

UNIVERSITY OF LONDON

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING

THE DEVELOPMENT AND CONTROL OF AN
AUTONOMOUS WIND DIESEL GENERATING SYSTEM

Thesis submitted for the degree of
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By

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ABSTRACT

This thesis deals with the development of an autonomous electrical power system fed from a wind turbine and a diesel generator set. The aim of the research is to determine how the wind turbine may be integrated with the diesel set to provide an acceptable quality of electrical supply while maximising fuel savings. Experimental work on full scale equipment is described and compared with the results of computer simulations.

Following a review of previous work the performance of a 6.4 kW diesel set, under the operating conditions of a wind diesel system, is studied experimentally. Particular attention is paid to fuel consumption, starting performance and the engine minimum loading constraint. An examination of the rates of wear of the engine components is carried out using spectrographic analysis of wear debris in the lubricating oil.

A series of experiments to evaluate the electrical and aerodynamic characteristics of a prototype 9 metre diameter horizontal axis wind turbine are described and the results compared with analytical studies.

Frequency control of the parallel wind diesel system is achieved using a fast acting dump load. Both an analogue and a microcomputer based dump load controller are developed, tested and shown to operate satisfactorily. Fuel savings of up to 50% are recorded in over 50 hours of stable parallel wind diesel operation.

Time step simulation models are constructed to allow long term prediction of system performance using pre-recorded wind speed data. After validation against experimental results the 1 minute simulation is developed to predict annual system performance using Weibull probability distributions of wind speed.

Finally dynamic simulation models of the wind diesel system are built using two microcomputer based simulation programs. These models are validated against experimental results and then used to predict system performance with alternative equipment configurations.

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The final part of this research was carried out while I was working for the Wind Energy Group, Taylor Woodrow Construction and I wish to thank Dr. D. Lindley for the facilities which allowed this thesis to be completed.

LIST OF PRINCIPAL SYMBOLS

(All symbols are defined in the text as they are used and only the principal ones are listed here).

a	Axial induction factor
a'	Rotational induction factor
A	Swept area of wind turbine rotor (m^2)
B	Barometric pressure (kPa/bar)
C ₅	5% confidence limit
C _p	Power coefficient
d'	diesel droop (%)
D	Torsional damping (Nm/rad/s)
E	E.M.F. (p.u.)
f	Fuel consumption (kg/h)
F	Frequency (Hz)
G	Electrical machine rating (VA)
I	Inertia (kg m^2)
I	Modulus of fault current (p.u.)
K _i	Controller integral gain
K _p	Controller proportional gain
M	Electrical machine angular momentum (J-s/mechanical radian)
N	Ratio of number of poles of diesel and wind turbine alternators
P	Power (W)
Q	Torque (Nm)
r	Wind turbine rotor radius (m)
R	Diesel governor droop constant (Nm/rad/s)
S	Torsional compliance (Nm/rad)
S _p	Synchronising power coefficient (p.u)
T	Temperature

V	Voltage (p.u.)
X	Reactance (p.u.)
X_d	Direct axis reactance (p.u.)
X_q	Quadrature axis reactance (p.u.)
X'	Transient Reactance (p.u.)
X''	Subtransient Reactance (p.u.)
Z	Impedance (p.u.)
Z_c	L.V. connection impedance (p.u.)
Z_T	Transformer impedance (p.u.)
δ	Power angle (rad)
η	Mechanical efficiency
θ	Angular displacement (rad)
λ	Tip speed ratio
ρ	Density (gms/cc)
τ	Time constant (s)
ϕ	Blade pitch angle ($^\circ$)
ω	Angular velocity (rad/s)
$\dot{\omega}$	Angular acceleration (rad/s/s)

Subscripts

a	Ambient
c	Equilibrium
d/D	Diesel engine
e	Electrical
g	Electrical alternator/generator
l	Load
m	Mechanical
r	Standard conditions

s	Sump
sm	Synchronous mechanical
t	Wind turbine rotor
w	Wind turbine
x	Test conditions
z	Set point

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CHAPTER 1

INTRODUCTION

1.1 Historical Review of Wind Energy Conversion Systems

For thousands of years wind energy has been used for the convenience of mankind. Sailing ships were the earliest users of wind power but vertical axis windmills were in use in Persia two thousand years ago. In Northern Europe, by the 14th century, wind turbines were extensively used for pumping and milling and their commercial use continued into the early part of this century. Small, multi-bladed, horizontal axis wind turbines have been widely used for borehole pumping in the USA and Australia and are still in service in remote areas. The number of operational windmills and windpumps reached a maximum in the early 1900's and then declined as cheaper diesel and electric power became available.

Pioneering work on the use of wind turbines for electricity generation began in the 1920's with small d.c machines and a number of large a.c. generating wind turbines were built around the time of the second world war. Among the more notable of the large machines were the 1250 kW, 53 metre diameter machine at Grandpa's Knob, Vermont (1.1), the 100kW, 24 metre diameter Andreau-Enfield machine (1.2) and the 200kW, 24 metre diameter 3 bladed Gedser machine (1.3). These projects were not commercially successful and interest in wind power continued only sporadically until the first oil crisis of 1973.

In response to the quadrupling of the price of oil the U.S. government initiated a major research and development programme in wind energy (1.4). After a series of smaller prototypes the 2MW, 91 metre diameter MOD-2 was developed and a cluster of 3 machines erected. It is planned to erect an even larger MOD-5 machine on Hawaii. A number of other countries also initiated development programmes for megawatt size wind turbines. Sweden is now operating two 75 metre diameter wind turbines (1.5) while a 100 metre diameter German machine has been less successful and is being dismantled. Canada is building a 4 MW 96 metre Darius wind turbine and a U.K. 3 MW 60 metre diameter horizontal axis wind turbine is due for commissioning on Orkney in 1986.

In parallel with the national research programmes on large wind turbines a number of small machines have been developed by private industries. These have mainly been installed in California where energy tax credits and legislation forcing the utilities to buy power at guaranteed rates have created attractive commercial conditions for the development of large wind farms. At the end of 1984 over 8,000 wind turbines had been installed in California. In other countries, with the exception of Denmark, where the commercial climate has been less favourable, wind energy has not been able to compete with power supplied from large central generating stations via high voltage grids.

However, there exists a large number of isolated locations throughout the world where the only present source of electricity is local diesel generation and which also experience favourable winds. Because of the high costs of operating small

diesel sets with imported fuel the cost of electricity on remote Pacific islands is as high as 80 pence/kWh while even on islands around the U.K. it is more than 10 pence/kWh (1.6). The availability of increasingly reliable wind turbines offers an opportunity to reduce these electricity costs by installing hybrid wind diesel systems. However, there are a number of problems associated with the operation of integrated wind diesel systems and several national groups are actively working to solve them. This research is now briefly reviewed and the main results to date noted. Much of the work reviewed was being carried out simultaneously with the research described in this thesis and useful dialogues were established with the main European research teams.

1.2 Recent Developments in the Integration of Wind and Diesel Generation

1.2.1 Australia

In Western Australia there are a number of outback towns supplied with electricity from local diesel power stations and the State Electricity Commission annually spends about A\$60 million subsidising electricity supply in these rural areas (1.7).

As an experiment an 11m diameter 20kW Aeroman, a 15m diameter 55kW Nordtank and a 17 x 11 metre 30kW Daf Indal vertical axis wind turbine were installed to operate in parallel with the existing diesel generators, rated at 700kW, at Rottnest Island near Perth. The wind

turbines were intended to reduce the load on the continuously running diesel sets. There was a dump load for frequency control during periods of high wind and low consumer demand. Although it is believed that the system operated satisfactorily, detailed results of system performance and fuel savings have not yet been published.

1.2.2 Canada

The main research effort in Canada has been undertaken by Daf Indal, supported by federal funding, in response to the need to reduce the diesel fuel costs of the remote communities in Northern Canada. Daf Indal manufacture vertical axis Darius wind turbines and these machines allow easy mechanical power take off at ground level. Therefore this work has concentrated on mechanical coupling of the wind turbine to the diesel.

Research commenced in 1976 with a 12kW pilot scheme (1.8) and progressed to a 100kW demonstration unit (1.9). This demonstration unit was tested over a 6 month period in 1982. During this time it operated reliably, some power was available for 90% of the time, and fuel savings of 7.5% were achieved. This low fuel saving was due to the system configuration of one 30kW wind turbine operating to assist two 50kW diesel sets. Frequency control of the system was by a dump load fed through a motor driven variable transformer. This

operated satisfactorily and maintained the system frequency to within $\pm 2\text{Hz}$.

A more recent paper (1.10) describes how the system was reconfigured to allow stand alone wind turbine operation. However, difficulties were experienced with torsional oscillations of the wind turbine drive train but stand alone operation and electrically coupled parallel operation were achieved. Future work will concentrate on the use of batteries as an energy store for the system.

1.2.3 Denmark

Denmark has a thriving wind turbine industry with over a dozen well established manufacturers and 1200 wind turbines installed throughout the country. In general Danish wind turbines are 3 bladed upwind stall regulated machines fitted with induction generators.

The wind diesel development programme is centred on the Test Station for Small Windmills at the Riso laboratory. Two systems are under examination: a state of the art system and an advanced design (1.11). The state of the art system will attempt to couple a 55kW, 15 metre diameter wind turbine with a 30kW turbocharged 3000 rpm diesel set. The alternator of the diesel set is oversized to allow reactive power to be supplied to the induction generator of the wind turbine. In periods where the diesel engine is not required it is declutched

from the alternator which continues to act as a synchronous capacitor. Frequency control is by a dump load and a small flywheel is mounted on the diesel alternator shaft for energy storage. Preliminary results of tests on the diesel set have been reported (1.12) but the results of parallel wind diesel operation have not been published.

The development of the advanced system is being carried out in collaboration with Chalmers University of Technology, Sweden. Again a 55kW wind turbine will be used but connected to the diesel set via a d.c. link (1.13). A feature is the connection of battery storage directly across the d.c. link. So far only laboratory experiments have been carried out on this system.

Two Danish manufacturers have fitted eddy current brakes to the high speed shafts of their wind turbines to provide accurate frequency control under stand alone operation. This facility also allows parallel wind diesel operation without the necessity of a dump load. No results of any tests have so far been published.

1.2.4 Germany (F.R.G.)

Two industrial groups M.A.N. (1.14) and Dornier (1.15) have carried out wind diesel experiments supported by theoretical work at the national aerospace research institute, DFVLR (1.16).

The M.A.N. research has been centred on the application of their 20kW, 11 metre diameter, horizontal axis wind turbine Aeroman. This has rapid hydraulic blade pitch control which allows accurate regulation of the rotational speed or power. It may be fitted with a synchronous or an 8% slip induction generator. The major demonstration of this system is on the Greek island of Kythnos where, in collaboration with the Public Power Corporation, a wind park of 5 machines has been installed. This operates in parallel with a diesel power station of 1700kW installed capacity and a 100kW solar panel system. The installation has worked well and the wind turbines supply approximately 9% of the annual electrical energy of the island.

Dornier have tested a wind diesel system which allows stand alone wind turbine operation. Although an Aeroman wind turbine was used in the experiments the active pitch control was disabled and the system frequency controlled by a dump load. The frequency was maintained at $\pm 2.5\text{Hz}$ of nominal but details of the system voltage have not been published. A brief economic analysis indicated payback periods in excess of 12 years unless the consumers were to adapt their energy demand to make use of the dumped power.

1.2.5 Holland

Research into wind diesel systems is now carried out at the Netherlands Energy Research Foundation, ECN, having been started at Eindhoven University of Technology in 1978. Two systems have been developed: a 12kW laboratory system, where the wind turbine is represented by a d.c. motor, and a 50kW site system. The site system uses two 11 metre diameter variable speed wind turbines which are connected to a 50kW/90kVA diesel set by a d.c. link. Frequency control is by a dump load and a small quantity of energy is stored by the varying speed of the wind turbine rotors. When the diesel engine is not required it is declutched from its alternator which is left on the system to provide reactive power. The system has been run successfully in both parallel wind diesel and wind turbine stand alone modes. Further developments planned are to include battery storage to improve the system performance at low loads (1.17).

1.2.6 U.K.

Wind diesel work carried out in the United Kingdom has been rather fragmented with several groups pursuing different approaches.

Northern Engineering Industries (NEI) have adopted the technique of modifying the consumers load to optimally load the wind turbine. Each consumers load is divided

into three priorities and each priority is controlled by a frequency sensitive relay. The higher the priority the lower is the set frequency. Thus lighting is almost always available but as more wind power is generated the lower priority loads such as water and space heating are supplied. As well as extracting all the available power from the wind the consumers loads also form a distributed proportional frequency controller. All the existing NEI wind diesel systems use a 55kW stall regulated wind turbine and usually parallel wind diesel operation is not permitted. The systems installed on Lundy Island (1.18) and Fair Isle (1.19) have been very successful partly because the islanders have modified their pattern of consumption of electricity to use the wind power when it is available.

Sir Henry Lawson-Tancred in collaboration with the Overseas Development Administration is developing a wind diesel system based on a 17.5m diameter wind turbine (1.20). A single alternator is driven via hydraulic circuits from the wind turbine and diesel engine. The use of hydraulics allows both variable speed operation of the wind turbine and a convenient energy store using a hydraulic accumulator. Test results of the system have so far not been published.

Reading University, together with the Rutherford Appleton Laboratory, have carried out extensive analytical and simulation studies on wind diesel systems. Recent work has been centred on short term

energy stores using batteries (1.21) or hydraulic accumulators (1.22). It has been shown that fuel savings may be improved dramatically if an energy store is included in the system and hence wind turbine stand alone operation permitted.

Hawker Siddeley Power Plant together with Imperial College and the Rutherford Appleton Laboratory are developing a prototype wind diesel system (1.23) and the work described in this thesis was carried out as part of this programme. This system is now being extended to include flywheel energy storage.

1.2.7 U.S.A.

Medium size wind turbines have been installed to operate in parallel with a number of small diesel networks in the U.S.A. (1.24; 1.25). One of the more successful systems was the 150kW MOD-OA on Block Island (1.26; 1.27).

The Block Island Power Company operates a small diesel power station with an installed capacity of 3400kW but with a winter minimum load of only 260kW. Thus a maximum wind penetration of 60% was possible. Frequency control was by the continuously running diesel sets and a dump load was not used. The system operated

satisfactorily with the wind turbine pitch fixed, but the active pitch control interacted with the diesel governors when the wind turbine was limiting its output power. Over a 2 month test period the wind turbine reduced the fuel consumption of the station by 7% while generating 11% of the total electrical energy. The difference between these figures was due to the change in diesel efficiency with load and the consumption of the wind turbine auxiliaries, particularly the air conditioning of the nacelle.

A number of small U.S. companies have begun offering autonomous wind diesel systems for sale. These are based on direct current with battery storage. Test results of the operation of these systems are not yet available.

1.2.8 Summary

The wind diesel systems described vary from small laboratory experiments to large working demonstrations and they are located in very different wind regimes. The level of wind power penetration varies from a few percent where a single wind turbine is installed on a small diesel grid to 100% wind diesel or stand alone wind turbine operation. All sorts of wind turbines have been used and a number of differing control strategies have been examined. However, there appears to be agreement on a number of general points:-

- i) Reliable wind turbines are essential. These are now becoming available and should encourage the installation of more systems. Fixed speed operation is simpler and hence more reliable than variable speed operation.
- ii) High mean annual wind speeds and low levels of turbulence obviously improve the system performance.
- iii) For maximum fuel savings wind turbine stand alone operation is needed and if uninterrupted power is required then an energy store is necessary.
- iv) Parallel wind diesel operation is possible but difficulties may be encountered with interactions between the various control systems of the diesel, wind turbine and loads.
- v) The fuel saving of the system may be considerably improved if the consumers can be encouraged to modify their demand in accordance with the availability of the wind power.

1.3 Thesis Outline

The research described in this thesis was an early contribution to the joint Hawker Siddeley Power Plant/Imperial College/Rutherford Appleton Laboratory wind diesel project. The aim of the project was to build and investigate the performance of a

6kW wind diesel system capable of continuously supplying good quality electrical power. The experimental system was based on a Hawker Siddeley Power Plant Nova II 6.4kW diesel set and a North Wind Power Company 9 metre diameter 16kW wind turbine. In addition to the experimental work, analytical and computer simulation studies were carried out.

Chapter 2 describes the experiments performed to characterise the diesel set. Up to the time of this work little attention had been paid to the performance of the diesel engine in a wind diesel system and the engine manufacturers could give only limited information.

In Chapter 3 work to evaluate the change in wear rates of the diesel engine, when used as part of a wind diesel system, is described. No previous research in this area appeared to have been done. The experiments gave only tentative results but did indicate that higher than expected numbers of diesel starts could be tolerated.

The main wind turbine experimental installation and data logging is described in Chapter 4. In addition, the results of a short electrical study carried out before connecting the wind turbine to the 415V network are reviewed.

A series of experiments were carried out to examine the electrical performance of the wind turbine when connected to the 415V network and the results of these are given in Chapter 5.

The main characteristic of a wind turbine is its Power Curve and, as described in Chapter 6, the determination of this curve is not straightforward. After a review of a number of experimental procedures the results of 75 hours of Power Performance Testing are described together with the effects of data averaging times.

Parallel autonomous wind diesel operation was successfully achieved using a variety of dump loads and controllers for frequency control. This work and the associated reduction in fuel consumption of the diesel set is discussed in Chapter 7.

Chapter 8 describes two time series simulation models which were built to examine the logistic performance of wind diesel systems. The models were validated against experimental results and then used to predict system annual performance.

In Chapter 9 the dynamic performance of the wind diesel system is examined using models built with two microcomputer aided simulation tools. After validation of the models different equipment configurations were considered and their performance assessed.

Finally, Chapter 10 summarises the main conclusions of the thesis together with the original contributions. Suggestions for further work are also included.

CHAPTER 2

DIESEL GENERATOR SET PERFORMANCE

2.1 Introduction

In an autonomous wind diesel system the role of the diesel generator set is to provide a secure source of power when the wind speeds are too low or too high for the load to be met by the wind turbine. To reduce fuel consumption the diesel engine should only be run when needed and then at the minimum required load. This is likely to result in frequent stop/start cycling of the diesel with prolonged periods of running at light load. In addition, the turbulence of the wind will cause rapid governor action of the engine during parallel operation.

This onerous operating regime, at constant speed, is not recommended by the diesel engine manufacturers and detailed information on the response of a diesel engine to these conditions was not available (2.1). Other wind diesel projects have reported some general results from larger diesel generator sets. Stiller et al (2.2) have examined the effect of governor action on fuel consumption of diesel generating sets of the size range 225–500 kW and Volling (2.3) and de Bonte et al (2.4) have reported the part load performance of 50 kW units. Unfortunately these results are not directly applicable to much smaller diesel generator sets. Therefore an experimental programme was initiated to examine how the operating conditions of a wind diesel system would effect small diesel generator set performance. The experiments were performed at RAL and

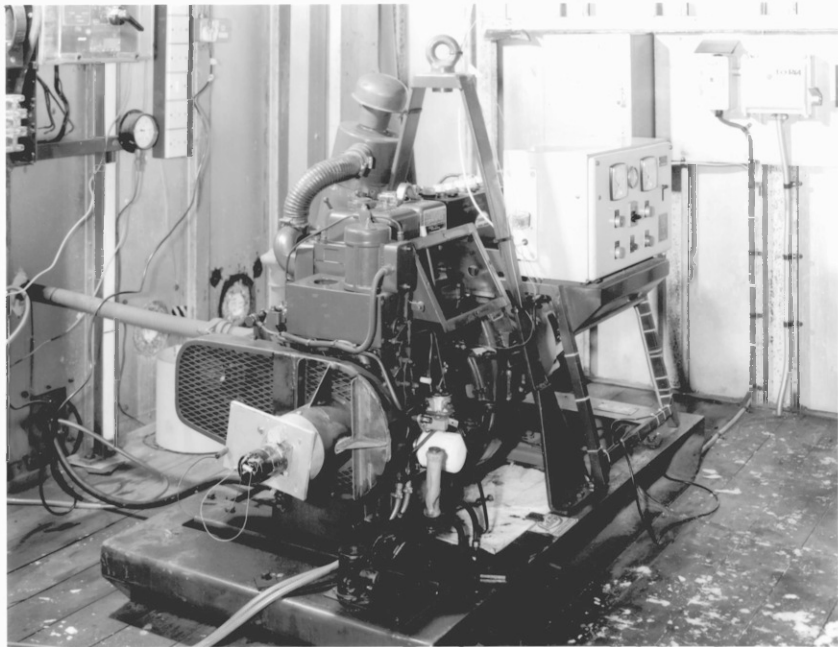


FIGURE 2.1 DIESEL GENERATOR SET TEST RIG



FIGURE 2.2 CONSUMER LOAD (SHOWING kWh METERS)

investigated the behaviour of the entire generating set with the engine, alternator and auxiliary systems considered as a complete unit.

2.2 Experimental Procedure

2.2.1 Experimental Equipment

The diesel generator set used for the tests was a Hawker Siddeley Power Plant Nova II set, shown in Figure 2.1, with a continuous rating of 6.4 kW. The diesel engine was an R.A. Lister type ST2. This was a 2-cylinder, 1.27 litre cylinder capacity, direct injection, normally aspirated, air cooled engine. It was fitted with an electric start and a 12 Volt dynamo battery charging system. The nominal rotational speed was 1500 rpm with Class A2 governing to BS 649 (2.5). The alternator, which was close coupled to the engine, was an Electric Construction type SCTF. This was a 3 phase 4 pole synchronous alternator with a rotating exciter and series compounding of the field. The field was located on the stator with the armature connections made by slip rings on to the rotor.

The alternator output was connected to a 3 phase resistive load, shown in Figure 2.2. The load was in 7 steps. Each step was approximately balanced across each phase and the first 6 steps were in an approximate binary sequence. Each step was fed via 3 solid state relays. The relays were controlled from an 8 way

DIESEL GENERATOR SET TEST RIG

FM - FUEL FLOW METER
 kWh- PULSE GENERATING kWh METER
 kW - INSTANTANEOUS kW TRANSDUCER

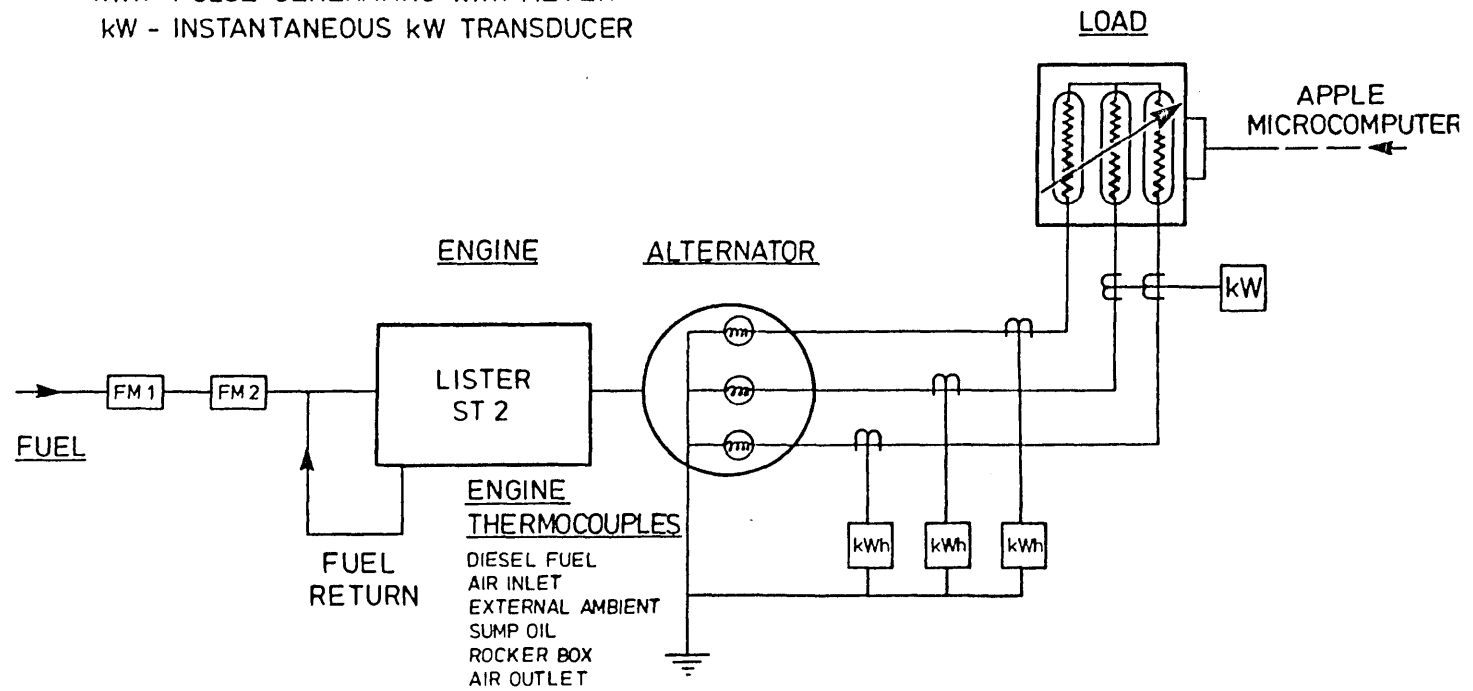


FIGURE 2.3

parallel output interface from an Apple II+ microcomputer. Using this load it was possible to load the diesel generator set from 0 to 7.5 kW in 200W steps. As the value of the load was controlled from the software of the microcomputer rapid cycling was easily accomplished. The actual absorbed load of each step varied with the temperature of the resistor banks and also with the voltage supplied from the alternator. The voltage supplied from the alternator was itself dependent on the temperature and condition of the generating set. Figure 2.3 shows schematically the main equipment and transducers.

In order to overcome the difficulties of the load changing during testing, integrating kWh meters were used to measure output power. These were domestic tariff meters modified, by drilling their disks and fitting optical switches, to give 4 pulses per revolution of the disk or 960 pulses per kWh. The optical switches each consisted of an encapsulated light emitting diode and photo transistor. As the meters were 240 Volt devices the 3 wattmeter connection was used and the pulses of all 3 meters summed to give the total energy. The kWh meters were calibrated in the laboratory against a standard indicating wattmeter. The loading of the meters was carried out by segregating the voltage and current coils. The calibration of each meter was confirmed over the range 200W to 4 kW. The

maximum errors of each meter were added in quadrature to give a standard error of $\pm 1\%$ for the 3 wattmeter connection.

The fuel consumption of the diesel engine was measured using pulse generating flow meters. These commercially available meters consisted of a small paddle and magnetic pick up. The fuel flow rotated the paddle and gave a pulse train output. The operation of the injectors of a diesel engine results in a large return flow of fuel. The flow meters were therefore connected to measure only net fuel consumption. Two flowmeters were connected in series and the mean value used to calculate fuel flow rates. The fuel flow meters were calibrated on the test rig during operation of the diesel by measuring the passage of a known weight (200 gms) of fuel. The calibration of the fuel flow meters was determined as:-

Flowmeter No. 1 2.023 ± 0.002 counts/cc.

Flowmeter No. 2 2.021 ± 0.003 counts/cc.

The density of the diesel fuel was significantly temperature dependent. This relationship was measured by RAL chemistry staff, using a hydrometer technique, over the range 0-70°C, and found to be:-

$$\rho = 0.852 - (7 \times 10^{-4} \times T) \text{ gms/cc}$$

where T is diesel fuel temperature (°C).

DIESEL GENERATOR SET DATA ACQUISITION SYSTEM

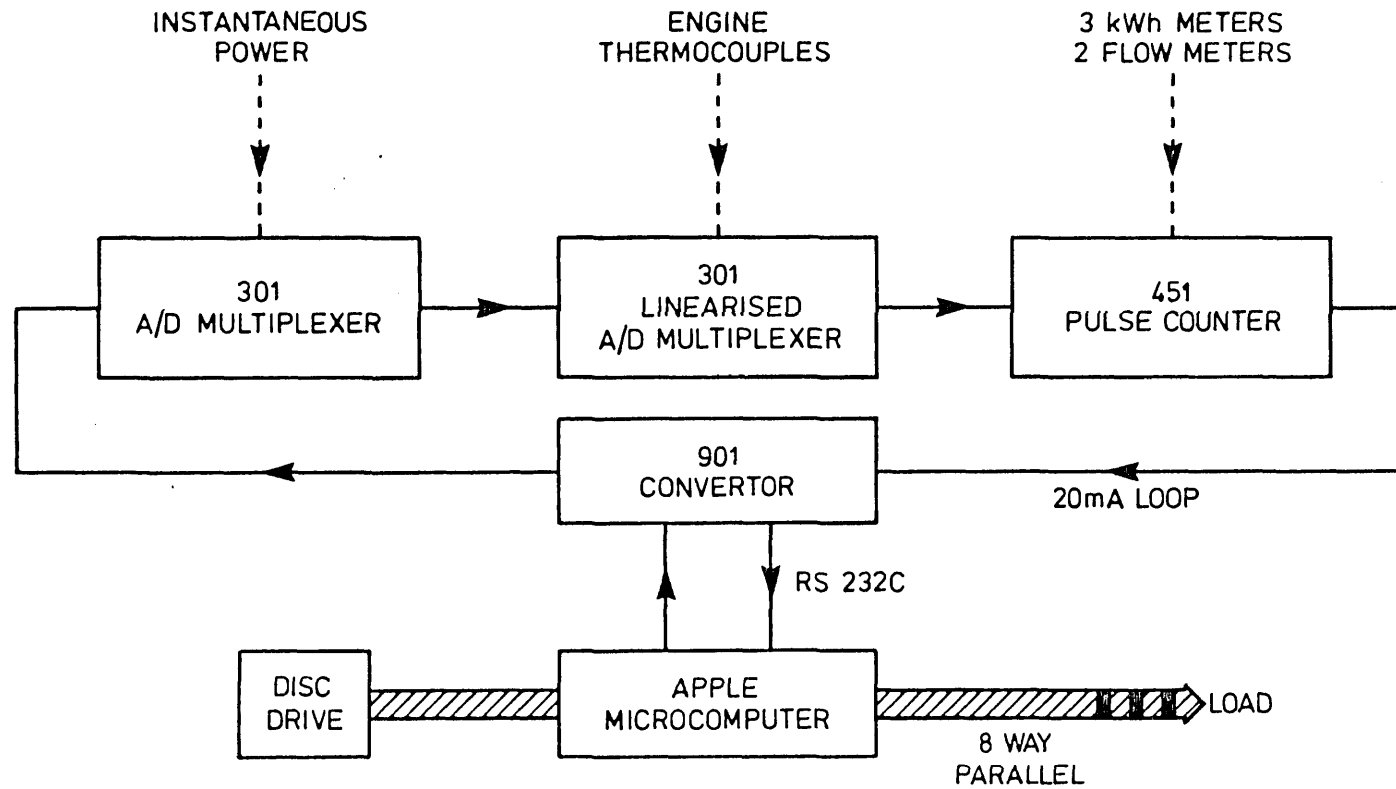


FIGURE 2.4

At 15°C this measurement had a standard error of $\pm 0.6\%$.

Temperatures at various points of the experimental rig were measured using Type K (Chromel-Alumel) thermocouples. These were calibrated at 3 points, with the data acquisition system, and gave standard errors of $\pm 2^\circ\text{C}$. Ambient pressure and relative humidity were measured once during each period of testing.

2.2.2 Data Acquisition System

The data acquisition equipment used for the tests was a distributed current loop type. The Apple II+ microcomputer was used to control simultaneously the load and the data acquisition system. A single floppy disk drive was used to store the programs and experimental data. Program development and data processing were carried out on a second Apple II microcomputer. Figure 2.4 shows schematically the data acquisition system.

Communication between each module in a 20mA current loop was achieved by transmitting ASCII characters at 300 baud. The microcomputer and the 901 unit were located in the load cabin while the remaining units were located in the diesel cabin. Towards the end of the experiments the microcomputer and the 901 unit were moved to the wind turbine control room.

The data acquisition system was 12 bit binary plus sign (1 in ± 4096). The manufacturer quoted the measurement accuracy of the 301 analogue unit as $\pm 0.1\%$ of range.

Control of the load and the data acquisition system was carried out by programs written in BASIC on the Apple II+ using DOS 3.3 operating system. Data from all 24 channels was accepted by the microcomputer and stored on a disc for subsequent processing and analysis. For one minute logging the system was triggered by the hardware watchdog timeout of the modules. For more frequent logging use was made of an assembler routine, DRIVER, supplied by the manufacturer which allowed the units to be interrogated at a frequency defined by the BASIC program. Details of the programs developed for these tests are given in Appendix A.

2.2.3 Reduction of Data to Standard Conditions

The performance of internal combustion engines is dependent on atmospheric conditions. Therefore it is necessary to adjust the experimental data to a standard base and a number of semi-empirical equations are available for this (2.6). The British Standard recommendations (2.7) agree with the D.I.N. and I.S.O. formulae for normally aspirated engines and so these were used.

The corrections are:-

$$P_x = a P_r$$

$$a = k - 0.7 (1 - k) \left(\frac{1}{\eta} - 1 \right)$$

$$k = \frac{T_r \cdot B_x}{T_x \cdot B_r}$$

P_x : output power under test conditions (kW)

P_r : output power under standard conditions (kW)

η : mechanical efficiency of generating set (0.7)

T_r : air inlet temperature of standard conditions
(300°K)

T_x : air inlet temperature under test conditions
(°K)

B_r : ambient pressure of standard conditions (100kPa)

B_x : ambient pressure under test conditions (kPa)

2.3 Results and Analysis

2.3.1 Steady State Fuel Consumption

The steady state fuel consumption was measured at various loads and the results are as shown in Figure 2.5. All tests were carried out under steady state conditions with a sump oil temperature of greater than 65°C. The tests were usually of 10 minutes duration

STEADY STATE FUEL CONSUMPTION

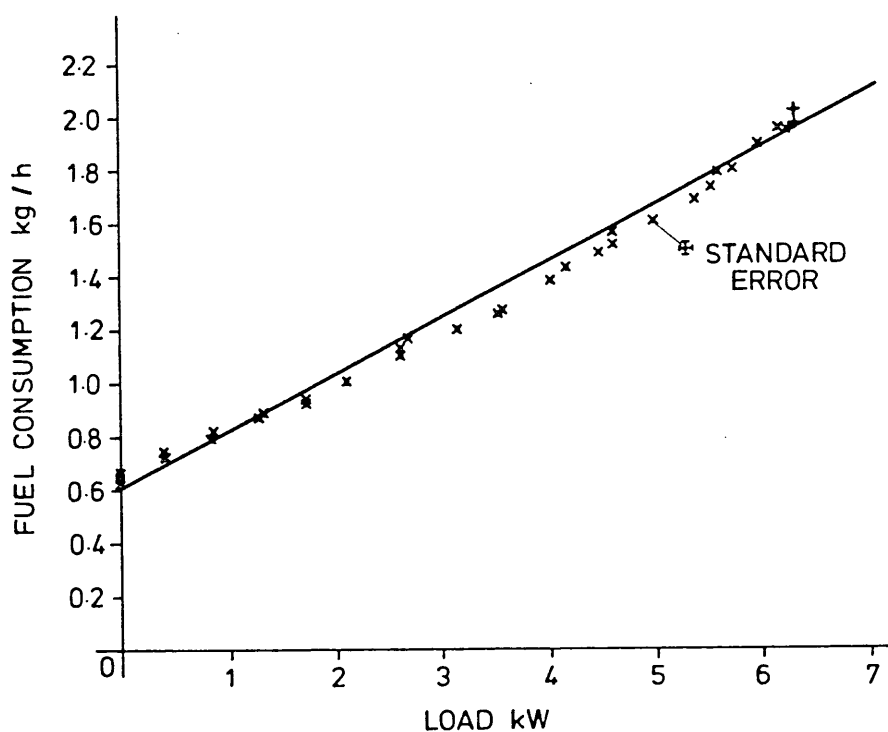


FIGURE 2.5

EFFECT OF LOAD VARIATION

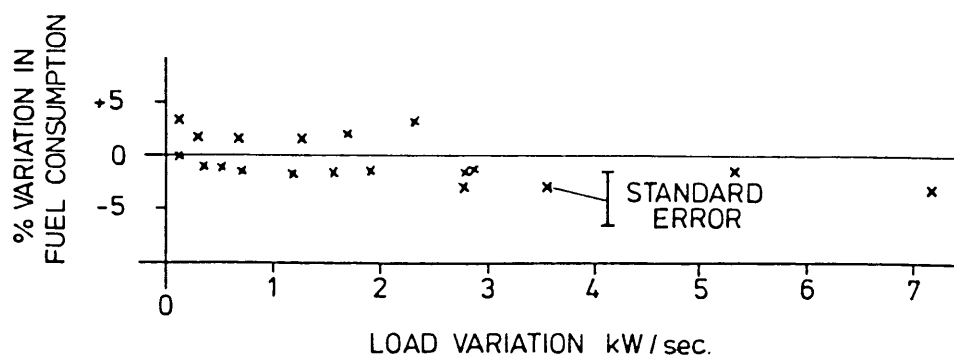


FIGURE 2.6

although at low loads the tests were extended in order to reduce the effects of resolution errors on the kWh meter readings. Standard errors for each point were calculated from the instrument calibrations.

The points of Figure 2.5 could be fitted with a straight line similar to the Willans Line (2.8) conventionally shown when testing diesel engine torque/fuel consumption at constant speed. An unweighted least squares linear regression (2.9) was carried out on the points to give the relationship:-

$$f = aP + b \text{ kg/h} \quad (2.1)$$

$$a = 0.206 \pm 0.004 \text{ kg/h/kW}$$

$$b = 0.602 \pm 0.0125 \text{ kg/h}$$

The coefficient of determination was 0.989. This coefficient is defined as the ratio of the square of the covariance of the dependent and independent variables divided by the product of the variances of the variables. It may not be used directly to give a quantitative measure of correlation (2.10) but values approaching 1 indicate a high degree of correlation and justify the fitting of a straight line. However examination of the residuals showed that at a number of points they were in excess of 3 standard errors. This would not be expected if a completely linear relationship existed between the variables.

An error weighted chi squared curve fitting routine (2.11) was then applied to the data points and associated standard errors. Polynomial fits up to fifth order were attempted and the best fit was obtained with the cubic:-

$$f = 0.637 + 0.185P - 0.096P^2 + 0.0022P^3 \text{ kg/h} \quad (2.2)$$

Although no attempt was made to assign physical significance to the coefficients it is reasonable to assume that the performance of the complete diesel generator set will not be described exactly by a linear relationship of the form of Equation 2.1. The losses of the set are unlikely to be constant or proportional only to power. Further, Ricardo and Hempson (2.12) state that the Willans line of direct injection engines will show a deviation at high loads due to imperfect combustion and at low loads due to overcooling. However, if the higher order terms of Equation 2.2 are caused by losses and incomplete combustion it is important to note that Equation 2.2 only describes the set under test in a particular condition and is unlikely to be of general significance. Therefore Equation 2.1 is an adequate representation for most purposes.

By setting the fuel consumption to zero in Equation 2.1 a value of the generating set mechanical and electrical losses of 2.9kW was obtained. This gave an overall electrical and mechanical efficiency of 69% at the 6.4

kW rating. This figure indicates the significant losses associated with the alternator and with the frictional, pumping and auxiliary losses of the engine.

Using the measured calorific value of the diesel fuel of 45.5 MJ/kg a brake thermal efficiency of 26% at the 6.4 kW rating, was calculated.

2.3.2 Fuel Consumption with Rapid Variation of Load

The effect of governor action, caused by variation of the load, was then examined. The load was cycled, at various combinations of amplitude and frequency, up to a maximum rate of 7kW/sec. The test durations varied between 100-600 seconds and all tests were carried out with a sump oil temperature greater than 65°C. From the integrating kWh meters, it was straightforward to determine the mean load of each test. Similarly the fuel consumption was available from the fuel flow meters.

The measured fuel consumption of each test with a cycled load was compared with that predicted by the steady state relationship of Figure 2.5. As may be seen by Figure 2.6 there is no apparent effect on fuel consumption due to a rapidly varying load. This result agreed with that found by Stiller et al (2.2). After the experiment had been completed, de Bonte (2.13) and

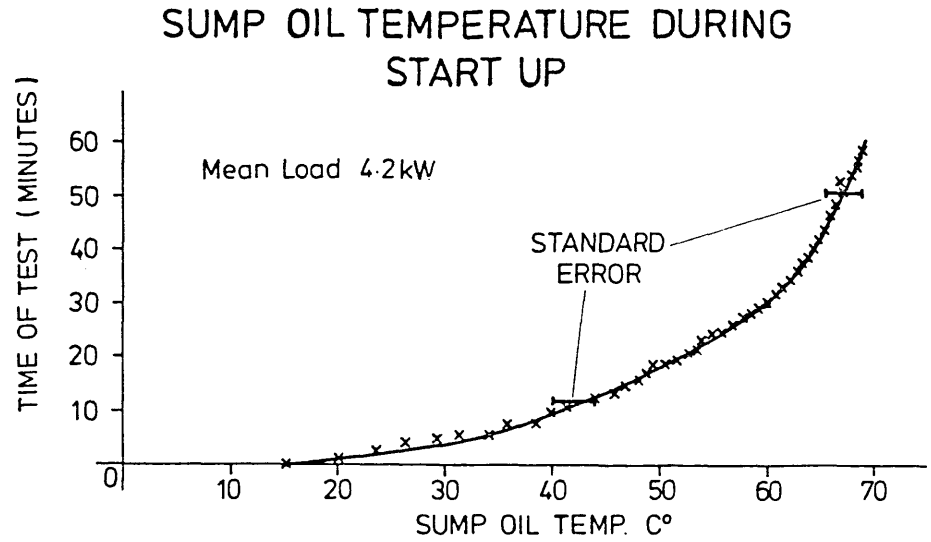


FIGURE 2.7.1

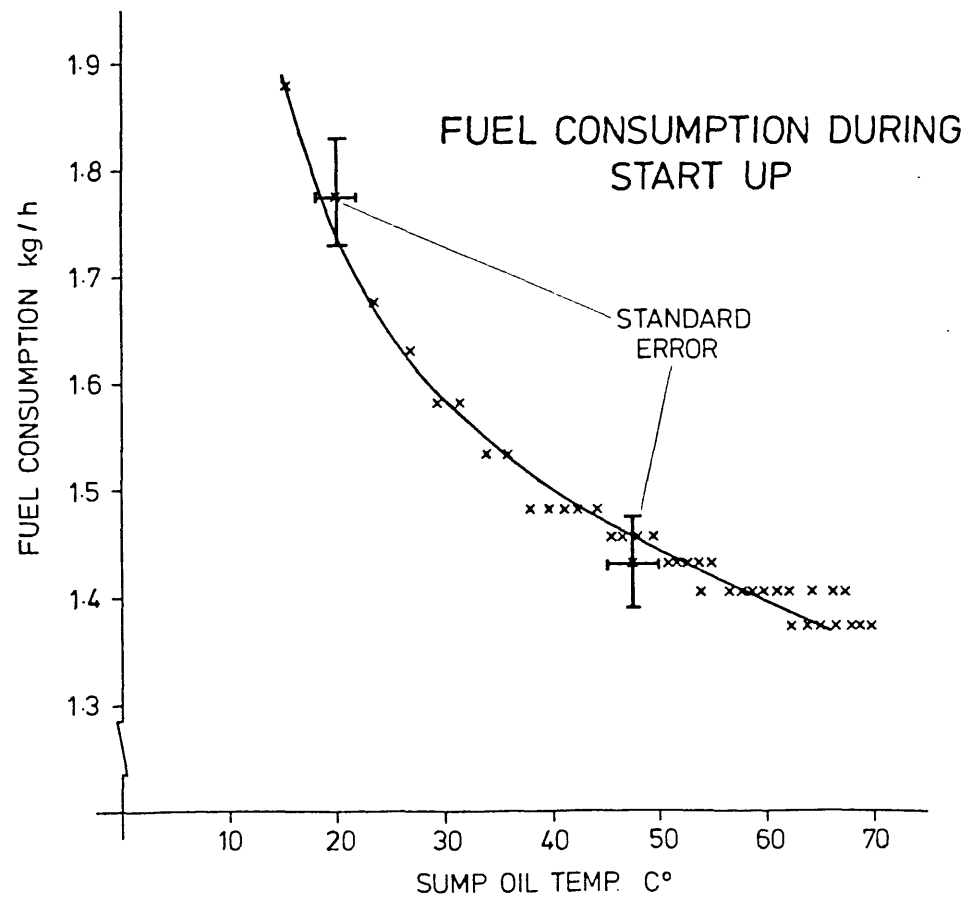


FIGURE 2.7.2

FIGURE 2.7 START UP PERFORMANCE

Caselitz et al (2.14) published results which also showed no significant fuel penalty associated with varying load.

2.3.3 Fuel Consumption During Start Up

The steady state power/fuel consumption relationship was measured only with the generating set warmed up, i.e. with the sump oil temperature greater than 65°C. However it was noted during the tests that there appeared to be a fuel penalty associated with the initial warming up of the set. A series of 9 tests were then carried out to investigate the effect of start up on fuel consumption. Fuel flow rate and power were measured at 1 minute intervals and referred to the mean sump oil temperature at that minute. The sump oil temperature was considered to be a good single indicator of engine temperature.

Figure 2.7 shows results of one of the tests. The rate of rise of sump oil temperature, Figure 2.7.1, was approximately exponential as would be expected. The increase in fuel consumption at low sump oil temperatures was shown in all tests although the shape of the curve varied with test conditions. The results of all tests at sump oil temperatures of 20°C, 30°C, 40°C and 50°C are shown in Figure 2.8. The mean excess fuel consumption during start up, in excess of the steady state line, is shown in Figure 2.9.

FUEL CONSUMPTION DURING START UP

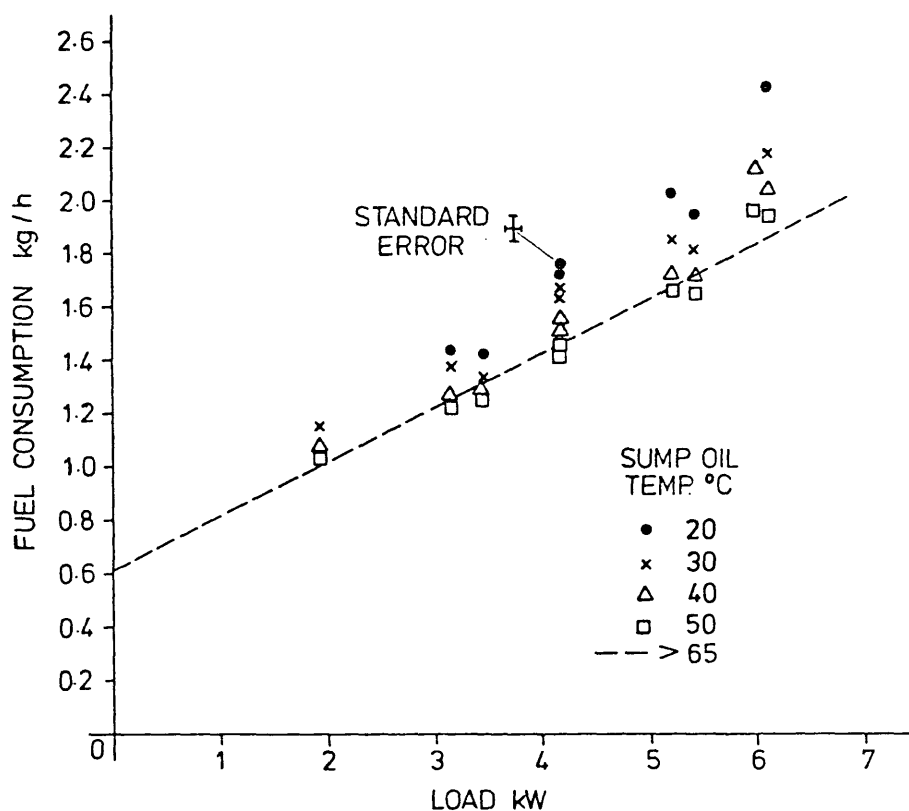


FIGURE 2.8

EXCESS FUEL CONSUMPTION DURING START UP

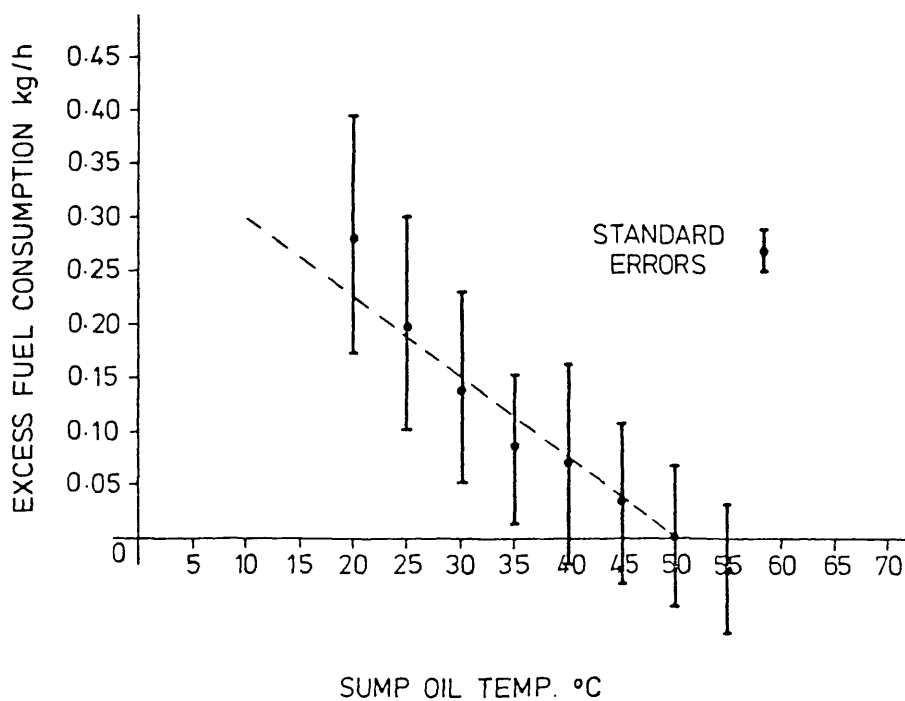


FIGURE 2.9

The excess fuel consumption during start up was caused by a number of effects including:-

- a) Increased mechanical losses at low engine temperatures.
- b) Less efficient combustion at low cylinder and inlet air temperatures.
- c) High battery charging requirement immediately after starting.
- d) Specific heat requirement of the generating set.

As shown in Table 2.1 (2.15) the rolling torque of the engine itself was highly temperature sensitive.

TABLE 2.1

ST2 Rolling Torque. (Torque to rotate bare engine in compression).

Engine Temperature °C	Rolling Torque N-m
-15	29
4	21
15	12

It was not possible to isolate the various effects causing the excess fuel consumption as a number of the effects were not dependent on sump oil temperature alone.

Figure 2.9 showed that the effect was not measurable at sump oil temperatures above 50°C and a simple least squares linear regression was performed on this data (2.16) to give:

$$f' = a (50 - T_s) \text{ kg/h} \quad (2.3)$$

f' : increase in fuel consumption kg/h

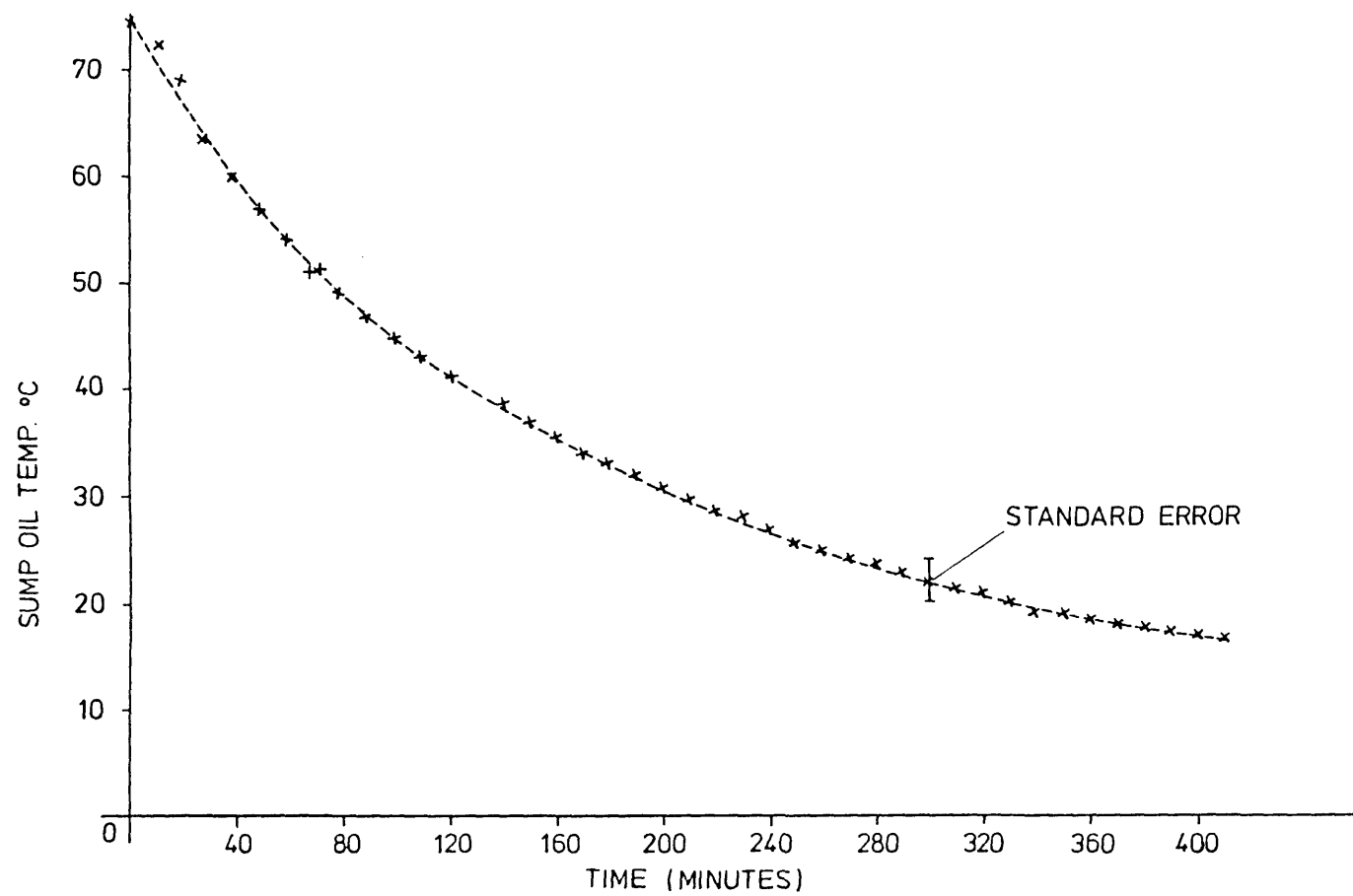
T_s : sump oil temperature 20°C - 50°C

$$a = (8.08 \pm 0.48) \times 10^{-3} \text{ kg/h/}^\circ\text{C}$$

with a coefficient of determination of 0.979 indicating a reasonable fit.

2.3.4 A Simple Thermal Model

To allow simulation of temperature dependent effects of the generator set a thermal model of the diesel generator set was required. A thermal model to fully describe the diesel engine and the enclosure would have been complex and the significance of the effects did not justify the development of such a model. Instead a simple thermal model, based on classical heat flow



DIESEL ENGINE COOL DOWN

FIGURE 2.10

concepts and using the results of the tests directly, was used. The assumptions underlying this model were that:-

- 1) The sump oil temperature adequately represented the temperature of the entire engine.
- 2) The heat input during running was constant and independent of load.
- 3) The ambient air temperature was constant and the air flow adequate to allow Newtons Law of cooling to hold.

$$\text{i.e. } \frac{dT}{dt} = k (T - T_a) \quad (2.4)$$

Figure 2.10 shows the results of a test carried out to determine the rate at which the sump oil temperature dropped once the diesel was stopped.

Equation 2.4 may be solved to give:-

$$T' = T_c e^{\frac{-t}{\tau}} \quad (2.5)$$

T' : instantaneous sump oil temperature above ambient
°C.

T_c : equilibrium sump oil temperature above ambient
°C.

T_c was evaluated to be $60^{\circ}\text{C} \pm 4^{\circ}\text{C}$ from readings taken during a 3 day period of continuous operation of the diesel.

The time constant τ_1 was evaluated to be 128 ± 4 minutes from a least square regression analysis of t v $\ln \frac{T'}{T_c}$. The coefficient of determination was 0.991.

The behaviour of the diesel during warm up was modelled using the results shown in Figure 2.7.1. This curve was of the form

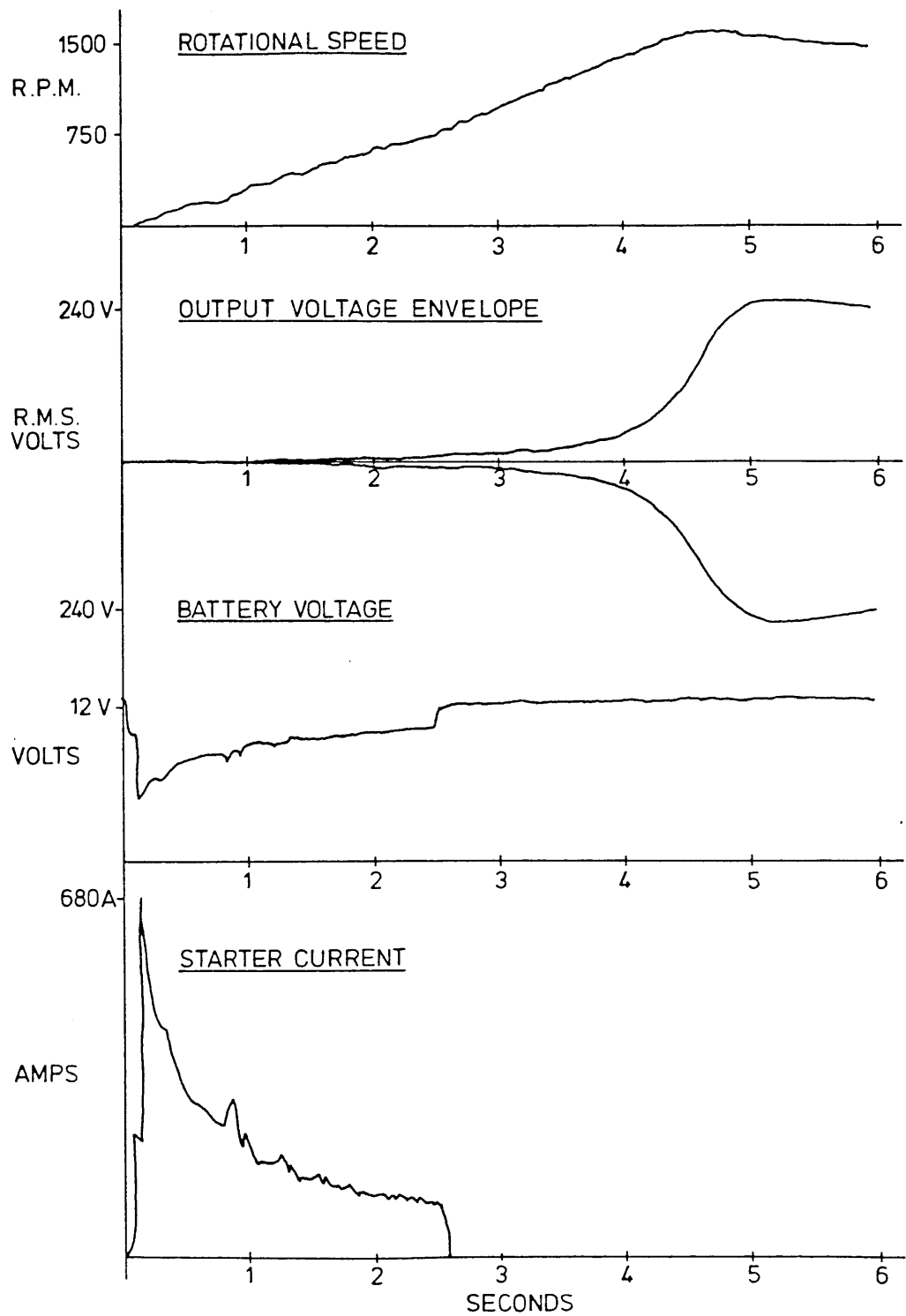
$$T' = T_c \left(1 - e^{-\frac{t}{\tau_2}} \right) \quad (2.6)$$

The time constant τ_2 was evaluated from a least squares regression of t v $\ln \left(1 - \frac{T'}{T_c} \right)$ and gave a result of 23.1 ± 0.4 minutes with a coefficient of determination of 0.997.

This simple model of Equations 2.5 and 2.6 together with the values determined for the constants gave an adequate representation of the diesel engine temperature and allowed the temperature dependent effects to be included in the simulation model described in Chapter 8.

2.3.5 Starting Performance

The diesel generator set was fitted with a remote start circuit operating a 12 volt pre-engaged starter motor



DIESEL SET STARTER PERFORMANCE

FIGURE 2.11

via a solenoid. The battery charging system was a dynamo fitted with a compensated voltage field control system (2.17). The operation of the starter system was monitored using an ultra violet chart recorder. Typical results are shown in Figure 2.11. The rotational speed measurement was made using a tachogenerator mounted on the alternator shaft and the starter motor current was measured using a 1200 amp/ 100mV shunt. The alternator output voltage was recorded as a 5 volt 50 Hz signal and was applied to the chart recorder via an isolating transformer.

A series of 12 tests were carried out and the time taken from initiation of start to production of 230 V was obtained from each trace. A mean time of $5.77 \pm .51$ seconds was deduced. The time was dependent on:-

- a) Engine temperature and condition.
- b) Battery temperature and condition.
- c) Time from last start.
- d) Load (the effect of the current compounding was such as to increase the speed of voltage rise under load).

It was not considered useful to attempt to examine the effect of each of these factors and so the worst case observed with a value of 7 seconds was used in the simulation model. This would give a pessimistic result of the simulations.

From the ultra violet chart it was calculated that the battery was required to produce 0.2Ah for a 7 second start. A battery size of 75Ah, at the 20 hour rate, was recommended for this engine. At very high rates of discharge a battery's capacity is much reduced; however after standing open circuit a battery will recover its apparent capacity. The battery capacity for repeated starts is therefore difficult to determine but an estimate of 40 starts without recharge appears reasonable. BS 3911 (2.18) specifies for vehicle batteries that they should be capable of 70 5 second starts at 25°C and 36 5 second starts at -18°C.

The energy required from the battery to start and accelerate the set, up to a firing speed of 750 rpm, was calculated from the 7 second start ultra violet trace to be 6.2 kJ.

The operation of the charging system was tested by partially discharging the battery and monitoring the battery voltage and current during the charging period. The results of this test are shown in Figure 2.12. It may be seen that assuming a 90% Ampere hour efficiency of the battery the 0.2 Ah for a single start may be resupplied to the battery in less than 2 minutes. From these tests it was shown that the battery and charging system were suitable for over 700 starts per day. However the projected life time of the starter equipment is only 10,000 starts (2.15). Therefore high numbers of

BATTERY CHARGING PERFORMANCE

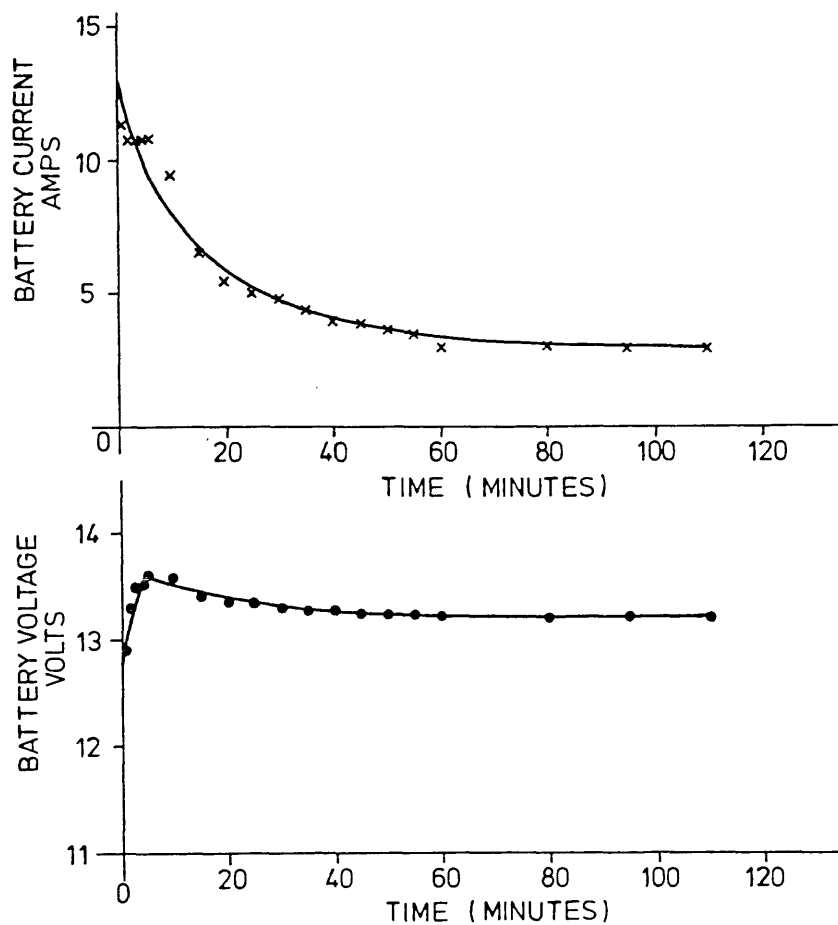


FIGURE 2.12

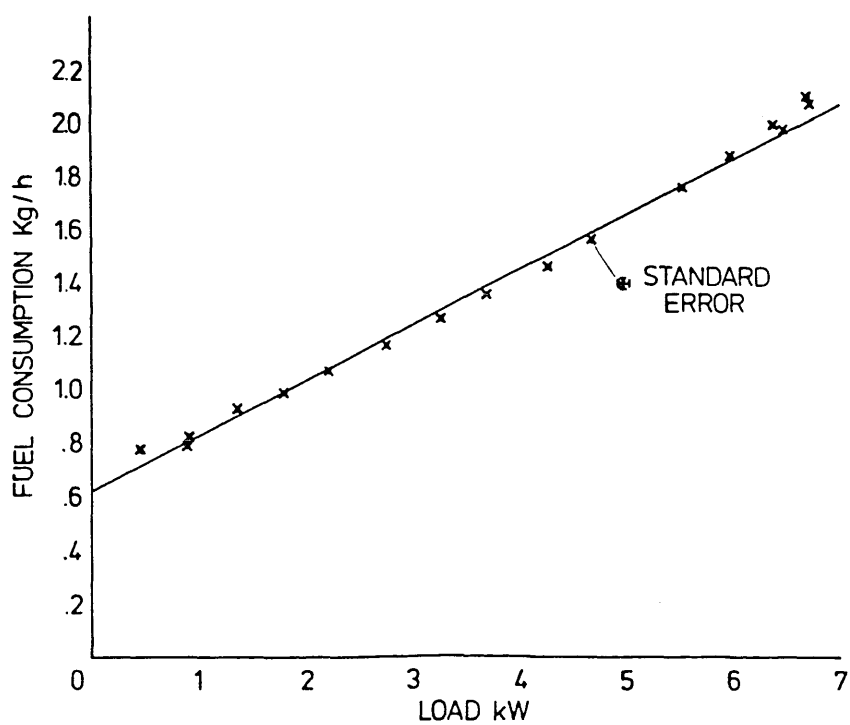
STEADY STATE FUEL CONSUMPTION
(NEW INJECTORS)

FIGURE 2.15

starts, although possible with this arrangement, will result in rapid failure of the starter system.

It is conventional practice in rotating uninterruptible power supply sets to start the diesel engine from a rotating flywheel (2.19). The flywheel is directly coupled to the electrical generator. The generator is fed from the electrical system and so maintains the flywheel at synchronous speed. When the diesel set is required the flywheel is clutched on to the diesel crank shaft and rapidly accelerates the engine to synchronous speed. This technique gives both rapid and reliable starting and avoids the limitation of starter lifetime. It is proposed that this method of engine starting should be used for the wind diesel system.

2.3.6 Effect of Injector Condition

Towards the end of the fuel consumption tests it was noticed that the maximum output power available from the generating set had decreased. A test was therefore carried out to examine the condition of the diesel by measuring the output voltage and frequency at various loadings. The results are shown in Figure 2.13. Both the output voltage and frequency of the set collapsed before the 6.4 kW rating was reached. These results showed that the diesel engine was not functioning correctly, probably due to carbonisation of the injectors. The injectors were then changed and the test

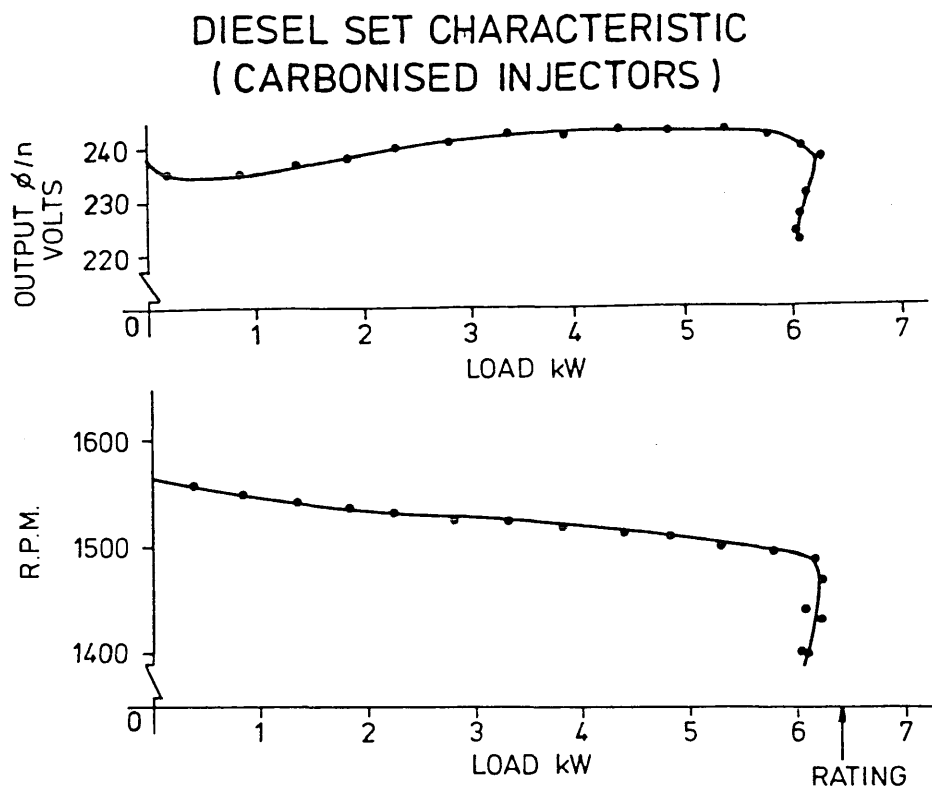


FIGURE 2.13

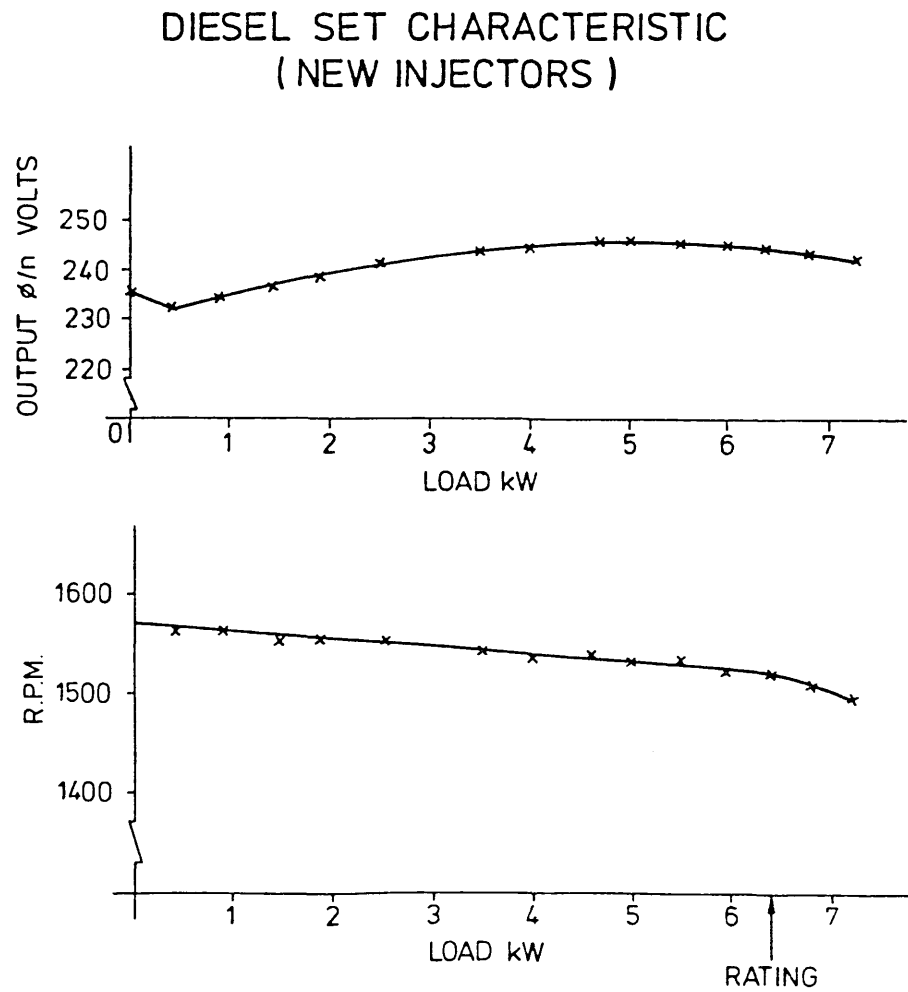


FIGURE 2.14

repeated. The results are shown in Figure 2.14 and indicate a correctly functioning engine with the voltage and frequency maintained over the entire operating range of the set.

The replaced injectors were badly carbonised. Direct injection engines, such as the ST2, due to their limited air swirl, use multi-orifice injectors with small individual orifices. These orifices are liable to blocking from carbon formation due to:-

- a) Dribbling, due to sluggish closure of the injection valve.
- b) The frying of the fuel left in the orifice passage.

It was a cause of concern that the injectors had carbonised sufficiently to reduce the maximum output of the set to below its rating in less than 100 hours of running. However discussions with Trinity House, who operate an extensive diesel generator set test programme, indicated that such problems were common. The solution adopted by Trinity House to injector carbonising is to reset the injector cut off spring loading after the initial 50 hours of running.

After the injectors had been replaced, and the cut off spring loading adjusted, the steady state fuel consumption tests were carried out once again. Figure

2.15 shows the results of these tests. The curve remained linear for rather longer at high loads, as would be expected. Interestingly at low loads the specific fuel consumption was increased with the clean injectors.

A least squares linear regression was carried out on these points to give:-

$$f = aP + b \text{ kg/h} \quad (2.7)$$

$$a = 0.207 \pm 0.004 \text{ kg/h/kW}$$

$$b = 0.625 \pm 0.017 \text{ kg/h}$$

with a coefficient of determination of 0.993.

Figure 2.14 shows the relationship between diesel generator output power and rotational speed (or frequency). This is the droop line of the set. The droop (d') is expressed as:-

$$d' = \frac{\text{change in speed from no load to rated load}}{\text{speed at rated load}}$$

and is usually between 3% -5%. This feature is built into the governors of all diesel generator sets to allow them to work in parallel with other diesel generators. During the autonomous parallel wind diesel operation described in Chapter 7, the droop line was used to

maintain a minimum loading on the diesel engine, by targeting the dump load control at the appropriate frequency.

2.4 Diesel Engine Minimum Loading

The manufacturers of the diesel engine, R.A. Lister, insisted that the diesel engine should not be run continuously at low load and constant speed. For continuous operation a minimum loading of approximately 2.5 kW should be maintained on the engine.

If the load drops below this value a number of mechanisms may lead to a deterioration in the engine performance. Firstly, over oiling may occur. At low cylinder pressures lubricating oil may be forced past the piston rings. This is only partially burnt and forms soft carbon deposits in the cylinder and also causes seating problems for the valves. Secondly, the low cylinder temperatures will lead to poor combustion of the diesel fuel and further carbon formation. Thirdly, the low cylinder temperature may cause accelerated corrosive wear of the cylinder liner. All these mechanisms are temperature dependent and their effect may be reduced by raising the operating temperature of the engine at low load. At high cylinder temperatures any oil passing the piston rings will be completely burnt. However, the ST2 is an air cooled engine with a centrifugal fan fixed to the flywheel. It was therefore not straightforward to alter the cooling system in order to increase the cylinder temperature at low load but maintain adequate cooling at high loads.

It is only necessary to run the engine at high loads for short periods to burn away the carbon deposits formed by low load running. If a supervisory controller were fitted to the wind diesel systems this could be programmed to provide periodic high loads which would give a negligible fuel penalty. Alternatively certain wind and load profiles will naturally give periods of high engine load.

A literature survey was carried out to look for the results of investigations of low load, constant speed running of diesel engines. No relevant work was found. However, other researchers working on wind diesel integration in the USA (2.20) and West Germany (2.21) have reported similar restrictions placed on the operation of diesel engines by the manufacturers. On the other hand Canadian workers (2.22) operated an autonomous wind diesel system allowing the load of a Lister ST3 engine to drop to zero with no apparent damage to the engine but no data was available on the wind and load profiles.

It was beyond the scope of the project to experimentally investigate the long term effects of low load running. However, the design of the dump load controller, described in Chapter 7, was such as to allow easy modification of the minimum loading constraint. Most experiments were carried out with a 40% (2.56 kW) minimum loading although some tests were performed with a 20% (1.28 kW) minimum load with no apparent problems.

2.5 Conclusions

The experimental work described in this chapter provided part of the foundation of the subsequent wind diesel study. The steady state fuel consumption of the generator set was measured and the change in consumption with injector condition noted. It was shown that there was an increase in fuel consumption associated with start up. A thermal model of the diesel engine was developed to allow this effect to be included in the time step simulation model described in Chapter 8. It was also shown that there was no significant penalty associated with rapid variations of the load.

The starting performance of the diesel generator set using the starter motor, was examined and shown to be suitable for frequent starting. However, the limitations caused by the wear on the starting equipment indicated that alternative means of starting the engine were necessary. A flywheel coupled to the main crankshaft of the engine by a clutch was proposed as a preferable method of starting.

The droop line of the generator set was measured together with the variation of output voltage with system load. The use of the droop line for maintaining a minimum loading on the diesel engine by controlling the system frequency to the appropriate value was discussed.

CHAPTER 3

DIESEL ENGINE WEAR RATE INVESTIGATION

3.1 Introduction

The examination of the behaviour of the diesel generator set was described in Chapter 2 but it was also a cause of concern that the operating conditions experienced by the diesel engine in a wind diesel system might give increased rates of wear on the engine components. Two main areas of wear in a diesel engine may be identified. These are firstly, the pistons and cylinders and secondly, the engine bearings.

Engine cylinder wear has been studied in detail (3.1; 3.2) and is caused by both corrosive and abrasive wear mechanisms. It has been shown experimentally (3.3) that if the cylinder wall temperature falls below 90°C there is a rapid increase in both cylinder and piston ring wear. These studies also indicated that this increased wear was caused by condensation of the corrosive products of combustion on to the cylinder wall. The action of the condensate was to break down the oil film and also to cause acidic attack on the cylinder wall. The products of combustion are particularly corrosive if high sulphur fuels are used. Tests carried out on a water cooled single cylinder petrol engine showed that apart from temperature dependent effects there was no additional cylinder wear due to starting and stopping. However, in a diesel engine excess fuel is injected at start up to allow the initial compression ignition.

This excess fuel washes the lubricant from the cylinder walls and so increases cylinder wear. For a hot start the duration of the excess fuel injection is short as once the diesel runs up to speed the fuel is reduced. With cold starting this abrasive wear mechanism will cause significant additional wear.

The engine bearings are also subject to abrasive wear mechanisms. Both the crankshaft and big end bearings on the ST2 engine were pressurised oil fed journal bearings while the small end bearings were splash lubricated. The main causes of wear on these bearings were lack of oil pressure caused by low rotational speed and dilution of the lubricant by diesel fuel (3.4). The design of the ST2 engine was such that any leaks in the fuel system resulted in the diesel flowing into the lubricating oil sump and so diluting the lubricant.

Discussion with the manufacturers and a survey of the literature gave general indications of the type of wear to be expected (3.5). However, no detailed information was available and so a short experimental programme was carried out.

3.2 Techniques for Wear Rate Evaluation

Four possible techniques for evaluating wear rates were examined.

3.2.1 Spectrographic Analysis (3.6)

When an engine wears, particles of various sizes are detached from the wearing surfaces and are washed into

the lubricating oil. The shape and size of the particles of debris are determined by the mechanism of the wear. Examination of the debris in the lubricant oil allows the engine wear to be monitored. By identifying the elements of the wear particles the source of the wear may be determined.

Spectrographic analysis uses their atomic spectrum to identify the constituents of the debris in the lubricating oil and measure their quantity. It is a relatively low cost approach and allows detection of both ferrous and non ferrous particles up to a size of $2 \times 10^{-6}\text{m}$. This technique only gives information on the quantity of each element in the lubricating oil and does not directly indicate the wear mechanism.

3.2.2 Ferrographic Analysis (3.7).

This is a more recently developed method, and allows analysis of the particles which are suspended in the lubricating oil by separating them with a magnetic force. Ferromagnetic materials and also materials such as aluminium and bronze which have worn against ferrous materials and so become slightly ferromagnetic may be examined using this technique. The major advantage of ferrography over spectrographic analysis is that particles of size greater than $2 \times 10^{-6}\text{m}$ may be examined and also information on the type of wear may be obtained by microscopic examination of the particles (3.8). However

as large particles may be considered, more care is necessary when sampling the lubricant and the analysis is more time consuming and expensive than spectrographic analysis.

3.2.3 Surface Activation (3.9).

For detailed analysis of the wear of parts of the engine the component under examination may be irradiated. Analysis is then carried out by evaluating the radiation level of the wear debris in the lubricant. An alternative technique is to coat the surface of the component with an easily detectable element. Dutch workers are carrying out an experiment to evaluate bearing wear of a diesel engine by using gold plated crankshaft bearings (3.10). Results are not yet available. Surface activation allows detailed inspection of wear on a particular component but is not suitable for a general examination of wear within the engine.

3.2.4 Direct Measurement.

The classical approach to wear evaluation was to strip the engine at intervals and measure the change in component sizes. This is a time consuming technique and requires skilled labour.

For a general assessment of engine wear, suitable to our purposes, the most appropriate technique was Spectrographic Analysis. This was a low cost technique which allowed overall examination of the wear within the engine and required a simple

TABLE 3.1Sources of Wear Elements in a Diesel Engine

Iron	-	Cylinder liners, crankshaft, piston rings
Chromium	-	Piston rings, cylinder liners
Aluminium	-	Pistons, bearings
Copper	-	Bearings
Lead	-	Bearings
Silicon	-	Ingested dirt
Sodium	-	Oil contamination (anti freeze in water cooled engines)
Tin	-	Bearing overlay.

TABLE 3.2Wear Rate Experiments

Experiment No.	Date	Running hours	Load kW	Cycle (mins)	No of Starts
1	5/4/84-19/4/84	134	4	Continuous	-
2	30/4/84-11/5/84	88	4	15 ON/30 OFF	350
3	16/7/84-29/7/84	116	4	4½ ON/1½ OFF	1550
4	7/11/84-16/11/84	216	6	Continuous	-
5	16/11/84-28/11/84	207	6	4½ ON/1½ OFF	2800

EQUIPMENT INTEGRITY ANALYSIS

FILE NUMBER : A.0010501

SWANSEA LABORATORY SERVICES
MECHANICAL ENGINEERING DEPARTMENT
UNIVERSITY COLLEGE OF SWANSEA
SWANSEA SA2 8PP U.K.
TELEPHONE : 0792 295219

DATE : 2 MAY 84

FILE : A.001

DEALER : 05

COMPONENT : 01

CLIENT : WIND/DIESEL PROJECT
RUTHERFORD APPLETON LAB
CHILTON DIDCOT
OXFORDSHIRE OX11 0QX

DEALER :

UNIT NO. : N/P

UNIT TYPE : N/P

MODEL : N/P

COMPONENT : ENGINE

LUBRICANT : SHELL

GRADE : ROTELLA 20W?20

		SAMPLE DATE		15 APR 84	18 APR 84	19 APR 84	30 APR 84	2 MAY 84
OPERATING	LUB.HRS/KM	N/P	N/P	N/P	N/P	N/P	N/P	N/P
DATA	EQUIP HRS/KM	N/P	N/P	N/P	N/P	N/P	N/P	N/P
WEAR METALS	IRON	35	40	42	45	43		
PPM	CHROMIUM	3	4	4	4	4		
	ALUMINIUM	8	9	9	9	10		
	COPPER	23*	27*	30	29*	29*		
	LEAD	16	17	17	17	18		
CONTAMINANTS	SILICON	11	10	11	11	12		
PPM	SODIUM	111***	115***	115***	118***	121***		
PHYSICAL	FUEL	>5***	>5***	>5***	>5***	>5***		
PROPERTIES	WATER	NEG	NEG	NEG	NEG	NEG		
	DISPERSANCY	NORM	NORM	NORM	NORM	NORM		
VISCOSITY (CST AT 40C)		N/A	N/A	N/A	N/A	N/A		
RESULTS		D21	D21	D21	D21	D21		
DEALER SAMPLE NUMBER		5	6	7	8	9		

SAMPLE DATE - 2 MAY 84 :-

CONDITION:

CRITICAL-THIS UNIT SHOULD RECEIVE IMMEDIATE ATTENTION

DISCREPANCY:

HIGH SODIUM LEVEL

RECOMMENDATION:

INSPECT UNIT FOR PROPER OPERATION

RESAMPLE AT REDUCED INTERVAL TO VERIFY PROBLEM CORRECTED

! - REPORTABLE, ## - UNACCEPTABLE, *** - URGENT

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FIGURE 3.1 SPECTROGRAPHIC ANALYSIS OF LUBRICATING OIL

(TYPICAL RESULTS)

oil sampling technique. The analysis of the oil samples was carried out by the Department of Mechanical Engineering of the University of Swansea on a contract basis. An atomic absorption spectrometer was used. The oil sample was diluted with 10 parts of white spirit and burnt in a nitrous oxide and acetylene flame. The spectrum generated was compared with that of a standard concentration of the element under investigation. The accuracy of this technique for determining the concentrations of the various contaminants was $\pm 5\%$. Figure 3.1 shows a typical set of results of this analysis. The main elements of interest and their sources are shown in Table 3.1.

3.3 Experimental Procedure*

The diesel engine was modified to allow easy sampling of the lubricating oil. A small stopcock was fitted to the tapped hole available for fitting an oil pressure gauge. This allowed direct access to the pressurised oil flow being passed to the bearings and valve gear. Samples were always taken with the engine running.

At the start of the test and at approximately 24 hour intervals during the experiment a small (5cc) oil sample was taken for analysis. As wear rates were low, tests involved approximately a week of diesel operation. During the tests the diesel engine and load were controlled by the Apple II+ microcomputer. Engine temperatures, fuel consumption and load were monitored during the tests.

* The experimental programme was carried out in collaboration with Dr. D. Infield assisted by Mr. C. Tucker and Mr. R. Reynolds of RAL.

Throughout the tests fuel dilution of the lubricating oil was experienced. This is a typical problem on an ST2 engine and efforts to cure the fuel leak were unsuccessful. The wear test programme was subsidiary to the main wind diesel experimental programme and so the tests were carried out over almost a year. It may be assumed that the condition of the diesel components varied within this period due to wear experienced during wind diesel experiments.

Table 3.2 shows the sequence of tests carried out. Experiment 1 was with continuous operation of the diesel engine to establish a base rate of wear. Experiment 2 was a slow on off cycle to examine the effects of the cylinder temperature cooling during the off period. It was believed that this cycle would result in increased corrosive cylinder wear. Experiment 3 was a rapid cycle and attempted to detect increased abrasive wear both within the cylinders and on the bearing surfaces. Experiment 4 was a further base case at a higher load and hence higher cylinder temperature. Experiment 5 was a rapid cycle at a 6kW load and was carried out immediately after the completion of experiment 4. In addition to the main elements of interest, tin residues were also examined during experiments 4 and 5 as wear on a lead/tin crankshaft bearing overlay was suspected. Throughout the tests the diesel engine and starter worked satisfactorily.

3.4 Results and Analysis

The oil samples taken during the 5 tests were analysed and the incremental wear was plotted against the running time of the diesel engine. Then an unweighted least squares linear regression analysis (3.11) was carried out to determine the wear rate. Because the incremental wear rate was used the regression line was forced through the origin.

The slopes of the various regression lines gave the wear rates in parts per million per 100 hours of engine running. The standard errors of the regression lines gave the standard errors of the wear rates. The number of pairs of data points used in the regression analyses were small (< 12) and so to establish confidence limits on the wear rates a students t distribution was used (3.12).

The 5% confidence limits (C_5) of the wear rates show the band within which there is a 95% probability of the true wear rate being located.

The 5% confidence limits are given by:-

$$C_5 = \pm S.E. \times t \quad (3.1)$$

where S.E.: standard error of slope or wear rate.

t : t value corresponding to a 5% confidence level and
n-1 degrees of freedom.

n : number of pairs of data points.

Due to the complex nature of the equation to derive t it is usually looked up in statistical tables.

To compare the significance of the difference in the wear rates of 2 tests the t distribution may again be used. A t value is calculated by:-

$$t = \frac{a_1 - a_2}{(S.E_1^2 + S.E_2^2)^{\frac{1}{2}}} \quad (3.2)$$

where a : slope of the regression line or wear rate.

The calculated t value is then compared with the tabulated t values for the 5% confidence level and $n_1 + n_2 - 2$ degrees of freedom.

Where the number of points in the regression analysis is small a better estimate of the t value may be obtained by calculating a variance of the difference of the two slopes being compared.

The t value is then calculated (3.13) by:-

$$t = \frac{a_1 - a_2}{(S^2 + (\frac{1}{\sum x_1^2} + \frac{1}{\sum x_2^2}))^{\frac{1}{2}}} \quad (3.3)$$

where $S^2 = \frac{S.S.D_1 + S.S.D_2}{n_1 + n_2 - 2}$ and is the variance of the

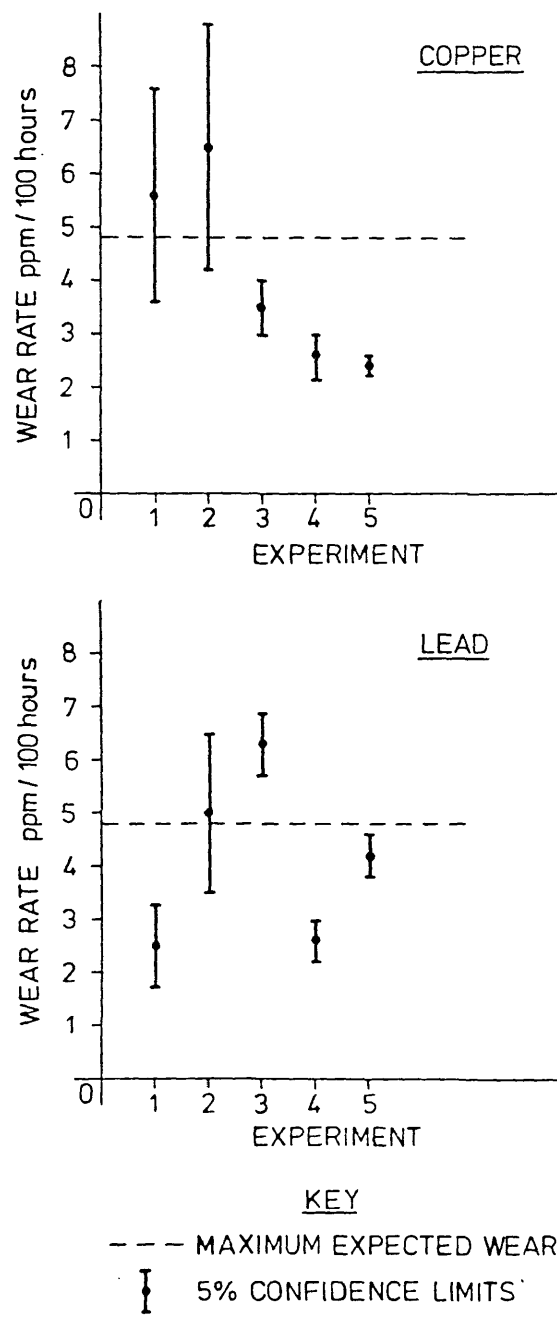


FIGURE 3.2.1 DIESEL ENGINE WEAR RESULTS

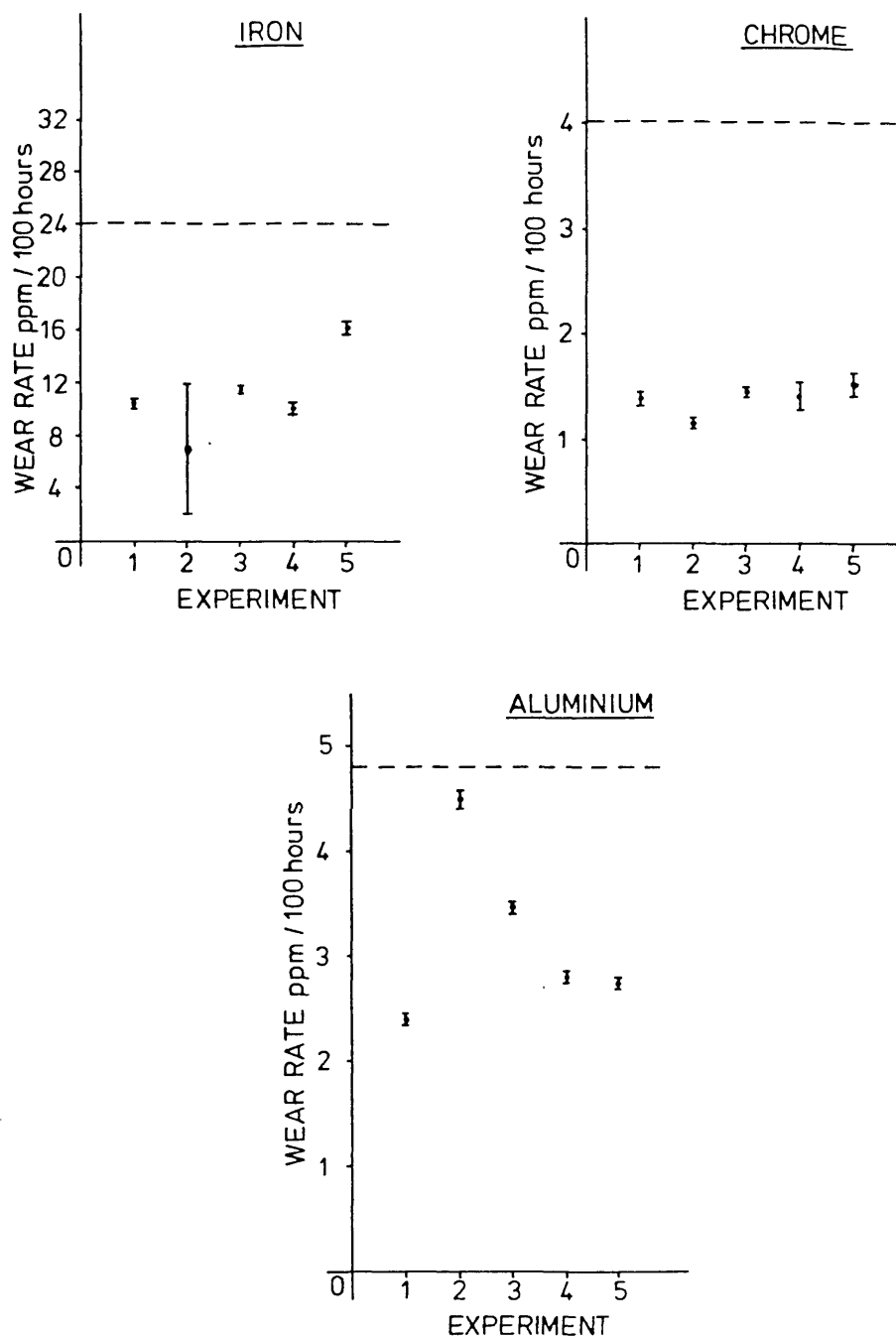


FIGURE 3.2.2 DIESEL ENGINE WEAR RESULTS

difference of the two slopes.

S.S.D: sum of the squares of the deviations about the regression.

Σx^2 : sum of the squares of the independent variable of the regression.

The wear rates measured during the 5 tests, together with error bars indicating the 5% confidence limits, are shown in Figure 3.2. In addition the maximum expected wear rates for air cooled diesel engines of this type are shown as the dashed lines.

Inspection of the results for Iron, Chrome and Aluminium shows that the wear rates were not excessive in any of the experiments. Copper showed high rates of wear in the early experiments, 1 and 2, but this decreased in the later experiments. This was surprising as experiments 3 and 5 were rapid cycling which, it was expected, would have increased bearing wear. A possible explanation is that one of the bearings was not fully run in at the start of the tests. Lead also showed high rates of wear. The main lead component of the engine was a lead/tin overlay of the main bearings. This was designed to wear away during the early part of the engine life and so the high wear rates were not considered detrimental to engine lifetime.

The expected increase in cylinder wear, caused by temperature cycling, in experiment 2 was not seen. This was probably due to the low operating temperatures of the diesel generator set even under continuous full load conditions. The ST2 engine has a

TABLE 3.3
Results of Wear Rate Experiments 4 and 5

Element	Wear rate continuous (4) ppm/100 hrs	Wear rate intermit- tent (5) ppm/100 hrs	Increase/ Decrease %	Significant at 5% confidence level.
Iron (Fe)	10.24	16.78	+ 64	Yes
Chrome (Cr)	1.40	1.53	+ 9	No
Aluminium (Al)	2.78	2.72	- 2	No
Copper (Cu)	2.65	2.37	- 11	No
Lead (Pb)	2.62	4.21	+ 61	Yes
Tin (Sn)	1.72	2.99	+ 73	Yes

maximum rating of 15kW at 2600 rpm and has a cooling system sized for this rating. It is therefore rather overcooled when used in a generating set rated at 6.4kW and 1500 rpm. Low operating temperatures would give rise to continuous corrosive wear and the effect of on off cycling would then not be detectable.

Experiments 4 and 5 were carried out sequentially and each entailed over 200 hours of running. This method of testing allowed the effects of rapid cycling to be determined more accurately. The increase in wear rates caused by the rapid cycling is shown in Table 3.3. The significance of the change in wear rates, estimated at the 5% confidence level using equation 3.3, is also listed. A 64% increase in Iron wear occurred. This was probably due to the over fuelling of the engine at start up washing the lubricant from the cylinder walls. Another possible source of Iron was wear on the crankshaft. Significant increases in Lead and Tin wear were also recorded indicating destruction of the bearing overlay. In no cases were the wear rates greater than the manufacturers maximum expected values.

3.5 Conclusions

If a diesel engine is used to provide supplementary power on a wind diesel system it will be subject to large numbers of starts and stops. These experiments showed that neither slow cycling (1.3 starts per hour) or rapid cycling (10 starts per hour) caused excessive wear on the main engine components. The tests

were carried out with high level of fuel dilution of the lubricating oil which would artificially increase wear rates.

Any general conclusions drawn from only 760 hours of running must be preliminary. Techniques have been developed to assist in the prediction of long term wear rates from short tests (3.14) but these require an existing data base of wear rates which is not yet available for these operating conditions. However the experimental results indicate that mean start stop cycle rates of up to 85,000 per year will not reduce engine life. Energy storage and particular control strategies may be used to reduce diesel starts but only with an associated cost penalty. The results of the work described in this chapter enable these costs to be minimised by allowing the highest number of starts before significant damage occurs to the diesel engine.

CHAPTER 4

THE WIND TURBINE AND INSTRUMENTATION

4.1 Introduction

Hawker Siddeley Power Plant provided, for use in the development of the wind diesel system, a type L916 aerogenerator manufactured by the North Wind Power Company of Vermont, USA. The wind turbine generator was a prototype and no detailed drawings or test data were available. It was assembled and erected on a 20 metre tower at the Rutherford Appleton Laboratory in February 1984. It was initially connected to the RAL 415V network for testing and subsequently used for the integrated wind diesel experiments.

4.2 The Wind Turbine

The wind turbine was a 9 metre rotor diameter, horizontal axis, down wind free yawing machine with passive blade pitch control. It was originally developed under a US Federal funding programme and was then fitted with a 4 kW Lundel permanent magnet alternator and spring control of the blade pitch mechanism (4.1). The model supplied to the project was fitted with a 16 kW, 3 phase, wound field alternator with a pneumatic blade pitch mechanism. It had been designed for connection to a 60Hz low voltage network but the control scheme had been modified, by the manufacturer, for 50Hz operation. The wind turbine is shown in Figures 4.1 and 4.2.



FIGURE 4.1 R.A.L. WIND TEST SITE SHOWING L916 WECS

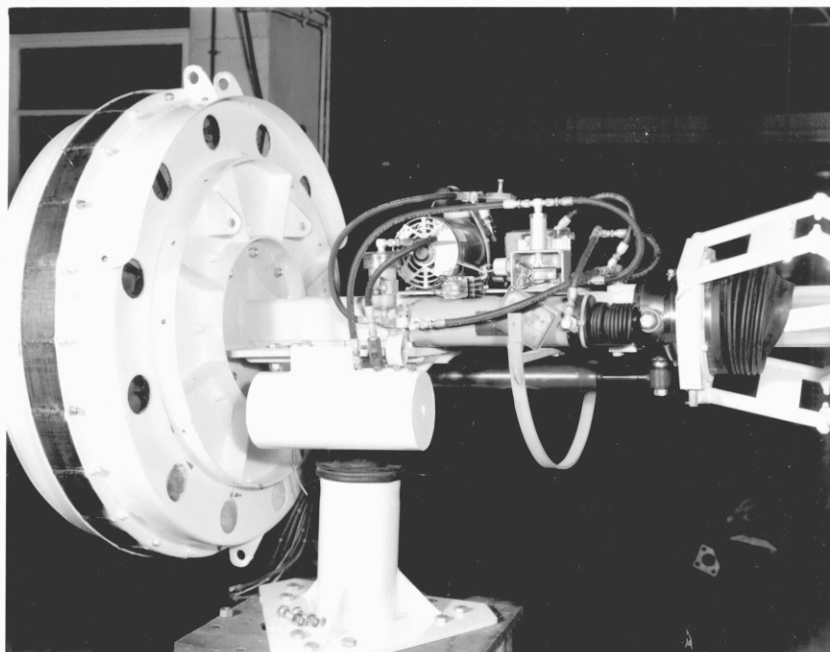


FIGURE 4.2 L916 WIND TURBINE WITH NACELLE COVER REMOVED (NOTE PNEUMATIC SYSTEM)

The blades were of laminated birch with a Go 797 aerofoil section. The blade pitch control mechanism consisted of an air compressor, solenoid valve and two pneumatic rams, with a damper connected in parallel, all mounted in the nacelle. With no electrical supply to the compressor and valve, air was vented from the pneumatic system and the blades adopted a fully feathered or coarse pitch position. In this condition the machine autorotated at up to 5 r.p.m., depending on the wind speed. No brake was fitted either to the main drive or to the yaw shaft. When the blade pitch control system was powered the compressor operated, the solenoid valve closed and blades were moved into the run or fine pitch position by the pneumatic rams. At wind speeds in excess of 4.5 m/s the machine could then run up to its synchronous speed of 125 r.p.m.

The geometry of the blade pitch mechanism was such that in the event of excessive blade thrust or high rotational speeds the blades would partially feather against the pneumatic rams which held them in the run position. This gave a safe mode of operation in wind speeds above the rating of the machine (14 m/s) or if an overspeed resulted from loss of load. The pressure of the pneumatic system was set to 49 p.s.i. on the manufacturer's recommendation.

The drive from the blades was transmitted via a teeter and delta 3 mechanism directly to the main shaft. This shaft was coupled to the alternator by a centrifugal sprag clutch and a flexible coupling across which two dampers were fitted. The torsional

TABLE 4.1

WIND TURBINE GENERATOR MECHANICAL PARAMETERS

Wind Turbine Rotor Inertia (complete)	$301 \text{ kg m}^2 \pm 20 \text{ kg m}^2$
Wind Turbine Alternator Rotor Inertia	$17 \text{ kg m}^2 \pm 2 \text{ kg m}^2$
Torsional Stiffness of Flexible Coupling	$9400 \pm 520 \text{ Nm/radian}$
Angular momentum of wind turbine rotor	68 Joule-sec/mech. degree
	2.85 Joule-sec/elec. degree
Angular momentum of wind turbine alternator rotor	3.9 Joule-sec/mech. degree
	0.16 Joule-sec/elec. degree

TABLE 4.2

WIND TURBINE GENERATOR ELECTRICAL PARAMETERS

Alternator Rating at 220 V, 125 rpm	21 kVA
No. of poles	48
Armature resistance R_a	0.12 p.u.
Direct axis synchronous reactance X_d	1.87 p.u.
Direct axis transient reactance X_d'	1.04 p.u.
Direct axis subtransient reactance X_d''	0.85 p.u.
Quadrature axis synchronous reactance X_q	1.58 p.u.
Direct axis open circuit transient time constant T_{d_o}'	300 ms

stiffness of the flexible coupling was measured by applying static loads. The polar moments of inertia of the wind turbine were also measured. An acceleration technique (4.2) was used for the rotating masses while the moment of inertia of the blades was measured by timing the oscillations of the blades mounted as a pendulum on a knife edge.* The results of these tests are shown in Table 4.1.

The alternator was a 48 pole, 3 phase synchronous machine wound for 220/127 volt operation. It was rated at 21 kVA at 125 r.p.m. The machine was tested by H. Bleijs (4.3) and the main machine parameters are given in Table 4.2. The voltage rating of the wind turbine alternator necessitated the use of a 415/220 volt transformer for connection to both the L.V. system and the diesel generator set.

The high transient reactance of the alternator, together with the multipole winding and flexible coupling, obviated the need for synchronising equipment. As soon as a control frequency relay sensed that the frequency of the alternator output was in the range 47-53Hz it applied an auxiliary voltage to close the main utility contactor. Thus, paralleling was permitted at any speed between 117.5 - 132.5 r.p.m. irrespective of the relative angles of the voltage of the machine and supply. The field was not reduced for paralleling.

* This experiment was carried out in collaboration with D.G. Infield of RAL.

EXCITATION SYSTEM

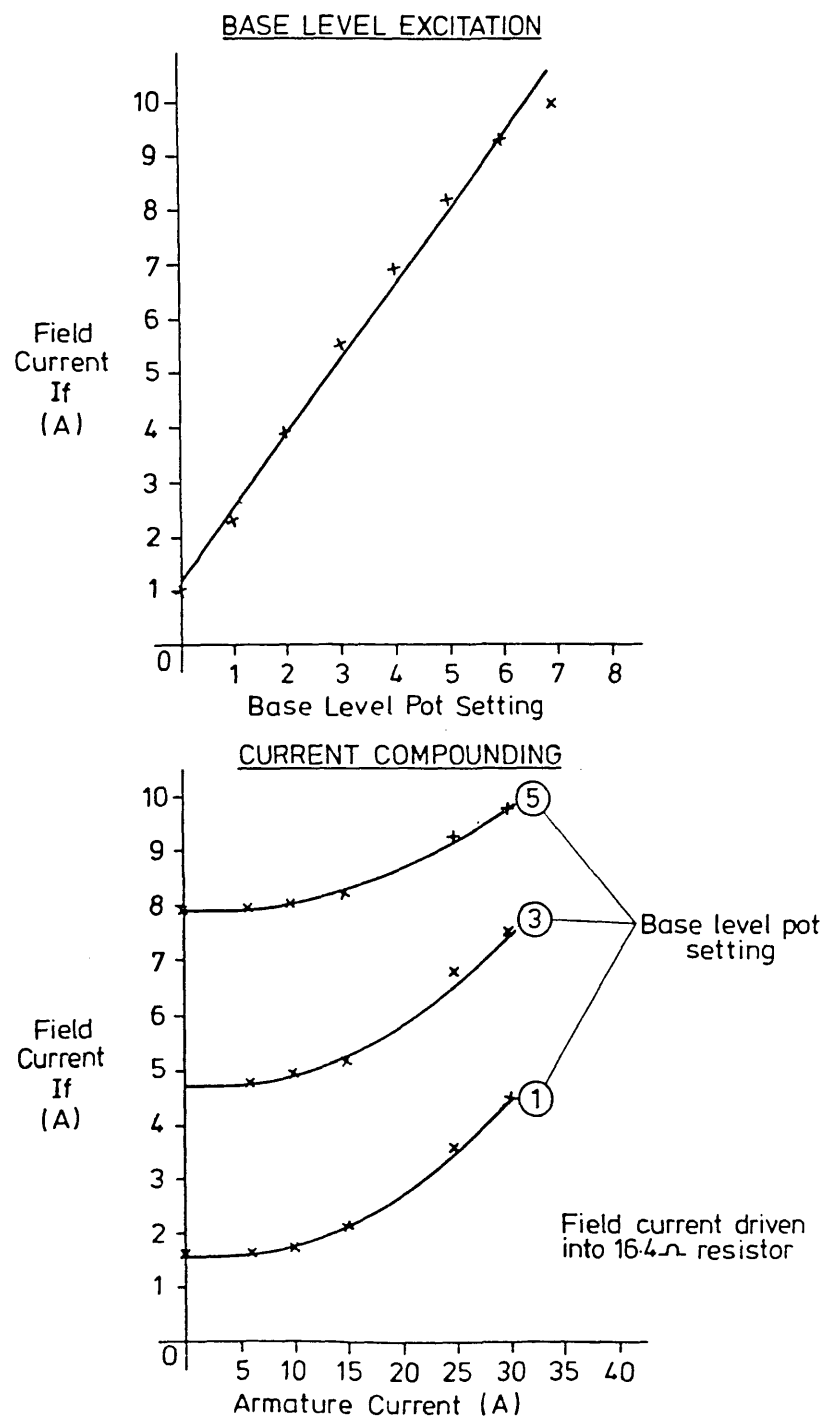


FIGURE 4.3

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	1	REVISE & REDRAW	12 SEP 83	

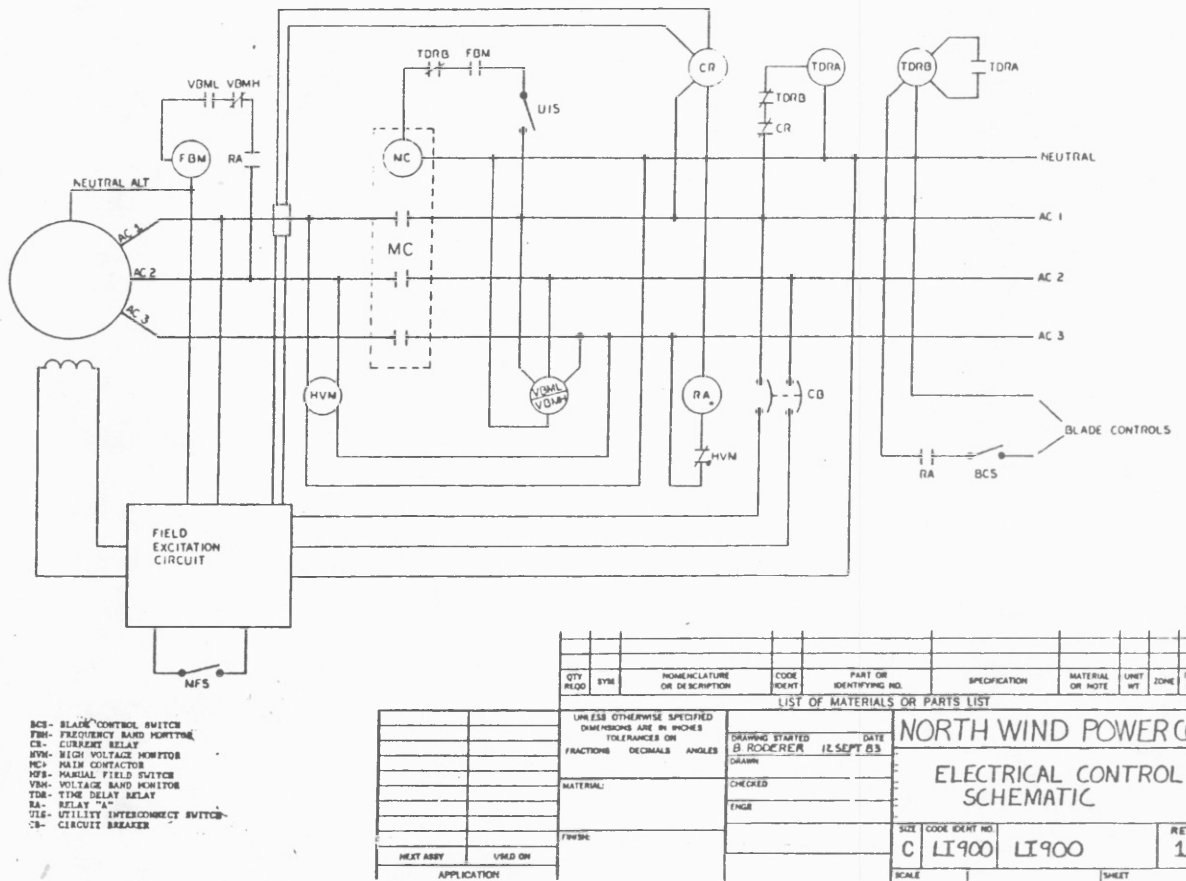


FIGURE 4.4 L916 CONTROL SYSTEM (NORTH WIND POWER COMPANY)



FIGURE 4.5 ERECTION OF L916 WECS (NOTE BOOM ANEMOMETER)

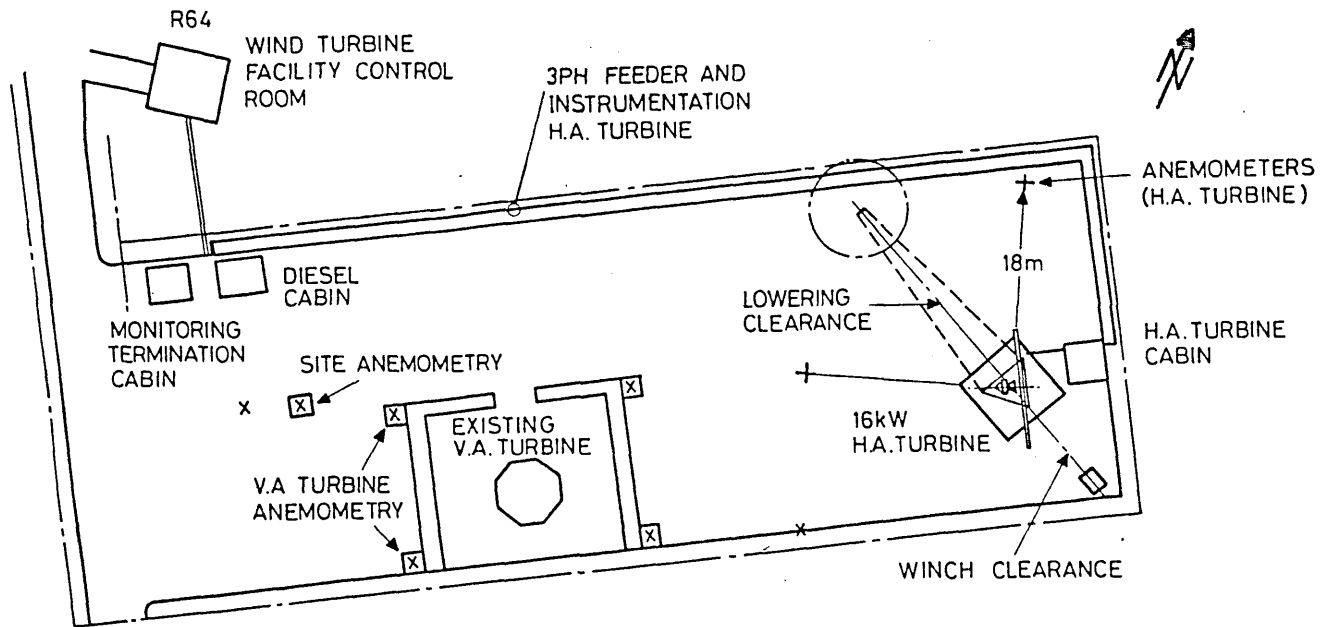
Power for the excitation of the field was supplied from a connection on the 220V network. There was no AVR but the field control circuit was arranged to provide an adjustable base level setting with compounding proportional to the magnitude of the generator armature current. As supplied by the manufacturer this circuit was defective but after repair was tested in the laboratory and the results are shown in Figure 4.3. The excitation control equipment was located in a control cubicle together with the control scheme. This scheme is shown in Figure 4.4.

4.3 The Site

The wind turbine was erected by RAL staff using a manual main and backing winch. The final stage of erection is shown in Figure 4.5.

The location of the wind turbine is shown in Figure 4.6. The site is open to the South but partially obstructed by laboratory buildings to the North West and by a small hill to the North East. Data was not taken when the vertical axis wind turbine was upwind and in operation, as the turbulence in the wake of this machine would have led to inaccurate readings.

The control cubicle supplied by the manufacturer was located in the turbine cabin together with the 25 kVA 415/220 volt transformer and an instrumentation marshalling and power supply cubicle. The data logging and wind turbine control equipment were located in the wind turbine control room building, R64.

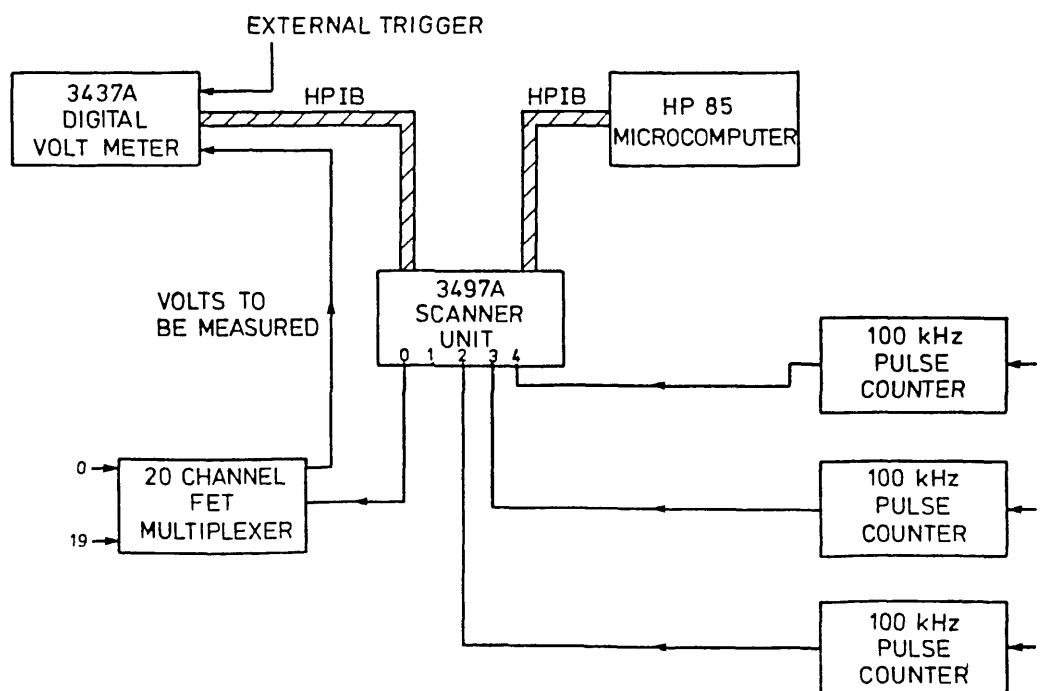


LOCATION OF L916 H.A.WIND TURBINE

FIGURE 4.6

FIGURE 4.7

DATA ACQUISITION SYSTEM



4.4 The Data Acquisition System

At the start of the project no data acquisition system was available to monitor the proposed wind diesel system and the selection and commissioning of a suitable system was necessary. The various data logging requirements of the proposed experiments were assessed and a performance specification for a data acquisition system was drawn up.

After consideration of various types of data logger the following equipment was selected:-

- HP 3054A Data Acquisition System
- 20 Channel FET multiplexed A/D convertor
- 3 100 kHz pulse counters
- HP85B microcomputer.

The data acquisition system is shown schematically in Figure 4.7.

In order to make use of the computing facilities available at RAL it was necessary to arrange for the transfer of data on to the RAL CMS interactive computing system. Access was then possible to the main SERC Atlas computers. This was a requirement shared by the RAL vertical axis wind turbine test facility. Therefore an additional HP85B was purchased and the data link commissioned by RAL staff. In this way it was possible to perform the main data processing on the CMS system using FORTRAN 77. Control of the data logging system and initial processing of the data was performed on the HP85B in HP

Basic. Details of the programs developed are given in Appendices A and B.

4.5 Wind Turbine Instrumentation

The wind turbine was instrumented both to allow performance testing of the machine and to monitor the behaviour of the wind diesel system.

Instrumentation was installed to measure the following parameters:-

Free wind speed at hub height

Wind speed 1 rotor radius upwind of the rotor disk

Rotational speed of the wind turbine

Rotational speed of the wind turbine alternator

Blade pitch angle

Yaw angle of the nacelle

Power, phase current, line voltage and frequency from the wind turbine

Alternator field current

The anemometers to measure free wind speed were mounted on towers at the wind turbine hub height. The towers were sited 18 metres from the wind turbine. This corresponded with the IEA recommended minimum clearance for measuring an undisturbed wind stream (4.4). The towers were positioned to ensure that one set of anemometers was always in the free wind stream irrespective

of wind direction. The data from the anemometer in the wake region of the wind turbine was discarded. On each tower a Porton type 100K anemometer and a Reading type were mounted on a 1.5 metre cross member. The Reading anemometers were cup anemometers made by the Meteorology Department of Reading University while the Porton anemometers were commercial cup anemometers. Both types gave a 0-12V square wave output. The outputs of the Porton anemometers were fed directly into the data acquisition equipment as pulse trains while the Reading anemometers outputs were passed through frequency to voltage convertors and input as analogue voltage signals. All anemometers were calibrated in the Central Electrical Research Laboratory wind tunnel at Leatherhead before erection.

A boom was fitted to the wind turbine which allowed the installation of a Porton 100K anemometer and Porton W200P wind vane 4.5 metres upwind of the rotor. The anemometer output was fed into the data acquisition equipment as a pulse train while the wind vane potentiometer was supplied from a constant voltage source to give an analogue input. The orientation of the wind turbine nacelle was measured using a rotary potentiometer fixed below the main yaw bearing. The pitch angle of the blades was monitored by a linear potentiometer mounted parallel to the main pneumatic pitch control rams. This transducer failed to work satisfactorily because vibration led to spurious readings. The rotational speeds of both the wind turbine rotor and alternator rotor were measured using optical switches reflecting infra-red light from painted marks on the rotating surfaces of the two rotors. Although most useful during commissioning these optical switches failed after some weeks operation.

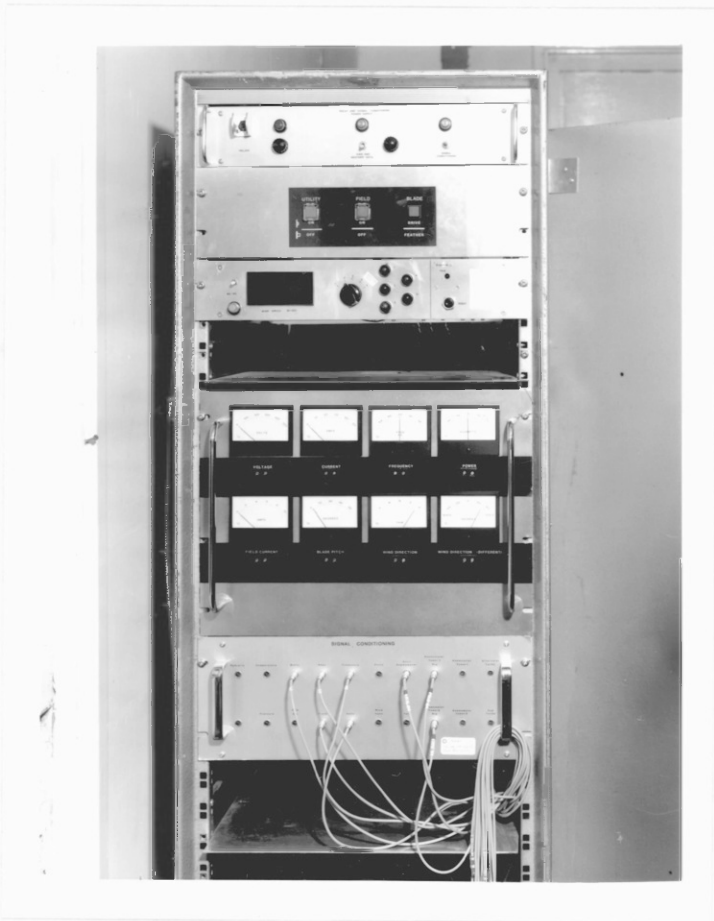


FIGURE 4.9 DATA ACQUISITION RACK



The main electrical transducers were mounted in the control room although provision was made to allow easy transfer of them to the turbine cabin. These transducers measured frequency, three phase power and single phase voltage and current. The outputs of the transducers were 0-10mA current signals which were passed through precision resistors to provide a voltage input to the data logging system. The field current was measured by a d.c. current transformer which was fitted into the wind turbine manufacturers control cubicle. In addition to the data acquisition system inputs the main instrument signals were displayed on analogue meters on a control rack in the control room R64. This control rack also housed remote control buttons for the wind turbine field, blade pitch and contactor controls. The remote control scheme was a 24V d.c. relay arrangement. From the control rack it was possible to operate the wind turbine with indication of the main system parameters. The control and data acquisition racks are shown in Figures 4.8 and 4.9.

4.6 Connection of the Wind Turbine Generator to the RAL 415V Network

To gain operating experience with the wind turbine and also to allow power performance testing it was desirable to connect the wind turbine generator to the RAL 415V network.

The direct connection of a consumer owned synchronous generator to a low voltage public main has not normally been permitted in the UK (4.5). The main reason for this restriction was that in the event of an open circuit in the feeding system the

synchronous generator could continue to supply the local load. This autonomous operation was considered unacceptable as it posed a danger to the utilities personnel engaged in the repair of the breakdown and also could result in poor quality of supply being given to consumers in the area being fed from the generator. The primary document covering the connection of consumer owned generators to the low voltage public network was Engineering Recommendation G47/1 (4.6) and this specifically excluded the direct connection of synchronous generators. This document has now been withdrawn but not yet replaced. It is expected that the recommendations which will supercede Engineering Recommendation G47/1 will permit the parallel operation of directly connected synchronous generators (4.7).

Practice in the US, however, has been to allow the direct connection of synchronous generators. The protection requirements are identical to those for the direct connection of induction generators (4.8).

As the RAL operates its own 11kV system, permission was obtained for the connection, for test purposes, of the wind turbine generator directly on to a 415 volt feeder. The electrical connection was as shown in Figure 4.10. The control scheme provided by the wind turbine manufacturer did not include any protection against electrical faults and only limited protection against autonomous operation. A protection scheme was therefore designed based on the requirements of Engineering Recommendations G47/1 and G26 (4.9).

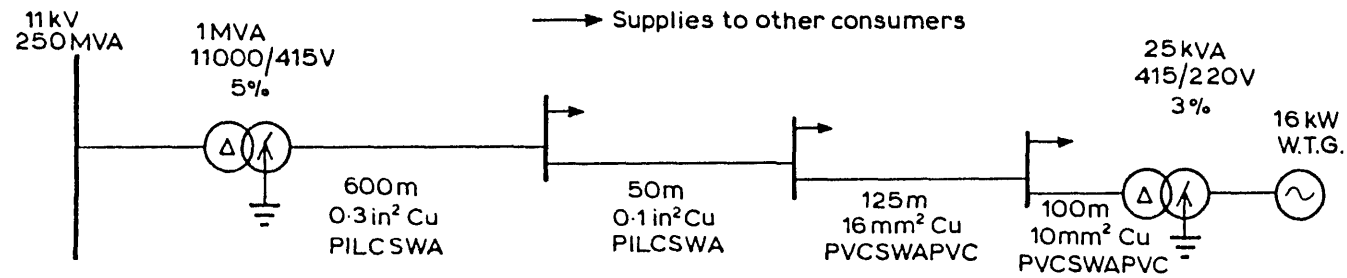


FIGURE 4.10 ELECTRICAL CONNECTION OF L916 ON TO RAL NETWORK

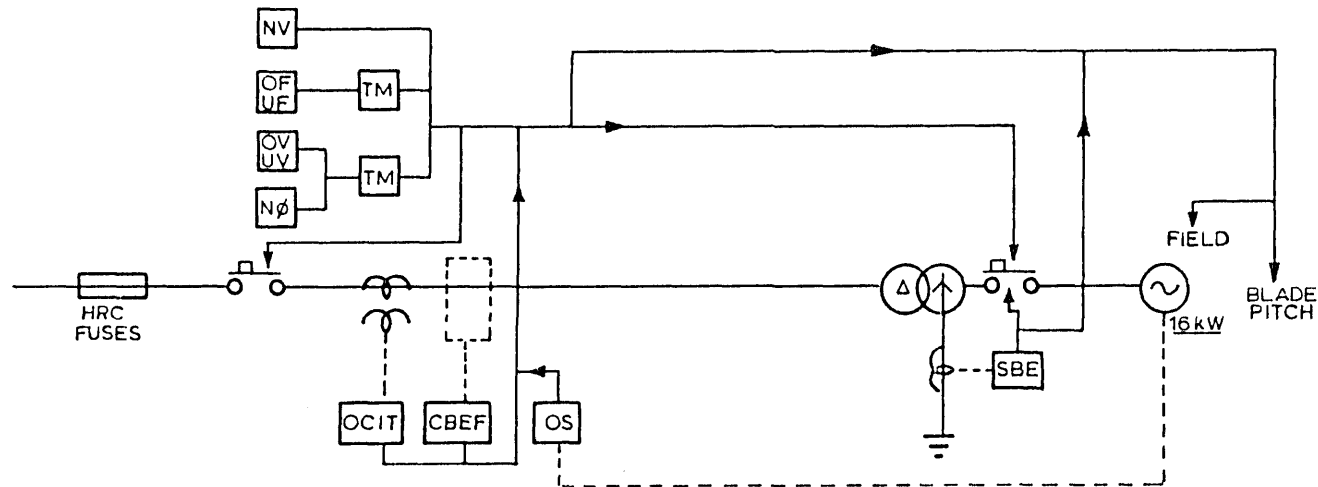


FIGURE 4.11 ELECTRICAL PROTECTION OF L916 WIND TURBINE GENERATOR

Neither of these documents were directly relevant but they did provide some guidance. The scheme is shown in Figure 4.11 and the relays and settings are listed in Appendix C.

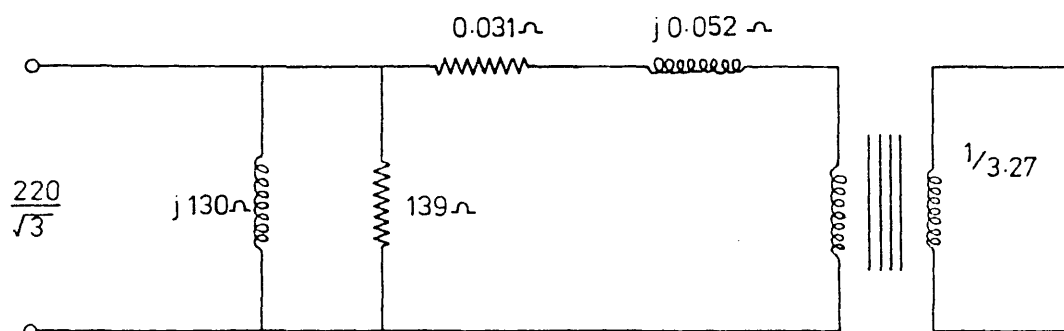
Protection against faults was provided by the HRC fuses, the two earth fault relays and the overcurrent relay. Protection against sustained autonomous operation was provided by the over and under frequency relays, the over and under voltage relays and the negative phase sequence voltage relay. Overspeed protection of the generator was provided by an optical tachometer feeding a voltage sensing relay. Loss of excitation protection was not fitted although the field current was displayed at the control rack. The relays used were of the industrial type and the tripping arrangement was such that the main contactor was released in the event of relay failure.

The transformer used to connect the wind turbine generator to the 415V network was a 25 kVA 415/220V unit. Detailed parameters were not available for this unit and so the transformer was tested using standard techniques (4.10). An equivalent circuit is shown in Figure 4.12.

4.7 Electrical Study

To calculate the protective relay settings and to check stability of the proposed systems a short electrical system study was carried out. Electrical system computer aided design facilities were not readily available and so classical techniques were used to obtain approximate, but generally pessimistic, results.

FIGURE 4.12
415 / 220 VOLT TRANSFORMER



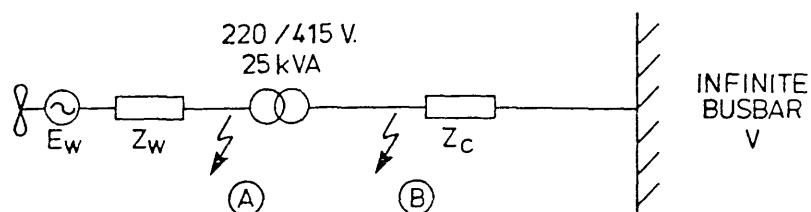
VECTOR GROUP Dyn1

Zero sequence impedance 0.014Ω

Impedance voltage 3.14% on 25 kVA base

FIGURE 4.13

L.V. CONNECTION OF WECS



The main assumptions implicit in classical transient stability calculations are:

- a) Damping is ignored.
- b) Each machine is represented by a constant transient reactance in series with a constant transient internal voltage.
- c) Only synchronous frequency voltages and currents are considered.

For fault analysis the main assumptions are:

- a) The impedance of the fault is zero.
- b) Each machine is represented by a constant subtransient reactance in series with a constant subtransient internal voltage.
- c) Only synchronous frequency voltages and currents are considered.

The machine parameters of the wind turbine generator and the diesel generator are shown in Tables 4.1, 4.2, 4.3 and 4.4.

4.7.1 Faults on the L.V connected system

The wind turbine generator and its connection on to the RAL system are shown schematically in Figure 4.13. The impedance of the connection from the generator transformer to an infinite busbar (Z_c) was calculated to be:

$Z_C = 0.189 + j0.039$ per unit on a 100kVA base.

A 3 phase fault on the 220V network at position A was considered. No phase fault protection was fitted to the 220V system and so it was important to ensure the 415V protection would operate for the fault infeed from this system.

The magnitude of the fault current was calculated from:

$$|I| = \frac{V}{Z_C + Z_T} \text{ per unit} \quad (4.1)$$

Where

V : infinite busbar voltage

Z_C : connection impedance

Z_T : transformer impedance

This was evaluated to give a fault current of 560A at 415V which would operate the 40A H.R.C. fuses in 30 milliseconds.

A 3 phase fault on the 415V network at position B was considered. This fault would rapidly be cleared by the fuses of the feeding network but fault current would also flow from the wind turbine generator.

The magnitude of this fault current contribution was given by:

$$|I| = \frac{E''_w}{Z''_w + dZ_C + Z_T} \text{ per unit} \quad (4.2)$$

Where

E''_w : W.T.G. subtransient internal voltage

Z''_w : W.T.G. subtransient impedance

d : fraction of distance to fault

With $d = 0.5$ this was evaluated to be 33A at 415V. Clearly this was inadequate to operate the 40A HRC fuses but would operate the IDMT protection in approximately 10 seconds provided the fault current was sustained. It is more likely however that a voltage or frequency trip would occur.

Unbalanced faults would be cleared by the IDMT relay which had a fixed time (2s) element which operated for unbalanced currents greater than 15 Amps.

Earth fault protection was provided using a core balance relay on the 415V network and a neutral connected standby earth relay on the 220V system. The sensitivity of each relay was 3 Amps to ensure operation under all credible conditions.

4.7.2 Overcurrents on Paralleling with the L.V. connected system

The WECS was not synchronised with the network but paralleled as soon as the generated frequency reached 47Hz. Therefore overcurrents were likely, due to out of phase paralleling. The maximum overcurrent on paralleling would occur with the voltage vectors 180° out of phase. The magnitude of this current was given by:

$$|I| = \frac{V + E''_w}{Z_w'' + Z_C + Z_T} \text{ per unit} \quad (4.3)$$

This was evaluated to be 68 amps at 415V. The experimental results, described in Chapter 5, were rather lower than this.

4.7.3 Stability of the L.V. connected system

The power angle equation for transient operation of a salient pole alternator may be derived from the vector diagram of the machine (4.11) and is given by:

$$P = E'_q V \frac{Z_q}{Z^2} \sin(\gamma + \delta) - \frac{V^2 r}{Z^2} + V^2 \frac{(X'_d - X_q)}{2Z^2} \sin 2\delta \quad (4.4)$$

$$\text{Where: } \gamma = \tan^{-1} \frac{r}{X_q}$$

$$Z_q^2 = r^2 + X_q^2, \quad Z^2 = r^2 + X'_d X_q$$

Where:

E'_q : quadrature axis transient internal voltage

δ : power angle of the rotor

r : armature resistance

X_d : direct axis synchronous reactance

X'_d : direct axis transient reactance

X_q : quadrature axis synchronous reactance.

In 4.4 the second term includes the effects of resistance of the machine armature while the third term represents the effects of saliency. If both resistance and saliency are neglected the equation reduces to the well known form for power transfer down a transmission line.

$$P = \frac{EV}{X} \sin \delta \quad (4.5)$$

Equation (4.4) was solved using the machine parameters of the wind turbine generator and the calculated connection impedance. For simplicity the quadrature axis transient internal voltage E'_q and the voltage of the infinite busbar V were assumed constant at 1p.u. Figure 4.14 shows the calculated power angle curve.

This shows the stability limit for small oscillations to be at 17.8kW. This was a pessimistic estimate as the compounding of the field would increase the internal voltage E'_q . However the more complete simulations of the wind turbine generator carried out by A. Tsitsovits (4.12) did indicate that instability was possible at high wind speeds where the field current reached its maximum value.

A straightforward application of the equal area criterion showed that with no initial power output a single step input of power of 11.5kW could be stably sustained. This was in excess of any credible wind gusts on the RAL site.

POWER ANGLE CURVE FOR L.V. CONNECTED WECS

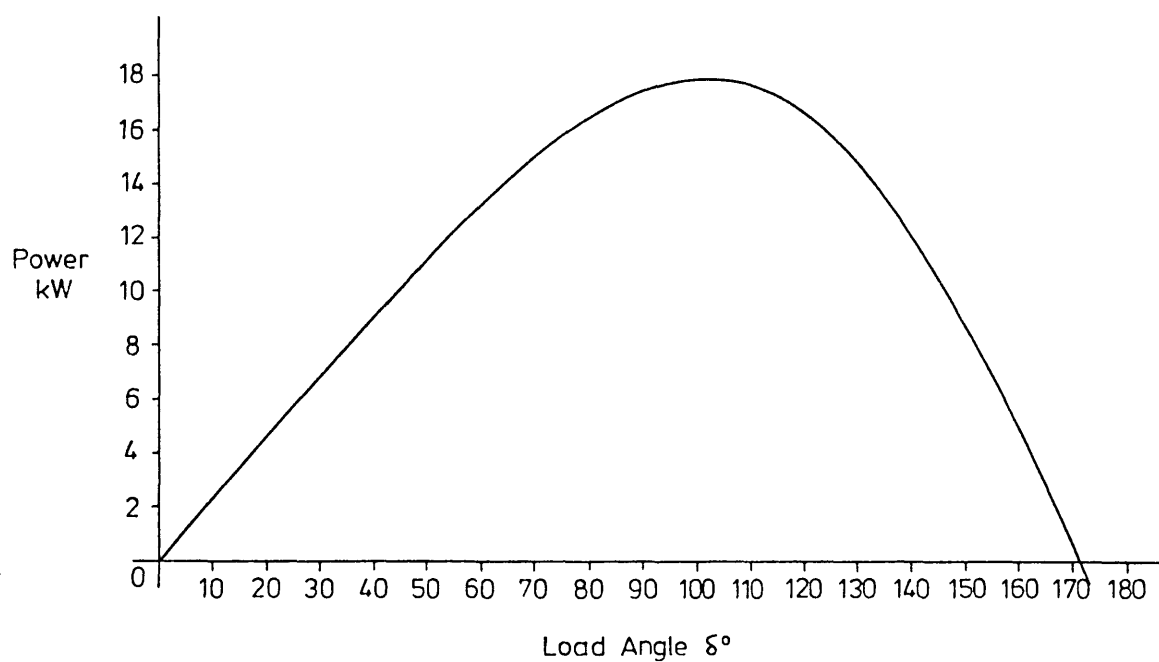


FIGURE 4.14

PARALLELING TRANSIENT

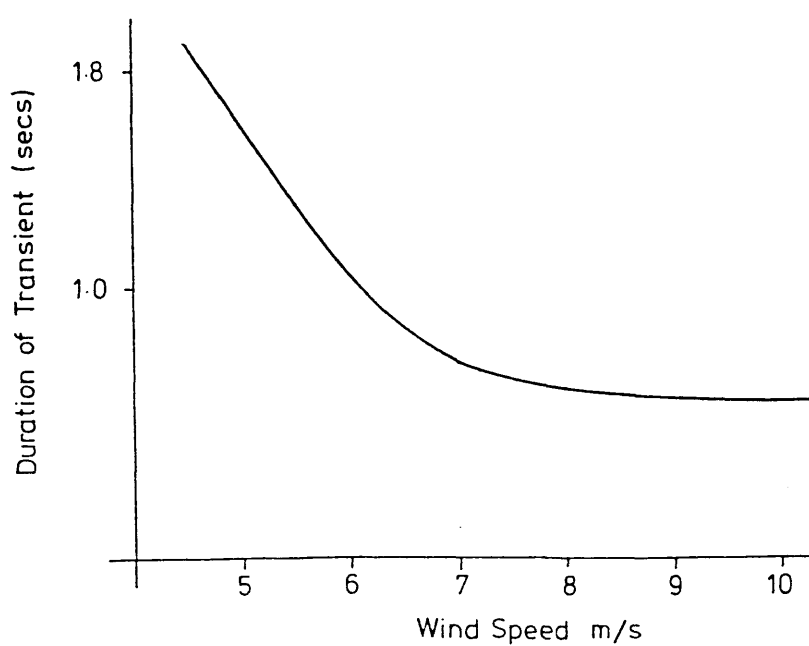


FIGURE 4.15

The power angle curve may also be used to gain an initial understanding of the small signal oscillations of the wind turbine generator against the infinite busbar.

The swing equation for a machine connected to a busbar (4.13) is given by:

$$M \frac{d^2 \delta_m}{dt^2} = \Delta P \quad (4.6)$$

Where

$M = I \omega_{sm}$: angular momentum (J-s/mechanical radian)

δ_m : power angle (mechanical radians)

$\Delta P = P_m - P_e$: instantaneous mechanical input power
-instantaneous electrical output power (W).

Conventionally an inertia constant H is also defined as:

$$H = \frac{\frac{1}{2} M \omega_{sm}}{G} \quad \text{kJ/kVA} \quad (4.7)$$

and represents the stored rotational energy of the machine at synchronous speed expressed on a per unit basis.

Combining (4.6) and (4.7) gives:

$$\frac{2H}{\omega_{sm}} \frac{d^2 \delta_m}{dt^2} = \frac{\Delta P}{G} \quad (4.8)$$

G : machine rating VA

ω_{sm} : synchronous mechanical angular velocity

As both the power angle δ_m and the synchronous speed ω_{sm} are expressed in mechanical radians equation (4.8) may be rewritten in per unit form as:

$$\frac{2H}{\omega_s} \frac{d^2\delta}{dt^2} = \Delta P \quad \text{per unit} \quad (4.9)$$

provided both δ and ω_s have consistent units of mechanical or electrical degrees or radians.

For small oscillations about an operating point the power angle curve may be linearised to give a synchronising power coefficient S_p :

$$S_p = \left. \frac{dP}{d\delta} \right|_{\delta = \delta_o} \quad \text{per unit} \quad (4.10)$$

As may be seen the slope of the power angle curve of Figure 4.14 is approximately constant for power angles up to 50° . This was evaluated to be 0.218kW/elec deg or 0.595 p.u. (electrical radians) and corresponded to a spring of stiffness 22,900 Nm/mechanical radian.

For the linearised condition, (4.9) and (4.10) may be combined to give:

$$\frac{d^2 \delta_o}{dt^2} + \frac{\omega_s}{2H} Sp \delta_o = 0 \quad (4.11)$$

For this undamped case the natural frequency of oscillation (ω_n) is given by:

$$\omega_n = \left(\frac{\omega_s Sp}{2H} \right)^{\frac{1}{2}} \quad \text{elec radians/sec} \quad (4.12)$$

For the complete aerogenerator $H = 1.23 \text{ kJ/kVA}$

While for the alternator alone $H = 0.069 \text{ kJ/kVA}$

Evaluating equation 4.12 gave an undamped natural frequency of the aerogenerator against the L.V. network of:

Complete aerogenerator $f_n = 1.4\text{Hz}$

Aerogenerator alternator $f_n = 5.9\text{Hz}$

These were in reasonable agreement with the experimental results described in Chapter 5 which gave frequencies of 1Hz and 6Hz respectively. The calculation of the natural frequency of the complete aerogenerator against the electrical network neglected the effect of the flexible coupling and assumed a rigid shaft for the entire wind turbine.

4.7.4 Duration of Paralleling Transient

As shown above the paralleling power transient consisted of two modes of oscillation. The first was a higher frequency caused by the aerogenerator alternator alone oscillating against the L.V. network and the second was the complete aerogenerator oscillating against the network.

The control system allowed paralleling as soon as the aerogenerator output frequency reached 47Hz. The centrifugal clutch allowed the alternator to be accelerated immediately up to 50 Hz while the remainder of the aerogenerator was accelerated more slowly by the wind. To calculate the duration of the initial higher frequency transient it was necessary to calculate the time required for the aerogenerator to accelerate from 117.5 to 125 rpm in various wind speeds.

On a rotating body the accelerating torque is given by:

$$T = I \frac{d\omega}{dt}$$

$$P = \omega I \frac{d\omega}{dt} \quad (4.13)$$

The performance of a wind turbine is described by the conventional equation:

$$C_p(\lambda) = \frac{P}{\frac{1}{2} \rho A V^3} \quad (4.14)$$

Where C_p is the power coefficient and $\lambda = \frac{\omega R}{V}$ and is known as the tip speed ratio.

Combining 4.13 and 4.14 gives:

$$\frac{d\omega}{dt} = \frac{C_p \frac{1}{2} \rho A V^3}{I \omega} \quad (4.15)$$

If the windspeed V is assumed constant then the tip speed ratio will only vary 6% over the speed range 117.5 - 125 rpm. C_p may be assumed linear over this range (4.14) and so let:

$$C_p = a\omega + b$$

Therefore, over the range of interest 4.15 may be rewritten as:

$$\frac{d\omega}{dt} = \frac{(a\omega + b) \frac{1}{2} \rho A V^3}{I \omega} \quad (4.16)$$

For convenience let:

$$c_1 = \frac{AV^3 a \rho \frac{1}{2}}{I} \quad c_2 = \frac{AV^3 b \rho \frac{1}{2}}{I}$$

and so:-

$$\frac{d\omega}{dt} = c_1 + \frac{c_2}{\omega} \quad (4.17)$$

Integrating* (4.17) gives:-

$$t = \frac{1}{c_1} \left(\omega - \left(\frac{c_2}{c_1} \right) \ln \left(\frac{c_2}{c_1} + \omega \right) - k \right) \quad (4.18)$$

(*this solution was suggested by D.G.Infield)

For the initial conditions $t = 0$

$$\omega_0 = 12.3 \text{ mechanical rad/sec}$$

$$\text{or } 117.5 \text{ rpm}$$

and so:

$$k = \omega_0 - \left(\frac{c_2}{c_1} \right) \ln \left(\frac{c_2}{c_1} + \omega_0 \right) \quad (4.19)$$

Equation (4.18) was evaluated for a number of constant windspeeds and the results are shown in Figure 4.15. The values of the constants a and b were calculated at each wind speed from the experimentally derived C_p/λ curve. It should be noted that this calculation ignored the effect of non-linear frictional losses and of the centrifugal clutch. The results were in general agreement with the experimental results, described in Chapter 5, although they could not be accurately validated as the mean wind speed across the rotor disk was unknown.

4.7.5 Autonomous wind diesel operation

Transient operation of the autonomous wind diesel system was briefly examined. The system is shown schematically in Figure 4.16 and the parameters of the diesel generator set are shown in Table 4.3 and 4.4.

To simplify the calculation both saliency and resistance of the electrical machines were neglected. It has been shown (4.11)

FIGURE 4.16

AUTONOMOUS WIND DIESEL SYSTEM

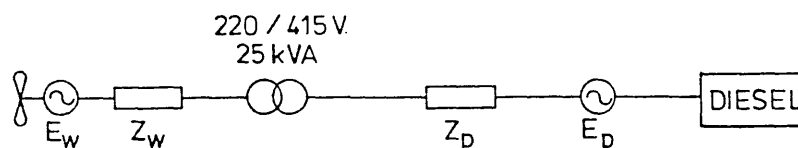


TABLE 4.3

Diesel Generator Set Mechanical Parameters

Diesel engine and flywheel inertia	1.39 kg m ²
Diesel alternator inertia	0.07 kg m ²
Angular momentum of diesel generator set	4.0 Joule-sec/mech degree
	2.0 Joule-sec/elec degree

TABLE 4.4

Diesel Generator Set Electrical Parameters

Alternator Rating at 415 V, 1500 rpm	8.5 kVA
No. of poles	4
Armature Resistance R_a	0.03 p.u.
Direct axis synchronous reactance X_d	1.21 p.u.
Direct axis transient reactance X_d'	0.14 p.u.
Direct axis subtransient reactance X_d''	0.14 p.u.
Quadrature axis synchronous reactance X_q	0.66 p.u.
Direct axis open circuit transient time constant T_{d_o}'	790 ms

that neglecting saliency has only a small effect on the accuracy of classical transient stability studies and the resistances of the machines were small compared to their transient reactances.

The power angle equation therefore reduced to equation (4.5) and

$$P = \frac{E'_w E'_D \sin \delta}{X'_w + X_T + X'_D} \quad (4.20)$$

E'_w and E'_D were assumed constant at 1.1 per unit.

On a 100 kVA base this was evaluated to be:

$$P = 0.18 \sin \delta \quad \text{per unit}$$

giving a maximum power transfer of 18kW.

For paralleling with a 90° power angle the instantaneous torque loadings on the shafts of the aerogenerator and of the diesel generator were 1375Nm and 115Nm respectively. The flexible coupling of the aerogenerator was capable of accepting this loading while the diesel engine manufacturer stated that the permitted maximum instantaneous loading of the engine crankshaft was 1128Nm. The relative angular displacements of the shafts to bring the machines into synchronism were controlled by the relative angular momentum of each machine. The values of the angular momenta are given in Tables 4.1 and 4.3. It may be seen that the angular momentum of the

aerogenerator alternator was less than 10% of that of the diesel generator set. Therefore the estimated torque loadings and angular displacement of the diesel generator set under paralleling conditions, were within the capability of the machine.

The overcurrents on paralleling 180° out of phase were calculated for the autonomous wind diesel system using:

$$|I| = \frac{E''_w + E''_D}{Z''_w + Z_T + Z_D''} \text{ per unit} \quad (4.21)$$

This was evaluated to be 53 amps at 415V which was rather higher than the experimental results, described in Chapter 7.

4.7.6 Conclusions of Electrical Study

These calculations, using classical techniques indicated that the protection system would give adequate protection against faults on the network. They also showed that the transients on paralleling the wind turbine generator with the L.V. system would be small. Similarly, paralleling the wind turbine generator with the diesel generator set appeared to be possible and would not require modifications to the main equipment. The results were generally in agreement with the subsequent experiments although the overcurrents on paralleling were overestimated by the calculations. Reasons for this are discussed in Chapter 5 together with the experimental results.

The natural frequencies of oscillation of the wind turbine against the L.V. network were calculated and agreed with experiment. The duration of the high frequency paralleling transient was also correctly calculated.

CHAPTER 5

PERFORMANCE OF THE WIND TURBINE CONNECTED TO THE

RAL 415 VOLT NETWORK

5.1 Commissioning

The design of the L916 wind turbine included two major novel features. These were the special synchronous machine which allowed paralleling without synchronising and also the passive blade pitch control mechanism with the absence of any mechanical brakes. Because of these features, and the lack of test records available from the manufacturer, considerable care was taken with the commissioning of the wind turbine generator on to the RAL 415V system.

The control and excitation system had been tested in the laboratory and these tests were repeated when the machine was assembled and erected. The overspeed protection devices of the wind turbine were thoroughly tested with the exception that the aerogenerator was not permitted to go into a sustained overspeed to fully test the passive blade pitch control mechanism or the operation of the vibration sensor. The base level of the field excitation was set by motoring the alternator and reducing the armature current to a minimum. The compounding setting was unchanged from the laboratory tests.

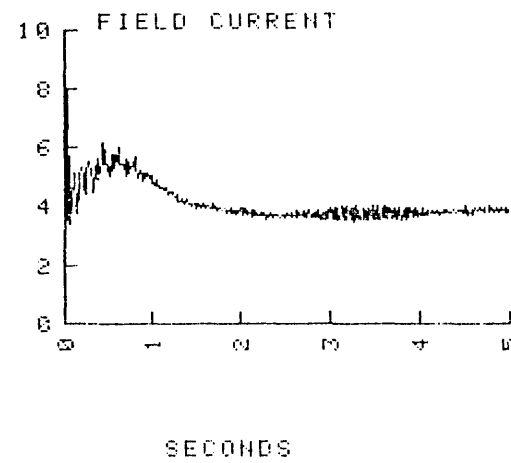
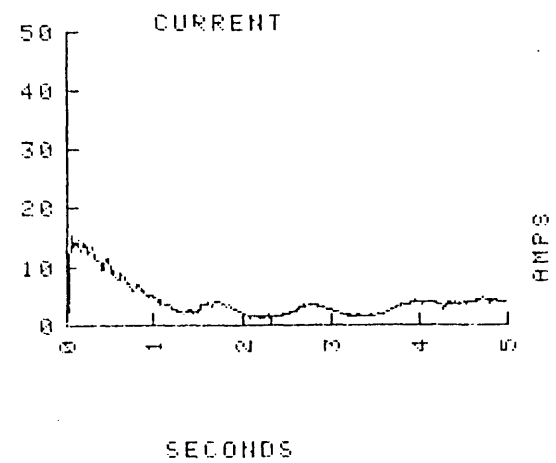
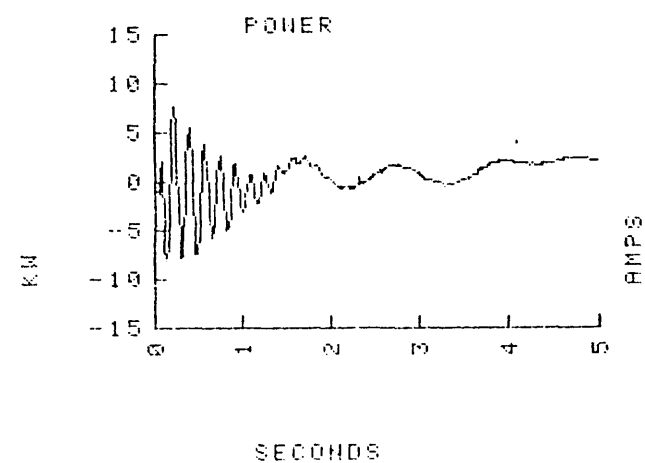
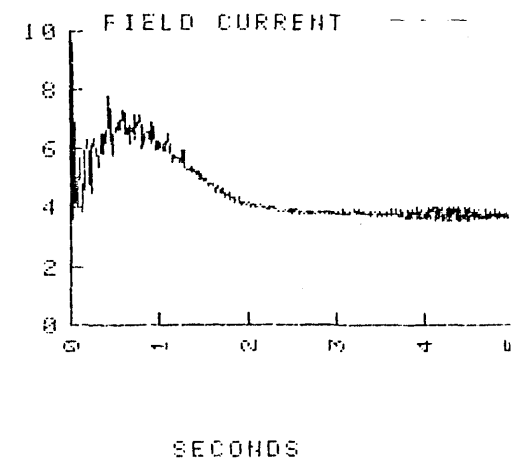
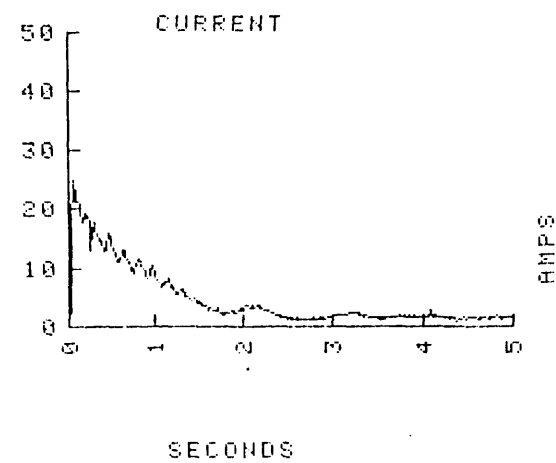
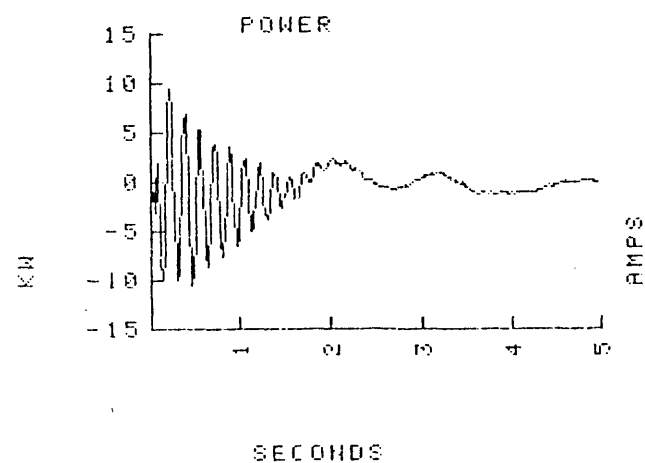


FIGURE 5.1 L.V. CONNECTED PARALLELING

5.2 Paralleling

It is not usual practice to connect a synchronous machine directly on to an electrical network without synchronising. The design of the L916 alternator was such as to allow this mode of operation but it was considered important to examine experimentally the transients present during paralleling. A series of experiments was therefore carried out to determine the power, armature and field currents present during paralleling with the L.V. network. These results were then compared with the calculations described in Chapter 4 and shown to be in good agreement.

A data logging program SYNT0 was written for the HP data acquisition equipment. This program allowed each of the outputs of the power, red phase current and field current transducer to be sampled every 15ms. A graph plotting routine was added to the program to allow results to be displayed on completion of the test. The data logger was initiated from a high speed relay which itself was operated from the same signal as the main utility contactor. Thus the data logger was triggered immediately before the closure of the main contactor.

A series of 14 paralleling tests was carried out at various windspeeds up to 9m/s. Typical results at windspeeds of approximately 6m/s are shown on Figure 5.1. The magnitude and direction of the initial power transients were dependent on the relative positions of the alternator and system voltage vectors

at the instant of paralleling. The power transients recorded had a peak magnitude of 17kW and a mean magnitude of 9.4kW. The phase current similarly had a peak magnitude of 36A and a mean magnitude of 19A. During this series of tests, or during subsequent operation none of the protective relays or the 40A HRC fuses operated on paralleling.

The power traces showed two distinct frequencies of oscillation. The initial higher frequency (6Hz) was caused by the alternator alone oscillating against the RAL electrical system. The lower frequency (1Hz) was caused by the entire aerogenerator oscillating against the L.V. system after the wind turbine blades had reached 125 r.p.m. and the centrifugal clutch was closed. The duration of the high frequency oscillation was dependent on the windspeed, as the rotor blades accelerated, and varied between 0.8-2 seconds. The two modes of oscillation were reflected in the armature and field current traces. The field current also showed the effect of the current compounding of the field control circuit.

Table 5.1 shows that the experimental results agreed with the calculations of Chapter 4 although the peak current on paralleling was rather lower than that calculated. This was partly due to the time constant of the current transducer cutting off the transient peak and also, probably, due to not paralleling at the worst position of the voltage vectors. Further the calculated values are likely to be slightly high due to the approximations inherent in the classical calculation techniques used. The calculation for the frequency of

oscillation of the complete aerogenerator neglected the effect of the flexible coupling and dampers. However these were included in the dynamic simulation of Chapter 9 and the results of the simulation are included in the Table.

TABLE 5.1
Paralleling Transients

Parameter	Experiment (Chapter 5)	Calculation (Chapter 4)	Dynamic Simulation (Chapter 9)
Frequency of alternator oscillating against network (Hz)	6	5.9	6
Frequency of aero- generator oscillating against network (Hz)	1	1.4	0.8
Duration of paralleling transient (secs)	0.8-2.0	0.6-1.8	-
Peak current on paralleling (A)	36	68	-
Peak power on paralleling (kW)	17	17.8	-

In summary these tests showed that paralleling this wind turbine generator without synchronising could be done safely and with modest power and current transients. The experiments also served to validate the calculations of Chapter 4 and supported the prediction that the aerogenerator could be safely paralleled with the diesel set.

5.3 Steady State Operation

5.3.1 L.V. Connected Operation

In the proposed experimental wind diesel system the wind turbine would be an important and at times the sole generator of power. To understand its steady state electrical performance a data logging program DYNAM was written. This program sampled the outputs of the power, current and field current transducers every 500ms over a 50 second period. The program was initiated manually from the data logger keyboard. A graph plotting routine was included.

Figure 5.2 shows typical output traces in windspeeds of approximately 6-8m/s.

The power trace showed the large variations in power caused by the turbulence of the wind. As shown, rates of power variation of 1kW/s were not uncommon. This trace also showed small amplitude 1Hz oscillations similar to those previously noted in

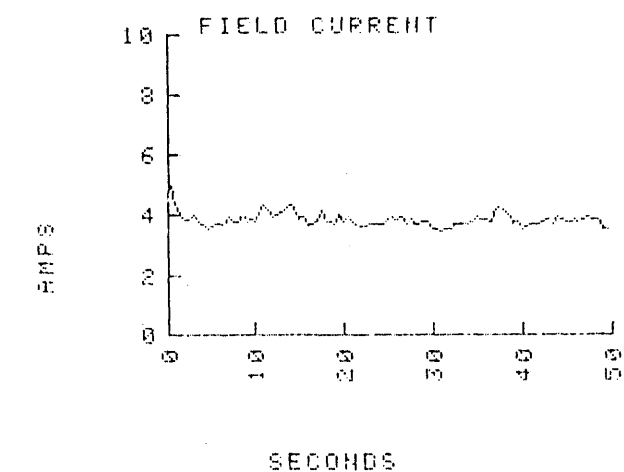
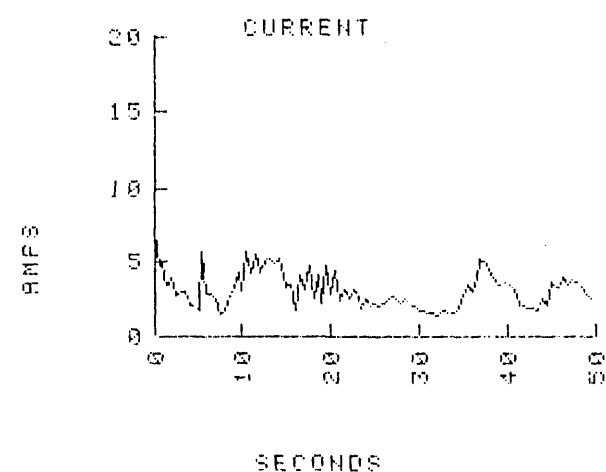
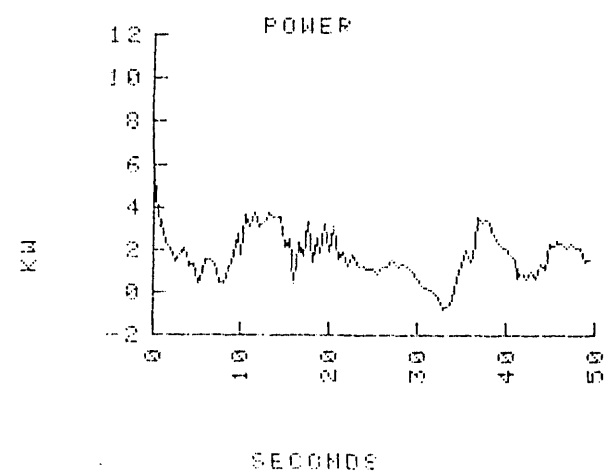
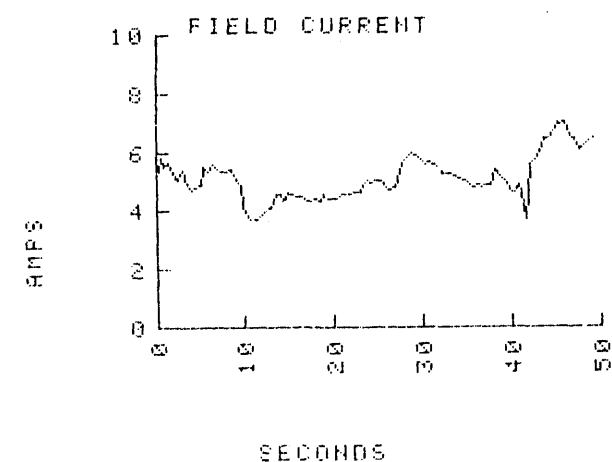
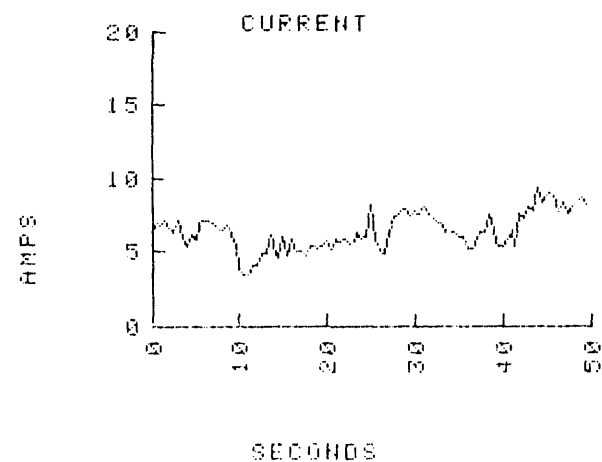
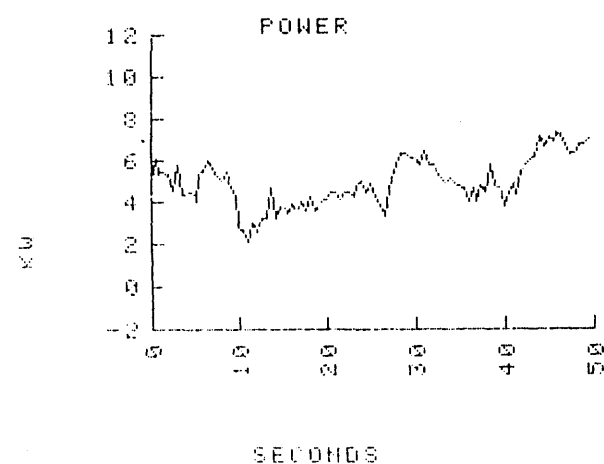


FIGURE 5.2 L.V. CONNECTED STEADY STATE

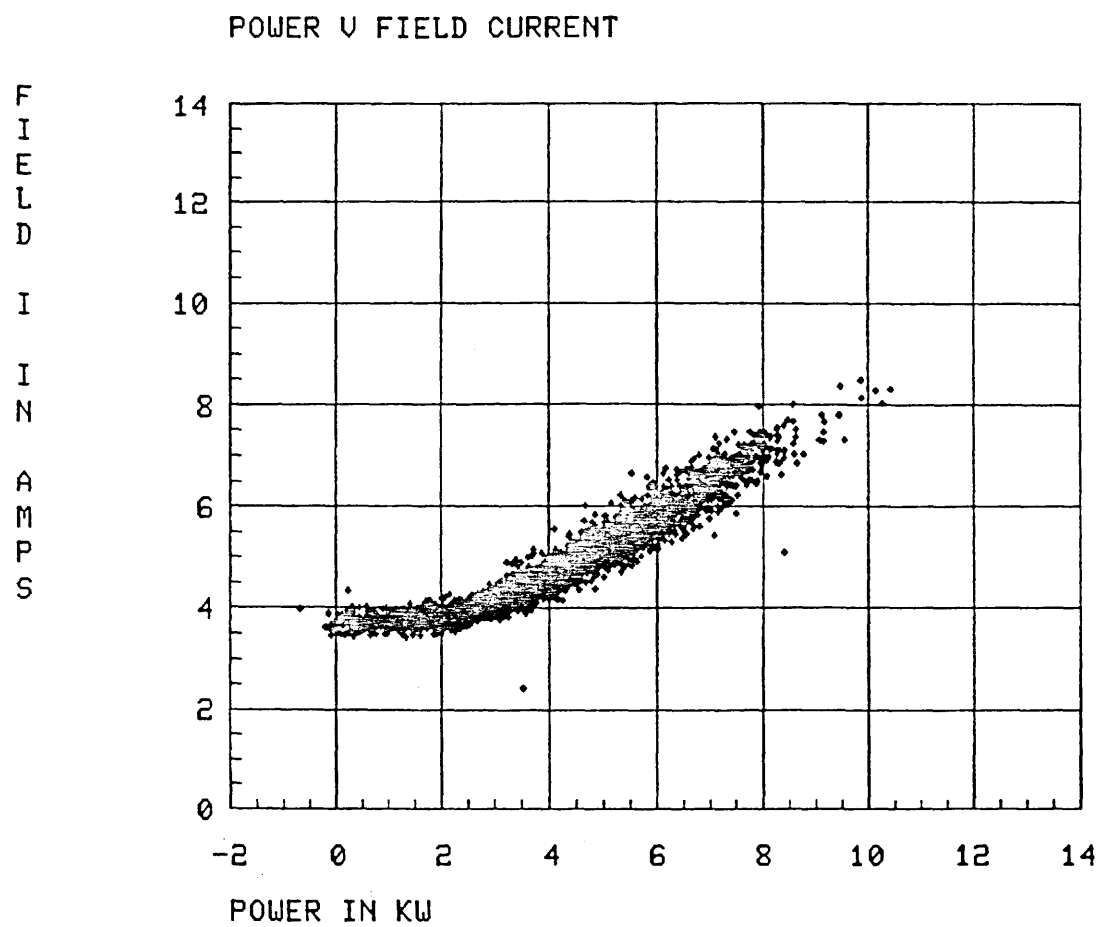


FIGURE 5.3

OPERATION OF EXCITATION SYSTEM

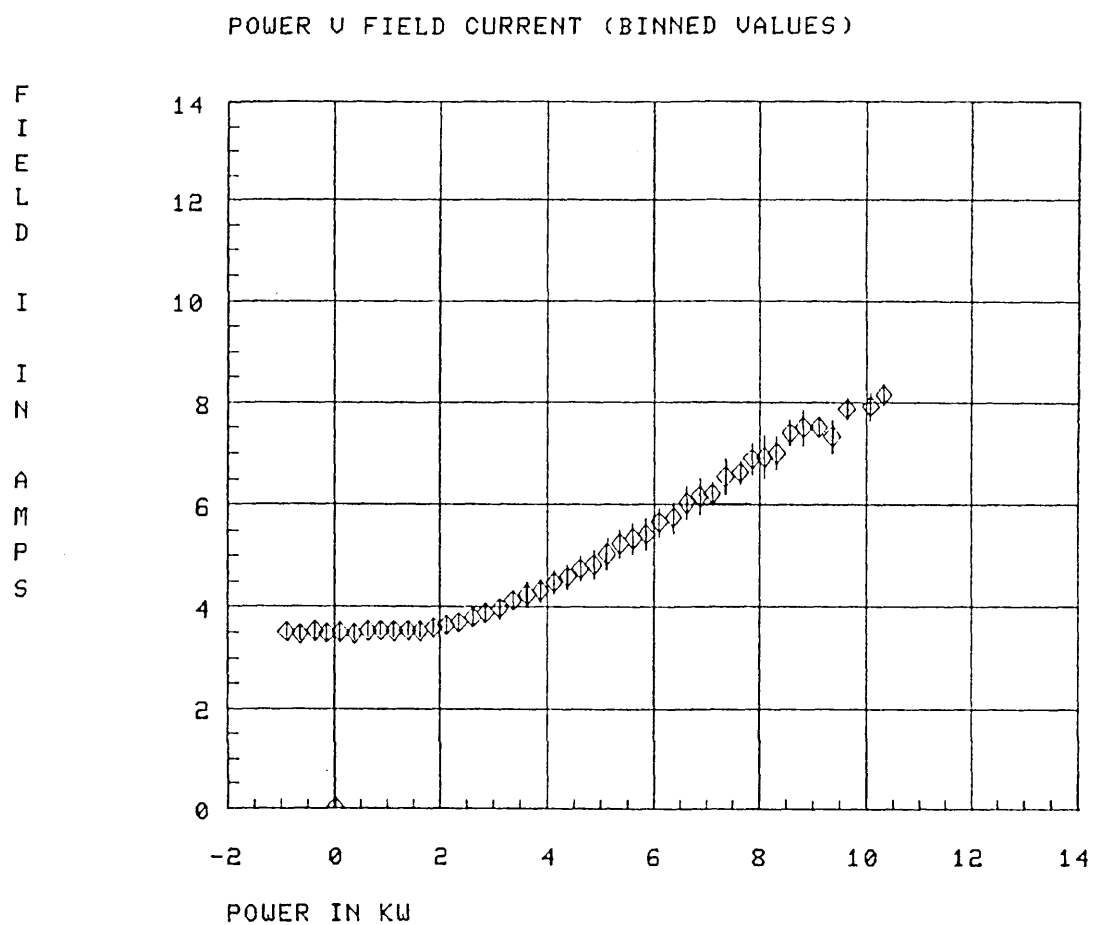


FIGURE 5.4

OPERATION OF EXCITATION SYSTEM (BINNED RESULTS)

the paralleling experiments. The voltage and frequency of the network were held constant by the RAL system. Therefore the power variations were reflected in the red phase current trace. The field current showed the effect of the magnitude compounding circuit of the excitation control and so followed the phase current.

5.3.2 Operation of the Excitation System

To examine the operation of the field excitation under a range of operating conditions a data logging program FCOR, was written. This sampled the output power and field current of the alternator every second over a 50 minute period. The data was stored on an HP cartridge file and subsequently transferred to the RAL CMS computer system. Figure 5.3 shows the results of 1 test (3000 values) plotted using graph plotting routines available on the CMS system. The scatter present is partly due to resolution errors of the data acquisition equipment but also due to the changing performance of the excitation circuit during the period of the tests. The field control circuit was an open loop scheme and the field current was dependent on both the resistance of the field winding and the voltage of the RAL system. Figure 5.4 shows binned values derived from the test results of Figure 5.3. These results were similar to those obtained from the laboratory tests and shown in Figure 4.3.

5.3.3 Power Factor Measurement

The measurement of the power factor of the wind turbine generator under operating conditions was rather involved. Funds were not available to buy a power factor transducer and so it was necessary to measure instantaneously voltage, current and power and compute the power factor. The data logger did not have a sample and hold facility on its multiplexed analogue inputs and so all measurements were taken sequentially. Further, at low values of output power the resolution errors of the data acquisition equipment became significant. Therefore for useful power factor measurement it was necessary to use averaged readings.

A further difficulty was that the power supply to the alternator field was taken from the Red and Yellow phases of the 220V/127V winding of the 25kVA transformer. This unbalanced current on the star side of the delta star transformer was reflected on the 415/240V side as a 1:2:1 R:Y:B current distribution. Because a triac was used to control the field current the phase angle of these unbalanced currents was unknown and so measuring a single phase current could not give an accurate measurement of the power factor. Therefore for the purpose of power factor measurement the field supply was removed from the 220/127V network and fed from the auxiliary instrumentation supply in the wind turbine cabin.

The data logging program DYNAM was then modified to include power factor measurement. The power factor was calculated at

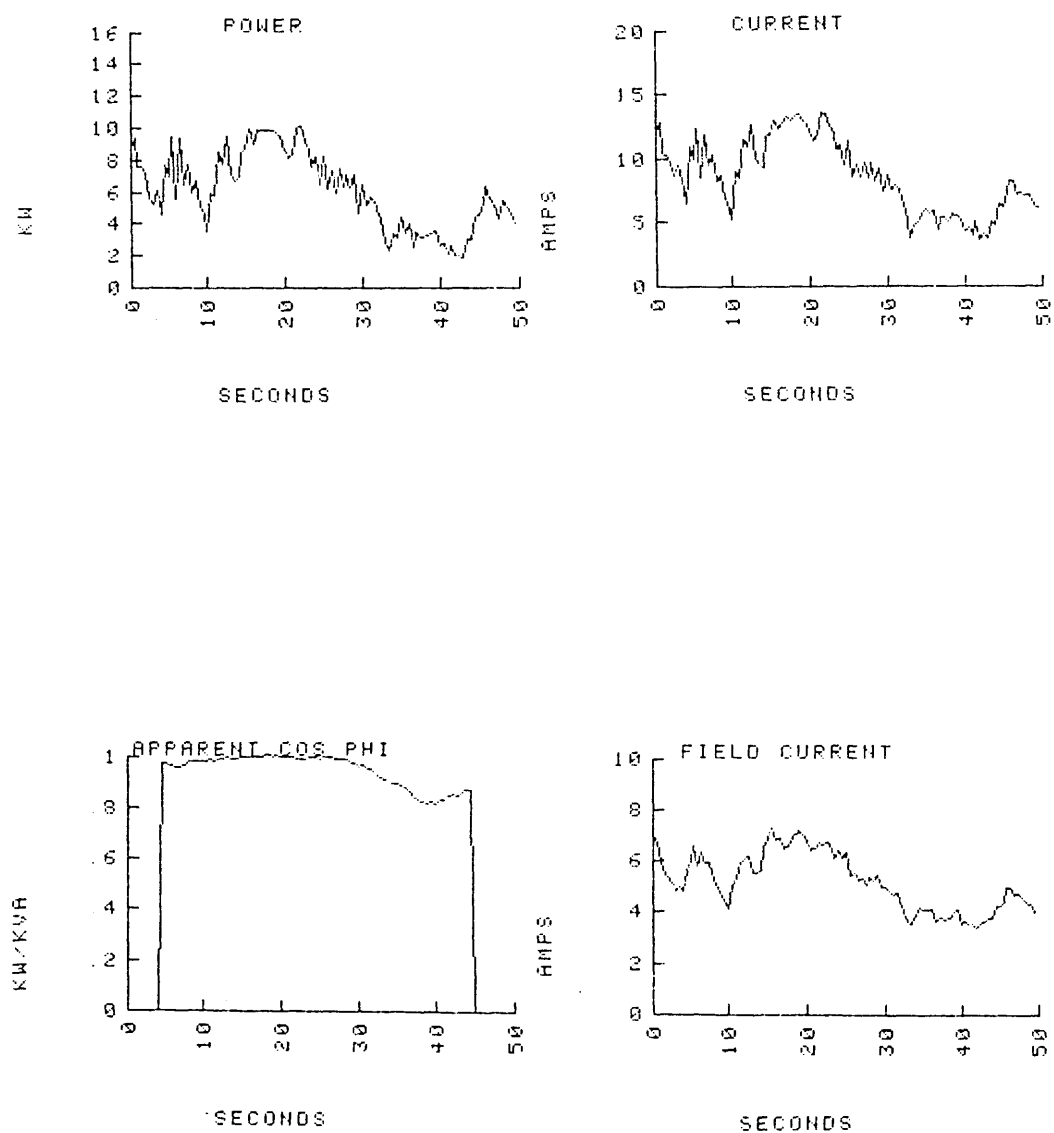


FIGURE 5.5 L.V. CONNECTED STEADY STATE

(INCLUDING MEASUREMENT OF POWER FACTOR WITH SEPARATE EXCITATION)

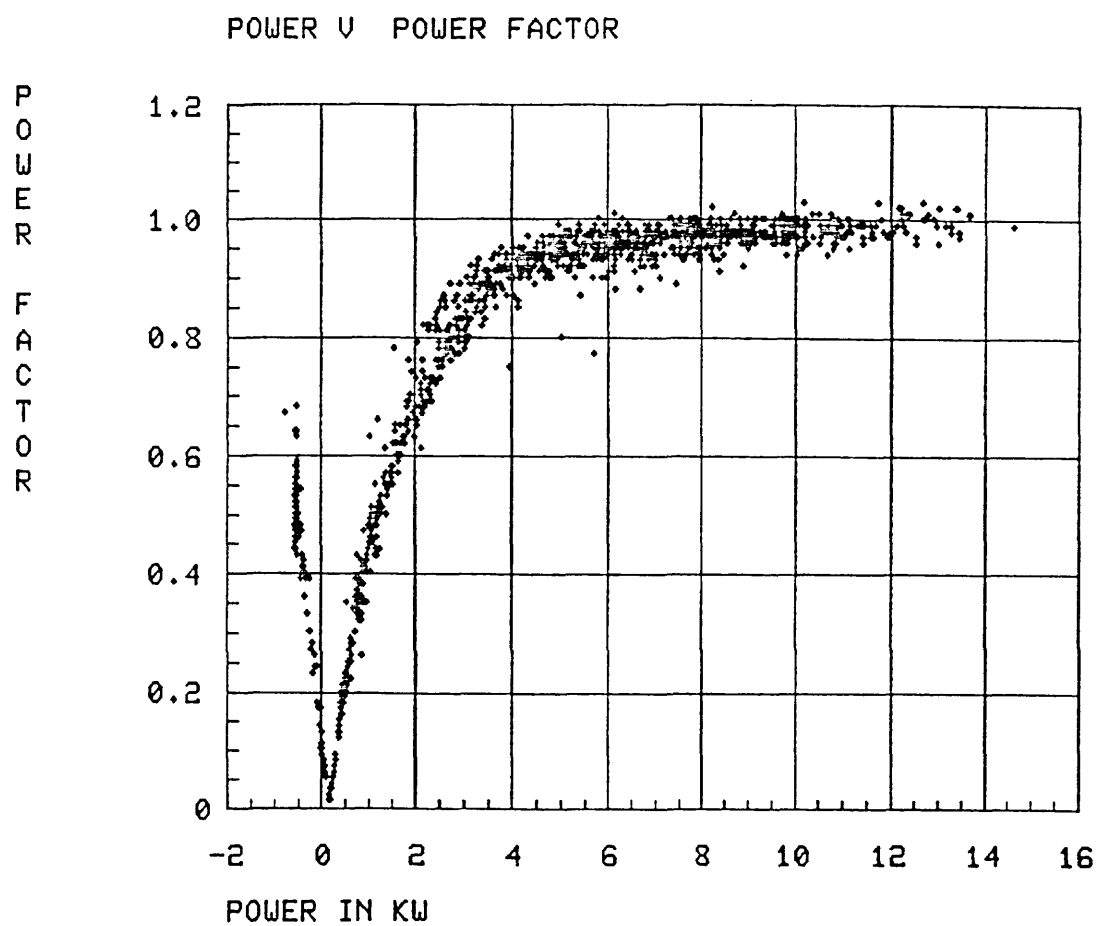


FIGURE 5.6

EFFECT OF EXCITATION SYSTEM OF L.V. CONNECTED WECS

each of the sampling intervals but displayed as a block averaged value of 20 samples. Figure 5.5 shows typical results. It may be seen that the power factor is maintained close to unity for output powers above 4kW. Below this value the power factor is reduced and reactive power absorbed by the alternator.

DYNAM gave only a time series indication of power factor and for a more detailed examination of the relationship between output power and power factor a further data logging program PFCOR was written. This was a rather more sophisticated program which sampled the output power and current 20 times at 5ms intervals and calculated the mean value of power and power factor. This measurement was repeated at 20 second intervals over a 100 minute period. The results were stored on an HP cassette file and transferred to the CMS system.

The results of these tests are shown in Figure 5.6. The excitation system maintained the power factor at close to unity over most of the operating range. At low motoring and generating powers there was a small reactive power demand. This reactive power requirement was within the capabilities of the excitation system of the diesel alternator for the proposed wind diesel operation. These results agree with the computer simulations carried out by A. Tsitsovits (5.1).

5.3.4 Spectral Analysis

The output power of the wind turbine was then investigated by Fourier Analysis. A program SPECT was written to sample the

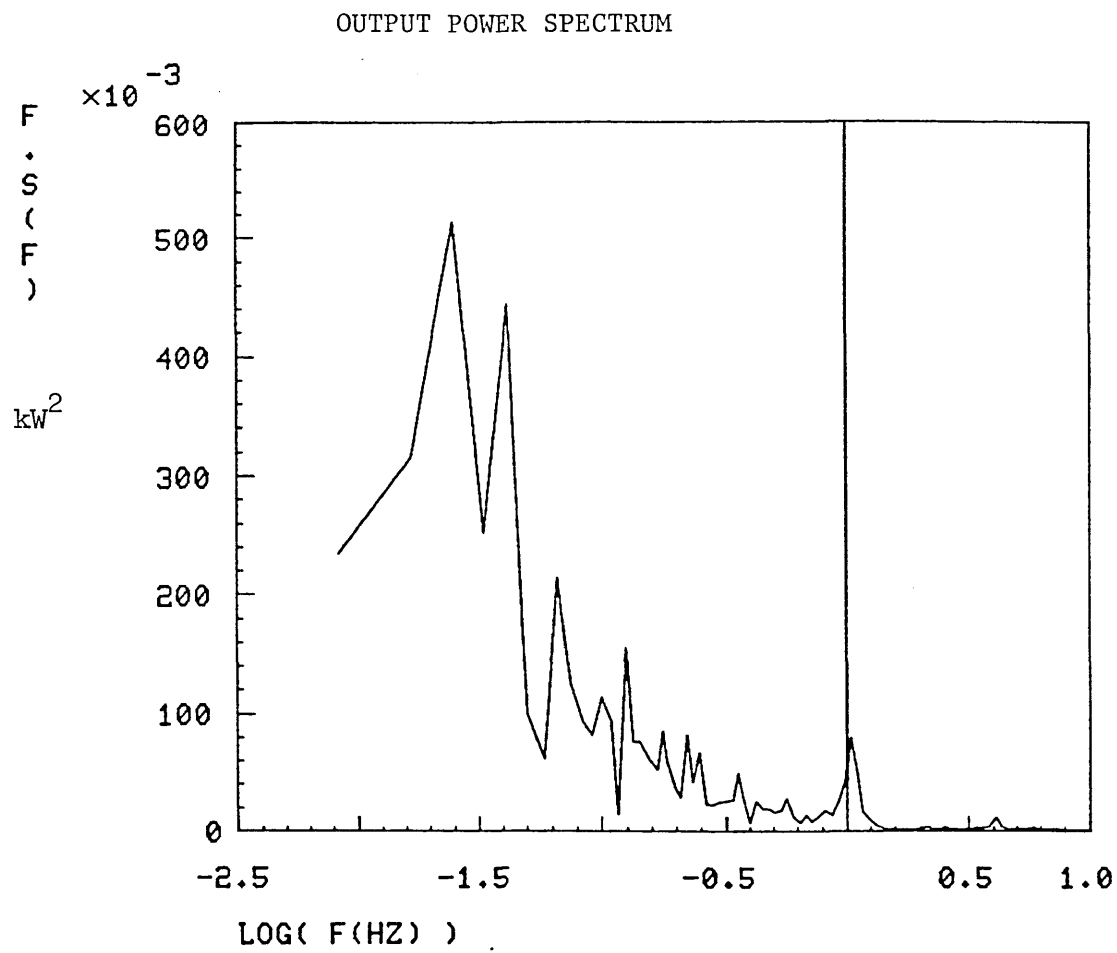


FIGURE 5.7

RESULTS OF FOURIER ANALYSIS ON WECS POWER OUTPUT

output of the power transducer at 50ms intervals. 7200 readings were taken over a 6 minute test period. The data was analysed on the CMS system using a Fourier Analysis program*. The results are shown in Figure 5.7. The blade passing frequency is just visible at 4Hz and the natural frequency of the wind turbine drive train is shown at 1Hz. The drive train natural frequency oscillation was of a low magnitude and not a cause for concern. The blade passing frequency oscillation was heavily attenuated by the flexible coupling and electrical damping and was unlikely to cause problems.

5.4 Conclusions

These experiments had shown that the aerogenerator produced a highly variable power output which was successfully maintained at close to unity power factor by the excitation control. The reactive power demand at low output powers was small enough to be supplied from the diesel generator in a wind diesel system. The power and current transients on paralleling were slightly lower than the calculated values and were not likely to present problems when paralleling with a diesel set.

In summary, the experiments supported the theoretical predictions of Chapter 4 that the wind turbine generator was suitable for parallel operation with a small diesel generator set.

*This program was written by Dr E A Bossanyi and Mr J A Halliday of RAL.

CHAPTER 6

POWER PERFORMANCE TESTING

6.1 Introduction

The performance of a wind turbine generator may be represented by a characteristic curve relating free wind speed to net output power. This is known as the Power Curve and is unique for fixed blade pitch and rotational speed. An alternative representation of performance is the Power Coefficient (C_p) versus Tip Speed Ratio (λ) curve which relates that fraction of the available energy which has been extracted from the windstream (C_p) to the ratio of the tip speed to the free wind speed (λ). Using the C_p/λ curve, performance at various rotational speeds may be calculated and the Power Curve for a single rotational speed may be drawn.

Conventionally the Power Curve is used to illustrate the performance of the entire WECS, usually for the purposes of estimating long term energy yield. The C_p/λ curve is normally used to show the aerodynamic performance of the rotor alone. The C_p/λ curve for a rotor of given geometry, aerofoil section and pitch angle may be calculated by a number of techniques (6.1). Suitable computer aided design programs are now commercially available (6.2). A calculated Power Curve may then be drawn by subtracting the losses of the transmission and alternator from the gross output power predicted by the C_p/λ curve for the rotational speed of interest. Calculated Power

Curves have tended to be inaccurate. Often losses are incorrectly estimated and no account is taken of loss of energy due to poor yaw performance (6.3). A downwind free yawing machine will not maintain itself normal to the free wind velocity but, depending on tip speed ratio, will sit at up to 20° off the wind (6.4). Further, small changes in blade pitch angle may seriously modify the output power of the WECS.

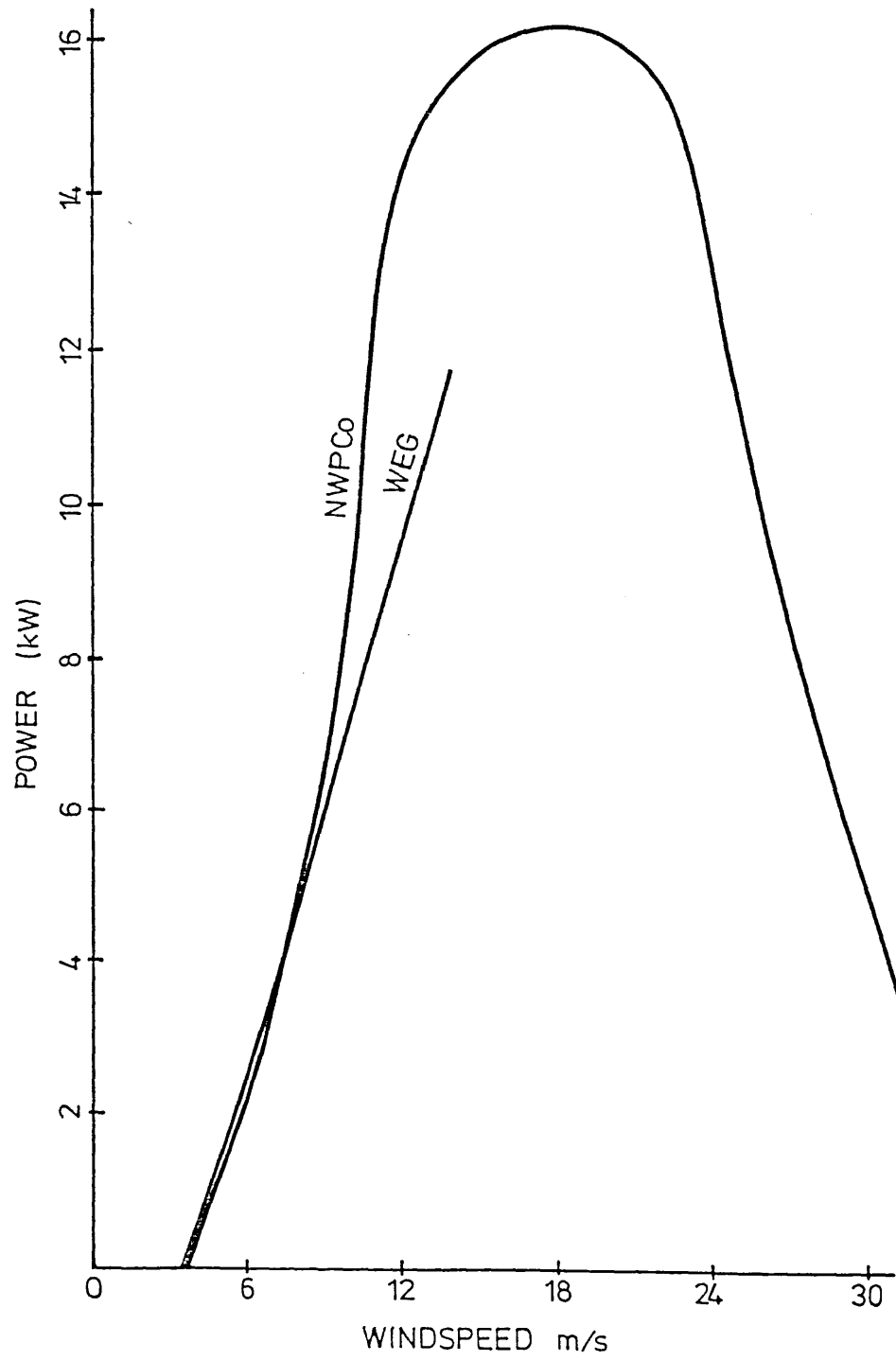
The manufacturers of the L916 wind turbine generator supplied a calculated Power Curve, Figure 6.1, but were unable to provide test results to support it. The manufacturers calculated Power Curve was therefore checked against a curve produced by a Wind Energy Group performance prediction code and in addition a test programme was undertaken to determine experimentally the Power Curve of the L916 WECS operating at 125 rpm while connected to the RAL L.V. network.

6.2 Power Performance Prediction

The program used to predict the performance of the L916 WECS was the Wind Energy Group PERFORM code (6.5). This is a comprehensive program allowing the calculation of power output over a specified range of axial windspeeds and also the generation of detailed local aerodynamic information for each of 19 blade stations along the blade length.

FIGURE 6.1

CALCULATED POWER CURVES



The general aerodynamic analysis is based on the strip theory equations of Wilson et al (6.1). Strip theory was developed by combining momentum theory and blade element theory and is the commonly used theory for analysing horizontal axis wind turbine rotors (6.6; 6.7). Due to the non-linear nature of the relationship between the lift and drag coefficients (C_L and C_D) and the angle of attack (α) an iterative process is necessary to determine the aerodynamic behaviour at each blade station. Iteration is continued until both the axial induction factor (a) and the rotational induction factor (a') are essentially constant.

The axial induction factor (a) is defined by:-

$$V = V_{\infty} (1-a) \quad (6.1)$$

where V : axial wind velocity at rotor

V_{∞} : axial free stream wind velocity

The rotational induction factor (a') is defined by:-

$$a' = \frac{\omega}{2\Omega} \quad (6.2)$$

where ω : angular velocity of the wind at the rotor

Ω : angular velocity of the rotor

If tip losses are ignored it can be shown that the coefficient of performance (C_p) is given by:-

$$C_p = \frac{8}{\lambda^2} \int_0^{\lambda} x_L^3 a' (1-a) dx_L \quad (6.3)$$

where x_L : local tip speed ratio = $\frac{r_L \Omega}{V_\infty}$

λ : tip speed ratio = $\frac{r \Omega}{V_\infty}$

r : rotor radius

r_L : radius of blade element

Now the coefficient of performance (C_p) is defined by:-

$$C_p = \frac{P}{0.5 \rho A V^3} \quad (6.4)$$

where ρ : air density

A : swept area of rotor

P : rotor output power

and so it may be seen that once the induction factors a and a' , are determined iteratively from strip theory the performance of the rotor may be calculated.

In addition to this elementary theory PERFORM was able to include corrections for tip loss using a Prandtl tip loss factor.

The aerodynamic data of the Go 797 aerofoil section was obtained from Riegels (6.8) and the blade geometry from the manufacturer (6.9). The wind turbine had a passive blade pitch control system and the operation of this was predicted from the manufacturers test reports (6.10). An attempt was made to measure the change in pitch with windspeed during the experiments but the transducer, a linear potentiometer, malfunctioned. This limited the upper wind speed to which the performance could reliably be predicted.

The results of the power performance prediction calculations are shown in Fig. 6.1. The measured mechanical and electrical losses of the WECS have been subtracted. This prediction does not agree well with that of the manufacturer but it was not clear that the manufacturers curve was for 125 rpm (50 Hz) operation.

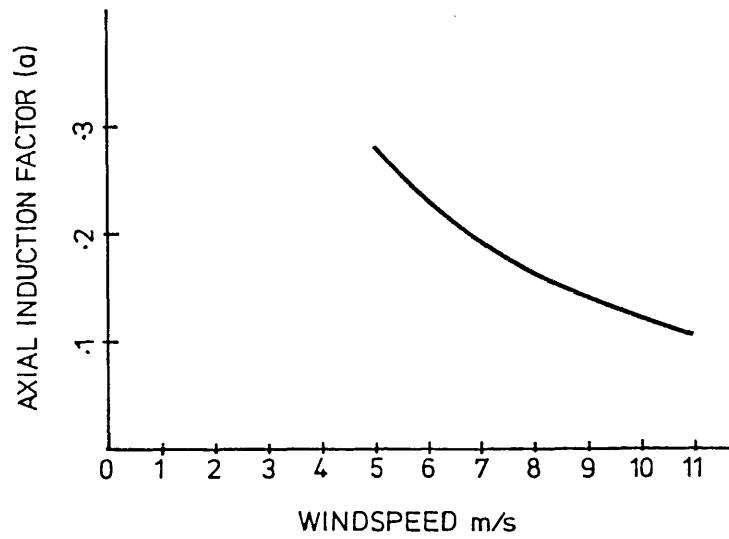
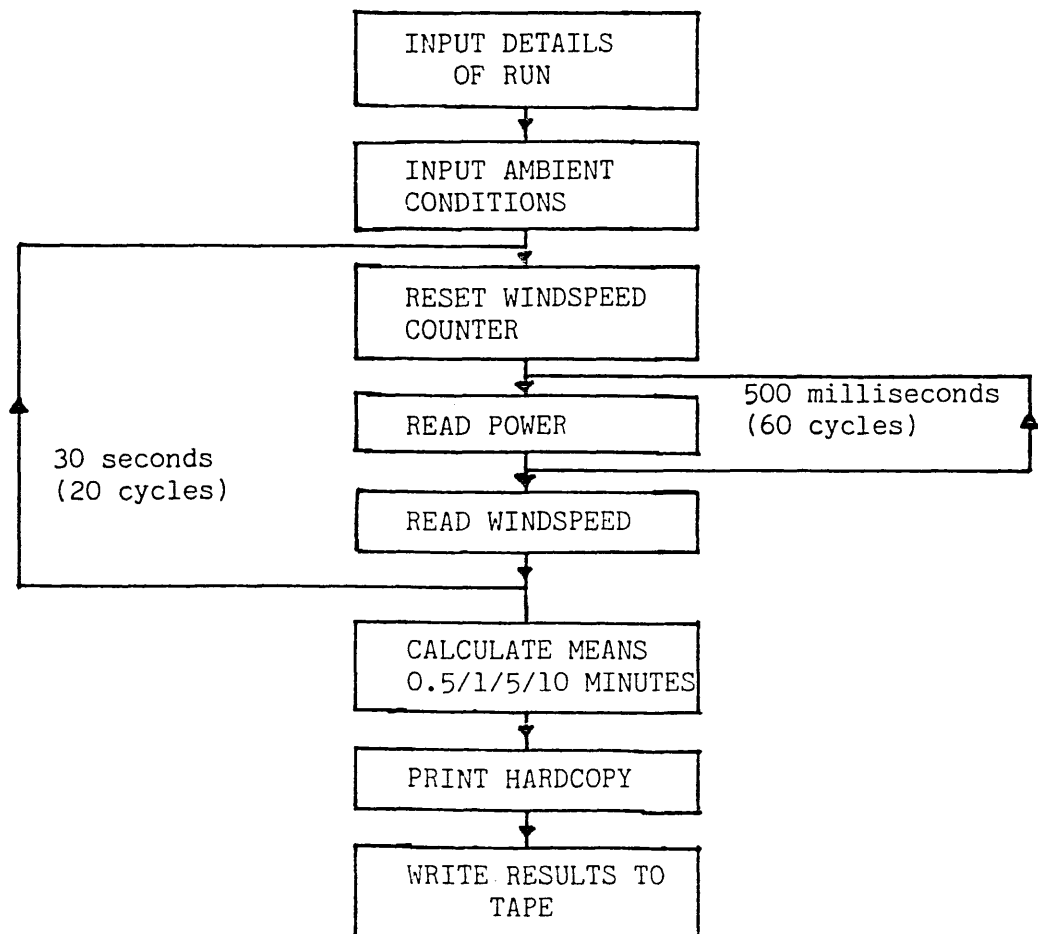
In addition the predicted variation of the axial induction factor (a) with free windspeed is shown in Fig. 6.2. The axial induction factor varies along the blade length and so these results are the mean values for the outer 50% of the blade but neglecting the blade station nearest the tip where tip losses predominate.

6.3 Review of Testing Procedures

The experimental determination of the performance of a wind turbine generator is not straightforward. The difficulties are mainly due to the turbulence of the wind causing poor spatial and temporal coherence between single instantaneous values of measured wind speed and measured output power. The coherence may be improved by placing the anemometer close to the WECS but the modified air flow around the rotor will then give errors in the anemometer reading. A certain amount of research has been carried out to try to determine the best performance testing techniques for a WECS. This is now reviewed and the main results noted.

The question of the poor coherence between instantaneous power measurements and windspeed measurements made with a remote

CALCULATED AXIAL INDUCTION FACTOR

Figure 6.3Simplified Flow Chart For Power Performance Data Logging

anemometer was first addressed by researchers at the Sandia Laboratory where Akins (6.11) developed what is known as the "method of bins". Instantaneous wind speed and torque measurements were taken at a frequency of 4Hz and the results binned according to windspeed in 0.25 m/s bins. The mean power in each bin was then calculated and a histogram plotted to give a Power Curve. For the constant speed machine which was under test a C_p/λ curve was derived from the Power Curve.

In a subsequent paper (6.12) a distinction was drawn between establishment and verification of performance. Performance Establishment tests required high coherence between power and windspeed measurements and rapid sampling to detect transient effects. Data of this kind were necessary to check the design of the aerogenerator. Therefore for Performance Establishment testing the anemometer was required to be close to the WECS and corrected for the modification of the wind flow by the rotor. As it is not practical to place the anemometer adjacent to the WECS a time of flight correction was required. This required knowledge of the wind direction. For horizontal axis machines a further requirement was to know the angle of incidence of the wind on to the rotor disk. If the disk swept by the wind turbine blades is not normal to the wind the power available is reduced by approximately $\cos^3 \gamma$ where γ is the yaw tracking error.

On the other hand Performance Verification tests were required only to verify the performance of a WECS and to predict energy yield at a particular site. This less onerous requirement was

satisfied by using a remote anemometer and averaging the data before binning. This averaging improved the coherence of the data but the transient effects were lost.

6.4 Performance Verification Tests

Akins' approach to Performance Verification formed the basis for both the International Energy Agency (IEA) and US (AWEA) recommended testing procedures (6.13; 6.14). In these tests, which are broadly similar, an undisturbed scalar windspeed is measured and mean power and windspeed values are binned to form a Power Curve. The IEA (6.15) recommend 1 m/s bins up to the maximum power output of the machine and above this windspeed, 2 m/s bins and require 10 minute averaging periods. However, the Riso laboratory, which has extensive experience of testing of WECS, uses 0.5 m/s bins and collects both 30 second and 10 minute means of the same data (6.16). The pre-averaging of data which is subsequently binned has been shown to give rise to systematic errors, if the standard deviation of the points in the bin is large (6.16; 6.17; 6.18; 6.19). Increased standard deviation of the points in the bin tends to rotate the power curve clockwise about the point of maximum probability density of the windspeed of the data set used. Pre-averaging times of 30 seconds and above reduce the standard deviation of the bins to a level where this effect is not significant. Akins (6.20) has also shown that combining data sets of instantaneous power and windspeeds measured under differing conditions has a similar effect to pre-averaging providing the probability density of the reference windspeed of the combined data set is reasonably constant.

The use of 10 minutes mean values of wind speed and power data is often justified on the basis of the so called "10 minute gap" in the wind speed power spectrum described by Van der Hoven (6.21). However, work by Bossanyi (6.22) analysing data from the RAL site has failed to show a consistent "10 minute gap" in the wind speed power spectrum. The main benefit of such a large pre-averaging time appears to be that all transient effects are filtered out and the scatter of the data points is very much reduced. A major disadvantage is that its use significantly increases testing time.

Performance Verification may be carried out in a straightforward manner using a remote anemometer providing either the data is pre-averaged or a large number of instantaneous data sets are combined. An assumption implicit in the interpretation of the results of this method of testing is that the velocity and directional turbulence at the test site is similar to that of the site where the WECS is to be installed.

6.5 Performance Establishment Tests

A number of differing techniques have been used for Performance Establishment depending on the aspect of the WECS performance which is of interest. In an attempt to assess the rotor behaviour of the Swansea University horizontal axis variable speed machine a modified method of bins was used to measure C_p/λ and C_T/λ curves (6.23). Instantaneous wind speed, torque and rotational speed measurements were taken. As this was a variable speed machine a correction was made for the kinetic

energy change due to acceleration of the aerogenerator. A similar technique was used by Stacey (6.24) on the RAL variable speed vertical axis machine and refined by Stacey and Musgrove (6.25) to a cubic binning method. In this technique bin lines of the form $C_p = K_n \lambda^3$ are drawn and a more accurate representation of C_p is possible at high values of λ . A rather different approach suggested by Sharpe is that of measuring the acceleration of the unloaded rotor in a constant windspeed (6.26). This has the major advantage of allowing the complete C_p/λ curve to be evaluated with one test but requires a constant wind velocity for accurate results.

A number of workers (6.27; 6.28; 6.29) have suggested corrections to the testing procedures to take account of the additional energy available in the turbulence of the wind. This additional energy is apparently available because of the assumed cubic relationship between the WECS output power and the free wind speed. However, for fixed speed, horizontal axis machines the output power is approximately linear between cut-in and rated wind speed. Therefore for practical purposes these corrections may be neglected for fixed speed, horizontal axis wind turbines.

When carrying out Performance Establishment tests the effects of transient wind conditions are important and the response of the anemometer may become significant. The transient response of a cup anemometer is usually characterised by a distance constant giving that wind run (in metres) which would correspond to a change in anemometer response of 63%. This is analogous to a

time constant but takes account of varying wind speeds. The transient response of a cup anemometer is not symmetrical (6.3) and the distance constant refers to the acceleration of the rotor cups. Deceleration normally has a longer time constant, depending on the cup design. Ower and Pankhurst (6.30) have shown that in a sinusoidally varying windspeed described by:-

$$V_o = V + A \sin \omega t \quad (6.5)$$

then the speed indicated by a vane anemometer (V_i) is given approximately by:-

$$V_i = V_o \left(1 + \frac{1}{2} \left(\frac{A}{V_o} \right)^2 \right) \quad (6.6)$$

The overestimation of windspeed in the turbulent wind conditions of field testing may result in experimental results differing from calculated values and if very accurate results are required fast response anemometry must be used.

For such detailed measurements of transient wind conditions various types of anemometry have been used including propellor type, ERA gust type, hot wire and even laser doppler devices. As the response time is decreased both cost and complexity rapidly increase and for general use in both Performance Verification and Performance Establishment cup type anemometers with a distance constant of 5m are suitable.

6.6 Experimental Procedure

The object of the experiment was to verify the Power Curve of the L916 wind turbine which had been calculated by the manufacturer. Performance Verification was required and so the experimental procedure adopted was that of the IEA recommended practices (6.15). However, in addition to the 10 minute mean values recommended, the same data was used to calculate 30 second, 1 minute and 5 minute mean values. A total data set of 450 10 minute runs was collected during 75 hours of testing. As the tests were carried out during the months of April and May it was not possible to test at very high wind speeds.

The free wind speed was measured by cup anemometers mounted at hub height a distance of 18m (2 rotor diameters) from the aerogenerator. The anemometer in the free wind speed, uninfluenced by the wake, was recorded as having a negative windspeed. Tagging the free wind velocity as negative allowed it to be easily identified in the data analysis programs. Selection of the free wind speed was done manually at the beginning of each test. As well as the two anemometers on towers the anemometer on the boom was used to record the wind speed 4.5m upwind of the rotor disk. These three anemometers produced pulse train outputs which were counted and reset every 30 seconds. The anemometers were all calibrated in a wind tunnel before the start of the testing and run against each other for 24 hour periods at the beginning and end of the tests. The calibrations remained consistent during the tests. No correction for transient overspeeding of the anemometers was made.

An attempt was made to use an integrating single phase kWh meter to measure net power output. However, the imbalance of the output power, caused by the connection of the alternator field supply, was such as to require the 3 wattmeter method of power measurement. As only one digital data logger channel was available the use of integrating kWh meters was abandoned. Instead the instantaneous power transducer, which gave an analogue output, was sampled every 500ms and 30 second mean values calculated.

The IEA recommendations require that the mean net power output is corrected to a standard air density of 1.225 kg/m^3 (dry air at 15°C and 1013.3 mbar) using the formula:-

$$\rho_x = 1.225 \left(\frac{288.15}{T} \right) \left(\frac{B}{1013.3} \right) \quad (6.7)$$

where ρ_x : test air density (kg/m^3)
 T : air temperature ($^\circ\text{K}$)
 B : barometric pressure (bar)

The corrected mean power is then given by:

$$P_r = P_x \frac{\rho_r}{\rho_x} \quad (6.8)$$

where P_r = Power corrected to standard conditions
 P_x = Uncorrected mean power of test
 ρ_r = Standard air density 1.225 kg/m^3

```

RUN NUMBER 440    5 / 6 / 84
DIR 240 TEMP 10 PRESSURE 742
ANEMOMETER IN FREE WIND B
LENGTH OF RUN 30 SECS
W/S(WTG)  W/S(A)  W/S(B)  POWER
M/S      M/S      M/S      KW
7.09      7.12     -7.41     3.75
7.16      8.12     -7.36     3.91
7.63      7.72     -7.91     4.59
6.51      6.27     -6.94     2.97
5.22      5.85     -5.75     .85
5.5       6.09     -6.12     1.64
4.95      5.02     -5.49     .72
6.89      7.31     -7.45     3.72
6.37      6.68     -6.59     2.92
7.8       8.1      -8.49     4.58
8.82      8.91     -9.03     6.36
7.33      7.53     -7.6      4.28
6.84      7.92     -7.09     3.3
5.88      6.18     -5.96     2.16
5.47      6.79     -6.26     1.52
6.11      6.11     -6.04     2.54
6.23      6.24     -6.21     2.53
4.92      4.68     -4.86     1.06
4.15      5.48     -4.91     -.1
4.12      4.76     -4.67     -.31
LENGTH OF RUN 60 SECS
7.12      7.62     -7.38     3.83
7.07      6.99     -7.43     3.78
5.36      5.97     -5.93     1.25
5.89      6.13     -6.47     2.22
7.09      7.39     -7.54     3.75
8.07      8.22     -8.32     5.32
6.36      7.05     -6.53     2.73
5.79      6.45     -6.15     2.03
5.54      5.43     -5.5      1.79
4.14      5.09     -4.79     -.21
LENGTH OF RUN 5 MINS
6.51      6.82     -6.95     2.96
5.97      6.45     -6.24     2.33
LENGTH OF RUN 10 MINS
6.24      6.63     -6.6      2.65

```

FIGURE 6.4 HP85 HARDCOPY OF POWER PERFORMANCE DATA

FIGURE 6.5 CMS INPUT FILE OF POWER PERFORMANCE DATA

```

440 TEST 5/6/84    DATE 240 DIR 10 TEMP 742 PRESSURE
7.09 7.12 -7.41 3.75 7.16 8.12 -7.36 3.91 7.63 7.72 -7.91 4.59
6.51 6.27 -6.94 2.97 5.22 5.85 -5.75 .85 5.5 6.09 -6.12 1.64
4.95 5.02 -5.49 .72 6.89 7.31 -7.45 3.72 6.37 6.68 -6.59 2.92
7.8 8.1 -8.49 4.58 8.82 8.91 -9.03 6.36 7.33 7.53 -7.6 4.28
6.84 7.92 -7.09 3.3 5.88 6.18 -5.96 2.16 5.47 6.79 -6.26 1.52
6.11 6.11 -6.04 2.54 6.23 6.24 -6.21 2.53 4.92 4.68 -4.86 1.06
4.15 5.48 -4.91 -.1 4.12 4.76 -4.67 -.31 7.12 7.62 -7.38 3.83
7.07 6.99 -7.43 3.78 5.36 5.97 -5.93 1.25 5.89 6.13 -6.47 2.22
7.09 7.39 -7.54 3.75 8.07 8.22 -8.32 5.32 6.36 7.05 -6.53 2.73
5.79 6.45 -6.15 2.03 5.54 5.43 -5.5 1.79 4.14 5.09 -4.79 -.21
6.51 6.82 -6.95 2.96 5.97 6.45 -6.24 2.33 6.24 6.63 -6.6 2.65

```

This correction was included in the data logging program and the air temperature and pressure were entered manually at the beginning of each test. An outline flow chart of the data logging program is shown in Figure 6.3. Typical outputs are shown in Figures 6.4 and 6.5.

The data was recorded using the HP85 based data logging system and then transferred on to the RAL CMS system for analysis.

6.7 Experimental Results and Analysis

The data obtained during the test period is shown in Figures 6.6 - 6.17. The 30 second mean graphs, Figures 6.9, 6.13, 6.17, each show 9,000 points corresponding to the 75 hours of data. It may be seen that as the averaging time was increased the maximum wind speed was reduced. This is shown more clearly by the Probability Density Functions of the windspeeds measured during the test period (Appendix D). Increasing the averaging time also reduced the scatter on the data points, e.g. Figures 6.9, 6.8, 6.7, 6.6. The higher coherence between the boom anemometer and the power output is shown by significantly reduced scatter when compared to the free wind speed anemometer plots, e.g. Figures 6.8 and 6.12. The test site was obstructed on two sides by buildings and so the scatter associated with the free wind speed measurements, and attributed to lateral incoherence caused by turbulence, was not unexpected. The power required by the wind turbine for excitation of the field and to supply motoring losses is clearly shown for wind speeds below cut in (4.5 m/s).

FIGURE 6.6 (FREE WIND SPEED)

POWER PERFORMANCE (10 MIN)

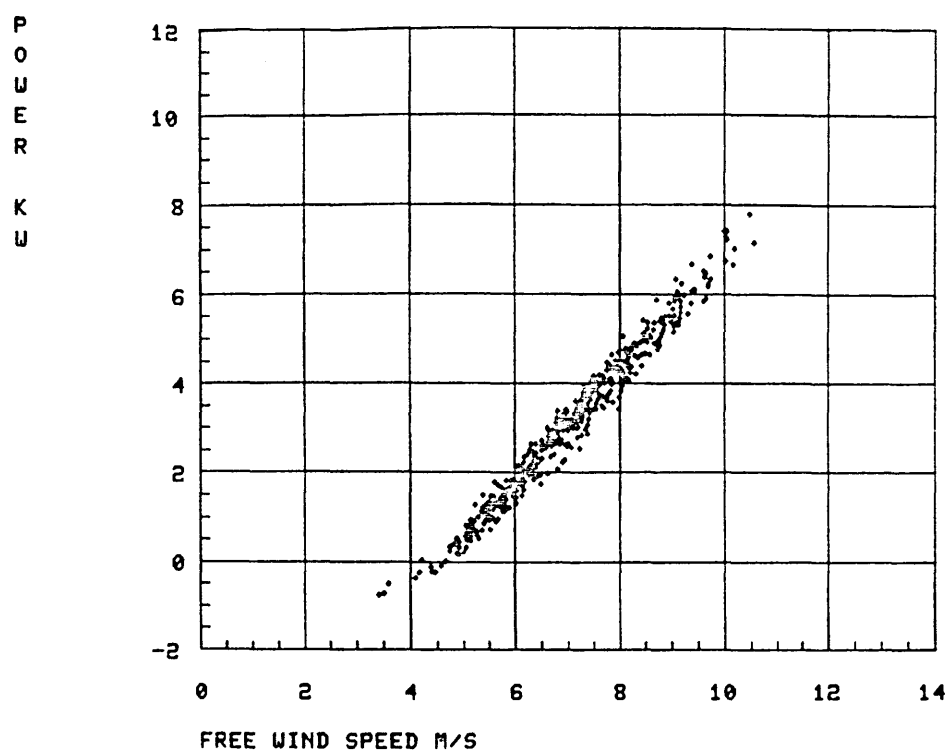
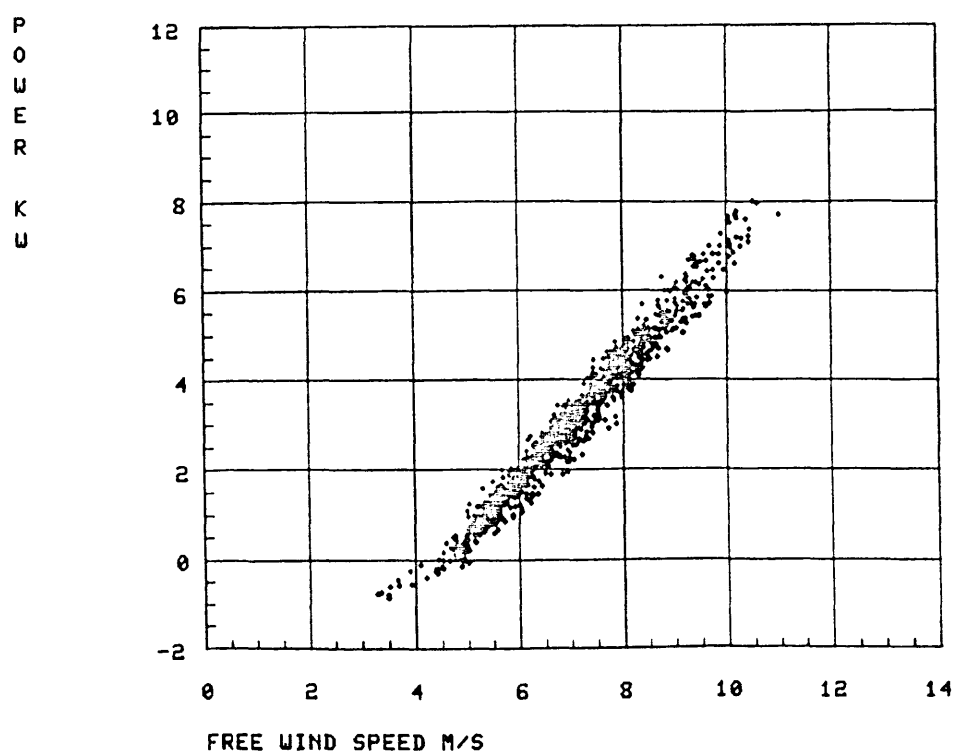


FIGURE 6.7 (FREE WIND SPEED)

POWER PERFORMANCE (5 MIN)



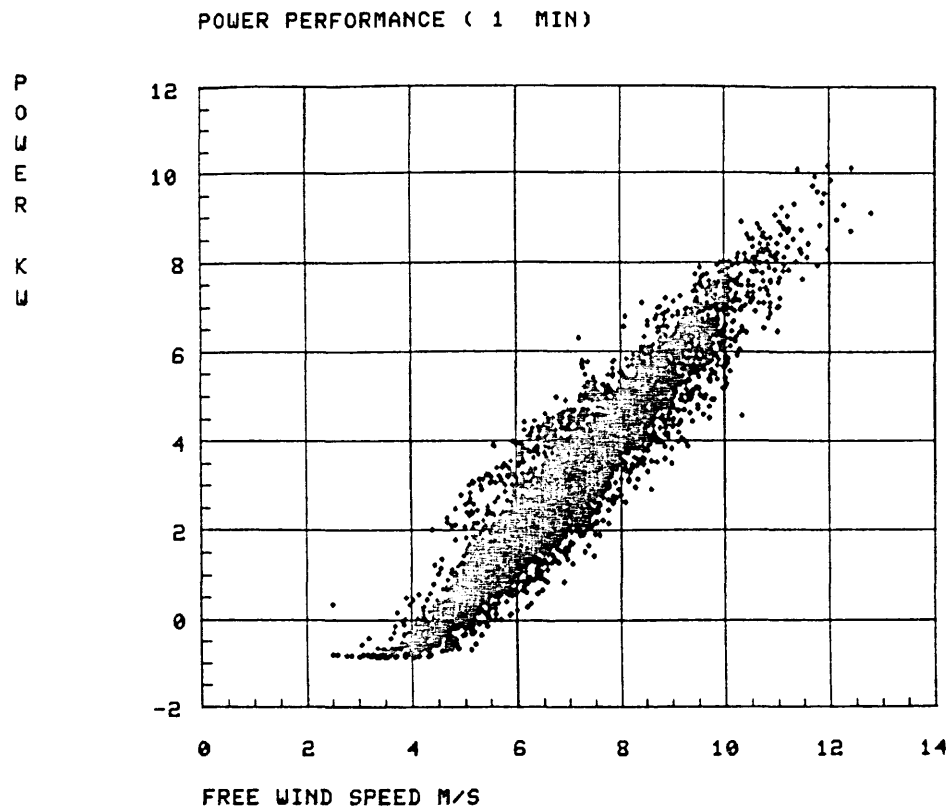
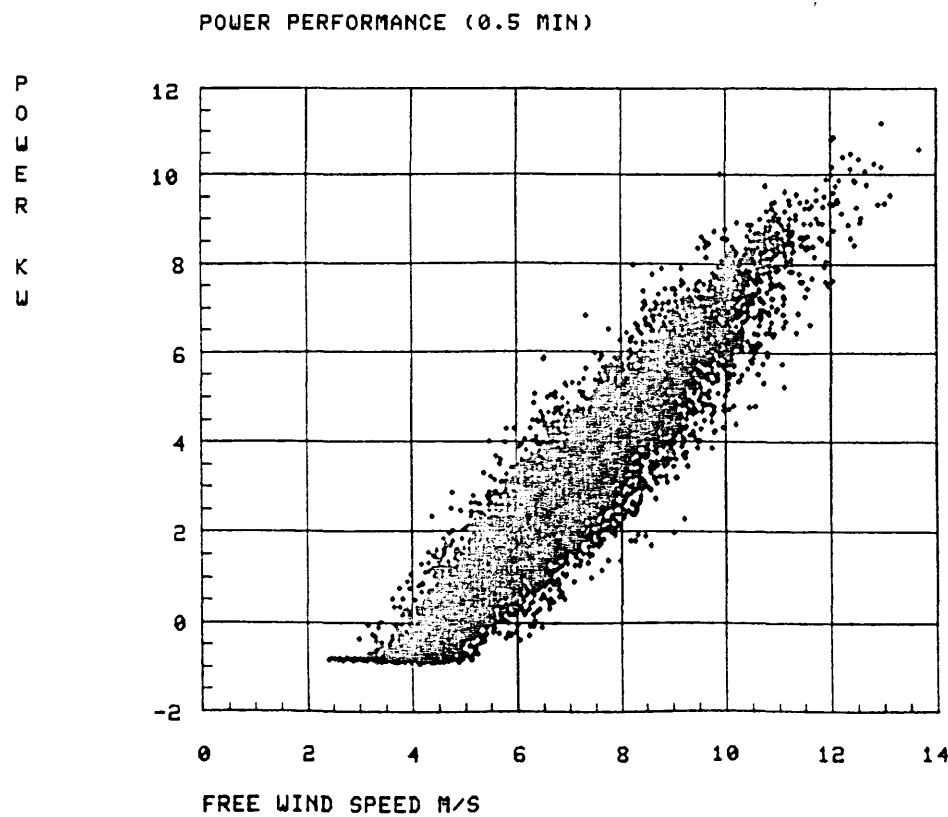


FIGURE 6.9 (FREE WIND SPEED)



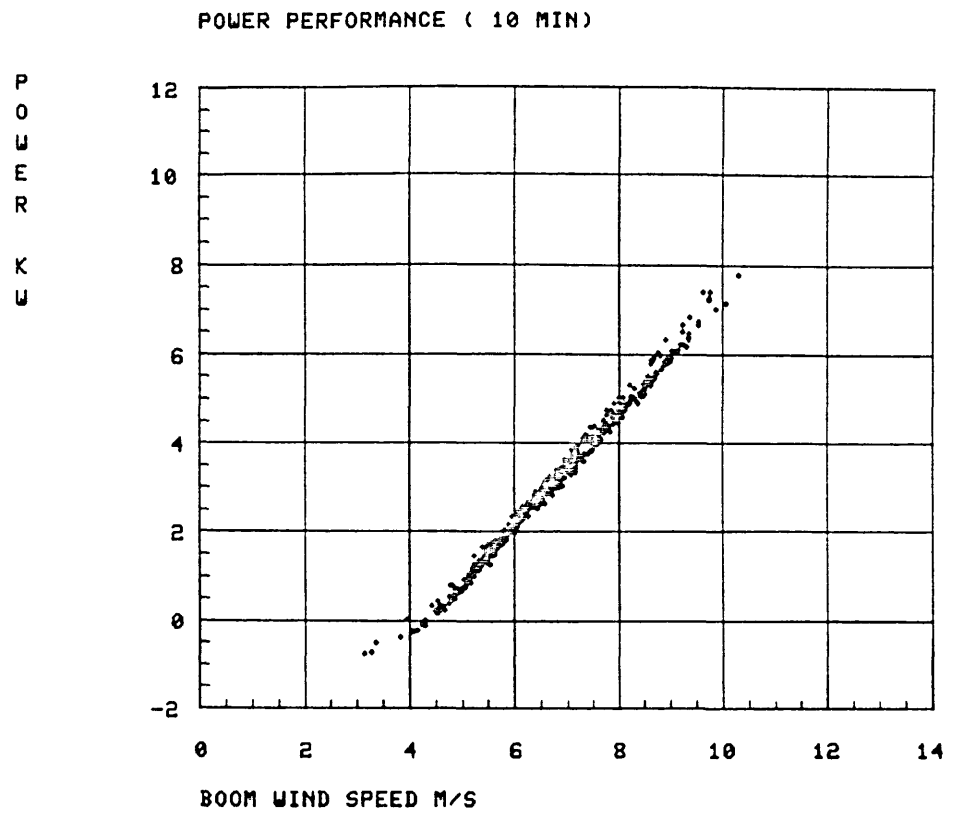


FIGURE 6.11 (BOOM WIND SPEED)

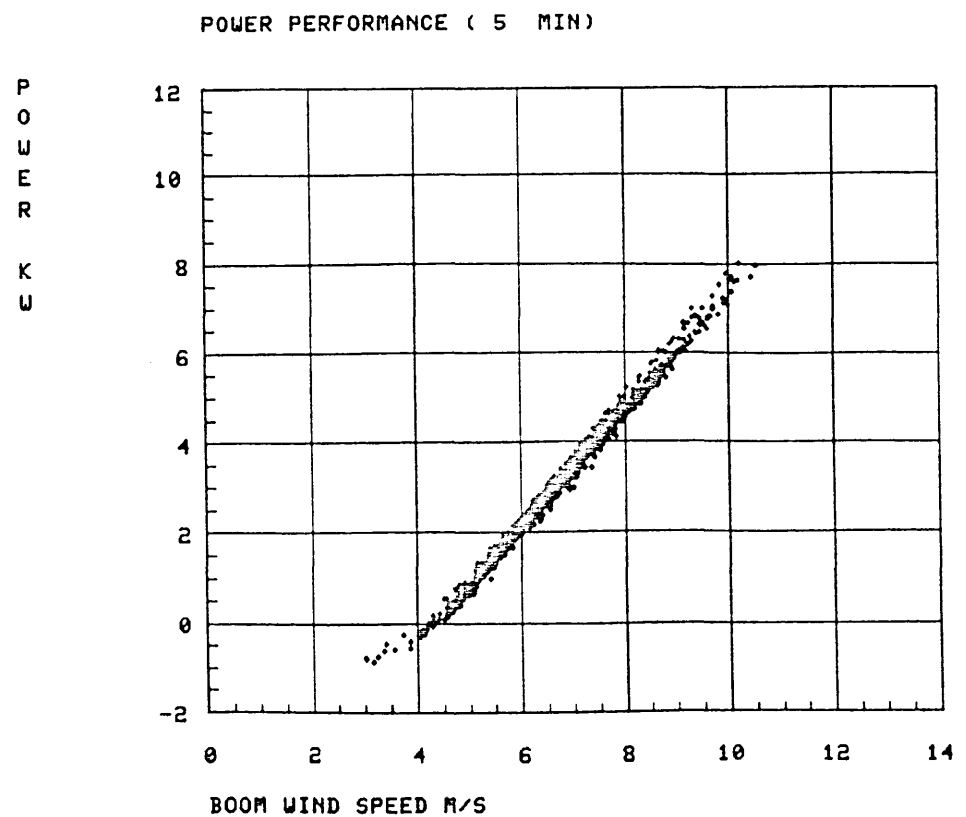


FIGURE 6.12 (BOOM WIND SPEED)

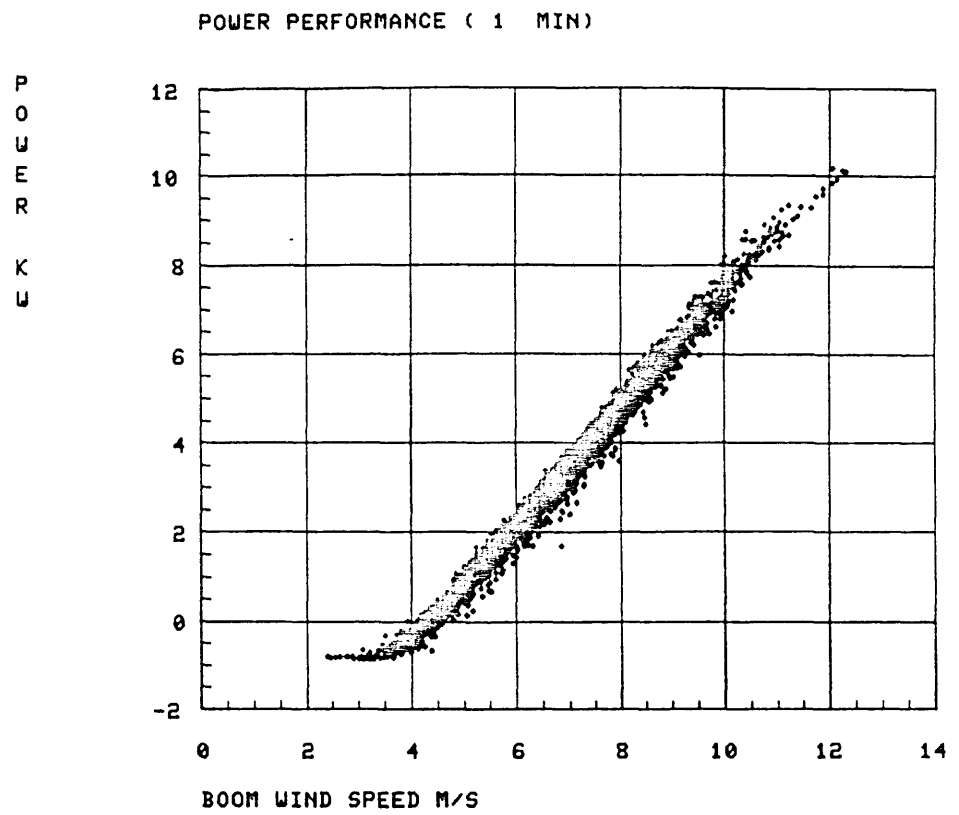


FIGURE 6.13 (BOOM WIND SPEED)

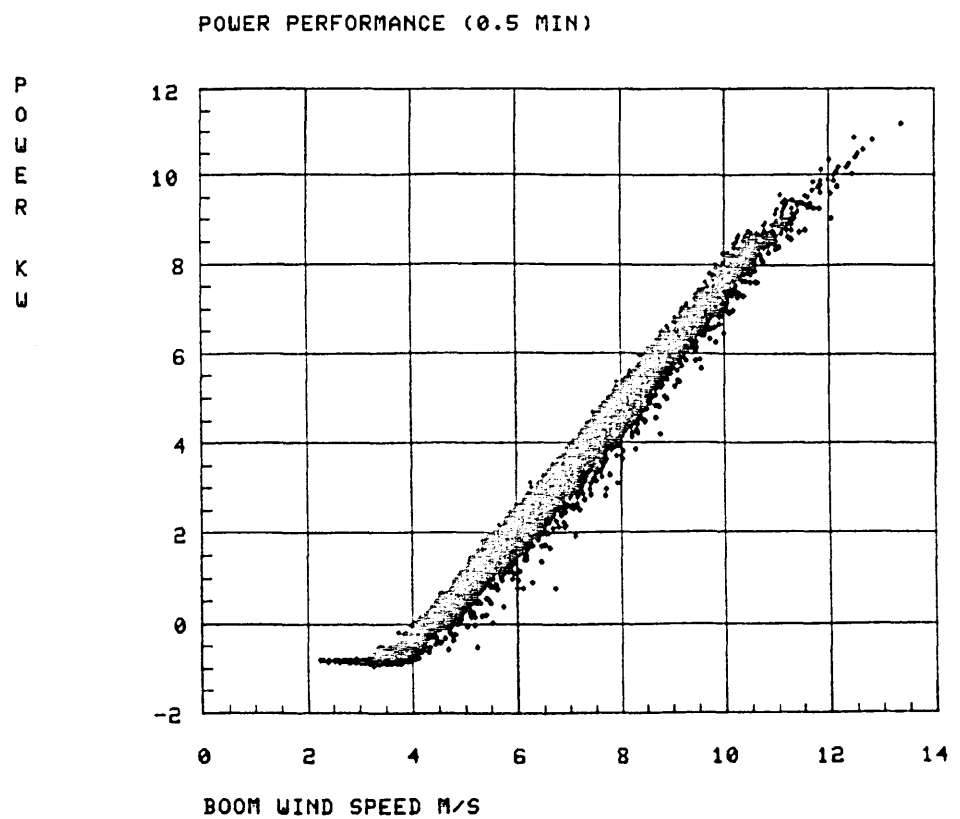


FIGURE 6.14

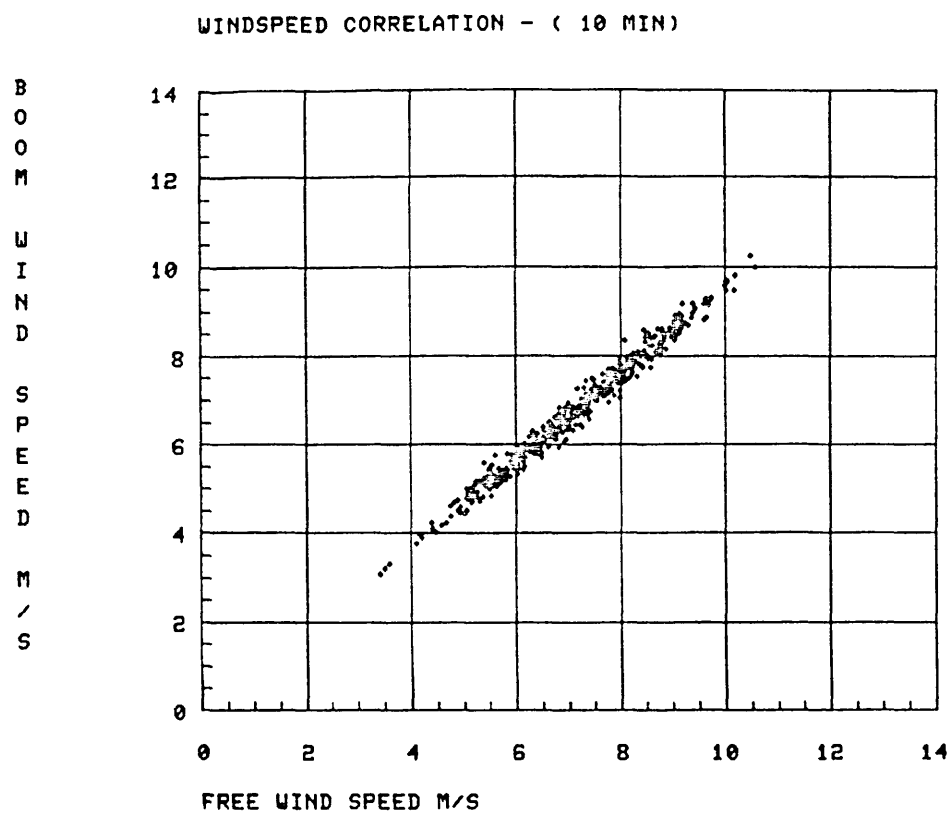


FIGURE 6.15

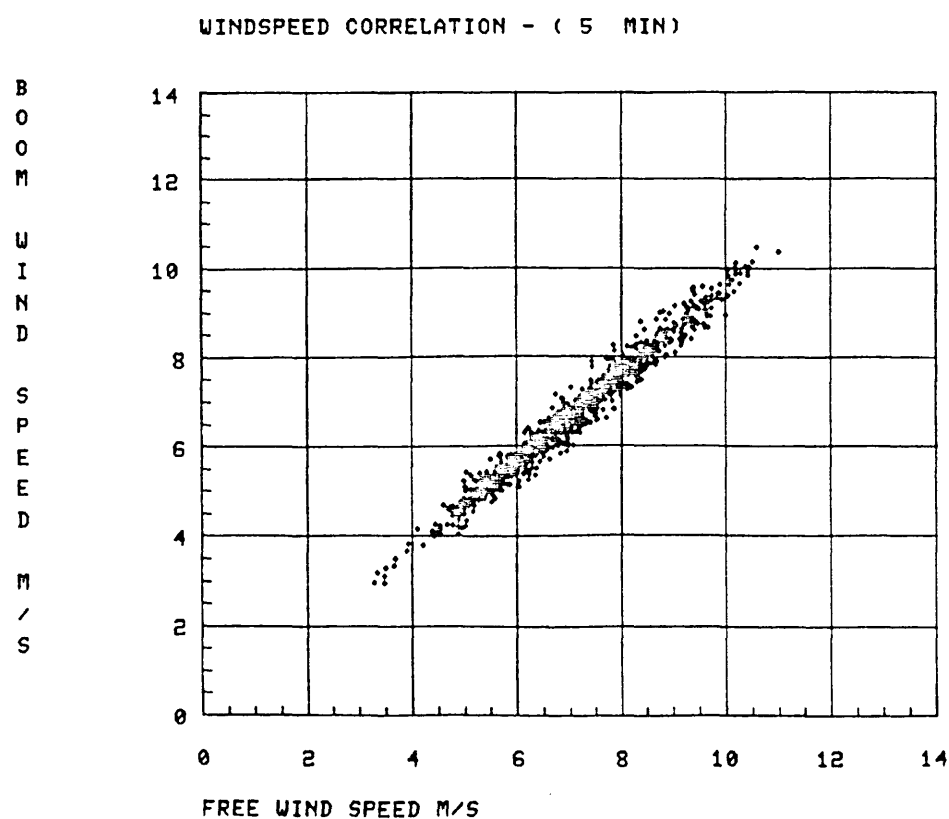


FIGURE 6.16

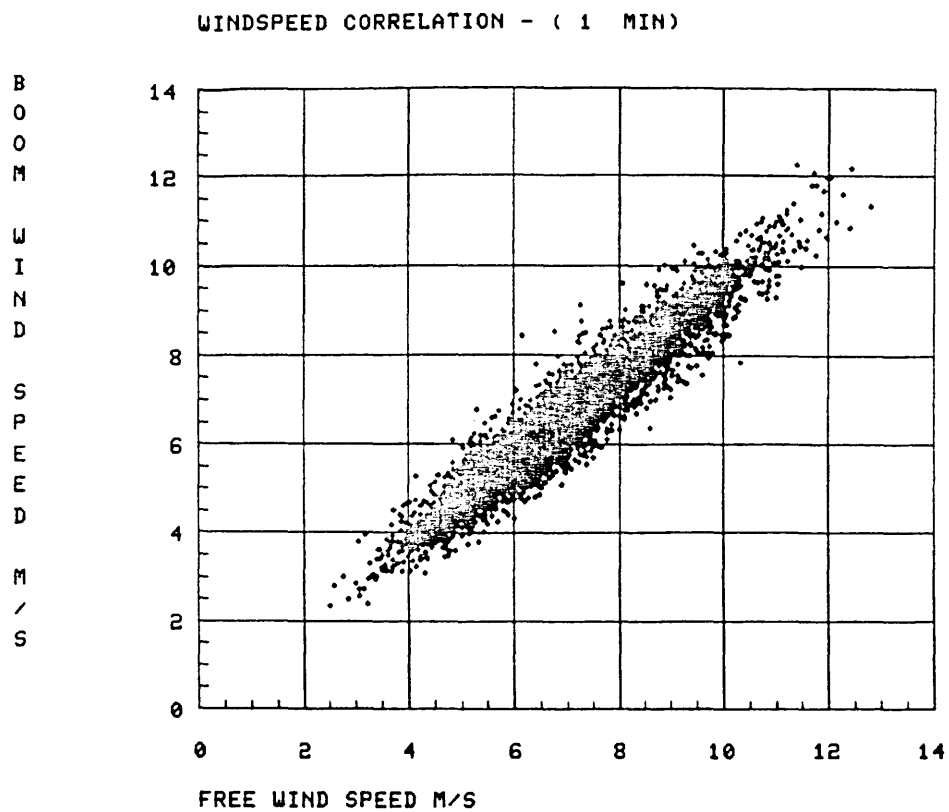


FIGURE 6.17

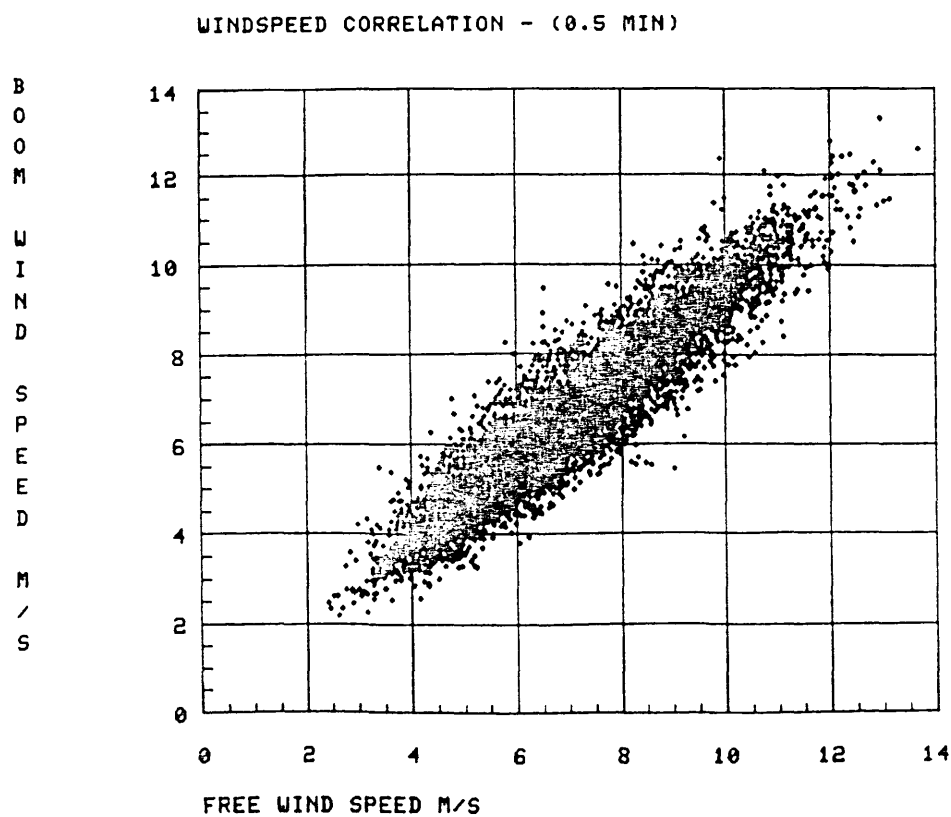
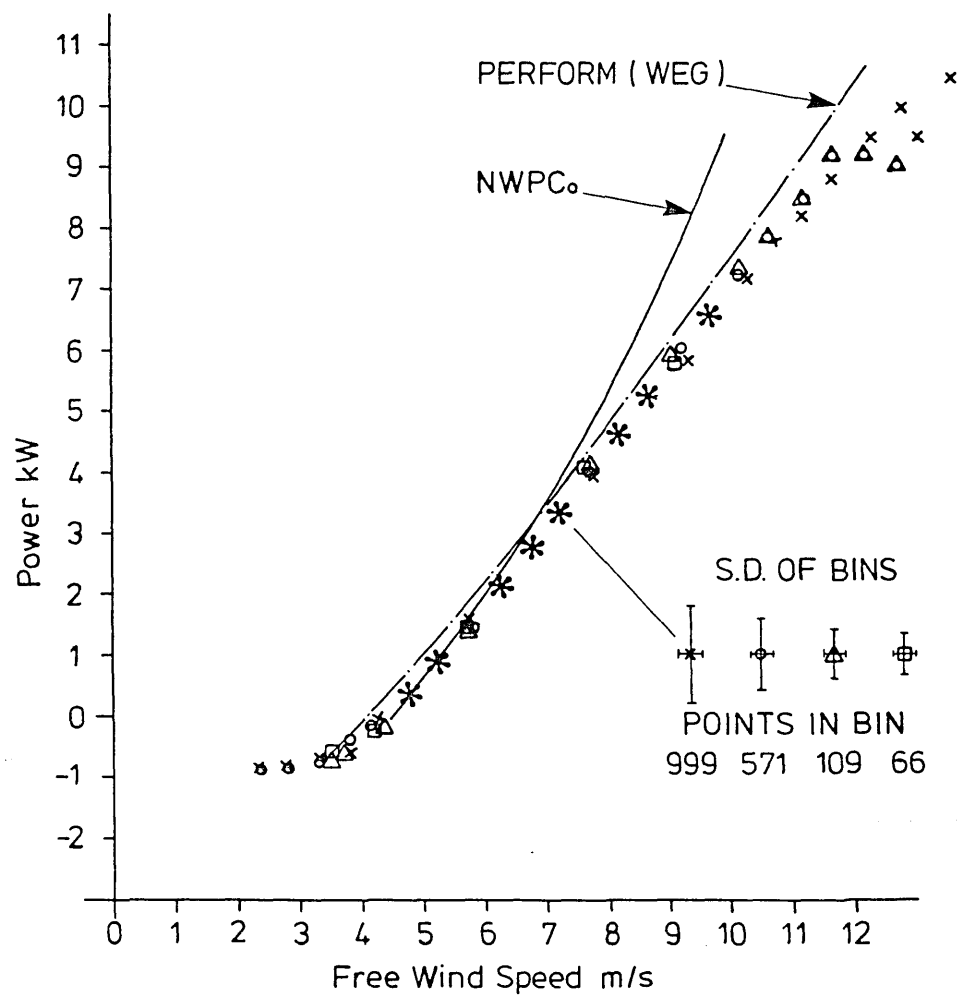


FIGURE 6.18

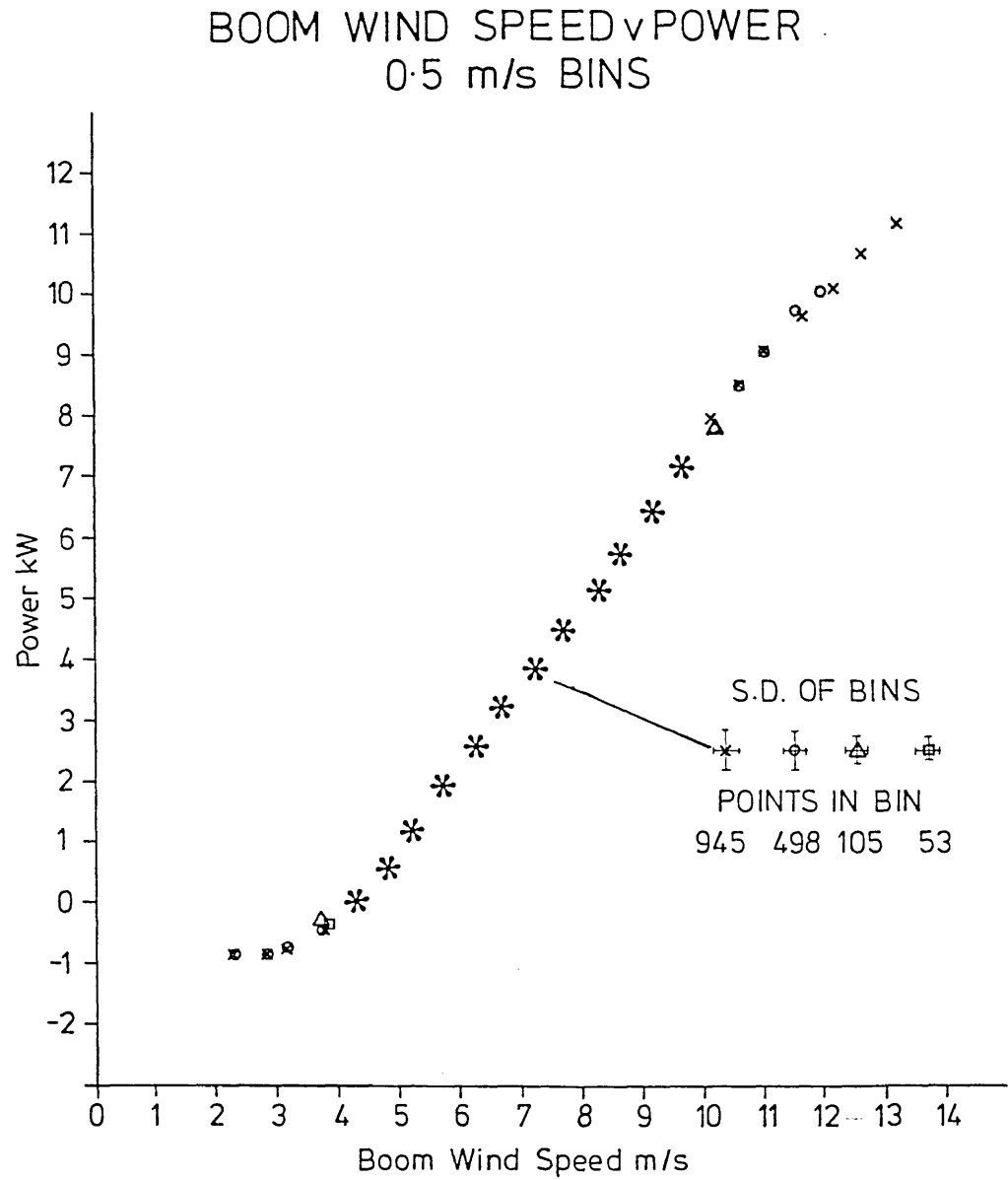
FREE WIND SPEED v. POWER 0.5 m/s BINS



KEY

- 10 min. means
- △ 5 min. means
- 1 min. means
- × 30 sec. means
- * All values coincident

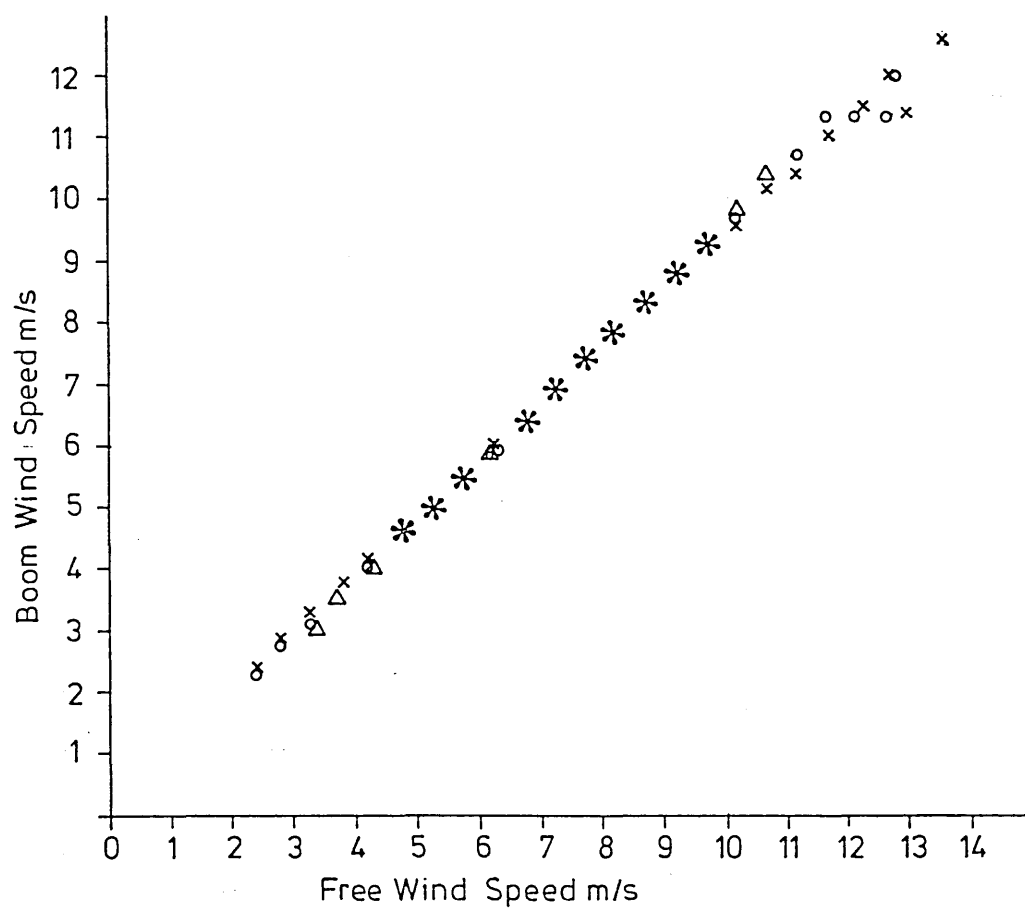
FIGURE 6.19

KEY

- 10 min means
- △ 5 min means
- 1 min means
- × 30 sec means
- * All values coincident

FIGURE 6.20

FREE WIND SPEED ν BOOM WIND SPEED 0.5 m/s BINS



KEY

- 10 min means
- △ 5 min means
- 1 min means
- × 30 sec means
- * All values coincident

FIGURE 6.21

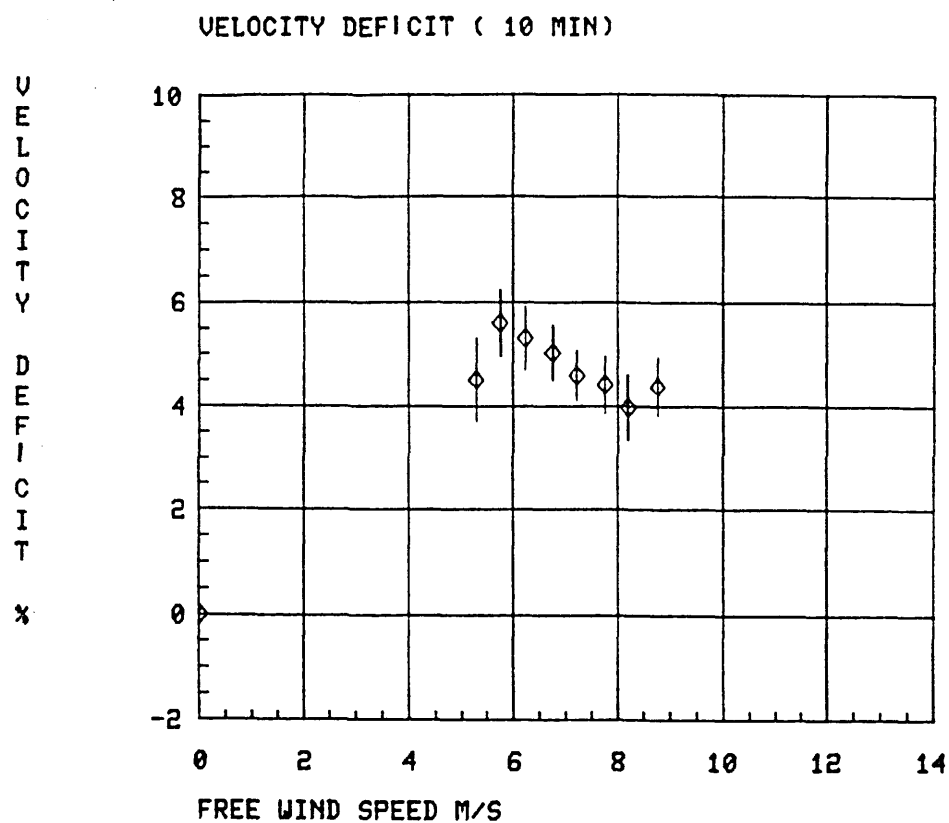


FIGURE 6.22

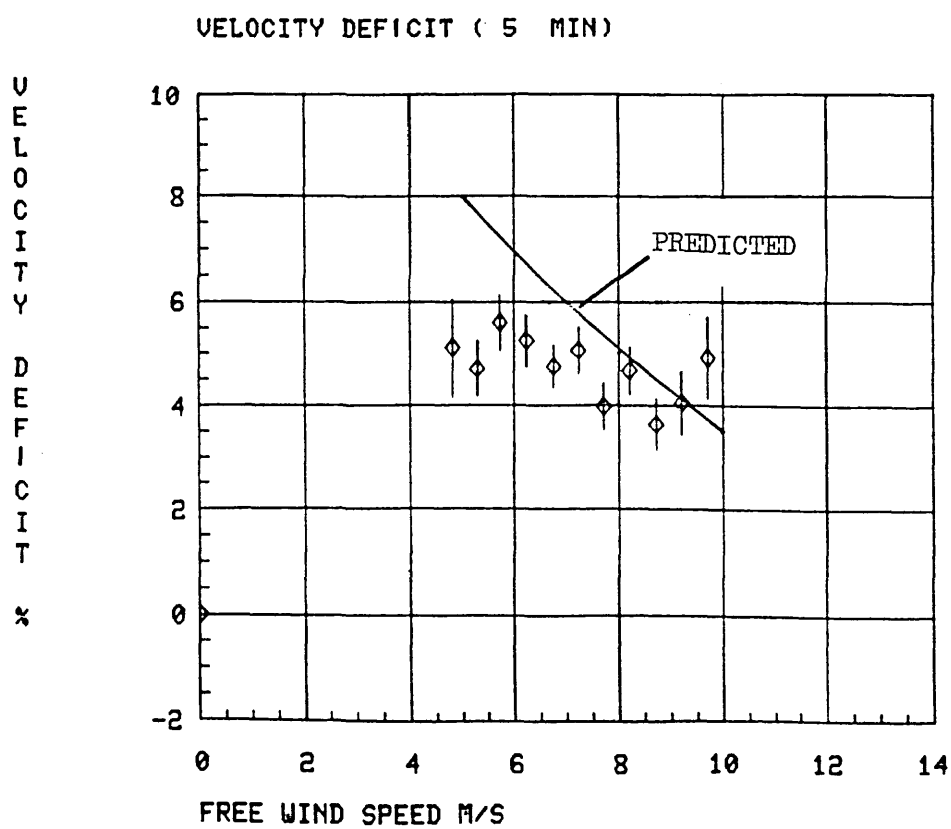


FIGURE 6.23

VELOCITY DEFICIT (1 MIN)

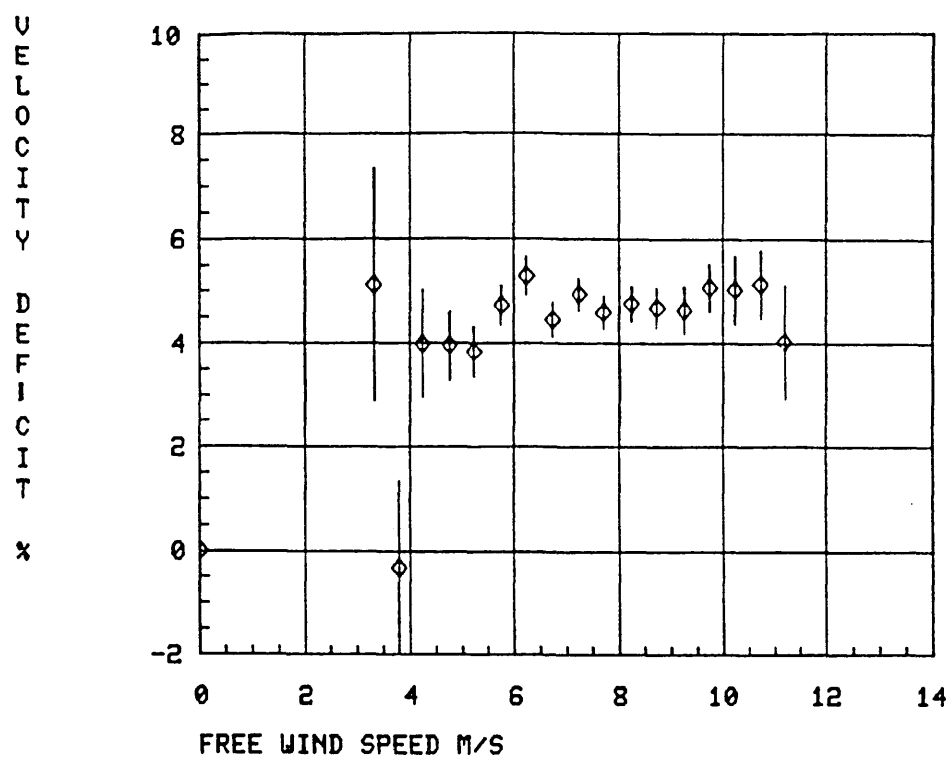
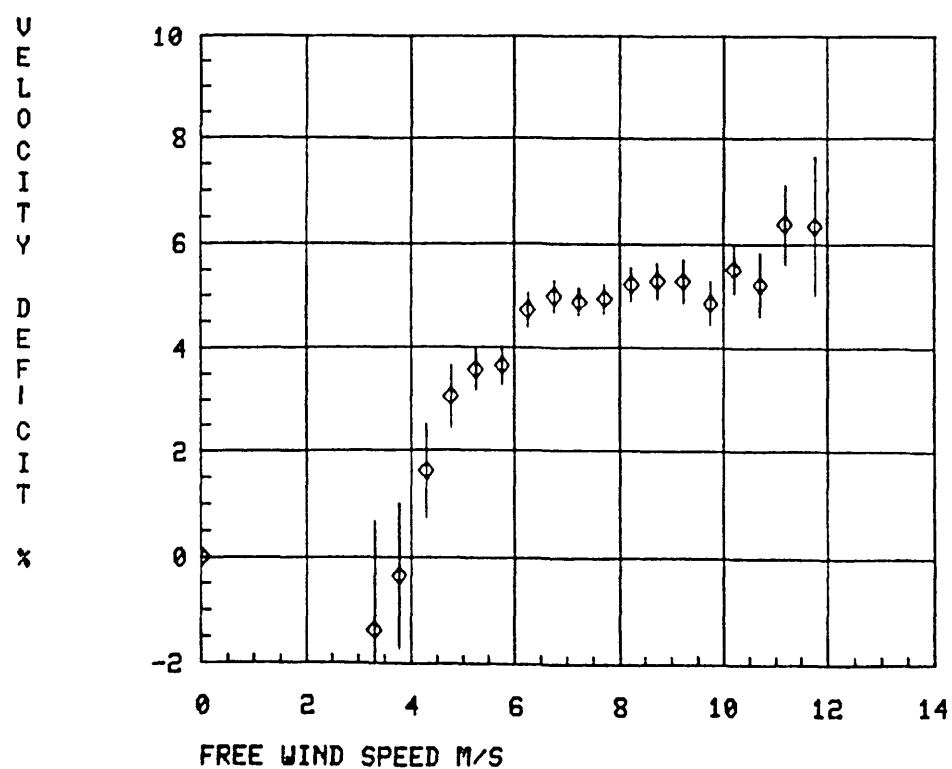


FIGURE 6.24

VELOCITY DEFICIT (0.5 MIN)



Two approaches were used to analyse the data, both of which were implemented in the program ANALYSE. The first approach was to bin the data according to the IEA recommendations although using 0.5 m/s bins. The results of this analysis are shown in Figures 6.18 - 6.20. Inspection of the curves indicates no significant difference in results due to different averaging times. In particular there was no apparent rotation of the curve with the decrease in averaging time.

The calculated power curves are shown in Figure 6.18. Agreement is good at low windspeeds but the manufacturers predicted curve tended to overestimate power output at the higher windspeeds.

The prediction using PERFORM gave better agreement although there was still some discrepancy at windspeeds above 10 m/s. These was probably due to a number of factors including a split which developed in the trailing edge of one of the blades, incorrect estimation of the operation of the blade pitch mechanism and poor yaw performance.

The second approach to analysing the data was to apply an unweighted least squares linear regression analysis (6.31) to the data points. The results are shown in Table 6.1. The standard errors of the regression coefficient were low, less than 1%, and the coefficients of determination were high for all results except those with a 30 second averaging time. This reflected the increased scatter of these points caused by the shorter averaging time. At wind speeds below cut in, the Power Curve was non-linear as the alternator motoring losses

Table 6.1

Power Performance Testing Experimental Results

AVERAGING TIME (minutes)	REGRESSION COEFFICIENT	STANDARD ERROR OF COEFFICIENT	REGRESSION CONSTANT	STANDARD ERROR OF CONSTANT	COEFFICIENT OF DETERMINATION
10 5 1 0.5	1.252 1.257 1.237 1.214	POWER/FREE WIND SPEED		0.068 0.058 0.041 0.035	0.975 0.964 0.913 0.873
		0.010	-5.654		
		0.008	-5.688		
		0.006	-5.549		
10 5 1 0.5	1.281 1.288 1.302 1.303	POWER/BOOM WIND SPEED		0.038 0.028 0.015 0.012	0.991 0.991 0.987 0.983
		0.006	-5.439		
		0.004	-5.482		
		0.002	-5.578		
10 5 1 0.5	0.976 0.974 0.944 0.921	FREE WIND SPEED/BOOM WIND SPEED		0.046 0.041 0.031 0.027	0.981 0.969 0.913 0.868
		0.006	-0.160		
		0.006	-0.148		
		0.004	0.068		

predominated. This effect was particularly noticeable with the shorter averaging times. In general, however, this regression analysis confirmed that the Power Curve of the L916 could be considered linear between cut in and 12 m/s.

The deficit of the wind velocity measured by the boom compared to the free wind speed shown in Figures 6.14 to 6.17 was also examined. The results, shown in Table 6.1, show a rotation of the regression lines which was caused by the low wind speed values of the shorter averaging times. This effect may be seen more clearly in Figures 6.21 - 6.24. At wind speeds below cut in the velocity deficit drops to zero but at wind speeds above 5 m/s the deficit is reasonably constant at 5%. The error bars show the standard deviation of the points in the 0.25 m/s bins. Bins having less than 10 points are not shown.

The measured results of the velocity deficit experiments may be compared with theoretical predictions.

The axial induction factor (a) was calculated using the program PERFORM. This gave the reduction in axial wind velocity at the rotor disk. However, the boom anemometer was located 4.5m upwind of the rotor.

Koning (6.32) using vortex theory developed a relationship for the change in axial induction factor with distance upstream of the rotor disk (Y):-

$$a_1 = a \left[1 - \frac{\beta}{\sqrt{1 + \beta^2}} \right] \quad (6.9)$$

where $\beta = \frac{Y}{r}$, r : radius of rotor (m)
 Y : distance upstream (m)
 a_1 : translated axial induction factor

The boom anemometer was fixed 1 rotor radius upwind and so Equation 6.9 reduces to:-

$$a_1 = a \times 0.29 \quad (6.10)$$

Therefore using the results shown in Figure 6.2 and Equation 6.10 the velocity deficit of the boom anemometer may be predicted. This is shown in Figure 6.22. At mean wind speeds below 6 m/s the instantaneous wind speed was sometimes below cut in. Therefore the machine was not always rotating at 125 rpm and so the experimental values are rather lower than the predictions. In general, however, agreement with the experimental results was good. Similar results were obtained for the velocity deficit of an anemometer situated on the nacelle behind an upwind rotor on the WEG Orkney 20 metre wind turbine (6.33).

6.8 Conclusions

The Power Performance testing described in this section allowed the main characteristic curve of the wind turbine generator to be determined. It differed significantly from the manufacturers predicted value. Improved agreement was obtained using the PERFORM code. The comparison of the pre-averaging times showed that there was no apparent benefit in using averaging times

greater than 30 seconds for this size of wind turbine. The deficit in velocity measured by the boom anemometer 1 rotor radius upwind was found to be 5% independent of averaging times. The coherence between boom wind speed and output power was much better than that between free wind speed and output power. With a known velocity deficit it is possible to use the boom anemometer to examine transient effects. Strip theory, combined with Equation 6.9 was successful in predicting the upwind velocity deficit.

CHAPTER 7

AUTONOMOUS PARALLEL WIND-DIESEL OPERATION

7.1 Introduction

On completion of the experiments on the wind turbine generator connected to the L.V. system a test programme of autonomous parallel wind diesel operation was carried out. The calculations described in Chapter 4 and the experimental results of Chapter 5 had indicated that no major modifications to the wind turbine or diesel were required. The equipment was reconfigured to the autonomous wind diesel system which is shown schematically in Figure 7.1. During these experiments there was no connection to the RAL L.V. system.

7.2 Parallel Operation

Initially a dump load was not available and so the wind turbine generator and diesel were connected in parallel feeding only the consumer load which was set to a high fixed value. The diesel generator set was loaded to 6.5kW with the consumer load and the wind turbine generator field was supplied from the site auxiliary instrumentation supply. Separate excitation of the wind turbine generator gave additional stability for commissioning. In a wind speed of 7 m/s the wind turbine was run up and paralleled with the diesel set. The power from the wind turbine acted to remove load from the diesel engine. System voltage and frequency were stable. The wind turbine

FIGURE 7.1

AUTONOMOUS WIND DIESEL SYSTEM

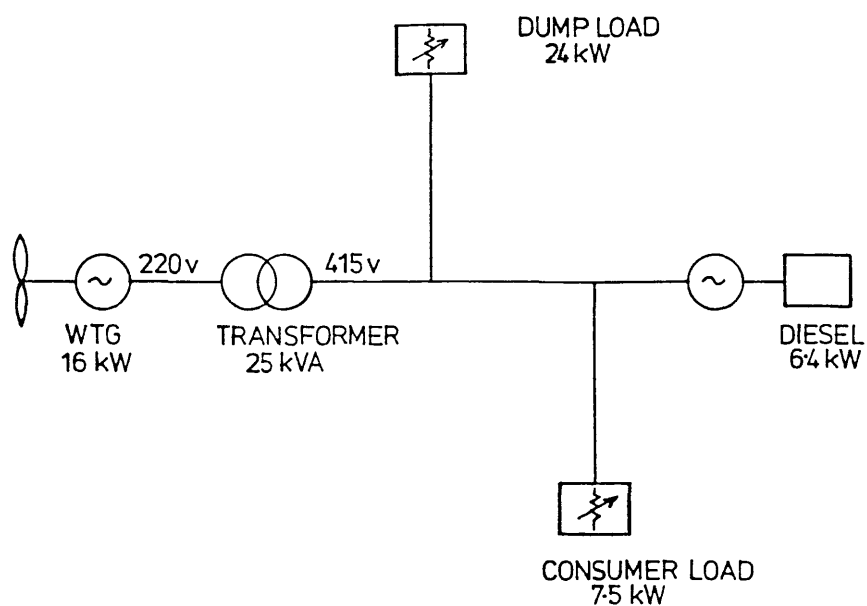
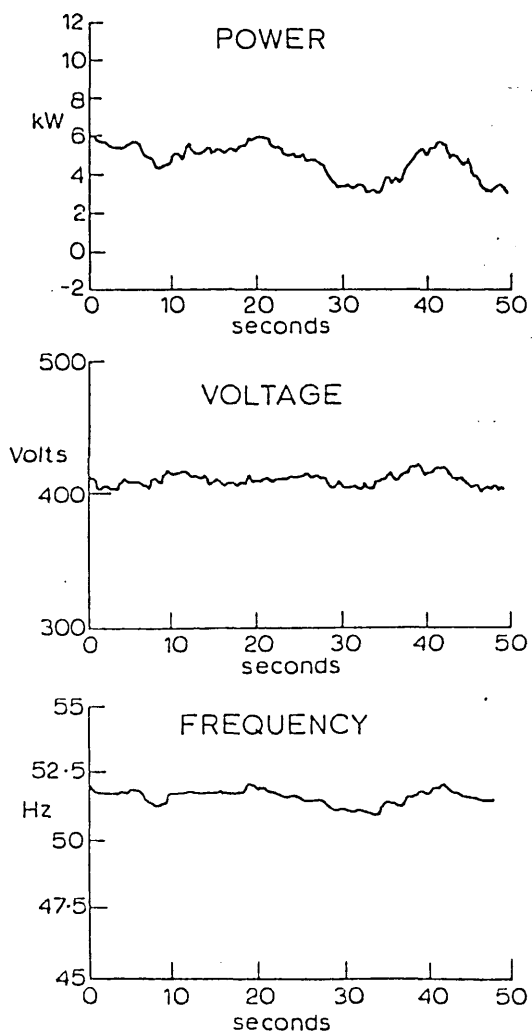


FIGURE 7.2 STEADY STATE WIND DIESEL OPERATION (NO DUMP LOAD)



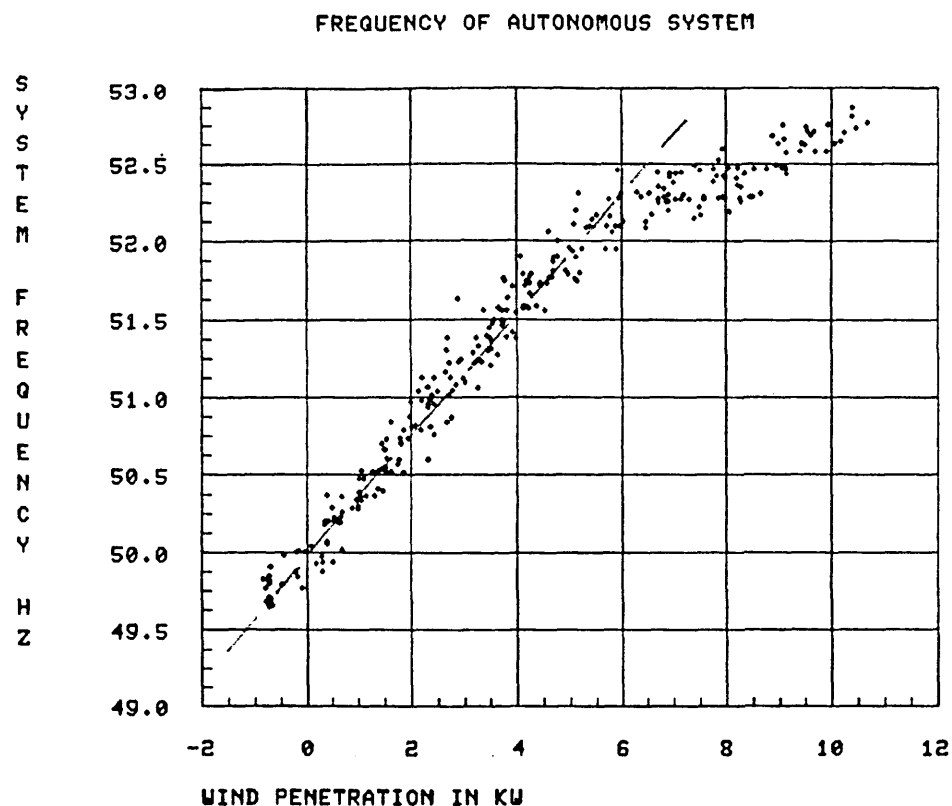
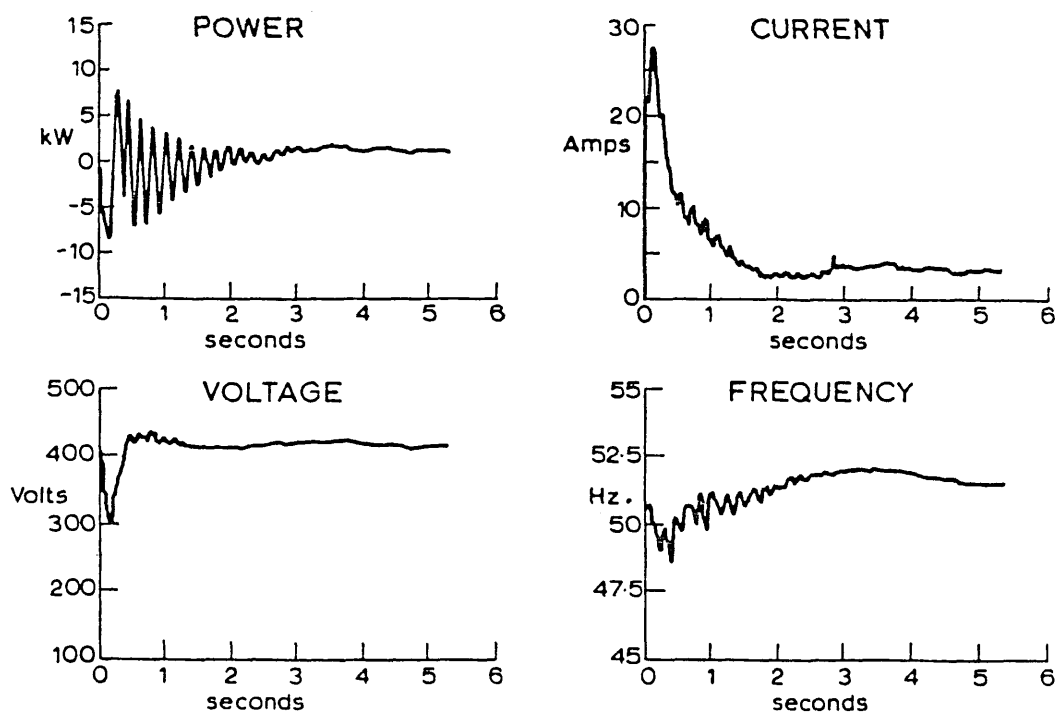
field supply connection was then rewired so that the alternator excitation power was derived from the autonomous system and the excitation base level adjusted. Parallel operation was then repeated and the system voltage and frequency were again stable.

A data logging program DYNPAR was written to examine the steady state performance and results are shown in Figure 7.2. The traces show output power of the wind turbine, system voltage and system frequency with each transducer sampled every 500 ms. The system voltage was maintained at approximately 415 Volts and it may be seen that as the power from the wind turbine removed the load from the diesel the frequency rose corresponding to the droop line of the diesel engine. This is shown more clearly in Figure 7.3 where the droop line is shown dashed. For these tests the program PARCPF was used and each point is a 200ms mean value taken at 10 second intervals.

A change of slope is noticeable when the windpower exceeds the fixed consumer load value (6.5 kW). In this mode of operation the diesel engine losses are being supplied from the wind turbine and the diesel governor is no longer operating in its linear region. The governor was a mechanical "Watt governor" type and did not maintain the droop line when the engine was being partially motored.

With a fixed consumer load the system was stable up to a wind penetration equal to the sum of the consumer load and the diesel

FIGURE 7.3 OPERATION OF WIND DIESEL SYSTEM (NO DUMP LOAD)

FIGURE 7.4
WIND DIESEL OPERATION (WORST CASE PARALLELING TRANSIENT)

set losses. Above this value of wind power the system frequency rapidly rose and the system became unstable. This rapid rise of frequency, which caused tripping of the over frequency relay, set at 53 Hz, occurred on a number of occasions when operating without a dump load in high winds.

The effect of the paralleling transient on the system stability was also examined over a series of 23 paralleling tests. The program SYNPAR, in which wind turbine power, current, system voltage and frequency were sampled every 16 ms, was written for these experiments. The severity of the transient disturbance depended on the point on wave of the paralleling switching. The worst recorded waveforms are shown in Figure 7.4. Although experiencing a significant voltage depression the system rapidly recovered. Other tests showed small voltage and frequency depressions on paralleling. At no time during the parallel wind diesel experiments did the system collapse due to the paralleling transient. These tests confirmed the predictions that the wind turbine could be satisfactorily paralleled with the diesel set although the maximum overcurrent on paralleling was rather lower than that predicted.

The waveshape of the system voltage was examined using a storage oscilloscope. The operation of the triac of the wind turbine excitation system was visible as well as a pronounced 5th harmonic distortion of the no load voltage produced by the diesel set. A Camille Bauer type 50-1Y1 harmonic analyser was used to measure harmonic distortion of the autonomous system voltage. The results of these tests are shown in Table 7.1. Although all odd harmonics up to 23rd were measured these

results are expressed as total harmonic distortion calculated as the root of the sum of the squares of relative harmonic magnitude.

The improvement of the diesel generator wave shape as it is loaded may be seen and the addition of the motored wind turbine generator also served to improve the wave shape. It was not possible to measure the system harmonics with the wind turbine generator producing power as the conditions were too transient for measurements to be made.

TABLE 7.1

Harmonic Distortion of Parallel Wind Diesel Operation

Consumer Load (kW)	Test Voltage Connection	Harmonic Distortion %	
		Diesel only	Diesel plus motored WTG
0	Yellow/Neutral	8.03	4.21
0	Yellow/Red	7.88	5.92
4	Yellow/Neutral	4.31	3.64
4	Yellow/Red	3.69	3.70
6.5	Yellow/Neutral	3.69	3.61
6.5	Yellow/Red	3.29	3.33

In summary these experiments showed that parallel wind diesel

operation was possible in modest wind speeds with a large fixed consumer load. The voltage and frequency of the system were acceptable and the waveform of the diesel generator was improved by the addition of the wind turbine alternator. It was also shown that the wind turbine could be satisfactorily paralleled on to the diesel set with only modest frequency and voltage excursions.

7.3 Frequency Control

The diesel engine manufacturer was insistent that at constant speed the diesel engine should not be run continuously at less than 40% of its rated output. It was therefore necessary to provide a dump load controller to maintain this loading. The control policy adopted was that proposed by Volling (7.1) and developed by Tsitsovits (7.2) and is shown in Figure 7.5. The target frequency of the controller is set to be that frequency corresponding to the required minimum load on the diesel generator set droop line. Control of the frequency is implemented by switching in a suitable dump load as the diesel engine becomes unloaded below the minimum load. Initial experiments were carried out using an analogue proportional and integral controller and 2 load banks each of 3kW. The load banks were made up of domestic convector heaters and the controller is shown in block diagram form in Figure 7.6. The system frequency was measured using the Camille Bauer transducer which was also used for the data logging. The output driver stages were Schmidt triggers with a hysteresis band corresponding to 1.4Hz while the proportional and integral stages were implemented on operational amplifiers. The system operated stably using this controller with wind penetrations up

FIGURE 7.5

WIND DIESEL CONTROL POLICY

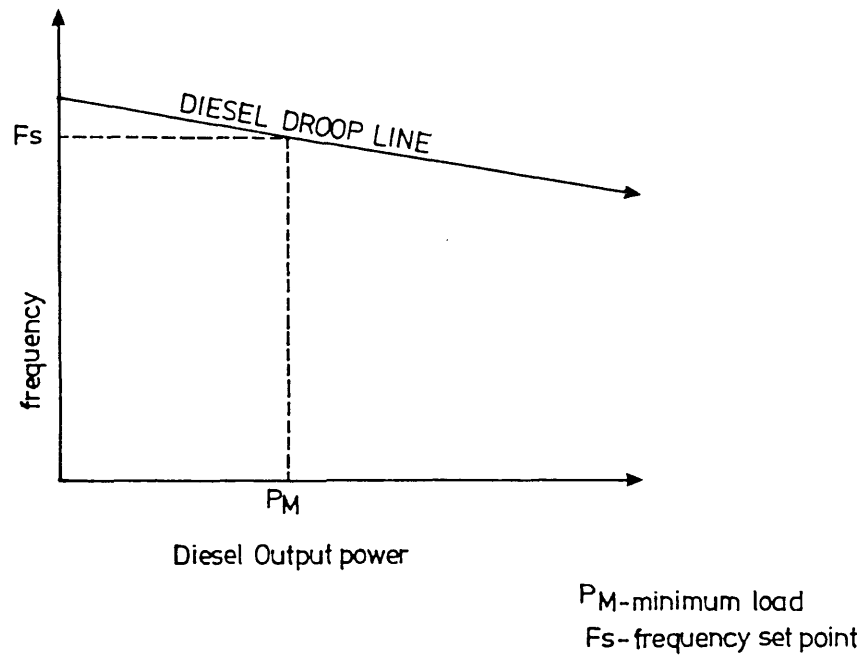


FIGURE 7.6

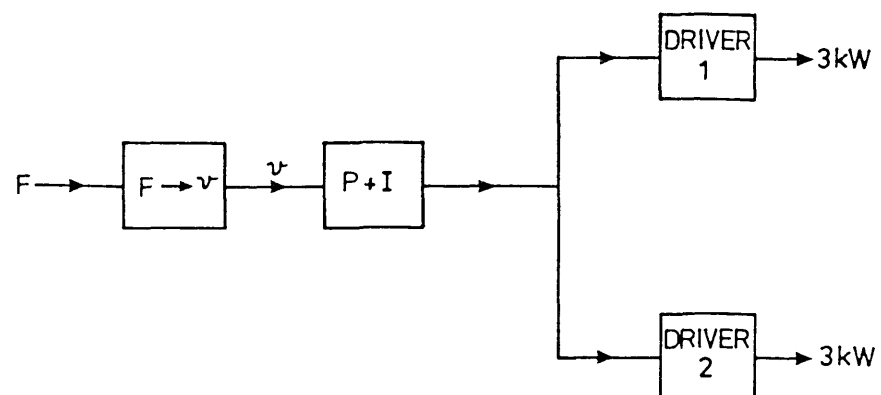
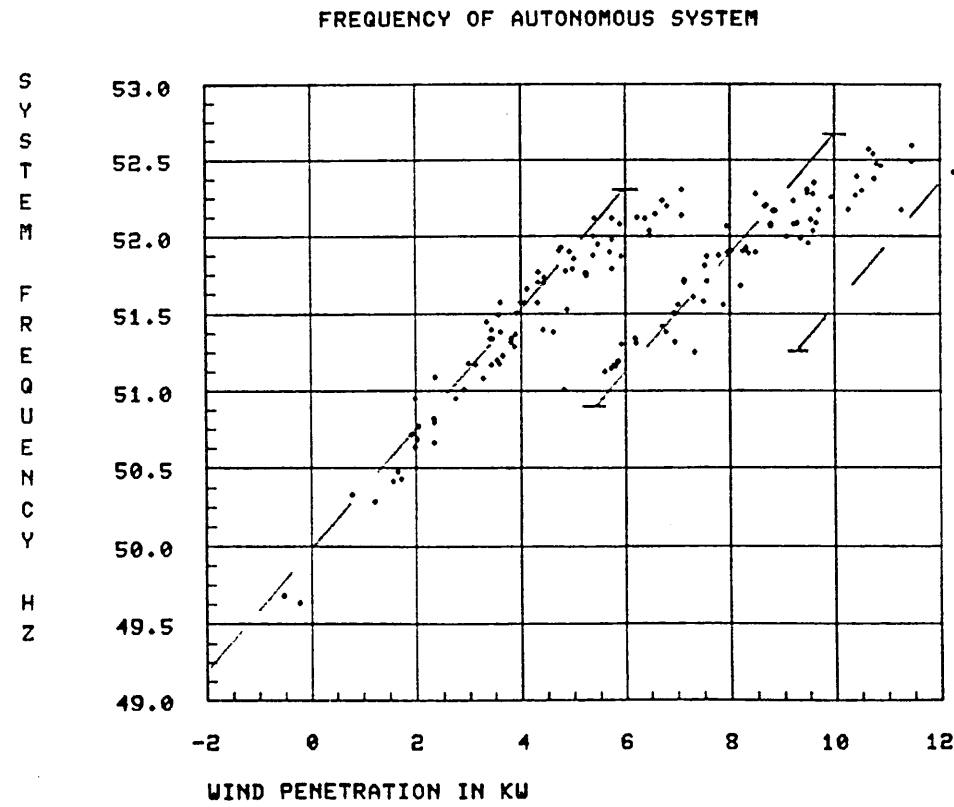
BLOCK DIAGRAM OF INITIAL DUMP
LOAD CONTROLLER

FIGURE 7.7 OPERATION OF WIND DIESEL SYSTEM WITH INITIAL DUMP LOAD
AND CONTROLLER (PROPORTIONAL ACTION ONLY)



to 12kW.

Figure 7.7 shows the operation of the controller with only proportional control. The droop lines with no additional load, 3 kW and 6 kW applied load are shown dashed. The translation of the diesel droop line by the 3kW of the first load step may be seen.

7.4 A Microcomputer Frequency Controller

Although allowing stable operation the two step load was not suitable for fine frequency control. A 6 bit binary 24kW load was therefore designed at Imperial College (7.3). This load is shown diagrammatically in Figure 7.8.

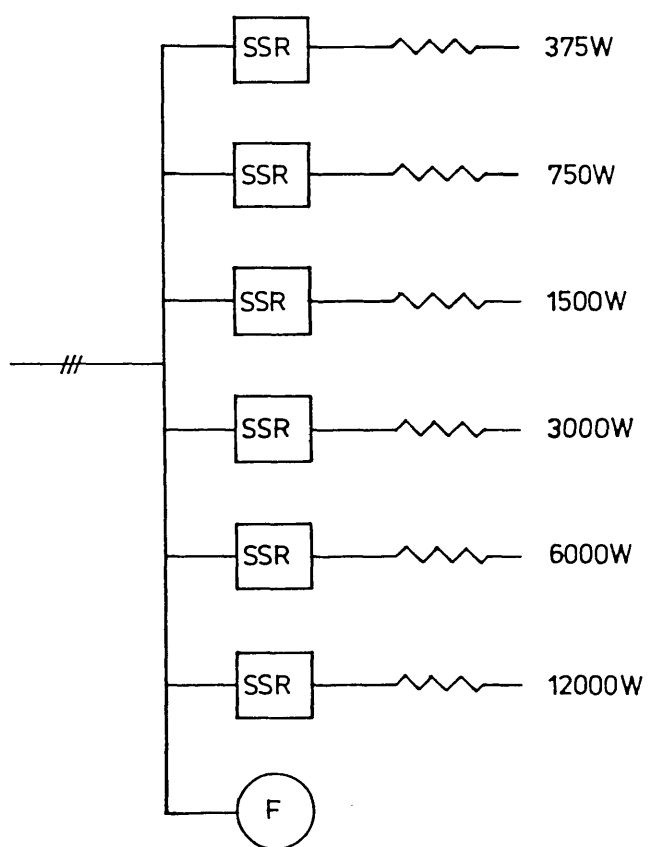
A sampled data controller was implemented using an Apple IIe microcomputer. Apple microcomputers are particularly useful for real time control as they have a number of option slots for the input and output of signals. The frequency signal was input to the microcomputer by a 12 bit A/D convertor located in one of the 6 option slots and the output load signal was fed out by a 16 bit parallel driver card located in a second option slot.

After some experimentation a suitable sampled data proportional and integral algorithm was developed. The main parameters of the controller were:-

Target Frequency	50.2 Hz
Hysteresis	0.3 Hz
Proportional Gain	0.75kW/Hz

FIGURE 7.8

SCHEMATIC OF 24kW DUMP LOAD



F - fans
SSR- solid state relays, 1 per phase
Power dissipations are nominal

Integral Gain	1kW/Hz
Program cycle time	230 ms

The control program was written in interpreted BASIC running on the D.O.S. 3.3 operating system. A program listing is given in Appendix A.

The target frequency corresponded to a 40% minimum load as the governor droop characteristics had been reset to operate between 51Hz and 49Hz. A hysteresis band was introduced to reduce cycling caused by the finite size (375W) of the smallest bit of the dump load. The program cycle time was rather long as the code had not been optimised.

Integral action was introduced by the algorithm.

$$P(n,T) = K_i(F(n,T) - F_Z) + P(n-1,T) \quad (7.1)$$

where F_Z : set point frequency

T : cycle time

n : number of cycle

K_i : integral gain

P : power setting of dump load

Proportional action was implemented using the algorithm.

$$P(n,T) = K_p(F(n,T) - F(n-1,T)) + P(n-1,T) \quad (7.2)$$

K_p : proportional gain

FIGURE 7.9 STEADY STATE OPERATION (MICROCOMPUTER CONTROLLER)

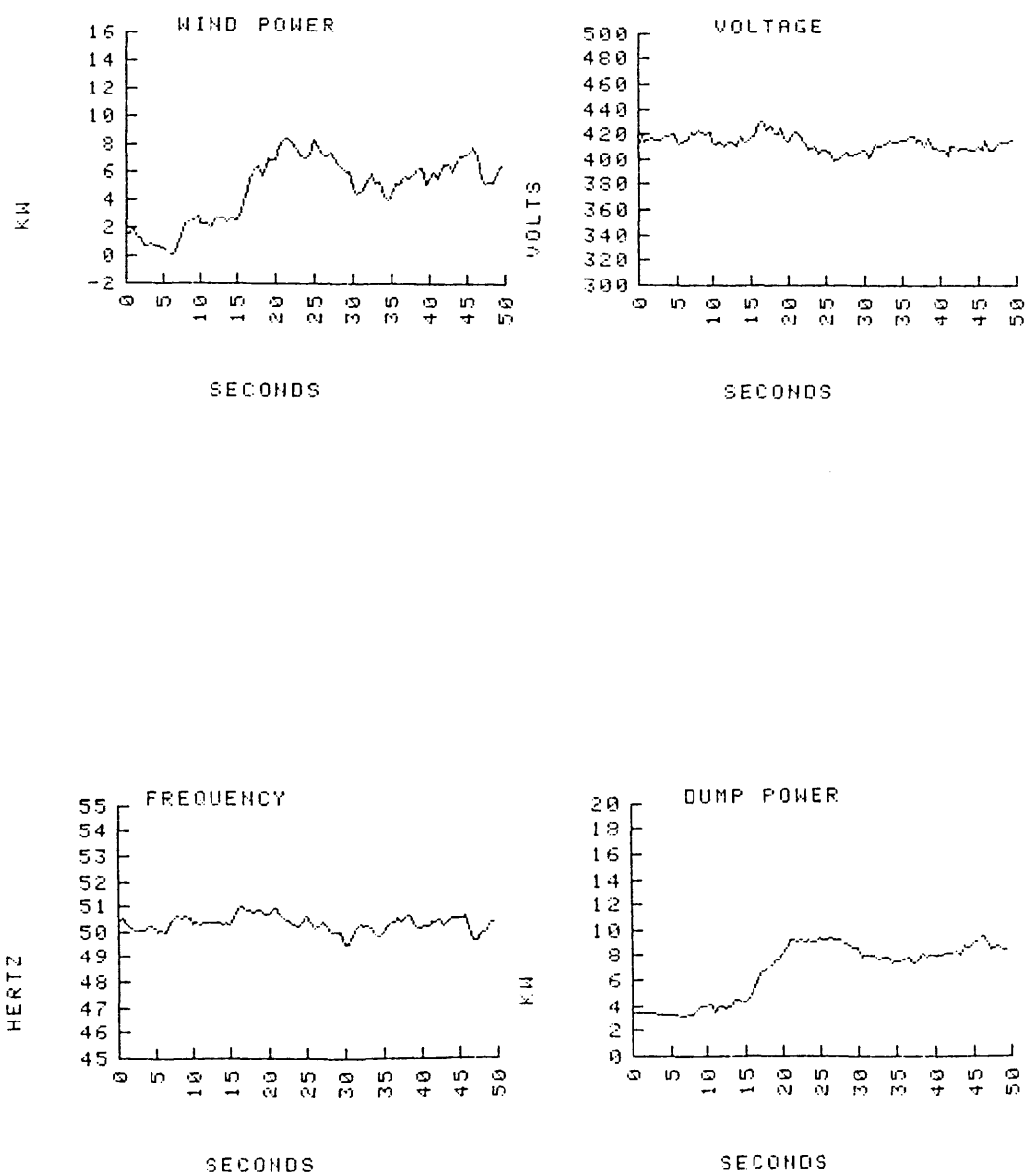


FIGURE 7.10 VOLTAGE STABILITY (MICROCOMPUTER CONTROLLER)

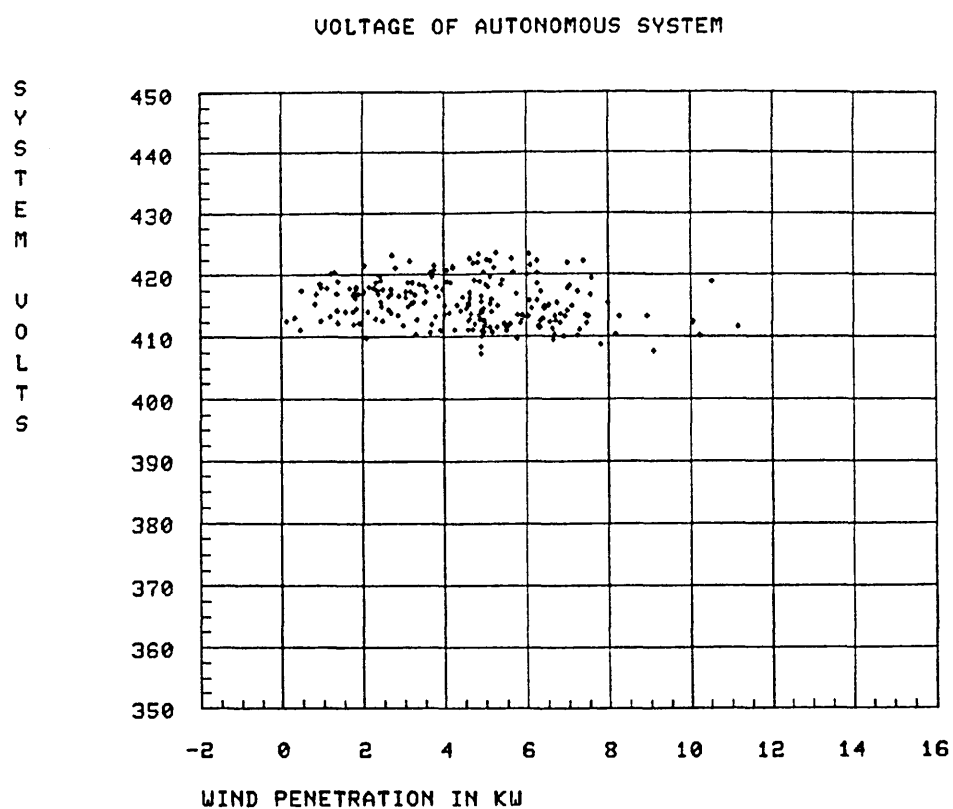
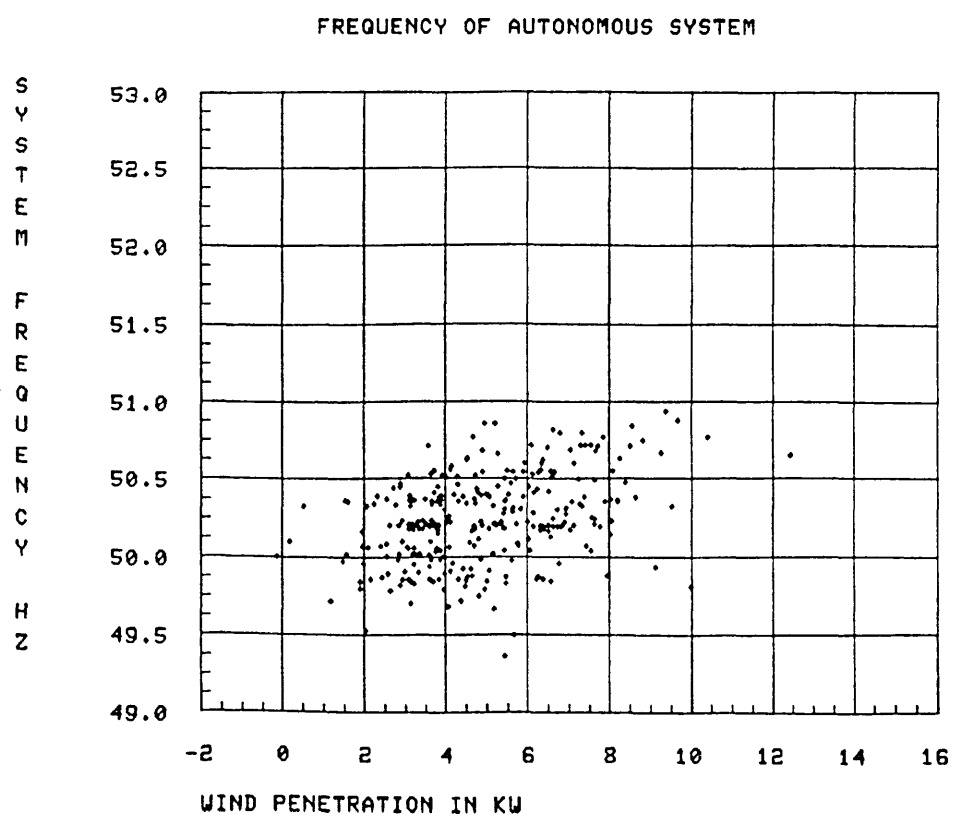


FIGURE 7.11 FREQUENCY STABILITY (MICROCOMPUTER CONTROLLER)



BLOCK DIAGRAM OF ANALOGUE DUMP LOAD CONTROLLER

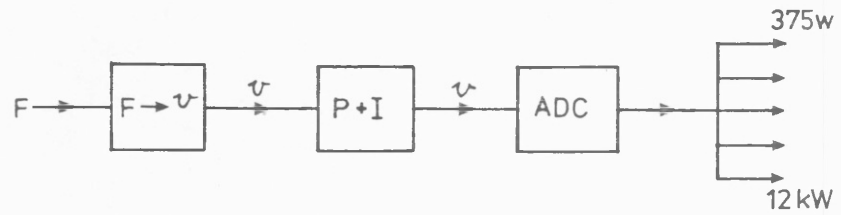


FIGURE 7.12

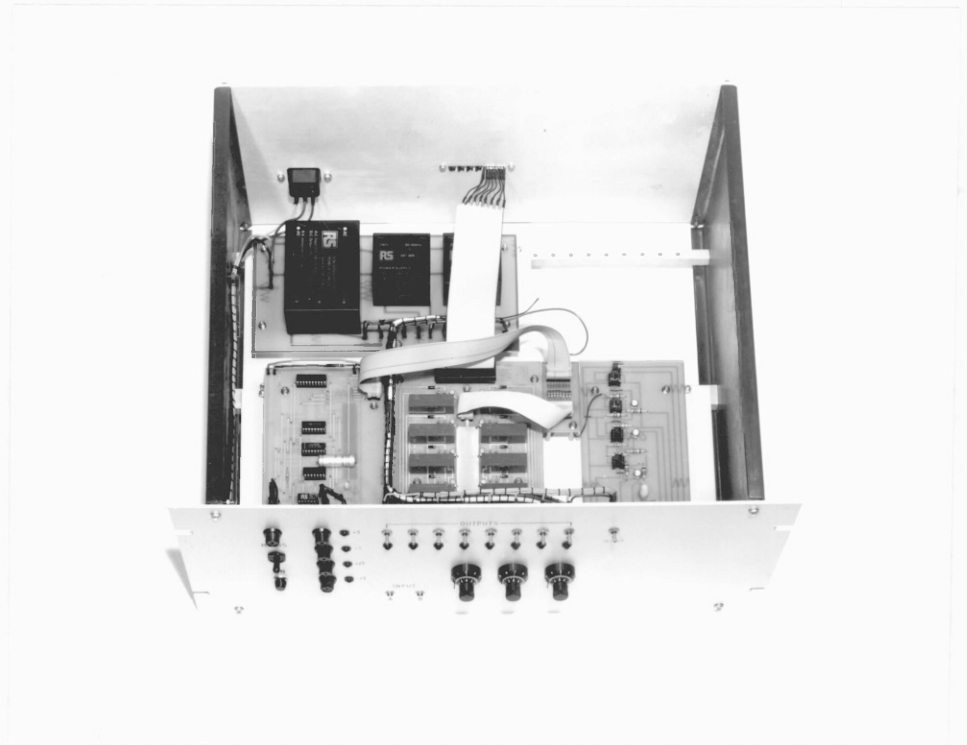


FIGURE 7.13 ANALOGUE DUMP LOAD CONTROLLER

These algorithms are not in the usual form for sampled data proportional and integral control (7.4) but they worked satisfactorily.

This microcomputer controller was tested extensively in wind speeds up to 14m/s and gave stable operation. Figures 7.9, 7.10 and 7.11 show parallel wind diesel operation using the controller. These tests were carried out with a fixed consumer load of 3 kW. Frequency excursions were limited to less than $\pm$ 1Hz and voltage variations less than $\pm$ 15 volts.

7.5 An Analogue Frequency Controller

Although the microcomputer controller gave satisfactory performance it was an expensive method of controlling the dump load. The cost of the microcomputer, monitor, disk drive, and interface cards was over £1000. In addition the speed of operation of the controller was limited by the use of interpreted BASIC.

An analogue controller was therefore designed. The controller is shown schematically in Figure 7.12 and the circuit diagram is given in Appendix E. The controller consisted of a frequency transducer together with proportional and integral stages implemented on operational amplifiers feeding on to a CMOS analogue to digital converter chip. An 8 bit successive approximation parallel output A/D converter was used. The binary parallel output interfaced directly with the binary dump load. As this was a tri-state device, output latching circuits were required. The total cost of components of the controller

was less than £50.

After a prototype had been built the controller was constructed by RAL apprentices and is shown in Figure 7.13. This gave better frequency control than the microcomputer controller and its performance is shown in Figures 7.14, 7.15 and 7.16. The test of Figure 7.14 was carried out with a fixed consumer load of 4kW while the tests of Figures 7.15 and 7.16 were carried out with a fixed consumer load of 6kW and show 200 ms means taken every 10 seconds during a 1 hour test.

The controller settings were:-

Target frequency	50.2Hz
Proportional Gain	1.125kW/Hz
Integral time constant	250 ms
Clock rate of A/D converter	70 ms

The models used to simulate the frequency behaviour of the wind diesel system, described in Chapter 9, had not been developed when this experimental work was carried out. Therefore both the microcomputer and analogue controller were tuned experimentally by applying step loads to the diesel set with the wind turbine shut down. It was not possible to tune the controllers with the highly variable wind power. Accurate determination of the controller performance was not useful as the diesel engine governor characteristics were so variable. Therefore the settings selected were a compromise to ensure stable operation with rapid control of frequency under all operating conditions. Increasing the proportional gain of either controller and

FIGURE 7.14 STEADY STATE OPERATION (ANALOGUE CONTROLLER)

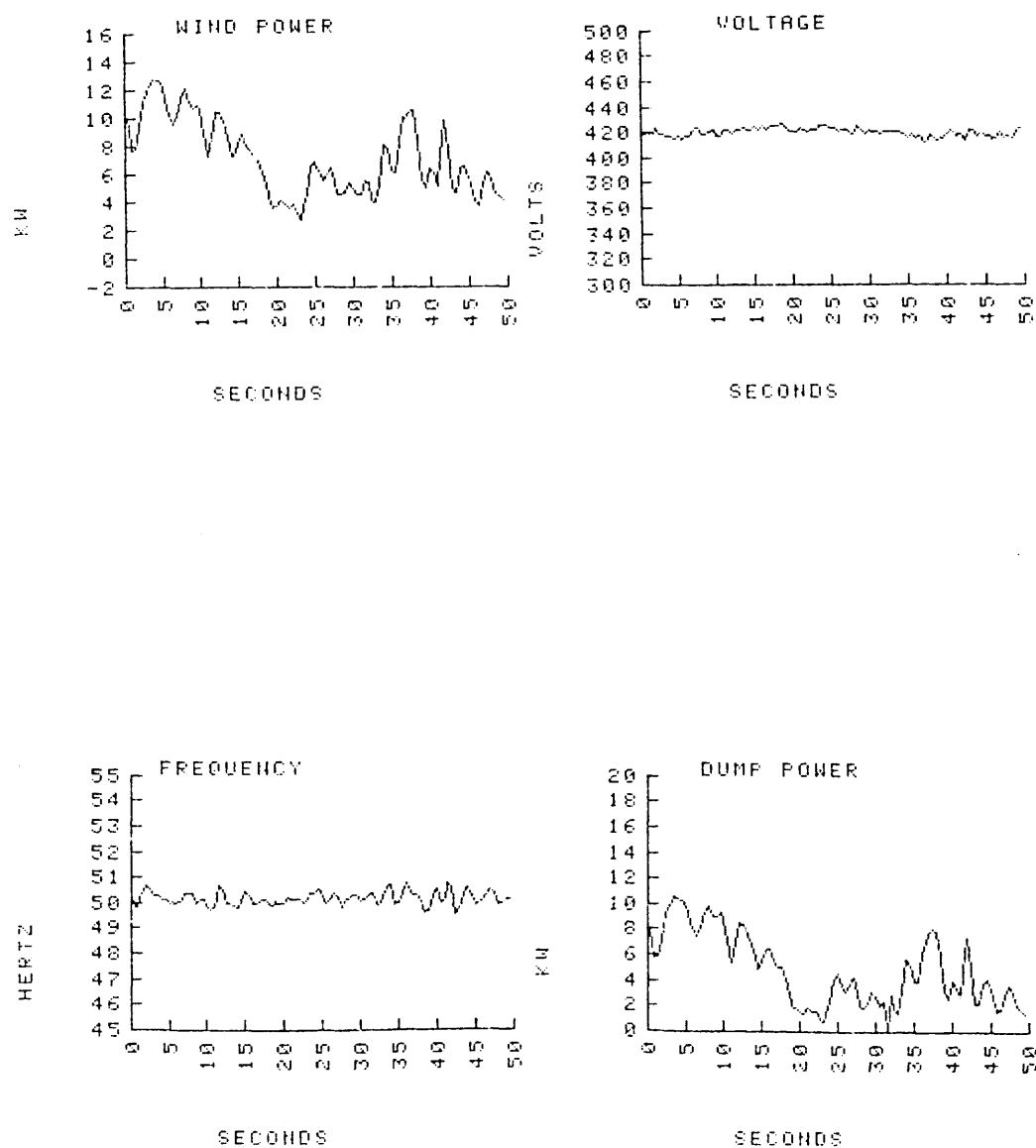


FIGURE 7.15 VOLTAGE STABILITY (ANALOGUE CONTROLLER)

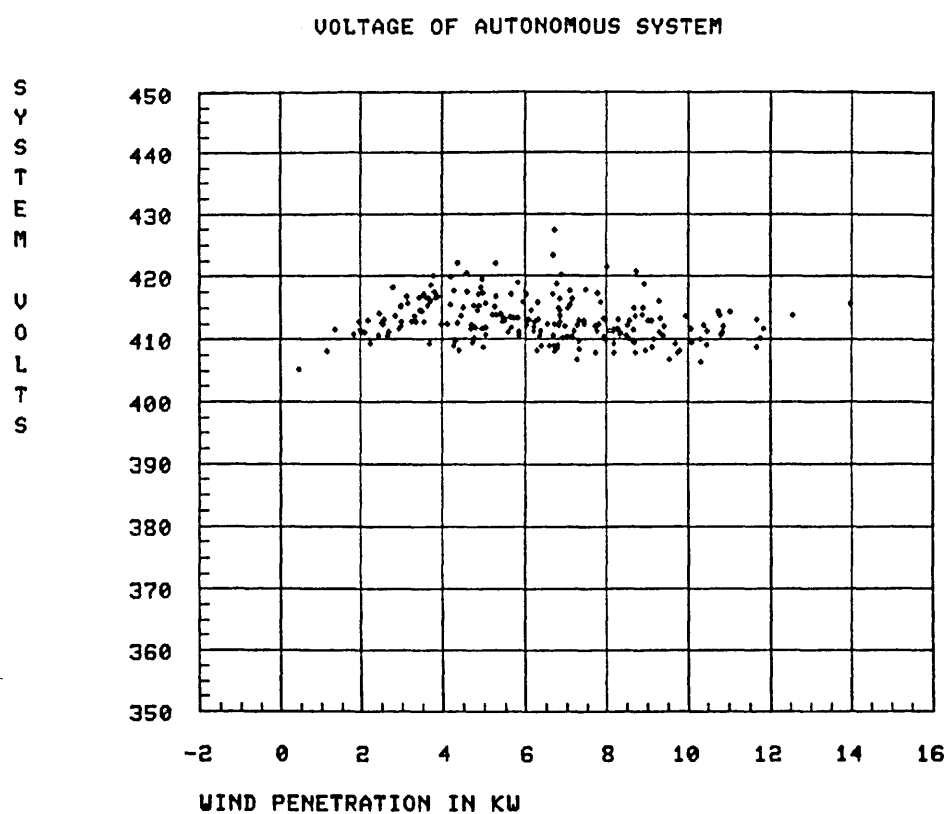
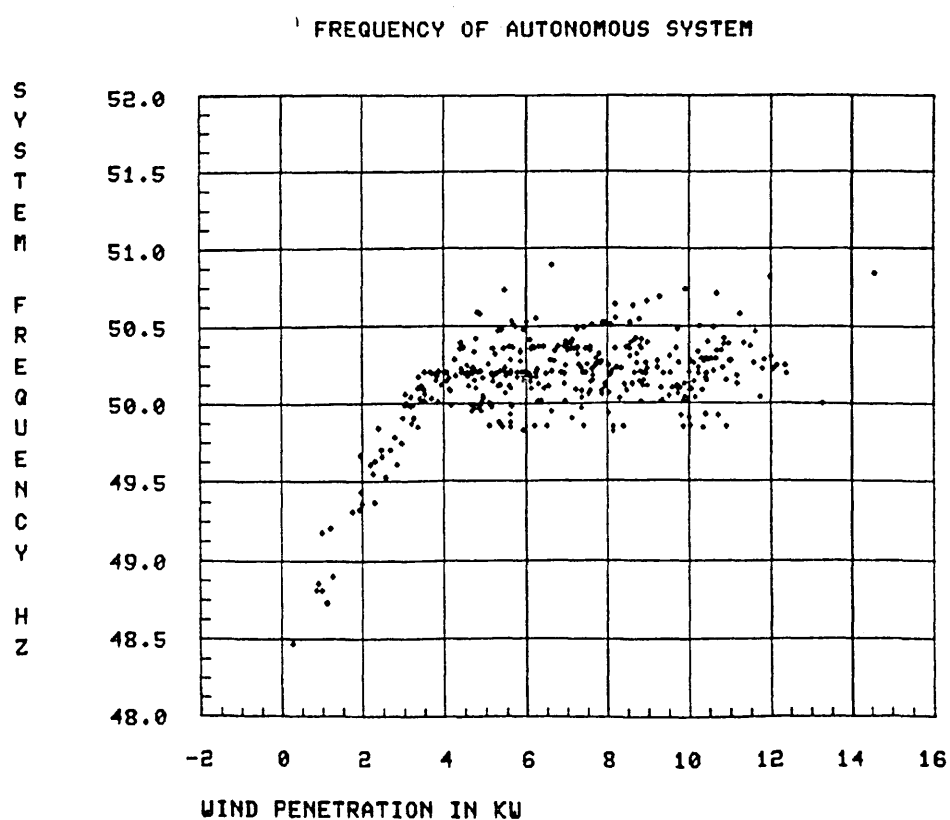


FIGURE 7.16 FREQUENCY STABILITY (ANALOGUE CONTROLLER)



decreasing the integral time constant of the analogue controller resulted in increasing frequency swings and eventual tripping of the system on the over and under frequency relays. The results of the simulations of Chapter 9 confirmed that the controller settings were suitable for parallel wind diesel operation and that this method of tuning was successful.

7.6 Logistic Performance

Once a suitable controller had been developed, allowing stable wind diesel operation, a series of experiments were carried out to investigate fuel savings.

In all 50 1 hour tests were carried out using both the microcomputer and analogue controllers. These unattended tests also served to confirm that both controllers could successfully maintain the frequency stability of the system.

During each test the following parameters were measured:-

- Free wind speed
- Output power from the WECS
- Power delivered to dump load
- Power delivered to consumer load
- Diesel engine fuel consumption
- Diesel engine sump oil temperature

Initially 36 hours of testing at a constant 6kW consumers load and a 40% (2.6kW) minimum load on the diesel engine were carried out. The diesel minimum loading was then reduced to 20% (1.3kW)

by increasing the controller target frequency to 50.5Hz. A further 12 tests were then performed. The results of these tests are shown in Figure 7.17 and show the change in fuel use over diesel only operation plotted against mean hourly windspeed. At windspeeds below cut in there was a fuel penalty of 14% associated with parallel wind diesel operation. This was caused by the power required to drive the dump load cooling fans and also to motor the wind turbine alternator. In a commercial system these losses could be eliminated by disconnecting the wind turbine and dump load fans during prolonged periods of low wind speed.

At high wind speeds the fuel consumption reached a constant value determined by the minimum loading of the diesel.

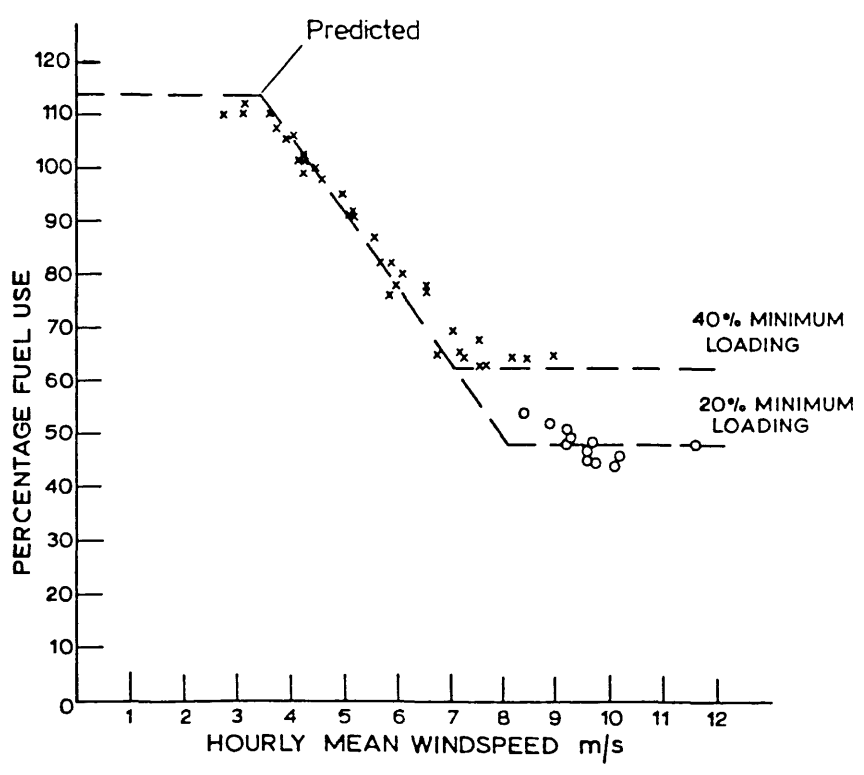
The curve relating free wind speed to fuel consumption shown in Figure 7.17 may be predicted from the steady state power versus fuel consumption relationships of the diesel set and the 10 minute mean power curve of the wind turbine generator.

Immediately before these logistic performance tests commenced the power versus fuel consumption curve of the diesel generator set was remeasured. This was necessary as the alternator had been changed and, as discussed in Chapter 2, the state of the diesel engine changes with use.

The relationship derived from these tests was :-

$$f = (0.198 \pm 0.005) \times P + 0.564 \pm 0.020 \text{ kg/hour} \quad (7.3)$$

FIGURE 7.17 FUEL USE OF WIND DIESEL SYSTEM (6kW LOAD)



where P is in kW.

The 10 minute mean power curve is expressed as:-

$$P = V \times 1.252 \pm 0.010 - 5.654 \pm 0.068 \text{ kW} \quad (7.4)$$

for $3.8 < V < 14$ and where V is in m/s.

Now let:-

V_K : initial cut in wind speed of wind turbine

V_L : wind speed at which the diesel reached its minimum
loading

P_C : consumers load and dump load fan losses

P_M : minimum load on diesel

P_F : wind turbine motoring losses

P_D : diesel engine power output

Therefore for:-

$$V < V_K \quad ; \quad P_D = P_C + P_F \quad (7.5)$$

$$V > V_L \quad ; \quad P_D = P_M$$

$$V_K < V < V_L \quad ; \quad P_D = P_C - (V \times 1.252 + 5.564)$$

and in all cases:-

$$f = P_D \times 0.198 + 0.564 \text{ kg/hour} \quad (7.6)$$

This predicted curve is shown on Figure 7.17 as the dashed line and shows good agreement with the experimental values. The

residual scatter is due to experimental error, the changing atmospheric conditions, as the diesel engine and wind turbine performances were not normalised to standard conditions, and also because of wind turbulence. The main effect of the wind turbulence was to slough off the corners of the predicted curve at the points of change of gradient.

Most wind turbines have a power curve which is approximately linear up to their rating and diesel engine power versus fuel relationships are also approximately linear. Therefore a simple steady state analysis may be used to provide a good indication of the potential fuel savings available in parallel operation of a wind diesel system with continuous diesel. This conclusion is supported by the simulation results described in Chapter 8.

A further 2 hours of testing were carried out with the consumer load cycled between 2kW to 6kW in 1kW steps. The steps were changed at 1 minute intervals and the mean windspeed was approximately 9m/s. The measured fuel consumptions were 98% and 97% of the values predicted by the steady state analysis.

7.7 Conclusions

The work described in this chapter showed that parallel wind diesel operation could be achieved. Voltage control well within $\pm 6\%$ was achieved by adjustment of the setting of the excitation of the wind turbine generator. Frequency control within $\pm 2\%$ was achieved by a dynamic dump load controlled either by a microcomputer or an analogue controller. The microcomputer controller allows greater flexibility but the analogue

controller was much cheaper. A further important result was that the fuel savings of the system could be estimated with reasonable accuracy by the steady state relationships of the wind turbine and diesel generator set.

These results are supported by over 50 hours of parallel wind diesel operation in wind speeds up to 14 m/s and it is considered that parallel wind diesel operation, with a continuously running diesel set, has been demonstrated to be both reliable and to give hourly fuel savings of up to 50%.

CHAPTER 8

TIME STEP SIMULATION

8.1 Introduction

The object of adding a wind turbine to an electrical network supplied by a diesel engine is to reduce the diesel fuel consumption. As a basis for investigating the economic benefit of a wind diesel system a thorough understanding of the system performance with different wind and load regimes is required. This understanding may be achieved either by analytical or simulation techniques.

The experimental results of Chapter 7 showed that the fuel consumption of a parallel wind diesel system, with continuous diesel operation, could be predicted from a steady state analysis of the system. In the case considered the analysis was straightforward as both the power curve of the wind turbine generator and the power versus fuel consumption relationship of the diesel set were approximately linear. However, even with non-linear functions a similar steady state analysis may be used to estimate fuel consumption, although additional assumptions are required concerning the turbulence of the wind and the variance of the load. de Bonte (8.1) adopted this technique for the analysis of a wind diesel system while Rockingham (8.2) developed the approach to examine the economics of wind turbines on large electricity grids.

The advantage of this type of analysis is that it requires relatively small amounts of computer time. However, it is not possible to take account of the time dependent effects of complex systems. To achieve maximum fuel saving on a wind diesel system it is essential to shut down the diesel engine when it is not required. For the analysis of a wind diesel system which allows intermittent diesel operation the time dependent effects, particularly of the diesel starts, are of great importance and steady state analysis is not suitable. Time step simulation may be used to examine these effects.

Time step simulation is, in concept, a straightforward technique. The system under investigation is modelled on a digital computer and pre-recorded real wind and load data is applied to the model. At each time step the system performance is evaluated and any decisions by the system controllers may be made. The time step usually corresponds to the rate at which the data has been sampled. Complex non-linear systems and control strategies may be studied, as an analytical representation of the system is not required. However, large amounts of data and hence computer time are necessary for these simulations if reliable results are to be obtained.

Time step simulation models have been used successfully to study the impact of wind turbines on the CEEB network (8.3) and the application of a hydraulic accumulator store on a simple wind diesel system (8.4). This technique was therefore used to examine the performance of the proposed parallel operation wind diesel system.

8.2 A 1 minute time step simulation model

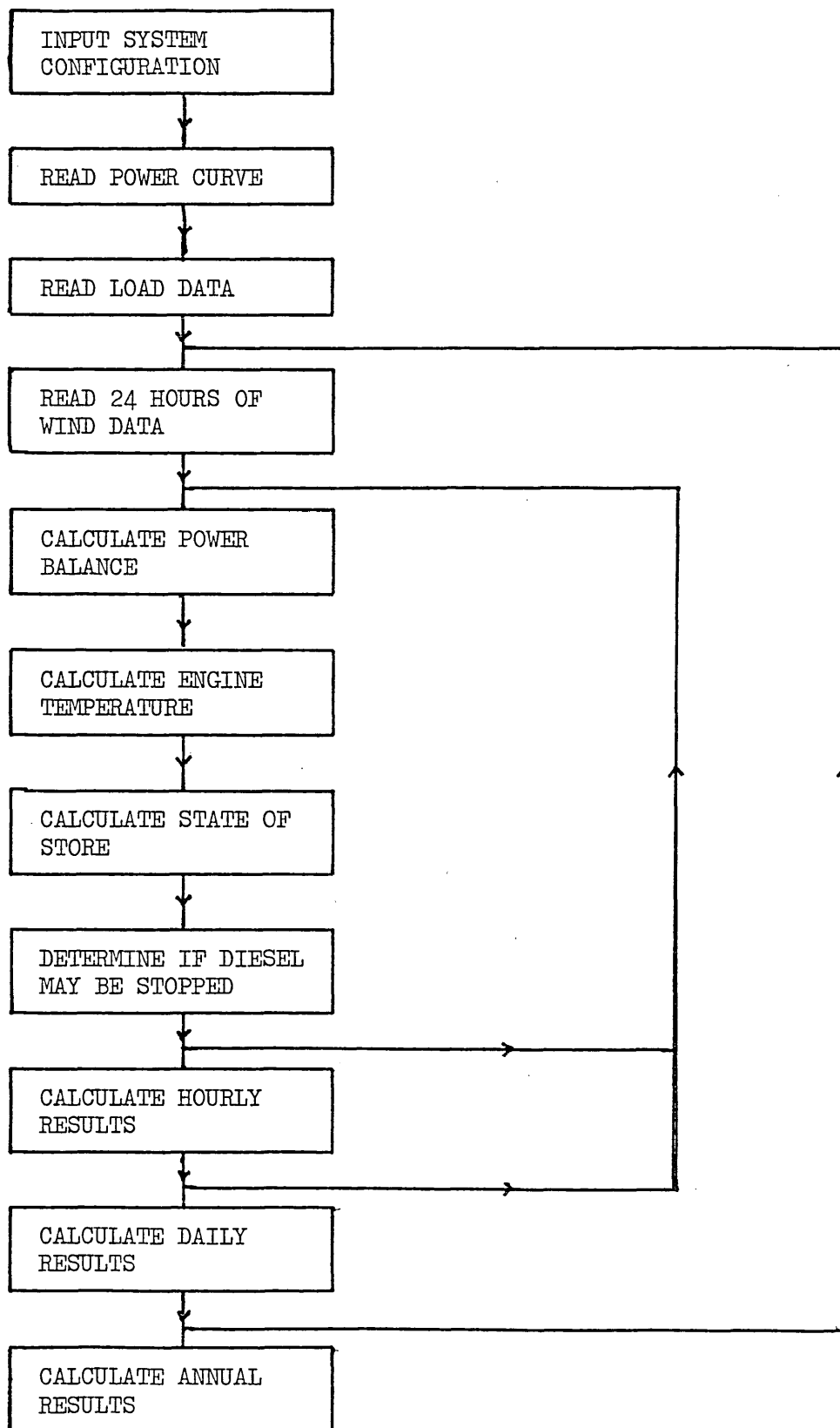
8.2.1 Description of the model

The model was written in FORTRAN 77 to run on the IBM system at RAL. Initially it was intended to use PASCAL as the programming language in order to achieve a structured source code more easily. However, PASCAL was not supported at RAL and so a structured subroutine based code was written in FORTRAN 77. The program was developed interactively and then transferred to batch processing.

A 1 minute time step was used because mean wind speed data is collected at this frequency by the Meteorological Office. 82 days of data were used from meteorological stations at Valley and Stornoway. The load data available was 30 minute mean values from the Electricity Council and 10 minute means from a housing estate in South Wales. However, to allow easier understanding of the results and to avoid the problems of scaling load profiles most simulations were carried out using a constant consumer load.

The source code consisted of a small main program and 14 effective subroutines. A flow diagram of the program is shown in Figure 8.1. The program is flexible due to its modular structure and an initial interactive section allows easy definition of the system to be studied without the necessity of recompiling the program.

FIGURE 8.1

Outline Flow Chart for 1 minute Time Step Simulation Model

Wind speed is read one day at a time (1440 values) and the load is either fixed or a profile read in. With a 1 minute time step, transient performance of the system cannot be studied. Therefore, at each time step, a simple energy balance was used to determine if the diesel was required and its loading. The thermal model developed in Chapter 2 was built into the simulation to allow the fuel penalty associated with cold starts of the diesel to be included. An energy storage facility was also represented which allowed the effect of energy storage, and its associated losses, to be considered. A diesel minimum loading constraint was included together with a diesel minimum run time control.

The results are given for each day of the simulation as Starts, Fuel Consumption, Mean wind speed, Standard Deviation of wind speed, Mean load and Standard Deviation of load. The results of the complete simulation are given which include histograms of the run times of the diesel and of the diesel loadings and total values of diesel starts, dumped energy and fuel consumption. A typical output of the simulation is shown in Appendix B. This simulation was carried out with the following system configuration:-

WTG rating	16kW (L916)
Diesel rating	6.4kW
Minimum loading	40%
Consumer load	5kW (fixed)
Diesel minimum run time	5 minutes
Energy storage	0.0kW
Intermittent diesel operation.	

FIGURE 8.2 TYPICAL DAILY RESULTS (FUEL CONSUMPTION)

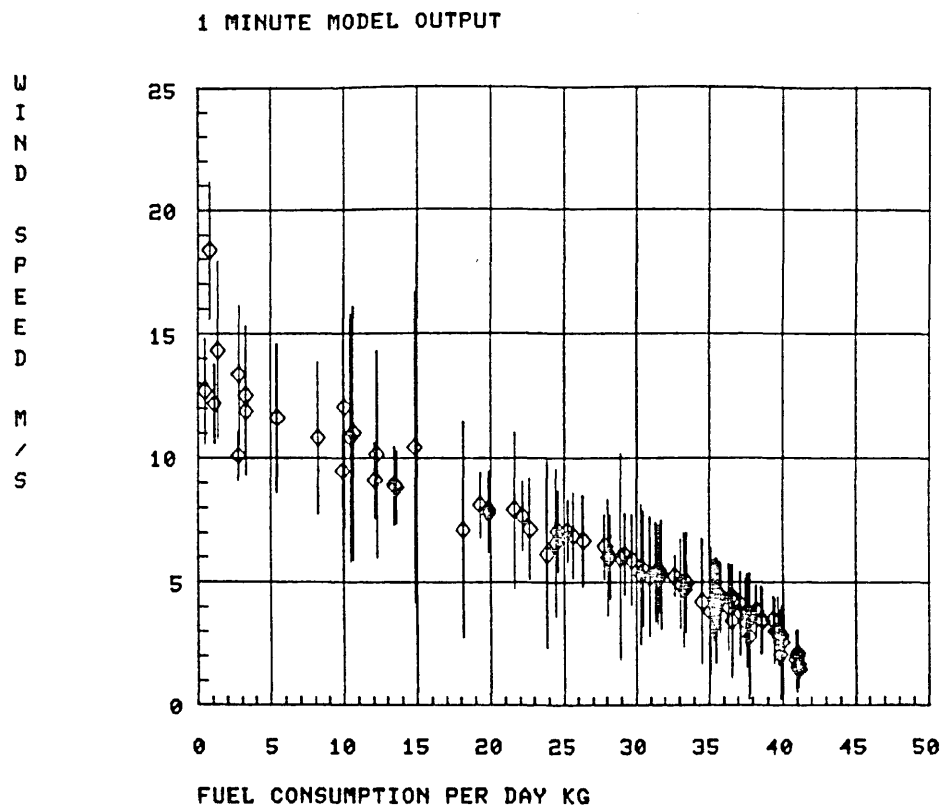


FIGURE 8.3 TYPICAL DAILY RESULTS (STARTS)

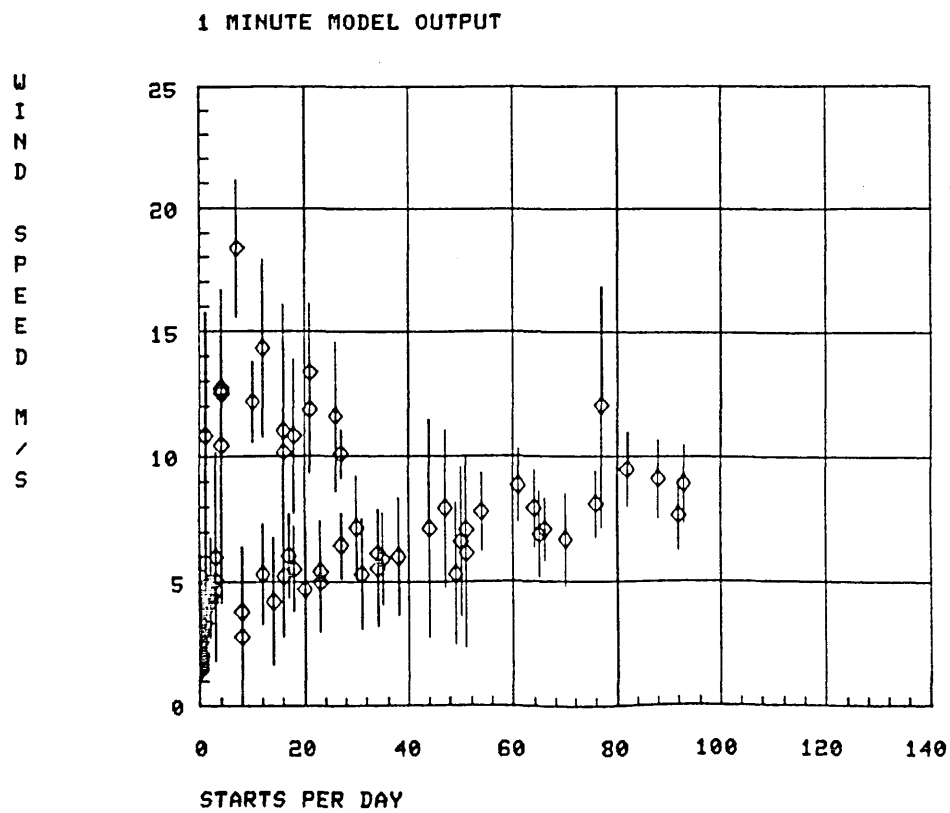


FIGURE 8.4 TYPICAL HOURLY RESULTS (FUEL CONSUMPTION) 187

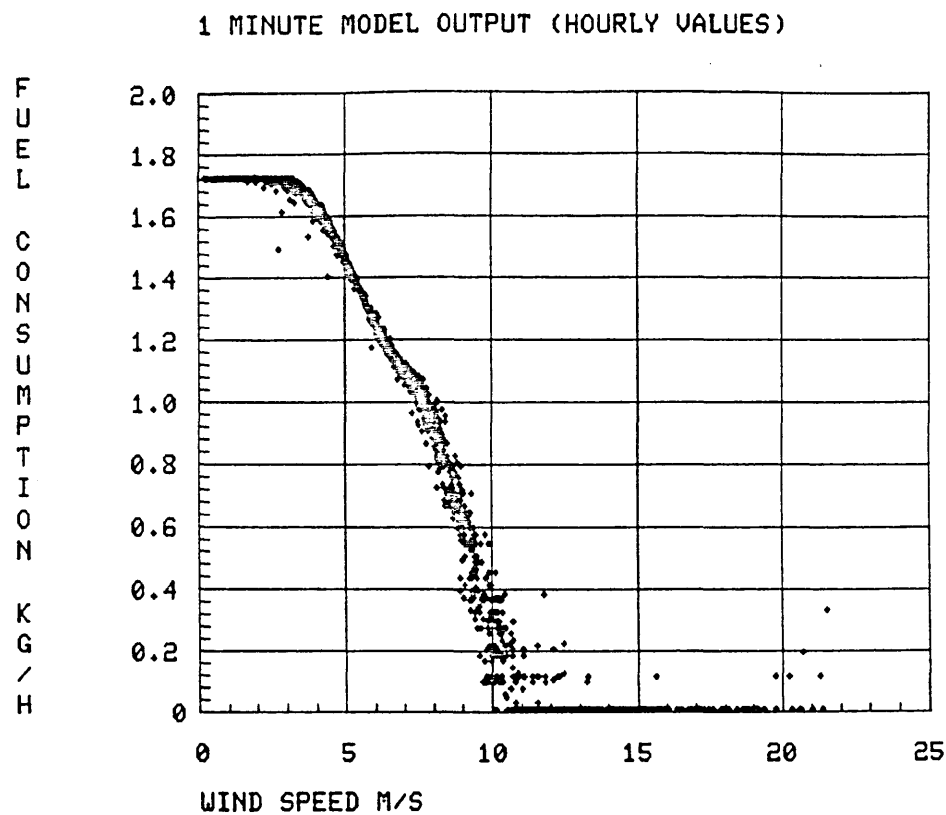


FIGURE 8.5 TYPICAL HOURLY RESULTS (STARTS)

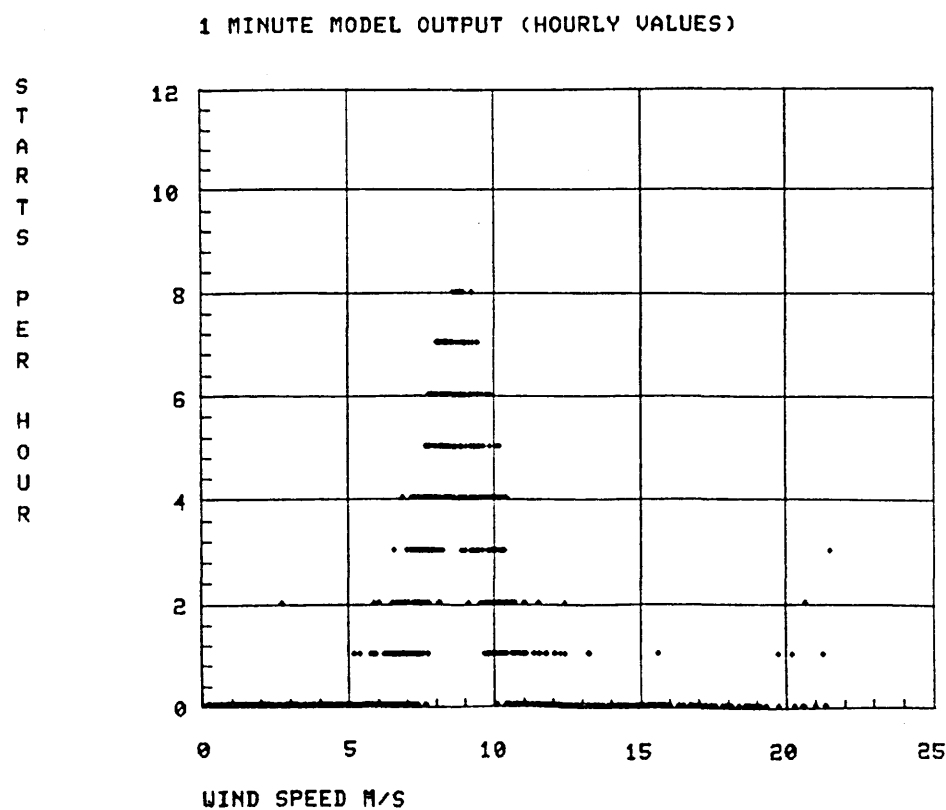


FIGURE 8.6 TYPICAL HOURLY BINNED RESULTS (FUEL CONSUMPTION)¹⁸⁸

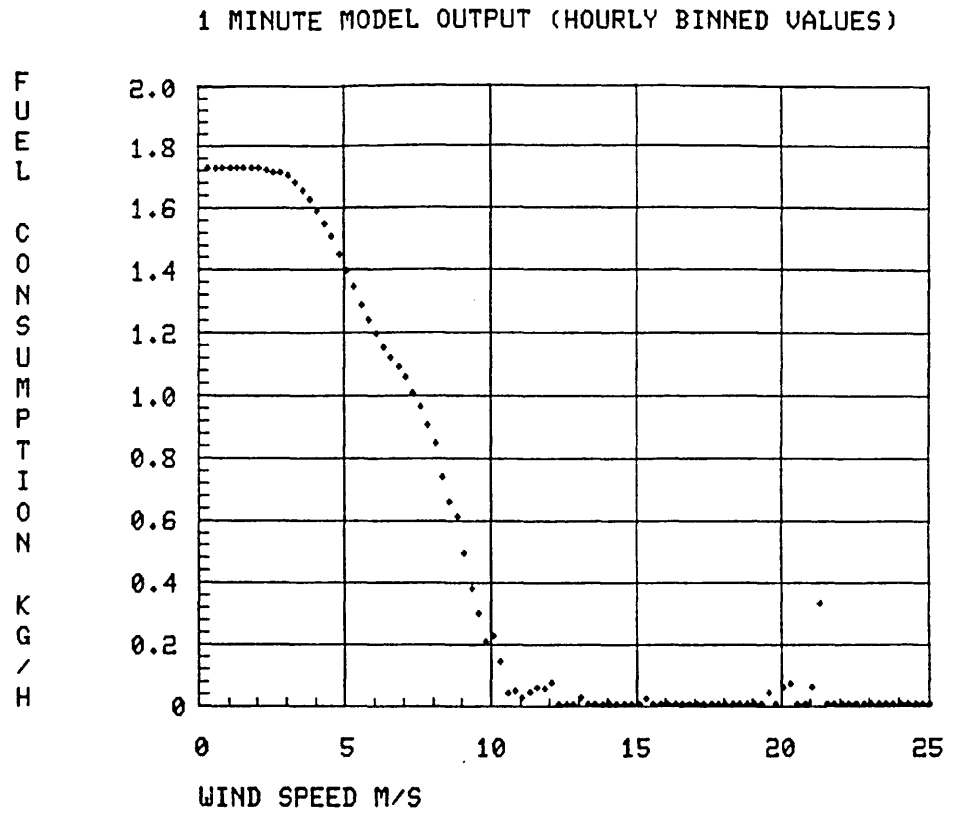
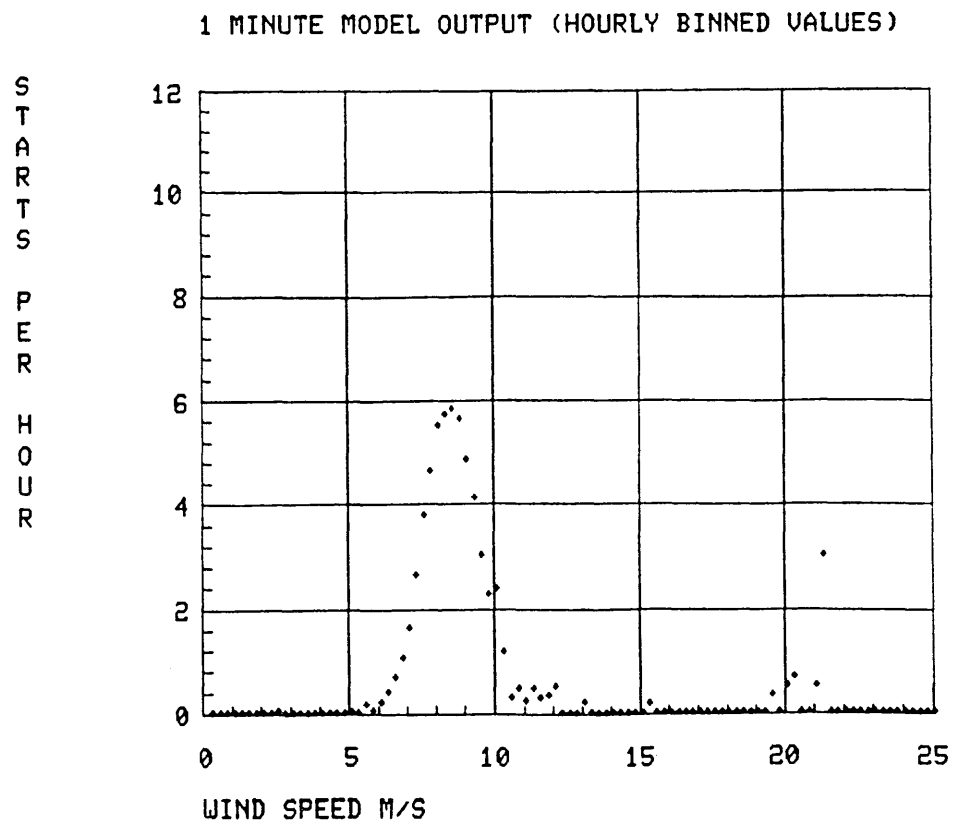


FIGURE 8.7 TYPICAL HOURLY BINNED RESULTS (STARTS)



Graphical output of the model is also available. Daily results are shown in Figures 8.2 and 8.3. The error bars show the standard deviation of the windspeed through the day and indicate that diurnal variations in wind speed can be large due to meteorological changes. Individual hourly results (1968 values) are also produced as shown in Figures 8.4 and 8.5, while the hourly results have been binned according to windspeed in 0.25 m/s bins to give the results of Figures 8.6 and 8.7. The hourly results, particularly those of fuel consumption show a strong relationship with windspeed and are significantly less scattered than the daily results. The change of gradient shown between 8-9 m/s on Figure 8.6 was due to the fuel penalties associated with cold starts and with the minimum run time control. Figure 8.7 shows that the starts peak at a windspeed of 8.5 m/s. This value is the windspeed at which the output power of the wind turbine corresponds to the consumer load. The isolated starts at 22m/s are caused by the wind turbine output power dropping below the consumer load at high wind speeds.

A further section of the model uses the Weibull probability distribution of windspeeds to allow prediction of the system annual performance at any site where the annual site windspeed may be represented by a Weibull probability distribution.

8.2.2 Annual Performance

The long term variations of windspeeds at a site may be described by a Weibull probability distribution (8.5).

The Weibull probability density function $p_w(V)$ is defined as:-

$$p_w(V) = \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} \exp\left\{-\left(\frac{V}{c}\right)^k\right\} \quad (8.1)$$

and the cumulative probability function $P_w(V)$ is given by:-

$$P_w(V) = \int_0^V p_w(V) dV = 1 - \exp\left\{-\left(\frac{V}{c}\right)^k\right\} \quad (8.2)$$

where k is the shape factor, usually $1 < k < 3$

c is the scale factor in m/s.

The relationship between the site mean wind speed $\bar{V}$ and the Weibull parameters is given by:-

$$\bar{V} = c \Gamma\left(1 + \frac{1}{k}\right) \quad (8.3)$$

where Γ is the gamma function and is defined as:-

$$\Gamma(x) = \int_0^{\infty} e^{-t} t^{x-1} dt$$

It has been shown (8.6) that for values of $1.6 < k < 3.0$ this may be approximated to:-

$$\bar{V} = \frac{1}{2} \pi^{\frac{1}{2}} c \quad (8.4)$$

with an error of $\pm 1\%$.

The Weibull parameters for a site are usually derived from mean hourly windspeeds collected over periods in excess of 1 year.

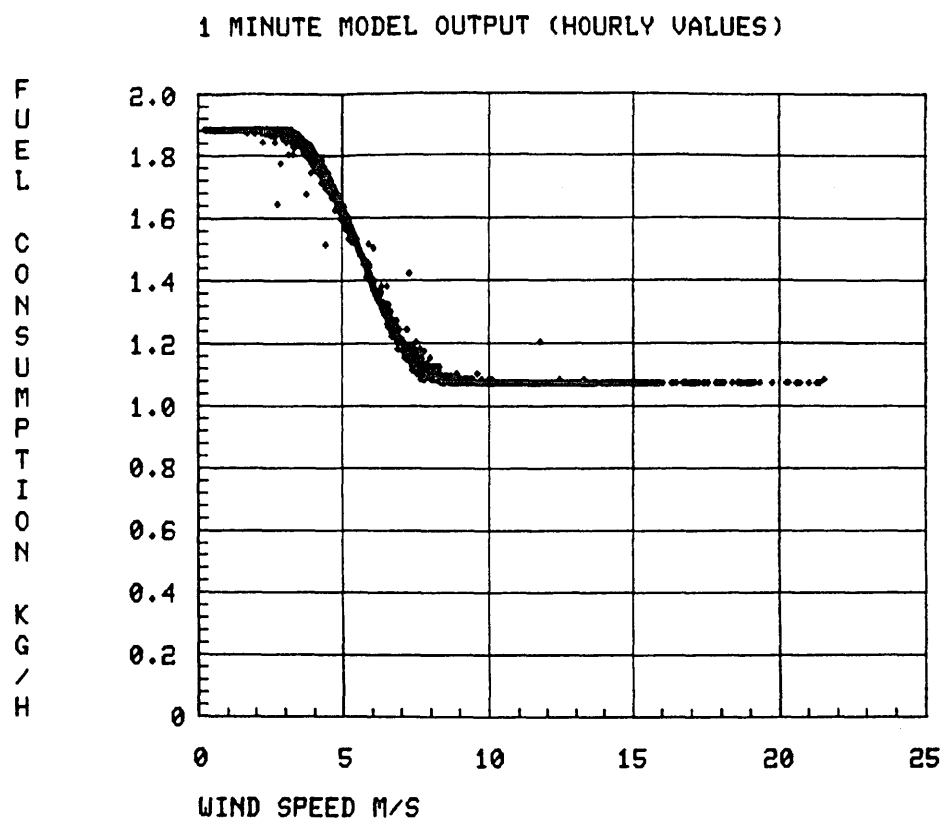
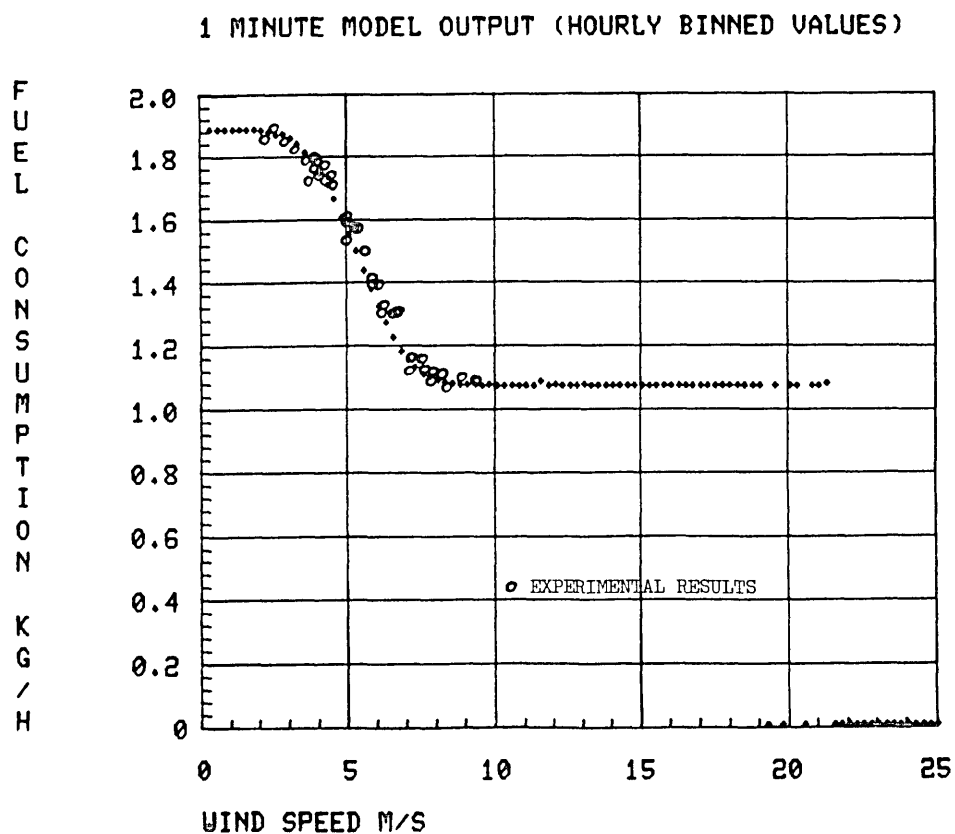


FIGURE 8.9 VALIDATION RESULTS (HOURLY BINNED VALUES)



It has been noted (8.7) that there are significant variations in windspeeds from one year to the next.

8.2.3 Validation

The model was validated against the experimental results described in Chapter 7. As these experiments were carried out with continuous diesel operation, only the fuel consumption results could be compared.

The model was run using the 82 days of Valley/Stornoway data. The system configuration was:-

WTG rating	16kW (L916)
Diesel rating	6.4kW
Minimum loading	40%
Consumer load	5.8kW (fixed)
Continuous diesel operation	
No energy storage.	

The consumers load of 5.8kW was the mean consumers load of the experiments. The hourly results are shown in Figure 8.8 and the binned hourly results in Figure 8.9. Superimposed on Figure 8.9 are the experimental results of the 36 hours of testing in this configuration. There is good agreement between the simulation and experimental results. There is also good agreement between the simulation results and the fuel consumption predicted from the steady state equations of Chapter 7. Therefore, these simulation results using 1968 hours of data

support the conclusion of Chapter 7 that the fuel savings of the system can be estimated from the steady state relationship of the wind turbine and diesel generator set.

8.2.4 Results and Analysis

The 1 minute time step model was used to examine the behaviour of the wind diesel system. Continuous diesel operation gave only modest fuel savings because of the high losses of the diesel generator set. With a diesel engine minimum loading constraint the possible fuel savings were further reduced. To maximise fuel savings, therefore, it was necessary to stop the diesel set when it was not required.

However, if intermittent operation of the diesel set was allowed a large number of engine start/stop cycles occurred. This cycling was caused by the output power level of the wind turbine crossing the consumer load power level. For a constant consumer load the starts were distributed about the wind turbine output power corresponding to the mean wind speed. This is shown in Figures 8.5 and 8.7. For a random consumer load profile the distribution of starts with wind speed was random.

Inspection of the outputs of the model showed that the annual fuel consumption of a wind diesel system is dominated by the days of low wind speed when the diesel operates continuously supplying the consumer load. The annual starts are dominated by those times when the power output of the wind turbine crosses the consumer load power.

ANNUAL PERFORMANCE

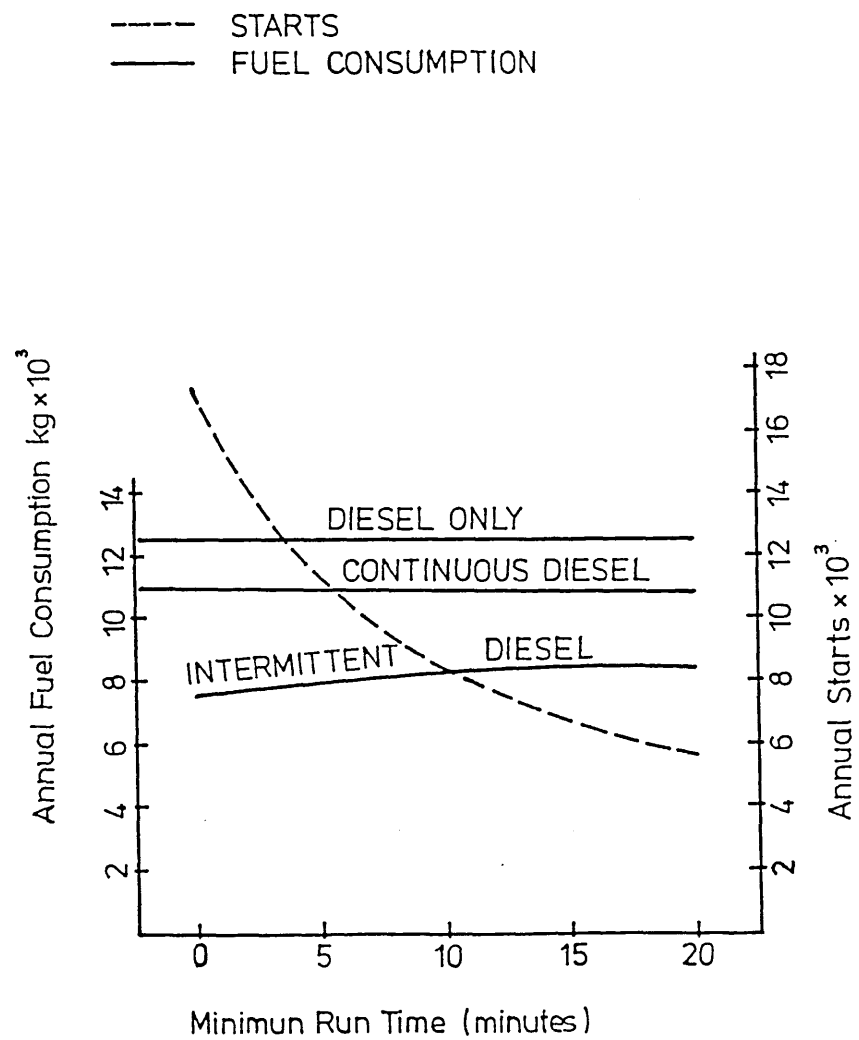


FIGURE 8.10 EFFECT OF DIESEL MINIMUM RUN TIME

Therefore control strategies may be devised to give a significant reduction in annual starts with only a small increase in annual fuel consumption. A time step simulation model is a useful tool to examine the effects of these control strategies on the wind diesel system.

The simplest control strategy is to introduce a minimum run time on to the diesel control. With this control the diesel is only switched off if not required, if the minimum run time has elapsed. The control inhibits rapid on off cycling. This has a beneficial effect as starts are reduced but there is an associated fuel penalty.

Figure 8.10 shows the results of a series of simulations to examine the effect of a diesel minimum run time control. The system configuration was:-

WTG rating	16kW (L916)
Diesel rating	6.4kW
Minimum loading	40%
Consumer load	4.0kW (fixed)
No energy storage	
Weibull parameters	$c = 6.76, k = 2.00$.

With a 20 minutes minimum run time control the annual starts were reduced to 33% of the initial value while the fuel consumption was increased to 111% of its initial value.

An alternative strategy to a diesel minimum run time control is to use a hysteresis control. In this control the diesel engine

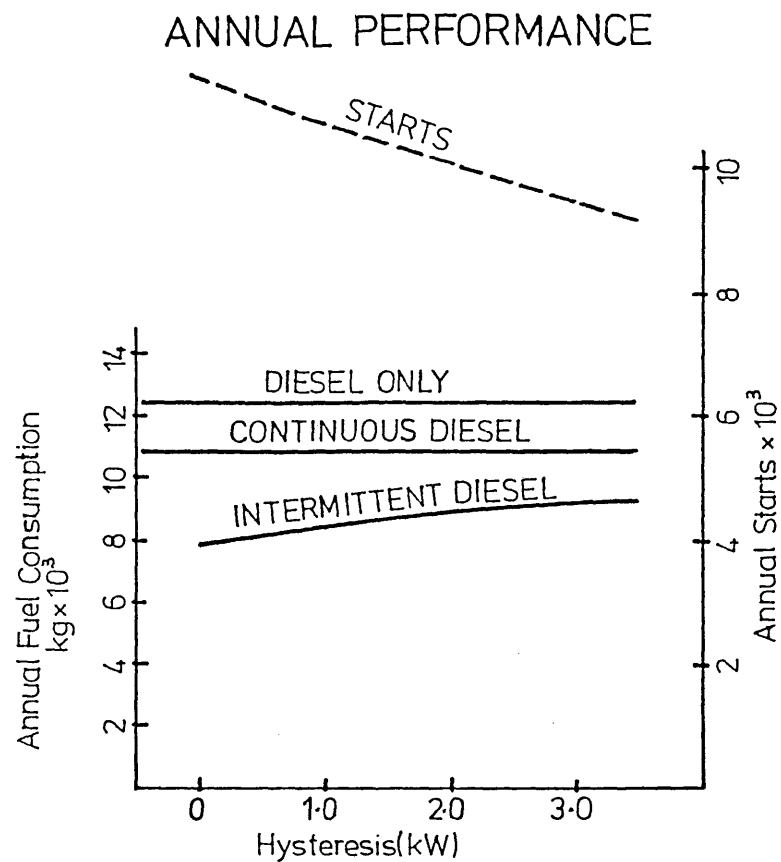


FIGURE 8.11 EFFECT OF HYSTERESIS CONTROL

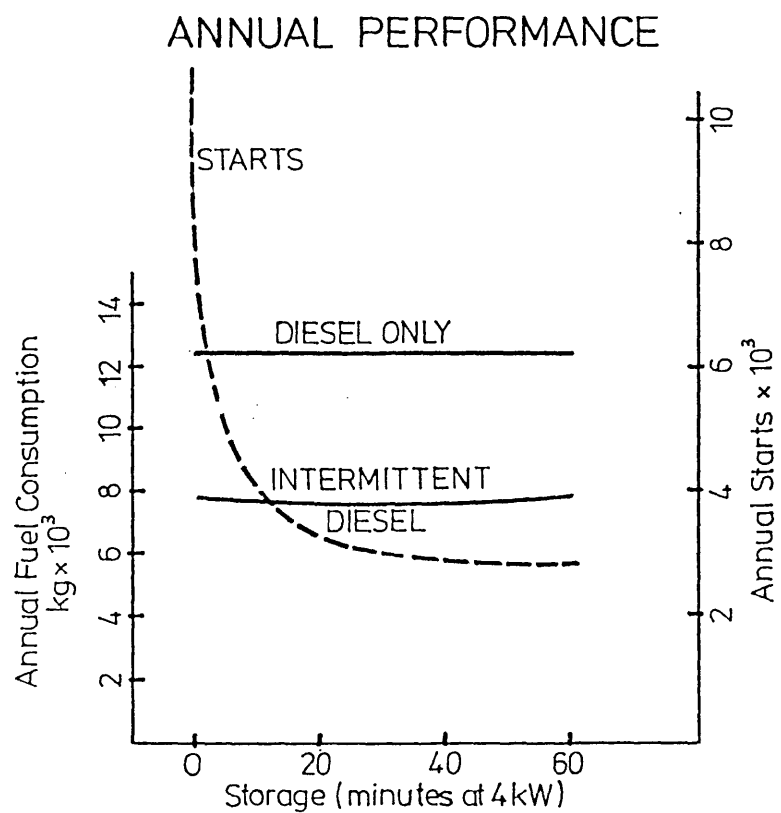


FIGURE 8.12 EFFECT OF ENERGY STORAGE

is only switched off if the wind power is able to supply the consumer load and the hysteresis. Figure 8.11 shows the effect of this control strategy when added to that of a 5 minute minimum run time control. The 5 minute minimum run time was maintained to ensure that the diesel auxiliary alternator could recharge the battery after each start. This strategy appeared to be less effective than a long minimum run time as for 3.0 kW of hysteresis the starts were reduced to 55% of their initial value and the fuel consumption was increased to 116% of its initial value.

Both the addition of minimum run time control or hysteresis control required only the addition of control equipment. However the application of energy storage was also investigated. The storage device modelled was an evacuated flywheel driven from a variable speed electric drive. The constant losses were calculated as a function of the capacity of the energy store and its state of charge. For a fully charged store of 1200 kJ the constant losses were 720W. The input and output efficiencies of the transmission were assumed to be 75%. It was noticeable that the constant losses were more significant than the transfer losses as only a small fraction of the system power was transmitted via the energy store.

The effect of energy storage on the system is shown in Figure 8.12. There is a very significant reduction in the number of starts and no associated fuel penalty. There would of course be a large increase in the capital cost of the system if an energy store were included.

ANNUAL PERFORMANCE

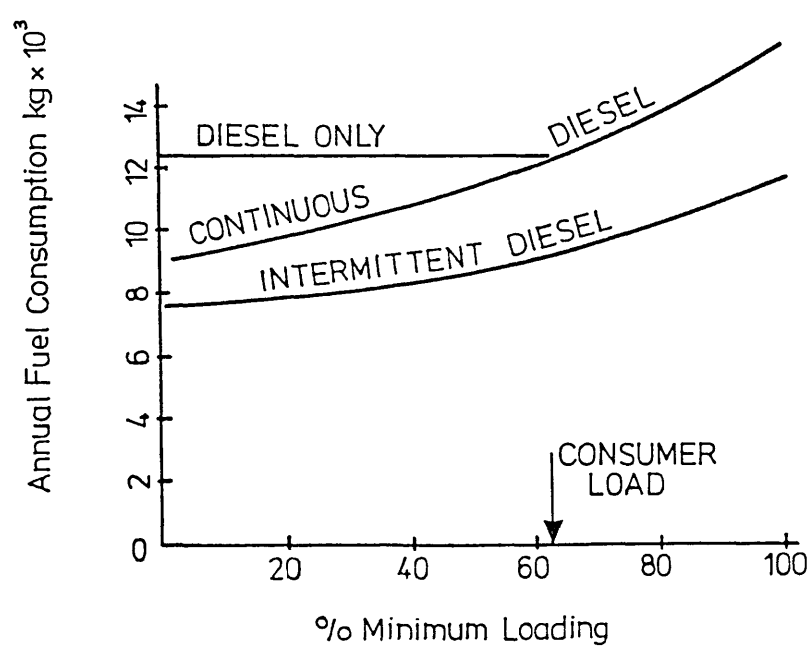


FIGURE 8.13 EFFECT OF DIESEL ENGINE MINIMUM LOADING

The effect of the diesel minimum loading constraint on the fuel consumption of the system was also examined. With a 4kW load, and 5 minutes minimum run time but no storage or hysteresis control the effect of the minimum loading constraint is shown in Figure 8.13. The results are similar for both continuous and intermittent diesel operation. With a lower consumer load or a higher mean wind speed the penalty associated with the diesel minimum loading is more significant.

This time step simulation model gave results based on 1 minute wind speed data. It was not able to examine any higher frequency effects. The model gave validated results for continuous diesel operation and would also be correct for systems where the size of the energy store, or the control strategies restricted the diesel starting and stopping frequency to that of 1 minute. However, for maximum fuel saving it is necessary to allow more frequent starting and stopping of the diesel. Therefore a higher frequency time step model was developed.

8.3 A 2 second time step model*

Long periods of continuous windspeed data are required if reliable results are to be obtained from a time step simulation model. 23 hours of 2 second mean windspeed data were available from the NSHEB site at Bargar Hill, Orkney. The 1 minute time step model was therefore modified to use this data.

*This model was developed in collaboration with D G Infield of RAL.

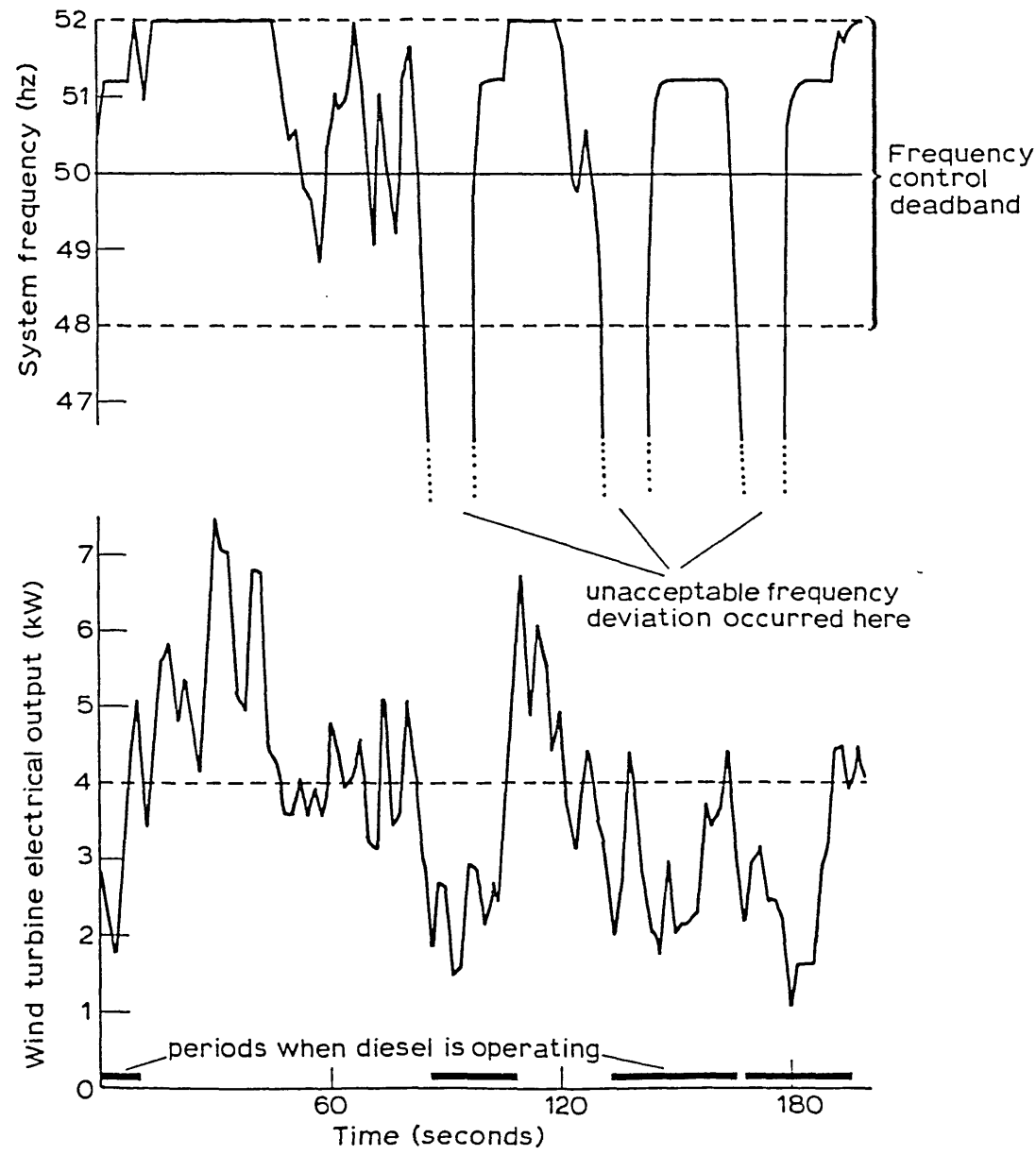


FIGURE 8.14 2 SECOND SIMULATION RESULT

With a 2 second time step it is possible to represent the frequency of the system although it is not possible to simulate voltage variation. Frequency control was represented by the diesel governor droop line for parallel wind diesel operation and by a dump load, which maintained a maximum frequency of 52Hz during high wind speed operation. The time taken to start the diesel was included as a delay of 4 iterations. Energy storage in the system was simulated by increasing the inertia of the 125 rpm shaft of the wind turbine generator. This was a convenient way to include storage but the losses associated with storage were not represented. In addition to the minimum run time and hysteresis control a moving average control facility was introduced. This allowed the decision to switch the diesel off to be made on a historical moving average of power developed by the wind turbine. The decision to switch the diesel on was always made by the frequency dropping to below 48Hz.

With no energy storage in the system this resulted in unacceptable frequency variations while the diesel started. This may be seen in Figure 8.14 which shows a sample output of the 2 second model. Due to the mean power output of the wind turbine being approximately equal to the consumers load, 3 starts and associated loss of frequency, occurred within 3 minutes. With no controls to reduce the number of starts the 23 hours of simulation gave approximately 900 starts. This very high figure was caused by the consumer load (4kW) being equal to the wind turbine power output at the mean windspeed of the data (7.3 m/s).

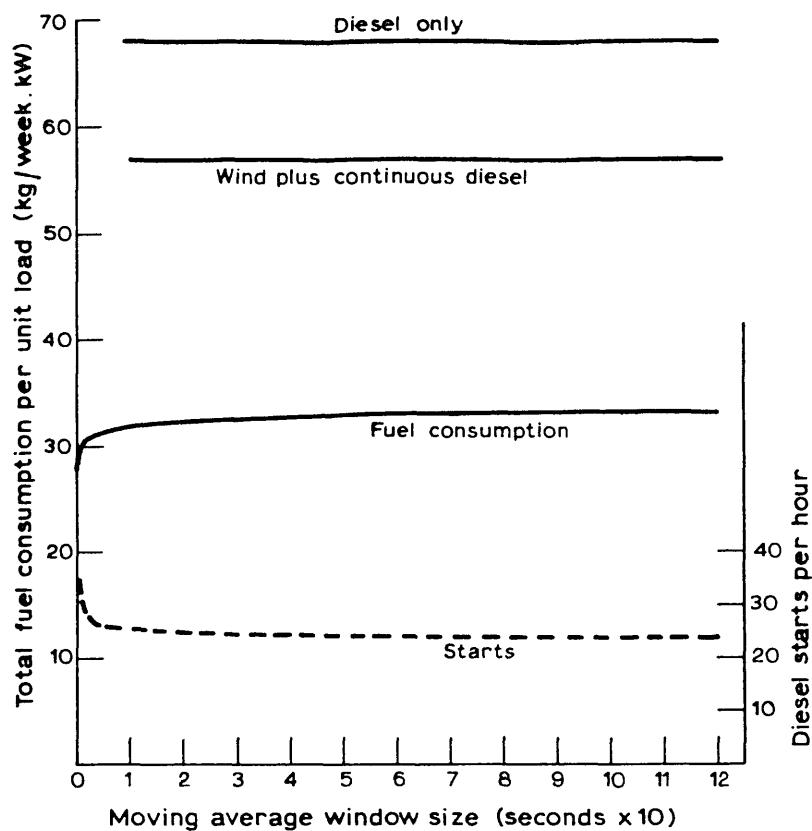


FIGURE 8.15 EFFECT OF MOVING AVERAGE CONTROL

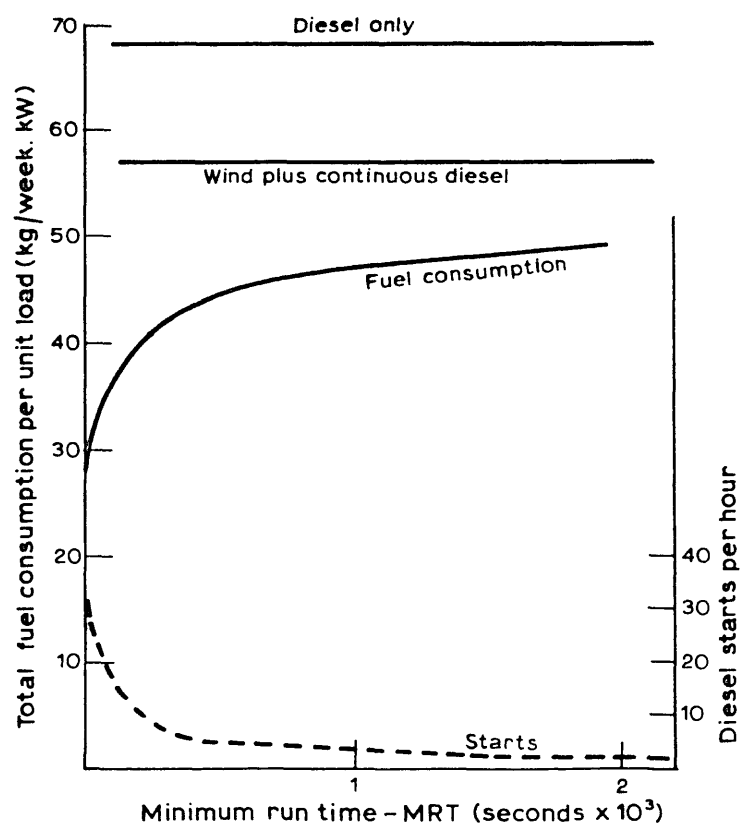


FIGURE 8.16 EFFECT OF DIESEL MINIMUM RUN TIME

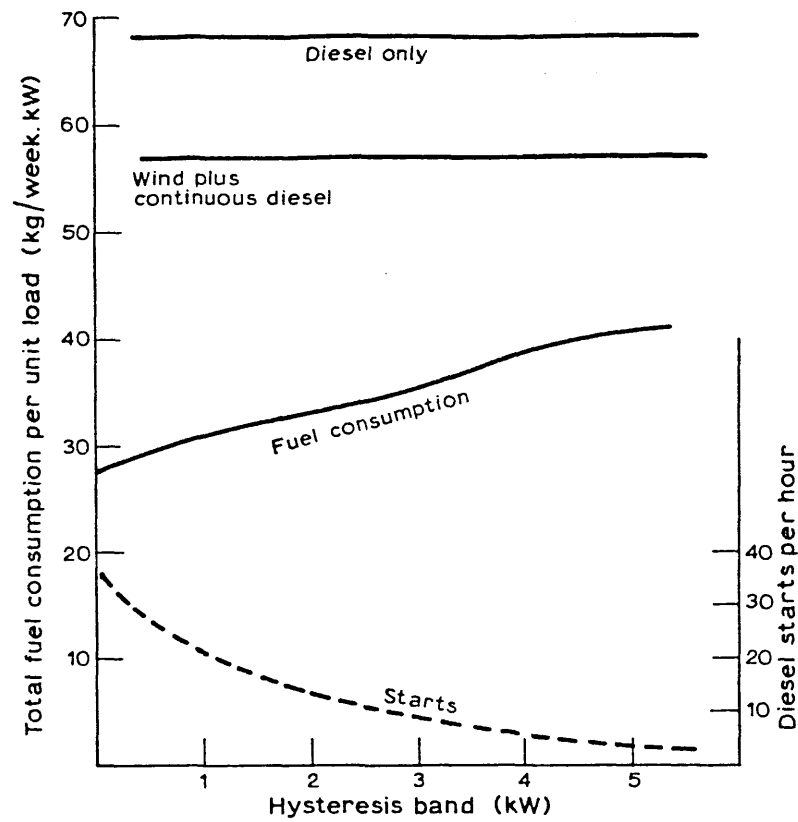


FIGURE 8.17 EFFECT OF HYSTERESIS CONTROL

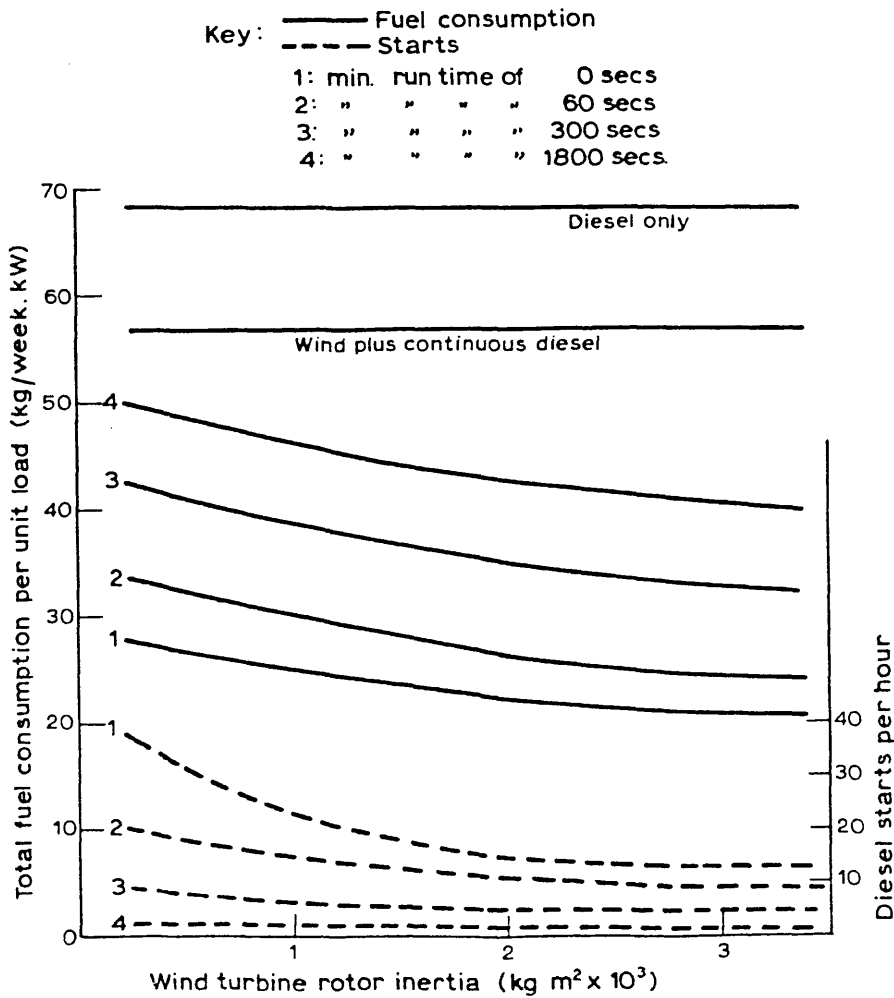


FIGURE 8.18 EFFECT OF ENERGY STORAGE

The effects of the various control strategies were then examined using the simulation. The consumer load was set to 4kW. The minimum loading of the diesel was 40%. The moving average control, Figure 8.15, had a small effect up to a window size of 10 seconds. The minimum run time control, Figure 8.16, and the hysteresis control, Figure 8.17, were both effective in reducing starts although there was, in each case, an associated fuel penalty. The effect of storage, Figure 8.18, was to reduce both the starts and the fuel consumption. The reduction in fuel consumption would be modified by the losses associated with a real energy storage device.

With only 23 hours of windspeed data available it was not justified to extend the simulation to give annual performance predictions.

8.4 Conclusions

The 1 minute time step model was a useful tool for predicting the annual performance of a wind diesel system. If 11,000 starts per year may be tolerated the fuel consumption of a diesel, on a site with a mean windspeed of 6 m/s, may be reduced by 36%. With continuous diesel operation the fuel saving was 12%. The 1 minute model assumed that energy storage was available to eliminate effects of any frequency higher than 1 minute.

The 2 second time step model allowed examination of these high frequency effects. Energy storage is required to supply the

system load during the starting of the diesel. Either storage or control strategies may be used to reduce starts to an acceptable level.

The performance of any wind diesel system is critically dependent on the system configuration and the site wind conditions. Therefore the time step simulations did not allow a unique optimal control strategy to be defined but the models did provide a useful tool to allow various techniques to be assessed. After this work was completed Bossanyi (8.8) showed that further reductions in starts could be achieved by using stochastic wind prediction techniques. As these are inherently self tuning it is likely that they will be of major benefit at installations where variable wind conditions are experienced.

CHAPTER 9

DYNAMIC SIMULATION

9.1 Introduction

The experimental results, described in Chapter 7, showed that stable parallel wind diesel operation was possible. However, to examine the system performance in detail and assess other equipment configurations it was necessary to develop models to simulate the dynamic behaviour of the wind diesel system. In this chapter, the development of these models, their validation against the experimental results and use as predictive tools are described.

The dynamic behaviour of the components of a wind diesel system may be described by a series of time dependent differential equations. These equations may then be combined and solved to describe the overall system performance. In general these sets of equations, which may be non-linear, are so complex that computer based techniques are necessary to develop the time domain solution.

At Imperial College, analogue computer simulations have recently been used to examine wind turbine dynamics (9.1) while a digital simulation model has been used to study the dynamic behaviour of a wind diesel system (9.2). Analogue computers are no longer widely available while the construction of a complete digital simulation model is rather time consuming.

However, recently a number of computer aided modelling programs have been developed which allow dynamic models to be constructed on mini and microcomputers in a straightforward manner (9.3; 9.4). Dynamic models are constructed either using the conventional block diagram form or using bond graph (9.5) or structure graph (9.6) representations. These programs are broadly similar in that each includes sections to allow the input of the model, to form the state equations, to integrate the equations and produce a graphical output.

Two of these programs, MEDIEM which uses a structure graph representation and TUTSIM which uses block diagrams were used to investigate the dynamic behaviour of the wind diesel system.

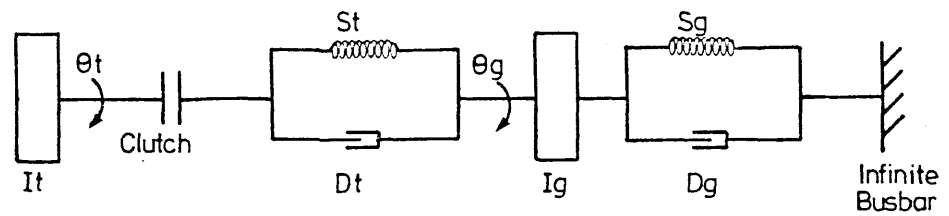
9.2 Simulation Programs (TUTSIM and MEDIEM)

TUTSIM (Twente University of Technology Simulator) is a well established simulation program originally developed for DEC PDP11 computer systems in 1974. It has been adapted for use on microcomputers and is now commercially available in the UK. The version used for the simulations ran on an IBM P.C., with 256k byte of memory and twin floppy disk drives under a DOS operating system. With TUTSIM the model may be formulated as a block diagram or as a bond graph. If bond graphs are used the causal bond graphs are transformed into block diagrams by the program.

The state equations of the system are formed by the program from the block diagram and integrated either using the Euler or an Adams Bashforth 2nd order routine. Graphical or tabulated output is available and hard copy is obtained using a conventional dot matrix printer. At present TUTSIM is unable to accept non-linear bond graph elements but does include a large number of blocks including PID controller blocks and first order exponential lag blocks.

MEDIEM (Multi Energy Domain Interactive Element Modelling) was developed by the City University in 1981. It uses structure graphs to formulate the model and can give results in both the time and frequency domain. In both structure and bond graphs energy flows, rather than signals, are represented. This gives a very compact analogue of the system and the model may be built by inspection without first explicitly writing the system equations. MEDIEM may be used to model energy flows in a number of energy domains but in the fixed axis rotational energy domain inertias are represented by inductances, torsional springs by capacitors and torsional dampers, by resistors. The through variable, analogous to current, is torque and the across variable, corresponding to voltage, is angular velocity. The model may be input to the program in graphical form and the state equations of the system are then formed and integrated using an Euler process (9.7). Again, graphical or tabular output is available. The version used was run on an ICL Perq work station under a Unix operating system. MEDIEM is not yet a fully developed system and a number of difficulties were experienced during its use.

FIGURE 9.1 WIND TURBINE DRIVE TRAIN

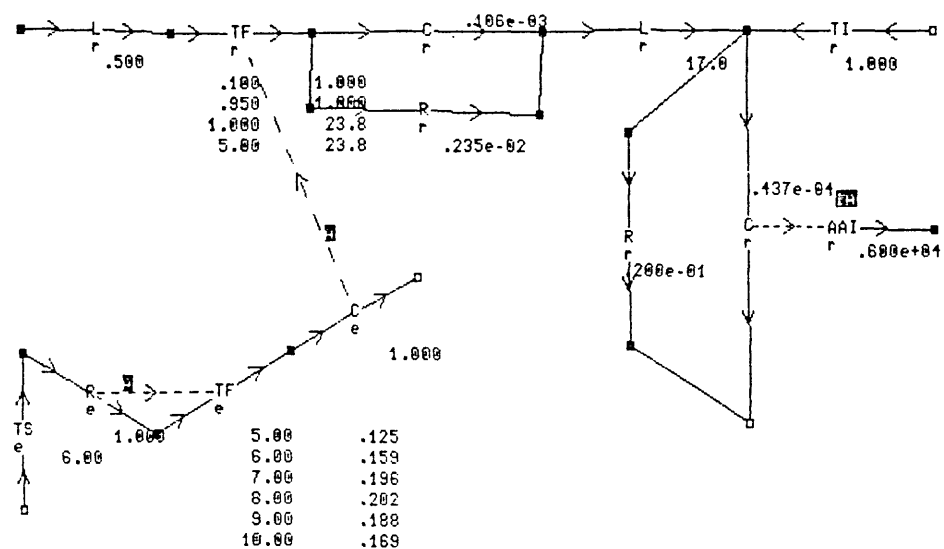


It : Wind Rotor Inertia	(284 Kg m ²)
Dt : Torsional Damping	(425 Nm/rad/s)
St : Flexible Coupling Compliance	(9,400 Nm/rad)
Ig : Alternator Rotor Inertia	(17 Kg m ²)
Dg : Electrical Damping	(50 Nm/rad/s)
Sg : Electrical Compliance	(22,900 Nm/rad)

FIGURE 9.2. WIND TURBINE DRIVE TRAIN MODEL(MEDIEM)

New	Old	Save	Nodes	Elements	Zero	Domain/	Outputs	Name	Convert											
				or lines	Nodes	Parameters														
AI	AS	AR	AA	TA	C	R	L	AT	TT	TI	TS	TR	4TF	46V	2TF	26V	ATI	AAI	TTI	TA

model name: parall(models paralleling transients)



9.3 Wind Turbine drive train dynamics

It has been reported on a number of occasions that the drive trains of grid connected wind turbines have experienced large amplitude torsional oscillations. These may be due to interactions of the drive train and pitch control system e.g. Solano County Mod 2 machine in the USA (9.8) or alternatively may be due only to the dynamic response of the drive train to wind gusts e.g. WTG MP-200 machine at Carmarthen bay (9.9). Experience has shown that fixed speed wind turbines, with synchronous alternators are particularly susceptible to drive train oscillations unless additional damping is introduced. As discussed in Chapters 4 and 5 the L916 did experience drive train oscillations, particularly on connection to the L.V. network, and these were investigated using models based on both MEDIEM and TUTSIM.

The drive train of the L916 wind turbine coupled to the L.V. system, is shown in Figure 9.1. The main elements were the wind turbine rotor, a sprag over running clutch, the flexible coupling across which two dampers were fitted, the alternator and its connection to the electrical network. The values of the rotor inertias and the torsional stiffness of the flexible coupling were obtained by experiment. The effect of the torsional dampers was calculated from manufacturers data. The equivalent torsional stiffness to connect the alternator to the electrical network was calculated from synchronous machine theory described in Chapter 4. The asynchronous electrical damping was estimated from experimental results.

Consider the drive train at its operating speed of 125 r.p.m. (50 HZ). With the clutch open the system is described by the single equation of motion:-

$$Q_g = I_g \dot{\omega}_g + D_g \omega_g + S_g \theta_g \quad (9.1)$$

With the clutch closed the system is described by the two equations of motion:-

$$Q_t = I_t \dot{\omega}_t + D_t (\omega_t - \omega_g) + S_t (\theta_t - \theta_g) \quad (9.2)$$

$$Q_g = I_g \dot{\omega}_g + D_g \omega_g + S_g \theta_g + D_t (\omega_g - \omega_t) + S_t (\theta_g - \theta_t) \quad (9.3)$$

This system was modelled on MEDIEM using structure graphs and the graphical input is shown in Figure 9.2.

The inertias are represented as inductances (L), the spring compliances by capacitors (C) and the dampers by resistances (R). The compliance and damping are entered as their reciprocal values. The clutch was a non-linear device which closed when the rotational speed of the rotor blades was greater than that of the generator but opened when the direction of torque transfer was from the generator to the rotor blades. It was not possible to represent the action of the clutch using structure graphs and so a non-linear transformer (TF) was used to add the extra inertia of the wind turbine rotor when the clutch closed. The system was perturbed by a unit torque impulse (TI) and the scaled electrical power of the alternator was plotted as the

FIGURE 9.3 SIMULATION OF PARALLELING TRANSIENT (MEDIEM)

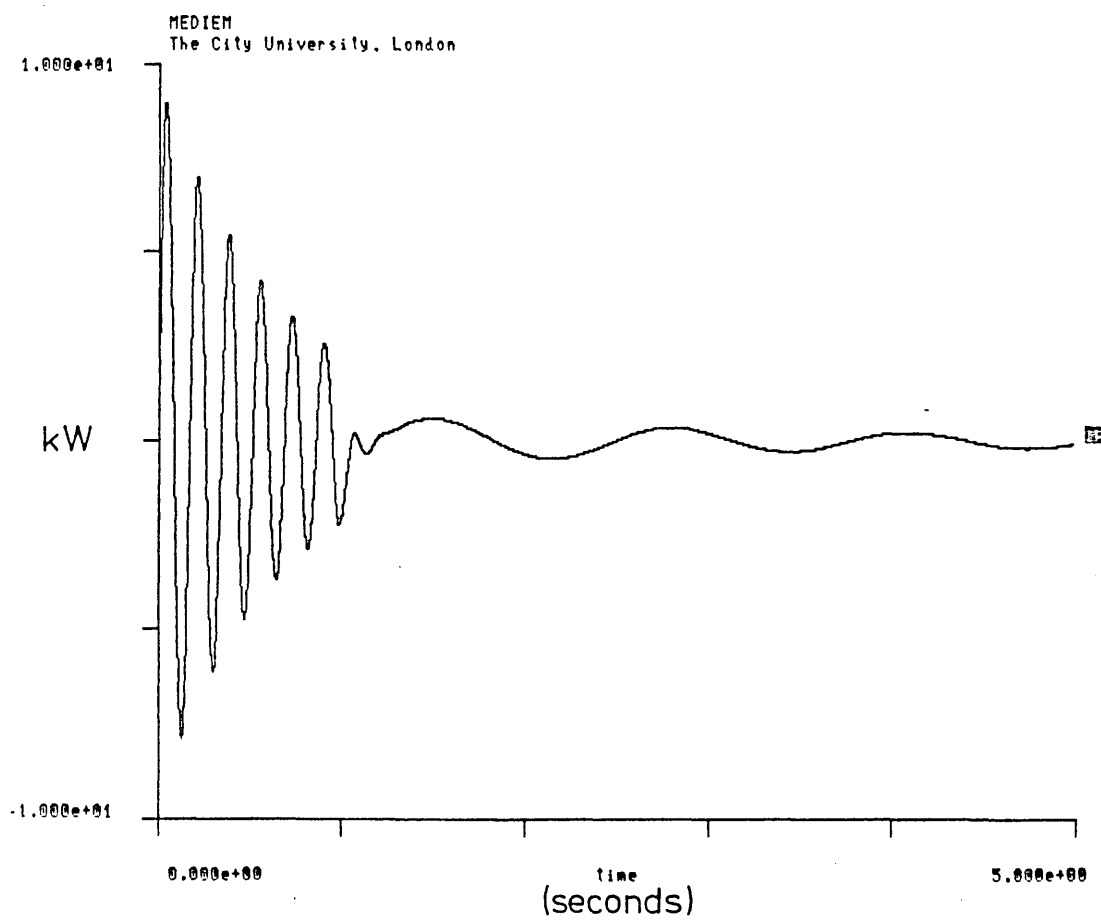
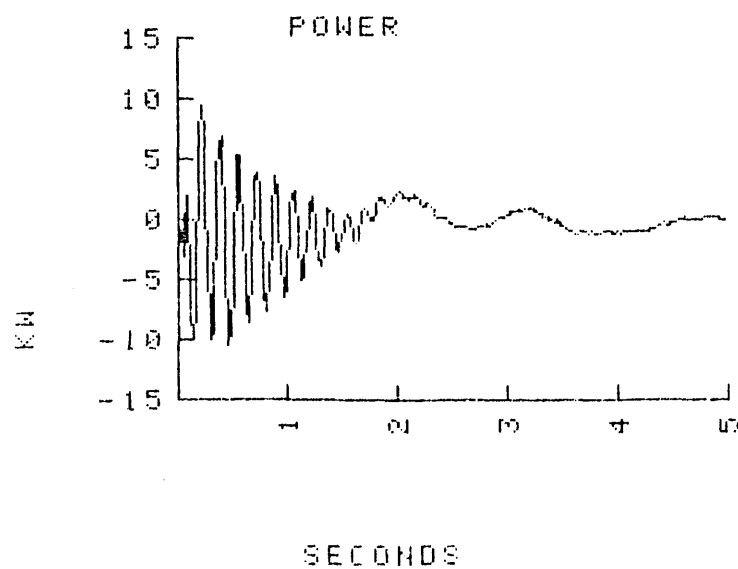


FIGURE 9.4 PARALLELING TRANSIENT (EXPERIMENT)



output. To simplify the model the rate of acceleration of the wind turbine rotor under constant wind speed was found using the predetermined relationship of Figure 4.15.

The results of the simulation of a paralleling transient in a constant wind speed of 6 m/s is shown in Figure 9.3. An experimental result is shown in Figure 9.4 to allow comparison.

The high frequency oscillation (6 Hz) of the wind turbine alternator against the electrical network was correctly represented. However the low frequency oscillation of the entire wind turbine had a frequency of 0.8 Hz rather than the 1 Hz seen in the experimental results. The simulations carried out by Tsitsovits (9.10) on the same system also gave a frequency of 0.8 Hz for this mode of oscillation. It is believed that this discrepancy between simulation and experiment was due to the non-linear response of the torsional dampers. In other respects the agreement between experiment and simulation was good and allowed confidence to be placed in the model of the wind turbine drive train.

The same simulation was also carried out using the TUTSIM program. The block model diagram was more complex than the structure graph but did show explicitly how the equations are solved. The results obtained using TUTSIM were in good agreement with the MEDIEM and experimental results.

9.4 Diesel set, load and wind turbine rotor models

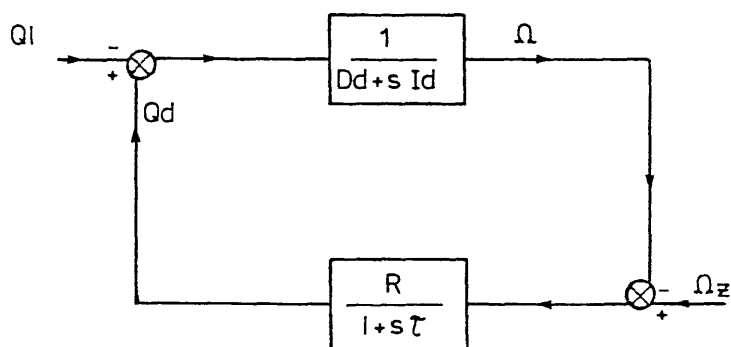
A large number of models, of varying complexity, have been developed to represent the dynamic performance of diesel engines (9.11; 9.12). One representation (9.13) is to model the engine itself by its inertia and internal losses and the governor and fuel system by a proportional term representing the droop and a first order lag which includes the governor and combustion time constants. As discussed in Chapter 2 the performance of the diesel was very dependent on the injector condition and engine temperature. These effects were not included in the dynamic simulation and so this straightforward model was preferred. The model is shown in Figure 9.5 and is described by the following equations using Laplace notation:-

$$\Omega = \frac{Q_d - Q_l}{D_d + sI_d} \quad (9.4)$$

$$Q_d = \frac{R(\Omega_z - \Omega)}{1 + s\tau} \quad (9.5)$$

All parameters other than the governor and combustion time constant were available from manufacturers data or from test results. The governor and combustion time constant was estimated from experimental results to be 180 milliseconds. The model was implemented on both MEDIEM and TUTSIM. Similar results were obtained with both simulations. The models were validated against experimental results and typical results are shown in Figures 9.6 and 9.7. The simulations were in agreement with the experimental results and so the model of the diesel set was considered adequate.

FIGURE 9-5 DIESEL GENERATOR SET BLOCK DIAGRAM



Q_l : Electrical Load Torque

Q_d : Engine Torque

Ω : Angular Velocity

I_d : Set Inertia (1.46 Kg m²)

D_d : Rotational Damping (0.113 Nm/rad/s)

Ω_z : Governor Set Point (51 Hz, 160.2 rad/s)

R : Governor Droop (5%, 5.02 Nm/rad/s)

τ : Governor and Combustion Time Constant (180 ms)

FIGURE 9-6. SIMULATION OF 6kW LOAD APPLICATION AND REJECTION TO DIESEL

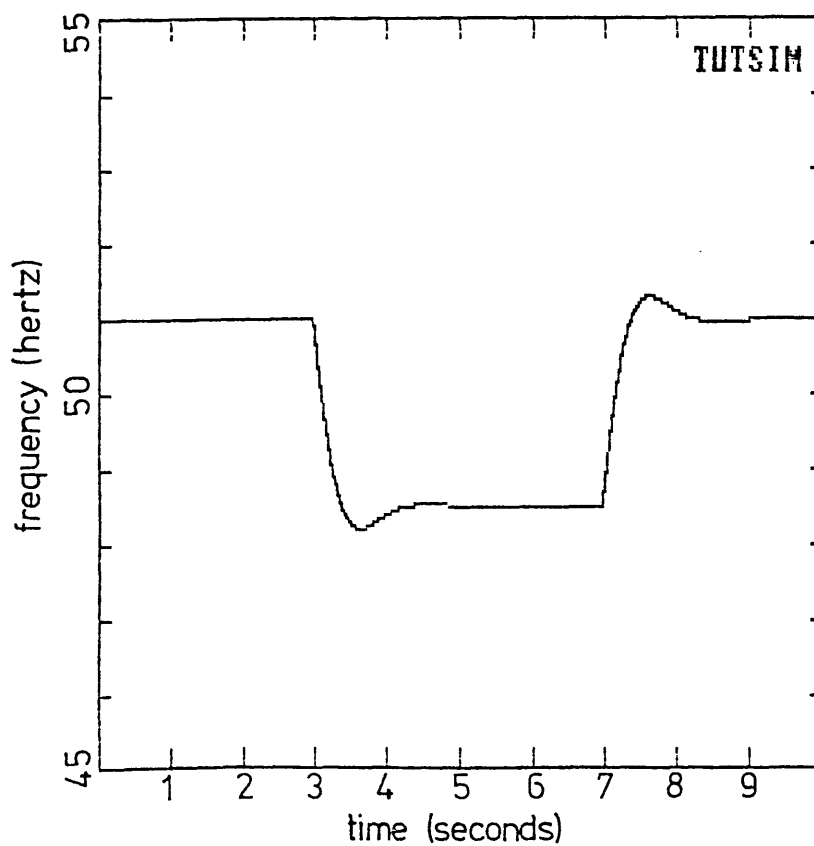


FIGURE 9.7. 6kW LOAD APPLICATION AND REJECTION TO DIESEL(EXPERIMENT)

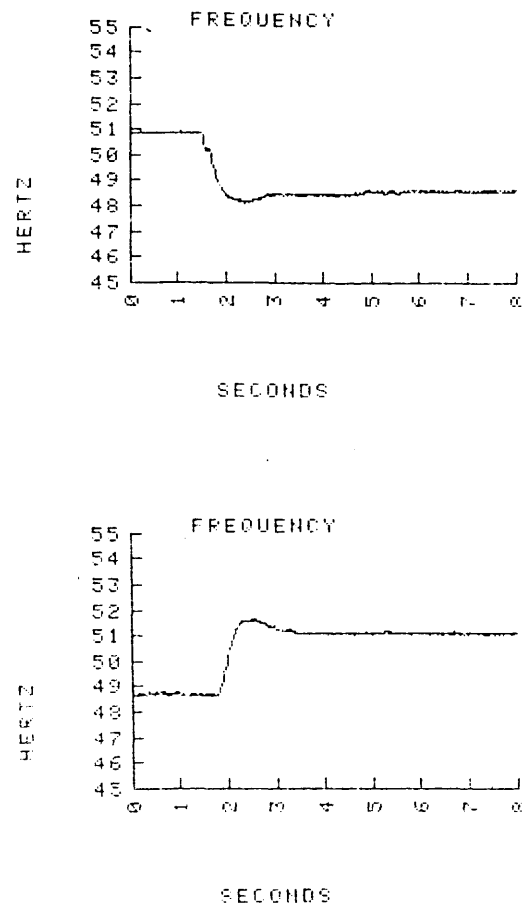
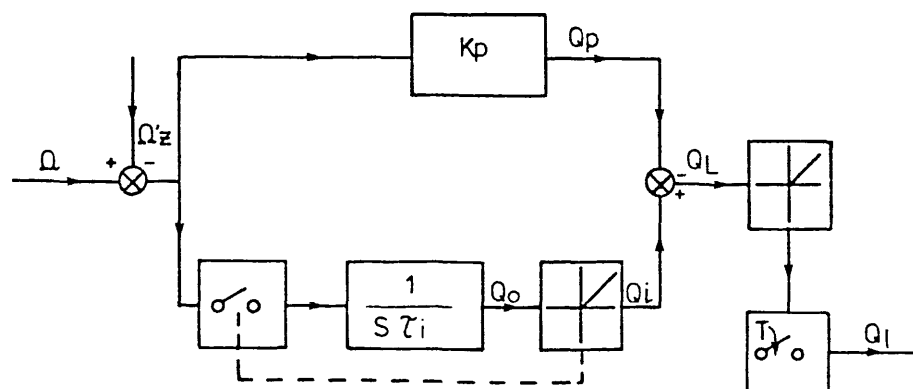


FIGURE 9.8 DUMP LOAD and CONTROLLER BLOCK DIAGRAM



$\Omega'z$: Dump Load Set Point (50.4 HZ, 158.3 rad/s)

T: Cycle Time of ADC (70 ms)

K_p : Proportional Gain (2.28 Nm/rad/s)

T_i : Integrator Time Constant (250 ms)

Q_I : Dump Load Torque

For most of the experiments the dump load was controlled by an analogue proportional and integral controller. This is shown schematically in Figure 9.8. The dump load and controller action is described by:-

For $Q_L < 0$

$$Q_L = 0 \quad (9.6)$$

For $Q_L > 0$

$$Q_L = Q_i + Q_p \quad (9.7)$$

$$Q_p = K_p (\Omega - \Omega'_Z)$$

For $Q_0 < 0$ and $\Omega < \Omega'_Z$

$$Q_i = 0 \quad (9.8)$$

For $Q_i > 0$ or $\Omega > \Omega'_Z$

$$Q_i = \frac{1}{\tau_i} \int_0^t (\Omega - \Omega'_Z) dt \quad (9.9)$$

The additional non-linearity of the integral action, Equations 9.8 and 9.9, was necessary to prevent the integrator drifting into saturation during periods of low system frequency. This was implemented in the hardware of the controller by a diode clamp on the integrator.

Both MEDIEM and TUTSIM were used to examine the behaviour of the dump load and diesel set. However due to the small size of the Unix window on the Perq the MEDIEM graphical input became very congested and so MEDIEM was not used to examine any further models.

FIGURE 9-9 DIESEL GENERATOR SET and DUMP LOAD
MODEL (TUTSIM)
ANALOGUE DUMP LOAD CONTROLLER

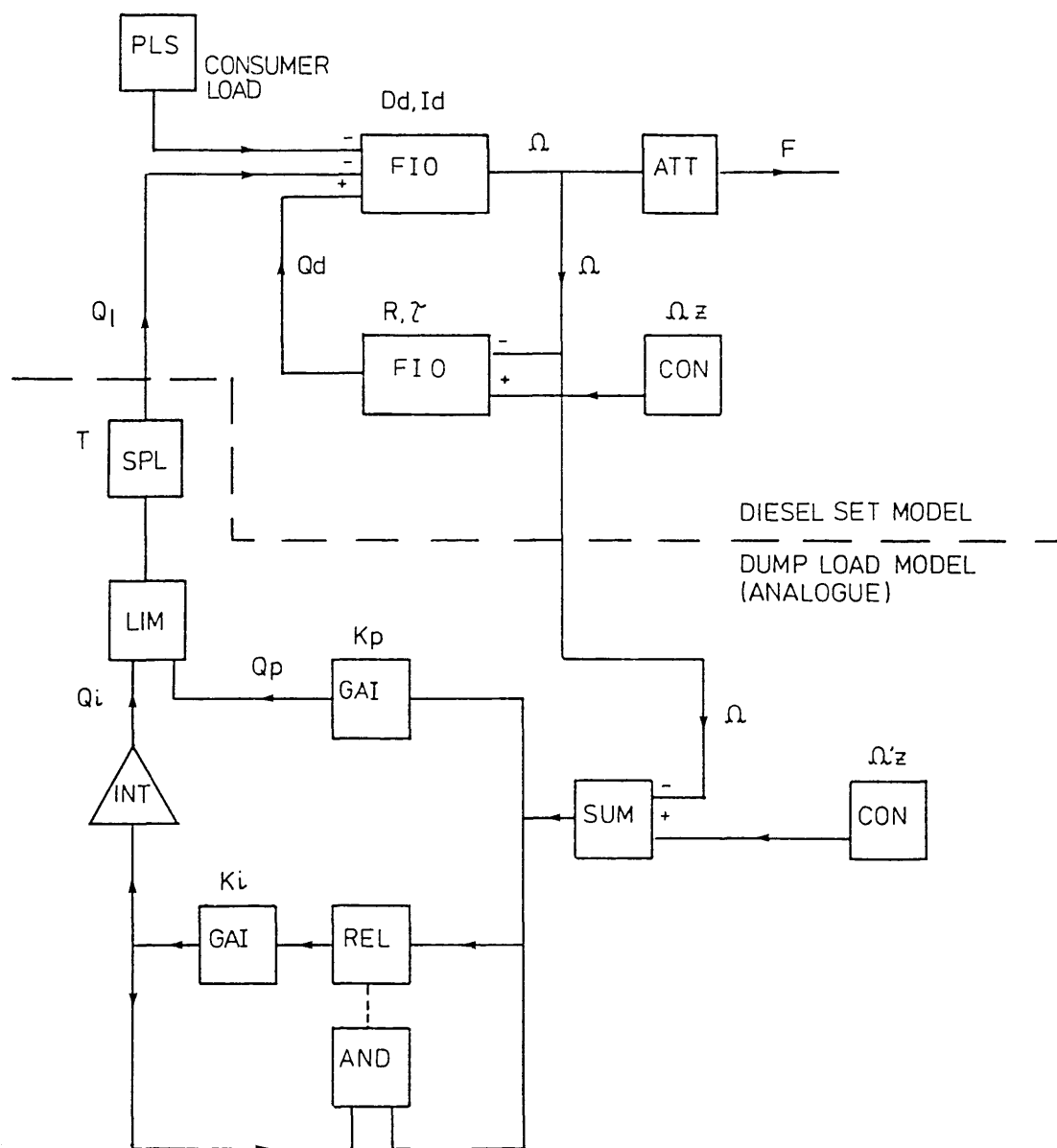


FIGURE 9.10 SIMULATION OF 6kW LOAD APPLICATION AND REJECTION TO WIND TURBINE AND DUMP LOAD (ANALOGUE CONTROLLER) 219

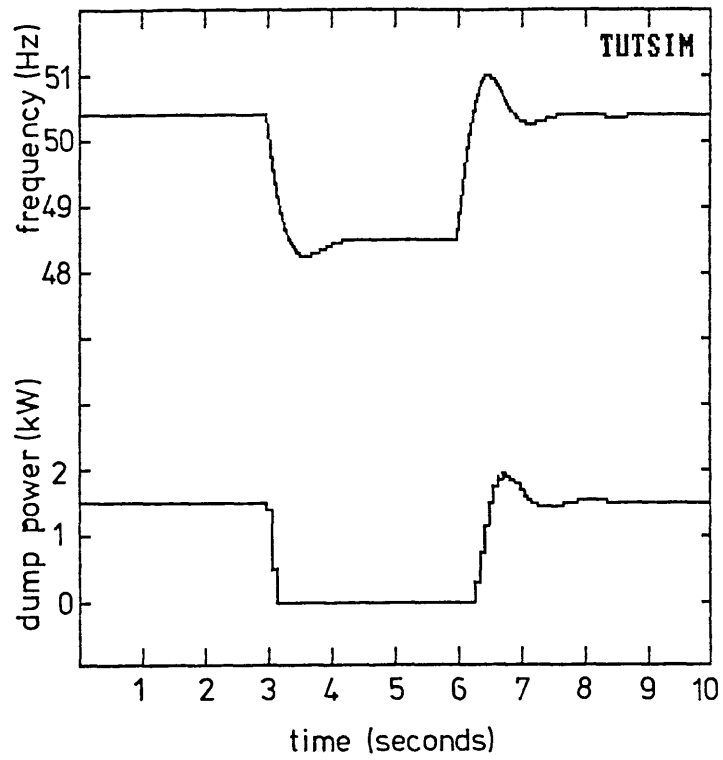


FIGURE 9.12 SIMULATION OF 6kW LOAD APPLICATION AND REJECTION TO WIND TURBINE AND DUMP LOAD (MICROCOMPUTER CONTROLLER)

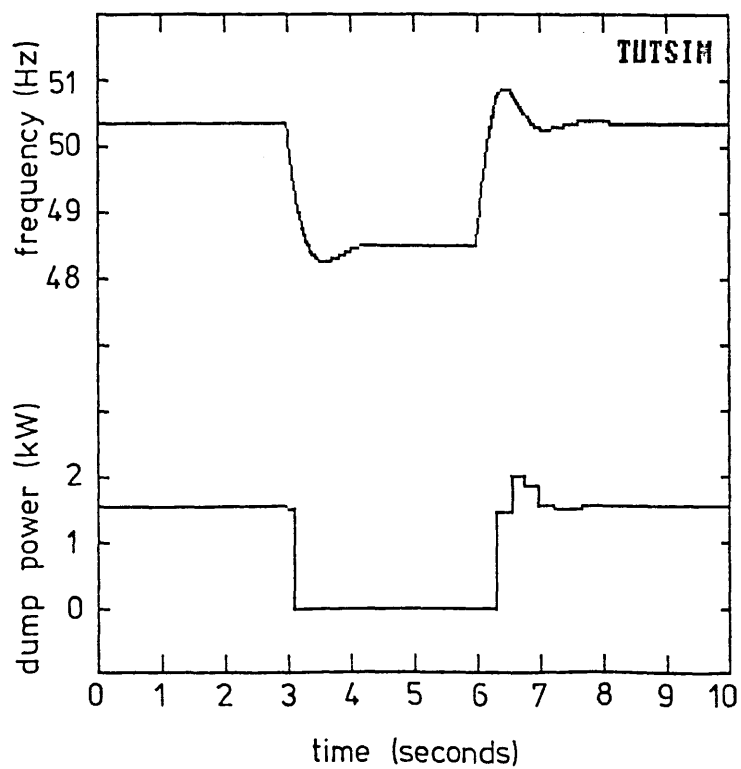
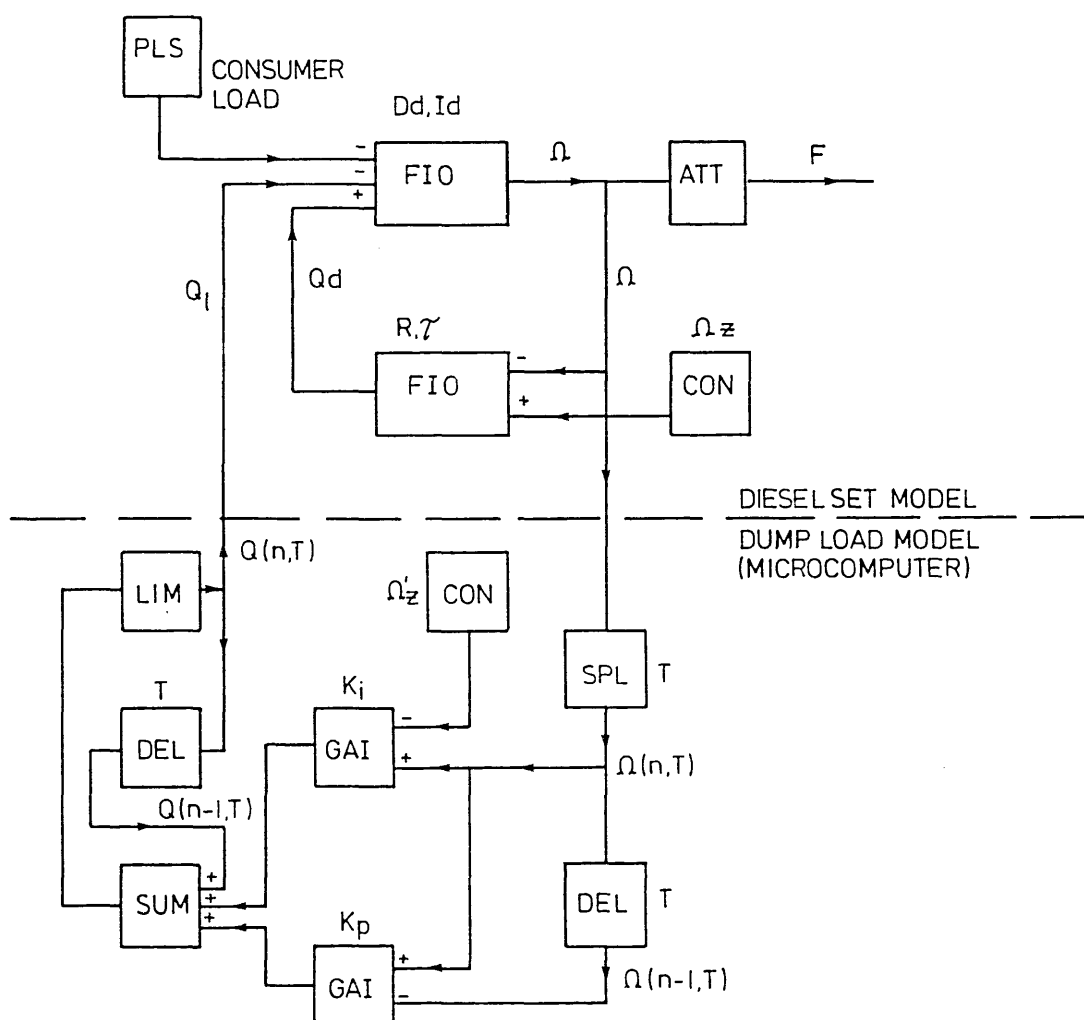


FIGURE 9-11. DIESEL GENERATOR SET and DUMP LOAD
MODEL (TUTSIM)
MICROCOMPUTER DUMP LOAD CONTROLLER



The TUTSIM block diagram representing the diesel set and dump load is shown in Figure 9.9. The function of the TUTSIM blocks used and their abbreviations are listed in Appendix F. The effect of a 6 kW consumer load application and rejection is shown in Figure 9.10. This response was in good agreement with the experimental results and indicated the correct operation of the dump load model. The effect of the cycle time of the analogue to digital convertor may be seen by the discrete control action.

The microcomputer based sampled data controller was also simulated and the model is shown in Figure 9.11. The algorithm (Equations 7.1 and 7.2) was implemented directly using sample and hold and algebraic delay blocks. The response to a 6kW change in consumer load is shown in Figure 9.12. The frequency deviation was similar to that with the analogue controller (Figure 9.10) but the longer cycle time (230 ms) of the microcomputer is clearly visible in the discrete action of the dump load.

The major advantage of a processor based controller is that changes to the structure of the algorithm as well as the parameters may be made in software. However, it is likely to be significantly more expensive than an analogue controller and unless a dedicated microprocessor system is developed its cycle time will be rather slow. If a microprocessor system were to be developed this could also be used to control the switching decision of the diesel set as well as providing data logging and

monitoring facilities. However, for the particular task of controlling the system frequency a low cost analogue controller appears to be more suitable.

The wind turbine was represented in the conventional manner by its torque/tip speed ratio curve. Recalling that the tip speed ratio (λ) is given by:-

$$\lambda = \frac{\omega r}{V} \quad (9.10)$$

$$\text{then} \quad Q_w = \frac{1}{N} f(\lambda) \quad (9.11)$$

where N is the ratio of the number of poles of the two alternators (12).

The non-linear function relating torque to tip speed ratio was determined from the experimental results of Chapter 6.

9.5 Parallel wind diesel operation

Using the models of the components described above a full model of the wind diesel system was constructed, Figure 9.13. This was used to examine the frequency stability of the parallel wind diesel system under varying consumer load and wind speed conditions.

The excitation systems of both the wind turbine and diesel alternators used open loop series compounding to boost their fields with increasing armature current. Experimentally it was

FIGURE 9.13. WIND DIESEL SYSTEM MODEL (TUTSIM)

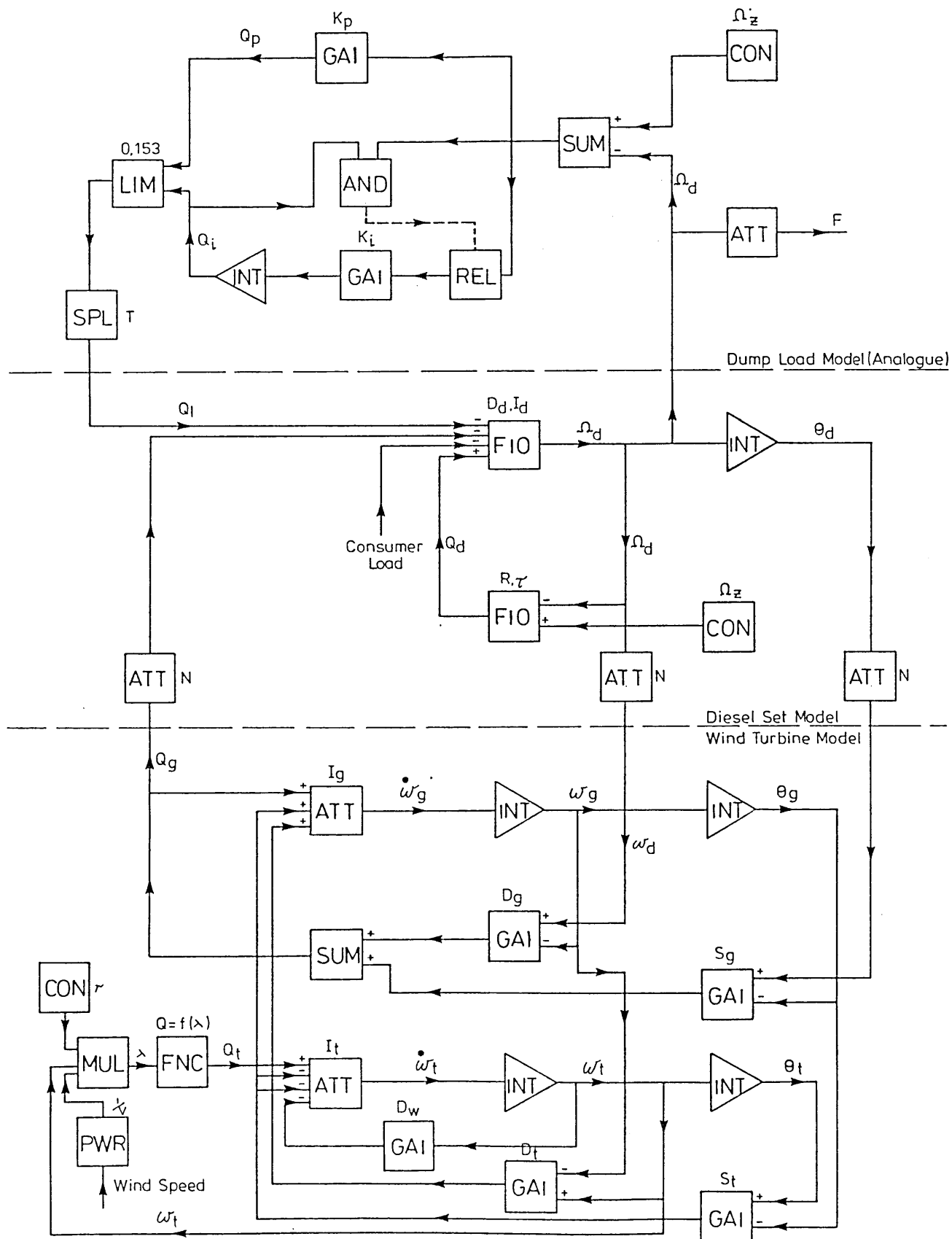


FIGURE 9.14 VALIDATION OF WIND DIESEL MODEL (EXPERIMENTAL RESULTS ARE SHOWN IN FIGURE 7.14).

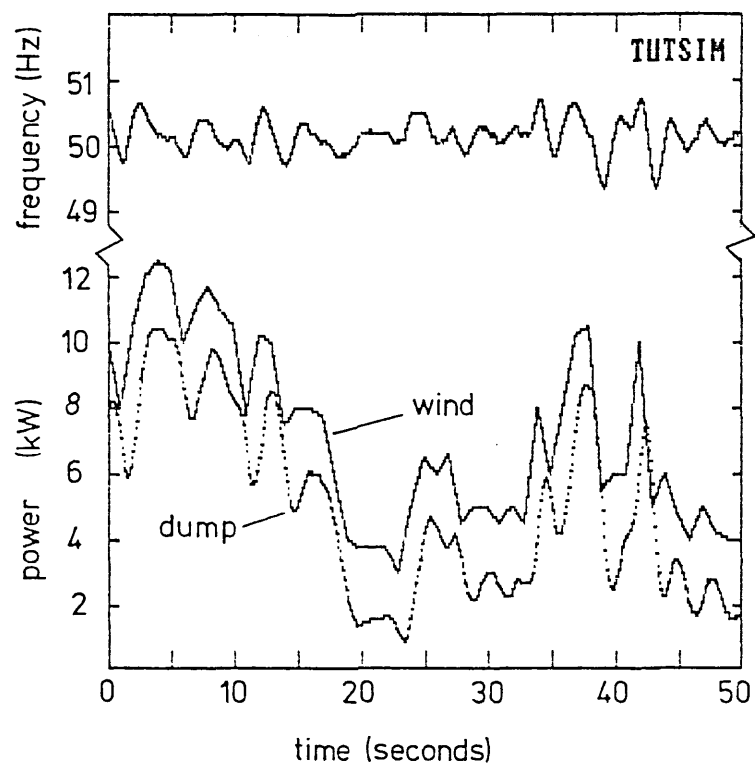
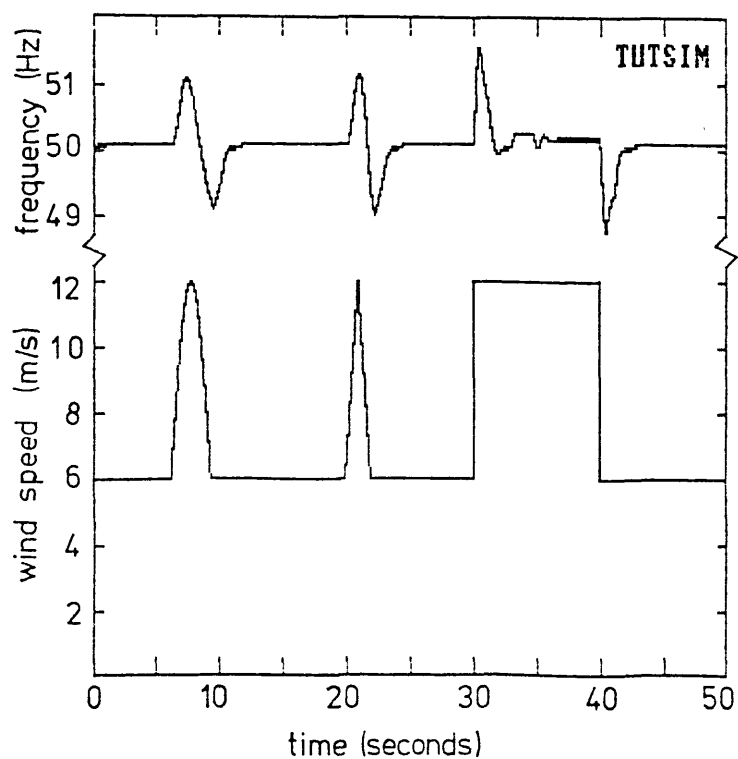


FIGURE 9.15 SIMULATION OF WIND DIESEL SYSTEM PERFORMANCE WITH VARYING WIND CONDITIONS.



shown that these could be adjusted to give a constant system voltage during parallel wind diesel operation. The excitation systems of both alternators were highly non-linear and hence difficult to model. Therefore in the simulation a linearised representation of constant voltages behind their transient reactances was used for the generators. This approximation is commonly used when analysing the control systems of variable pitch wind turbines (9.14; 9.15) and appears to be justified as it gives good agreement with experimental results.

Each component of the full wind diesel model had been validated separately. It was not possible to validate the complete model because of the difficulties of determining experimentally the effective wind speed across the wind turbine rotor disk. However the model was validated against the experimental results of Figure 7.14 by using the measured wind power as the input to the simulation. The results are shown in Figure 9.14 and are in good agreement with the experimental results. The target frequency of the controller was 50.2 Hz (40% diesel set minimum loading) and the consumer load was fixed at 4kW.

Using the validated model the effect of changes in wind speed was examined. A composite function of gusts was applied:-

- i) Sine gust of amplitude 6m/s and period 6.3s
- ii) Ramp gust of amplitude 6m/s and slope 6m/s/s
- iii) Step gust of amplitude 6m/s and duration 10s

The initial wind speed was constant at 6m/s and the consumer load was fixed at 4kW. The results of the simulation are shown

in Figure 9.15. The response of the system frequency to the sine and ramp showed that the dump load worked effectively and limited the frequency to 51Hz. With the theoretical step gust a frequency of 51.5Hz is reached and there is a small overshoot when the frequency returns to its set point.

Similarly the effect of changes in the consumer load was examined. The following load functions were applied:-

- i) Sine load of amplitude 4kW and period 6.3s
- ii) Ramp load of amplitude 4kW and slope 4kW/s
- iii) Step load of amplitude 4kW and duration 10s

The initial load was constant at 2kW and the wind speed was fixed at 12m/s. The results of the simulation are shown in Figure 9.16. The response of the system to the sine and ramp loads was similar with maximum frequency excursions of $\pm 0.6\text{Hz}$. The response to the step load showed a double peak caused by the high inertia wind turbine rotor oscillating against the diesel set. However the maximum frequency excursions were limited to $\pm 0.7\text{Hz}$.

These simulations showed that for a number of onerous wind speed and load conditions the system would remain stable and exhibit only small frequency excursions. The dump load controller worked satisfactorily under all conditions.

9.6 Autonomous wind turbine operation

The model was then modified to examine the frequency stability

FIGURE 9.16 SIMULATION OF WIND DIESEL SYSTEM PERFORMANCE
WITH VARYING LOAD CONDITIONS.

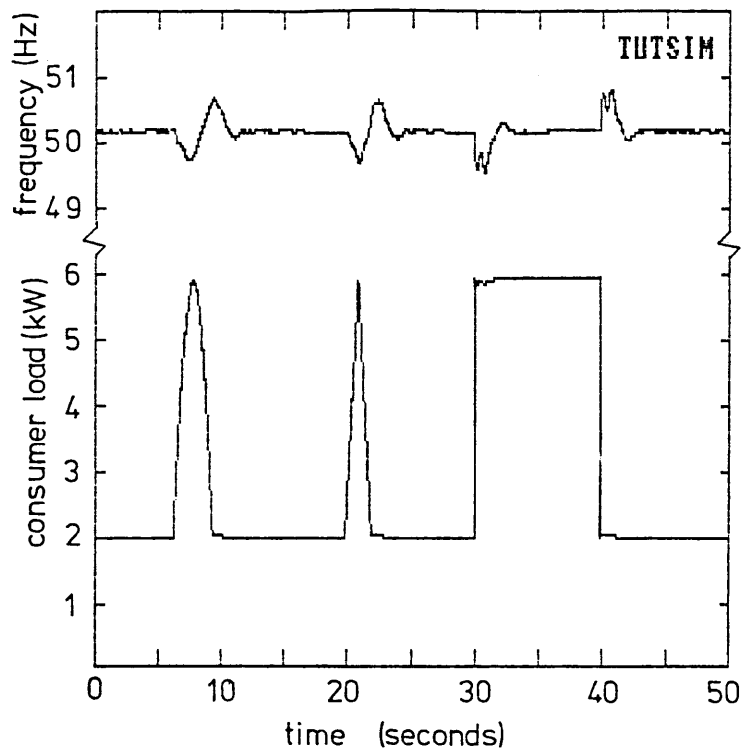
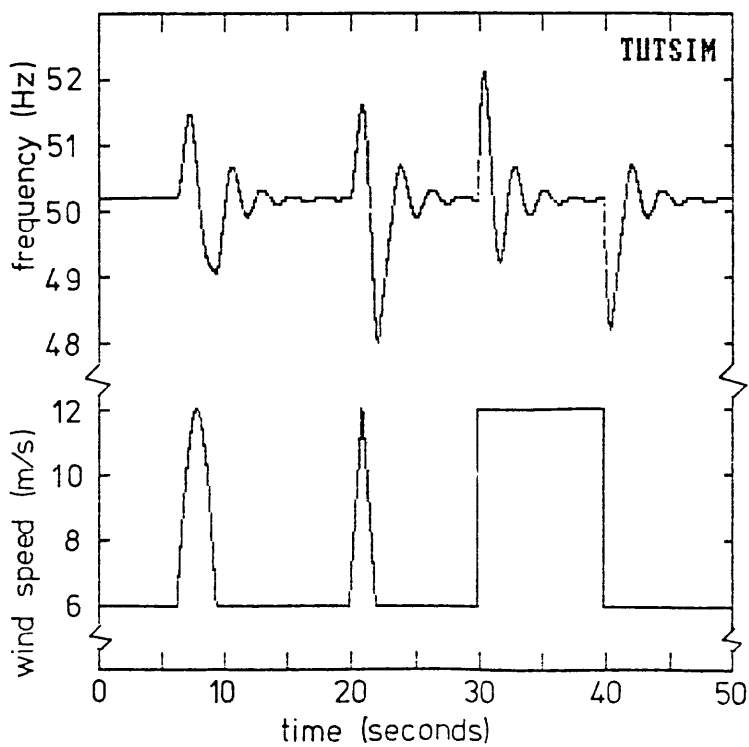


FIGURE 9.17 SIMULATION OF AUTONOMOUS WIND TURBINE OPERATION
WITH VARYING WIND CONDITIONS.



of autonomous wind turbine operation. The terminal voltage of the wind turbine alternator was assumed constant in this simulation. In the parallel wind diesel system the majority of the damping had been provided by the diesel engine. With the diesel set switched out of the system the only damping was that provided by the friction of the wind turbine drive train, the edgewise aerodynamic damping of the blades and the load.

Figure 9.17 shows the response of the frequency of the autonomous wind turbine to the wind speed function described in Section 9.5. The dump load controller settings were the same as for parallel wind diesel operation. As expected the system frequency was more oscillatory in the absence of the diesel engine and larger frequency excursions occurred. The ramp gust was more onerous than the step gust because of the lag associated with the integral action of the controller. The proportional gain of the controller was then increased from 1kW/Hz to 5kW/Hz. This resulted in better frequency control and maximum frequency excursions were limited to less than ± 1 Hz.

Therefore, for autonomous wind turbine operation the proportional gain of the controller should be increased when the diesel set is switched out. This may easily be implemented in an analogue controller by using a variable gain amplifier or by modifying the coefficients in a digital system. It may be noted that the autonomous wind turbine systems already operating successfully on Lundy and Fair Isle (9.16) use a distributed form of proportional controller.

Autonomous wind turbine operation was attempted experimentally. The experiments were unsuccessful because the electrical load of the wind turbine auxiliary circuits, particularly the excitation supply, was not symmetrically balanced across the phases and so the control system tripped out on voltage imbalance.

However these simulation results, supported by the experience of Lundy and Fair Isle, predict that once a suitable excitation system is fitted to the alternator then stable autonomous wind turbine operation will be possible provided the proportional gain of the dump load controller is increased.

9.7 Variable pitch wind diesel operation

If a variable pitch wind turbine is used in a wind diesel system then the frequency may be controlled using the blade pitch mechanism rather than by a dump load. This approach is attractive as it eliminates the dump load and is presently under investigation in Germany (9.17). For a preliminary assessment of the frequency stability of such a system the wind turbine model was modified to represent a variable pitch machine.

For a variable pitch wind turbine:-

$$Q_w = \frac{1}{N} f(\lambda, \phi) \quad (9.12)$$

where ϕ is the blade pitch angle. This function was evaluated from the aerodynamic performance predictions of Chapter 6.

Pitch angle limits of 1° and 40° were applied and the pitch actuator mechanism was represented by an exponential lag:-

FIGURE 9-18. VARIABLE PITCH WIND DIESEL SYSTEM MODEL (TUTSIM)

K_p : Proportional gain ($5^\circ / \text{rad/s}$)
 τ_i : Integrator time constant (200 ms)
 τ_a : Actuator time constant (400 ms)

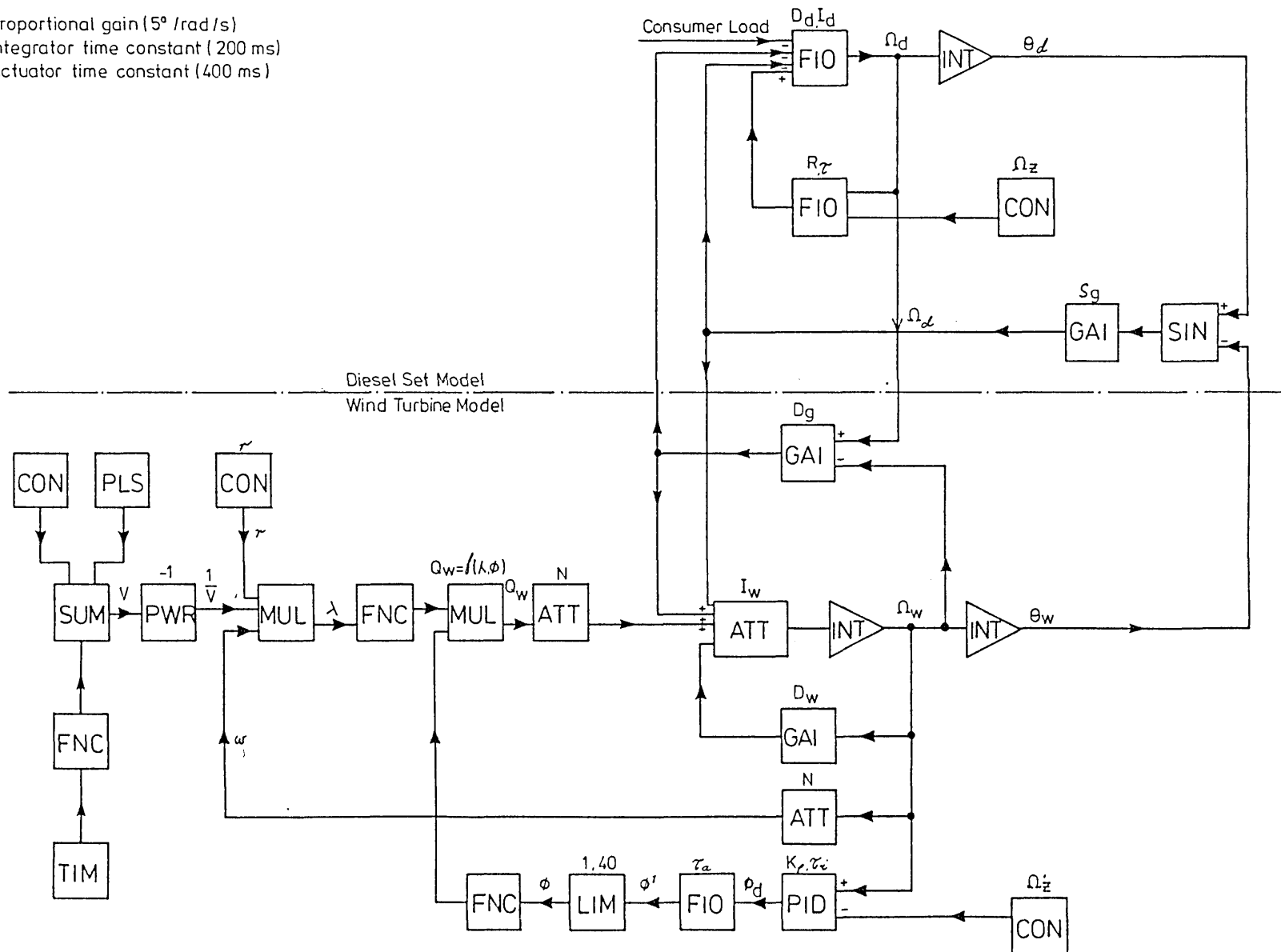
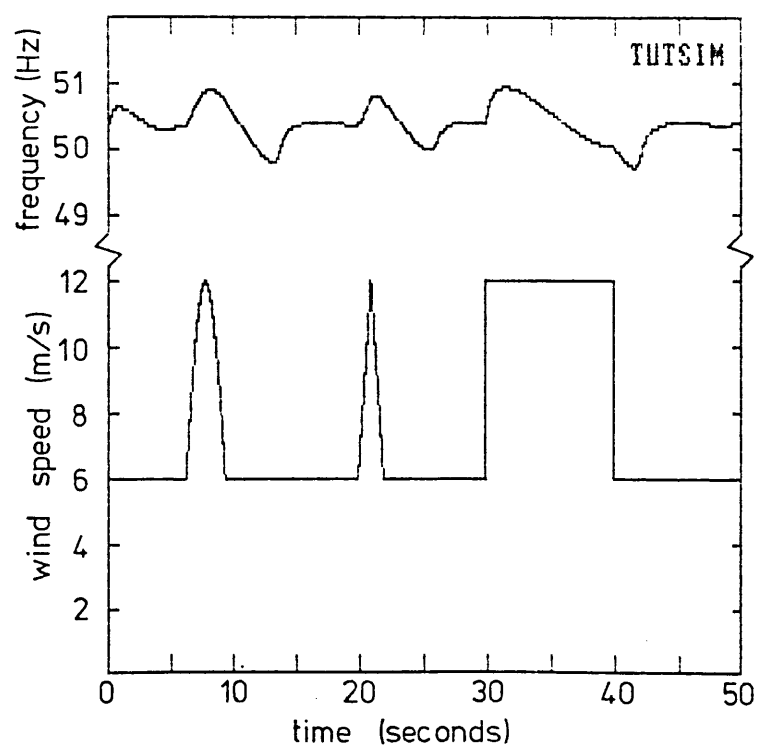


FIGURE 9.19 SIMULATION OF VARIABLE PITCH WIND DIESEL SYSTEM.



$$\phi' = \phi_d \left(\frac{1}{1 + s\tau_a} \right) \quad (9.13)$$

where τ_a , the pitch actuator time constant is 400ms. This is a realistic estimate for a small hydraulic system (9.18).

The blade pitch controller was proportional and integral:-

$$\phi_d = (\Omega'_z - \Omega_w) \left(1 + \frac{1}{s\tau_i} \right) K_p \quad (9.14)$$

The torque transfer between the diesel and wind turbine generators was represented by a linear damping term and a sinusoidal compliance term in accordance with classical synchronous machine theory:-

$$Q_g = D_g (\Omega_d - \Omega_w) + S_g \sin(\theta_d - \theta_w) \quad (9.15)$$

The complete model is shown in Figure 9.18 and Figure 9.19 shows the frequency response to the wind speed function described in Section 9.5. The maximum frequency excursions were only $\pm 0.6\text{Hz}$ and the frequency rapidly returned to the set point.

In the model the wind turbine torque pitch gain was assumed constant and no pitch change rate limits were applied. The significance of both of these assumptions would need to be investigated using specific machine data for any practical installation. However, the simulation does indicate that if rapid active blade pitch control were used the frequency of an

autonomous wind diesel system could be accurately controlled. Although this introduces additional complexity on the wind turbine it eliminates the requirement for a dump load.

9.8 Conclusions

Dynamic simulation models were built using two microcomputer aided simulation tools. The programs used may be mounted on a large variety of microcomputers and because of their low cost, are widely available. They allow much faster construction of models than a full digital simulation because all the input, output and integration routines are already available. The use of structure graphs was found to be very useful as they can be used to help formulate the system equations. With a block diagram or state space representation the equations must be defined at the outset.

Models were developed for the wind turbine, the diesel set and the dump loads. These adequately represented the frequency behaviour of the system and were validated against experimental results. The simulations showed that for a number of onerous wind and consumer load conditions the parallel wind diesel system would be stable with acceptable frequency excursions provided the system voltage was maintained. The frequency stability of autonomous wind turbine operation was predicted to be acceptable once the wind turbine excitation system had been modified and the controller proportional gain increased. The possibility of using an active pitch controlled wind turbine was investigated and it was shown that this could accurately maintain the system frequency of a parallel wind diesel system.

CHAPTER 10

CONCLUSIONS

10.1 Summary of Conclusions

After a detailed examination of its components, a wind diesel system was built and successfully operated. Its performance was monitored and shown to agree with predictions obtained from computer simulations.

Initially the steady state fuel consumption and governor droop characteristics of the diesel set were measured and shown to depend on the engine condition and particularly that of the fuel injectors. An increase in fuel consumption at start up was measured but there was no increase associated with rapid load variations. The engine starter gave a rather slow start and had only a limited life. Therefore a flywheel clutched on to the engine crankshaft was proposed as a preferable method of starting. The results of the diesel engine wear experiments, which should be regarded as preliminary, showed that start/stop cycle rates of up to 10 per hour would not seriously reduce the engine life.

Operation of synchronous generators in parallel with a 415V network is unusual in the U.K. but after an electrical study a suitable protection scheme was designed. The wind turbine was successfully operated on the RAL 415V network and it was shown that the magnitude of the paralleling transients had been correctly predicted.

The Power Curve of the wind turbine was calculated using steady state aerodynamic theory and was in agreement with the experimental results. It was shown that there was no benefit in using data averaging times of longer than 30 seconds for this size of wind turbine. The velocity deficit of the boom anemometer, 1 rotor radius upwind, was 5%.

Autonomous parallel wind diesel operation was achieved and the system voltage maintained within $\pm 6\%$ and the system frequency within $\pm 2\%$. Both a microcomputer and analogue dump load controller were built and successfully tested. It was shown that the hourly fuel savings of the system of up to 50% could be estimated with good accuracy from the steady state characteristics of the wind turbine and diesel generator set.

The time step simulations, validated by experimental results, showed that, with a mean annual wind speed of 6m/s, fuel savings of 36% were possible with intermittent diesel operation, and a 1 minute energy store. Only 12% fuel savings were possible with continuous diesel operation. For maximum fuel savings, wind turbine stand alone operation is necessary and energy storage is required for the continuous supply of electricity and to reduce the number of diesel starts.

Finally the dynamic simulations showed that the frequency performance of the wind diesel system could be accurately predicted using straightforward models. For wind turbine stand alone operation an increase in the proportional gain of the controller is recommended. The use of an active variable pitch wind turbine appears to be attractive as this eliminates the requirement for a dump load.

In summary, the research described in this thesis allows the design and prediction of performance of wind diesel systems which use at least one continuously running diesel generator set. The models and predictive programs have been validated by experiment and this technology is now ready for further commercial development. Fuel savings in this configuration will be modest and the research indicates how stand alone wind turbine operation will allow much higher annual fuel savings but requiring the added complexity of a short term energy store.

10.2 Original Contributions

It is believed that the following items were original contributions to the understanding of wind diesel systems and their components:-

- (i) The comprehensive study of a small diesel generator set when subject to the operating conditions of a wind diesel system.
- (ii) The use of spectrographic analysis of the lubricating oil to evaluate the increase in wear rates of the diesel engine with frequent on/off cycling. (The experiments of this work were carried out in collaboration with D.G. Infield).
- (iii) The design of a protection scheme to allow a wind turbine with a synchronous alternator to be connected to a 415V network.

- (iv) The demonstration that data averaging periods of 30 seconds were adequate for the power performance testing of a 9 metre diameter wind turbine. Also the theoretical and experimental determination of the velocity deficit 1 rotor radius upwind of the rotor disk.
- (v) The design and testing of both an analogue and a microcomputer based dump load controller. The operation of a parallel wind diesel system with 100% wind penetration and the demonstration that the fuel savings could be predicted from the steady state characteristics of the components.
- (vi) The use of a validated 1 minute time step simulation model to predict annual system performance.
- (vii) The construction of models using microcomputer aided simulation tools to allow the dynamic performance of the wind diesel system to be analysed and the performance of alternative systems to be predicted.

10.3 Suggestions for further work

The following work is suggested to allow the fuel savings of a wind diesel system to be maximised. It should be noted that some of this work is already in hand.

- (i) The experimental investigation of stand alone wind turbine operation. This will require modification to the excitation system of the wind turbine.
- (ii) The installation of a short term energy store by mounting a flywheel on the alternator shaft of the diesel generator set. This will also provide the means of starting the diesel via a clutch on to the engine crankshaft.
- (iii) The continuation of the experiments to determine more accurately the wear rates of the diesel engine with frequent start/stop cycles.
- (vi) The investigation of the use of predictive control techniques for the start stop decision of the diesel engine(s).

The L916 wind turbine has not proved reliable and it is suggested that it is replaced with one of the more common stall regulated types. This will allow either a synchronous or induction generator to be used for the WECS. It is further suggested that the L916 wind turbine be modified for active blade pitch control and so a wind diesel system could be configured without a dump load.

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APPENDIX A

GENERAL PURPOSE MICROCOMPUTER PROGRAMS

NAME	FUNCTION	COMMENTS
<u>Hewlett Packard data logging</u>		
DIGITAL	Test program for digital inputs	
ANALOG	Test program for analogue inputs	
2HOUR	Power Performance testing program	Allows 12 No. 10 minute Tests
LOGISTIC	Logistic test program	Allows 1 hour logistic test
FREAD	Allows inspection of HP data files	
SPECT	Program to collect data for spectral analysis	
SYNTO	Logs synchronising transients for L.V. connected operation	Power, Current, Field Current. Triggered by Contactor.
DYNAM	Logs steady state operation (50 sec) for L.V. connected operation	Power, Current, Apparent Power Factor, Field Current.
SYNPAR	Logs synchronising transient on parallel wind diesel system	Power, Volts, Frequency. Triggered by contactor.
DYNDUM	Logs steady state operation (50 sec) for parallel wind diesel operation.	Power, Volts, Frequency. Dump Power.
PITCH	Shows action of pitch control mechanism.	
PARCPF	Collects data for Power v Frequency scatter plots	
PARCPV	Collects data for Power v Voltage scatter plots	
DUMP	Logs operation of dump load controller (8 second shot)	Frequency, Dump Power
FCOR	Collects data for field current v power correlation.	

NAME	FUNCTION	COMMENTS
<u>Apple IIe dump load control</u>		
INTERFACE	Tests output card interface and dump load.	
ADTEST2	Tests A/D interface card.	
PROP	Proportional control of dump load	Not modified for bipolar A/D
PIFAST	Proportional and integral control of dump load.	No additional delay loops
<u>Apple II+ consumer load control and Field unit logging</u>		
PROG LOAD 2	Tests consumer load	
LDLOG1	1 value of load and 1 minute logging	Requires NJFILE START and NJDATA PRINT
NJFILE START	Prepares file header for logging	
NJDATA PRINT	Prints logging files	
NJPEEK	Allows inspection of data files	
LOGISTIC	Comprehensive program for logistic testing parallel wind/diesel	Fixed value of load
LOGOUT	Output program for LOGISTIC	Outputs to printer
LOGVAR	As LOGISTIC but allows varying load	Also uses LOGOUT for output.

APPENDIX A

SAMPLED DATA DUMP LOAD CONTROL PROGRAM

```

100 REM PROGRAM NAME PIFAST
110 REM PROVIDES PROPORTIONAL AND INTEGRAL CONTRAL OF DUMP LOAD
120 REM MODIFIED FOR BIPOLAR A/D CONVERTOR
130 REM N.JENKINS 13/12/84 NO DELAY LOOP
140 REM PG=PROPORTIONAL GAIN
150 REM FL=FREQUENCY DEVIATION LAST ITERATION
160 REM F=MEASURED FREQ
170 REM FD=FREQ CHANGE REQUIRED
180 REM PD=POWER ASSOCIATED WITH FD
190 REM PL=INST POWER
195 REM IG=INTEGRAL GAIN
210 INPUT "TARGET FREQUENCY OF CONTROLLER";OF
220 INPUT "INPUT SIZE OF HYST BAND HZ ";FV
230 INPUT "INPUT DUMP LOAD INITIAL VALUE IN KW";PL
240 INPUT "INPUT PROPORTIONAL GAIN IN KW/HZ";PG
245 INPUT "INPUT INTEGRAL GAIN ";IG
250 HOME
260 CT = 0.227
270 PRINT "CYCLE TIME IS ";CT;"SECS"
280 PRINT "TARGET FREQUENCY IS ";OF;" HZ"
290 PRINT "HYSTERISIS BAND IS ";FV;" HZ"
300 PRINT "PROPORTIONAL GAIN ";PG;" KW/HZ"
310 PRINT "INITIAL POWER IS ";PL;" KW"
320 A = 49280 + 4 * 16
330 N = (PL * 63) / 23.625
340 POKE A,N
350 FL = 0
356 PRINT "INTEGRAL GAIN IS ";IG;" KW/HZ"
360 INPUT "READY TO COMMENCE CONTROL Y/N";R$
370 IF R$ < > "Y" THEN GOTO 100
380 POKE - 16235,0
390 POKE - 16230,0
400 FOR I = 1 TO 10
410 DU = DU + 1
420 NEXT I
430 HB = PEEK ( - 16239)
440 HL = PEEK ( - 16240)
450 T = HL + (HB - 16) * 256
460 F = ((T / 4096) * 10) + 45
470 PRINT "FREQUENCY ";F
480 FD = F - OF
490 IF ABS (FD) < FV / 2 THEN GOTO 590
500 PD = (FD * IG) - (FL * PG)
510 PL = PL + PD
520 IF PL > = 23.625 THEN PL = 23.625
530 IF PL < = 0.0 THEN PL = 0.0
540 N = PL * 63 / 23.625
550 POKE A,N
590 FL = FD
600 DU = 0
610 GOTO 400
620 END

```

APPENDIX A

POWER PERFORMANCE TEST LOGGING PROGRAM

```

10 ! N.JENKINS 06/04/84
20 ! PROGRAM NAME 2HOUR
30 ! 2HOUR POWER PERFORMANCE TEST PROGRAM
35 GOSUB 1830
36 FOR L9=1 TO 12
40 SHORT X1,Y1,Z1,P1
50 T=30
60 N=20
70 C=60
80 OPTION BASE 1
90 DIM Q(20)
100 DIM R(3,20)
110 DIM D*(80)
120 DIM F1(4,20)
130 DIM F2(4,10)
140 DIM F3(4,2)
150 DIM F4(4)
170 DISP H;T1
190 ! INITIALISE DATA AQUISITION
200 CLEAR 709
210 OUTPUT 724 ; "FIR2E0S"
220 ! DUMMY PASS FOR TIMING
230 OUTPUT 709 ; "CS2,0;CS3,0;CS4,0"
240 OUTPUT 709 ; "CF2,1;CF3,1;CF4,1"
250 OUTPUT 709 ; "AC0"
260 OUTPUT 724 ; "T3T3"
270 ENTER 724 ; A9
280 ! END OF DUMMY PASS
290 FOR I=1 TO N
300 ON TIMER# 1,T*1000 GOTO 450
310 A1=0
320 OUTPUT 709 ; "CS2,0;CS3,0;CS4,0"
330 OUTPUT 709 ; "CF2,1;CF3,1;CF4,1"
340 FOR L=1 TO C
350 ON TIMER# 2,495 GOTO 420
360 OUTPUT 709 ; "AC0"
370 OUTPUT 724 ; "T3T3"
380 ENTER 724 ; A
390 A1=A1+A
400 DISP L,A
410 GOTO 410
420 NEXT L
430 OFF TIMER# 2
440 GOTO 440
450 OFF TIMER# 2
460 OUTPUT 709 ; "CR2,1"
470 ENTER 709 ; R(1,I)
480 OUTPUT 709 ; "CR3,1"
490 ENTER 709 ; R(2,I)
500 OUTPUT 709 ; "CR4,1"
510 ENTER 709 ; R(3,I)
520 Q(I)=A1
530 DISP "END OF LOOP";I
540 DISP R(1,I);R(2,I);R(3,I)
550 OFF TIMER# 1
560 NEXT I
570 OFF TIMER# 1
580 FOR K=1 TO N
590 DISP R(1,K);R(2,K);R(3,K)
600 NEXT K
610 GOSUB 2030
620 PRINT "LENGTH OF RUN";T;"SEC S"
630 GOSUB 2080
640 FOR J=1 TO N
650 P=Q(J)
660 X=R(1,J)
670 Y=R(2,J)
680 Z=R(3,J)
690 GOSUB 1540
700 GOSUB 1590
710 GOSUB 2110
720 F1(1,J)=X1
730 F1(2,J)=Y1
740 F1(3,J)=Z1
750 F1(4,J)=P1
760 NEXT J
770 T=T*2
780 C=C*2
790 PRINT "LENGTH OF RUN";T;"SEC S"
800 FOR J=1 TO N STEP 2
810 P=Q(J)+Q(J+1)
820 X=R(1,J)+R(1,J+1)
830 Y=R(2,J)+R(2,J+1)
840 Z=R(3,J)+R(3,J+1)
850 GOSUB 1540
860 GOSUB 1590
870 GOSUB 2110
880 N9=(J+1)/2
890 F2(1,N9)=X1
900 F2(2,N9)=Y1
910 F2(3,N9)=Z1
920 F2(4,N9)=P1
930 NEXT J
940 T=T*5
950 C=C*5
960 PRINT "LENGTH OF RUN ";T/60;"MINS"
970 FOR J=1 TO N STEP 10
980 P=0
990 X=0
1000 Y=0
1010 Z=0
1020 FOR M=1 TO 10
1030 M1=J-1+M
1040 X2=R(1,M1)
1050 X=X+X2
1060 Y2=R(2,M1)
1070 Y=Y+Y2
1080 Z2=R(3,M1)
1090 Z=Z+Z2
1100 P2=Q(M1)
1110 P=P+P2
1120 NEXT M

```

APPENDIX A

POWER PERFORMANCE TEST LOGGING PROGRAM

```

1130 GOSUB 1540
1140 GOSUB 1590
1150 GOSUB 2110
1160 N8=IP(J/10+1)
1170 F3(1,N8)=X1
1180 F3(2,N8)=Y1
1190 F3(3,N8)=Z1
1200 F3(4,N8)=P1
1210 NEXT J
1220 T=T*2
1230 C=C*2
1240 PRINT "LENGTH OF RUN";T/60;
      "MINS"
1250 P=0
1260 X=0
1270 Y=0
1280 Z=0
1290 FOR J=1 TO N
1300 X2=R(1,J)
1310 X=X+X2
1320 Y2=R(2,J)
1330 Y=Y+Y2
1340 Z2=R(3,J)
1350 Z=Z+Z2
1360 P2=R(4,J)
1370 P=P+P2
1380 NEXT J
1390 GOSUB 1540
1400 GOSUB 1590
1410 GOSUB 2110
1420 F4(1)=X1
1430 F4(2)=Y1
1440 F4(3)=Z1
1450 F4(4)=P1
1460 GOSUB 2130
1470 R1=R1+1
1480 T=30
1490 C=60
1500 NEXT L9
1510 ! FUNCTION DEFINITIONS
1520 DEF FNR(F9) = INT(F9*100+.5
      )/100
1530 END
1540 ! CALIBRATION OF INST POWER
1550 P1=P/C*17.97
1560 D1=288.5/T1*(H/1013.3)
1570 P1=P1/D1
1580 RETURN
1590 ! CALIBRATION OF ANEMOMETER
      S
1600 X1=X/(19.5*T)
1610 Y1=Y/(19.5*T)
1620 Z1=Z/(19.5*T)
1630 IF X1<2.5 THEN X1=X1+.09 @
      GOTO 1680
1640 IF X1<5 THEN X1=X1+.07 @ GO
      TO 1680
1650 IF X1<10 THEN GOTO 1680
1660 IF X1<15 THEN X1=X1-.12 @ G
      OTO 1680
1670 X1=X1-.28
1680 ! CONTINUE
1690 IF Y1<2.5 THEN Y1=Y1+.09 @
      GOTO 1740
1700 IF Y1<5 THEN Y1=Y1+.07 @ GO
      TO 1740
1710 IF Y1<10 THEN GOTO 1740
1720 IF Y1<15 THEN Y1=Y1-.12 @ G
      OTO 1740
1730 Y1=Y1-.28
1740 ! CONTINUE
1750 IF Z1<2.5 THEN Z1=Z1+.09 @
      GOTO 1800
1760 IF Z1<5 THEN Z1=Z1+.07 @ GO
      TO 1800
1770 IF Z1<10 THEN GOTO 1800
1780 IF Z1<15 THEN Z1=Z1-.12 @ G
      OTO 1800
1790 Z1=Z1-.28
1800 Y1=Y1*G5
1810 Z1=Z1*G6
1820 RETURN
1830 ! INPUT OF DATA
1840 G5=1 @ G6=1
1850 DISP "INPUT DATE 12,34,56"
1860 INPUT E1,E2,E3
1870 DISP "INPUT RUN NUMBER 1234
      "
1880 INPUT R1
1890 DISP "INPUT WIND DIRECTION
      123"
1900 INPUT D5
1910 DISP "INPUT ANEMOMETER IN F
      REE WIND A OR B"
1920 INPUT G$
1930 IF G$="A" THEN G5=G5*(-1)
1940 IF G$="B" THEN G6=G6*(-1)
1950 DISP "G5";G5;"G6";G6
1960 DISP "INPUT PRESSURE IN MM
      OF HG"
1970 INPUT H1
1980 H=H1*1.3333
1990 DISP "INPUT TEMPERATURE IN
      DEGREES C"
2000 INPUT T2
2010 T1=T2+273
2020 RETURN
2030 ! PRINTER
2040 PRINT "RUN NUMBER";R1;" ";E
      1;" ";E2;" ";E3
2050 PRINT "DIR";D5;"TEMP";T2;"P
      RESSURE";H1
2060 PRINT "ANEMOMETER IN FREE W
      IND ";G$
2070 RETURN
2080 PRINT "W/S(WTG)";TAB(11);"W
      /S(A)";TAB(19);"W/S(B)";TAB
      (27);"POWER"
2090 PRINT TAB(3);"M/S";TAB(12);
      "M/S";TAB(20);"M/S";TAB(28)
      ;"KW"

```

APPENDIX A

POWER PERFORMANCE TEST LOGGING PROGRAM

```

2100 RETURN
2110 PRINT FNR(X1);TAB(11);FNR(Y
1);TAB(19);FNR(Z1);TAB(26);
FNR(P1)
2120 RETURN
2130 ! FILE SUBROUTINE
2140 Y$[1,6]="RN"&VAL$(R1)
2150 CREATE Y$,4
2160 ASSIGN# 2 TO Y$
2170 D$[1,54]=" "
2180 D$[1,4]=VAL$(R1)
2188 D$[55,80]=" "
2190 D$[6,9]="TEST"
2200 D$[11,18]=VAL$(E1)&"/"&VAL$
(E2)&"/"&VAL$(E3)
2210 D$[26,28]=VAL$(D5)
2220 D$[34,35]=VAL$(T2)
2230 D$[42,44]=VAL$(H1)
2240 D$[21,24]="DATE" @ D$[30,32
J="DIR" @ D$[37,40]="TEMP"
@ D$[46,53]="PRESSURE"
2250 PRINT# 2 ; D$
2260 D$=" "
2270 J3=1
2280 FOR K3=1 TO 7
2290 FOR N3=1 TO 3
2300 FOR M3=1 TO 4
2310 X3=FNR(F1(M3,J3))
2320 D$=D$&VAL$(X3)&" "
2330 NEXT M3
2340 J3=J3+1
2350 IF J3>20 THEN 2400
2360 NEXT N3
2370 PRINT# 2 ; D$
2380 D$=" "
2390 NEXT K3
2400 J3=1
2410 FOR M3=1 TO 4
2420 X3=FNR(F2(M3,J3))
2430 D$=D$&VAL$(X3)&" "
2440 NEXT M3
2450 PRINT# 2 ; D$
2460 D$=" "
2470 J3=J3+1
2480 FOR K3=1 TO 3
2490 FOR N3=1 TO 3
2500 FOR M3=1 TO 4
2510 X3=FNR(F2(M3,J3))
2520 D$=D$&VAL$(X3)&" "
2530 NEXT M3
2540 J3=J3+1
2550 NEXT N3
2560 PRINT# 2 ; D$
2570 D$=" "
2580 NEXT K3
2590 J3=1
2600 FOR N3=1 TO 2
2610 FOR M3=1 TO 4
2620 X3=FNR(F3(M3,J3))
2630 D$=D$&VAL$(X3)&" "
2640 NEXT M3
2650 J3=J3+1
2660 NEXT N3
2670 FOR M3=1 TO 4
2680 X3=FNR(F4(M3))
2690 D$=D$&VAL$(X3)&" "
2700 NEXT M3
2710 PRINT# 2 ; D$
2720 ASSIGN# 2 TO *
2730 DISP "END OF RUN"
2740 PRINT " "
2750 PRINT " "
2760 RETURN

```

APPENDIX B
FORTRAN COMPUTER PROGRAMS

NAME	FUNCTION	COMMENTS
MODEL	1 minute time step model	CMS batch
ANALYSE	Power Performance testing analysis	CMS interactive includes graphics
MOD2	2 second time step model	CMS interactive
GRAPH 1-10	Graph plotting program	CMS interactive

APPENDIX B

TYPICAL OUTPUT OF 1 MINUTE SIMULATION MODEL

1 MINUTE MODEL SAMPLE OUTPUT

 ***** DAILY RESULTS *****

DAY	SITE	STARTS	FUEL CONSUMPTION KG	MEAN W/S M/S	S.D. OF W/S M/S	MEAN LOAD KW	S.D OF LOAD KW
1	VALL	1	10.45	10.81	4.96	5.00	0.00
2	VALL	26	5.39	11.60	3.02	5.00	0.00
3	VALL	12	1.32	14.33	3.58	5.00	0.00
4	VALL	8	37.75	2.80	2.56	5.00	0.00
5	VALL	17	28.20	6.02	1.67	5.00	0.00
6	VALL	27	2.75	10.06	0.98	5.00	0.00
7	VALL	61	13.56	8.81	1.45	5.00	0.00
8	VALL	4	0.42	12.69	2.15	5.00	0.00
9	VALL	21	3.26	11.86	2.54	5.00	0.00
10	VALL	47	21.63	7.89	3.13	5.00	0.00
11	VALL	16	10.64	11.00	5.12	5.00	0.00
12	VALL	4	14.81	10.42	6.28	5.00	0.00
13	VALL	3	28.91	5.98	4.18	5.00	0.00
14	VALL	21	2.76	13.35	2.82	5.00	0.00
15	VALL	16	12.22	10.14	4.18	5.00	0.00
16	VALL	7	0.74	18.37	2.75	5.00	0.00
17	VALL	10	1.07	12.16	1.64	5.00	0.00
18	VALL	51	24.59	7.02	1.64	5.00	0.00
19	VALL	0	39.69	2.99	1.44	5.00	0.00
20	VALL	0	39.87	2.03	1.83	5.00	0.00
21	VALL	0	41.03	2.11	0.93	5.00	0.00
22	VALL	49	30.32	5.30	2.83	5.00	0.00
23	VALL	0	37.15	3.72	1.70	5.00	0.00
24	VALL	18	8.19	10.80	3.08	5.00	0.00
25	VALL	4	3.23	12.49	2.86	5.00	0.00
26	VALL	77	10.02	12.03	4.85	5.00	0.00
27	VALL	54	19.84	7.74	1.56	5.00	0.00
28	VALL	93	13.46	8.89	1.57	5.00	0.00
29	VALL	65	25.65	6.86	1.70	5.00	0.00
30	VALL	8	35.12	3.79	2.58	5.00	0.00
31	STOR	1	35.48	3.84	2.14	5.00	0.00
32	STOR	70	26.37	6.65	1.85	5.00	0.00
33	STOR	50	24.46	6.57	2.96	5.00	0.00
34	STOR	14	34.56	4.20	2.55	5.00	0.00
35	STOR	88	12.13	9.09	1.55	5.00	0.00
36	STOR	44	18.12	7.09	4.37	5.00	0.00
37	STOR	23	31.36	5.39	2.02	5.00	0.00
38	STOR	12	31.49	5.28	2.01	5.00	0.00
39	STOR	0	35.35	4.27	1.66	5.00	0.00
40	STOR	2	35.73	4.46	1.40	5.00	0.00
41	STOR	35	29.69	5.88	1.81	5.00	0.00
42	STOR	0	39.36	3.47	0.97	5.00	0.00
43	STOR	2	36.61	4.19	1.47	5.00	0.00
44	STOR	23	33.46	4.96	2.01	5.00	0.00
45	STOR	20	33.33	4.68	2.32	5.00	0.00
46	STOR	51	23.85	6.11	3.78	5.00	0.00
47	STOR	82	9.88	9.46	1.47	5.00	0.00

APPENDIX B

TYPICAL OUTPUT OF 1 MINUTE SIMULATION MODEL

48	STOR	66	25.22	7.05	1.24	5.00	0.00
49	STOR	38	28.06	5.98	2.33	5.00	0.00
50	STOR	0	38.55	3.44	1.38	5.00	0.00
51	STOR	34	30.51	5.50	2.33	5.00	0.00
52	STOR	0	41.03	2.01	0.87	5.00	0.00
53	STOR	0	40.93	1.84	1.15	5.00	0.00
54	STOR	2	33.03	4.94	1.83	5.00	0.00
55	STOR	0	32.63	5.23	0.82	5.00	0.00
56	STOR	0	37.61	3.81	1.52	5.00	0.00
57	STOR	0	39.51	2.99	1.36	5.00	0.00
58	STOR	31	31.71	5.30	2.20	5.00	0.00
59	STOR	0	41.07	1.52	1.03	5.00	0.00
60	STOR	0	38.65	3.42	1.32	5.00	0.00
61	STOR	0	39.91	2.83	1.21	5.00	0.00
62	STOR	2	35.58	4.39	1.55	5.00	0.00
63	STOR	0	35.83	4.34	1.40	5.00	0.00
64	STOR	1	37.56	3.35	1.84	5.00	0.00
65	STOR	76	19.30	8.09	1.32	5.00	0.00
66	STOR	64	19.85	7.88	1.54	5.00	0.00
67	STOR	92	22.16	7.63	1.40	5.00	0.00
68	STOR	34	29.19	6.10	1.65	5.00	0.00
69	STOR	0	37.52	3.77	1.38	5.00	0.00
70	STOR	18	31.57	5.49	1.71	5.00	0.00
71	STOR	30	22.69	7.12	2.03	5.00	0.00
72	STOR	16	30.97	5.21	2.41	5.00	0.00
73	STOR	0	40.00	2.57	1.46	5.00	0.00
74	STOR	0	36.57	4.41	0.84	5.00	0.00
75	STOR	27	27.84	6.42	1.30	5.00	0.00
76	STOR	0	36.58	3.41	2.31	5.00	0.00
77	STOR	0	38.22	3.84	1.02	5.00	0.00
78	STOR	0	41.12	1.66	0.71	5.00	0.00
79	STOR	0	41.13	1.41	0.71	5.00	0.00
80	STOR	0	36.38	3.96	1.77	5.00	0.00
81	STOR	0	37.16	4.10	1.09	5.00	0.00
82	STOR	3	33.38	5.04	1.19	5.00	0.00

```

*****
***** RESULTS *****
*****
DIESEL RATING IS 6.400 KW
DIESEL MINIMUM LOADING IS 0.400
DIESEL MINIMUM RUN TIME IS 5MINUTES
*****
AEROGENERATOR POWER/WIND SPEED CHARACTERISTIC
-0.860 -0.860 -0.860 -0.450 0.600 1.900 3.150 4.400 5.700 6.900
8.200 9.400 11.000 12.500 13.000 12.500 12.000 11.500 11.000 10.000
9.000 8.000 6.500 5.000 3.000 1.000 0.000 0.000 0.000 0.000
*****
DIESEL RUN TIMES MINUTES
0 0 0 866 216 98 77 68 42
28 29 20 23 22 18 11 11 9 11
12 10 7 5 5 5 5 3 2 5
2 2 3 4 4 3 1 4 3 5
1 4 2 3 6 5 2 1 0 1
2 3 1 1 1 1 0 1 5 91
*****
WINDSURPLUS IS 1839.1KW-HOURS
DIESEL SURPLUS IS 514.4 KWH
TOTAL FUEL CONSUMPTION IN KILOGRAMS IS 2204.3
NUMBER OF DIESEL STARTS 1771
*****
MEAN WIND SPEED IS 6.288M/S
VARIANCE IS 17.091
MEAN LOAD IS 5.000KW
VARIANCE IS 0.000
*****
DIESEL RUNNING FOR 92003 MINUTES STOPPED FOR 26077 MINUTES
*****
DIESEL LOADINGS(MINUTES/HOURS)
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80 80-90 90-100
0 0 0 0 27957 6458 6902 8304 12619 29763
0.0 0.0 0.0 0.0 465.9 107.6 115.0 138.4 210.3 496.0
*****
DIESEL LOADINGS IN PERCEENT OF RUN TIME
0.0 0.0 0.0 0.0 30.4 7.0 7.5 9.0 13.7 32.4
*****
DIESEL MEAN RUN TIME IS 51.950MINUTES
DIESEL MEAN STOP TIME IS 14.724MINUTES
DIESEL MEAN LOADING IS 4.404KW
STORAGE LOSSES ARE 0.000 KWH
CAPACITY OF STORE IS 0.000 KW-MIN
*****
DAILY WIND SPEED HISTOGRAM M/S
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 GT 24
0 4 8 12 11 12 7 8 3 2 5 3 4 1 1 0 0 0 0 1 0 0 0 0 0
*****

```

APPENDIX B

TYPICAL OUTPUT OF 1 MINUTE SIMULATION MODEL

```

*****
*****      HOURLY BINNED RESULTS      *****
*****
WIND SPEED  POINTS IN BIN  STARTS  FUEL CONSUMPTION  PROBABILITY
0.125      14      0.000      1.724      0.001
0.375      19      0.000      1.724      0.004
0.625      29      0.000      1.724      0.007
0.875      32      0.000      1.724      0.009
1.125      37      0.000      1.724      0.012
1.375      45      0.000      1.724      0.014
1.625      48      0.000      1.723      0.017
1.875      53      0.000      1.722      0.019
2.125      37      0.000      1.717      0.021
2.375      47      0.043      1.709      0.023
2.625      45      0.000      1.710      0.025
2.875      53      0.000      1.696      0.026
3.125      45      0.000      1.677      0.028
3.375      39      0.000      1.649      0.029
3.625      53      0.000      1.622      0.030
3.875      61      0.000      1.583      0.031
4.125      43      0.000      1.545      0.031
4.375      74      0.000      1.502      0.031
4.625      54      0.000      1.447      0.032
4.875      66      0.030      1.393      0.032
5.125      53      0.000      1.343      0.032
5.375      56      0.143      1.285      0.031
5.625      57      0.035      1.236      0.031
5.875      43      0.186      1.193      0.030
6.125      45      0.400      1.151      0.029
6.375      39      0.667      1.117      0.029
6.625      44      1.045      1.087      0.028
6.875      52      1.615      1.055      0.027
7.125      48      2.625      1.005      0.026
7.375      41      3.756      0.959      0.025
7.625      36      4.611      0.903      0.023
7.875      32      5.500      0.842      0.022
8.125      24      5.708      0.734      0.021
8.375      28      5.821      0.653      0.020
8.625      24      5.625      0.604      0.019
8.875      35      4.829      0.489      0.017
9.125      21      4.095      0.376      0.016
9.375      25      3.000      0.296      0.015
9.625      31      2.258      0.204      0.014
9.875      25      2.360      0.221      0.013
10.125     18      1.167      0.139      0.012
10.375     14      0.286      0.038      0.011
10.625     15      0.467      0.044      0.010
10.875      9      0.222      0.022      0.009
11.125     11      0.455      0.041      0.008
11.375     11      0.273      0.053      0.007
11.625      6      0.333      0.050      0.007
11.875      8      0.500      0.069      0.006
12.125     14      0.000      0.000      0.005

```

APPENDIX B

TYPICAL OUTPUT OF 1 MINUTE SIMULATION MODEL

12.375	10	0.000	0.000	0.005
12.625	13	0.000	0.000	0.004
12.875	10	0.200	0.020	0.004
13.125	11	0.000	0.000	0.003
13.375	11	0.000	0.000	0.003
13.625	14	0.000	0.000	0.003
13.875	12	0.000	0.000	0.002
14.125	9	0.000	0.000	0.002
14.375	6	0.000	0.000	0.002
14.625	10	0.000	0.000	0.001
14.875	10	0.000	0.000	0.001
15.125	6	0.167	0.018	0.001
15.375	8	0.000	0.000	0.001
15.625	1	0.000	0.000	0.001
15.875	2	0.000	0.000	0.001
16.125	1	0.000	0.000	0.001
16.375	4	0.000	0.000	0.001
16.625	8	0.000	0.000	0.000
16.875	3	0.000	0.000	0.000
17.125	2	0.000	0.000	0.000
17.375	2	0.000	0.000	0.000
17.625	3	0.000	0.000	0.000
17.875	2	0.000	0.000	0.000
18.125	4	0.000	0.000	0.000
18.375	4	0.000	0.000	0.000
18.625	4	0.000	0.000	0.000
18.875	1	0.000	0.000	0.000
19.125	0	0.000	0.000	0.000
19.375	3	0.333	0.036	0.000
19.625	0	0.000	0.000	0.000
19.875	2	0.500	0.053	0.000
20.125	3	0.667	0.064	0.000
20.375	0	0.000	0.000	0.000
20.625	1	0.000	0.000	0.000
20.875	2	0.500	0.055	0.000
21.125	1	3.000	0.330	0.000
21.375	0	0.000	0.000	0.000
21.625	0	0.000	0.000	0.000
21.875	0	0.000	0.000	0.000
22.125	0	0.000	0.000	0.000
22.375	0	0.000	0.000	0.000
22.625	0	0.000	0.000	0.000
22.875	0	0.000	0.000	0.000
23.125	0	0.000	0.000	0.000
23.375	0	0.000	0.000	0.000
23.625	0	0.000	0.000	0.000
23.875	0	0.000	0.000	0.000
24.125	0	0.000	0.000	0.000
24.375	0	0.000	0.000	0.000
24.625	0	0.000	0.000	0.000
24.875	0	0.000	0.000	0.000

APPENDIX B

TYPICAL OUTPUT OF 1 MINUTE SIMULATION MODEL

```
*****
***** ANNUAL RESULTS *****
*****
ANNUAL FUEL CONSUMPTION      9815.5 KG
ANNUAL STARTS      9950.4
WEIBULL PARAMETERS C 6.760 K 2.000
*****
```

APPENDIX C PROTECTION RELAYS AND SETTINGS

415 V Protection Equipment

FUNCTION		RELAY TYPE	SETTING	TEST
Earth Leakage Relay	CBEF	MORIARTY ELR/A2	3 A	2.7 A
Overload Relay	OCIT	ENBRAY R.U.N.	7 A 6 secs	-
No Volts Relay	NV	MODEX UVR 500	192 V Diff 10 V	On 209 V Off <u>193 V</u>
Under Voltage Relay	UV	MODEX UVR 500	226 V Diff 4 V	On 234 V Off <u>227 V</u>
Over Voltage Relay	OV	MODEX OVR 500	254 V Diff 4 V	On 245 V <u>Off 254 V</u>
Voltage Unbalance Relay	NØ	MODEX PFR 500-R	390 V	On 414 V <u>Off 391 V</u>
Voltage Timer	TM	MODEX TR 1300	6 sec	6
Under Frequency Relay	UF	MODEX UFR 500	48 Hz	
Over Frequency Relay	OF	MODEX OFR 501	51 Hz	
Frequency Timer	TM	MODEX TR 1300	6 sec	6
Overspeed Relay	OS	MODEX CVT 500-2		

NWPCo Control Equipment

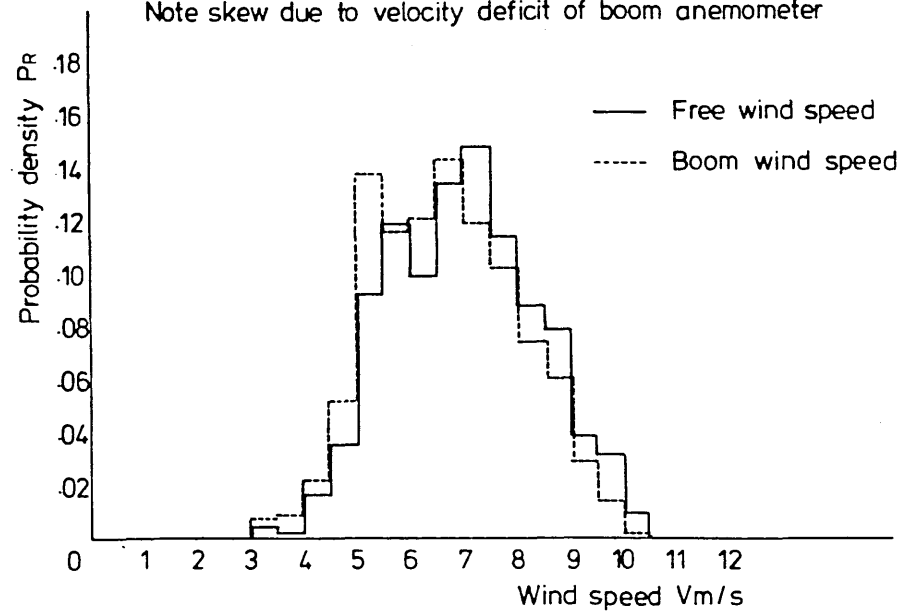
N.W. Frequency Band Monitor	SF 110	47-53 Hz	-
N.W. High Voltage Monitor	SJ 185 (100 - 350 V)	250 V	270 V
N.W. Voltage Band Monitor (Low)	SY 155 (85 - 115%)	95	On 215 V <u>Off 199</u>
N.W. Voltage Band Monitor (High)		105	<u>On 237 V</u> Off 222
N.W. Current Relay (Field Only)	SG 195 (1 - 10)	1	On 6.2 A Off 5.6 A
N.W. Timer A	SA 145 (3 - 60 Min)	30 Min	30
N.W. Timer B	SB 175 (3 - 60 Sec)	60 Sec	60

APPENDIX D
WINDSPEEDS OF POWER PERFORMANCE TESTING

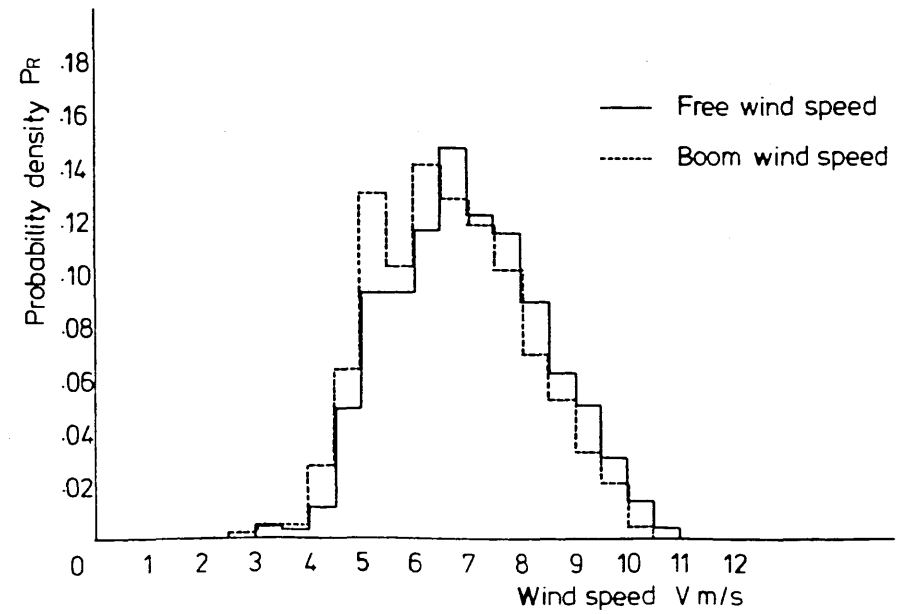
PROBABILITY DENSITY FUNCTIONS (0.5m/s bins)

10 MINUTE FREE WIND SPEED/BOOM WIND SPEED

Note skew due to velocity deficit of boom anemometer

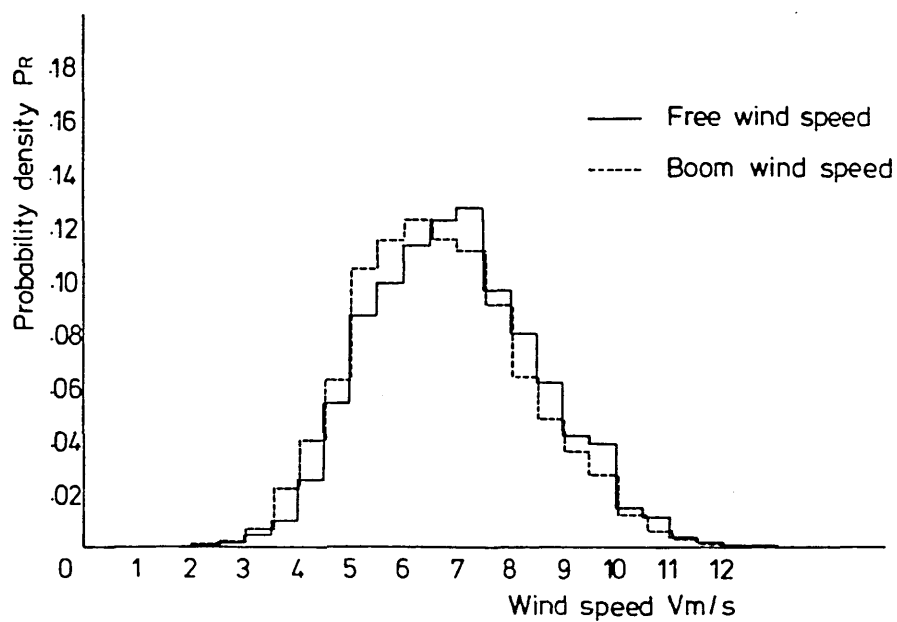


5 MINUTE FREE WIND SPEED/BOOM WIND SPEED

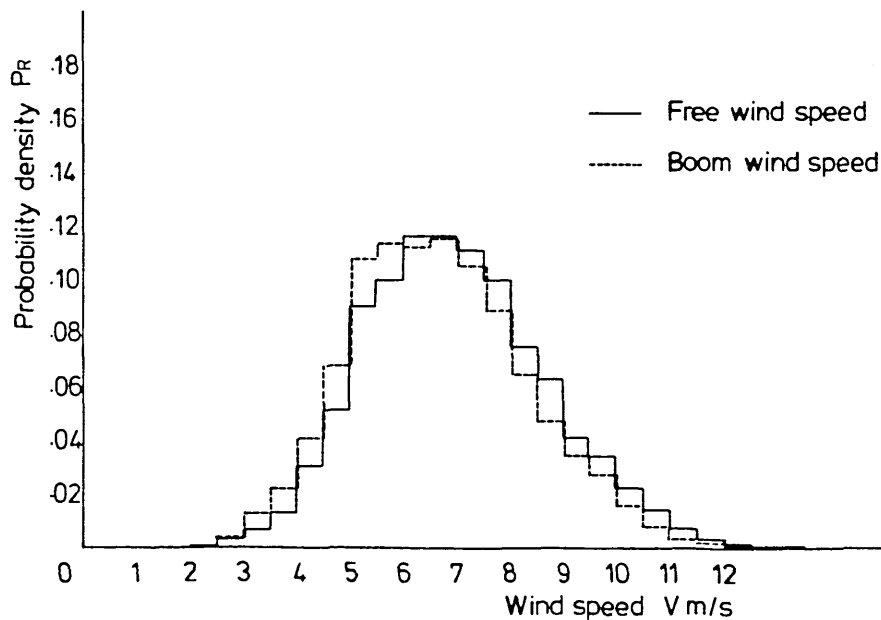


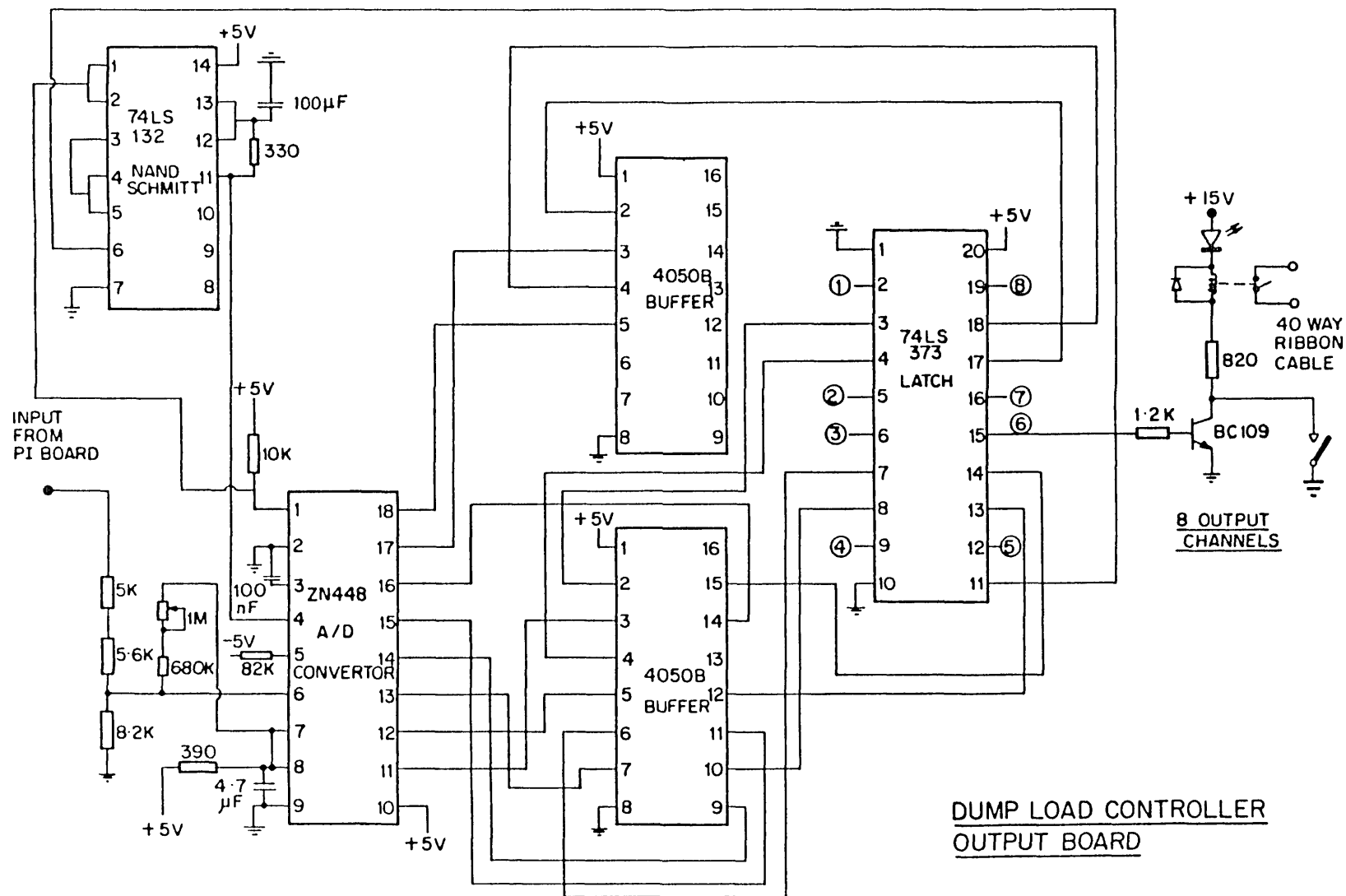
APPENDIX D
WINDSPEEDS OF POWER PERFORMANCE TESTING

1 MINUTE FREE WIND SPEED/BOOM WIND SPEED



30 SECOND FREE WIND SPEED/BOOM WIND SPEED

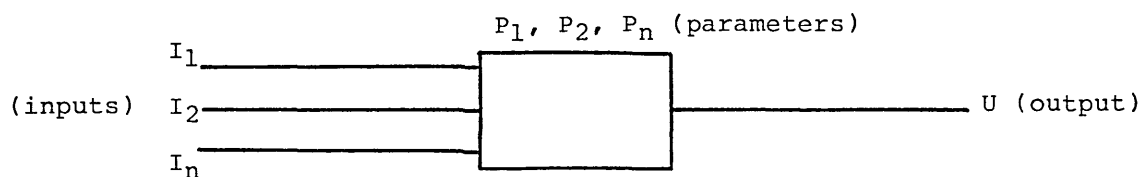




APPENDIX E ANALOGUE DUMP LOAD CONTROLLER

APPENDIX F

TUTSIM FUNCTION BLOCKS



AND - and $U = \text{true}$ if $(I_1 \text{ AND } I_2)$ is true

ATT - attenuator $U = 1/P \times \sum I_n$

CON - constant $U = P$

DEL - delay $U(t) = \sum I_n (t - T_d)$

FIO - first order $U(s) = \sum I_n(s) \times \frac{K}{(1+sT)}$

FNC - function $U = F(\sum I_n)$, F is defined by $P_1 \dots P_n$

GAI - gain $U = P \times \sum I_n$

INT - integrater

$$U = U(t - \Delta) + 0.5 \times \Delta \times (3 \times \sum I_n(t - \Delta) - \sum I_n(t - 2\Delta))$$

LIM - limit $U = P_1$ if $I_n < P_1$
 $U = P_2$ if $I_n > P_2$

PID - 3 term controller $U(s) = \sum I_n(s) \times K \times \left(\frac{1}{sT_i} + \frac{1 + sT_d}{1 + s\alpha T_d} \right)$

PLS - pulse $U(t) = P_3$ if $P_1 < \text{time} < P_2$

PWR - power $U = (\sum I_n)^P$

REL - relay $U = I_1$ if $I_4 > P$
 $U = I_2$ if $I_4 = P$
 $U = I_3$ if $I_4 < P$

SIN - sine $U = \text{sine } \sum I_n$

SUM - sum $U = \sum I_n$

SPL - sample and hold $U(t) = \sum I_n$ if $t = N \times P$ else
 $U(t) = U(t - \Delta)$

TIM - time $U = \text{time}$