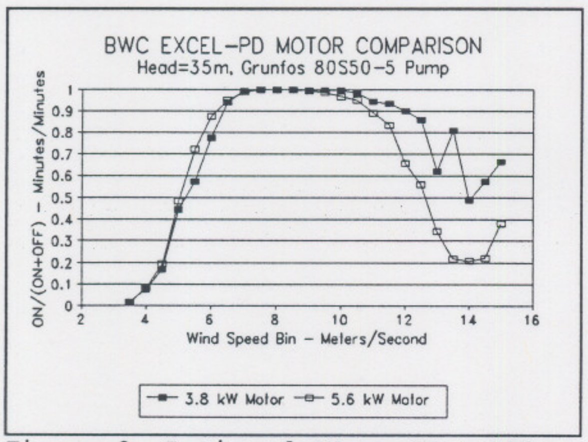


Figure 9. Ratio of ON to ON + OFF Samples (0 = OFF, 1 = ON).

moderate wind speeds (6.5 to 9.5 m/s) the motor/pump systems pump water all the time. For high wind speeds (above 10 m/s) the 3.8 kW motor/3.8 kW pump system pumps water more often than the 5.6 kW motor/3.8 kW pump system. These data differ from the data shown for the WPT Whisper 1000 where the motor/pump systems pumped water all the time for higher windspeeds. The reason for the WPT Whisper 1000 staying on at high windspeeds is it begins furling out of the wind at a wind speed of about 10 m/s. While the flow may decrease at higher windspeeds for the WPT Whisper 1000 as it furls out of the wind -- it continues to provide power to keep it on. The BWC Excel-PD won't begin to furl until the windspeed reaches about 18 m/s and above that windspeed the motor/pump system pumps water all the time. When the windspeed gusts above 15 m/s then the motor will stall and the motor/pump system will quit pumping water. The motor/pump system will stay off until the windspeed gets down to 8 m/s (5.6 kW motor) or 9 m/s (3.8 kW motor) when the motor/pump system will begin to pump water again.

Figure 10 shows the measured voltage and frequency of the BWC Excel-PD for both the 3.8 and 5.6 kW motors. For the 3.8 kW motor the voltage is higher and the

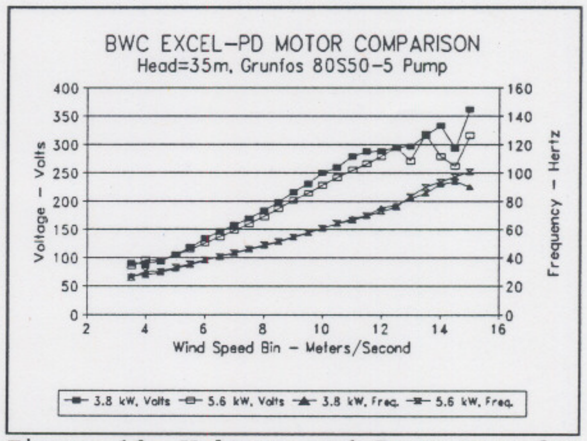


Figure 10. Voltage and Frequency for BWC Excel-PD.

frequency is lower when compared to the 5.6 kW motor. Therefore the 3.8 kW motor has a higher voltage to frequency ratio than the 5.6 kW motor as seen in Figure 11.

Since the voltage to frequency ratio was closer to 4.0 for the 3.8 kW motor than the 5.6 kW motor, then one would expect the flow rate and system efficiency to always be better for the 3.8 kW motor. As can be seen in Figure 12 this indeed is not the case. The 5.6 kW motor has a higher flow rate and system efficiency than the 3.8 kW motor until a wind speed of 11 m/s was reached. The maximum system efficiencies for the 3.8 kW and 5.6 kW motors were 10% and 11% respectively.

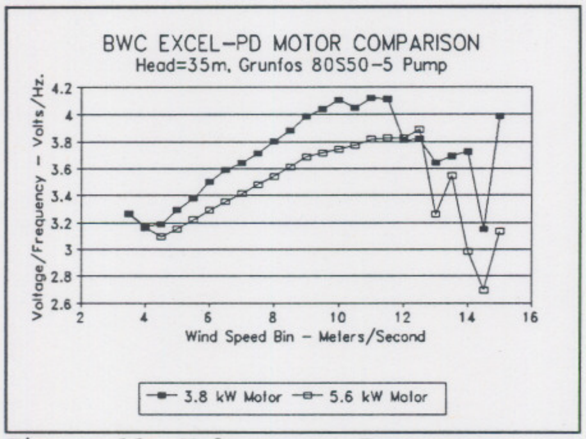


Figure 11. Voltage to Frequency Ratio for BWC Excel-PD.

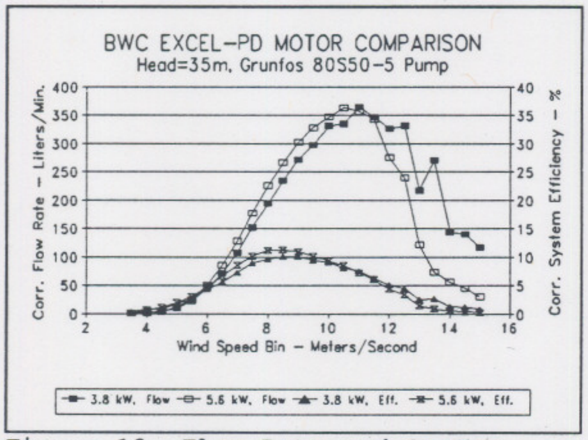


Figure 12. Flow Rate and System Efficiency for BWC Excel.

Figure 13 shows the daily water volume pumped by the BWC Excel-PD with the 3.8 kW and the 5.6 kW motors. The wind speed distribution used for this calculation was the same as that which was used for Figure 7. The 5.6 kW motor pumps more water than the 3.8 kW motor for every month. The average daily volume of water pumped during the year for the 5.6 kW motor was 170,900 L/day. The lowest volume of water pumped by the 5.6 kW motor was during August and was 132,300 L/day. This amount of water would be enough for about 400 people in the U.S.

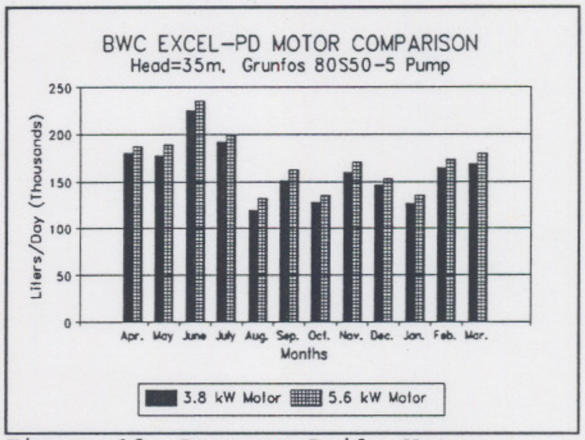


Figure 13. Average Daily Water Volume for BWC Excel-PD.

**CONCLUSIONS**

Depending on the wind regime either the 0.38 kW or the 0.56 kW motor could be used with the WPT Whisper 1000 wind turbine when a McDonald 21075P pump is used. For lower winds the 0.56 kW motor is better for pumping water and for higher winds the 0.38 kW motor will pump more water. Only one well depth was simulated with the WPT Whisper 1000 wind turbine but additional data are presently being gathered for deeper wells. For the BWC Excel-PD the 5.6 kW motor appeared to be the motor of choice when the Grunfos 80S50-5 pump was used. Although the voltage to frequency ratio was higher for the 3.8 kW motor, the flow rate and system efficiency were higher for wind speeds below 11 m/s. While the 3.8 kW motor was burned up during the testing -- this would not have occurred with the manufacturer's pump controller. Also, the 3.8 kW motor could have been saved if the frequency cut out had been lower which is easy to do with the manufacturer's controller.

The testing discussed in this paper reported the testing of two different motors on two different size wind turbines. The motors tested on these wind turbines were 10.16 cm (4 in) in diameter. However, 15.24 cm (6 in) motors were also tested on the BWC Excel-PD, but the pumping performance was poor. Three different size 15.24 cm motors were tested on the BWC Excel-PD.

The three motors tested were rated at 3.8 kW (5 hp), 5.6 kW (7.5 hp), and 7.5 kW (10 hp). The current and voltage ratings for the 15.24 cm 5.6 kW motor were very close to the ratings on the 10.16 cm 5.6 kW motor. All three 15.24 cm motors were tested on the utility and the pump curves were close to the pump curves published by the manufacturer. The pump used in the 15.24 cm motor testing was a Grunfos 135S75-4 which is rated at 5.6 kW. Since the pump used in the 10.16 cm motor testing on the BWC Excel-PD was rated at 3.8 kW, additional testing is planned for next year to investigate a 15.24 cm 5.6 kW motor with a 3.8 kW pump.

**ACKNOWLEDGMENTS**

We would like to thank Mike and Karl Bergey at Bergey Windpower Corp. for their advice and counsel during the testing of the BWC Excel-PD. We would also like to thank Elliott Bayly at World Power Technologies for his advice and counsel in testing the WPT Whisper 1000. Last, but definitely not least, we would like to thank Mike Bayless for keeping the wind turbines, motors, pumps, and instrumentation operating during the testing.

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