UMR-MEC Conference on Energy / UMR-DNR Conference on Energy

13 Oct 1977

A Small Horizontal Axis Wind Turbine Feeding Power Into The Utility Grid

G. C. Thomann

M. Jong

M. H. Snyder

Recommended Citation

Thomann, G. C.; Jong, M.; and Snyder, M. H., "A Small Horizontal Axis Wind Turbine Feeding Power Into The Utility Grid" (1977). *UMR-MEC Conference on Energy / UMR-DNR Conference on Energy*. 328.
https://scholarsmine.mst.edu/umr-mec/328

A SMALL HORIZONTAL AXIS WIND TURBINE FEEDING POWER INTO THE UTILITY GRID

G.C. Thomann, M. Jong and M.H. Snyder
Wind Energy Laboratory
Wichita State University
Wichita, Kansas

Abstract

A small horizontal axis wind turbine, with about a 2 kW power output, was constructed to convert wind energy into AC power to be fed into the utility grid. The machine is intended to model operation of the larger wind generators now being built. The variable pitch rotor is 18 ft in diameter and has a GA(W)-1 blade airfoil. The rotor is fabricated from sitka spruce mounted on a commercial propeller/hub system. Rotor speeds of from 75 to 150 rpm are used in operation. A chain drive and helical gear drive system steps up rotor speed to 1800 - 3600 rpm to drive a generator connected to the utility grid. The generator can be operated in either an induction or synchronous mode; only the induction mode has been used at the present time. Rotor speed, rotor pitch, turbine azimuth, wind speed and direction, and power output are monitored during operation. Tower azimuth and rotor pitch are controlled during experiments. An automatic data recording system is presently being installed. A microprocessor automatic control system for adjusting azimuth direction and rotor pitch will be installed shortly. A complete set of experiments is planned for the spring of 1978.

1. INTRODUCTION

Recently interest in wind power in the United States as a source of alternate energy has been revived. Under the sponsorship of the Energy Research and Development Administration (ERDA) several large wind generators are being constructed. A 100 kW machine has been built and is presently in operation. Three similar machines, with a 200 kW rating, are being placed at demonstration sites in the United States. One of these 200 kW machines will soon begin operation in Clayton, New Mexico. A 2000 kW machine is presently being built, and a 2500 kW machine is being designed. These larger machines will also be placed at demonstration sites and operate in conjunction with utility networks.

All of the large systems being developed by NASA operate similarly. They are horizontal axis machines with variable pitch rotors. Yaw (azimuth) control is electrically or hydraulically provided to turn the system into the wind. Synchronous generators are driven from the rotor through a gear box which steps up the relatively slow rotor speed (17.5 - 40 rpm for the machines discussed here) to generator speed (1800 rpm).

A much smaller, but similar, wind generator has been built at Wichita State

University (WSU) to test the operation of this type of system in the Kansas wind environment. A photograph of the WSU wind generator is shown in Fig. 1. The maximum output of the system is about 2 kW, using an 18 ft diameter rotor which can be set to rotate from 75 to 180 rpm. The tower height is 40 ft. The housing at the top of the tower contains the generator and the speed up system for converting rotor speed to generator speed. The generator operates as either a synchronous or induction generator, although only the induction mode has been used at the present time. With an induction generator, rotor speed does not have to be controlled as closely as when a synchronous generator is used. However, the induction generator does not have as good a power factor as the synchronous machine, and for this reason the induction generator has not seen much use in large scale turbines. Speed control of the WSU system is accomplished using rotor pitch control similar to that used in the larger turbines, or by turning the system out of the wind to control power input. The latter method allows power output to be controlled without changing rotor pitch, which is attractive because constant pitch rotors can be constructed more cheaply than variable pitch rotors. The output of the generator is connected directly to the utility grid.

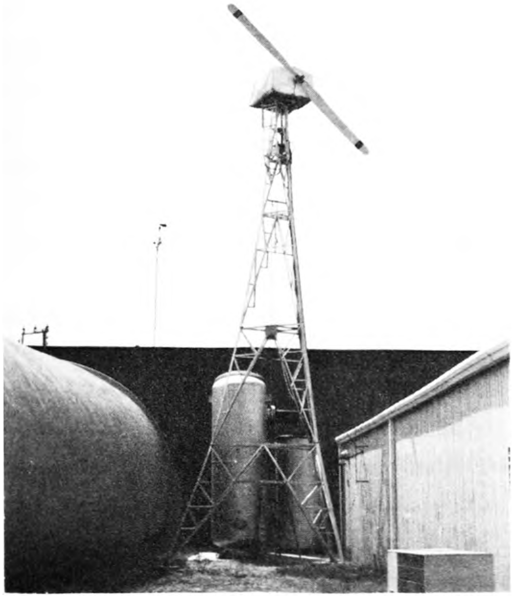


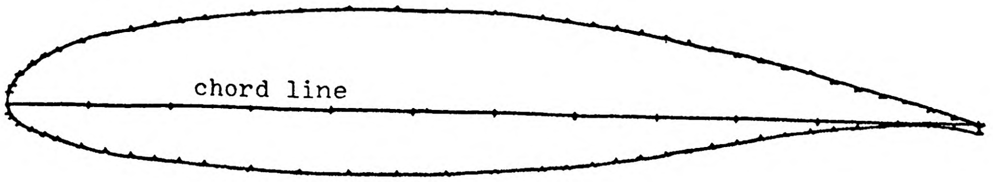
Figure 1. WSU horizontal axis wind turbine shown in operation.

2. SYSTEM DESCRIPTION

2.1 ROTOR

The blade section of the 18 ft diameter rotor is a GA(W)-1 airfoil. The GA(W)-1 airfoil is a 17% thick airfoil developed by NASA for general aviation aircraft; its profile is shown in Fig. 2. At the time the rotor was designed, tests of GA(W)-1 and GA(W)-2 airfoils were being conducted at WSU. These experiments were at considerably higher Reynolds numbers (2.2×10^6) than would be experienced in wind turbine operation. However, data obtained in these experiments indicated that a wind turbine rotor constructed with a GA(W)-1 airfoil would have a significantly smaller chord than one using other conventional airfoils. For example, in one design study the blade volume with a Clark-Y section would be 1.398 cu.ft., but with a GA(W)-1 section the blade volume would be only 0.412 cu.ft.

Since the time of the blade construction, additional tests of GA(W)-1 and GA(W)-2 airfoils have been conducted at Reynolds numbers of $.37 \times 10^6$, $.51 \times 10^6$, and $.67 \times 10^6$. Results of these experiments are similar to those obtained from the higher Reynolds number experiments, except that the advantage of the GA(W)-1 airfoil over the other airfoils is not as marked as in the first experiments. Detailed results of these tests are given in another report;[1] the principal results for the GA(W)-1 airfoil are listed in Table I. As is usual, the value of $C_{\ell_{max}}$ decreases as



Upper Surface		Lower Surface	
X/c	Z/c	X/c	Z/c
0.00000	0.00000	0.00000	0.00000
0.00200	0.01300	0.00200	-0.00930
0.00500	0.02040	0.00500	-0.01380
0.01250	0.03070	0.01250	-0.02050
0.02500	0.04170	0.02500	-0.02690
0.03750	0.04965	0.03750	-0.03190
0.05000	0.05589	0.05000	-0.03580
0.07500	0.06551	0.07500	-0.04210
0.10000	0.07300	0.10000	-0.04700
0.12500	0.07900	0.12500	-0.05100
0.15000	0.08400	0.15000	-0.05430
0.17500	0.08840	0.17500	-0.05700
0.20000	0.09200	0.20000	-0.05930
0.25000	0.09770	0.25000	-0.06270
0.30000	0.10160	0.30000	-0.06450
0.35000	0.10400	0.35000	-0.06520
0.40000	0.10491	0.40000	-0.06490
0.45000	0.10445	0.45000	-0.06350
0.50000	0.10258	0.50000	-0.06100
0.55000	0.09910	0.55000	-0.05700
0.57500	0.09668	0.57500	-0.05400
0.60000	0.09371	0.60000	-0.05080
0.62500	0.09006	0.62500	-0.04690
0.65000	0.08599	0.65000	-0.04280
0.67500	0.08136	0.67500	-0.03840
0.70000	0.07634	0.70000	-0.03400
0.72500	0.07092	0.72500	-0.02940
0.75000	0.06513	0.75000	-0.02490
0.77500	0.05907	0.77500	-0.02040
0.80000	0.05286	0.80000	-0.01600
0.82500	0.04646	0.82500	-0.01200
0.85000	0.03988	0.85000	-0.00860
0.87500	0.03315	0.87500	-0.00580
0.90000	0.02639	0.90000	-0.00360
0.92500	0.01961	0.92500	-0.00250
0.95000	0.01287	0.95000	-0.00260
0.97500	0.00609	0.97500	-0.00400
1.00000	-0.00070	1.00000	-0.00800

Figure 2. GA(W)-1 airfoil coordinates. t - maximum chord thickness, c - chord length, X and Z are coordinates, t/c = .17.

Reynolds number decreases. The design value of $C_{\ell_{max}}$ used was 1.625 at $\alpha = 14°$. This value is higher than that obtained in operation.

The rotor design process involved assuming design values of:

Wind speed = 16 knots
Air density = 0.002265 slugs/ft^3
Power to be developed by turbine = 3.3 kW = 4.43 h.p.
Diameter = 18 feet
Rotational speed = 150 rpm = 2.5 r.p.s.
Tip speed ratio, X = 5.23
C_p = 42.5%
α = 14° at all stations

The design procedure was programmed for an IBM 360 computer which accepted these design values as input and calculated the chord size and blade angle at all stations. Blade weight and centrifugal loading were also computed.

The desired blade angle, β, as a function of radius is shown in Fig. 3. For ease of construction, this desired distribution was approximated by the two straight line variations also shown in the figure. To manufacture the blade, sitka spruce was cemented and pinned onto a commercial aircraft propeller, and then milled to the desired airfoil shape. A Beechcraft model 78FF propeller with a 2AF hub was used. The propeller blades were straightened before the spruce was attached. The original propeller had a 77 inch diameter, with a power rating of 260 Hp at 2600 rpm. The hub is variable pitch, with a total range of 64°. Minor modifications were made to the hub, consisting of removing a latching mechanism which latched the propellers into low pitch for engine starting. A photograph of the completed blade is shown in Fig. 4.

Rotor pitch can be changed by hydraulic or air pressure or mechanical force applied to the hub through a hollow mounting shaft.

Table I. Principal parameters of the GA(W)-1 airfoil.

Reynolds number =	$.37 \times 10^6$	$.51 \times 10^6$	$.67 \times 10^6$
$c_l = 0.0$ at α =	-4.2°	-4.3°	-4.4°
$\alpha = 0.0$ at c_l =	.47	.50	.52
$c_{l_{max}}$ =	1.35	1.39	1.43
$c_{d_{min}}$ =	.0010	.0102	.0077
L/D_{max} =	66.69	76.16	86.27
at			
α =	6.2°	6.2°	2.2°
Stall + α	16.2°	16.2°	16.2°
Range - α	-11.8°	-11.8°	-11.8°

c_l - section lift coefficient

c_d - section drag coefficient

α - angle of attack

L - lift

D - drag

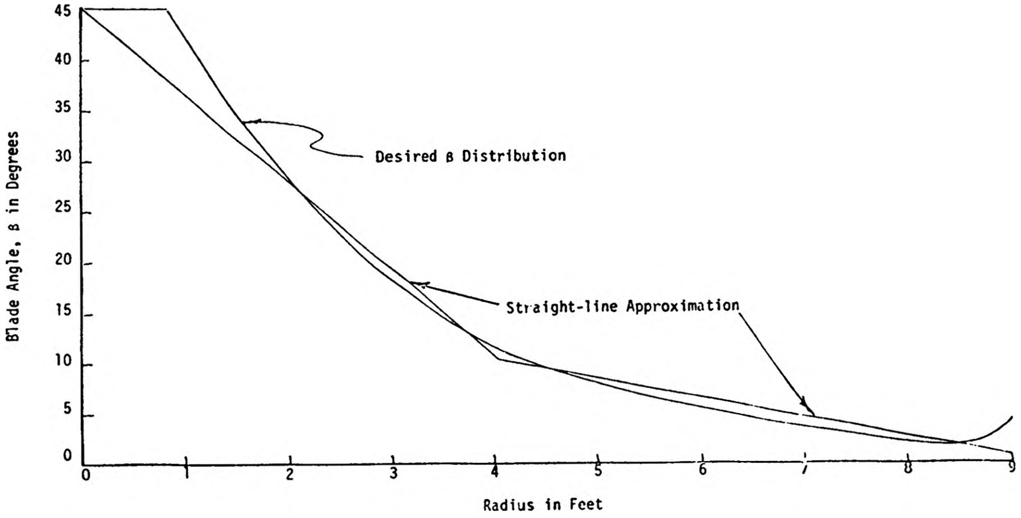


Figure 3. The calculated variation of blade angle, β, as a function of blade radius, and the linear approximation used for manufacturing the rotor.

At the present time air pressure is used to adjust rotor pitch. An air reservoir in the housing receives high pressure air from the ground and stores air at a pressure adjusted by a valve at the input of the tank. Rotor pitch is changed using two solenoids which either connect the hub directly to the air reservoir or by venting into the atmosphere. If power fails for any reason, the pressurizing solenoid closes and the release solenoid opens so the rotor goes to the full feather position.

The performance of the blade was analyzed over speed ranges from 75 to 150 rpm, blade angles from -15° to 30°, and wind speeds from 4 to 16 m/s. A C_p curve for the rotor (power out divided by power in

Figure 4. The 18 ft diameter GA(W)-1 airfoil rotor.

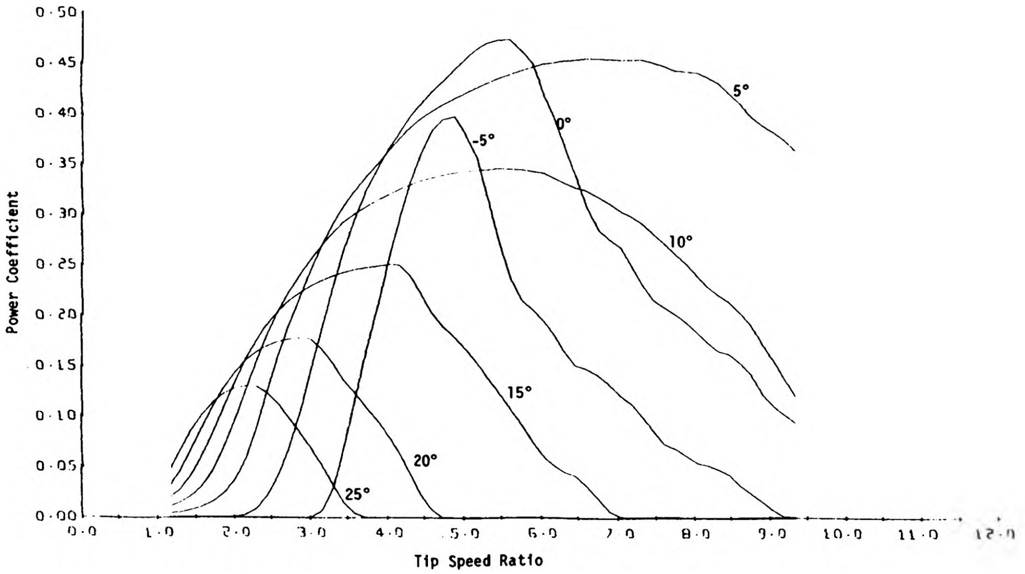


Figure 5. C_p curve for the 18 ft GA(W)-1 rotor.

as a function of tip speed ratio) is shown in Fig. 5. A curve of power out versus blade angle is shown in Fig. 6 for various wind speeds at a rotor speed of 120 rpm.

The low pitch operating point for the rotor is about 5°. From Fig. 5 it can be seen that for the 5° blade angle high values of C_p are obtained for tip speed ratios from about 4 to 9. It will be shown later that a good rotor speed for operation in Wichita, Kansas, is about 120 rpm. The tip speed ratio range of 4 to 9 thus

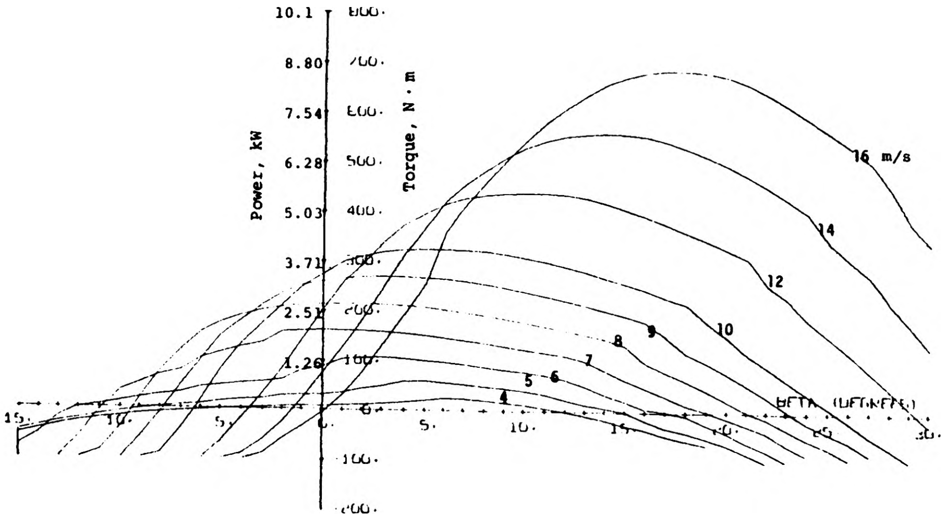


Figure 6. Rotor output torque at 120 rpm as a function of blade angle for wind speeds from 4 to 16 m/s.

corresponds to a wind speed range of from 3.8 to 8.6 m/s, which covers a large portion of Wichita's winds. The rotor output power for this speed range can be seen in Fig. 6. At the higher wind speed the power is over 2 kW, the nominal rating of the generator, and it would appear that the rotor should be feathered to about 10 or 15°. In practice, however, tower shadow, wind turbulence reduce the power so feathering is probably not necessary in this range. The 5° blade angle thus provides good operation over a considerable wind range. A complete set of rotor characteristics for speeds other than 120 rpm are also available.[2]

2.2 MECHANICAL DRIVE SYSTEM

The mechanical drive system and associated components in the housing on top of the tower are shown in Fig. 7. The rotor is mounted on the hollow main shaft which can be seen in the figure. The speed increase from rotor to generator is accomplished with two chain drives and a helical gear speed increaser. The overall gear ratio necessary depends upon the operating point of the rotor. At the time the photograph was taken, the nominal rotor operating point was 75 rpm, so a speed increase of 24 was needed to drive the generator at 1800 rpm. Integer speed increase values are usually not obtainable. In this instance the first chain drive consists of a 112 tooth sprocket on the main shaft and an ANSI No. 40 chain driving a 60 tooth sprocket on a secondary shaft. The 60 tooth sprocket is mounted on a torque reducer which can be set to slip and reduce high torque fluctuations in the drive train. The second chain drive consists of a 40 tooth sprocket mounted on the secondary shaft driving an 18 tooth sprocket on the input shaft to the speed increaser. Number 40 chain is also used for this drive. The helical gear speed increaser provides a speed step up of 5.867. The generator, at the top of the platform, as it is displayed in Fig. 7, is driven by the speed increaser through a flexible coupling. The actual overall speed step up obtained is 24.34. To change the speed step-up value sprocket substitutions are made in either the first or second chain drive.

At a 75 rpm main shaft speed the power transmission capability of the chain drive is about 2 kW, the first drive system being the limiting factor. The rating of the helical gear drive is also about 2 kW at an 1500 rpm output shaft speed. Class two operation was assumed for estimating the rating of the helical gear transmission. The chain ratings were calculated at 10% of yield strength. Higher chain power capabilities are possible at increased rotor speeds, but to obtain higher ratings for the gear box requires a higher generator speed. The rotating drive system absorbs some rotor power; current estimates of about 50 watts are lost in the chain drives and speed increaser.

Various other components can also be seen in Fig. 7. Angle iron brackers and pillow blocks are used for holding the shafts. The housing cover is shown pulled back from its frame, which is also constructed from angle iron. An electromechanical brake is mounted on the main shaft; it is available for emergency stopping or holding the rotor during maintenance. At the back of the platform is the air reservoir; the solenoids for driving the rotor hub are under the brackets at the lower right portion of the platform. Air through the solenoids to (or from) the rotor hub passes through the hollow main shaft, the rotating coupling, and the air hose from the coupling to the solenoids. An electrical junction box is at the lower left corner of the platform. An intercom, which is used for communication and monitoring system operation is sitting on top of the junction box. A tab for lifting the entire platform can be seen just to the right of the brake. The entire housing is mounted on a hollow shaft which inserts into bearings at the top of the

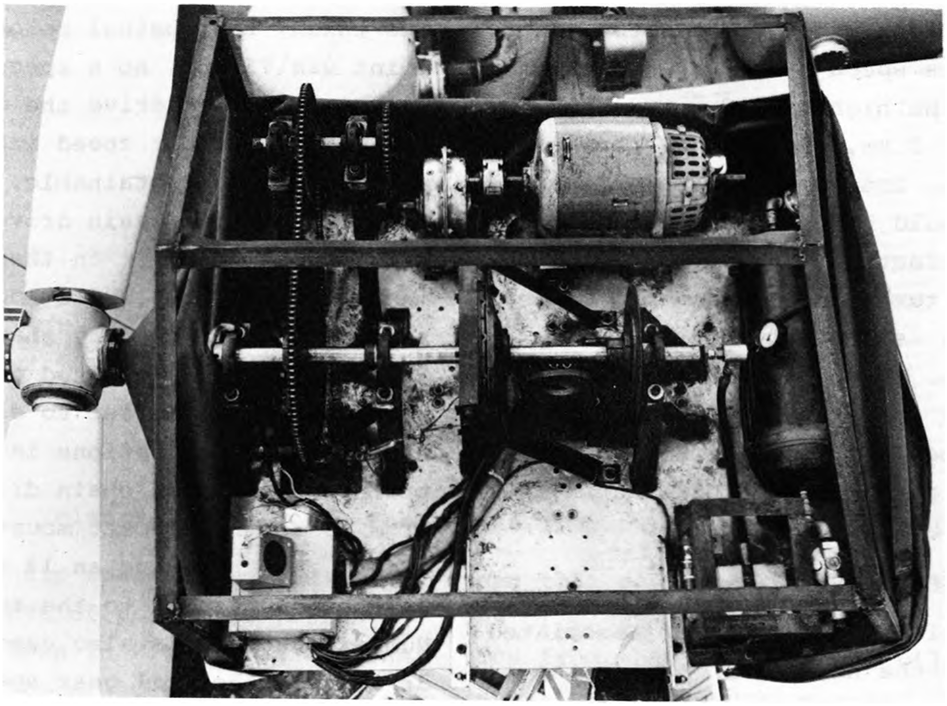


Figure 7. The housing containing the mechanical drive system, generator, and associated components.

tower; the housing turning mechanism, discussed later, drives this hollow shaft. All power and signal cables go through this hollow shaft to the ground. Two brackets seen at the bottom of the platform connect to a ladder when the housing is rotated to proper orientation with the tower.

2.3 TOWER

The tower was designed and built at WSU. It is free standing, forty feet high, made in four ten foot sections. Each section is welded from angle-steel and the sections are bolted together at the time it is erected. The base section is anchored to buried concrete cylinders through bolts and reinforcing rod in the cylinders. The tower is designed to withstand a 100 mile per hour wind with a safety factor of four. The weight of the tower is estimated to be about 2100 lbs. for the four sections.

2.4 GENERATOR

The generator is a machine originally used in the WSU electrical engineering laboratories. It is a wound rotor four pole AC machine which can be connected as either a synchronous or induction generator. Either three phase or single phase operation is possible. The rotor coils are connected in a Y configuration. Stator coils can be connected in either a Y or Δ configuration. Each phase of the stator coils consists of two coils which can be connected either series or parallel to allow different operating voltages for the machine. The normal synchronous speed of the machine is 1800 rpm; as an induction generator it can be operated at higher speeds than 1800 rpm using external rotor resistance. The machine is mechanically rated to 3600 rpm.

At the present time all operation has been as an induction machine connected for three phase operation at a line voltage of either 220 or 208 VAC. As an induction generator operation can be either at a near constant speed or at variable speed. For constant speed operation the generator is run within a few percent slip range at some speed above synchronism. The nominal speed is determined by the external resistance added to the rotor circuit. In the variable speed mode, the external rotor resistance is varied to allow slip to change easily.

Performance calculations can be made from the generator equivalent circuit and a knowledge of friction and windage losses. An equivalent circuit is shown in Fig. 8 for no external rotor resistance, three phase operation with stator coils connected in a Y configuration. The equivalent

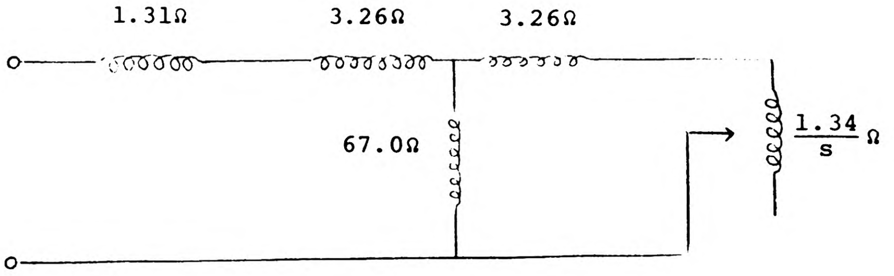


Figure 8. The per phase equivalent circuit for the generator being used as an induction machine with the stator windings connected in series.

circuit is per phase. Stator windings are in series; with the windings in parallel all values in Fig. 8 would be divided by four assuming a Y connection were still used. Because the generator was of an old design and not being manufactured anymore, it was not possible to obtain much information about the generator from the manufacturer. Therefore, all parameters in the equivalent circuit were measured. Friction and windage losses were measured to be 100W and core losses were measured to be 50W at a speed of 1800 rpm. It is assumed that these losses are constant over the ranges of speed the generator is used.

The mechanical power, real power, and efficiency are shown for the induction generator over a slip range of from .20 to -.20 in Fig. 9. The electrical power is real power at the stator terminals and mechanical power is shaft output power. Efficiency is mechanical power divided by real power in the motor region (positive slip) and real power divided by mechanical power in the generator region (negative slip). Since the rating of the machine is about two horsepower, mechanical power into the generator should be held to about 2000 W or less. As can be seen from the figure, this means operation in about the -.03 to -.05 slip range. This is also the area of highest efficiency for the generator, about 80%. The power factor in this region is about .8; the power factor decreases for other slips. When operating in the near constant speed mode, the rotor output must be matched to the generator for the range of wind speeds the turbine is to operate in. As wind speed increases, the power delivered to the generator is adjusted by changing rotor pitch or by turning the system out of the wind. Since generator speed can be allowed to vary

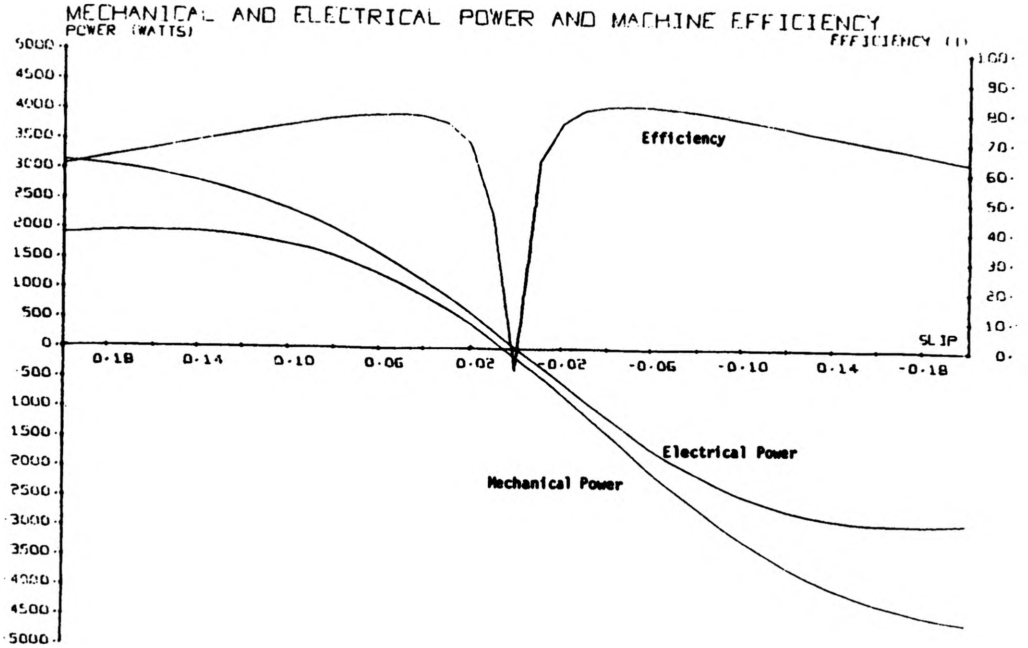


Figure 9. The stator electrical power, shaft mechanical power, and efficiency as a function of slip for the induction generator with no external rotor resistance and 208V three phase operation.

somewhat the pitch change mechanism, or whatever mechanism is used to limit power, does not have to operate very quickly. It must merely be quick enough to keep the generator from overheating or to keep from having long periods where little power is generated.

The generator can be run at higher speeds by adding external rotor resistance. However, for the same output power, more mechanical power must be supplied because of the power dissipated in the external resistor, which causes an efficiency drop. The change in mechanical power and efficiency is illustrated in Table II for the induction generator used on the WSU turbine. The referred rotor resistance is the per phase resistance of Fig. 8. Real power is that delivered at the stator terminals and mechanical power is the input power to the machine. As can be seen from the table, as the rotor resistance is increased the same real power occurs at a greater slip and the increase in required mechanical power is exactly that lost in the external resistance. If the power dissipated in the external resistance can be used, however, then it isn't considered a power waste and the efficiency would actually increase.

A more sophisticated mode of operation with the induction generator is to vary the generator slip and therefore the rotor speed as a function of wind velocity to keep the tip speed ratio for the rotor constant. The rotor can then always be run at its maximum power coefficient. The advantages of this mode of operation for any particular rotor generator combination depends both on the shape of the C_p curve and the generator characteristics.

2.5 MONITORING SYSTEMS

Power output, rotor speed, rotor pitch, turbine azimuth, wind direction, and wind speed are monitored during turbine operation. A tachometer on the main rotor shaft provides an output voltages directly proportional to rotor speed. This voltage is transmitted to the ground for display and recording. The display and recording instruments are discussed later. Rotor pitch is sensed by a potentiometer mounted on the rotor hub and driven by a timing belt around the mounting flange of one of the blades. A blade pitch change varies the potentiometer resistance. A constant current is delivered through the potentiometer and the voltage across it is a measure of rotor pitch. Two slip rings transmit the voltage signal from the rotating hub to the stationary platform. A very similar system is used to measure the azimuth position of the rotor axis. A chain and sprocket drive system, discussed in the next section, drives the housing mounting shaft and also drives a potentiometer.

Table II. The power output and efficiency of the WSU turbine generator as a function of external rotor resistance.

Referred Resistance	Slip	Real Power	Mechanical Power	Power Factor	Rotor Power Loss	Real Power / Mech Power
1.34	-.06	1673 W	2058 W	.81	0 W	81.3%
2.68	-.12	1673	2166	.81	108	77.2%
4.02	-.18	1673	2274	.81	216	73.6%
5.36	-.24	1673	2382	.81	324	70.2%

A voltage proportional to axis position is generated as in the pitch measurement system. No slip rings are required in this system. Wind speed and wind direction are monitored by commercial weather instruments manufactured by Electric Speed Indicator Company. These instruments meet National Weather Service standard F420C, and are in common use in weather stations. Power generated by the system is monitored by a commercial wattmeter, which supplies a DC output voltage directly proportional to power generated.

The outputs from each monitoring circuit are transmitted to the control room through signal cables, and into shaping circuits which adjust gain and offset to provide a standard 0-10V output from each sensor. The shaper circuit outputs drive meters for display of rotor pitch, etc. Low pass filters can be inserted between the shaper circuit and the meter to reduce high frequency fluctuations to produce an average output which is easier to read from the meters. This averaging is most useful for viewing wind direction and wind turbine power output; the parameters seem to fluctuate considerably at the present wind turbine location.

Data taking is presently done by manually reading the instruments during operation. An automatic system is being installed which will soon be operational. The automatic system consists of a custom built data recorder which records the output from the shaping circuits or the low pass filter if averaging is desired. The data recorder is a dual floppy disc microprocessor controlled storage. The recorder has 16 0-10V analog channels and eight 8-bit digital channels. Any combination of channels can be used during a particular experiment. The channels can be sampled and recorded at rates varying from .1 to 100 seconds/sample, with up to 10,000 samples recorded during a single experiment.

Experiment parameters and header information are inserted into the recorder through a keyboard before beginning an experiment. The sample rate, channels to be sampled, the channel sampling sequence, the total number of samples to be obtained, and the time it will be at the start of the experiment are inserted to control the recorder operation. Header information consists of the date, experiment number, and a limited amount of auxiliary information about the experiment which can be inserted if desired.

After completion of an experiment the data on the floppy disc is transferred to a HP 21 MX minicomputer operated by the WSU electrical engineering department. The transfer is accomplished through a microcircuit interface card. Processing of the wind turbine data can be done in the HP 21 MX or data can be subsequently transferred to one of the university's larger computers for processing. Complete software systems exist for programming each experiment on the recorder, operating the recorder during the experiment, and for transferring data from the recorder to the minicomputer.

2.6 CONTROL CIRCUITS

At the present time turbine rotor pitch, turbine axis azimuth angle and external rotor resistance in the induction generator are manually controlled.

The rotor pitch control system has been previously described and will not be treated in much detail here. Increasing or decreasing of the rotor pitch is accomplished by manually energizing either the pressurizing solenoid, which raises hub air pressure, or the release solenoid, which decreases hub pressure. Turbine azimuth is controlled by a chain and sprocket system connected to the vertical shaft on which the housing at the top of the tower is mounted. A small universal motor rotates the shaft through leverage gained by the sprockets. The motor is reversible and also speed controlled. Resistance is added to the rotor of the induction machine using a large three section variable resistance originally designed to be used with the machine in the electrical engineering laboratories. Extra resistance is put in the rotor circuit for starting the system; during starting the generator operates as a three phase induction motor. Extra resistance can be left in the rotor circuit if it is desired for the rotor to drive the generator above 1800 rpm.

An automatic control system is presently being installed which will automatically control turbine azimuth, rotor pitch, and will turn the wind turbine on and off in response to wind conditions. The control system is based on an Intel 80/10 microprocessor. This microcomputer is an 8080 microprocessor chip with associated clock circuits, RAM, PROM and I/O ports. A block diagram of the automatic control system is shown in Fig. 10.

Wind speed and direction, rotor speed and rotor pitch, and turbine azimuth data are modified in the previously discussed shaping circuits. An analog switch, controlled by the microprocessor, selects the channel to be digitized. The 8-bit digitized data is then input to the microprocessor. The digitized data from the sensors is averaged for predetermined periods of time by programs in the microprocessor; at selected intervals this averaged data is compared to turbine azimuth and rotor speed and changes in azimuth or rotor pitch are made if necessary. The entire system is switched off and on in response to wind speed.

The microprocessor approach affords several advantages for testing of an experimental wind turbine system. These include repeatable methods of control, the ability to change pitch and azimuth very quickly, and the ability to run experiments at variable pitch or at constant pitch with power control accomplished by turning of the turbine out of the wind. Automatic

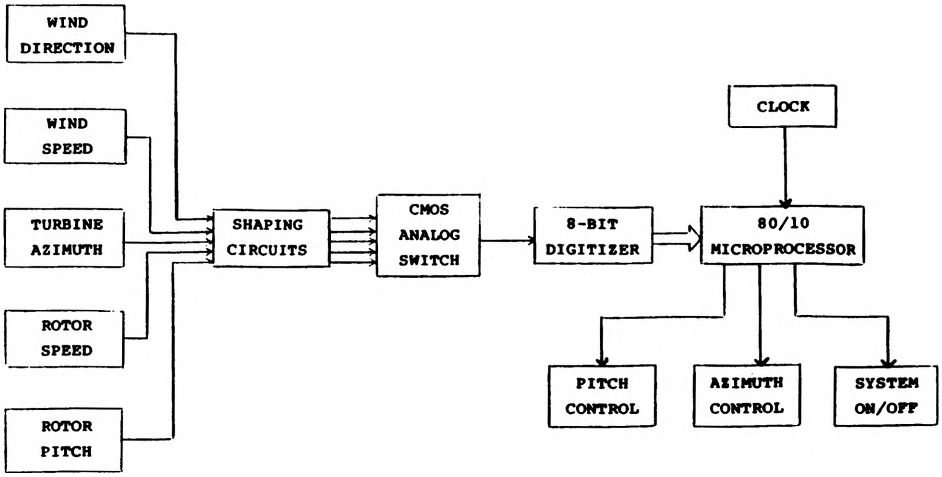


Figure 10. A block diagram of the microprocessor system for control of wind turbine operation.

slip control to keep the rotor at maximum C_p can also be programmed.

3. PERFORMANCE CALCULATIONS

The yearly energy output from the wind turbine can be estimated from the rotor output curves, the wind distribution for the site at which the turbine is located, and the generator efficiency. The energy generated is also dependent upon the cut-in and cut-out wind speeds of the turbine, i.e., the range of wind speeds over which the turbine is capable of operating.

The output of the WSU turbine was calculated using a wind speed distribution for Wichita, Kansas. A wind speed velocity frequency plot for Wichita is shown in Fig. 11. The graph displays wind speed and the number of hours per year or probability the wind is in a one knot range centered on a particular wind speed value. The points were calculated from National Weather Service (NWS) data acquired at the Wichita Mid-Continent airport during the years 1954 - 1975. Wind speed was sampled by NWS every three hours during this time period. The sensor was located at a height of 25 ft above the ground in a level area with no nearby terrain feature or buildings to influence the wind flow around the instrument.

To facilitate calculations the Weibull distribution, shown in Eq. (1), was fitted to the data. This curve is the probability density function for the wind speed.

$$p(V) = \frac{\beta}{\alpha}\left[\frac{V}{\alpha}\right]^{\beta-1} e^{-\left[\frac{V}{\alpha}\right]^{\beta}} \qquad (1)$$

In the equation V is wind speed and α and β are parameters which are adjusted to provide a least squares fit. Further discussion of the use of this curve for fitting wind velocity frequency data can be found in other papers.[3,4]

The total yearly energy generated by the rotor as a function of rotor speed calculated from the Wichita wind speed probability density function and the rotor output curves is shown in Fig. 12 for several generator sizes. In these calculations perfect generator efficiency is assumed. Some method of power limiting is assumed; when power output from the rotor would exceed generator capacity the rotor power is cut back to the generator rating. The cut-in speed for these calculations was assumed to be 5 knots. No cut-out speed was used; there are so few hours of really high wind speeds in Wichita that the energy

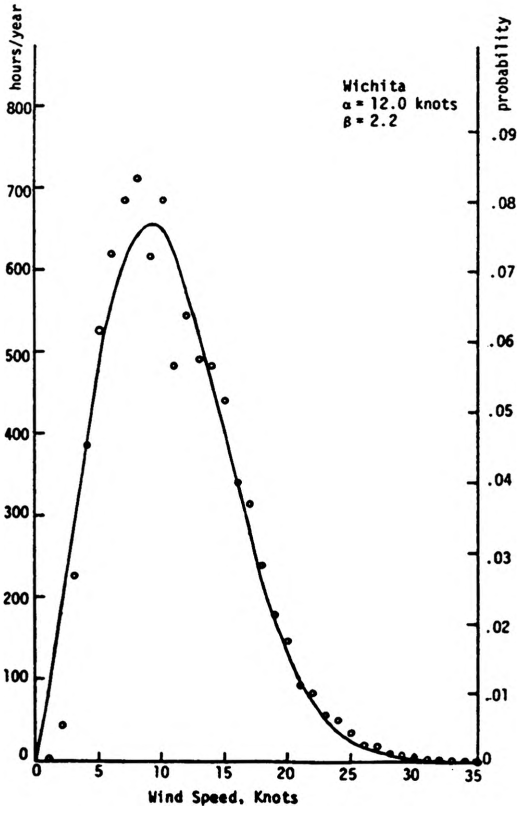


Figure 11. Velocity frequency data for Wichita, Kansas, showing wind speed and the hours or probability the wind is in a one knot range centered on that wind speed value. The curve fitted to the data is described by Eq. (1).

output calculations are not significantly influenced by this assumption. The low pitch position of the rotor is 5°. For a 2 kW generator size, which is approximately the rating of the machine presently being used, the optimum rotor speed is about 120 rpm and the yearly energy output from the rotor would be 8500 kW hr. This figure is rotor power output, not generator output, however. A calculation of generator output would require the use of the generator efficiency and power train losses; this calculation would not be difficult. This energy output figure also assumes perfect operation of the rotor and steady wind speeds. Factors such as wind turbulence, tower shadow, and inoperation due to maintenance would significantly reduce this figure, and it can be considered as an upper bound of energy available.

4. EXPERIMENTS

A set of experiments will be run in the Spring of 1978 to evaluate the operation of the system in the Wichita wind regime. At that time both the data recording system and the automatic control system should be operational. Experiments using pitch control of the rotor to limit power will be run and power limiting by turning the turbine axis slightly out of the wind will also be attempted. The latter method is particularly attractive because it allows the use of a constant pitch rotor. An attempt will also be made to evaluate the effect of wind turbulence on the turbine output. In initial experiments it has been observed that turbulence does affect the system output. It has been noted that the turbulence is much less marked for north winds than for those from the south, so a range of turbidity conditions will hopefully be available. An attempt will also be made to determine the effect the tower is having on the turbine output, although this effect may be quite difficult to estimate. The first experiments will be run with the generator connected as an induction machine. Similar experiments will then be run with the generator connected synchronously to allow a comparison of induction and synchronous generators.

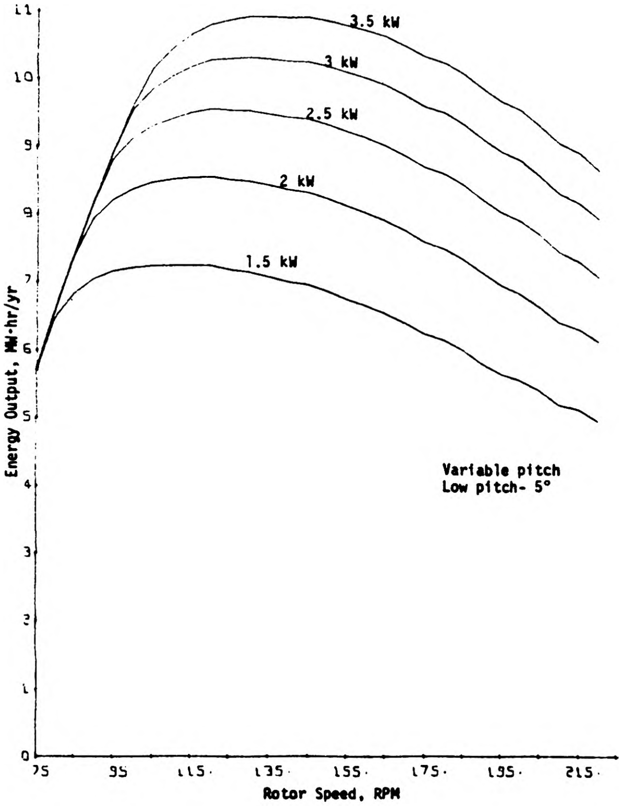


Figure 12. The yearly energy output from 18 ft rotor for different generator sizes assuming no drive train and generator losses.

5. REFERENCES

1. Satran, D., and M.H. Snyder, "Two-dimensional tests of GA(W)-1 and GA(W)-2 airfoils at angles-of-attack from 0 to 360 degrees," WER-1, Wind Energy Lab., Wichita State University, Wichita, KS, 67208, 1977.

2. Thomann, G.C., "The Wichita State University 2 kW horizontal axis variable pitch rotor wind generator," WER-3, Wind Energy Lab., Wichita State University, Wichita, KS, 67208, 1977.

3. Thomann, G.C., and M.T. Jong, "Wichita, Kansas wind characteristics estimated from 1968-1973 NWS data; performance of the NASA 100 kW prototype wind generator in the Wichita wind regime," WER-2, Wind Energy Lab., Wichita State University, Wichita, KS, 67208, 1977.

4. Justus, C.G., "Annual power output potential for 100-kW and 1-MW aerogenerators," Proc. Second Workshop on Wind Energy Conversion Systems, The MITRE Corp., McLean, VA, 22101, 1975.