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NORTH WIND 4kW WIND SYSTEM DEVELOPMENT

Phase II Fabrication and Test

January 1983

**Jonathan Lynch
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**Rocky Flats
Wind Energy Research Center**

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For
Rockwell International Corporation
Energy Systems Group
Rocky Flats Plant
Wind Energy Research Center
Golden, Colorado 80402

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UNITED STATES DEPARTMENT OF ENERGY
WIND ENERGY TECHNOLOGY DIVISION
FEDERAL WIND ENERGY PROGRAM

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ABSTRACT

This report presents the results of Phase II (testing and fabrication) of a program funded by the U.S. Department of Energy to design, fabricate, and test a cost-effective wind system in the 3-6 kW class. During Phase II, using the design developed during Phase I, a prototype 4 kW machine was fabricated and tested in Waitsfield, Vermont. Several problems were encountered and subsequently analyzed. Design modifications, including the use of a larger alternator, are described. Test performed by North Wind and by Rockwell International (which monitored the program) demonstrated the predicted performance characteristics and the validity of the North Wind design.

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NOMENCLATURE

ac	-	alternating current
AOM	-	annual operating and maintenance (cost)
ASTM	-	American Society for Testing of Materials
C	-	centigrade
c	-	distance between neutral axis and extreme fiber of stress
C _p	-	coefficient of performance (rotor)
cc	-	cubic centimeter
CDR	-	Critical Design Review
cm	-	centimeter
COE	-	cost of energy
dBA	-	decibels (A-weighted scale)
dc	-	direct current
F	-	Fahrenheit
FCR	-	fixed charge rate
FDR	-	Final Design Review
ft	-	feet
gm	-	gram
Hz	-	Hertz
I	-	moment of inertia
IC	-	installed cost
in.	-	inch
IPS	-	isolated power system
kg	-	kilogram
kVA	-	kilovolt amperes
kW	-	kilowatt
kWh	-	kilowatt hours

NOMENCLATURE (cont.)

kWh/yr.	-	kilowatt hours per year
λ	-	(lambda) failure rate
LEU	-	local electric utility
lb	-	pound
m	-	meter
m^2	-	square meter
mm	-	millimeter
mph	-	miles per hour
M_c	-	control moment about pitch axis
MTBF	-	mean time between failures
NDT	-	nil-ductility temperature
N-m	-	Newton meter
NWPCo	-	North Wind Power Company
%	-	per cent
$\pm$	-	plus or minus
PDR	-	Preliminary Design Review
$\emptyset$	-	phase
r/R	-	variation (r) from blade chord line at nondimensional radial station (R) of blade
Re	-	Reynolds number
RPM	-	revolutions per minute
SWECS	-	small wind energy conversion system
t	-	one year
V	-	Volt
$\bar{V}$	-	annual average (mean) wind speed
V_∞	-	free stream wind speed
Vac	-	Volts alternating current

NOMENCLATURE (cont.)

VAR	-	Volts Ampere Reactance
χ	-	tip speed ratio
z	-	plastic section modulus
Δ_3	-	delta three angle
θ_p	-	blade pitch angle

1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

The North Wind Power Company 4kW SWECS was developed under a contract awarded by the Department of Energy (DOE) and administered by Rockwell International. The contract goals were to design and build a SWECS capable of 7,500 to 15,000 kWh/yr in a wind regime having a mean annual average of 4.6 m/s (10 mph).

The 4kW SWECS development program was comprised of two phases. Phase I covered trade-off studies and analysis, scale model testing, alternator development, detailed design work, and generation of detailed engineering drawings (Ref. 1). The final engineering drawings and support analysis were presented and reviewed at the Final Design Review (FDR). Following a successful FDR, authorization was granted to proceed with Phase II. The work in Phase II consisted of three task areas: (1) fabrication of the prototype 4kW SWECS; (2) contractor testing and improvement at North Wind Power Company's facilities; and (3) contractor support of system performance testing by Rockwell.

The SWECS as designed and constructed employs two innovations. The all mechanical passive pitch control with a teetering rotor is an evolution of the soft rotor design philosophy. The second innovation is the use of a direct drive multi-pole synchronous alternator interfaced directly to the utility grid. Figure 1 is an overall view of the as-constructed prototype. The final design that emerged from Phase I is a horizontal axis, two-bladed rotor with blade pitch and hub teeter capabilities, and a diameter of 9m; a direct drive 48 pole synchronous alternator designed to operate at 150 RPM while interfaced with the grid; a passive mechanical blade pitch control system; and a 60-foot guyed, wooden pole tower.

Based upon the design that was formulated in Phase I, a prototype fabrication and field testing program was completed in Phase II. The results are presented in this report.

1.2 PHASE II SCHEDULE SUMMARY

This section presents the ten major milestones which were achieved by the completion of the Phase II contract. Figure 2 presents a summary of these milestones.

Field testing was begun in late summer of 1981. Since an alternator that met contract goals of 3-6kW rated output had yet to be developed, the latest Phase I version was installed for testing. The alternator development program continued concurrently with this free-stream test program. In late December 1981, the new larger capacity alternator was installed on the prototype, replacing the Phase I version. Testing continued until June 1982 when the prototype was refurbished and shipped to Rocky Flats.

Figure 1
North Wind 4 kW Prototype

Figure 2
North Wind Power Company 4 kW Phase II Milestone Chart

2.0 DESIGN OVERVIEW

2.1 PROTOTYPE FABRICATION

The Phase I SWECS design, as approved at the Final Design Review, was to be built, tested and modified in Phase II. The original prototype machine was fabricated using elements developed during Phase I. Principal among these elements was the alternator which was tested in Phase I. The effort to develop an alternator with more capacity continued while the prototype was being built and tested. Documentation on this 40½" 48 pole salient pole alternator is presented later in this report. Section 2.0 - Design Overview, primarily describes the fabrication of the SWECS from Phase I drawings. Modifications to the SWECS are also documented in section 3.0 - Phase II Design Changes.

2.2 TOWER

The tower is a guyed Class I wooden utility pole 60 feet in height. Three ½" steel guy cables are through-bolted to the wood pole and attached to the guy anchors with turnbuckles. A pivot for tower tilting at the base of the pole is composed of a weldment through-bolted and lagged to the pole (Figure 3). The tower/machine interface is a fabricated steel structure bolted to the wood pole.

The fabricated structure was field assembled using normal wood working tools and a chain saw. The utility pole specification called for a pressure treated Douglas Fir or Southern Pine pole, however, a treated Western Red Cedar pole was delivered. The pole was used and the problems associated with this change are documented in Sections 3.1 and 6.4.1.

2.3 CARRIAGE

The carriage is a bolted assembly of welded steel elements. The carriage consists of three main pieces (Figure 4):

- Pedestal
- Yaw Column
- Main Shaft Support Tube

The yaw column rotates in the pedestal on two bearings. The upper bearing is a deep groove bolt bearing and the lower bearing is a RulonTM sleeve bearing. The upper bearing supports the 4kW SWECS weight and absorbs the rotor thrust. Both bearings carry the moments about the joint and both are sized for a 25 year life and can be lubricated via grease fittings.

The main shaft support tube is bolted to the yaw column. The main shaft runs the length of the support tube and is supported at each end by a sealed deep groove ball bearing. The rotor hub is mounted on one end of the shaft with a key and captured by a castellated nut. The rotating alternator field is mounted on the other end of the shaft via an elastomeric torsional bearing which provides a soft coupling in the drive train (Figure 5).

All welded steel sections were stress relieved after welding prior to

Figure 3

TOWER ASSEMBLY

- 1- Pedestal
- 2- Yaw Column
- 3- Main Support Tube
- 8- Yaw Bearing
- 9- Bearing Seal
- 11-Needle Bearing Race
- 12-Dry Bearing
- 13-Retaining Ring
- 17-Pullout Chain Pivot
- 18-Jib Furling Swivel

Figure 4

CARRIAGE LAYOUT

- 1- Main Drive Shaft
- 2- Rear Bearing
- 5- Alternator Housing
- 8- Thrust Washers
- 9- Dry Bearing
- 10-Alternator Ass'y
- 11-Soft Shaft Coupling
- 14-Field Slip Rings
- 15-Inst. Slip Rings
- 18-Sleeve
- 19-Stator Ass'y

Figure 5
DRIVE TRAIN LAYOUT

machine operations. The rotor end of the main shaft support tube was chrome plated to protect the sliding spool wear surface. All steel elements were primed with zinc rich paint and overpainted with epoxy.

The two prototype nacelle halves were sheet metal fabrications. Thermoformed plastic nacelles, front and back, are anticipated on the production version.

2.4 ALTERNATOR

At the time of the Phase II prototype fabrication, an alternator that met the contract goals of 3-6kW rated output had not been developed. A decision was made to begin prototype testing with the latest Phase I alternator and refit the machine when a larger alternator became available. The alternator installed originally was a 48 pole design with a Lundel field capable of 2.3kW maximum power. The layout of the alternator assembly is shown in Figure 5. The field rotor is mounted on dry bearings on the drive shaft to accommodate the torsional flexing in the soft shaft coupling.

When the final 40 $\frac{1}{4}$ " 48 pole salient alternator was installed midway in the test program, a one-way overrunning clutch was incorporated into the drive train (Figure 6).

2.5 ROTOR

The rotor hub is designed with $\pm 10^\circ$ of teetering freedom and 85° of pitching freedom. The hub is fabricated from cast and machined steel elements (Figure 7). The teeter hub casting is keyed to the main shaft. The teeter shaft is clamped to the teeter hub. Elastomeric teeter bearings are pressed onto the rotor hub castings and taper-locked to the teeter shaft. The teeter bearings are designed for a 20 year lifetime.

The inner blade shafts are pressed into the rotor hub castings. The outer blade tubes are mounted to the blade shafts on two bearings. The outer bearings are tapered roller bearings designed to carry the blade centrifugal and thrust loads. Preload is provided with spring washers. The inner bearing is a plain sleeve bearing. Outboard of each pitch bearing is a rotary adjustable hydraulic damper. The blades are bolted to the blade shaft assemblies using steel blade-root brackets. The entire assembly is designed to withstand the worst-case loading which is the loss of one blade.

The blades are fabricated of laminated Birch veneer molded to a Gö 797 airfoil shape and finish carved on the flat side. They are sealed with a two-part clear epoxy and finish coated with marine varnish with u.v. inhibitor. The leading edges are protected with 3" polyurethane tape (Figure 8).

2.6 MECHANICAL CONTROLS

The mechanical control system layout is shown in Figure 9. The major elements are:

- 1) the rotating spool, pitch links and anti-rotation brackets.
- 2) the non-rotating slider spool.

Figure 6. ALTERNATOR & SHAFT LAYOUT

END VIEW FROM HUB

- 1 - Rotor Hub Ass'y
- 2 - Blade Shaft Ass'y
- 3 - Pitch Link
- 4 - Blade Root Bracket
- 5 - Wooden Blade

Figure 7. ROTOR PICTORIAL

<u>STA.</u>	<u>CHORD</u>	<u>TWIST</u>	<u>C/4</u>	<u>ΔC/4</u>	<u>ZTHK</u>	
4.50	80	5.5°	16	0	16	
4.05	100	5.5°	20.5	↓	↓	
3.60	120	6.0°	25			
3.15	140	6.5°	29.5			
2.70	160	7.0°	34			
2.25	180	7.5°	38.5			
1.80	200	8.2°	43	↓	↓	
1.35	220	10.0°	47.5			
.90	270	20.0°	↓	16.5	16	
.81	280	23.0°		20.1	16.3	
.72	290	26.0°		24.0	16.6	
.63	300	29.0°		27.0	16.9	
.60	300	30.0°		28.0	17.0	
.54	↓	↓		↓	↓	↓
.18						
.14						

DIM UNITS

METER

MM

MM

MM

Figure 8. 9 M BLADE SECTION OVERLAY

- 1-Blade
- 2-Hub
- 3-Blade Root Bracket
- 4-Blade Pitch Hinge
- 5-Blade Pitch Link
- 6-Link Arm
- 7-Control Cam
- 8-Spring Assembly

Figure 9
ORIGINAL ROTOR CONTROL SYSTEM

- 3) the two arm double throw linkages.
- 4) the spring, chain and cam assemblies.

The rotor control system is activated by a moment about the pitch shaft produced by a combination of aerodynamic and centrifugal forces. In the "on" position, the blades are placed in the run mode, or zero degrees collective pitch. The blades are self-starting at 3 m/s and remain in the zero collective pitch position until the SWECS reaches rated power. Above rated power the blade is automatically feathered to reduce lift and maintain rated power as the wind speed increases. At higher wind speeds, the rotor blades are pitched to decrease power output so that at 20 m/s the rotor can no longer produce power. As the wind speed increases above 20 m/s, the rotor speed decreases.

This initial prototype control system is designed for easy adjustability and modification during the test program. Future refinements of the concept will combine elements and construction techniques intended to reduce system cost and complexity.

3.0 SUMMARY OF DESIGN CHANGES IN PHASE II

Throughout the test period, numerous changes were incorporated in the design. A summary of these changes is presented in this section.

3.1 TOWER

The wooden pole had the tower top adapter lengthened to cut down local deflection and to reduce the loads on the lag bolts. A 2nd set of tower guys was also installed from the guy anchors to the 25 foot level to raise the second tower frequency. The tower problems were attributed to the species of wood pole delivered. A Western Red Cedar pole was supplied rather than Douglas Fir or Southern Pine as specified. Western Red Cedar is a considerably softer wood having 60% of the modulus of elasticity and 50% of the lag bolt capacity of the wood originally specified.

3.2 CARRIAGE

A one-way clutch was added to the drive train when the larger alternator was supplied. Figure 6 shows the newer drive train configuration.

3.3 ALTERNATOR

The 40 $\frac{1}{4}$ " O.D. 48 pole alternator with salient pole field replaced the original 24" O.D. 48 pole alternator with Lundel field. This configuration is shown in Figure 6.

3.4 ROTOR

Although many changes were tried on the rotor over the test period the final configuration was identical to the original version made from Phase I drawings.

3.5 MECHANICAL CONTROLS

The spring/cam system originally designed was modified to improve feathering control and performance. The springs were replaced by a combination of 4 tension springs per side rather than 3. In addition, dampers (automotive shock absorbers) were added to the collective pitch as shown in Figure 17.

4.0 PHASE II COST ANALYSIS

The 4kW system costs are presented in Table 1. These are the Phase I costs which were prepared based on the prototype in its Phase II configuration. These costs are in 1978 dollars.

5.0 PHASE II RELIABILITY ANALYSIS

The reliability analysis presented in the Phase I report has not been changed appreciably for the Phase II prototype. The only significant change was in the Drive Train where the one-way clutch was added. This increased the calculated annual downtime of the machine by 1.1 hours to 46.1 hours, with availability

TABLE I
SWECS COST ANALYSIS

COST SUMMARY
(Labor & Materials)

Standard Case	Total Cost 1st Unit (\$)	Total Cost 1000th Unit (\$)	Total Cost 10,000 Unit (\$)	Weights (lbs.)
100 Drive Train	708	210	177	88
200 Rotor	2,528	565	478	220
300 Control Linkage	2,107	382	323	54
400 Carriage	2,323	732	619	190
500 Alternator	6,000	1,175	993	420
600 Tower Hardware	1,153	420	355	300
700 Tower	602	330	330	3,600
800 Electrics	320	210	180	55
900 Electronic Controls	514	374	320	24
1300 Manual Shutdown	75	53	45	15
SWECS Total	16,330	4,451	3,820	4,966
G&A @ 27%	4,409	1,202	1,031	--
Fee @ 15%	2,449	668	573	--
Total 1980 \$	23,188	6,321	5,423	--
Total 1978 \$	19,164	5,224	4,483	--

still well above 99% (refer to Table 2).

6.0 SUMMARY OF CONTRACTOR TESTING

6.1 FIELD TEST PROGRAM OBJECTIVES

The test program was designed to learn in detail the performance parameters of the SWECS as well as the dynamic and structural characteristics of the prototype configuration. Performance evaluation included power output, yaw alignment characteristics and control function operation as its primary objectives while gaining general experience with the overall operation of the system. The SWECS prototype was structurally proof load tested and then operated in the available winds.

Dynamically, the SWECS was analyzed to verify theoretical predictions of structural frequencies and exciter inputs. Subsequent dynamic system tuning was performed to either add damping or shift primary frequencies away from the forcing functions.

6.2 TEST SITE

The test site in Waitsfield, Vermont is located about seven miles from the North Wind factory (Figure 10). The site has fairly good exposure to the prevailing north and west winds, but, according to kite anemometer tests, this could have been improved markedly by going to an 80 or 100-foot tower. Site anemometry indicated an 8 mph annual average at the 60 foot height.

A reinforced concrete foundation 10'x6'x5' was installed to support the wind turbine. Three guy anchors 3'x3'x3' were also installed 43 feet from the tower base (Figure 3).

The tower erection procedure takes about twenty minutes and can be performed by two people. The tower and machine are tilted up with an 8000 lb. capacity electric winch using a 40 ft. gin pole (Figures 11 and 12).

The 4kW prototype was first installed at the test site in August 1981.

6.3 TEST PROGRAM SCHEDULING

For the performance testing, the program was broken down into two segments. The first segment was the testing with the first alternator which had a peak power capacity of 2.3kW. This segment of the test program was devoted primarily to understanding the control system in the unloaded operating mode. In January of 1982, the new 48 pole 40 $\frac{1}{4}$ " alternator with a 6kW rating was installed on the prototype. With this new configuration, the second segment of testing was undertaken concentrating on understanding the control system in the fully loaded mode.

The primary performance test objectives were power curve documentation and operational evaluation of the control system in the loaded mode. Throughout the test program, the dynamic and structural concerns were being evaluated to better understand the system operation.

TABLE 2

AVAILABILITY CALCULATION

Series No.	Sub-Assembly	TD	+	RT	+	TTR	=	MTTR	x	Lambda	=	DT
100	Drive Train	24		120		16		160		.030		4.8
200	Rotor	24		120		5		149		.025		3.7
300	Control Linkage	24		120		4		148		.041		6.1
400	Carriage	24		340		32		396		.032		12.7
500	Alternator	24		340		20		384		.011		4.2
600	Tower Hardware	24		340		32		396		.009		3.6
700	Tower	24		340		48		412		.006		2.5
800	Electrics	24		120		4		148		.008		1.2
900	Electronic Controls	24		120		4		148		.037		5.5
1300	Manual Shutdown	24		120		3		147		.012		<u>1.8</u>
Total Downtime =												46.1
Availability =												99.5%
												$\frac{8,760 - 46.1}{8,760}$

LEGEND:

TD - Time to Detect & Diagnose (hours)
 RT - Time to Obtain Necessary Parts
 TTR - Time to Repair
 MTTR - Mean Time to Repair
 Lambda - Failure Rate (Phase I Analysis)
 DT - Downtime

Figure 10

North Wind 4 kW at Test Site

Figure 11
Tower Erection Procedure

Figure 12
Tower Erection Procedure

6.4 TEST PROGRAM CONCLUSIONS & DISCUSSION

6.4.1 DYNAMICS

Natural frequencies of the 4kW prototype system were determined experimentally. They are presented in Figure 13 in Campbell plot form.

An important problem can be identified on the Campbell plot. The tower 2nd bending frequency is at 4.9 Hz, very close to the 5.0 Hz, 2 per revolution input frequency at synchronous speed. In operation, this mode is very noticeable and is potentially serious in terms of fatigue life. The situation was improved slightly by the installation of a second set of guys at a height of 25 feet. This increased the 2nd bending frequency to 5.3 Hz which reduced the severity of the tower shake at synchronous speed. This problem was not predicted by the Phase I tower analysis. The prototype tower is red cedar which is lighter and less stiff than other Class 1 pole materials. Cedar poles will be avoided for future installations.

6.4.2 ALTERNATOR TESTING

The 40½" 48 pole salient alternator was finished in early January 1982. Due to the limited capacity of the North Wind dynamometer, full bench testing could not be performed before installing the alternator in the 4kW prototype. The dynamometer tests did demonstrate that, as in previous versions, the 48 pole alternator synchronized easily to the grid regardless of phase angle, and at ±20% rated voltage and RPM. The alternator was only loaded to 4kW for steady-state operation, and to 7kW for short periods of time. This gave enough operational experience to lend confidence to field testing. In subsequent field operation, a peak alternator output of 9.5kW at .95 power factor has been documented and operation at 5-8kW with a unity power factor for several hours at a time has been recorded.

Typical voltage and current wave forms were documented during operation and are shown in Figure 14. Figure 15 illustrates the current envelope when the unit is synchronized in phase (Figure 15a) and 180 degrees out of phase (Figure 15b). The current ripple prevalent in both wave forms is a result of the low drive train frequency which, during these tests, was undamped. Dampers were later added to eliminate this ringing phenomenon. The current transient shown in Figure 15b represents the worst case transient possible for the machine in normal operation. This transient condition does not present a problem for electronic control equipment. It could, however, create a minor disturbance (brief flickering of lights, etc.) to the SWECS owner if the utility grid is particularly susceptible to such conditions.

It was found during the synchronized tests with the early 24" alternator that the motoring power required to keep the rotor at 150 RPM during momentary lulls in the wind was higher than the alternator's motoring capability. This would cause the unit to be pulled off the grid while energized. This was considered unacceptable. Two solutions were proposed; (1) using another electronic sensor to disengage the unit from the grid during any momentary lulls or (2) installing a

Figure 13
North Wind 4 kW Campbell Plot

WAVE FORMS

Figure 14a- No Load Voltage at
150 RPM (340V p/p).

Figure 14b- Alternator Current
3-4 Kw Output; Base
Level Field.

CURRENT TRANSIENT

Figure 15a- Current Envelope during Synchronization - In Phase with Grid

Figure 15b- Current Envelope during Synchronization - 180 degrees Out of Phase

one-way clutch. The one way or overriding clutch would allow the alternator to motor itself at 150 RPM while the rotor could slow down and was selected as it maximized energy gain in light winds since the system was always ready for short pulses of power. Additionally, it eliminated numerous control logic "on" sequences thereby sparing the contactor and electronics from a large number of cycles.

When the larger output alternator was installed, a one-way clutch was added to the drive train. The control logic was modified to account for the operating scenario. Primarily, this was done in the "off" function. The "off" criteria was set as the amount of time the unit motored. Motoring the alternator alone draws 250 watts. When motoring is sensed for a preset time period, the main contactor is opened and the unit is electrically shut down. The prototype was operated in this configuration with good results during the second segment of the test program.

6.4.3 POWER OUTPUT

Rocky Flats personnel performed a test evaluation on the 4kW prototype in April 1982. Power data was taken which will be compared to the testing planned at Rocky Flats after the Phase II program. The affects of altitude on machine performance will be evaluated and compared with theory.

Data was taken using a computer data acquisition system with 1 second sampling. Both loaded and unloaded data were taken. The following parameters were monitored:

- 1) V_{∞} (m/sec)
- 2) power (Watts)
- 3) RPM
- 4) wind azimuth angle
- 5) machine yaw angle
- 6) blade pitch angle
- 7) temperature ($^{\circ}$ C)
- 8) pressure (in. Hg.)

The power versus wind speed results are presented in Figure 16 along with control response for the same data base. These data were accumulated over approximately one week of running time using a method of bins program. Three cases with different control settings are shown. Case 2 is considered the normal setting of the control springs.

The power curve for Case 2 approaches the theoretical predicted curve reasonably well at low winds and falls short from 8 to 11 m/s. This under-shooting in power is due to excessive feathering of the blades. The spring/cams control system designed and built could not deliver the specified pitch schedule accurately enough. Modification of control system elements is possible to improve the accuracy of the pitch schedule. However, there is clear evidence that the control system works to limit power.

The power output curve is graphic proof that the blade's aerodynamic

performance may be slightly better than predicted due to higher power output in low winds. Electrical generating efficiency had been previously confirmed during dynamometer tests. More test information is presented in the Appendix A.

6.4.4 MECHANICAL PITCH CONTROLS

The passive mechanical pitch control uses a spring/cam assembly loaded by the blade pitch moment to deliver the desired pitch schedule. Several iterations were needed to develop the exact cam geometry, spring rate and preload to obtain the desired pitch schedule. When testing first began, the control forces were found to be significantly higher than those originally predicted. Upon reexamination of the computer predictor, several deviations between predicted and "as built" values were found. These include some very critical values of blade weight and c.g. location as well as pitch axis offset. These original assumptions all contributed to low values for blade pitch moment. Appropriate "as built" values were subsequently used in the computer code and the spring/cam system was modified. Satisfactory performance was obtained with the new mechanism as illustrated by the power curve in Figure 16.

During Phase I analysis, a pitch/flap instability was predicted for the control system. To eliminate the instability, damping was added to the blade pitch motion. Pitch dampers were originally placed on each blade shaft. These dampers were adjustable and an evaluation of the required damping was initiated. To test the computer prediction and after numerous hours of safe operation, the pitch dampers were removed. The prototype was operated for several days in winds to 8 m/s without incident. However, on March 26, 1982, with winds to 12 m/sec, an aeroelastic event which can be characterized as a divergence was observed. Running unloaded near 150 RPM, the blades would suddenly pitch a full 85° and return within about 1.5 seconds. This behavior was accompanied by severe tower bending with a deflection at the tower top of approximately 5 feet from the neutral position. This process occurred periodically with a frequency of about .2 Hz. No similar occurrences were noted while the unit was operating with pitch damping.

While pitch damping is effective in eliminating any potential pitch/flap instabilities, it was found that higher damping rates slowed the control response sufficiently to adversely affect energy capture. From the standpoint of both aeroelastic stability and rapid control response, it was found that one-way damping, as the blades feather from the full run position, gave the best results. Any significant damping on the return motion results in a slow response time. During the program, the Houdaille rotary dampers in the pitch tubes were replaced by one-way linear dampers acting on the spool control arms (Figure 17).

Operation with the one-way dampers on the spool provided a better configuration for numerous reasons. The dampers were adequate to eliminate the aeroelastic instability, their primary function, when operated in the collective pitch motion. These dampers were placed in

V_{∞} vs. POWER

- 1-Springs Not Fully Loaded
- 2-Springs at Rated Tension
- 3-Springs Beyond Rated Tension

V_{∞} vs. PITCH

- 1-Springs Not Fully Loaded
- 2-Springs at Rated Tension
- 3-Springs Beyond Rated Tension

FIGURE 16

Figure 17
CONTROL ASSEMBLY

the non-rotating frame and represented a cost of approximately one fifth the cost of the rotary dampers employed in the blade pitch tube. The added simplicity, lower cost and more accessible location were the primary reasons for the change.

The passive rotor control system was also designed to limit rotor overspeed during unloaded operation. Unloaded tests of the controls were run for each control configuration. Safe RPM levels were always maintained during the test program. During operation with a control setting that limited peak power to 8kW, the peak unloaded rotor speed was 190 RPM. The speed was much lower than the early prediction of 225 RPM for which the system had been designed.

6.4.5 YAW RESPONSE

In the second part of the test program, it became apparent that the prototype established poor yaw performance. The unit tended to run off the wind and during negative gusts or lulls it would yaw 90° or more from the wind azimuth angle. This behavior diminished somewhat in winds over 10 m/sec but was still significant. Energy capture was adversely effected by this phenomenon.

A yaw sensitivity test program was undertaken to study and document the prototype's yaw behavior. During the first part of the test program, no yaw tracking errors were noticed. When the larger alternator was installed, several changes were made. This necessitated a program for systematically evaluating the changes and isolating which change or changes caused the yaw misalignment. Initially, the primary variable was thought to be the impact of the larger alternator in c.g. location and aerodynamic response. Other suspected causes included tower deflections, and changes in rotor configuration, control elements and the main shaft tilt angle.

The first conclusion reached was that the rotor itself was generating the yaw tracking error, i.e. the rotor wanted to run off the wind. This focused the efforts on understanding rotor behavior and artificially inducing variations to rotor degrees of freedom and blade setting. Since the yaw instability was more pronounced in lighter winds, the rotor control system was not suspect. A larger tail vane was added but no noticeable improvement occurred once the rotor was running. The larger tail did help the unit orient prior to rotor start-up (wind less than 3 m/s).

During the course of the test program, it was found that increasing teeter damping reduced the severity of the tracking error. Teeter damping was introduced by reinstalling the Houdaille rotary dampers on the pitch shaft. While these dampers were primarily thought of as pitch dampers, they also provided damping to teeter motion due to delta three coupling. Pitch stops of hard rubber, which effectively increase the teeter spring constant and also limited total teeter motion to ± 1 degree, were installed next. This change seemed to eliminate the yaw problem. The SWECS then yawed quickly in either direction in response to changes in wind direction.

As a result of the yaw sensitivity study, it was concluded that the instability was related to cyclic pitch of the blades. It was determined that the problem arises from the teeter-pitch coupling due to $\Delta 3$. Teeter vs. blade azimuth position traces for the rotor at both low (hand turned) and running speeds are shown in Figure 18. Note that the maximum teeter deflection occurs with the blades in a horizontal position. This is due to a gravity-induced blade moment coupling to teeter. Refer to Figure 19. When the blades are in a horizontal position, a moment about each pitch axis is present due to gravity-induced forces. These pitch moments are resolved into moments about the teeter axis due to $\Delta 3$ coupling. Because the gravity-induced pitch moments are in opposite directions, the resulting teeter moments for each blade are additive. Blade "B" (Figure 19) teeters toward the wind and Blade "A" away. In practice, the teeter due to this phenomenon was about 3° from the neutral position with blade angle changes of $+2^\circ$ and -2° for blades "A" and "B" respectively. The non-equal blade angles result in non-equal thrusts on the two blades. This non-symmetrical thrust pattern, which occurs when the blades are horizontal, results in a net moment about the yaw axis which causes the machine to run off-wind.

From the information gained in this investigation, specific design changes can be recommended with the confidence that they will improve the yaw performance to an acceptable level, without resorting to teeter damping. Specifically, the $\Delta 3$ angle should be reduced from a present level of 30° to 10° or less, and the teeter spring rate should be increased significantly. It is expected that these modifications will result in good yaw performance.

Due to the complexities of the machine "as built", it was difficult to effect the optimum solution after the problem had been identified. Therefore, the prototype was configured with the rotary dampers on the pitch shaft as the best configuration within the scope of this program.

6.4.6 DRIVE TRAIN

In the first segment of the test program, the drive train was composed of the main shaft and the elastomeric coupling to the alternator. This configuration worked adequately but some significant improvements were made during the second segment of the test program which were incorporated when the larger alternator was installed. The drive train modifications were (1) the addition of damping across the elastomeric coupling to eliminate the 1 to 2kW power ripple as noted in Figure 15 a and b and (2) the placement of a one-way clutch to disengage the rotor from the alternator. Since the alternator could then run at a different speed than the rotor, this required adding separate alternator bearings.

Operation with the new drive train was significantly improved. Power quality was greatly enhanced and damping of power transients was accomplished in 3 to 4 cycles. Decoupling the rotor and the alternator improved energy capture in light winds, simplified the electronic control logic and decreased alternator motoring current.

Teeter Angle
($3.5^\circ/\text{cm}$)

Blade Azimuth
Indicator
(Blade B @
9:00 o'clock)

Teeter Angle vs. Blade Azimuth Angle
Rotor Turned by Hand
(Blade B)

Teeter Angle
($3.5^\circ/\text{cm}$)

Blade Azimuth
Indicator
(Blade B @
9:00 o'clock)

Teeter Angle vs. Blade Azimuth Angle
Running Speed (Blade B)

FIGURE 18

Teeter Moments for Blades

FIGURE 19

7.0 CONCLUDING REMARKS

The North Wind Power Company 4kW SWECS, which was conceived and designed during Phase I of the contract, was successfully fabricated and tested during Phase II. The innovative features of the design were validated during the test program. Within the scope of the test program, the slow-speed, direct-drive, synchronous alternator designed for this machine was shown to be a reliable, practical and efficient design and the passive mechanical blade pitch control system demonstrated its simplicity, accuracy and reliability.

The problems encountered during the test program were for the most part of a minor nature. The exceptions were the yaw performance and the tower dynamics. The factors impacting the yaw performance were investigated and solutions proposed. These solutions, which include a reduction of the $\Delta 3$ angle and a stiffening of the teeter elastomerics, will be incorporated on the production version of this machine. The tower dynamics problem indicated the need for sophisticated analysis of tower structures for 2nd and higher order natural frequencies for adherence to rigid specifications for material selection.

The 4kW met the design requirements for related power and energy capture. All systems operated as designed, substantially confirming the innovative design concepts developed throughout the program.

8.0 REFERENCES

1. Coleman, C., and Mayer, D. J., North Wind 4 Kilowatt Wind System Development Phase I - Design and Analysis, North Wind Power Co., Inc, May 1982. (RFP-3424-1 and RFP-3424-2).

APPENDIX A

RESULTS OF RF TESTING

Atmospheric testing of the North Wind 4 kW prototype was accomplished by RF personnel at Waitsfield, Vermont during April, 1982. Major objectives of this effort were to ensure that design specifications for power output--after the alternator design was changed--were met and to enable a proper close-out of the development contract in compliance with DOE instruction to terminate prototype contracts. A secondary objective of testing was to collect performance data at a lower altitude for comparison with those obtained at RF (approximately 1830 m [6000 ft] above sea level).

Since the prototype was in the process of being tested by North Wind, it was already installed on an 18.3 m (60 ft) red cedar tower. The site is approximately 381 m (1250 ft) above sea level. RF mobile instrumentation/data collection equipment, which had been previously employed in remote tests, was used during testing.

The machine mainframe attachment had recently been modified to 8° of tilt. This was done to minimize teeter-induced cyclic force imbalance. A new spring assembly had also been installed for rotor control. The field controller (necessary to allow unattended operation) was being bench tested and was not used during testing. After calibration of instrumentation and a thorough examination of the machine, testing was ready to begin.

Initial testing of the North Wind prototype showed that the unit would startup in winds of 3-4 m/s (7-9 mph). Immediately after startup, however, the rotor would yaw 90° out of the wind and remain in that position until the blades were manually feathered. If the machine was allowed to startup again, the same behavior was observed.

After investigation into this problem, the manufacturer decided there were two possible causes: 1) excessive $\Delta 3$ response to rotor teeter motion, and 2) a lack of aerodynamic stability. It was conjectured that the $\Delta 3$

response problem might be alleviated by installing Houdaille hydraulic pitch dampers at the blade roots. Parts to install these dampers were in-house.¹ It was the manufacturer's opinion that yaw stability might be enhanced by simply increasing the nacelle tail fin area.

The first period of prototype testing with the dampers installed was accomplished with winds averaging 2-12 m/s (5-27 mph). The machine still exhibited a tendency to yaw out of the winds in speeds up to 7 m/s (16 mph), but showed improved tracking in winds above this range (Figure 20). The absence of the field controller created another problem during this initial test period. The field current settings had to be constantly adjusted to prevent the alternator from "slipping poles" during motoring or at high power output levels. This made it impossible to leave the system unattended, even for a short period of time.

Shortly thereafter, the larger nacelle tail fin was installed and testing resumed. Over thirteen hours of data were obtained in winds up to 14 m/s (31 mph), and machine tracking was improved (Figure 21). Nevertheless, as explained in Section 6.4.5, later investigations of yaw response showed that added damping and stability were not totally adequate solutions. Instead, a reduction of $\Delta 3$ angle and an increase in the teeter spring rate were recommended for any future designs. Incorporation of these changes was not within the scope of the prototype development program.

The only problem encountered during the remainder of testing was with the winch cable, which snapped at the tower top where it connects to the chain-spring assembly. A thimble was installed where the cable bends around the lowest chain link to prevent a recurrence.

1. The original prototype design had included Houdaille dampers in the hub assembly. However, negative effects on teeter motion and stress levels in the pitch links had warranted their removal. They were replaced by shock absorbers between the mainframe and spool bearings.

All data presented herein were obtained with the system interconnected to the utility; with the modified tail fin (except for comparative plot in Figure 24); and with the spring tension setting--which controls blade feathering--optimized. A number of different spring settings were tried (through trial and error) during testing. Some of these settings had significant effects on system power output. All data were reduced and analyzed using the "method-of-bins" technique.² Adjustment to standard day conditions was accomplished on a point-to-point basis.³

Figure 22 reflects power output prior to adjustment to standard day conditions and is derived from over 20,000 individual data points. The differences between Figure 22 and the same curve adjusted to sea level (Figure 23) are extremely small. Power output at the rated wind speed of 9.4 m/s (21 mph) is approximately 5.1 kW for both curves.

Figure 24 compares adjusted power output of the North Wind prototype with and without the modified nacelle tail fin. The difference between the two configurations at rated wind speed is approximately 1.3 kW (3.8 kW vs. 5.1 kW). This fact indicates improved yaw stability had a significant impact on system performance. Table 3 shows that predicted annual energy output of the prototype with the modified tail meets the design specification of 7500 to 15000 kWh/yr at an average wind speed of 4.47 m/s (10 mph).

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2. Akins, R.E., Performance Evaluation of Wind Energy Conversion Systems Using the Method-of-Bins - Current Status, March 1978, Sandia Laboratories (SAND 77-1375).
 3. Hansen, A.C., "Adjustment of SWECS Power Curves for Air Density Variations," Wind Systems Technical Notes; 1979-1980, Feb. 1982, pp. 39-49, Rockwell International Corporation, Rocky Flats Plant (RFP-3339).

Figure 20

Yaw Tracking Error (Original Tail Fin)

Figure 21

Yaw Tracking Error (Modified Tail Fin)

Figure 22

Power vs. Wind Speed
(Unadjusted - 1250' above Sea Level)

Figure 23

Power vs. Wind Speed
(Adjusted to Standard Day Conditions)

Figure 24

Comparison of Adjusted Power vs. Wind Speed
(Original and Modified Tail Fins)

TABLE 3

ESTIMATED ANNUAL ENERGY PRODUCTION
(Using a Rayleigh Wind Distribution)

Average Wind Velocity		Annual Energy Output
(m/s)	(mph)	(kWh)
3.58	8	8230
4.47	10	13180
5.36	12	17850
6.26	14	21420
7.15	16	23490

NOTE: The annual energy output is based on the adjusted RF power curve for the North Wind 4 kW. The power curve is superimposed on the Rayleigh Wind Distribution (velocity duration curve) generating a power duration curve which is then integrated over time to obtain energy. Data contained in Table 3 are adjusted to sea level.