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Projektleitung Energieforschung
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Implementing Agreement for Co-Operation in the Development of Large Scale Wind Energy Conversion Systems

10th Meeting of Experts – Utility and Operational Experiences and Issues from Major Wind Installations

Organised by:
Project Management for Energy Research (PLE) of the
Nuclear Research Establishment Jülich (KFA) on behalf of the
Federal Minister of Research and Technology,
the Fluid Mechanics Department
of the Technical University of Denmark
and the Electric Power Research Institute,
Palo Alto, California

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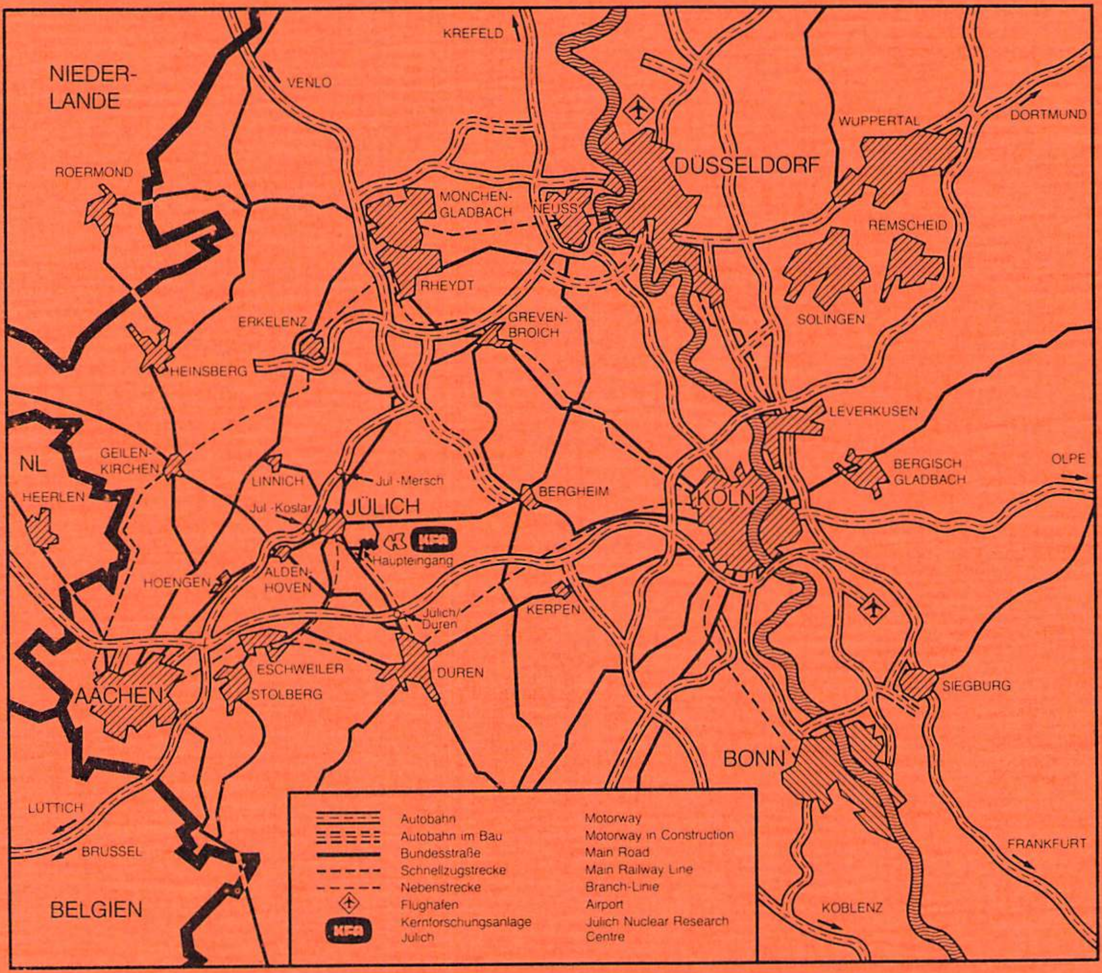

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CONTENTS

Contributions from

UTILITY OPERATING EXPERIENCES AND ISSUES WITH LARGE-SCALE WIND ENERGY UTILIZATION

by

W. A. Vachon
Arthur D. Little, Inc.
Cambridge, Massachusetts USA 02140

INTRODUCTION

At the present time, there are approximately 10 megawatt-scale wind turbines that are operational in the world, and these machines are primarily intended for operation by utilities. Seven of the machines are located in the United States, with the remainder in Sweden and West Germany. The first such unit was installed approximately three years ago. Since then, these machines have accumulated approximately 6,000 hours of test operating time. The major reason why so little operating time has been logged when compared to expected levels is that many components and systems proved unreliable or actually failed.

Concurrently, approximately 3,000 machines with rated powers of 20 kW to 1 MW have also been installed; many of them arranged in clusters with as few as five to as many as several hundred units. The vast majority (>95 percent) of machines in this size range have a rated power below 100 kW. The total amount of on-line service for these machines cannot be accurately estimated, but some units may have accumulated 10,000 to 20,000 hours of operating time on them.

In general, the major questions resulting from all this hardware experience are:

(1) What has been learned?

(2) Were test results consistent with expectations?

(3) What new developments are required?

The brief summary that follows will put some of these overall questions relating to test results in perspective by providing a series of more specific questions aimed at meeting the needs of electric utilities involved in the purchase and installation of, and interface with, wind power systems.

RELIABILITY AND MAINTAINABILITY QUESTIONS

(1) Have the reliability and availability of wind turbines increased in a manner that is consistent with the normal engineering process associated with a new technology?

(2) Has a statistical reliability data base been developed yet for machines of any size or type? If so, what do the data indicate?

(3) Can wind turbines be maintained by normal utility powerplant service personnel, or is a higher level of qualification required?

(4) What is the difference in operation and maintenance (O&M) costs and manpower requirements per MWh generated for small-scale machines ($\leq$100 kW) versus megawatt-scale units?

(5) What logistics, manning, and spare parts approaches are best for maintaining wind turbine clusters?

WIND TURBINE INTERCONNECTION QUESTIONS

(1) What are the best approaches for integrating, relaying, and coordinating the utility connection of synchronous and induction generators, as well as line-commutated inverters at the transmission, subtransmission, or distribution level of a utility?

(2) How should individual wind turbines be controlled to minimize transient effects on the network?

(3) What schemes are recommended for interconnecting several hundred (even thousands) of 50- to 100-kW induction generators to various types of networks?

(4) How is reliability of conventional utility generation, transmission, and distribution equipment affected by the introduction of wind turbines in the network?

(5) Have there been any unusual adverse interactions between wind turbines and the network caused by voltage or power swings by either the wind turbine or the network?

(6) Have any network problems or customer complaints resulted from the interconnection and operation of wind farms in California? If so, how were the problems addressed and overcome?

WIND TURBINE CONTROL AND DISPATCH QUESTIONS

(1) What guidelines have been developed for defining spinning reserve requirements for networks in which a high penetration of wind power is expected?

(2) Have any problems with harmonics or local voltage control been identified?

(3) Of the several methods used to control the speed and power output of wind turbines and to damp out drivetrain and other oscillations, which approaches hold the most promise for long-term reliable operation of machines?

ENGINEERING AND DESIGN QUESTIONS

(1) What is the status of our engineering knowledge that can be used to predict loads, vibrations (accelerations), and the expected life for horizontal-axis wind turbines (HAWT's) of all sizes?

(2) How accurate are wind turbine lifetime predictions based on fatigue estimates derived from discrete gust models?

(3) Has the technology of vertical-axis wind turbines (VAWT's) reached a level of maturity at which solutions to key engineering problems associated with aerodynamics, dynamics, and controls are sufficiently advanced that reliable hardware can be produced?

(4) Can wind turbines, especially megawatt-scale units, be simplified so that there may be a greater probability of meeting reliability and availability targets?

(5) Now that more is known about the construction processes and costs for HAWT blades, does a three-bladed, megawatt-scale machine make more sense from dynamics, reliability, and overall cost viewpoints than a two-bladed unit?

PERFORMANCE-RELATED QUESTIONS

(1) What are the best methods for evaluating the performance (i.e., power curve) of wind turbines at the engineering prototype and acceptance test levels?

(2) How accurate are estimates of annual energy production based on measured wind data, a wind turbine power curve, real-time control issues (i.e., startup and shutdown losses) and cluster wake losses?

ECONOMIC QUESTIONS

(1) If engineering and reliability goals for megawatt-scale machines are met, what is the probability that cost-of-energy (COE) targets will be met?

(2) How would the widespread introduction of wind turbines in a network influence the economics of utility operations planning and real-time operations?

GENERAL

We hope that this series of questions will prove helpful in identifying the major issues that should be addressed by the IEA Experts Meeting.

OVERVIEW

UTILITY OPERATING EXPERIENCES AND ISSUES WITH LARGE-SCALE WIND ENERGY UTILIZATION

BY

W. A. VACHON
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CAMBRIDGE, MA 02140 USA

PRESENTED AT THE IEA EXPERTS MEETING ON
UTILITY OPERATING EXPERIENCES

PALO ALTO, CALIFORNIA
OCTOBER 12-14, 1983

MOD-2 PERFORMANCE BREAKDOWN

(SEPTEMBER 23, 1983)

MACHINE LOCATION	SYNCHRONIZED HOURS	ENERGY (MWH)
GOODNOE HILLS-1	918	1,060.
GOODNOE HILLS-2	1,157	1,472.
GOODNOE HILLS-3	1,462	1,695.
MEDICINE BOW, WY	437	508.
SOLANO COUNTY	∿ 850	∿ 1,300.
TOTALS	∿4,824	∿ 6,035.

SUMMARY OF KEY OPERATIONAL LARGE-SCALE (> 1 MW) WIND SYSTEMS

COUNTRY	MACHINE DESIGNATION	LOCATION	PERFORMANCE TOTAL HOURS	ENERGY (MWH)
UNITED STATES	MOD-2	5 AT 3 LOCATIONS	4,824	6,035
UNITED STATES	WTS-4	MEDICINE BOW	437	724
UNITED STATES	SWT-3 (BENDIX)	PALM SPRINGS, CA	~ 370	164
SWEDEN	WTS-3	MAGLARP	~ 965	1,390
SWEDEN	KAMEWA	NÄSUDDEN	110	150
GERMANY	GROWIAN I	KAISER WILHELM KOOG	NOT YET OPERATIONAL	
		10 MACHINES (TOTAL)		

MAJOR QUESTIONS TO BE ADDRESSED WITH REGARD TO UTILITY OPERATING EXPERIENCES WITH LARGE-SCALE WIND SYSTEMS

- WHAT HAS BEEN LEARNED?
- WERE TEST RESULTS CONSISTENT WITH EXPECTATIONS?
  - WHERE DID DIFFERENCES ARISE?
  - CAN DIFFERENCES BE EXPLAINED?
- WHAT NEW DEVELOPMENTS ARE REQUIRED?
  - WHAT ARE THE MAJOR OUTSTANDING ISSUES?

TYPICAL UTILITY CONCERNS (ASSOCIATED WITH THE USE OF WIND POWER)

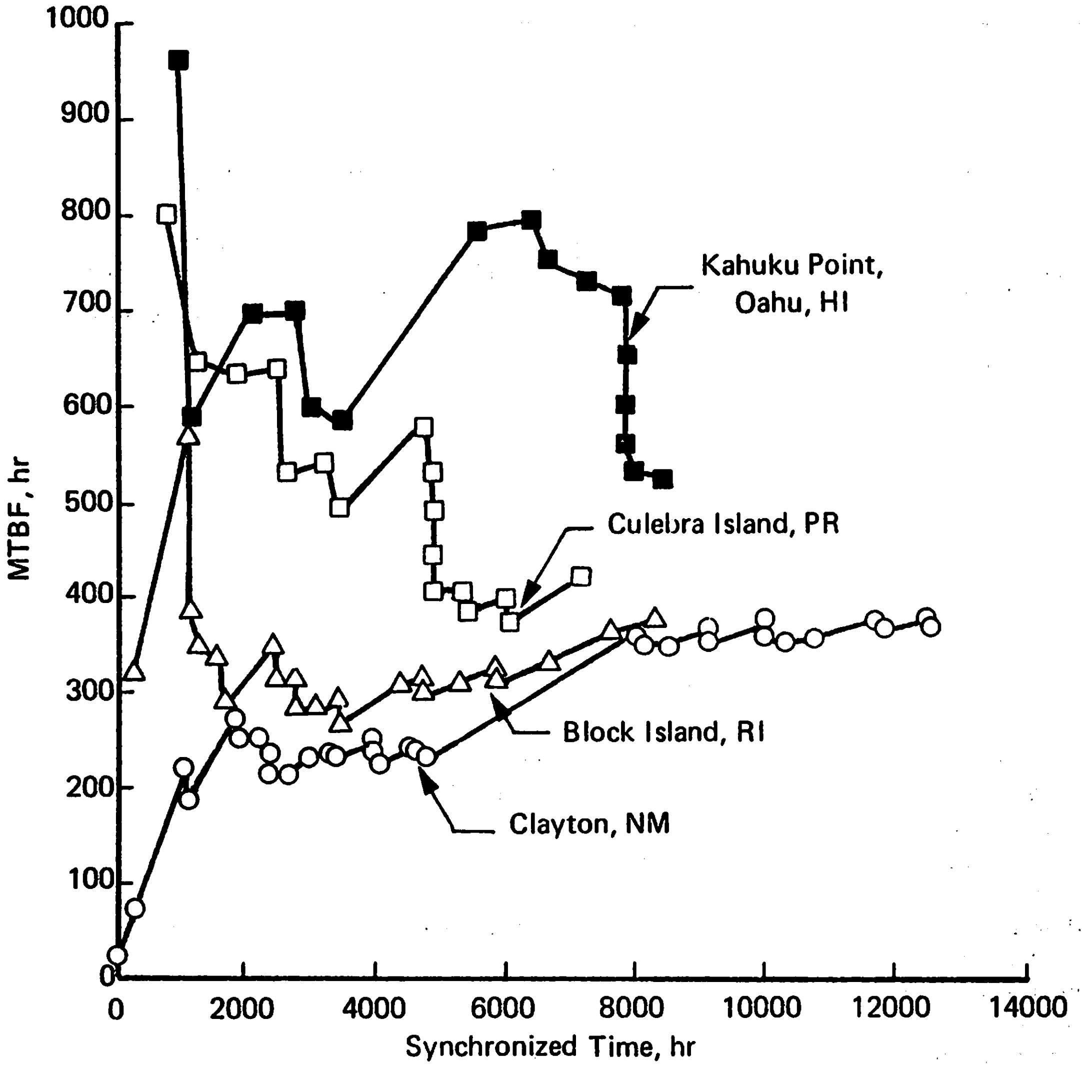
- QUALITY OF DELIVERY
  - STATIC AND DYNAMIC CONTROL
  - RELIABILITY
  - OPERATION & MAINTENANCE (O&M) COSTS
- COST OF SERVICE
  - GENERATION EXPANSION & REPLACEMENT
  - ECONOMIC DISPATCH
- SAFETY

TYPICAL UTILITY CUSTOMER CONCERNS

- VOLTAGE
  - LEVEL
  - RATE OF CHANGE (I.E., FLICKER)
- FREQUENCY
- HARMONIC CONTENT
- RELIABILITY
- COST OF SERVICE

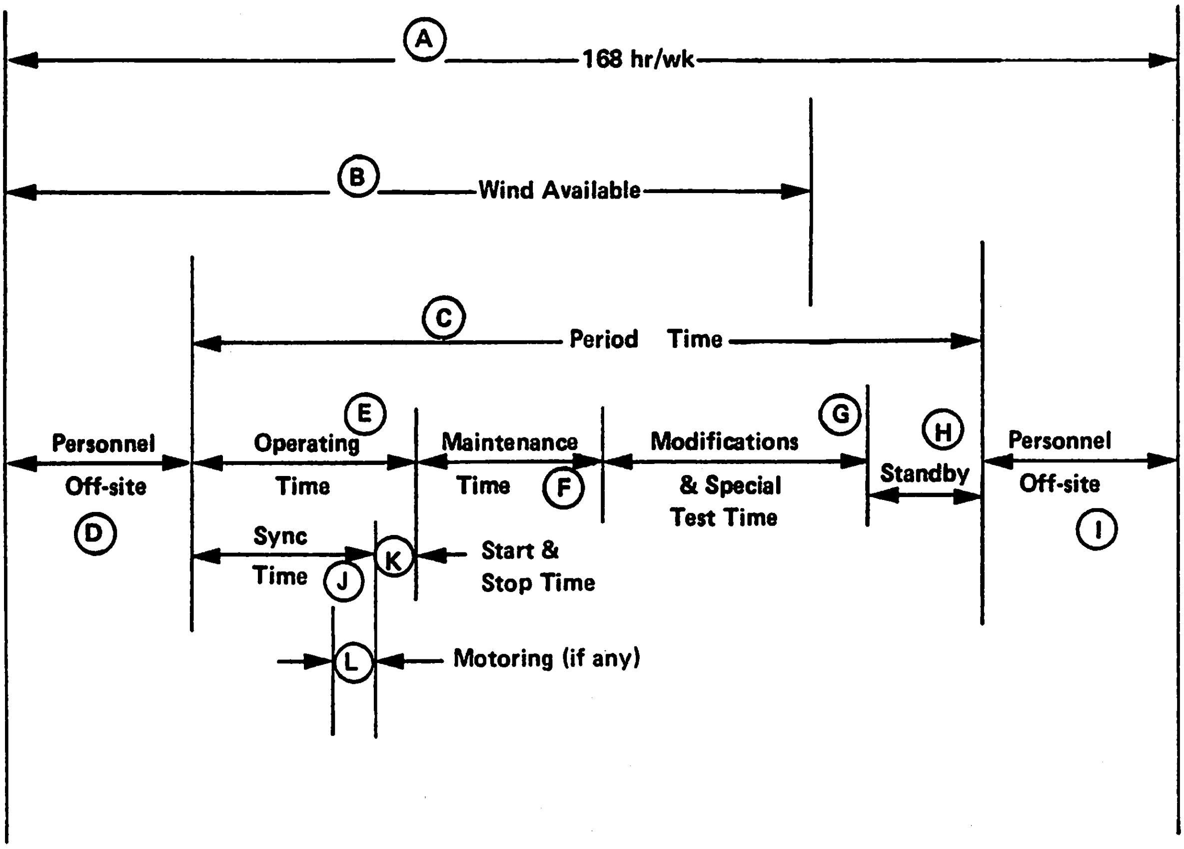
QUESTIONS ADDRESSING RELIABILITY & MAINTAINABILITY

- WHAT IS THE STATE OF OUR RELIABILITY DATA BASES?
  - FOR MEGAWATT-SCALE
  - FOR SUBMEGAWATT SCALE
- HAVE RELIABILITY AND AVAILABILITY OF LARGE-SCALE WIND SYSTEMS INCREASED IN AN EXPECTED MANNER FOR A NEW TECHNOLOGY?
- CAN WIND TURBINES BE MAINTAINED BY NORMAL UTILITY POWERPLANT SERVICE PERSONNEL?
- WHAT UNIQUE LOGISTICAL, MANNING, & SPARE PARTS APPROACHES APPEAR TO BE BEST?
- WHAT ARE O&M COST DIFFERENCES PER MWH AS A FUNCTION OF MACHINE SIZE?



Source: NASA

MEAN TIME BETWEEN FAILURE (MTBF) DATA FROM DOE/NASA MOD-0A 0.2-MW WIND TURBINES



A = Full Weekly Period = 168 Hours = D + E + F + G + H + I
B = Wind Available (Hours) = 168 x (Wind Available Fraction)
C = Period Time = Total Time that Personnel Are On-site = E + F + G + H
D = Personnel not On-site but Winds Available
E = Operating Time = Time WT is Rotating = J + K
F = Maintenance Time not Associated with WT as Research Tool
G = Modifications and Special Test Time = Time WT is Undergoing Design or Component Changes and/or Special Tests
H = Standby Time = WT Enabled and Waiting for Wind
I = Personnel not On-site and Winds not Available
J = Synchronous Operating Time (Positive or Negative Power)
K = Start and Stop Time = Rotation Time not Connected to Network
L = Motoring Time = Period When WT Acts as Motor (Usually in Winds near Cut-in Speed)

MOD-2 WEEKLY DATA REPORTING BREAKDOWN

MOD-2 WIND TURBINE PERFORMANCE PARAMETERS

- A_{wt} = WT MACHINE AVAILABILITY = $\dfrac{t_p - t_{st} - t_{mod} - t_{main}}{t_p}$ = (IDEALLY) $\dfrac{t_w}{t_p}$

- A'_{wt} = ADJUSTED WT MACHINE AVAILABILITY = $\dfrac{t_p - t_{st} - t_{mod} - t_{main}}{t_p - t_{st} - t_{mod}}$

WHERE: t_w = HOURS WHEN WIND IS BETWEEN CUT-IN AND CUT-OUT SPEED

t_p = HOURS OF PERIOD TIME; TOTAL TIME THAT PERSONNEL ARE ON-SITE = $t_o + t_{st} + t_{mod} + t_{main} + t_h$

t_{st} = HOURS OF DOWNTIME DUE TO SPECIAL TEST ACTIVITIES

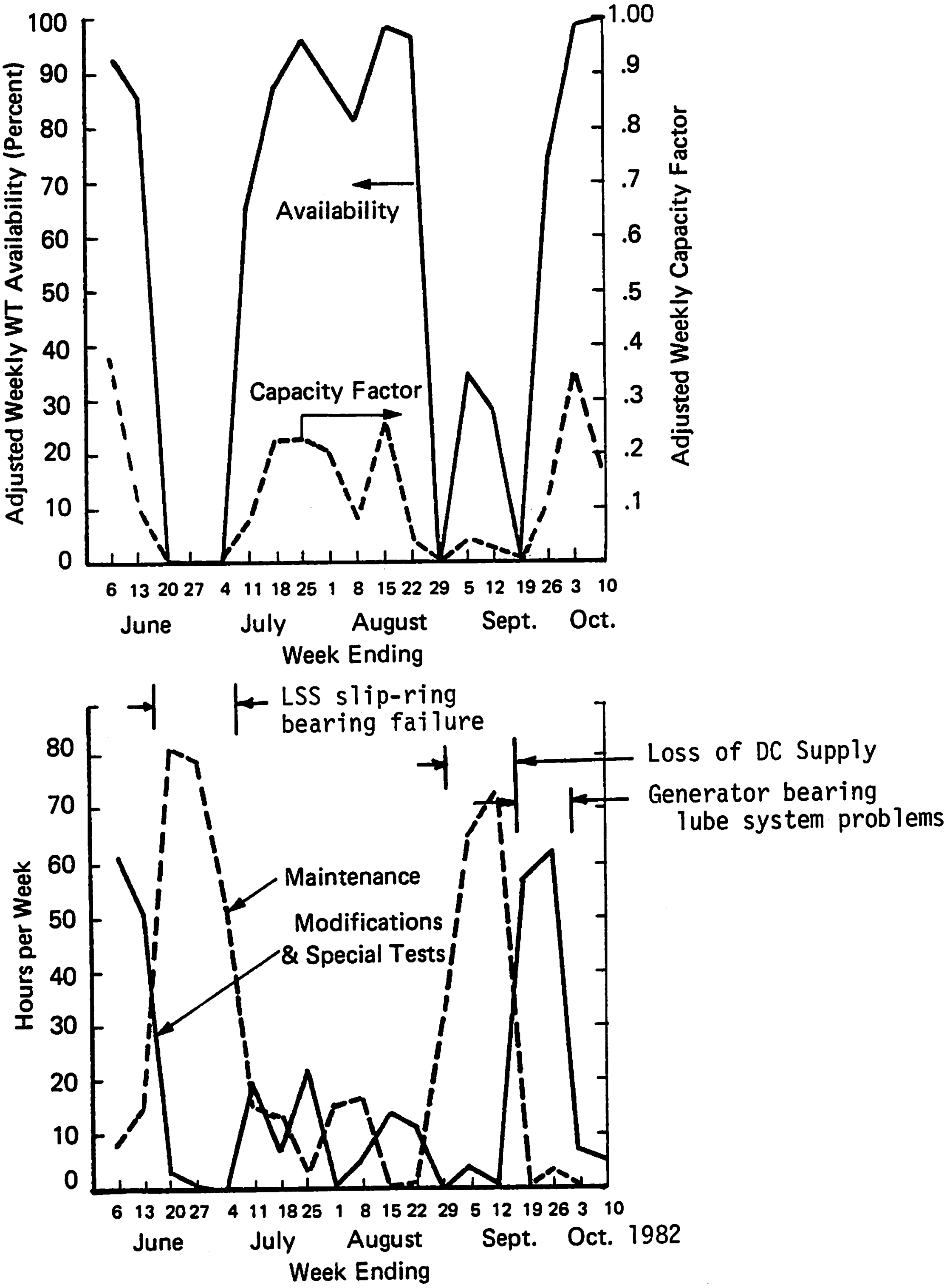
t_{mod} = HOURS OF DOWNTIME DUE TO MODIFICATIONS

t_{main} = HOURS OF DOWNTIME DUE TO MAINTENANCE ACTIVITIES

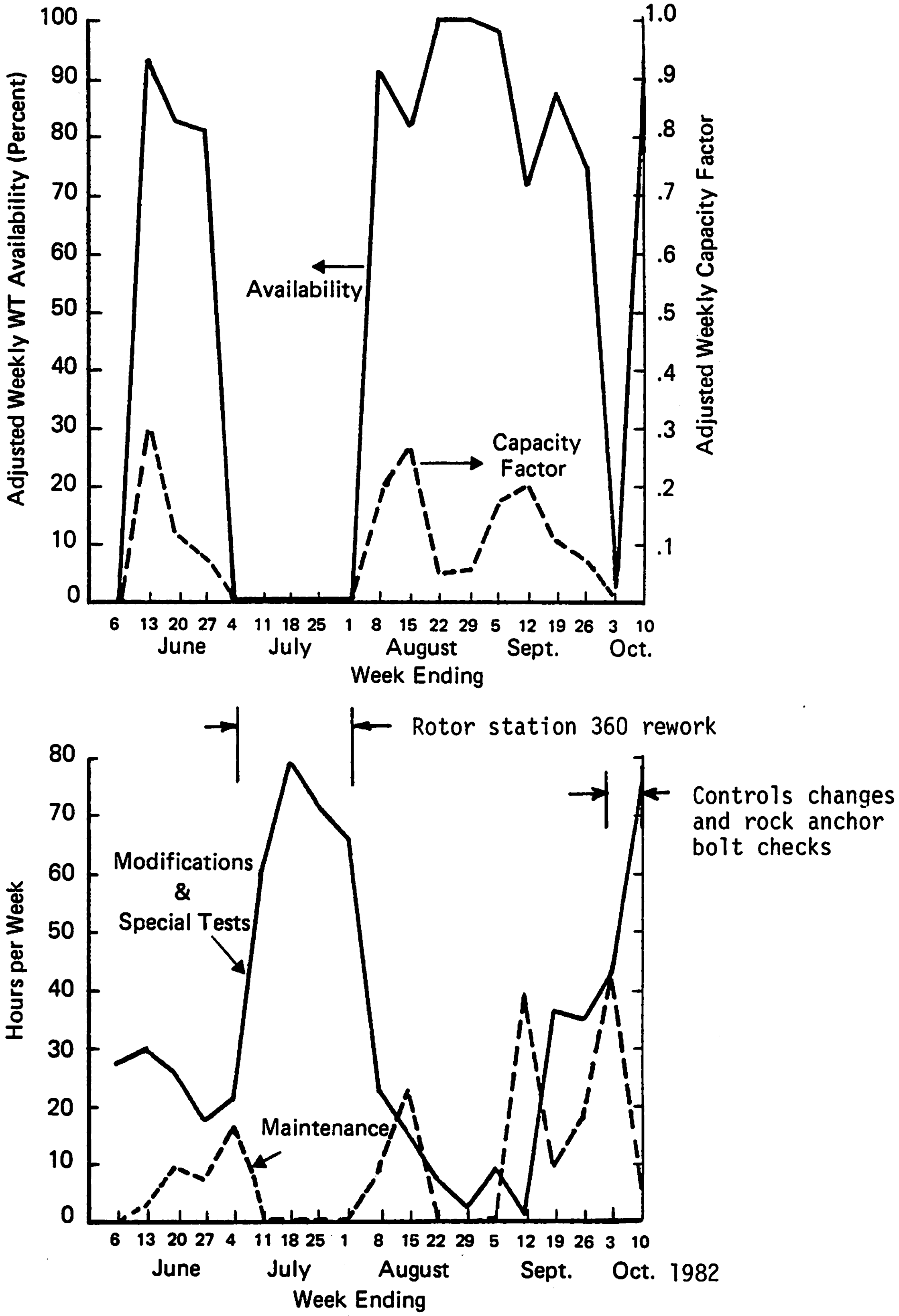
t_o = HOURS OF OPERATING TIME WITH WT ROTATING (SYNC + START/STOP)

t_h = HOURS OF STANDBY TIME; WT ENABLED AND WAITING FOR WIND

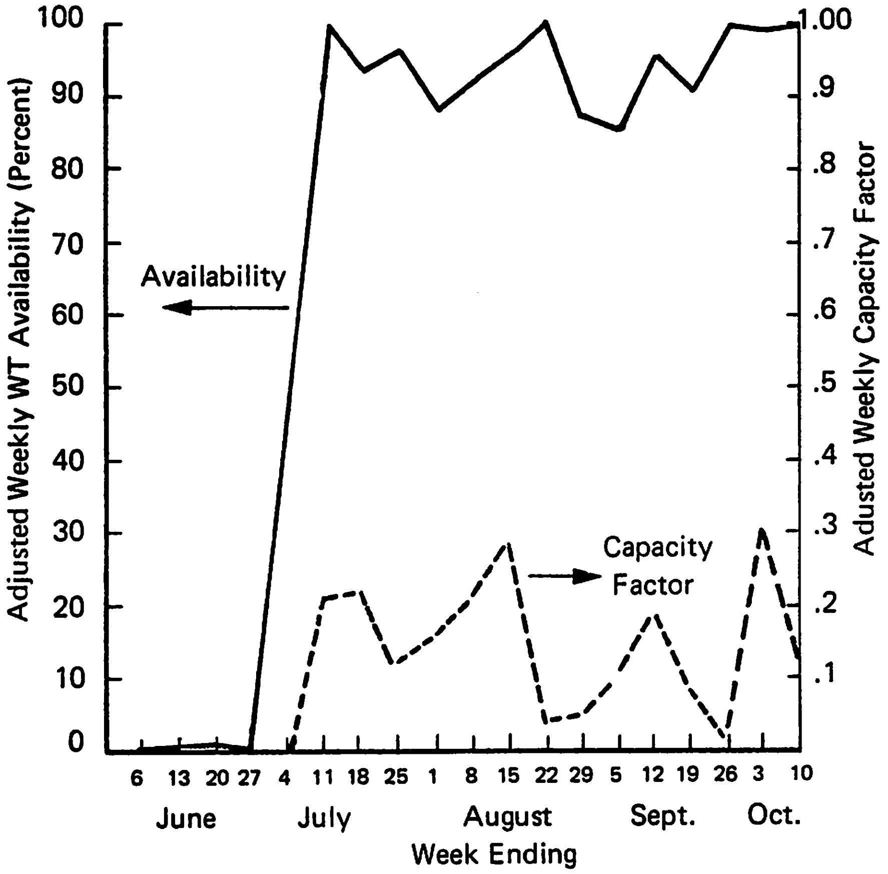
- ADJUSTED WEEKLY CAPACITY FACTOR = $\dfrac{\text{MWh generated in period } t_p}{2.5\text{ MW }(t_p - t_{st} - t_{mod})}$

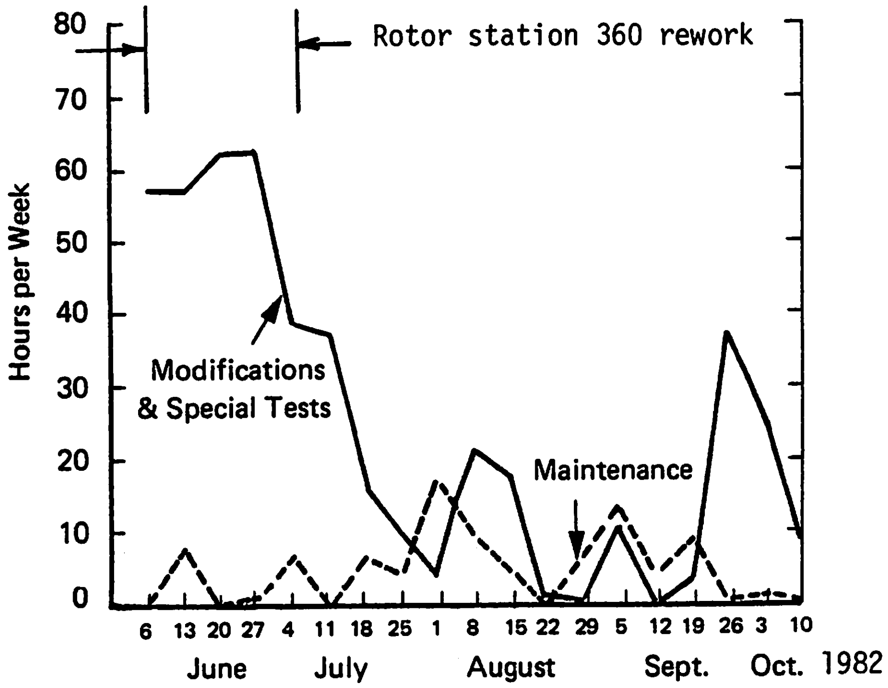


SUMMARY OF WEEKLY PERFORMANCE AND OUTAGE DATA FOR MOD-2, UNIT 1



SUMMARY OF WEEKLY PERFORMANCE AND OUTAGE DATA FOR MOD-2, UNIT 2





SUMMARY OF WEEKLY PERFORMANCE AND OUTAGE DATA FOR MOD-2, UNIT 3

WIND TURBINE CONTROL AND DISPATCH QUESTIONS

- HAVE ANY HARMONICS OR LOCAL VOLTAGE PROBLEMS BEEN IDENTIFIED ON LINES WITH SUBSTANTIAL WIND POWER INPUT?
  - CALIFORNIA WIND PARK EXPERIENCE VERY VALUABLE

- WHAT ARE THE MOST PROMISING OPTIONS FOR CONTROLLING WIND TURBINE SPEED AND POWER OUTPUT?
  - MUST ALSO DAMP OUT DRIVETRAIN & OTHER OSCILLATIONS
  - OPTIONS MUST INCORPORATE RELIABILITY CONCERNS

WIND TURBINE INTERCONNECTION QUESTIONS

- WHAT ARE THE BEST APPROACHES FOR INTERCONNECTING VERY MANY 50-TO-100-KW INDUCTION GENERATORS?
  - ANY PROBLEMS IN CALIFORNIA? REMEDIES?

- HAS THERE BEEN A SIGNIFICANT VARIATION IN RELIABILITY OF CONVENTIONAL GENERATORS AND T&D EQUIPMENT AS A RESULT OF INTRODUCING WIND SYSTEMS?

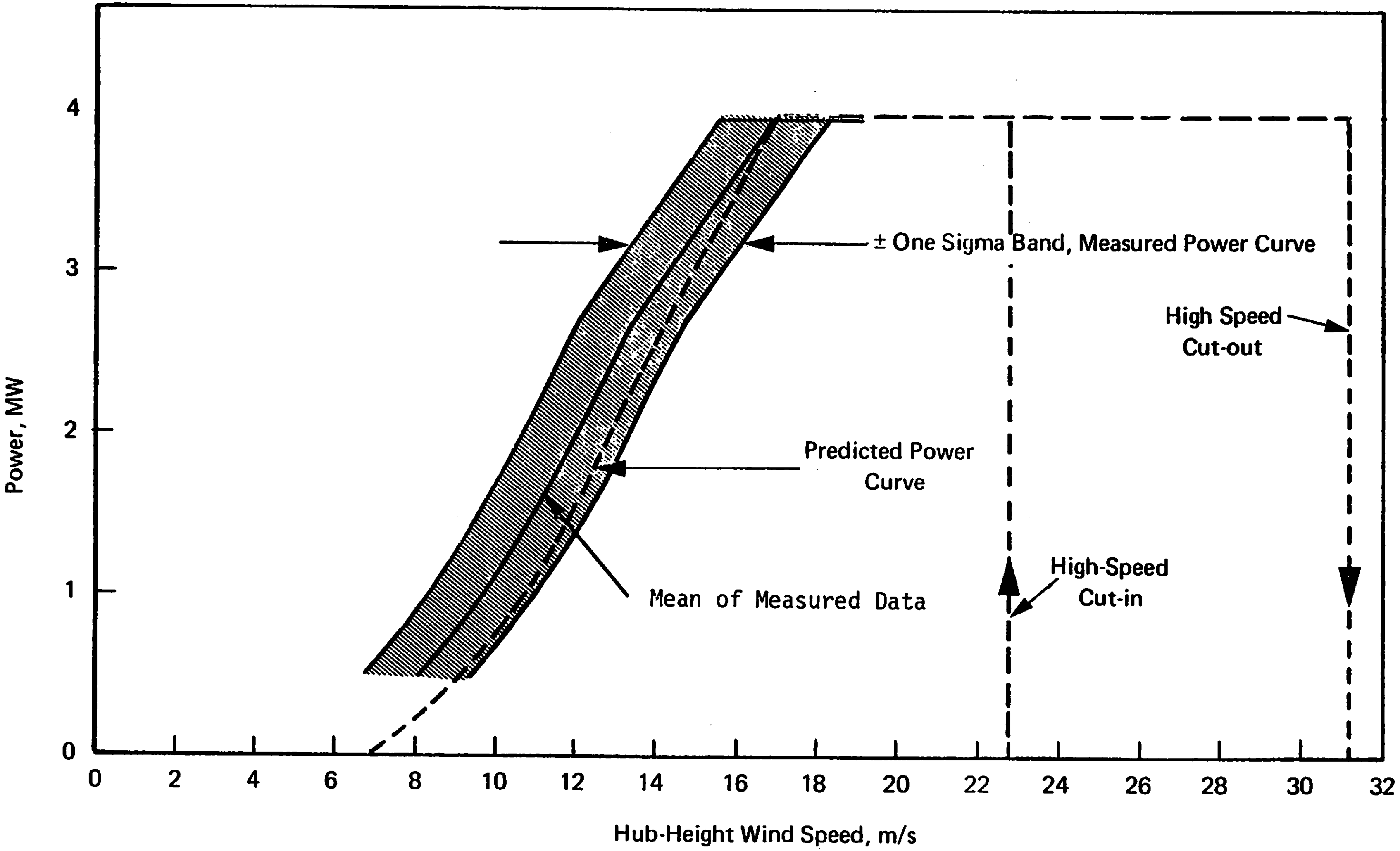
- WHAT APPROACHES AND EXPERIENCES WITH RELAYING AND FAULT PROTECTION HAVE BEEN DEVELOPED?
  - CLUSTERS OF ALL SIZES
  - ALL TYPES OF INTERFACES

ENGINEERING AND DESIGN QUESTIONS

- HOW ACCURATE ARE WIND TURBINE LIFETIME PREDICTIONS BASED ON FATIGUE ESTIMATES?
  - APPLIED MOST TO ROTOR, DRIVETRAIN, & TOWER
  - VALUE OF DISCRETE GUST MODELS
- CAN WIND TURBINES BE SIMPLIFIED TO INCREASE THE PROBABILITY OF MEETING RELIABILITY & AVAILABILITY TARGETS?
- DO TECHNICAL BENEFITS OF A THREE-BLADED HAWT ROTOR OUTWEIGH COST PENALTIES?
- HAS VERTICAL AXIS TECHNOLOGY ADVANCED FAR ENOUGH TO EXPECT THAT RELIABLE HARDWARE CAN BE PRODUCED?

PERFORMANCE AND ECONOMIC QUESTIONS

- WHAT ARE THE BEST METHODS FOR EVALUATING THE ENERGY PRODUCTION POTENTIAL OF A WIND TURBINE?
  - POWER CURVE?
  - ENERGY PRODUCTION TEST?
- HOW ACCURATE ARE ESTIMATES OF ANNUAL ENERGY PRODUCTION?
- WHAT IS THE PROBABILITY THAT DOE-PUBLISHED TARGETS FOR COE WILL BE MET (AFTER INFLATION)?
  - EXAMPLE: MOD-5 COE TARGET $\leq$ 3.75¢/KWH (1980 DOLLARS), FOR MACHINE CLUSTERS AT A 6.3-M/S (14-MPH) SITE)
- HOW WILL THE WIDESPREAD USE OF WIND TURBINES IN A UTILITY NETWORK INFLUENCE UTILITY COSTS?



MEASURED AND PREDICTED POWER CURVE FOR
HAMILTON STANDARD WTS-4, 4-MW WIND TURBINE

FUTURE ISSUES SURROUNDING UTILITY OPERATIONS WITH WIND TURBINES

(MOSTLY FOR HIGH PENETRATION CASES; 10-15% OF INSTALLED CAPACITY)

- VARIATIONS IN UNIT COMMITMENT SCHEDULES
- CONTROL OF OPERATING UNITS
    - UNIT RAMP RATE VARIATIONS OR CHANGES IN MIX OF FAST RESPONSE UNITS
    - CHANGES IN SPINNING RESERVE CRITERIA AND USE OF UNLOADABLE GENERATION

OPERATIONAL RESULTS FOR THE EXPERIMENTAL DOE/NASA MOD-OA, MOD-1 & MOD-2 PROJECTS

by Richard L. Puthoff
NASA Lewis Research Center
Cleveland, Ohio

FEDERAL WIND ENERGY LARGE WIND TURBINE PROGRAM

- SPONSORED BY THE DEPARTMENT OF ENERGY (DOE)
- MANAGED BY NASA LeRC FOR DOE
- PROJECTS INCLUDE WIND SYSTEMS FROM 100 KW TO 7.3 MW

PROGRAM OBJECTIVES

To obtain early operation and performance data while gaining experience in the operation of a large wind turbine in various utility environments by demonstrating or observing:

Compatibility with utility grid

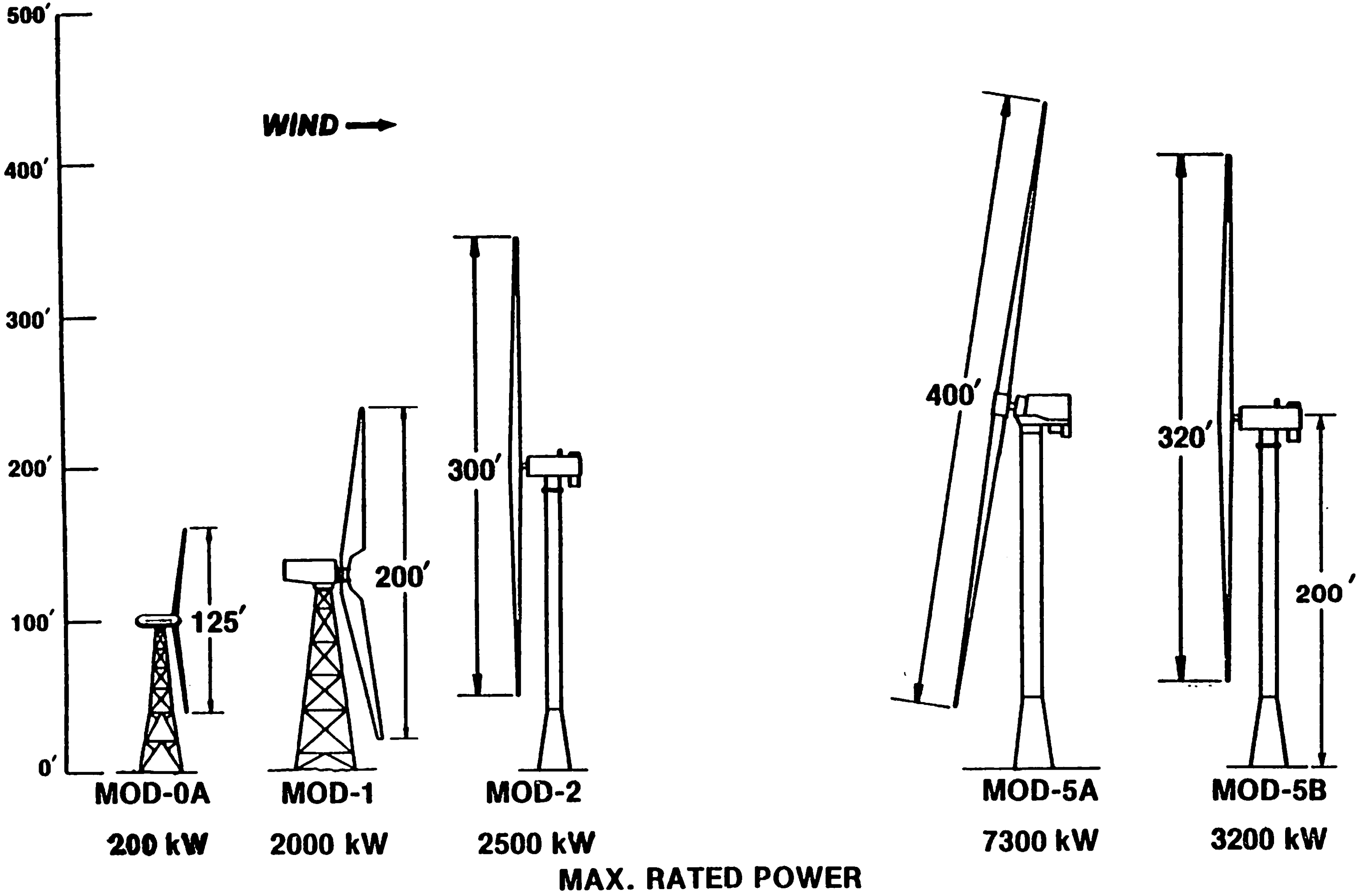
Safe unattended operation

Wind turbine reliability and maintainability

Operations and maintenance support requirements

Public and utility reaction and acceptance

LARGE HORIZONTAL AXIS WIND TURBINES



ELECTRICAL INTERFACE

	LOCATION	NUMBER OF MACHINES	RATED POWER Kw	TYPE OF GENERATOR	ELECTRICAL INTERFACE	TYPE OF CONTROL
MOD-OA						
#1	CLAYTON	1	200	SYNCH.	DIESEL 1-3 Mw	VAR
#2	CULEBRA	1	200	SYNCH.	PREPA (2) GRID	VAR
#3	BLOCK IS.	1	200	SYNCH.	DIESELS 250 Kw TO 1 Mw	VAR (PF & VOLT) (1)
#4	OAHU	1	200	SYNCH.		VAR
MOD-1	BOONE, NC	1	2000	SYNCH.	BREMC GRID	PSS (VOLT/SPEED)
MOD-2						
#1-3	GOODNOE HILLS, WA	3	2500	SYNCH.	BPA GRID 125 Kw	PF
#4	MEDICINE BOW, WY	1	2500	SYNCH.	WAPA GRID	PF

(1) PF - POWER FACTOR

(2) 20 MILE UNDERSEA CABLE - SOFT INTERFACE WITH UTILITY

PERFORMANCE DATA

	MONTHS OF OPERATION	SYNC. TIME HOURS	ENERGY Mw HR.	AVERAGE POWER Kw	MAXIMUM PENETRATION PERCENT
MOD-OA					
CLAYTON	55	13,045	1,145	88	20%
CULEBRA	48	8,094	683	84	<1%
BLOCK IS.	37	8,509	588	69	60%
HAWAII	25	8,444	1,261	149	<1%
MOD-1	17	200	42	210	30%
MOD-2	28	3,537	4,226	1,194	<1%

UTILITY INTERACTION STUDY

- INVESTIGATE AND QUANTIFY THE INTERACTION OF A WIND TURBINE WITH HIGH PENETRATION ON AN ISOLATED DIESEL UTILITY.

- STUDY ADDRESSED:

  (1) DYNAMIC INTERACTION
  (2) THREE MODES OF VOLT-AMPERE REGULATION OF THE WIND TURBINE

- BIPCO DIESELS AND WIND TURBINE INSTRUMENTED AND DATA SIMULTANEOUSLY RECORDED DURING STUDY PERIOD (FEB-APRIL 82)

- STUDY CONDUCTED WITH BIPCO OVER A THREE MONTH PERIOD OF SEVERELY GUSTING WINDS

- UP TO 60% OF THE TOTAL LOAD WAS SUPPLIED BY THE WT DURING THE STUDY PERIOD.

UTILITY ACTION STUDY (CONT'D)

- DYNAMIC INTERACTION

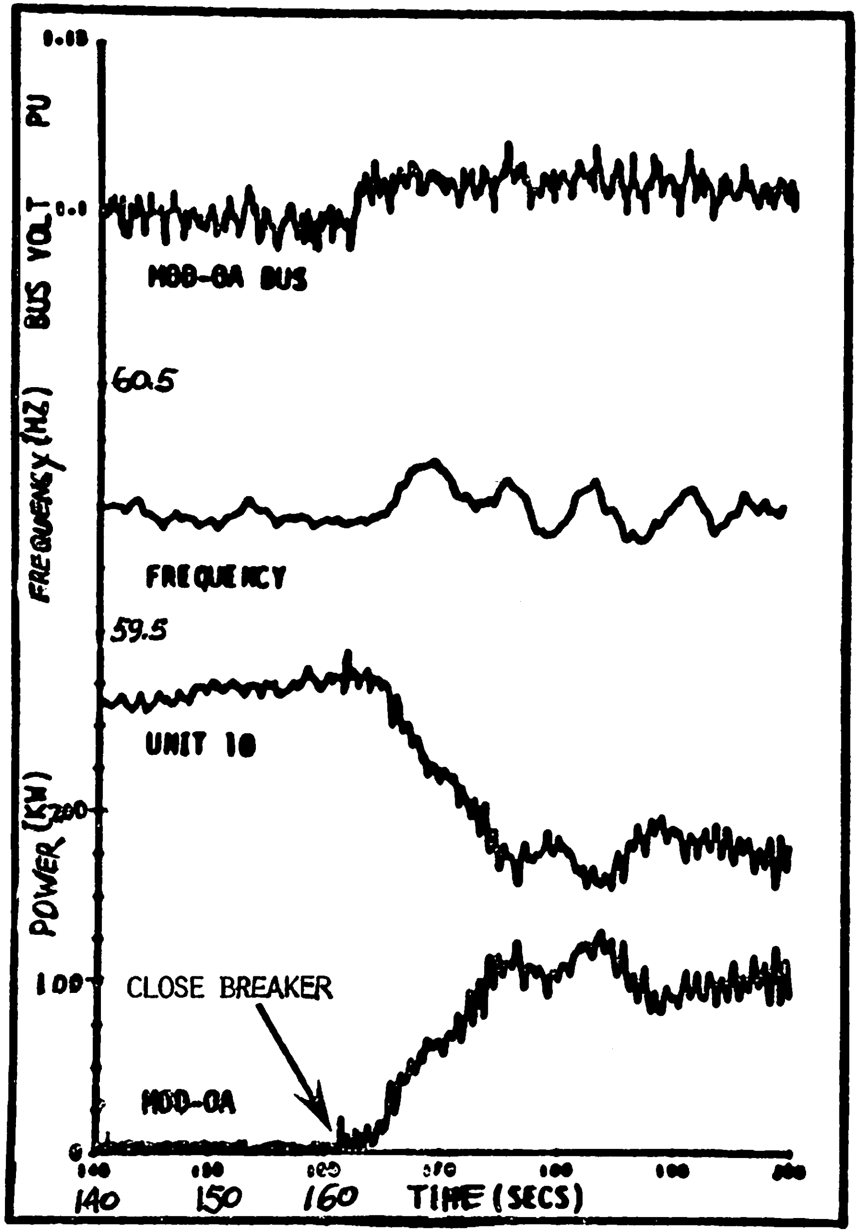
OBJECTIVE WAS TO EXAMINE INTERACTION OF DIESELS AND THE MOD-OA.

MODES EVALUATED:

(1) BIPCO SYSTEM ALONE

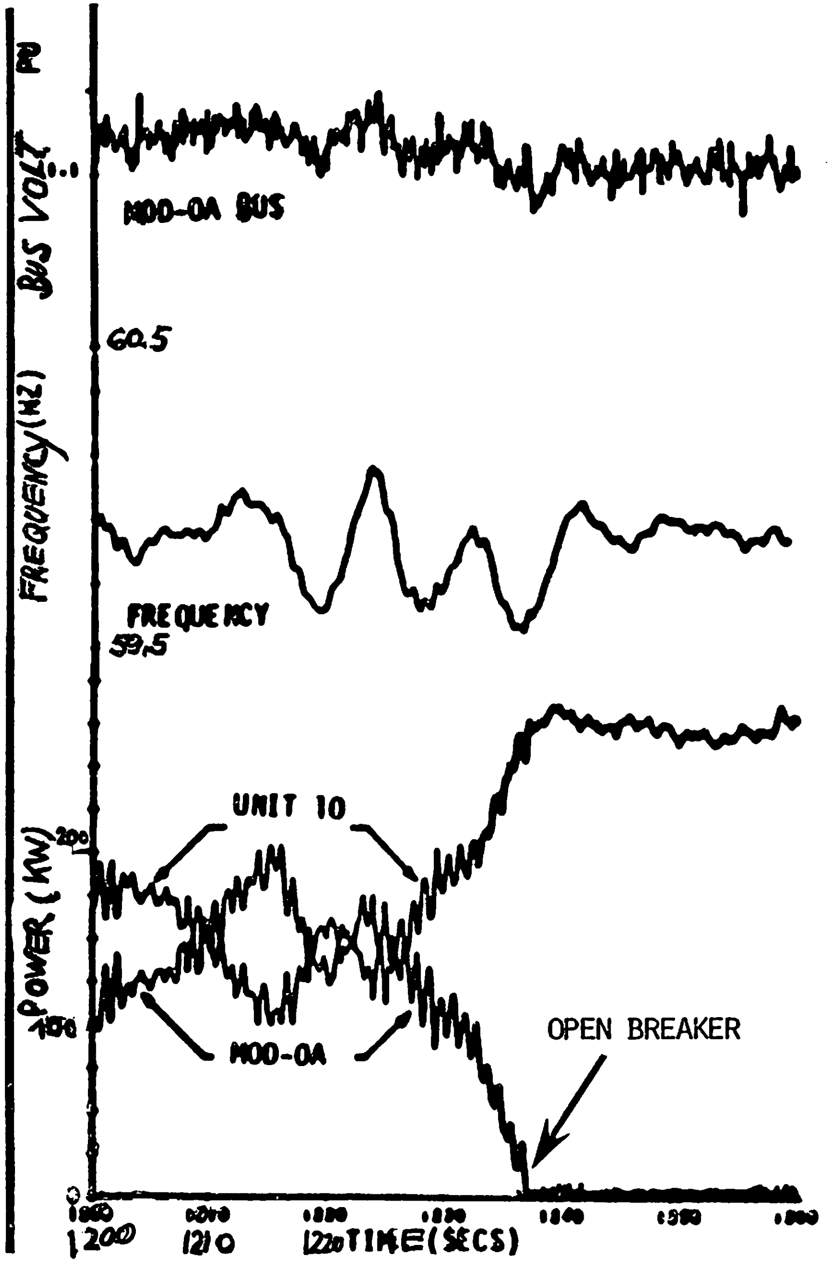
(2) BIPCO SYSTEM WITH MOD-OA

    (A) STARTUP AND SYNCHRONIZATION
    (B) SHUTDOWN AND CUTOUT
    (C) FIXED PITCH OPERATION
    (D) VARIABLE PITCH (CONSTANT POWER) OPERATION



STARTUP AND SYNCHRONIZATION

OF THE MOD-OA WTG



NORMAL SHUTDOWN AND CUTOUT

OF THE MOD-OA WTG

● DYNAMIC INTERACTION

CONCLUSIONS

- POWER AND VOLTAGE TRANSIENTS DUE TO MOD-OA STARTUP AND SHUTDOWN WERE INSIGNIFICANT.

- CYCLIC POWER (2P) VARIATIONS DUE TO MOD-OA TOWER-SHADOW EFFECT WERE INSIGNIFICANT.

- POWER FLUCTUATIONS DUE TO MOD-OA FIXED PITCH OPERATION CAUSED FREQUENCY FLUCTUATIONS OF THE SAME MAGNITUDE AS THOSE CAUSED BY MAJOR LOAD FLUCTUATIONS ALONE.

- MOD-OA OPERATION UNDER VARIABLE PITCH (CONSTANT POWER) CONTROL RESULTED IN AN INCREASE IN THE AMPLITUDE OF THE UNDER-DAMPED BIPCO SYSTEM NATURAL FREQUENCY (0.9 RAD/S).

- THE MOD-OA UNDER VARIABLE PITCH (CONSTANT POWER - 150 KW) OPERATION CAUSED FREQUENCY VARIATIONS OF 1% UNDER THE MOST SEVERE CONDITIONS.

UTILITY ACTION STUDY (CONT'D)

- VOLT-AMPERE REGULATION MODES

  OBJECTIVE WAS TO EXAMINE THREE MODES OF MOD-OA REGULATION

  - MODES EVALUATED:

    CONSTANT REACTIVE POWER (VAR)
    CONSTANT POWER FACTOR (PF)
    CONSTANT VOLTAGE

- VOLT-AMPERE REGULATION MODES

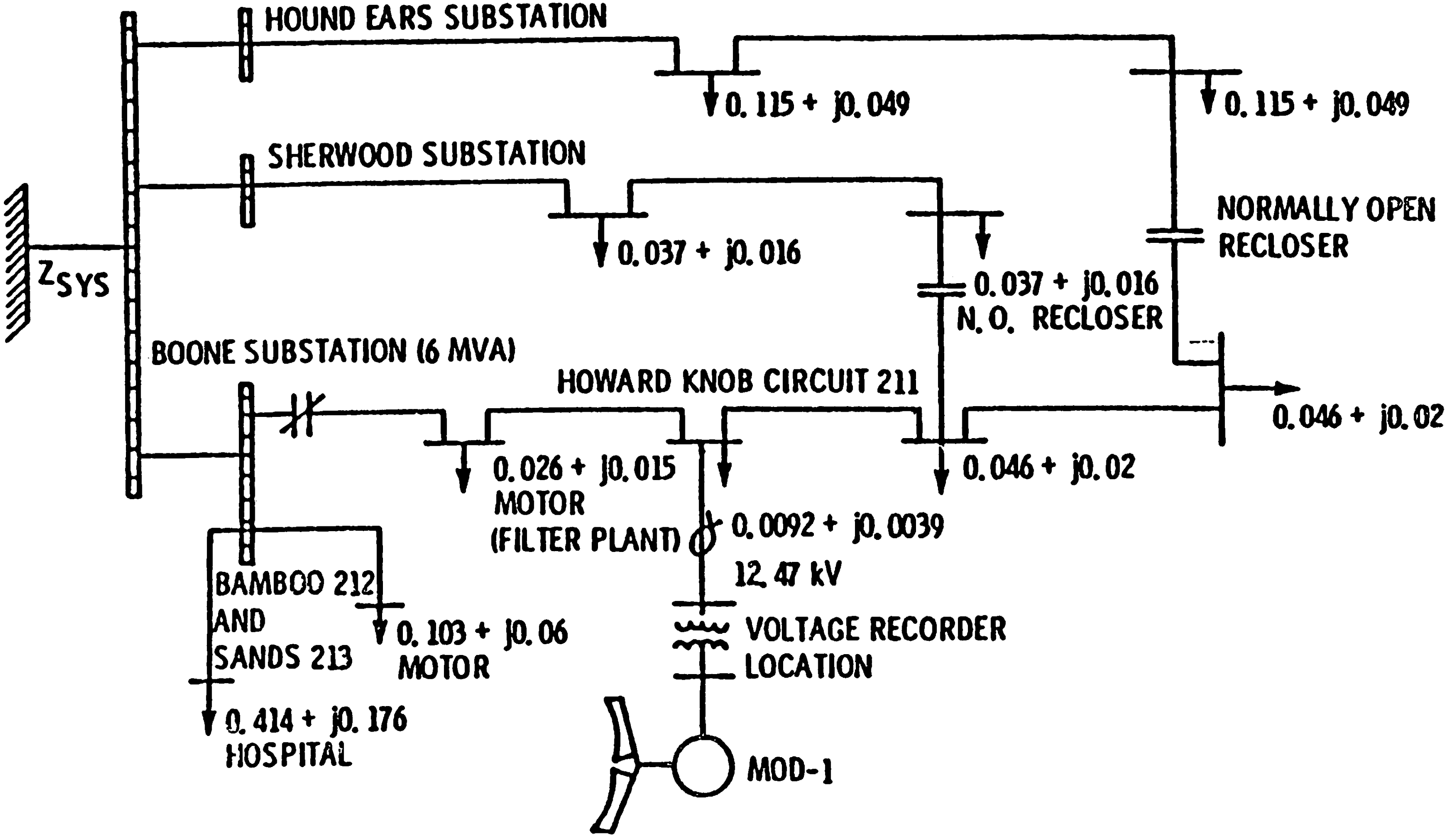
  CONCLUSIONS:

  - MOD-OA SUCCESSFULLY OPERATED IN ALL THREE REGULATION MODES:

    CONSTANT VAR, CONSTANT PF, CONSTANT VOLTAGE

  - OPERATING MODE FOR ANY SPECIFIC MOD-OA INSTALLATION IS SYSTEM DEPENDENT.
  - CONSTANT VAR MODE WAS OPTIMUM FOR BIPCO SYSTEM.
  - CONSTANT PF MOD WAS SATISFACTORY FOR BIPCO SYSTEM.
  - CONSTANT VOLTAGE MODE WAS IMPRACTICAL FOR UNATTENDED BIPCO SYSTEM.

MOD-1 UTILITY INTERACTION

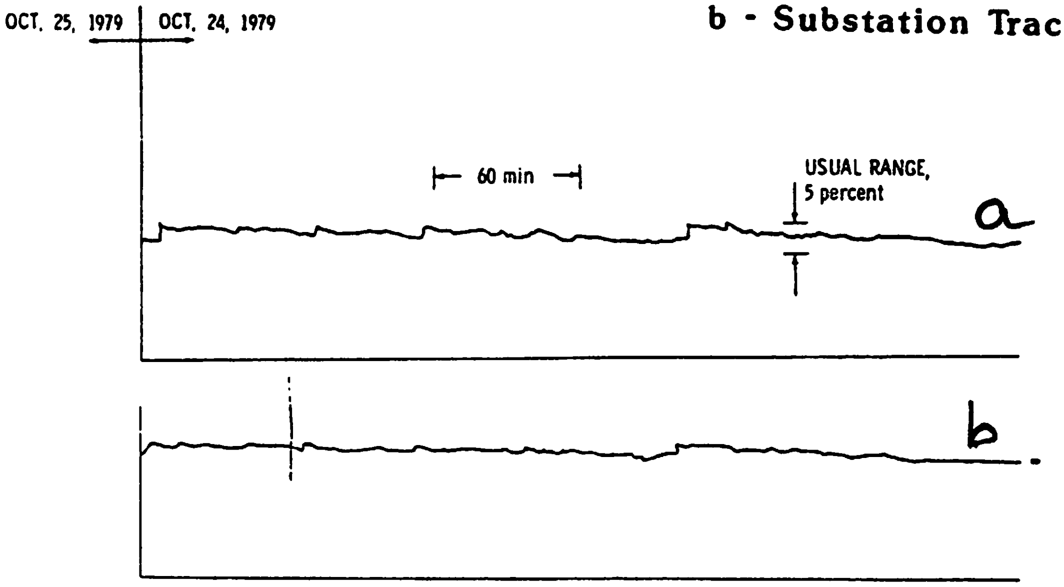


- Simplified one-line diagram of Blue Ridge Electric Membership Corp. distribution system. (All loads on 10-MVA base.)

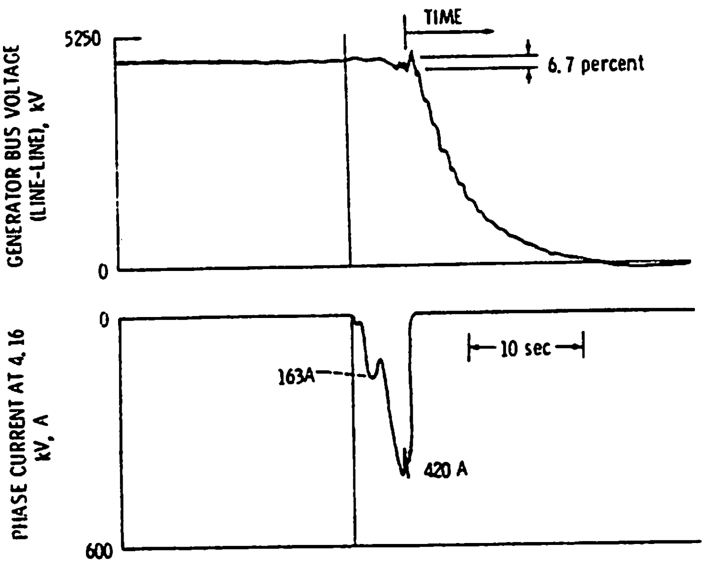
MOD-1 UTILITY INTERACTION (cont'd)

a - Meteorological Tower Trace

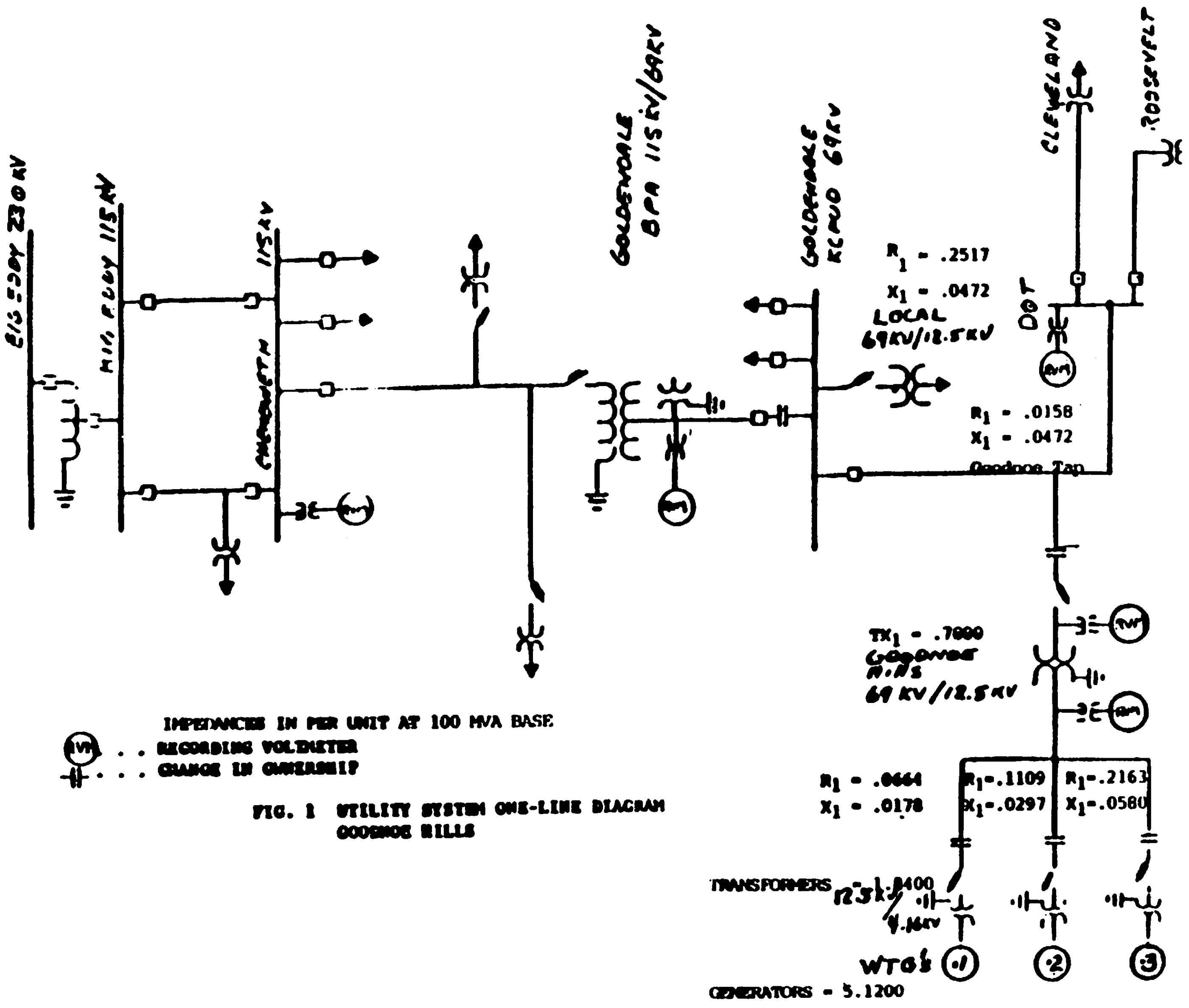
b - Substation Trace



UTILITY VOLTAGE RECORDER TRACES



Transient on Oct. 24, 1979 due to overload shutdown



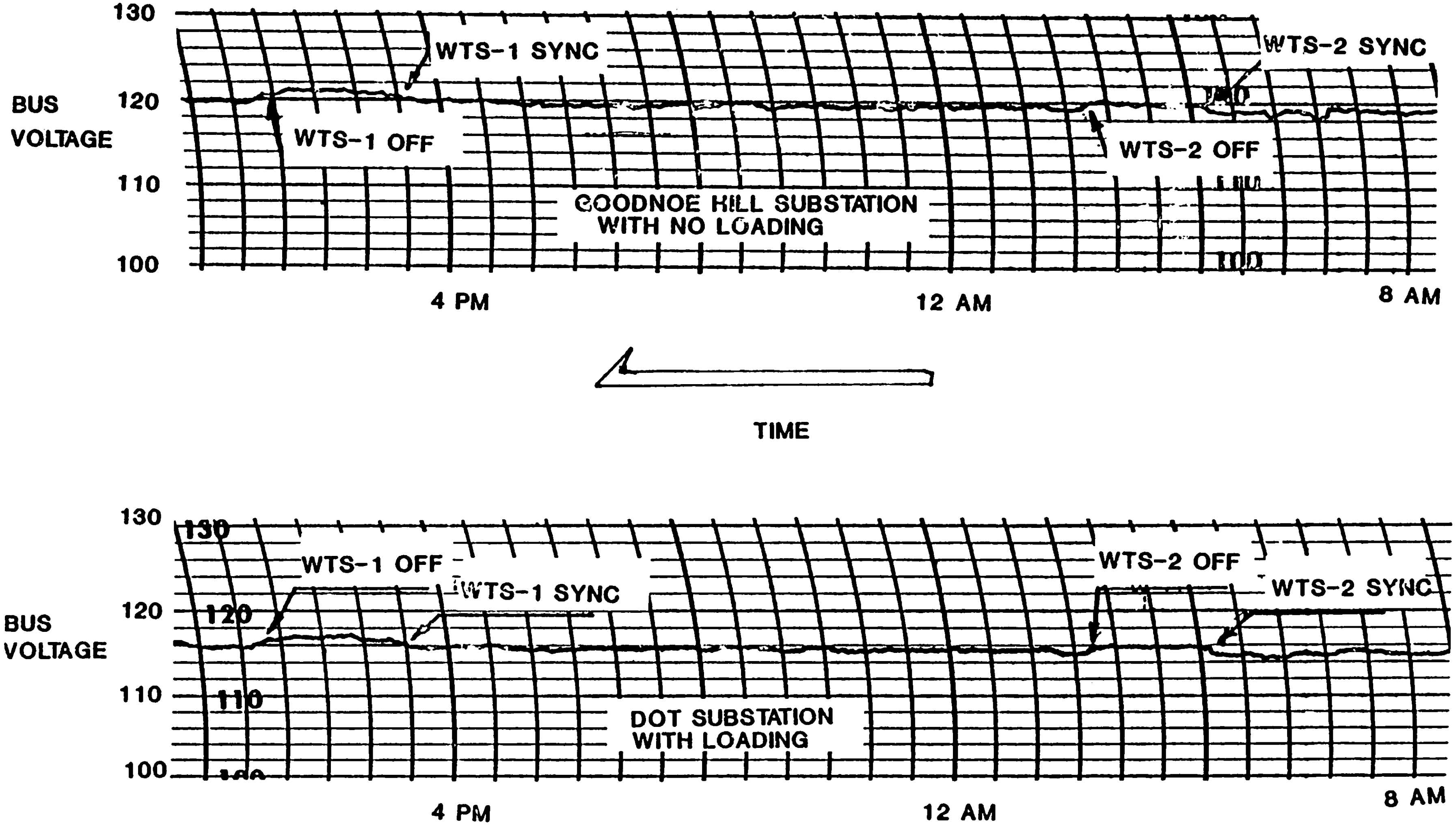
IMPEDANCES IN PER UNIT AT 100 MVA BASE

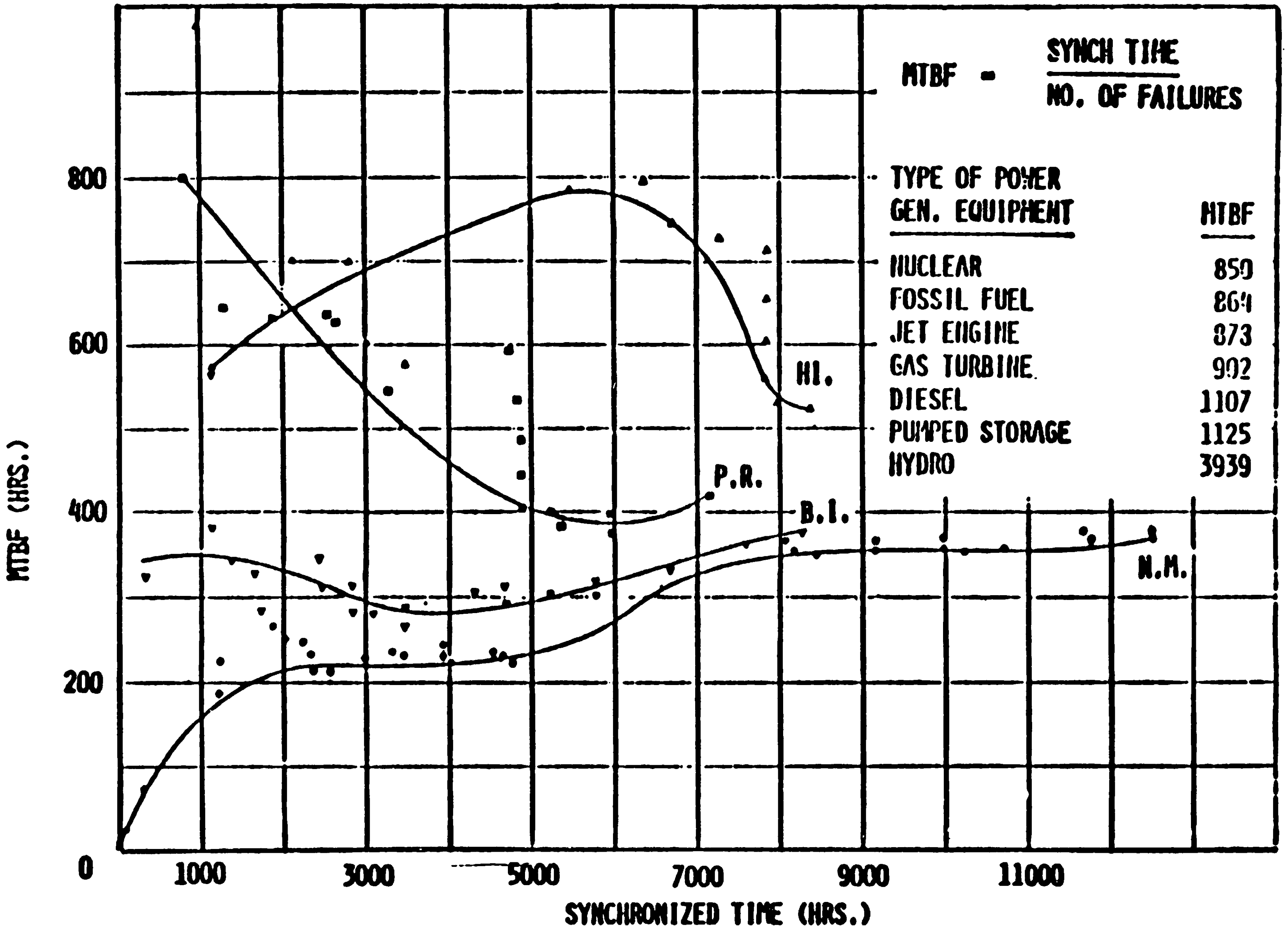
VM . . . RECORDING VOLTMETER

. . . CHANGE IN OWNERSHIP

FIG. 1 UTILITY SYSTEM ONE-LINE DIAGRAM
GOODNOE HILLS

MOD-2 WTS EFFECT ON POWER SYSTEM BUS VOLTAGES





MOD-OA MEAN TIME BETWEEN FAILURE (MTBF) VS. SYNCHRONIZED TIME (HRS)

CONCLUSION

GRID INTERACTION ON ALL MACHINES HAS BEEN ACCEPTABLE

- MOD-OA BI SYSTEM STUDY CONCLUDED THAT AT HIGH PENETRATIONS SYSTEM DISTURBANCES WERE NO GREATER THAN CONVENTIONAL DIESEL SYSTEMS

EARLY MTBF VALUES INDICATE POTENTIAL FOR PERFORMANCE COMPARABLE TO DIESEL UNITS

FUTURE MACHINES

MOD-5 MACHINES ARE DESIGNED TO OPERATE WITH VARIABLE SPEED DRIVE TRAINS

VARIABLE SPEED DRIVE TRAINS WILL PROVIDE CONSTANT FREQUENCY OUTPUT BY MEANS OF

- INDUCTION GENERATOR/DOUBLY FED ROTOR
- CYCLOCONVERTER TO SUPPLY VARIABLE FREQUENCY FOR ROTOR EXCITATION

The Status of Wind Turbine Development In Southern California Edison's Service Territory

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INTRODUCTION

The Southern California Edison (SCE) wind energy program is divided into three major areas. These three areas are: 1) wind resource assessment; 2) wind turbine demonstration units; and 3) wind commercialization. The resource assessment part of the program locates and quantifies the wind resource in the SCE service territory. The wind turbine demonstration part gives SCE experience in operation of wind turbines and helps advance new wind turbine designs. Wind commercialization deals with private developers who generate electricity with wind turbines.

WIND RESOURCE ASSESSMENT

The earliest investigations of the wind energy potential in the SCE service territory were started in 1976, at Devers

Substation near Palm Springs. A 50-meter meteorological tower was erected near Devers Substation at the end of 1976 by the U.S. Energy Research and Development Administration (now the Department of Energy). This site was later to become the SCE wind energy test site. In order to better define the extent and quality of the wind resource in the San Gorgonio Pass area near Palm Springs, a field measurement study was conducted by AeroVironment Inc., under contract to SCE and the California Energy Commission. Nineteen sites were monitored for wind for one year. Results of this first study were used to modify the monitoring network to better pinpoint the best wind resource areas. Initial measurements were also made in a number of promising areas: Cajon Pass, Portal Ridge, Sierra Pelona, Tehachapi and others suspected of having winds useful for generation of electricity.

At the present time, wind data are being collected at 22 different sites in the San Gorgonio Pass/Coachella Valley area. Located at two of these sites are meteorological towers: a 100-meter tower located near Whitewater and the former DOE 50-meter tower (operated by SCE since October 1982). The other 20 sites are all monitored at the 10-meter height (16 wind run and 4 wind speed/direction).

Wind energy potential is also being measured in other parts of the SCE service territory: three sites in Cajon Pass; six sites in Tehachapi; one site on Portal Ridge; one site in the Antelope Valley; three sites on Sierra Pelona; and two sites on Catalina Island. In addition to these sites, data from six other cooperative stations is being obtained.

Future studies will concentrate on obtaining better long-term data for the known sites. This will enable more detailed studies of how wind-generated electricity will impact the SCE system.

DEMONSTRATION PROJECTS

The testing of wind turbine designs can produce real data on their economics, performance, and environmental impacts. At this time, four wind turbine designs are being tested at the SCE wind test site located near Palm Springs. These are: the 1300 kW Bendix; the 50 kW DAF Indal; the 100 kW Wenco; and the 500 kW DAF Indal.

The Bendix wind turbine was initially operated in December 1980 as a 3 MW, three-bladed, horizontal axis, variable speed machine. Due to reliability problems, the hydraulic system used to achieve variable speed was replaced with a constant speed drive train. In October 1982, the modified wind turbine, with a 1.5 MW induction generator was first put in service.

Limitations on gearbox capacity established the wind turbine rating at 1.3 MW. As of September 30, 1983, the wind turbine had operated for 363 hours and generated 161,711 kilowatt-hours. Since the modification, some problems have been encountered with the pitch system and its controls. Generally, the wind turbine has been operating satisfactorily.

The DAF Indal 50 kW wind turbine is a two-bladed, vertical axis machine. It was first operated in March 1982. After some startup problems, the wind turbine operated quite reliably, achieving 100 percent "corrected" availability from July 1982 through May 1983 (down time due to problems not related to the wind turbine were not counted). In June 1983, a broken rotor strut and complete mechanical inspection caused the wind turbine to be inoperative from June 4 through July 14. Since then, it has returned to reliable operation. A measured power curve for the wind turbine at the SCE test site has been obtained. It appears to exceed the manufacturer's predictions in moderate wind speeds and falls short of the predictions in higher winds. As of September 30, 1983, the wind turbine had operated for 5,736 hours and generated 110,574 kilowatt-hours.

This spring two new wind turbines were installed at the test site, the 100 kW Wenco and the 500 kW DAF Indal. The Wenco wind turbine is a two-bladed, horizontal axis, upwind rotor machine with a tail vane to orient it into the wind. Initial testing is being conducted at this time. As of September 30, 1983, the wind turbine had operated for 66 hours and generated 2,040 kilowatt-hours.

The 500 kW DAF Indal wind turbine is a vertical axis, two-bladed machine. It is a scaled-up version of the previously mentioned 50 kW DAF Indal wind turbine. Startup testing and final instrumentation work is now in progress. As of September 30, 1983, the wind turbine had operated for two hours for startup and check-out tests.

A fifth wind turbine is planned for installation at the SCE test site in the next couple of months. It is the Windfree Magnus effect wind turbine. In place of the blades of a normal horizontal axis wind turbine, rotating cylinders provide the necessary lift to spin the rotor. This test machine will not be connected to the SCE electrical grid, but will serve as a test bed for the innovative rotor design.

Several new machines, promising improved performance and innovative features, are being investigated for future testing, but at this time no commitments have been made.

WIND COMMERCIALIZATION

Today, due to improved wind turbine designs and a favorable tax credit situation, private developers are finding it profitable to erect wind turbines and sell the power to SCE. Major development is now taking place in the Tehachapi area. As of the end of August 1983, 644 wind turbines with a total name plate rating of 29.17 MW have been installed. Of these, 28.41 MW are now connected to the SCE system. This installed capacity is divided between wind turbines manufactured in the United States and Europe: 23.675 MW are American and 5.495 MW are European.

The San Gorgonio Pass area is beginning to be developed. Initial development was delayed until the completion of a Master Environmental Impact Assessment for wind energy development in this area. Permitting and construction is now proceeding. At the end of August 1983, 65 wind turbines with a name plate rating of 1.75 MW were connected to the SCE system.

Turning now to energy considerations, as of the end of August 1983, the total amount of energy purchased by SCE from the wind developers was 9,505,864 kilowatt-hours. Of this amount, 2,219,383 kilowatt-hours were purchased in the month of August. The capacity factor for August was about 11 percent. This is somewhat lower than expected and it indicates that many of the wind turbines are operating with poor availability.

At present, 28 Wind Park Power Purchase and Sales Agreements have been executed between SCE and wind park developers. The total capacity covered under these agreements is 555 MW excluding optional phases. Active negotiations are in progress for an additional 250 MW. These agreements will provide a substantial amount of the SCE 1992 goal of 800 MW nameplate (200 MW firm capacity, nameplate capacity is derated by a factor of four to account for the variable nature of the wind resource) of wind-generated electricity for the SCE system.

CONCLUSION

Southern California Edison is committed to the advancement of wind-generated electricity. Among the reasons for this are: 1) its present large portion of expensive fossil fuel generation; 2) the existence of an excellent wind resource in its service territory; and 3) the belief that wind will be the first alternate energy source to reach commercialization. The knowledge gained from SCE's three-pronged wind program will enable the Company to properly judge the role that wind energy will play in meeting the future electrical needs of its customers.

Appendices

The Southern California Edison Wind Turbine Generator Test Program

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This paper deals with the second area of Edison's wind energy R&D program: the demonstration of various WTG designs to provide, over a period of two to three years, the data needed to support the planning, installation and operation of WTGs on a commercial scale. The overall scope of the program is to document the performance of the WTGs being tested, to assess the operation and maintenance requirements of future WTGs, to train Edison personnel as WTG operators, and to evaluate the impact of WTGs on the Edison electrical system. The Company is currently assessing horizontal-axis and vertical-axis WTGs. The results from the test program will provide information about specific performance characteristics and, at the same time, give Edison general operating experience with wind turbines. From this program Edison will be better able to properly judge the role that wind turbines can play in meeting future electrical generation needs.

INTRODUCTION

The demonstration testing of WTGs is only one aspect of Southern California Edison's wind energy program. As illustrated in Figure 1, other aspects include a continuing evaluation of the wind resource in Edison's service territory with particular emphasis on the San Gorgonio Pass region, evaluation of WTG designs proposed by the DOE and others, system integration and economic studies. Recently, the development of joint wind park projects, has also become an important part of the program.

The evaluation of WTG designs and systems are aimed at determining the technical, economic, socioeconomic, land use and environmental factors associated with the installation of multi-unit wind farms.

The evaluation of the wind resource, started in 1975, has continued with the installation by the DOE of a 150-foot (45.7 m) meteorological tower near the Edison Devers Substation, the monitoring of winds in the San Gorgonio Pass through the installation of 19 monitoring stations as part of a study sponsored by Edison and the California Energy Commission, and the installation of a 330-foot (100 m) meteorological tower.

The development of joint wind park projects was initiated with the preparation of a Wind Park Opportunity Announcement (WPOA). Response by private entrepreneurs and corporations was excellent, leading to promising negotiations. Through the purchase of energy produced by wind parks Edison hopes to meet a significant portion of its wind-generated resource goal.

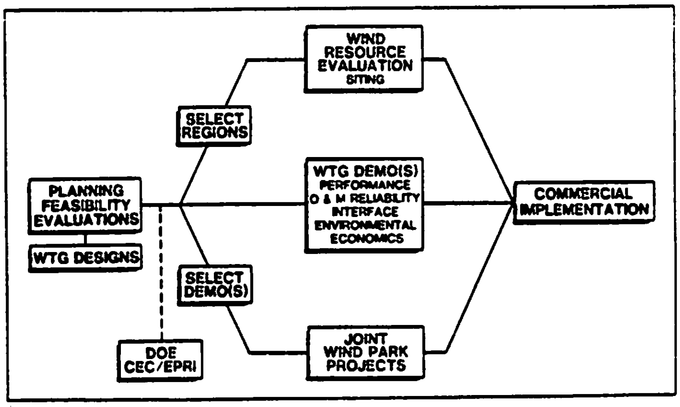

FIGURE 1: SOUTHERN CALIFORNIA EDISON WIND ENERGY PROGRAM

The demonstration testing of large WTGs originated when Edison identified the Schachle variable rotor rpm WTG concept as a promising design. A joint effort with Bendix Corporation resulted in the installation of a large horizontal axis machine placed in first operation in December 1980. Edison's interest in alternate concepts included the vertical axis designs and led to the installation in March 1981 of a 135 foot (40.8 m) unit designed and fabricated by Alcoa (Figure 2).

TEST PROGRAM OBJECTIVES

The test program was designed to provide, over a period of two to three years, the data needed to support the planning, installation and operation of WTGs on a commercial scale. Although originally developed for the testing of two specific WTG designs,

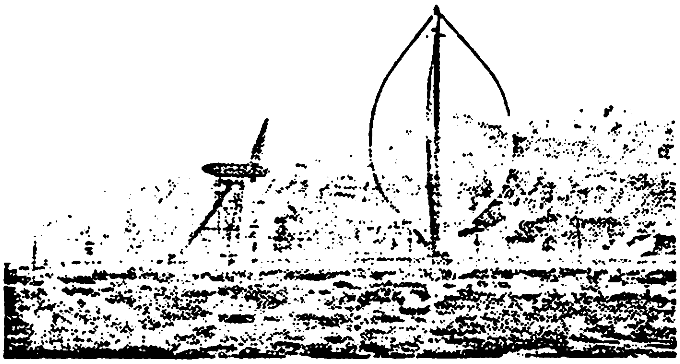

FIGURE 2: ALCOA VERTICAL AXIS AND BENDIX/SCHACHLE HORIZONTAL AXIS WTGS

the program was designed to accommodate any wind turbines aimed at the utility market.

The overall scope of the program is to document the performance of the WTGs being tested, to train Edison personnel as WTG operators, to assess the operation and maintenance requirements and to evaluate the system impact of the WTGs. The environmental issues associated with WTGs will also be explored and the design criteria of commercial units will be identified.

The WTG's tested at the Edison wind test site will be evaluated in accordance with procedures matching the particular design of each wind turbine. An outline of the parameters and items of concern relative to each test area follows:

Performance

- Power output
- Energy output
- Aerodynamic efficiency (Cp)
- Mechanical efficiency (power train losses)
- Overall efficiency
- Yaw response (horizontal axis WTG's)
- Auxiliary power requirements
- Vibration levels
- Wake decay downstream of WTG and spacing requirements

Operation and Maintenance Requirements

- Operator manhours
- Operator interventions
- Unattended operation criteria
- Routine maintenance manhours
- Routine maintenance material costs
- Unscheduled maintenance costs
- Features required for improved O & M
- Analysis of failure modes
- Resistance to climatic conditions
- Adequacy of controls and alarms

System Operation Impact

- Capacity factor
- Dynamic response (output) to wind gusts
- Power factor control capability
- Vars consumption (induction generators)
- Adequacy of electrical protection devices
- Harmonics content
- Start/stop impact

Design Criteria

- Tower stress levels (horizontal axis WTG's)
- Guy cable stress levels (vertical axis WTG's)
- Rotor stress levels and life
- Power train design
- Starting System
- Controls logic
- Foundations requirements
- Instrumentation required for commercial units
- Seismic design criteria required

Environmental Impact

- Noise
- Electromagnetic interferences
- Visual (Public reaction)
- Bird population

INSTRUMENTATION AND PROCEDURES

Three major sources of data are used during the test program:

Continuous Performance Data

- Data Logger
- Computer Tabulations

Special Test Data

- Dynamic Tests
- Noise Data
- Other

Manually Logged Data

- Station Log
- O&M Costs
- Shutdown Causes
- Environmental impact (public reaction, bird population, etc.)

Continuous performance data are obtained throug the use of a data acquisition system. This system, as illustrated on Figure 3 uses a data logger and a

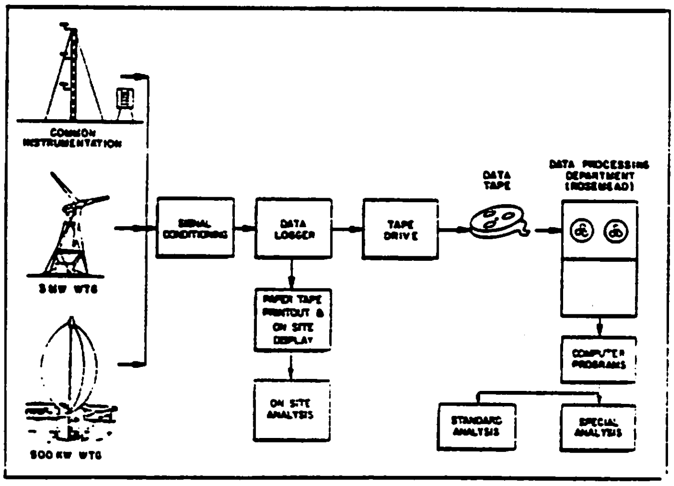

FIGURE 3: DATA ACQUISITION SYSTEM

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                                        DAILY WIND DATA SUMMARY
                                         DEVERS WTG TEST SITE
                                              DATE: 175

     HOUR          WIND SPEED AT DOE TOWER       WIND SPEED    PREVAIL WIND    DRY BULB      BAROMETRIC      POWER AT
    ENDING             MILES PER HOUR              SHEAR       DIRECTION AT   TEMPERATURE     PRESSURE       100 FEET
      AT          30 FEET  100 FEET  150 FEET   COEFFICIENT      100 FEET    DEGREES FAHR.   INCHES HG.    KW/ SQ FOOT

    15:00           25.1     27.6      29.4        0.099            5           107.4          29.28          0.102
    16:00           24.0     27.9      29.4        0.130            5           106.6          29.30          0.104
    17:00           25.7     29.6      31.4        0.127            5           105.2          29.30          0.124

 DAILY AVERAGES     24.7     28.2      29.9        0.120            5           106.5          29.29          0.108

                  TOTAL ENERGY IN THE WIND FOR THIS DAY -- 0.226 KWH PER SQUARE FOOT
                  EQUIVALENT AVERAGE WIND SPEED FOR THE DAY --  28.7 MILES PER HOUR
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TABLE 1: DAILY WIND DATA SUMMARY

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                                     DAILY WTG PERFORMANCE SUMMARY
                                         BENDIX/ SCHACHLE WTG
                                              DATE: 175

     HOUR          WIND SPEED      WIND POWER FOR     ELECTRICAL        ELECTRICAL          NET           COEFFICIENT
    ENDING           AT HUB          SWEPT AREA    POWER PRODUCED    POWER ABSORBED  ELECTRICAL POWER         OF
      AT         MILES PER HOUR      KILOWATTS        KILOWATTS         KILOWATTS       KILOWATTS        PERFORMANCE

    15:00             27.8             2356.8           378.2             100.8            277.4             0.1177
    16:00             28.3             2432.9           523.0              95.5            427.6             0.1757
    17:00             29.9             2877.9           474.6              94.9            379.7             0.1319

 DAILY AVERAGES       28.5             2518.4           470.9              96.9            374.0             0.1485

                                          DAILY STATISTICS

   ENERGY PRODUCED (KILOWATT-HOURS)        983.0                   NUMBER OF HOURS BETWEEN MACHINE
   ENERGY ABSORBED (KILOWATT-HOURS)        202.2                        CUT-IN AND CUT-OUT SPEEDS    0
   NET ENERGY (KILOWATT-HOURS)             780.8                   HOURS OF WIND TURBINE OPERATION    0
   NUMBER OF MACHINE STARTS                  0                     WTG AVAILABILITY (PERCENT)         0
   NUMBER OF WIND-RELATED SHUTDOWNS-         0                     WTG CAPACITY FACTOR (PERCENT)      0
   NUMBER OF NON-WIND-RELATED SHUTDOWNS      0

                                   CUMULATIVE STATISTICS TO DATE

   ENERGY PRODUCED (KILOWATT-HOURS)          0                     WTG AVAILABILITY (PERCENT)         0
   HOURS OF MACHINE OPERATION                0                     WTG CAPACITY FACTOR (PERCENT)      0
```

TABLE 2: DAILY WTG PERFORMANCE SUMMARY (illustrative data)

magnetic tape drive to sample and record performance parameters at predetermined time intervals. Computer programs have been developed to process the data and summarize performance statistics under three tabulation formats: daily wind data, daily WTG performance summary and monthly performance analyses.

These tabulations are illustrated in Tables 1, 2, and 3. The flow charts of the computer programs used are shown on Figures 4 and 5.

As an illustration of a specific test procedure the investigation of the noise impact of WTG's is planned as follows:

Noise Surveys

The noise surveys will be coordinated to coincide with various operating conditions of the WTG. Requests for the WTG operating conditions and test site weather data will be made daily during the survey.

The noise survey will consist of three phrases using the instrumentation shown on Figure 6 and measuring:

- o Infrasonic noise
- o "A" weighted and 1/3 octave band noise levels
- o Twenty-four hour statistical noise measurements

The first phase will be performed with the instrumentation involving infrasonic measurements. The infrasonic noise results from the disruption of the downsteam airflow caused by the blade path traversing the tower structure. Analysis of these near-field measurements will identify other specific noise sources (e.g. air cooler fans and generators, etc.). The measurements will progress radially outward from the WTG. Analysis of the data's frequency components will be used to identify the infrasonic noise levels equal to the wavelength of the tone. Half and quarter wavelengths will be surveyed and evaluated.

Noise Data

The near-field data will consist of graphed, narrow band spectra displaying amplitude in decibels versus frequency. The far-field data will contain graphed narrow band data, "A" weighed and 1/3 octave band noise levels, and 24 hour "A" weighted statistical noise data presented as noise level versus time graphs. The data will be evaluated to identify:

- o Noise sources
- o Tonal components

MONTHLY WTG PERFORMANCE ANALYSIS
BENDIX/ SCHACHLE WTG
DATE : 175 - 175

WIND SPEED AT 100 FEET	NUMBER OF -OBS-	CONTROL ANEMOMETER MPH	ROTOR RPM	GENERATOR AMPS	WIND POWER AVAILABLE KILOWATTS	REAL POWER KILOWATTS	REACTIVE POWER KILOVARS	POWER FACTOR	AUXILIARY POWER KILOWATTS	COEFFICIENT OF PERFORMANCE	YAW ERROR DEGREES	BLADE PITCH DEGREES
BELOW CUT-IN	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
15	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
16	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
17	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
18	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
19	1.00	23.1	19.0	66.9	735.	509.	-73.	0.990	101.2	0.555	3.9	
20	2.00	21.4	19.1	57.8	935.	438.	22.	0.997	93.6	0.367	-6.6	
21	2.00	13.6	18.8	35.1	1062.	271.	-4.	0.951	100.8	0.160	-5.9	
22	4.00	15.0	18.2	38.0	1141.	266.	-54.	0.941	95.9	0.146	1.3	
23	9.00	18.8	19.6	56.2	1368.	409.	-24.	0.970	97.2	0.225	-0.9	
24	7.00	19.1	19.0	62.4	1575.	456.	-27.	0.723	98.1	0.227	-1.3	
25	13.00	17.3	18.9	70.4	1749.	491.	-49.	0.987	99.1	0.227	-2.7	
26	10.00	19.9	19.4	69.4	1929.	520.	-29.	0.806	97.4	0.218	-6.8	
27	12.00	19.1	19.9	61.6	2217.	490.	-11.	0.997	95.1	0.177	-1.2	
28	10.00	16.9	18.8	49.5	2417.	366.	-15.	0.914	96.0	0.112	-4.5	
29	12.00	23.2	19.8	65.0	2754.	493.	-16.	0.995	96.3	0.145	-2.6	
30	9.00	17.3	19.4	49.9	2973.	383.	-31.	0.990	95.1	0.096	-0.2	Inoperative Sensor
31	11.00	18.0	19.5	73.1	3297.	546.	-28.	0.994	96.7	0.136	-1.4	
32	9.00	16.1	20.1	83.0	3643.	609.	-34.	0.994	96.7	0.140	-6.0	
33	6.00	19.2	20.0	76.9	3916.	560.	-36.	0.995	96.7	0.118	0.3	
34	3.00	19.0	19.3	63.9	4275.	475.	-59.	0.939	98.9	0.087	-1.3	
35	4.00	16.6	19.1	58.1	4738.	440.	15.	0.996	97.8	0.073	-7.6	
36	1.00	19.8	20.4	63.5	5247.	476.	-55.	0.993	94.4	0.073	5.8	
37	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
38	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
39	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
40	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
41	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
42	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
43	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
44	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
45	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
46	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
47	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
48	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
49	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
50	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
51	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
52	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
53	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
54	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
55	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
56	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
57	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
58	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
59	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
60	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
ABOVE CUT-OUT	0.0	0.0	0.0	0.0	0.	0.	0.	0.0	0.0	0.0	0.0	
AVERAGES		19.0	19.4	63.4	2518.	471.	-27.	0.953	96.9	0.167	-2.6	
TOTALS	175.0											

TABLE 3: MONTHLY WTG PERFORMANCE ANALYSIS (illustrative data)

- o Impacted noise levels
- o Rate of attenuation
- o Ambient noise levels

The above data will be correlated to weather data and WTG's operating status. The data will also be evaluated to determine compliance to applicable noise ordinances. This information will be compiled into a report for assessment of the existing and future WTG sites.

THE SOUTHERN CALIFORNIA EDISON WTG TEST SITE

The site selected for the tests is located near the eastern end of the San Gorgonio Pass, approximately eight miles north of the city of Palm Springs, California. The site is adjacent to Edison's Devers Substation which has a long history of wind data collection. Partial wind speed and direction records were kept as early as 1968 as part of an effort to solve wind-related problems with distribution lines in the Palm Springs area. In mid-1976 the site was proposed to DOE (then ERDA) as a candidate site for the MOD-OA WTG. The site was later selected by DOE to be one of the 17 candidate sites in the program and was instrumented with a 150-foot (45.7 m) meteorological tower. The close proximity of the substation to the WTGs afforded a cost effective electrical connection to the Edison grid. Recent data have shown that average wind velocities are in the order of 18 mph (8 m/s) at 150 feet (45.7 m). Maximum wind velocities of 90 mph (40 m/s) have been recorded.

WTG TESTED AND PROGRAM STATUS

The Bendix/Schachle WTG is a horizontal axis machine with a 165 foot (50.3 m), three-bladed rotor operating at variable rotational speeds in order to maintain a constant relationship between the speed of the blade tips and the speed of the wind. The proprietary blade design and tip speed control are expected to yield high rotor wind energy conversion efficiencies. Fixed displacement pumps and variable displacement motors are used to maintain a constant 1200 rpm generator speed (Figure 7). Electrical power is transmitted from the WTG to the test site substation through slip rings mounted at the base of the tower. The rotor is designed to operate at a constant blade pitch angle up to the rated wind speed. At and above rated wind speed the rotor blades are moved toward their feathered position. The WTG nacelle is supported by a 110-foot (33.5 m) rotatable tower.

The Bendix/Schachle WTG was first operated on-line on December 15, 1980. A gearbox bearing failure and low winds prevented operations until March 3, 1981. Problems were also encountered with synchronization of the generator with the Edison grid. A new procedure and the installation of additional equipment were necessary to allow for reliable synchronization

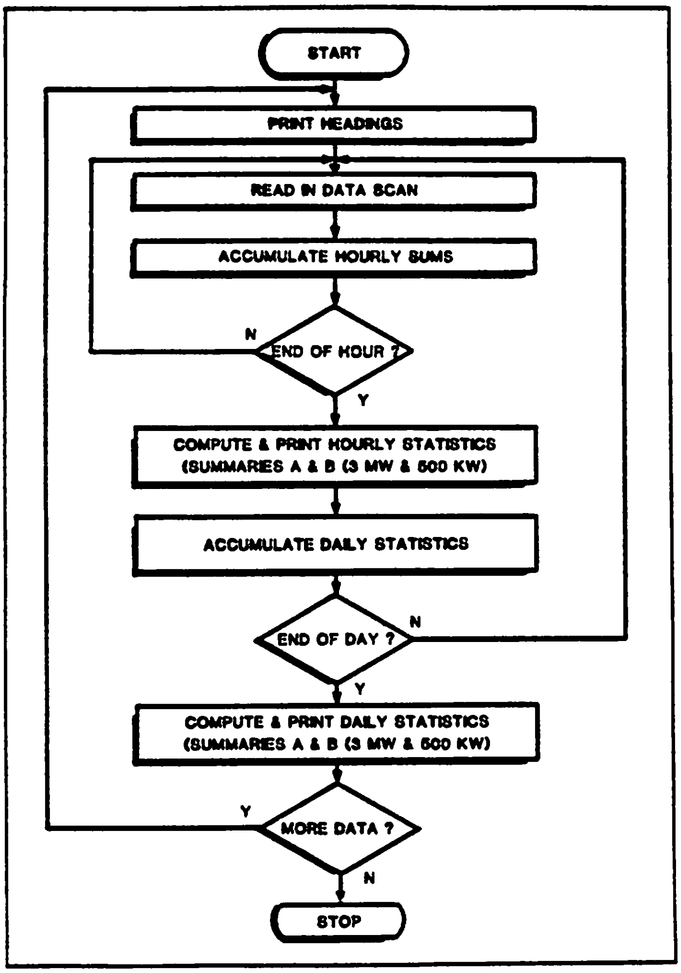


FIGURE 4: FLOW CHART FOR DAILY WIND DATA AND WTG PERFORMANCE SUMMARIES

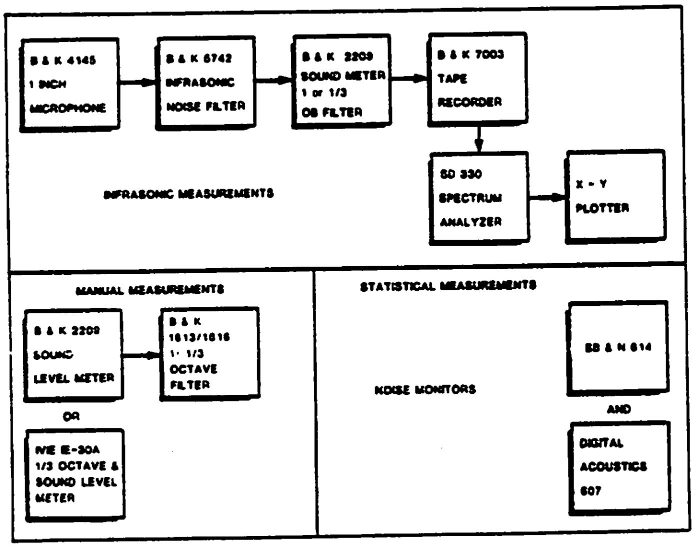


FIGURE 6: INSTRUMENTATION FOR NOISE SURVEYS

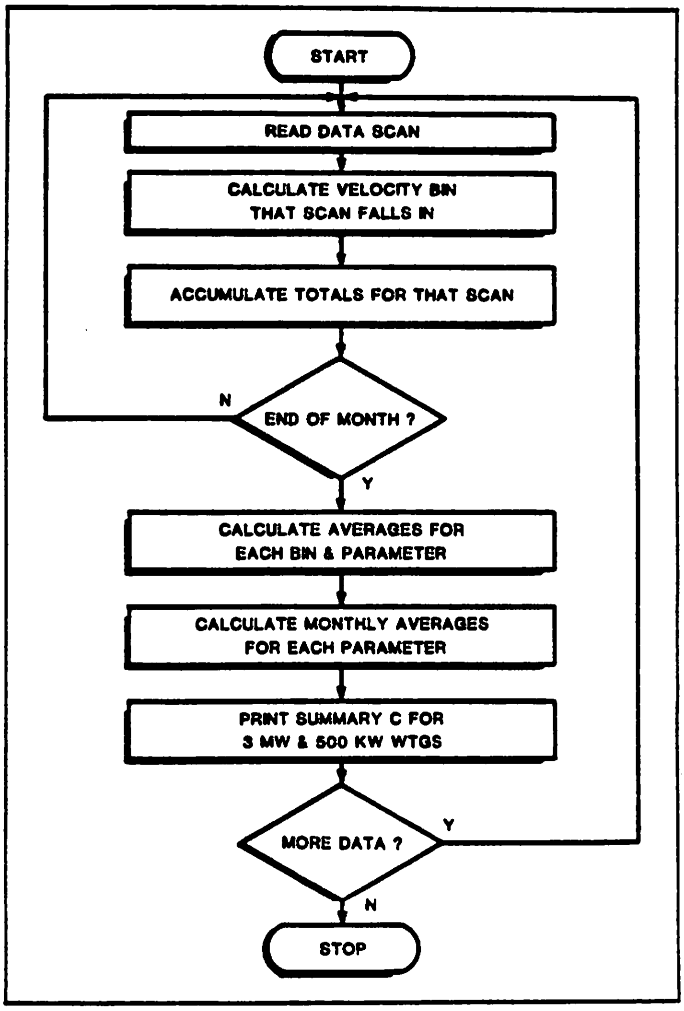


FIGURE 5: FLOW CHART FOR MONTHLY WTG PERFORMANCE ANALYSIS

of the unit. The WTG is rated at 3 MW in 40 mph (17.9 m/s) winds at hub height. However, the current operating envelope is limited to lower power and wind speed values to allow for measurement and analysis of blade stresses. As of August 1981 power levels in excess of 1 MW have been reached. Development efforts are currently focused on the implementation of automated controls, the expansion of the operating envelope and the training of operators.

The Alcoa WTG is a vertical axis machine with a 123-foot (37.5 m), three-bladed rotor driving a 500 kW induction generator through a fixed ratio gearbox. The rotor is held by 6 guy cables anchored 165 feet (50.3 m) away from the generator enclosure. The aluminum blades have a 29-inch (.737 m) chord and a symmetrical NACA 0015 airfoil. The WTG is started by a 30 hp motor and stopped by a parking brake and emergency brake mounted on the generator shaft (Figure 8).

The Alcoa WTG was first operated on-line on March 17, 1981 by Alcoa personnel and started preacceptance tests. On April 3, 1981 the rotor failed and was destroyed. The cause of failure was an overspeed condition related to controls software and a malfunction of the brakes. At approximately 60 rpm the blades separated from the torque tube and hit the guy cables. The overspeed was 50% in excess of the 40 rpm normal rotor speed. Test data and analyses have indicated that the aerodynamic performance of the rotor notably exceeded Alcoa's predictions and contri-

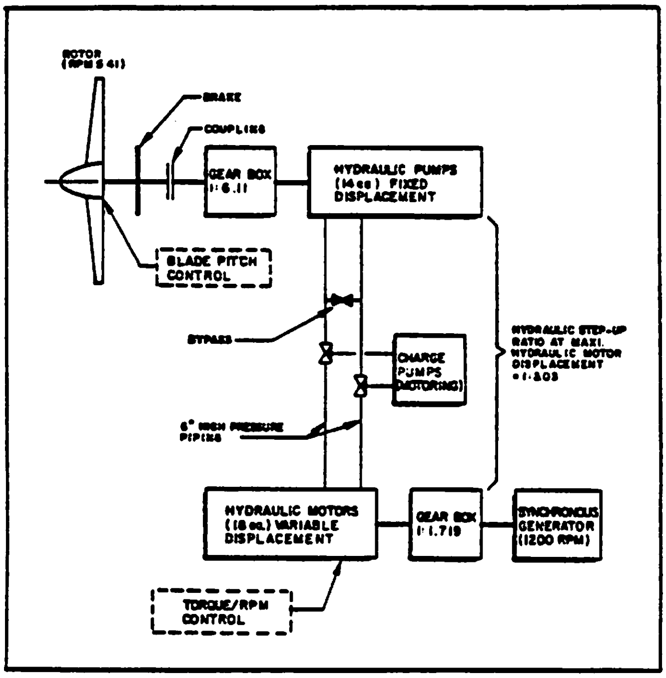


FIGURE 7: BENDIX/SCHACHLE WTG POWER DRIVE TRAIN

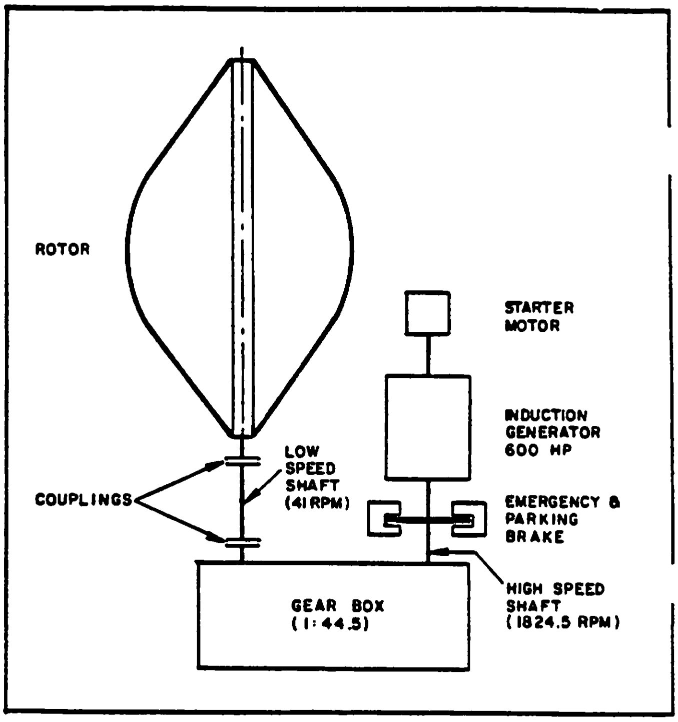


FIGURE 8: ALCOA WTG POWER DRIVE TRAIN

buted to the overspeed condition. Plans are being formulated to rebuild the WTG following tests of a modified WTG installed in Oregon. The new turbine would be extensively redesigned.

Plans are also being formulated for the testing of other WTG designs and to explore the characteristics of WTG arrays. The cost and availability restrictions of land in regions with a good wind resource dictate that commercial installations of WTG maximize the energy captured. To this effect Edison plans studies and experiments aimed at the optimization of the spacing and combination (types, sizes)

CONCLUSION

Southern California Edison's early interest in wind energy has been spurred by the Company's large proportion of oil-fired generation, the existence of an excellent wind resource within its service territory and the belief that wind would be the first alternate energy source to reach commercializatior The results from the Edison wind turbine test progra will provide information about the performance characteristics of selected units and, at the same time, give Edison in-depth operating experience with a new technology. From this program Edison will be better able to properly judge the role that wind energy can play in meeting the future electrical needs of its customers and therefore accelerate the practical use of this important resource.

FACT SHEET:
Wind Energy Development

Wind machines have been used for centuries to pump water and to process grain, but the emphasis today is on using them to produce electricity. During the 1900s through the 1930s, wind machines were used on some farms, especially those isolated from central utility service.

Wind machines faded from use because of the availability of abundant supplies of low-cost oil and natural gas. At that time it was less expensive to purchase electricity generated with oil or natural gas than to purchase, install and maintain wind machines.

Today, however, many residential customers and private companies are finding it profitable to sell power produced by wind energy systems to utility companies. The federal Public Utility Regulatory Policies Act (PURPA) of 1978 requires utilities to purchase power from wind energy producers. PURPA also exempts small power producers from the regulations to which utilities must adhere.

Wind energy machines vary substantially in size, from a few kilowatts (KW) for some residential units, to several megawatts (MW) for utility-owned systems. Small wind machine technology is much more advanced than the technology for large systems, since farmers have been using smaller units for several decades.

It's unlikely that a homeowner can supply all of his electricity needs with energy from wind turbines, but many individuals are supplying 25 percent or more of their electricity by harnessing the power of the wind. When more power is produced than needed, such as during the late night hours, it can be sold to the local utility.

When considering the installation of a wind energy system, the first step is to find a site where sufficient winds are available. Such data are available from state or federal meteorological stations. If the annual wind speed averages at least 12 miles per hour, chances are that it is a good site for capturing energy from the wind.

Power in KW available from winds is approximately equal to the cube of the wind speed in miles per hour. As the wind speed doubles, the potential power that could be produced with a wind machine increases eight times. But wind speed at any location is highly variable. Another important factor is that the speed of the wind increases with height, so the higher the placement of wind machines, the more energy output obtained.

Before installing a wind energy system, however, deed restrictions, local zoning laws and building codes should be thoroughly researched. A good place to start is at the local government's building department. Even if restrictions exist, there is the right to seek an exemption from any restrictive regulations.

TAX BENEFITS

Federal and state tax credits are available to individuals and companies that install wind energy systems. For residential applications, the federal government allows a tax credit equal to 40 percent of the costs of a wind energy system, up to $4,000. The credit is subtracted from taxes owed, and the amount can be carried over to future years. The federal wind energy tax credit expires on December 31, 1985.

California's state energy tax credit for residential wind energy systems is 55 percent, but any federal tax credits must be subtracted. The state credit cannot exceed $3,000.

For commercial applications, the state tax credit is 25 percent, and there is no limit on the amount of the tax credit that can be obtained.

State and local tax agencies should be contacted to obtain full details about wind energy tax credits. For instance, the state requires that a wind energy system have a three-year warranty from the manufacturer.

SOUTHERN CALIFORNIA EDISON WIND ENERGY

Southern California Edison Company announced an increased commitment to alternative and renewable resources in October 1980. Edison strongly encourages wind energy development, and also carries out demonstration projects with various types of wind turbine generator (WTG) designs.

By 1992 Edison expects to obtain 200 megawatts (MW) of firm capacity from wind energy, enough electricity to supply the power needs of 100,000 typical homes. The Company offers to purchase electricity produced by wind turbines within Edison's 50,000-square-mile service territory in Southern and Central California. Both individuals and firms may sell electricity produced from wind to Edison.

Edison relies mainly on fossil fuels, such as oil or natural gas, to produce electricity in power plants. But rising costs for traditional power plant fuels, coupled with increasing expenses for constructing new generating facilities, have led Edison to look for other ways to obtain electricity.

Since 1972 Edison's formal energy conservation programs have encouraged customers to make the most efficient possible use of the energy sources we already have. Now the Company also encourages the development of alternate and renewable energy sources, including wind, solar, geothermal and hydroelectric energy. Development of these alternate and renewable resources reduces the need to construct expensive new generating facilities.

WIND ENERGY RESOURCES

Several geographical areas of California are especially suited to the development of wind energy. In 1975, after carefully reviewing wind measurement data, Edison determined that the area just north of Palm Springs might be a good site for constructing WTGs, due to strong and frequent winds. The following year, the U.S. Department of Energy (DOE) installed a meteorological tower on an Edison site near Palm Springs to obtain more accurate wind measurement data.

Since that time, Edison and the California Energy Commission have recorded additional wind data at several other sites in Southern California. The most promising site still seems to be the San Gorgonio Pass area near Palm Springs, but the Tehachapi Wind Resource Area, about 100 miles north of Los Angeles, is also an excellent site for WTGs.

Edison will continue to collect wind measurement information in an effort to identify potential wind energy sites and to obtain the maxiumum use of existing sites.

WIND TURBINES: A BRIEF HISTORY

Wind can be captured to turn a turbine and generate electricity. For more than 100 years, small WTGs have been producing power, but mostly in rural areas isolated from utility power lines. Today several private developers in Edison's service territory are constructing large-scale wind energy parks, consisting of several WTGs.

The Smith-Putnam WTG, built in Vermont in the early 1940s, was one of the first successful models constructed. It produced 1.25 MW of electricity in a 32 mile-per-hour wind. The blade span was 175 feet. But it was built at a time when natural gas and oil were abundant and inexpensive, and it did not prove to be a cost-effective way to generate electricity.

Serious development of WTGs did not begin until the United States felt the impact of the 1973 foreign oil embargo. Soon after the embargo occurred, the U.S. Department of Energy began to sponsor the development of large-scale WTGs to stimulate use of wind energy.

Southern California Edison Company, a leader among utilities in the development of alternate and renewable energy sources, established a Wind Energy Center north of Palm Springs in 1980 to test and evaluate WTGs.

Before today's WTG technology can be fully developed, actual operating experience must demonstrate a high level of reliability for the various WTG designs. In addition, data on construction, operating and maintenance costs must prove to be low enough to allow wind energy development to compete with more conventional energy sources.

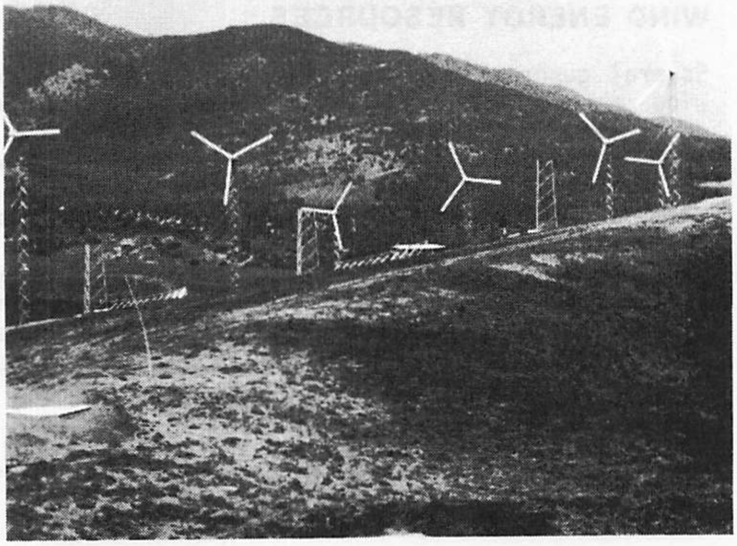
At Edison's Wind Energy Center, technicians are collecting data on the operation of WTGs, including information on energy output, reliability and operation and maintenance costs. Actual WTG operation at the Wind Energy Center has already led to design modifications for WTGs, and these design changes may speed up commercialization for certain types of WTGs.

WIND PARKS

In October 1980, Edison announced that it would cooperate with private developers on joint wind park projects. A wind park consists of numerous WTGs, and the electrical output of the wind park can be placed in a utility's power grid.

Several private developers have already begun plans to construct wind parks in Edison's service territory. As of September 1982, contracts were signed for up to 100 MW of wind energy, and negotiations are under way concerning another 630 MW. In each of these projects, the developer owns and finances the WTGs, while Edison makes a long-term commitment to purchase the electrical output.

These joint projects allow Edison to obtain wind-generated electri-



A WIND PARK IN THE TEHACHAPI AREA

city for its grid without a major capital investment. This approach allows the developer to gain certain state and federal tax benefits, some of which are unavailable to utilities, and permits Edison to gain a valuable energy resouce at minimum cost to its ratepayers and shareholders.

Wind energy can make a significant contribution to meeting the future energy needs of Edison and its customers.

Sources of additional wind energy information:

American Wind Energy Association
2010 Massachusetts Ave. N.W.
Washington, D.C. 20036

California Energy Commission
1111 Howe Avenue
Saramento, Calif. 95825

Office of Appropriate Technology
1600 Ninth Street, 3rd Floor
Sacramento, Calif. 95814

Bibliography: Outlet 429, 418, 413, 402, 399, 397, 366, 364, 362.

Approved: Research and Development, Law.

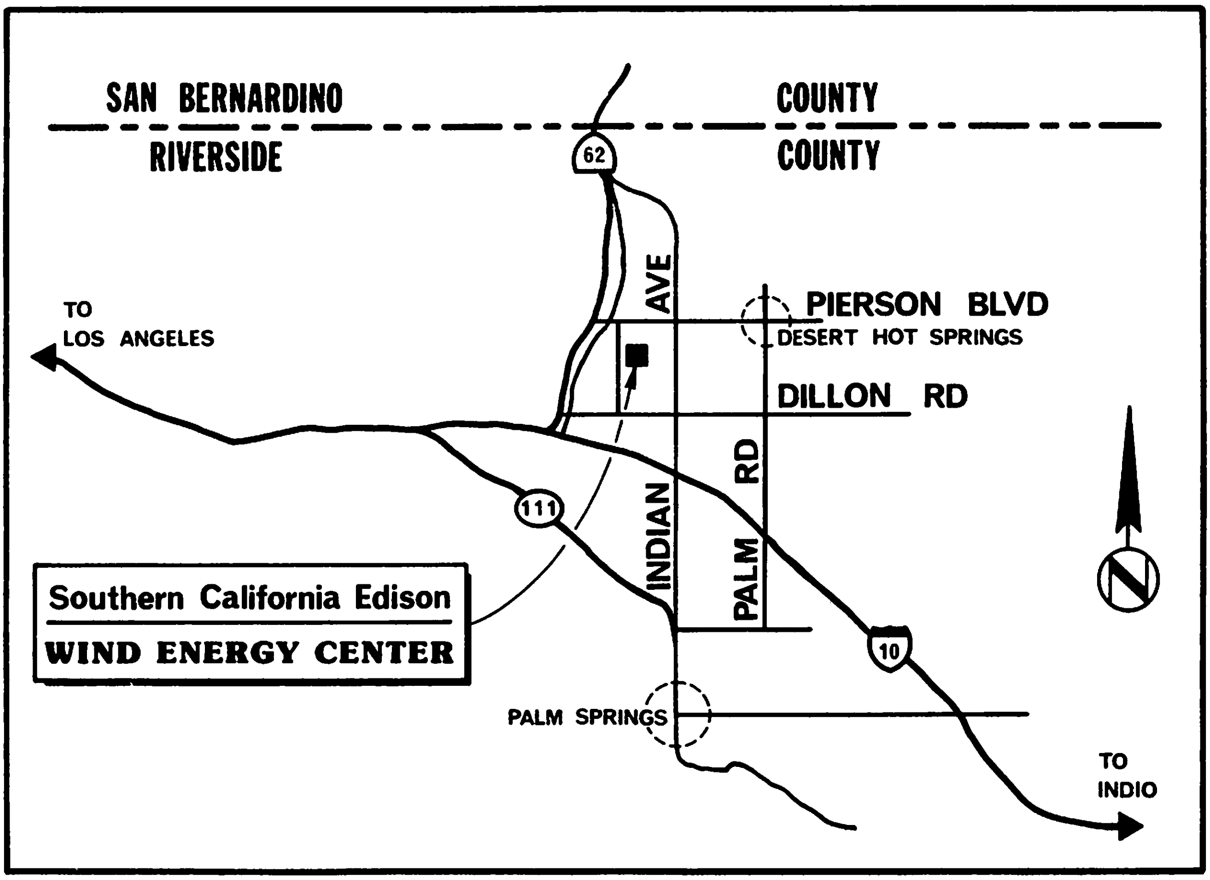
FACT SHEET:
Wind Energy Projects

Southern California Edison Company is involved with both demonstration and commercial wind energy projects. Edison's Wind Energy Center near Palm Springs serves as a test site for promising experimental wind turbine generator (WTG) designs. Actual operation of the WTGs allows Edison to obtain data on performance, reliability and operating and maintenance costs. Testing also leads to improvement in WTG designs, which can speed up commercial development.

In addition to these demonstration projects, Edison cooperates with private wind developers to plan wind energy parks. Such projects allow private developers to obtain state and federal tax benefits for owning and financing WTGs, and permit Edison to obtain the electrical output of the energy produced through long-term contracts with the private developers.

WIND ENERGY CENTER

Strong and frequent winds make the San Gorgonio Pass area near Palm Springs one of the most suitable sites in California for producing energy from wind. In 1980, Edison established a Wind Energy Center just a few miles north of Palm Springs to test innovative WTG designs.



The following two demonstration projects are currently underway at the Wind Energy Center:

BENDIX/SCHACHLE HORIZONTAL AXIS WTG

Edison's 1.3-MW Bendix/Schachle WTG resumed test operation in October 1982, following extensive modifications. This large horizontal-axis wind turbine towers 191-feet above the desert floor. The three-bladed wind machine looks similar to a massive airplane propeller attached to a tower structure. It first began operating in December 1980. In late 1981, a decision was made to modify the unit to improve operating reliability and bring it closer to a commercial design configuration.

One of the changes involved replacing the hydraulic pump/motor power drive with a gearbox, and another was installing an induction generator in place of the synchronous generator originally used.

Edison technicians are gathering data on wind characteristics at the site, and on the Bendix unit's performance and maintenance requirements. WEST (Western Energy Supply and Transmission) Associates, a regional planning group of utilities in the western United States, is cooperating with Edison in testing the unit.

DAF 50-kW WTG

A 66-foot vertical axis WTG manufactured by DAF-Indal Ltd. of Canada produces power that is fed into existing transmission lines at Edison's Devers Substation. Edison purchased the two-bladed WTG to evaluate its performance characteristics, reliability and its impact on the Company's power distribution system. It began operation in March 1982.

Basic advantages of the vertical axis design include ease of installation and maintenance, a fail-safe braking system and a built-in device that protects against overspeed of the rotor.

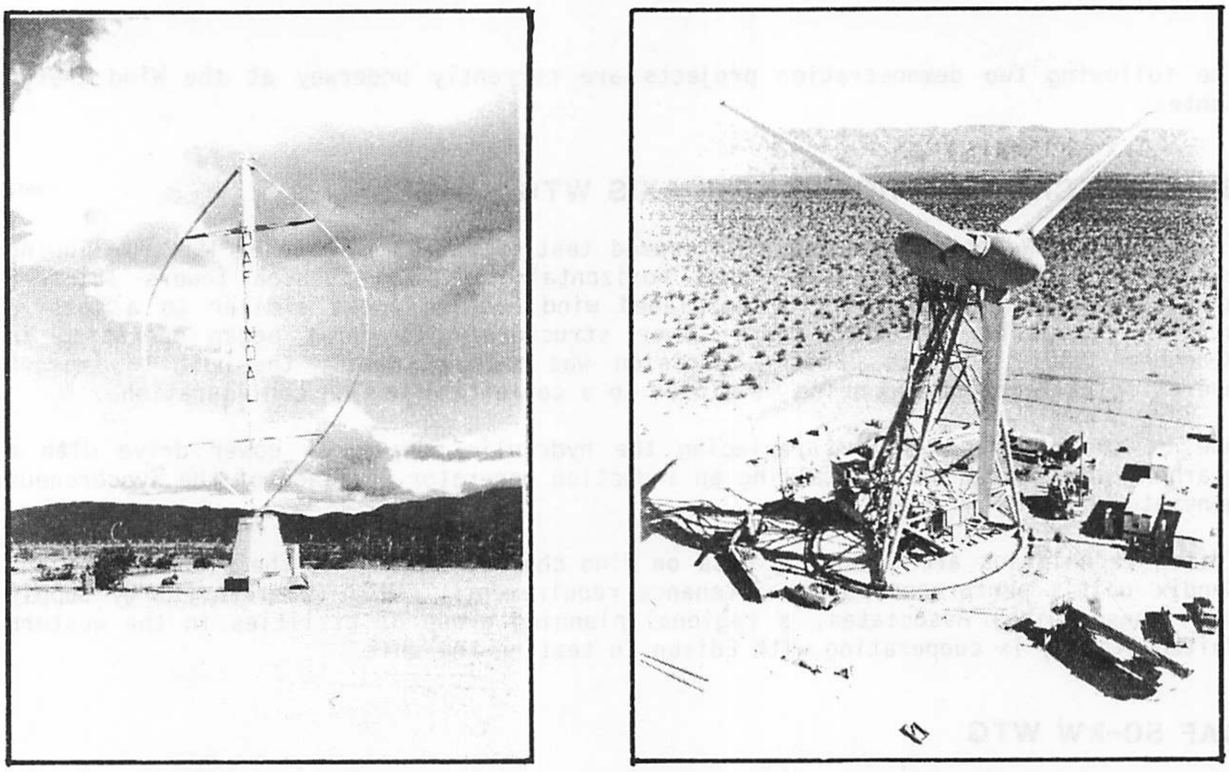
Output is rated at 50 kilowatts (KW) in a 45 mile-per-hour wind. However, winds of only 14 mph are sufficient for the unit to begin generating electricity.

WIND PARKS

Wind parks, consisting of arrays of several WTGs, can produce electricity to help Edison meet the power demands of its customers. Since October 1980, Edison has encouraged private developers to consider building wind parks and to sell the electrical output to Edison.

To assist developers, Edison may in some instances provide supporting facilities such as interconnection apparatus and land. Developers can benefit from tax credits, some of which are unavailable to utilities, and from accelerated depreciation.

Such arrangements also minimize Edison's technical and capital investment risks and allow new generation facilities to come on-line without construction expenses that would affect customers or shareholders.

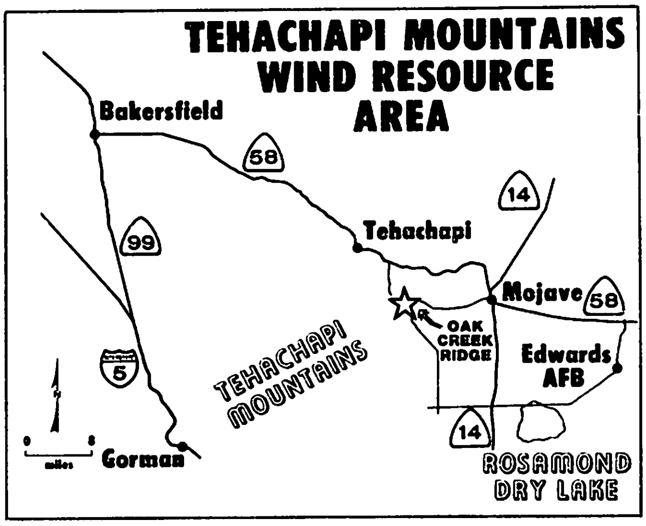


Above are pictured two WTGs Edison has been testing. At left is the DAF-Indal Vertical Axis unit, and at right is the Bendix WTG.

Wind parks do require large areas of land. On October 13, 1982, Edison leased 889 acres of land for wind parks from the federal Bureau of Land Management and also took steps to excercise options for more than 2,000 additional acres of land. This land could help Edison's bargaining position in negotiations with wind park developers.

Edison first began discussions with private developers concerning wind parks in October 1980. As of October 1, 1982, contracts or letters of intent concerning 14 projects were signed, involving between 155 and 260 MW. When projects under negotiation are included, the potential output from wind farms increases to between 590 and 820 MW.

In Edison's 50,000-square-mile service territory, two major areas have been identified to date which are particularly suited for wind park development: the San Gorgonio Pass area near Palm Springs and the Tehachapi Mountains Wind Resource Area about 100 miles north of Los Angeles.



Bibliography: Outlet 429, 418, 413, 402, 399, 397, 366, 364, 362.

Approved: Research and Development, Law

Southern California Edison Company
Research and Development Fact Sheet

PROJECT TITLE: Wind Resource Assessment

LOCATION: Wind monitoring systems are currently located near Palm Springs, California in the San Gorgonio Pass and Coachella Valley, on Catalina Island, in the Tehachapi Mountains, Cajon Pass and the Palmdale area.

OBJECTIVE: Collect, organize and analyze wind energy data from the Southern California Edison (SCE) Service Territory for siting wind turbines and for evaluating the performance and economics of wind energy conversion systems.

DESCRIPTION: Wind speed data are being collected at 22 different sites in the San Gorgonio Pass and Coachella Valley area. Twenty of these sites are monitored at 10-meters above the ground. More detailed data are collected at the SCE 100-meter tower at Whitewater and at the 50-meter tower at the Wind Energy Center north of the City of Palm Springs. Additional 10-meter towers are located in the following areas: six in the Tehachapi Mountains, five in the Palmdale area, three in the Cajon Pass and two at Catalina Island.

SCHEDULE/ MILESTONES: Wind measurements in the San Gorgonio Pass were first taken in 1968. The SCE 50-meter tower located at the Wind Energy Center began collecting data in December 1976, and the 150-meter tower at Whitewater has been operating since 1980. Measurements continue to be taken in the Pass on SCE owned/leased land and on Catalina Island. Wind monitoring was expanded to the Tehachapi Mountains, Cajon Pass and the Palmdale area in October, 1982.

Southern California Edison Company
Research and Development Fact Sheet

PROJECT TITLE: Wind Turbine Generator (WTG) Test Program

LOCATION: Southern California Edison (SCE) Service Territory - Primarily the SCE Wind Energy Center, approximately eight miles north of the City of Palm Springs, California.

OBJECTIVE: The test program is focused on the demonstration of WTGs near commercialization. The WTGs are operated on the SCE grid in conditions similar to the commercial use of WTGs. At the end of the test period, sufficient data will have been collected to support decisions relative to the large-scale use of WTGs.

DESCRIPTION: Southern California Edison is conducting a "hands on" test program to evaluate horizontal axis and vertical axis wind turbine generators of promising and original design.

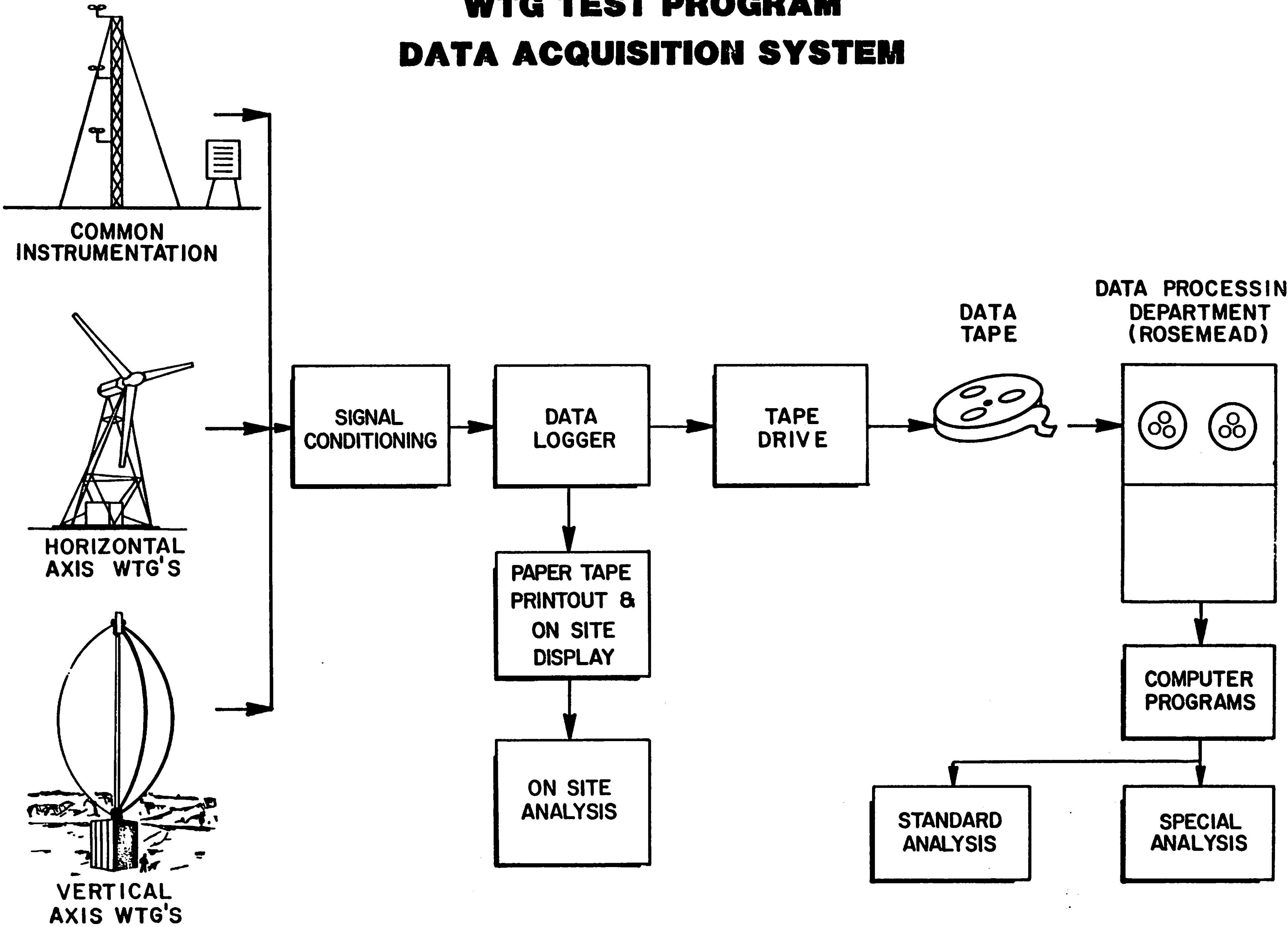
The performance of the WTGs will be documented and analyzed. Operation and maintenance requirements will be assessed. System operation and environmental effects will be evaluated. Design criteria for commercial WTG specifications will be identified.

Continuous performance data are being collected and processed by a data acquisition system. Special test data are being recorded for dynamic analyses, sound surveys, TV interference, impact on biota, etc. Manually logged data are being used for operation and maintenance analyses.

SCHEDULE/ ILESTONES:

First operation of Bendix Horizontal Axis WTG	- December 1980
First operation of Alcoa 500 kW Vertical Axis WTG	- March 1981
First operation of DAF Indal 50 kW Vertical Axis WTG	- March 1982
On-line operation of Modified 1.3 MW Bendix Horizontal Axis WTG	- October 1982
First operation of Wenco 100 kW Horizontal Axis WTG	- June 1983
Planned first operation of DAF Indal 500 kW Vertical Axis WTG	- August 1983

WTG TEST PROGRAM
DATA ACQUISITION SYSTEM



Southern California Edison Company
Research and Development Fact Sheet

PROJECT TITLE: Bendix 1300 kW Horizontal Axis Wind Turbine Generator (HAWTG) Demonstration Project.

LOCATION: Southern California Edison (SCE) Wind Energy Center near the eastern end of the San Gorgonio Pass, approximately eight miles north of the city of Palm Springs, California. Wind data collection, started in 1968, has shown that the area has an excellent wind resource with average annual wind speeds in the order of 18 mph at 150 feet above ground level.

OBJECTIVE: To provide further data in support of the planning, installation, and operation of WTGs on a commercial scale. The performance characteristics, reliability and system impact of this alternative and promising HAWTG design will be evaluated.

DESCRIPTION: SCE has installed and is operating the Bendix WTG at its Wind Energy Center near Palm Springs, California. Electricity produced by the WTG is being fed directly into existing SCE transmission and distribution lines. This WTG is a prototype unit which will provide a basis for the future Bendix megawatt size commercial WTG design. The induction generator driven by its rotor through a fixed ratio gearbox is the largest of its kind used in a WTG application.

WTG UNIT SPECIFICATIONS:

Type: Horizontal axis WTG with an upwind 3-blade rotor mounted atop a rotatable tower.

Size:
Rotor Diameter - 169.5 feet
Maximum Blade Chord - 14 feet
Hub Height - 110 feet
Overall Height - 195 feet

Rated Output: 1300 kW in a 30 mph wind at 110 feet above ground level.

Energy Output: Estimated at up to 3,500,000 kWh/year for the wind regime at the SCE Wind Energy Center. This is enough to supply the average annual needs of 580 customers and could eliminate the need to burn up to 5,800 barrels of fuel oil a year.

SCHEDULE/ MILESTONES:

First On-Line Operation - December 1980 (Phase I)
Blades and Drive Train Modification - December 1981 to September 1982
Start of Phase II Tests - October 7, 1982

NOTES ON BENDIX 1300 KW WTG

1.3 MW - 30 mph - 23 RPM

3.5 x 10^6 kWhr/year at Devers WTG Test Site

"Cut-in" Wind Speed: 19 mph

"Cut-out" Wind Speed: 45 mph

3 Blade Rotor - Diameter: 169.5' - Nacelle Height: 110'

Total Weight: 800,000 lbs

Rotor Blades: 3 x 20,000 lbs (Root: 14', Tip: 5', Length: 72.5')

Nacelle: 270,000 lbs

Rotor Shaft Diameter: 30" Torque @ 1.3 MW: 450,000 ft lb

Gearbox Ratio: 1:51.9

Blade Tip Speed @ 23 RPM = 135.5 mph

Blade Tip Speed Ratios: 9 (15 mph) 5.4 (25 mph) 3.8 (35 mph)

Blade Pitch: 7° to 97°

Maximum System Cp: .45 Rotor Swept Area: 22,565 ft^2

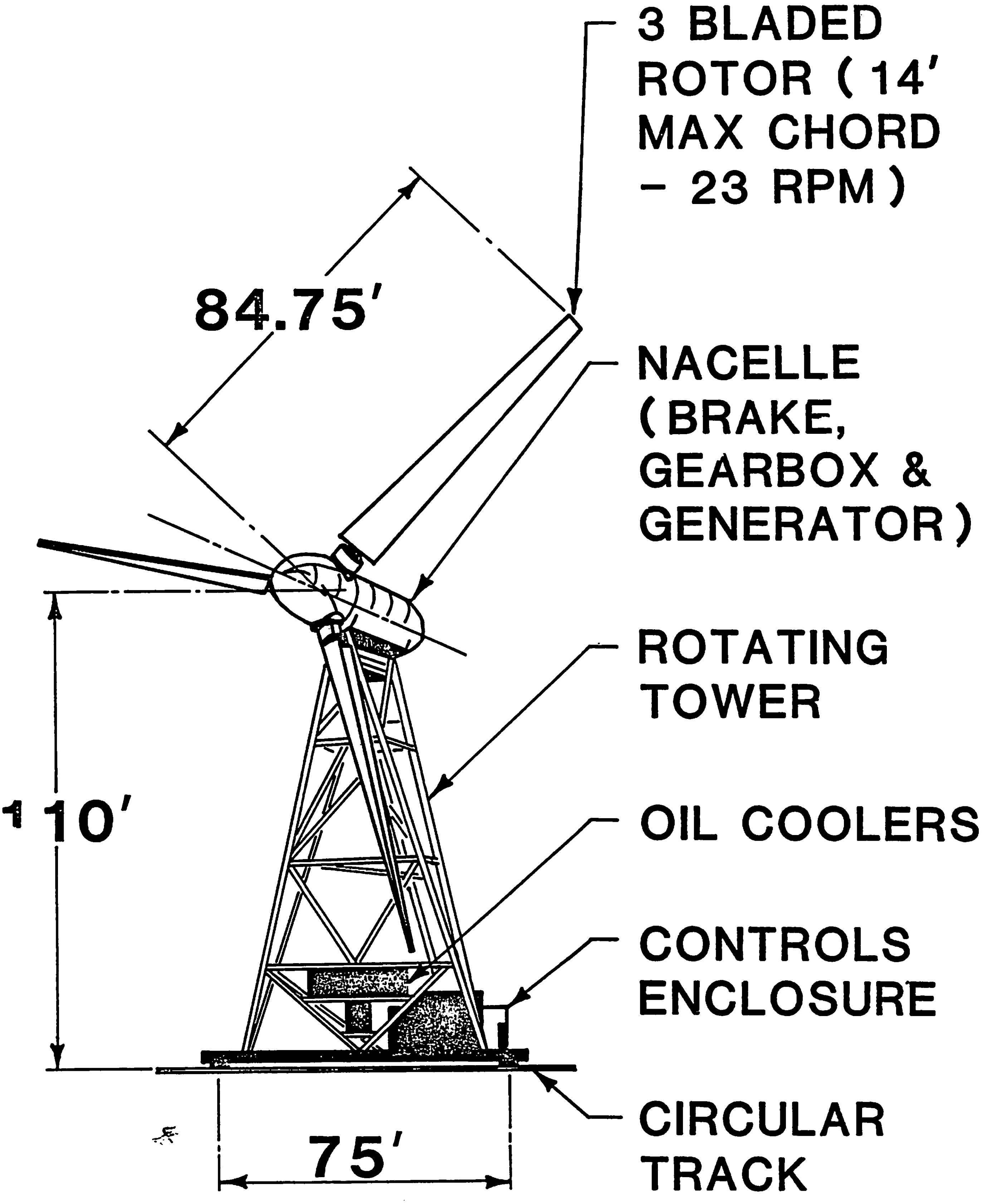
Centrifugal Force Near Blade Root at 23 RPM: 120,000 lbs

Generator RPM: 1,200 - 1,220 Generator Voltage: 4,160 (Induction)

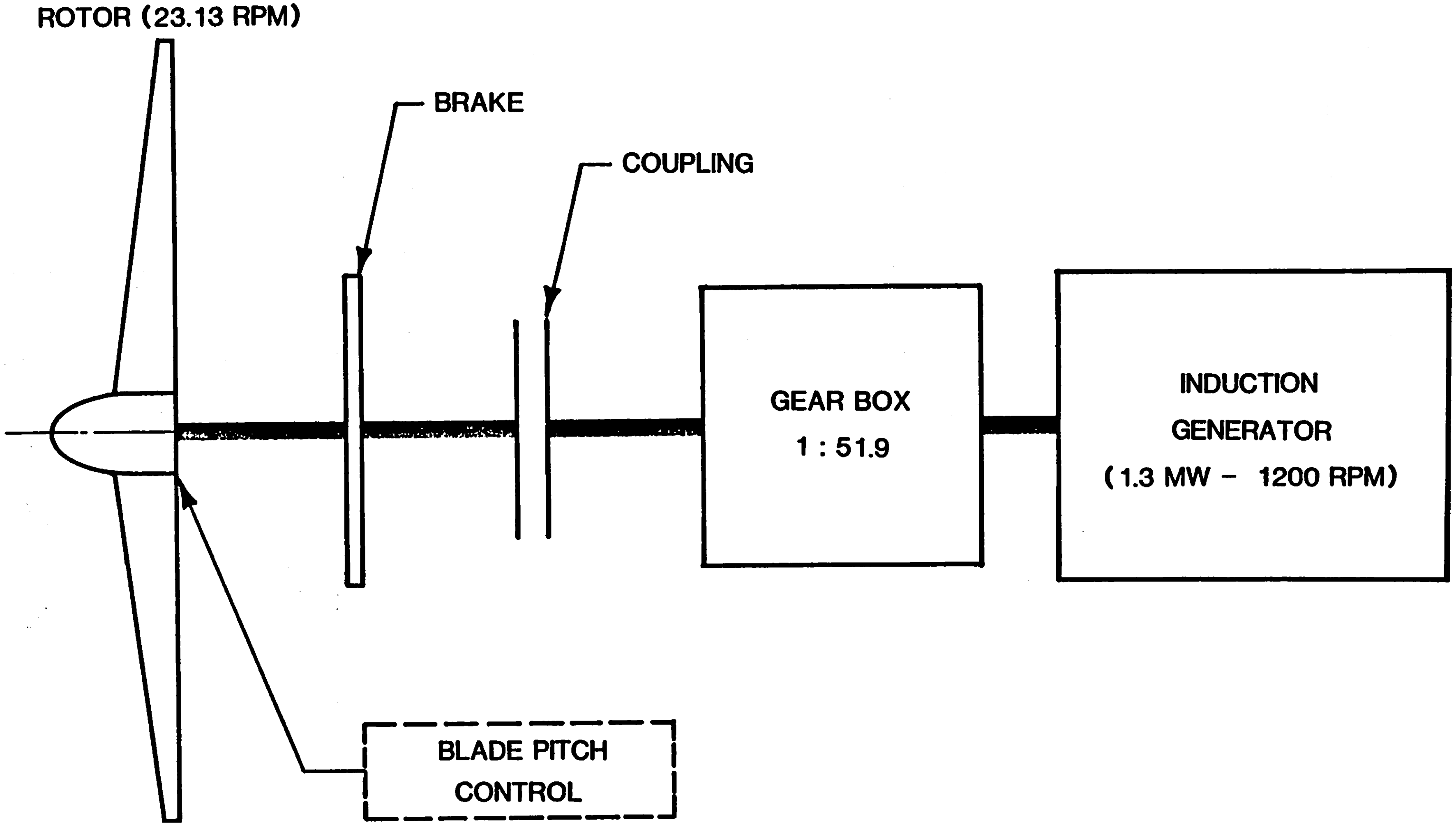
Transformers: 4,160/12,000 - 12,000/115,000

Transmission Line Voltage: 115,000

Approx. Land Area Needed: 16 acres (5 rotor dia.)
16 acres (10 rotor dia.)



1300 KW BENDIX HORIZONTAL AXIS WTG



1300 KW BENDIX HORIZONTAL AXIS WTG

DRIVE TRAIN DIAGRAM

Southern California Edison Company
Research and Development Fact Sheet

PROJECT TITLE: DAF Indal 50 kW Vertical Axis Wind Turbine Generator (VAWTG) Demonstration Project.

LOCATION: Southern California Edison (SCE) Wind Energy Center near the eastern end of the San Gorgonio Pass, approximately eight miles north of the city of Palm Springs, California. Wind data collection, started in 1968, has shown that the area has an excellent wind resource with average annual wind speeds in the order of 14 mph at 30 feet above ground level.

OBJECTIVE: To provide further data in support of the planning, installation, and operation of WTGs on a commercial scale. The performance characteristics, reliability and system impact of this alternative and promising VAWTG design will be evaluated.

DESCRIPTION: SCE has purchased and installed a 50 kW VAWTG manufactured by DAF Indal, Ltd. of Canada. Electricity produced by the VAWTG at the Wind Energy Center is fed into existing SCE transmission and distribution lines. The basic advantages of the Darrieus vertical axis design include the absence of yaw and blade pitch controls, ease of installation of the system and location of the generator at ground level for ease of maintenance. In addition to this, the DAF VAWTG has several original features: a unique two-blade rotor design, automatically adjusted guy cable tension, a fail-safe braking system mounted directly at the base of the rotor and a redundant rotor overspeed mechanical protection device. Rotor speed is constant at 80 rpm.

WTG UNIT SPECIFICATIONS:

Type: Vertical Axis WTG with a two-blade rotor.

Size:

Rotor Diameter	-	37 feet
Rotor Axial Height	-	58 feet
Blade Chord	-	14 inches
Overall Height	-	66 feet

Rated Output: 50 kW in a 45 mph wind speed at 37 feet above ground level.

Energy Output: Estimated at up to 83,000 kWh/year for a wind regime at the Wind Energy Center. This is enough to supply the average annual needs of 14 customers and could eliminate the need to burn up to 140 barrels of fuel oil a year.

SCHEDULE/ MILESTONES:

Unit Received	- November, 1981
Initial Operation	- March 10, 1982
Test Period	- 1 to 2 years

NOTES ON DAF 50 KW WTG

50 kW - 45 mph - 80 RPM

83,000 kWh/year at Devers WTG Test Site

"Cut-in" Wind Speed: 14 mph (5 min. average)

"Cut-in" Wind Speed: 45 mph (1 min. average)

2 Blade Rotor - Diameter: 37' - Blade Chord: 14"

Rotor Overspeed Protection: 87 RPM

Blade Material: 6061-T6 Alloy

Overall Height: 66'

Rotor Weight: 7,000 lbs

Rotor Column Diameter: 2'

Rotor Swept Area: 1300 ft^2

Total WTG Weight (excluding foundations): 17,000 lbs

Gearbox Ratio: 1.15

Generator RPM: 1200 to 1240 Generator Voltage: 480 V

Est. System Cp: .30 (25 mph)

Rotor Maximum Velocity (equator - 80 RPM): 108 mph

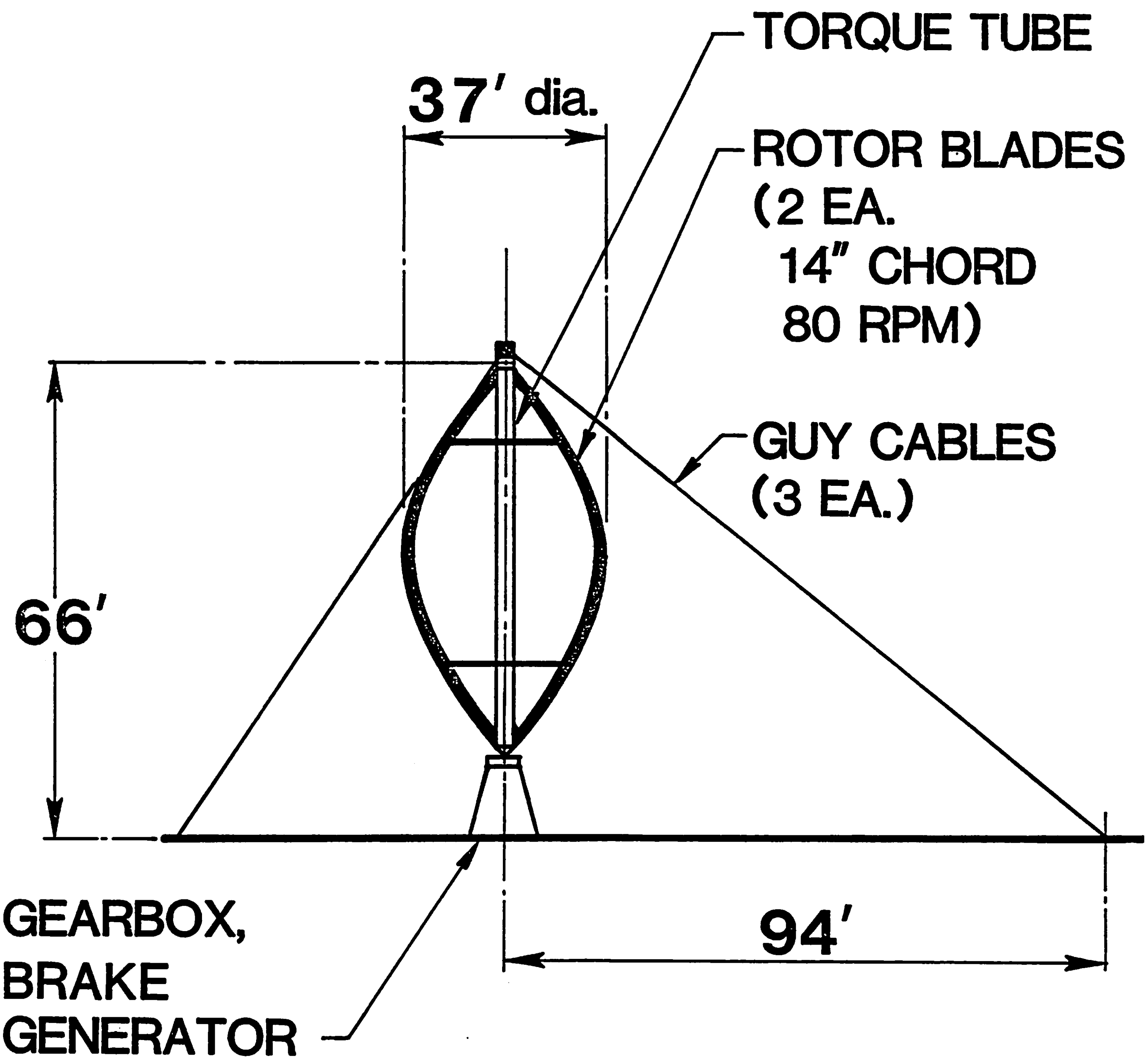
Rotor Tip Speed Ratios: 7.2 (15 mph) 4.3 (25 mph) 3.1 (35 mph)

Wye Operation: 1200 to 1240 RPM
14 to 27 mph
0 to 25 kW

Delta Operation: 1210 to 1220 RPM
25 to 40 mph
20 to 50 kW

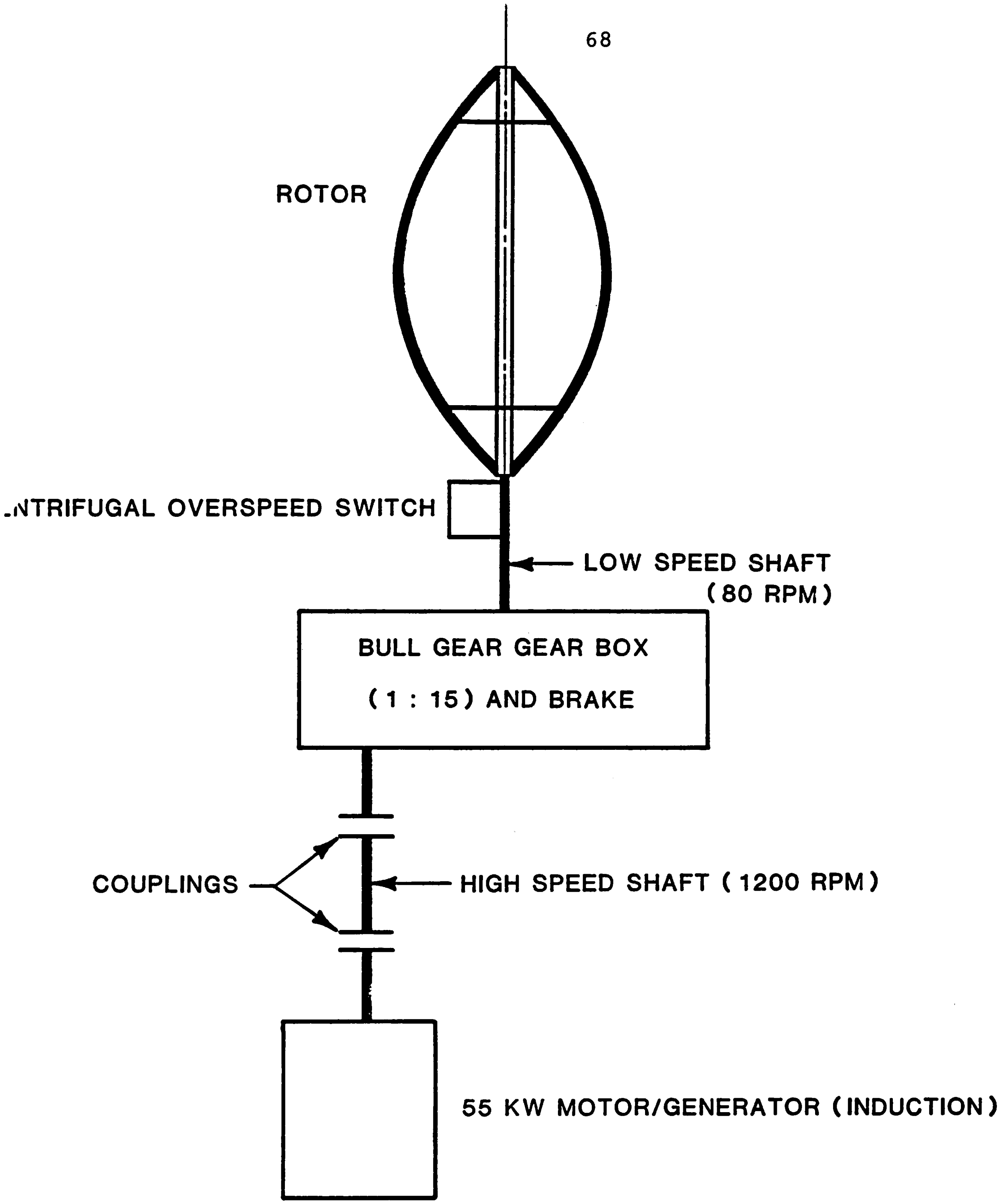
Tie-in Voltage: 480 V (test site auxiliary power)

Approx. Land Area Needed: 8 acres (5 rotor dia)
3 acres (10 rotor dia)



DAF VERTICAL AXIS WTG

50 KW



DAF VERTICAL AXIS WTG

50 KW

DRIVE TRAIN DIAGRAM

Southern California Edison Company
Research and Development Fact Sheet

PROJECT TITLE: Wenco 100 kW Horizontal Axis Wind Turbine Generator (HAWTG) Demonstration Project.

LOCATION: Southern California Edison (SCE) Wind Energy Center near the eastern end of the San Gorgonio Pass, approximately eight miles north of the city of Palm Springs, California. Wind data collection, started in 1968, has shown that the area has an excellent wind resource with average annual wind speeds in the order of 14 MPH at 30 feet above ground level.

OBJECTIVE: To provide further data in support of the planning, installation, and operation of WTGs on a commercial scale. The performance characteristics, reliability and system impact of this alternative and promising HAWTG design will be evaluated.

DESCRIPTION: SCE will install a 100 kW HAWTG manufactured by Wenco of Lumino, Switzerland. Electricity produced by the HAWTG at the Wind Energy Center will be fed into existing SCE transmission and distribution lines. The basic advantage of this HAWTG is a projected high benefit/cost ratio. Wenco uses off the shelf components and proven design concepts to lower manufacturing costs, which should result in a low cost of energy and good reliability.

WTG UNIT SPECIFICATIONS:

Type: Horizontal axis WTG with an upwind two-blade variable pitch rotor.

Size:
Rotor Diameter - 63.0 feet
Hub Height - 60 feet
Overall Height - 91.5 feet

Rated Output: 100 kW in a 28 mph wind speed at 60 feet above ground level.

Energy Output: Estimated at up to 260,000 kWh/year for the wind regime at the SCE Wind Energy Center. This is enough to supply the average annual needs of 43 customers and could eliminate the need to burn up to 430 barrels of fuel oil a year.

SCHEDULE/MILESTONES:

Start Installation - March 1983
Start Operation - June 1983
Test Period - 1 to 2 years

NOTES ON WENCO 100 KW WTG

100 kW - 28 mph - 60 RPM

260,000 kWh/year at Devers WTG Test Site

"Cut-in" Wind Speed: 11 mph

"Cut-out" Wind Speed: 50 mph

2 Blade Rotor - Diameter: 63' - Blade Chord: 16.3"

Blade Material: Steel and Aluminum Alloy

Overall Height: 91.5 ft.

Rotor Weight: 2,800 lbs.

Rotor Swept Area: 3,117 ft^2

Blade Pitch Angles: -24° (stalled) +32° (start)

Blade Pitch Control: pneumatic (80 psi)

Total WTG Weight (excluding foundations): 17,000 lbs.

Gearbox Ratio: 1:20

Generator RPM: 1200-1220

Generator Voltage: 480 V (Induction)

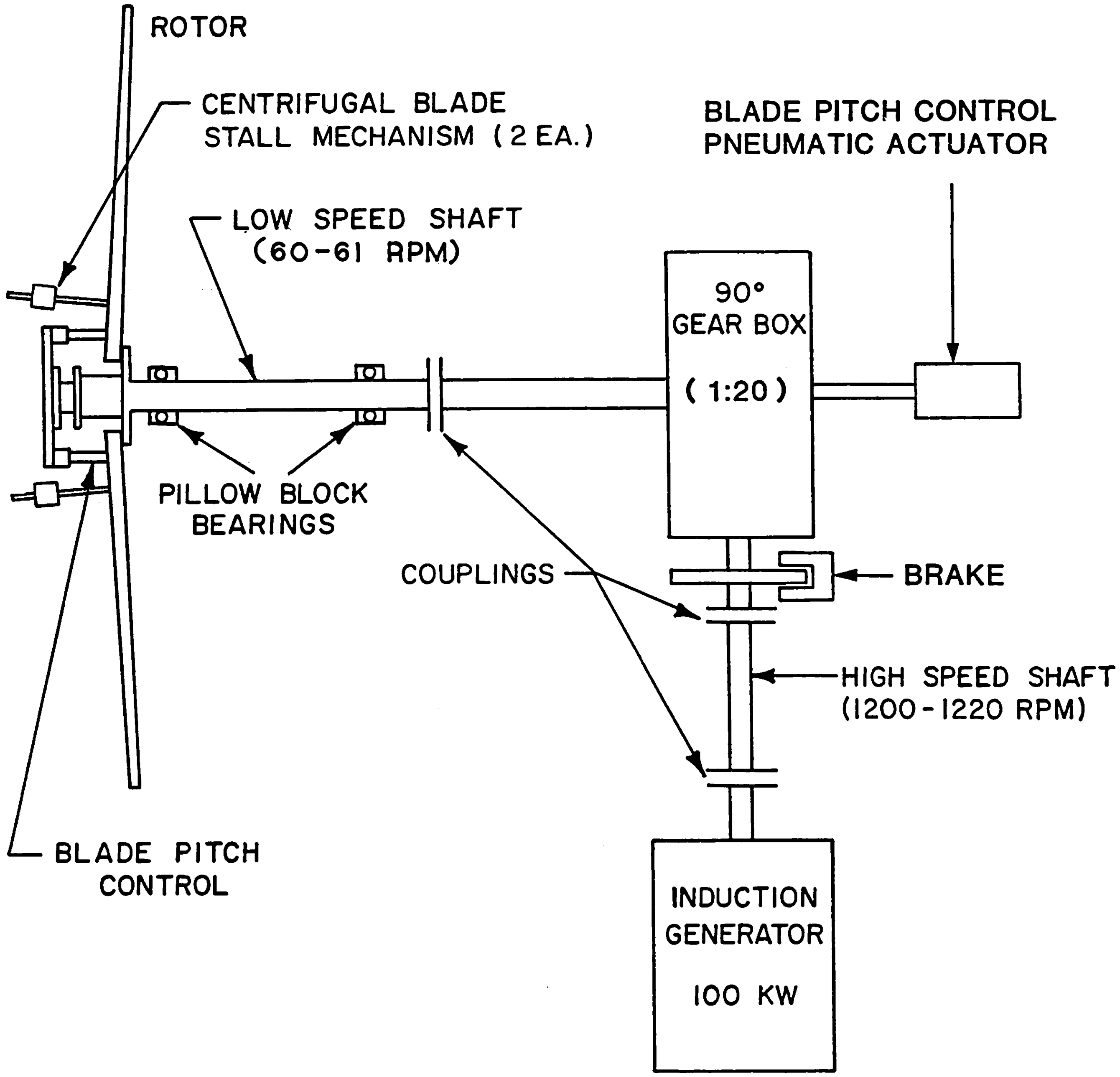
Estimated System Cp: .29

Blade Tip Speed @ 60 RPM: 135 mph

Blade Tip Speed Ratios: 12.3 (11 mph) - 5.4 (25 mph) - 2.7 (50 mph)

Yaw Control: free (vane)

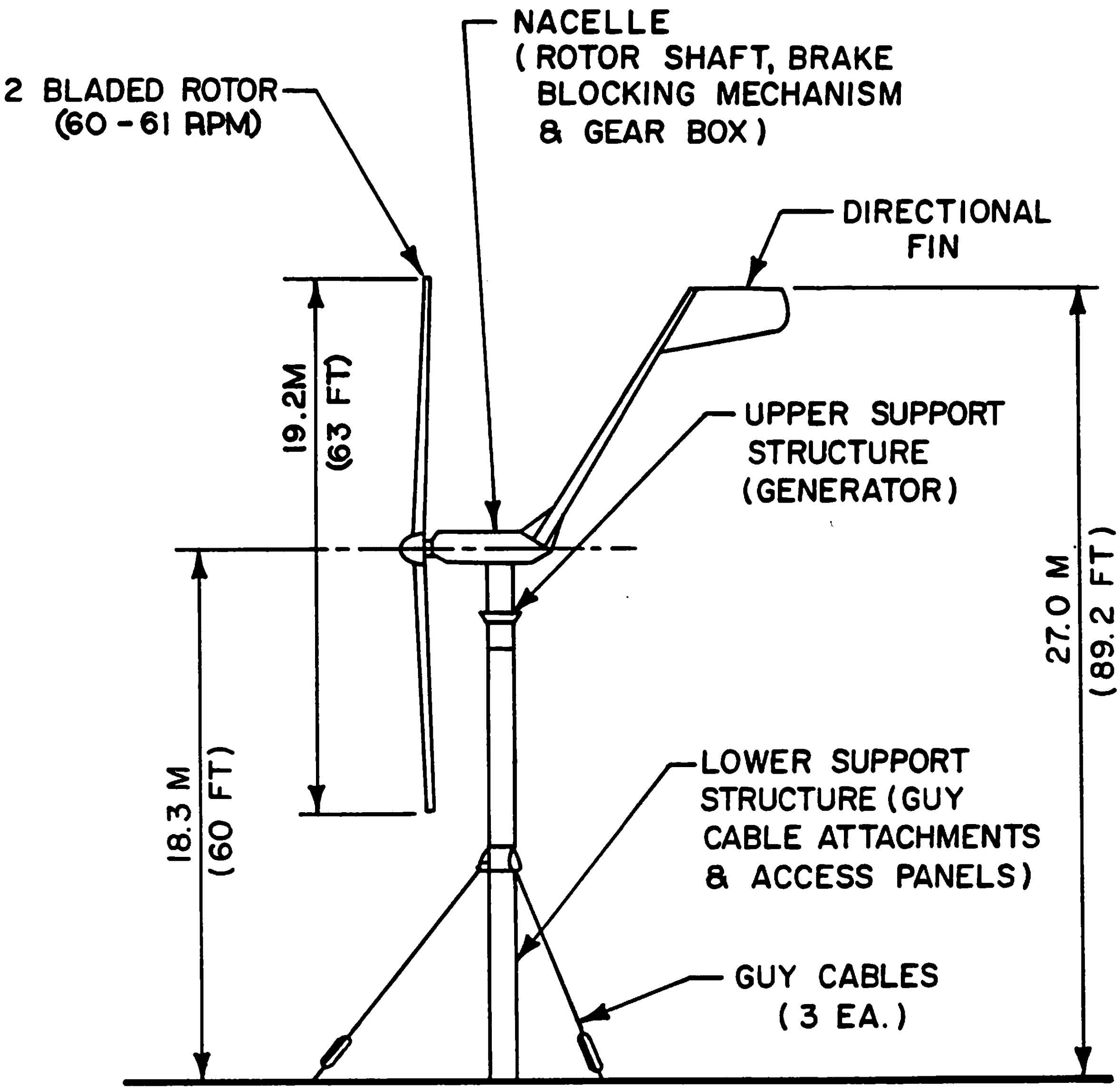
Approximate Land Area Needed: 2.3 acres (5 rotor dia.)
9 acres (10 rotor dia.)



WENCO HORIZONTAL AXIS WTG

100 KW

DRIVE TRAIN DIAGRAM



WENCO HORIZONTAL AXIS WTG
100 KW

Southern California Edison Company
Research and Development Fact Sheet

PROJECT TITLE: DAF Indal 500 kW Vertical Axis Wind Turbine Generator (VAWTG) Demonstration Project.

LOCATION: Southern California Edison (SCE) Wind Energy Center near the eastern end of the San Gorgonio Pass, approximately eight miles north of the city of Palm Springs, California. Wind data collection, started in 1968, has shown that the area has an excellent wind resource with average annual wind speeds in the order of 18 mph at 150 feet above ground level.

OBJECTIVE: To provide further data in support of the planning, installation, and operation of WTGs on a commercial scale. The performance characteristics, reliability and system impact of this alternative and promising VAWTG design will be more fully explored.

DESCRIPTION: SCE will install a 500 kW VAWTG manufactured by DAF Indal Ltd. of Canada. Electricity produced by the VAWTG at the Wind Energy Center will be fed into existing SCE transmission and distribution lines. The basic advantages of the Darrieus vertical axis design include the absence of yaw and blade pitch controls, ease of installation of the system and location of the generators at ground level for ease of maintenance. In addition to this, the DAF VAWTG has several original features: a unique two-blade rotor design, automatically adjusted guy cable tension, a fail-safe braking system mounted directly at the base of the rotor, a redundant rotor overspeed mechanical protection device and two 250 kW generators for better efficiency. Rotor speed is constant at 45 rpm.

WTG UNIT SPECIFICATIONS:

Type: Vertical axis WTG with a two-blade rotor.

Size:

Rotor Diameter	-	80 feet
Rotor Axial Height	-	125 feet
Blade Chord	-	29 inches
Overall Height	-	135 feet

Rated Output: 500 kW in a 43 mph wind speed at 72.5 feet above ground level.

Energy Output: Estimated at up to 675,000 kWh/year for the wind regime at the Wind Energy Center. This is enough to supply the average annual needs of 112 customers and could eliminate the need to burn up to 1120 barrels of fuel oil a year.

SCHEDULE MILESTONES:

Start Installation	-	February 1983
Start Operation	-	August 1983
Test Period	-	1 to 2 years

NOTES ON DAF 500 KW WTG

500 kW - 43 mph - 45 RPM

675,000 kWh/year at Devers WTG Test Site

"Cut-in" Wind Speed: 14 mph (5 min. average)

"Cut-out" Wind Speed: 54 mph (1 min. average)

2 Blade Rotor - Diameter: 80' - Blade Chord: 29"

Rotor Overspeed Protection: 46.75 RPM

Blade Material: 6061-T6 Alloy

Overall Height: 135'

Rotor Weight: 41,250 lbs.

Rotor Column Diameter: 5' at center - 3' at ends

Rotor Swept Area: 6400 ft^2

Total WTG Weight (excluding foundations): 90,000 lbs.

Gearbox Ratio: 1:16.08

Number of Generators: 2

Generator RPM: 720-727   Generator Voltage: 480 V

System Cp: TBD

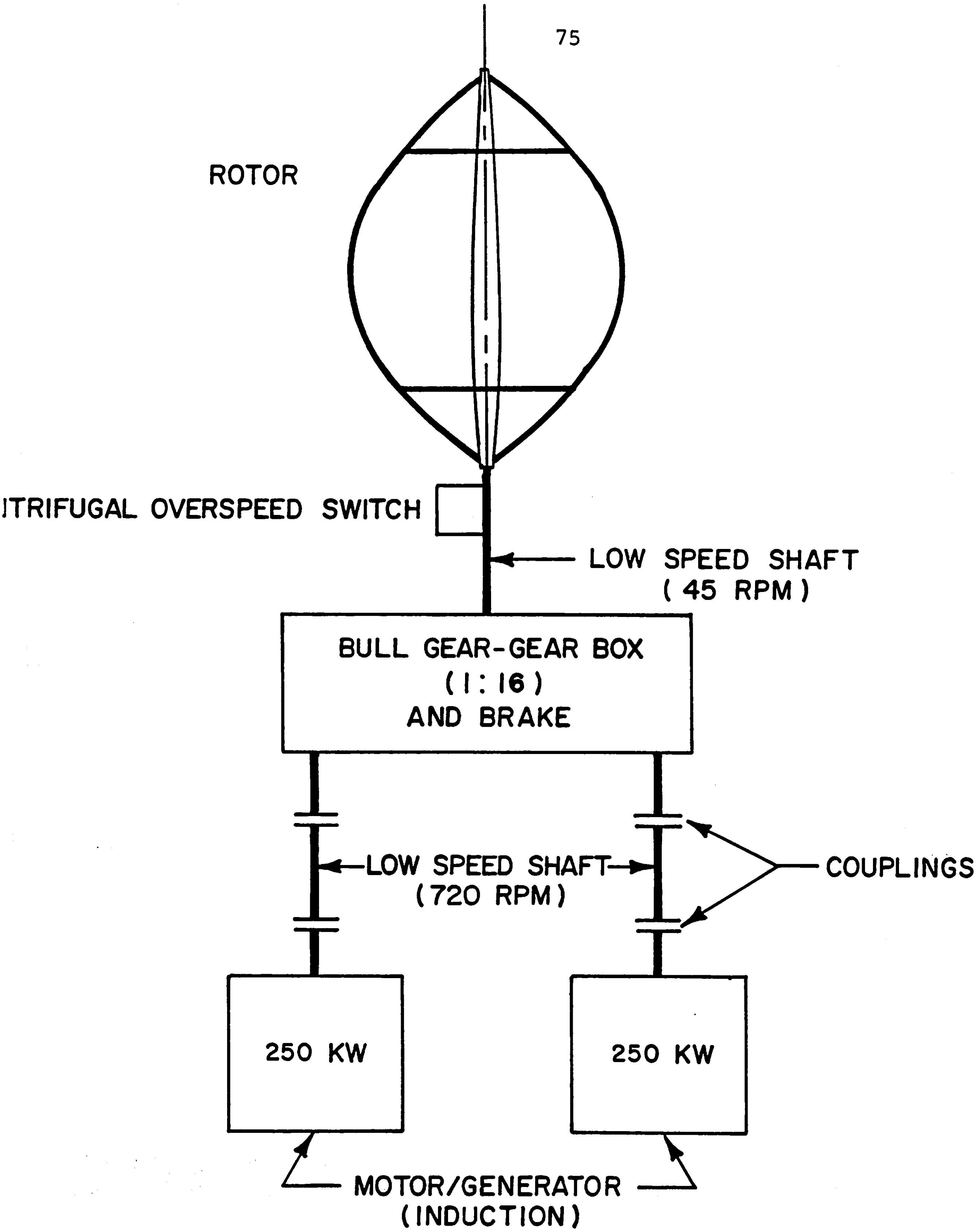
Rotor Maximum Velocity (equator - 45 RPM): 128 mph

Rotor Tip Speed Ratios: 9.1 (14 mph) 5.1 (25 mph) 2.9 (43 mph)

One Generator: 0 kW to 255 kW

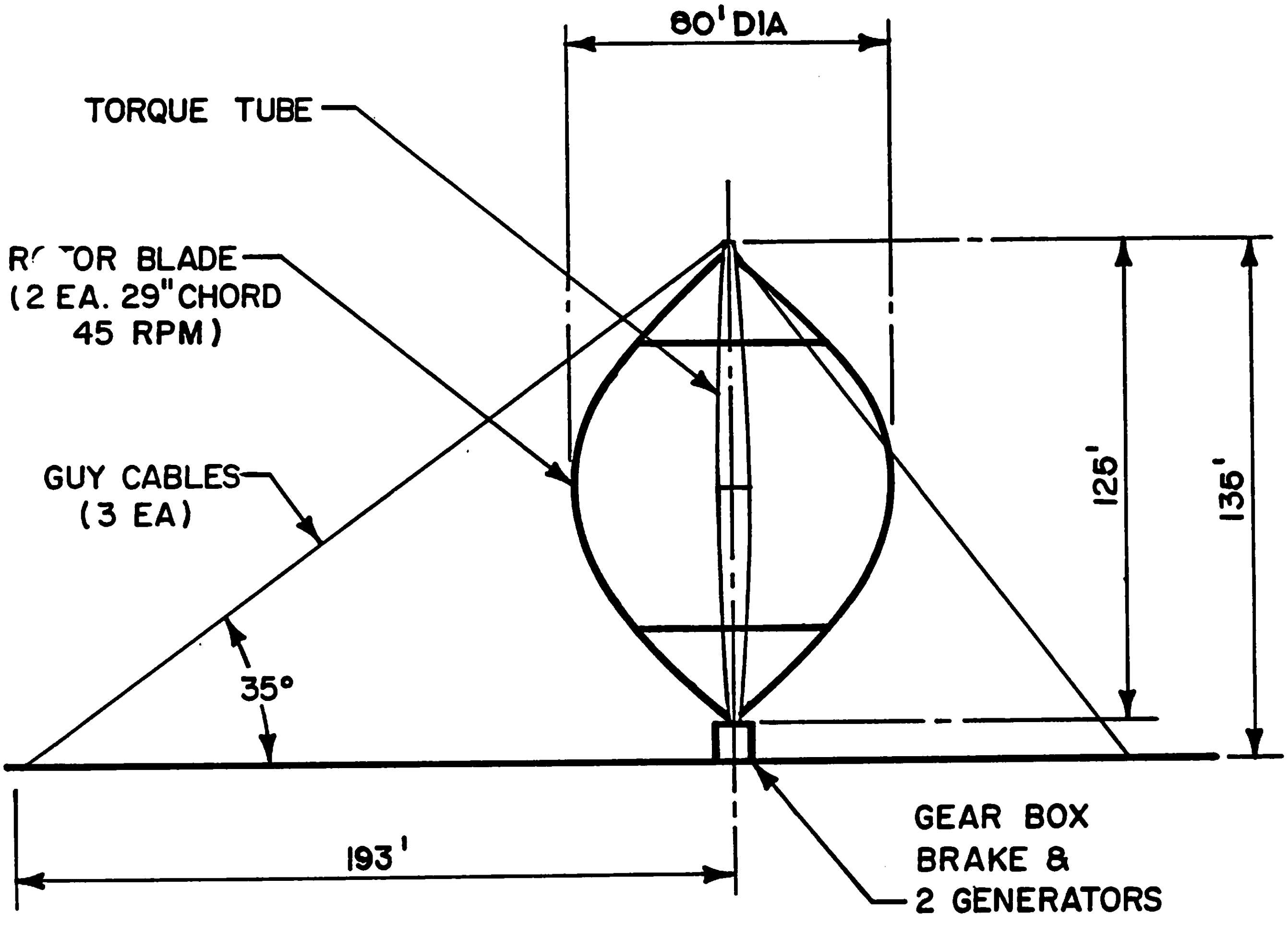
Two Generators: 220 kW to 500 kW

Approx. Land Area Needed: 3.7 acres (5 rotor dia.)
15 acres (10 rotor dia.)



DAF VERTICAL AXIS WTG
500 KW

DRIVE TRAIN DIAGRAM



DAF VERTICAL AXIS WTG
500 KW

Southern California Edison Company
Research and Development Fact Sheet

PROJECT TITLE: Windfree Magnus Air Turbine (MAT) Horizontal Axis Wind Turbine Demonstration Project

LOCATION: Southern California Edison (SCE) Wind Energy Center near the eastern end of the San Gorgonio Pass, approximately eight miles north of the City of Palm Springs, California. Wind data collection, started in 1968, has shown that the area has an excellent wind resource with average annual wind speeds in the order of 14 mph at 30 feet above ground level.

OBJECTIVE: To provide further data on the design, installation and operation of the "Magnus-effect" concept wind turbine. The performance characteristics, reliability and future potential of this alternative and promising design will be evaluated.

DESCRIPTION: SCE has provided funding to Windfree for the installation of Windfree's prototype Magnus Air Turbine, at SCE's Wind Energy Center. The unique feature of the barrel-bladed MAT is that it is designed to use the same aerodynamic force that curves a spinning baseball in flight. This force, called the "Magnus effect," is created by the MAT's three spinning cylinders and will rotate the horizontal-axis central hub. Once installed, the non-electrically interconnected turbine's mechanical performance will be jointly tested by Windfree and SCE, with engineering support from the Harvey Mudd Engineering Clinic. After mechanical performance has been determined, Windfree will consider fitting the prototype with an interconnected electric generator.

WTG UNIT SPECIFICATIONS:

Type: Horizontal axis WTG with a downwind, three cylinder, "Magnus-effect" rotor.

Size:
Rotor Diameter – 55 feet
Cylinder Diameter – 3.8 feet
Hub Height – 46 feet
Overall Height – 73 feet

Rated Output: Approximately 200 horsepower mechanical power output in a 40 mph wind at 46 feet above ground level.

Energy Output: No electrical energy will be produced during the mechanical performance test period. If after mechanical tests it is decided to install an electrical generator, it would be expected to produce approximately 300,000 kWh/year for the wind regime at the SCE Wind Energy Center.

SCHEDULE/ MILESTONES:
First operation at Windfree site – August 1982
Start test at SCE site – December 1983
Test period – up to two years

WINDFREE FACT SHEET

WINDFREE, INC.
24204 Heritage Lane
Newhall, CA 91321
Thomas Hanson, President
(805) 259-1861

Model 55-40

Prototype Design Specifications

Rotor Diameter	55 feet
Tower Height	46 feet
Cylinder Diameter	3.8 feet
Mechanical Power	200 HP
Rotor RPM	19 RPM
Cylinder RPM	332 RPM
Design Tip-Speed-Ratio	1.75
Design Cp.	.20
Power Absorption by Rotor	10-15%
Rotor Orientation	Down wind
Cut-in Wind Speed	Unknown
Rated Wind Speed	40 MPH
Cut-out Wind Speed	130 MPH
Survival Wind Speed	200 MPH

Design Features

Magnus Air Turbine Prototype

Advantages

High Controllability

Inherent Overspeed Protection

Reduced Stress Concentrations

Disadvantages

Very Little Historical Data

Rotor Complexity

Edison Commitment

Early Design Funding

Test Facility

Performance Data Acquisition

WIND SYSTEM - UTILITY INTERACTION ISSUES
A Wind System Point of View

John C. Balcerak

October 1983

Introduction

Methods of interconnecting wind turbines to a utility range from simple, wall-receptacle plug-ins for small dispersed systems to isolated transformer and independently-metered systems for large systems or for a cluster of smaller systems. In many cases, these systems have operated without serious incident either in relation to the utility or in relation to the machine owner or manufacturer. On the other end of the spectrum, there is ample evidence to suggest that machine failures are still quite common and on the basis of incomplete evidence there is a tendency to infer that failures stem only from wind-induced loadings. The question then arises as to whether there is any problem at all relating to machine failures which stem from the utility interconnect?

In the overall area of wind system-utility interaction issues, problem priorities depend on whether the utility or wind generator viewpoint is being represented. As far as the utilities are concerned, it is generally true that electrical problems have been minimal, and the consensus appears to be that until installations become a significant portion of the line capacity and customer load, the effect on the distribution systems can be considered to be negligible. In most cases, the problems studied are conditional on the existence of sufficient installed wind generation to establish a cause-effect relationship on the system. Utility concerns do arise, however, over operating voltage, rates and amplitudes of power flow, flicker, machine self-excitation, power factor and power quality. From the manufacturers viewpoint, most probably do not consider the detailed role of utility distribution systems, particularly in dispersed interconnections. This paper addresses some of the utility interconnect issues from the wind machine point of view which should be of concern to the user and/or manufacturer.

Background:

The electrical characteristics of a wind system, particularly in a dynamic sense, appear to be a secondary design issue as rotor performance and structural characteristics remain paramount. Further, although structural dynamics are considered in some component design, consideration of system dynamics, which include the electrical behavior of the wind turbine interacting with the utility system, has been sorely neglected. Especially open to question is the dynamic or transient behavior of a wind system when significant variations in power flows are dictated by wind or by utility-related events. Hard evidence that transient inputs through the electro-mechanical system lead to failures in dispersed wind systems or in cluster applications is difficult to document. Failures that could have been caused by utility-line fault conditions have, however, been observed. Events such as total rotor separation and coupling failures indicate that very large torque loadings have had a role. Although manufacturers try to compensate for large transient loadings in design, most do not have the resources or an isolated facility to determine the extent of these problems.

During utility recloser operations, for example, several factors can determine how the machine's electro-mechanical and structural subsystems respond to the resultant transient utility input. Among these factors are the incremental recloser time, local line properties, the inertial properties of the wind system, the type of generator, control system characteristics, etc. Wind system structural response upon reconnection could range from a negligible impact on loading to an order of magnitude increase over steady-state values.

Particularly sensitive to such events are the shaft torque loadings. The shaft dynamic responses to the transient inputs are reflected in other system components, e.g., the gearbox. For most cases involving transient utility inputs to a wind system, it is generally conceded that the occurrence of these phenomena is a problem affecting the entire wind system. There is a wide difference of opinion, however, relative to the magnitude of the problem. The perspective given to the problem, is to some extent, also dependent on system size and control system characteristics. Larger systems, for example, tend to utilize synchronous generators and have relatively large inertia constants, while smaller systems utilize several types of generation modes and have much smaller inertia constants. Protection for many systems is provided by reverting to a shutdown mode when any utility failure is detected. For systems which do not incorporate this feature, the response to transient power flows can depend on system type.

The most common electrical system in use with wind machines is the induction generator. Two reasons for this fact are that induction generators are 1) mass-produced and 2) inexpensive. Wind systems up to approximately 20 kW output tend to have a single phase generator and are generally seen in dispersed installations. Wind systems above 20 kW output tend to have three-phase generators and a common application of these is in cluster configurations. Another system in common use is the variable frequency ac system. In these systems the variable frequency ac power is rectified to dc and fed to the utility through an inverter. Less frequently, this type of system feeds the dc output into a battery bank, which then feeds the utility through a dc-driven line commutated inverter. As noted above, many large wind systems utilize synchronous generators. Although these generators are not common on small systems, their use has intrigued several manufacturers, and a prototype system (North Wind 4 kW,) which utilizes a synchronous generator has been developed for DOE under contract to Rockwell.

Currently, there exists much interest in variable speed, constant frequency (VSCF) generators in utility interties to increase annual energy output and soften the electrical/mechanical intertie. Several VSCF schemes have potential for application. Current development efforts on both large or small systems is considering the performance and the dynamics of the electro-mechanical system in applications.

All of these systems operate under a widely varying, time-dependent wind input and even under "normal" conditions produce a widely varying, time-dependent power output. The power output as a function of wind speed is almost always represented (or reported) as a steady-state phenomenon (power curve) which is derived from the time-dependent output using the method-of-bins. Under the proper testing procedures, this information can give the user a good representation of the annual energy output of the system. What has not been investigated in detail is the dynamic behavior of the electro-mechanical wind system, together with its effect on various interconnected components as a function of the time-dependent wind input or under various utility line-fault operations. For example, static and dynamic blade loads due to steady winds, gusts, and directional variations are under intensive study, but the study of torque transients in the electro-mechanical system and their effect on blade loads or the drive system itself has been generally neglected. Design safety factors are generally used in most applications, and some handbooks view transient torque loads of approximately six times the steady-state loadings as acceptable (to the motor and user). Nevertheless, questions remain relative to the actual magnitude of torque changes in wind systems under various time-dependent conditions; the frequency of occurrence of these changes; and whether these changes and their frequency are "acceptable" to the mechanical system, as well as the generator and user.

The discussion thus far has concentrated on a single wind system and its tie-in to a large utility grid which maintains voltage and frequency to within narrow limits. At present, small wind systems are also being considered in areas serviced by a small utility where control of voltage and frequency may not as stringent as on the large grids. The condition of voltage and frequency control may be further aggravated if the power supplied by wind systems becomes a significant portion of that supplied by the entire utility. Irrespective of the problems that increased penetration levels can cause on the utility, the localized effects on the wind system, the user load, and on the load of other utility customers are more pronounced. Operation of wind systems in marginally power-producing winds (i.e., near cut-in) or in strong, gusty winds, for example, can produce transient voltage variations with concomittant effects ranging from annoyance (i.e., light flicker) to equipment damage. With tie-in to a large grid or to a small utility the primary issue is that there is almost no knowledge of the transient behavior of the wind turbine as an electromechanical system.

In recent years, the popularity of wind farms as utility generators has increased. Wind farms use multiple installations to obtain their overall rating. A "chance" wind farm can also exist when many independent machines are intertied to a common utility feeder line. "Chance" wind farms, for example, may consist of a variety of cogenerating systems ranging from 1-100 kW intertied to a single small feeder. One of the unknowns in cluster (wind farm) applications is under what conditions dynamic machine-to-machine interactions can occur through the common electrical intertie. Electrical compatibility of these systems in the transient mode of operation has not been addressed. Questions arise as to whether system responses are induced by transients in the farm power flow, and whether these transients are a contributory factor in the failures?

The question will remain unanswered unless a direct effort is made to document not only the time-dependent inputs, but also the system characteristics of the various types of intertie applications and their response to the transient inputs.

Research Needs:

The primary problem in WECS-intertie application is that wind system designers and researchers have very little knowledge as to how the electromechanical system responds dynamically to various external inputs. Particularly needed are data during gusting or highly turbulent wind conditions and/or under start/stop operations, including operations during utility transients. Wind systems utilize several methods of utility tie-in. An analytical tool is needed to establish the dynamic behavior of the various electro-mechanical subsystems in these intertie applications. The analysis should be capable of predicting the WECS response as well as the dynamic interaction among the utility, the user load, and the other wind systems on line.

Without the knowledge of the transient characteristics of wind systems, broader issues of WECS/utility interties, such as electromechanical instabilities, effects of machine-load interactions, machine-to-machine interactions on feeders, etc., cannot be addressed. Characterization of the dynamic behavior of the various wind system configurations will result in a quantum jump toward the design of more reliable wind systems and reduce annoyance factors which hinder public or user acceptance.

Summary

- Commercial wind systems are experiencing machine failures and breakdowns which are not, in many cases, readily explained by mechanical, structural, or aerodynamic effects. Loads caused by utility transients are suspected.
- Technical discussion among utilities, wind system manufacturers, and researchers regarding wind system - utility tie-in continues to be dominated by opinion, with some groups saying "there is no problem" and others saying "there is a major problem."
- Utilities (in particular, the rural electric cooperatives) continue to express concern regarding a long list of potential dangers related to wind system/utility interconnection. These include degraded utility power quality, personnel safety hazards, damage to utility and user equipment, and lack of utility control.
- Any combination and penetration of wind system electro-mechanical configurations may be present on a utility feeder. The specific effects on machine-to-machine interactions, user loads, and the utility are generally unknown.
- The effect of different wind system electro-mechanical configurations and utility power excursions on system operation continues to be a secondary design issue because of a poor understanding of the problem and the lack of analytical tools.
- No one outside the Federal Government is willing to take the risk of financing a comprehensive research program of wind system-utility intertie problems, particularly as related to the wind system aspect of the problem.

WIND POWER IN THE DANISH ELECTRICITY SUPPLY SYSTEM.

Jan Møller

1. Introduction.

During the last five years appr. 600 hundred small-scale and three large-scale grid-connected wind turbines have been installed in Denmark. This has caused a number of activities to be undertaken by the Danish electric utilities, especially with respect to the many small-scale wind turbines:

1. General technical guidelines for grid-connection.
2. Accounting rules for purchase and sales of electricity.
3. Power grid integration study.

This report reviews shortly the present status of activity 1 and 2, but the main purpose is to outline the results of the third activity.

2. Technical considerations.

When wind turbines are installed, it is often necessary to reinforce the distribution network in order to avoid unacceptable reductions in the quality of voltage. The voltage is influenced by fluctuations in the wind production and cutting-ins of the wind turbines.

Special attention must be paid to the cutting-ins of the wind turbines, as switchings (governed by the actual wind speed) give rise to high inrush currents and correspondingly deep voltage dips.

In cases where the inrush current is limited by e.g. thyristors, a short circuit level at the point of connection of at least 20-30 times the maximum output power of the wind turbine is necessary.

If the inrush current is not limited by additional equipment, a higher short circuit level may be necessary. One Danish utility company demands for instance a short circuit level 80 times the maximum instantaneous output, if the inrush current is not limited.

Another possibility is to limit the number of cutting-ins. Manufacturers of wind turbines hesitate, however, to accept this, because it causes a reduction of the energy production and also a substantial increase of the number of brakings.

Fluctuations in the wind power output also influence the requirements as to the short circuit level in order to limit the voltage fluctuations. Preliminary investigations indicate that a short circuit power of 20-30 times the maximum output should be sufficient. With this short circuit level over-voltages, which often occur during low load periods with a high wind production, should be avoided.

3. Accounting Rules.

An important problem in relation to wind power has been to establish reasonable rules for accounting of the wind energy production. Reinforcements of the supply network has sometimes been needed, but fixed rules for the accounting of this has still to be established.

DEF (The Danish Association of Electricity Supply Undertakings) published in 1976 directional guidelines for the accounting with privately owned wind turbines. These guidelines have been supplemented by later editions and are usually followed by most of the utilities. A revised edition of the present accounting rules is in preparation and may come into force by the end of 1984.

The produced wind energy can be divided into two categories: Energy delivered directly from the wind turbine to the owner, and energy delivered to the public network when the instantaneous production exceeds the actual consumption by the owner.

By receiving the electricity directly from the turbine, the owner avoids to buy the electricity from the utility company. The owner thereby saves about 8 c/kWh (the present average price of electricity, including 3 c/kWh covering VAT and a special electricity tax).

Fixing a price for the electricity delivered to the public network is more difficult, as a suitable payment for the capacity must be found. According to the existing rules, the capacity charge amounts to 50% of the capacity charge paid by the utility company to the generating company. The total charge of electricity delivered from the turbine to the public network amounts to 3-4 c/kWh.

It is presently discussed how the expenditures covering reinforcements of the network should be billed in the future. Until now the individual owners had to cover all expenditures caused by their individual wind turbines. This ment that some owners did not have to pay anything, while others received substantial bills. It has therefore been proposed that the charge should be an average charge for all installations, yet taking into account the specifications of the individual wind turbines.

4. The Value of the Wind Production.

4.1. Grid integration.

The future role of wind power in the electricity supply system will of course depend very much on the value which can be attributed to wind produced electricity. This value depends on several elements of technical, economical and operational character: The type of fuel used in the power stations, the possibility of utilizing the wind production regardless of its variations, the availability of storage facilities (e.g. hydro power), the way of operating the power system without wind power, and finally the costs of operating a thermal and a wind power system in parallel. The composition and structure of the electricity system is of great importance to the valuation of the wind production.

The Danish electricity system has some special features: Coal amounts to 90% of the fuel consumption in the power stations, there is no hydro or nuclear power, there is a very high degree of combined heat and power production which presumably will increase during the next 5-10 years, and the load curve shows pronounced diurnal variations. If the Danish electricity supply system is supplemented with wind power plants, some of these conditions could cause severe problems.

The control range of the individual power plant units has a lower limit above zero. For conventional oil-fired power plants only producing electricity, this lower limit - the technical minimum of the unit - is typically 20-30% of the maximum output power. For a coal-fired unit the lower limit is about 50% of the maximum output power. Below this limit fuel-oil is added. As fuel-oil is more expensive than coal this situation is usually avoided.

For units producing heat and power in a combined production (CHP = combined heat and power production), the lower limit for the electricity output is not a fixed figure but depends on the actual heat output (fig. 1). This lower limit dependent on district heating is called the forced electricity output.

In case of a modest extension of the electricity supply system with wind turbines, the limited control range of the power plants will hardly cause any problems. But in case of larger extensions, the electricity production from wind power plants may have a major influence on the operational conditions and operational costs of the electricity supply system.

As can be seen in fig. 2, a somewhat larger extension with wind power plants may cause a "surplus production", especially during the night hours, when there is only a small difference between the technical/economical minimum of the units (for CHP units, the forced electricity output) and the electricity consumption. The term "surplus production" is explained more detailled in section 4.2.

One could expect that it would be possible to allow for the wind production by stopping the necessary number of thermal power units. The wind is, however, characterized by a limited predictability and frequent substantial variations (fig. 3). As it may take several hours to restart a non-operating unit, the wind may drop again before the unit has been put into operation, thus creating a situation with less operating capacity than needed by the actual demand.

The composition and structure of the Danish electricity supply system indicates that a substantial surplus production of wind energy could occur, if a considerable extension with wind power plants is implemented. As mentioned, the reason for this is a lot of coal-fired units with a high lower limit of production, rapidly increasing co-generation of heat and power and, finally, a load curve with considerable diurnal variations.

Two years ago the Danish utilities and DEFU therefore initiated a study project in order to determine the extent of the expected surplus production, in the case it is decided to install a considerable wind power capacity in the Danish electricity supply system. The objective of the investigation was, furthermore, to determine the economic value of both the surplus production and the directly utilized wind production. It was also decided to evaluate the control problems caused by the fluctuating wind output power.

4.2. Simulation Study.

In order to determine the magnitude of the surplus production, a simulation model has been developed. In fact the model was originally not developed for this specific task, but after some modifications it serves its purpose.

The model simulates the day by day and hour by hour planning of the operation of the available power units. It determines for each unit, whether it is put into or out of operation (unit commitment), and calculates the optimal load dispatch.

The operational planning is simulated on the basis of the following information:

- The electrical load variations during the next 24 hours.
- The heat load variations during the next 24 hours.
- Scheduled exchanges of power with other countries.
- Costs of starting and stopping the available power units.
- Maintenence requirements and forced outage risks.
- Marginal running costs of the available power units.
- Other running and maintenance costs for each unit.
- Requirements in relation to spinning reserve.
- The technical minimum of each unit.

The unit commitment and the load dispatch planning is carried out in order to make the electricity and heat production as cheap as possible.

From the above said, it can be derived that the model as a basic assumption includes predictability of the load variations, which experience shows is a rather reasonable assumption. When a time series of simulated wind power production is included in the system, the situation is, however, quite different as the wind velocity is characterized by a very limited predictability.

The simulation model has therefore been modified as follows: The unit commitment procedure is carried out before the wind power production is subtracted from the predicted load. The load dispatching is carried out after the subtraction. In this way, there will allways be a sufficient power capacity in operation to meet the total expected electricity demand.

The control range of each power unit is limited as previously described. If the difference between the load demand and the sum of the minimum production of all power units exceeds the actual wind production, a surplus production results (fig. 2).

This surplus production is in the simulation not eliminated by stopping the necessary number of thermal units, as this could cause a situation, where the production cannot meet the load demand, because the wind velocity suddenly decreases.

In reallity the surplus production has to be eliminated, but how this should be done is not considered in this simulation study.

5. Results of the Simulation Study.

5.1. Introduction.

Simulations have been performed for different degrees of extensions with elements of wind power increasing from 50 to 1500 MW. As Denmark is electrically separated into two areas without inter-connection lines (ELKRAFT and ELSAM, fig. 4), the calculations have been repeted for each area, in both cases with the above mentioned increasing degree of wind power capacity. The simulation study is based on a concept of the power system as this is supposed to be in the years 1987 and 1995, the latter including both a nuclear and a non-nuclear alternative (table 1).

Table 1

	ELKRAFT		ELSAM	
	1987	1995	1987	1995
Max. load (MW)	2650	3200	3000	4200
Energy demand (TWh)	13	16	15	21

5.2. Magnitude of Surplus Production

Fig. 5 shows the "surplus production" (percentage of generated wind energy) as a function of the wind energy penetration level (generated wind energy in relation to total electricity consumption).

The figure shows that the surplus production at a wind energy level of 10 and 20% amounts to 15% respectively 25% of the total wind energy production. Fig. 6 shows the marginal magnitude of the surplus production (percentage of the increase in the wind energy production) as a function of the wind energy penetration level. From this figure it can be seen that the surplus production from the latest installed wind turbine at a wind energy level of 10% is about 25%. The corresponding magnitude at a wind energy level of 20% is more than 40% of the production from the latest installed turbine. This increasing marginal surplus production is considered to be of great importance.

5.3. Valuation of the Wind Production.

The simulation study also shows that the economic value of the directly utilized wind energy production amounts to 1 1/2 - 2 c/kWh corresponding to the savings in fuel and operating costs of a new coal-fired unit.

The question arises which economic value to attribute to the surplus production. If the surplus production is eliminated by stopping the necessary number of turbines, the value is zero. If, on the other hand, the surplus production can be utilized for some purpose, e.g. in electro-boilers in oil-fired heat plants or for export, the value will be higher, but yet less than the previously mentioned 1 1/2 - 2 c/kWh. Electric storage heating presents another possibility as surplus production mainly occurs during winther nights.

This preliminary analysis indicates that

1. Utilization of the surplus production implies additional investments.
2. The economic value of the surplus production is normally considerably lower than the value of the directly utilized production.

A more detailed analysis has to be carried out in order to determine the economic value, and especially the marginal value, of the surplus production. The results of this analysis could have a decisive effect on the future utilization of wind power in Denmark.

6. Control Considerations.

6.1. Introduction.

Widespread utilization of wind power may cause serious concerns in relation to the control of the power grid.

Today the hour by hour load variations can be regarded as predictable, and this enables every day the power companies to arrange a scheme of operation for each power unit, which allows for the expected variations. All minor unpredictable load variations are corrected by fast acting power units, whereby the frequency of the grid is stabilized.

As the Danish electricity supply system is considerably smaller than the interconnected neighburing systems, which include fast acting oil-fired units and hydro plants, a major part of these short term load deviations is automatically corrected by the foreign systems. These corrections lead to unintended deviations from the agreed power level on the interconnection lines, and they must as soon as possible be eliminated through manual control of the load level of the Danish power units. These manual control actions are not taken very often, because the load level, as mentioned above, can be predicted reasonably well.

At higher levels of wind power penetration these operational circumstances are presumably changed, as the wind power output fluctuates frequently and unpredictably.

A considerable increase in the number of manual control actions must therefore be anticipated. This will make the daily operations more complicated.

It might be possible to use the deviation between agreed and measured power exchange as a control signal to adjust the Danish power stations to an output level, which counteracts the deviation caused by the wind power plants.

It is, however, uncertain whether the Danish thermal power units will be able to respond quickly enough to match the power variations from a wind power system. One of the reasons for this is that the Danish power system mainly consists of coal-fired steam power units, which are slow acting to load changes as compared with oil-fired units or hydro plants.

It complicates the control problems furthermore that it is not possible to initiate any control action until the power change has actually taken place. This is due to the unpredictable nature of the wind.

The previously mentioned simulation study also includes preliminary computations of the output power variations from a system of wind power plants. This is intended as a first step in direction of defining and solving the control problems.

6.2. Power Variations.

The wind velocity changes all the time, partly due to turbulence in the wind and partly as a result of changes in the pressure field. The power variations due to the turbulence will to a certain degree be equalized in a system of wind turbines, as the turbulent fluctuations are uncorrelated. The equalization of the power variations caused by changes in the pressure field tend to be limited, as the propagation of the pressure changes takes place quickly in a small territory as the Danish one.

Simultaneous wind measurements from five different locations have been used for calculations of the power variations from a system of wind turbines. The number and location of the meteorological masts give an equalization of that part of the computed power variations that are caused by synoptical changes. This equalization corresponds reasonably well to the equalization in a system of widespread wind power plants. This does not apply to the turbulent fluctuations.

Based on these assumptions and the above mentioned measurements (the wind velocity has been recorded every 10 minutes throughout a year), the frequency distribution of the power variations occuring within 10 minutes and 1 hour has been calculated for a system of 300 turbines, each of 2 MW.

The results are shown in fig. 8, which shows that power changes exceeding +/- 80 MW/hour only occur once a day, while power changes exceeding 110 MW/hour occour once a months. A maximum power variation of 140 MW/hour occur once a year. It is furthermore seen that power fluctuations exceeding 12 MW/10 min. occur once an hour, and once a day the fluctuations exceed 18 MW/10 min. The maximum value of the short term fluctuations is 30 MW/10 min.

6.3. Discussion of solutions.

It is at present not possible to state, whether or not the Danish thermal power system will be able to absorb these load variations. If not, certain precautions must be taken as a provision for integration of wind power.

Installation of electric boilers in oil-fired heat plants seem to be an obvious solution to the control problems created by wind power plants. This will also eliminate the problem with the surplus production. In this way, the unpredictable load variations can be absorbed by load changes of the boilers.

Interruptible electric heating is a similar possibility. The control range is of course limited during the summer period, when there is no heat load. On the other hand, the load of the electric water heaters is presumably higher, and the power variations from the turbines occur at a lower level due to the calm wind conditions during this period.

An improvement of wind forecasts is another possibility to solve the control problems. The existing forecast models do not give a sufficient reliability for the purpose of operational planning. The meteorologists are, however, quite optimistic regarding the possibility of improving the accuracy of the models. It is unfortunately not possible to predict power variations due to turbulence in the wind.

If none of these solutions are applicable (which they should be at a limited level of wind power), the control problems can be solved by installation of oil-fired power units. As fuel oil is 2-3 times as expensive as coal, this solution implies a considerable economical setback to wind power, which in reality puts severe restrains on the use of wind power.

All together, these restrictions show that wind power in larger quantities necessitates a new way of operating the electric power system. How this should be done, and the additional costs, are not known. Further work must be carried out in order to find the answers.

7. Concluding Remarks.

From a geographical and meteorological point of view Denmark is an ideal country for wind power because of its flat terrain and many westerly shorelines.

The existing Danish electricity production system is, however, less suited for wind power, as there are no storage facilities, a high degree of cogenerated heat and power, substantial variations of the diurnal load curve and a number of big coal-fired power units with slow control characteristics.

As a results of this, the economic value of a wind power production decreases as the wind power system is extended. Additional investments in order to solve the control problems caused by wind power will be necessary, if the wind power system is extended beyond a certain limit. It is, however, not possible to state this limit at the moment.

In the foreseeable future wind power will not be able to cover a substantial part of the electricity demand in a cost effective way. On the other hand, wind power plants may yet pay a certain role within the electricity supply system as a supplement to the thermal power plants.

Fig. 1

Forced Electricity Output as a Function of the Heat Demand

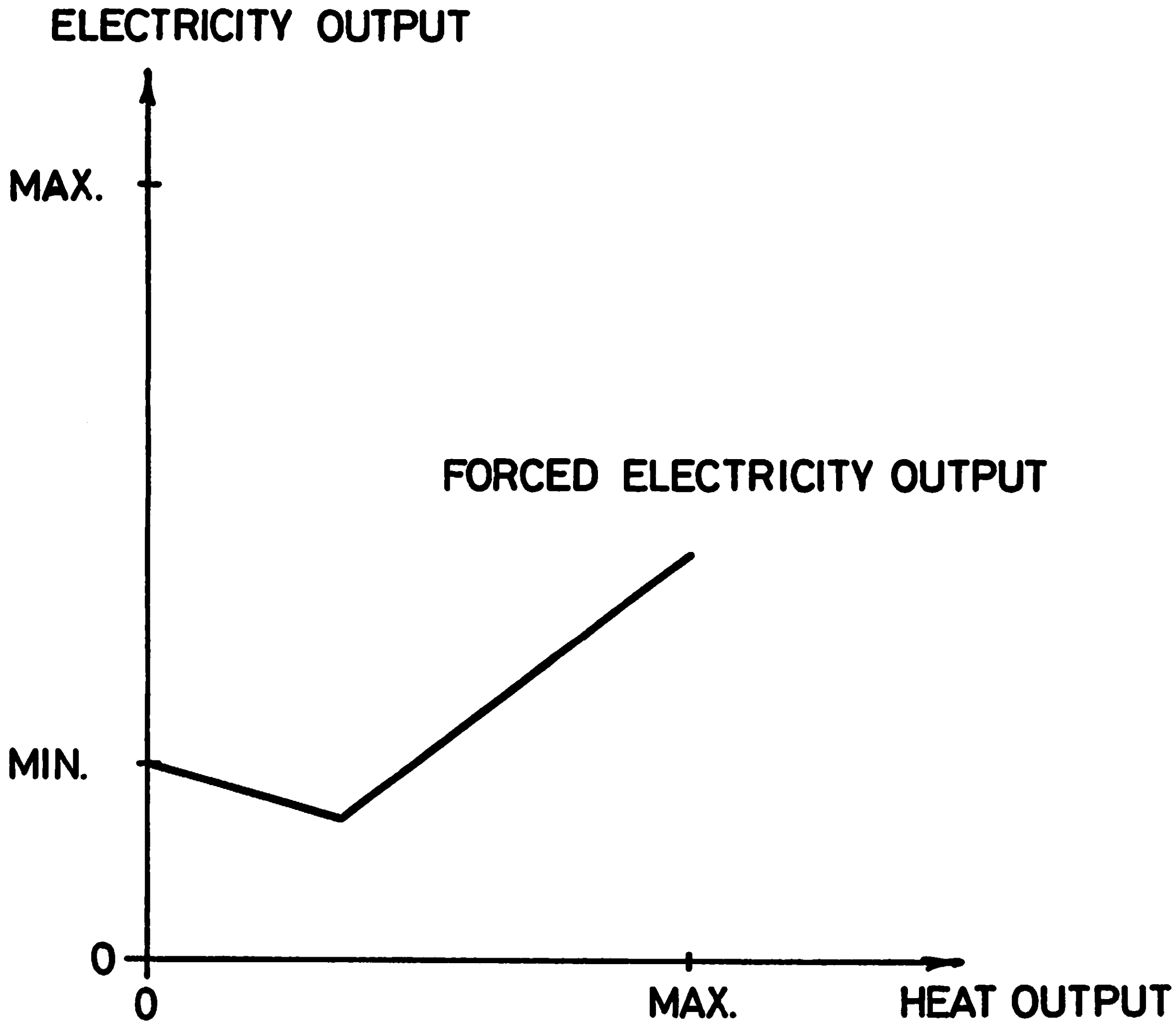


Fig. 2

Demand and Minimum Production During a Winter Day

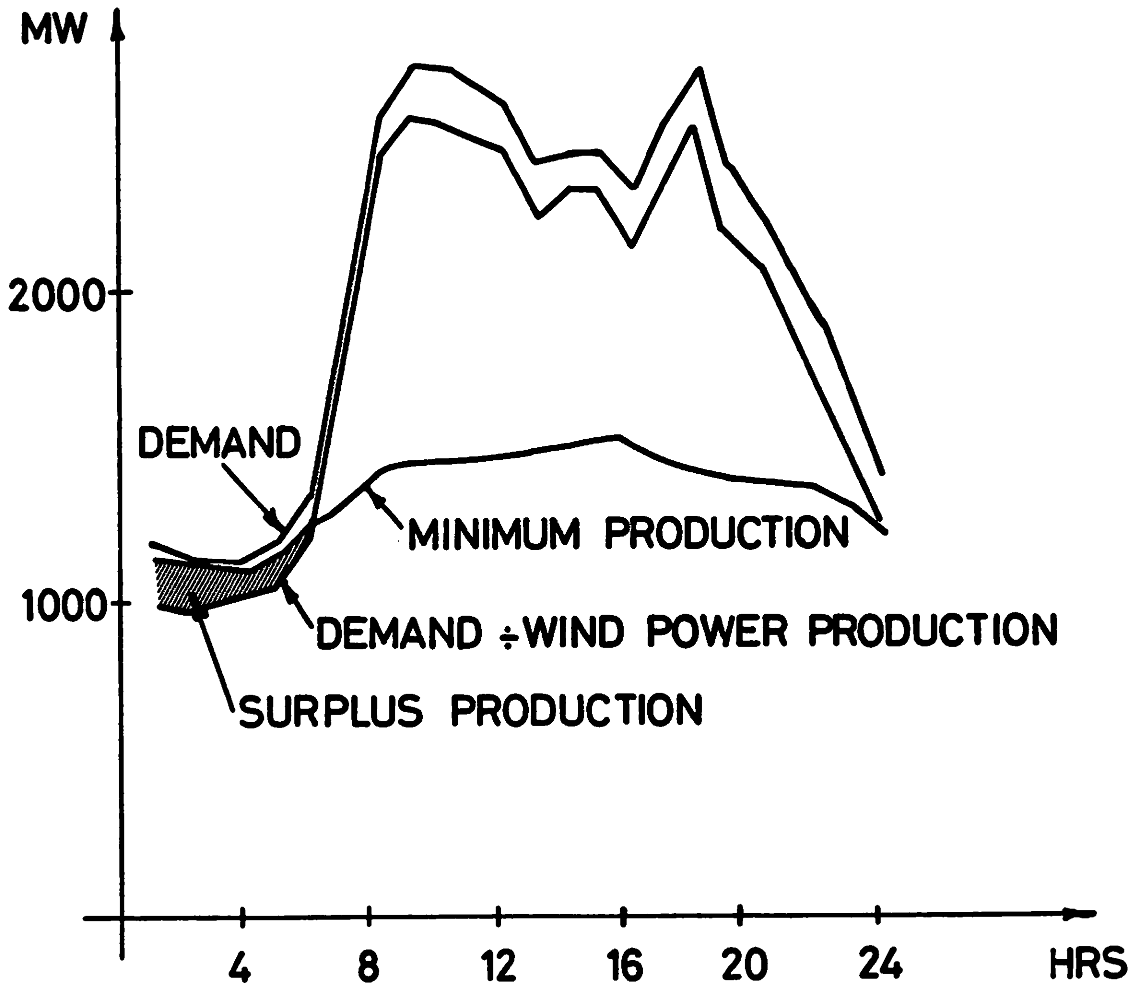


Fig. 3

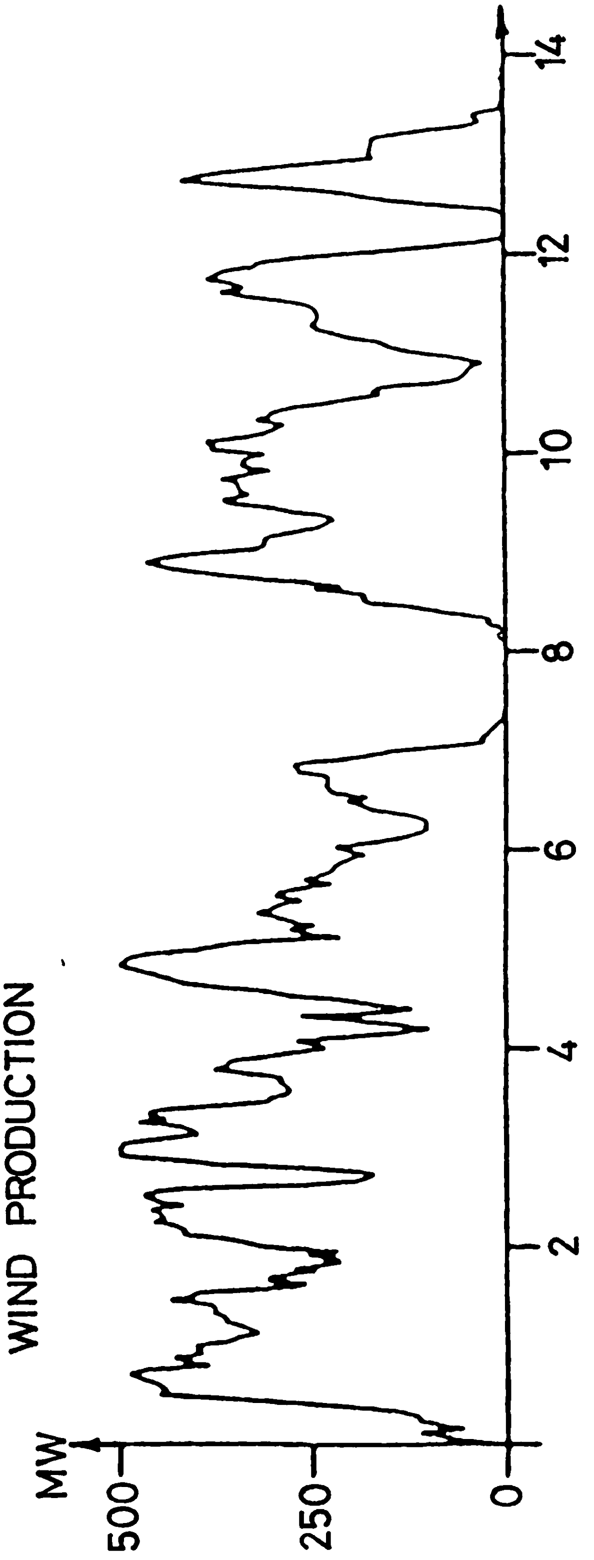
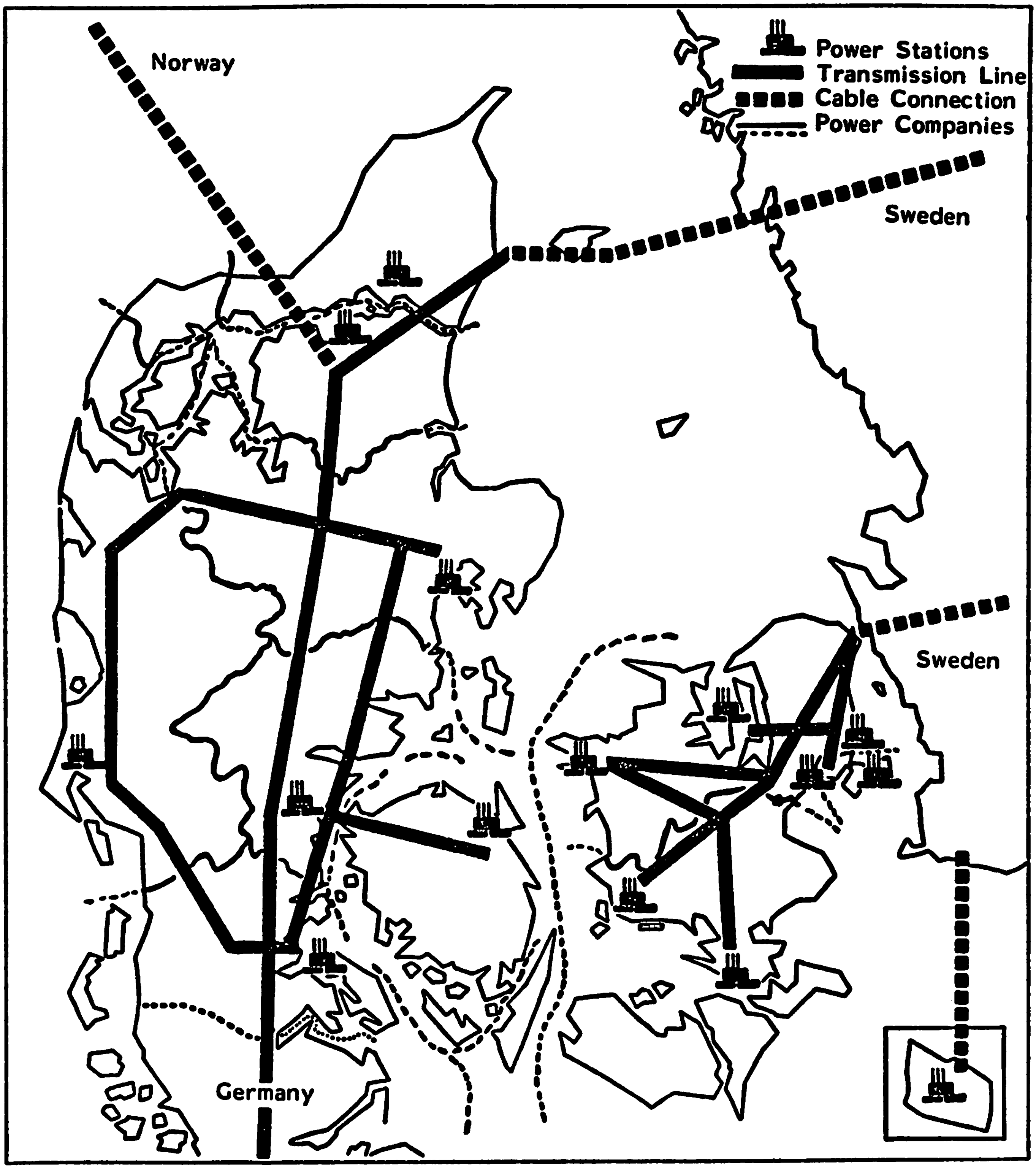


Fig. 4



Danish Electricity Supply System: ELSAM-area left. ELKRAFT-area right.

Fig. 5

SURPLUS PRODUCTION AS A FUNCTION OF THE ENERGY SHARE OF THE WIND ENERGY PRODUCTION.

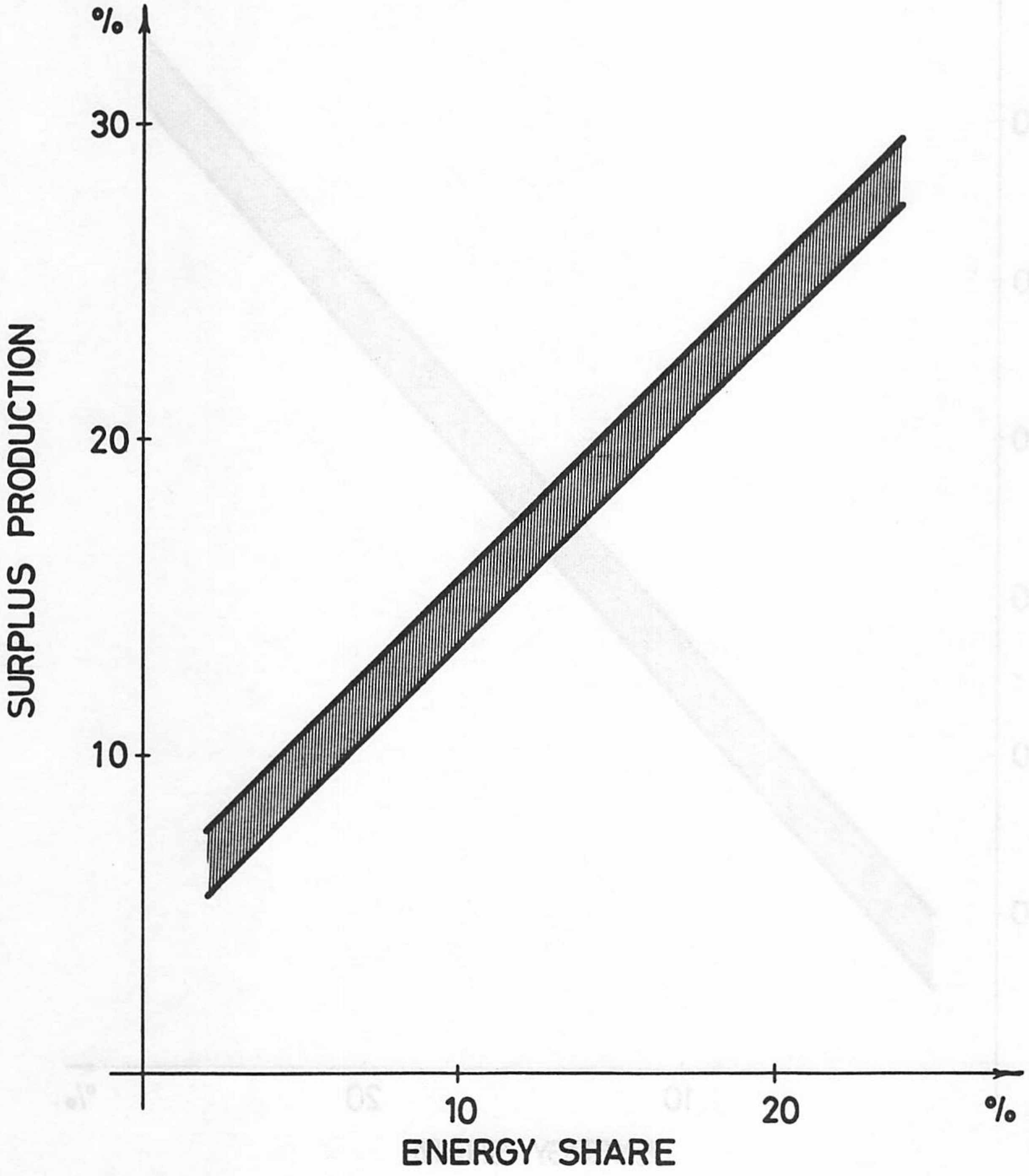


Fig. 6

MARGINAL SURPLUS PRODUCTION AS A FUNCTION OF THE ENERGY SHARE OF THE WIND ENERGY PRODUCTION.

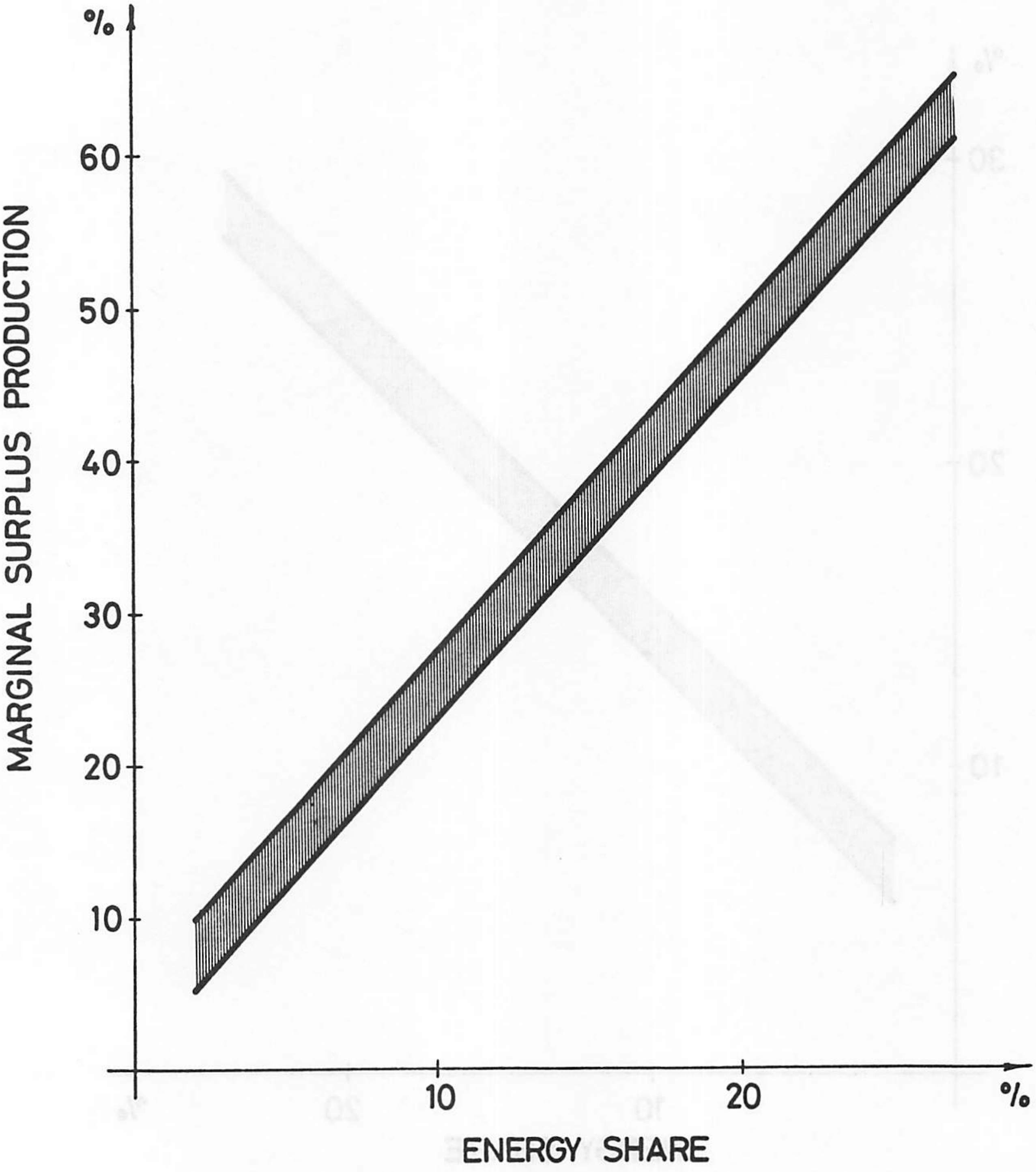


Fig. 7

✱ : Wind measurement.

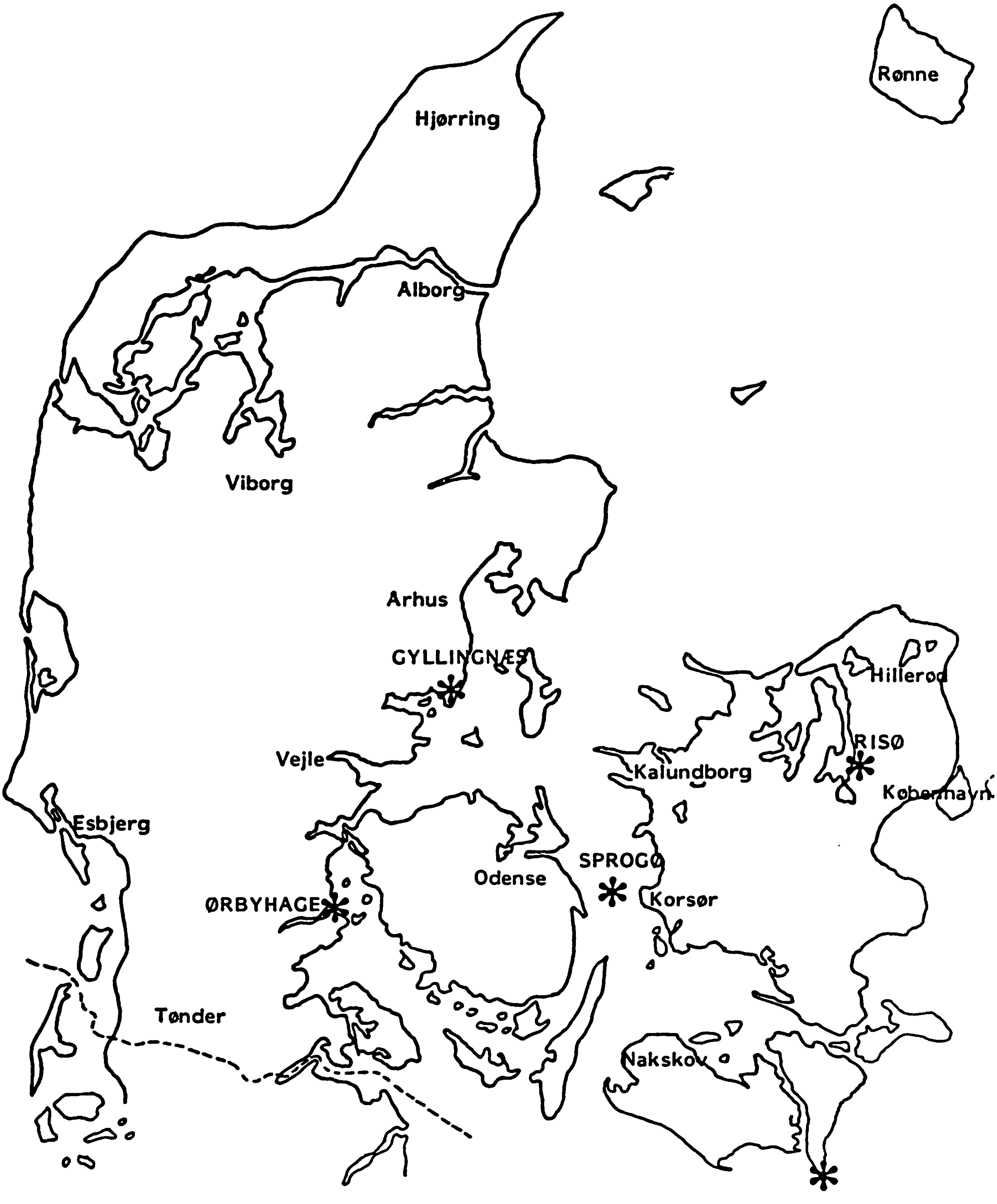
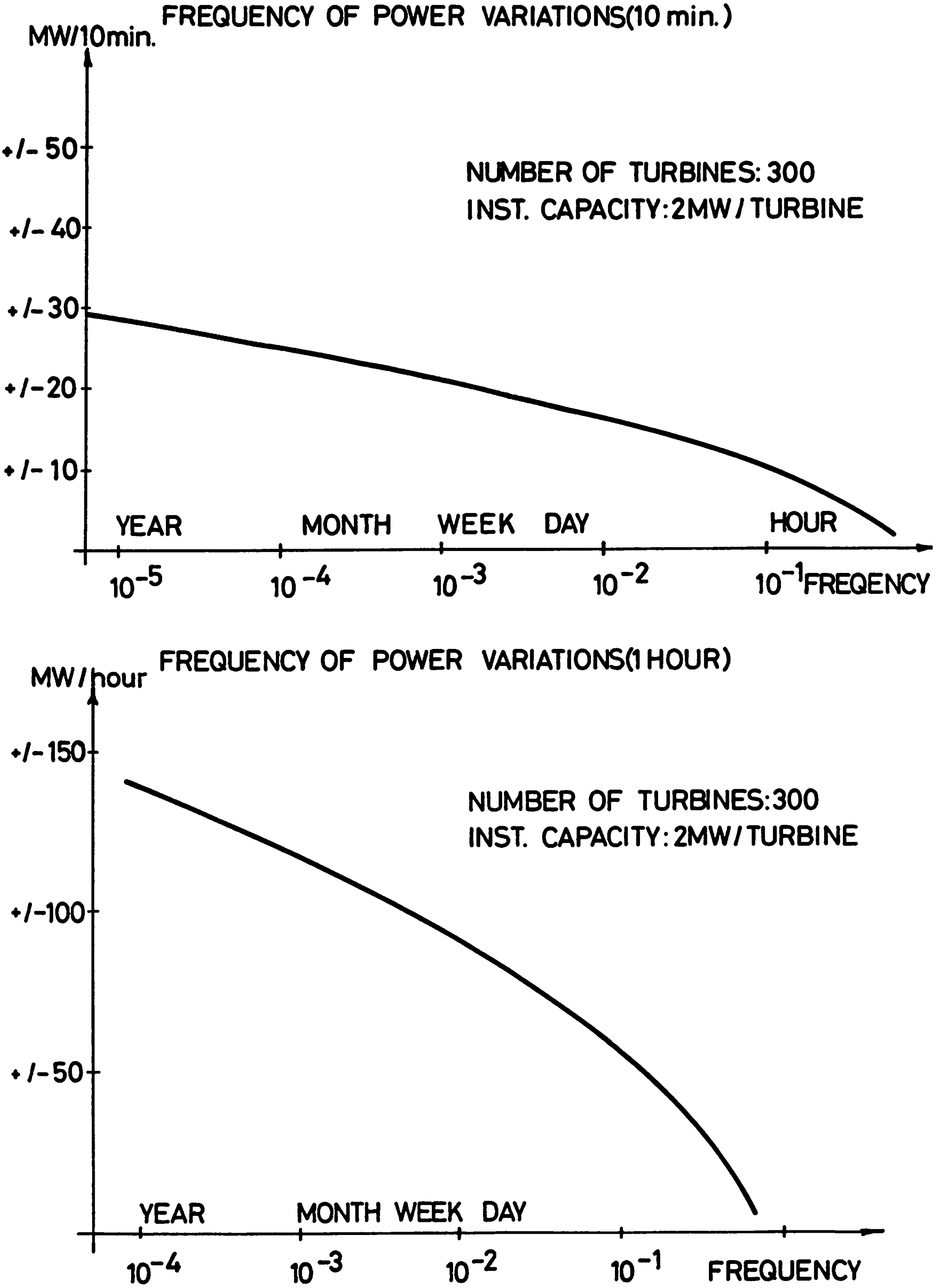


Fig. 8


FREQUENCY OF POWER VARIATIONS(10 min.)
MW/10min.
+/- 50
+/- 40
+/- 30
+/-20
+/- 10
NUMBER OF TURBINES: 300
INST. CAPACITY:2MW/TURBINE
YEAR
MONTH
WEEK
DAY
HOUR
10^-5
10^-4
10^-3
10^-2
10^-1
FREQENCY
FREQUENCY OF POWER VARIATIONS(1 HOUR)
MW/hour
+/-150
+/-100
+/-50
NUMBER OF TURBINES:300
INST. CAPACITY:2MW/TURBINE
YEAR
MONTH
WEEK
DAY
10^-4
10^-3
10^-2
10^-1
FREQUENCY

Control of Variable Speed Double-Fed Winddriven Induction Generator

W. Vollstedt

1. Introduction

The 3 MW wind turbine GROWIAN is equipped with a double-fed induction generator. This type of Generator combines the advantages of a fluctuating speed of rotation with the desireable electric properties of a synchronous machine. As shown in Fig. 1, the generator may be operated above or below synchronism and with positiv or negativ reactive power. Besides the stabilization of the machine a decoupled speed-independent control of active or reactive stator power flow is possible when the amplitude and phase rotor currents are properly determined by the control-system.

Fig. 2 shows a possible control system for a double-fed generator, where the stator is coupled to the grid and the rotor is supplied by a variable frequency source (cycloconverter). Depending on the required speed range, the cyloconverter can be employed to feed slip-proportional active power and the excitation of the machine to the rotor. The power flow shown in Fig. 2 is concerning only the active power, the reactiv power does not depend on the speed (slip) and will be considered later on.

2. Control System

In order to realize a decoupled speed-independent control of active or reactive power a mathematical model of the generator has been developed (|1, 2, 3|), which is suitable for this purpose. This model is based on the magnitude and direction of a flux vector and the proper control is called field orientated control. A simplified block diagramm of a double-fed induction machine (Fig. 3) is the result of the mentioned theory. The input quantities are the three rotor currents (quasi-impressed by fast acting current control), the mains frequency and voltage and the mechanical torque. The output are the mechanical angular velocity and the active and reactive stator power. The d-q-components of the rotor currents are directly related to reactive and active power, and this leads to the field orientated control scheme of a double fed machine as shown in Fig. 4.It has been designed for a 22-kW-generator with all the control functions implemented in a microcomputer. A cascade control has been chosen, with inner current loops around the cycloconverter and superimposed active and reactive power control loops. The references can be assigned within the permitted operating-range of the machine. Finally the output signals of the power controllers are transformed into the rotor axes - suffix a, b - and splitted into the three rotor current references in order to obtain consistant signals for the control of the cycloconverter.

In the interest of an improved dynamic response, the voltage induced in the rotor windings may be cancelled by an appropriate voltage feed-forward. The required signal is obtained from a EMF-computation and the real and imaginary components are be added to the references $i_{ra\ ref}$, $i_{rb\ ref}$. In addition, the phase lag caused by the leakage inductance and the delay of the converter can be neutralized by an appropriate lead-lag element.

The coordinate transformation at the input end of the machine model is retransformed at the outputs of the power controllers, whereby the transformation angle is obtained by help of culculation of the modified magnetizing current vector i_{ms}.

In order to obtain superior dynamic performance the control unit consists of two 16-bit microcomputers - CPU 8086 - connected to each other via bidirectional data/command-bus. Sample rates of about 1 ms can be actieved with this assembly.

3. Experimental Results

In order to confirm the theoretical predictions an experimental drive with a 22 kW slip-ring machine was installed. The behaviour of a large windmill was simulated by a 50 kW DC-motor with torque control.

The fast step-function response of the active power controller - for a step from 0.5 to 0.8 rated reference - is shown in Fig. 5 a. In addition the actual reactive power is plotted in this diagram.

A comparison between both diagrams confirms the decoupling of stator power flow when the control scheme is realized by a microprocessor.

In order to stress the superior dynamic response of the applied control scheme the electrical torque and angular velocity of the double-fed generator is shown in Fig. 5 b during a rapid transition from subsynchronous (1400 Rpm) to supersynchronous speed (1600 Rpm).

It is seen, that there is a very fast control action. The speed of the shaft increases without noticeable effects on the electrical torque and on the active stator power of the generator.

The cycloconverter operating with natural commutation draws varying amounts of reactive power from the line. In order to get a good power factor for the whole system, the cycloconverter has to supply much more apparent power than the active power flow of the rotor circuit is requiring. In Fig. 6 it is seen, that the reactive power in the rotor circuit is nearly constant over the whole speed range but increases considerably while changing from underexcitation to overexcitation. The reactive power can be much higher than the active power in the rotor circuit.

4. Synchronous generator with active damper winding

The cost for the excitation circuit of a double-fed induction generator are very high relating to the corresponding expenditure of a synchronous machine. Otherwise a normal synchronous generator tends to oscillate with low frequency if it is connected to the grid, whereby high mechanical stresses are caused espessially in windturbines. The oscillation can be avoided by introducing in the quadrature axis of the rotor an active damper winding which is fed with transient current by a second field voltage supply; in steady state condition this current is reduced to zero.

With that type of generator the advantage of variable speed range is lost but the dynamic performance is much better than that of common synchronous machines.

In Fig. 7 a step response of active power of an undamped synchronous generator can be seen. The weakly damped oscillation can be suppressed by means of a rotor winding in the quadrature axis and a control in field coordinates as seen in Fig. 8. The step responses are recorded with the help of the same machine (22 kW).

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Abschlußbericht BMFT-Vorhaben 03E-4362-A
Januar 1983

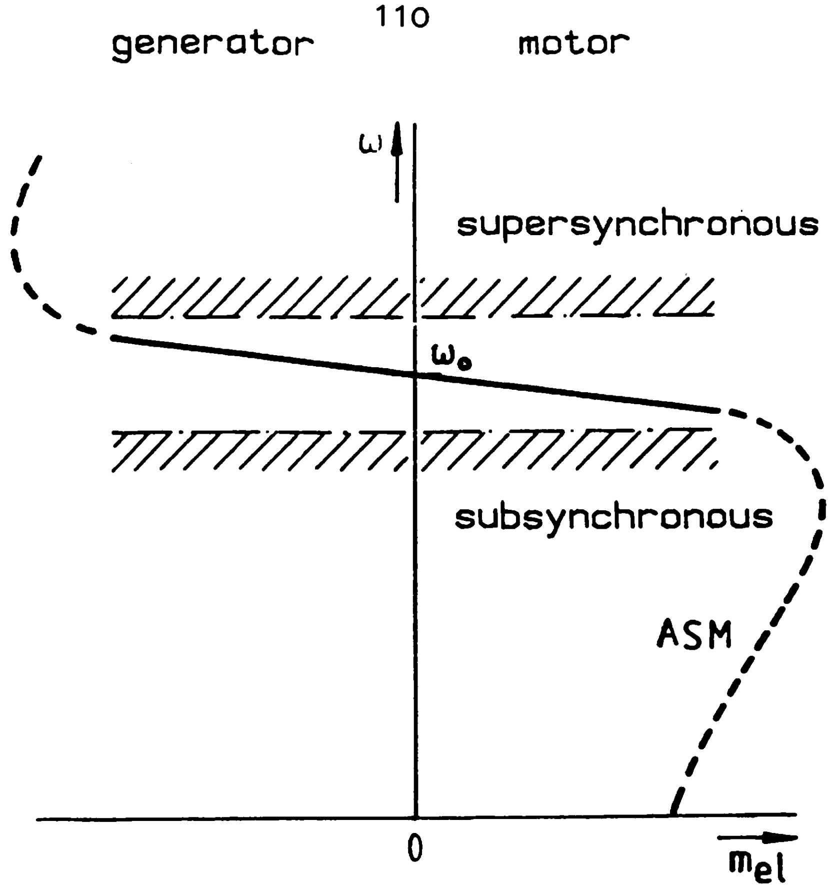


Fig. 1.a: Operating range

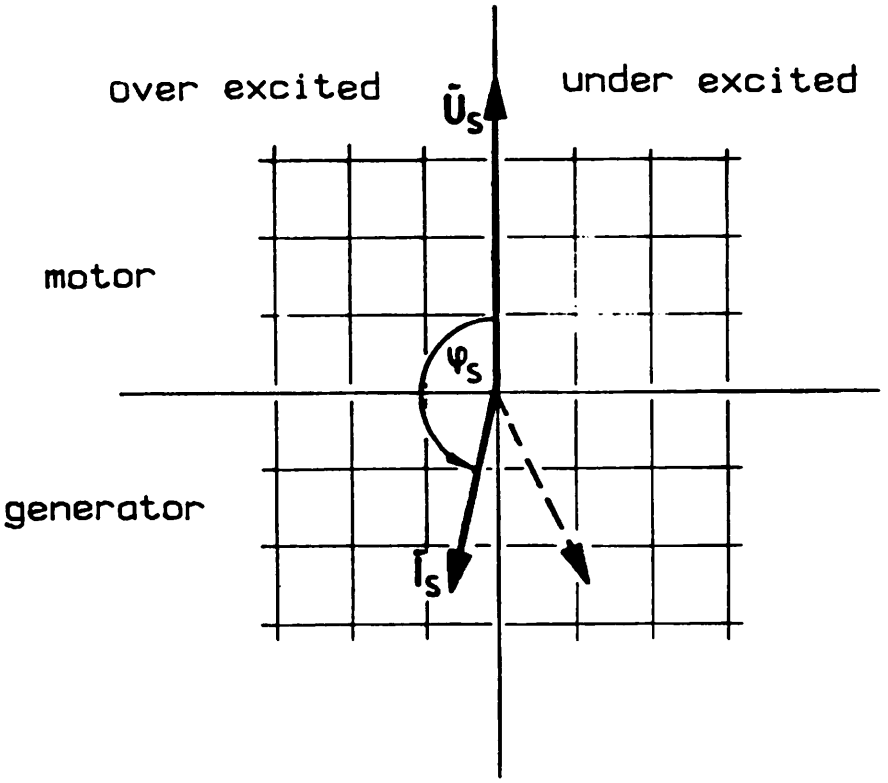


Fig. 1.b: Voltage- and current-vector of the stator

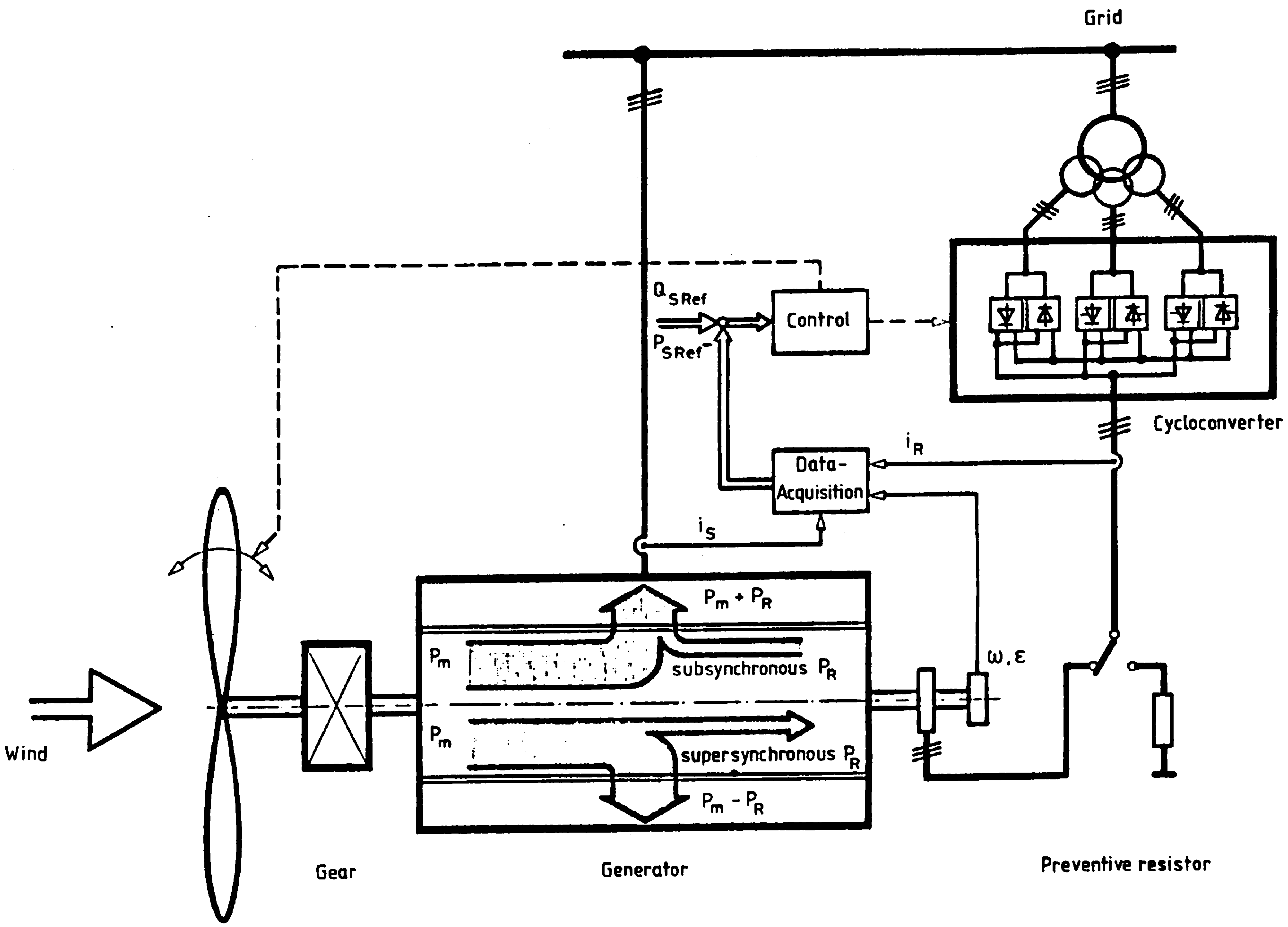


Fig. 2 : Double - fed generator control system

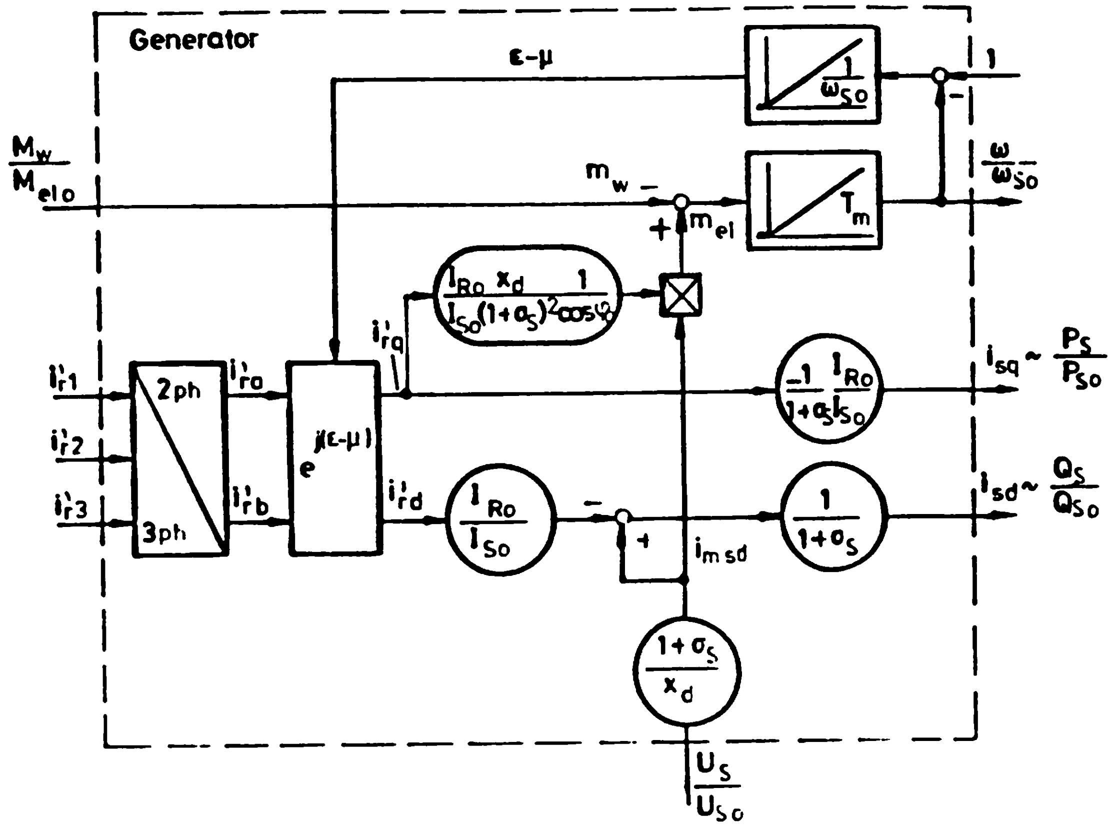


Fig. 3: Simplified block diagramm of a double-fed machine with impressed rotor currents

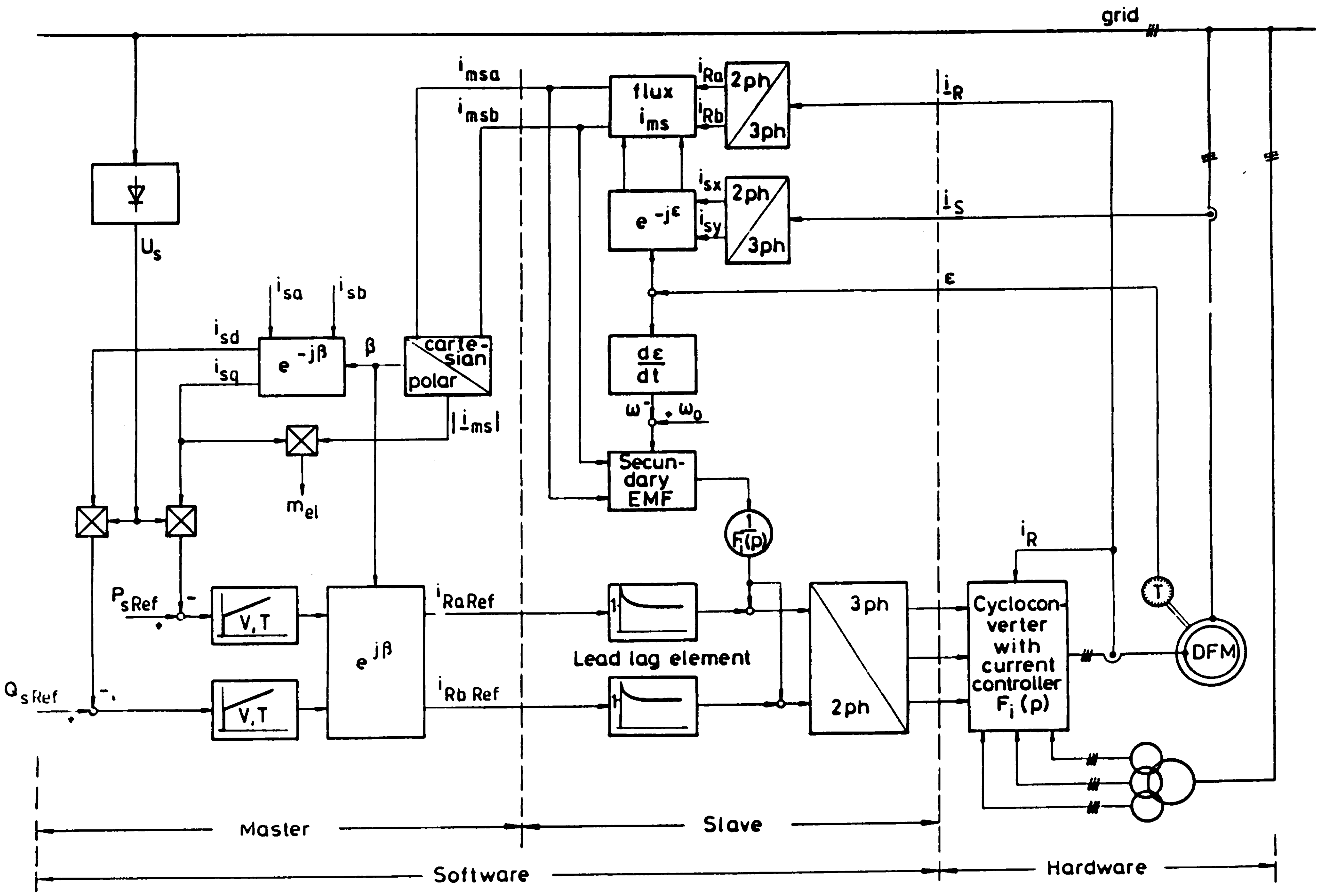


Fig.4: Structure of the field orientated control.

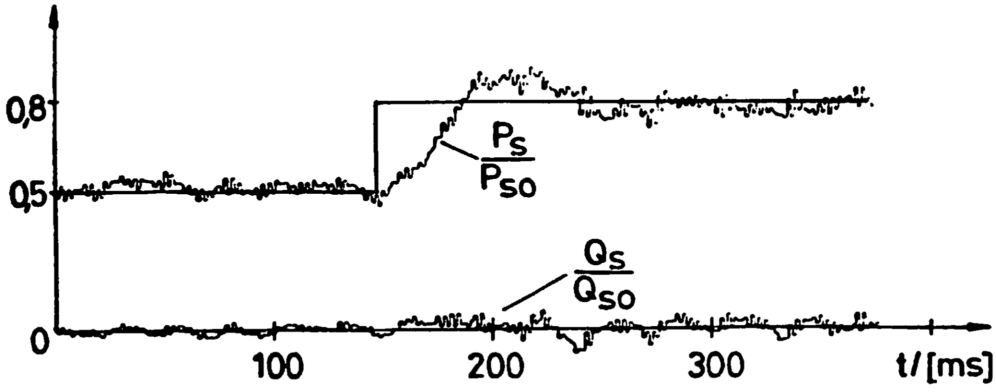


Fig 5a: Step response (P_{SO} =22kW, Q_{SO} =10kVA)

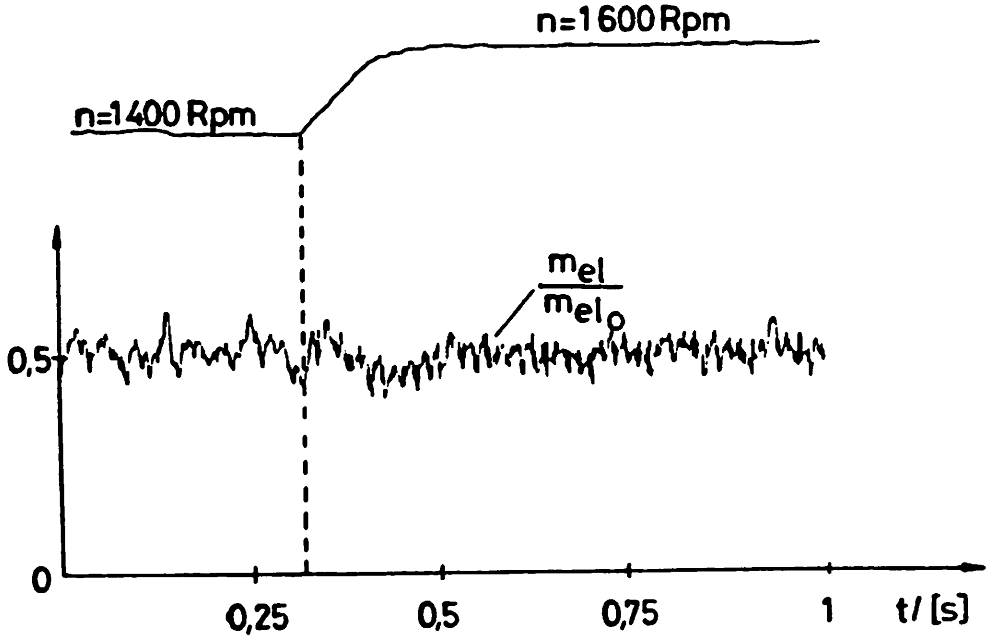


Fig.5b: The electrical torque during a rapid change of speed

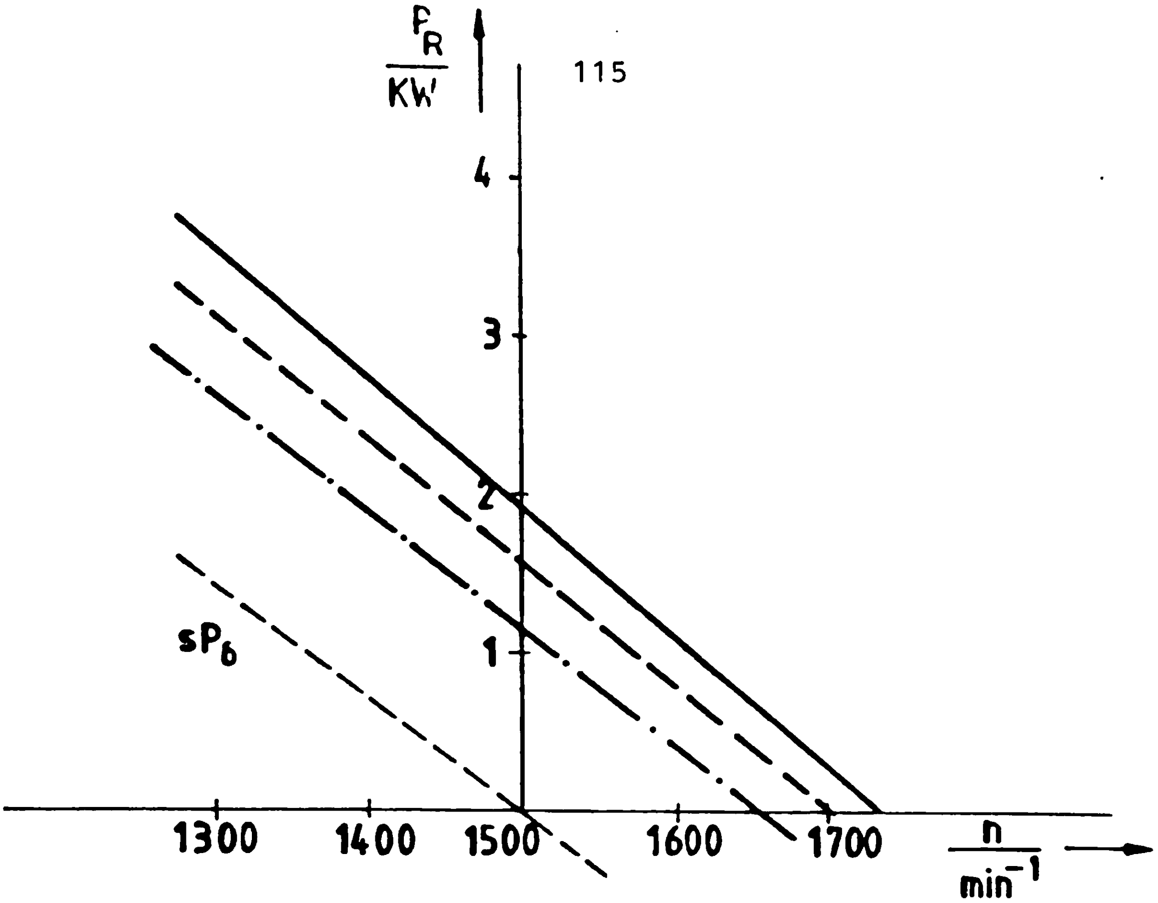
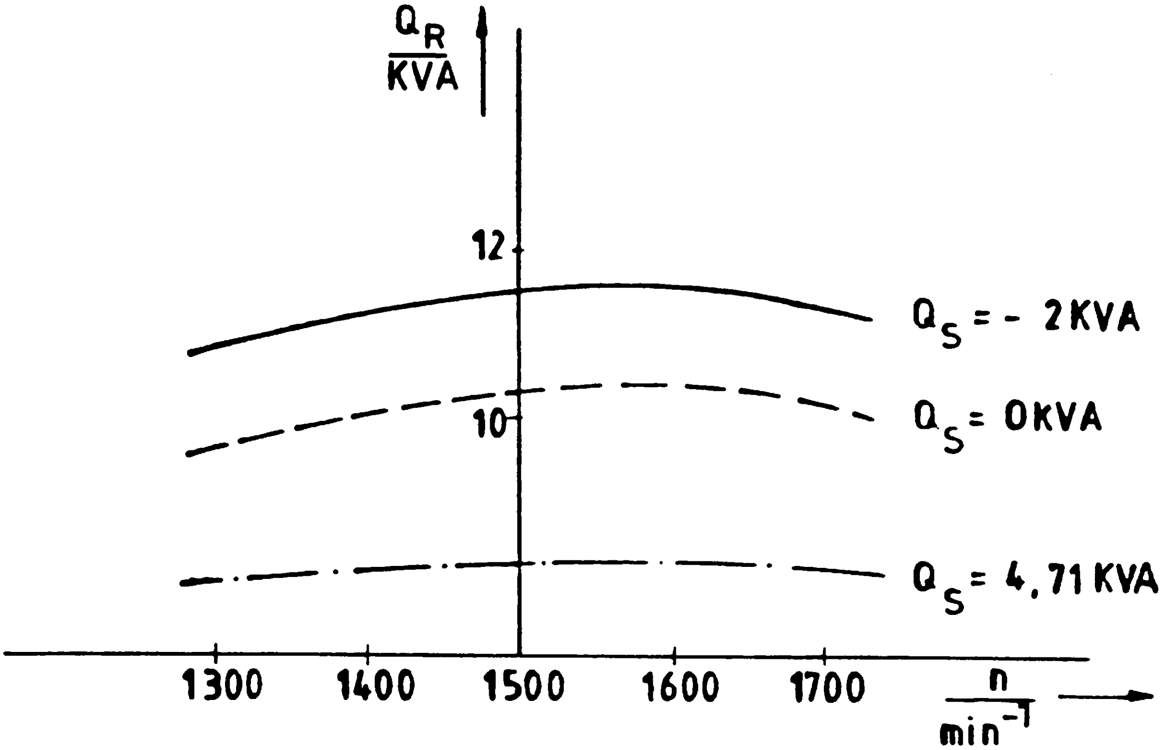


Fig 6a : Active power of the rotor circuit



$P_S = 0{,}5 P_N$

Fig.6b : Reactive power of the rotor circuit

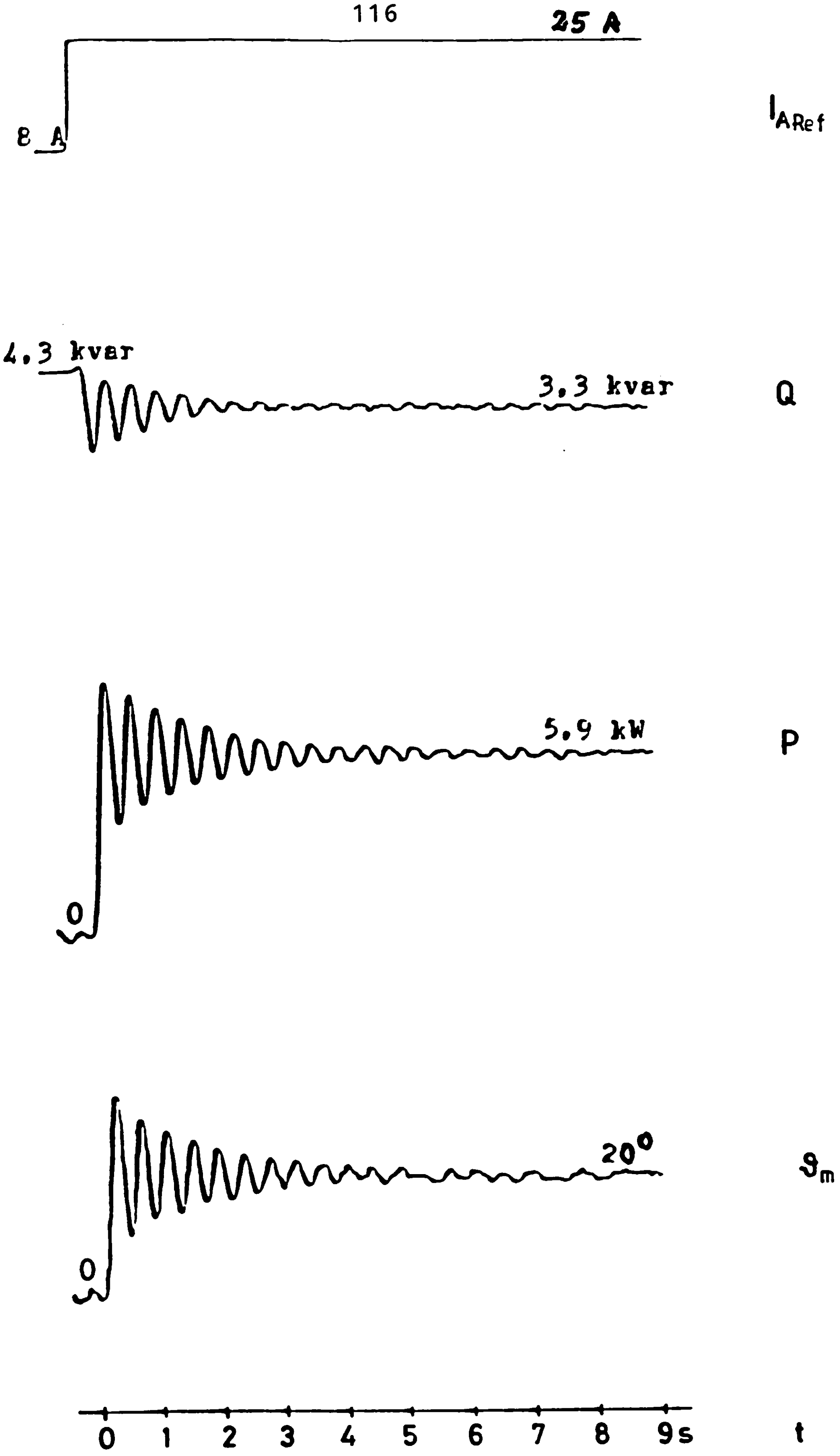


Fig.7 : Step response of active power of an undamped synchronous generator

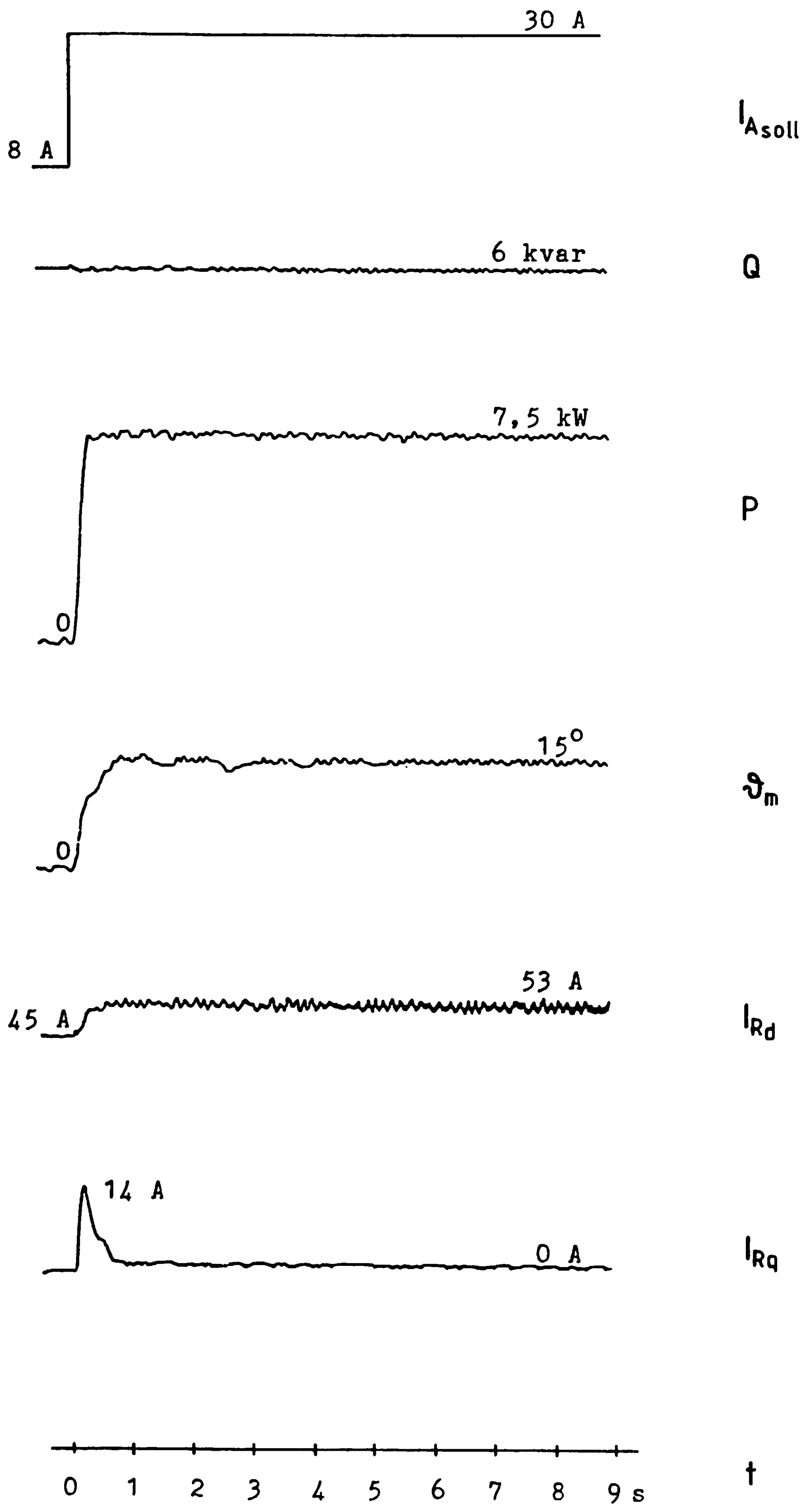


Fig.8: Step response of active power of a synchronous generator with active damper winding

WINDPARK KYTHNOS

Dipl.-Ing. Siegfried Heier, Prof. Dr.-Ing. Werner Kleinkauf

Abstract

Essentially, the electrical equipment for a windpark on the Greek Island of Kythnos being operated in connection with the electric utility grid will be explained. The requirements on control and supervisory of single units as well as the tasks of the coordination unit used for converter-co-operation will be described and a possible technical design will be shown. Measuring results and operating experience of one year are in evidence of the functionality of the whole plant.

1. Introduction

Favourable meteorological conditions for wind energy utilization have been offered throughout extensive areas of Greece. Numerous old Greek windmills are proof of that.

On the island an electrical power supply is very expensive. Therefore, favourable economic conditions for energy supply by means of wind energy plants are given. For this reason a project was borne in the scope of the German-Greece agreement on scientific and technological cooperation between the Minister of Research and Technology of the Federal Republic of Germany and the Minister of Coordination of Greece the subject of which is the utilization of wind energy for power supply of small local grids on the islands. The Greek partner ist the Public Power Corporation (PPC). The German firm Maschinenfabrik Augsburg-Nürnberg Aktiengesellschaft (MAN) has been entrusted with project execution and converter delivery.

The concepts for control and supervisory of single units as well as of the complete park have been elaborated at the University of Kassel. Development and production of these units including the switching units required have been undertaken by the firm SMA Regelsysteme GmbH Kassel. In summer 1982 the windpark consisting of 5 converters (see Fig. 1) was put into operation on the electric utility grid of the island.

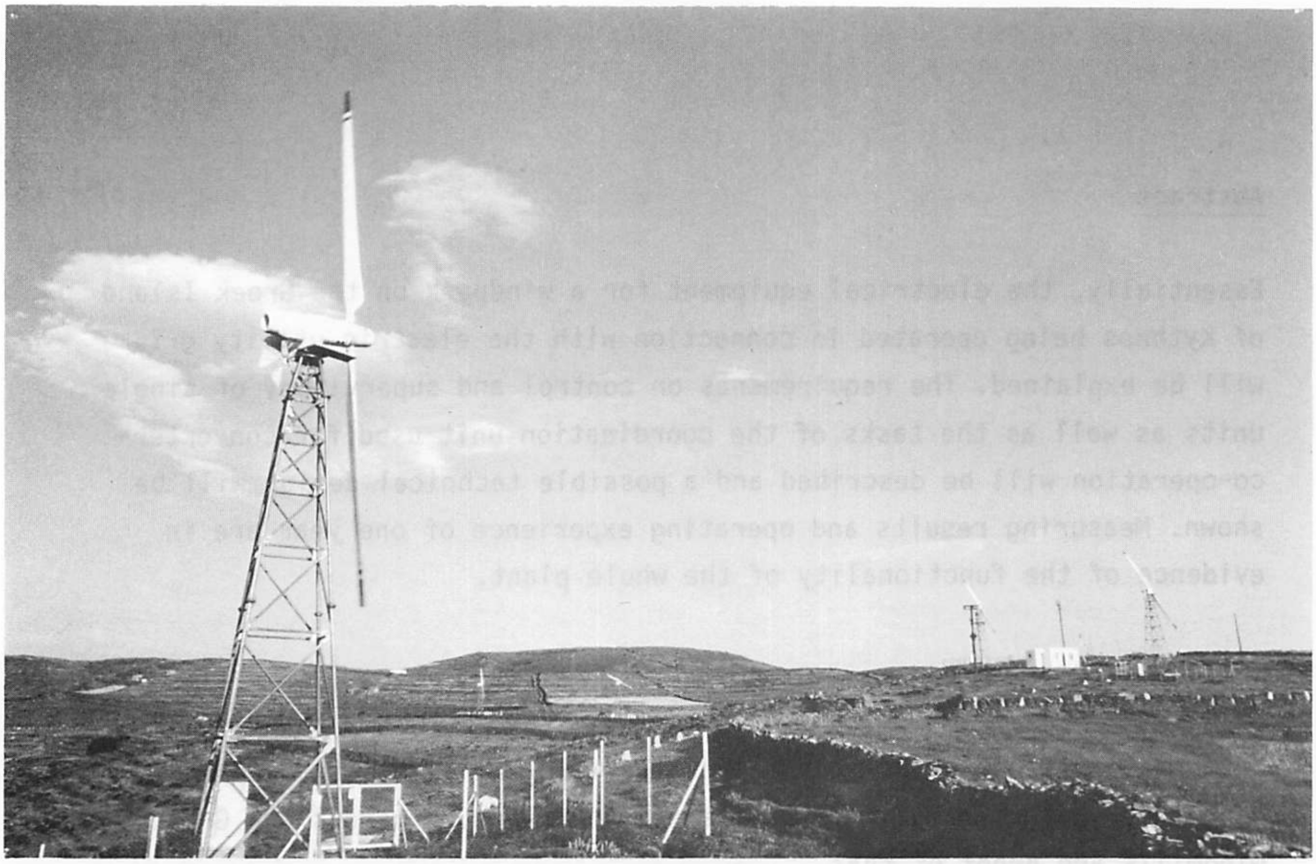


Fig. 1: Total view of the windpark on Kythnos

2. Single unit

The primary energy available for a wind energy plant is determined by the velocity of wind which is subject to short- and long term variations. Consequently the different components of the plant (see Fig. 2) must be protected against overload and it must be provided that the utility grid cannot be impaired by extreme power output variations.

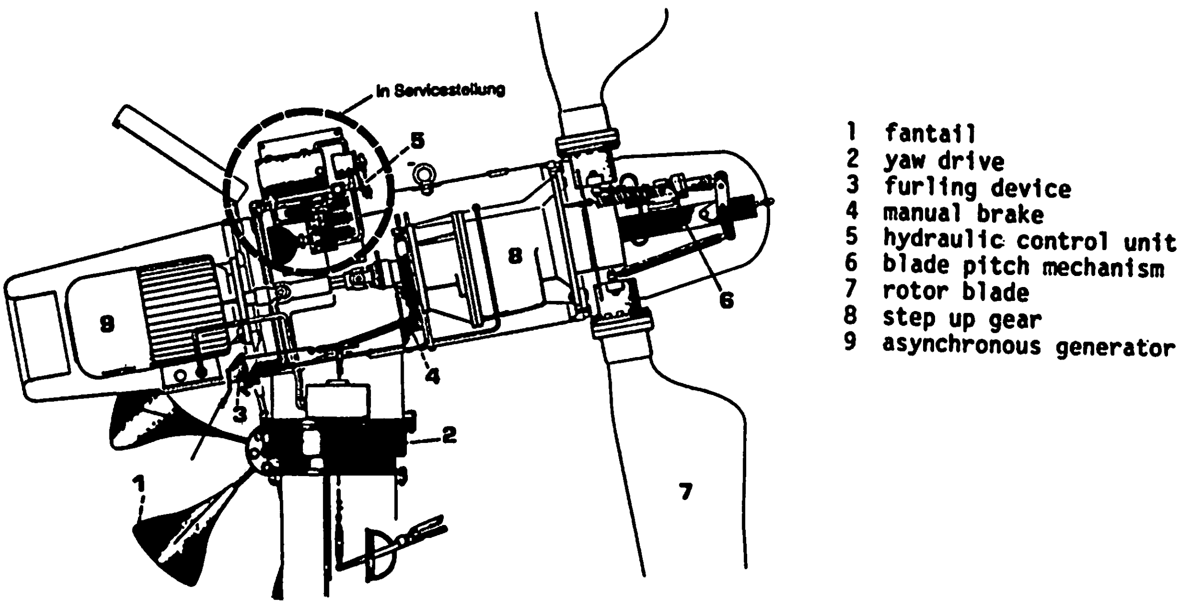


Fig. 2: Sectional view of the wind energy converter AEROMAN (20 kW), M.A.N.

In normal operation the plant is connected to the utility grid. Because of the given frequency the power input of each converter must be restricted by means of the blade pitch mechanism in order to avoid overload (power regulation). This power control is superimposed by a speed control interfering in case of the following operating conditions:

- start of the plant
- shut down of the plant
- interception of the plant in case of grid failure.

The course of power output may be equalized and frequency fluctuations may be avoided (df/dt-regulation) by predetermination of sliding power reference inputs via supervisory. However, loss in power must be accepted in this case.

In Fig. 3 the structure for regulation of a plant in grid operation is shown.

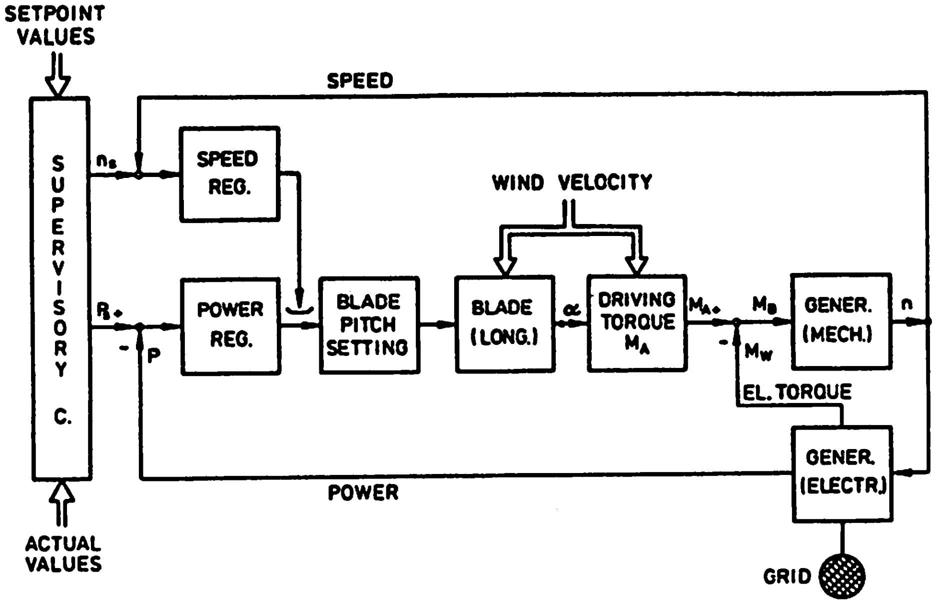


Fig. 3: Principle structure for the regulation of a wind energy converter with asynchronous generator in grid operation

The blade pitch angle is changed via an electric-hydraulic control unit. The converter will automatically be tracked to the wind direction by means of a side wheel. 20-kW-asynchronous generators, simply structured and therefore being extremely robust, with an extended slip range ($s_n = 8\%$) are used as mechanical-electric energy converters. This ensures operational safety, good stability in case of discontinuous wind speed and the possibility for speed variation in the range of the slip values (decrease of component load). Furthermore, extremely simple switching to grid operation is possible. However, reactive power must be made available for excitation of the asynchronous generators. The generators are partly compensated separately and connected to each other on the 380-V-level. A compensation adapted to the entire windpark performance is undertaken by the coordination unit (see Fig. 6). The electronic and power current equipment (control, supervisory, grid parameter supervisory, generator protection, line protection, fixed compensation etc.) forgrid operation of the AEROMAN converter is installed in a switching cabinet being situated at the base of the tower (see Fig. 4).

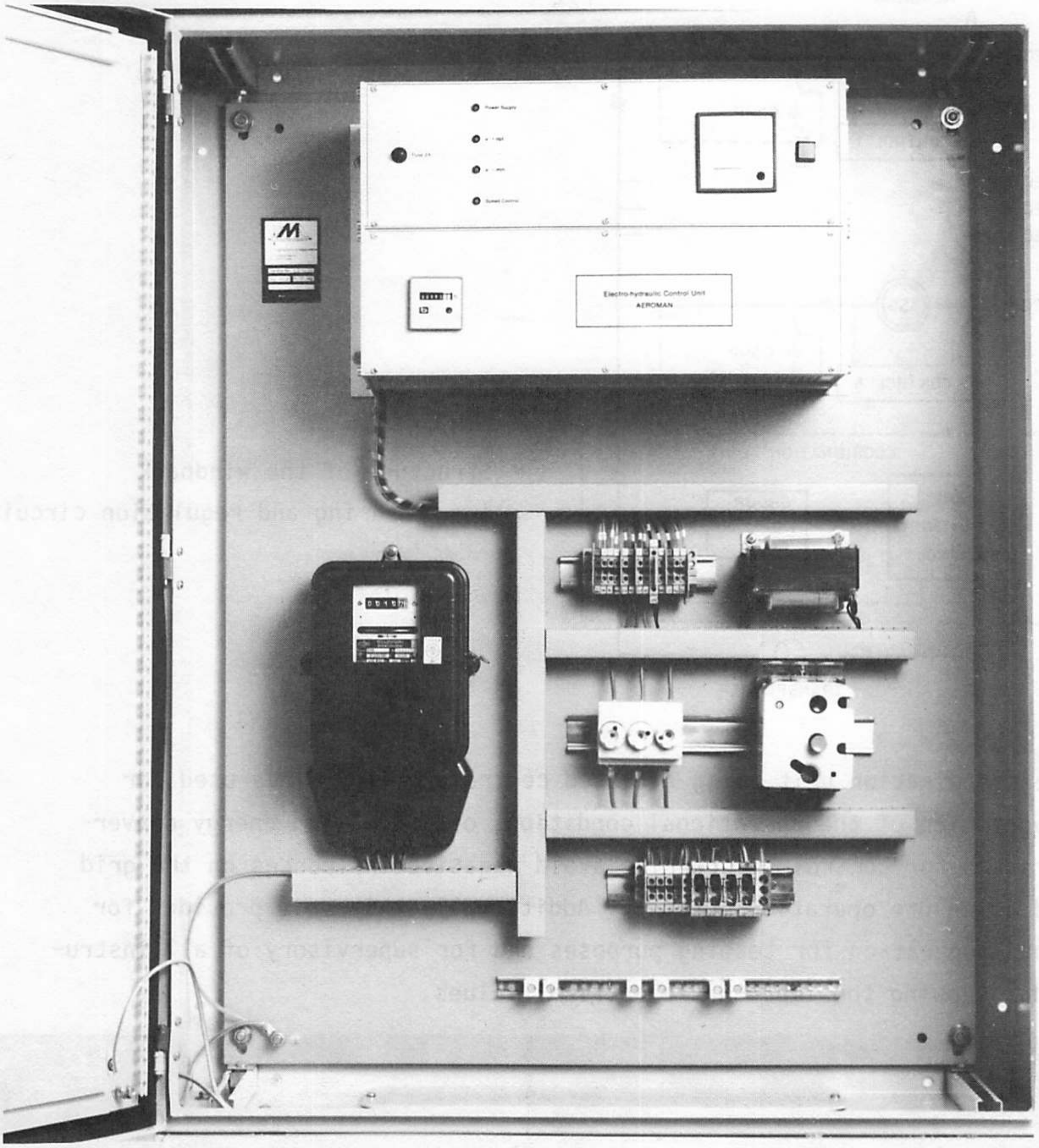


Fig. 4: 'Electro-hydraulic control unit' for AEROMAN (grid operation)

3. Interconnected operation with the grid

The utility grid of the island has been supplied by Diesel generators up to now (see technical data). Mutual influences of the three-phase connection of the 5 wind energy converters and the relatively weak grid are to be expected. As the possible total power output of the windpark amounting to P_N = 100 kW is very high in comparison to the power input of the consumers (approximately 25% annual average with the wind energy being higher than the consumption at certain times) special problems in the dynamic interaction of the windpark with its discontinuous power output and the utility grid will arise.

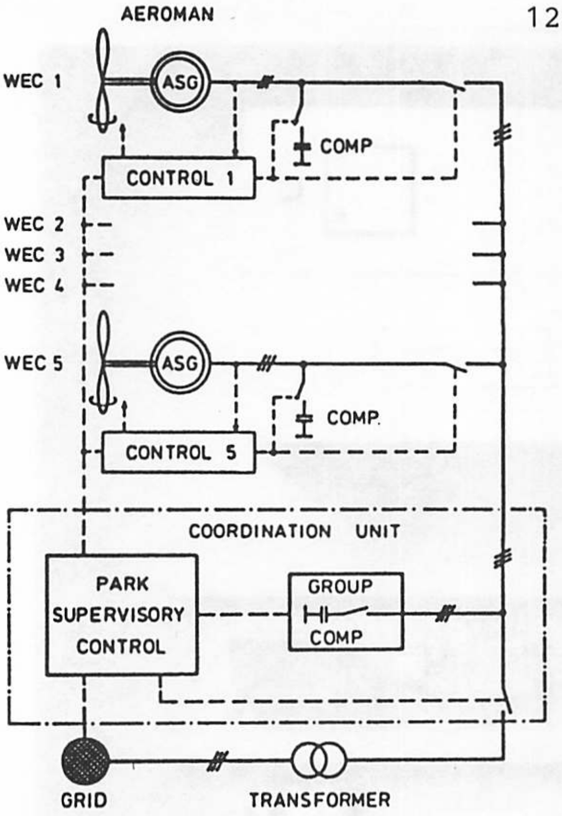


Fig. 5:
Structure of the windpark
(-- measuring and regulation circuits)

The coordination unit being situated centrally (Fig. 6) is used for supervision of the operational conditions of the 5 wind energy converters and for control in order to avoid negative influences on the grid and to ensure operational safety. Additionally this unit provides for manual operation for testing purposes and for supervisory of all instruments showing the important electrical values.

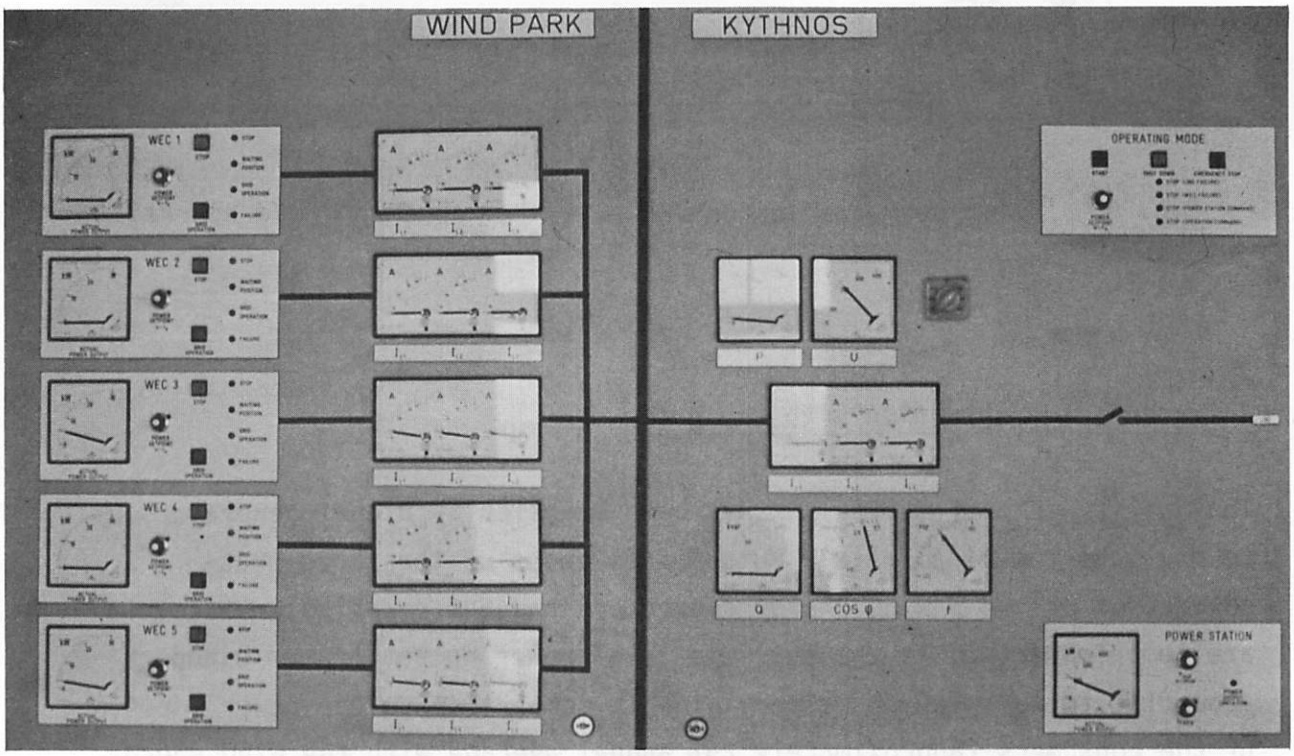


Fig. 6: Frontal view of the coordination unit on Kythnos

By means of this unit the complete grid is tracked in a way so that the Diesel generators may predetermine the frequencies as well as they may maintain the grid voltage. For this purpose the minimum load values of the Diesel generators must be observed. Because of operational reasons this value has been determined to be 35 kW at present. Therefore, by means of the coordination unit, the windpark power supply is continuously limited in a way so that in times of minimum load the Diesel generators only may be unloaded to the (predeterminable) minimum extent. So the windpark is in a position to deliver a maximum of 80% of the total power amount.

As mentioned above, in order to raise the operational safety of the park the several converters have been equipped in a way so that they can work on the grid even without being influenced by the main supervisory. Normally, however, the order for start and shut down considering the special grid characteristics and the reference input of the elctric power output is predetermined by the main supervisory.

In Fig. 7 a direct measurement record of the power output of the windpark during start and shut-down procedure is shown. An equalization of the power output in case of interconnected operation is obvious, too.

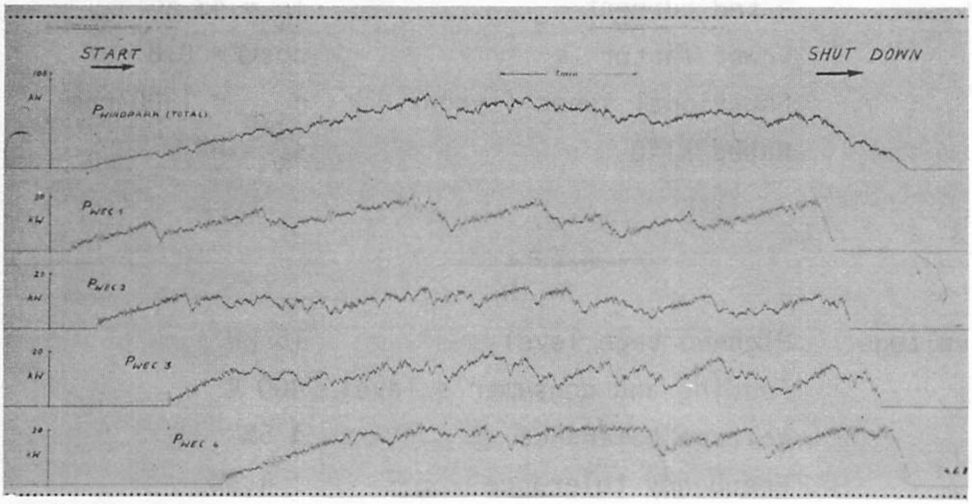


Fig. 7: Measurement record - start and shut down -

4. Technical data

4.1 Generating plant

Old plants:	4 Diesel generator sets of 125 kVA each
	2 Diesel generator sets of 250 kVA each
New plants:	2 Diesel generator sets of 633 kVA each

4.2 Wind energy plants of the AEROMAN type

Wind turbine:	Cut-in wind speed	$v_{start} = 3{,}2$ m/s
	Cut-out wind speed	$v_{ab} = 24$ m/s
	Nominal rotational speed	$n_N = 88$ rpm
	Optimum blade pitch angle	$\alpha = 88°$
	Rotor radius	$r = 5{,}8$ m
Generator:	Asynchronous generator produced by Schorch	
	Rated power	$P_N = 22$ kW (for $v_W = 14$ m/s)
	Rated voltage	$U_N = 400$ V
	Rated current	$I_N = 43$ A
	Power factor	$\cos\varphi = 0{,}8$
	Rotational speed (synchr.)	$n_{syn} = 1500$ rpm
	Rated slip	$s_N = 8\%$

4.3 Grid

Rated voltage:	High-voltage level	15 kW
	Feeding and consumer's level	400 V
	Voltage tolerance	± 5%
	Frequency tolerance	± 1,5%

5. Conclusions

Operating experience of one year has shown that even in case of small wind energy plants a very good operational behaviour may be attained by means of an appropriate system design. In addition to a facility for quick blade pitch angle adjustment and to correspondingly optimized control loops for speed and power control it is especially favourable to use asynchronous generators for small wind energy plants in grid operation. Not only grid operation is facilitated by an asynchronous generator, additionally a decrease of component load and a relatively constant power output is rendered possible by an appropriate design (as high slip values as possible). Single units may be connected to a plant and may be operated on weak grids even in case of direct three-phase current side connection. A great number of units in this case favourably affects the grade of performance equalization.

After the windpark had satisfied the expectations in principle, a measuring program financed by the BMFT has been started in summer 1983. By means of an equipment for data acquisition and evaluation delivered by the firm SMA detailed knowledge about windpark behaviour in grid operation is to be gained permitting conclusions for similar operative ranges.

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SOME CURRENT ACTIVITIES IN THE CANADIAN WIND ENERGY PROGRAM

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1.0 INTRODUCTION AND PROGRAM OVERVIEW

1.1 Objectives

The requirement of wind energy research in today's context of finite fossil energy resources is to determine if modern scientific and engineering knowledge can be applied to create wind energy conversion systems which will make cost-effective contributions to current and future energy supplies. Hence, the broad objectives of the Canadian Wind Energy R&D (WERD) program are

- to determine under what circumstances wind energy can make a viable contribution to Canadian energy supplies
- to establish the technology of wind energy conversion systems (WECS) appropriate to Canadian conditions
- to encourage and support Canadian industrial initiative in the design and manufacture of WECS for both domestic and export markets

1.2 Focus

Research at the National Research Council of Canada (NRC) during the 1960's resulted in reinvention of the low-solidity vertical axis wind turbine (VAWT) first patented by Georges Darrieus in 1927. Considerations of larger systems confirmed several attractive features of this configuration related to the precept that a simple arrangement was likely to be most reliable and most cost-effective. Such features include

- omnidirectionality - eliminating need for yaw controls and drives
- drive train at ground level - especially meaningful for megawatt-scale systems where drive train and generator weigh several hundred tons
- Troposkien blade shape - minimizing centrifugal bending stress and simplifying structural design

- stall-control aerodynamics - eliminating need for variable geometry elements to control peak power output at high winds

These features have been verified at a variety of scales and in several applications; thus the VAWT has been accepted as the primary technical approach within the NRC program.

1.3 Structure

The Canadian WERD program comprises four major interactive components as follows:

1.3.1 Resource Assessment and Site Evaluation

This activity involves quantification of the nature and distribution of the wind energy resource; it also involves compilation of the meteorological data required to assess potential wind energy applications and to design WECS. Projects include

- correlation of existing meteorological data
- analytical and experimental modelling techniques
- calibration and deployment of wind measuring instruments
- site evaluations and assessments of wind energy potential

1.3.2 Research and Technology Development

This activity includes establishment of the fundamental performance, structural, systems and environmental characteristics of WECS. A major portion of this research has been contracted to Canadian industries, using the NRC experience as the core about which to elaborate. Example activities are

- analytical and experimental aerodynamic investigations of airfoils and rotors
- aeroelastic modelling and testing
- development of structural dynamic design methods
- system performance and economic predictions
- examination of alternative energy extraction devices
- wind tunnel tests of innovative concepts and small commercial wind turbines
- establishment of safety and performance standards and testing techniques

1.3.3 Field Trials and Technical Support to Industry

Experimental systems have been installed throughout Canada, ranging from less than 1 kW to about ½ MW rated output. A national facility, the Atlantic Wind Test Site (AWTS), has been established to provide experienced personnel and proper equipment for testing WECS manufactured in Canada and elsewhere.

- Six Savonius/Darrieus VAWT systems rated at 1 to 3 kW were installed in partnership with telecommunications companies. These systems comprised aerodynamically self-starting rotors, direct drive alternators, and battery packs to provide continuous energy supply. All but two units have completed scheduled tests and have been removed from service.

- A 30 kW VAWT has been mechanically coupled to a 50 kW diesel-electric set as part of a prototype 100 kW remote-community powerplant. The project included calibrations of the individual components of the powerplant package, as well as assessment of the effects of the wind turbine on the diesel load-following duty cycle, and the ramifications on diesel operating economy and maintenance requirements.

- Five field trial projects have been initiated to permit electrical utility companies to gain experience with the operational characteristics of VAWT generating systems. A 50 kW VAWT grid-coupled system was chosen as being large enough to provide realistic data on data on operational and energy production performance, yet small enough to permit design changes suggested by the operating experience.

- A 224 kW VAWT was installed in cooperation with Hydro-Québec on Iles de la Madeleine during July 1977. The 595 m^2 experimental unit was extensively instrumented to measure structural as well as performance characteristics. The gearbox/belt transmission system permitted grid-synchronized operation at several rotor speeds to explore vibrational modes, structural dynamics, and aerodynamic stall-limiting of output power. Experimental testing was completed in November 1982 and the VAWT system is now operated by Hydro-Québec staff.

- A 500 kW production version of the Iles de la Madeleine VAWT system was erected in October 1983 at AWTS for performance and structural evaluation. This unit is identical to the system installed at Southern California Edison's test site near Palm Springs, and exchange of operating experience, and perhaps test data, is anticipated.

1.3.4 Megawatt Grid-Coupled Systems

Based on extensive parametric studies, and the VAWT technology being developed at the sub-megawatt scale, it was decided to construct a 4 MW VAWT prototype system in conjunction with a major Canadian utility company. The resulting Projet EOLE, jointly funded by NRC and Hydro-Québec, was initiated in 1981. Preliminary design was completed in 1982. Rotor dimensions of 96 m × 64 m define a swept area of 4000 m^2 and will produce 4.0 MW at 14.5 rpm via a direct-driven synchronous alternator and static frequency conversion equipment to match network frequency and phase angle. Detailed design, fabrication, assembly, and commissioning will take two and a half years.

2.0 50 kW GRID-COUPLED VAWT FIELD TRIALS

2.1 Background

During the past few years the NRC Wind Energy R&D (WERD) program has initiated several field trial projects in conjunction with provincial electric utility companies. The major objectives of these field trial projects were twofold:

(a) to obtain technical data on the performance and structural integrity of the units over significant periods

(b) to expose potential users of grid-coupled WECS to the operational characteristics of these novel generation systems, and to derive from their feedback needs and directions for further development of the technology

The WECS selected for this program was the nominally 50 kW VAWT system designed and built by DAF Indal Ltd. It was felt that this machine was large enough to be representative of the generic type, yet inexpensive enough to permit several concurrent installations. The general appearance of a typical field trial installation is shown in Figure 1 and the schematic drawing of current units is shown in Figure 2.

The first installation was commissioned at Holyrood, Newfoundland, in 1978. Since that time three more sites have been commissioned at Swift Current, Saskatchewan; Christopher Point, British Columbia; and Churchill, Manitoba (see Figure 3). In May 1982 an updated unit replaced the original VAWT at Holyrood after approximately 4500 h of operation. A detailed examination of this first unit revealed no serious structural damage (1). The status of these projects as of 31 August 1983 is shown in Table I. To date, they have achieved a cumulative total of about 25,000 operating hours, including about 20,000 grid-connected generating hours during which the net output has exceeded 200,000 kWh, giving a while-generating average output of about 10 kW. This 0.2 output factor is considered acceptable as most sites were chosen for convenience of access rather than for maximum windiness, even within the local areas.

The Swift Current installation is extensively instrumented for both performance and structural data, and analysis and interpretation are still in progress, both at NRC and at the Saskatchewan Power Corporation. Performance/operational reports on the remaining four installations are scheduled for release in about one month (2-5). Typical results, from the Churchill installation, are presented in Figures 4, 5, 6, and 7 and are discussed below.

2.2 Typical Results - Churchill, Manitoba

The Churchill 50 kW vertical axis wind turbine (VAWT) was erected during October 1981. Its commissioning tests were complete on November 4, when it began producing power for Manitoba Hydro. Since then, it has been jointly monitored and tested by the National Research Council and the Churchill Research Centre. Being installed near to the 60th parallel, this machine endures a particularly severe climate. Temperatures vary from -40°C to +30°C. Heavy snow and some icing storms occur during most winters.

2.2.1 Description of Turbine

The DAF Indal 50 kW VAWT system at Churchill, Manitoba, comprises a rotor of 55 ft height and 36.7 ft diameter, mounted on a power module pedestal and supported by four guywires; the module contains a single stage 15:1 step-up gearbox, a 75 hp induction motor/generator, controls, and accessories such as hydraulic and lubrication pumps. The rotor mid-height is about 40 ft above local terrain (see Figure 1). This model of turbine uses a single-mesh bullgear and pinion to connect the 80 rpm rotor to the 1200 rpm induction motor/generator. The rated power, nominally 50 kW, is about 45 kW at 80 rpm in 15 m/s wind. When operating, the rotor and bullgear "float" on hydraulic oil above four stationary brake pads attached to the module structure. Whenever hydraulic pressure is released the rotor descends and the web of the bullgear serves as a brake disc to stop the rotor from turning. This arrangement also provides for constant guy tension as determined by the hydraulic pressure in the rotor support system (see Figure 2).

2.2.2 Power Curve

Prior to installation at Churchill the VAWT was erected and calibrated by the manufacturer, DAF Indal Ltd, outside their factory in Mississauga from March to July 1980 (6). The result of this test was a plot of electrical power output versus wind speed as shown in Figure 4. One can note the measured cut-in wind speed of 6.6 m/s, hence the controls were adjusted to that value for the entire evaluation period at Churchill. During the calibration testing wind speed did not exceed 15.4 m/s for long enough to obtain meaningful performance data.

2.2.3 Operational Experience/Reliability

During 1½ years operation at Churchill, three major problems occurred.

(1) In April 1982 the lower half of the main rotor coupling was found to have failed. Detailed examination in the NRC Structures and Materials Laboratory (7) determined that fatigue was not a factor, but that four design/manufacturing factors possibly contributed to the failure, viz:

   (a) high stress concentration at the corners of the keyway
   (b) low wall thickness due to the keyway's presence
   (c) manganese sulfide inclusions in the coupling hub material
   (d) precracking due to excessive draw on installation of the coupling on the tapered shaft

   A replacement coupling without a keyway was welded to the tapered stub shaft without dismounting the rotor.

(2) In July 1982 a spoiler hinge pin fell out and had to be replaced. Eventually it was decided that the hydraulic lift/braking system provided sufficiently reliable protection against rotor overspeeding so as to make the spoilers unnecessary. Therefore they were removed and fairings were installed to cover the attachment points on the blades in September 1982.

(3) In August 1982 a guywire turnbuckle failure was discovered when it was noticed that the opposite guywire was slack. The cause was determined to be tensile failure at a necked-down section of the upper screw where it had been machined to improve the guywire tension readings. All of the turnbuckles were replaced with non-necked ones in October 1982.

Other minor malfunctions detracted somewhat from overall system reliability, especially in the extreme winter weather conditions following commissioning in November 1981. A summary of down time incidents, taken from the operational log is shown in Table II. Monthly percentage availability (i.e., the fraction of total time during which the entire VAWT system was in fully operational condition) is plotted in Figure 5. For the entire 21-month period the overall availability was 67%. However, it can be noted that down time periods were extended considerably while waiting for parts and/or repair crews. If these are discounted, availability increases to over 80%. Since January 1983 availability has consistantly remained above 90%.

2.2.4 Performance/Energy Production

Energy production data were recorded monthly from integrating meters, together with the wind histogram data describing the site wind regime. These data were checked and processed by TES Limited in Ottawa (8) and were presented to NRC in the form shown in Table IIIA. Terminology is explained in Table IIIB.

The significance of average wind speed on potential energy production is illustrated in Figure 6. This plot shows (as shaded bars) the energy that a "perfect" windmill would have produced each month, without cut-in or cut-out limitations, and based on monthly average wind speed data from the Churchill VAWT site. For the entire reporting operation period, these ideal values total about 357 MWh. Figure 6 also shows (as solid bars) the actual net energy output from the turbine each month.

Realistic expectations from existing machinery with reasonable limits suggest that a well-designed windmill system could achieve one third of the ideal energy output. In 1982, the Churchill VAWT produced only 25.15 MWh of energy, i.e., only 10.8% of the available wind energy for the year. This is mostly due to the very poor availability in 1982. However, for the first five months of 1983 availability was over 90% and energy production 20.3 MWh (24% of available wind energy), which is better, but still leaves room for considerable improvement.

Figure 7 is a plot of the measured monthly energy output against the monthly energy output predicted by integrating the power curve of Figure 4 over the wind regime measured by the Generate-Only Wind Histogram Recorder (GO-WHR). These co-ordinates deliberately exclude the effects of unavailability and focus on energy actually produced under the prevailing operating conditions. Data from three 50 kW field trial units are shown, including the Churchill machine. Correlation is good, indicating the machines when operating produce energy at predicted rates. Indeed, measured output is slightly better than predicted, probably because the power curve used was for a VAWT with aerodynamic spoilers (aerobrakes) and currently all 50 kW units in the field trial program are devoid of spoilers, thereby reducing parasitic losses and increasing performance somewhat.

3.0 AIRFOIL DATA FOR VAWT PERFORMANCE AND AERODYNAMIC LOADS PREDICTIONS

3.1 Requirements

A WECS that is coupled directly to the grid operates at near-constant speed in order to maintain constant frequency electrical output. In this contant blade speed mode a VAWT can be designed such that aerodynamic stall limits power output as wind speed increases beyond a prescribed value. For the curved-blade Darrieus configuration the aerodynamic stall progresses smoothly from the top and bottom ends of the blades (which are rarely unstalled) towards the equator where the majority of the power is captured. Thus it is very important for the Darrieus VAWT designer to have accurate information on the stalling characteristics of candidate airfoil sections in order to be able to calculate maximum power output and the concomitant cyclic aerodynamic loads transmitted to the rotor structure. To date, most VAWT blades have used simple, uncambered, relatively-thick airfoils (such as the NACA 0018) for which many traditional airfoil data are available. However, three operational characteristics of VAWT's demand more than the traditional scope of airfoil data

(a) greater angle of attack range:
During each revolution a VAWT blade experiences angles of attack which vary over substantially ±180°.

(b) high Reynolds Numbers:
The equatorial sections of a megawatt-scale Darrieus VAWT blade will operate at Reynolds Numbers of 10×10^6 and higher.

(c) dynamic stall:
The rapidly changing angle of attack modifies the airfoil stalling behaviour from that determined by the traditional quasi-steady-state wind tunnel tests.

3.2 Reynolds Number Effects

Sandia Report 80-2114 (9) has contributed significantly to knowledge of symmetrical airfoil characteristics through 180° angle of attack up to Reynolds Numbers of 5×10^6. To augment these data in support of the 4 MW VAWT prototype EOLE, tests were conducted on a 10 in. chord, 5 ft span, NACA 0018 airfoil in NRC's tri-sonic blowdown tunnel (12). The tests were run at $M = 0.15$, with a stagnation pressure up to about 10 atmospheres, giving a maximum Reynolds Number of 9×10^6. Results are compared with Ref. 9 in Figures 8 and 9. Although in general agreement with the Sandia data, the NRC results show a sharper stall and perhaps a greater effect of variations in Reynolds Number.

3.3 Dynamic Stall Effects

The rapidly-changing angle of attack experienced by a VAWT blade can significantly affect the stalling characteristics of the airfoil. An empirical model of dynamic stall developed by Gormont (10) has been used in VAWT performance and loads prediction codes. Recent modifications to the Gormont approach, introduced by Massé at IREQ (11), appear to give better agreement with turbine performance. Experimental investigations of this phenomenum were conducted in NRC's 6 ft × 9 ft wind tunnel in June 1982. A 6 ft segment of the 24-in. chord extruded aluminum blade used on the 230 kW Magdalen Island VAWT was mounted on a hydraulic servo actuator which changed angle of attack as a function of time. Test conditions simulated a variety of angle of attack wave forms, amplitudes, and frequencies, and resulted in an enormous amount of data, much of which is still being analyzed and will be reported in detail in the near future. The results presented here are for conditions representative of Iles de la Madeleine VAWT operation well into the stall-controlled regime. The non-sinusoidal variation of angle of attack is shown in Figure 10. The 1.83 s period corresponds to 33 rpm. Figures 11 and 12 illustrate the comparison of static and dynamic stall characteristics, together with the analytic predictions of the Gormont and Massé dynamic stall models. Clearly, the dynamic effects are large, especially in the case of lift. Considerable effort is now being spent on the reduction of data from this experiment and the interpretation of the effects in terms of VAWT performance and aerodynamic loads on the blades.

4.0 50/100 kW WIND/DIESEL POWERPLANT EVALUATION

4.1 Background

The high cost of electrical power in remote areas of Canada has encouraged investigation of wind/diesel powerplants. In appropriately windy locations the additional cost of the WECS components can be justified by the fuel savings experienced by the diesel generators which guarantee continously available power. Early experiments with a 12 kW wind/diesel unit in 1976 (13) proved technical feasibility and confirmed predicted fuel savings on a very small-scale system. Parametric studies of hybrid powerplants with various ratings of the wind and diesel prime movers, in various wind regimes, and for several cost scenarios were published by DAF Indal Ltd in 1979 (14).

These efforts led to a co-operative project (between the Ontario Ministry of Energy, NRC, Ontario Hydro, and DAF Indal) to construct and evaluate a wind/diesel powerplant appropriate for eventual deployment in a remote community in northern Ontario. The test unit was installed for initial evaluation near Sudbury, Ontario, whose wind regime is similar to several areas of northern Ontario.

4.2 Powerplant Configuration

The powerplant comprises two 46 kW diesels driving 50 kW alternators. A 30 kW VAWT is mechanically coupled to the shaft of the primary alternator (see Figure 13). The VAWT is an adaptation of the nominal

50 kW DAF Indal unit, with a right-angle gearbox in place of the induction motor/generator, and with a separate starting motor connected into the right-angle gearbox. Output power is limited to about 30 kW by rescheduling rotor speed to 71.4 rpm. The output of the two alternators is combined by a autosynchronizer to feed a computer-controlled load whose time/demand history simulates in 10-min steps a fraction of the demand measured at Attawapiskat on the west coast of James Bay. An integrated control/instrumentation system controls and monitors the powerplant during unattended operation.

The primary diesel generator runs continuously and the second diesel is started if demand exceeds the capability of the primary unit. VAWT power output is recognized as "negative load" by the primary diesel. Minimum diesel load is set at 20% of rated output. A "dump load" resistor is applied by the control system when instantaneous VAWT output, plus prescribed minimum load on the primary diesel, exceeds instantaneous demand. The wind/diesel powerplant operates independently from the grid, including provision of its housekeeping and accessory power requirements. Preliminary calculations suggested that, at the Sudbury test site, the wind turbine should provide about 10% of the total energy supplied to the computer controlled demand load.

4.3 Results from SUDBURY I Tests

The purpose of the initial evaluations of the wind/diesel powerplant at Sudbury was to verify fuel savings predicted by the DAF Indal program PLANT (16) and to investigate operating reliability prior to deploying the system in a remote community.

The system was commissioned late in 1981 and the SUDBURY I test sequence ran for about 6 months between 12 February and 2 September 1982. Table IV summarizes SUDBURY I operations. Both diesel generator sets had been calibrated in the supplier's shop prior to incorporation into the Sudbury powerplant. Figure 14 shows the VAWT performance curve as determined from measurements made during the hybrid powerplant evaluation.

Four categories of operation were defined to describe the powerplant configuration selected by the control system to meet the demand load at any point in time under the prevailing wind condition, viz:

CATEGORY	CONFIGURATION
A.	Diesel #1 running for the complete test period with diesel #2 and the wind turbine running for all or part of the test period. Data sets chosen for detailed analysis represented a total of 536 h of operation.

B. Diesel #1 running for the complete test period with diesel #2 running for all or part of the test period. Data sets chosen for detailed analysis represented a total of 38 h of operation.

C. Diesel #1 running for the complete test period with the wind turbine running for all or part of the test period. Data sets chosen for detailed analysis represented a total of 62 h of operation.

D. Diesel #1 running for the complete test period. Data sets chosen for detailed analysis represented a total of 5 h of operation.

Summaries of processed performance data from each of these operational categories are shown in Table V. Comparison of predicted and measured fuel savings is shown in Figure 15 to be very close, especially considering the error multiplication often encountered in "differenced" measurements. The greatest percentage fuel savings occur in high winds and at low demand loads where the percentage contribution of wind energy is highest.

Control responsiveness for the complete powerplant is shown in Figure 16 where both diesels and the VAWT are contributing to supply the demand power requirement of 35 kW. The wide oscillations of turbine power output are illustrated by the VAWT torque trace. The two-per-rev power fluctuations are clearly evident, as is the lagging yet sensitive response of VAWT power to wind speed. These fluctuations are reflected in the instantaneous output of the primary diesel generator and, to a lesser extent, the secondary diesel generator. Despite these intra-system fluctuations the output frequency is seen to remain constant within 0.5 Hz.

System reliability is summarized in Table VI. Overall system availability was 89.5% for the entire test period. The majority of the forced outage hours were caused by the diesel generators and related equipment. Some of these malfunctions (e.g., overheating) were caused in turn by secondary problems relating to system packaging or installation (e.g., insufficient ventilation in powerplant building). The VAWT achieved 97.9% availability during the 3353 h the primary diesel was in operation.

4.4 Plans for SUDBURY II TESTS

The encouraging results from the SUDBURY I tests, and the existence of a functional instrumented test system, persuaded the sponsors to defer deployment to a remote community in order to perform further tests on variants of the initial powerplant configuration. The major objectives of the extended SUDBURY II test program are to investigate electrically coupled and VAWT stand-alone configurations and the concomitant control functions.

Mechanically coupling the VAWT to the primary diesel was specified for SUDBURY I based on earlier experimental work and subsequent analytic studies by DAF Indal. Pragmatically, however, mechanical coupling is awkward in retrofit applications, and moreover it constrains the VAWT to being located at the powerhouse (seldom the windiest site near a remote community). Because of the strong dependence of wind energy on wind speed, optimal siting of the wind turbine may well outweigh the decreased coupling efficiency and the cost of a short transmission link. To compare relative efficiencies of mechanical and electrical coupling (using the same components) a clutch will be installed between the primary diesel and its alternator. Thus the VAWT/primary alternator can be coupled electrically via the antosynchronizer to the autosynchronizer to the secondary diesel generator set. The computer controlled demand load will have to be further scaled to match the reduced capability of the revised powerplant.

Under the existing control strategy the optimum ratio of wind to diesel power rating is limited by dumped energy when demand is less than wind power plus minimum diesel load setting. This is primarily because the diesel governor characteristic is an inherent part of the system control. Thus the primary diesel must run at all times to provide the 60 cycle intelligence to which the VAWT is governed, and a minimum diesel load (20% rated power) was prescribed to avoid system instability. Significant improvement in optimum fuel savings can be achieved if the wind turbine can provide controlled electrical power without either diesel operating - the "VAWT stand-alone" mode. To achieve this on the Sudbury equipment the dump load controller is being modified to provide faster response (than the 5 kW/s used in the SUDBURY I test program) in an attempt to maintain acceptably constant frequency under typical gusty wind conditions.

Also, as part of the SUDBURY II programs, a series of dynamic and steady state tests will be performed to provide verification data for a comprehensive dynamic hybrid computer model of generic wind/diesel systems under development by GasTOPS Ltd in Ottawa. The computer model, when completed and verified, will represent a design tool for determining optimum system configuration for a specific application; for predicting fuel savings for any specified system/load/wind regime combination; and for investigating various control system analogues and strategies.

5.0 WIND-DRIVEN WATER PUMPS

Interest in wind-driven water pumps is reviving in certain parts of Canada where additional agricultural acreage is being established by irrigation. In some areas with salty subsurface water, a combination of irrigation and drainage is used to "wash" high concentrations of certain undesired elements from the soil. This procedure calls for two rather different wind-driven water pumps. Large units can be used to supply the irrigation water to gravity distribution networks of pipes or canals. However, many much smaller units with running-dry capability (or protection) are needed for the drainage operation.

The Alberta Department of Agriculture has established a test site for water pumping wind turbines near Lethbridge (see Figure 17). Currently five units are under test as shown in Table VII. Meteorological data and overall performance parameters from each machine are monitored continuously. Five-minute readouts and various integrated averages are relayed automatically to Alberta Agriculture offices in Lethbridge, and detailed data are transmitted daily to the Alberta Research Council in Edmonton for analysis.

Based on the delta-blade concept invented by Prof. John Kentfield at the University of Calgary, ABAX Energy Services Limited of Canada have built a prototype 52.5 ft diameter, eight-bladed, horizontal axis WECS with integral twin cylinder reciprocating low-head high-volume pumps (see Figure 18). Intended for irrigation and pumped-hydro storage applications, the prototype has a predicted flow capacity of about 20 acre feet/day (4500 USgpm) at a site with an annual average wind speed of 18 mph at the hub height of 103 ft. The unit has recently been erected and commissioned at the ABAX factory in Calgary and will shortly commence a six-month performance and structural integrity test program.

6.0 PROJET ÉOLE

Projet ÉOLE is a co-operative venture by Hydro-Québec and NRC to design, build, and evaluate a 4 MW Darrieus VAWT. The general configuration and major components are shown in Figure 19. Figures 20 and 21 give some indication of scale. Principle characteristics are listed below.

Rotor	● height	315 ft
	● equatorial diameter	210 ft
	● swept area	43000 ft^2
Blades	● number	2
	● airfoil	NACA 0018
	● chord	8 ft

Rating	● power	4.0 MWe
	● wind speed	51.4 mph
	● rotational speed	14.5 rpm
Operation	● cut-in wind speed	12.3 mph
	● cut-out wind speed	60.0 mph
	● survival wind speed	145 mph

The preliminary design was completed in Spring 1983, and perhaps the most notable decision was to incorporate a directly driven generator, operating at rotor speed. Electrical conformity to the grid will be achieved by power conditioning equipment including static frequency converters and power factor controls. This system appears to be about the same cost as a high-speed synchronous alternator plus a gearbox, but it offers an attractively simple drivetrain as shown in Figure 19. Because of the large generator diameter (about 40 ft) this option may **only** be practical with a vertical axis rotor configuration.

Following extensive measurements for over a year at four candiate sites, the selected location for EOLE is at La Fonderie, a small community some 275 miles east of Québec City on the south shore of the St. Lawrence River. Annual average wind speed at rotor mid-height 183 ft) is expected to be approximately 20 mph, giving a predicted energy output of about 11400 MWh/y.

Detailed design of ÉOLE is now underway and tender specifications for the rotor and the electrical/control systems are now complete. Major suppliers will be chosen by Hydro-Québec early in 1984. Fabrication, site preparation, assembly, and erection are scheduled to take about two years, thus it is expected that ÉOLE will be commissioned in the Autumn of 1985.

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TABLE I: NRC WIND ENERGY R&D PROGRAM 50 kW VAWT FIELD TRIAL SYSTEMS
PERIOD ENDING AUGUST 31, 1983

LOCATION	PARTNER	START OF GEN. SERVICE	OPERATING HOURS		NET OUTPUT kWh	CURRENT STATUS
			IDLING	GEN.		
HOLYROOD, NFLD (I)	NL HYDRO	JUNE 78	1567	3015	21,600	Removed for study NOV 81
HOLYROOD, NFLD (II)	NL HYDRO	MAY 82	976.9	2,919.6	27,033.0	OPERATIONAL
SWIFT CURRENT, SASK	SASK POWER	AUG 80	40.2 (estimated)	2,943.0	20,115.0	OPERATIONAL
CHRISTOPHER POINT, BC	BC HYDRO	MAR 81	1,614.1 (estimated)	4,780.4	71,463.4	OPERATIONAL
CHURCHILL, MAN	CHURCHILL RESEARCH CENTER	NOV 81	978.0 (estimated)	3,887.1	50,580.0	OPERATIONAL
	TOTALS		5,176.2	17,545.1	190,791.4	

TABLE II: CHURCHILL 50 kW FIELD TRIAL OPERATIONAL MALFUNCTION SUMMARY

MONTH	DOWN TIME (HOURS)	CAUSE
NOV. 1981	148	- many small mechanical problems
DEC.	547	
JAN. 1982	504	
FEB.	259	
MAR.	240	
APR.	192	- lower half of main rotor coupling failed
MAY	* 724.8	- turbine awaiting repair
JUNE	* 638.4	- turbine awaiting repair
JULY	144	- replacement of coupling - replacement of missing spoiler hinge pin
AUG.	216	- guywire turnbuckle failed, replaced
SEPT.	12	- spoilers replaced with fairings
OCT.	336	- all turnbuckles replaced with non-necked ones - one guywire anchor eyebolt tightened - malfunctioning PCB in control system
NOV.	* 770.4	- PCB awaiting repair
DEC.	171.6	- PCB repaired
JAN. 1983	0	-
FEB.	0	-
MAR.	0	-
APR.	5.3	- down time due to tests performed to determine cause of instrumentation problems
MAY	72.7	- N/A
	4981.2	

*Down time awaiting parts and/or service team (2133.6 h)

TABLE IIIA: CHURCHILL 50 kW VAWT FIELD TRIAL PERFORMANCE DATA 1982

PERFORMANCE SUMMARY FOR VAWT FIELD TRIAL CHURCHILL, MANITOBA

CUT IN WIND SPEED 6.60
CUT OUT WIND SPEED 15.65

YEAR: 1982				ESTIMATED PERFORMANCE (NO DOWN TIME)			ACTUAL PERFORMANCE						ESTIMATED OUTPUT ENERGY FROM GENERATE ONLY HISTOGRAM DATA	ACTUAL OUTPUT % OF AVAIL. WIND ENERGY	ACTUAL OUTPUT % OF EST. OUTPUT ENERGY NO DOWN TIME	ACTUAL GEN. % OF EST. GEN. TIME	DOWN TIME % OF TOTAL TIME PERIOD	ESTIMATED OUTPUT ENERGY NO DOWN TIME NO CUTOUT WIND SPEED
APPROX. MONTH OF RECORD	TOTAL TIME IN PERIOD HR	AVERAGE WIND SPEED M/S	K	AVAIL. WIND ENERGY BETZ LIMIT KW-HR.	EST. GEN. TIME HR	EST. OUTPUT ENERGY KW-HR	DOWN TIME HR	STOP TIME HR	IDLE TIME HR	ACTUAL GEN. TIME HR	ACTUAL INPUT ENERGY KW-HR	ACTUAL OUTPUT ENERGY KW-HR	KW-HR	%	%	%	%	KW-HR
JAN.	737.4	7.2	1.77	29682	3384	5103.8	504	216	25	15.2		100	N/A	0.34	1.96	*9 .45	68.40	6353.0
FEB.	657.3	7.7	3.03	23218	442	6308.9	259	136	6	256		4940	4036.3	21.28	78.30	57.92	39.39	6402.4
MAR.*2	701.5	7.7	2.29	27992	407	6929.7	240	184*3	0*3	276*3		5970	4855.7	21.33	86.15	67.81	34.25	7460.0
APR.	746.0	6.8	2.02	20876	377	4385.6	192	366*3	11.5*3	135*3		1480	1274.0	7.09	33.75	41.28	25.72	4948
MAY	724.0	5.8	2.10	12878	311	2983.8	724.8	0	0	0		0	N/A	0	0	0	100.0	3115.8
JUNE	637.5	4.6	2.39	6422	169	1478.5	638.4	0	6	0		0	N/A	0	0	0	100.0	1478.5
JULY	758.6	5.0	2.10	8151*10	277	1816.2	144	491	10.9	108.8		1060	1236.0	15.16	68.05	47.93	18.99	1826.1
AUG.	750.5	5.2	1.74	7923	197	1354.3	216	397.2	9.1	108.1		480	454.7	6.06	33.57	54.87	28.75	1425.8
SEPT.	709.1	7.3	2.59	20817	396.4	6021.7	12	309.5	22.3	362.6		5760	5691.5	27.67	94.52	91.47	1.69	6161.9
OCT.*8	668.0	7.0	2.06	20420	298.6	4607.3	336	136.6	33.8	162.1		2000	1897.8	9.79	43.41	54.29	50.36	5334.5
NOV.	770.9	7.5	1.97	34658	407.7	8363.7	770.4	0	0	2.0		0	15.8	0	0	0	100.0	9568.2
DEC.	846.3	5.9	1.67	19170	291.9	4127.7	171.6	454	4.7	215.3		3360	7487.1	17.53	81.4	73.76	20.25	4576.5
SUM	8707.1	6.48	1.86	232207	6868.6	53481.2	4207.4	2690.3	123.3	1641.1		25150	21948.9	10.83	47.03	23.93	48.32	58650.7

NOTES: Explanation on following page.

TABLE IIIB: LIST OF TERMINOLOGY USED IN TABLE IIIA

ACTUAL INPUT ENERGY: Electrical energy consumed by the motor when starting the turbine, and by the turbine controls and accessories.

ACTUAL GENERATION TIME: Time during which the turbine actually produced power.

ACTUAL OUTPUT ENERGY: Gross electrical energy produced by the turbine.

AVERAGE WIND SPEED: Average omnidirectional wind speed as determined from a CR-WHR and anemometer.

CONTINUOUSLY-RUNNING WIND HISTOGRAM RECORDER (CR-WHR): Wind Histogram Recorder that recorded the turbine site wind data continuously.

CUT-IN WIND SPEED: The wind speed at which the turbine began generating power, and above which turbine operation was initiated.

CUT-OUT WIND SPEED: The maximum wind speed at which the turbine was allowed to generate power. At wind speeds higher than the cut-out, the turbine was shut off automatically.

DOWN TIME: Time during which the turbine was not in operational condition because of maintenance, mechanical failures, electrical failures, time spent waiting for fault diagnosis and for replacement parts and service.

ESTIMATED GENERATION TIME: Time, based on CR-WHR data, during which the wind speed was between the turbine's cut-in and cut-out wind speeds.

ESTIMATED OUTPUT ENERGY: Amount of electrical energy the turbine should have produced (assuming no down time), based on the CR-WHR and the power curve in Figure 4, and cut-in/cut-out wind speed settings.

ESTIMATED OUTPUT ENERGY (FROM GENERATE-ONLY HISTOGRAM DATA): Amount of electrical energy the turbine should have produced during the actual generation time, based on GO-WHR data, the power curve in Figure 4, and cut-in/cut-out wind speed settings.

ESTIMATED OUTPUT ENERGY (NO DOWN TIME, NO CUT-OUT WIND SPEED): Amount of electrical energy the turbine should have produced if the turbine had not been limited by either down time or cut-out wind speed, based on CR-WHR data and the power curve in Figure 4.

GENERATE-ONLY WIND HISTOGRAM RECORDER (GO-WHR): Wind Histogram Recorder that recorded the wind data only when the turbine is actually generating power.

IDLE TIME: Time during which the turbine was turning but not generating any power (wind speed was below cut-in).

K: The Weibull shape parameter, used to determine the Weibull distribution of wind speed.

NET OUTPUT ENERGY: Electrical energy produced by the turbine minus electrical energy consumed by turbine controls and accessories and by motor for starting the turbine.

OPERATIONAL EFFICIENCY: Actual energy output as a percentage of the estimated output energy.

STOP TIME: Time during which the turbine was operational, but was not turning because the wind speed was too low or too high.

TIME EFFICIENCY: Actual generation time as a percentage of estimated generation time.

TABLE IV: SUDBURY I WIND/DIESEL OPERATION

Elapsed real time for the period	4844 h
Time that power was supplied to the load	3865.4 h
Wind turbine generating time	1418.8 h
Wind turbine idling time (rotor turning but disengaged from the alternator)	349.4 h
Total wind turbine turning time	1768.2 h
Wind energy (shaft) supplied to the alternator	11,887 kWh
Total electrical energy delivered by the system*	130,289 kWh
Diesel generator #1 running time	3562.1 h
Diesel generator #2 running time	1558.2 h
Total fuel consumption	44,553 L
Wind turbine starts	311
Overrunning clutch engagements	6,388
Ambient temperature range while site was manned	-35 to 31°C
Maximum two second average wind speed recorded while the wind turbine was in operation	22 m/s
Average wind speed for the period March 1st to August 30th, 1982**	5.42 m/s

*About 20 h of data missing due to failure of the instrumentation backup batteries.

**Three weekly averages missing in this period.

TABLE V: SUDBURY I WIND/DIESEL PERFORMANCE

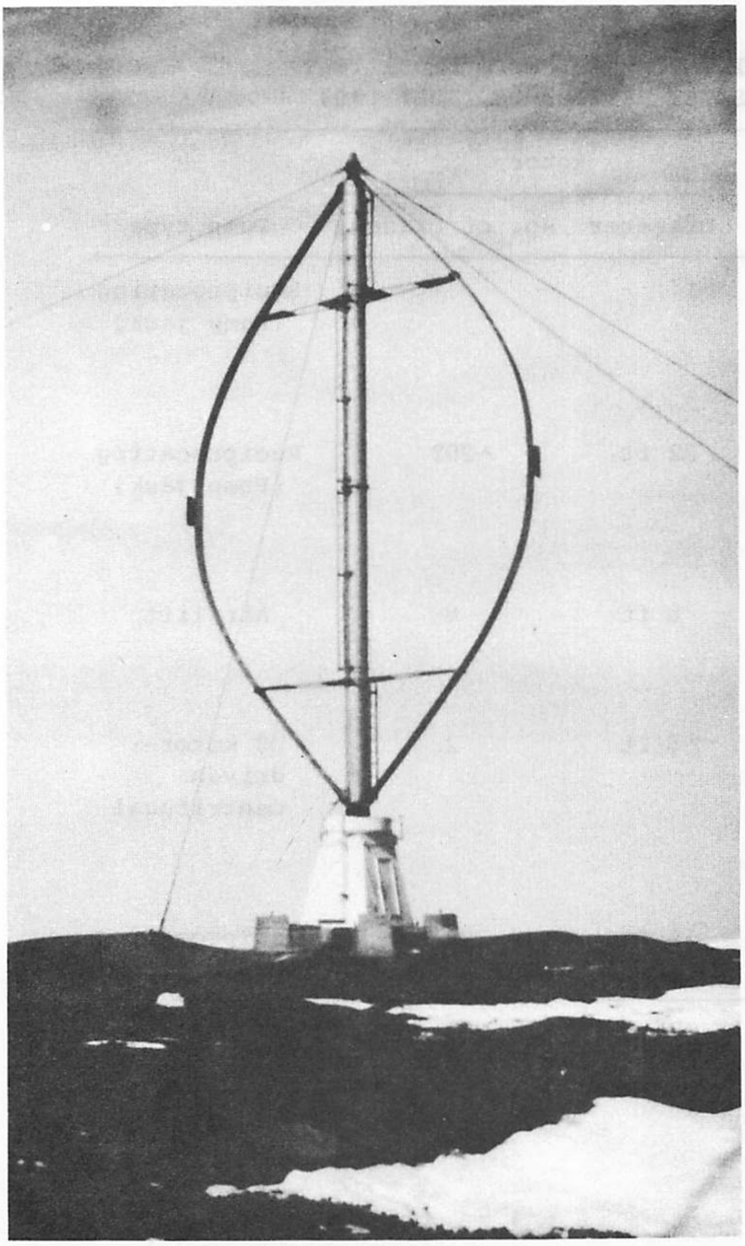
	Category			
Parameter	A	B	C	D
Operating Hours	535.8	38.2	61.5	5.3
Predicted Plant Output (OP)	22,561 kWh	1746	2169	167
Actual Plant Output (OA)	22,938 kWh	1751	2216	172
Predicted VAWT Energy (EP)	3216 kWh	-	648	-
Actual VAWT Energy (EA)	3311 kWh	-	689	-
Predicted Fuel Consumption without Wind Assist (FPW)	5883 kg	470	542	44
Actual Fuel Consumption without Wind Assist (FPA)	-	482	-	46
Predicted Fuel Consumption with Wind Assist (FP)	5297 kg	-	437	-
Actual Fuel Consumption with Wind Assist (FA)	5443 kg	-	447	-
Predicted Fuel Saving (SP)	586 kg	-	115	-
Actual Fuel Saving (SA)	440 kg	-	105	-
OP/OA	0.984	0.997	0.979	0.967
FP/FA	0.973	-	0.978	-
SP/SA	1.332	-	1.095	-
EP/EA	0.971	-	0.940	-
FPW/FPA	-	0.975	-	0.937

TABLE VI: SUDBURY I WIND/DIESEL RELIABILITY

Test Period or Period Hours (PH) (hours that system should have been providing some electrical power)	4314.4 h
Service Hours (SH) or Demand Load on Period (actual recorded time that the plant provided some power to the load)	3865.4 h
Demand Load Period 100% Available (recorded time that the plant actually operated against the load)	3030.8 h
Load Period or Derated Output Period (recorded time that the plant supplied power to the demand load but the load pattern was inactive and plant power output capability was less than 100%)	834.6 h
Forced Outage Hours (FOH) for the diesel generator system	449 h
Total Maintenance/Planned Outage for Diesel/Generator System (MOH)	2.0 h
Wind Turbine Forced Outage Hours	68.0 h
Wind Turbine Planned Maintenance Hours	2.5 h
Diesel Generator Plant Derated Hours and Power Level	539.6 h @ 50% power 259.00 h @ 20% power
Scheduled Derated Hours and Power Level	8.9 h @ 50% power
Equivalent Forced Derated Hours (EFDH)	505.8 h
Hours Available for VAWT to Provide Power to Alternator #1 (Diesel Gen. #1 and Power Train Available)	3353 h

TABLE VII: AGRICULTURAL WIND-POWERED PUMPS UNDER TEST AT ALBERTA AGRICULTURE SITE, LETHBRIDGE, JULY 1983

Make	Type	Application	Rotor		Pump type
			Diameter	No. of blades	
Dempster	HAWT	Irrigation	1		Reciprocating (Pump jack)
Wind Baron	HAWT	Irrigation	22 ft	~20?	Reciprocating (Pump jack)
Bowjon	HAWT	Drainage	8 ft	8	Air lift
Windcharger II	HAWT	Drainage	~8 ft	2	DC motor-driven centrifugal
Wind Dynamics	HAWT	Irrigation	14 ft	24	Reciprocating (Pump jack)



ROTOR:
- Height: 16.8m (55 ft)
- Diameter: 11.2m (36.7 ft)
- Mid height: 12m (39.4 ft)

BLADES:
- Number: 2
- Airfoil: NACA 0015
- Chord: 35.6 cm (14 in)
- Material: ext'd al.

GUYWIRES:
- Number: 4
- Diameter: 2.2 cm (0.875 in)

TRANSMISSION:
- Single stage
- Ratio 15:1

GENERATOR:
- Induction type
- Rating 56 kW
- Speed 1200 rpm
575 V, 60~, 3Ø

Figure 1. 50 kW VAWT installation at Churchill, Manitoba

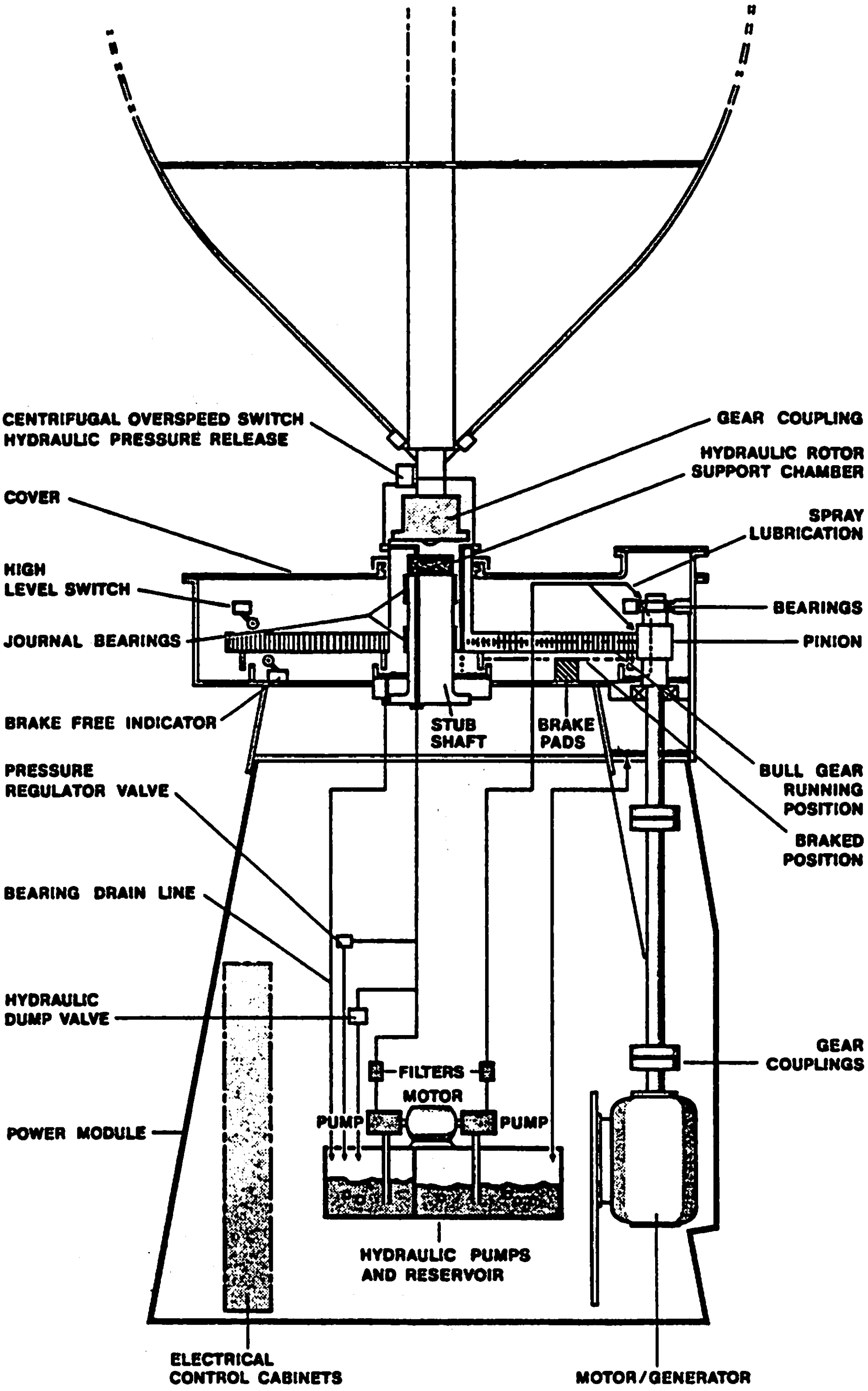


Figure 2. 50 kW VAWT power module schematic

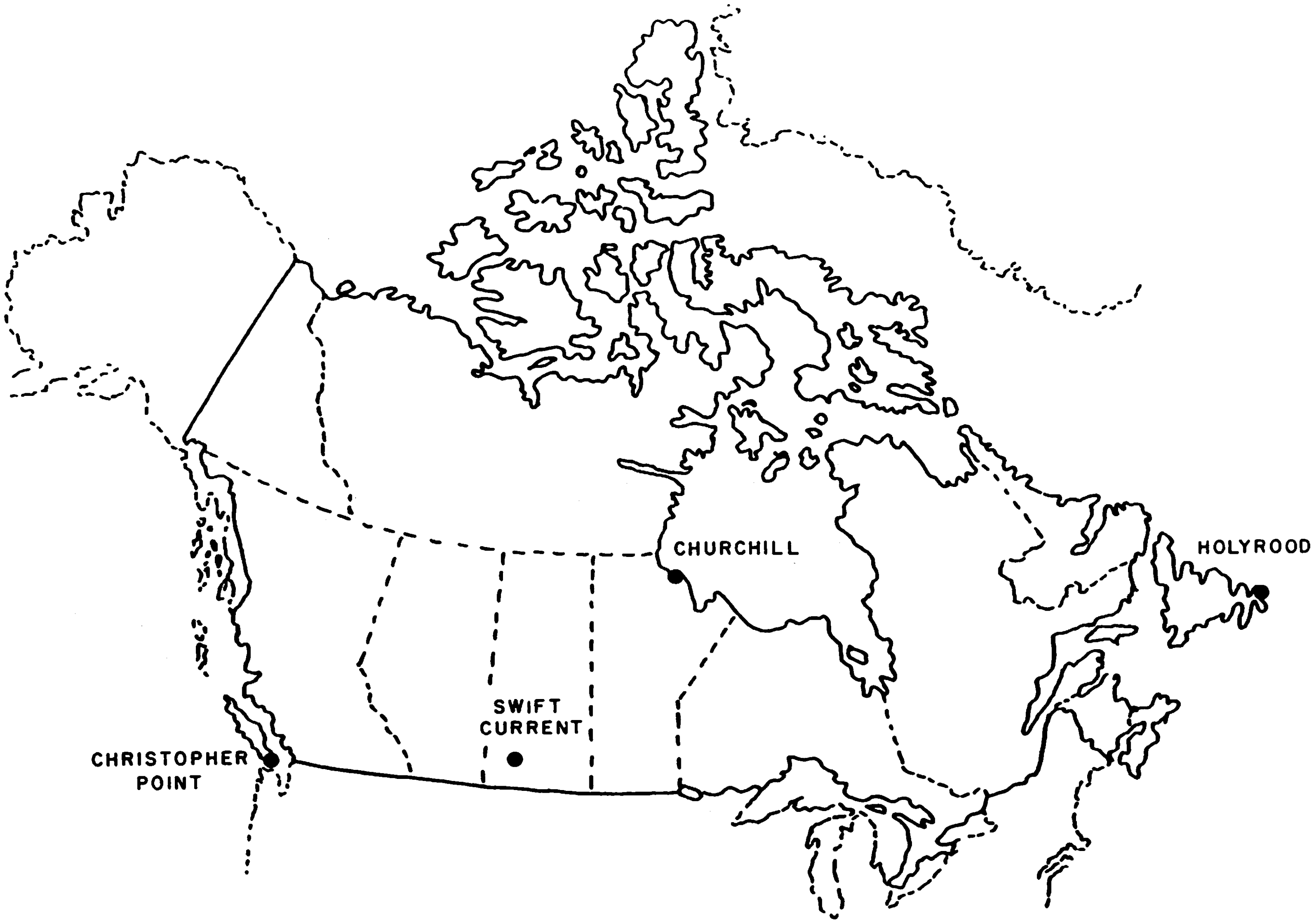


Figure 3. 50 kW grid-coupled VAWT field trial locations

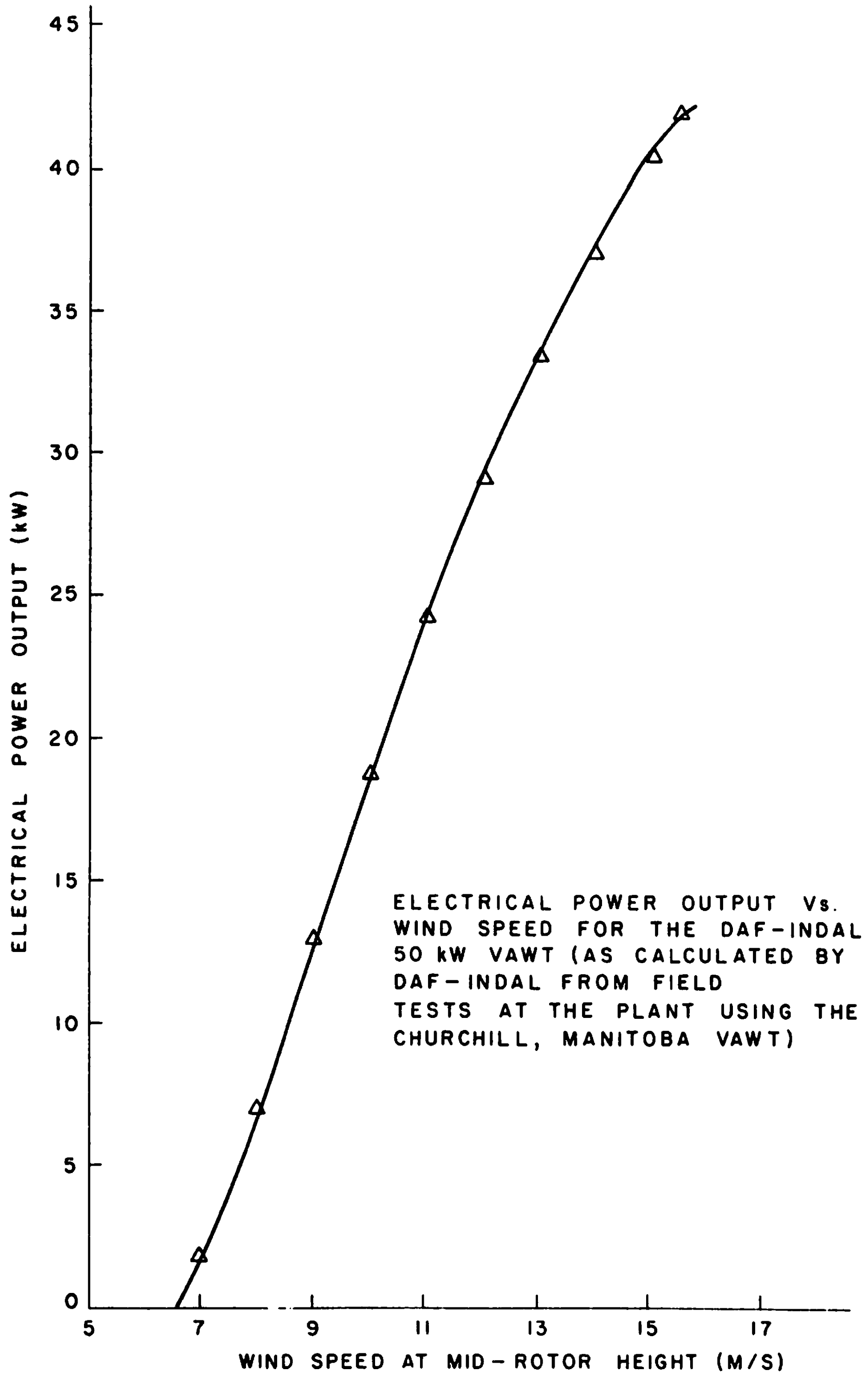
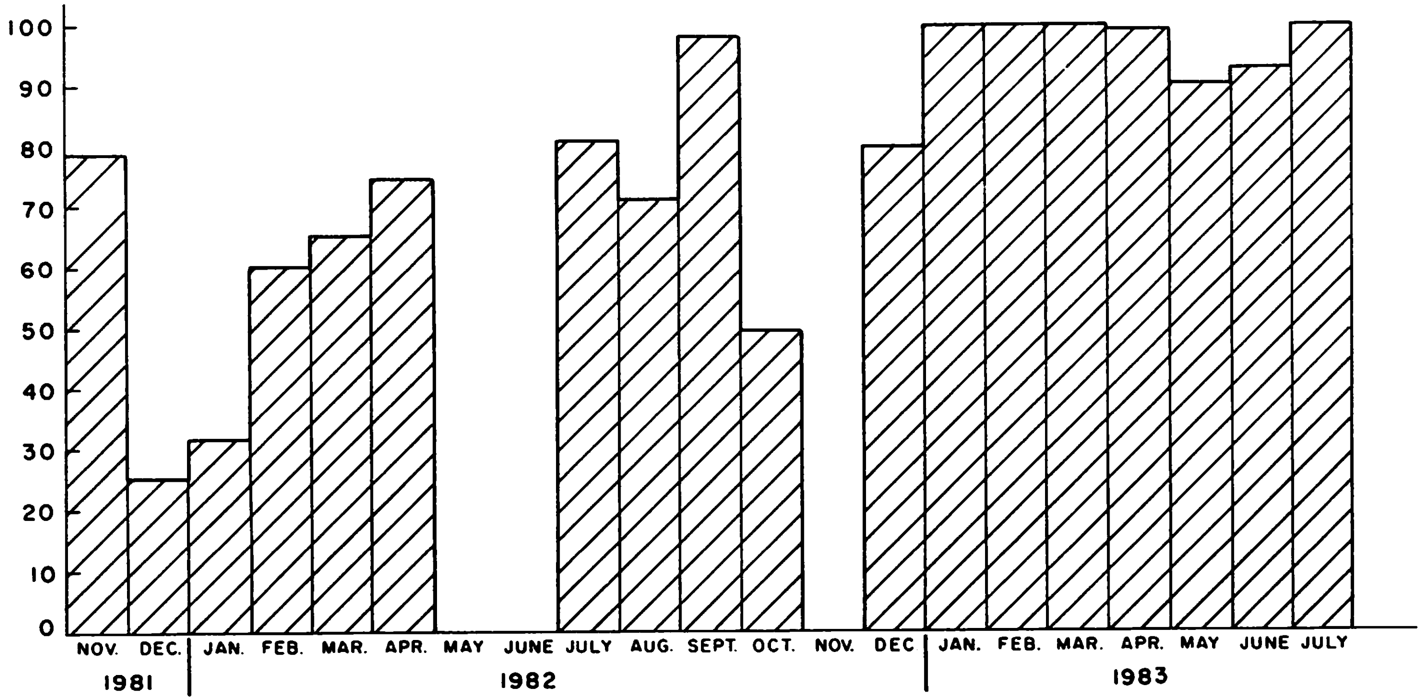


Figure 4. 50 kW VAWT - Churchill, Manitoba - power curve



TOTAL TIME = 15,229 HOURS
TOTAL DOWN TIME = 5,030 HOURS
TOTAL DOWN TIME CAUSED DIRECTLY BY TURBINE MALFUNCTIONS = 2849 HOURS
AVAILABILITY = 79.3% (DISCOUNTING TIME WAITING FOR PARTS AND SERVICE)
OVERALL AVAILABILITY = 67%

Figure 5. 50 kW VAWT - Churchill, Manitoba - availability

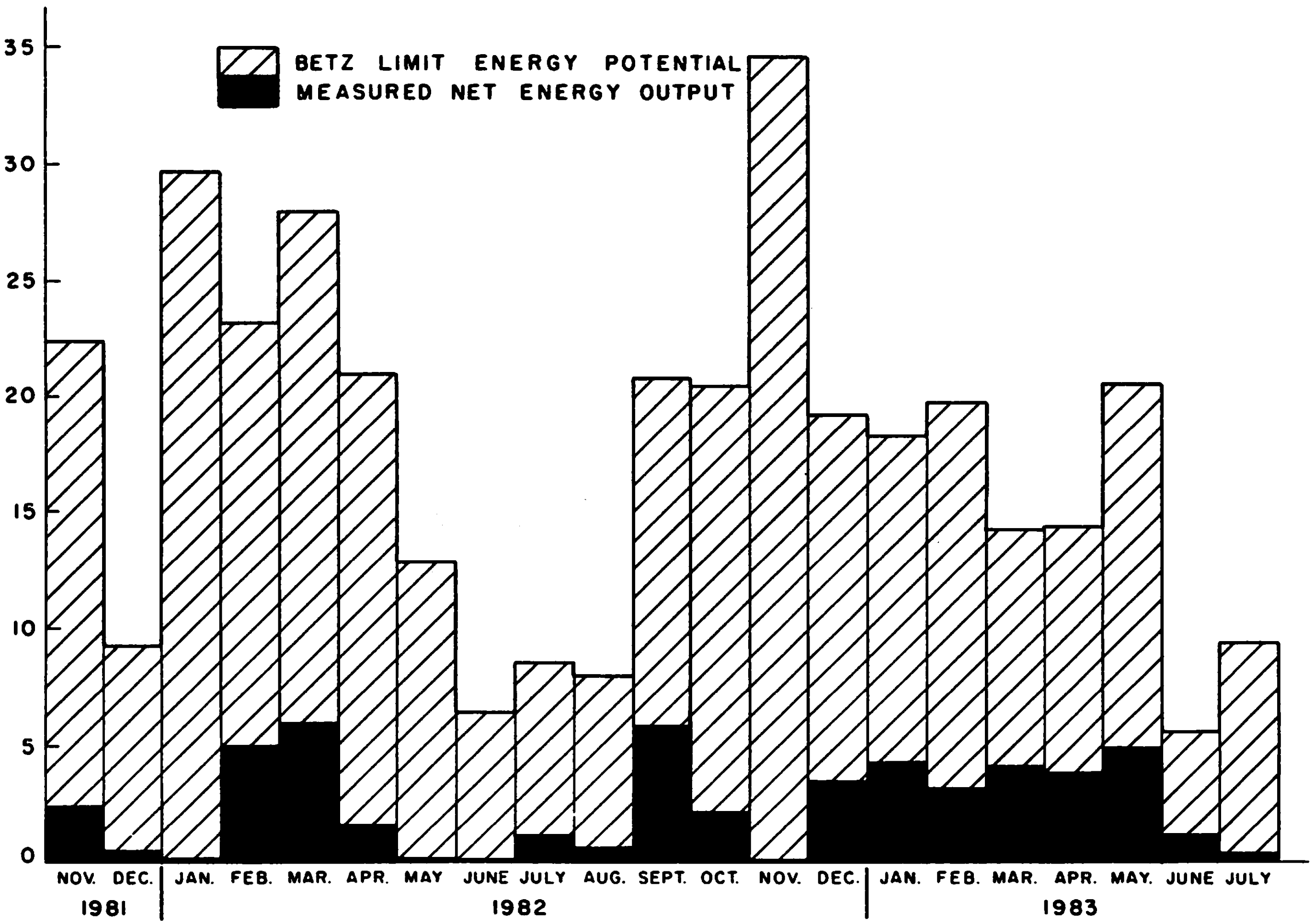


Figure 6. 50 kW VAWT - Churchill, Manitoba - energy output

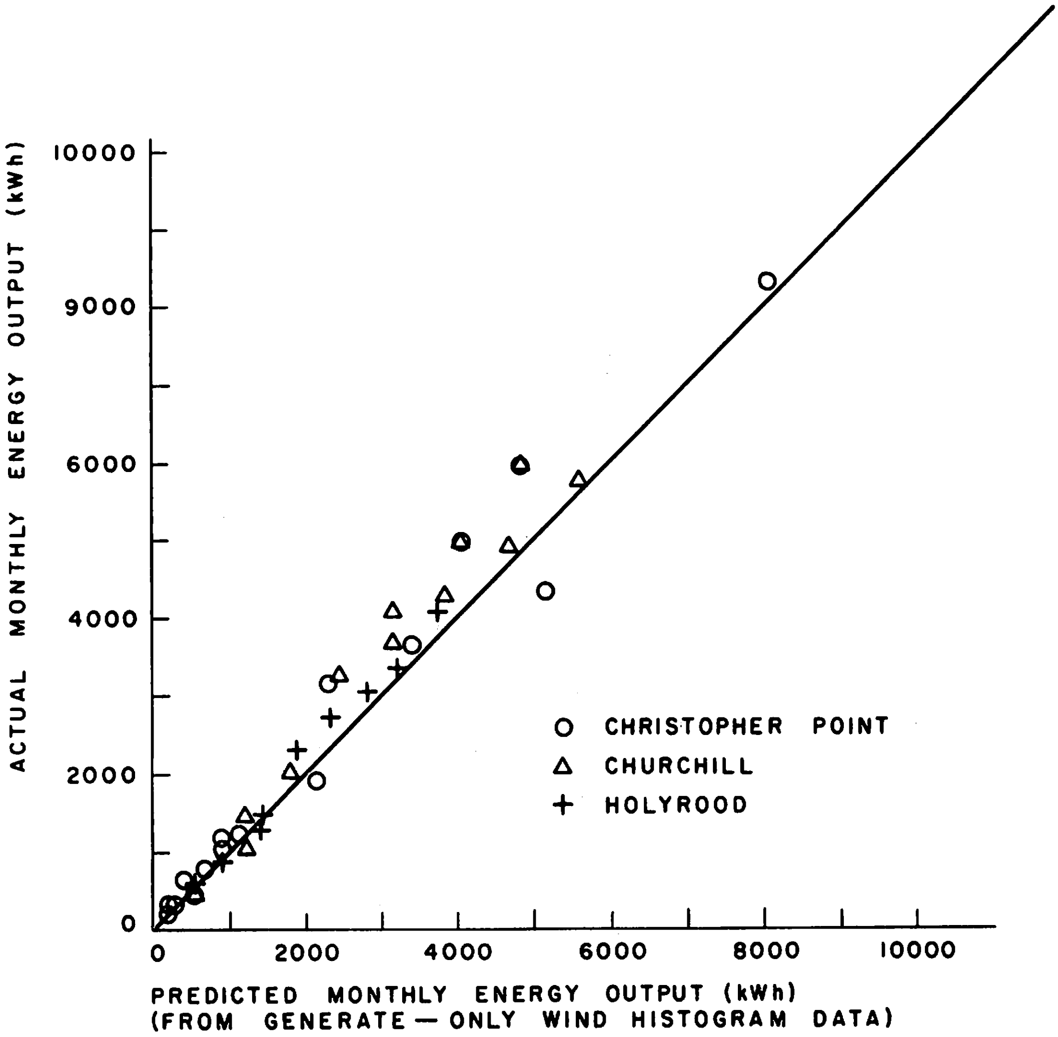


Figure 7. Actual vs. predicted energy output

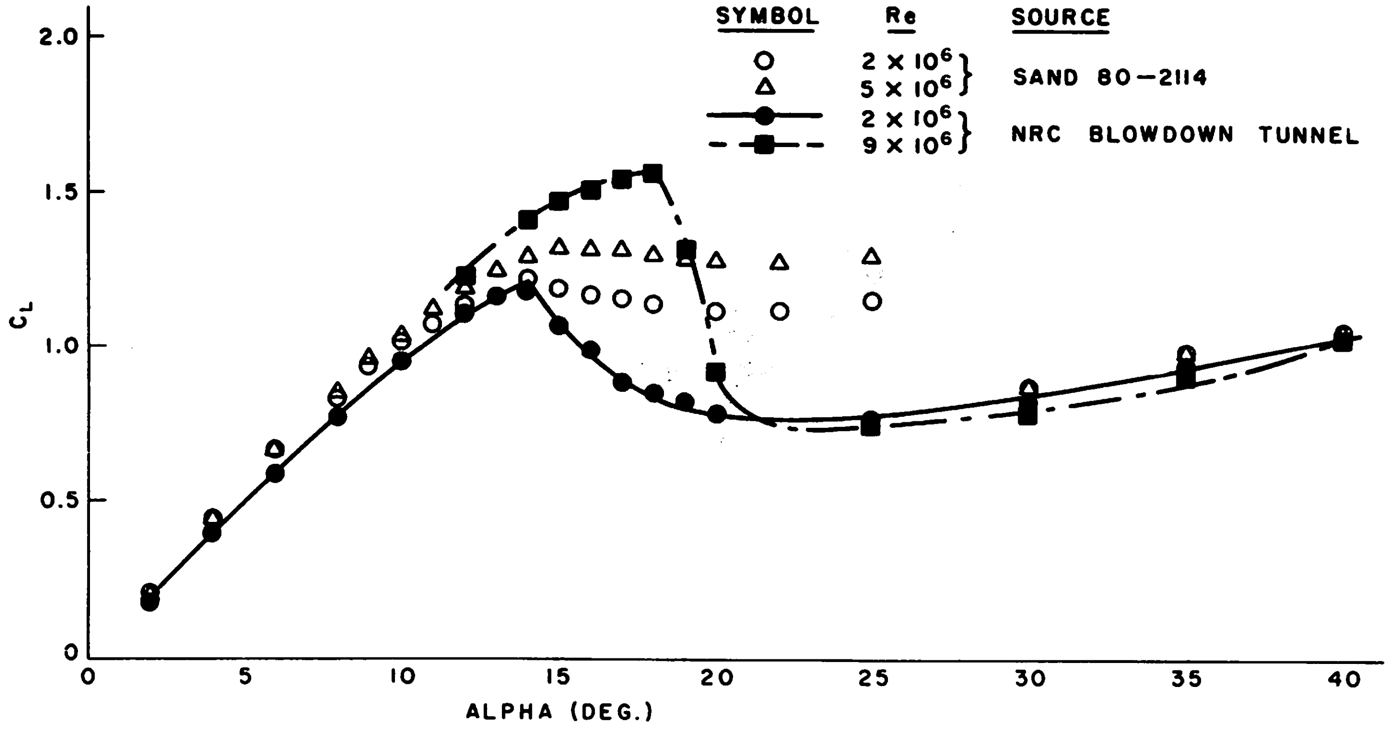


Figure 8. Reynolds Number effects on lift coefficient of NACA0018 airfoil

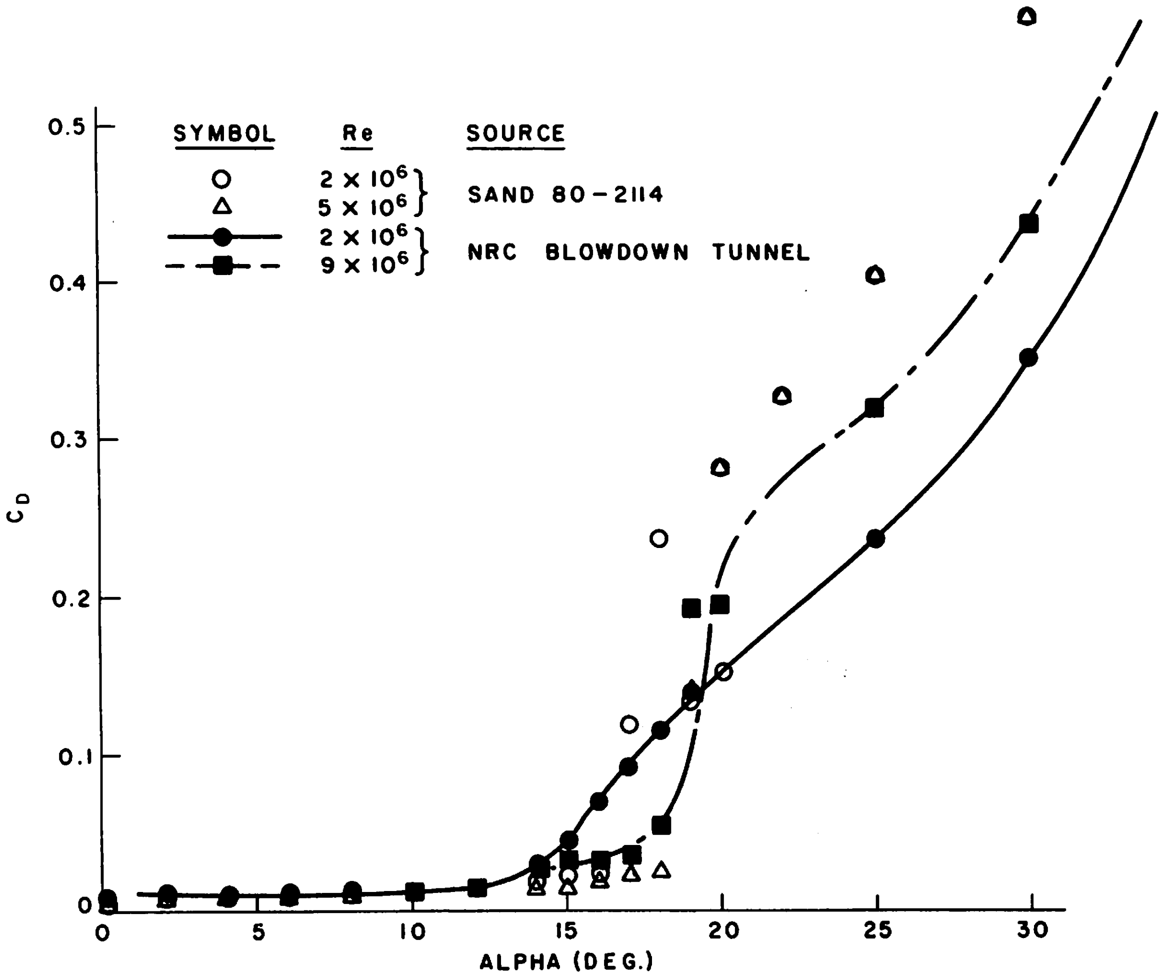


Figure 9. Reynolds number effect on lift coefficient of NACA0018 airfoil

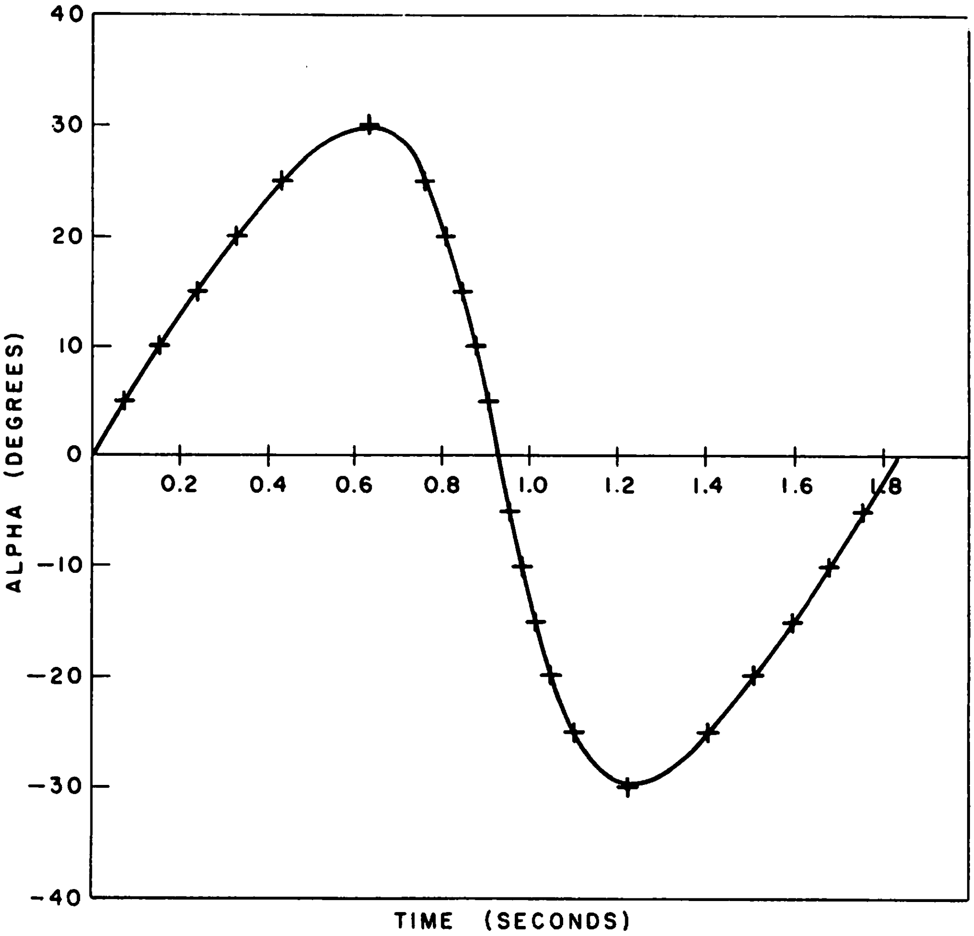


Figure 10. Angle of attack waveform typical of VAWT equatorial locations
(Time period appropriate to Iles de la Madeleine unit)

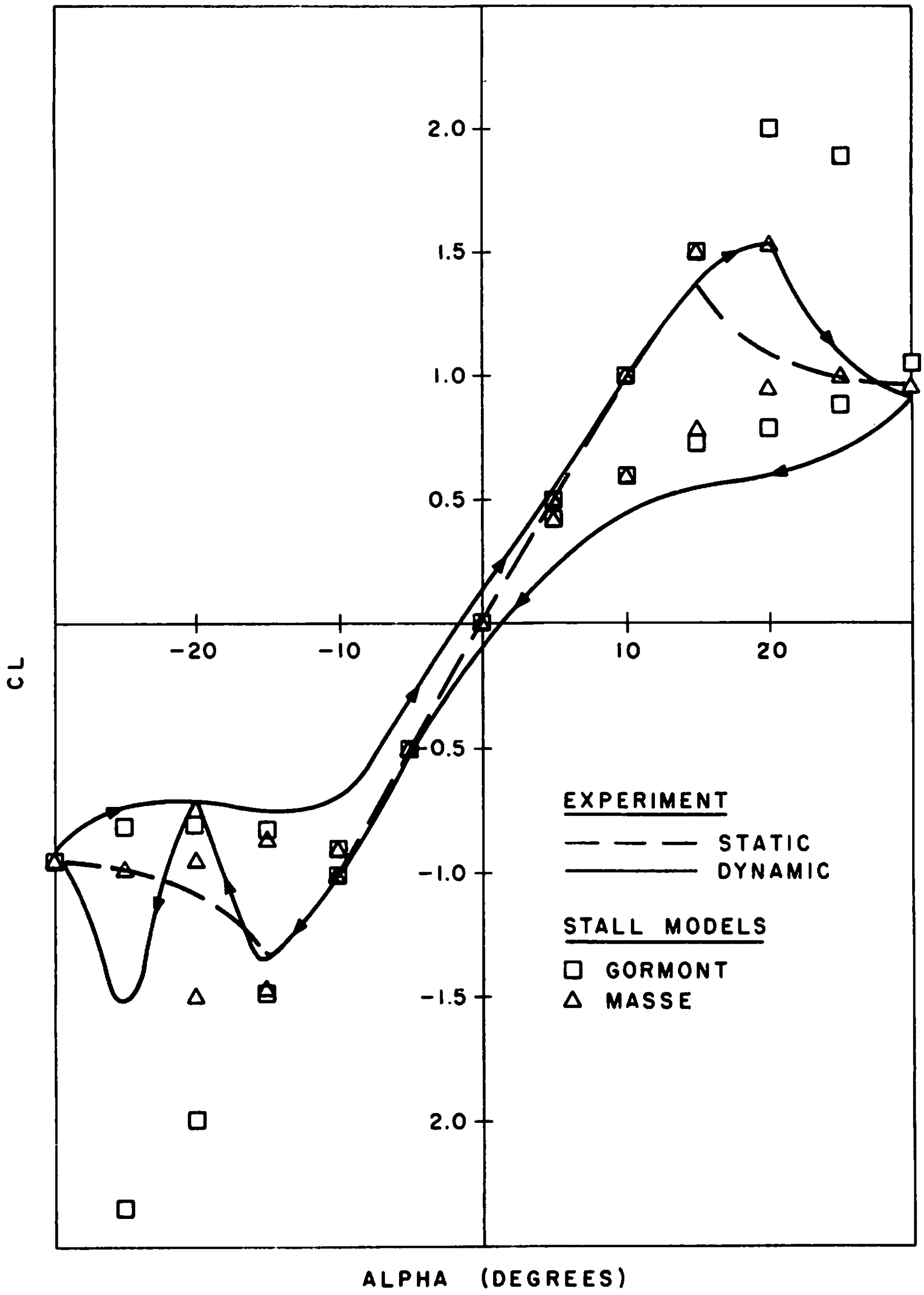


Figure 11. Dynamic effects on lift coefficeint of NACA0018 airfoil (oscillation waveform per Fig. 10)

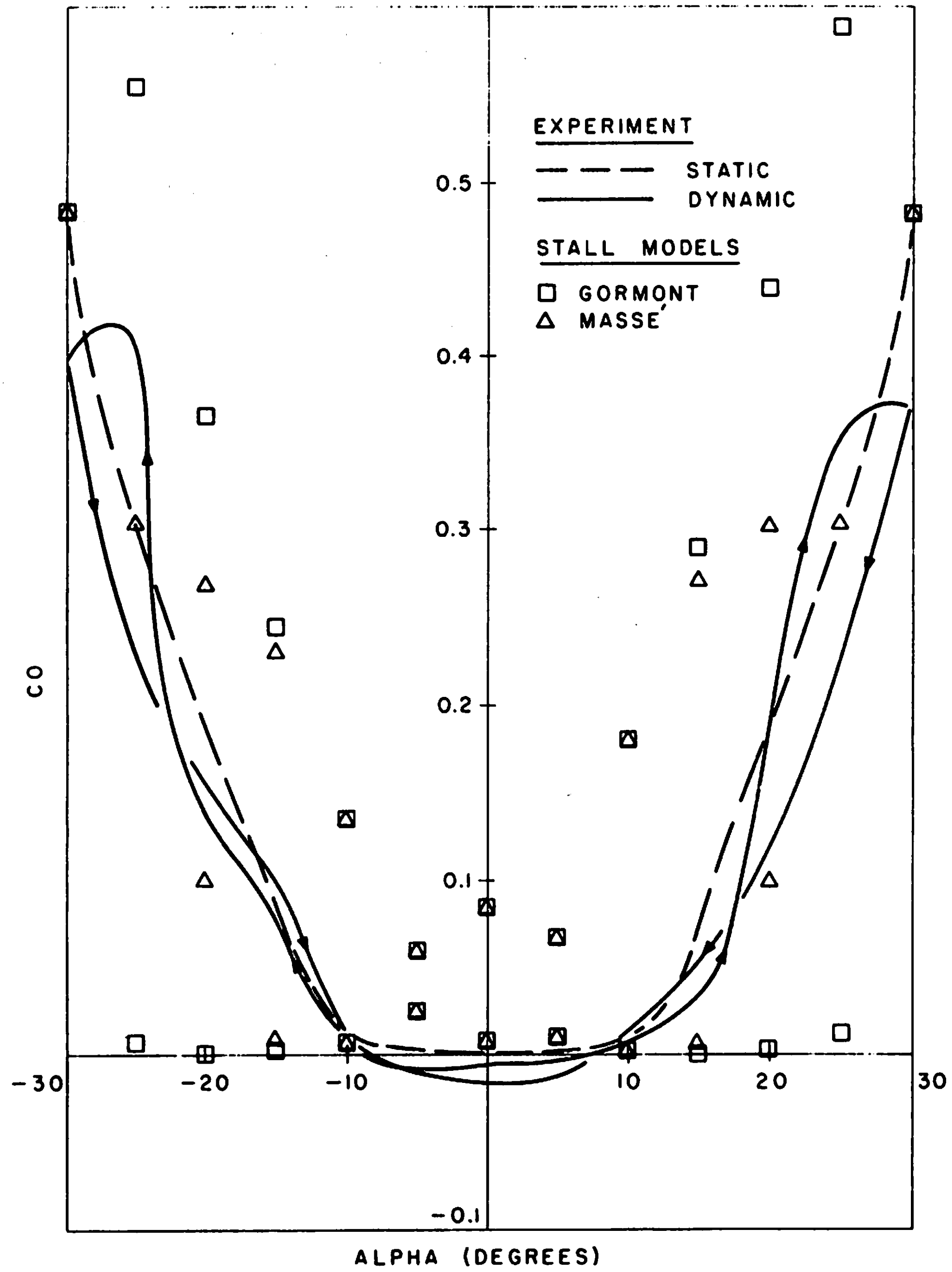


Figure 12. Dynamic effects on drag coefficient of NACA0018 airfoil (Oscillation waveform per Fig. 10)

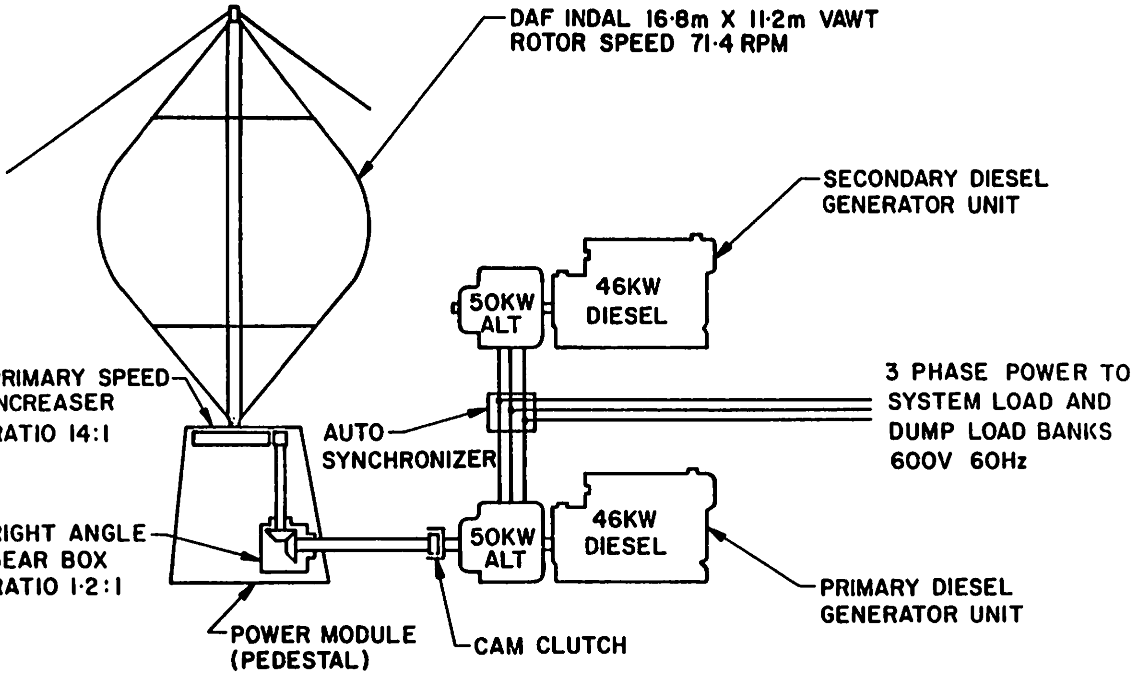


Figure 13. 100 kW wind turbine assisted diesel generator system near Sudbury, Canada

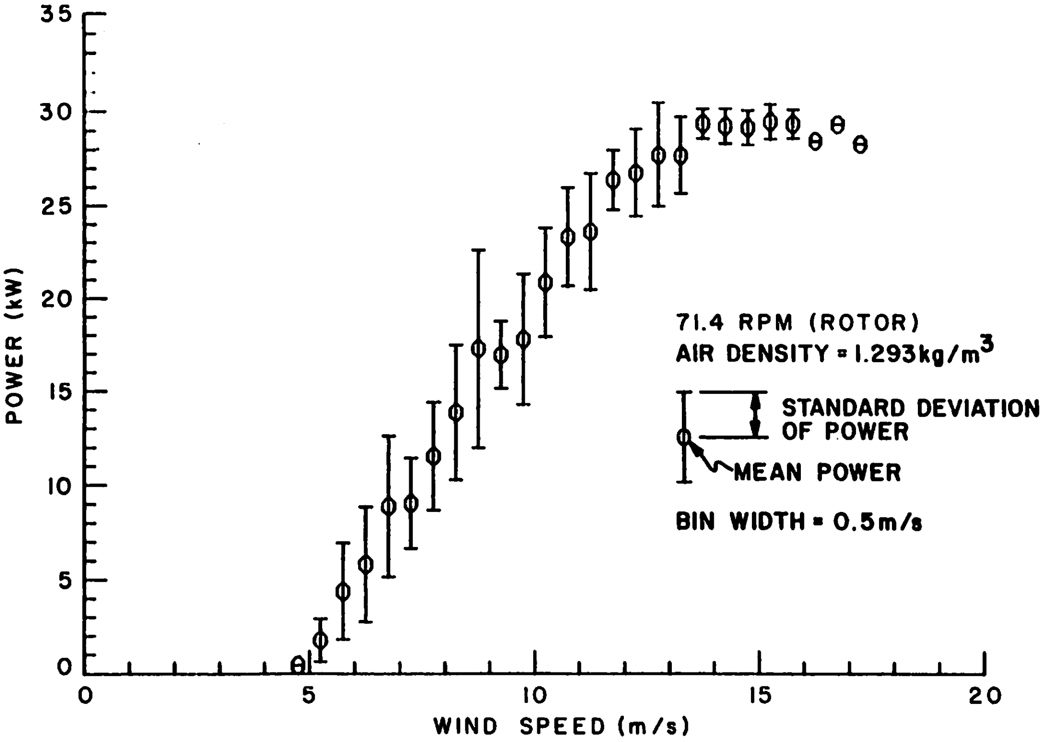


Figure 14. Sudbury VAWT power output vs. wind speed

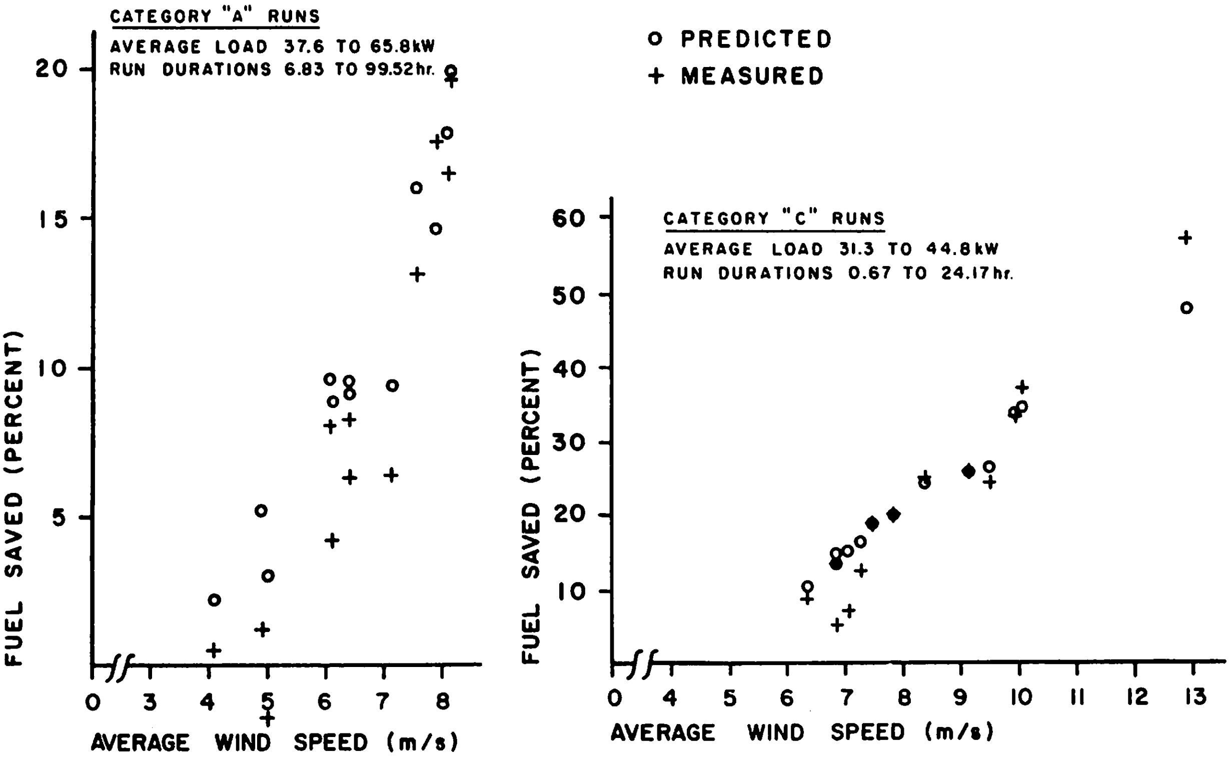


Figure 15. Sudbury wind/diesel fuel savings

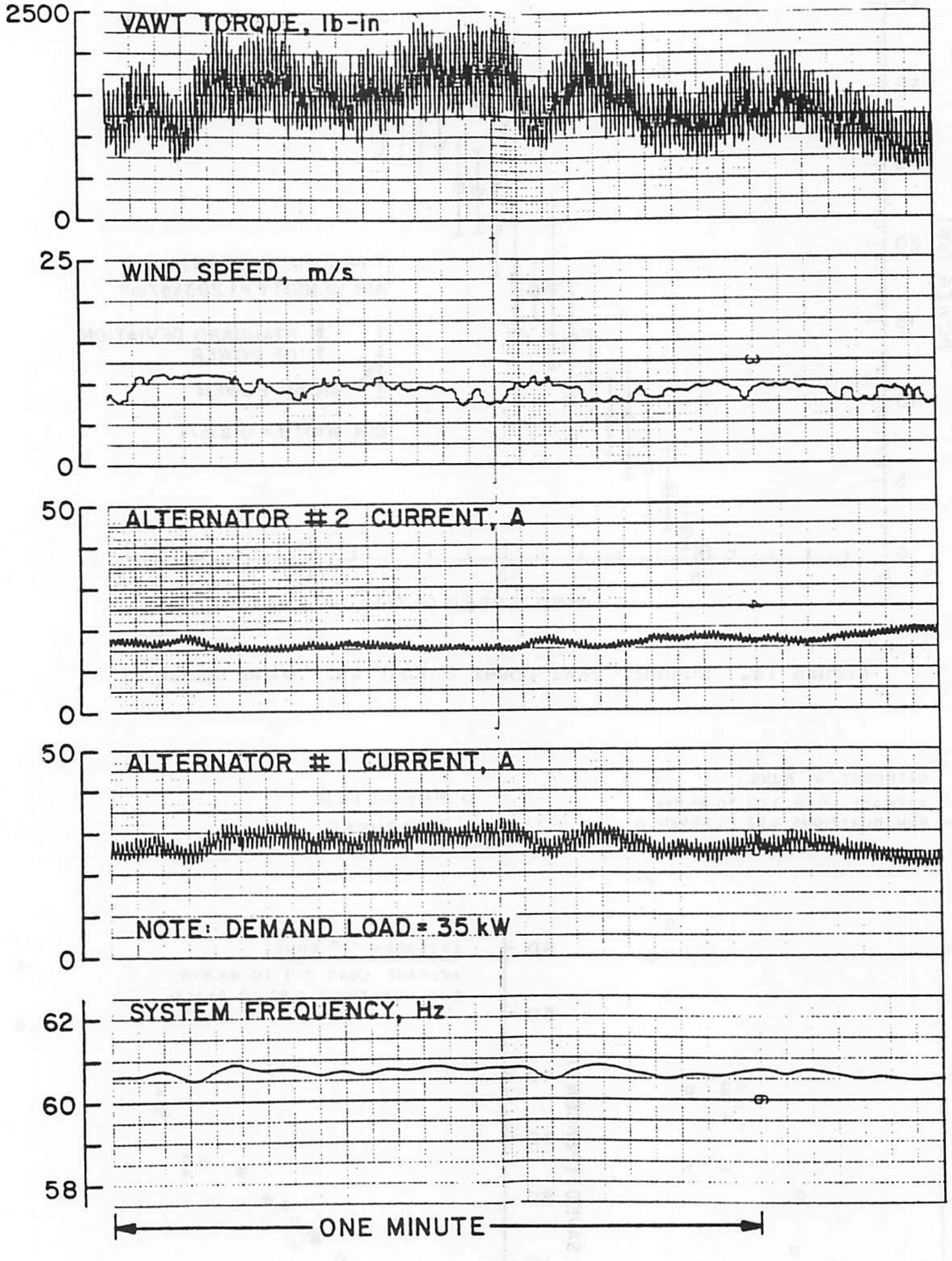


Figure 16. High speed chart records of two diesel operation - Sudbury I

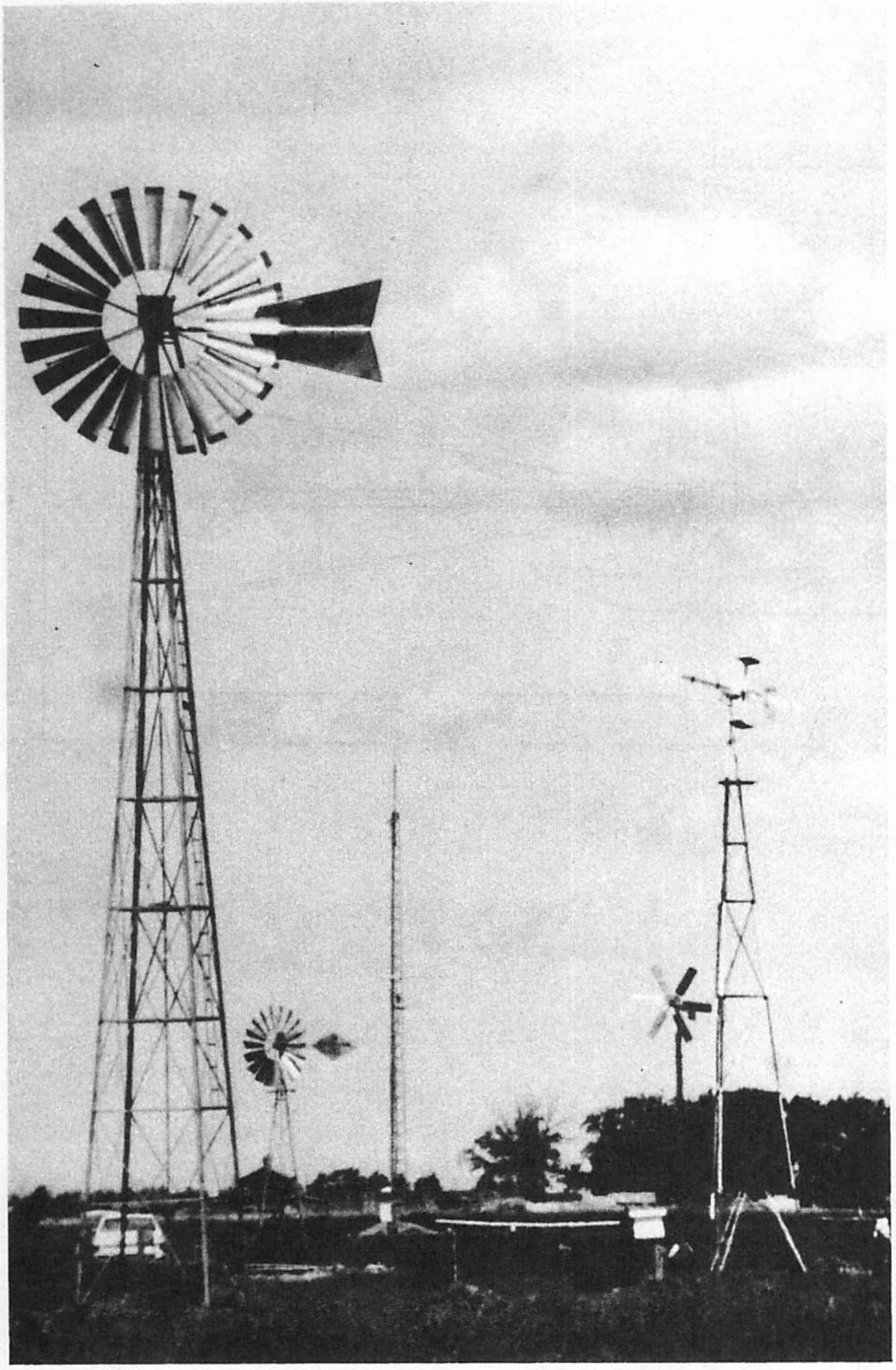


Figure 17. Wind turbine pump test site at Lethbridge, Alberta

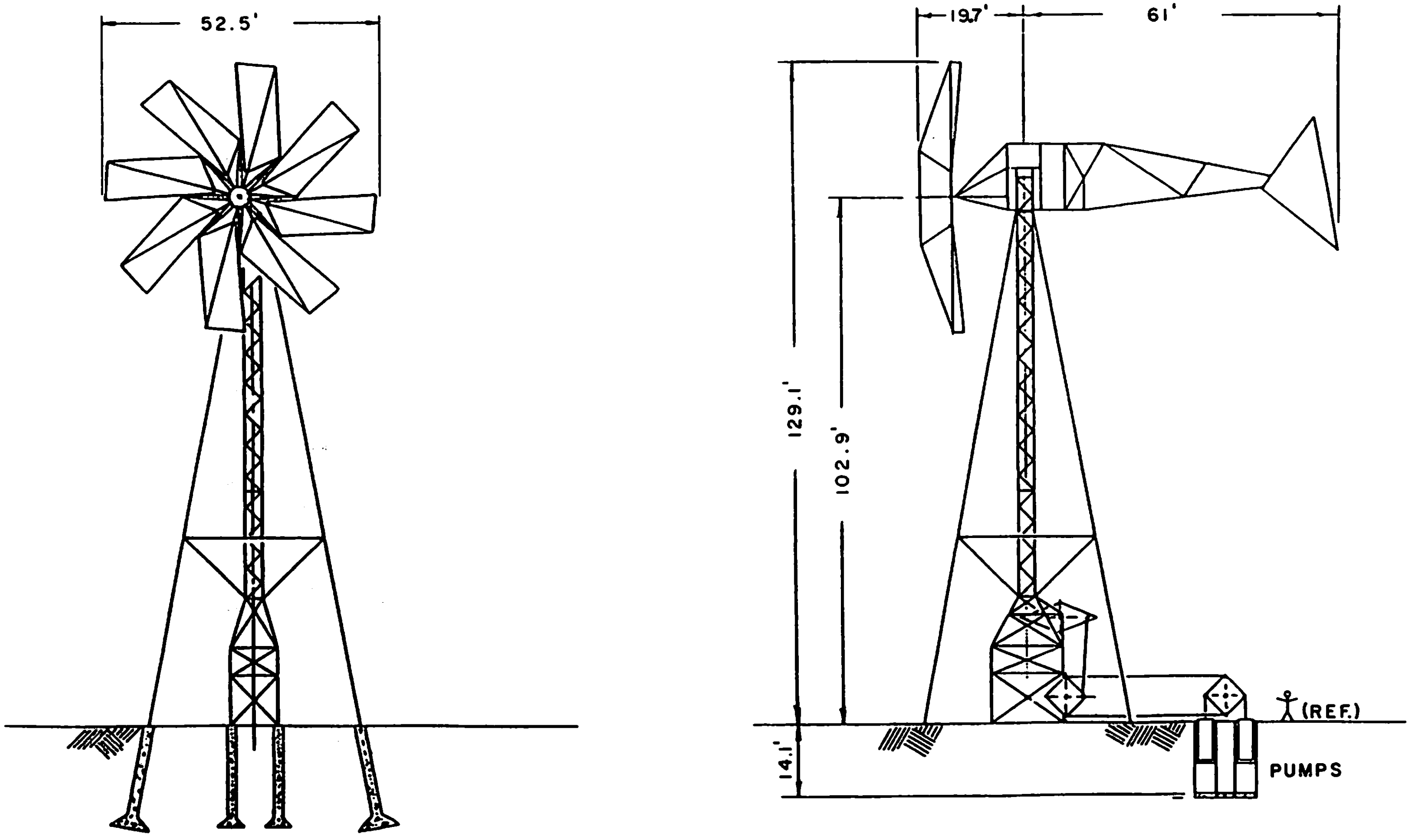


Figure 18. ABAX Delta blade wind turbine pump

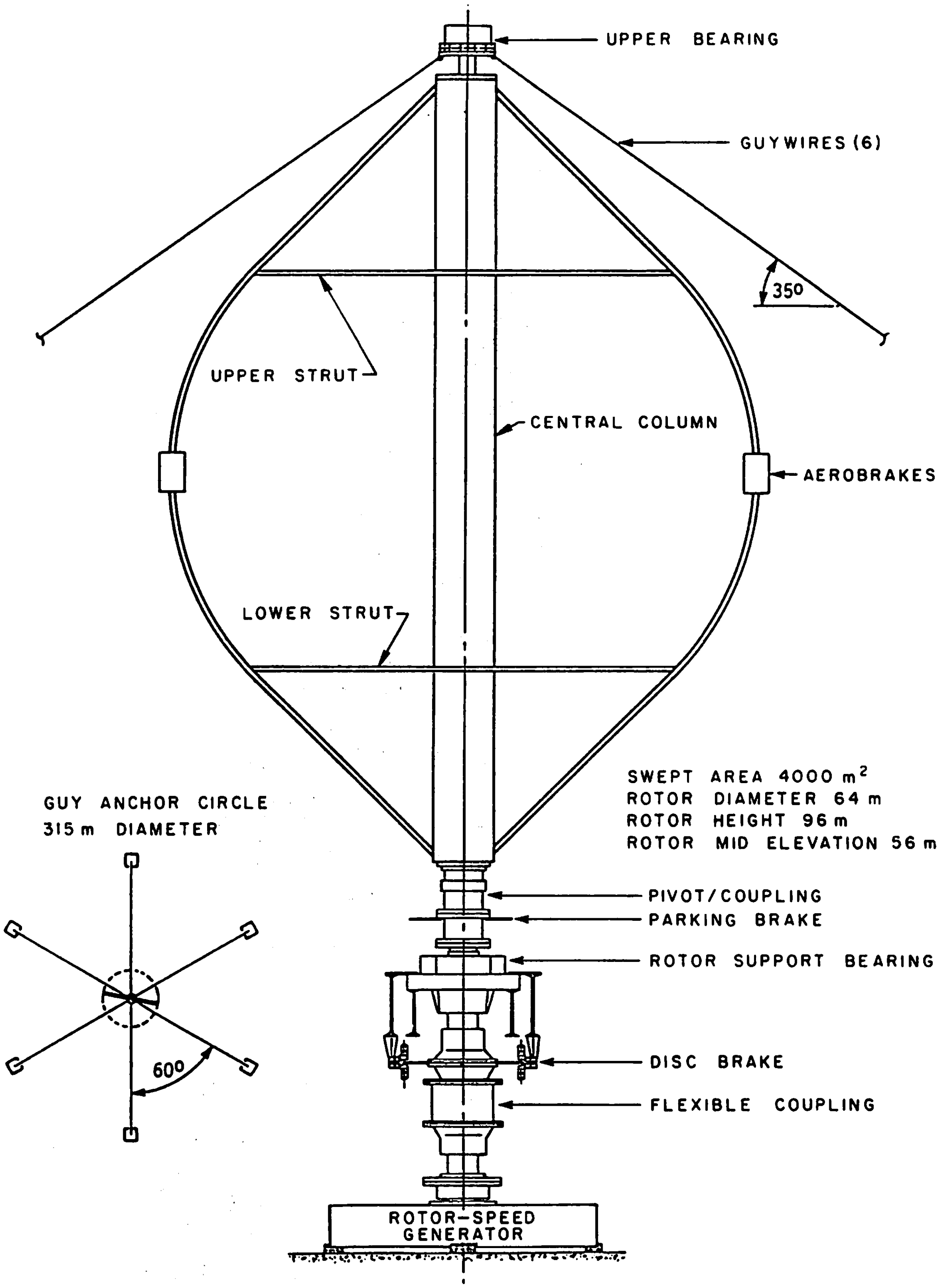


Figure 19. 4 MW VAWT "ÉOLE" general configuration

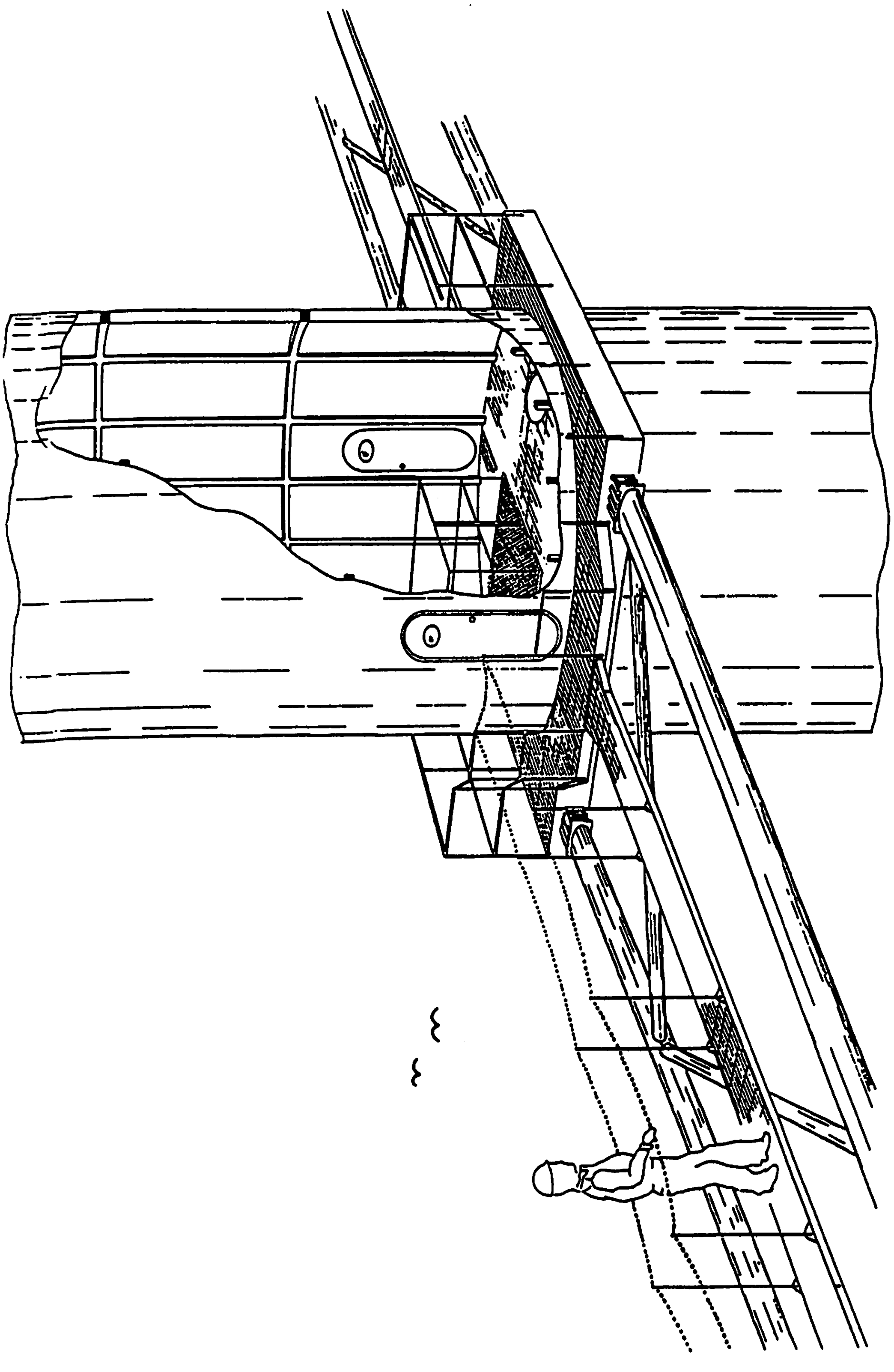


Figure 20. ÉOLE - column/strut joint

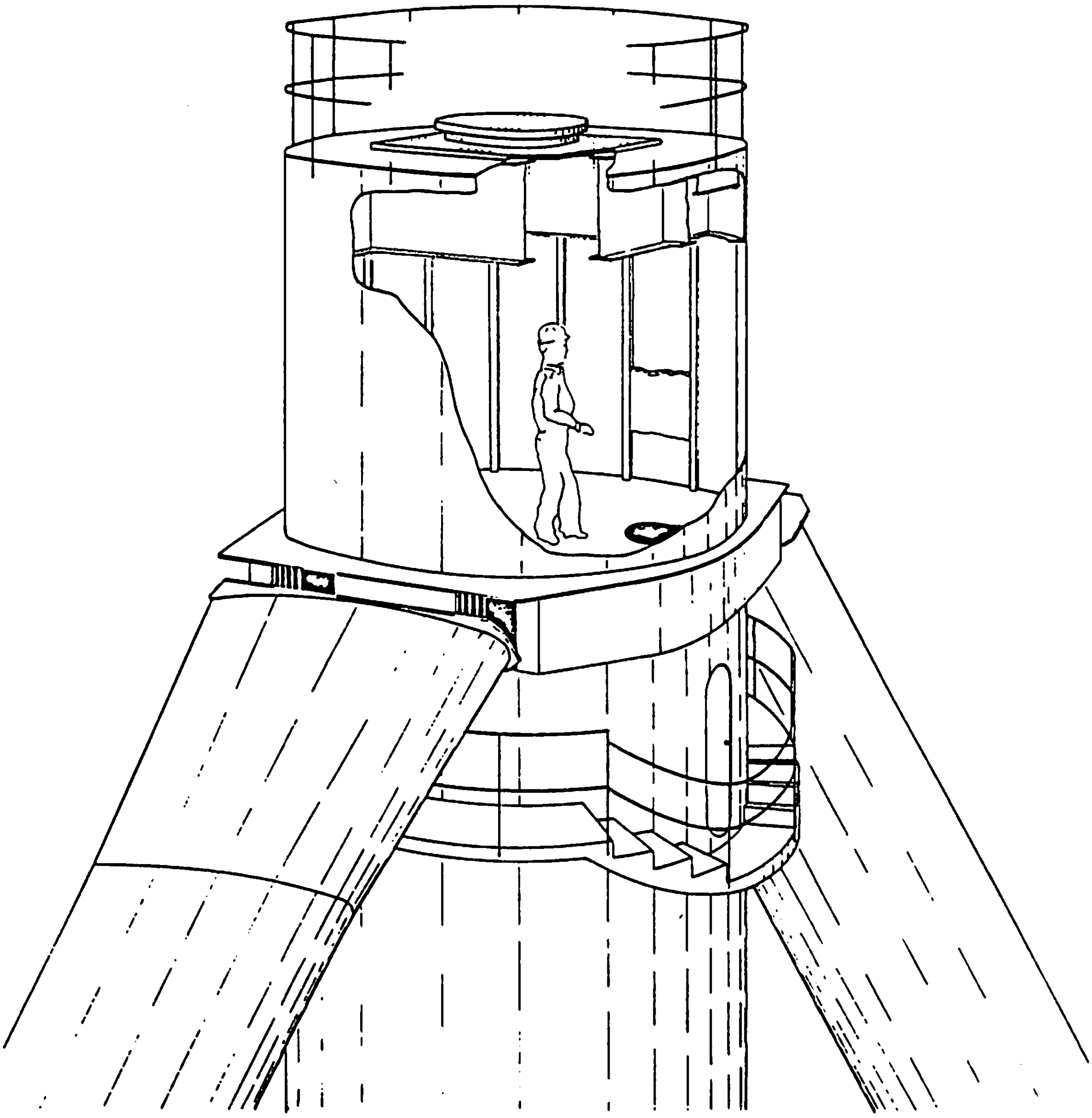


Figure 21. ÉOLE - upper blade/column joint

Mats Agrell

MAGLARP WTS-3. REVIEW OF TESTING ON SITE AND ACCEPTANCE

Maglarp Wind-Power-project Summary

WTS-3 at Maglarp, Sweden, was accepted by the National Energy Administration (Statens Energiverk) on the recommendation by the projekt group of Sydkraft utility on the 22. of september 1983.

On that day the unit had run on-line for 859 hours and had produced 1212 MWh during the test-period.

WTS-3 is now run and maintained by Sydkraft on a contract basis with the National Energy Administration. The wind-power-unit is run under remote control from Malmö (distance 25 km) and maintenance personnel is immediately called for, when an abnormal stop situation ocurres.

The delivery was one and a half years late according to the original time schedule. One year of the delay was spent on the site in Maglarp.

The extended test period on the site was caused by low winds and a few technical problems. The main problems during the test period are listed below:

- yaw system changed to active yaw
- hydraulic accumulators, loss of pressure
- sensors, e.g. rotor speed sensor
- cracks in painting and outer layer of blades
- cracks in weldings and struts in spinner
- oil leakage in several points

All the main technical problems were solved in a satisfactory manner by the time of the acceptence. Inspektions and special investigations will be made during the guarantee-period and test-period in order to keep watch over the problem areas.

Maglarp WTS-3 diary:

Contract date	26 June 1979
Transport to Maglarp	Mars 1982
Erection of tower	May 1982
First rotation	July 1982
Connection to the grid	August 1982
Rated power 3 MW	October 1982
Approved 100 hour test	Febr. 1983
Approved inspection	June 1983
Spinner approved	Sept. 1983
Total approval and delivery	22 Sept 1983

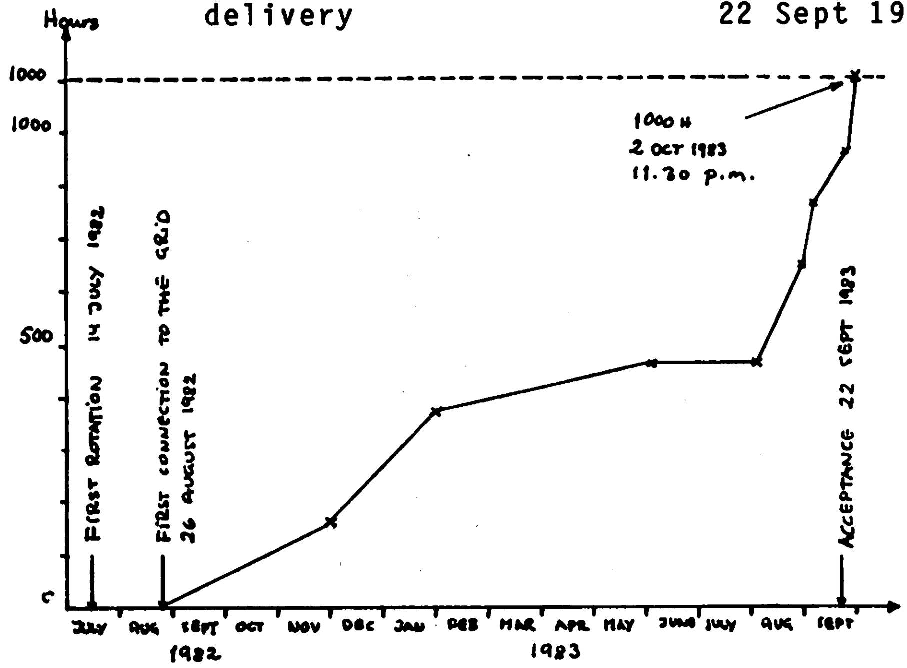


Fig 1. Total sync. hours of WTS-3 during on-site testing

Experience of on-site-testing

A general experience of testing on site in Maglarp is that every phase of the testing took ten times the expected amount of time. The problem is to have the wind turbine running, the measurment computer system available and the right wind for that specific test, at the same time.

The turn-around time for measurment, processing and plotting of data on the computer system was typically one hour. This was not satisfactory as a tool for testing and evaluating the wind turbine. By adding new facilities to the computer system, like new software and plotting on the line-printer, the time was reduced. The most important instrument during the tests turned out to be the eight pen strip-chart recorder. The recorder is connected to the control system and a "monitor" in the measurment system PCM-flow. All the 200 sensors in the measurment system can be plotted in real time on the recorder.

The control system has a special feature in presenting past history data after an emergency stop. 24 channels of data, programmable by the operator, are recorded for 2 minutes. The recording stops at an abnormal stop of the turbine and the recorded data can be plotted out on paper, eight by eight, on the strip chart recorder.

The sensors in control- and measurment-system need a lot of calibration work in order to get reliable data. WTS-3 is equipped with approximately 300 sensors and since many of the sensors, e. g. strain gauges in rotorblades, work in a difficult enviroment, problems with "dying" sensors are common.

The great number of sensors demand methods in:

- Calibrating each sensor
- Function test. (Do I have the right sensor to the right channel?)
- Deciding and documenting the correct convertion functions
- Checking for cross-talk between sensors and between channels.

Yaw mechanism problem

During the last part of the construction phase Karlskronavarvet, (KkrV), and Hamilton Standard expressed suspiscion that the free yaw mechanism, which was intended, was not stable. The yaw-control was then changed to active yaw. A hydraulic motor was already installed for inching purpose.

The first test-runs of WTS-3 showed that the nacelle turned clockwise out of the wind. Some tests were performed in order to find the first stable angle out of the wind, but no such angle was found in the area possible to test. The speed of the turning depends on the windspeed and is approximately 5 degrees in 20 seconds. (The limit is set to 5 degrees).

Since the yaw-motor is working almost half the time this causes wear on the yaw gear. In order to minimize this wear a secondery yaw motor was installed in january 1983.

Both motors have an hydraulic damping which works as a soft break on the yaw movement.

The constructors had to compromize in setting the pressure of the two motors. Too little pressure can result in problems bringing the nacelle back to the wind direction and too much pressure gives a shorter lifetime to the yaw gear.

During high turbulent wind in september 1983 the wind turbine had some difficulties in staying in the wind and was therefore automaticly shut down by the control system. In order to increase the security a redudant wind-direction-sensor is mounted on the top of the nacelle and a redundant yaw-angle-sensor is planned.

The yaw behavior will be carefully studied in the full-scale-test period.

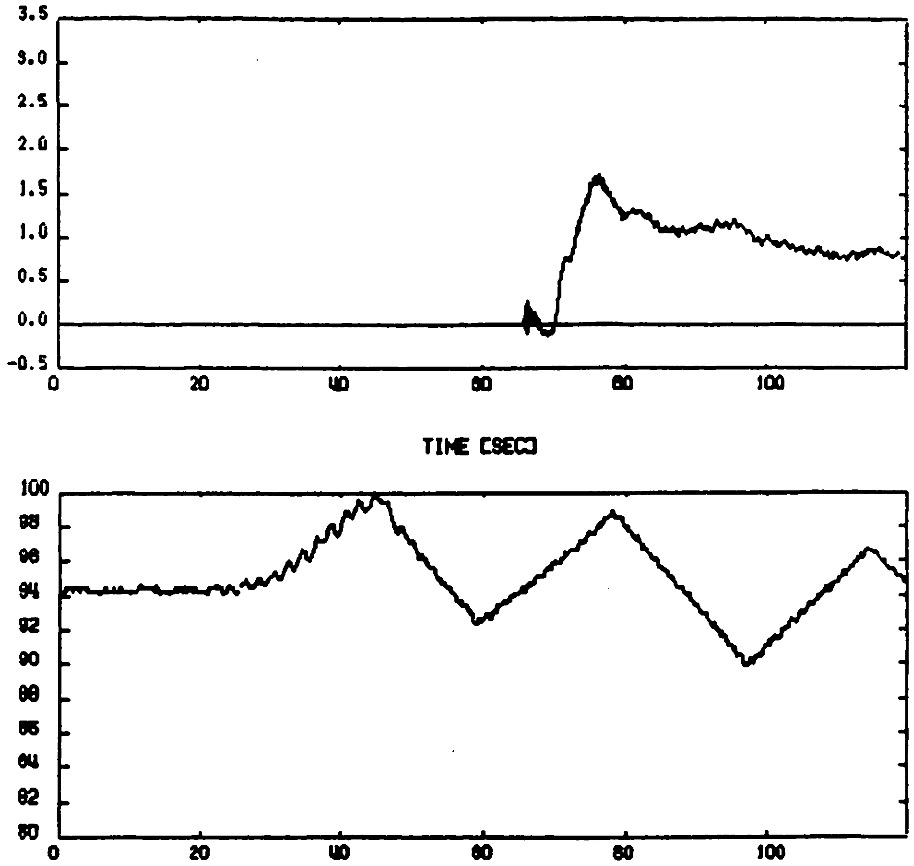


Fig 2. Start at low windspeed (9 m/s)
Top: Produced power
Bottom: Nacelle direction

Hydraulic accumulators

Eight hydraulic accumulators are mounted in the spinner. The accumulators are a part of the emergency feather system which serves as a back-up for the normal pitch change system. The accumulators are rotating with the spinner at 25 rpm and KkrV had at first problem in finding a suitable type of accumulator for the purpose. Since the control system always tests the pressure of the emergency feather system as a prestart check this caused many problems especially when attempting to start the turbine after a long period of standstill.

The accumulators were changed to a new type in may 1983. The new accumulators had been used for 300 hours of operation at the time of acceptance with no problems.

TV-interference

Very soon after the first test-runs of WTS-3 complains came in on TV-interference from a little village "Skåre" situated 2 km from the site. 30 to 40 homes in the village have severe disturbances all the time the unit is running. The village is in the "shadow" of the wind-power-plant seen from the transmitter, which is on a distance of 50 km.

In Skåre most of the homes use the UHF-band for both Swedish TV-channels. The "Channel 2" can also bee received with no disturbances from another transmitter i Malmö, using a separate antenna for the UHF-band. A few houses outside the village have the same severe TV-interference and there are reports on other occational disturbances in the area.

The rotor blades are made of reinforced fibre glass which should give very little signal reflection. Strips of aluminum foil is however glued to the blades on the leading and trailing edge. Wires to the 38 sensors on each blade can also make the plastic blade look like a metallic surface to TV-signals.

The projekt is paying for a slave-transmitter, which probably will be set up in the village Skåre. Some measurments remains to decide the appropriate place and power for the transmitter. The frequency and power of the transmitter must be aggreed to by the surrounding countries Denmark, DDR and BRD. This means that the transmitter can be operating at the earliest 3 to 4 months after the measurments are completed.

A solution with cable-TV is not probable because it will be too expensive to install cables in the isolated houses outside the village. Cable-TV is also very little in use in Sweden (yet). The noise from the WTS-3 has been measured during the acceptance tests.

Noise

During autumn 1983 noise-measurments will be made by IFM, Akustikbyrån, according to recommendations by the IEA expert group. (Trenka, Gustafson).

A prediction of the sound from WTS-3 is presented by Stig Soderquist, IFM. The first measurments were compared by Soderquist and the result was:

- the dBA-curve is 8 dB below predicted
- the octave band analysis shows that the measured curve is 10 dB higher than the predicted curve at a wind-speed of 12 m/s and low frequences.

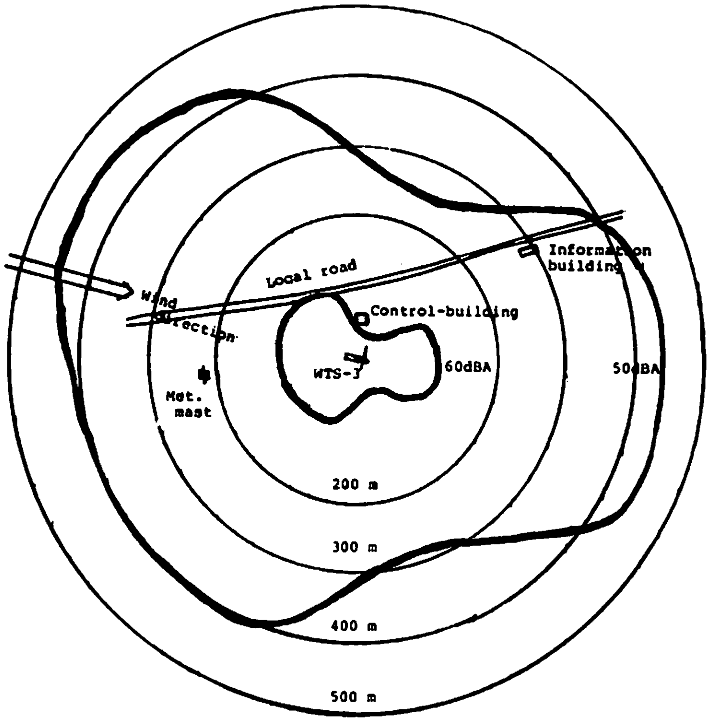


Fig 3. WTS-3. Noise Windspeed 5-10 m/s
50 dBA and 60 dBA limit at Maglarp

Until the report from the measurment is presented we can only add the personal experience of the sound on the site at Maglarp. The "swisching" sound from the rotor-blades can be heard up to 500 meters downwind from the turbine. The nearest home is about 550 meters north-east of the turbine.

Every time a rotorblade passes behind the tower a "thump" sound can also be heard. This sound varies strongly with the angle and can be totaly different within a few meters. It is easy to hear this sound in the Information building 300 meters east of the turbine.

Neighbours have complained about the noise and even claimed that the wind turbine has given them headache. Measurments in one home have showed no high levels at low frequences or of sub-sonic sound.

Wake-studies in the region between the tower and the blade was performed in september 1983 by FFA, Sweden, and the results may give a better knowledge of down-wind-turbines and sound problem.

Cracks in blades

At an inspection of the rotorblades in february 1983 cracks were found in painting and outer layer of blades. The glass fibre is wound in many layers. The fibres which carry the load on the blade are oriented at a 60 degree angle to the longitudinal blade axis. No cracks could be found in that layer. Outside the 60 degree layer is a 90 degree layer with the purpose of giving the blade a better surface. This layer had cracks in some sections of the blade. An analysis showed that the cracks had no influence on the strenght of the blade. The blades had however to be repaired to prevent water from beeing absorbed in the glass-fibre layers. Cracks in the painting were found in many parts of the blades. The lightning tape was also damaged and had to be glued to the blade. Some traces of suspected lightning strokes was found. The damages were very small and no disturbance to the computers or any electronics were observed.

The blades were repaired and painted in june 1983. The work demanded dry and warm weather and was successfully accomplished from the maintance platform. The paint was changed to a more elastic type. Some cracks were left unrepaired and were later inspekted for determining the speed of crack propagation.

The blades were again inspekted in september 1983. Some small cracks in the new paint were discovered but no new cracks in fibre glass layers were found. The propagation of unrepaired cracks was slow. Unfortunately the new paint has a slightly darker colour, which makes the blades look "dirty".

Spinner problems

During a 100 hour test-run in november 1982 some cracks in struts in the spinner were found. The spinner is a construction of aluminum shell and struts in steel and the spinner serves as a weather protection for maintenance personnel and pitch change mechanism. The spinner is no vital part for the function of the wind-turbine but a breakdown of the struts in spinner could cause secondary damage to the pitch mechanism.

Attempts were made to repair the weldings and strengthen the struts. A number of strain gauges were also put on to the struts and the forces were measured during different conditions. The forces turned out to be higher than predicted and the spinner was consequently underdimensioned.

During july 1983 the spinner was radicaly reconstructed. The work could be done without removing the spinner.

The "new" spinner had by the time of the acceptance been in use for about 300 hours. The weldings and the struts have been inspected by external experts and no remarks were left at the acceptance.

Oil leakage

The WTS-3 in Maglarp is certainly not the only windturbine in world with oil leakage problems. The main gear for stepping up the speed from the rotor (25 rpm) to the generator (1500 rpm) is one of the parts with oil leakage problems. The leak from the gear has been minimized by modifying the gear and by installing a oil collection system on the upwind side of the gear.

Oil leakage from rotating parts were considered especially unwanted because of the oil mist that could fill the nacelle. The oil is not only unpleasant for the personnel but could also meen a danger of fire.

The lubrication system on the down-wind bearing was changed from oil to grease. The bearing is close to the disc parking brake were oil (and grease) is not wanted.

At the acceptance the leakage in the nacelle was diminished by installed collections systems or modifications. On the list of remaining remarks were still a few points were KkrV had to make further efforts to minimize the oil leakage.

Evaluation program

The WTS-3 at Maglarp is studied in the swedish "full-scale-evaluation program" together with the WTS-75 at Näsudden on Gotland.

The two large scale wind turbines are studied and compared in these sub-programs:

1 Power Performance Testing
2 Interaction with the power grid
3 Operational experience
4 General performance
5 Loads and stresses
6 Ice - Lightning - Noise - TV
7 Project rewiew, general experience

The intention is to run the WTS-3 at Maglarp as a normal production plant with the ordinary routines for operation and maintenance at Sydkraft utility.

The evaluation program should as little as possible restrain the normal operation of the wind power plant.

THE COMMISSIONING OF THE SWEDISH 2 MW WTS PROTOTYPE AT NÄSUDDEN.

by
Göran Svensson

ABSTRACT

Experiences during the commissioning of the swedish 2 MW WTS prototype at Näsudden on the island of Gotland is summarized.

The WTS was formally delivered to the customer, the Swedish Energy Agency, on August 4, 1983.

The operation has so far been very succesful and the evaluation has just started and will be reported in the middle of 1984.

1 BACKGROUND

The Swedish wind energy program was formed during the so called energy crisis in the middle of 1970.

The program is administered by the National Swedish Board for Energy Source Development (NE) now part of the newly formed National Energy administration (STEV). The main objective for the program is to until 1985 give a base for the Swedish government to decide what further development is needed to introduce wind power into the Swedish power system. This of course if the evaluation indicates that wind can be competitive with other energy sources

The total cost for the 10 year program is close to 300 MSEK (38 M$). The major part of this are the two prototypes. The Maglarp unit in the province of Skåne and the Näsudden unit on the island of Gotland on the east coast of Sweden.

The other activities inside the program are summarized in figure 1.

2 The Näsudden project.

The 2 MW WTS at Näsudden has the Swedish company KAMEWA AB as main contractor. The contract for the prototype was signed in September 1979 and at the same time the Swedish State Power Board (SSPB) was contracted, by NE, to be their operating agent during the project phase as well as responsible for the operation and maintenance and for the evaluation of the prototype.

The main characteristics of the WTS is summarized in figure 2.

A more detailed technical presentation is available in Ref.1.

The status of the project is that acceptance and formal delivery to the customer was reached on August 4,1983. The turbine has up to now been connected to the grid over 100 hours since April 22,1983 when the first synchronization was done.

The energy production during this period is close to 150 000 kWh.

The major milestones in the project are presented in figure 3.

3 Commissioning

3.1 Shop test

The preparation for the commissioning at the site started already with the shop test during the first six months of 1982. The complete nacelle and hub was at this time assembled inside the KAMEWA work shop. The different subsystems were tested one at the time and also together in a complete rotating system, except for the blades. The software for the control system was also to some extent tested. All programs were not available at that time which meant a somewhat more extensive site testing than otherwise necessary.

During these tests the stiffness of the pitch mechanism was thoroughly investigated in order to be quite certain that flutter would not occur during operation. The results showed a somewhat lower stiffness than anticipated which led to the decision to change one of the two cylinders per blade into one with bigger diameter. Such a modification could rather easily be made with access to a well equipped work shop.

Another big advantage with the shop test was that the personnel responsible for the site tests learned about the behaviour of the system at ground level and without dependence of the wind.

3.2 Site testing

The actual commissioning period started already in November 1982 with checking that the installation was according to the design. Successively all systems were taken into operation, tested and integrated into the automatic sequences inside the control system.

To test the software in the PC-system and the regulators a special simulator was designed.

This made it possible to simulate a rotating turbine and to debug the programs without having to operate the WTS. In this way the testing was partially independent of the wind and without any risk that a malfunction or a mistake would end up in an unwanted mode of operation. This procedure also explains the rather few operating hours during the commissioning period. After the first connection to the grid, only one and a half month was needed before the acceptance tests could start.

During the commissioning the responsibility for the tests was inside the contractors comittments. The activities were though planned and discussed in cooperation with SSPB personnel. Also during the tests the customer followed the progress very closely. Twice a week the results were discussed in a small group with members from both parties. Beside the persons inside the customers project group also representatives from the operating department inside SSPB were participating in order to learn how to operate and maintain the unit. The experience with this way of working is extremely good and made the take over of the unit much more simple.

4 Summary of the commissioning period

The commissioning period lasted for almost 7 months. Although the time is rather long the problems that occured during the period were mainly related to practical matters and there was always a solution found that made it possible to continue.

There was also a strong wish from both the contractor and the customer to really learn the behaviour of the system to have a base for the following evaluation. This of course also prolongs the activities.

Some of the problems experienced can be worth mentioning.

4.1 Timeschedule

Although a lot of preparation work had been done in advance and the persons involved in the site testing were the designers of the systems

it turned out to be very difficult
to predict the time needed for the different
activities

It is of course also difficult to coordinate
work that has to be performed when the turbine
is in operation and several subcontractors are
involved. Especially in the low wind season
and at a remote location.

The conclusion must be to try to do as much as
possible before the site activities starts

4.2 Components

A design philosophy has been to utilize well
proven components used in other similar
applications.

Some problems occured with an electronic buffer
card, used for measuring the blade angle. This
was caused by a fault inside the manufacturing
process and it took quite some time to get a
sample with the right behaviour.

The signal from one of the speed sensors also
gave a lot of ripple and caused some delay
before proper filters were built in. The cause
for this is still unknown.

The hydraulic systems have behaved as expected
after the final adjustments. The design pressure
level for the pitch setting system is 80 bar
which means that more rigid components can be
used,less sensitive to particles in the hydraulic oil.

The ventilation system inside the nacelle
had to be modified to keep the temperature down.
The rather complicated nacelle made it difficult to predict the airflow.

The ice detectors on the blades have not yet
worked satisfactory and a redesign in the
method of analyzing the signal from the detectors
has to be developed, before the winter period

4.3 The data aquisition system (DAS)

The delivery of the DAS was split between the customer and the contractor. The gauges and the PCM-system was inside the turn-key delivery. The computers and the software was purchased separately and contained quite a lot of development work. This caused a delay in the delivery of an operational computer system. As the main contractor for the prototype was promised, inside the contract, to have access to the total system during the commissioning this caused some disturbances and a lot of coordination work from the customer.

5 Acceptance tests

The acceptance tests were specified inside the contract and were divided in two parts. One part before the delivery and a second part after delivery. The activities inside the programs are shown in figure 4 and figure 5.

The tests were performed with one responsible person from KAMEWA, as main contractor, and one from SSPB, as representative for the customer.

As most of the tests had been run during the commissioning period the behaviour of the system was known to both parties, but at this phase the results were recorded and reported to a much higher level.

The first part of the acceptance tests was performed during June and July and the second part will start in the middle of October 1983.

The aim with the acceptance test was not to fully evaluate the WTS but to show that the behaviour and performance was inside the contractual requirements.

The available results are therefore very preliminar and the more thorough evaluation has just started.

Some observations and comments to the results can yet be of interest.

5.1 System behaviour

The changes between modes of operation works very satisfactory. The criterions for starting and stopping at low wind speeds are yet not optimized. From an energy point of view the cut-in wind speed is not so sensitive but the public is very sensitive to a WTS that is not in operation, especially in the demonstration phase.The optimization is in other words not just scientific.

The acceleration in the nacelle, during operation is quite tolerable due to the stiff system. This makes it possible to do visual inspection in the nacelle also when the turbine is running.

The turbine has been tested also at high wind speeds and has several times been disconnected from the grid due to high wind, at 21 m/s, without any unexpected behaviour.

5.2 Synchronization and interaction with the grid.

The electrical grid at the site is very weak. Short circuit power level in the order of 40 MVA: Simulations showed that a direct connection of the asynchronous generator to the grid would result in a voltage drop of about 17%. To be able to fulfil the requirements of a voltage variation, on the 30 kV side, inside ± 5% during the connection to the grid a special design had to be incorporated.

The electrical diagram is shown in figure 6. When the rotational speed, during a start procedure, is close to the synchronous speed the generator is connected to the 0,6 MVAr capacitor. Due to the residual magnetization in the generator the voltage in the curcuit is built up to approximately 6kV. At this time the generator is synchronized in the same way as if it had been a synchronous generator. As soon as the generator is working together with the grid it behaves as an asynchronous generator and the capacitor supplies reactive power to the system.

The procedure has worked almost better than expected. The voltage variation , when synchronizing, is in the order of 1%.

The allowable voltage variation,when the turbine is in operation,is± 0.5%. Although the power variations at some occasions have been rather high the voltage is inside the tolerances.

5.3 Performance and load situation

The power curve for the turbine has not yet been measured because of the limited time of operation.

During the test phase was the wind situation at some occasions rather severe. The actual wind shear deviated a lot from the normal and specified wind shear. This of course influenced the power variations and also the load situation for the blades. It has been confirmed from the meteorological measurments that these occasions were rather special. The power variations at this time were sometimes in the order of± 400 kW during one revolution.

Operation after this period has though showed much smaller variations and inside the calculated values.

In figure 7 is an example of the power output and the wind speed at the top of the nacelle.

It is too early to draw any conclusions about the load situation , but the DAS makes it possible to continuosly collect the load spectrum for 20 different points in the structure. First after some months of undisturbed operation is it meaningful to compare the actual load-spectrum with the calculated spectrum.

5.4 Other observations

At a blade inspection before the delivery it was observed that a lightning stroke had hit the "tip cap", of stainless steel, in one of the blade tips. This caused a damage to the corrosion protection in an area of about 150×50 mm on both sides of the blade. No other damage has been observed.

At one occasion some 40 goldcrests were found dead beside the tower. The accident had happened during the night with the turbine parked.

Ice on the blades has up to now not been a problem. Some ice build up on the platform around the tower was observed during the last winter.

6 Operation after acceptance tests

The operation, after the first part of the acceptance tests, has been performed with a manned control room. The system is fully capable of operating remote-controlled, but this was a decision taken to increase the knowledge of the system. It also gives the persons responsible for the operation inside SSPB a deeper understanding of the system.

About 60 hours of operation has been gained during this period and the system has worked very well. The disturbances that has occured have been limited and have, without problems, been handled by the operating staff from SSPB.

After the 100 hours test, expected to start in the middle of October this year, the WTS will be operated unattended and remote-controlled from the SSPB operating centre outside Visby some 80 km from the prototype site.

Once a week there will be a visual inspection at the site and in between only if a fault occurs.

Plans for maintenance have been made in cooperation between KAMEWA and SSPB.

References.

1. Status and experiences with the 2 MW WTS 75 at Näsudden, Gotland. Sept. 1983

   V Mets and O Hermansson.

The Swedish Wind Energy Program

- Two full scale prototypes
- Prototype evaluation
- Adaption for series production
- Basic research
- Wind prospecting
- Siting studies, environment
- Test unit
- Integration study
- Support small wind turbines

Fig. 1

NÄSUDDEN

Main characteristics

Rated power	2 MW
Rotor diameter	75 m
Hubheight	77 m
Rotor speed	25 rpm
Wind speed	
Cut-in	6 m/s
Rated	12,5 m/s
Cut-out	21 m/s
No of blades	2
Blade materials	Steel - Grp
Type of hub	Rigid
Pitch control	Full span
Orientation of rotor	Upwind
Tower	Stiff, concrete
Electronic control	Programable controlers

Fig. 2

NÄSUDDEN

Major milestones

Contract signed	Sept 1979
Start of site activities	March 1981
Tower completed	July 1981
Shop assembly completed	Feb 1982
Shop test performed	March-June 1982
Blades completed	June 1982
Erection at site	June-Sept 1982
First rotation	Feb 1983
First connection to grid	April 1983
Acceptance test completed	July 1983
Delivery	Aug 1983

Fig. 3

NÄSUDDEN

Acceptance tests

1. Investigation of all modes of operation
2. Emergency stop from low wind speed
3. Stop due to low wind speed
4. Overspeed test
5. Loss of computers in the control system
6. Loss of grid
7. Measurments of vibrations and noice
8. Measurments of mechanical stresses during start up and operation
9. Measurments of mechanical stresses during emergency stop
10. Investigation of grid parameters at connection to the grid at high wind speed

Fig 4

NÄSUDDEN

Acceptance tests part two

1. Cut-out due to high wind speeds
2. Cut-in at high wind speeds
3. Emergency stop at high wind speeds
4. Control system stability
5. Efficiency in drive train
6. Local power demand
7. Measurments at stand still, high wind speeds
8. Power curve
9. Energy production
10. 100 hours test
11. Loss of grid at high wind speeds

Fig. 5

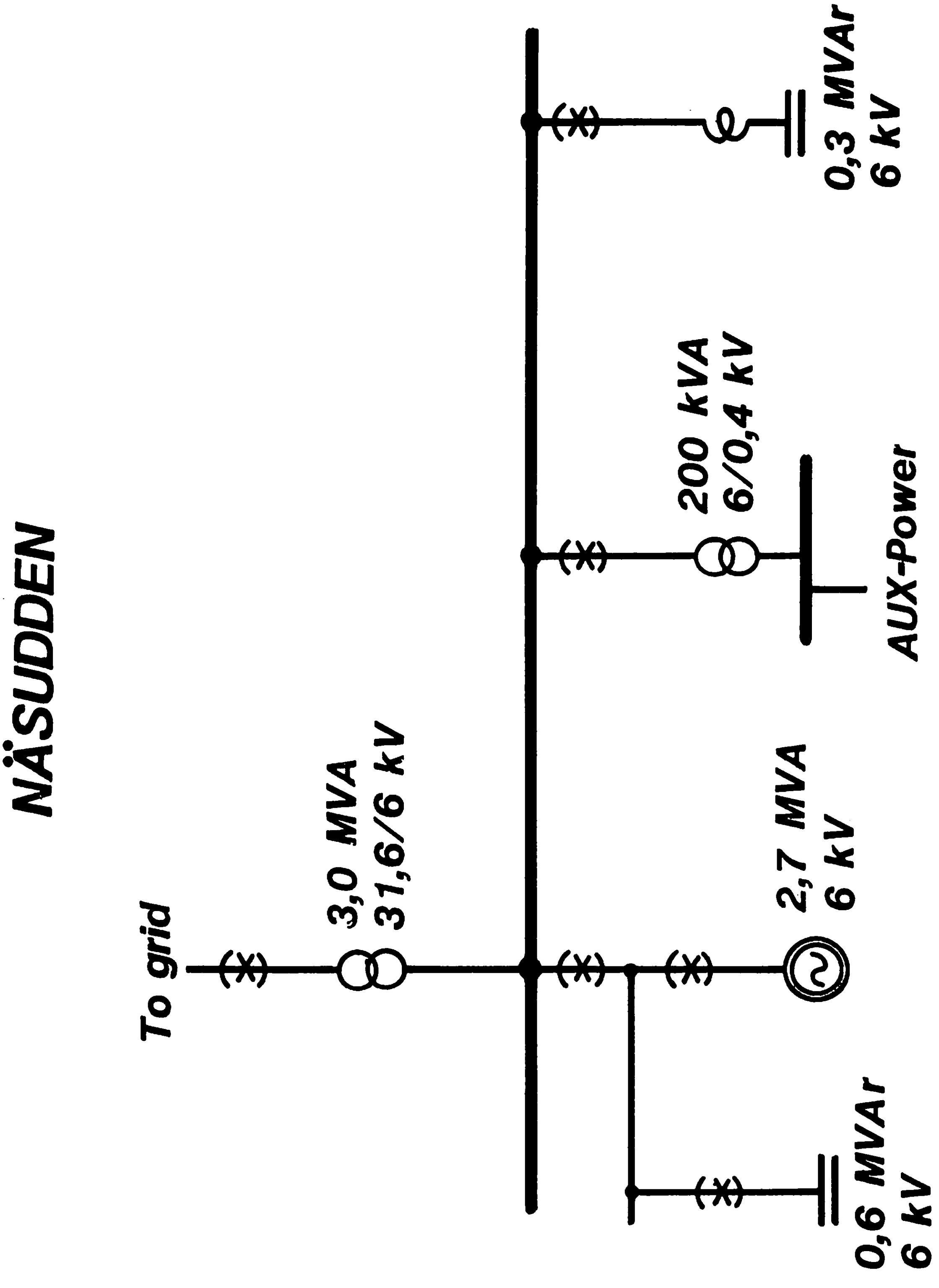

NÄSUDDEN
To grid
3,0 MVA
31,6/6 kV
2,7 MVA
6 kV
0,6 MVAr
6 kV
200 kVA
6/0,4 kV
AUX-Power
0,3 MVAr
6 kV

Fig 6

TIMESIGNALS

LOAD TESTING CONNECTION

DATE : 17/5/1983 TIME: 18:15:21
NUMBER : 0
SOURCEFILE : KALLE

FREQUENCY : 10.00 HZ
CHANNEL 186 : POWERS
CHANNEL 76 : NACHINOSP
VALUES/CHAN : 200

2 MW- Test

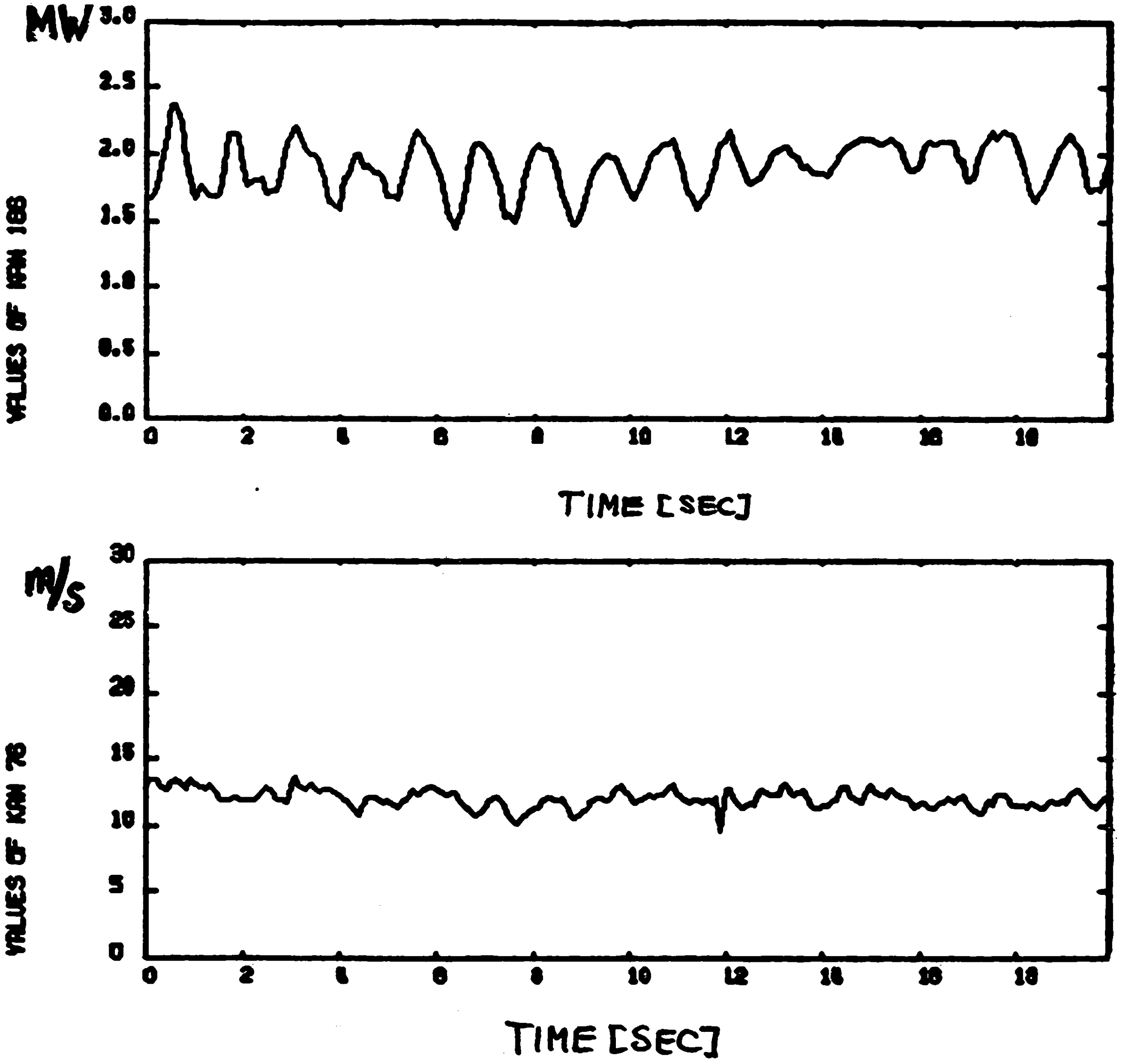


Fig. 7

STATUS OF WIND POWER AT PACIFIC GAS AND ELECTRIC COMPANY

by

Thomas Hillesland, Jr. and William J. Steeley

I. Introduction

To reduce use of fossil fuels, PGandE plans to increase the proportion of renewable resources in its future generation mix. Wind energy is expected to be a significant part of the Company's electric supply additions. PGandE owns and operates, on an experimental and performance monitoring basis, a 2.5 MW wind turbine in Solano County California. Many power purchase negotiations are in progress and several such agreements with private wind developers are in force.

This paper summarizes PGandE's wind prospecting and measurement programs, describes our site and machine selection process and reports on the construction and performance of the Solano WT. Progress in association with private wind developers and future wind energy plans are also discussed.

II. Wind Prospecting and Measurement

Beginning in 1976, PGandE participated in a DOE sponsored program to measure wind speeds at Point Arena, California. And the Company's meteorologists systematically reviewed the available historical wind data to identify promising wind areas in the service territory[1]. In 1979, results of a joint PGandE/California Energy Commission wind prospecting study confirmed the feasibility of developing wind energy in Solano and Alameda Counties[2]. So the Company embarked on a comprehensive wind measurement program in those regions. Data on the wind was gathered at eight locations in each region from 1980 until the beginning of 1982.

III. Site Selection Process

Wind study results were used to identify four candidate areas from more than 20 possibilities for siting PGandE's first large wind turbine. Two were in Solano County, one in Alameda County and the fourth at Point Arena in Mendocino County.

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[1] Davis, Earl and Ron Nierenberg, An Assessment of Potential Wind Energy from Historical Data, August 1979, Pacific Gas and Electric Company, Meteorological Office.

[2] Davis, Earl and Ron Nierenberg, Wind Energy Prospecting in Alameda and Solano Counties, May 1980, Pacific Gas and Electric Company, Meteorological Office.

A two-phase site selection process began which led to the final site selection. The first phase was a general process aimed to reveal problems that would prevent installing a wind turbine on a desired schedule. Two areas were dropped but one candidate area in Solano County and the other in the Altamont Pass region of Alameda County remained for further study.

The second phase was a detailed process to determine which site in the two remaining candidate areas would best meet the Company's requirements. These included:

1) Potentially favorable site effects on project economics, reliability, electrical compatibility and public acceptance.

2) Good accessibility from centers of operations and maintenance.

3) Accessible and variable enough to stimulate effective generic field research.

The following elements were considered in the detailed site selection process:

- Wind Resource
- Geological Constraints
- Ecological Impacts
- Noise Impacts
- Radio Interference/Television Interference Impacts
- Site Access and Development
- Regulatory Requirements
- Visual Impacts
- Socio - Political Constraints
- Site Acquisition
- Value of Generated Power
- Research and Demonstration Value

The Solano site was selected for installation of PGandE's first large wind turbine[3]. The site has a mean wind speed of 18.5 mph at a 30 foot height averaged over 10 months[2]. The winds were strongest during the months from April through October and blew primarily from the SSW-W directions. Since the site was selected, wind measurements at several levels show the wind speed decreases with height above ground most of the time, sometimes dramatically.

---

[3] Shikuma, Rae M., <u>Siting The First PGandE Wind Turbine Generator</u>, 1981, Pacific Gas and Electric Company, Siting Department.

IV. Machine Selection Process

The competitive bidding process used for wind turbine selection was started before site selection was completed. Four manufacturers responded to the PGandE specification. The winning proposal came from Boeing Engineering and Construction Company (BEC) for a wind turbine (BWT 2560) based on the MOD-2 design. PGandE contracted for the construction and installation of the wind turbine system.

V. Construction and Performance

Construction started in late April 1981. The WT was installed and first rotated in April 1982. System start-up and testing began in April and continued into May. During this period, machine performance data was gathered by BEC and PGandE. The machine did not reach rated power for ten-minute averaged winds over 30 mph. The wind was measured at the 200 foot level (hub height) of a meteorological tower located about 600 feet north of the turbine, along the same ridge perpendicular to the prevailing wind.

On July 30, 1982 the unit was transferred to PGandE's ownership for regular operation and a contract was signed with BEC to keep two WT specialists on site for the next 90 days. Recent performance data is shown in Figure 1. The latest Solano WT status is shown in Figure 2.

VI. Customer - Owned Wind Farms

The two areas identified in PGandE's siting study - Altamont and Solano - have attracted many wind farm developers. Over 470 MW of projects proposed for installation near our Solano site and in Altamont Pass are under contract to PGandE. About 60 MW have been installed, as of September 1, 1983. In 1982, about 3.6 million kilowatthours were generated and sold to PGandE by these independent power producers. Through August 1983, about 25.9 million kilowatthours were produced.

VII. Future Plans

PGandE's wind program calls for:

1) meteorological data collection,

2) gaining experimental knowledge and operational experience on the large horizontal axis BWT 2560,

3) assisting third parties to implement wind electric developments, and

4) cooperating with the utility industry, wind industry manufacturers and government agencies to expedite the advent of truly commercial and competitive wind electric technology.

SOLANO WIND TURBINE PERFORMANCE CURVE

WITH VORTEX GENERATORS

Low Wind Shear (<10%)
Wind Direction 200-290 Degrees

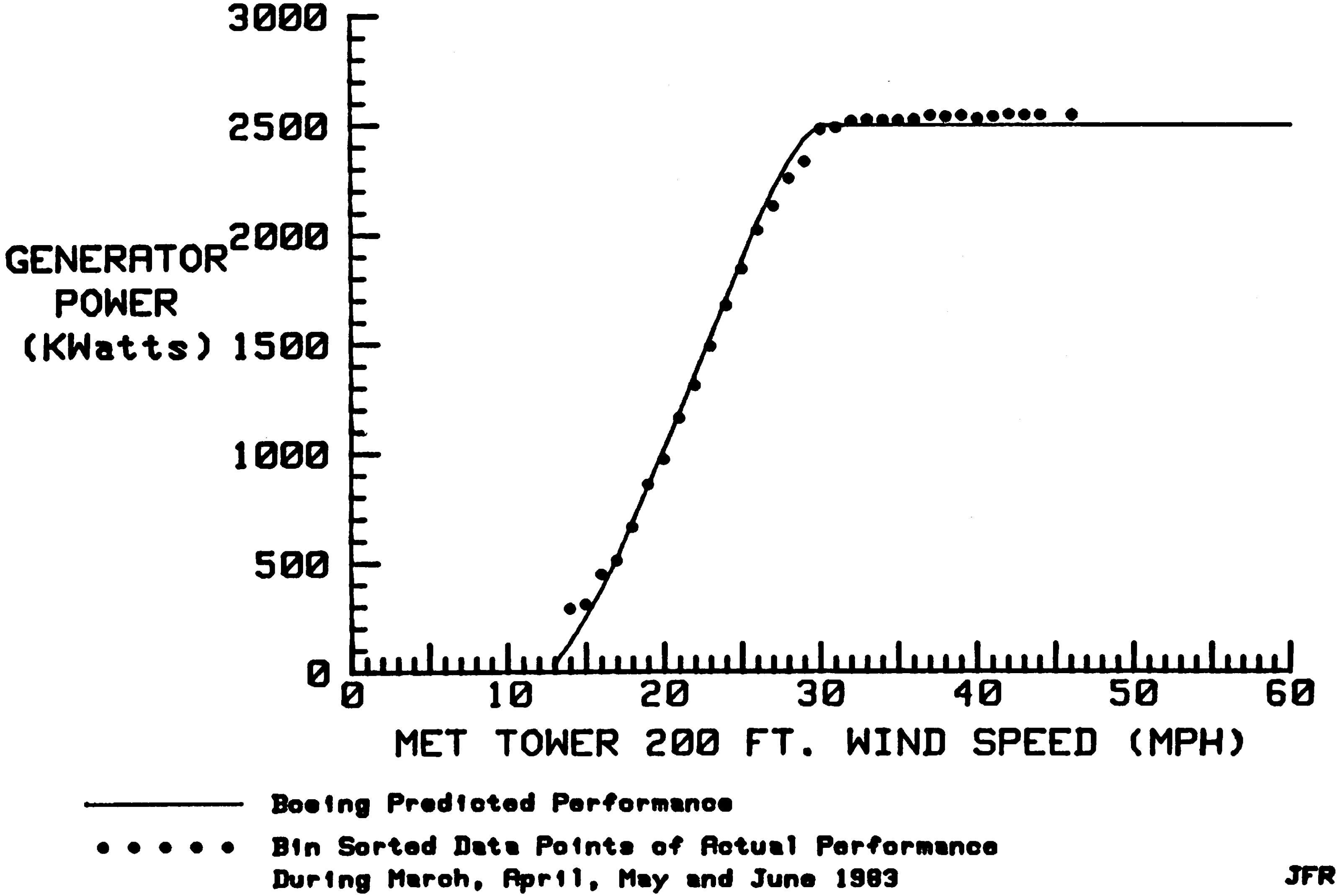


Fig. 1

JFR 7-19-83

Report Issued: OCT 04 1983 Report 420-83.251

Pacific Gas and Electric Company
Department of Engineering Research

SOLANO WIND TURBINE STATUS REPORT No. 30

Reporting Period: 12:05 September 15, 1983 to 11:45 September 30,1983

Operating Statistics for Reporting Period

Time of Bus-Synchronized Operation: 135 Hours
Gross Energy Produced: 232520 Kilowatt-Hours
Net Energy Produced: 231493 Kilowatt-Hours
Max. 5 Min. Ave. Wind Speed during Operation: 40 MPH
Max. 5 Min. Ave. Wind Speed recorded at Site: 43 MPH
Wind Availability during Reporting Period: 259 Hours

Wind Turbine Totals to Date

Bus-Synchronized Operation: 1012 Hours
Hours of Rotation: 1089 Hours
Gross Energy Produced: 1,665,014 Kilowatt-Hours

Operating Notes:

1. The wind turbine has been in normal operation for this two week period.

2. One of the small wires on the low speed shaft (LLS) crack detection system was accidentally separated while replacing a bracket on the LLS. This resulted in a wind turbine shutdown for a weekend until the crack detection system could be repaired

Fig. 2

Hugo Mühlöcker

Electrical Concept of GROWIAN 1 and first Experience

The construction and trial operation of GROWIAN 1 is being carried out by an association set up for this purpose and known as the "Große Windenergieanlagen Bau- und Betriebsgesellschaft" founded by the power utilities HEW, SCHLESWAG, RWE. The GROWIAN 1 program is financed from funds of the Federal Ministry for Research and Technology, represented by the Jülich Nuclear Research Station, Energy Research Project Management.

Under the leadership of MAN-Neue Technologien, which is supplying the nacelle and the turbine, Siemens AG was commissioned to plan the complete electrical installation for the GROWIAN 1 prototype.

Figure 1

The GROWIAN 1 wind-power plant is among the world's largest projects for the utilization of wind energy.

At the end of 1983 it is due to go into trial operation at the Kaiser Wilhelm Polder on the Lower Elbe.
With a power rating of 3 MW, GROWIAN 1 will feed power into the public supply system. It will be used to investigate the technical and economic preconditions for the utilization of wind energy for electricity generation in the Federal Republic of Germany.

Figure 2

A double-blade horizontal axis wind turbine with a rated speed of 18.5 rev/min was selected in 1978 for the GROWIAN 1 project. This wind turbine has an overall diameter of 100.4 m with a tower height of 100 m and has an electrical rating of 3 MW.

It is designed to generate electricity starting from a wind velocity of 6 m/s (about force 4). Rated power of 3 MW is attained at 12 m/s (V_N). At wind velocities above V_A = 24 m/s (force 9) the plant is automatically shut down.

When in service at its intended location, GROWIAN 1 will supply around 12 GWh of energy a year.

Figure 3

Fig. 3 shows the single line diagram of GROWIAN 1 equipped with a double-fed asynchronous generator which feeds power to the system via two 20 kV ring mains, of which only one is normally in operation. The transmission transformer makes it possible to operate the generator at 6.3 kV - a favourable voltage for a machine of this rating - irrespective of the voltage level of the medium voltage system. A switchover facility is provided in the rotor circuit. To prevent overloading of the converter, upon unacceptable acceleration of the turbine by strong gusts of wind the generator is switched to asynchronous operation, a resistor taking the place of the converter in the rotor circuit.

It must be borne in mind that DC voltage is applied to the switchgear in the rotor circuit during synchronous operation. In the normal operating range the generator produces an AC voltage of variable frequency from 0 to 5 Hz, which can rise dynamically to 7.5 Hz and in overload operation in the asynchronous range the frequency rise to as much as 25 Hz.

In order to limit the number of sliprings used to transmit power across the swivel joint, separate station-service supplies are provided to the machine room and to the operations building and stationary part of the tower. In both these locations separate DC equipment and AC busbars with uninterruptible supply are installed, e.g. for control and monitoring. A diesel generator set is also on hand to limit the battery size and supply vital loads in the event of prolonged power system failures.

Figure 4

In view of its relatively low power output and the distance from the nearest dispatching centre, it was decided that GROWIAN should operate fully automatically. Depending on the wind velocity, which is detected by the wind vane, the plant must automatically be switched on and off and the nacelle turned into the wind.

As with the station-service supply, so the whole monitoring and control system is divided as far as possible into a section assigned to the nacelle and a section assigned to the tower and operations building. In this respect it is necessary for the monitoring and control equipment concentrated in the machine room to be so designed that all vital monitoring and control functions for shutting down the generator remain operative in the event of a slipring fault.

The control station in the switchgear room is the heart of GROWIAN. From here electrical and mechanical control of the wind-power plant can be carried out by hand or automatically. All monitoring and control circuits are brought together at this control station.

The electrical concept of GROWIAN 1 is mainly determined by use of the double-fed asynchronous machine as generator and a converter controlled variable speed asynchronous motor for blade pitch control. As this type of equipment is used for the first time in a large wind power plant I will concentrate my presentation to this two items only.

Figure 5

The main spindle of the blade pitch drive is directly coupled to 4-pole asynchronous motor of 70 kW rated output, which is connected via sliprings to static frequency converter with DC link. The motor is designed for short-time overloads and for producing torque at standstill condition too. Therefore the converter is designed with 140 kVA input. As it is necessary to bring the blades in feathered position even without 3-phase auxiliary network the DC link is connected to a battery of special design for motor operation and with a thyristor controlled braking resistor for generator operation of the motor.

Figure 6

Figure 6 + 7 show two oscillograms each taken in our factory testing field. In figure 6 for both cases the motor was operated with constant counter moment when the 3-phase voltage was switched away. Only the overload condition shows some deviations in the motor speed after 3-phase voltage disconnection and re-connection.

Figure 7

This figure shows the oscillograms with heavy variations of the counter moment. One with speed 350 r.p.m. and one with zero speed. The later is specially scaled for motor speed deviation. It shows that the battery buffering works well even under standstill condition of the motor.

Measurements at site during the present no-load test runs of the GROWIAN 1 have confirmed the factory test results.

I will now step over to the main machine of the GROWIAN 1 the double-fed asynchronous generator.

Figure 8

As can be seen from the operating diagram a machine had to be selected as a generator which permits speed flexibility within a certain range. After the advantages and disadvantages had been considered, preference was given to double-fed asynchronous machine with a frequency converter in the rotor circuit against a synchronous machine with a frequency converter in the stator circuit. In operation within a given speed range, this machine can supply a constant frequency at the stator terminals. Hence, the vector of the magnetic flux in the stator rotates at a speed proportional to the frequency of the power system. By suitable control of the converter frequency, a condition is produced whereby the sum of the frequency proportional to the mechanical speed and the frequency of the converter is always equal to the power system frequency. As a result of this type of excitation, the asynchronous machine behaves in a similar manner to a synchronous machine. This enables the requirements regarding constant system frequency and uniform active power to be met, since intermediate storage in the rotating masses takes place during speed variations.

Apart from the losses in the converter transformer, the converter and the rotor winding, the slip power in supersynchronous operation is fed to the power system via the converter and added to the stator power. In subsynchronous operation, the slip power is subtracted from the stator power. This produces the slip-proportional limit lines shown in the operating diagram for the active power supplied to the system.

The switchover facility in the rotor circuit, shown in figure 3, allows the generator to remain connected to the system during short-time asynchronous operation. In this case the generator supplies a sharp increase of active power due to the sudden acceleration. The rise in active power serves in turn to brake the generator.

Naturally, the system has to cover the generator reactive power during the brief period of approximately 0.5 min of this operating state. Simultaneously with the asynchronous operation, the blades are feathered, thus reducing the power from the wind to zero. When the speed for rotation is sufficiently low the asynchronous generator is separated from the system.

Figure 9

The cycloconverter in the rotor circuit comprises three reversible converters each with two six-pulse three-phase bridges in circulating current-free inverse parallel connection. One of these reversible converters is shown in figure 9. It represents one phase of the converter system starting from the 6 kV/50 cps feeder down to the rotor terminals.

Growian, unlike some earlier projects, has been equipped with an advanced modular control system which has already proved successful in other drive applications. In the new system the neutral points of the rotor and cycloconverter are not connected; therefore the sum of the three rotor currents is always zero.

Figure 10

The firing angle of each reversible converter is changed constantly so that a sinusoidal current of the required frequency is produced at the output. One of the reversible converters in the cycloconverter converts the three-phase supply-system voltage to single-phase of a different frequency directly without a DC link. The output frequency is always lower than the input frequency of the converter, the output generally being less than 50 % of the input.

The output currents of the three reversible converters are displaced at 120° from each other and form a three-phase system of controlled frequency. The current of each reversible converter is controlled by a current controller. The rotor currents are impressed so as to be oriented to the flux; the control for this is called field-oriented control. The field-oriented control system issues set points to the current controllers of the reversible converters and also forms the converter output frequency, i.e. the slip frequency of the rotor, from the supply-system frequency and the speed. In addition, depending on the master control values issued by the voltage regulator and active-power controller the amplitudes of the rotor currents and their phase angle to the cycloconverter output voltage are formed and appropriate set points at 120° apart issued to the current controllers.

The field-oriented control system incorporates a controller operating with d.c. variables, thus ensuring symmetry and a good sinusoidal form for the three rotor currents. The converter output voltages, referred to the converter neutral point, are controlled to trapezoidal form so that the utilization of the reversible converters is better and the cycloconverter requires less reactive power. The phase voltages in the rotor are sinusoidal.

By altering the phase angle between the cycloconverter output voltage and the rotor current it is possible to vary the active power and reactive power of the double-fed asynchronous generator independently of each other. The link between the two values is so small that it can be neglected. In relation to the supply system the double-fed asynchronous generator behaves similarly to a synchronous generator.

The double-fed asynchronous generator including cycloconverter and converter-transformer had been installed in our factory test field for some weeks of operation tests prior to site installation. As driving unit we used a calibrated variable speed dc-motor. In the next figures I will show some of the test results.

Figure 11

This figure shows the no-load and short-circuit saturation characteristics of the double-fed asynchronous generator at converter operation. Over the whole operating speed range the curves show nearly unchanged the characteristic typical for a synchronous machine.

Figure 12

This figure shows the no-load voltage of the 3 stator phases at three different speeds. There is no serious change of the wave shape deviations for the different rotor speeds.

Figure 13

This figure shows synchronization tests: one with fail angle and voltage difference between generator and grid and one without these differencies. The reaction of stator current and reactive power output are as usual for synchronous machines.

Figure 14

These two oscillograms show reaction on reactive power impulses at nearly synchronous speed and at -10 % slip condition. It is shown that reactive power impulses have no influence on active power output independent from load and speed condition of the generator.

Figure 15

These two oscillograms show reaction on active power impulses of different height. It is shown that active power impulses have no influence on the reactive power output of the generator.

Besides this it is shown how the rotor frequency is changing with speed alteration due to the active load change, as the speed control of the dc-motor did not act fast enough.

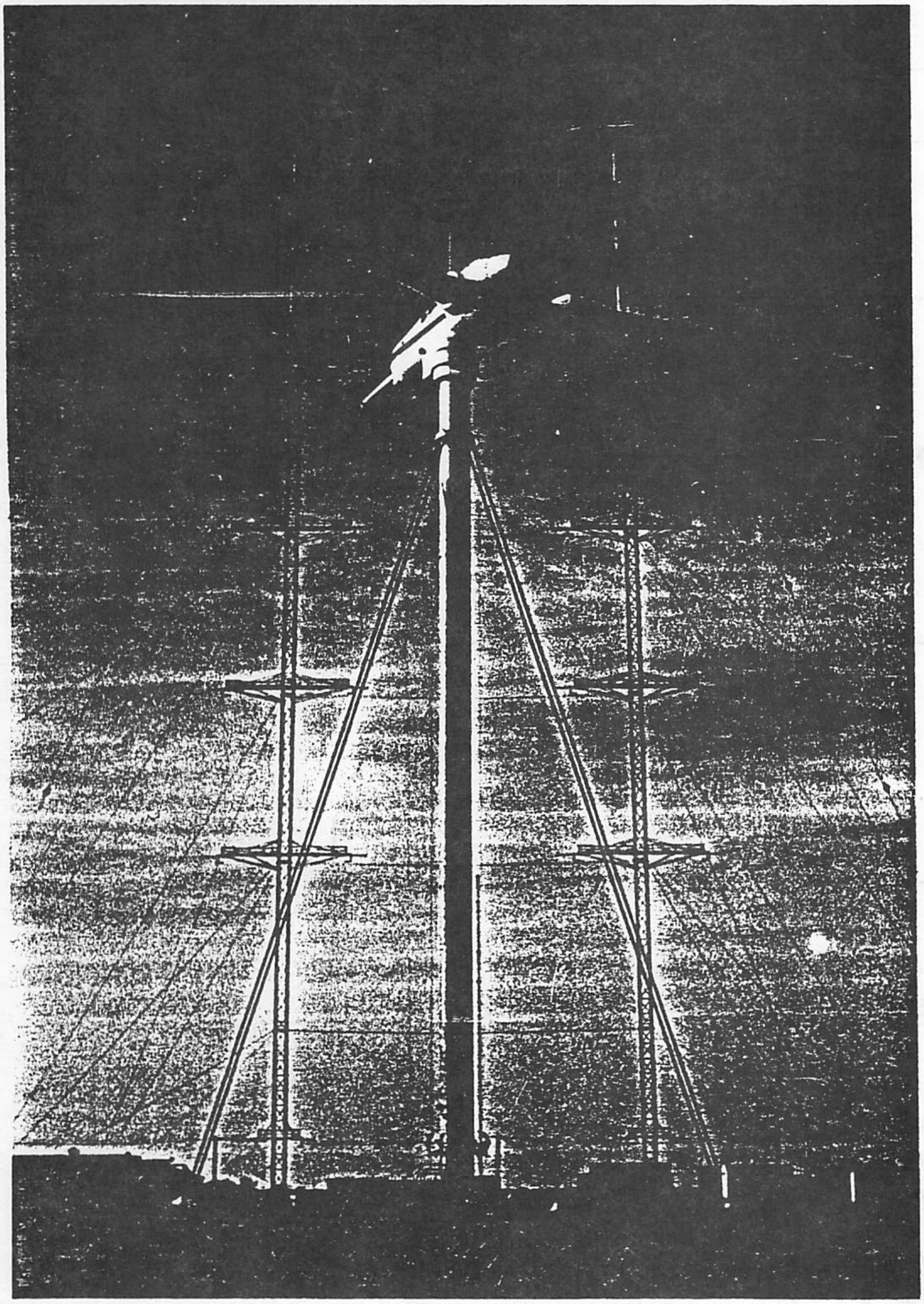
Figure 16

This figure shows efficiency curves at different speed and power factor. Not included are power consumption of the external air circuit fans of the generator and the cycloconverter including auxiliary power supply of the control system. As expected a good efficiency for partial loads was reached. The efficiency curves at synchronous speed are taken at partial loads only, as the GROWIAN-converter and converter transformer are not designed for continuous rated power output at this operating point.

COMPARISON OF WIND-POWER PLANTS

	UNIT	GROWIAN/F.R.G.	MOD-2/US	NÄSUDDEN/SW	MAGLARP/SW
TYP OF HUB	-	TEETERED	TEETERED	STIFF	TEETERED
RATED SPEED	R P M	18.5 (± 15 %)	17.5	25	25
ROTOR DIA.	M	100.4	91.44	75	78
HIGHT OF HUB	M	100	61	77	80
WEIGHT OF ROTOR AND NACELLE	T	380	171	205	191
WEIGHT OF TOWER	T	332	113,8	1500	281
TYP OF GENERATOR	-	DOUBLE-FED ASYNCHRONOUS WITH WOUND ROTOR	SYNCHRONOUS	ASYNCHRONOUS WITH SQUIRREL CAGE ROTOR	SYNCHRONOUS
RATING	KW	3000	2500	2000	3000
AT WIND SPEED	M/S	2.0	12.07	12.5	14.0
POWER PRODUCTION	MWH/A	12,000	12,000	6,000	8,000

FIG. 1



SITE:

Standort: Brunsbüttel

Große Windenergieanlage 3 MW (GROWIAN)
gefördert vom Bundesministerium für Forschung und Technologie

LARGE WIND-POWER PLANT

PROMOTED BY MINISTRY OF RESEARCH AND TECHNOLOGY

FIG. 2

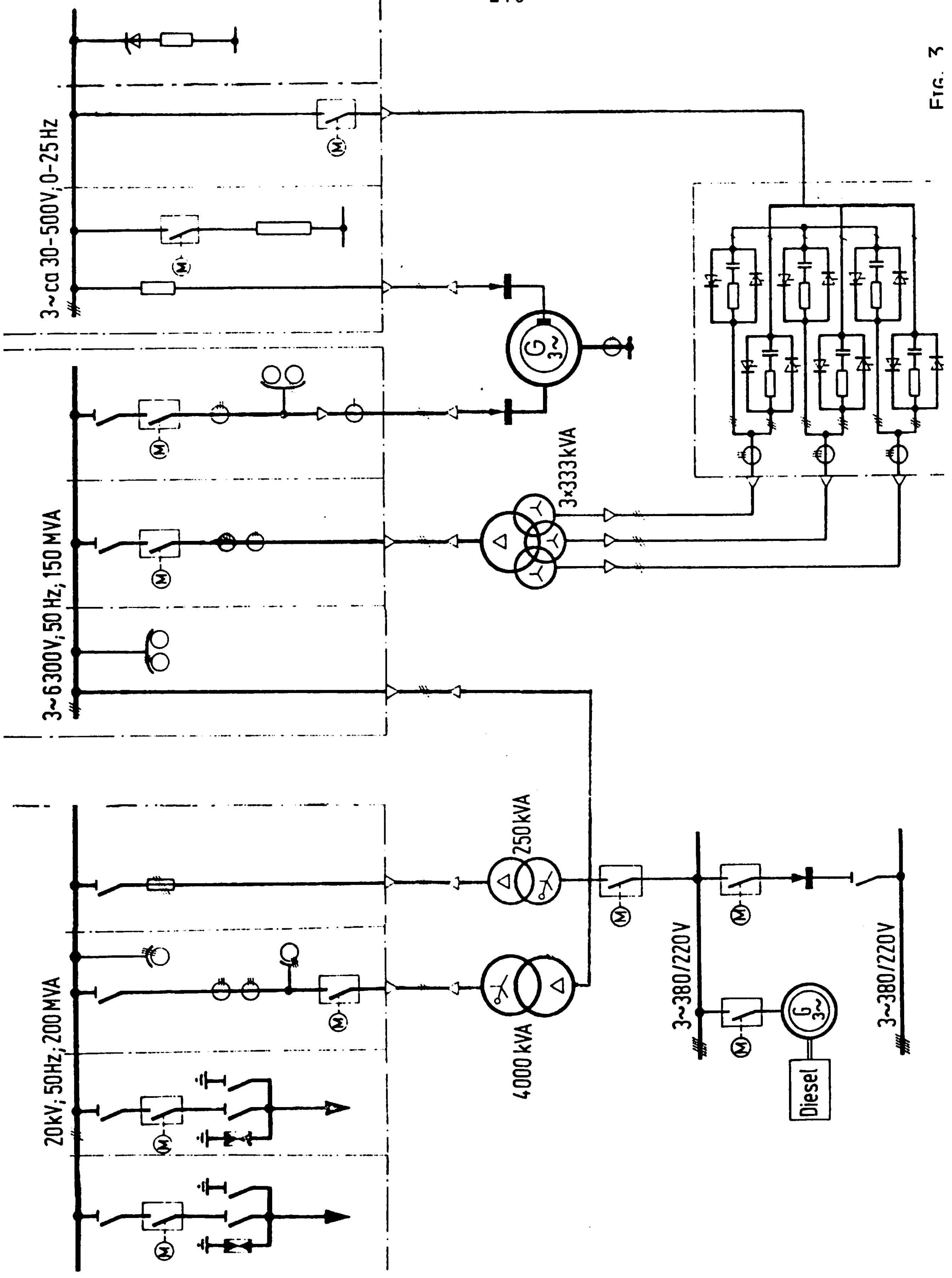
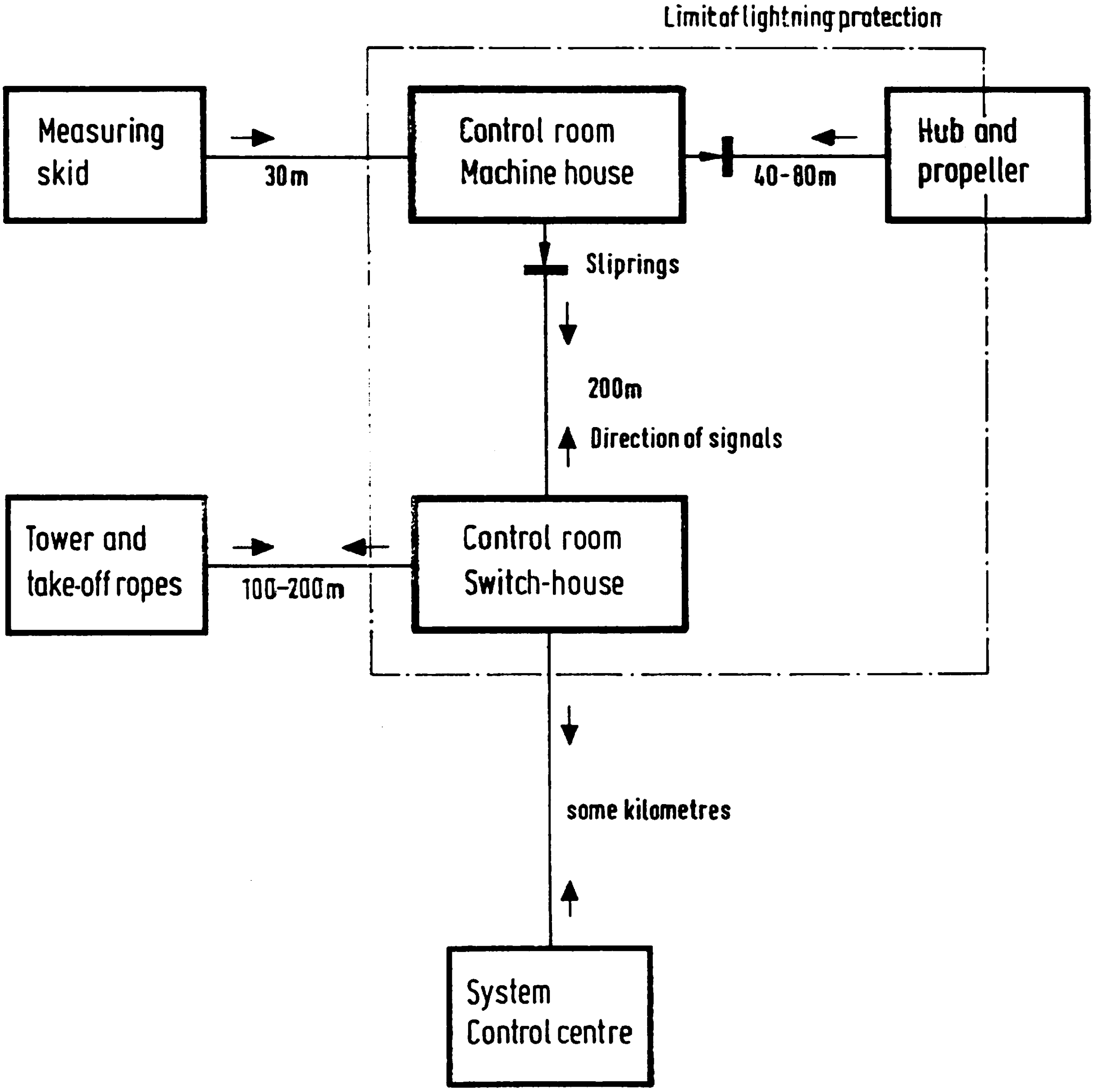
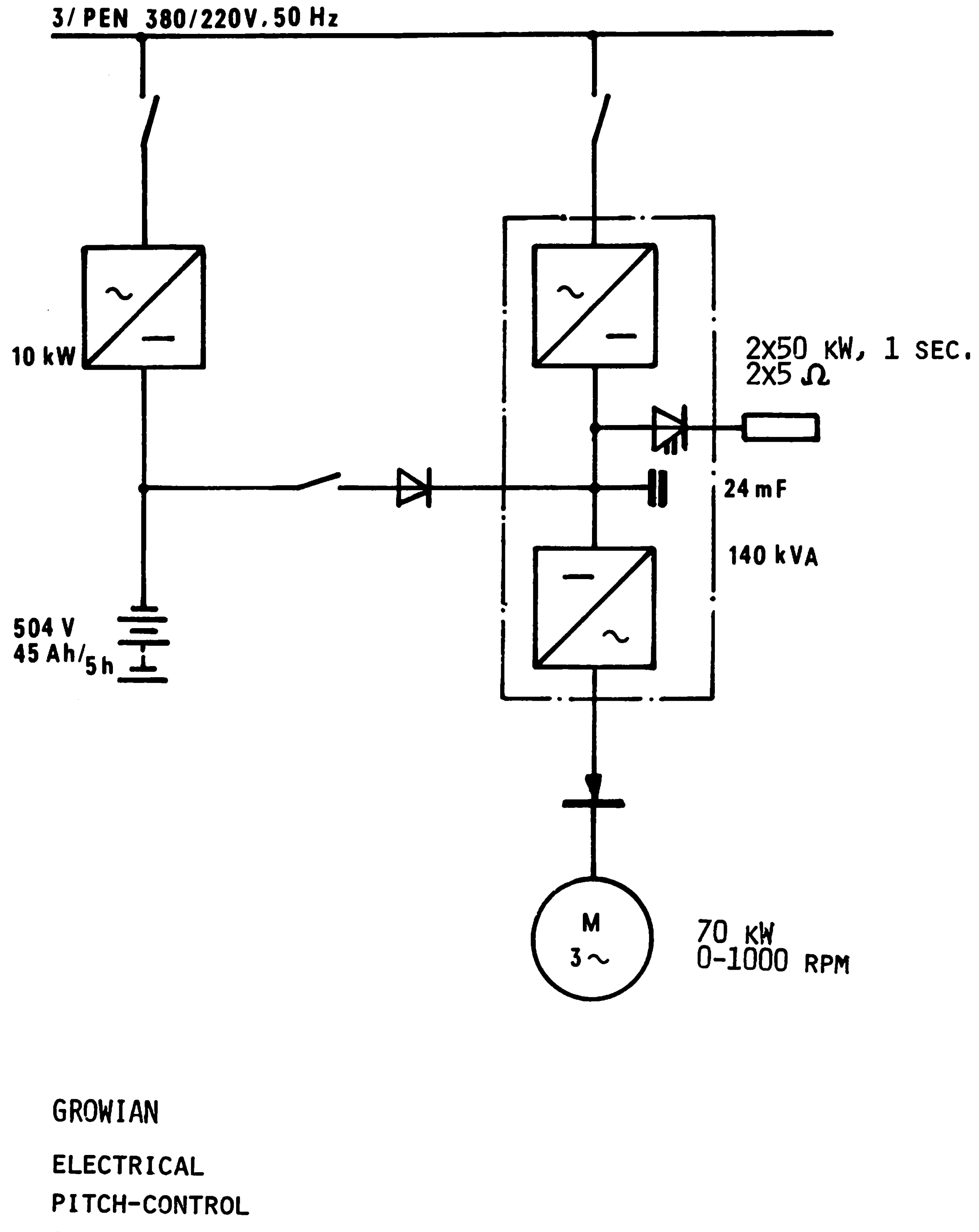

3~ca 30-500V; 0-25Hz
3~6300V; 50Hz; 150MVA
20kV; 50Hz; 200MVA
3×333kVA
250kVA
4000kVA
3~380/220V
3~380/220V
Diesel
G 3~
M

FIG. 3



Supervision schema

FIG. 4



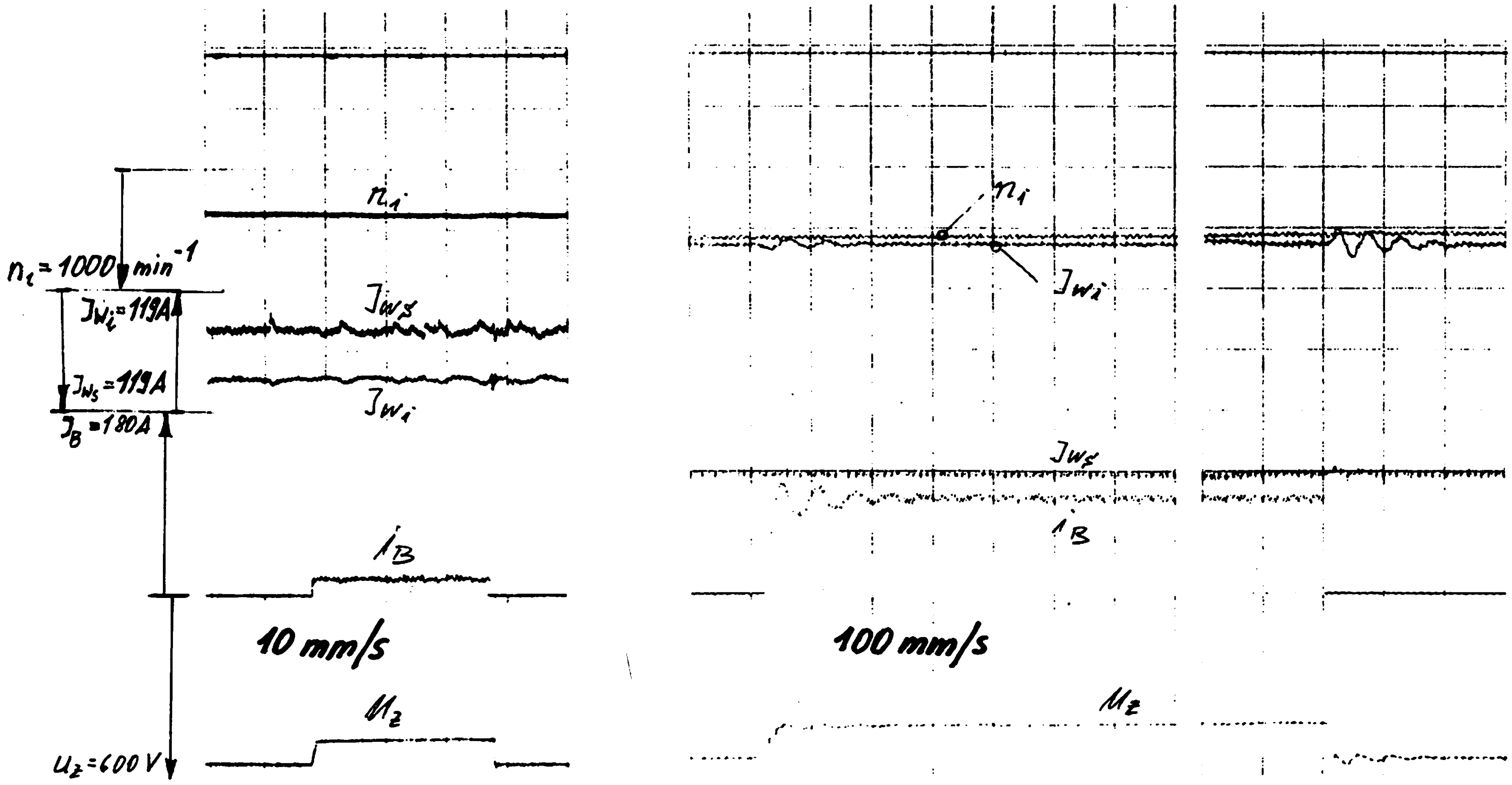
GROWIAN

ELECTRICAL
PITCH-CONTROL
SYSTEM

FIG. 5

ELECTR. PITCH CONTROL SYSTEM GROWIAN

BATTERY BUFFERING AT CONSTANT COUNTER MOMENT

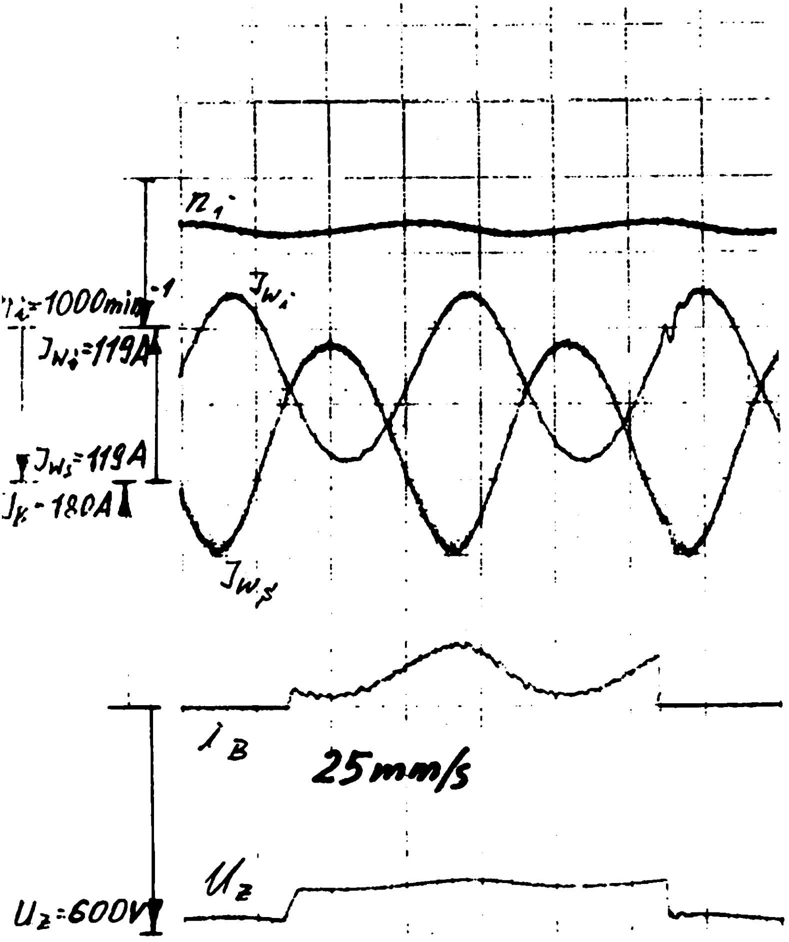


M = 1/3 M_N, N = 400 RPM

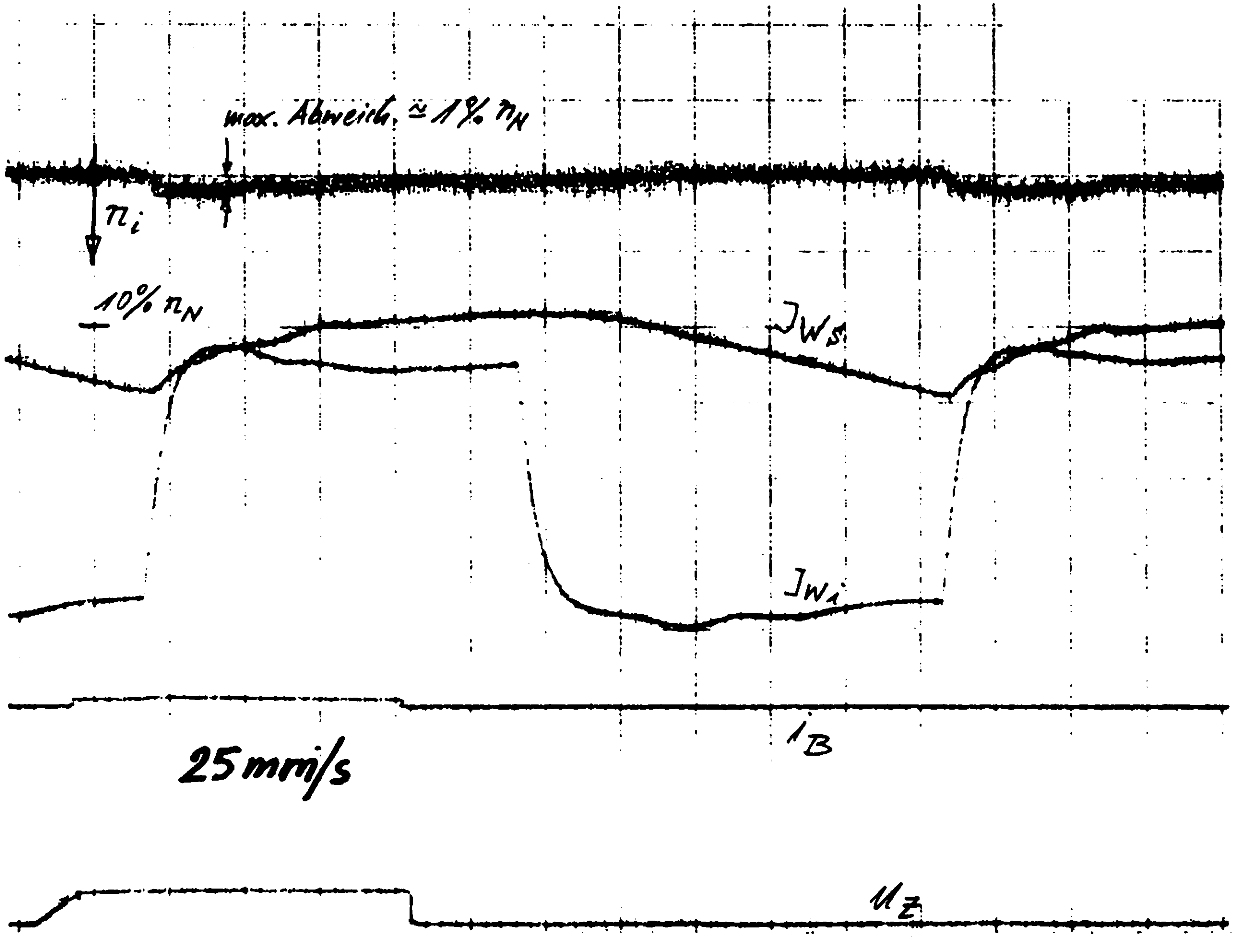
M = 1,5 M_N, N = 600 RPM

ELECTR. PITCH CONTROL SYSTEM GROWIAN

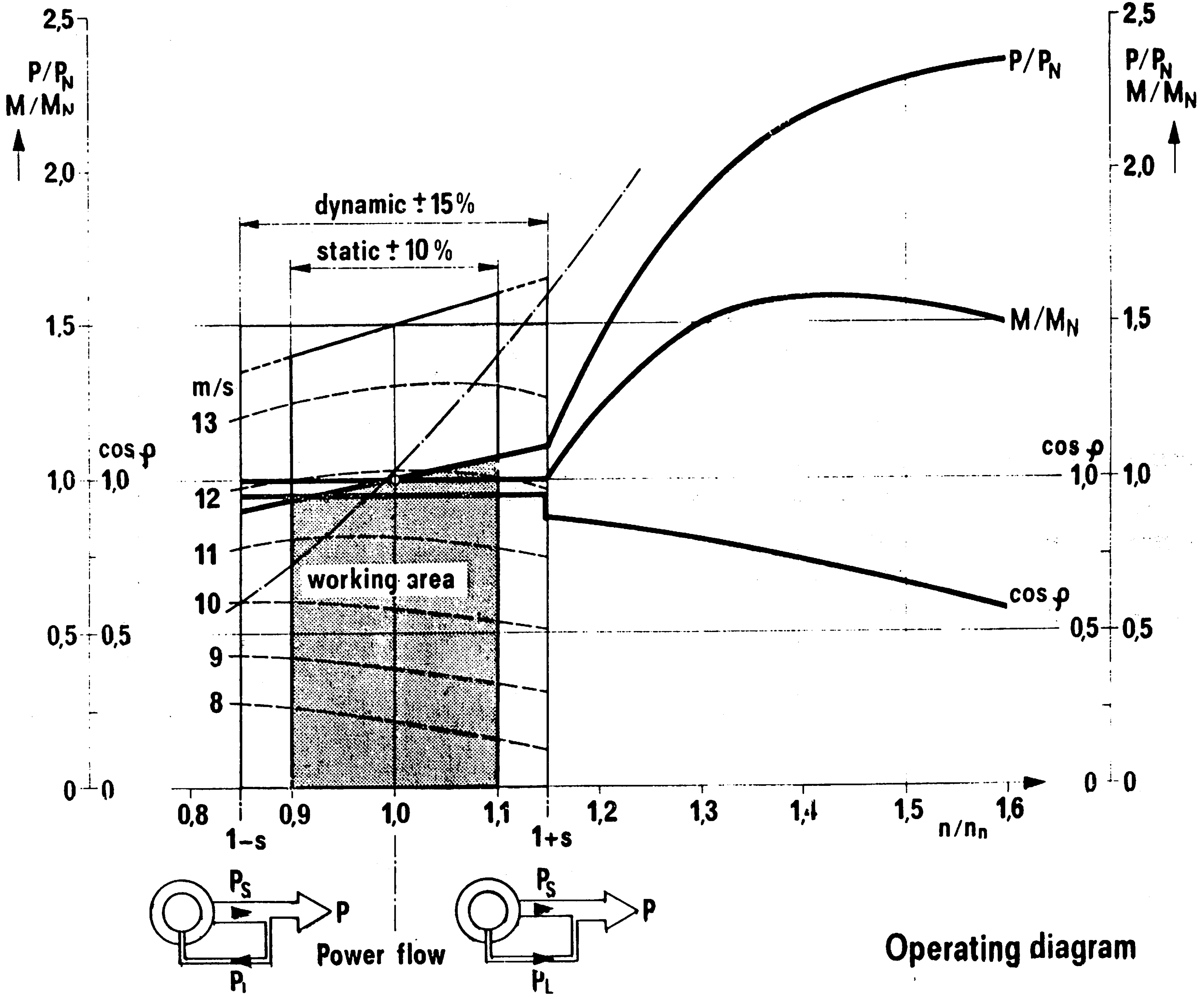
BATTERY BUFFERING AT ALTERNATING COUNTER MOMENT



M = 3/4 M_N ± 3/4 M_N, N = 350 RPM

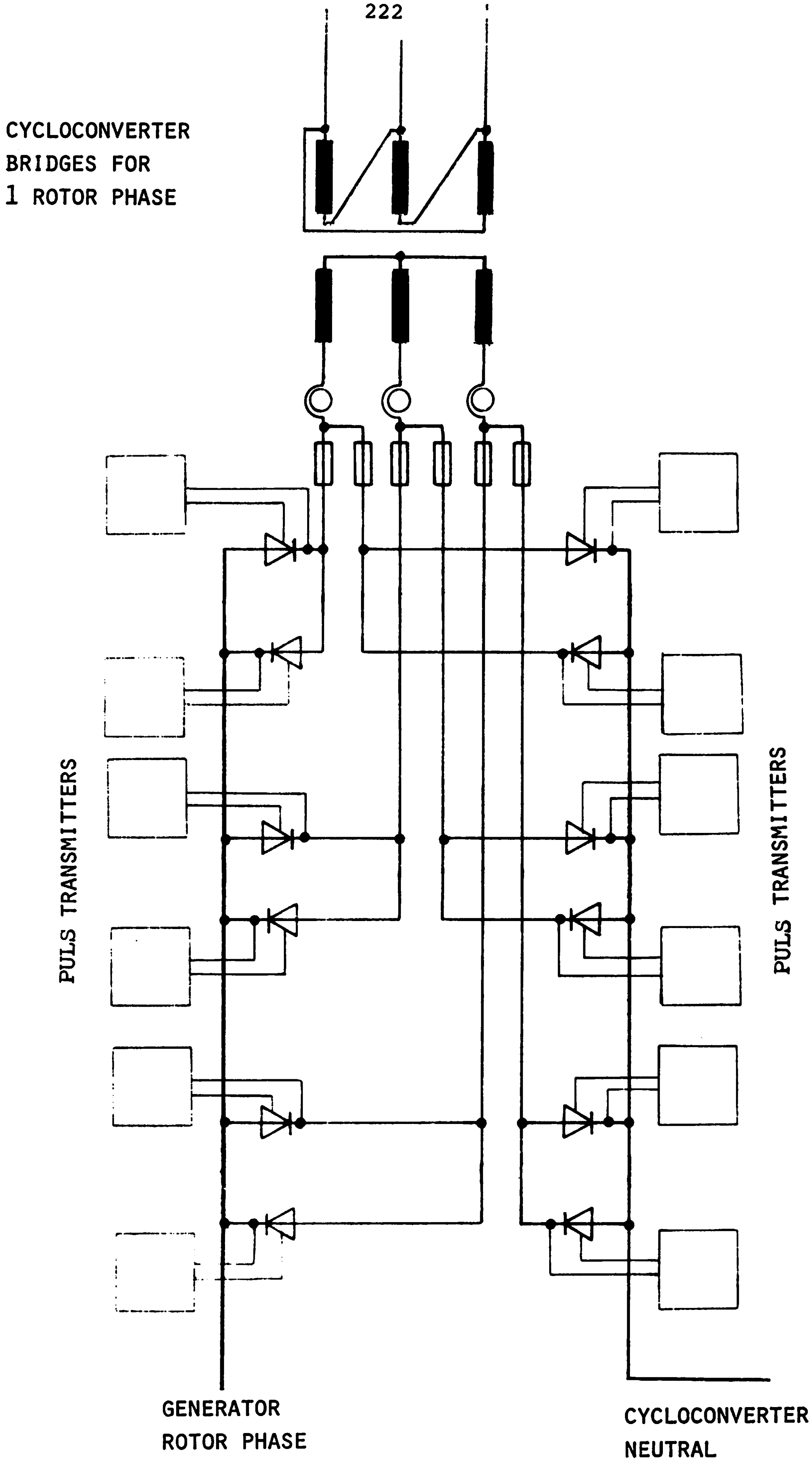


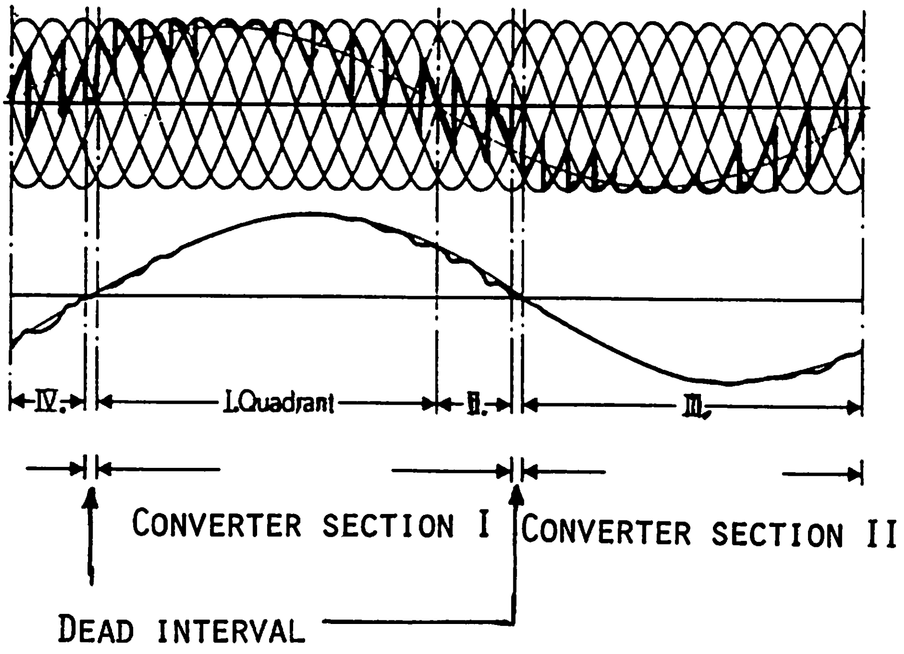
M = 3/4 M_N ± 1/4 M_N, N = 0 RPM



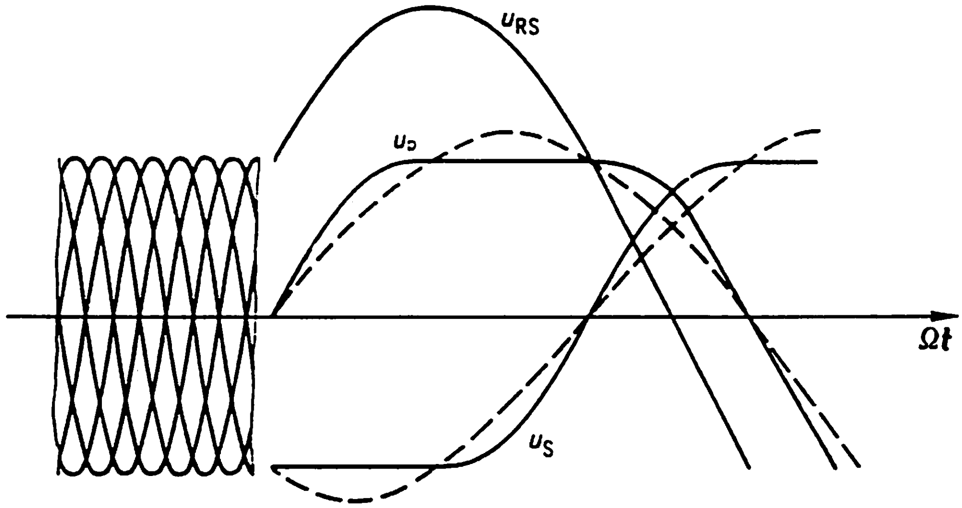
Operating diagram

FIG. 8


CYCLOCONVERTER
BRIDGES FOR
1 ROTOR PHASE
PULS TRANSMITTERS
PULS TRANSMITTERS
GENERATOR
ROTOR PHASE
CYCLOCONVERTER
NEUTRAL



OUTPUT VOLTAGE WAVEFORM OF A CYCLOCONVERTER



U_R, U_S STAR VOLTAGE

U_{RS} CONDUCTOR VOLTAGE

OUTPUT VOLTAGES DURING TRAPEZOIDAL-WAVE OPERATION

FIG. 10

NO-LOAD- AND SHORT CIRCUIT SATURATION CHARACTERISTIC OF THE DOUBLE-FED ASYNCHRONOUS GENERATOR

GROWIAN

AT CONVERTER OPERATION

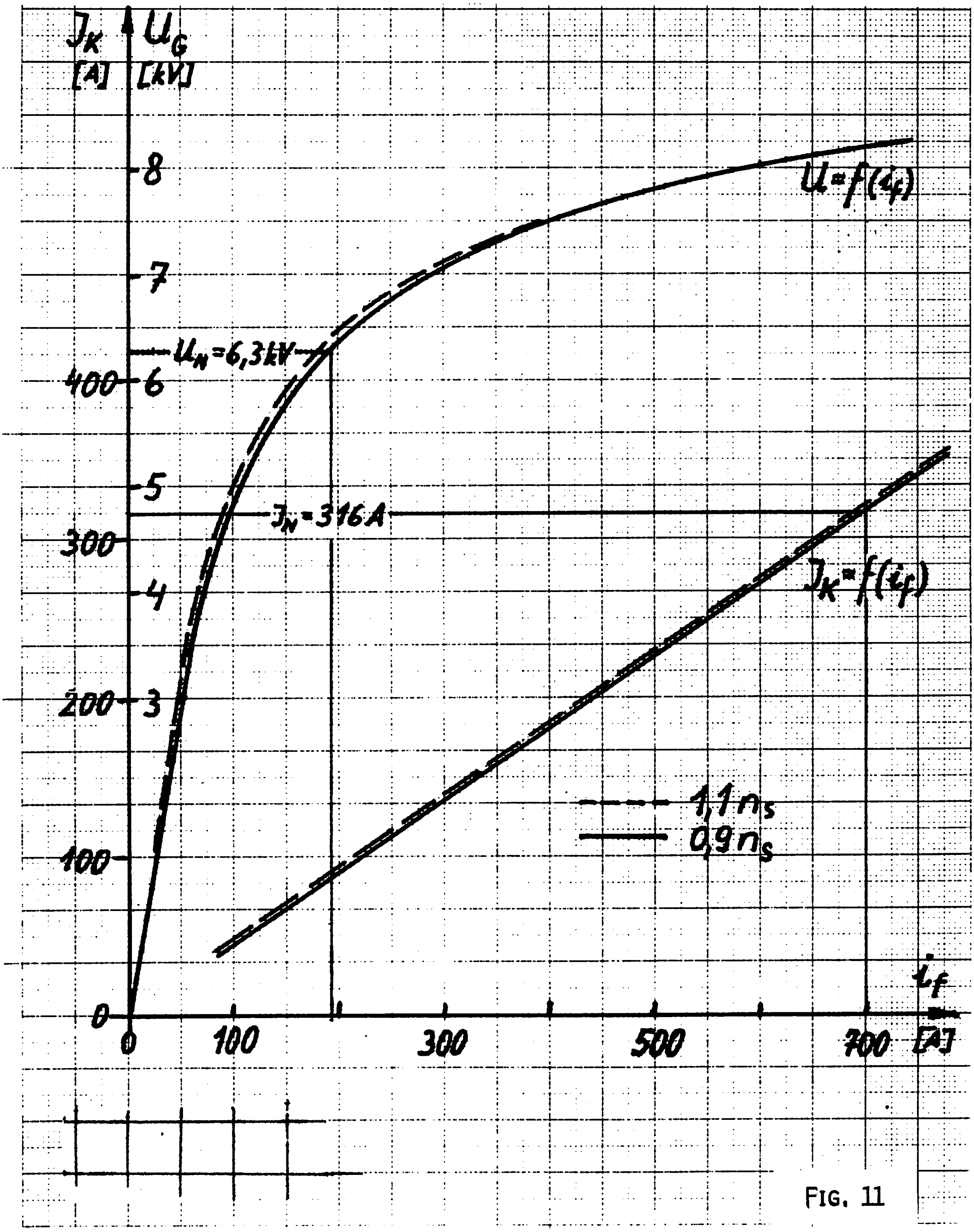


FIG. 11

DOUBLE-FED ASYNCHRONOUS GENERATOR

NO-LOAD VOLTAGE $U = U_N$

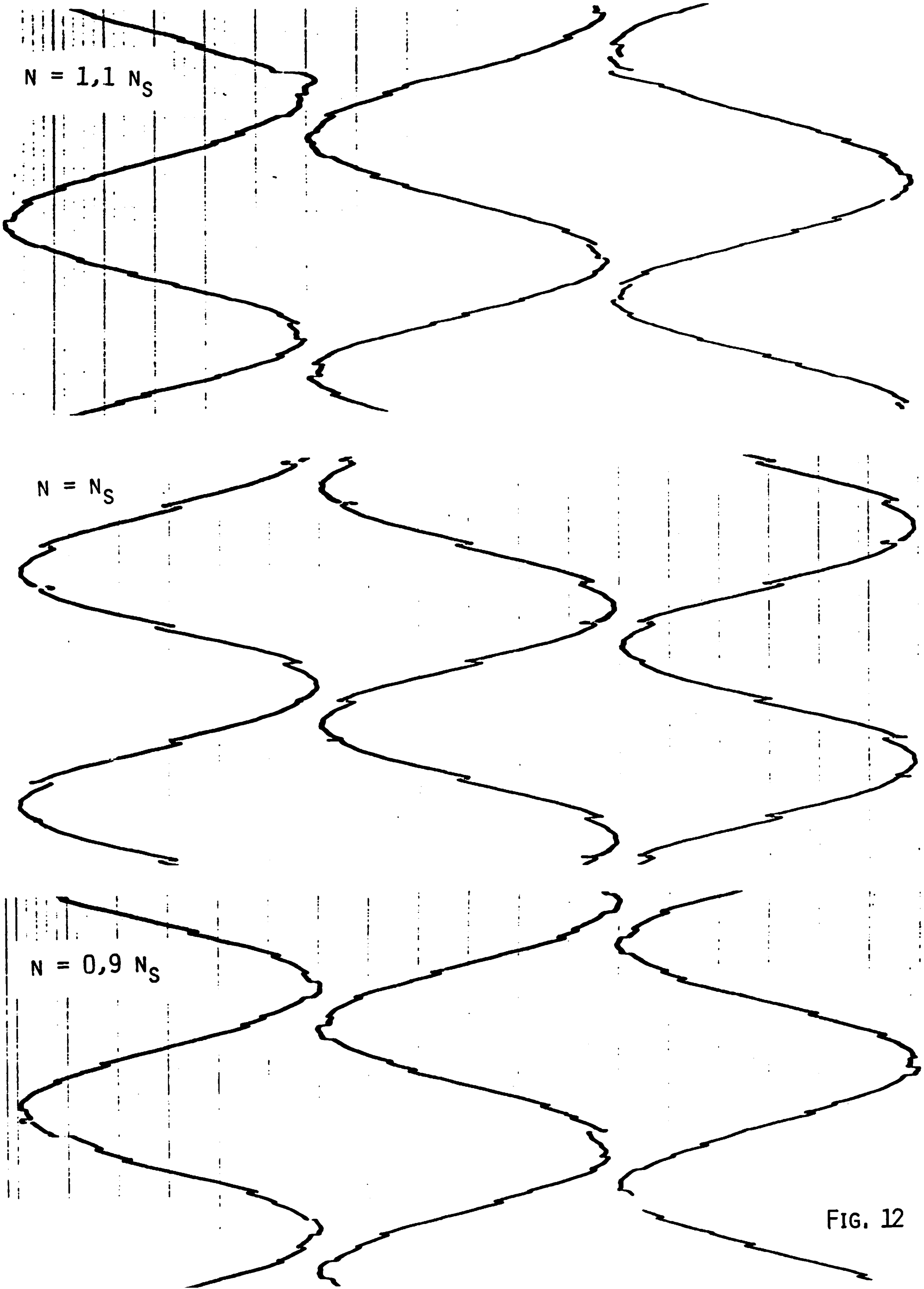
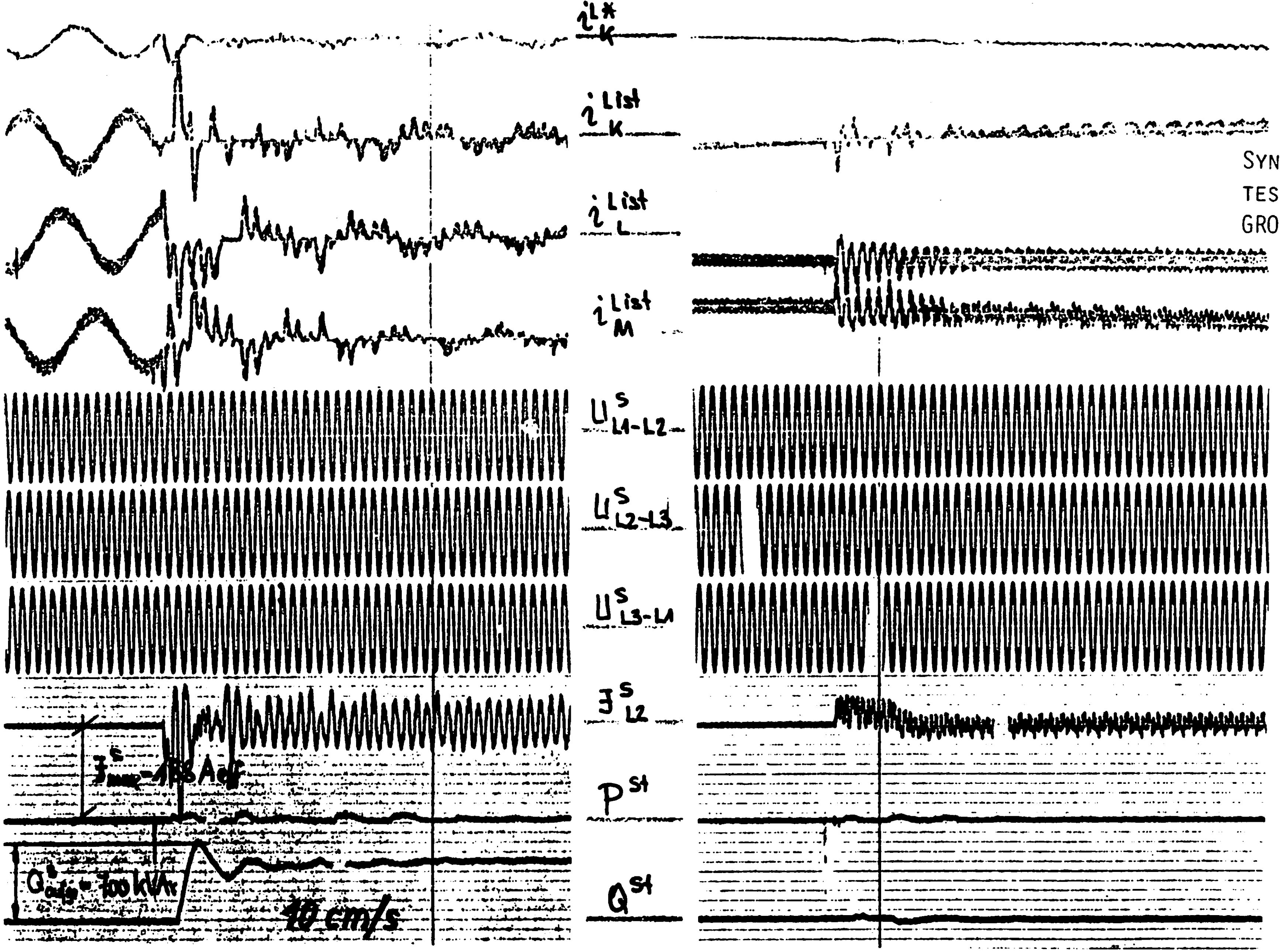


FIG. 12

$N = 0{,}9\ N_S,\ U_G = 0{,}95\ U_{GRID},$ [illegible]

$N = N_S,\ U_G = U_{GRID},$ [illegible] $= 0^0$



SYNCHRONIZATION
TESTS
GROWIAN

FIG. 13

DOUBLE-FED ASYNCHRONOUS GENERATOR GROWIAN, REACTIVE POWER IMPULSES

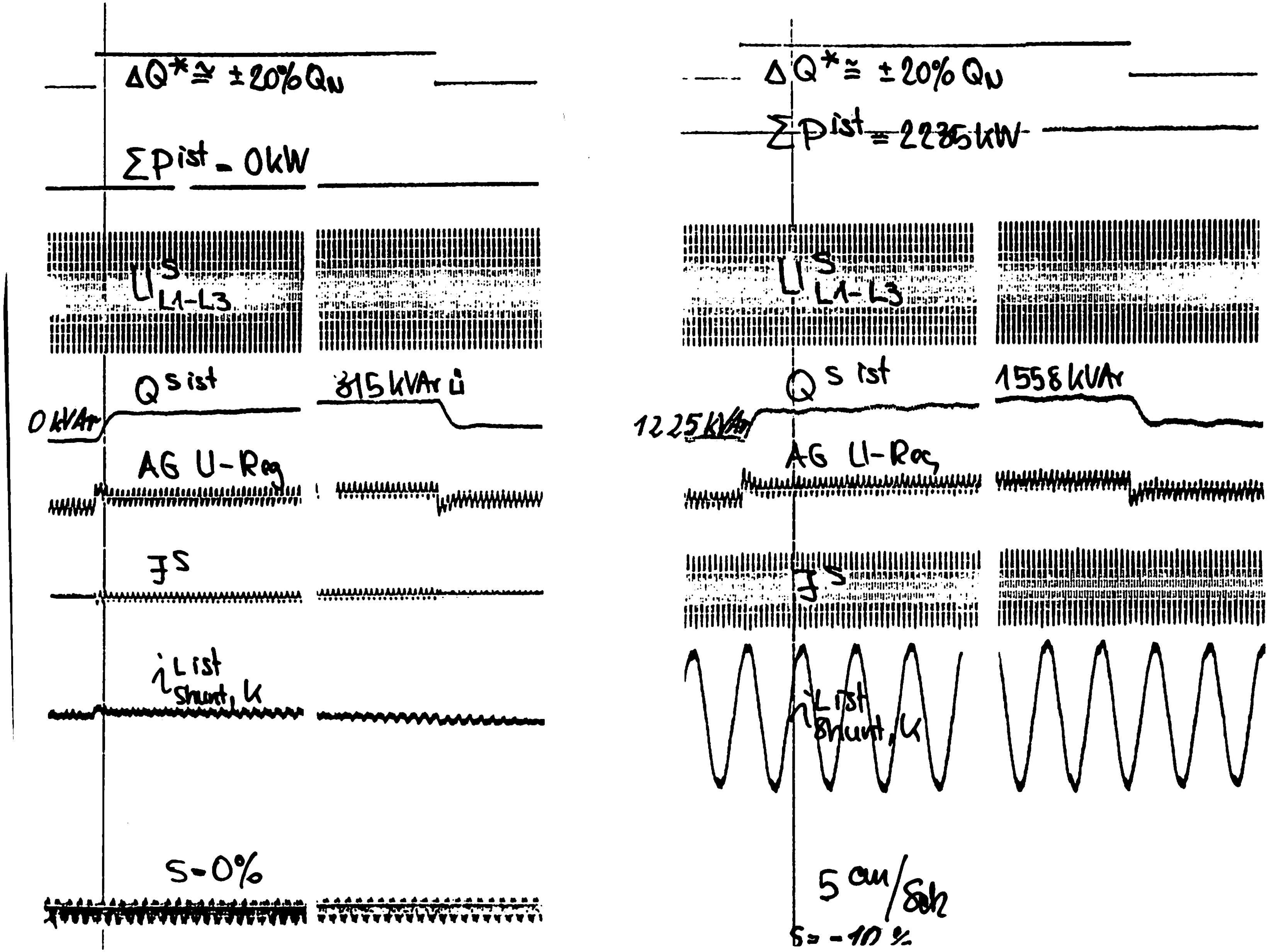


FIG. 14

DOUBLE-FED ASYNCHRONOUS GENERATOR, GROWIAN, ACTIVE POWER IMPULSES

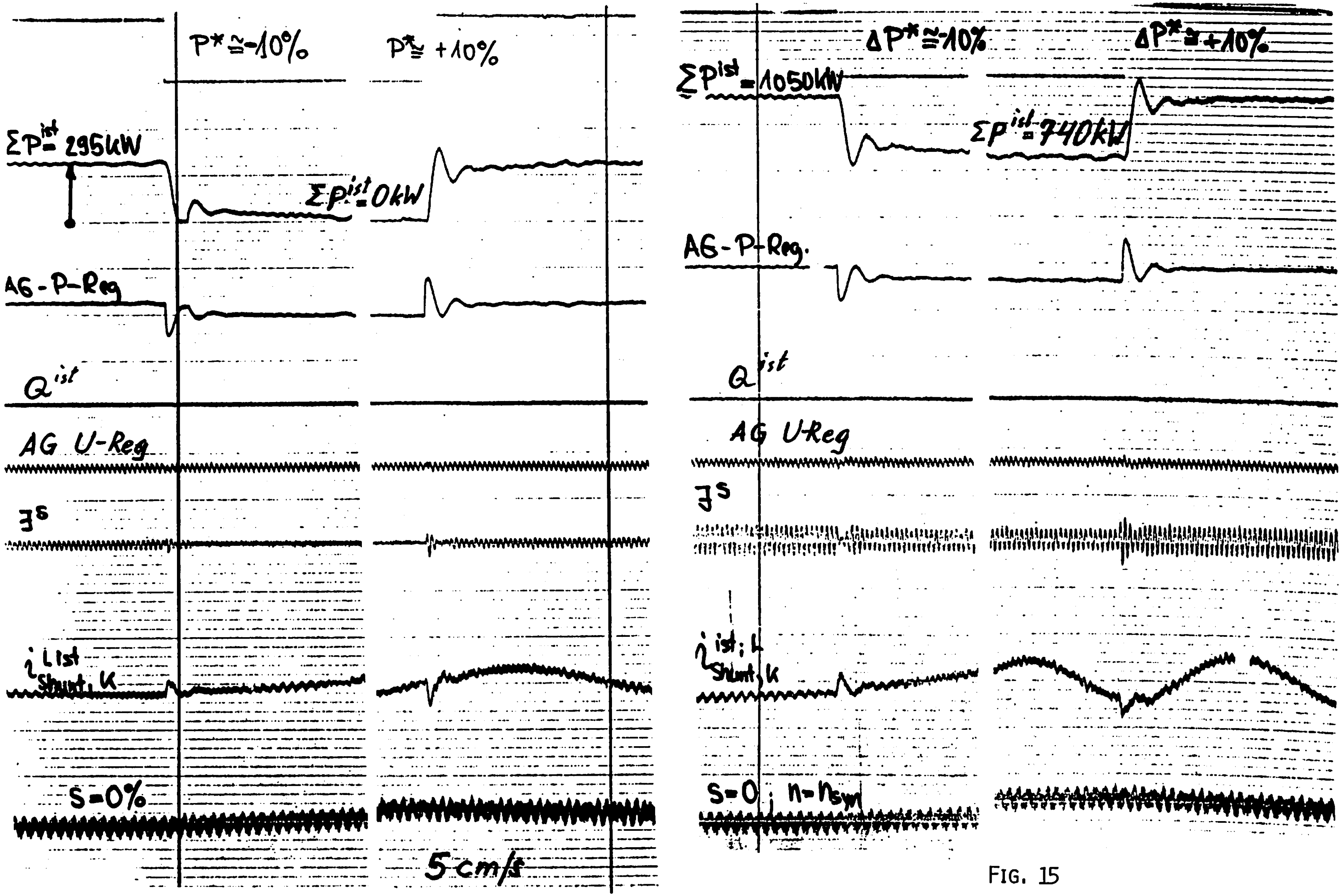


FIG. 15

EFFICIENCY CURVES OF THE DOUBLE-FED ASYNCHRONOUS GENERATOR

GROWIAN P_N = 3030 KW N_S = 1500 RPM

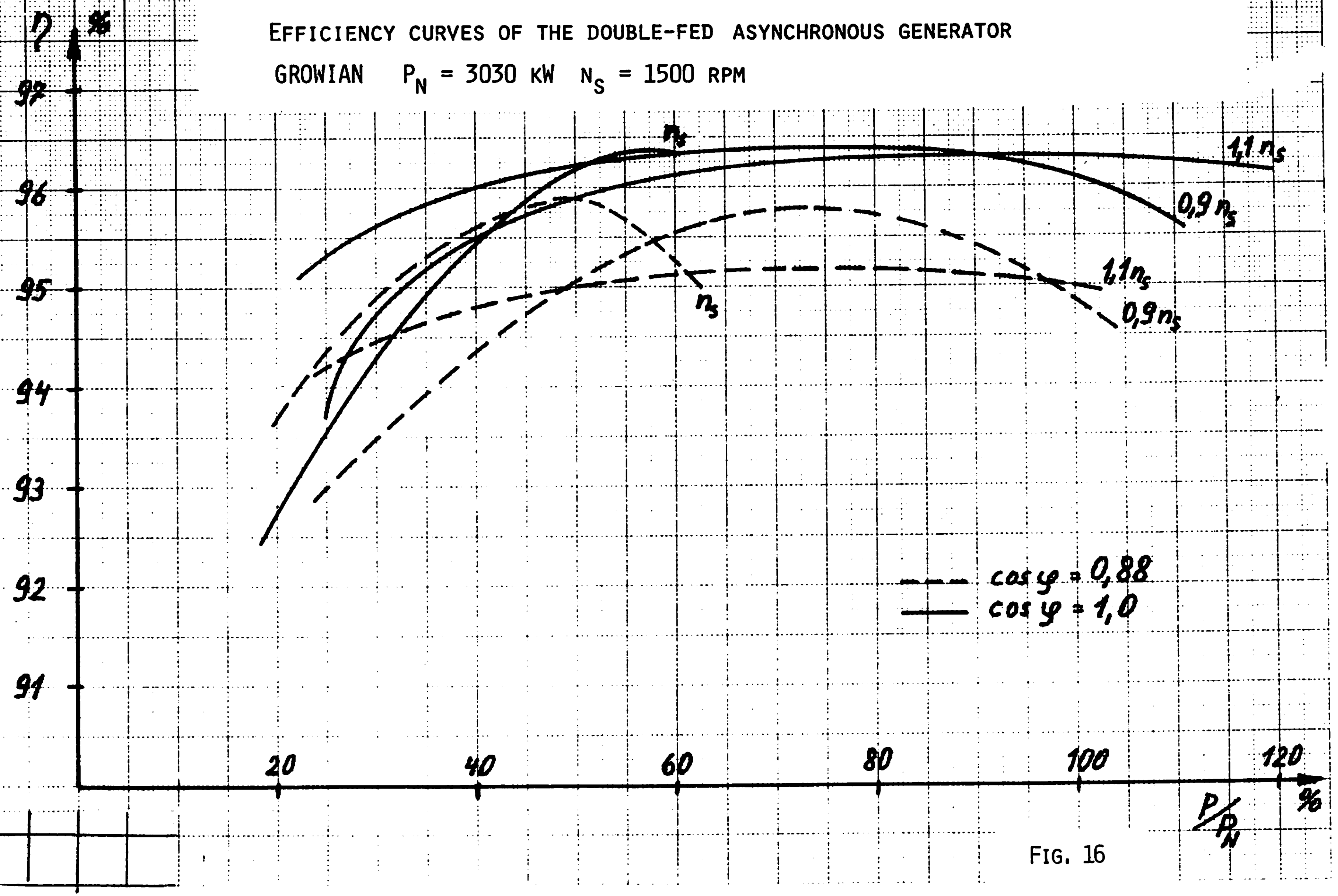


FIG. 16

STATUS OF BUREAU OF RECLAMATION'S TWO SVU WIND TURBINES AT MEDICINE BOW, WYOMING

S. J. Hightower

ABSTRACT

This paper gives the status of the studies and operational testing being accomplished on the Bureau of Reclamation's two System Verification Unit wind turbines at Medicine Bow, Wyoming. A Hamilton Standard WTS-4 unit rated at 4 MW and a Boeing MOD-2 unit rated at 2.5 MW are currently in operation.

1. INTRODUCTION

The Bureau of Reclamation's windpower program began in 1976. During the energy crisis at that time, the Bureau was asked to consider the possible use of solar and windpower systems as a way of increasing the output of its hydroelectric system. Preliminary studies indicated that large wind turbine systems would be cost effective if coupled with existing hydroelectric facilities to provide energy storage. The technique actually increases the value of both systems, since hydro systems rarely have sufficient water to run the hydro turbines at peak capacity. During the peak wind periods, the extra power from the wind turbines will allow the output of the hydro turbines to be adjusted downward so that extra water will be available to generate higher levels of hydropower later when wind is not available. The dams and hydropowerplants essentially serve as huge storage batteries for the combined system. Between the two systems a considerable amount of additional power can thus be made available to the Bureau's customers.

As a result of these initial studies, a 100 MW multiple unit project was proposed to be constructed at Medicine Bow, Wyoming. The project was not proposed as a demonstration project, but rather a project which would be paid back with interest (the same as the Bureau's hydroelectric projects) by marketing power at reasonable rates.

During the first phase, two System Verification Unit (SVU) wind turbines were constructed at the same time that a detailed feasibility study was accomplished for the proposed 100 MW project. Primary objectives of the first units were to verify the wind/hydro energy concept, test the two completely different designs under exactly the same wind conditions, and perform the required environmental studies. Together the two SVU units, which are two of the world's largest wind turbines, will provide enough power to meet the energy needs of about 3,000 homes.

The wind turbines are located in the high plains of southern Wyoming, at an elevation of 2060 m, 10 km southwest of Medicine Bow and 90 km northwest of Laramie, Wyoming. The location of the lowest point in the Continental Divide, just to the west of the site, plus the funnelling effect created by local topographical features make the SVU site one of the windiest sites in the United States. The University of Wyoming has assisted the Bureau in performing studies of the wind characteristics for design of the wind turbines.

2. DESCRIPTION OF SVU UNITS

The WTS-4 wind turbine was constructed jointly by Hamilton Standard in the United States and Swedyards in Sweden. It has the largest generation capacity of any wind turbine in the world today at 4 MW. It has a two-bladed filament-wound fiberglass rotor with a diameter of 78.1 m and faces downwind. The gearbox and generator are enclosed inside a nacelle about the size of a railroad boxcar on top of a hollow-steel tower, 80 meters above the ground.

The MOD-2 wind turbine was constructed by the Boeing Company and is rated at 2.5 MW. It is of considerably different design from the WTS-4 having a two-bladed rotor of welded, hollow-steel shell construction with controllable tips. The blade diameter, which is larger than that of the WTS-4, is about the length of a football field at 91 m, and faces upwind.

Both wind turbines are designed to function completely unattended and to be remotely operated from the Bureau's Casper Control Center located 150 km north of the site.

3. CONSTRUCTION

The National Aeronautics and Space Administration (NASA), is assisting the Bureau, through an Interagency Agreement, for the contracting, construction, and testing of the units, plus training its engineers and operations personnel. The Department of Energy (DOE) also assisted with the construction of the MOD-2, and the Western Area Power Administration markets the power through their transmission facilities.

The contract for the WTS-4 unit was awarded in February 1980; the first rotation was accomplished in August 1982; and the unit was conditionally accepted for operational testing in December 1982. The contract for the MOD-2 was awarded in March 1981, and the first rotation was accomplished in December 1981. Due to funding constraints, the MOD-2 was secured in standby configuration until March 1982 when acceptance tests were resumed. It was accepted for operational testing in August 1982. Dedication ceremonies were held for both wind turbines on September 4, 1982.

4. ENVIRONMENTAL MONITORING

Although wind energy is generally considered to be less disruptive from an environmental standpoint than other energy sources, a number of studies have been made to be certain this is the case. The Wyoming Game and Fish Department and the U.S. Fish and Wildlife Service are working closely with the Bureau in planning and conducting the environmental studies. Results have already shown that the wind turbines will most likely have no significant adverse effect. Information is still being collected and evaluated, but no problems are anticipated.

A team from NASA Langley has taken independent noise data on both the MOD-2 and the WTS-4 units. Preliminary results indicate that the acoustic output from the MOD-2 is very similar to that reported by Bonneville Power Administration (BPA) in Reference (1). The MOD-2 acoustic output appears to be totally broadband in nature with no strong periodic components and can best be described as a "heavy whoosh." The sound can be heard up to about 30 to 45 m away from the turbine, but as the distance from the machine is increased further, the "whoosh" is rapidly blocked out by wind noise.

The WTS-4 has a perceptible "thump" sound that may be heard approximately 2 to 3 km downwind and approximately 1 km upwind resulting from the effects of the downwind blade and tower shadow. However, the sound is not objectionable at the control building, which is only about 200 m upwind of the unit. Noise therefore is not considered to be a problem, since no one is living within 3 km of the site.

5. OPERATIONAL TESTING RESULTS

Since being placed into service, both SVU wind turbines have operated very well, including in an automatic unattended mode. The MOD-2 unit by May 20, 1983, had generated a total of 468,000 kWh, with a total sync time of 392 hours and an average power of 1,194 kW. The WTS-4 had generated 587,000 kWh, with a total sync time of 270 hours and an average power of 2,174 kW. The WTS had also operated somewhat higher than its rated 4 MW, having attained a sustained power generation of 4.8 MW.

Power output results from the MOD-2 versus wind speeds are close to the predicted values. Power quality is exceptionally good from both the MOD-2 and WTS-4 units.

Operational testing of the WTS-4 has produced results that are very close to the design values predicted for all loads and performance. Many different modes of operation including startup, shutdown, and load rejection have been tested.

As in any prototype system, one must expect to have some unforeseen problems requiring design modifications and repairs. The two SVU units are no exception, as some problems have occurred during their first year of operation. The WTS-4 passive yaw control system has not operated as well as anticipated, but it has not been a problem, since it also has an active yaw system which is activated during the startup sequence. Further testing of the passive yaw system is planned. Other minor problems with software and sensor set points that were set too conservatively have caused a large number of nuisance shutdowns, but as the operational testing progresses there are less nuisance shutdowns. When attempting to synchronize the WTS-4 to the grid for the first time a reverse power swing momentarily peaking at 8 MW went into the machine driving it as a motor. This resulted in blade loads significantly above normal operating loads. However, the blades and retention studs were thoroughly checked, and no damage occurred.

The cable tray attached to the inside wall of the WTS-4 tower has been vibrating excessively during operation. A vibration absorber is currently being installed in the nacelle, which is expected to resolve this problem. Some problems have occurred in the struts for the WTS-4 hub spinner, but it is expected that redesigning the truss structure as a bolted configuration will resolve this problem.

Most of these items have been categorized as minor problems. The most serious problem has arisen for the MOD-2 SVU unit which has only been operated on a limited basis since November 1982 pending funding of major design modifications and repairs which are necessary if the unit is to continue its operational testing in an automatic unattended mode. The problem arose as a result of a crack that was found in the low speed shaft of three similar units built for Bonneville Power Administration near Goldendale, Washington. It has been determined from ultrasonic tests that the Bureau's MOD-2 has not cracked as yet, apparently because it has operated only about 460 hours to date. Since the shafts in the Goldendale units did not crack until after 1,000 hours of operation, it has been determined that the Bureau's unit will operate another 500 to 600 hours before a crack will occur. Unless funds are provided to replace the low speed shaft and some cost sharing is provided from others, current plans are to only run the unit during high wind periods of the winter this year, then shut the unit down until funds become available.

6. IMPORTANCE OF OPERATIONAL TESTING

Experience has shown that before pure basic research can be made useful in real world situations, there is a considerable amount of "engineering development" work required. All existing power generation technologies, including large hydro turbines, gas turbines, oil, coal, or nuclear-powered steam plants, had to be tested extensively before any significant numbers of these systems were installed by utilities. This is because in any prototype system, one can expect to have problems that were unforeseen when the system was initially designed. The only way these design problems can be found and corrected is to continue to operate the prototype systems until a failure occurs, perform the needed design modifications or repairs, and then continue the operation. Therefore in many respects, operational testing of prototype units over an extended period of time is one of the most important phases of the entire design and development process. Since defining problems of this nature was the primary reason for building the SVU units, it is important to continue their testing. Many private utilities and other agencies have also expressed the need for long-term operational data from wind turbines like the two SVU units, if utilities are expected to use wind turbines as a portion of their overall power generation mix. As evidence of this, the Electric Power Research Institute (EPRI) and Hamilton Standard have recently signed a three party agreement with the Bureau to operate and test the WTS-4 through the end of 1984.

7. SUMMARY

Construction of the two SVU wind turbines was accomplished as planned, and both units have been operating very well.

Test results of loads and performance appear to match predicted design values better than anticipated. Like all prototype systems, there have been operational problems which could only have been corrected by operating the machines over an extended period of time and periodically performing the needed design modifications as required. These test results will continue to be shared with private utilities and others to help develop the confidence needed to start using wind turbines as a portion of their overall power generation mix.

The Bureau's Feasibility Study Report, Reference (2), published in August 1982 concluded that the rest of the 100-MW project at Medicine Bow is feasible and that the total capital cost of the project can be paid back with interest by marketing the power for approximately 6.7¢/kWh. By comparison, a major West Coast utility is currently offering to pay 11¢/kWh for power from a wind project in northern California, and another is offering 6.4¢/kWh for power from a project in southern Montana (400 miles from Medicine Bow). Based on these power values, with the current upward trend in the economy and the correspondingly greater demands for power, it appears that it will soon be cost effective to build additional wind turbines at Medicine Bow and in other high-wind areas.

8. NOMENCLATURE

km - kilometer
kW - kilowatt
kWh - kilowatt hour
m - meter
MW - megawatt

9. REFERENCES

(1) Seely, D.B. "Interfacing the MOD-2 Complex with the Bonneville Power Administration's Transmission System," Proceedings Fifth Biennial Wind Energy Conference and Workshop (1981), pg. 464.

(2) Wind Hydroelectric Energy Project - Wyoming, Executive Summary - Feasibility Report - Environmental Assessment, U.S. Department of the Interior, Bureau of Reclamation, August 1982.

Fig. 1 MOD-2 System Verification Unit (6/'83)

Fig. 2 WTS-4 System Verification Unit (6/'83)

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Jan Möller	DEFU	Denmark
Hugo Mühlocker	Siemens HG	Erlangen, Germany
Gerald Park	Michigan State University	E. Lansing, Michigan
Hans Payer	Germanischer Lloyd	Hamburg, Germany
B. Maribo Pedersen	Technical University Denmark	Copenhagen, Denmark
Joe Praino	Battelle Pacific Northwest Lab	Richland, Washington
Richard Puthoff	NASA Lewis Research Center	Cleveland, Ohio
Tom Reddoch	Oakridge National Labs	Oakridge, Tennessee
Goran Svensson	Swedish State Power Board	Sweden
Karl-Erik Svensson	KEMA Nord	Sweden
Andy Trenka	Rockwell/Rocky Flats	Golden, Colorado
Bill Vachon	Arthur D. Little, Inc.	Cambridge, Massachusetts
Werner Vollstedt	Tech. Univ. Braunschweig	Braunschweig, Germany
Rolf Windheim	KFA-Jülich	Jülich, Germany
Bob Yinger	Southern California Edison	Rosemead, California

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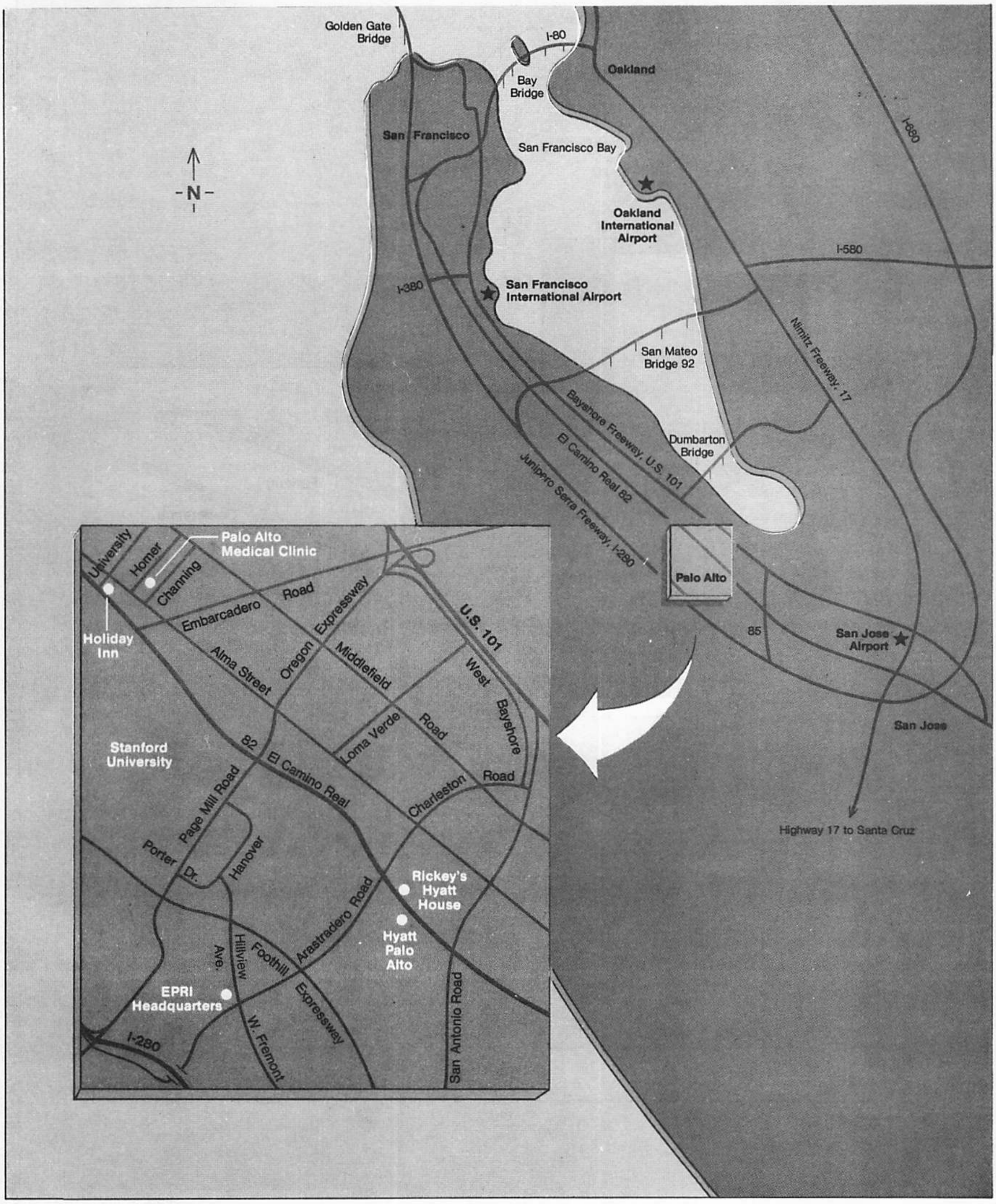
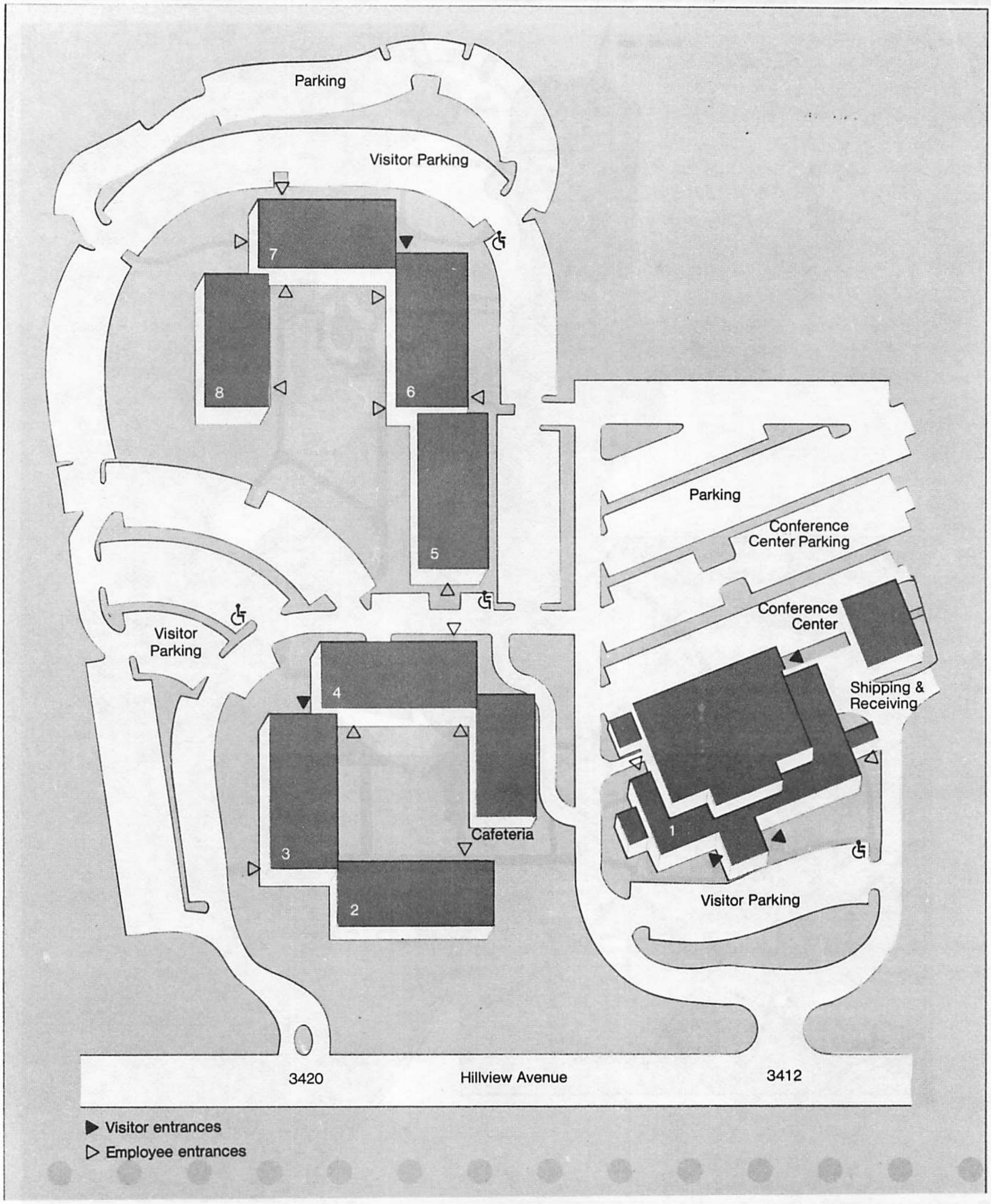
LOCATER



See reverse side for detail facilities map


Parking
Visitor Parking
7
8
6
5
Parking
Conference Center Parking
Conference Center
Shipping & Receiving
Visitor Parking
4
3
2
1
Cafeteria
Visitor Parking
3420
Hillview Avenue
3412
▶ Visitor entrances
▷ Employee entrances

IEA - Implementing Agreement LS-WECS
Previous Expert Meetings

1. Seminar on Structural Dynamics, Munich, October 12, 1978
2. Control of LS-WECS and Adaptation of Wind Electricity to the Network, Copenhagen, April 4, 1979
3. Data Acquisition and Analysis for LS-WECS, Blowing Rock, North Carolina, Sept. 26-27, 1979
4. Rotor Blade Technology with Special Respect to Fatigue Design Problems, Stockholm, April 21-22, 1980
5. Environmental and Safety Aspects of the Present LC WECS, Munich, September 25-26, 1980
6. Reliability and Maintenance Problems of LS WECS, Aalborg, April 29-30, 1981
7. Costings for Wind Turbines, Greenford, March 7-8, 1983
8. Utility Operating Experiences and Issues with Large-Scale Wind Energy Utilisation, Palo Alto, October 13-14, 1983
9. Structural Design Criteria for LS WECS, Greenford, March 7-8, 1983

11. General Environmental Aspects to be held in Germany, May 1984