WIND ELECTRIC GENERATOR PERFORMANCE DURING 12 YEARS OF OPERATION

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ABSTRACT. *A wind electric generator with a 13.4-m (44-ft) rotor diameter was installed in the Southern Great Plains at the USDA Conservation and Production Research Laboratory, Bushland, Texas, in May 1982 and was operated to provide utility grade electricity to an irrigation pump motor. The wind turbine has been used for a number of application experiments and this article presents a summary of long-term performance data. The original turbine was a 240-V, single-phase generator with a rated capacity of 25 kW. This prototype unit was changed to a three-phase, 40-kW generator production unit in 1984 and later that year, a three-phase, 480-V generator rated at 60 kW was installed. All three units used the same size rotor and design. The wind turbine has generated power for over 61,600 h during the 12 years and produced almost 930,000 kWh of electricity. The wind turbine operated for 61.6% of the hours since installation and recorded a capacity factor of 23.4%. Although several component failures occurred during the testing period, the wind turbine had an availability of 97%. The 3% downtime was estimated as 1% for routine maintenance and service, 1% for repair of component failures, and 1% for weather related events, mainly icing.* ***Keywords.*** *Windmills, Wind turbines, Electric power, Energy, Generators.*

Wind electric systems were used extensively during the 1930s and 1940s to provide small amounts of electric power in rural areas. These units had DC generators that produced enough power to keep several batteries charged, providing electricity for lights and radio. Rotor sizes ranged from 2 to 5 m (6 to 16 ft) and consisted of two to four blades (Park, 1981). Systems based on these old designs are still manufactured and used mainly for battery charging.

The development of the modern wind turbine began in the late 1970s and the transition from prototypes to production units in the 1980s was rapid with over 10,000 units sold by 1985. Most early prototypes utilized either DC generators or an alternator using a synchronous inverter to make the electricity utility compatible. Machines that use either DC generators or alternators require an external mechanism to regulate rotor speed. This regulation is normally provided by a mechanism to vary the pitch of the rotor blades or to turn the rotor out of the wind. With increased machine size, the variable pitch mechanism became more complicated and costly. In 1978, two manufacturers began using induction generators consisting of induction motors operated above synchronous speed. An induction generator operates at essentially constant speed with a gearbox between the rotor and generator. The induction generator offered several advantages over the other systems—the main ones being that the pitch control system could be eliminated and that interfacing to the electric utility was greatly simplified (Park, 1981). A disadvantage of the induction generator is that it requires excitation from an external source, usually the utility line. Almost all wind electric generators sold today use induction generators.

The USDA-ARS began experimental studies with wind electric generating systems in 1976 and acquired several prototype machines in the 1978 to 1983 time period. This article reports on tests results of a wind electric generator acquired in 1982 as a prototype and later converted to a production machine. The wind turbine has been used for a number of application experiments and this article presents a summary of long-term performance data. Daily kilowatt hour meter records and a datalogger have been maintained on this system since it was installed. The datalogger was used to monitor wind speed, wind direction, electrical power, air temperature, and barometric pressure at a rate of 1 Hz and averaged data over 5 min. Also, these data were averaged and recorded on a hourly and daily basis, thus producing three different data tables for each day. In addition to these computerized data, daily recordings were made each morning of the run-time hours, number of starts, electrical energy produced by the wind turbine, and electrical energy purchased from or sold to the utility. At other times during the 10-year period, data were recorded at 15-s averaging intervals with data being sampled at 5 Hz. Power curves were developed using the high frequency data, while daily data were used to determine annual or monthly performance.

WIND TURBINE DESCRIPTION

The horizontal-axis wind turbine had a 13.4-m (44-ft) diameter, three-blade, fixed pitch rotor mounted on a

Article has been reviewed and approved for publication by the Information and Electrical Technologies Div. of ASAE. Presented as ASAE Paper No. 93-3022.

Contribution from USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas. Mention of a manufacturer or product name does not constitute a recommendation or endorsement for use by the USDA-Agricultural Research Service, but is given for informational purposes only.

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24.4-m (80-ft) free-standing tower. Rotor blades were fabricated from laminated epoxy-wood and attached to a steel hub. Specifications of the wind electric generating system are listed in table 1. The 25-kW prototype had a single-phase generator operating at 240 V, while the 40- and 60-kW units both had three-phase generators operating at 480 V. The wind turbine was manufactured by Enertech Corporation as a model 44 (Enertech Corporation ceased operation about 1987).

Wind turbine start-up and shut-down was controlled by signals from an anemometer located on the tower just below the blade tips. The parking brake held the rotor fixed until the control system determined that adequate wind was available to produce power. Then the brake was released and the generator was utilized as a motor to accelerate the rotor to its operational speed. Normally about 15 s were required to bring the system from a stopped position to full operational speed. The controller was set to start the wind turbine when wind speed averaged 5.4 m/s (12 mph) and to stop when average wind speed dropped to 3.2 m/s (8 mph). A 45 s moving average wind speed was used. A high wind speed shut-down occurred when the controller sensed an average wind speed of 22 m/s (50 mph) or higher. The controller would not restart the turbine until the average wind speed dropped to less than 16 m/s (36 mph).

Dates when the machine was modified or when significant repair was required are reported in table 2. Continuous operation of the 25-kW prototype was started on 1 July 1982 and continued until 27 February 1984. The 25-kW prototype was changed to a 40-kW production model with the same rotor size. After eight months of operation, the 40-kW unit was changed to a 60-kW unit. Even though the 60-kW unit was the first 60-kW built, only the generator and gearbox were different and all parts were interchangeable with the 40-kW unit. During operation since the 60-kW was installed on 13 November 1984, two significant events required the turbine to be removed from the tower for repair. In October 1987, the up-wind tower leg cracked just below the turbine mounting plate. Three months were required to determine the proper corrective action and secure repair parts. Then in 1988, the front gearbox oil seal began leaking excessively and the turbine was again removed from the tower. At this time we chose to replace the 60-kW gearbox with a 40-kW gearbox to reduce rotor speed. Each of these events are discussed under the reliability section.

Table 1. Specifications of ENERTECH 44 wind turbine installed at Bushland, Tex., 1982 to 1994

System	
Type	Utility interface
Axis of rotor	Horizontal
Location of rotor (with respect to tower)	Downwind
Number of blades	Three
Centerline hub height	25 m (82 ft)
Rotor	
Rotor diameter	13.4 m (44 ft)
Rotor type	Fixed pitch
Rotor speed at rated power	53 rpm (25 kW), 57 rpm (40 kW) and 67 rpm (60 kW)
Blade material	Wood/epoxy laminate, fiberglass coat
Generator	
Type	Induction, single-phase (25 kW) and three-phase (40 and 60 kW)
Output voltage	240 V (25 kW) and 480 V (40 and 60 kW)
Frequency	60 Hz
Transmission	
Type	Triple reduction, helical
Ratio	1:34 (25 kW), 1:32 (40 kW) and 1:27 (60 kW)
Yaw System	
Yaw control	None, rotates freely 360°
Brakes	
Normal stops	Dynamic brake
Parking brake	Electro-mechanical, fail safe spring
Rotor Speed Control	
Rotor overspeed (normal operation)	Blades stall in high winds
Rotor overspeed (emergency)	Control system applied braking
Rotor overspeed (emergency back up)	Blade tip brakes deploy
Tower	
Type	Galvanized self-supporting
Height	24.4 m (80 ft)
Performance	
Rated wind speed	13.4 m/s (30 mph)
Start-up wind speed	5.4 m/s (12 mph)
Shut-down wind speed	3.2 m/s (8 mph)
Cut-out wind speed	22.3 m/s (50 mph)

Table 2. Significant events during the testing of ENERTECH 44, Bushland, Tex., 1982 to 1994

Date	Month	Activity
28 May 1982	0	Installed 25 kW
1 July 1982	1	Began performance testing
27 February 1984	20	Removed 25 kW
20 March 1984	21	Installed 40 kW
5 November 1984	29	Removed 40 kW
13 November 1984	29	Installed 60 kW
27 October 1986	53	Removed 60 kW (tower leg cracked)
12 February 1987	56	Reinstalled 60 kW
13 May 1988	71	Removed 60-kW gearbox (leaking seal)
19 July 1988	73	Installed 40-kW gearbox
1 July 1994	144	Still running

Reliability

The wind turbine did experience several failures and problems during the testing period. Considering that the 25- and 60-kW units were both prototypes and the 40-kW was an early production unit, these units performed well. The significant down-time events are summarized in table 3. A significant down-time event was defined as one having an off-time in excess of 100 h. Most repairs and routine maintenance would not be included in this list.

All major downtimes connected with the 25-kW generator were concerned with the controller and in particular the rotor speed sensor that was used to engage the electric generator. Details of the performance and reliability of the 25-kW system were reported by Vosper

Table 3. Downtime in excess of 100 h during testing of ENERTECH 44, Bushland, Tex., 1982 to 1994

Date	Month	Problem	Hours
29 December 1982	6	Broken control relay	130
11 February 1983	8	Rotor rpm sensor failure	166
29 August 1983	14	Rotor rpm sensor failure	204
27 February 1984	20	Rotor shaft failure	530
5 November 1984	29	Replaced 40 kW with 60 kW	192
20 August 1985	38	Tip brake deployment	211
27 October 1986	53	Cracked tower leg	2592
5 January 1988	66	Ice on rotor blades	118
13 May 1988	71	Gearbox seals leaking	1595
21 December 1990	102	Ice on rotor blades	156
12 March 1991	105	Tip brake deployment	151
29 June 1992	120	Replacement of parking brake pads	168
8 January 1993	127	Ice on rotor blades	122

and Clark (1985a). The rotor speed sensor was eliminated in the 40- and 60-kW designs. On 27 February 1984, a blizzard roared through Bushland causing numerous electric power outages. The wind turbine stopped and started 11 times during a 3-h period. During one of those periods, the rotor shaft failed and the entire rotor crashed to the ground. The new 40-kW wind turbine was already at Bushland and a crane had been scheduled for the next day to replace the 25-kW wind turbine with the 40 kW turbine. Failure resulted from an improper lathe cut on the rotor shaft. Two other prototype 25-kW wind turbines manufactured at the same time experienced similar failures. Unfortunately, we were not able to remove the unit before failure.

The original 40-kW unit ran for eight months without any downtime except for service. It had an availability of 99.9% during the period (Clark and Vosper, 1984). The prototype-60 kW unit, installed immediately after the 40-kW unit, operated for nine months before problems developed with the tip-brakes. Tip-brakes are emergency brakes located at the rotor blade tips and are activated by centrifugal force. The internal spring mechanism that controlled the tension on the tip-brake would not stay adjusted, thus allowing early deployment of one tip-brake. A new mechanism was installed in August 1985 on all three tip-brakes.

In October 1986, 4.5 years after installation, a 5-cm (2-in.) long crack developed in the up-wind tower leg just below the top mounting plate. Similar cracks were found on this manufacturer's wind turbines located in the wind parks in California. After careful study by several groups, it was concluded that the crack was caused by loads translated from the free yaw movement of the rotor. Several "fixes" were suggested and we chose to replace the top tower section legs (schedule 40 pipe) with schedule 80 pipe. This was done and the turbine was returned to service four months after locating the crack. There were 22,437 operating hours on the tower when failure occurred.

The turbine was shut off for extended periods at three times because of ice on the rotor blades. Two of these occurred in January and one in December (table 3). Each occurrence involved a weekend when the ice thawed and no one was available to restart the machine until Monday. Ice often causes the rotor to lose its airfoil shape. Then the system operates as giant fan, using electricity rather than producing power. Other icing events have caused shut-downs of less than 100 h.

The machine was removed from the tower in May 1988 to replace the leaking seals in the gearbox and while the gearbox was being repaired, the gear ratio was changed to the same one as used in the 40-kW systems to reduce the rotor speed. Since 19 July 1988, the wind turbine has operated as a 40-kW unit. An additional tip-brake mechanism modification was required to strengthen the spring to avoid unwanted releases. Also in June 1992, parking brake pads were replaced after a broken brake wire in the drop cable caused the brake to engage while the machine was operating.

Overall availability for the wind turbine has been 97% during the total period. About one-third (1%) of this downtime is attributed to icing and other weather related events, another one-third (1%) to repair of component failures, and an estimated 1% of the time for routine maintenance and servicing. This machine has operated extremely well as a new technology prototype and has demonstrated the manufacturer's ability to choose good component products.

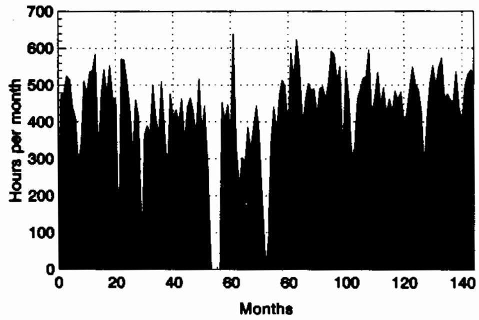

Figure 1–Monthly hours of on-line turbine operation, July 1982 to June 1994.

Performance Data

The annual average wind speed during the 12 years was 5.71 m/s (13 mph) measured at the 10 m (33 ft) height. Wind speed at hub height [25 m (82 ft)] was calculated to average 7.1 m/s (16 mph), about 25% higher. Total run hours for each month are presented in figure 1. During the 144 months reported by these data, the turbine was in operation for 137 complete months. The four dips in this curve show the time the turbine was removed from the tower, either to replace the generator with a different size, or to repair the tower. These replacement or repair dates are listed in table 2. The other dips in the curve can be identified with significant off-times as listed in table 3. Total number of hours in operation during the 12 years was 61,644 h. The wind turbine averaged running about 5,400 h/year or 61% of the time. It is interesting to note that the 60-kW ran fewer hours, months 29 to 71, than either the 25- or 40-kW units, averaging about 4,400 h/year.

Monthly energy generated by the wind turbine is shown in figure 2. Again, the four times the turbine was removed from the tower are clearly shown; however, other downtimes show their impact in this chart. During the period 1 to 20 months, the result of using the smaller 25-kW generator is seen; however, the influence of the 60-kW generator is not clearly shown during months 29 to 71. The turbine produced 928,791 kWh during the 12 years

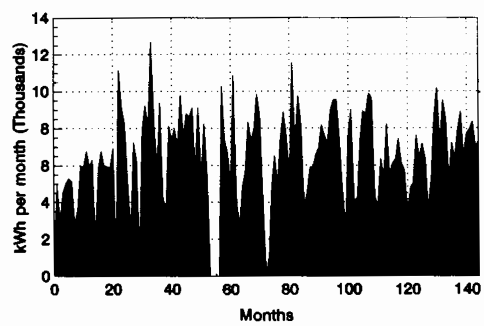

Figure 2–Monthly energy (kWh) produced by the wind turbine, July 1982 to June 1994.

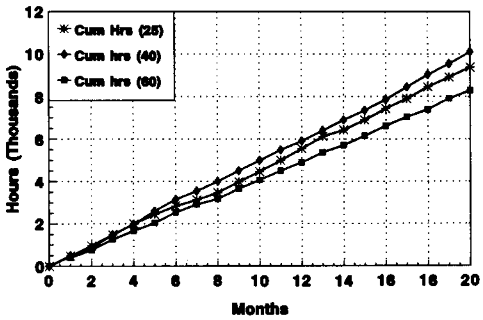

Figure 3–Comparison cumulative monthly run-hours for 20 consecutive months for each size generator.

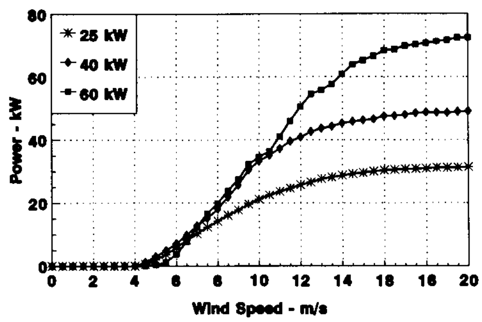

Figure 5–Measured power curves (Enertech 44) for each generator tested. The power was corrected to standard density and the wind speed was measured at 25-m, hub height.

and averaged 6,700 kWh/months or about 80,000 kWh/year.

As a comparison of the three generator configurations studied during the operation of this wind turbine, 20 consecutive months of data with no significant downtimes were selected for each generator type and the energy production and hours of operation were compared. The cumulative hours for 20 continuous months of operation for the three generator configurations are shown in figure 3. Notice that the 40-kW generator ran more total hours than either the 25- or 60-kW. When comparing the energy produced (fig. 4), the 40- and 60-kW generators clearly out produced the 25-kW, but the differences between the 40- and 60-kW were less than 5%. Since these data were collected at different times and the average wind speed were not exactly the same, the differences could have been reduced because of wind speed. However, all data presented show that the 60-kW generator does not exhibit a clear advantage over the 40-kW. Actually, an optimum generator for this 13.4-m (44-ft) rotor may be 50-kW rather than the 40- or 60-kW studied (Vosper and Clark, 1985b).

Power curves were determined for each configuration of the wind turbine during the 12 years using measured hub-height wind speeds. The three power curves for 25-, 40-, and 60-kW operation are shown in figure 5. In each case, the machine reached or exceeded its rated power at a wind speed of 13.4 m/s (30 mph). Two significant features of these power curves are the point where power is first produced, and how the 40- and 60-kW curves follow closely until they diverge when the wind speed exceeds 11 m/s (25 mph). Although the 60-kW generator produced more power at high wind speeds, it didn't necessarily operate the same number of hours. The 25- and 40-kW generators both produced about 5 kW at a wind speed of 5.5 m/s (12.5 mph) while the 60-kW was just beginning to produce power. This feature becomes significant because of the large number of hours the wind blows at that speed. The effect of the difference in starting wind speed is clearly shown by the efficiency (power coefficient) curves (fig. 6). The power coefficient is the ratio of the actual electrical power produced at a given wind speed to the theoretical power available at that wind speed. Although there is significant differences between the 40- and 60-kW power curves at higher wind speeds, these curves are not too different at wind speeds between 7 and 11 m/s (16 and 25 mph); where most of the wind power is produced by turbines located in the U.S. Great Plains.

Conclusions

The 13.4-m (44-ft) diameter horizontal-axis wind turbine performed well during the 12 years with an overall availability of 97%. About one-third (1%) of the 3% downtime was attributed to icing and other weather-related events, another one-third (1%) to repair of component failures, and an estimated 1% of the time for routine maintenance and servicing. This machine operated extremely well as a new technology prototype and demonstrated manufacturer's ability to choose good component products.

The actual on-line generation time was slightly above 61% or around 450 h/month. The wind turbine produced almost 930,00 kWh of electricity and averaged about

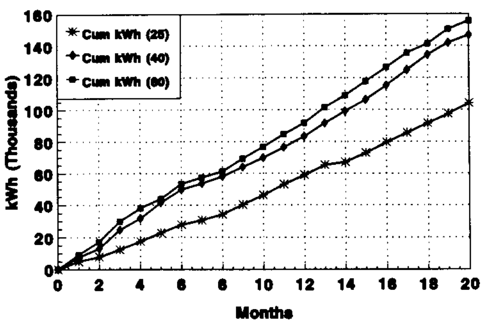

Figure 4–Comparison cumulative monthly energy (kWh) for 20 consecutive months for each size generator.

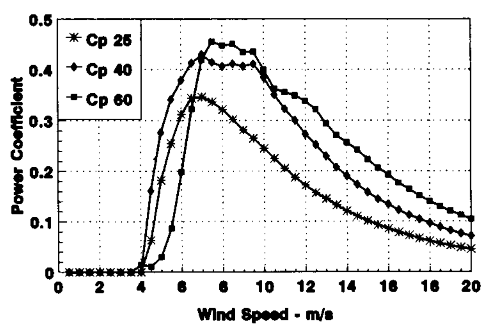

Figure 6–Power coefficients (Enertech 44) of the wind electric generators as determined by the ratio of actual electrical power to theoretical wind power.

80,000 kWh/year. The capacity factor for the machine was 23.4%, indicating that the machine performed well and that the Southern Great Plains has good wind sites for wind energy systems. A comparison of 20 continuous months of data for the three different generator sizes showed that the 25-kW generator was clearly too small for the 13.4-m (44 ft) diameter rotor. The power curve comparison also showed this condition. The 60-kW generator configuration did not perform as well as the 40-kW generator because of the higher start-up wind speed requirement for the 60 kW. This higher start-up wind speed requirement was significant because of the large number of hours the wind blew at speeds between 4 and 6 m/s (9 and 14 mph). The power curves for the 40- and 60-kW turbines are similar at wind speeds between 7 and 11 m/s (16 and 25 mph) where most of the wind power is produced by turbines located in the U.S. Great Plains.

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