

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING

DYNAMICS AND CONTROL OF POWER SYSTEMS
FED FROM DIESEL AND WIND GENERATORS

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ABSTRACT

This thesis deals with autonomous power systems supplied from diesel-generator sets in which fuel is economised through the incorporation of Wind Energy Conversion Systems (WECS). The aim of the research is to understand and solve the stability and control problems so that maximum fuel is saved and acceptable quality of supply is maintained.

At the outset, an assessment of the economic feasibility for the introduction of WECS is presented. Given the wind and load demand statistics and the relevant economic factors such as fuel cost, wind turbine cost, maintenance cost and amortisation rate, and minimum allowable diesel loading, the approximate optimal design characteristics of the wind power contribution, i.e. rated power and rated wind speed, are calculated and the economic feasibility in terms of the expected net present benefit is assessed.

Next the dynamics of a diesel-wind system consisting of a WECS driving an induction generator, a diesel-set and a thyristorised dump load are studied. A steady state optimization determines the optimal operating modes of the system given the wind speed regime, real and reactive load demand, and the frequency and voltage deviation limits.

A frequency control system is then developed and the resulting performance is investigated by simulation using fictitious and real wind data. A simplified linearized system model is analytically investigated in order to gain a qualitative insight in the system's dynamic behaviour and the control requirements. Finally the system's stability is assessed using eigenvalue analysis and the participation matrix technique is applied in order to evaluate the influence of the system parameters to stability.

The study is followed by a similar one in which the induction generator has been replaced by a synchronous generator. The equipment parameters used in this study represent the actual parameters of a test system under construction by Imperial College, Hawker Siddeley Power Plant Ltd, and Rutherford Labs.

The digital computer simulation deals with the two cases of

- (a) the WECS connected to infinite bus &
- (b) autonomous operation of the WECS/diesel system.

For such systems appropriate control policies are developed to ensure stability and quality of supply.

Finally, methods for on-line stochastic identification and adaptive control for WECS are presented. Some predictive and control algorithms are investigated as applied to the WECS/Diesel system under test and the performance of adaptive and fixed-parameter frequency control is compared.

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LIST OF SYMBOLS

A	area
AoA	angle of attack
AVR	automatic voltage regulator
a	factor
b	factor
C	cost, capacitance
C_p	power coefficient
C_q	torque coefficient
Cap	capacitor
CB	circuit breaker
CD	drag coefficient
CL	lift coefficient, controlled load
CM	moment
c	Weibull scale parameter
D	diesel power, frictional loss coefficient
DB	dead band
Dr	droop
d	normalized diesel power
E	EMF
e	economic factor, error sequence
f	frequency, fuel consumption, function
H	inertia time constant
I	current, investment
Im	imaginary part
i	discount rate

J	inertia
K	gain, factor
k	Weibull shape parameter
L	load duration function, load, Laplace operator
LF	load factor
ℓ	normalized load
m	life years, number of machine types, mass
N	power
NPB	net present benefit
n	normalized power
P	real power, cumulative probability
p	probability density, number of poles
Q	reactive power
q	forward time shift operator
r	resistance
Re	real part
RN	Reynolds number
S	torsional stiffness, complex frequency
STA	station
Sw	switch
s	slip
T	time constant, torque
TCR	thyristor controlled rectifier
t	time
V	wind speed, voltage
v	normalized wind speed
W	wind speed

WECS	wind energy conversion system
WG	wind generator
WTG	wind turbine generator
X	impedance
x	reactance
α	firing angle
β	blade pitch angle
Γ	gamma function
γ	non-linearity exponent
Δ	increment operator
δ	impulse function, power angle
ϵ	accuracy, tolerance, error
η	efficiency
θ	mechanical angle, stochastic model parameter vector
λ	tip speed ratio
ρ	air density
σ	standard deviation
ϕ	load angle
ω	rotational speed

Subscripts

A	area
a	armature
act	actuator
app	apparent
b	base
c	cut-in, control, capacitive
cap	capital
cd	conduction
comp	compounding
D	diesel
DG	diesel generator
d	direct axis, damping
dc	direct current
E	exciter
e	electric
exc	excitation
f	field, furling
fd	field
fix	fixed
G	generator
GB	gear box
I	induced, current
IG	induction generator
i	internal
int	integration
inst	installed
L	load

m	maximum, magnetizing, maintenance, mechanical
N	power
nom	nominal
p	peak
q	quadrature axis
R	regulator, rectifier
r	rated, rotor
SG	synchronous generator
s	synchronous, shaft, stator
sat	saturation
sh	shaft
st	stabilizer
T	turbine
tot	total
W	wind, speed, wind turbine
Ø	base, nominal, rated, reference

Superscripts

M	maximum
m	minimum
r	rated
'	transient
"	subtransient
^	estimated
-	phasor, vector, average

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CHAPTER 1

INTRODUCTION

1.1 The development of wind energy conversion systems
 for electricity generation

Since the early days of human civilization, and up to the industrial revolution, wind was the major non-animal source of mechanical power. The invention and development of the steam and later the internal combustion engines and the rapid expansion of the electricity networks, which provided an instantly available and controllable power source, caused the demise of windmills and sailing ships. The few remnants of windmills have become a tourist attraction in the industrial countries and a sign of underdevelopment and retarded technology elsewhere.

The seemingly unlimited amounts of fossil fuel available and the overoptimistic assessment of the future contribution from nuclear power utilization rendered wind energy irrelevant. Nevertheless a few enthusiasts such as Golding and Putnam in the 50's were not discouraged but pursued research (Refs. 1.1, 1.2).

The oil crisis of 1973 and the growing public disquiet of the real or imaginary dangers of nuclear power alerted the scientific community to the fact that development of a modern technology for renewable energy sources was urgently needed. On grounds of familiarity, potential and cost wind power is one of the best options.

The knowledge accumulated on aircraft design gave the impetus to the design of modern high efficiency wind turbines. Although progress has been made recently in all wind power applications

(water pumping, sailing ships), we will be looking in this thesis solely at the use of Wind Energy Conversion Systems (WECS) for electricity generation.

Since 1975 when the first 100kw Mod 0 machine was connected to the local grid near Cleveland, Ohio, several types of WECS, in the power range from 10kw to 3MW, alone or clustered in wind farms, have been constructed and successfully connected to grids in the USA, the Netherlands, Denmark, Sweden, W. Germany, Canada, the U.K. and in other countries (Ref. 1.3).

Recent tax incentives in the USA led to the installation of more than 2000 wind machines in farms, mostly in California, with a total installed capacity of 450 MW (Ref. 1.4)

Although the scale economics seem to favour, in the long term, the development of multi-MW machines (Ref. 1.5), the recent growth, both in size and number, of large single WECS installations, has revealed some shortcomings in the design and operational reliability (material fatigue, control system design, mechanical and electromechanical resonance phenomena) (Ref. 1.6).

Apart from these technical difficulties, there are also at the moment, economic factors to the disadvantage of the very large machines. Firstly, such machines are essentially all prototypes and consequently have enlarged R+D, installation, instrumentation and control, and maintenance costs. Secondly, very large machines have to be connected to a strong grid where they are bound to compete with conventional generation schemes having low generation cost.

At the present state of the technology and with the present electricity generation costs from fossil fuel plants, the most

promising application area for WECS is therefore to be found where the wind power can be supplied from one or several small to medium size WECS, (where proven, low cost machines are already available), into small grids where the generation cost from other sources is relatively high.

These conditions are met in isolated small networks supplied by diesel sets.

1.2 Overview of existing combined wind-diesel generation schemes

Two of the four MOD-OA machines constructed in the US in 1978/79 have been used in an isolated system supplied by diesel sets:

a) Clayton, New Mexico (Ref. 1.7)

The MOD-OA installed in Jan. 1978, rated at 200 kw, is a downwind two-bladed, horizontal-axis, 40 m diameter machine with a rated wind speed of 11 m/s. The output power is limited for wind speed exceeding the related wind speed by blade pitch control. The cut-in wind speed is 4.6 m/s, the furling wind speed 17.6 m/s and rotational speed is 40 rpm.

The WECS synchronous generator is connected through a 480/2400V transformer to a grid supplied by diesel of 400, 1700, 2x1000 and 3x1250 kw rated power. As the power demand of the system varies from 1 MW to 3.3 MW the maximum penetration is 20%.

The addition of the WECS to the system is reported to cause no larger frequency variations than the permitted ± 1 Hz on the nominal 60Hz. The annual fuel cost savings have been estimated to \$11400 based on an average output of 40kw.

b) Block Island (off Rhode Island)(Refs. 1.8, 1.9)

The MOD-OA machine installed in mid-1979 was modified to 150 kw maximum output. Otherwise the specifications were the same as for the Clayton machine.

The diesel plant consists of 7 units with a total capacity of 3615 kw in size from 150 to 1140 kw. Transient measurements during synchronization, shut-down and wind gusts with the WECS connected in parallel to typically two diesel units of 400 and 225kw and wind penetration up to 60% have indicated satisfactory performance, the effect of MOD-OA connection or disconnection being "of about the same magnitude as that produced by normal load fluctuations" whereas a wind gust from 5 to 11 m.s in approx. 3 seconds causes a peak to peak frequency variation of 0.7 Hz on the 60 Hz at a penetration level of about 60%. The fuel savings have been calculated to be 6.7% , while the wind energy contribution is 11%.

c) Cuttyhunk Island (Ref. 1.10)

This system differs from the two above in the important aspect that the wind turbine and the control system have been specifically designed to achieve a 100% penetration on an isolated diesel system. The 26m diameter, 3-bladed, horizontal-axis upwind turbine is designed to operate at 30 rpm and drives a 250kVA synchronous alternator

through a 1:40 transmission. The fixed speed WECS has - unusually - a fixed blade pitch and the speed is regulated during wind or load transients by a controllable 400kw load bank using solid-state thyristor switches.

The WECS is operating with a diesel plant of 455 kW total capacity with 6 sets ranging from 30 to 175 kw. The start-up, shut-down, synchronization, speed and voltage regulation are controlled through a central microprocessor operating hardware subsystems.

The performance of the system has been reported to be very good in winds up to 12 m/s degrading above that level. Worst case accuracy of $\pm 0.7\text{Hz}$ is required in stand-alone operation mode. Phenomena of loss of synchronism for wind speeds above 12 m/s and penetration above 20% are hinted at in the reference report.

The wind energy production is estimated to exceed the energy demand for 8 months of the year.

d) The Ireland project (Ref. 1.11)

A Windmatic 3-blade, fixed pitch, fixed speed machine with a rated output of 63 kw at 11.8 m/s wind speed has been installed on one of the Aran Islands.

The WECS is to operate in conjunction with a 45kw diesel set, backed up by a 10kw diesel set. The frequency here is also regulated through a controllable load bank.

The control system does not provide for parallel operation of WECS and the 45kw diesel, so operation is limited to an either/or mode according to wind and load conditions.

Early reports on the system efficiency show it to be

rather low.

e) The Canadian experiment at Sudbury, Ontario

The prototype plant consists of a 100kw vertical axis Darrieus type wind turbine coupled *mechanically* to one of two identical 50kw diesel units by means of an overrunning clutch. The alternator coupled to the WECS runs continuously, while WECS and the second diesel set are brought in according to wind power available and load demand.

A variable resistive load is provided to absorb excess wind power and to maintain minimum diesel loading. The variable load is regulated through a VARIAC.

Frequency fluctuations are within $\pm 2\text{Hz}$ during highly fluctuating winds. Availability of more than 86% has been achieved for the WECS during the first 4840 test hours, with the WECS generating for 1418 hours. It is expected that the turbine will have a pay back period of 4-8 years for wind speeds above 7 m/s and fuel cost between 40 and 60 ¢/litre.

Two systems with somehow special features have been developed in Holland (Ref. 1.12)

f) The Eindhoven System

Development at the Eindhoven University this system comprises a variable speed wind turbine with a synchronous generator and AC/DC/AC converter system to supply power at the nominal frequency, a diesel set and a thyristor controlled variable load.

The diesel engine is connected to the diesel generator through an electromagnetic clutch so that when diesel power is not needed the diesel generator is running as synchronous capacitor for voltage maintenance purposes. The application of the AC/DC/AC conversion allows the wind turbine output to be maximized at all operating wind speeds. Tests results of the system are not yet available.

g) The Goppel System

In this system the only synchronous generator can be driven either by the wind turbine or the diesel engine or both in parallel. The wind turbine is a variable speed machine coupled to the generator through an infinitely variable speed mechanical interface which maintains the synchronous speed at the generator shaft while the wind turbine speed varies, to allow output maximization under varying wind speeds. The diesel engine is coupled to the generator shaft through an electromagnetic clutch which is operated according to the balance between wind power supply and load demand.

It is understood that the development of this system is not pursued further because early tests have shown a very low conversion efficiency due to high losses in the mechanical speed changer.

In the U.K. two systems have been operated successfully on Fair Isle and Lundy Island.

h) The Fair Isle system (Ref. 1.13)

A 3-bladed, Windmatic turbine with a rated wind speed of 13 m/s is driving a 60 kw synchronous generator. The WECS is

supplying a separate distribution network parallel to the old one which was and is supplied by a two-set diesel plant (50 and 20kw). Surplus wind energy is used for controllable heating loads at each consumer switched according to the amount of available power in a sequential priority order. Frequency is maintained additionally by a controllable resistive dump load.

The WECS and diesel sets are not allowed to operate synchronously although they can operate simultaneously through the two parallel networks when needed. Apart from minor mechanical parts failures the system has been operated successfully for more than two years. The electricity supply availability has been doubled and the consumption increased by more than 2.5 times while the unit cost is 4.18p/kwh.

i) The Lundy Island system (Ref. 1.14)

This system is virtually similar to (h) above, with a Windmatic 55kw WECS operating alternatively with a diesel power plant. Here, also, very good performance of the system has been reported for the first 100 days of operation.

h) The Napier College scheme (Ref. 1.15)

In this scheme, which is believed to be in the laboratory stage, the wind generator is a slip ring induction generator and the rotor slip power is recovered and fed to the grid through an AC/DC/AC converter. The rotor slip is controlled by the firing angle of the line commutated DC/AC inverter and this serves to control the slip. In this way the generator can be run at optimal speed for

a given wind speed in a range of 100 to 200% of the synchronous speed. Excess wind power is dumped to a controllable load.

The diesel engine can be declutched from the synchronous diesel generator, which then acts as synchronous capacitor for voltage maintenance. Field test results have not yet appeared in the literature.

Other schemes with varying configuration of electrical/mechanical coupling between diesel and wind generator and various intermediate storage media have been developed by Dornier in Germany (Ref. 1.16), by Tema in Italy (Ref. 1.17) and at Reading University (Ref. 1.18). As far as it is known these schemes are still at the laboratory stage.

i) Kythnos project (Ref. 1.19)

The first WECS cluster operating in a small autonomous grid has been taken into operation in July 1982 on the Greek Island of Kythnos.

The system involves 5×20 kw variable pitch two-bladed downwind Aeroman machines fitted with induction generators. They are connected in parallel to the existing diesel power plant with 2×150 and 2×530 kw sets.

Although test results are not yet available, it is understood that over the first year the system performed satisfactory, without major technical failures. The fuel savings have been much as expected, indicating an investment pay back period of 7-9 years.

Further details on this scheme can be found in Sec. 2.4.4.

j) The RAL/IC/HSPP project (Ref. 1.20)

A WECS/diesel combined system is under development at the Rutherford Appleton Laboratory (RAL) in an industry cooperative project founded by SERC and Hawker Siddley Power Plant Ltd (HSPP). The research is pursued by RAL and Imperial College (IC) and aims at the development of a fully integrated autonomous system for isolated operation.

This system will be extensively described in Chapter 4 of this thesis.

The above review of wind/diesel schemes reveals a great variety of types of machines involved, configurations and control strategies. It is not possible to evaluate definitively the merits and demerits and the future prospects of these schemes, as the relative value of the special features of each one depends very much on factors determined by the concrete applications. Some of the important factors are :

- a) The correlation between load demand and wind speed for a particular site.
- b) The fuel cost.
- c) The amortisation rate required for the investment.
- d) The cost of the system components.
- e) The maintainance requirements and facilities available.
- f) The requirements on frequency and voltage maintenance.
- g) The harmonic distortion allowable.
- h) The features of the diesel set(s) possibly already installed.

From the limited experience gained from commercially operated systems it can be concluded that the dynamic stability problems are solvable and that the integration of wind power is likely to be economic for reasonable wind regimes (over 6 m/s mean annual wind speed) and relatively high diesel generation costs.

The degree of wind power utilization is decisive, and this depends on WECS availability and maximum level of wind power penetration allowable. The former is a matter of design and construction of the WECS components and is continuously improving through evolution. The latter is a matter of control system design and policy.

1.3 The wind power penetration level and associated problems

The research associated with the design and control of integrated wind/diesel systems, like number, size and capacity of the machines, energy storage medium if any, load and generation control, is intimately related to the problem of supplying a varying source, with high capital cost and zero fuel cost (the WECS) complemented by a source with exactly opposite characteristics (the diesel).

A thorough investigation of an example case is presented in Ref. 1.21. A comprehensive study of the long term logistic problems is given in Ref. 1.22.

The energy storage media in this context are reviewed in technical and economic terms in Refs. 1.23, 1.24

Problems associated with minimum diesel load and/or run

time effects on number of diesel start-ups and overall system efficiency are discussed in Ref. 1.25. All researchers agree that the level of wind power penetration allowable (ratio of WECS output power to load demand) is crucial for the sizing of the components and the economics of the integrated system.

From the research done so far it seems that the economics of active storage are not favourable for conventional methods (batteries, flywheels) for energy reserves corresponding to more than about 1 hour of system power output (long term wind regime variations) while a short term storage (seconds to minutes) can substantially reduce the number of required diesel start-ups and improve the economics and the quality of supply.

Virtually no research has been conducted until now on the aspect of load demand control although some forms have been practically implemented in integrated systems with very satisfactory results, namely on the Fair Isle and Lundy Island .

1.4 Aim of research work

The general aim of this work was to investigate the dynamics of integrated wind/diesel systems, to suggest suitable control schemes and to assess in terms of stability and quality of power supply the effects of a 100% wind penetration on such systems.

As the economic implications of the wind power penetration level have not yet been dealt for an economic assessment has been developed.

1.5 Thesis overview

A general statistical method for WECS optimal sizing and economic efficiency assessment taking into account the wind and load demand statistics, the economic factors and the level of wind penetration is outlined in *Chapter 2*. The implications and limitations of the method are discussed. The method is used to assess the exploitable wind power potential on all Greek islands not interconnected to the mainland grid and supplied by diesel plants.

The dynamics of an integrated system with equally sized diesel set and wind turbine driving an induction generator are investigated in *Chapter 3*. A steady state wind power maximization algorithm is developed and the optimal system performance characteristics outlined. A control scheme for frequency control is proposed. The response of the system to wind and load disturbances in parallel operation and WECS stand-alone operation is presented and discussed. Finally the participation matrix technique is implemented to supplement the system eigenvalue analysis for representative operating conditions.

In *Chapter 4* the system with a diesel set and a wind turbine with a synchronous multiple generator as installed and tested at RAL is described.

The techniques and results of the system parameter identification are outlined and discussed.

Simulation results of the system response are presented for representative operating conditions and disturbances and compared with the measured system behaviour.

In *Chapter 5* aspects of adaptive control applications on wind/diesel systems are presented and identification and prediction algorithms developed and discussed.

Finally in *Chapter 6* general conclusions are drawn, the original contributions claimed by the author are described and suggestions for further work made.

The literature relevant on the topic of each chapter is reviewed concisely in the Chapter introduction.

CHAPTER 2

A STATISTICAL METHOD FOR OPTIMIZING WIND POWER CONTRIBUTION IN SMALL ISOLATED NETWORKS SUPPLIED BY DIESEL SETS

2.1 Introduction

The optimum level of wind power capacity in a small isolated power network depends on the following factors.

- a. The local wind regime.
- b. The local load demand profile.
- c. Economic factors determining the operational and capital cost for diesel and wind machines
- d. Security of supply (dynamic stability, steady-state loss of load probability).

The last factor is very important because it determines an upper limit on the permitted amount of wind power penetration. However, it cannot be handled in a general way as it depends on the network structure and the dynamic characteristics of the diesel, the WECS and the load. One way to circumvent this methodological hurdle is to assume that a fraction of the diesel power is running continuously, and/or some kind of energy storage is available so that the fluctuation in the wind can always be handled by this reserve.

The methods that have been used for general optimization can be divided into two categories:

- a. Maximization of wind energy output according to wind statistics only (Ref. 2.1, 2.2).
- b. Maximization of economic benefit or diesel fuel savings using typical wind and load demand data compiled from corresponding

historical data for a particular case (Ref. 2.3, 2.4)

Method (a) is strictly valid when the installed wind power is less than the base load demand (i.e. when the available wind power can always be fully utilized) and the capital and operational costs for the wind machines are fixed or negligible when compared with the fuel savings. Both these assumptions are, in practice, unrealistic.

Method (b) when based on typical daily wind speed and load demand profiles depends absolutely on the "typicality" of these curves. The validity of such studies would be most credible if extended over a yearly period, however, the computational effort involved in this would be considerable.

The method proposed in this thesis considers only statistical parameters of the wind and load demand distributions and the relevant economic factors. It provides a first estimation of the real wind power potential in economic terms and the approximate optimal power and wind speed rating of the wind machines.

2.2 The statistics of wind power and load demand

2.2.1 The wind speed statistics

It has been established (Ref. 2.5, 2.6) that the wind speed probability density distribution $p_V(V)$ can be well approximated by the Weibull distribution

$$p_V(V) = \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^k\right] \quad (2.1)$$

where k , c are the Weibull distribution parameters and V is the wind speed

having a mean value

$$\bar{V} = c \cdot \Gamma(1 + \frac{1}{k}) \quad (2.2)$$

and variance

$$\sigma^2 = c^2 \cdot \{ \Gamma(1 + \frac{2}{k}) - [\Gamma(1 + \frac{1}{k})]^2 \} \quad (2.3)$$

where $\Gamma(x)$ is the Gamma function defined by

$$\Gamma(x) = \int_0^{\infty} e^{-t} t^{x-1} dt. \quad (2.4)$$

The cumulative probability function is

$$P_V(V) = \int_0^V p_V(V) dV = 1 - \exp \left\{ - \left(\frac{V}{c} \right)^k \right\}. \quad (2.5)$$

2.2.2 The wind turbine power output statistics

Under steady state conditions, the wind turbine power output is uniquely determined by the wind speed:

$$N = f(V). \quad (2.6)$$

The function $f(V)$ (power output vs wind speed characteristic of the wind turbine) has the following properties:

- a) $f(V) = 0$ for $V \leq V_c$
- b) $\frac{df}{dV} > 0$ for $V_c < V < V_r$
- c) $f(V_r) = N_r$ (2.7)
- d) $\frac{df}{dV} \leq 0$, $f(V) > 0$ for $V_r \leq V < V_f$
- e) $f(V) = 0$ for $V \geq V_f$

where

V_c = cut-in wind speed

V_r = rated wind speed

V_f = furling wind speed

N_r = rated power output.

For the region where $\frac{df(V)}{dV} > 0$ (characteristic monotonically increasing) the power output probability density function is

$$p_N(N) = \frac{dV}{dN} \cdot p_V(V) = \left(\frac{df}{dV} \right)^{-1} \cdot p_V[V(N)]. \quad (2.8)$$

For $V < V_c$ and $V > V_f$ it is

$$p_N(N) = \left(\int_0^{V_c} p_V(V) dV + \int_{V_f}^{\infty} p_V(V) dV \right) \delta(N) \quad (2.9)$$

where $\delta(x)$ is defined by

$$\int_{-\infty}^{+\infty} y(t) \delta(x-t) dt = y(x) \quad \text{for any } y(t), x. \quad (2.10)$$

A similar expression to Eqn. 2.8 can be developed for the part of the characteristic with $\frac{df}{dV} < 0$ (monotonically decreasing). To simplify matters and because most of the turbines with active blade pitch control have a constant power limitation for wind speeds exceeding the rated wind speed we will assume :

$$N = f(V) = N_r \quad \text{for } V_r \leq V < V_f. \quad (2.11)$$

Then the probability density function for the power output over

wind speed range defined in Eqn. 2.11

$$p_N(N) = \left[\int_{V_r}^{V_f} p_V(V) dV \right] \cdot \delta(N - N_r) \quad (2.12)$$

From the expressions Eqns. 2.6 - 2.12 and using eqns. 2.1 and 2.5 the probability density function for the power output over the whole range is given by

$$\begin{aligned} p_N(N) = & 1 \left[\exp \left[- \left(\frac{V_c}{c} \right)^k \right] + \exp \left[- \left(\frac{V_f}{c} \right)^k \right] \right] \delta(N) + \\ & + \left[\exp \left[- \left(\frac{V_r}{c} \right)^k \right] - \exp \left[- \left(\frac{V_f}{c} \right)^k \right] \right] \delta(N - N_r) + \\ & + \frac{k}{c} \left(\frac{V(N)}{c} \right)^{k-1} \exp \left[- \left(\frac{V(N)}{c} \right)^k \right] \frac{dV}{dN} \end{aligned} \quad (2.13)$$

$$\text{with } V(0) = V_c, \quad \left. \frac{dV}{dN} \right|_{N=0} = \left. \frac{dV}{dN} \right|_{V=V_c^+}, \quad \left. \frac{dV}{dN} \right|_{N=N_r} = \left. \frac{dV}{dN} \right|_{V=V_r^-}$$

$$\text{for } 0 \leq N \leq N_r$$

and

$$p_N(N) = 0 \quad \text{otherwise.}$$

2.2.3 The load demand statistics

Given a load duration curve $L(t)$ for the time period T with peak load $L_p = L(0)$ and base load $L_b = L(T)$ (Fig 2.2), the load demand probability density function is defined as

$$p_L(\ell) = - \left(\frac{dL(t)}{dt} \right)^{-1} \quad \text{for } L_b \leq \ell \leq L_p$$

$$p_L(\ell) = 0 \quad \text{otherwise.}$$
(2.14)

The load factor LF is then defined as

$$LF = \frac{1}{L_p} \int_{L_b}^{L_p} p_L(\ell) \cdot \ell \cdot d\ell .$$
(2.15)

2.2.4 The diesel power constraints

In order to take into account security of supply, two constraints are assumed for the diesel power D:

$$D_{\max} \geq L_p$$
(2.16)

meaning that there is always enough diesel power to meet the peak load when the wind power contribution is zero, and

$$0 < D_{\min} \leq D$$
(2.17)

meaning that at least one diesel set is running at least at its minimum power to ensure continuity of supply in the case of sudden wind changes.

2.2.5 Approximation of the wind turbine steady state performance characteristic

In the following the wind turbine characteristic will be assumed linear for $V_0 \leq V \leq V_r$ and constant for $V_r \leq V \leq V_f$ i.e.

$$\begin{aligned}
N &= \frac{V - V_c}{V_r - V_c} N_r & V_c \leq V \leq V_r \\
N &= N_r & V_r \leq V \leq V_f \\
N &= 0 & \text{otherwise.}
\end{aligned} \tag{2.18}$$

It will also be assumed that

$$\begin{aligned}
V_c &= a_c V_r \\
V_f &= a_f V_r
\end{aligned} \tag{2.19}$$

with a_c , a_f constant factors.

Both assumptions are justified by the actual performance characteristics of most WECS especially those operating at fixed speed. (Ref. 2.19, 2.21, 2.22, 2.23, 2.24).

Commonly $0.3 < a_c < 0.5$ and $2 < a_f < 3$.

Variations of a_c and a_f in this range do not affect substantially the energy capture for wind regimes with Weibull factor $1.5 \leq k \leq 2.5$ i.e. the cases worth considering for electricity generation WECS. With these assumptions the power output probability density function Eqn. 2.13 can be transformed to

$$\begin{aligned}
p_N(N) &= P_{N0} \delta(N) + P_{Nr} \delta(N - N_r) + (1 - a_c) \frac{V_r}{N_r} p_V[V(N)] \quad \text{for } 0 \leq N \leq N_r \\
p_N(N) &= 0 \quad \text{otherwise}
\end{aligned} \tag{2.20}$$

where

$$P_{N0} = 1 - \exp \left[- a_c^k \left(\frac{V_r}{c} \right)^k \right] + \exp \left[- a_f^k \left(\frac{V_r}{c} \right)^k \right] \tag{2.21}$$

and

$$P_{Nr} = \exp \left[- \left(\frac{V_r}{c} \right)^k \right] - \exp \left[- a_f^k \left(\frac{V_r}{c} \right)^k \right] .$$

2.2.6 Approximation of the load demand probability density distribution

A general model for the load demand probability distribution or, for that matter, the load duration curve, for small autonomous networks was impossible to obtain.

As will be shown later, the actual shape of the annual load duration curve, within reasonable limits, does not have a significant influence on the wind power optimal allocation (Ref. 2.20). In general, actual hourly statistics of the load demand in small autonomous networks, if kept at all, are not statistically processed but only collected in order to produce the peak load and the load factor - the usual parameters of interest to utilities.

It was therefore decided to base the model adopted for the load demand probability distribution on those two parameters only.

The models have been considered :

(a) Uniform distribution (Fig. 2.1)

This is described by the probability density function

$$p_L(L) = P_b \cdot \delta(L - L_b) + p_0 \quad \text{for } L_b \leq L \leq L_p$$
(2.22)

$$P_L(L) = 0 \quad \text{otherwise}$$

where L_b the base and L_p the peak load.

In order to fulfill the requirements

$$\int_{-\infty}^{+\infty} p_L(x) dx = 1$$

and

$$\int_{-\infty}^{+\infty} xp_L(x) dx = LF$$

(2.23)

where LF is the given load factor, the parameters in Eqn. 2.22 must satisfy the following :

$$1. \quad \text{For } LF \leq 0.5 \quad L_b = 0$$

$$P_b = 1 - 2 LF$$

$$P_0 = \frac{2 LF}{L_p}$$

$$2. \quad \text{For } 0.5 < LF < 1 \quad L_b = (2 LF - 1) \cdot L_p \quad (2.24)$$

$$P_b = 0$$

$$P_0 = \frac{0.5}{(1 - LF) \cdot L_p}$$

$$3. \quad \text{For } LF = 1 \quad L_b = L_p$$

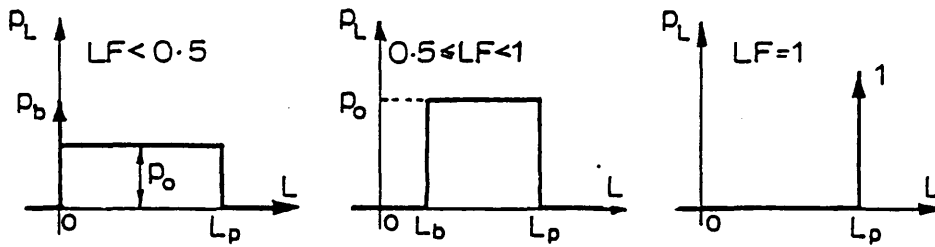
$$P_b = 1$$

$$P_0 = 0$$

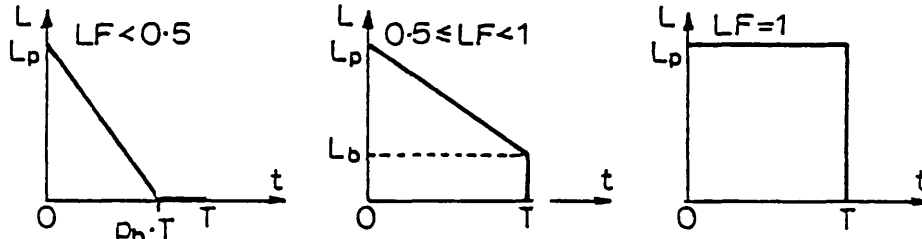
(b) Triangular distribution (Fig. 2.2)

This is described by the probability density function

$$\begin{aligned}
 p_L(L) &= (1 - 3 LF) \delta(L) + \left(1 - \frac{L}{L_p}\right) \cdot \frac{6 LF}{L_p} \quad \text{for } LF < \frac{1}{3} \text{ and } 0 \leq L \leq L_p \\
 &= \frac{2}{L_p} \cdot \frac{L/L_p}{3 LF - 1} \quad \text{for } \frac{1}{3} < LF < \frac{2}{3} \text{ and } 0 \leq L \leq L_m \\
 &= \frac{2}{L_p} \cdot \frac{1 - L/L_p}{2 - 3 LF} \quad \text{for } \frac{1}{3} < LF < \frac{2}{3} \text{ and } L_m < L \leq L_p \\
 &= \frac{2}{L_p} \cdot \frac{L/L_p + 2 - 3 LF}{9(1 - LF)^2} \quad \text{for } \frac{2}{3} < LF < 1 \text{ and } L_b \leq L \leq L_p \\
 &= \delta(L - L_p) \quad \text{for } LF = 1 \\
 &= 0 \quad \text{otherwise}
 \end{aligned} \quad (2.25)$$

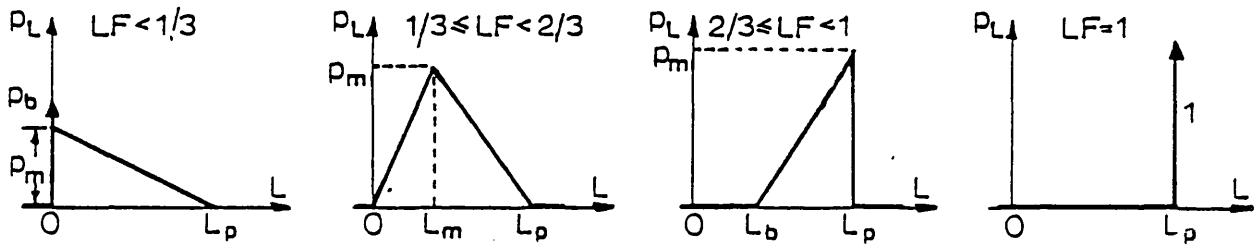


Load demand probability density function

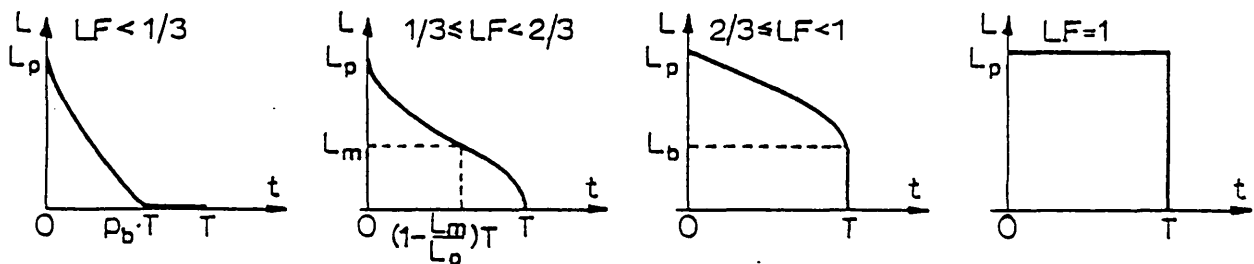


Load demand duration curve

Fig. 2-1 Uniform load demand probability distribution



Load demand probability density function



Load demand duration curve

Fig. 2-2 Triangular load demand probability distribution

where

$$L_b = (3 LF - 2) \cdot L_p \quad (2.26)$$

$$L_m = (3 LF - 1) L_p.$$

2.3 The economic optimization problem

2.3.1 The fuel consumption of the combined system

The problem can be more conveniently formulated using non-dimensional (per unit) quantities. For that matter we define as base power the peak load demand and as base wind speed the Weibull scale parameter c . We introduce then the new variables (measured in p.u.):

$$\begin{aligned} v &= V/c \\ n &= N/L_p \\ \ell &= L/L_p \\ d &= D/L_p \end{aligned} \quad (2.27)$$

all other quantities introduced previously are also expressed in p.u. using low case letters. The formulae for the probability density functions in terms of the new variable are immediately derived from Eqns. 2.20 and 2.22 or 2.25 :

$$\begin{aligned} p_n(n) &= P_{n0} \delta(n) + P_{nr} \delta(n - n_r) + (1 - a_c) \frac{v_r}{n_r} p_v[v(n)] \\ &\quad \text{for } 0 \leq n \leq n_r \\ &= 0 \quad \text{otherwise} \end{aligned} \quad (2.28)$$

where

$$P_{n0} = 1 - \exp[-(a_c v_r)^k] + \exp[-(a_f v_r)^k] \quad (2.29)$$

$$P_{nr} = \exp(-v_r^k) - \exp[-(a_f v_r)^k]$$

and

$$\begin{aligned} p_\ell(\ell) &= P_b \delta(\ell - \ell_b) + p_{\ell_c}(\ell) & \text{for } \ell_b \leq \ell \leq 1 \\ &= 0 & \text{otherwise.} \end{aligned} \quad (2.30)$$

For a given demand ℓ and wind power total output n , the required diesel output is

$$d(\ell, n) = \text{Max}\{\ell - n, d_{\min}\} \triangleq M(\ell, n) \quad (2.31)$$

where

$$\begin{aligned} \text{Max}(x, y) &= x & \text{if } x \geq y \\ &= y & \text{otherwise.} \end{aligned} \quad (2.32)$$

The average diesel output is then :

$$\bar{d} = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} d(\ell, n) p_{\ell v}(\ell, v) d\ell dv \quad (2.33)$$

where $p_{\ell v}(\ell, v)$ is the joint probability density function for load demand ℓ and wind speed v .

Assuming now a *diesel power station* fuel consumption versus power output characteristic $\phi(d)$, the average diesel fuel consumption will be

$$\bar{f} = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \phi[d(\ell, n)] \cdot p_{\ell v}(\ell, v) d\ell dv \quad (2.34)$$

2.3.2 The capital and operational cost of wind turbines

The price of small to medium (10-30m rotor diameter) wind turbines is with good approximation proportional to the rotor swept area (Ref. 27, 28).

The investment is then

$$I = C_A \cdot A \quad (2.35)$$

where A the rotor swept area and C_A the price per m^2 .

For a machine with rated power N_r at rated wind speed V_r the rotor swept area is

$$A = \frac{N_r}{(0.5\rho C_{pr} V_r^3) \cdot \eta_r} \quad (2.36)$$

where

ρ : the air density, C_{pr} : the power coefficient at rated wind speed, and η_r : the electromechanical conversion efficiency at rated power.

Or, through Eqn. 2.27

$$A = \frac{L_p}{\eta_r \cdot (0.5\rho C_{pr} \cdot c^3)} \cdot \frac{n_r}{v_r} \quad (2.37)$$

Assuming a discount rate i and a WECS expected life of m years, the capital cost per annum C_{cap} for the investment I will be (in fixed prices)

$$C_{cap} = \frac{i(1+i)^{m-1}}{(1+i)^m - 1} \cdot I \hat{=} r \cdot I, \quad (2.38)$$

Assuming also as usual that the operation and maintenance cost

per annum C_m , is a fixed proportion of the total investment

$$C_m = c_m \cdot I \quad (2.39)$$

the total fixed cost per annum for the machine is

$$C_{\text{fix}} = q \cdot \frac{L}{c} \cdot \frac{p}{3} \cdot \frac{n_r}{v_r} \quad (2.40)$$

where

$$q = \frac{r + c_m}{0.5 \cdot \rho \cdot C_{pr} \cdot \eta_r} \quad (2.41)$$

2.3.3 The general formulation of the optimization problem

In the general case if machines of more than one design say on m types, were to be installed, we can construct a composite wind power versus wind speed characteristic

$$n_{\text{tot}}(v) = f(\underline{v}, \underline{n_r}, \underline{v_r}) + n_{\text{inst}}(v) \quad (2.42)$$

where $\underline{n_r}$, $\underline{v_r}$ are m -dimensional vectors and $n_{\text{inst}}(v)$ the composite characteristic of machines already installed.

The total annual fixed costs for the machines to be installed will also be a function of $\underline{n_r}$, $\underline{v_r}$ (simply the addition of the cost for each machine as given in Eqn. 2.40)

$$C_{\text{tot}} = g(\underline{n_r}, \underline{v_r}) = \sum_{i=1}^m C_{\text{fix } i} \quad (2.43)$$

We can formulate then the 2m-parametric minimization problem for the total annual costs C

$$C(\underline{n_r}, \underline{v_r}) = c_{f,1t} \cdot \bar{f} + C_{tot} \stackrel{!}{=} \underset{\underline{n_r}, \underline{v_r}}{\text{Min}} \quad (2.44)$$

where $c_{f,1t}$: the diesel fuel price per unit volume and $\bar{f}$: is given by Eqn. 2.34.

In the case where the load demand and the wind speed are correlated the joint probability density function $p_{\ell v}(\ell, v)$ cannot be calculated from the probability functions $p_{\ell}(\ell)$ and $p_v(v)$ and must be given directly or through a cross-correlation coefficient $c_{cr}(\ell, v)$.

It can be stated now with some justification that although the general case does not present any unsurmountable conceptual or analytical difficulties, the amount of data required and the numerical difficulties involved justify some simplifying assumptions. This is particularly so when the problem dimensionality m is itself subject to optimization and as in general, the cost function evaluation includes calculation of multiple integrals for each point of the parametric space.

2.3.4 Simplifying assumptions and formulation of the simplified optimization procedure

1. The load demand and the wind speed are not correlated

There are indications that this assumption is well justified for extended systems (Ref. 2.9). For small systems, however, knowledge of the load demand and wind speed diurnal and seasonal profiles are required to justify the assumption. As the method presented here is intended as a first assessment of the wind potential at several sites

in order to select the promising ones and to initiate detailed measuring programs, the assumption is well justified. The simplified formula for the joint probability in Eqn. 2.33 therefore becomes :

$$p_{\ell v}(\ell, v) = p_{\ell}(\ell) \cdot p_v(v) \quad (2.45)$$

2. There are no wind machines already installed in the system
3. The machines to be installed are all of the same type

This is likely to represent a worst case assumption, as machine design diversification can produce an increased wind power availability leading towards higher fuel savings.

4. The average efficiency of the diesel power station is constant and independent of the average diesel power output

This is obviously not true in the case of a single diesel machine. Usually island power stations have at least three diesel machines, one unit being the reserve. It is taken for granted that the introduction of wind power is accomplished by a control system which ensures that the diesel power station operates at optimal efficiency (machine cycling, unit power diversification).

In this case Eqn. 2.34 can be written

$$\bar{f} = e_d \cdot \bar{d} \quad (2.46)$$

with e_d : constant.

The simplified optimization problem can now be formulated :

The average p.u. diesel power for the diesel/WECS system will be

$$\bar{d} = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} d(\ell, n) p_{\ell}(\ell) p_v(v) d\ell dv \quad (2.47)$$

or using Eqns. 2.28, 2.29, 2.30 and 2.31

$$\begin{aligned}
 \bar{d} = & P_{ro} \cdot [P_b M(1_b) + \int_{\ell_b}^1 M(\ell) p_{\ell c}(\ell) d\ell] + \\
 & + P_{nr} \cdot [P_b M(1_b - n_r) + \int_{\ell}^1 M(\ell - n_r) p_{\ell c}(\ell) d\ell] + \\
 & + P_b \cdot \int_0^{nr} M(1_b - n) p_{nc}(n) dn + \\
 & + \int_0^{nr} \int_b^1 M(\ell - n) p_{nc}(n) p_{\ell c}(\ell) d\ell dn
 \end{aligned} \tag{2.48}$$

where the function

$$\begin{aligned}
 p_{nc}(n) &= (1 - a_c) \frac{v_r}{n_r} p_v[v(n)] & v_c \leq v \leq v_r \\
 &= 0 & \text{otherwise}
 \end{aligned} \tag{2.49}$$

has been introduced to shorten the expression.

Taking into account Eqns. 2.46 and 2.40, the total annual costs for the combined system are given from eqn. 2.44

$$C(n_r, v_r) = c_{f,kwh} \cdot L_p \cdot \bar{d} \cdot T + q \cdot \frac{L_p}{c^{\frac{1}{3}}} \cdot \frac{n_r}{v_r^{\frac{1}{3}}} \tag{2.50}$$

where

$$c_{f,kwh} = \frac{C_{f,1t} \cdot e_d}{L_p \cdot T} \tag{2.51}$$

is the average fuel cost per kwh and $T = 8600$ h/a.

The minimization problem

$$C(n_r, v_r) \stackrel{!}{=} \min_{n_r, v_r} \tag{2.52}$$

is now obviously equivalent to

$$F(n_r, v_r) = \bar{d}(n_r, v_r) + \frac{e}{c} \frac{n_r}{v_r^3} \stackrel{!}{=} \text{Min}_{n_r, v_r} \quad (2.53)$$

where

$$e = \frac{q}{c_{f,kwh} \cdot 8600} \quad (2.54)$$

is a constant factor depending only on economic parameters of the combined system.

The net present benefit over the m life years is then

$$NPB = m \cdot L_p \cdot c_{f,kwh} \cdot (LF - F_{\min}(n_r, v_r)) \quad (2.55)$$

and the cost/benefit break even condition (marginal profitability) occurs when

$$F_{\min}(n_r, v_r) = LF \quad (2.56)$$

2.4 Program description and application

2.4.1 Program description

The program OPTWIND consists of four parts

(a) Data input and normalization

The following constants are read from a data file

- Air density (ρ) in kgm^{-3}
- Power coefficient at rated wind speed (C_{pr})
- WECS efficiency at rated power (η_r)
- Relative cut-in wind speed (V_c/V_r)
- Relative furling wind speed (V_f/V_r)
- Hub height (h) in m
- Specific turbine price (c_A) in £/m^2
- Maintenance costs (c_m) in %/a
- Discount rate (i) in %/a
- Life years (m)
- Peak load (L_p) in kw
- Load factor (LF) in %
- Minimum diesel loading (D_{min}) in kw
- Specific fuel cost ($c_{f,kwh}$) in p/kwh
- Annual aver.wind speed ($\bar{V}$) in m/s
- Weibull shape factor (k)

Using this data the annual capital service costs r (Eqn. 2.38) and overall economic factor e (Eqns. 2.41, 2.54) are calculated. From $\bar{V}$ and k the Weibull parameter c is calculated using a Gamma function routine and normalized to 10m hub height using the usual 1/7 exponent law. (see for instance Ref. 2.7).

b) Load demand statistics routine

The routine calculates shape parameters for a particular

distribution to fit the residual load distribution given the load factor, the peak load demand and the minimum diesel power. These parameters are used in a function routine PROBL to calculate the probability density function value for a load L .

These routines have to be supplied by the user. In the applications which follow later the distribution described in 2.2.6 have been used.

c) Optimization routine

The routine is used to solve the minimization described by Eqn. 2.53.

It uses a quadrature routine and a double quadrature routine for the calculation of the integrals involved in Eqn. 2.48 and the function routines for the calculation of the load demand and wind power output probabilities in the formula.

In the applications presented the Gauss-Legendre formula with 256 points has been used for the simple quadrature (Ref. 2.10) and an iterative procedure using the above formula with point number doubling to a desired accuracy for the inner and the outer integral is used for the double integral evaluation (Ref. 2.11).

The optimization routine itself is a Box "complex" algorithm (Ref. 2.12), with the number of vertices and initial points supplied by the user.

The routine converges when either the "complex" polygon has been reduced beyond a specified limit or when the maximum and the minimum function value on the polygon differ less than a specified accuracy.

The routine exits then with the located optimal point, the target function value for this point and the minimum and maximum value of the parameters on the final "complex" polygon (the latter are an indication of the "flatness" of the function surface near the optimal point).

A logical parameter enables the user to follow, if he wishes, the

stages of the optimization convergence.

(d) Optimized system parameter output

Finally the program outputs a list of the constants used as described in part a, the optimal rated wind speed and rated power, the fuel savings and the net savings in % of the fuel cost of the system without WECS, and finally the pay-back period.

2.4.2 The influence of statistical parameters on the net savings

In order to investigate the influence of the given statistical parameters of (a) wind speed (b) the load demand distributions and (c) the maximum allowable wind power penetration on the net savings and on the optimal design parameters, the program has been run for the range of parameters given in Table 2.4.2.1. This represents a total of 2100 cases

Table 2.4.2.1

Parameter	Symbol	Range							unit
Economic factor	e	100	200	300	400				(m/s) ³
Annual aver. wind speed	$\bar{V}$	4	5	6	7	8	9	10	m/s
Weibull shape factor	k	1.5	2.0	2.5					
Load factor	LF	0.2	0.3	0.4	0.5	0.6			
Max. allowable penetration	$i-D_{\min}$	100	95	90	85	80			%
Accuracy	ϵ	0.001							

The average run time on the CDC-Cyber 174 is around 0.5 sec per case.

Representative parts of the tables produced are given in the Appendix 2.1

The comparison between triangular and uniform load distribution shows a rather close agreement in savings (Fig. 2.3a). The divergence becomes smaller for increasing load factors and decreasing maximum allowable penetration. The assumption of triangular load demand distribution is in all cases, except for low load factors (<0.3), low penetrations ($<80\%$) and low wind speeds (<8 m/s), slightly more favourable.

In Figs. 2.3b and 2.3c the calculated optimal values for rated WECS output power and rated wind speed are shown for a *typical* case together with the upper and lower limit of the optimal "region" defined as the one with net savings within 0.001 from the optimal.

In relation to these figures some general comments can be made.

- a) In Fig. 2.3b we see that the net savings function surface is very flat around optimum point in the rated power output dimension, i.e. rather large variations in installed WECS power around the calculated optimal point do not affect the net present benefit significantly.
- b) The same function on the other hand (Fig. 2.3c) is rather sharp around the optimum point in the rated wind speed dimension, i.e. the profitability of the WECS installation is much more influenced by the accuracy of the calculated annual average wind speed and its accurate matching to the design rated wind speed of the WECS.
- c) The optimal regions for triangular and uniform load distribution match well, especially for significant NPB's (above 10%)

Considering that the shape of the load demand distribution has little influence on the results of the optimisation for credible case studies, the more realistic triangular distribution will be adopted for the studies that follow.

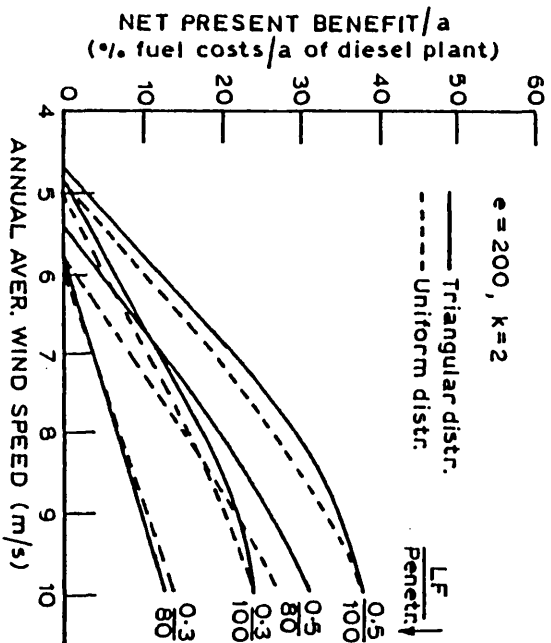


Fig. 2.3a

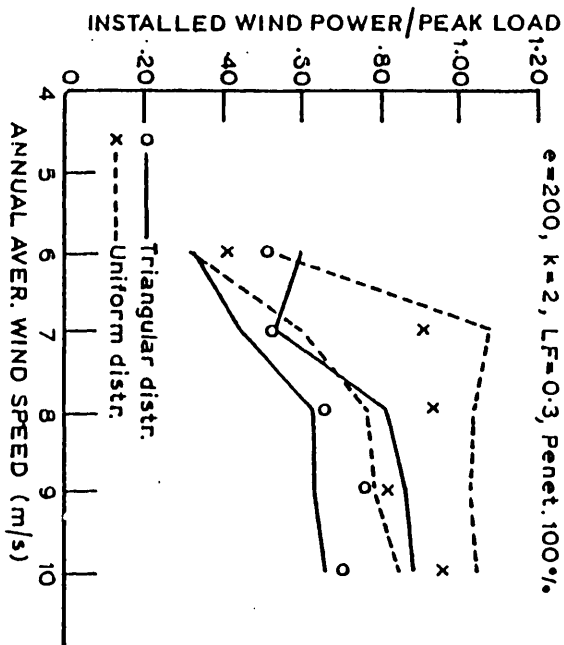


Fig. 2.3b

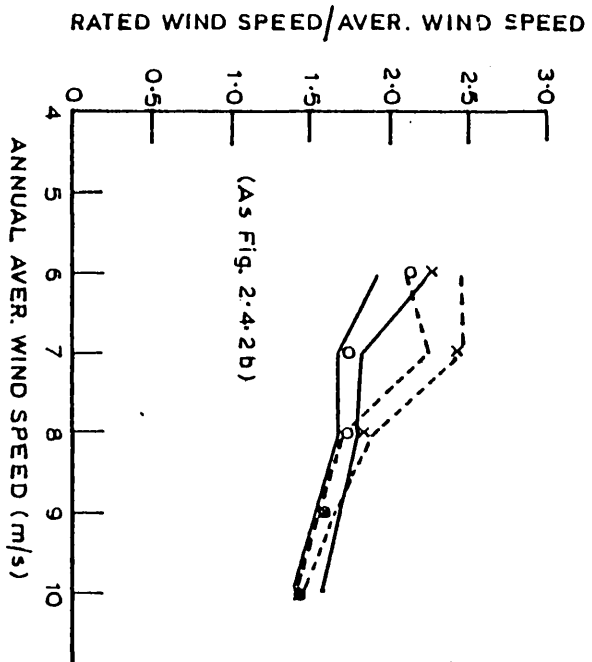


Fig. 2.3c

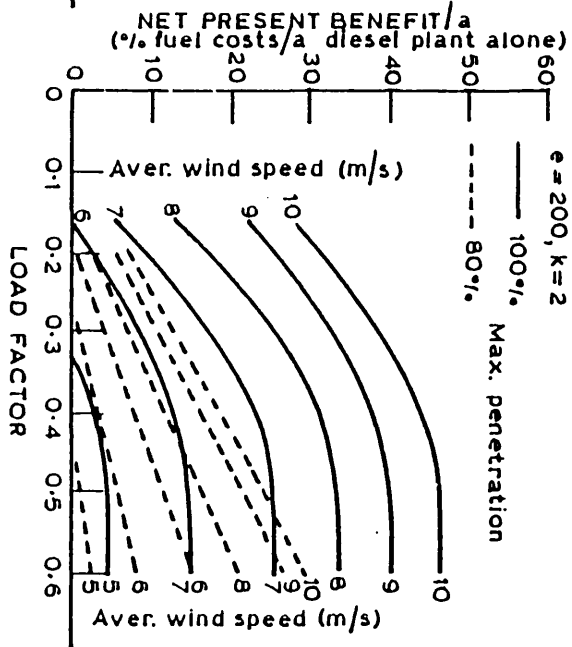


Fig. 2.3d

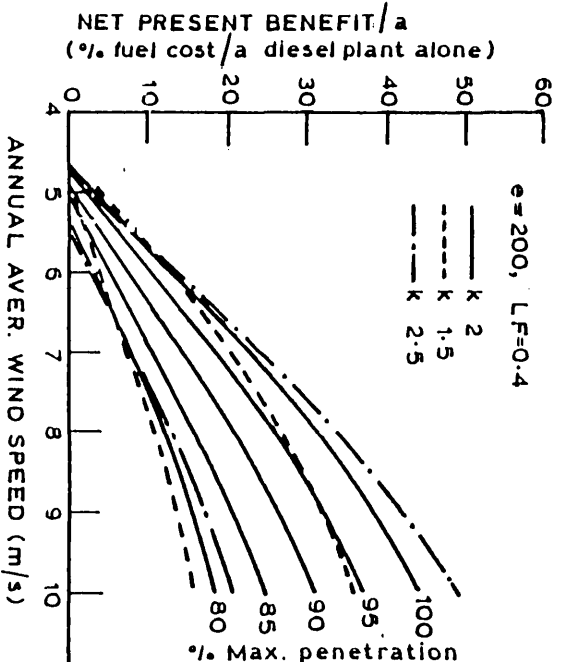


Fig. 2.3e

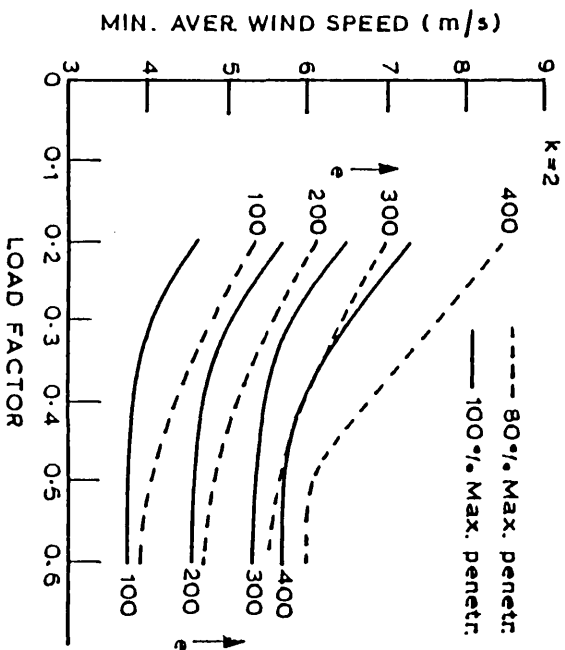


Fig. 2.3f

The influence of the load factor on the net savings, is illustrated in Fig. 2.3d. For 100% penetration the savings increase towards a limiting value reached around an L.F. of 0.5. This can be intuitively anticipated since with increasing load factor, the amount of wind power in excess of load demand and so the energy spilled, diminishes and the savings are increasingly determined by the wind power available and economic factors independent of the load factor (i.e. specific turbine and diesel fuel cost).

For 80% penetration the savings increase very nearly linearly with the load factor. Although not actually calculated, it is expected that for load factors above 0.6 (unlikely for a small autonomous system) the curves will bent towards a limit as in the case of 100% penetration.

The comparison of the net savings for a range of the Weibull shape factor in Fig. 2.3e shows, as expected, savings increasing with k for higher average wind speeds and decreasing for lower ones. The maximum allowed penetration is again very important, diminishing the significance of k as it decreases and accentuating it as it approaches 100%.

Finally the family of curves in Fig. 2.3f shows how the minimum annual average wind speed for marginal profitability (break even) depends on load factor, economic factor and penetration. The minimal average wind speeds appear to depend linearly on the economic factor and to be fairly constant for load factors above 0.4. The dramatic influence of the penetration allowable on the profitability of a particular site is again illustrated in this figure.

To give a concrete significance to the economic factor a table 2.4.2.2 has been compiled for a moderate specific turbine cost of £150/m² rotor swept area, 0 + M costs of 3 % per annum and 20 life years.

Table 2.4.2.2
Economic factor

Discount rate % per annum Fuel spec. cost p/kwh	0	5	10	15
2	142	505	649	802
4	71	253	325	401
6	47	168	216	267
8	36	126	162	200
10	28	101	130	160

2.4.3 Conclusion on the effect of parameters on the optimization

- a) For the expected range of load factors for small systems, i.e. between 0.3 and 0.5, and annual average wind speeds between 5 and 8m/s the net present benefit increased linearly with the annual average wind speed. This finding is somehow surprising as the wind power is theoretically proportional to the cube of wind speed, but it seems to be confirmed by other work (Refs. 2.13, 2.14).
- b) For the same range of parameters the NPB is decreasing significantly with the maximum allowable penetration.
- c) It can be stated that for a system with an average fuel price less than 7 p/kwh*, wind power is in general not economical for average annual

* (7 p/kwh is approximately the fuel cost for a diesel burning diesel fuel (~ £200-250/k1) and average overall efficiency ~ 30%. If the diesel is burning residual fuel - as the case for large diesels - the cost is nearly halved).

wind speeds below 5 m/s and maximum penetrations below 80%, unless subsidised. Wind power becomes economical for wind speeds above 4 m/s if maximum penetration of 100% can be achieved.

d) The influence of the Weibull shape factor k for the same range of parameters is not significant. The use of the Raleigh distribution ($k=2$) instead of the Weibull by some researchers (Ref. 2.2, 2.14) is therefore justified for rough overall calculations.

2.4.4 The allocation of wind power on the Greek Islands

The Greek Public Corporation (PPC) operates 45 power systems not interconnected with the mainland grid. The installed power range varies from below 100kw (Anafi, Megisti) to over 100 MW (Kriti). The two biggest systems on Kriti and Rodos include oil fuel steam power stations and gas turbine and diesel stations for peak load supply. The other islands are supplied from diesel power stations. For the vast majority of these islands sea-cable interconnection is not economical because of distance and/or low power levels.

The fuel required for the operation of these isolated systems is 300,000 ton per annum costing approximately (1982) £40m per annum and the energy production amounts to 4% of the total energy production of Greece (Ref. 2.15).

The Public Power Corporation is required by law to apply the same unit price for all domestic users throughout the greek state. As this price is at present approximately 5p/kwh, it can be seen from the tables in Appendix 2.2 that it does not even cover the fuel costs.

Measurements and assessments show a very good wind power potential for the region of the Aegaeis where the bulk of the islands are concentrated (Ref. 2.15, 2.16, 2.17, 2.18, 2.21).

The Public Power Corporation has since 5 years initiated a program for solar and wind power applications on the islands (Ref. 2.15, 2.18). The first wind park with 5×20kw AEROMAN machines has been operating for over one year on the island of Kythnos with encouraging results. Several other wind power installations are projected for the near future. The optimal wind power allocation program (OPTWALL) has been applied to this island complex for an overall feasibility and priority assesement.

The data for the autonomous systems are given by the Planning Department of the Islands Area Directorate of the PPC. The wind data are calculated from the PPC Department of Alternative Energy Sources publications (Ref. 2.18) where applicable, or assessed from published isovents for the region (Refs. 2.16, 2.17).

The program has been run for all the islands in four cases:

- 1.1 Hub height 10m, Specific Turbine Cost £150/m².
Continuously running diesel power 30% of the nominal capacity of the smallest set for each station (except for Kriti and Rodos, where the minimum continuously running capacity is assumed to be 20% of the peak load).
- 1.2 As above but with complete diesel switch-off when possible.
- 2.1 As in 1.1. but for Hub Height 30m and Specific Turbine Cost £250/m².
- 2.2 As in 2.1 with complete diesel switch-off when possible.

Detailed results are given in Appendix 2.2. an overview of which is presented in table 2.4.4.

Table 2.2.4

Overview on wind power allocation on the greek islands

Case	Total inst. WECS power (MW)		Fuel savings million Eper annum		Net savings million Eper annum	
	with Kriti	without Kriti	with Kriti	without Kriti	with Kriti	without Kriti
1.1	73	16	4.3(11%)	1.1 (6%)	2.0(5%)	0.5(3%)
1.2	117	31	8.6(22%)	2.0(11%)	3.6(9%)	0.7(4%)
2.1	68	17	4.1(10%)	1.1 (6%)	1.9(5%)	0.5(3%)
2.2	108	30	6.5(16%)	1.8(10%)	3.3(8%)	0.7(4%)

The significance of the maximum allowable penetration is obvious. Although the continuously running diesel power is for most stations less than 10% of the peak load, the savings are doubled if 100% penetration is permitted. Difference in savings are small between cases 1.1 and 1.2 and cases 1.2 and 2.2. This justifies the turbine cost normalization to 10m hub height used by Musgrove in (Ref. 2.7). The specific turbine cost ratio in the two cases was taken to be equal to the hub height ratio in the power of 3/7

$$\text{i.e.} \quad \frac{250}{150} \approx \left(\frac{30}{10} \right)^{3/7}.$$

A tentative confirmation of the optimisation results can be drawn from the island Kythnos where the first year operational results of the 100kw wind park of 5 turbines have produced fuel savings of 30t out of a total of 240t i.e. 12.5%. The program estimates an optimum power of 172kw at a rated wind speed 15.1 m/s and projected fuel savings of 13.2%.

Data on the actual turbine costs and the O+M costs are not available at the moment but the pay-back period of 7 years mentioned (Ref. 2.19) is not very different from the 9.7 years estimated by the program.

Finally, it must be stressed, that the calculation of the WECS allocation and the corresponding savings is based by the following pessimistic assumptions : (a) discount rate 10%, (b) fuel costs stable, (c) conservative wind speed estimates where no precise data available, (d) no correlation between wind speed distribution and load demand although it has been established that both the actual seasonal and the diurnal correlation is positive for most of the islands. The modest results obtained should therefore be regarded as the minimum expected.

2.5 Comments

1. The optimisation program in its present form is still rather expensive in computer time, however it is faster by several orders of magnitude compared to programs correlating historical time series of load demand and wind data.

The bulk of execution time is consumed in the numerical quadrature for the solution of Eqn. 2.48. The integrals involving the wind speed probability distribution can be normalized to

$$\Gamma_t(r,x) = \int_0^r e^{-t} t^{x-1} dt \quad (2.57)$$

which is a truncated gamma function.

If suitable analytical approximation formulae for Eqn. 2.57 can be developed, the numerical quadrature can be replaced by an explicit analytical quadrature.

This again makes the analytical differentiation of formula Eqn. 2.48 possible and the use of minimization algorithms involving the partial derivatives of the cost function in respect to the parameters n and v (e.g. Fletcher-Powell, or Fletcher-Reeves etc.). Such algorithms exhibit quadratic convergence rather than the linear convergence of Box's "Complex" therefore the execution time is likely to be reduced at least by an order of magnitude for the same accuracy.

2. It would be worth investigating possible improvements in the profitability of WECS allocation when more than one type of turbines are used. Although analytically straightforward, the increase in dimensionality would render the optimization procedure very expensive if the shortcuts suggested above are not implemented. The same algorithm could be used for the optimisation of additional WECS allocation in systems where a number of wind turbines is already allocated.

3. The method is shown to be useful for preliminary feasibility studies where a survey of many candidate sites and assessment of priority is intended. The accuracy of the expected NPB though can be affected by a strong seasonal or diurnal correlation between load demand and wind speed profiles. This is an important area as this correlation can be introduced intentionally either by pricing policy (special "wind power" tariff) or by load management or both. In this sense, the method used here gives the minimum expected NPB rather than the maximum achievable.

The method can be improved by introducing seasonal, diurnal and wind penetration correlation factors between load demand and wind speed. For detailed studies on a particular site the use of time series for wind speed and load demand based on historical data is still expected to be the method giving highest accuracy. Comparative studies using the two methods and actual data for particular autonomous systems would be the only validation procedure.

4. A very important result from the application of the method is that the profitability of a particular wind power site is extremely sensitive to the maximum wind power penetration allowed. However, this is limited by system stability and quality of supply considerations. The economic importance of effective system control policies is therefore evident. The development of such policies are the subject of the following chapters.

CHAPTER 3

DYNAMICS OF A NETWORK SUPPLIED FROM A DIESEL SET AND A WECS
WITH INDUCTION GENERATOR3.1 Introduction

The investigation of the economics of wind power introduction into autonomous diesel supplied systems shows significant savings if 100% wind power penetration is allowed. The optimal rating of the wind turbine for such penetration can be higher than the average or even the peak load demand and thus comparable to the installed diesel capacity.

In most WECS dynamic studies to date (Ref.3.1-3.6) the wind turbine generator is connected to a network having a very much larger generating capacity than the rating of the WECS (infinite-busbar connection). In such cases, the system voltage and frequency are virtually constant and independent of the wind power fluctuations, as would be the case for WECS connected to a national grid. In the case of autonomous systems, where small isolated networks must be considered, the frequency and the voltage depend, to a greater or lesser extent, on the amount of the wind power penetration and as a consequence on the wind speed fluctuations. The control policies in this case affect not only the performance of the WECS itself, but also the stability of the whole system and the performance of the other (diesel) generator(s) connected to the network.

In the references, where the parallel operation of WECS with diesel sets has been investigated (Ref.3.7,3.8), the rating of the diesel sets exceeds significantly the WECS output, and the dynamics of a stand-alone-WECS mode have not been considered.

In this chapter the simulation of the steady state and the dynamic performance of a system allowing 100% wind penetration is investigated, and a control strategy proposed. Further, a program for eigenvalue analysis is outlined and the state variable contribution to the eigenvalues is explored using the participation matrix technique (Ref. 3.9). In this way unstable modes and their probable causes can be identified and eliminated by appropriate design changes in the system's components or control policy.

3.2 System description

As shown in Fig. 3.1 system simulated consists of

- (a) Diesel machine driving a
- (b) Synchronous generator
- (c) Dump resistive load connected to the bus by a power transformer and controlled by thyristor rectifier
- (d) Variable pitch wind turbine
- (e) Gear box driving
- (f) An induction ^{uc} generator
- (g) Static two stage switchable capacitor connected to the induction generator

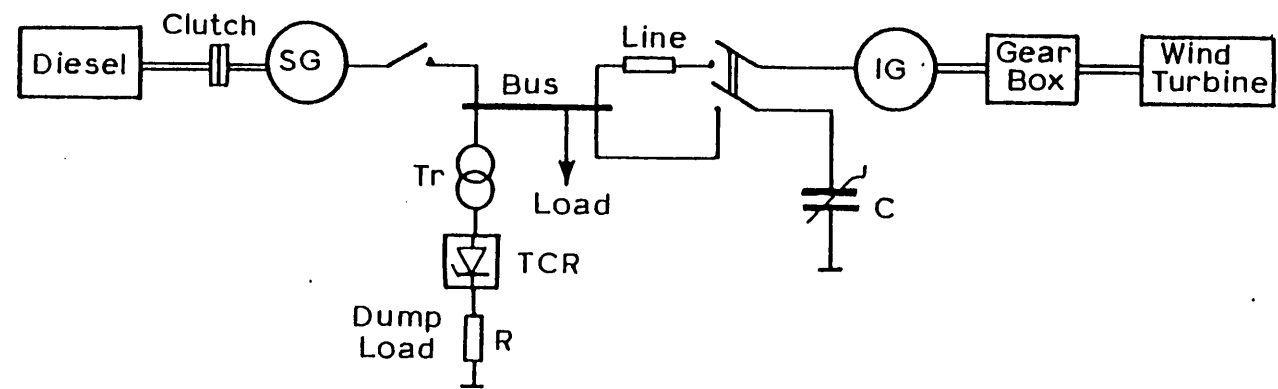


Fig.3-1 System lay-out

- (h) Transmission line between WECS and bus
- (i) Electromagnetic clutch between diesel machine and synchronous generator.

An induction squirrel-cage generator is employed on the WECS because it is the most commonly used generator type for small systems and acts as an electrical spring-damper component, thus enhancing stability.

The static capacitor provides part or the total of the reactive power required for the excitation of the induction generator. Two stages of capacitive power are achieved by a simple D-Y capacitor connection switch and have a ratio 3:4. The capacitor is disconnected and connected simultaneously with the generator by a double switch.

The electromagnetic clutch enables the synchronous machine to be disconnected from the diesel unit leaving the machine to operate as a synchronous capacitor.

A short term storage device (e.g. battery) is not included in the simulation. However, the thyristor control rectifier may easily be used as an inverter, and the simulation program modified accordingly. The dump load may be used for water or other heating or refrigeration purpose so that waste of the surplus wind energy is avoided.

3.3 Model of the components

Unless stated otherwise all equations in this chapter are given in per-unit.

3.3.1 Diesel engine

The exact simulation of the diesel engine dynamics is, in general, a difficult task (Ref. 3.7).

In the present study a simplified model as shown in Fig. 3.2 has been adopted. The parameter values are chosen to conform to the worst case of dynamic performance as specified in Table 3.3 which summarises BS 5514 Pt.4 1979. Most diesel machines would be expected to perform substantially better. The third order model includes representation of governor dead band, throttling valve action, combustion delay, power limitation, engine inertia and frictional losses.

The steady state performance of the diesel engine is described by the droop and loss equations:

$$P_D = P_{DO} + P_D^r \cdot \frac{1 - \omega_D}{D_r} \quad (3.1)$$

$$P_{shD} = P_D - D_D \cdot \omega_D^2 \quad (3.2)$$

where:

ω_D	diesel rotational speed
P_D	mechanical power from the cylinders
P_{DO}	governor set point
P_D^r	diesel engine rated power
D_r	droop
P_{shD}	diesel shaft power
D_D	diesel frictional loss coefficient

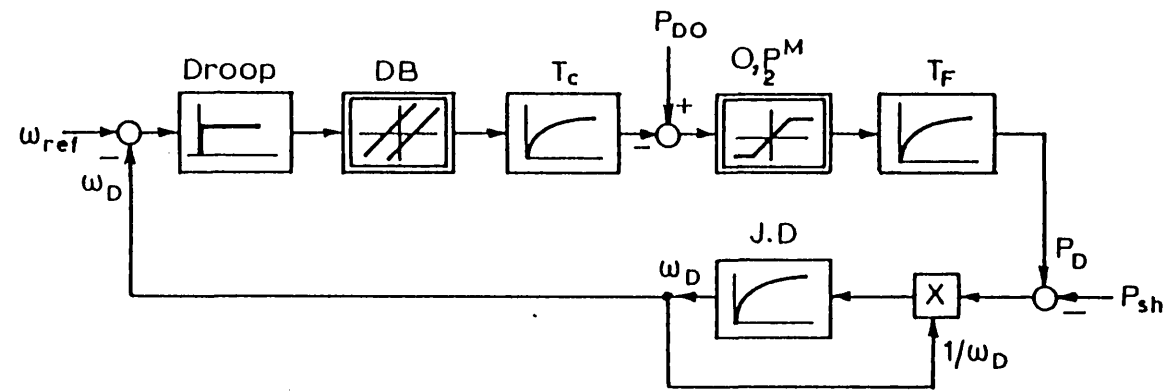


Fig 3.2 Diesel engine model

Table 3.3

BS 5514 Pt. 4 1979

Specification for Reciprocating Internal Combustion Engines:

Performance Part 4 Speed governing

Class A1 Engines

n_r : Nominal speed

n_i : Steady state speed

v : Steady state speed band

δ_{st} : Droop

δ_d : Transient speed difference

t_r : Recovery time

$$\text{Upward range } \Delta_{n_{\max}} = \frac{n_{i_{\max}} - n_i}{n_r} \times 100 \geq 2.5$$

$$\text{Downward range } \Delta_{n_{\min}} = \frac{n_i - n_{i_{\min}}}{n_r} \times 100 \geq \delta_{st} + 2.5$$

$$\text{For pu power } \geq 0.25 \quad v \leq \frac{n_r}{100}$$

$$\text{For pu power } < 0.25 \quad v \leq 1.0 \times \frac{n_r}{100}$$

$$100\% \text{ step unloading } \delta_d^+ = \frac{n_{\max} - n_r}{n_r} \times 100 \leq 10$$

$$100\% \text{ step loading (or equiv.) } \delta_d^- = \frac{n_{\min} - n_i}{n_r} \times 100 \leq 10$$

$$\text{For all cases } t_r \leq 8 \text{ sec}$$

The dynamic performance is described, as shown in Fig. 3.2, by the equations

$$2H_D \dot{\omega}_D = -D_D \cdot \omega_D - S_D(\theta_D - \theta_S) + \frac{P_D}{\omega_D} \quad (3.3)$$

$$\dot{\theta}_D = \omega_D \quad (3.4)$$

$$\dot{P}_D = (P_2 - P_D) / T_F \quad (3.5)$$

$$\dot{P}_C = (P_5 - P_C) / T_C \quad (3.6)$$

$$\dot{P}_5 = P_D^r \cdot \frac{\dot{\omega}_D}{\omega_D} \cdot \text{Max}\{0, |P_6 - P_5| - \frac{DB}{2}\} \quad (3.7)$$

where: $P_2 = \text{Max}\{0, \text{Min}(P_3, P_2^M)\}$ (3.8)

$$P_3 = P_{D0} + D_D - P_C \quad (3.9)$$

$$P_6 = P_D^r \cdot \frac{\omega_D - \omega_{ref}}{\omega_D} \quad (3.10)$$

and

- θ_D diesel engine shaft angle
- θ_S synchronous generator shaft angle
- S_D diesel shaft torsional stiffness coefficient
- H_D diesel engine inertial time constant
- T_F fueling and combustion system time constant
- T_C governor and throttling valve time constant
- DB governor dead band.

With the parameter values of Appendix 3.1 the step responses obtained on loading, Fig. 3.3, and unloading, Fig. 3.4, are in good agreement with the worst permissible responses given in the British Standard.

3.3.2 Synchronous Generator

The synchronous generator is represented by a simplified salient pole two axis model (Ref. 3.10, 3.11), the phasor diagram of which is given in Fig. 3.5. Subtransient effects and the transient magnetic flux changes on the q-axis are neglected. The synchronous generator performance in steady state is described by the equations

$$P_{sie} = P_{shD} - D_s \omega_s^2 \quad (3.11)$$

$$P_{sie} = \text{Re}\{\bar{E}_q \bar{I}_s^*\} \quad (3.12)$$

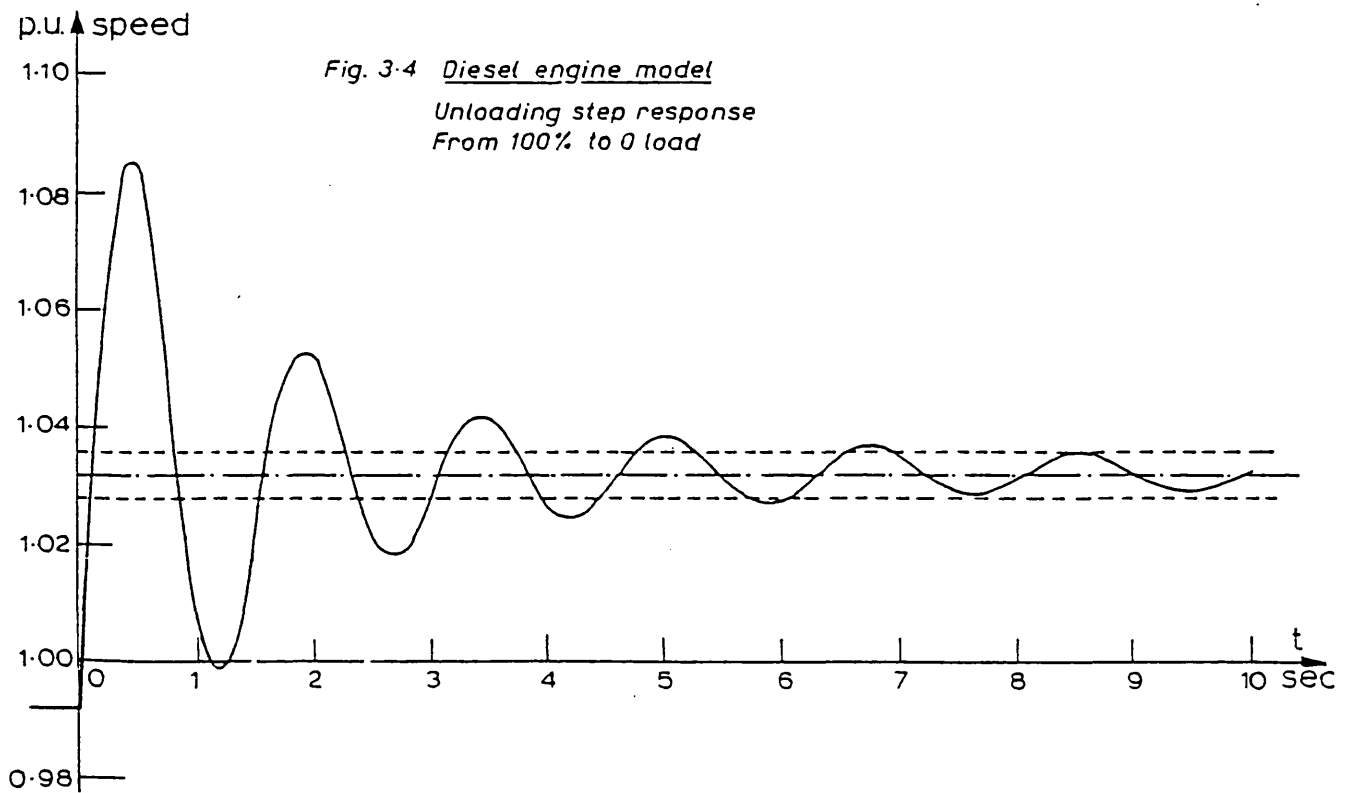
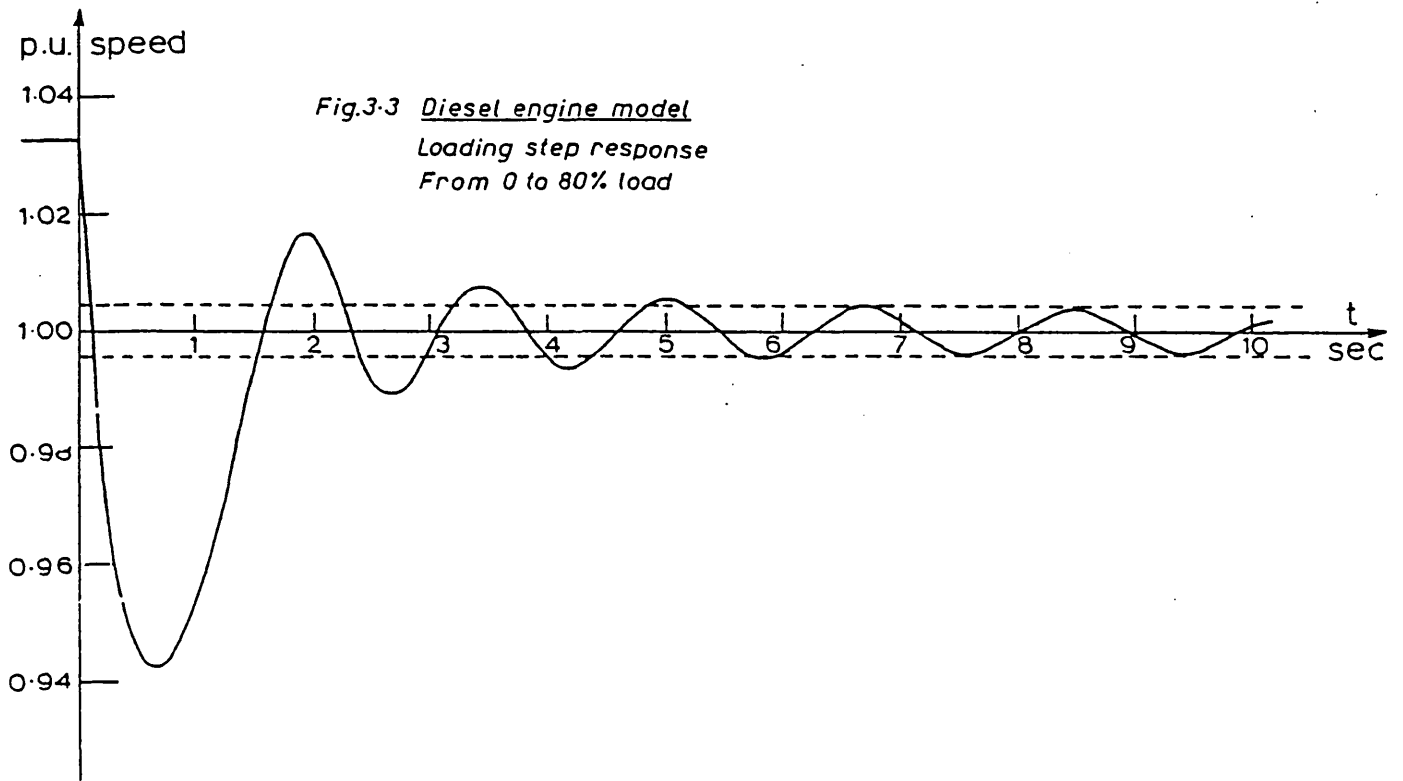
$$P_s = \text{Re}\{\bar{V} \bar{I}_s^*\} \quad (3.13)$$

$$Q_s = \text{Im}\{\bar{V} \bar{I}_s^*\} \quad (3.14)$$

$$\bar{E}_q = \bar{V} + r_a \bar{I}_s + j\omega_s x_q \bar{I}_s \quad (3.15)$$

$$\bar{E}_d = \bar{E}_q + j\omega_s (x_d - x_q) \bar{I}_d \quad (3.16)$$

$$\bar{I}_d = |I_s| \sin(\phi + \delta) \cdot \exp[j(\delta - \frac{\pi}{2})] \quad (3.17)$$



$$\phi = -\arg\{\bar{I}_s\} \quad (3.18)$$

$$\delta = \arg\{\bar{E}_q\} \quad (3.19)$$

$$f = \omega_s \quad (3.20)$$

$$E_{fd} = \left(\frac{|\bar{E}_I|}{f} + a_{sat} \exp(b_{sat} \frac{|\bar{E}_I|}{f}) \right) \quad (3.21)$$

$$\theta_s = \frac{2\delta}{p_s} \quad (3.22)$$

where	P_{sie}	internal electric power
	P_{shD}	diesel shaft power
	P_s	real power output
	Q_s	reactive power output
	D_s	synchronous generator damping coefficient (frictional, core, windage losses)
	E_q	quadrature axis voltage behind quadrature axis synchronous reactance
	I_s	terminal current
	V	terminal voltage
	r_a	armature resistance
	x_q	quadrature axis synchronous reactance
	x_d	direct axis synchronous reactance
	ω_s	rotational speed
	E_I	field induced voltage
	I_d	direct axis current
	ϕ	load angle
	δ	power angle

- f : frequency
 E_{fd} : EMF proportional to field current
 a_{sat}, b_{sat} : Saturation curve parameters
 (in exponential representation)
 p_s : number of generator poles.

The dynamic performance is described by the equations

$$2H_s \dot{\omega}_s = -D_s \omega_s + S_D(\theta_D - \theta_s) - \frac{P_{sie}}{\omega_s} \quad (3.23)$$

$$\dot{\theta}_s = \omega_s \quad (3.24)$$

$$\bar{E}'_q = \bar{E}_q - j\omega_s(x_q - x'_d)I_d \quad (3.25)$$

$$\frac{d}{dt} |E'_q| = (E_2 - E_I)/T'_{d0} \quad (3.26)$$

$$\frac{E_2}{f} = E_{fd} - a_{sat} \exp(b_{sat} \frac{E_2}{f}) \quad (3.27)$$

in addition to the steady state equations for the electrical quantities described earlier. The new symbols indicate:

- H_s : synchronous generator inertial time constant
 E'_q : transient quadrature-axis voltage
 T'_{d0} : direct-axis transient open circuit time constant .

It is assumed that the rotor exhibits isotropic transient behaviour and stator transients are ignored.

3.3.3 Automatic Voltage Regulator and Exciter

The full AVR model of Fig. 3.6 was chosen (Ref. 3.10-3.12), for simulation. Although small diesel sets usually are fitted only with a static exciter with current compounding, it is felt that a fully fledged AVR is required to avoid unacceptable voltage transients due to wind power fluctuations when an induction generator is used on the WECS. The exciter is modelled as a conventional rotating unit. The AVR and exciter steady state performance is described by the equations:

$$E_R = V_{ref} - V \quad (3.28)$$

$$E_A = K_A \left(\frac{E_0}{K_A} + E_R \right) \quad (3.29)$$

$$E_{Amin} \leq K_A \leq E_{Amax} \quad (3.30)$$

$$\frac{E_1}{f} = E_A - a_{exc} \cdot \exp(b_{exc} \cdot \frac{E_1}{f}) \quad (3.31)$$

$$E_{fd} = \frac{E_1}{K_E} \quad (3.32)$$

$$E_{fdmin} \leq E_{fd} \leq E_{fdmax} \quad (3.33)$$

V_{ref} : Reference (nominal) voltage

where

E_R : Amplifier output

E_0 : Nominal voltage amplifier output

- K_A : Amplifier gain
 E_{Amin}, E_{Amax} : Amplifier output limits
 E_1 : Exciter input
 a_{exc}, b_{exc} : Exciter saturation curve coefficients
 E_{fd} : Exciter output
 K_E : Exciter gain
 E_{fdmin}, E_{fdmax} : Excitation limits.

The dynamic performance is described by the equations

$$\frac{dE_R}{dt} = (V_{ref} - V - E_R) / T_R \quad (3.34)$$

$$\frac{dE_A}{dt} = [K_A (E_R + \frac{E_0}{K_A} - E_{st}) - E_A] / T_A \quad (3.35)$$

$$\frac{dE_{fd}}{dt} = (E_1 - K_E \cdot E_{fd}) / T_E \quad (3.36)$$

$$\frac{dE_{st}}{dt} = (K_{st} \frac{dE_{fd}}{dt} - E_{st}) / T_{st} \quad (3.37)$$

where:

- T_R : Regulator time constant
 T_A : Amplifier time constant
 T_E : Exciter time constant
 E_{st} : Stabilizer output
 k_{st} : Stabilizer gain
 T_{st} : Stabilizer time constant .

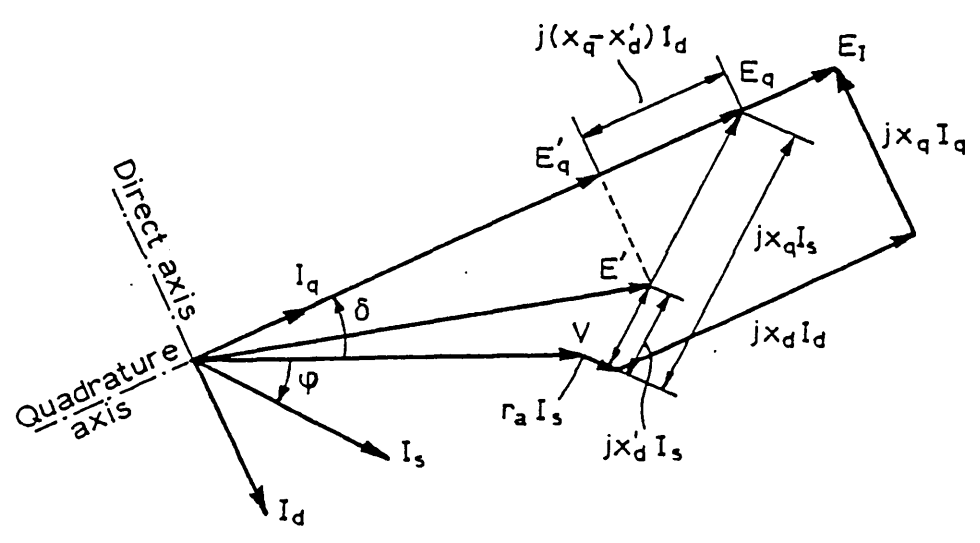


Fig. 3-5 Synchronous generator phasor diagram
Salient pole model

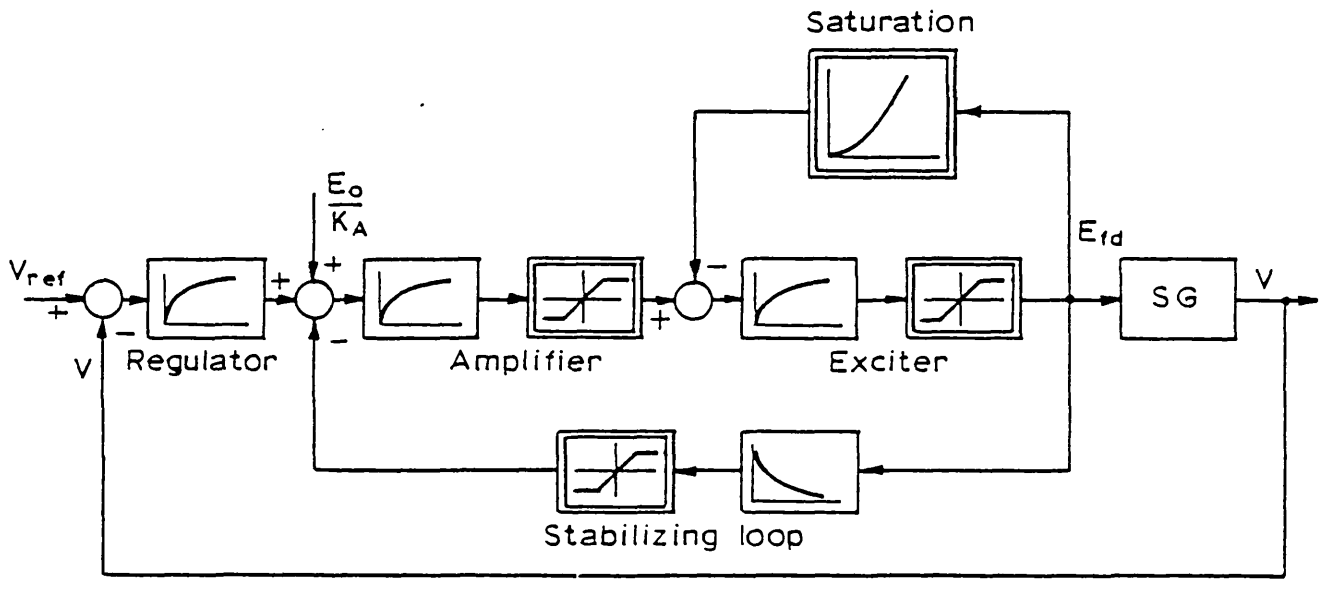


Fig. 3-6 AVR and exciter model

3.3.4 Load

The load is represented as an impedance on the bus. The real and reactive power absorbed by the load are :

$$P_L = \frac{1}{R_L} V^2 \quad (3.38)$$

$$Q_L = \frac{1}{X_L} \frac{V^2}{f} \quad \text{for } X_L > 0 \quad (3.39)$$

$$Q_L = \frac{1}{X_L} V^2 f \quad \text{for } X_L < 0 \quad (3.40)$$

3.3.5 Thyristor Controlled Rectifier (TCR)

The TCR is a six-pulse fully controlled bridge converter connected to the bus through the TCR transformer reactance. Its response is assumed to be instantaneous (Ref. 3.13, 3.14, 3.15).

The real and reactive power absorbed by the TCR load are given approximately[†] by the equations

$$P_R = \frac{1}{R_{dc}} \left(\frac{3}{\pi} V \right)^2 (1 + \cos 2\psi) \quad (3.41)$$

$$Q_R = \frac{1}{R_{dc}} \left(\frac{3}{\pi} V \right)^2 \sin 2\psi \quad (3.42)$$

with

$$\psi = \arccos \left(\frac{\cos \alpha}{1 + 6fX_{cd}/R_{dc}} \right) \quad (3.43)$$

[†] assuming the ratio $6fX_{cd}/R_{dc}$ to be small compared to 1.

where

α	TCR firing angle
X_{cd}	commutation reactance
R_{dc}	load resistance d.c. side.

The approximate power characteristic for the TCR is shown in Fig. 3.7.

3.3.6 Induction Generator

In the steady state, the induction generator is represented by the usual simple cage model (Fig. 3.8). Core losses are included in the mechanical friction losses (Ref.3.16). The dynamic model is represented by a simple differential equation neglecting subtransient effects and saturation (Ref. 3.10).

A block diagram for the dynamic model is given in Fig. 3.9. The steady state performance (including the line and the static capacitor) is described by the equations

$$s = \frac{\omega_s - \omega_{IG}}{\omega_s} \quad (3.44)$$

$$\bar{E}_{IG} = \frac{\bar{X}_2 \parallel \bar{X}}{\bar{X}_1 + \bar{X}_2 \parallel \bar{X}_m} \cdot \frac{r_r}{s\bar{X}_2} \bar{V} \quad (3.45)$$

$$\bar{X}_1 = r_s + r_{line} + j\omega_s(x_s + x_{line}) \quad (3.46)$$

$$\bar{X}_2 = \frac{r_r}{s} + j\omega_s x_r \quad (3.47)$$

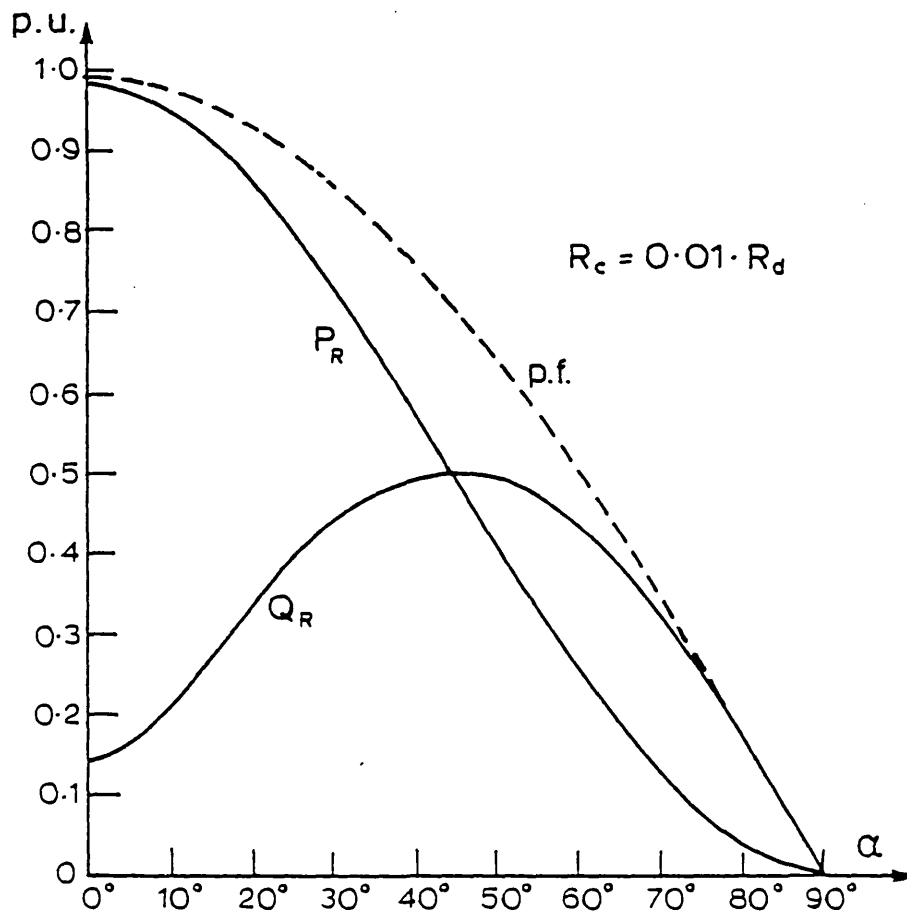


Fig. 3.7 Thyristor controlled rectifier power and power factor

$$\bar{X}_m = j\omega_s x_m \quad (3.48)$$

$$\bar{I}_{IG} = - \frac{\bar{V}}{\bar{X}_1 + \bar{X}_m \parallel \bar{X}_2} \quad (3.49)$$

$$P_{IG} = \text{Re}\{\bar{V} \bar{I}_{IG}^*\} \quad (3.50)$$

$$Q_{IG} = \text{Im}\{\bar{V} \bar{I}_{IG}^*\} \quad (3.51)$$

$$P_{IGi} = \text{Re}\{\bar{E}_{IG} \bar{I}_{IG}^*\} \quad (3.52)$$

$$P_{IGs} = P_{IGi} + D_{IG} \cdot \omega_{IG}^2 \quad (3.53)$$

$$Q_c = -K_c \cdot V^2 \cdot \omega_s \cdot C \quad (3.54)$$

where:

- s. : slip
- ω_s : synchronous speed
- ω_{IG} : induction generator rotor speed
- E_{IG} : induction generator EMF
- I_{IG} : induction generator terminal current
- r_s : stator resistance
- x_s : stator reactance
- x_m : magnetizing inductance
- r_r : rotor resistance
- x_r : rotor reactance
- P_{IG} : real putput power to bus
- Q_{IG} : reactive : output power to bus
- P_{IGi} : internal electric power

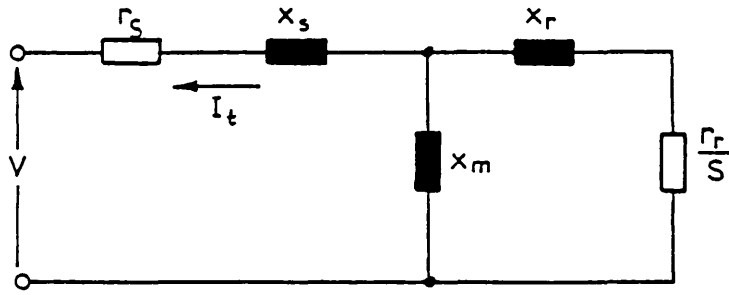
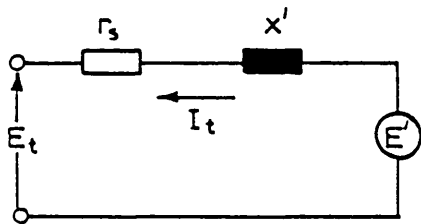


Fig. 3.8 Steady state positive sequence equivalent circuit of an induction machine



Simplified electrical model for transient analysis

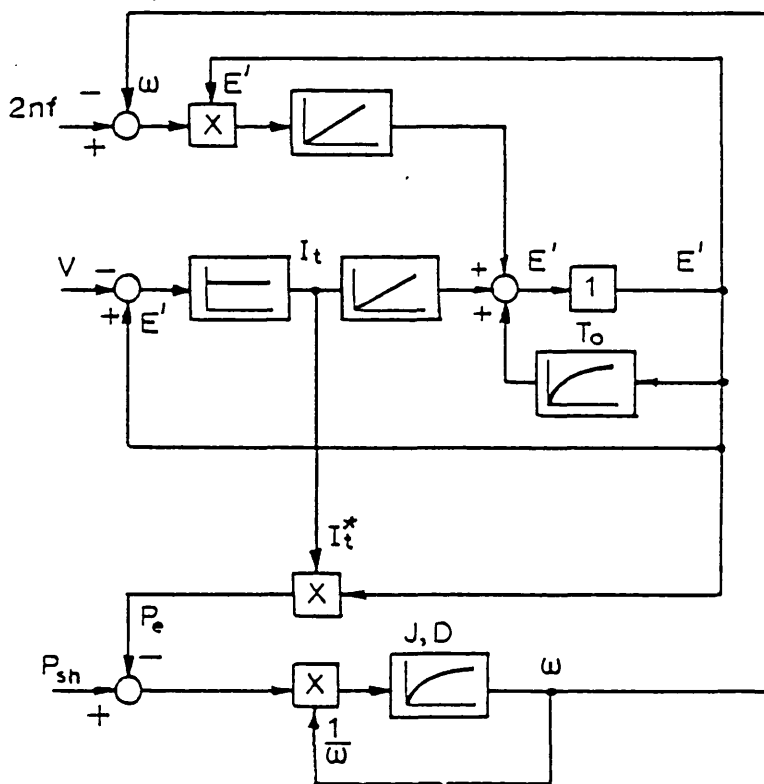


Fig. 3.9 Induction generator model

- P_{IGs} : shaft input power
 Q_c : reactive power consumed by the static capacitor
 K_c : static capacitor switch factor
 C : static capacitor normalized capacitance
 D_{IG} : induction generator damping (no-load loss) coefficient.

The dynamic performance is described by the equations

$$2H_{IG}\dot{\omega}_{IG} = -D_{IG}\omega_{IG} + (P_{IGs} - P_{IGi})/\omega_{IG} \quad (3.55)$$

$$\dot{\theta}_{IG} = \omega_{IG} \quad (3.56)$$

$$\frac{d}{dt} \bar{E}'_{IG} = -j2\pi f_0 (\omega_s - \omega_{IG}) \bar{E}'_{IG} - \frac{1}{T_0} [\bar{E}'_{IG} + j(X - X') \bar{I}_{IG}] \quad (3.57)$$

where:

$$T_0 = \frac{x_r + x_m}{2\pi f_0 \omega_s r_r} \quad (3.58)$$

$$X = (x_s + x_{line} + x_m) \cdot \omega_s \quad (3.59)$$

$$X' = \left(x_s + x_{line} + \frac{x_m x_r}{x_m + x_r} \right) \cdot \omega_s \quad (3.60)$$

$$\bar{I}_{IG} = \frac{\bar{E}'_{IG} - \bar{V}}{r_s + r_{line} + jX'} \quad (3.61)$$

$$P_{IGs} = S_{IGs} (\theta_{GB} - \theta_{IG}) \cdot \omega_{IG} \quad (3.62)$$

with

- S_{IGs} : Induction generator shaft torsional stiffness coefficient[†]
 θ_{GB} : Gearbox torsional angle
 θ_{IG} : Generator rotor torsional angle
 H_{IG} : Induction generator inertial time constant

3.3.7 Gear Box

The step-up gear box is represented as a rotating disc with composite friction and inertia (Ref. 3.17).

The steady state is described by the equations

$$P_{Ts} = P_{IGs} + D_{GB} \cdot \omega_{GB}^2 \quad (3.63)$$

$$P_{Ts} = S_T(\theta_T - \theta_{GB}) \cdot \omega_T \quad (3.64)$$

with:

- P_{Ts} : Turbine shaft output power
 S_T : Turbine shaft torsional stiffness coefficient
 ω_{GB} : Gear box speed
 D_{GB} : Gear box frictional losses coefficient.

The gear box dynamics are described by the equations

$$2H_{GB} \dot{\omega}_{GB} = -D_{GB} \omega_{GB} + (P_{Ts} - P_{IGs})/\omega_{GB} \quad (3.65)$$

[†]Note: All quantities in the representation of the mechanical transmission system between wind turbine rotor and induction generator rotor are referred to the low speed (turbine rotor) side of the generator and normalized in p.u. accordingly.

$$\dot{\theta}_{GB} = \omega_{GB} \quad (3.66)$$

with

H_{GB} : Gear box inertial time constant.

3.3.8 Wind Turbine

An ideal rotating disc representation is also chosen here.

If required, periodic mechanical transients may be approximately simulated by appropriate modulation of the wind torque input to the machine. The C_p/λ characteristics of the wind turbine (Fig. 3.10) chosen for the study are those of the well documented NASA-Lewis Research Center Mod OA machine (Ref. 3.2, 3.4).

The steady-state equations are:

$$P_w = \frac{1}{2} \rho A C_p(\lambda, \beta) W^3 / P_b \quad (3.67)$$

$$P_{Ts} = P_w - D_T \omega_T^2 = S_T(\theta_T - \theta_{GB}) \cdot \omega_T \quad (3.68)$$

where

P_w : wind input power in p.u.

ρ : air density in kg/m^3

A : turbine rotor swept area in m^2

λ : tip-speed ratio

β : blade pitch angle in degrees

W : wind speed in m/s

C_p : Aerodynamic power coefficient

P_b : Base power in W

D_T : Turbine rotor frictional losses coefficient

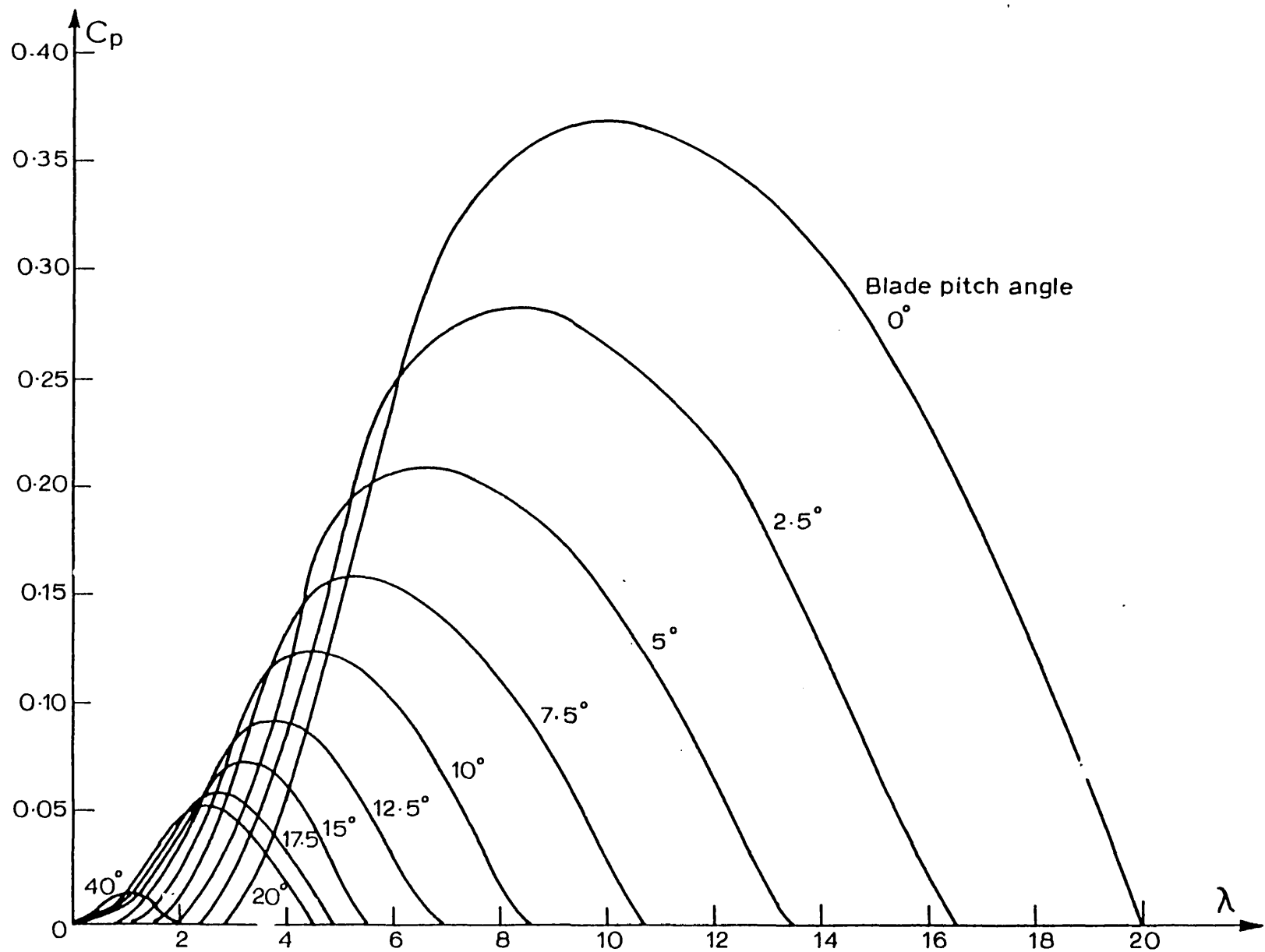


Fig. 3:10 Aerodynamical power efficiency factor vs. tip speed ratio and blade pitch angle
NASA-Lewis Research Centre 100kW machine

The equations describing the dynamics are:

$$2H_T \dot{\omega}_T = -D_T \omega_T - S_T(\theta_T - \theta_{GB}) + \frac{P_w}{\omega_T} \quad (3.69)$$

$$\dot{\theta}_T = \omega_T \quad (3.70)$$

3.4 System efficiency and dynamic control objectives

The objective of the control system for the combined diesel/WECS system in normal operation[†] is to extract the maximum possible power from the WECS, keeping the quality of electrical energy supplied within specified limits.

The first part of the control objective is concerned with the system operating in quasi steady-state and with quantities and control actions measured over time periods of several minutes or even hours. This part of the control system determines the set values of the controllers.

The second part is concerned with the system in transient state i.e. time periods over some seconds and determines the parameters for the chosen control system. As shown in Fig. 3.11 there are five control variables, two of which are continuous and three with on-off logic, namely the converter firing angle α , the blade pitch angle β , the switchable static capacitor Cap , the electromechanical diesel machine clutch Cl and the induction generator connecting switch Sw .

Whereas the state of the last two variables determines the steady state operation mode according to the wind speed and load demand

[†]Note: The operational modes of turbine run up and shut down, are not immediately connected to the electrical supply problem and will not be discussed here. These modes have other control objectives such as limiting the speed and the mechanical stresses on the wind turbine and require separate control strategies.

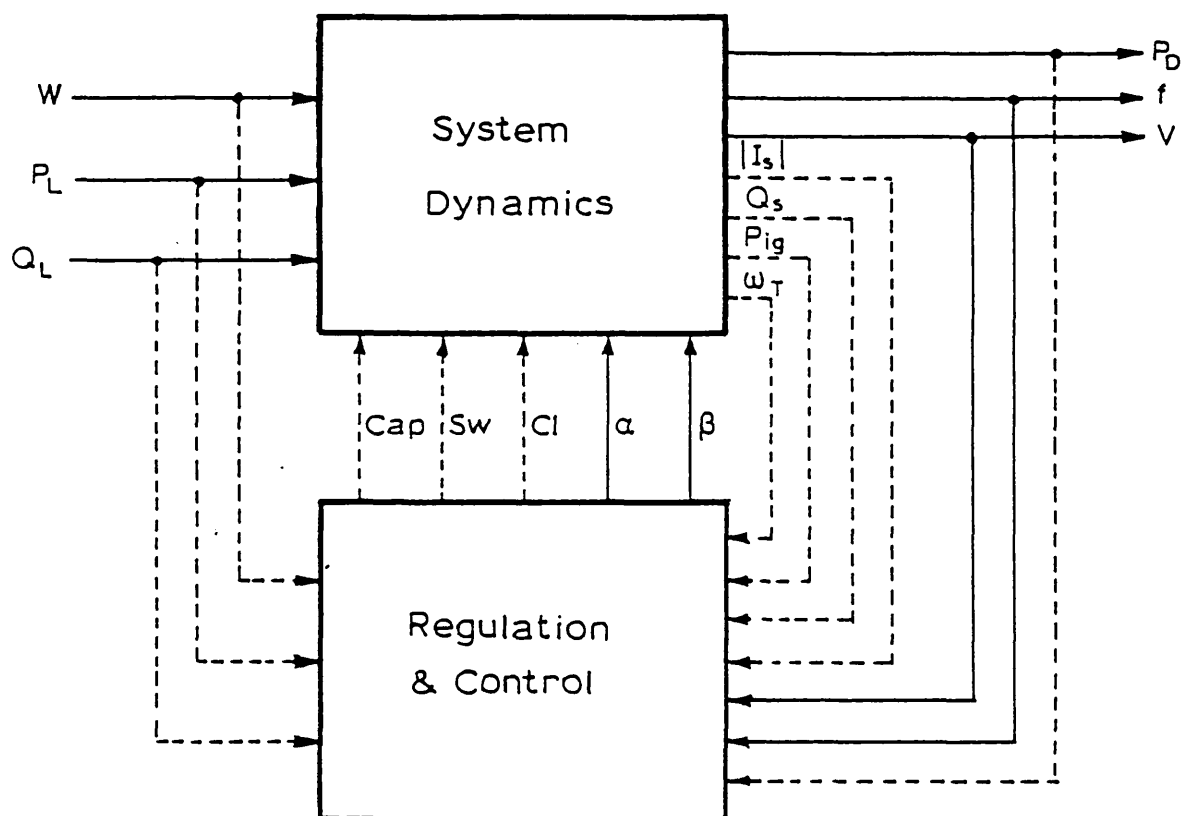


Fig. 3-11 Signal flow block diagram

conditions, the three former ones are used for steady state optimization and dynamic control of the system.

3.5 Steady state optimization

3.5.1 Optimal steady state operating point calculation

There are three distinct modes of operation of the system in steady state:

- (1) The load is supplied by diesel power only. The WECS is switched off.
- (2) The load is supplied by wind power only. The diesel generator acts as synchronous capacitor (diesel machine declutched).
- (3) The WECS and the diesel machine supply the load in parallel.

The steady state efficiency optimization algorithm determines the mode operation and the optimal operating point of the system by taking into account the wind speed, the available wind power and the load demand. The operating point is subject to the following constraints:

- (a) The power limits of the diesel engine when it is clutched. (A minimum allowable power for continuous operation should be specified, to avoid premature machine performance deterioration).
- (b) The real and reactive power limits of the synchronous generator.

- (c) The effective current limit of the synchronous generator.
- (d) The field current limitation of the synchronous generator.
- (e) The power limit of the induction generator
- (f) The voltage limits
- (g) The frequency limits - (synchronous generator speed).

The total system in steady state is described by the steady state equations for each part, developed in section 3.3 and the following equalities resulting from the steady-state torque and power balance in the total system:

$$\omega_T = \omega_{GB} = \omega_{IG} \quad (3.71)$$

$$\omega_D = \omega_s \quad (3.72)$$

$$P_{IG} + P_s = P_L + P_R \quad (3.73)$$

$$Q_{IG} + Q_s = Q_L + Q_R + Q_c . \quad (3.74)$$

In the system of equations obtained, there are only two independent variables : the TCR firing angle α and the blade pitch angle β . All other quantities may be expressed as functions of these two variables.

The optimization problem in mode 3 (parallel operation) is a two dimensional maximization of the induction generator output (or minimization of the synchronous generator output) with respect to the two control variables α and β subject also to the previously defined constraints.

$$P_{IG}(\alpha, \beta) \stackrel{!}{=} \text{Max} \quad (3.75)$$

$$P_{IGm} \leq P_{IG}^r \quad (3.76)$$

$$P_s^m \leq P_s \leq P_s^r \quad (3.77)$$

$$|I_s| \leq |I_s|^M$$

$$Q_s^m \leq Q_s \leq Q_s^M \quad (3.79)$$

$$E_{fd}^m \leq E_{fd} \leq E_{fd}^M \quad (3.80)$$

$$V^m \leq V \leq V^M \quad (3.81)$$

$$f^m \leq f \leq f^M \quad (3.82)$$

and $0 \leq \alpha \leq \frac{\pi}{2} \quad (3.83)$

$$\beta^m \leq \beta \leq \beta^M \quad (3.84)$$

In mode 1 (diesel only operation, wind turbine shut down) there is obviously no case for optimization as P_{IG} is zero. In mode 2 (diesel engine declutched, synchronous generator operating as synchronous capacitor) two additional equations must be included:

$$P_{shD} = 0 \quad (3.85)$$

$$\omega_s = 1. \quad (3.86)$$

An explicit relationship exists now between the total real electrical output power (including the TCR controlled load) and the mechanical wind input power to the turbine rotor. This leads to an implicit relationship between thyristor firing angle α and blade pitch angle β .

The independent variables are thus reduced to one, the TCR firing angle α and the induction generator output maximization is equivalent to

simply minimization of α .

The optimization in mode (3) is performed through Box's "Complex" method (Ref. 3.18) which, for our case, has four significant advantages:

- (a) Does not require gradient calculation
- (b) Rarely fails in non-convex regions
- (c) Handles the constraints simply
- (d) Can be immediately implemented in non-steady-state conditions with slowly varying parameters giving a fast nearly-optimal solution.

The routine begins by selecting 9 points in α and β , normally extrema and middle points. For these points, the system of equations is solved iteratively, and the constraints checked. If they are violated, the target function is penalized. After the construction of the polygon the worse point is rejected and replaced according to Box's algorithm until the polygon contracts sufficiently to satisfy the convergence test. The routine then localizes the optimum point and exits.

To enhance convergence in the case of on-line repetitive calculations, when a change in steady state conditions is detected, i.e. change of the average wind speed or the real or reactive load demand, the algorithm uses as starting points stored optimal points calculated for adjacent operating conditions. Alternatively the optimal operating points for a range of steady state conditions could be precalculated and stored in a look-up table.

3.5.2 Steady-state optimization example

For the system described in Appendix 3.1 the regions of the three modes of operation and the state of the TCR are shown in Fig. 3.12.

The induction generator real power output, and the optimal TCR firing angle α and blade pitch β curves are plotted as functions of wind speed and real load in Fig. 3.13.

The load demand power factor is 0.8 lagging.

The induction generator output curves have the familiar shape of fixed speed, variable blade pitch performance characteristics. The distortions are due to the reactive power limitation for the synchronous generator which imposes limitations in the TCR firing angle $\alpha^{\dagger}$.

The same effect can be observed in the non-regular shapes of the optimal α curves.

It follows that apart from the TCR capacity limitation due to harmonic distortion injected into the system there is a limit in the dump load capacity above which additional capacitive power compensation has to be added if the voltage regulation (excitation) limits of the synchronous machine are not to be exceeded. Other limitations, however, may be overriding such as the level of voltage harmonic distortion caused by the TCR.

For loads below the minimum diesel load, (50% in this case)

$\dagger$

Note: The change of α affects the reactive power to be supplied by the synchronous generator in two ways:

- a. By affecting immediately the reactive power absorbed by the TCR bridge
- b. By affecting the real and hence the reactive power of the induction generator

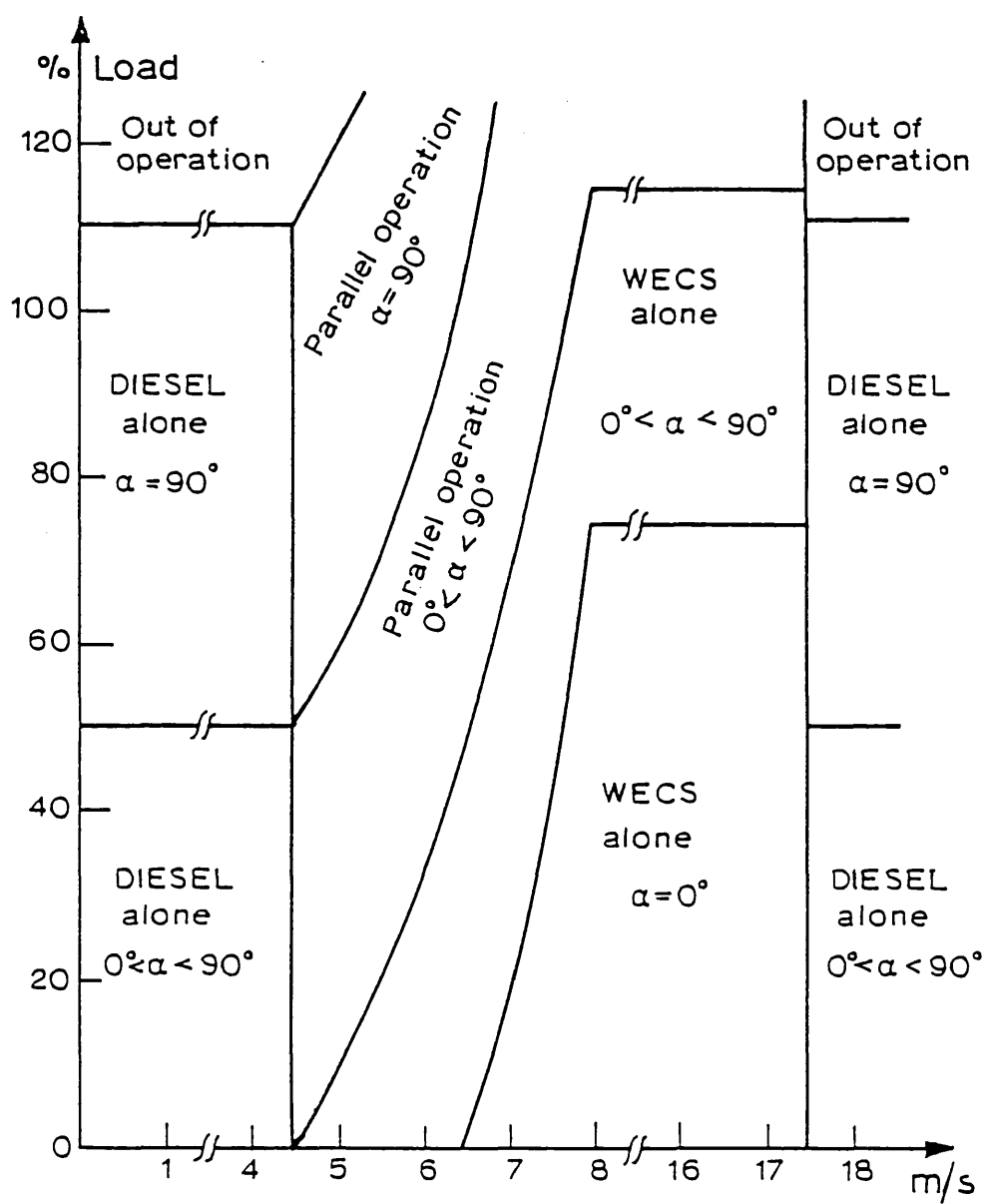


Fig. 3.12 Optimal mode of operation diagram

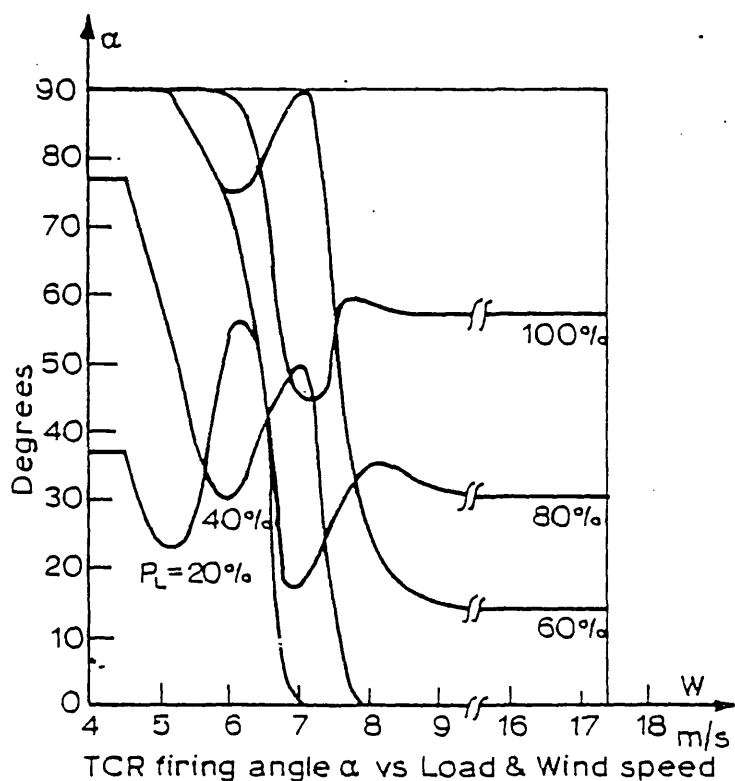
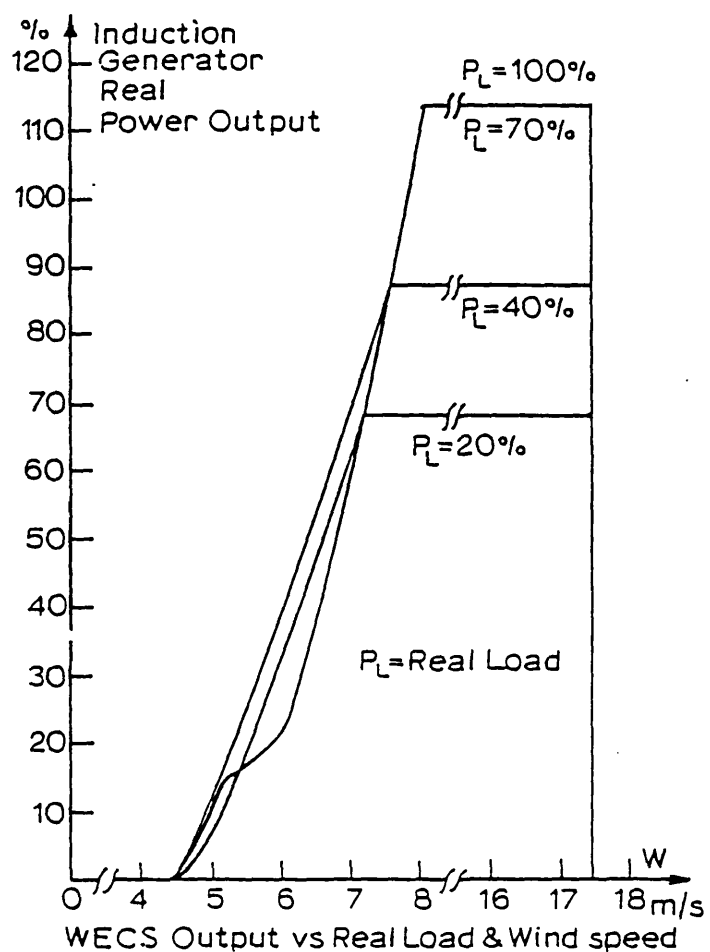
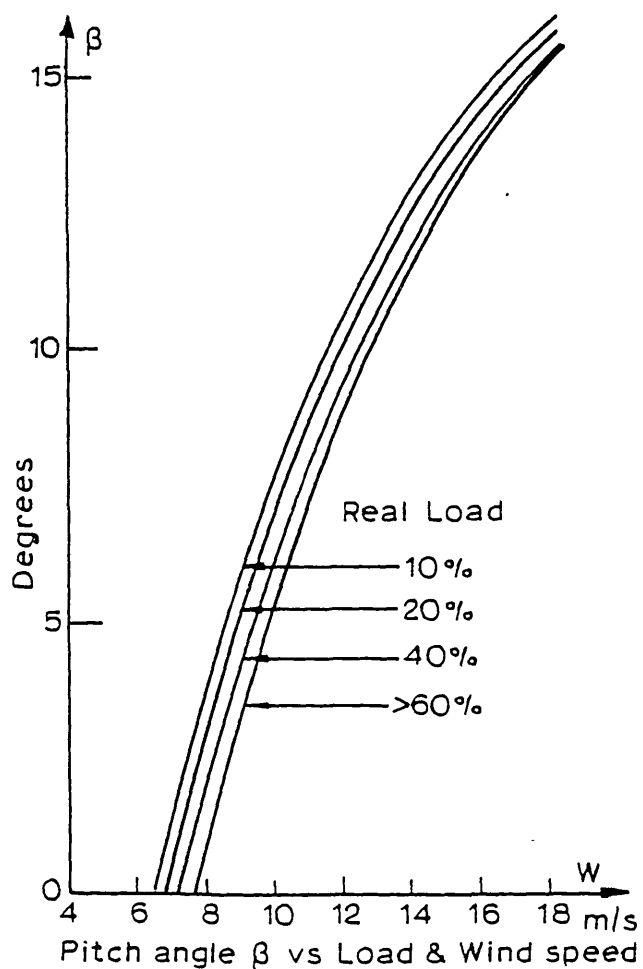


Fig. 3.13 System optimal steady state operation diagrams

the optimal firing angle is dictated by the lower bound of Eqn.3.77 as the wind speed increases. The run of the optimization procedure on a CDC 6600 requires 100-200ms CPU time including overhead and I/O routines.

3.6 System dynamics and control simulation

3.6.1 System dynamics simulation

Using the system differential equations and the power balance Eqns 3.73 and 3.74, the dynamics of the system are described by a 20th order system of non-linear differential equations. Excluding the synchronous and induction generator rotor and excitation system transient voltages, all other electric quantities are assumed to change instantaneously and so their relations are expressed by algebraic equations (algebraic 'electrical interface').

Single phase representation has been adopted based on a balanced three phase system. Subtransient effects have been neglected. Therefore if the synchronous generator is fitted with a damper winding, response to 'switching' transients will not be properly simulated. These simplifications have been made for two reasons:

a) The object of the simulation was mainly to study the behaviour and the controllability of the system during wind speed fluctuations, which have a low frequency spectrum. Torque-wise this spectrum is further restricted by the low pass filtering nature of the wind turbine.

b) Without the above simplifying assumptions, the program would require much greater CPU memory and run times prohibiting normal day-time runs on the College computer. The system of D.E.'s describing the dynamics has five continuous input parameters:

- d) Wind speed
- b) Real load demand
- c) Blade pitch angle
- e) TCR firing angle

and three boolean input parameters:

- a) Diesel clutch state
- b) WECS main circuit breaker state
- c) Static capacitor state.

The wind speed, real and reactive load demand and external disturbances to the system. The clutch, WECS CB and static capacitor states are determined by steady state or emergency considerations.

The blade pitch angle and TCR firing are determined by the control system as described in the next subsection. The system of D.E.'s representing the dynamics and the control system is integrated using a user fixed external step. For each external step integration a variable step, variable order Gear routine (Ref. 3.19, 3.20) is used.

Gear's routine is reputed to have very good convergence properties for numerically stiff problems. The numerical stiffness of a D.E. system is measured by the ratio of the largest to the smallest time constant. This good convergence has been confirmed in the present study in which the system stiffness is of the order of 10^4 .

The bus voltage and currents are determined at each internal integration step by solving, through the Gauss-Seidel method, the algebraic system relating them to the state variables.

3.6.2 Control system simulation

The dynamic control objectives are:

- (a) To keep the voltage constant, within specified limits.
- (b) To keep the frequency constant, within specified limits.

The continuous control variables α and β are simulated as analog PI controllers for frequency and induction generator speed control as shown in Fig. 3.14. The equations governing the control action are

$$\begin{aligned} \Delta\alpha = & -K_{t1}\Delta\omega_s - K_{t5}\Delta\omega_{IG} - \frac{1}{T_{t2}} \int_0^t \max\{0, \omega_s - \omega_{sul}\} dt - \\ & + \frac{1}{T_{t3}} \int_0^t \max\{0, \omega_{snom} - \omega_s\} dt + \frac{1}{T_{t4}} \int_0^t (\alpha_{opt} - \alpha) dt \end{aligned} \quad (3.87)$$

$$\begin{aligned} \Delta\beta = & K_{p1}\Delta\omega_{IG} + K_{p7}\Delta\omega_s + \frac{1}{T_{p2}} \int_0^t (\omega_{IG} - \omega_{IGnom}) dt + \\ & + \frac{1}{T_{p3}} \int_0^t (\omega_s - \omega_{snom}) dt + \frac{1}{T_{p4}} \int_0^t \left(\frac{\omega_{IG}}{\omega_s} - \omega_{IGnom} \right) dt + \end{aligned} \quad (3.88)$$

with $-\Delta\beta^M < \Delta\beta < \Delta\beta^M$

In Eqn 3.87 the first two terms represent proportional contributions. The third term is an integral part which comes into action

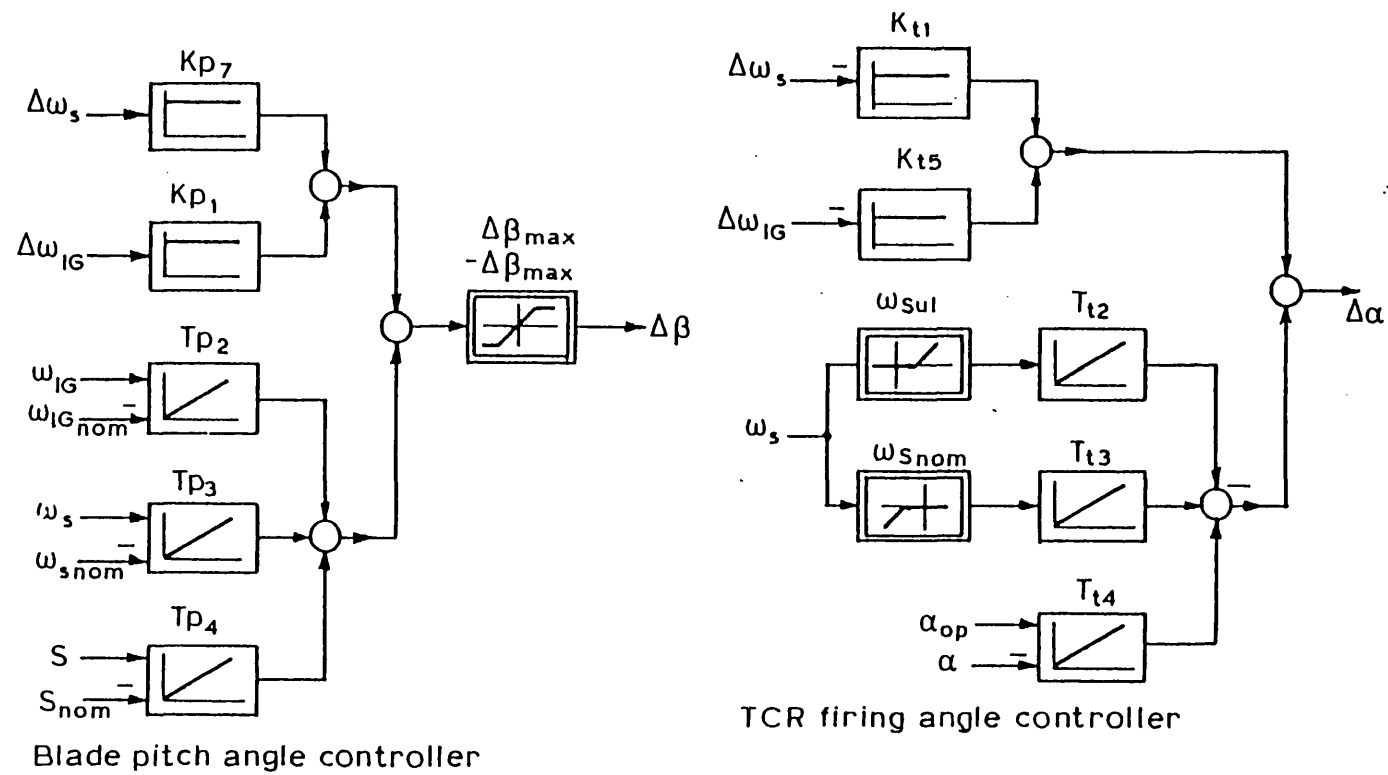


Fig. 3-14 Controller structure

only when the synchronous machine speed exceeds the diesel minimum load speed ω_{sul} . The fourth term is also an integral part which is active only when frequency falls below the nominal value. The last two terms enhance thyristor controller action when the frequency is outside the band f_{nom} to f_{ul} . This permits minimization of the diesel power. The fifth term is an integral part aimed at forcing the firing angle towards the optimal value calculated for steady state conditions.

Equation 3.88 has a similar structure, the integral parts biasing the controller action towards nominal wind turbine generator speed and slip corresponding to rated power output. The controller incorporates a rate of change limiter to avoid aerodynamic overstresses on the blades. This simple controller uses only two inputs, frequency and wind turbine generator speed, and allows easy decoupling between the two systems. It is suboptimal under dynamic conditions and optimal under steady state conditions.

The system remains controllable within limits, even if one of the inputs is lost, although for enhanced system security the power signal of the diesel and the wind turbine generator could be introduced as additional variables.

The control system parameters have been chosen in an empirical way in order to (a) achieve decoupling between the wind turbine speed-blade pitch and diesel generator speed-TCR firing angle subsystems and (b) good performance at 8 m/s wind speed and nominal load demand, the condition found to be the most critical region of operation.

Fig. 3.15 illustrates the linearised system basic structure having omitted the gear-box, frictional torques and electrical losses and assumed infinitely rigid shafts and no delays in the governor and exciter response.

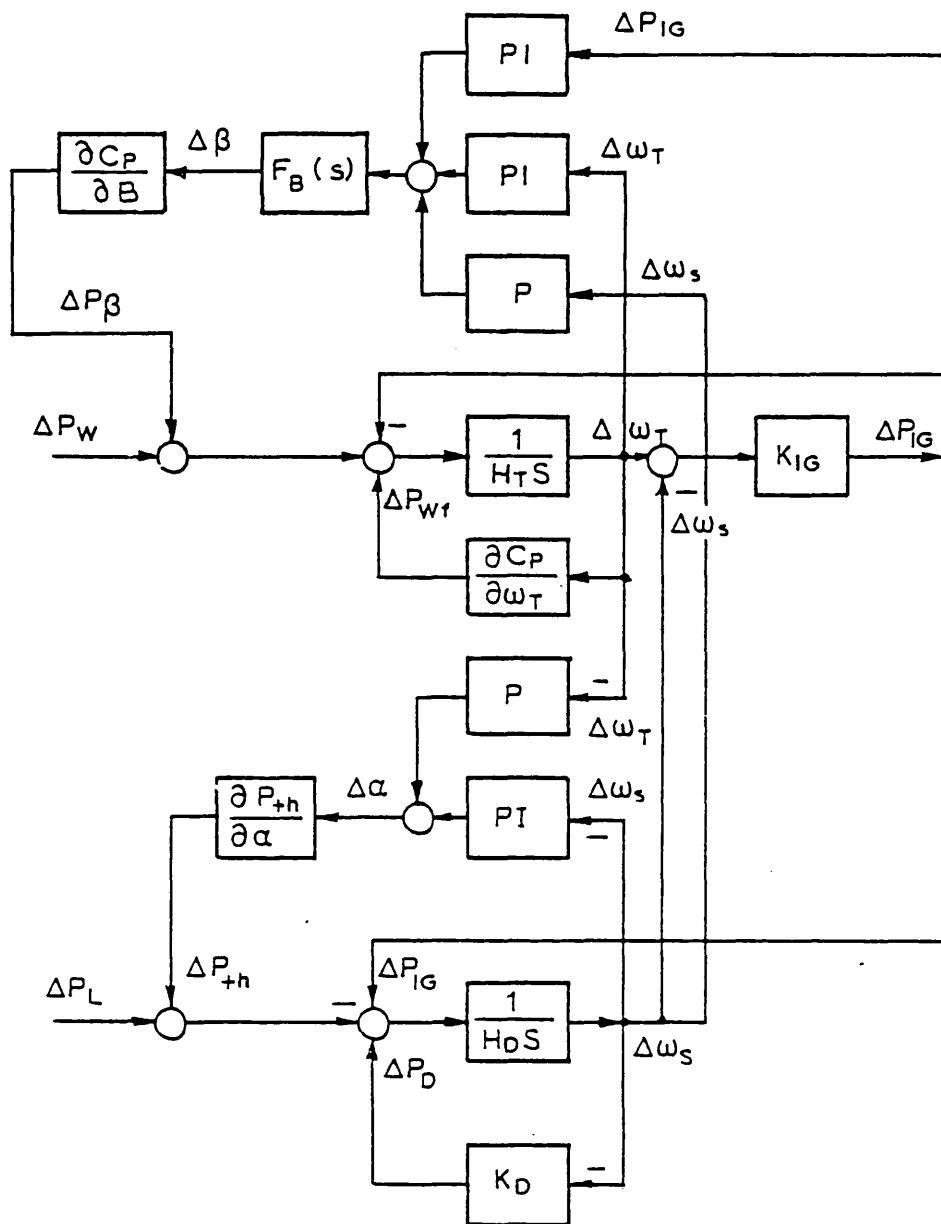


Fig. 3-15 Simplified control scheme for the combined Diesel/Wecs system

3.7 Program description

The program DYTEST is written in FORTRAN IV and consists of six main routines:

- a. An input routine SUBINP which reads from the screen or a specified file all the relevant system design parameters, the control system parameters, the numerical integration specifications (duration, external step, tolerances), output specifications (variables to be monitored, frequency of monitoring).
- b. A preliminary calculation routine PRECAL which transforms all system parameters in a consistent per unit system and creates all other constant parameters which are used in the simulation program.
- c. The steady state optimization and calculation routine STEADY which determines and outputs the mode of operation and the steady state control variable values for optimal operation at the steady state conditions specified by the user (wind speed, nominal real and reactive load demand).
- d. The dynamics initialization procedure INDYN which reads any step changes at the starting point of the dynamics simulation (i.e. load changes, switching actions, control parameter changes due to failure or malfunction), initializes all state variables according to the steady state calculation, and recalculates all other variables (e.g. voltage, currents), if there is any change in the initial conditions.
- e. The numerical integration routine DYNAM which at each point, reads the wind speed, performs the step integration using Gear's integration subroutine, and reinitializes the system in the case of emergency switching

actions during integration.

f. The output routine OUT which is called by DYNAM! at discrete frequency and outputs the variables specified in SUBINP.

The program structure is shown in the flow chart Fig. 3.16. Further details on these routines are given in Appendix 3.2.

3.8 Analysis of the simplified linearized system

The linearization and the development of analytical expressions (transfer functions) describing the system behaviour for small perturbations, although unacceptable in terms of accuracy for a highly non-linear system subject to large disturbances as the one under study, may provide some qualitative insights.

To develop the linearized model the following simplifying assumptions are made:

- a. Infinite shaft rigidities
- b. Negligible mechanical and electrical losses
- c. Constant bus voltage maintained by the synchronous generator excitation system
- d. Linear slip-power characteristic for induction generator
- e. Diesel governor without delay

With these assumptions the system equations reduce to

$$2H_T \dot{\omega}_T = (P_W - P_{IG}) / \omega_T \quad (3.89)$$

$$2H_D \dot{\omega}_S = (P_D + P_{IG} - P_L) / \omega_S \quad (3.90)$$

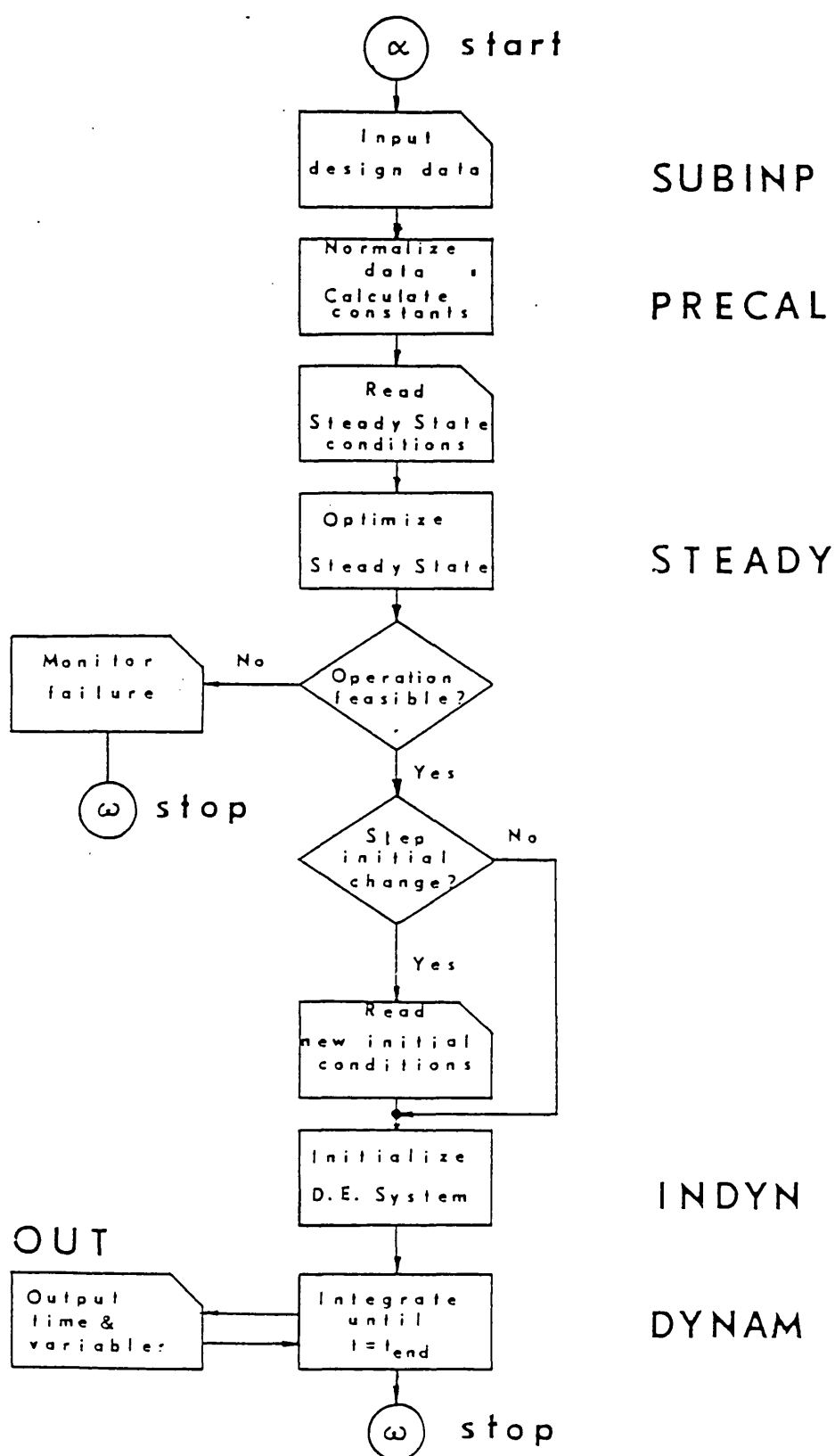


Fig. 3.16 Program DYTEST (WECS/Diesel Dynamics Test Simulation) Flow Chart

where H_T : the inertial time constant of the WECS (wind turbine,
transmission and induction generator)

H_D : the inertial time constant of the diesel set
(diesel engine and synchronous generator)

ω_T : the turbine speed

ω_S : the synchronous generator speed

P_w : the mechanical power input to the turbine rotor

P_{IG} : the real power output of the induction generator

P_D : the mechanical power output of the diesel engine

P_L : the real load (load demand and dump load)

We use the power/speed characteristics for the induction generator and the diesel engine:

$$P_{IG} = \frac{P_{IG}^r}{S_r} \frac{\omega_T - \omega_S}{\omega_S} \quad (3.91)$$

$$P_D = \frac{P_D^r}{D_r} \cdot \frac{\omega_{ref} - \omega_S}{\omega_{ref}} + P_{D0} \quad (3.92)$$

where S_r the rated induction generator slip and ω_{ref} the nominal diesel engine speed corresponding to nominal frequency operation.

For the mechanical power input to the turbine rotor we use Eqn. 3.67. Linearization of Eqns. 3.91, 3.92 and 3.67 around the steady state point $\omega_S = \omega_{ref} = 1$, $\omega_T \approx 1$ results in:

$$\Delta P_{IG} = \frac{P_{IG}^r}{S_r} (\Delta \omega_T - \Delta \omega_S) \quad (3.93)$$

$$\Delta P_D = \frac{P_D^r}{D_r} \cdot \Delta \omega_S \quad (3.94)$$

$$\Delta P_W = P_W \left[\frac{\lambda}{C_p} \frac{\partial C_p}{\partial \lambda} \Delta \omega_T + \left(3 - \frac{\lambda}{C_p} \frac{\partial C_p}{\partial \lambda} \right) \frac{\Delta W}{W} + \frac{1}{C_p} \frac{\partial C_p}{\partial \beta} \Delta \beta \right] \quad (3.95)$$

where λ the tip speed ratio and β the blade pitch angle.

For the real load the increment is calculated (including the dump load change due to TCR action and neglecting changes in commutation resistance due to frequency change) by

$$\Delta P_L = \Delta P_{LO} + \frac{\partial P_{TCR}}{\partial \alpha} \Delta \alpha \quad (3.96)$$

To abbreviate the expressions we introduce

$$K_{C_p} = P_W \cdot \frac{\lambda}{C_p} \frac{\partial C_p}{\partial \lambda}$$

$$K_{IG} = \frac{P_r^{IG}}{S_r} \quad (3.98)$$

$$K_D = \frac{P_D^r}{Dr} \quad (3.99)$$

$$\Delta P_{WO} = P_W \left[\left(3 - \frac{\lambda}{C_p} \frac{\partial C_p}{\partial \lambda} \right) \frac{\Delta W}{W} + \frac{1}{C_p} \frac{\partial C_p}{\partial \beta} \Delta \beta \right] \quad (3.100)$$

For the linearized system the Laplace transforms for the angular speed increments and the induction generator power can be obtained from Eqn 3.89-3.91.

Two modes operation have to be distinguished:

- a. WECS stand alone operation-diesel engine declutched.

In this case $\Delta P_D = 0$ and $H_D = H_S$ (H_S : the synchronous generator inertial time constant) and after some algebra the Laplace transform are found to be:

$$L\{\Delta\omega_S\} = \frac{K_{IG}}{4H_S H_T} \frac{L\{\Delta P_{W0}\} - (1 - \frac{K_{cp}}{K_{IG}} + \frac{2H_T}{K_{IG}} S)L\{\Delta P_L\}}{S^2 + [(\frac{1}{2H_T} + \frac{1}{2H_S})K_{IG} - \frac{K_{cp}}{2H_T}]S - \frac{K_{IG}K_{cp}}{4H_T H_S}} \dots(3.101)$$

$$L\{\Delta\omega_T\} = \frac{K_{IG}}{4H_S H_T} \frac{(1 + \frac{2H_S}{K_{IG}} S)L\{\Delta P_{W0}\} - L\{\Delta P_L\}}{S^2 + [(\frac{1}{2H_T} + \frac{1}{2H_S})K_{IG} - \frac{K_{cp}}{2H_T}]S - \frac{K_{IG}K_{cp}}{4H_T H_S}} \dots(3.102)$$

$$L\{\Delta P_{IG}\} = \frac{K_{IG}}{4H_S H_T} \frac{2H_S \cdot S \cdot L\{\Delta P_{W0}\} + (-K_{cp} + 2H_T S)L\{\Delta P_L\}}{S^2 + [(\frac{1}{2H_T} + \frac{1}{2H_S})K_{IG} - K_{cp}/2H_T]S - \frac{K_{IG}K_{cp}}{4H_T H_S}} \dots(3.103)$$

where $L\{x\}$ means the Laplace transform of x .

We can observe that the uncontrolled system behaviour depends on the slope of the $C_{p,\lambda}$ characteristic (see Fig. 3.10).

a) if $K_{cp} > 0$ (i.e. we are operating on the ascending part of the $C_{p,\lambda}$ curve) there is a positive real system eigenvalue which indicates instability.

b) if $K_{cp} = 0$ (i.e. we are operating on the flat top part of the C_p, λ curve) there is a zero eigenvalue and the system has an integral behaviour.

c) if $K_{cp} < 0$ (i.e. we are operating in the descending part of the C_p, λ (curve) the eigenvalues are both real and negative and the system is stable and overdamped.

The application of the final value theorem on Eqn 3.101 to 103 for case (c) results in:

$$\Delta\omega_S = \frac{1}{K_{cp}} (\Delta P_{W0} - \Delta P_L) \quad (3.104)$$

$$\Delta\omega_T = - \frac{1}{K_{cp}} (\Delta P_{W0} - \Delta P_L) \quad (3.105)$$

$$\Delta P_{IG} = \Delta P_L \quad (3.106)$$

As $|K_{cp}| < 1$ for the normal operating range ($K_{cp} < 0$), the above equations indicate that, although the uncontrolled system will eventually reach a new steady state, the relative speed deviation will be larger than the relative values of the incremental disturbances either in wind power or in load demand. So although the uncontrolled system is strictly stable when operating on the descending part of the C_p, λ curve, small disturbances in load demand or just wind speed will cause frequency excursions violating the tight-frequency limits.

b. System with parallel operations of WECS and Diesel generator.

In this case, we obtain the following system transfer equations

$$L\{\Delta\omega_S\} = \frac{K_{IG}}{4H_T H_D} \frac{L\{\Delta P_{W0}\} - (1 - \frac{K_{cp}}{K_{IG}} + \frac{2H_T}{K_{IG}} S) L\{\Delta P_L\}}{S^2 + [(\frac{1}{2H_T} + \frac{1}{2H_D})K_{IG} - \frac{K_{cp}}{2H_T} + \frac{K_D}{2H_D} + \frac{K_{IG} - K_{cp}(K_{IG} + K_D)}{4H_T H_D}]S}$$

... (3.107)

$$L\{\Delta\omega_T\} = \frac{K_{IG}}{4H_T H_D} \frac{(1 + \frac{K_D}{K_{IG}} + \frac{2H_D}{K_{IG}} S) L\{\Delta P_{W0}\} - L\{\Delta P_L\}}{S^2 + [(\frac{1}{2H_T} + \frac{1}{2H_D})K_{IG} - \frac{K_{cp}}{2H_T} + \frac{K_D}{2H_D}]S + \frac{K_{IG}K_D - K_{cp}(K_{IG} + K_D)}{4H_T H_D}}$$

... (3.108)

$$L\{\Delta P_{IG}\} = \frac{K_{IG}}{4H_T H_D} \frac{(K_D + 2H_D S) L\{\Delta P_{W0}\} + (-K_{cp} + 2H_T S) L\{\Delta P_L\}}{S^2 + [(\frac{1}{2H_T} + \frac{1}{2H_D})K_{IG} - \frac{K_{cp}}{2H_T} + \frac{K_D}{2H_D}]S + \frac{K_{IG}K_D - K_{cp}(K_{IG} + K_D)}{4H_T H_D}}$$

... (3.109)

In this case the critical stability limit (one pole at the origin) occurs when

$$K_{cp} = \frac{K_{IG} K_D}{K_{IG} + K_D} \quad (3.110)$$

as K_{IG} and K_D have values greater than K_{cp} by at least an order of magnitude (for usual nominal slip and droop values) the uncontrolled system is expected to be always stable. As previously, the final values of speed and induction generator power are:

$$\lim_{t \rightarrow \infty} \Delta \omega_S = \frac{1}{K_D - K_{cp} \left(1 + \frac{K_D}{K_{IG}}\right)} \left[\Delta P_{W0} - \left(1 - \frac{K_{cp}}{K_{IG}}\right) \Delta P_L \right] \quad (3.111)$$

$$\lim_{t \rightarrow \infty} \Delta \omega_S = \frac{1}{K_D - K_{cp} \left(1 + \frac{K_D}{K_{IG}}\right)} \left[\left(1 + \frac{K_D}{K_{IG}}\right) \Delta P_{W0} - \Delta P_L \right] \quad (3.112)$$

$$\lim_{t \rightarrow \infty} \Delta P_{IG} = \frac{1}{K_D - K_{cp} \left(1 + \frac{K_D}{K_{IG}}\right)} \left[K_D \Delta P_{W0} + K_{cp} \Delta P_L \right]. \quad (3.113)$$

As K_D is some orders of magnitude larger than the second term in the denominator, (for $P_D^r = 1$ and $Dr = 0.04$ $K_D = 40$, whereas for $s_r = 0.03$, $P_{IG}^r = 1$, $K_{cp} \left(1 + \frac{K_D}{K_{IG}}\right) \leq 2$), for the same relative disturbances the uncontrolled system is expected to exhibit excursions in frequency substantially smaller than in the previous case. The diesel engine governor has a stabilizing effect on the system as intuitively expected.

The above results are qualitatively confirmed by the simulation results and eigenvalue analysis performed subsequently in this chapter.

3.9 Dynamic simulation examples

3.9.1 Deterministic input signals

Several numerical studies with deterministic input signals (wind speed, real and reactive load demand, blade pitch control failure,

TCR failure) have been carried out in order to assess system performance. Although the signals (especially the deterministic wind speed changes) are not realistic, these studies give valuable information of the system response to various disturbances at different operating points.

The system parameters given in Appendix 3.1 are used in all the following studies in which the load demand is taken to be nominal 100KW, at 0.8 lagging power factor.

Step disturbances occur at time $t = 0$.

a) Wind speed step changes

The system has been subjected to step decrements and increments of 2 m/s in the low, middle and high wind speed operation range. This kind of disturbance represents a very severe test for the control system, as the mechanical power input changes instantaneously with the cube of the speed.

Satisfactory system performance in such unrealistically severe circumstances indicate that performance will also be satisfactory in the case of real gusts or lulls.

In all cases presented here the response of characteristic quantities of the uncontrolled system (fixed blade pitch and TCR firing angle) will be given to allow assessment of the control system performance.

a1) Increase 5-7 m/s (Fig. 3.17)

The system is operating in parallel generation mode.

The mechanical input power increases from 0.2 to 0.7 pu.

The turbine and synchronous generator speed responses are over-critically damped.

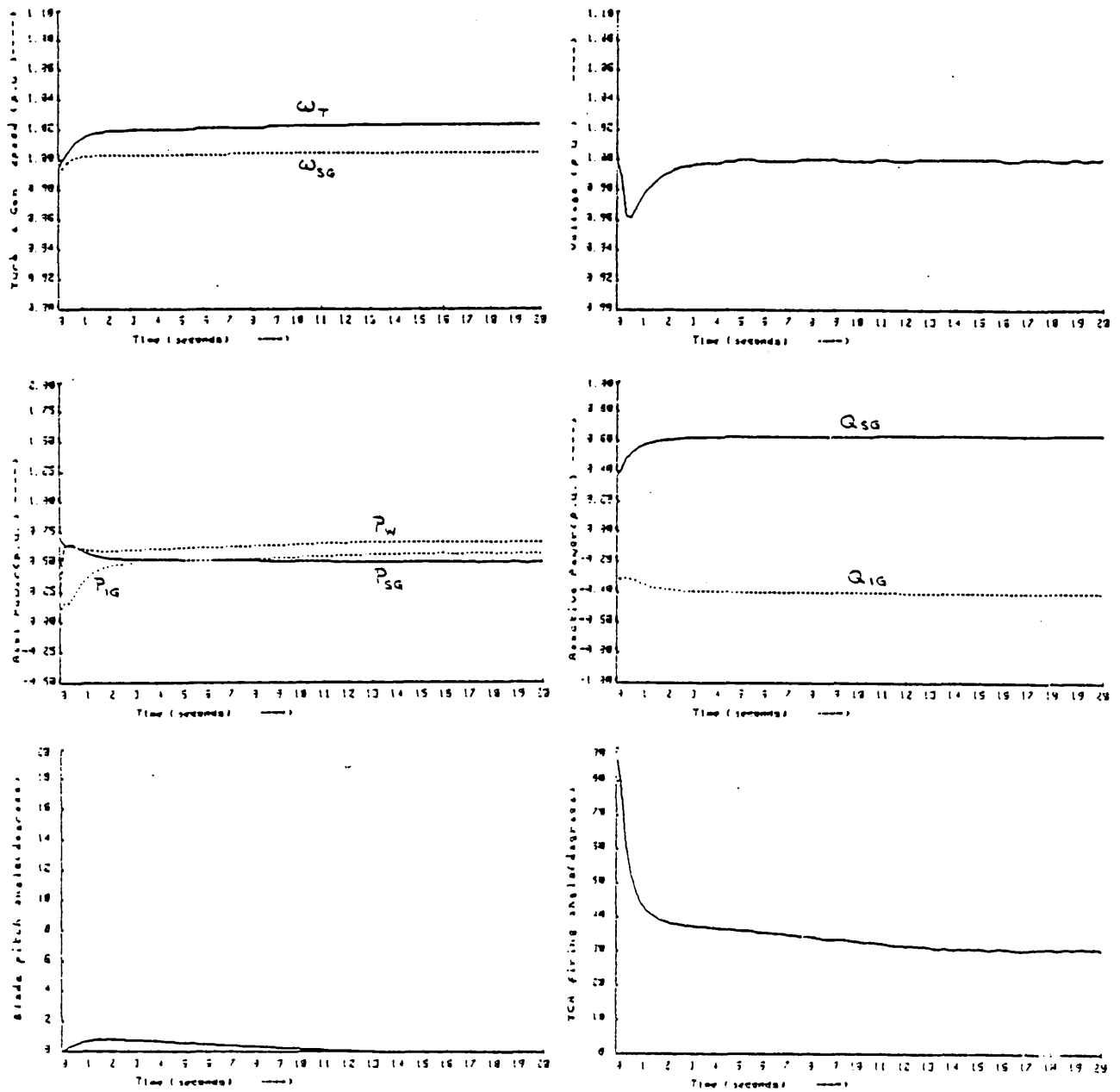


Fig. 3.17 a

Controlled system step response

Wind speed increase from 5 to 7 m/s

System in parallel generation mode

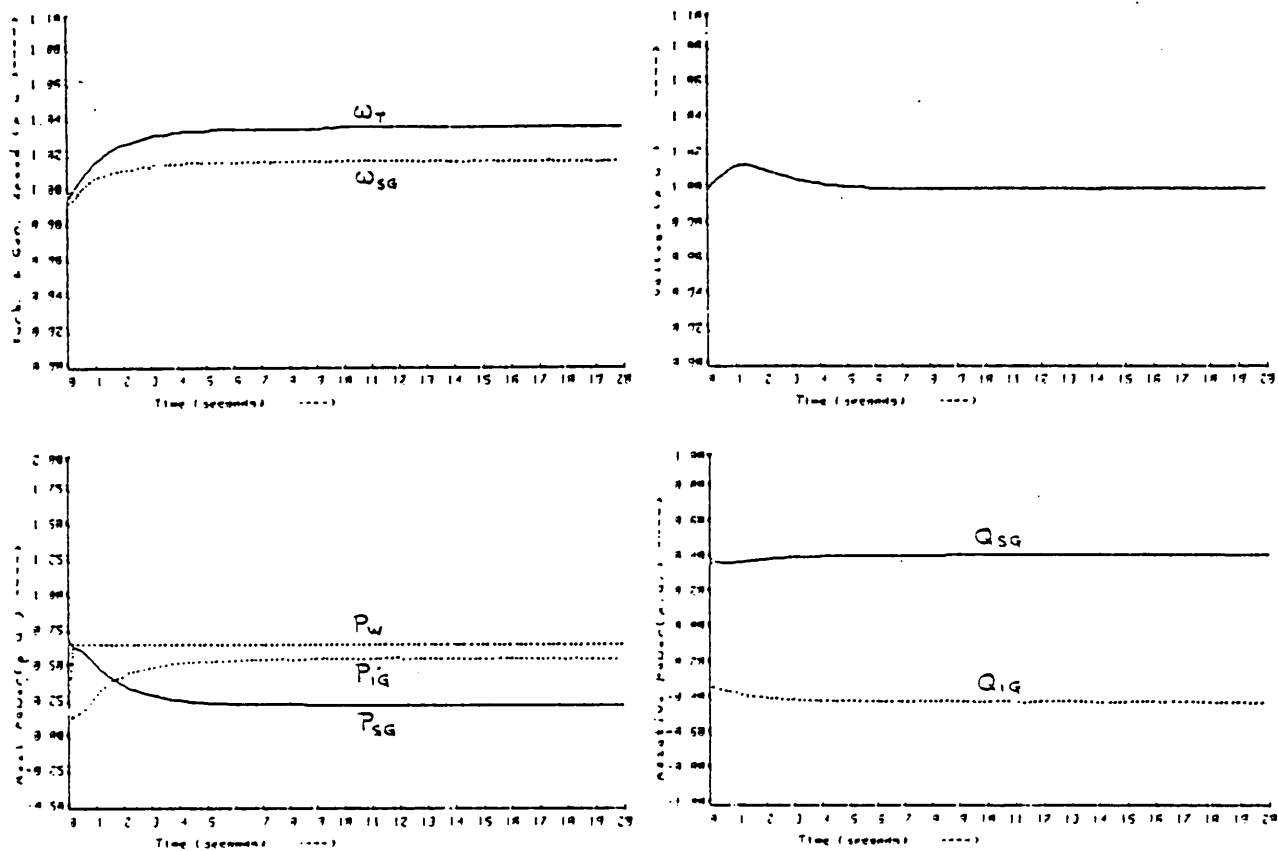


Fig. 3.17 b

Uncontrolled system step response

Wind speed increase from 5 to 7 m/s

System stable

The voltage exhibits a transient dip to 0.96 p.u. caused by the rapid increase in the reactive power absorbed by the TCR bridge.

The blade pitch angle after coarsening, in order to damp the input torque, returns to the fine (0°) position to maximize input power at the new steady state.

The increase in dump load power compensates partly the increase in wind power so that the diesel runs at the minimum power of 0.4 p.u.

The transient is practically over in 3 seconds

The response of the uncontrolled system is similar.

There is no inherent aerodynamical damping to be observed.

(The operation point at 7 m/s wind speed is at the flat top part of the C_p, λ curve - $\lambda = 11$, $\beta = 0^\circ$)

a2) Increase 10-12 m/s (Fig. 3.18)

The system is operating in the WECS alone generation mode.

The mechanical input power rises instantaneously from 1.10 to 1.80 p.u., and is damped exponentially by blade pitch control action.

The TCR firing angle decreases in less than 1 sec to 0° in order to brake the system electrically. The spike-like change in the reactive power absorbed by the bridge causes a voltage drop to 0.96 p.u.

The frequency reaches a peak of 1.02 p.u. and reverts to the nominal value again after about 8 seconds, when also all other transients are nearly over.

After this period the TCR firing angle α changes slowly towards

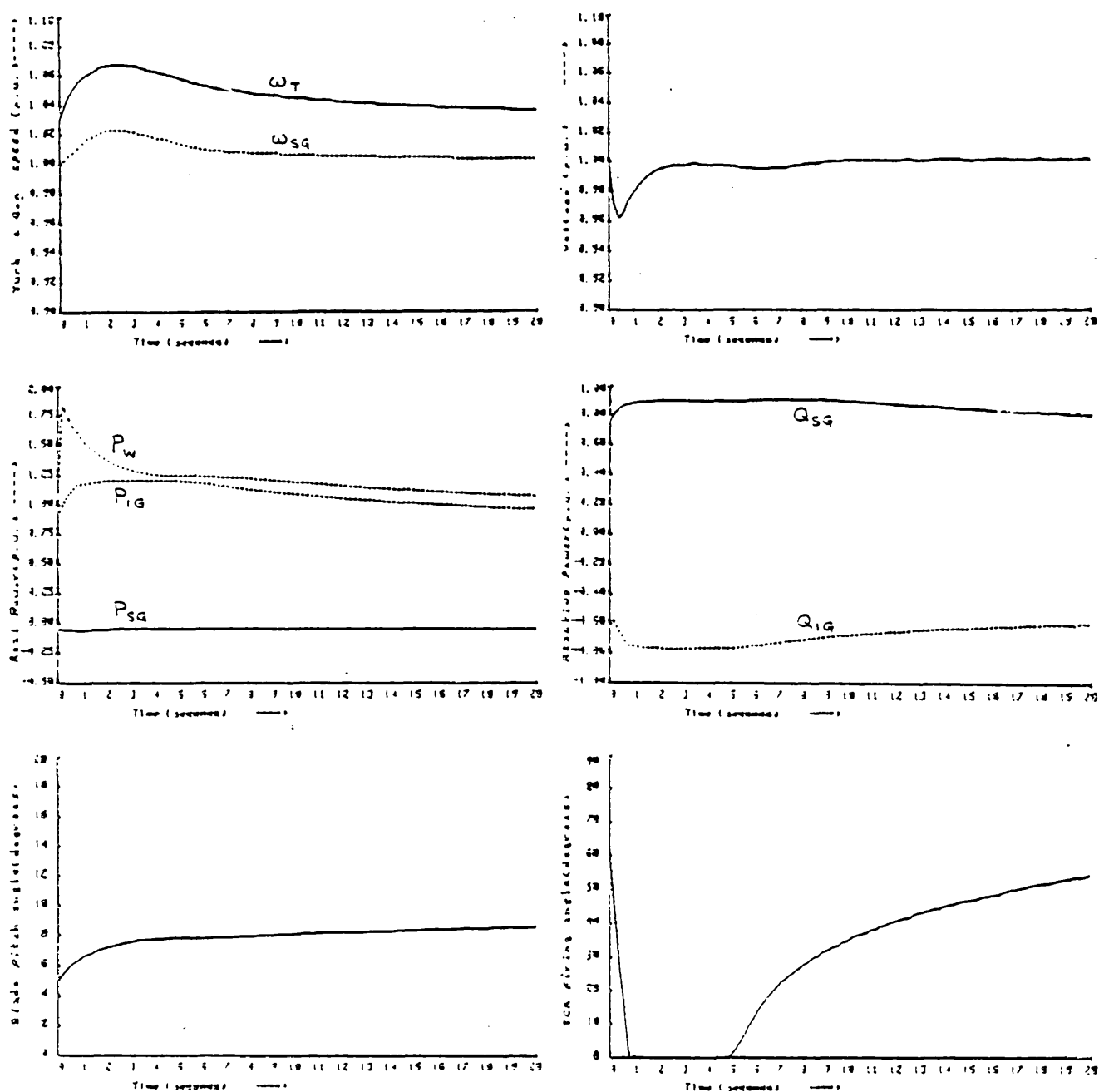


Fig. 3.18 a

Controlled system step response

Wind speed increase from 10 to 12 m/s

System in WEDS alone generation mode

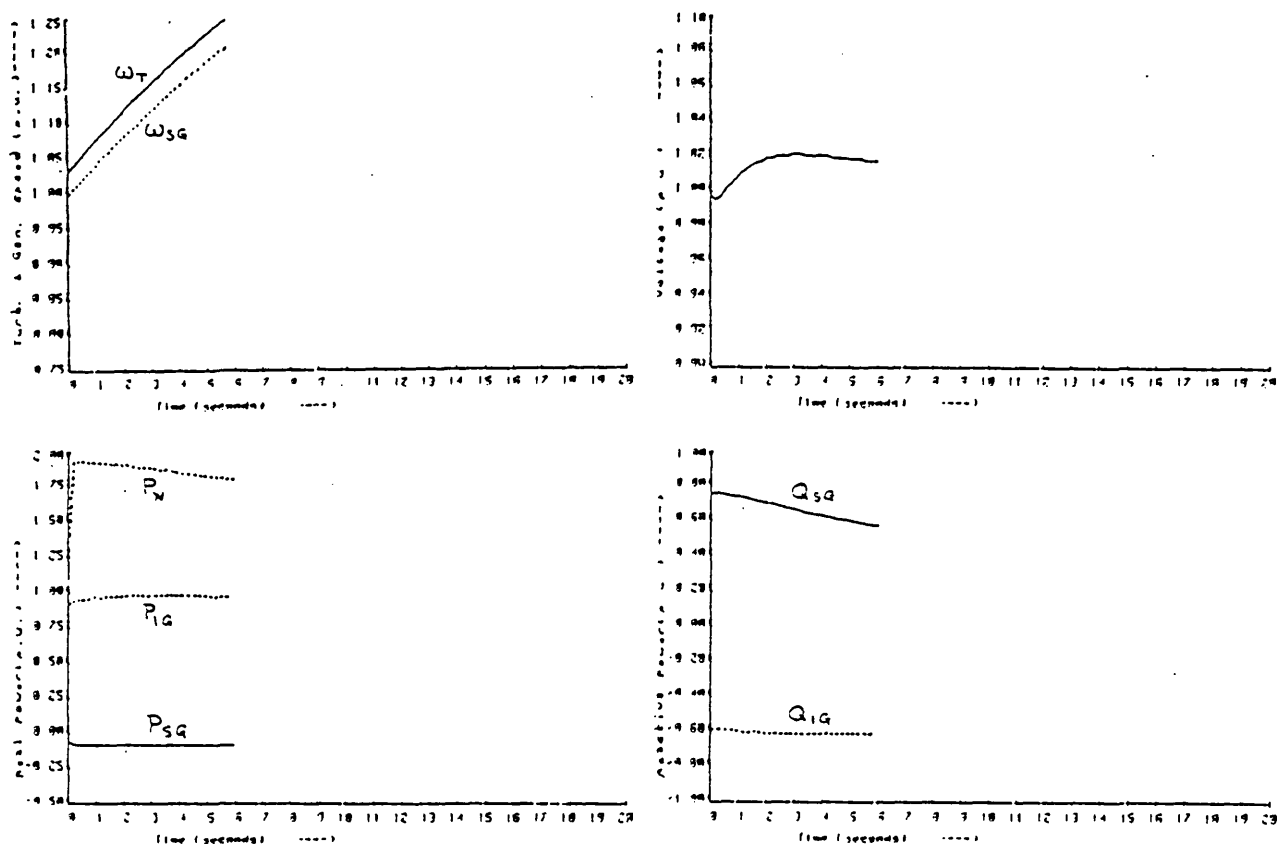


Fig. 3.18 b

Uncontrolled system step response

Wind speed increase from 10 to 12 m/s

System unstable

the new optimal steady state.

In the uncontrolled system, the turbine speed and frequency increase nearly linearly as the aerodynamical damping is very small and the turbine reaches the overspeed limit (125%) within 6 seconds. The frequency exceeds the upper limit of 1.04 p.u. after about 1 sec.

This again confirms the integrating behaviour, for small K_{cp} , predicted in the preceding section.

a3) Decrease 12-10 m.s (Fig 3.19)

The frequency reaches a low of 0.97 p.u. and the voltage exhibits a spike at 1.05 p.u. at the beginning of the transient.

α increases to 90° and stays there; system controls depends on blade pitch changes only. The voltage and power transients exhibits a slight overshoot indicating undercritical feedback damping.

The uncontrolled system speed response exhibits again nearly integrative behaviour, the frequency exceeding the lower limit of 0.96 p.u. after 2 seconds only. The inherent aerodynamic damping can be observed in the mechanical input power response which recovers slowly, after the initial instantaneous drop, as the operating point moves up on the $C_{p,\lambda}$ characteristic .

b) Triangular wind gust: 5-10-5 m/s-rate of change $.5 \text{ m/s}^2$ (Fig. 3.20)

This was simulated in order to demonstrate the system behaviour when the diesel engine is clutched and declutched.

The diesel engine is declutched on the ascending part of the gust at $t = 7\text{s}$ when the diesel generator output power has reached the

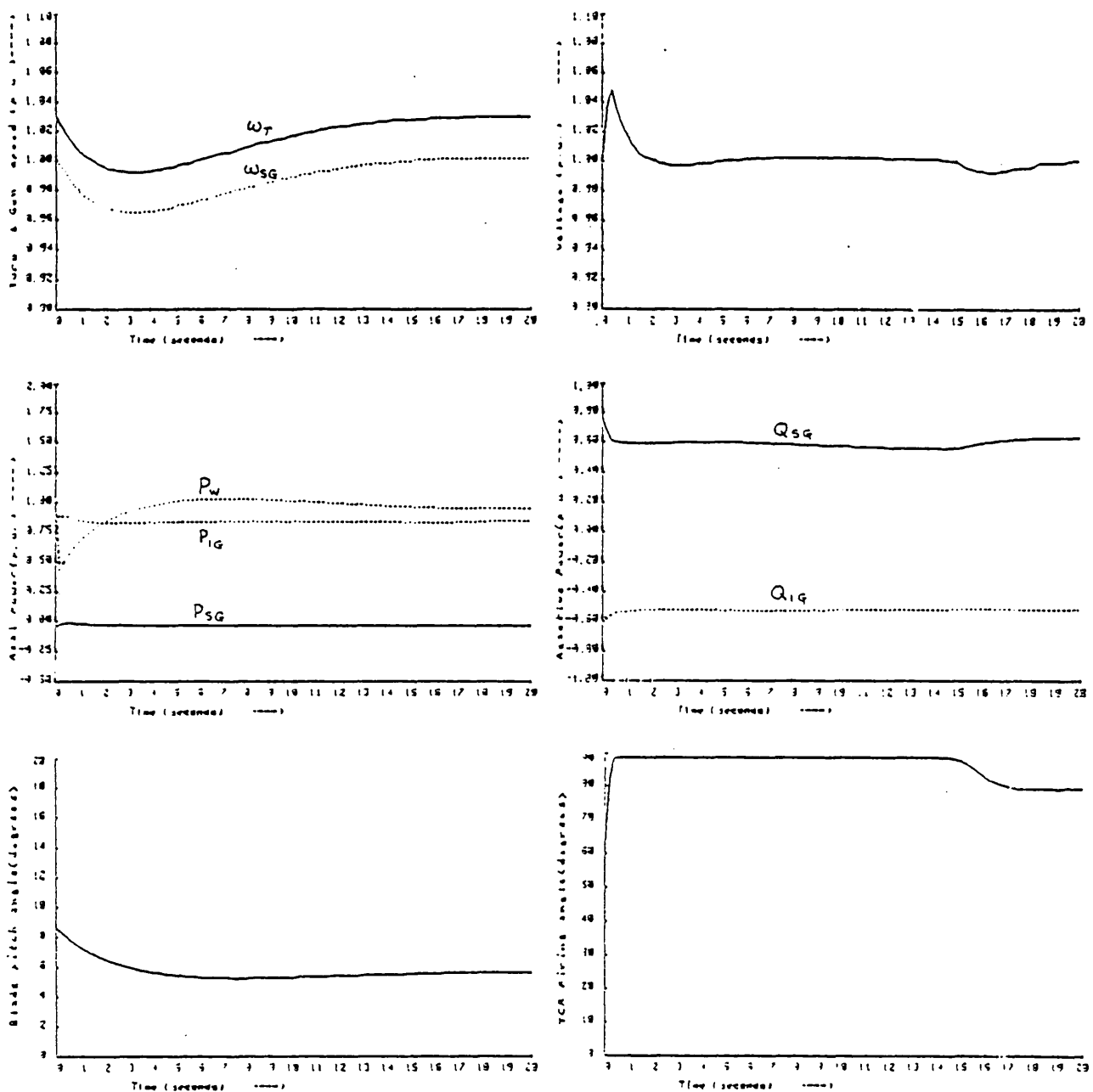


Fig. 3.19 a

Controlled system step response

Wind speed decrease from 12 to 10 m/s

System in WECS alone generation mode

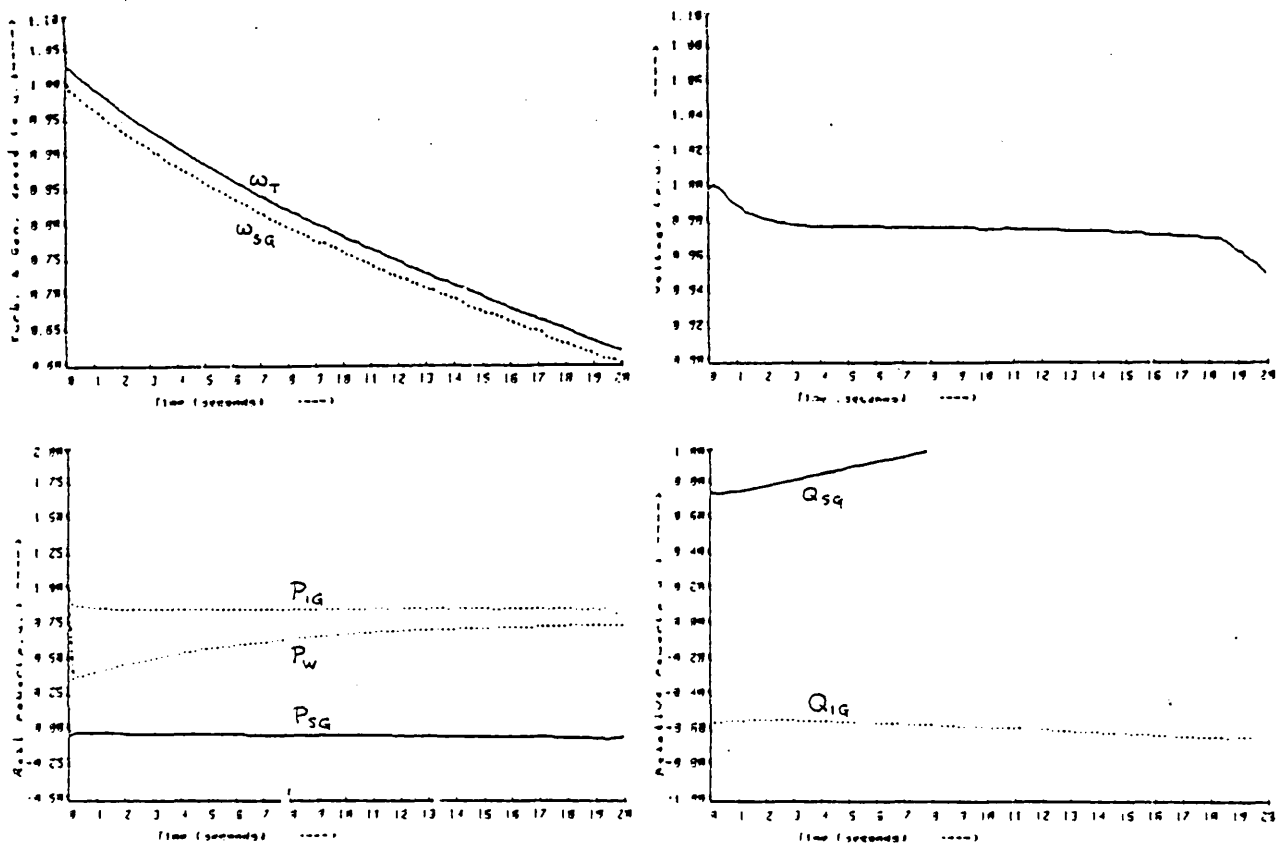


Fig. 3.19 b

Uncontrolled system step response

Wind speed decrease from 12 to 10 m/s

System unstable

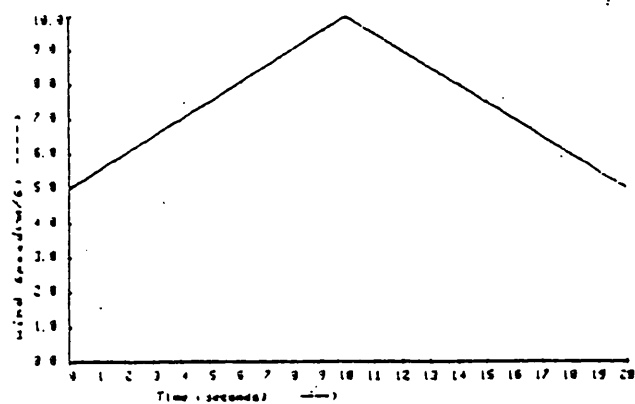
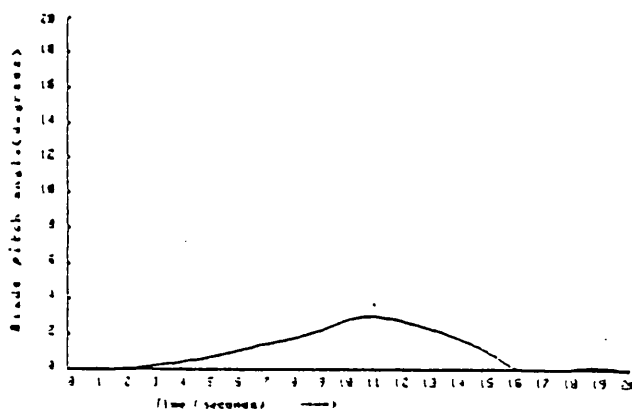
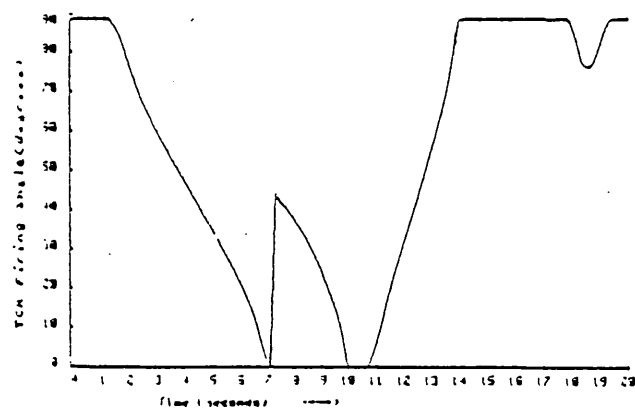
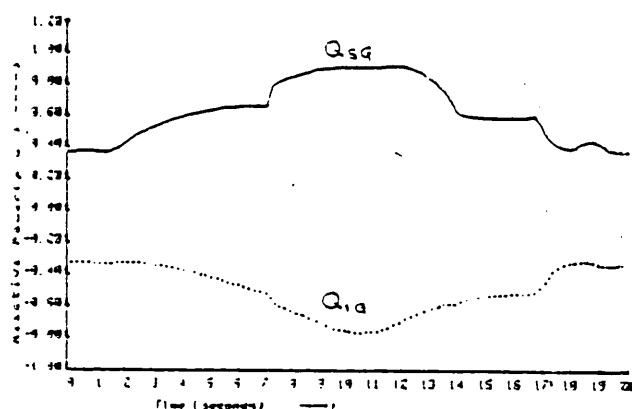
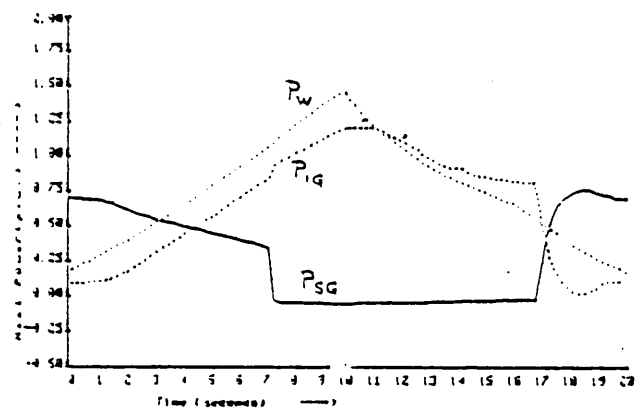
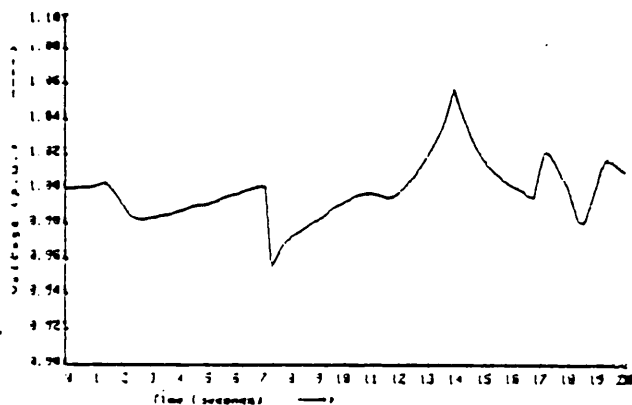
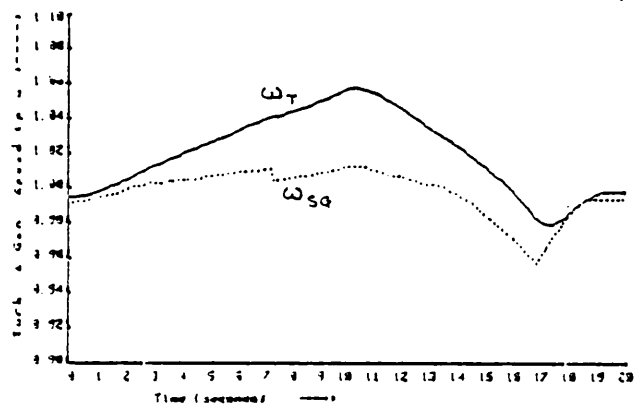


Fig. 3.20

Controlled system response to
triangular gust

Diesel engine declutched and clutched



minimum (0.4 p.u.) and the dump load is fully in. At the moment of declutching, there is a small frequency drop due to the loss of the mechanical power input from the diesel engine and a voltage dip at 0.95 p.u. due to the sudden increase in the reactive power absorbed by the TCR bridge as α changes almost instantaneously from 0 to 40° to compensate the frequency drop. As the power output from the induction generator continuous to increase, α is gradually restored to 0° .

The voltage spike of 1.06 p.u. at $t = 14\text{s}$ is caused again by the reactive power spike of the TCR as the firing angle is rapidly increased in order to unload the system during the wind speed decrease.

The diesel engine is clutched again at $t = 17\text{s}$ when the frequency has reached the lower limit of 0.96 p.u. (48 Hz).

The synchronous generator takes on power and the system is restored to the steady state after 3 seconds.

c) Loss of load (Fig. 3.21)

The system has been tested to a sudden load loss of 50% (100 to 50KW by 0.8 lagging power factor), while operating in WECS only generating mode at a constant wind speed of 8 m/s. At this wind speed the aerodynamical damping is nearly zero (worst case).

After the initial voltage spike to 1.09 p.u. the system recovers to steady state within 5 seconds without any significant frequency deviation. The uncontrolled system exhibits the predicted unstable behaviour overspeeding in 13 seconds.

d) Induction generator cut-in (paralleling) test (Fig. 3.22)

The run-up of the wind turbine and the paralleling process

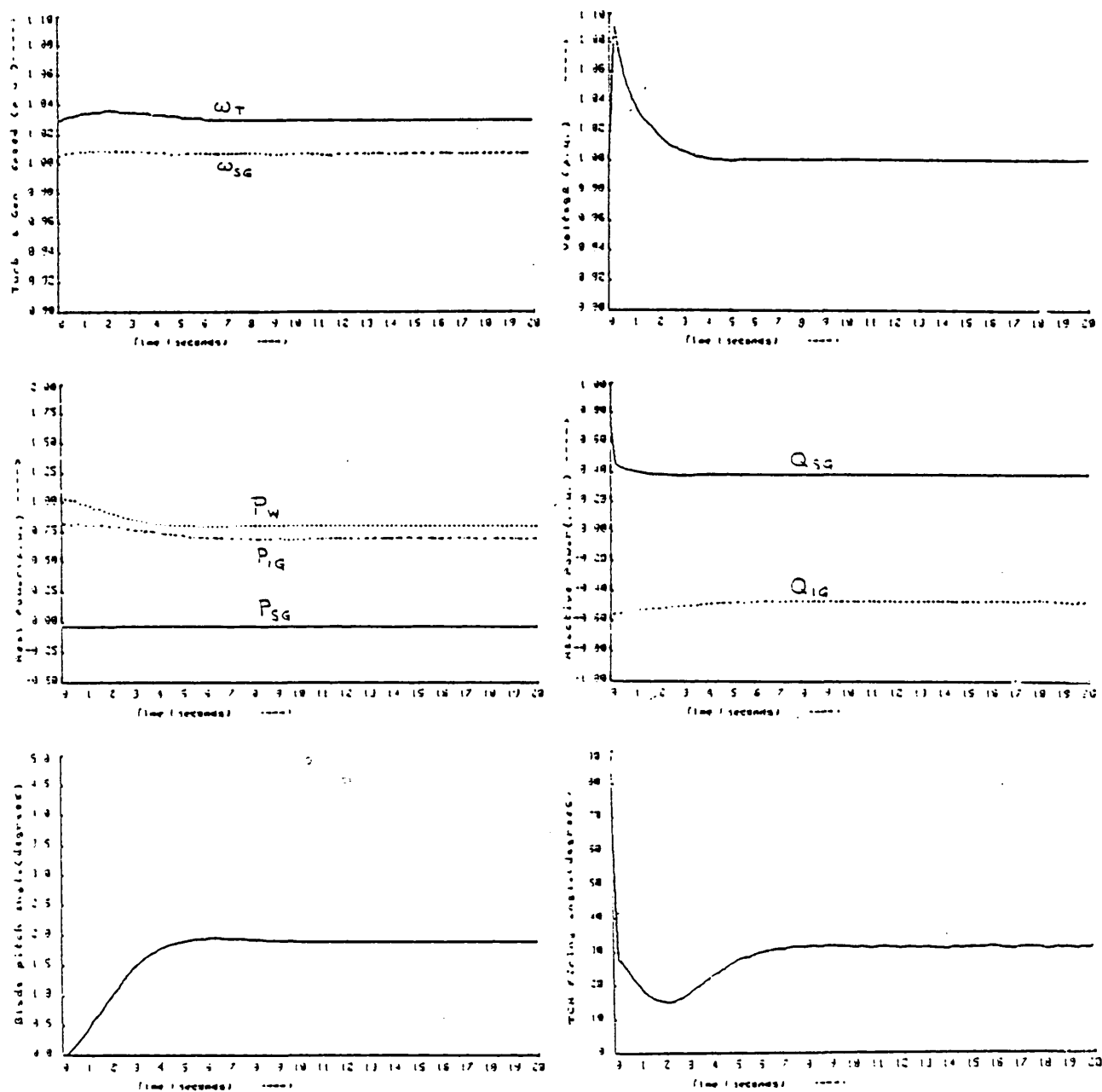


Fig. 3.21 a

Controlled system response to load reduction from 100 to 50 %

Wind speed constant 8 m/s

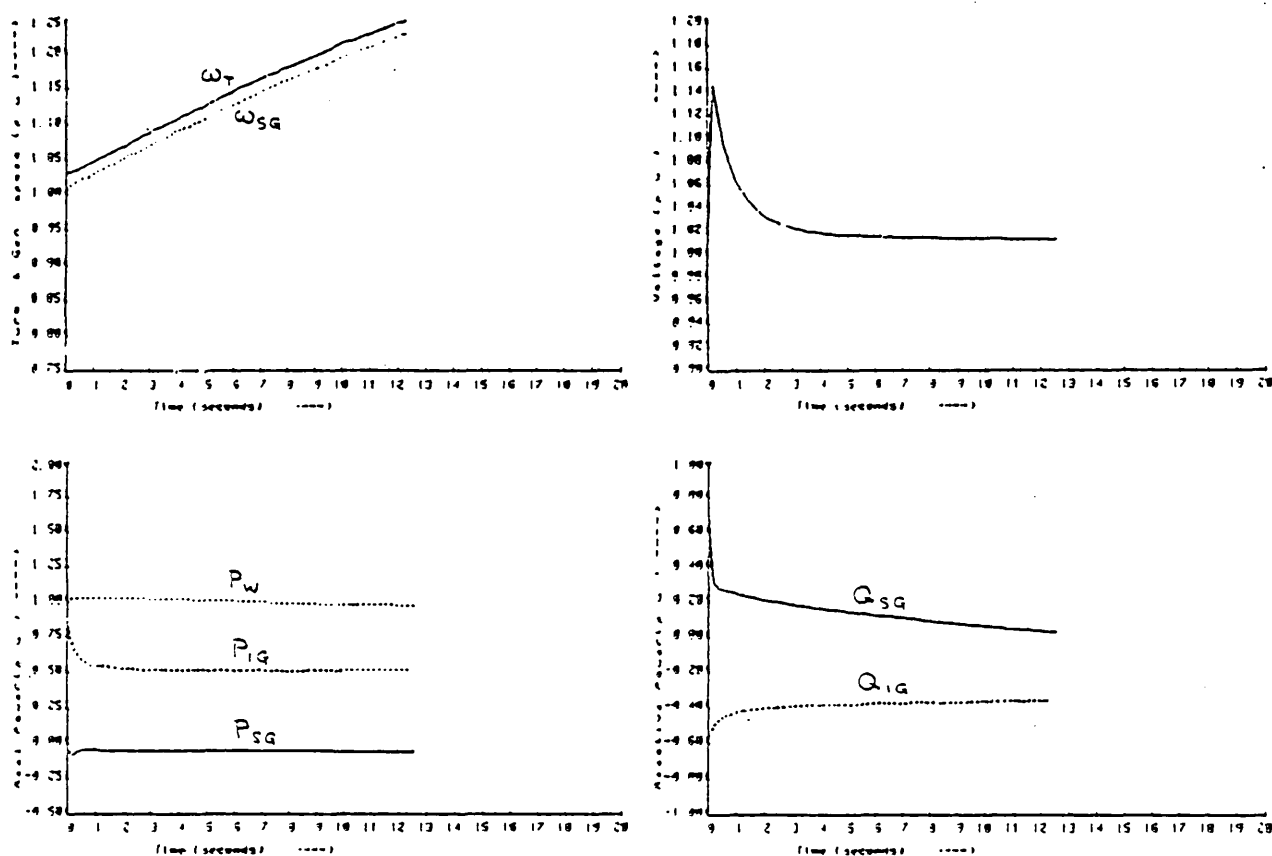


Fig. 3.21 b

Uncontrolled system response to load reduction from 100 to 50 %

Wind speed constant 8 m/s

System unstable

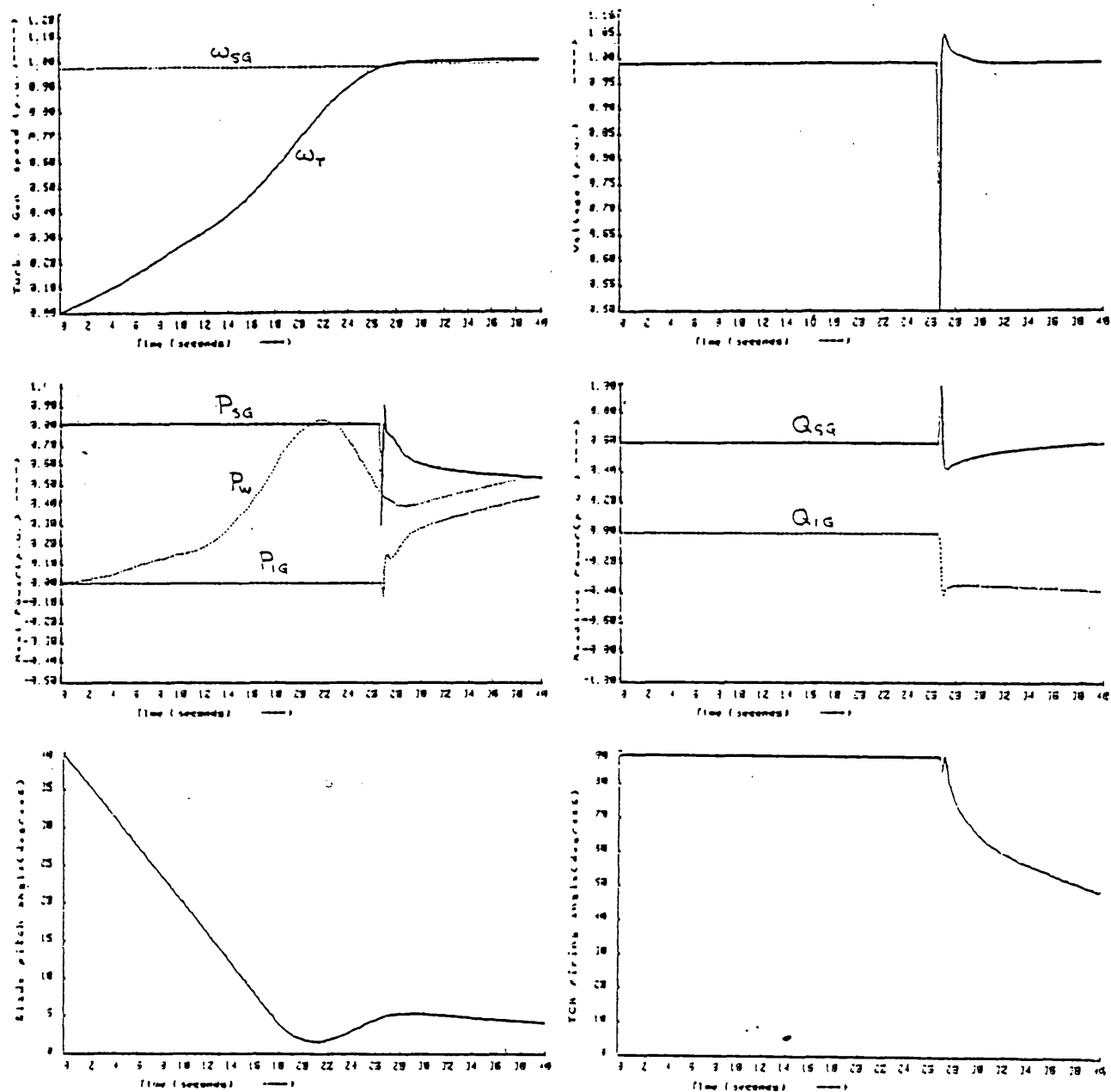


Fig. 3.22

WECS synchronization process

Wind speed constant 3 m/s

of the induction generator were simulated in order to assess possible system stability problems. As stated previously, the run-up and cut-out procedures require separate control algorithms as the optimality criteria are different from the normal operation mode.

In this case, as we were interested at the electromechanical transients after paralleling, the run-up of the turbine itself has not been optimized. (The pitch angle is not adjusted to maximum accelerating torque).

The paralleling process was studied under a constant wind speed of 8 m/s. The paralleling criterion (WECS circuit breaker closing signal) is that the induction generator runs at a slip less than 0.005.

Apart from the initial voltage drop to 0.5 p.u. at the instant of the CB closure, the process is smooth and the transient is over within 5 seconds.

The voltage drop in reality will be smaller as in the simulation (Ref. 3.21) and the voltage will be within the $\pm 10\%$ limits after approximately three periods (60 ms). (Ref. 3.21, 3.22). This is considered to be acceptable for small isolated networks. Otherwise the use of (a) a current limiting device or (b) Δ -Y switching of the induction generator winding or (c) separate excitation of the induction generator through the static capacitor and synchronisation has to be considered.

e) WECS cut-out (Fig. 3.23).

In this case the electromechanical transient during WECS cut-out was simulated by implementing a wind speed drop from 8 m/s

(WECS alone operation mode) to 1 m/s.

The frequency reaches the lower limit of 0.96 p.u. in approximately 0.9 sec when the diesel engine is clutched and begins to share power. The induction generator is switched off and the wind turbine stopped when motoring occurs after 2.2 seconds.

The transient is over after 4 seconds. The voltage fluctuations remain within $\pm 6\%$ due mainly to the fast TCR action.

From the tests with deterministic disturbances we are allowed to conclude that the dynamic behaviour of the system is close to what has been predicted in the simplified analysis in Sec. 3.8 and that the performance of the control system proposed is satisfactory. The frequency and voltage remain within the set of $\pm 4\%$ and $\pm 10\%$ respectively with the exception of case d. The voltage fluctuations could probably be further reduced at the expense of frequency fluctuations if the voltage were to be introduced as a feedback variable to the TCR controller.

To assess the performance of the system under realistic wind conditions the following studies were performed, using simulated stochastic wind speed time series and measured wind speed series.

3.9.2 Simulated stochastic wind speed time series

The simulation of a discrete time series of turbulent wind has been based on three hypotheses which are more or less generally accepted as valid for short time fluctuations (Ref. 3.23)

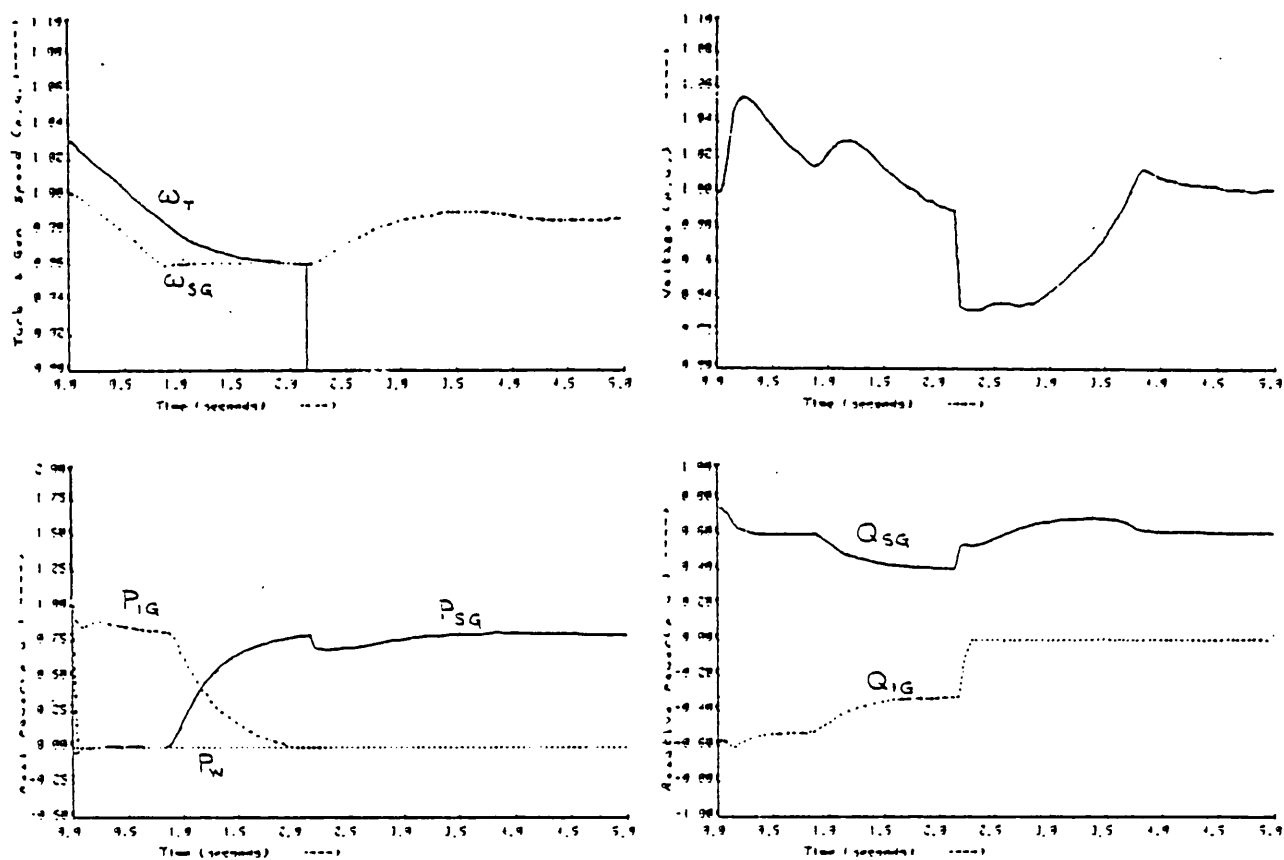


Fig. 3.23

WECS cut-off process

Wind speed reduction from 8 to 1 m/s

a) The wind speed deviation from the mean is generated by a stationary stochastic process with normal statistics.

b) There exists a fundamental spatial correlation function defining the longitudinal and transverse correlation coefficient of the wind fluctuation components between two points in the direction of flow, assuming isotropic turbulence.

For the simulation purposes, the flow has been assumed uniform in the transverse directions (unidimensional flow model) and so only the longitudinal correlation is considered.

The von Dreyden correlation function Eqn 3.114 resulting in a linear first order transfer function in space has been adopted rather than the nonlinear von Karman function, the difference being not significant for our purpose (Ref. 3.23).

c) The spatial correlation of the wind speed fluctuation between two points in the flow axis can be transformed to time correlation for two time instants on the same point by using Taylor's hypothesis ("frozen turbulence concept"), which is that the turbulence moves in space with the mean wind speed.

The above assumptions can be expressed by the following equations. The spatial correlation coefficient of the wind speed at two points in space having a longitudinal distance r is

$$f(r) = \exp(-r/L_p) \quad (3.114)$$

where L_p the 'integral length scale' depending on height and surface

roughness and not dependent on wind speed.

Taylor's hypothesis:

$$r = \bar{W} \cdot \tau \quad (3.115)$$

where $\bar{W}$ the mean wind speed.

Then the time correlation coefficient can be expressed as:

$$g(\tau) = \exp\left(-\frac{\tau}{T}\right) \quad (3.116)$$

where $T = \frac{L}{\bar{W}}$ a time constant for stationary wind speed ($\bar{W}$ constant).

This result with a first order autocorrelation function for the wind speed deviation from the mean seems to be confirmed by measurements (Ref. 3.24, 3.25), for short time sampling.

For the simulated wind runs a first order autoregressive gaussian standard random number generator has been used (Ref. 3.27).

The time constant T is 10 sec in all cases. A relatively high turbulence value of $\sigma_w/\bar{W} = 0.15$ was chosen. The load in all cases is the nominal 100 KW, at 0.8 lagging power factor. Two cases at low and high wind speed, were simulated.

(i) Mean wind speed 6 m/s (Fig 3.24)

The system is operating in parallel generation mode.

Although the mechanical input power to the turbine changes substantially in a band from 0.2 to 0.6 p.u. (25 to 75 KW) with a mean of 0.3 p.u., the frequency deviation is less than 0.5%. The voltage remains within $\pm 2\%$. The low-pass filter effect of the turbine rotor inertia can be observed when comparing the fluctuations of the mechanical input power to the electrical power from the induction generator. The damping effect of the TCR controlled load is apparent in the even smoother curve of the

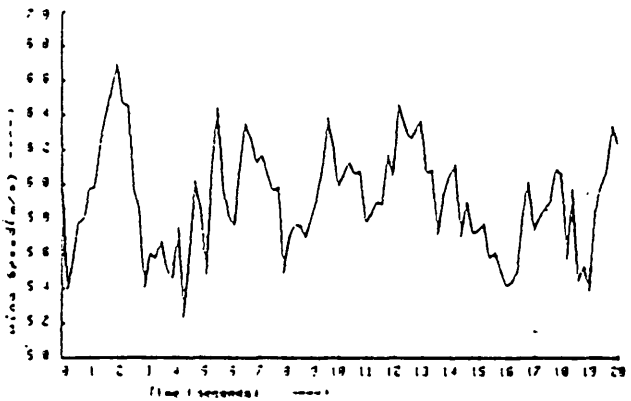
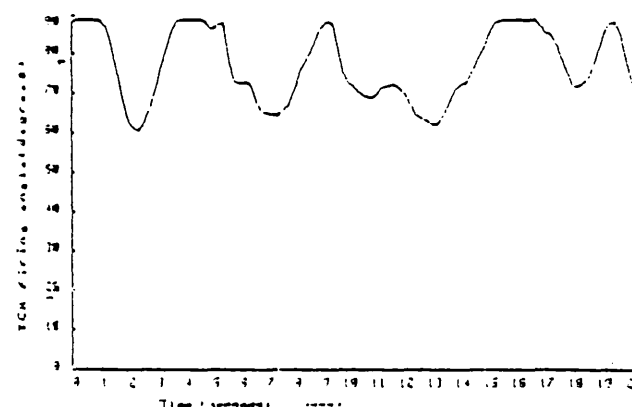
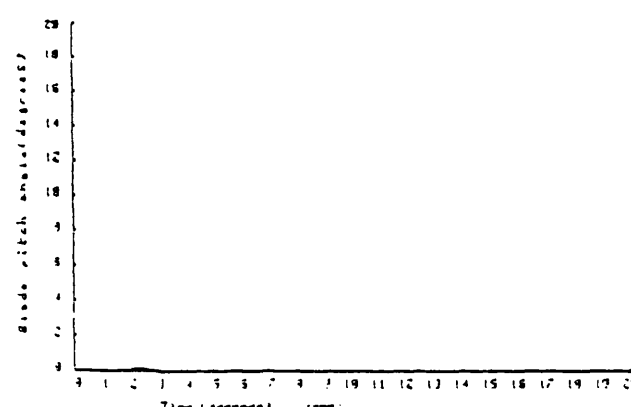
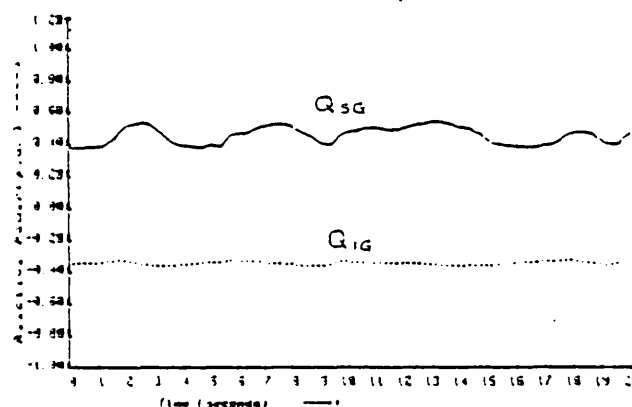
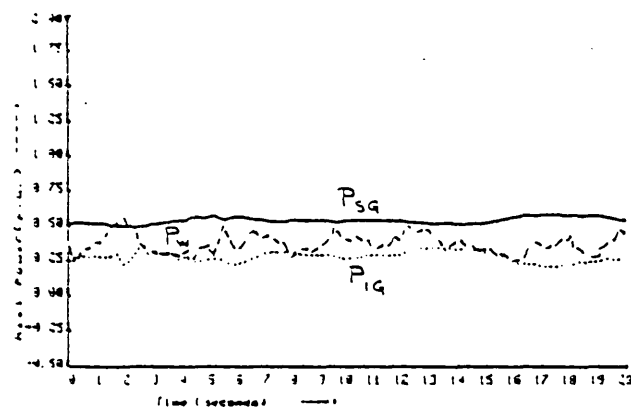
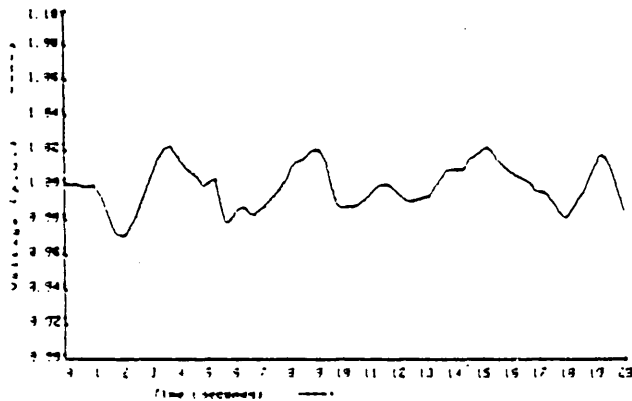
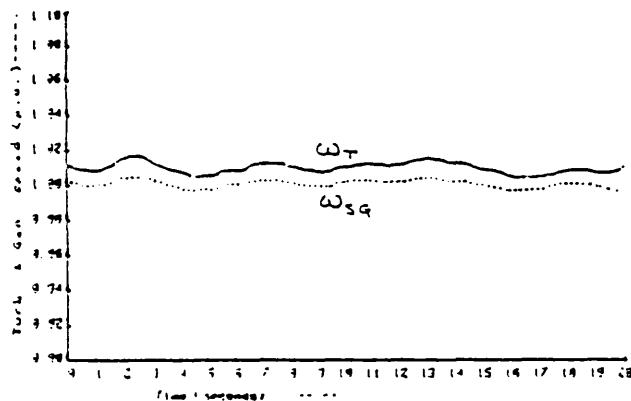


Fig. 3.24
System response to wind turbulence
Parallel generation mode
Wind speed average 6 m/s
Turbulence 15 %



diesel generator output power.

The blade pitch control is hardly activated, the blade pitch angle remaining at the fine position to ensure full utilization of the wind power input.

(ii) Mean wind speed 14 m/s (Fig. 3.25)

Due to the cubic power law the 15% turbulence is now much more apparent in the mechanical power input fluctuations which are in a band from 0.3 to 1.7 p.u. . Comparison of the wind speed with the mechanical power curve demonstrates the effect of the blade pitch control and the aerodynamic damping.

The frequency remains within the band of $\pm 1\%$ but the voltage fluctuations of $\pm 6\%$ are large. It should be noted that the wind turbulence assumed here is high and the maximum allowed rate of change of 2 degrees/second in the blade pitch controller is conservative and imposes a rather high control burden on the TCR.

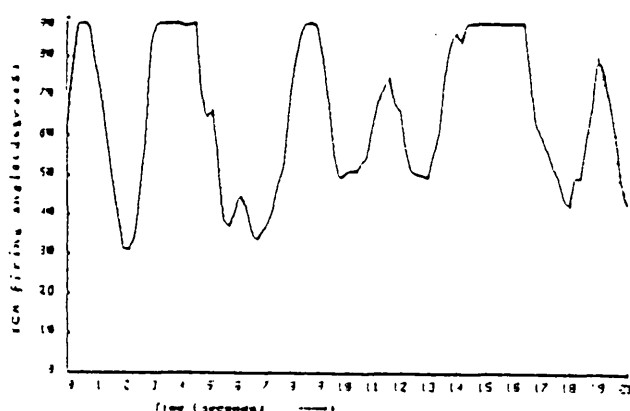
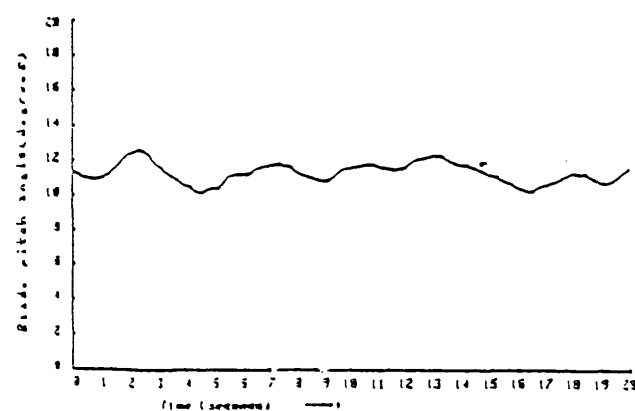
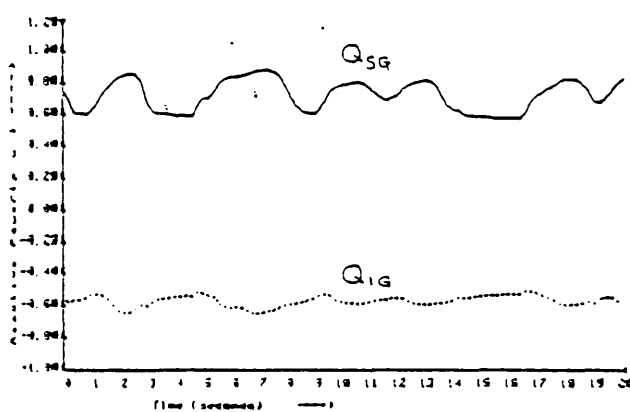
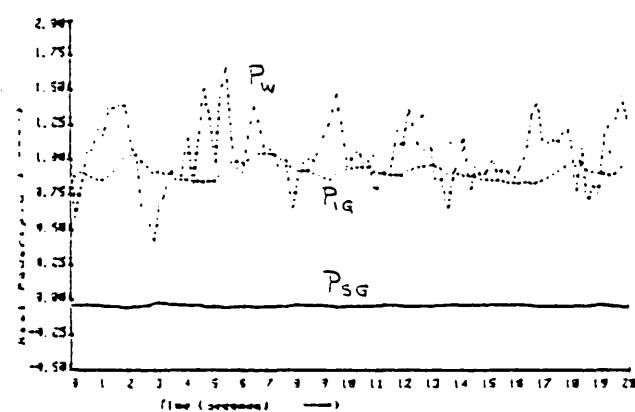
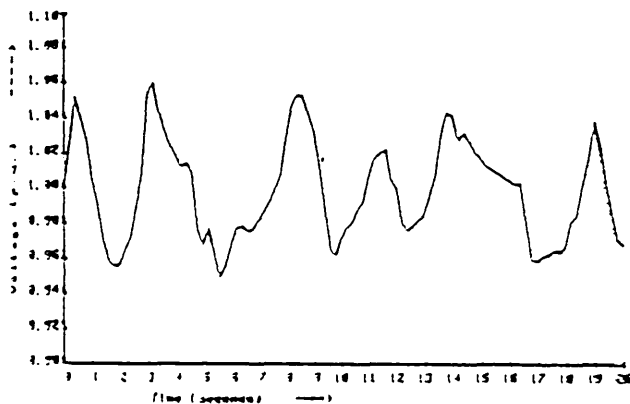
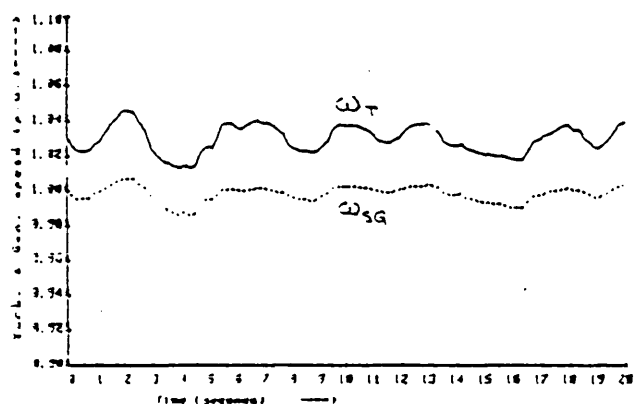
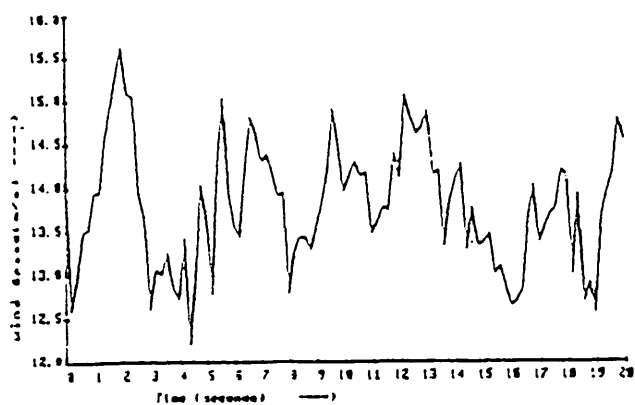
These tests demonstrate a satisfactory system performance, the frequency and voltage being kept well within the prescribed limits. No instability was observed.

3.9.3 Measured wind speed time series

The simulation tests on the system are concluded with two measured wind speed input runs. The wind speed time series are 20 seconds samples from 2 seconds measurements on the Orkney Islands. They have been chosen from 24h data as the samples with abrupt wind speed changes in the low and

Fig. 3.25

System response to wind turbulence
 WECS alone generation mode
 Wind speed average 14 m/s
 Turbulence 15 %



high wind speed region.

To reconstruct the continuous wind signal from the 2 second sample measurements a spectrum preserving interpolation routine has been used. Obviously the spectrum of the original continuous wind signal is distorted by the sampling for frequencies below the Shannon limit of 0.25 Hz and completely lost for frequencies above this limit. The interpolation is still meaningful as the spectral content of the wind signal for frequencies above this limit is expected to be relatively low (Ref. 3.24-3.26) and the high wind speed frequencies are anyway filtered through the turbine rotor inertia whose low pass filter characteristic has a cut-off frequency of 0.05 Hz.

(i) Low wind speed input (Fig. 3.26)

The characteristic feature of this signal is the sudden lull to values below the cut -off wind speed (4.47 m/s) and the rather abrupt gust to nearly 8 m/s. The system is operating in parallel generation mode. The frequency is well controlled within a $\pm 1\%$ band. The maximum voltage fluctuation is $\pm 2\%$. The blade pitch controller is activated when the wind speed rises above 7 m/s. The induction generator motors slightly for about 2 seconds during the lull.

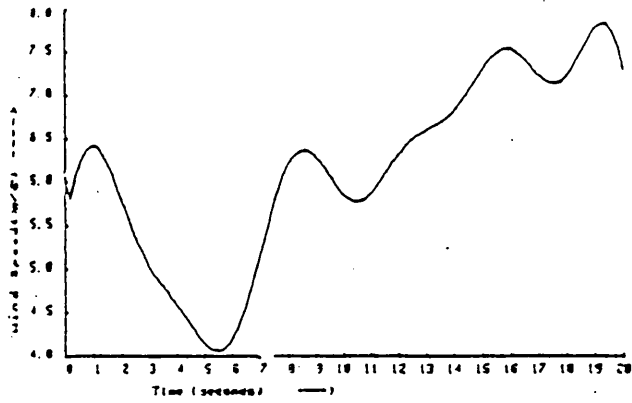
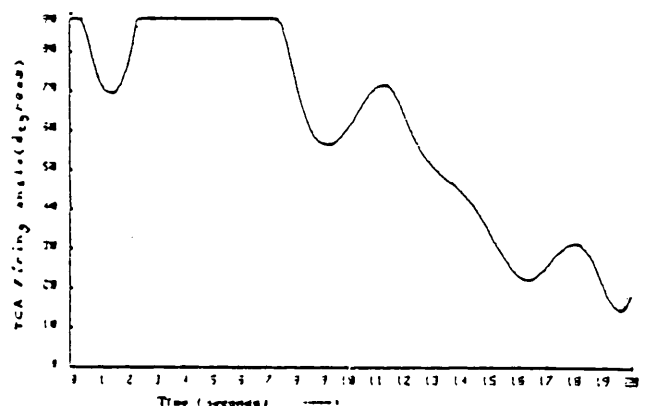
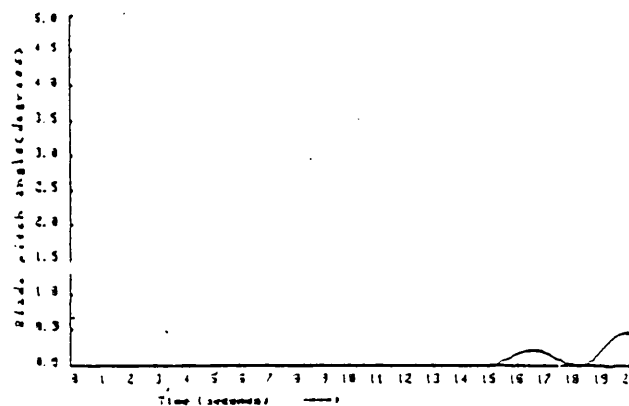
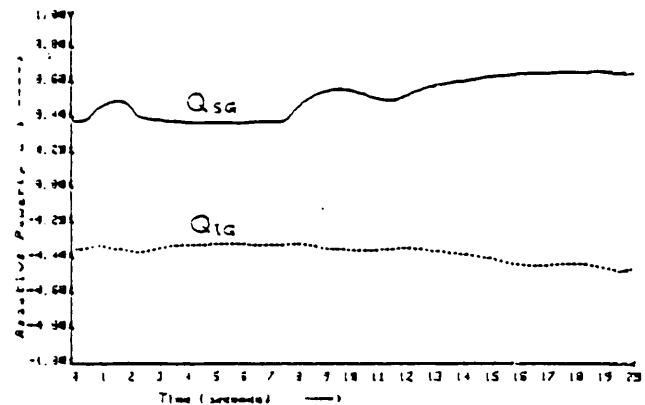
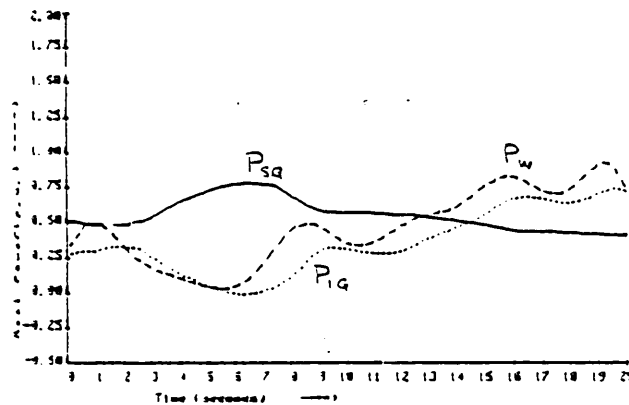
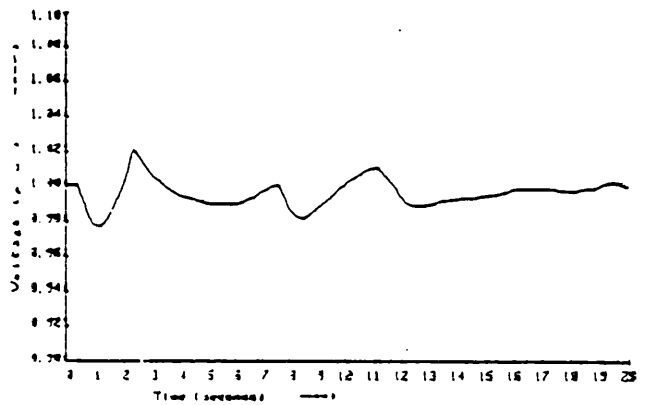
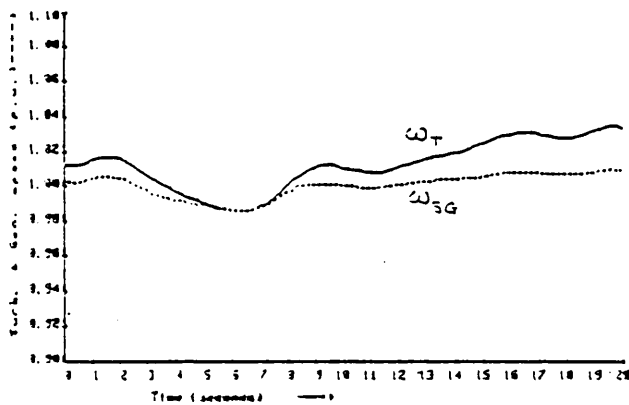


Fig. 3.26

System response to real wind sample
 Parallel generation mode
 Wind speed average 6 m/s



(ii). High wind speed input (Fig. 3.27)

This wind signal is strongly turbulent and includes a sharp gust from 9 to 14 m/s of 10 seconds duration.

The system is operating in WECS stand alone mode. The frequency is maintained within the $\pm 2\%$ band. There are voltage fluctuations to be observed within the $\pm 10\%$ band. These are again strongly correlated to fast changes in the reactive power absorbed by the TCR bridge.

3.9.4 Simulation conclusions

The system is observed to be stable and maintain the set regulation limits for frequency and voltage in all simulated cases even under extremely turbulent and gusty wind conditions.

If the initial voltage drop at the moment of the induction generator synchronization is considered not acceptable the measures suggested in paragraph 3.9.1d should be implemented. In any case frequent cut-in and cut-out of the wind turbine generator should be avoided. In this case a one-way clutch in the transmission system from the turbine rotor to the generator rotor is appropriate, with the additional benefit of cutting out, the undesirable reverse torque in the gear box when the generator is motoring. The implementation of such a one-way transmission clutch is discussed with the system described in the next chapter.

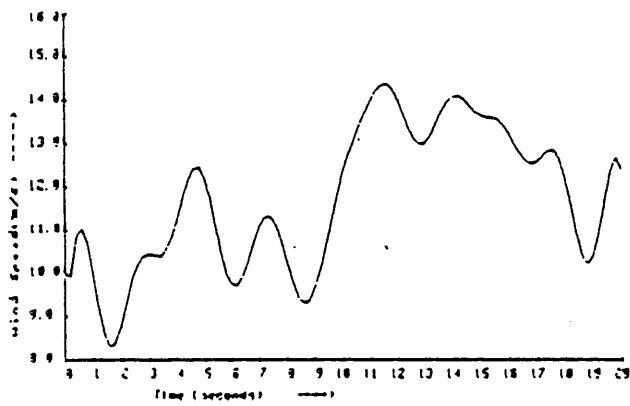
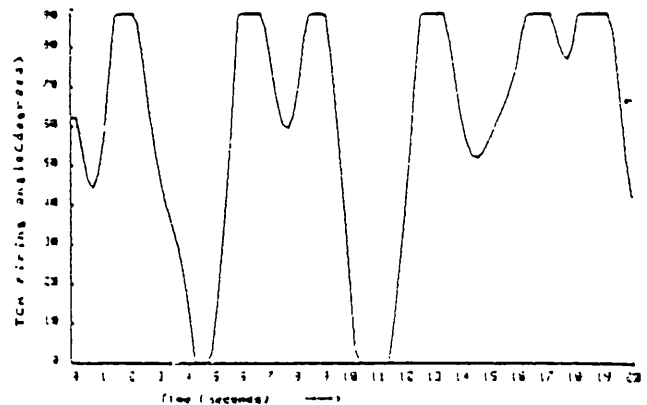
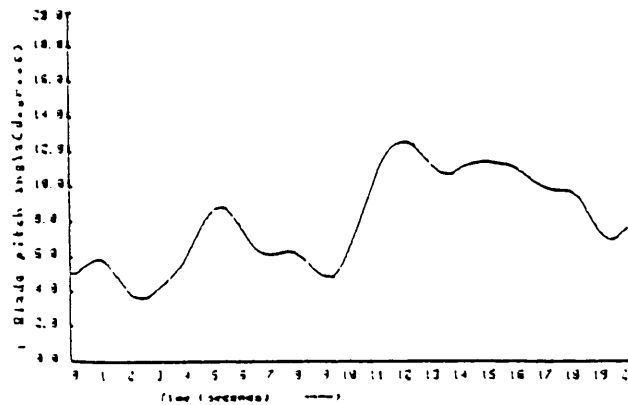
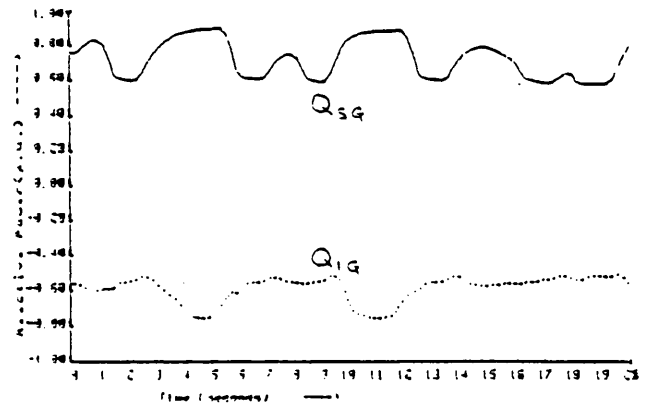
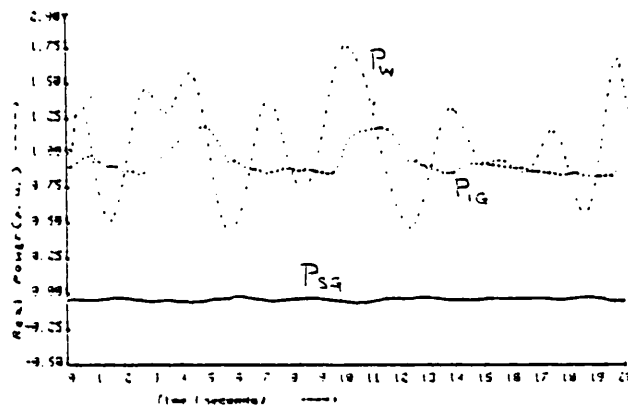
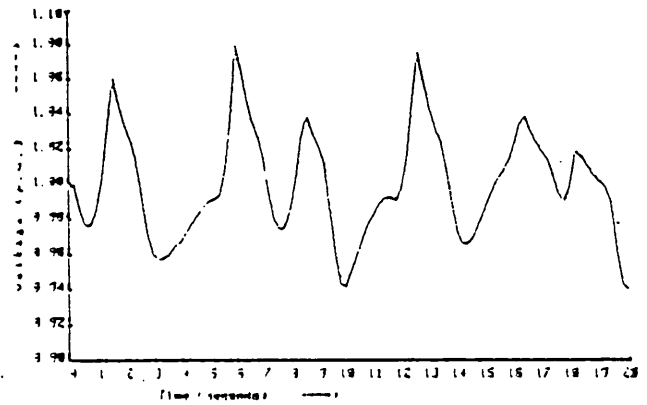
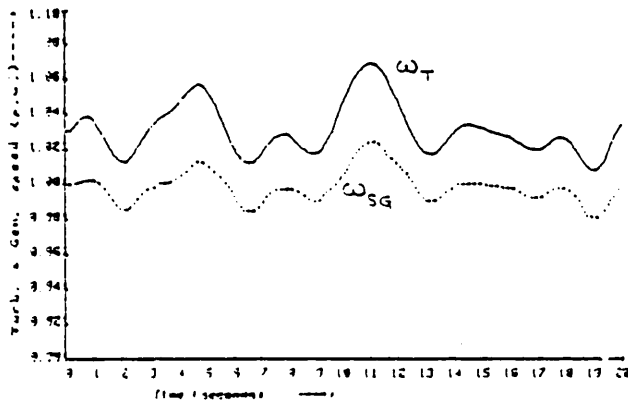


Fig. 3.27

System response to real wind sample
WECS alone generation mode
Wind speed average 10 m/s



The voltage fluctuations induced by the rapid changes in the TCR firing angle during strongly turbulent winds can be reduced either by enhancing the response of the diesel generator excitation or controlling the major part of the dump load by frequency or power signal controlled switches, thus reducing the reactive power fluctuations caused by the TCR.

3.10 Eigenvalue analysis and state variable participation matrix

In order to perform the eigenvalue analysis, the Jacobian matrix of the linearized system has been calculated for characteristic steady state operating points given in Tables 3.31-3 in Appendix 3.3.

The calculation of analytical expressions for the elements of the Jacobian from Eqns 3.1-3.70 is cumbersome or even impossible, as the state matrix elements are functions of non-state variables which in turn are either defined implicitly through a system of non-linear algebraic equations (in general not analytically solvable) or through numerically defined functions. For example, the aerodynamical power coefficient $C_p(\omega_T, W, \beta)$ is a function of the turbine rotational speed ω_T which is a state variable, the blade angle β which is a control variable and the wind speed W which is an input variable.

The program for the numerical calculation of the Jacobian elements has therefore to combine explicit analytical expressions, implicit calculation through iterative techniques and numerical differentiation wherever functions are defined only numerically.

With the participation matrix technique, a participation factor of each state variable [Ref . 3.9] is calculated for each eigenvalue of the system. The matrix of these factors forms the participation matrix. The sum of all row or column elements is theoretically one, although this may not be the case when the eigenvalues are close to each other. The contribution of each state variable to the unstable or weakly stable modes gives an indication of stability of the parts of the system where the state variables are physically attributed. The system is numerically extremely stiff with the ratio of the largest to the smallest non-zero eigenvalue being of the order of 10^4 . The general structure of the eigenvalue distribution depends on the mode of operation but does not change significantly for different operating points. The zero eigenvalues are attributed by the participation analysis to shaft angles. This is to be expected as the shaft angles are pure integrals of the angular velocities and the torsional motion equations include only a very small frictional damping and very high torsional stiffness.

There appear in all cases complex eigenvalue pairs with high imaginary parts and relatively weak damping attributed to the torsional characteristics of the shafts. However, for high torsional frequencies, a large inherent natural damping due to the shaft material is expected. The gear-box is characterised by the highest eigenfrequency and its torsional oscillations are very weakly damped. This suggested possible fatigue problems and requires measures to enhance the damping (e.g. flexible gear-box mounting, etc.), or gear-box overdimensioning.

The eigenvalues attributed to the excitation system are all real and negative in a range of -0.12 to -100 which suggests satisfactory voltage stability. This was observed in all simulated cases.

The comparison of the eigenvalues for the cases with and without the diesel machine indicates that, as expected, the system with the two generators operating in parallel shows better inherent stability properties due to the stability effect of the diesel machine speed governor.

Interesting is the comparison of the eigenvalues calculated for the controlled and the uncontrolled system (shown in the right on Appendix 3.3). The control system introduces two negative real poles in the case of parallel generation (wind speed poles) and a complex pair in the case of WECS only generation (wind speeds 8 m/s and 16 m/s). For the high wind speed of 16 m/s the eigenvalues are shifted to the left when compared with the case of 8 m/s wind speed which is an indication of the higher inherent aerodynamical damping in high wind speeds described previously.

It should be noted that the eigenvalue analysis performed above, only predicts the onset of small oscillations. As the system is non-linear, the results of this analysis predict only possible sources of instability. Confirmation of these results can only be obtained through fully fledged simulation studies.

3.11 Comments

The simulation results and the eigenvalue analysis of the proposed system indicate that stable operation and acceptable energy quality are achievable with 100% wind penetration. The performance of the system would of course be enhanced if an active short term storage

device (e.g. a battery or flywheel) could be included. This would also be desirable in cases where neither heating nor refrigerating load is required. Problems may arise in turbulent wind conditions if the electromechanical clutch is operated too frequently or if the diesel engine fails to start. As the start-up time of diesels is expected to be below 10 seconds and the components of the short time turbulence spectrum for frequencies above 1 Hz are small, the requirements on the storage capacity and discharge rate are modest and could be met by flywheels in a system of small capacity.

Smoothing of the WECS output fluctuations could also be achieved by installing a multi-machine park with individual machines of smaller capacity distributed over an extended area rather than one turbine rated at the total of wind power contribution. This would also ease significantly the problem of voltage drop during WECS cut-in, as the individual machines would be paralleled one by one. This policy has been implemented on the Kythnos project mentioned in Chapter 2 with very satisfactory results.

The controllable dump load which is an essential part of the system in order to permit 100% penetration should be ideally subdivided into switchable sections or consist of one large switchable section and one infinitely variable through a TCR bridge. This would reduce the voltage fluctuations and the likely wave form distortion.

Some of the above matters will be discussed further in the following chapter.

IDENTIFICATION, DYNAMICS AND CONTROL OF AN AUTONOMOUS WIND/DIESEL SYSTEM
WITH SYNCHRONOUS WIND TURBINE GENERATOR4.1 Introduction

The synchronous generator has an important advantage in WECS applications when compared with the induction generator i.e. the inherent capacity, by virtue of its field control system, to match the reactive power requirements of the network it feed and to contribute to voltage stabilization.

On the other hand this advantage is counterbalanced by increased electrical stiffness which together with the randomly fluctuating prime mover torque imposes stricter control requirements and more severe mechanical torques on the transmission system. In addition, synchronizing equipment is required which, in small networks, increases complexity, cost and maintenance (Refs. 4.1, 4.2).

In this chapter a commercial type of WECS equipped with a synchronous generator is discussed. (Refs. 4.3, 4.4, 4.5) This unusual machine has some special features, and therefore requires neither a gear box nor synchronizing equipment.

It should therefore, in principle, have high reliability and low maintenance cost.

The WECS under question is a Hawker Siddeley MP-9 which is tested at the Rutherford Appleton Laboratory (RAL) in conjunction with a 8.5 kVA, Hawker Siddeley Nova II diesel generator set. This industry cooperative project is funded by SERC and Hawker Siddeley Power Plant Ltd and is pursued by Imperial College and RAL.

In what follows the identification procedure of the system

parameters is outlined, the dynamic behaviour of the system is simulated, and the simulation results compared with measured recordings, where available. Finally suitable control policies are presented.

4.2 System description

Figure 4.1 describes the system under test at RAL which is the subject of study of this chapter. The system compared to that studied in Chapter 3 has the following features:

- a. There is no clutch between diesel engine and diesel generator
- b. The controllable dump load consists of a resistive load switched in discrete steps by TRIACS
- c. The WECS generator is a synchronous machine
- d. There is no gearbox in the mechanical transmission system.

There are further small differences in the system components which will be described later.

4.2.1 Wind turbine

The wind turbine at RAL is an horizontal axis two bladed

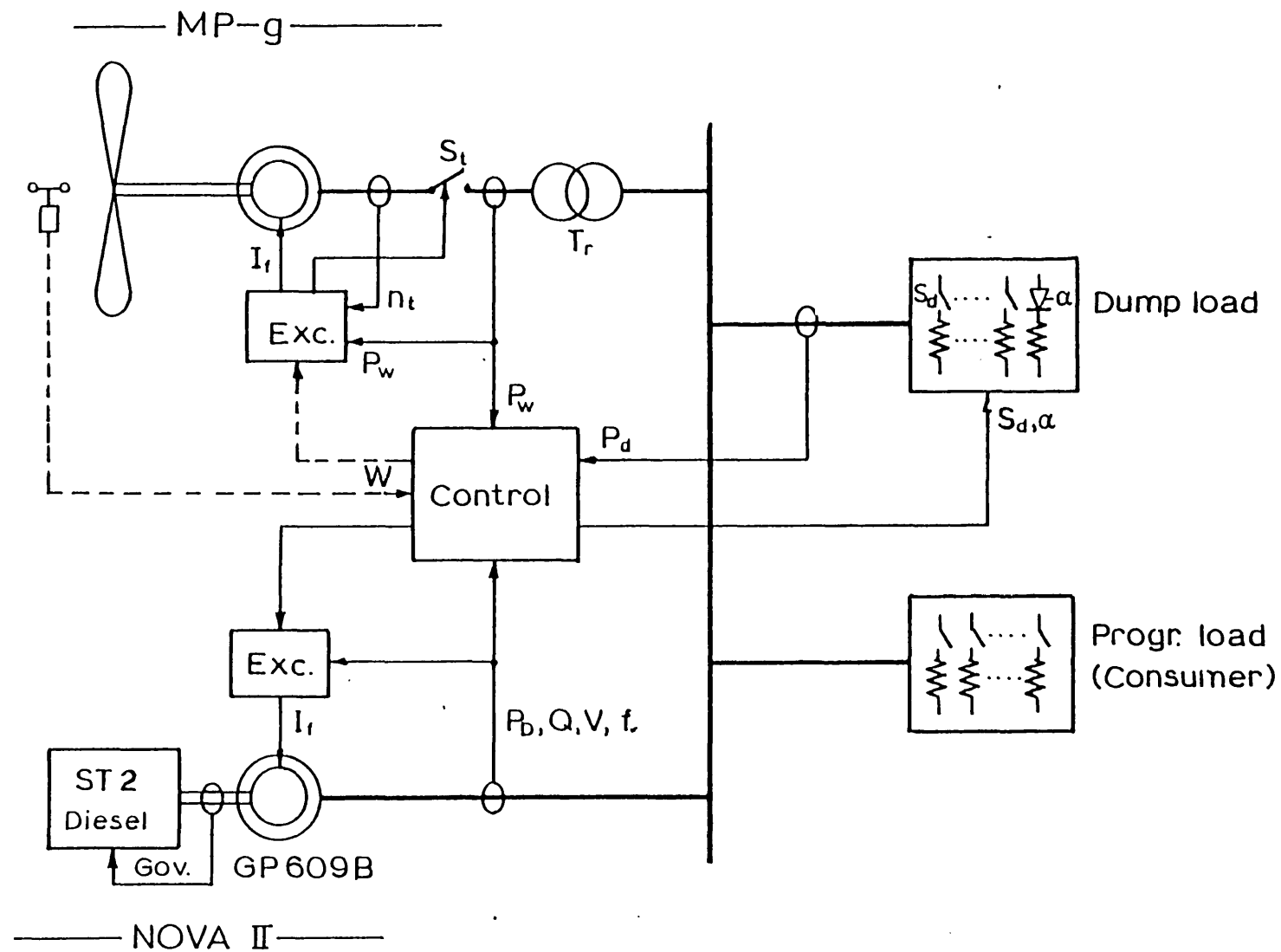


Fig. 4-1 Autonomous system with continuous Diesel operation

downwind machine of 9m diameter (Ref. 4.6). The rated speed for 50 Hz operation is 125 rpm. The wind power input is controlled by a passive blade pitch control system (Fig. 4.2) operated directly by the aerodynamical and centrifugal forces acting on the blades. The blades are hinged on the hub in such a way that a pitching torque is always developed. This torque is counterbalanced by a pneumatic spring-damper system pressurised by an electric compressor. A schematic block diagram is shown in Fig. 4.3. A solenoid operated escape valve allows instant system decompression. In the case where the valve is deactivated either manually or because of power failure, the aerodynamical forces cause full blade pitching and the turbine is braked.

The torque is transmitted to the generator rotor through a steel shaft, an elastomeric flexible coupling and a one-way clutch. The flexible coupling reduces the peak torque whereas the one way clutch decouples the generator rotor from the turbine rotor during lulls when the turbine rotor speed drops below the synchronous speed. In the latter case the generator motors against only its frictional, windage and electrical no-load losses until either the wind recovers and the wind turbine clutches again or a time interval, preset by a timing relay, elapses, in which case the WECS is disconnected from the grid.

A schematic block diagram of the transmission system is shown in Fig 4.4.

4.2.2 WECS generator and excitation system

The WECS generator is a 21 kVA, 3-phase, 48 salient pole

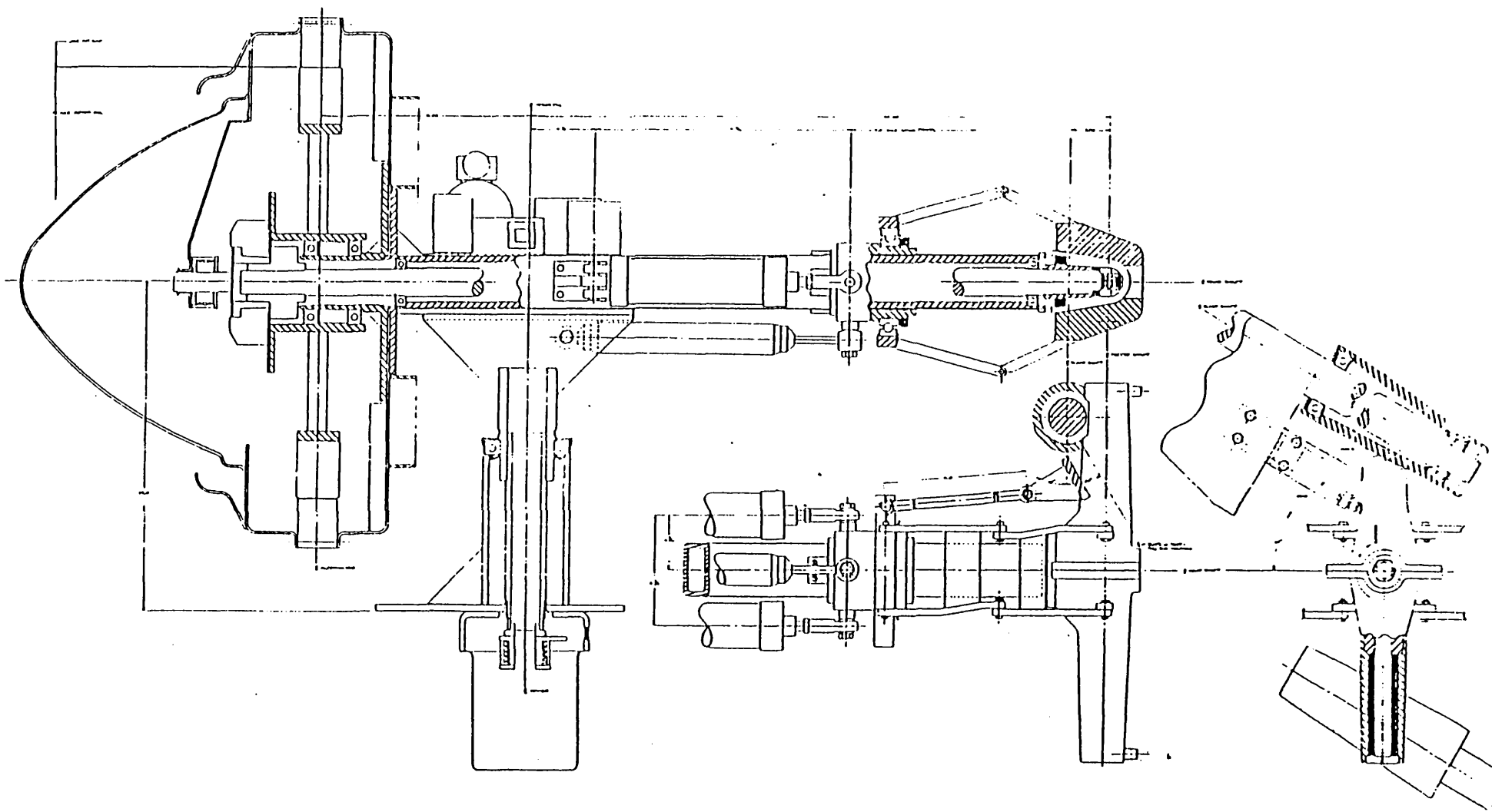


Fig. 4.2 Blade Pitch Control Mechanism
(Northwind Power Co.)

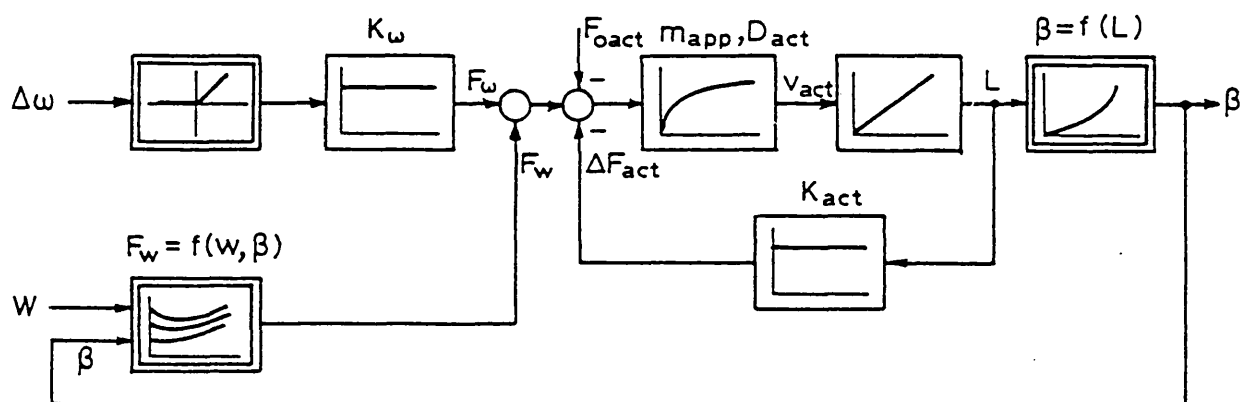


Fig. 4.3 Blade pitch control mechanism model

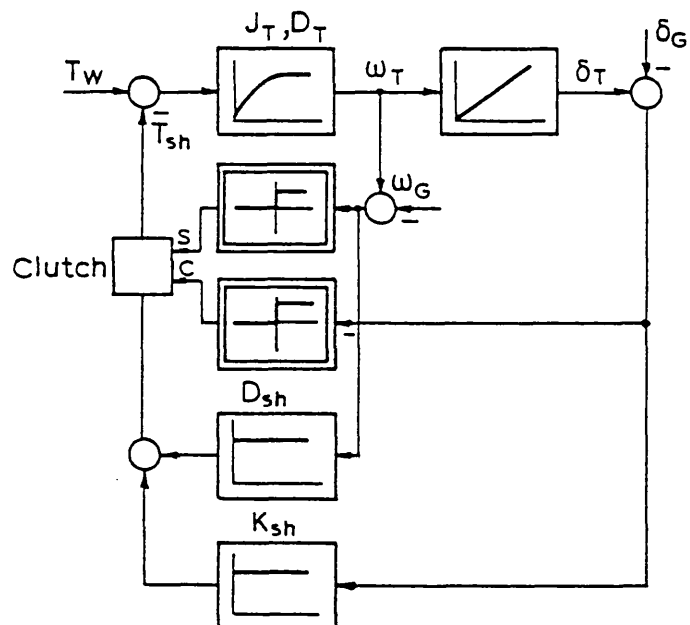


Fig. 4.4
Turbine rotor and
mechanical transmission
system model

machine. (Ref 4.5) A damper winding is not provided. Transient rotor oscillations are damped through two mechanical dampers (shock absorbers) arranged tangentially between the generator rotor and the one way clutch. The generator nominal line to line voltage is 240 volts so that a 240/415 transformer had to be used to inter-connect the generator to the grid.

This WECS is intended to supply energy to fixed voltage and frequency mains. Its excitation system is therefore designed to maintain approximately unity power factor over its whole operational range.

The excitation system (Fig. 4.5) is a static current compounding system. The excitation voltage is supplied from two of the three phases through a triac and a diode bridge. The excitation level is determined by the triac firing angle. The firing angle is decreased from a set point (corresponding to no load) as the a.c. current is increased. The current transformer supplying the compounding signal has a non-linear characteristic so that the generator is operating at power factor near to unity for the major part of the power range. In addition the compounding signal is smoothed through an RC circuit as excitation stabilizer.

4.2.3 Diesel set

The diesel engine is a 1500 rpm, 2-cylinder, 8.5 kW machine with a nominal droop of 4.5%. The governor is mechanical. The generator (Ref. 4.7) is a 3-phase, 10 kVA/415V machine with 4 salient poles and rotating armature. The excitation system is static with full

3-phase current compounding and power factor compensation. The excitation circuit diagram is shown in Fig. 4.6.

4.2.4 Controllable dump load

The controllable dump load is under construction and consists of a 3-phase symmetrical purely resistive load switchable through triacs from 0 to 18 kW in 48 discrete steps of 375W each by combining appropriately resistors of 125, 250, 500, 1000 and 2000 W, at 415V line voltage.

4.2.5 Programmable consumer load

The consumer load at this stage is a 3-phase symmetrical, purely resistive load which can be programmed in steps of 100W up to 7500W through an APPLE microcomputer.

Reactive loads are available as inductance banks of 2.5kVAR at 415V each and a capacitance bank which can be set in steps of 15VAR up to a maximum reactive power of 2.5 kVAR at 415V.

4.3 Identification of the WECS dynamic parameters

4.3.1 Wind turbine C_p/λ and C_q/λ characteristics

The families of curves relating the aerodynamic power

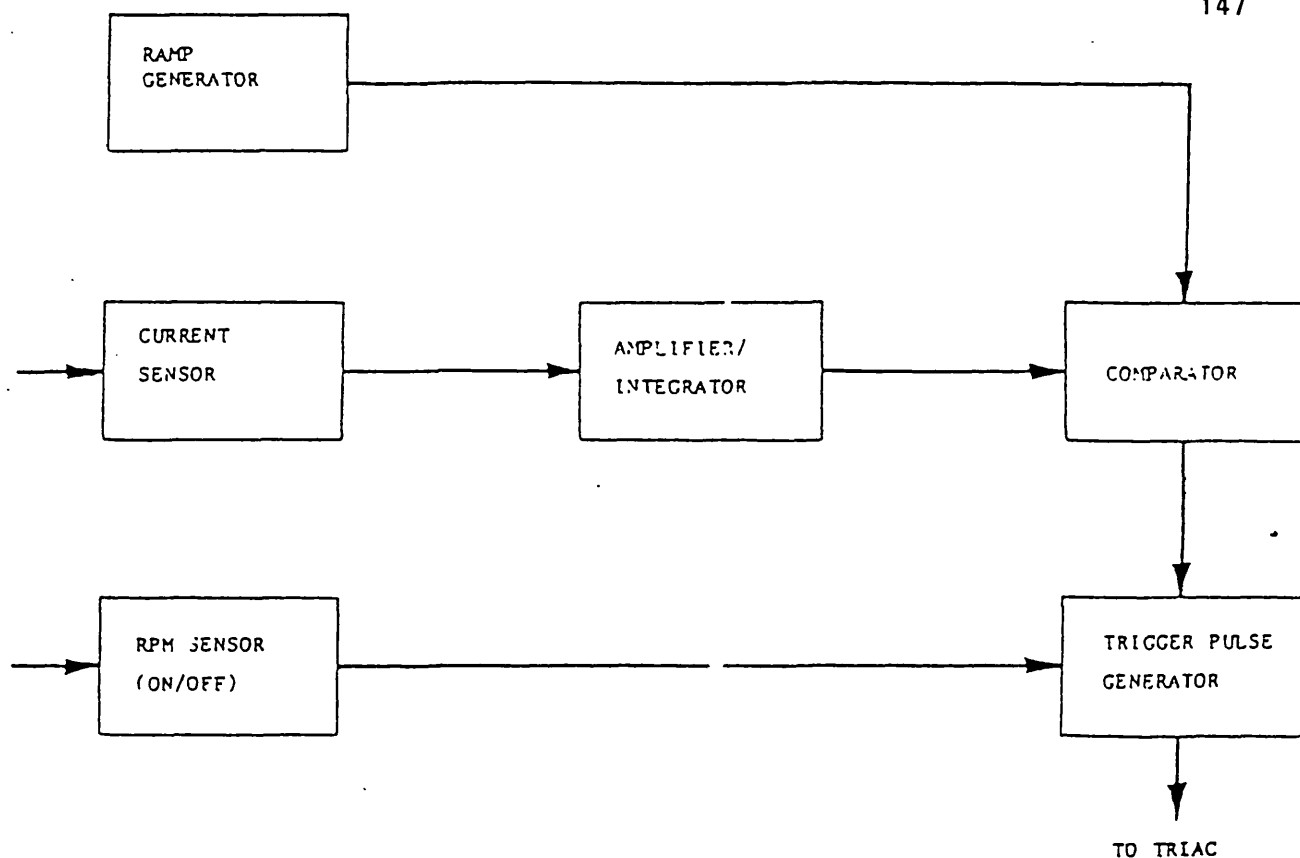


Fig. 4.5 Wind Turbine Generator Excitation Circuit
Functional Block Diagram
(Northwind Power Co.)

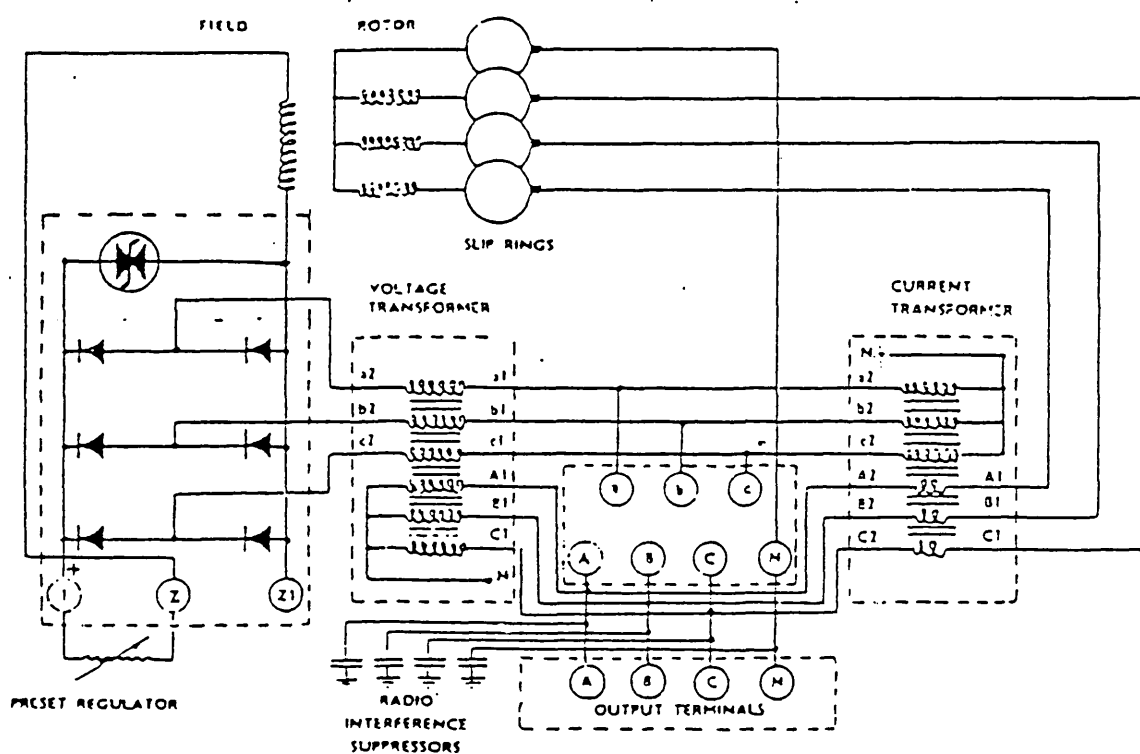


Fig. 4.6 Diesel Generator Excitation Circuit
(B.K.B. Electric Motors Ltd.)

coefficient C_p and torque coefficient C_q as functions of the tip speed ratio λ , with the blade pitch angle β as a parameter, are essential for the calculation of the power or torque input to the wind turbine rotor during wind speed transients.

These curves are characteristic of the aerofoil shape used for the blades and the blade chord twist (Ref. 4.6). The aerofoil used for the wind turbine under investigation is the Goe 797 (Ref. 4.8). Table 4.1(a) gives the lift and drag coefficients for this aerofoil as functions of the angle of attack α and Table 4.1(b) gives the blade chord and twist as functions of the distance from the blade root.

Table 4.1

Blade aerodynamical design characteristic

a) GÖ 797 aerofoil characteristics

b) Blade twist characteristic

$$RN = 3.8 \times 10^5$$

AGA	CL	CD	CM	STA.	CHORD	TWIST
-8.0	-.07	.0154	-	4.50	30	5.5°
-7.0	-.02	.0150	-.11	4.05	100	5.5°
-6.0	.11	.0148	-.11	3.60	120	5.0°
-5.0	.21	.0146	-.10	3.15	140	5.5°
-4.0	.30	.0143	-.10	2.70	160	7.0°
-3.0	.40	.0141	-.10	2.25	180	7.5°
-2.0	.50	.0139	-.10	1.80	200	8.2°
-1.0	.60	.0138	-.10	1.35	220	10.0°
.0	.71	.0137	-.11			
1.0	.80	.0137	-.11	.90	270	20.0°
2.0	.89	.0140	-.10	.81	280	25.0°
3.0	.98	.0147	-.10	.72	290	25.0°
4.0	1.05	.0158	-.09	.63	300	29.0°
5.0	1.11	.0175	-.09	.50	300	30.0°
6.0	1.16	.0200	-.08	.54		
7.0	1.21	.0256	-.08	.13		
8.0	1.25	.0256	-.08	.14		
9.0	1.29	.0355	-.07			
10.0	1.33	.0459	-.07			
11.0	1.33	.0615	-.07			
12.0	1.36	.0810	-.07			
13.0	1.33	.1015	-.08			
14.0	1.34	.1199	-.08			
15.0	1.32	.1366	-.08			
16.0	1.29	-	-			

DIM UNITS METER MM

The program for the calculation of the c_q/λ and C_p/λ characteristics is based upon the method developed by I. Buehring (Ref. 4.9) for the numerical integration of the aerodynamic forces acting on a blade element over the blade length.

The original program has been improved in terms of numerical efficiency by replacing the bisection method for the solution of the nonlinear equations by the Newton-Raphson method and replacing the orthogonal integration rule by Simpson's rule.

The C_q/λ and C_p/λ characteristics calculated are shown in Fig. 4.7.

4.3.2 Wind turbine mechanical parameters

The wind turbine rotor dynamics are described by the equations of motion

$$J_T \dot{\omega}_T = D_T \omega_T - S_T(\theta_T - \theta_G) - D_d(\omega_T - \omega_G) + \frac{P}{\omega_T} \quad (4.1)$$

$$\dot{\theta}_T = \omega_T - \omega_{T0} \quad (4.2)$$

where ω_T : turbine rotor angular speed
 θ_T : turbine rotor angle with respect to a synchronously rotating reference frame
 ω_{T0} : nominal (synchronous) turbine rotor speed
 θ_G : generator rotor mechanical angle with respect to the synchronously rotating reference frame

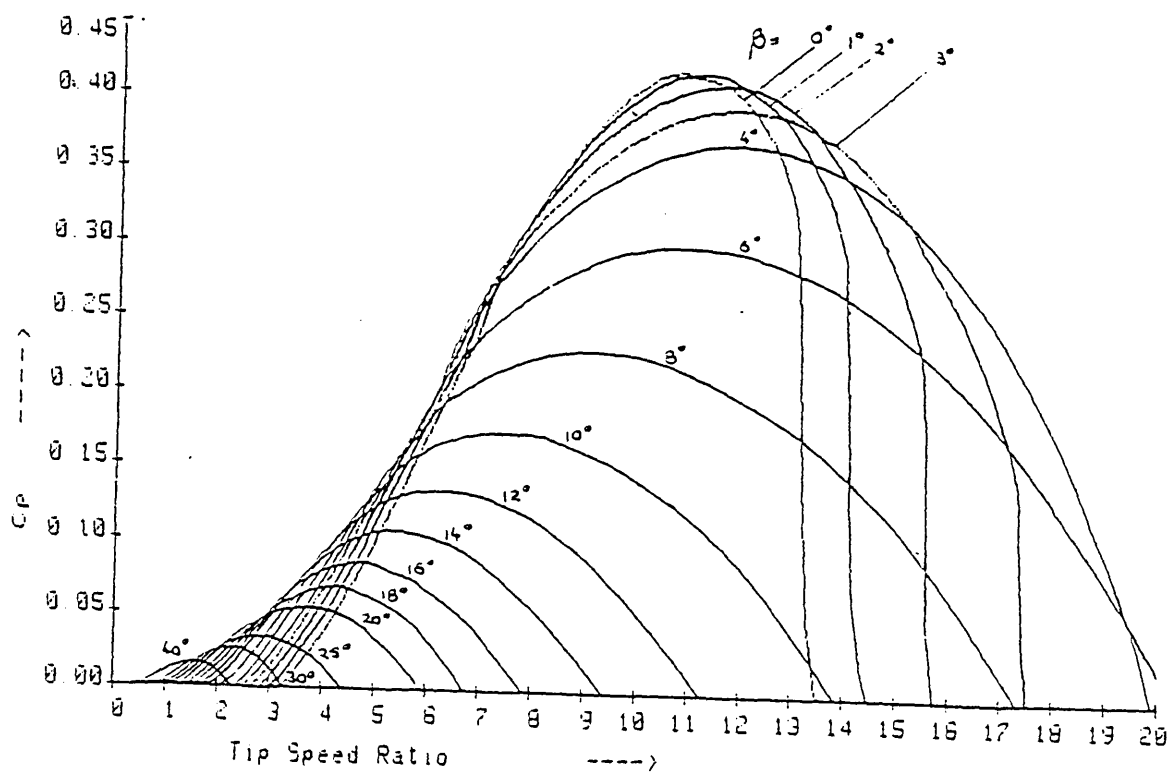
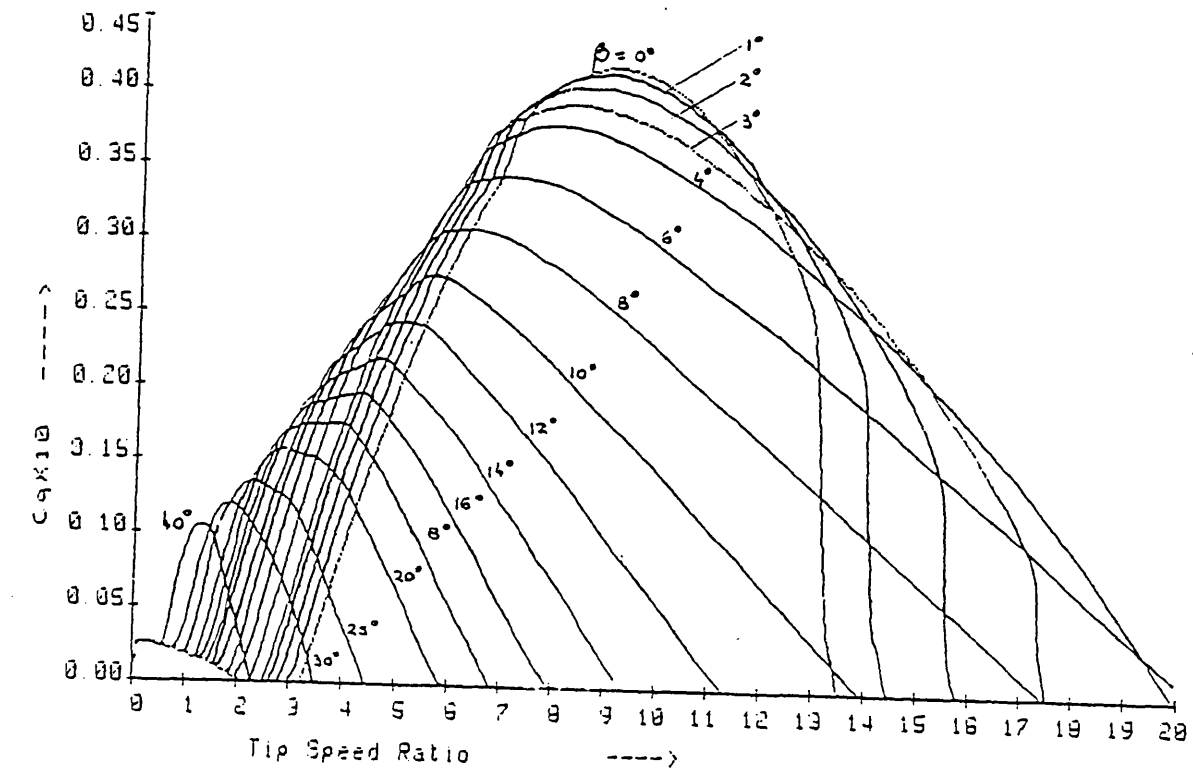


Fig. 4.7 Wind Turbine Rotor
Aerodynamic Performance Characteristics. (calculated)

P_w : wind power input to the turbine rotor

J_T : turbine rotor inertia

D_T : frictional damping coefficient

S_T : transmission system overall torsional stiffness

D_d : mechanical asynchronous damping coefficient

for the mechanical dampers (shock absorbers)

introduced between generator rotor and flexible coupling.

The parameters which have to be identified are:

- a) the turbine rotor inertia (blades+hub)
- b) the frictional damping coefficient
- c) the transmission system torsional stiffness and
- d) the asynchronous damping coefficient.

These have been either measured or estimated on the base of manufacturer's information.

The turbine rotor inertia has been measured separately for the blades and the rotor hub[†]. The blade inertia was measured by the pendulum method and after correction for eccentricity it was found to be 78 Nms^2 for each blade. The rotor hub inertia was measured by the standard acceleration test using a falling weight and found to be 125 Nms^2 . The total rotor inertia is then approximately 280 Nms^2 .

[†]The tests were designed and conducted by Dr D. Infield and Mr N. Jenkins at RAL

The flexible coupling torsional stiffness is established by the manufacturer as 10000 Nm/rad and was measured at RAL to be 9385 ± 518 Nm/rad. The torsional stiffness of the steel shaft is estimated to be larger by at least an order of magnitude, so the overall transmission system torsional stiffness was taken to be that of the flexible coupling.

According to manufacturer's information the linear damping coefficient for the two mechanical shock absorbers is 16 lbs/in sec for speeds up to 5 in/sec.

As the two absorbers are positioned at right angles to the rotational axis and at a radius of 275mm, the asynchronous torsional damping coefficient is calculated to be

$$D_d = 2 \times 16 \text{ lbs/in}^{-1} \cdot (0.275^2) \text{ m}^2 = 425 \text{ Nm/rads}^{-1}.$$

The frictional damping coefficient due to mechanical losses at the transmission system bearings is estimated to be 0.02 pu.

To complete the description of the turbine dynamics the function of the one-way clutch has to be introduced. The condition for declutching is

$$\theta_T < \theta_G \tag{4.3}$$

in which case the transmission torsional stiffness S_T and the asynchronous damping coefficient D_d are set to zero.

The condition for clutching is

$$\omega_T > \omega_G \tag{4.4}$$

and the clutch is assumed to engage immediately when the slip $\omega_T - \omega_G$ is positive. The turbine rotor angle is then reset to the value of the generator rotor angle as the torsional deflection angle at the instant of clutching must be zero.

4.3.3 Generator parameters

The same dynamic model as described in Ch. 3 has been used for the simulation of the WECS synchronous generator.

The special feature of the one-way clutch was used to determine from tests the alternator parameters. The steady state open circuit and short circuit characteristics were measured[†] as recommended in Refs. 4.11, 4.12, with the generator operating unloaded as synchronous motor connected to the mains through a variac. The excitation was provided by an external controlled DC source.

The open circuit and short circuit characteristics of the machine are shown in Fig. 4.8

The results of the steady-state parameter measurements are given in Table 4.2.

Table 4.2

WECS generator steady-state parameters

Parameter	Symbol	Value	Unit	pu. values
Armature resistance	R_a	324	m Ω	$r_a = 0.12$
d-axis synchronous reactance	$[L_d]$	17.0	mH	$x_d = 1.87$
q-axis synchronous reactance	$[L_q]$	13.8	mH	$x_q = 1.58$
No-load friction, windage and core losses		200	W	$D_G = 0.01$

[†] These tests were conducted at RAL by Mr H. Bleijs (Imperial College)

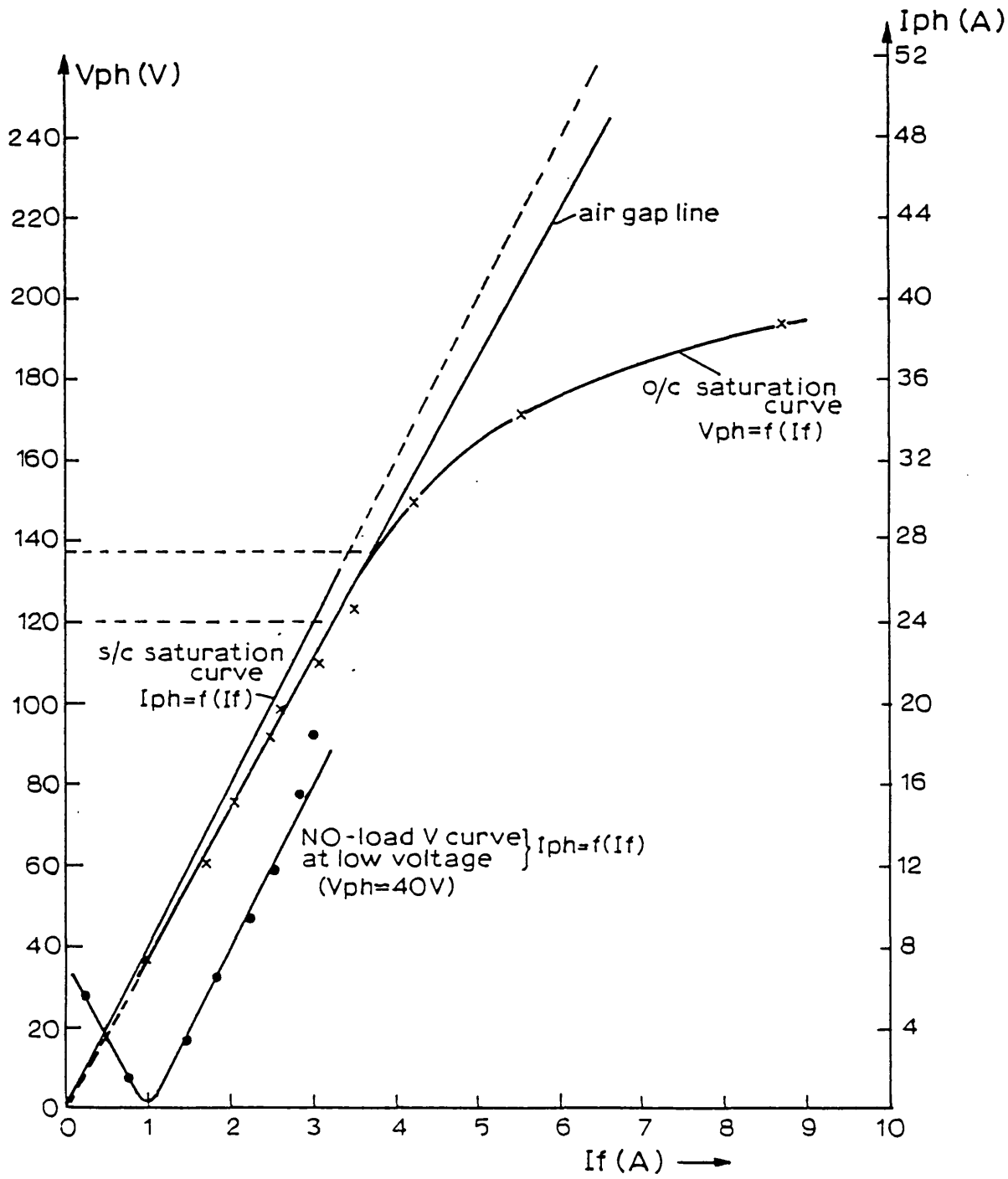


Fig. 4-8 WG o-c voltage characteristic

For the estimation of the transient and subtransient reactance the locked rotor frequency response method (Refs. 4.13, 4.14, 4.15, 4.16, 4.17) which is described in Ref. 4.3 was used.

The estimation procedure is based on a quadratic function minimization algorithm [Ref. 4.18] applied on the relative rms error function (separately for the d- and the q-axis):

$$e = \sum_{i=1}^N \sum_{k=1}^M \left(1 - \frac{|F_{ic}(j\omega_k)|}{|F_{im}(j\omega_k)|} \right) \quad (4.5)$$

where N : number of parameters

M : number of measured points in the frequency domain

$F_{ic}(j\omega_k)$ Complex value of the calculated transfer function for the parameter i at the frequency ω_k

$F_{im}(j\omega_k)$ the corresponding measured value.

The results of the measurements and the calculated curves for the magnitude and phase of the transfer functions with the estimated parameter values are shown in Fig 4.9a - 4.9c.

The estimated set of parameters is given in Table 4.3.

In Figure 4.9b we observe that the q-axis operational inductance magnitude response exhibits plateaus for the synchronous and the sub-transient reactance only. The transient q-axis reactance x'_q is shown to be equal to the synchronous reactance x_q as assumed in the model.

The relative r.m.s. error on the d-axis estimation is 3.1% and on the q-axis is 5.8%. This is due mainly to measurement errors at low frequencies and is considered to be satisfactory.

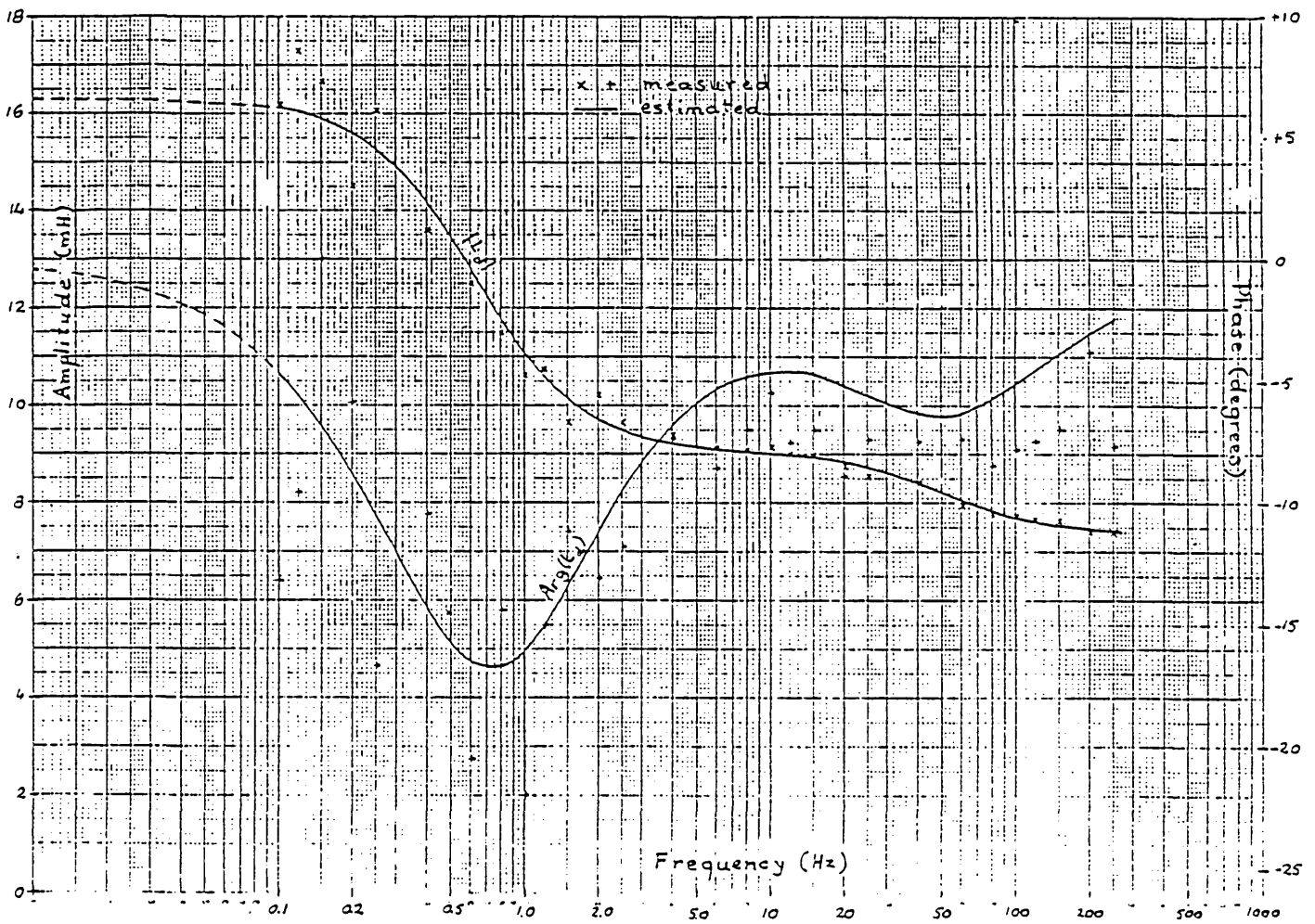


Fig. 4.9 a Wind Turbine Generator
Operational d-axis Inductance
Frequency Response

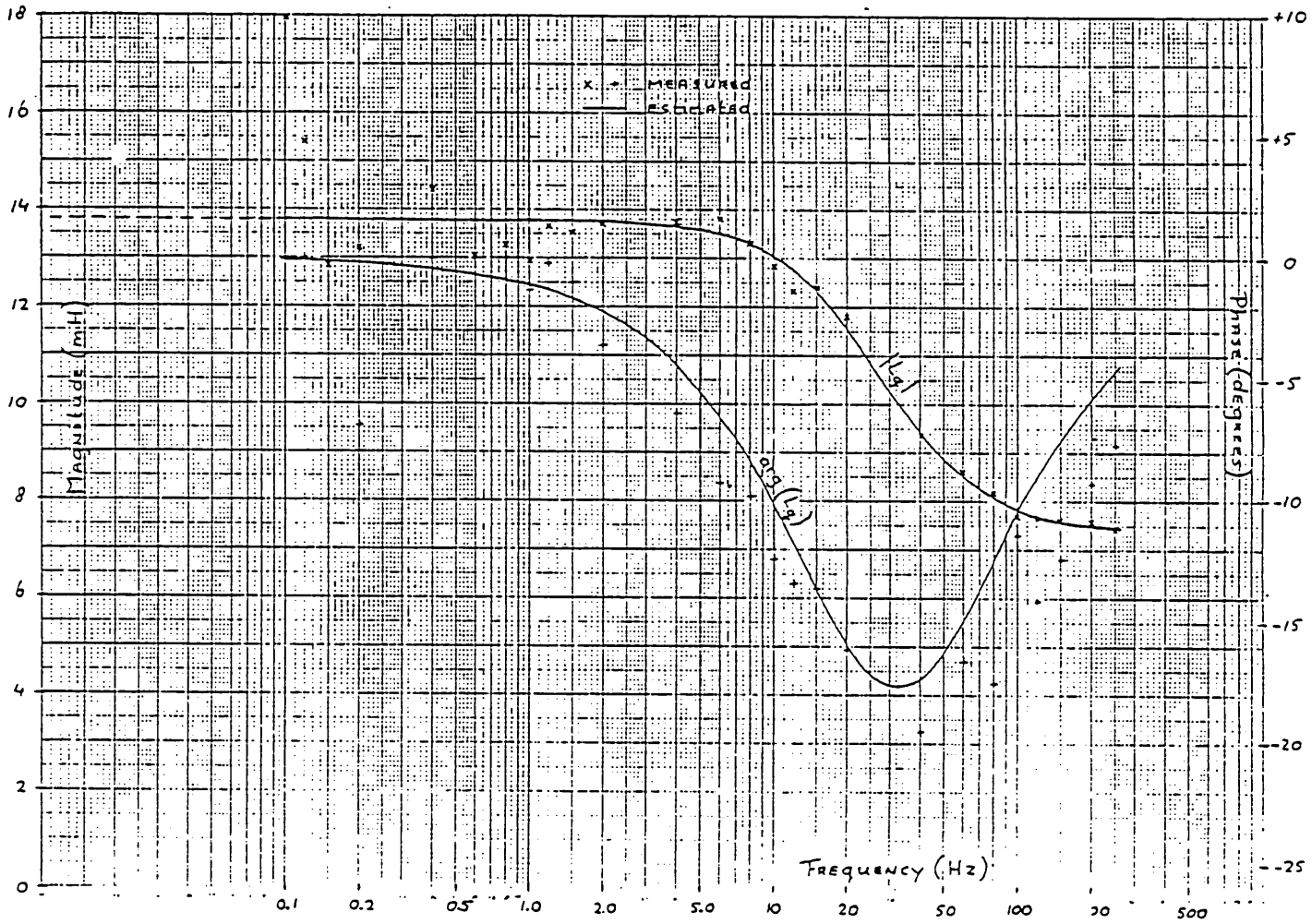


Fig. 4.9 b Wind Turbine Generator
Operational q-axis Inductance
Frequency Response

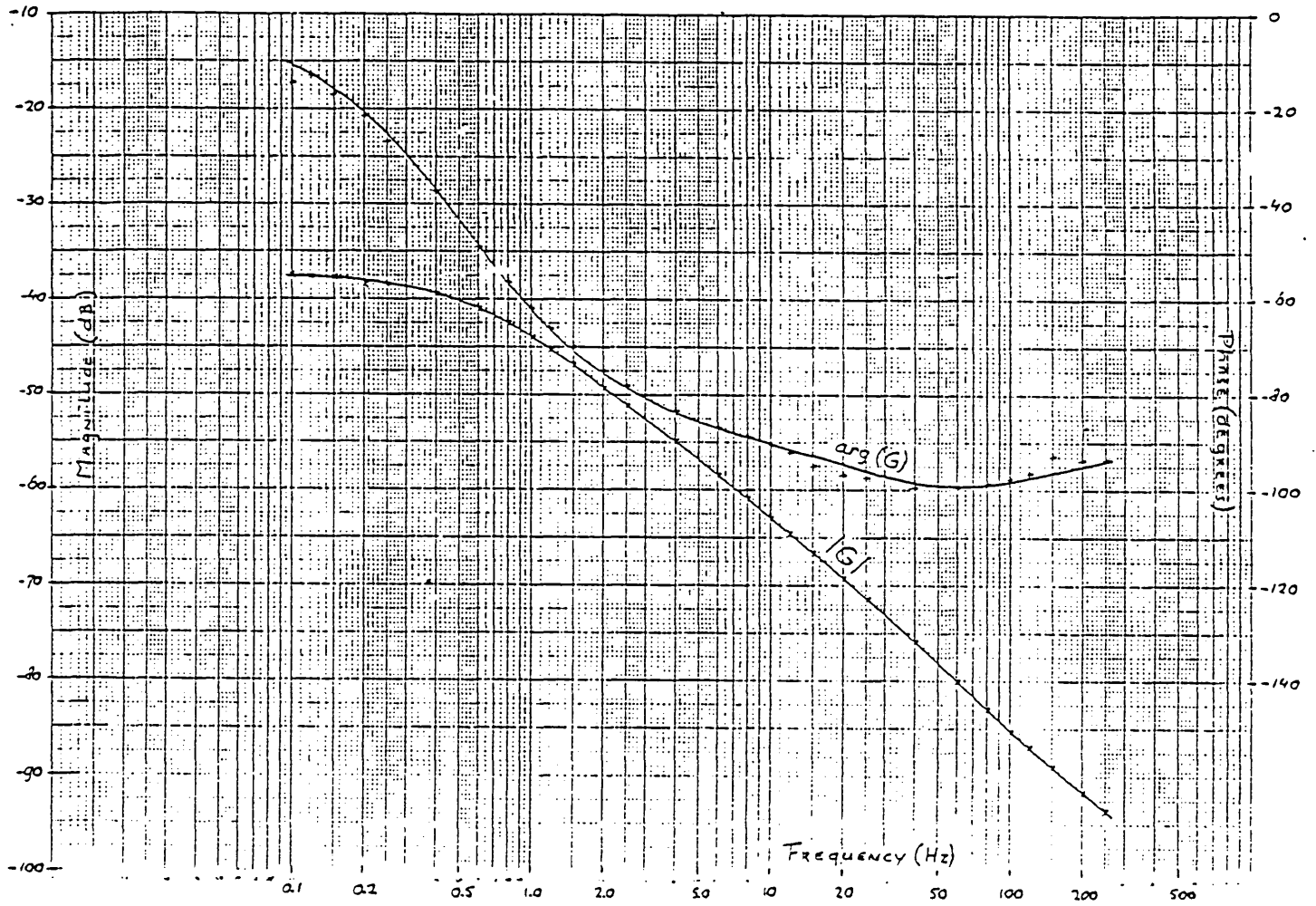


Fig. 4.9 c Wind Turbine Generator
Field/Stator Voltage Transfer Function
Frequency Response

Table 4.3

Estimated generator transient response parameters

Parameter				
d-axis transient reactance	$[L_d']$	9.1	mH	$x_d' = 104$
d-axis subtransient reactance	$[L_d'']$	7.4	mH	$x_d' = 0.85$
d-axis open circuit transient time constant	T_{do}'	298.2	ms	
d-axis open circuit subtransient time constant	T_{do}''	3.7	ms	
q-axis subtransient reactance	$[L_q'']$	7.4	mH	$x_q'' = 0.85$
q-axis open circuit subtransient time constant	T_{qo}''	6.7	ms	

The generator rotor inertia was calculated from the geometry of the machine as

$$J_G = 15.8 \text{ Nms}^2 .$$

4.3.4 Excitation system parameters

The steady-state of the excitation system as described in Sec. 4.2.2 can be expressed by the equations:

$$I_f = k_v \cdot V_s \cdot (1 + \cos \alpha) \quad (4.6)$$

$$\alpha = \alpha_0 - \left| \frac{I_s}{I_0} \right|^\gamma \cdot \Delta\alpha \quad (4.7)$$

$$0 \leq \alpha \leq \pi \quad (4.8)$$

where : I_f : field current

K_v : a.c. voltage/d.c. current conversion factor
for the triac, the rectifier bridge and the
field resistance

V_s : terminal line voltage

α : triac firing angle

α_0 : no-load triac firing angle set point

I_s : stator current

I_0 : rated stator current

γ : exponent for the nonlinear CT characteristic

$\Delta\alpha$: triac firing angle shift for rated stator current

To identify the steady state parameters the field current was measured for three zero level settings with the exciter connected to a dummy field resistor and the a.c. input supplied by a variac through the mains.

The current compounding (expressed by the firing angle shift $\Delta\alpha$) was held constant.

The parameters were then identified through the minimization routine described in Sec. 4.3.3. as the set minimizing the absolute r.n.s. error between measured excitation current values and values calculated from Eqns 4.6-4.8. The results are shown in Fig. 4.10.

The absolute r.m.s. error is 0.1A comparable with the measurement error, which is $0.01 \times 10 \text{ A} = 0.1 \text{ A}$.

The parameter values identified are given in Table 4.4.

Table 4.4

Estimation WECS excitation system steady-state parameters

Parameter	Symbol	Value	Unit
a.c. voltage/d.c. current conversion factor	k_v	0.021	A/V
CT characteristic exponent	γ	2	

With the above parameters the optimal values for the setting of the no-load firing angle α_0 and the compounding offset angle $\Delta\alpha$ have been estimated in order to achieve the broadest possible range of operation with a power factor of +0.95 at the nominal terminal voltage of 240V.

The optimal values are :

$$\alpha_0 = 107.4^\circ$$

$$\Delta\alpha = 185^\circ$$

The calculated optimal compounding characteristic and the corresponding power factor characteristic are shown in Fig. 4.11.

Finally the dynamics of the excitation system are modelled

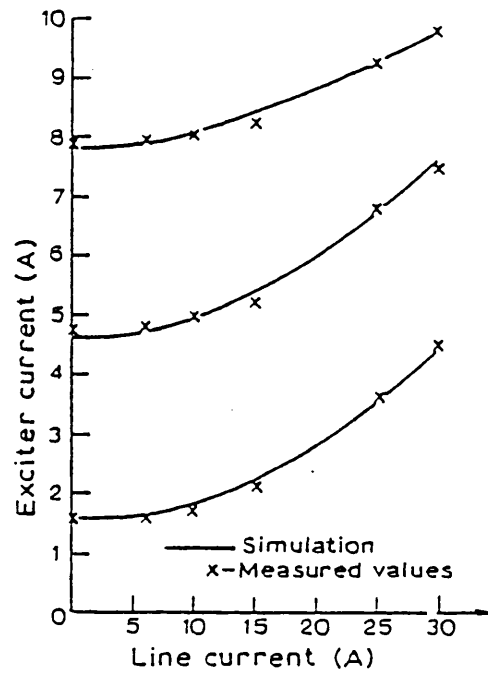


Fig. 4.10 Wind Turbine Generator - Excitation System Parameter Estimation

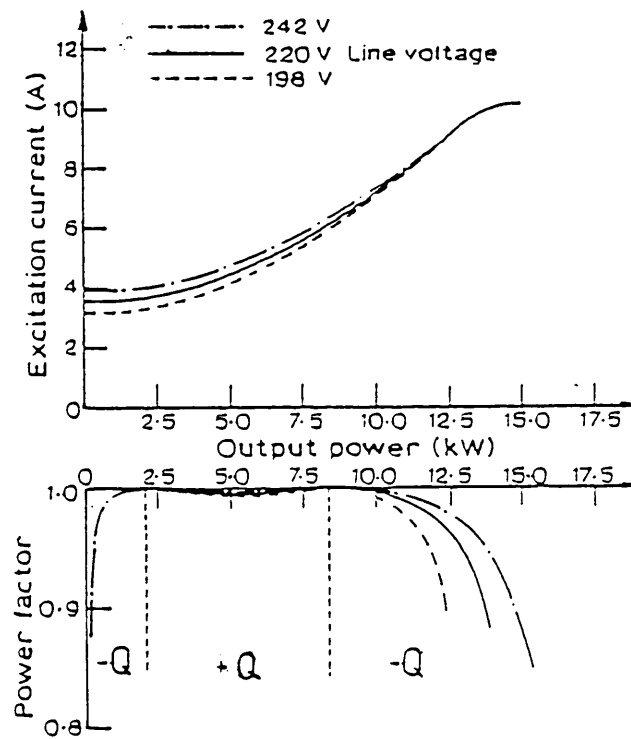


Fig. 4.11 Wind Turbine Generator - Excitation System Optimal Steady State Characteristic and corresponding Power Factor

through the set of equations (in p.u.).

$$E_{exc} = K_v' V_s [1 + \cos(\alpha_0 + E_{comp} \Delta\alpha)] \quad (4.9)$$

$$\dot{E}_{comp} = (|I_s|^2 - E_{comp}) / T_{int} \quad (4.10)$$

$$\dot{E}_{fd} = (E_{exc} - E_{fd}) / T_{exc} \quad (4.11)$$

where

E_{exc} = the excitation voltage

E_{comp} = the firing angle shift signal corresponding
to the current compounding

T_{int} : the smoothing circuit time constant

E_{fd} : the field voltage

T_{exc} : the excitation/field time constant.

From manufacturer's information the smoothing circuit time constant is estimated to be:

$$T_{int} = 200 \text{ ms.}$$

The excitation/field time constant was estimated from measured response to be:

$$T_{exc} = 300 \text{ ms.}$$

4.3.5 Tie-line and coupling transformer parameters

The tie-line impedance (150m, 10mm² Cu PVC cable) was estimated to be

$$0.325 + j0.067\Omega \text{ per phase.}$$

The coupling 240/415V, 25 kVA, Y- Δ transformer has an HV side per phase impedance of

$$0.11 + j0.187\Omega.$$

The total p.u. tie impedance from the WECS generator terminals to the bus is then

$$0.053 + j0.031.$$

4.4. WECS on infinite bus dynamic performance

The WECS under investigation was originally designed for operation on a strong 60 Hz grid. Operating the system at 50Hz, with unmodified excitation, results in a 20% reduction in the EMF. This could be a cause of instability at the upper range of the output power when the excitation current has reached the upper limit (triac firing angle zero).

Another unusual feature of this WECS is that the generator is paralleled to the grid only through speed detection (no phase

synchronization). The possible large instantaneous current and power peaks have also been a matter of concern.

To assess the transient stability of the system, before the commissioning tests, the WECS was simulated when connected to an infinite bus.

4.4.1 WECS synchronization

The synchronization process is governed only by the machine rotor speed.

A frequency detector senses the remanent voltage frequency at the generator terminals and enables the excitation when it reaches a preset value of 44Hz. The terminal voltage is sensed by a frequency relay, operating at normal voltage level, which causes the main contactor to close when the frequency reaches 47 Hz. There is an unknown time delay between frequency level detection and actual main contactor closure. This delay was omitted in the simulation as the immediate paralleling at a speed 6% below synchronous represents a worst case,

Four simulation cases are discussed here. Three cases represent synchronization under light winds, with a phase difference of 0, 180 and 270 degrees between generator terminal voltage and bus voltage at the instant of the main contactor closure. The last case shows a synchronization failure under strong gust conditions.

a) Synchronization in phase (Fig. 4.12)

The wind turbine is assumed to run idle at a speed of 0.87 p.u. when the wind power input is stepwise increased to 0.1 p.u. The turbine accelerates and when the speed reaches 0.88 p.u. after 0.5 sec. the excitation is activated increasing to the no load value. The main contactor is closed when the speed reaches 0.94 p.u. . The generator accelerates and performs damped oscillations at 6Hz around the synchronous speed. As the turbine speed is below synchronous for approx. 2 sec, the generator shaft is mainly declutched, clutching only shortly during the low oscillation peaks. This is clearly shown by the small spikes in the flexible coupling's torsional angle graph. The frequency of the oscillation is determined by the inertia and the 'electrical spring' stiffness of the generator.

The peak r.m.s current is 0.3 p.u. When the turbine reaches synchronous speed the generator clutches firmly to the turbine rotor shaft and the system performs damped oscillations around the synchronous speed with a frequency of approx. 1 Hz.

This lower eigenfrequency is determined by the much larger inertia of the turbine rotor swinging against the bus.

The voltage (at the bus side of the main contactor) remains within the 0.98-1.01 p.u. band.

b) Synchronization 180° out of phase (Fig. 4.13)

In this case, as expected, the synchronization current exhibits a high peak value of 1.3 p.u. and decays exponentially during the synchronization period.

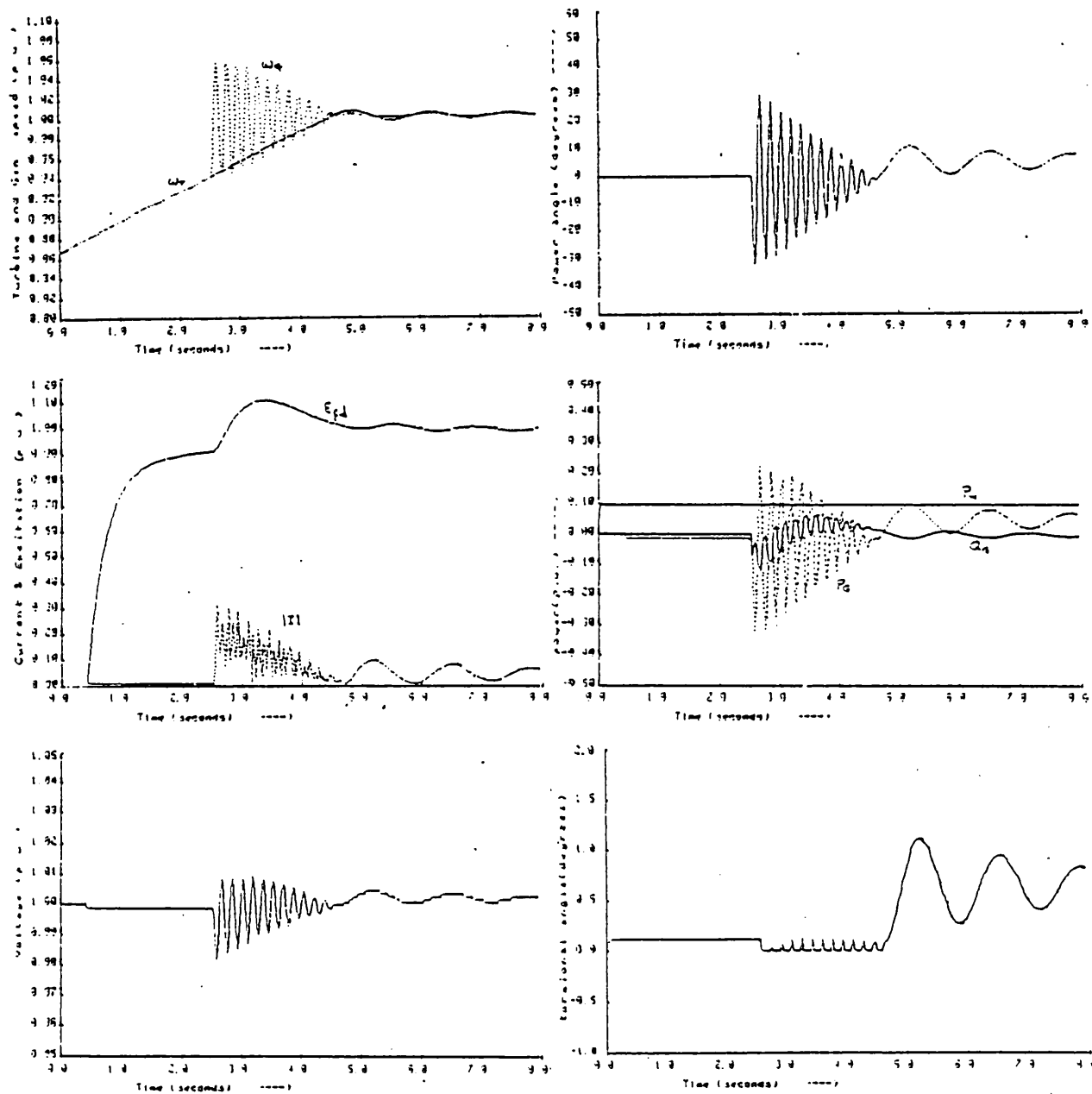


Fig. 4.12 Wind Turbine Run-Up and Synchronization (in phase)

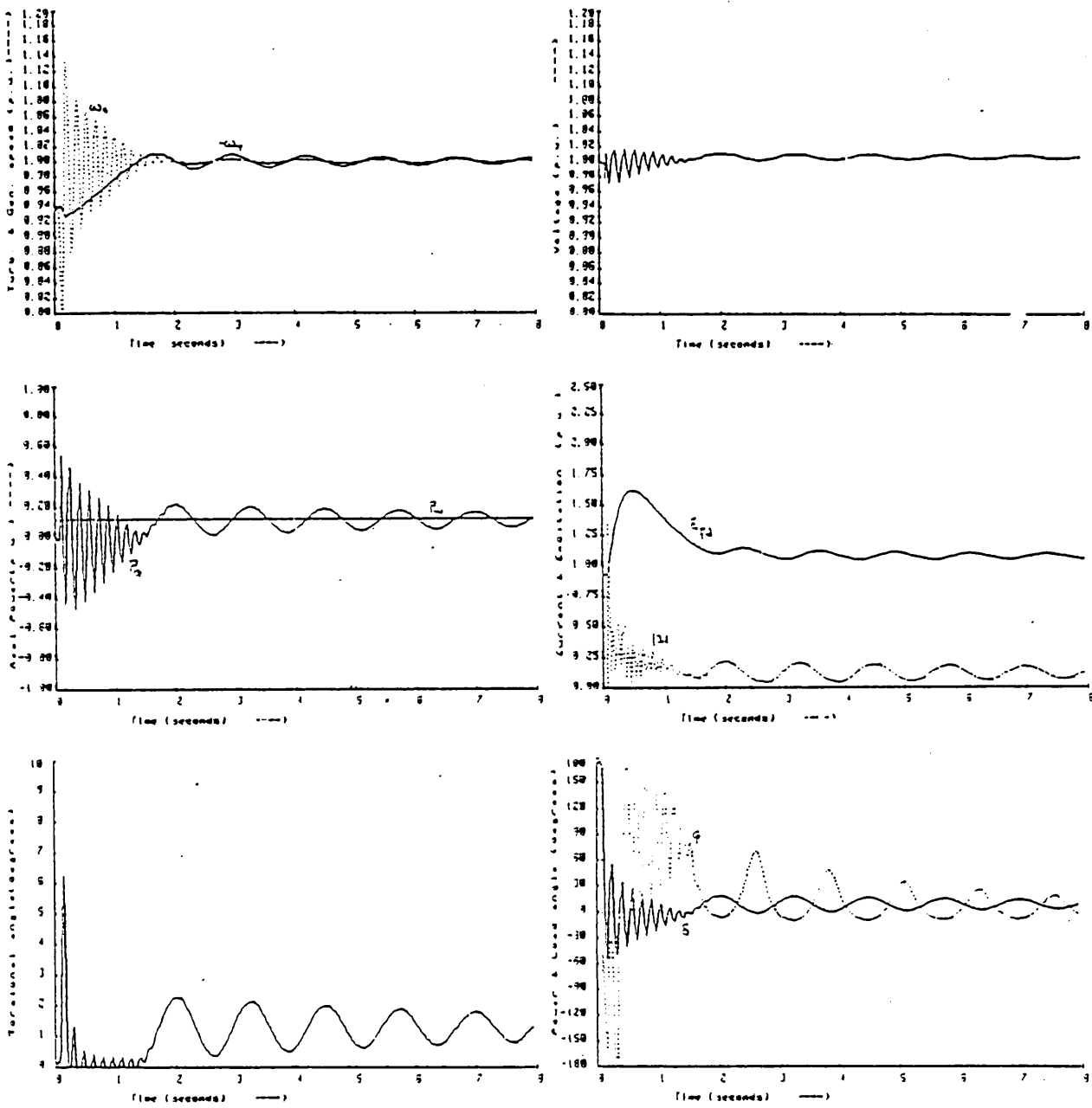


Fig. 4.13 WECS Synchronization (180 degrees out of phase)

As the simulation model considers r.m.s. values and the results have been output every 10ms it can be expected that the instantaneous current peak value is higher than the one recorded. Nevertheless the simulation in this worst case indicates that the magnitude and duration of the overcurrent remain at acceptable levels.

Voltage and power transients remain also within acceptable limits.

c) Synchronisation under 90° lagging phase difference (Fig. 4.14)

In this case, the highest real power peak is observed, as the generator rotor is accelerated to be pulled into phase. The instantaneous real power peak reaches -0.8 p.u. (machine motoring). The highest generator speed overshoot of 0.15 is also observed in this case.

The voltage is shown to dip to 0.94 p.u. at the instant of the main contactor closure and to recover fast and perform damped oscillations in the band 0.98 - 1.02 p.u. during the synchronous period.

The current peak is approx. 1 p.u.

In all three cases the synchronization process lasts for 1.5-2 sec, the peaks of current, voltage and power being surprisingly low. Two special features of this WECS contribute towards this described performance:

(i) The high transient reactance of 1.02 p.u. which limits the transient currents, and

(ii) The one-way clutch which allows the generator to be decoupled from the turbine when the former is accelerating.

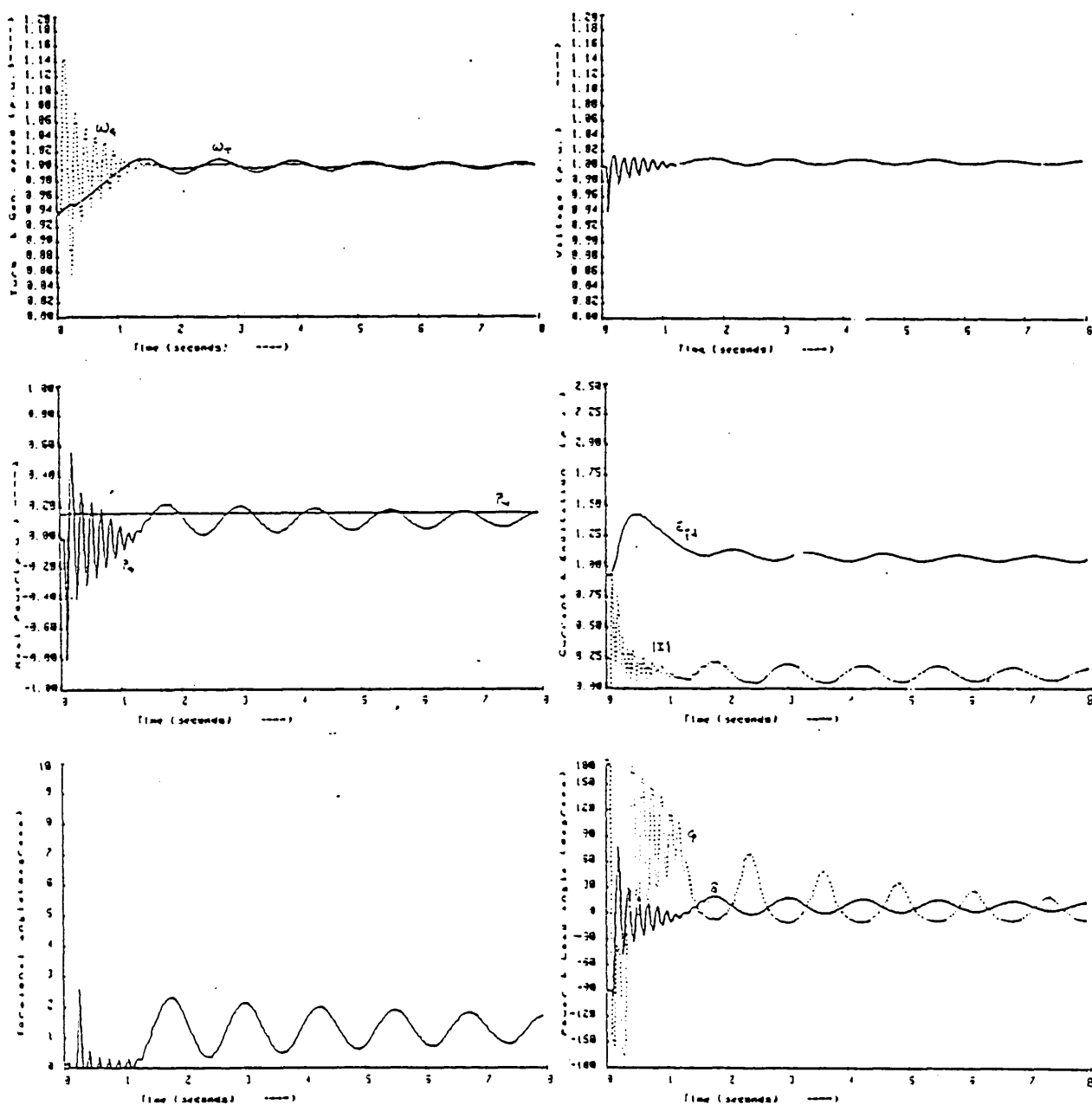


Fig. 4.14 WECS Synchronization (270 degrees out of phase)

In this way, as only the small generator rotor inertia is accelerated, the transient power swings are limited and pole slipping during synchronization is avoided. This stabilizing effect of the one-way clutch is also demonstrated later when the behaviour of the WECS during wind power transients is analysed.

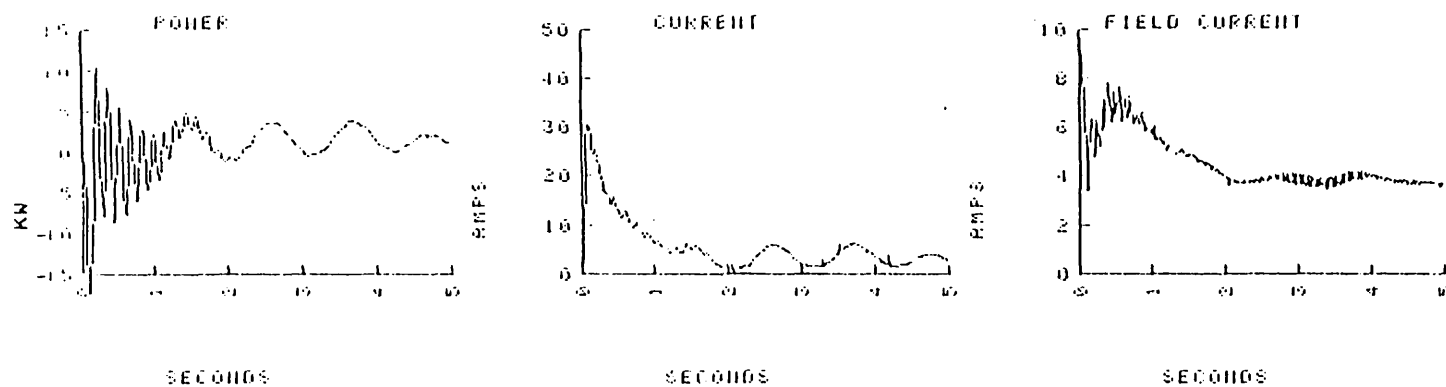
The multipole nature of the alternator and the flexible coupling may also contribute towards this desirable performance.

The measurements during actual synchronization processes, performed recently at RAL by Mr N. Jenkins, give an excellent confirmation of the simulation accuracy. Two sets of recorded measurements on real power, line current and field current are presented here in Fig. 4.15.

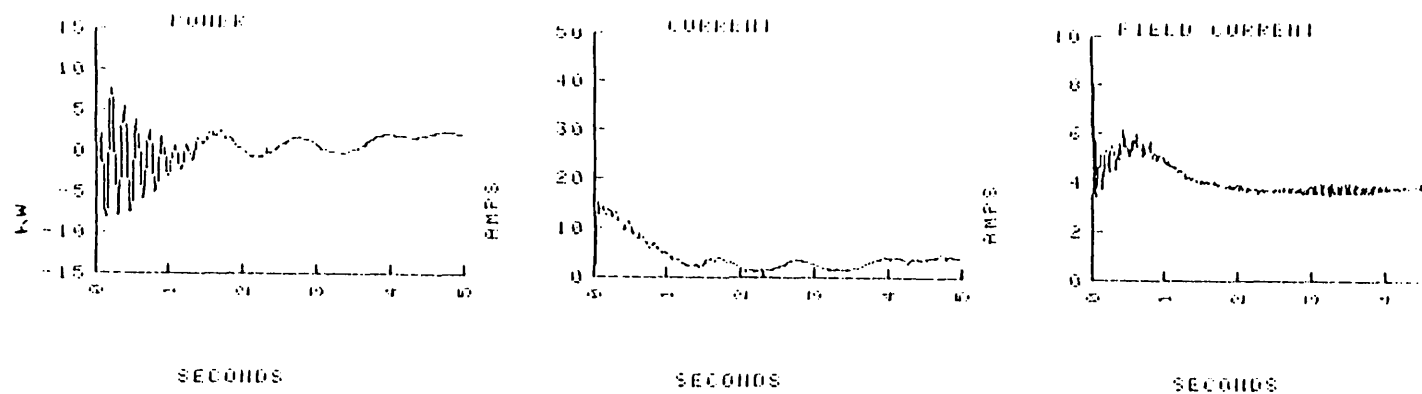
Due to transducer failures, measurements of the turbine speed and WECS terminal voltage were not recorded.

In Fig. 4.15a we observe the typical characteristics of synchronization at approx. 90° lagging phase difference. (Compare with Fig. 4.14). In Fig. 4.15b the WECS, is paralleled approx. in phase (Compare Fig. 4.12)

The eigenfrequency during the free generator oscillations is exactly as predicted. The eigenfrequency of the oscillations when generator and turbine are firmly coupled is slightly higher than that predicted. This may be due to nonlinear stiffness characteristic of the flexible coupling between the two shafts or incorrect assessment of the mechanical dampers characteristic at the generator rotor. The current recording does not show the oscillatory behaviour predicted. This is due to low pass behaviour of the r.m.s. current transducers, the time constant of which is over 50 m.s. . The high frequency components on the field current recording are due to stator



a. Phase difference approx. 270 degrees



b. In phase

Fig. 4.15 Recorded measurements of WECS Synchronization Process

back EMF transients and are not shown in the simulated excitation curves.

Apart from this minor discrepancies, the simulated and measured behaviour of the WECS during synchronization under light winds coincide qualitatively and quantitatively.

e) Synchronization failure under strong wind gust (Fig. 4.16)

The effect of the limited excitation voltage available is shown in the simulated case of synchronization under a strong wind gust represented by a step increase in wind power from 0.03 to 0.6 p.u. The paralleling is assumed to occur 180° out of phase. The generator starts slipping poles 0.7 sec after main contactor closure. The typical phenomena of pole slipping (violent current, voltage and speed oscillations) are observed.

This case is very untypical as it is expected that the WECS will run up to synchronous speed and be paralleled under light winds. However this case shows that in a gusty wind area improvements on the WECS excitation system might be advisable.

4.4.2 WECS transient response to wind power input disturbances

Several simulation studies were conducted in order to assess the system stability during wind power transients as affected by the mechanical generator damping and the one-way clutch.

A sample of these studies are described here all concerning the WECS response to wind power step changes.

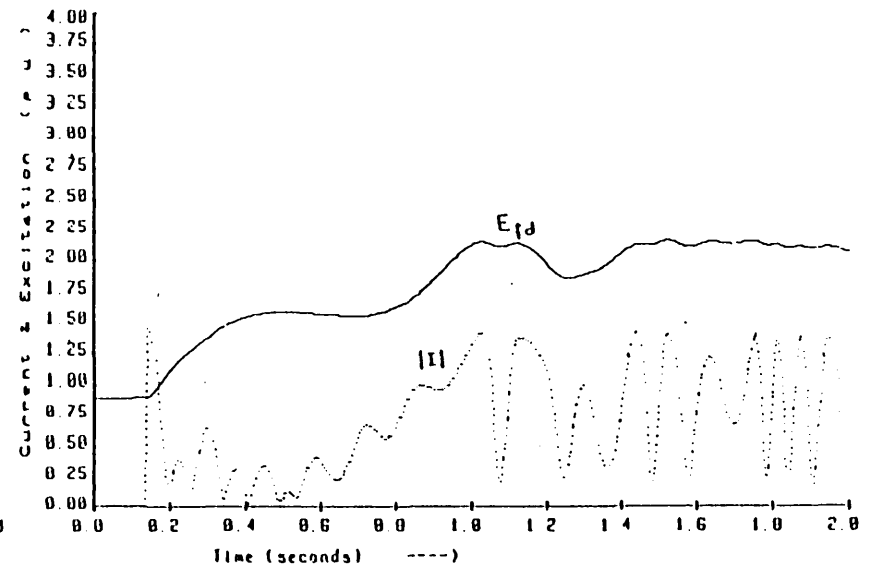
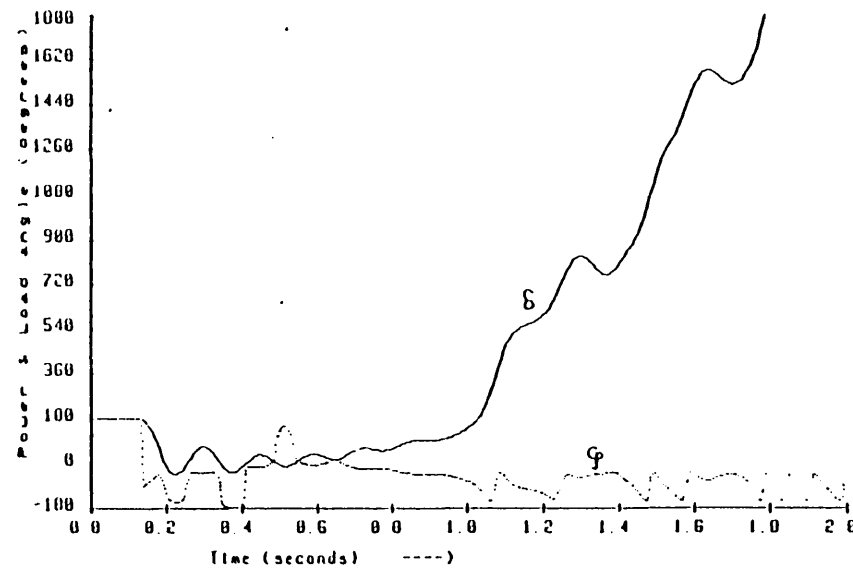
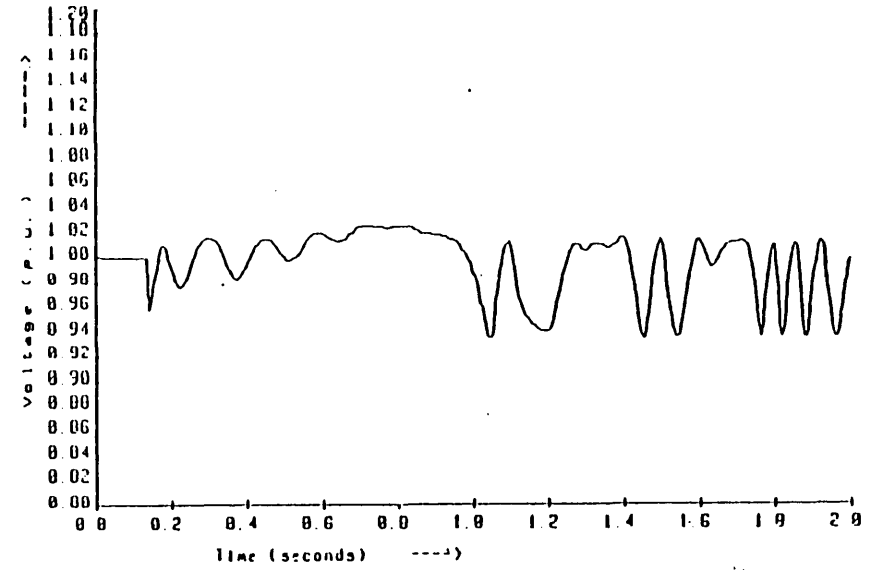
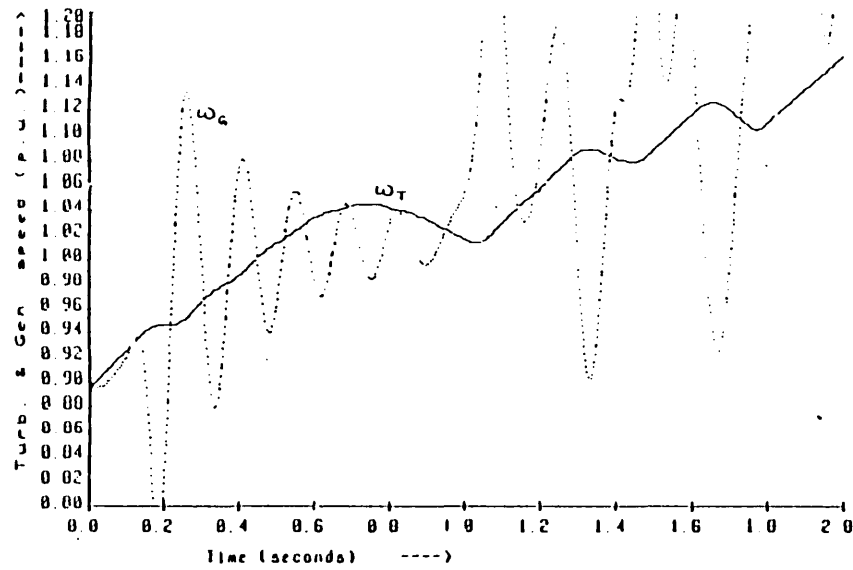


Fig. 4.16 WECS synchronization failure under strong wind gust

- a) Wind power step increase from 0.25 to 0.75 p.u. - (Fig. 4.17)

The response of the system to this severe disturbance is stable. The system oscillates with the 1 Hz eigenfrequency and stabilizes after 4 seconds. The maximum excursion of the turbine speed is less than 0.05 p.u. and of the generator less than 0.01 p.u.

The voltage disturbance is not significant.

- b) Wind power step decrease from 0.60 to 0.10 p.u. System response comparison with and without the one-way clutch - (Fig. 4.18)

The response enhancing effect of the one way clutch is clearly demonstrated in this study. The amplitude of the transient oscillations in the responses of all variables is reduced by a factor of 4. The turbine speed is within the band of ± 0.005 from synchronous in less than 2 sec with the one-way clutch and after 7 sec without. The same is valid for the generator terminal voltage transients. Of special importance is also the significant reduction in the amplitude of the torsional angle transient oscillations, indicating a corresponding reduction of the transient mechanical torques in the transmission system and consequently a reduction in mechanical fatigue.

4.4.3 Conclusions on the WECS dynamic performance

The dynamic performance of the WECS during synchronization

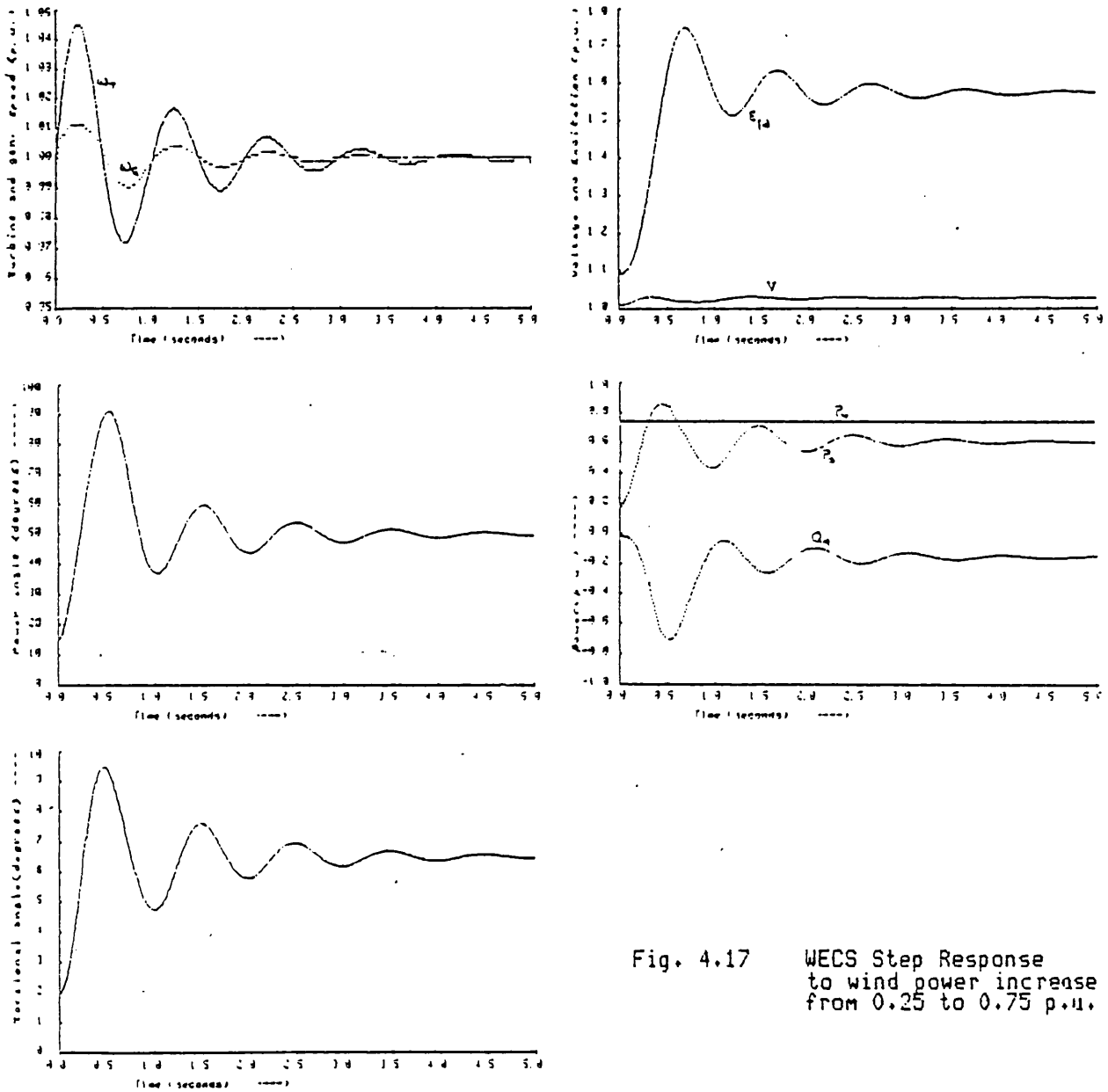


Fig. 4.17 WECS Step Response to wind power increase from 0.25 to 0.75 p.u.

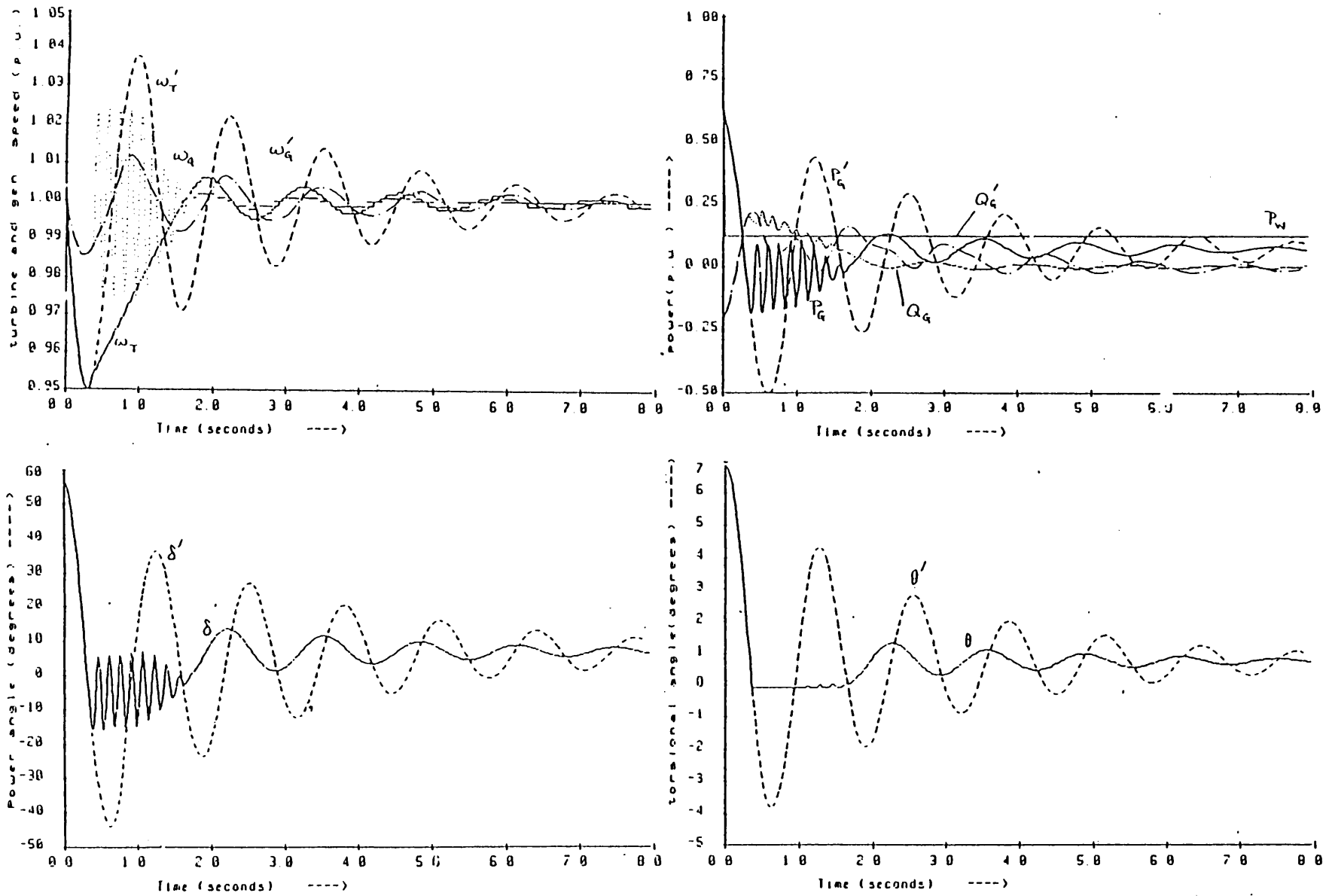


Fig. 4.18

Effect of one-way clutch
WECS Step Response to wind power decrease from 0.60 to 0.10 p.u.
(Primed Symbols: System without clutch)

under normal conditions and under severe wind power disturbances is shown to be excellent.

The generator can be synchronized without any problems under any phase difference. The response to wind gusts and lulls is fast and well damped. These good dynamic properties of the system are due to the unusually large transient reactance, the judicious choice of the generator rotor mechanical damper characteristics and the implementation of the one-way clutch between turbine and generator rotor.

According to the simulation results, stability problems might arise under gusty strong wind conditions due to the excitation EMF reduction caused by the lower operating speed (125 instead of 150 rpm) of the generator. If these predictions are confirmed in practice, compounding enhancement in the upper power range (perhaps by increasing the voltage supplied to the triac) should be considered.

Simulation studies with wind speed rather than wind power input could not be run as the control torques for the pitch control mechanism were not available from the manufacturer at the time of writing of this thesis. On-line identification was not possible due to failure of the linear potentiometer transducer which is installed at the turbine shaft for monitoring the pitch actuator displacement. This does not affect the conclusions about the system's dynamic performance, which are confirmed by measurement.

The inclusion of the pitch control mechanism in the system simulation is nevertheless necessary, in order to make an assessment of the system's behaviour under very strong turbulent winds, which are unlikely to be met during tests at RAL, but might be met at other sites.

4.5 Identification of the diesel set parameters and steady state system performance

4.5.1 Generator parameters

The diesel generator parameters were measured[†] according to Re... 4.12, 4.11. For the tests the generator was driven by a 30kw induction motor.

The measured 0-c voltage and s-c current characteristics are given in Fig. 4.19. The unsaturated generator parameters measured are:

$$\begin{aligned} r_a &= 0.0347\text{pu} \\ x_d &= 1.21\text{pu} \\ x'_d &= 0.14\text{pu} \quad (=x''_d = x''_q) \\ x_q &= 0.66\text{pu} \\ T'_{d0} &= 790\text{ms} \\ T'_d &= 93 \text{ ms} . \end{aligned}$$

The generator inertia is given by the manufacturer as

$$J_{DG} = 0.066\text{Nms}^2 .$$

The no-load generator losses have been estimated to 0.05 of the related power.

[†]By Mr H. Bleijs

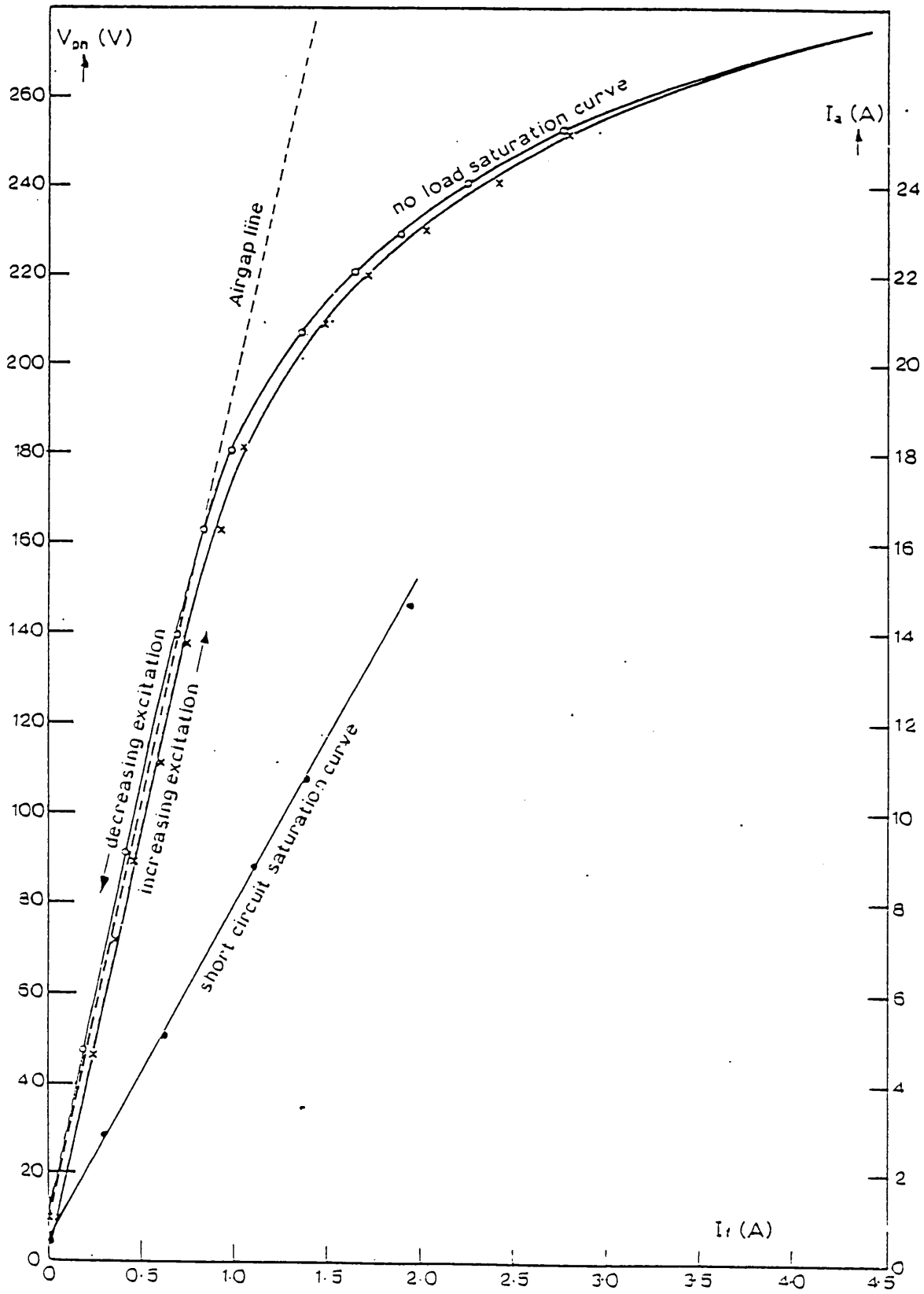


Fig. 4.19 Diesel Generator
O-c and s-c characteristics

4.5.2 Excitation system parameters

The excitation system can be modelled as recommended in Ref. 3.12 with slight modifications in order to take into account the fact that the system is a static one. The steady state equation describing the system is:

$$I_{fd} = k_R |k_v \bar{V}_s + k_I \bar{I}_s \exp[j(\frac{n}{2} + \theta)]| \quad (4.12)$$

where k_R is a voltage/current conversion factor for the rectifier bridge and the dc side circuit. k_v and k_I are the effective voltage and current transformation ratios respectively and θ is a phase shift to allow for non-ideal transformers.

This phase shift depends strictly on $\bar{V}_s$ and $\bar{I}_s$, but, for practical purposes, it has been assumed to be constant throughout the operational range. A minimizing r.m.s. error routine has been applied to the measured set of values for I_{fd} , $\bar{V}_s$ and $\bar{I}_s$ using Box's method.

The parameter values identified are :

$$k_R = 0.0326 \text{ A/V}$$

$$k_v = 0.150$$

$$k_I = 6.95 \text{ V/A}$$

$$\theta = 6.8^\circ$$

with an r.m.s. error in the I_{fd} of 64 mA which is within the measurement error ($\sim 100 \text{ mA}$).

4.5.3 Diesel engine parameters

Diesel engine speed transient response tests were not completed by the time of the writing of this thesis.

In order to assess the dynamic stability of the autonomous WECS/diesel system the parameters describing the diesel engine dynamics were partly obtained from manufacturer's information and partly estimated as:

Rated power	$P_D^r = 11 \text{ kw}$
Maximum power	$P_D^m = 12 \text{ kw}$
No-load losses	$D_D = 0.2 \cdot P_D^r$
Droop	$D_r = 0.05$
Governor set point	$P_{Do} = P_D^r$
Inertia	$J_D = 1.39 \text{ Nms}^2$
Governor time constant	$T_g = 50\text{ms}$
Combustion time constant	$T_c = 100\text{ms}$
Governor hysteresis	None
Shaft torsional stiffness	Rigid

4.5.4 Steady state performance

The steady state performance of the diesel set is characterized by the voltage and speed (frequency) regulation curves for varying loads. The measured speed curve has the linear droop characteristic, however the voltage regulation curves are rather

unusual, especially for capacitive loads. (Fig. 4.20a-b).

The application of the classical two-axis generator model, with the unsaturated values for the reactances and air gap saturation as measured in the o-c characteristic, failed to predict the measured voltage values by a large margin, especially for capacitive and large inductive loads. Several attempts have been made to correct for this, using saturated values for the machine reactances depending on the load and taking account the air gap saturation measured. As the power angle δ was not measured the effective x_d and x_q values for different loads could not be accurately assessed and the saturation characteristics of the reactances were based on guesswork.

The two-axis model representation for this machine was therefore abandoned and the voltage regulation characteristics were numerically constructed by bidimensional interpolation from the measured values. The generator characteristics calculated in this way are shown in Fig. 4.21.

Using the WECS parameters identified in Sec. 4.3 and the steady state characteristics of the diesel set, the expected steady state performance of the combined WECS/diesel system in autonomous operation was calculated for various wind power inputs and consumer loads. The frequency is regulated by the controllable load described in Sec. 4.2.4 in order to correspond to a given minimum allowable diesel output power as far as possible.

One set of calculated performance curves is given here in Fig. 4.22. The consumer load is set to 1,4 and 7 kw resistive. The minimum diesel loading is set to 20% of the rated power ($0.2 \times 6.8 = 1.36$ kw) . The frequency is regulated within ± 0.05 Hz

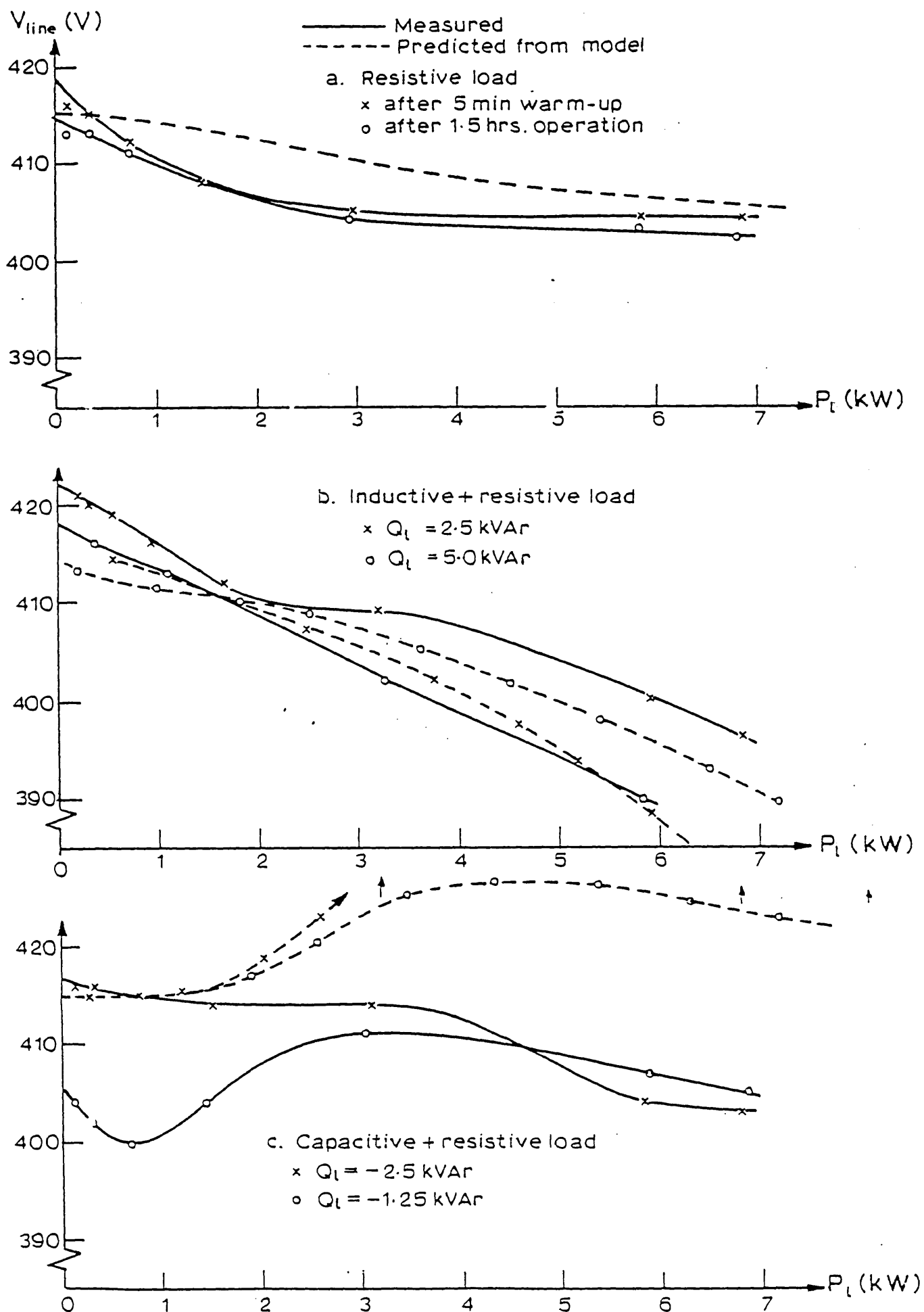


Fig. 4.20 a Diesel Generator Voltage/Power Characteristics
 (Measurements and two-axis, saturated machine reactances, simulation)

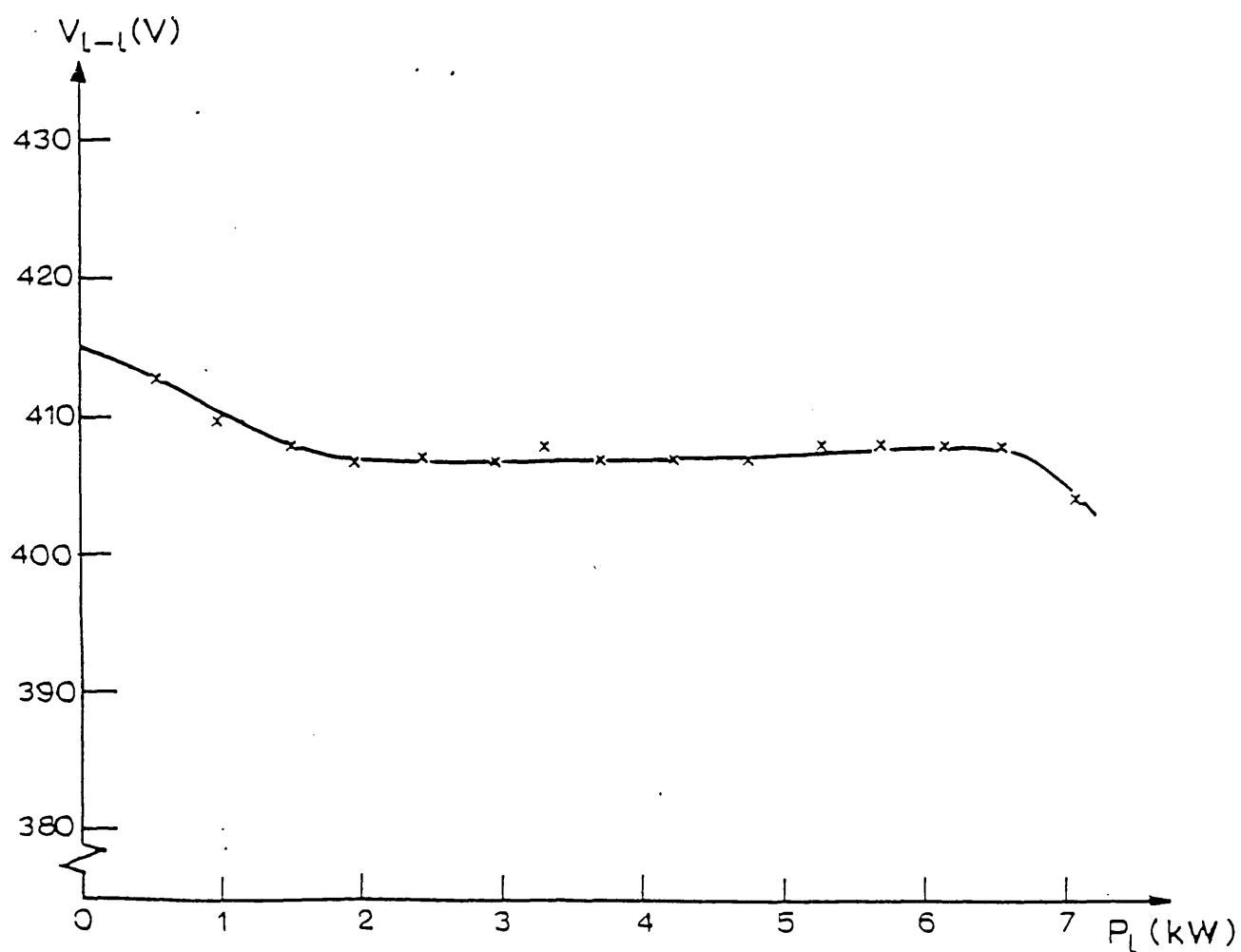
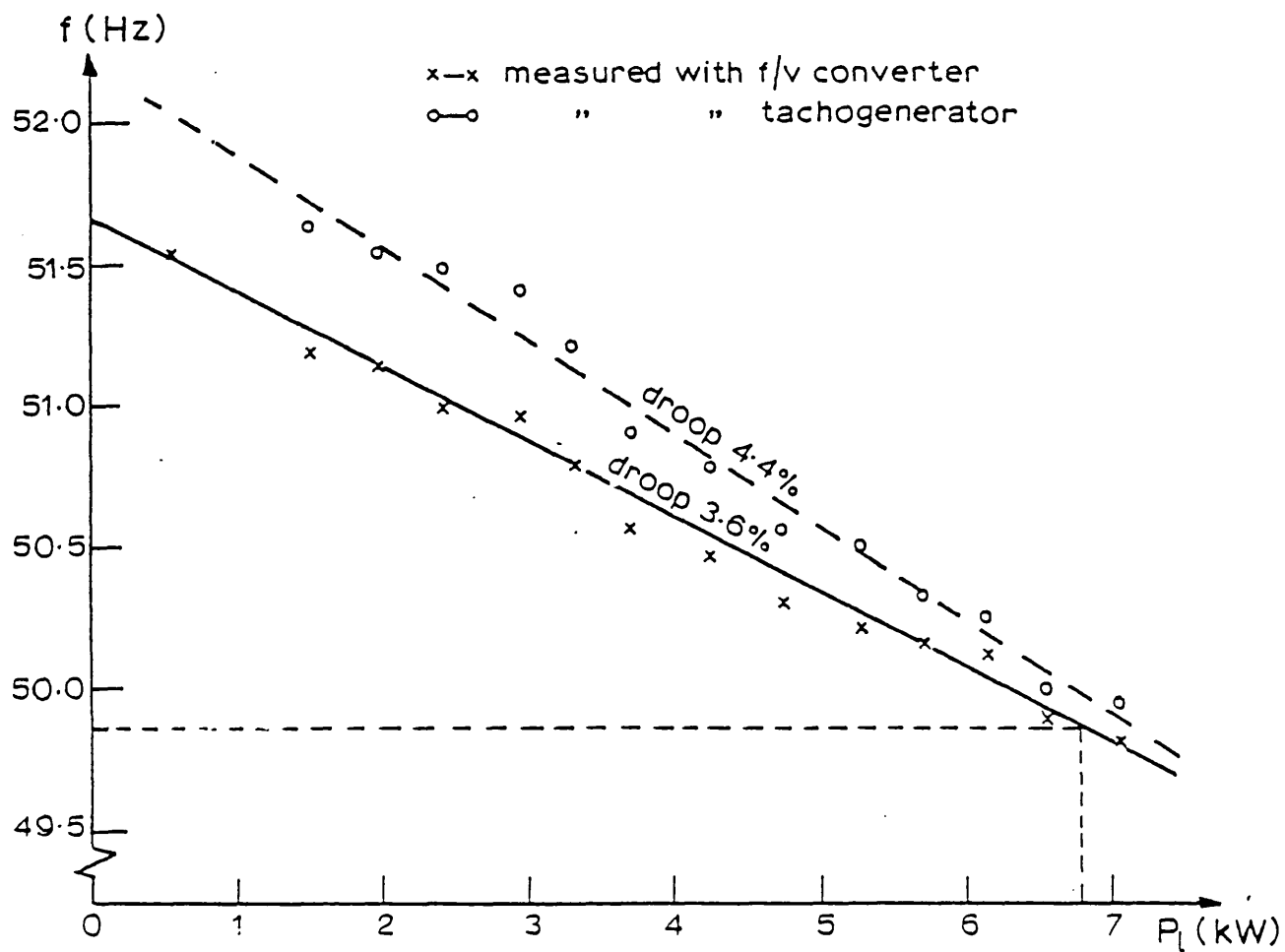


Fig. 4.20 b Diesel Set
 Droop and Voltage characteristics
 for resistive load

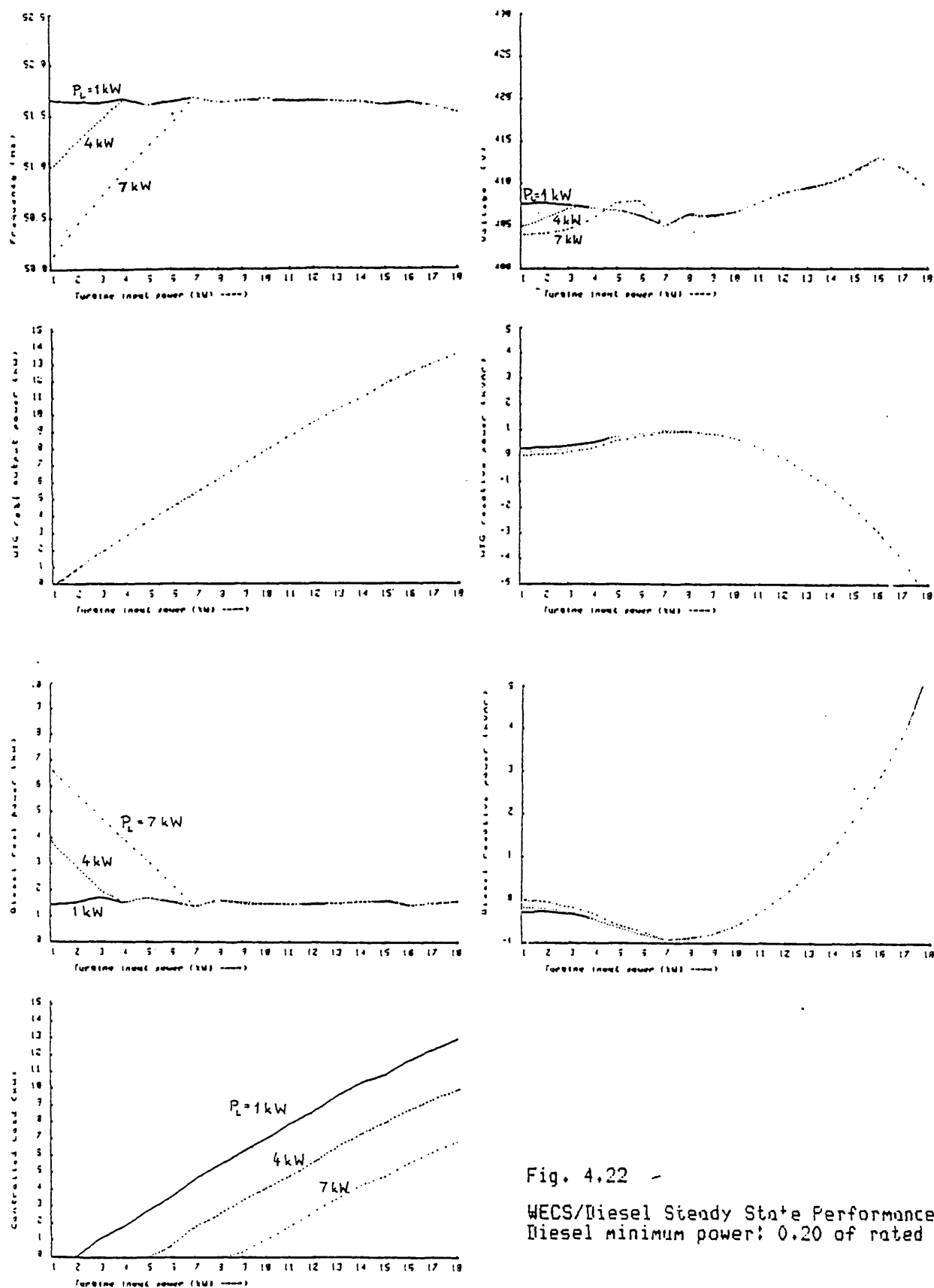


Fig. 4.22 -

WECS/Diesel Steady State Performance
 Diesel minimum power: 0.20 of rated

when the controller is active and the voltage is regulated within $\pm 6\%$ of the nominal.

A satisfactory steady state performance has been also calculated for loads with power factor in the range from 0.8 lagging to 0.9 leading (not shown here).

4.6 Frequency control and dynamic performance prediction

The dynamic behaviour of the WECS, in stand alone autonomous operation, is crucially depending on the blade pitch control performance. For the reasons explained in Sec. 4.4.3 this performance was not satisfactorily identified by the time of the writing of this thesis. Therefore the discussion of the frequency control and the prediction of the dynamic performance of the system is restricted to the parallel operation mode, where the diesel speed governor is the dominating frequency stabilizing device.

4.6.1 Dump load controller

In the parallel operation mode the dump load controller must keep the frequency constant at a set point which corresponds to steady state operation with minimum diesel loading. If the load demand minus the WECS power output exceeds the minimal diesel loading, the dump load has to be set to zero and the controller is obviously inactive. The frequency in this case is regulated only by the diesel

speed governor. As it will be shown in the next section fairly simple controllers achieve satisfactory performance when the diesel is kept in operation.

Three types of controller are described here:

a) The first controller simulated is a digital quasi-steady state with integral action and dead zone (Fig. 4.23), implemented on an Apple microcomputer by Mr. D. Boriani (IC). Although this controller had satisfactory performance with 20 ms sampling rate, (which is expected not to worsen for sampling rates up to 100-200ms), it behaves after large disturbances like a bang-bang controller. For this reason controller (b) has been simulated.

b) This controller is similar to the one above with the addition that the acceleration sign is also taken into account. This does not require any additional instrumentation or control hardware as it can be easily achieved by comparing successive frequency samples (Fig. 4.24).

c) For comparison a continuous PI controller with proportional gain of 17kw/Hz and integration constant of 1 sec (set empirically) was also simulated. The controllable load is simulated as a discrete step resistive load as described in Sec. 4.2.4.

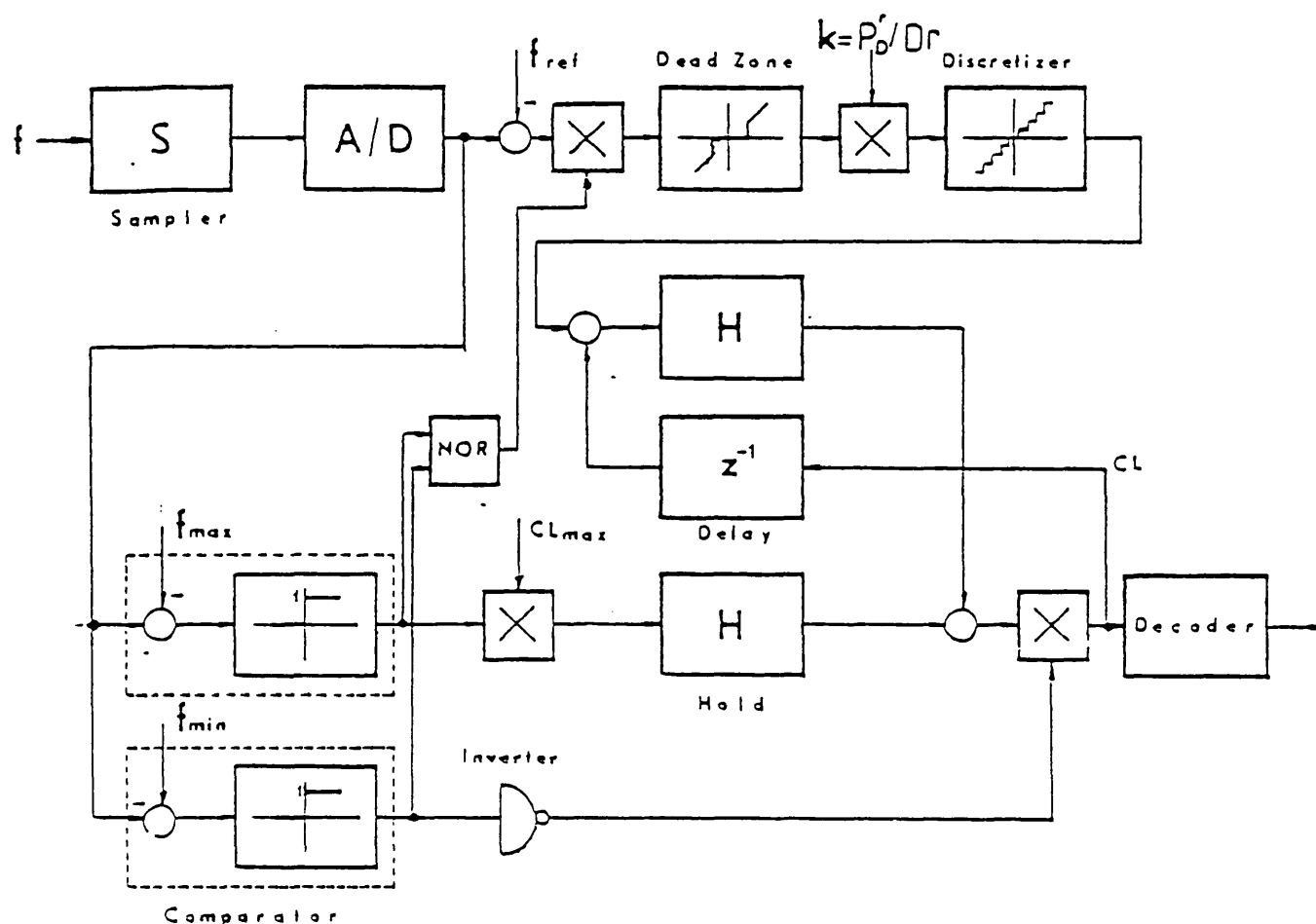


Fig. 4.23 'Integral' Digital Controller Functional Block Diagram

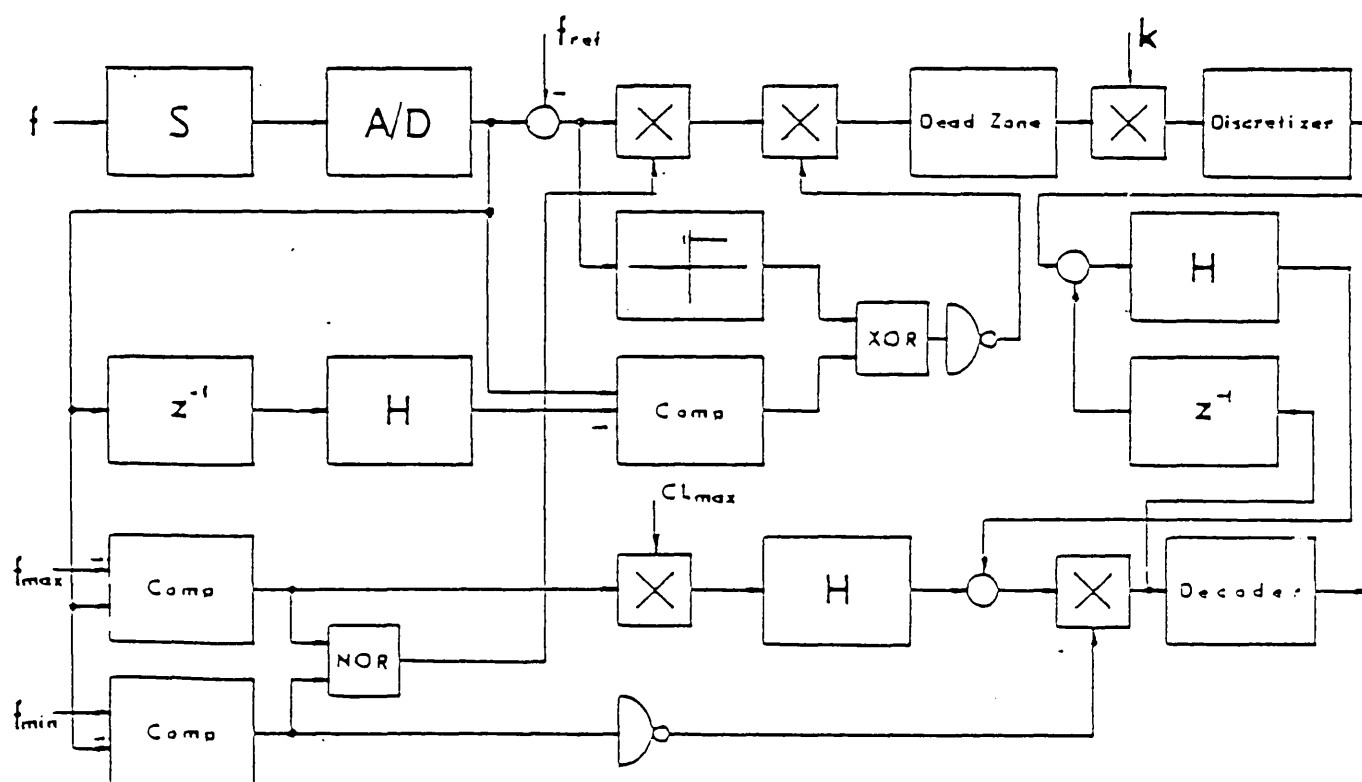


Fig. 4.24 'Integral' Digital Controller with 'acceleration dead zone' Functional Block Diagram

4.6.2 Dynamic performance simulation tests

The same basic models and integration method used in Chapter 3 and in Sec. 4.4 were also employed here. One important difference is that the diesel synchronous generator, for the reasons explained in Sec. 4.5.4, was simulated as EMF behind transient reactance, with the steady state terminal voltage values given as numerical functions of real and reactive power.

Five simulation cases are presented here. In all cases the disturbance is a step change in wind power. The load is assumed to be constant at 3 kw with unity p.f.

a) Wind power decrease from 10 to 1 kw (Fig. 4.25).

Following the disturbance, the dump load is reduced to zero after approx. 100 ms. The wind turbine generator (WTG) is declutched and free-wheels with the characteristic 6 Hz frequency after 300 ms. Small amplitude oscillations with the same frequency are induced in the diesel speed and the bus voltage. The transient is settled after 3 sec. It can be concluded that even for very abrupt and severe wind lulls the diesel speed governor and the WECS one-way clutch assure good frequency and voltage stability.

The four remaining cases compare the dynamic behaviour of the system in the case of a strong wind gust resulting in a wind increase from 5 to 10kw.

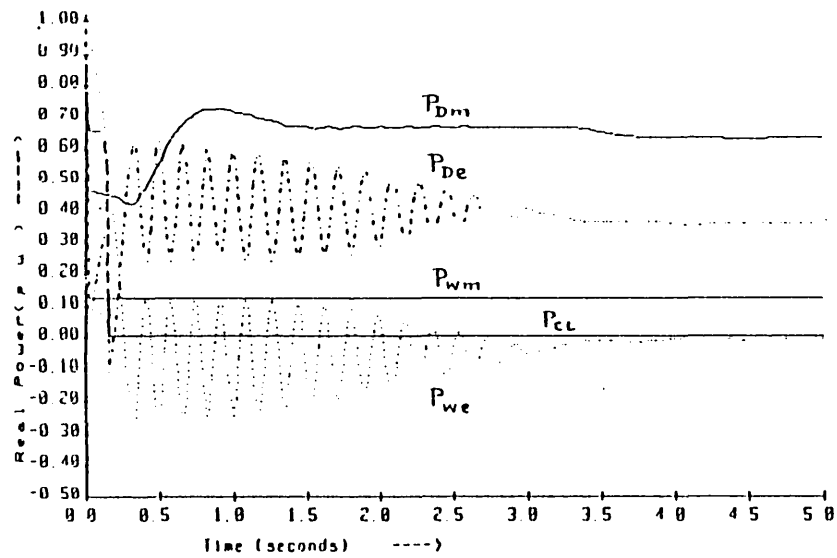
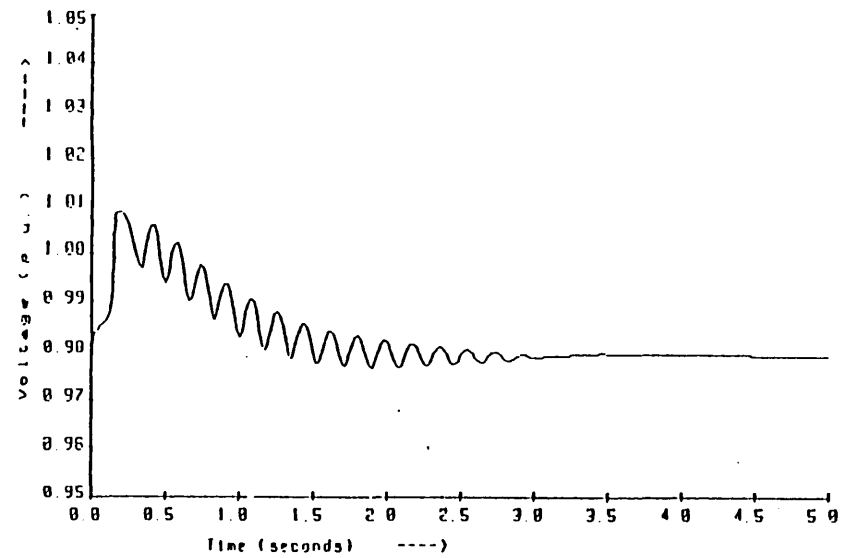
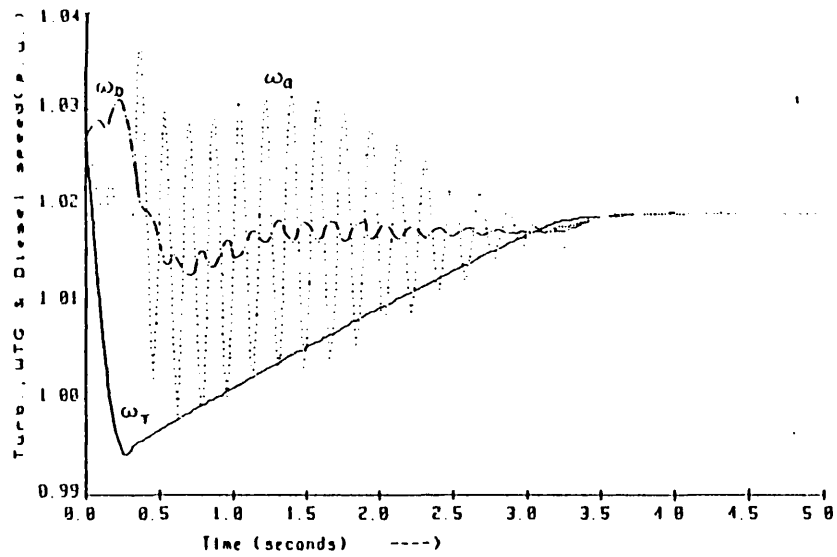


Fig. 4.25 System Step Response to wind power decrease from 10 to 1 kW
Load 13 kW ; Power factor 1.

b) System uncontrolled (Fig. 4.26)

In this case the stabilizing action of the diesel speed governor is demonstrated most clearly. The transient is over practically after 1 sec. Due to the static diesel governor droop characteristic the frequency remains at approx. 52.5 Hz in the new steady state, while the diesel generator is motoring and the diesel mechanical power input is reduced to zero.

Two important conclusions can be drawn:

- (i) Steeper droop characteristics (than the 5% assumed in this case) should be examined as a mean to achieve better frequency regulation.
- (ii) The possibility of direct fuel supply on-off modulation as frequency control should be examined, i.e. the possibility of leaving the diesel engine operating as compressor for short periods, driven by the wind power excess. The implications for the mechanical wear of the diesel engine, if such operation is allowed, are beyond the scope of this thesis.

c) System controlled by quasi-integral controller (Fig. 4.27).

The frequency control in this case is satisfactory. As it is shown in the real power curves the controller is compensating the WTG power output excess. The steep dump load changes result to changes in the diesel electrical power output while the WTG output is hardly affected. This is due to the fact that the transient reactance of the WTG (including tie-line) is approx. 4 times larger than the diesel generator transient reactance.

The transient is settled in approx. 4 seconds.

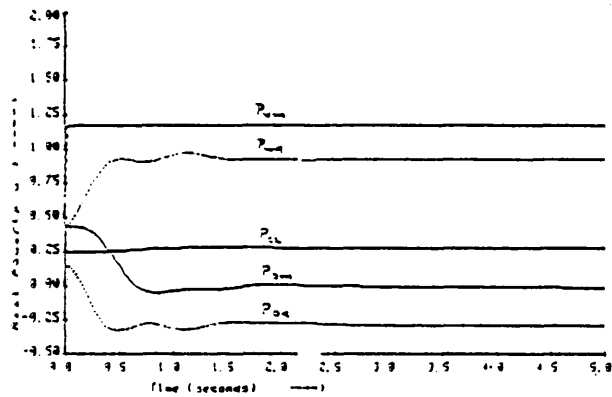
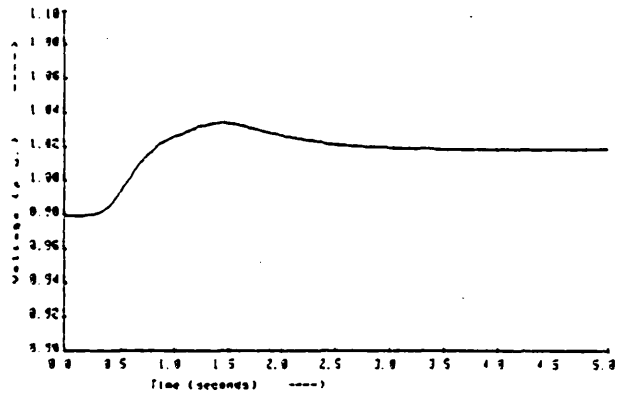
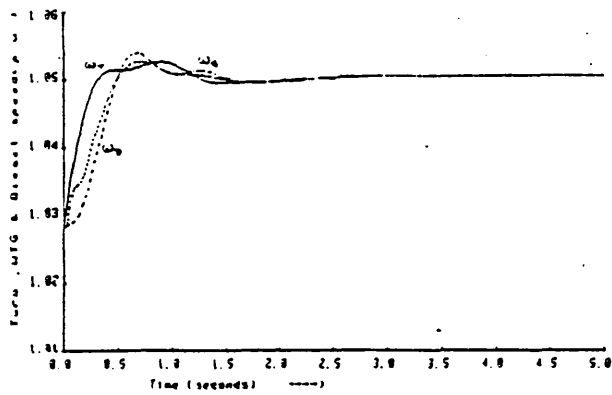


Fig. 4.26

Uncontrolled System Step Response
to wind power increase
from 5 to 10 kW

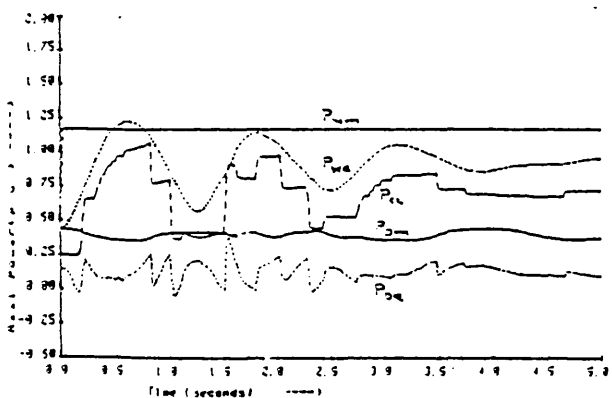
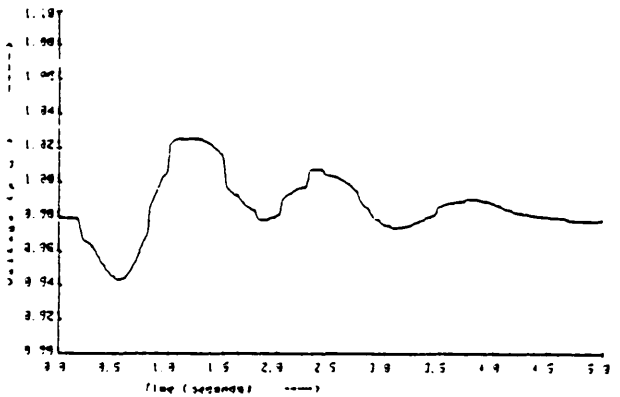
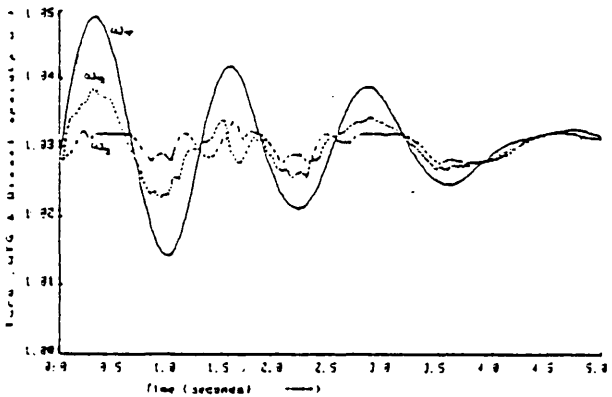


Fig. 4.27

System Step Response
with 'integral' controller

- d) System controlled as above but with acceleration sign
(Fig. 4.28)

The behaviour is similar to the case (c) above with the important difference that the diesel electrical power output changes are reduced by a factor of approx. 4 due to the smoother controller action. The settling time is slightly reduced.

- e) Continuous PI controller (Fig. 4.29)

The PI controller does not perform better than the digital controllers. The settling time is reduced to 2.5 sec. but at the cost of higher frequency and power fluctuations. It can be that optimization of the controller parameters will achieve better results but the improvement is not expected to be substantial.

From these simulation results it can be concluded that the system in parallel operation mode is expected to perform very well even under severe wind turbulence conditions by implementing simple digital control. Care should be taken that high frequency fluctuations due to transient oscillations of the diesel generator or the cycling of the diesel engine (which were not included in the simulation model) are smoothed either by direct filtering or by choosing an appropriately large sampling period.

4.7 Comments

The autonomous system under development at RAL is shown

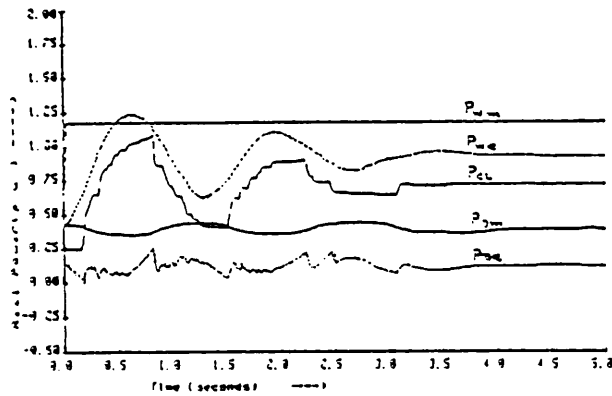
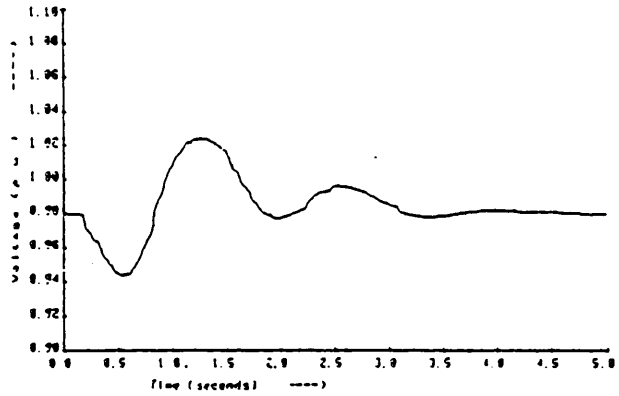
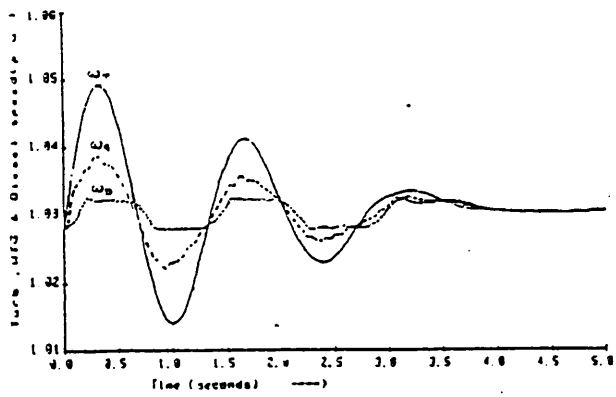


Fig. 4.28

System Step Response
with 'integral' controller
and 'acceleration dead zone'

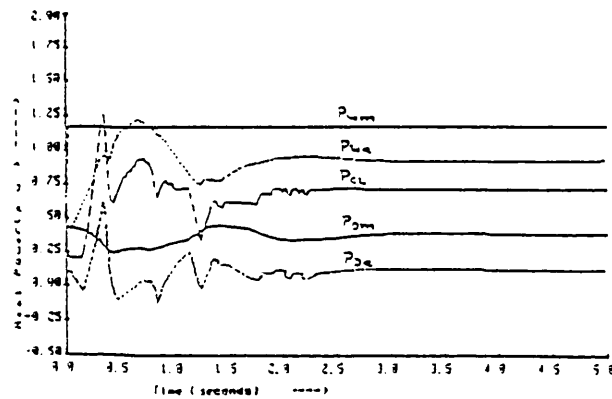
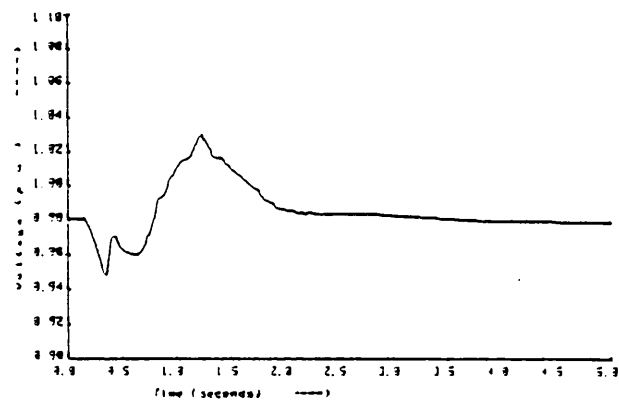
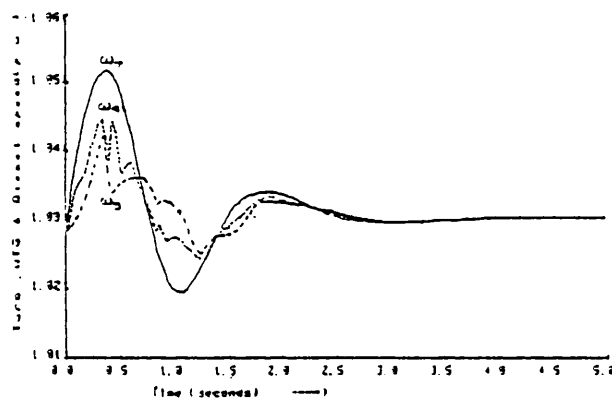


Fig. 4.29

System Step Response
with continuous PI controller
and dead zone

to possess stability enhancing features, which permit a good performance to be achieved with fairly simple (and robust) control algorithms, requiring a minimum of instrumentation and control hardware.

For WECS stand alone operation some modifications are required in the voltage and frequency regulation system, if it should be proven that the proposed fuel supply on-off modulation is not achievable:

- a) The WTG excitation system has to be replaced by a proper AVR if the diesel generator is switched off or
- b) An electromagnetic clutch has to be interposed between diesel engine and generator in order to allow the generator to be operated as synchronous capacitor.
- c) A short term storage device (5-10 sec rated power capacity) should be implemented to allow for frequency maintenance during diesel start-up.
- d) The control system has to be modified to allow for dual operation mode, incorporating the control of the additional devices required for WECS stand alone operation (electromagnetic clutch, active storage regulation and diesel start/stop). If the simulation results presented in this chapter are confirmed by measurements, and after the identification of the pitch control system parameters, the simulation programs outlined in this chapter can be confidently used for the performance evaluation of possible modification of the design or the operation parameters of the system components.

CHAPTER 5

ADAPTIVE CONTROL APPLICATIONS ON WIND/DIESEL SYSTEMS

5.1 Introduction

From the preceding chapters it can be seen that even relatively simple wind/diesel systems exhibit a highly non-linear behaviour and the adequate mathematical description requires the identification of a large number of parameters. Furthermore, some of these parameters do change in time, not only depending on the operation state history of the system but also in a random way, due to factors which we cannot or we cannot afford to measure or to estimate. To give a few examples :

- a) The turbine rotor performance characteristics, calculated or measured in the wind tunnel, for laminar standard uniform air stream, with constant velocity perpendicular to the rotor, diverge appreciably in the open field, where all these conditions rarely apply. (Refs. 5.1, 5.2, 5.3).
- b) The simple linear diesel droop characteristic is in general non-linear and varies with diesel temperature, condition of the injectors and the cylinders and so on. The same applies for the assumed time constants for the speed governor, combustion delay etc.
- c) The generator and excitation system parameters vary with temperature, which depends again on cooling conditions, time of operation, load history etc.

In the multimachine system the dimensionality of the

identification problem is increased accordingly. After successful parameter identification on a more or less idealized and time-invariant system model it is nevertheless possible, as it has been proven in practice, to design reasonable linear or non-linear time-invariant feedback controllers which perform well in a region of operating conditions and satisfactorily in others. This approach has been adopted in the control system design for WECS throughout until now (Refs. 5.4, 5.5, 5.6, 5.7). Random changes in the system parameters, the wind turbulence and changes in the network structure and load demand and combinations thereof, cannot be accounted for in any fixed parameter control system and could in some cases result in inferior performance.

As the input variables to the system (i.e. wind speed, real and reactive load demand) are random variables with relatively slowly varying statistics and low frequency spectra under normal conditions[†], the examination of on-line identification and adaptive control methods appears to be attractive.

In this chapter two problems associated with adaptive control of wind/diesel system, the diesel switching decision problem and the adaptive frequency control problem will be formulated. Some theoretical aspects will be presented and application examples discussed.

†

Note: The dealing with catastrophic events, like short-circuits, excitation loss, or unusually strong wind gusts, is a matter for the protection system and will not be discussed here.

5.2 The diesel engine switching decision problem

As the diesel-set losses at idle running conditions are high and, additionally, maintenance requirements impose usually a minimum loading on the diesel engine, the problem of stopping and starting the diesel by excess or deficit respectively of WECS output power in respect to load demand has a major economic importance.

The diesel-set is able to deliver power some time T_{start} after it has been started (4-10 sec). If an additional power source (storage) is not available, the prediction at each time t_0 of the likely power balance for the period $[t_0, t_0 + T_{\text{start}}]$ is crucial for the decision to change or not to change the operational status of the diesel engine. The accuracy of the prediction affects also the necessity or the size of the reserve power source required which is also of importance for the system economy and complexity.

The problem is similar to the determination of spinning and hot reserve in a power system and in terms of large scale integration and long term forecasting this was investigated in Ref. 5.8.

In the following the problem will be investigated only in terms of system stability without reference to logistic implications on quantities like fuel consumption, storage size, minimum diesel run time, or frequency of diesel starts which are beyond the scope of this thesis. An approach to some aspects of these problems is described in Refs. 5.9, 5.10, 5.11, 5.12, 5.13

5.2.1 Problem formulation

In general the problem can be formulated as follows:

Given the power balance between WECS output and load demand

$P_b = P_w - P_L$, to be a stochastic process, measured for the time from $-\infty$ to t_0 , that the diesel start time is T_{start} and that a storage device with power capacity of P_0 is available, what is the probability for the energy deficit over any part of the period $[t_0, t_0 + T_{start}]$ to exceed a specified level E_0 .

This is a level crossing problem, which, although theoretically approached (Ref. 5.14), is extremely difficult to handle in the general case of continuous processes. Numerical solutions have not yet been suggested (Ref. 5.15). The problem can be simplified if the process $P_b(t)$ is represented as a discrete time series $y(n)$ with sampling period Δt and $T_{start} = N \cdot \Delta t$.

Then, assuming that the decision time instant is n_0 , the decision criterion for keeping the diesel on or starting it can be simplified to

$$\text{prob}(y(n_0+k) \leq -P_0 - E_0/\Delta t) \leq p_0 \quad (5.1)$$

for all $k = 0, 1, 2, \dots, N$

where p_0 a specified probability level.

For the sake of simplicity the sums $\sum_{m=m_1}^{m=m_2} y(n_0+m)$ with $1 \leq m_1 < m_2 \leq N$ have not been included in the criterion. Adjusting the probability level p_0 could compensate for this.

Obviously the decision criterion includes the measured or estimated power balance at the decision instant.

This problem is reduced to a prediction problem and is readily solvable under the assumptions (Ref. 5.16) that :

'The process $y(n)$ is stationary, Gaussian with rational spectral density'.

This is in general not valid for the WECS power output unless:

- a) The prediction period is short enough for the wind speed to be considered stationary (for periods of some seconds this is normally the case)
- b) The wind speed is a Gaussian process with rational spectral density (which is also the case for short time periods)
- c) The wind speed/power output dynamics can be described by a linear differential equation (which is approximately true for small wind speed fluctuations over the time period considered, around an average wind speed sufficiently higher than the cut-in and lower than the furling speed).

The assumption of a Gaussian distribution with rational spectral density for the load demand is taken to be valid for a large number of consumers. If the number of consumers is small, the load is assumed to be kept sufficiently constant to avoid critical situations when the diesel set is not running and the power balance is marginally positive.

When the wind speed signal is available at some distance before the turbine rotor and the steady state wind speed/power characteristic is assumed to be time invariant and to hold approximately for transient conditions, it is possible to use the wind speed signal instead of the power signal to derive the decision criterion.

The problem is thus formulated as a prediction problem for a discrete time stationary process.

5.2.2 Optimal prediction of discrete time stationary processes

The short exposition of the prediction technique in this section follows closely Ref. 5.16 , where the proofs for the mathematical statements can be found.

A stochastic process $\{y(t), t = 0, \pm 1, \pm 2, \dots\}$ with the properties defined in the preceding section can be described as an ARMA (autoregressive-moving average) process

$$y(t) = \sigma \cdot \frac{C(q^{-1})}{A(q^{-1})} e(t) \quad (5.2)$$

where:

q^{-1} : the backward time shifting operator

$$q^{-1}x(t) = x(t-1)$$

$$C(q^{-1}) = 1 + c_1 q^{-1} + c_2 q^{-2} + \dots + c_n q^{-n} \quad (5.3)$$

$$A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-2} + \dots + a_n q^{-n}$$

and $e(t)$ is a sequence of independent normal random variables with zero mean and variance 1 (white noise). For the process $x(t)$ to be stable it is assumed that $A(q^{-1})$ has all the zeros outside the unit circle. The same is required for the zeros of $C(q^{-1})$ in order that the predictor is strictly stable.

It can be shown that the optimal k -step predictor $\hat{y}(t+k|t)$ for the process $y(t)$, in the sense of minimizing the variance of the prediction error, is given by

$$\hat{y}(t+k|t) = \frac{G(q^{-1})}{C(q^{-1})} y(t) \quad (5.4)$$

and the prediction error by

$$\tilde{y}(t+k|t) = \sigma F(q^{-1}) e(t+k) \quad (5.5)$$

where

$$G(q^{-1}) = g_0 + g_1 q^{-1} + \dots + g_{n-1} q^{-(n-1)} \quad (5.6)$$

$$F(q^{-1}) = 1 + f_1 q^{-1} + \dots + f_{k-1} q^{-(k-1)}$$

are polynomials of degree $n-1$, $k-1$ respectively which are uniquely determined by the equation

$$C(q^{-1}) = A(q^{-1})F(q^{-1}) + q^{-k}G(q^{-1}). \quad (5.7)$$

The coefficients of the polynomials $F(q^{-1})$ and $G(q^{-1})$ can be recursively determined from the equations

$$f_m = c_m - \sum_{i=0}^{m-1} a_{m-i} f_i \quad (5.8)$$

for $m = 1, \dots, k-1$ and $f_0 = 1$

and

$$g_p = c_{k+p} - \sum_{i=0}^{k-1} a_{k+p-i} f_i \quad (5.9)$$

for $p = 0, \dots, n-1$ and $c_{n+j} = a_{n+j} = 0$ for $j > 0$.

As it can be seen in Eq. 5.8 the coefficients f_m for the k -step and the $(k-1)$ -step predictor are the same except the last. So when predicting successively $1, 2, \dots, k$ steps ahead the $f_1, \dots, f_{k-1}$ need only to be calculated once.

Eq. 5.4 can be explicitly written in the difference equation form

$$\hat{y}(t+k|t) = - \sum_{i=1}^n c_i \hat{y}(t+k-i|t-i) + \sum_{i=0}^{n-1} g_i y(t-i) \quad (5.10)$$

where $\hat{y}(t+k-i|t-i)$ is the k -step prediction made at the time $t-i$.

The variance of the prediction error is

$$\text{var}[\tilde{y}(t+k|t)] = \sigma^2 \cdot \sum_{i=0}^{k-1} f_i^2 \quad (5.11)$$

with $f_0 = 1$.

Eq. 5.10 and 5.11 and the knowledge that $\tilde{y}(t+k|t)$ is a Gaussian process, as linear combination of Gaussian processes, allows the immediate solution of the decision criterion formulated in the inequality 5.1.

The construction of the k -step predictor is shown to be straightforward under the assumptions made about the process $y(t)$ and its generating process $e(t)$, once the coefficients of the ARMA model polynomials $A(q^{-1})$ and $C(q^{-1})$, and the mean and variance of $y(t)$ are known. When the process is slowly varying the prediction procedure must be preceded at each time step by a system parameter identification procedure.

5.2.3 Stochastic model parameter identification

The identification procedure for a linear univariate system described by the equation

$$y_t = \bar{x}_t^T \bar{\theta} + \epsilon \quad (5.12)$$

where y_t is the output observed at time t

$\bar{x}_t$ the model input vector at time t

$\bar{\theta}$ the model parameter vector

and ϵ_t the error at time t

amounts to the minimization of a function of the error for a number of past observations N . The most common cost function used is the sum of error squares to which we will restrict ourselves in the following. (Refs. 5.17, 5.18)

$$S(\theta) = \sum_{t=1}^N (y_t - \bar{x}_t^T \bar{\theta})^2 . \quad (5.12.a)$$

The least squares estimation of $\bar{\theta}$, based on the observations $y_1, y_2, \dots, y_N$ is given by

$$\hat{\theta}_N = (X_N^T X_N)^{-1} X_N^T Y_N \quad (5.13)$$

$$\text{with } X_N = \begin{bmatrix} \bar{x}_1^T \\ \bar{x}_2^T \\ \vdots \\ \bar{x}_N^T \end{bmatrix}, \quad Y_N = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} . \quad (5.14)$$

In the case described in the previous section, with $\epsilon(t) = \sigma \cdot e(t)$, it is

$$\bar{\theta}^T = [a_1, a_2, \dots, a_n, c_1, c_2, \dots, c_n] \quad (5.15)$$

$$\text{and } \bar{x}_t^T = [y(t-1), y(t-2), \dots, y(t-n), \epsilon(t-1), \epsilon(t-2), \dots, \epsilon(t-n)] .$$

The inversion of the matrix involved in Eq. 5.13 can be avoided by using the recursive least squares algorithm described in Ref. 5.18

By defining the inverse covariance matrix

$$P_N = (X_N^T X_N)^{-1} \quad (5.16)$$

the recursive least squares algorithm is described by the equations

$$K_{N+1} = P_N \bar{x}_{N+1} / (1 + \bar{x}_{N+1}^T P_N \bar{x}_{N+1}) \quad (5.17)$$

where K_N is a time varying gain vector,

$$\hat{\theta}_{N+1} = \hat{\theta}_N + K_{N+1} (y_{N+1} - \bar{x}_{N+1}^T \hat{\theta}_N) \quad (5.18)$$

and

$$P_{N+1} = I - P_N \left(\frac{x_{N+1} x_{N+1}^T}{1 + x_{N+1}^T P_N x_{N+1}} \right) P_N \quad (5.19)$$

The recursive algorithm is initialized either by computing P_0 explicitly from Eq. 5.16, using an initial data block, or setting $P_0 = I/\varepsilon$, where ε is small.

When the vector θ is time varying, the recursive estimation process will, after some time, be corrupted by a large amount of past data not relevant to the present process state. To avoid this, the more recent model errors have to be weighted more heavily when determining the performance function $S(\theta)$.

Three approaches for this problem (exponential weighting, fixed width sample and Kalman filtering) are discussed in Ref. 5.18.

Further modifications to the recursive least squares algorithm are required, when the residual sequence $\{\varepsilon_t\}$ is correlated, to overcome the estimator bias (Ref.s. 5.18, 5.19). A short exposition of the extended matrix method, which has been implemented in the following examples, is given in Appendix.5.1.

The choice of the extended matrix method was based on the assessment in Ref. 5.18 that 'the method has been found to have good convergence properties in almost all cases studied!'. This was not always the case in the present study, especially for large order predictors (3d and above), where the algorithm tended to numerical instability. It is probable that more recently developed numerically more robust algorithms like the 'square root' filters described in Ref. 5.19 will improve the prediction performance.

5.2.4 An example of wind speed and power balance prediction

The prediction algorithm described has been implemented and tested with several wind samples. An application example on a 300 points sample of free wind speed measured at RAL with a 2Hz sampling frequency is presented here. The sample statistics are given in Table 5.1

Table 5.1

Wind speed test sample statistics

Mean wind speed	5.4m/s
Standard deviation	0.9m/s
Maximum	7.2m/s
Minimum	3.2m/s

The process has been modelled with a first order and a second order ARMA model. The wind speed. was simultaneously predicted for 1, 2,3 and 4-time steps ahead.

In Fig. 5.1a to 5.1c the measured wind speed $w(t)$ is plotted together with the curves $\hat{w}(t+k) \pm \sqrt{\text{var}\{\tilde{w}(t+k)\}}$ (one standard deviation error band) for $k = 1, 2$ and 4 , for the first order ARMA model.

The ARMA coefficients are plotted in Fig. 5.1d.

In Fig. 5.2 a-d the same graphs are plotted for the second order ARMA model. The error statistics are given in Table 5.2 below.

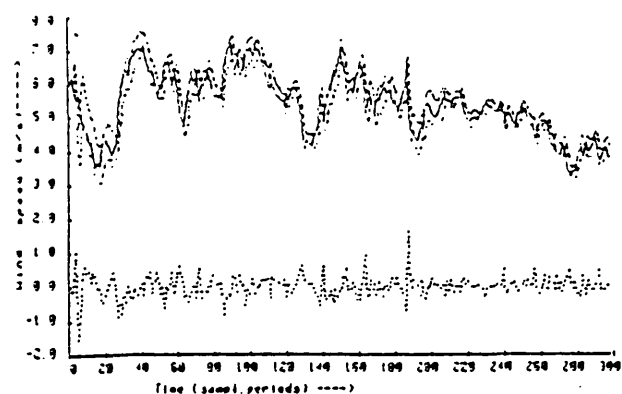
Table 5.2

Wind Speed prediction error statistics

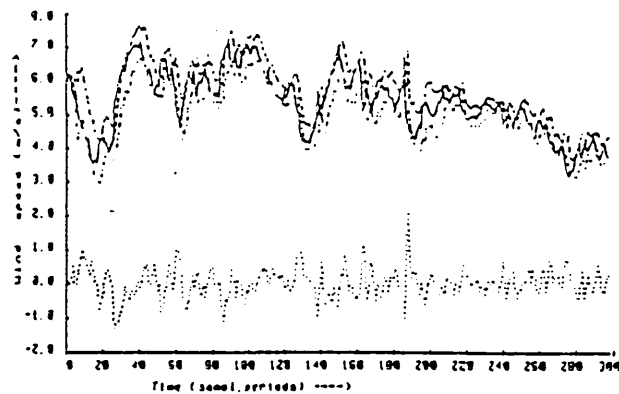
Predictor order	1				2				
Prediction lead	1	2	3	4	1	2	3	4	
Pos. error count	155	161	167	171	159	160	169	171	
Neg. error count	145	139	133	129	141	140	131	129	
Abs. rms error	0.28	0.39	0.46	0.52	0.29	0.39	0.46	0.52	m/s
Rel. rms error	0.05	0.08	0.09	0.10	0.05	0.08	0.09	0.10	
Max. pos. error	1.7	2.1	1.9	1.9	1.8	2.2	2.0	2.0	m/s
Max. neg. error	-1.0	-1.1	-1.3	-1.5	-1.0	-1.1	-1.3	-1.5	m/s

It is clear that the second order model does not improve the prediction accuracy.

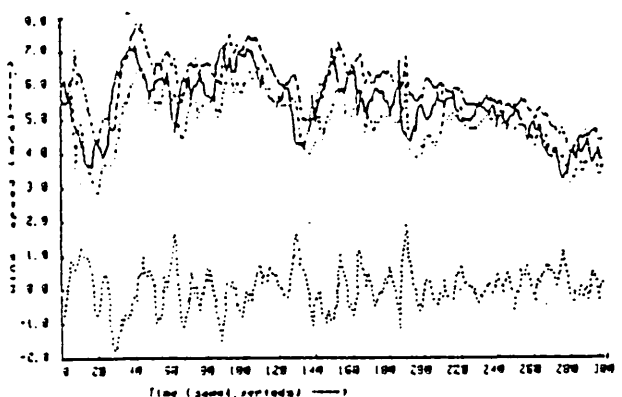
The average CPU time on the CDC Cyber 174 for a complete 4 step prediction is estimated approx. to 1ms and 3ms for the 1st



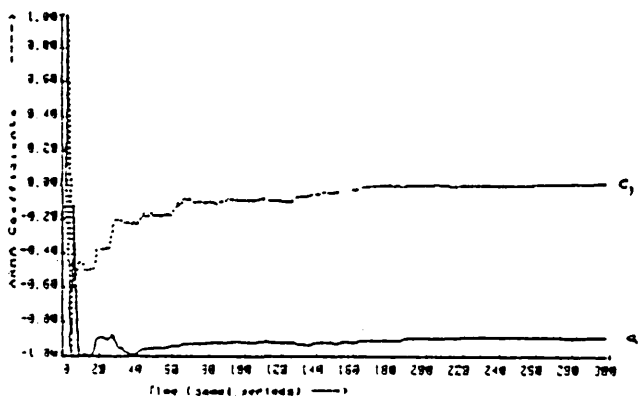
a. Prediction 1 step ahead



b. Prediction 2 steps ahead

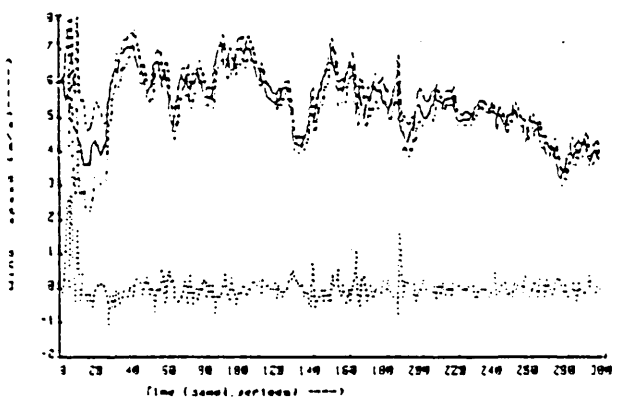


c. Prediction 4 steps ahead

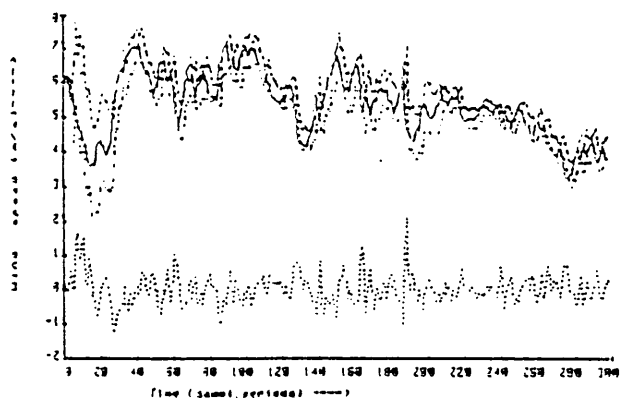


d. ARMA coefficients

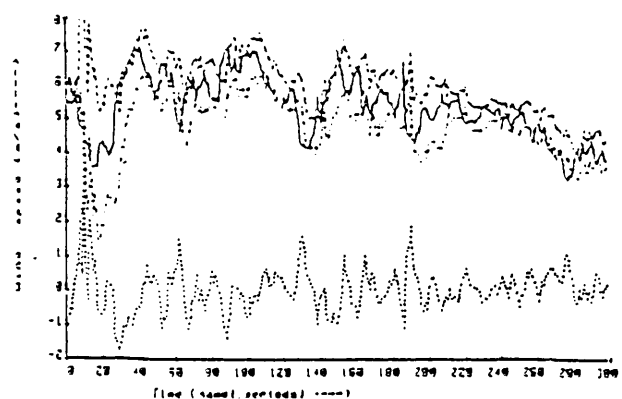
Fig. 5.1 Wind Speed Prediction with 1st order ARMA Model



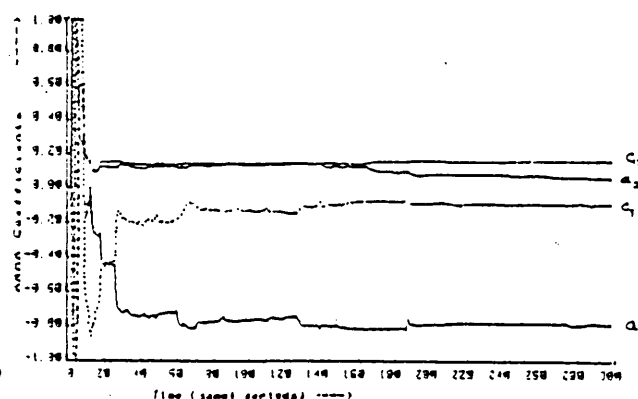
a. Prediction 1 step ahead



b. Prediction 2 steps ahead



c. Prediction 4 steps ahead



d. ARMA coefficients

Fig. 5.2 Wind Speed Prediction with 2nd order ARMA Model

and 2nd order predictor respectively. The time was found to increase approximately with the square of the predictor order and linearly with the prediction step number.

The next example is a test of power balance prediction applied to the diesel switching problem. A 10 min sample of WECS output recorded every 1 sec at RAL has been used to represent the power balance. The diesel starting time for the system in RAL is 4 seconds. The prediction is made accordingly each second for 1,...,4 seconds ahead. The power signal is modelled as a 1st order ARMA process.

The self-adjustment of the prediction confidence limit according to the turbulence of the input signal is demonstrated in Fig. 5.3, where the actual signal and the 95% (2σ) lower prediction confidence limit for the 1 step prediction are plotted for the first half of the sample.

In Fig. 5.4 the diesel status as controlled by the decision criterion Eq. 5.1 is plotted together with the power balance signal for 1σ prediction confidence limit. In this graph the diesel status 1 corresponds to the diesel running at minimum load, status 0 corresponds to the diesel being stopped, and values in between correspond to run up or run down status. The diesel outputs power only when at status 1.

The results of the test for 1σ , 2σ , 3σ prediction confidence limits are given in Table 5.3.

It should be noted that the WECS output power was recorded under light but turbulent wind and in this sense the power signal used is representing an extreme case as the process is obviously non-stationary. Increasing the order of the input signal model to 2nd and 4th order did not produce any prediction improvement.

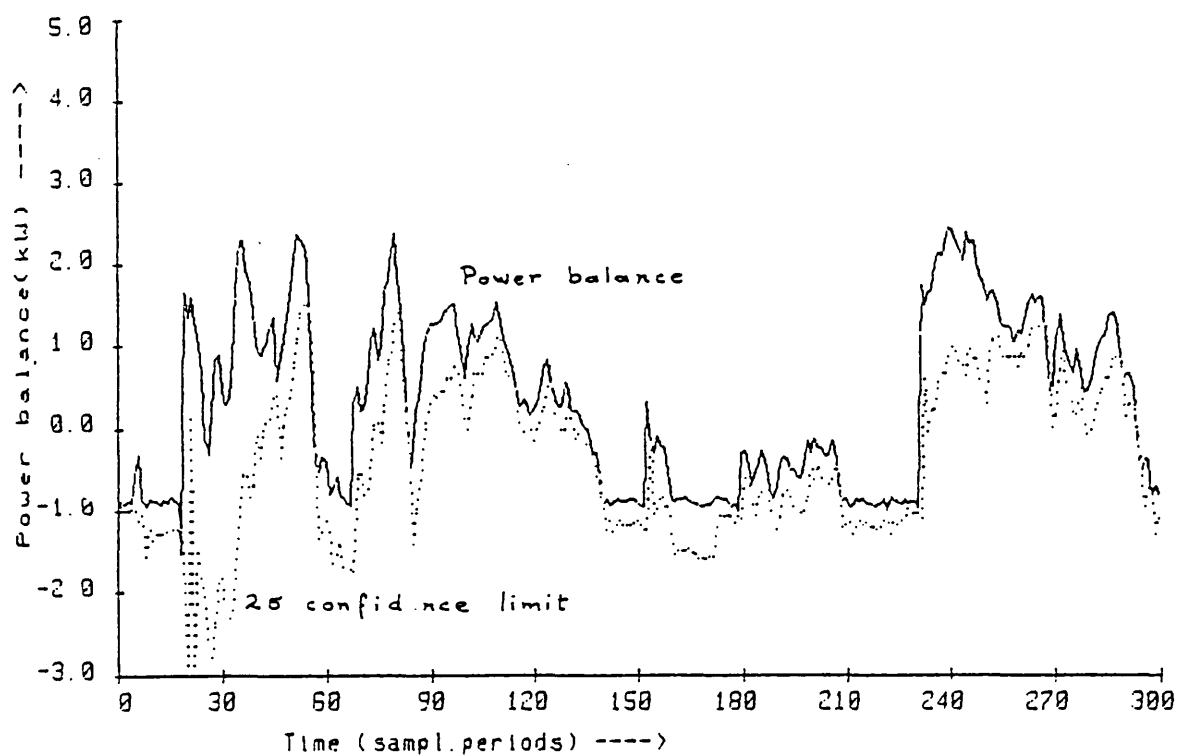


Fig. 5.3 Power Balance Prediction with 1st order ARMA Model
One step ahead prediction ; 2-sigma confidence limit

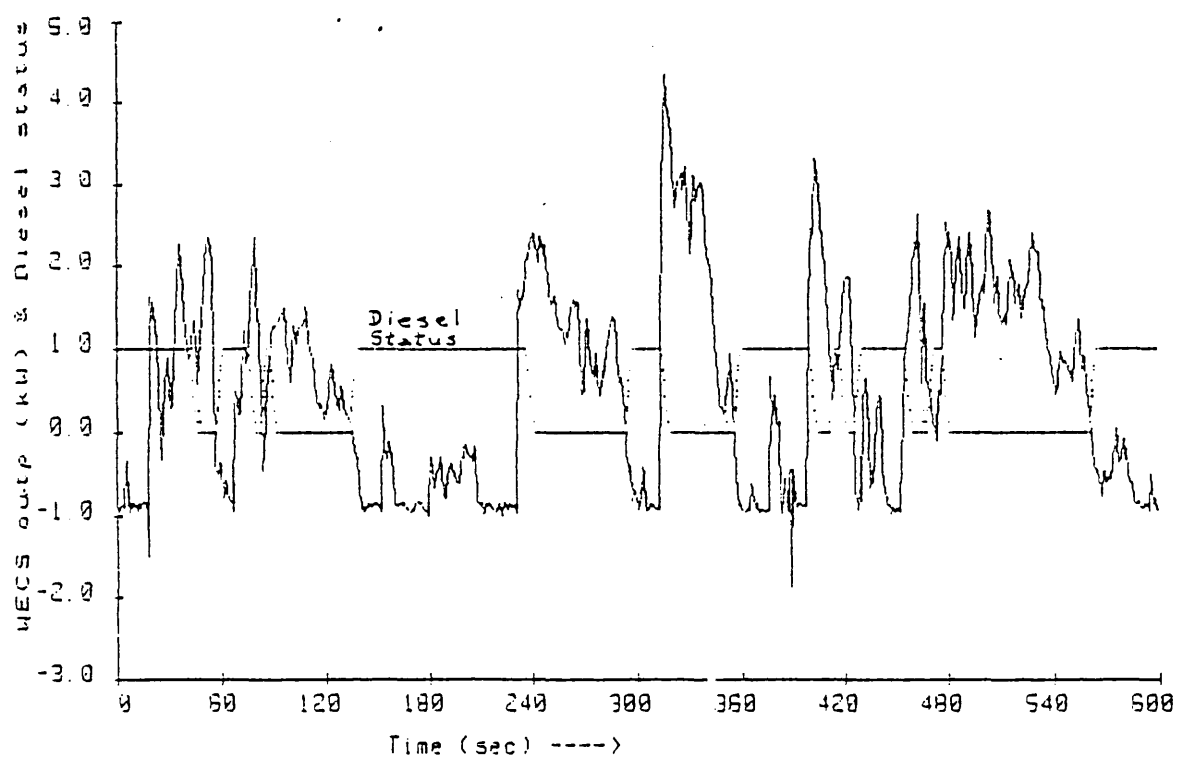


Fig. 5.4 Diesel Operational Status Control
1-4 steps prediction ; 1st order ARMA Model ; 1-sigma confidence

Table 5.3

Power prediction/diesel switching test

Prediction confidence limit	1σ	2σ	3σ
Failures to start on time	7	4	1
Max. frequency drop due to prediction failure	2.3Hz	1.6Hz	0.44Hz
Total seconds diesel running while not needed	68	151	258
Total seconds with positive power balance	355		

The significance of these results lies not so much on the absolute prediction error, in which in this case we are not so much interested, but in the self-adjusting error band. By defining the error band to be an appropriate multiple of the expected prediction error standard deviation, confidence limits for the diesel switching action can be easily set, tested and adjusted.

Nevertheless, the prediction method could possibly be further improved by using an adjustable window and more stable algorithms for higher order models. In the above examples, numerical implementation inadequacies of the algorithm led to numerical instability in some of the cases.

Other error weighting methods than the fixed window method and recursive estimators with improved convergence properties could also lead to improved prediction results (Refs. 5.18, 5.19).

5.3 Minimal variance adaptive frequency control

Frequency control, especially when the diesel/wind system is operating in the WECS stand alone mode, is the major task of the control system of an isolated system. The difficulty of the control task is aggravated when the WECS is not provided with an active blade pitch control mechanism. This could be used as speed governor in the WECS stand alone mode, so that the frequency control is not solely relied upon braking or accelerating the wind turbine generator electrically, by regulating the controlled load or storage device power supply. In the following a brief exposition of the theory of minimal variance control according to Ref. 5.16 is given and an application example for the system presented in Ch. 4 is discussed.

5.3.1 Minimal variance control

A sampled, time invariant, linear, univariate process with input $u(t)$, output $y(t)$ and disturbance $v(t)$ referred to the output, can be represented with the conventions introduced in the previous section by the equation

$$y(t) = \frac{B_1(q^{-1})}{A_1(q^{-1})} u(t-k) + v(t) \quad (5.20)$$

where $A_1(q^{-1}), B_1(q^{-1})$ are n -th order polynomials in q^{-1} . If $v(t)$ is assumed to be a stationary Gaussian process with rational spectral

density, it can be represented as

$$v(t) = \sigma \frac{C_1(q^{-1})}{A_2(q^{-1})} e(t) \quad (5.21)$$

where $e(t)$ is a normalized gaussian 'white noise' sequence and $C_1(q^{-1})$, $A_2(q^{-1})$ are polynomials in q^{-1} with their zeros outside the unit circle.

By introducing

$$\begin{aligned} A(q^{-1}) &= A_1(q^{-1}) \cdot A_2(q^{-1}) \\ B(q^{-1}) &= B_1(q^{-1}) \cdot A_2(q^{-1}) \\ C(q^{-1}) &= C_1(q^{-1}) \cdot A_1(q^{-1}) \end{aligned} \quad (5.22)$$

we can combine Eqs. 5.20 and 5.21 in

$$A(q^{-1})y(t) = B(q^{-1})u(t-k) + C(q^{-1})e(t) \quad (5.23)$$

With the obvious assumption that the control system is causal, it can be proven that, the control law, which minimizes the variance of the output signal, is obtained by predicting the output signal k -steps ahead and adjusting the control signal so that the predicted value is zeroed. The stochastic control problem can be thus separated into a prediction problem and a control problem (separation theorem)

The optimal predictor is constructed as shown in Section 5.2.2 by calculating the coefficients of the polynomials $F(q^{-1})$ and $G(q^{-1})$ defined with Eqs. 5.7 - 5.9.

The minimal variance control law is given then by

$$u(t) = - \frac{G(q^{-1})}{B(q^{-1})F(q^{-1})} y(t) \quad . \quad (5.24)$$

The regulation error is equal to the prediction error and is given by Eq. 5.5.

5.3.2 Application example of minimal variance frequency control

In order to make a comparison of performances between minimal variance (m.v.) adaptive control strategy and deterministic time invariant control strategies the WECS described in Chapter 4 is simulated as a single inertia neglecting losses and assuming the voltage to be kept constant. The WECS is assumed to be operated in stand alone mode in steady state at nominal frequency. The system is subjected to a power balance disturbance represented by a time series with 0.5 sec sampling period recorded in RAL during the WECS tests as power output to the infinite bus. The load-frequency dynamics are, under these assumptions, described by

$$\omega(t) = \omega(t-1) + \frac{k}{2} \cdot (p(t) + p(t-1)) - k \cdot x(t-1) \quad (5.25)$$

where

t the sample time measured in sampling periods
 $\omega(t)$ the frequency error
 $p(t)$ the power balance between WECS and consumer load
 $x(t)$ the controlled load or storage power
 and k an inertia characteristic parameter which
 for this system is 0.5 Hz/kW sampling period

Eq. 5.25 can be written in the notation introduced in this chapter

$$\omega(t) = \frac{k}{2} \frac{1+q^{-1}}{1-q^{-1}} p(t) - k \frac{q^{-1}}{1-q^{-1}} x(t) \quad (5.26)$$

The deterministic control and stochastic control performance will be compared in two cases:

- a) assuming that only the frequency is measured (feedback)
- b) assuming that both frequency and power balance are measured (feedback-feedforward control).

In both cases the stochastic models used are first order ARMA models and the deterministic controllers are also first order controllers (only variables at time t used).

Case a:

The information about the system is supposed to lead to the system model of Fig. 5.5, where $H(q^{-1})$ is unknown and $R(q^{-1})$ is to be determined. For the deterministic controller it has been assumed that

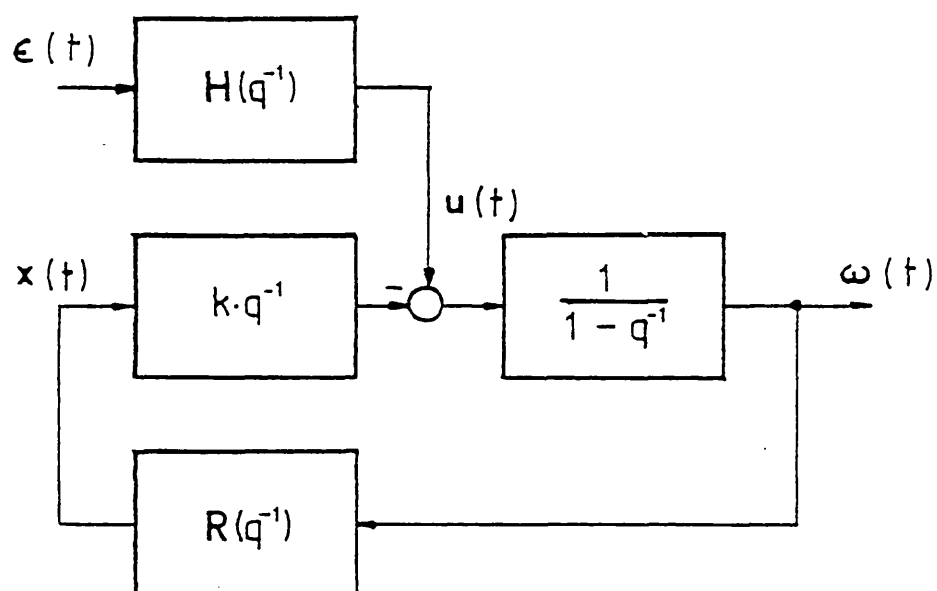


Fig. 5.5 System model with frequency feedback only

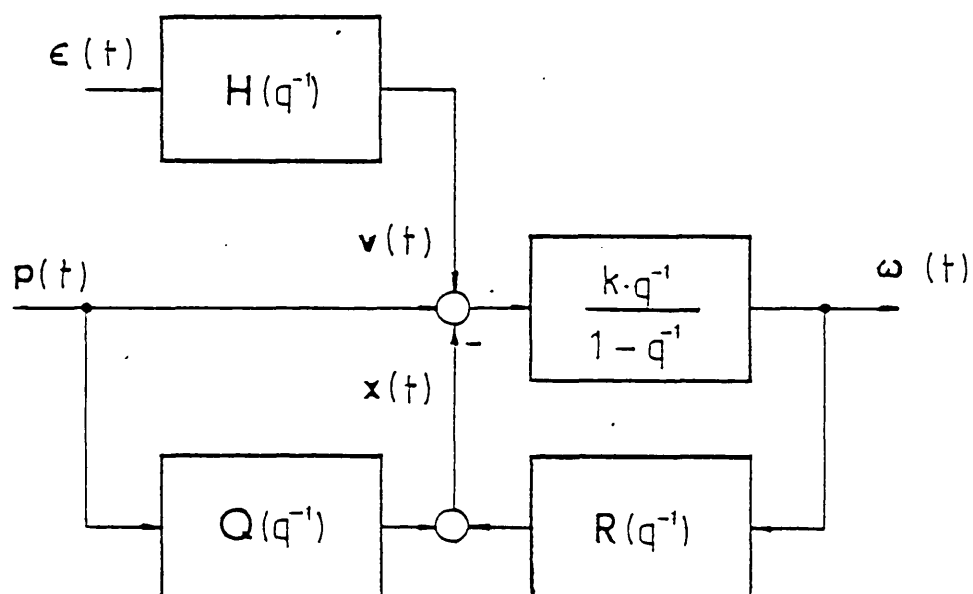
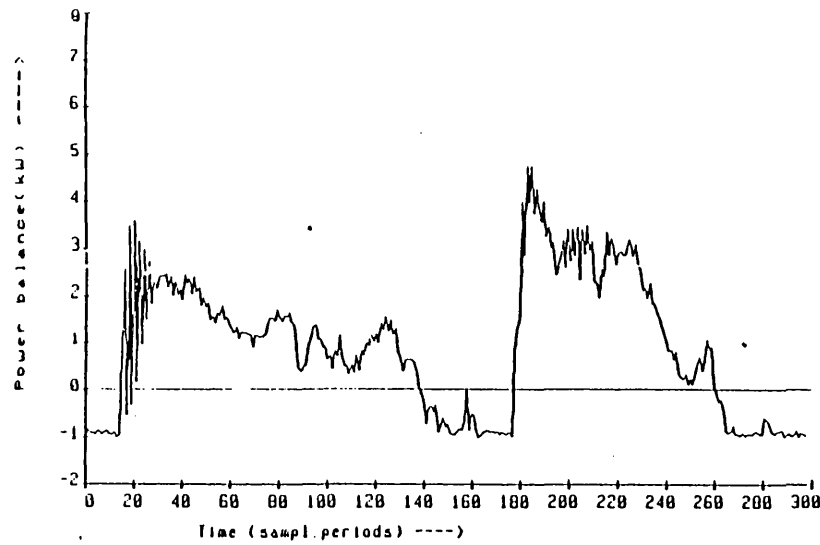
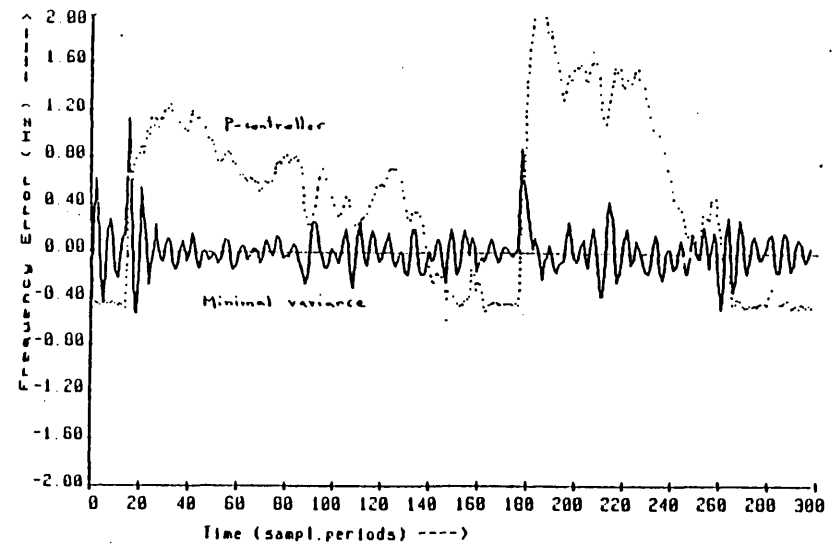


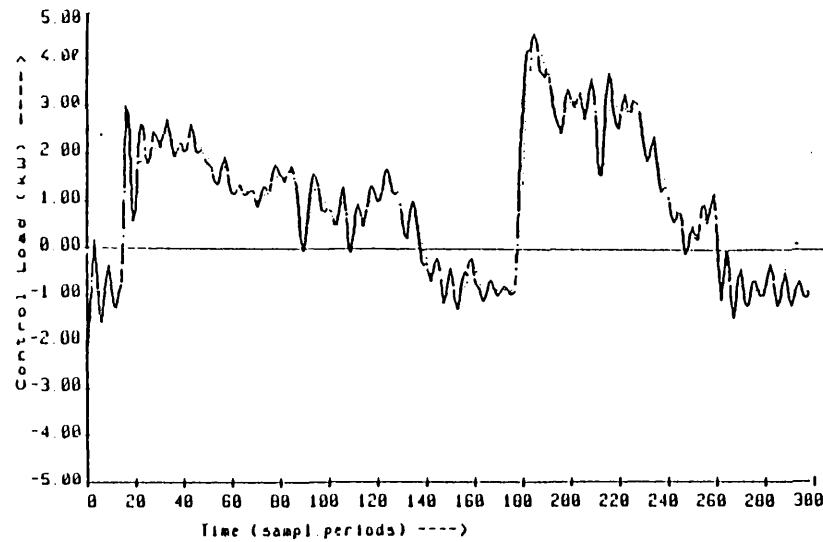
Fig. 5.7 System model with frequency feedback and power feedforward



a. Power Balance



b. Frequency Error



c. Control Power(+ Load;- Source)

Fig. 5.6

P-controller and m.v. adaptive controller
Performance comparison with frequency feedback

$$R(q^{-1}) = \frac{1}{k} \quad (5.27)$$

that is a P-controller is implemented.

For the adaptive controller a first-order function

$$H(q^{-1}) = \frac{1+c_1q^{-1}}{1+a_1q^{-1}} \quad (5.28)$$

has been assumed for the disturbance transfer function.

The $\hat{w}(t+1|t)$ is calculated and the controller action $x(t)$ is determined according to the technique described in Sec. 5.3.1 in order to make $\hat{w}(t+1|t) = 0$. The results are shown in Fig. 5.6 a-c.

The superior performance of the minimal variance controller is obvious. The comparison of the control signals in Fig. 5.6c shows that the success is due to the fact that the 1-step predictor approximately compensates the phase shift (time delay) in control action.

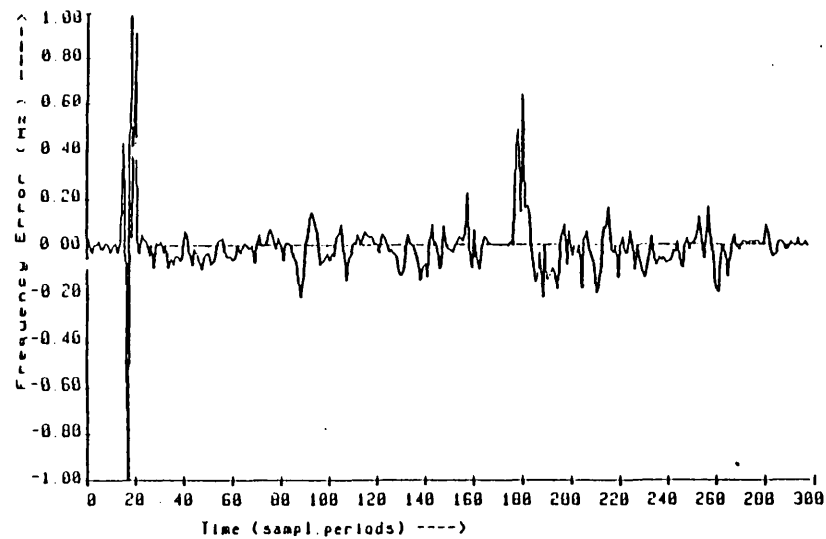
Case b:

In this case the information about the system is supposed to lead to the model of Fig. 5.7. For the deterministic controller, it has been set

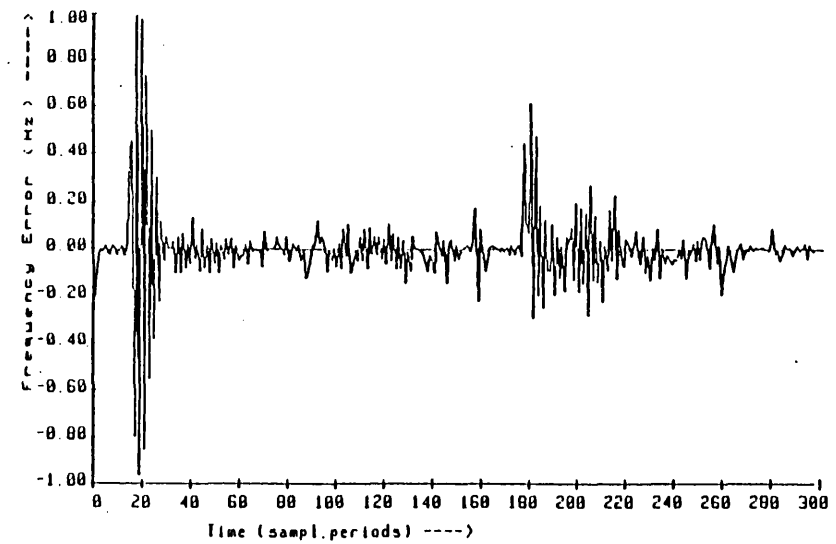
$$Q(q^{-1}) = R(q^{-1}) = \frac{1}{k} . \quad (5.29)$$

For the m.v. controller $R(q^{-1})$ has been set to the same value $\frac{1}{k}$ and, as before, the disturbance transfer function was modelled as a first order ARMA function

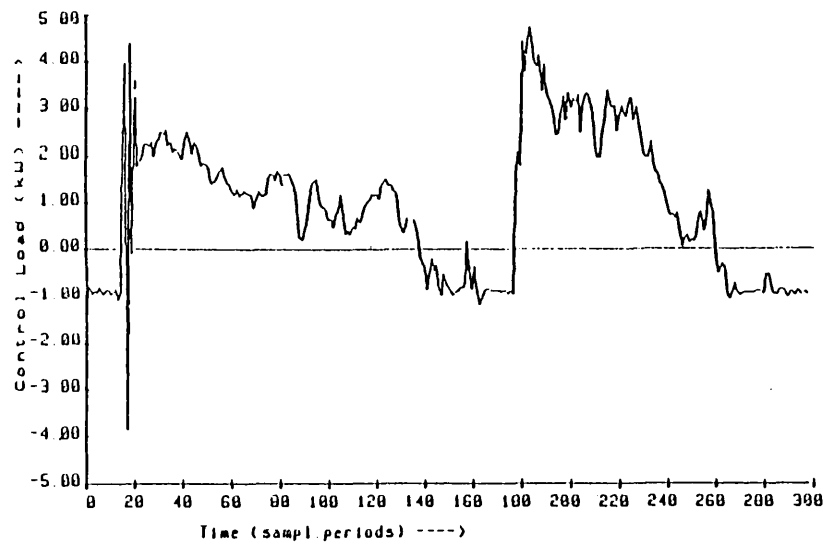
$$H(q^{-1}) = \frac{1+c_1q^{-1}}{1+a_1q^{-1}} \quad (5.30)$$



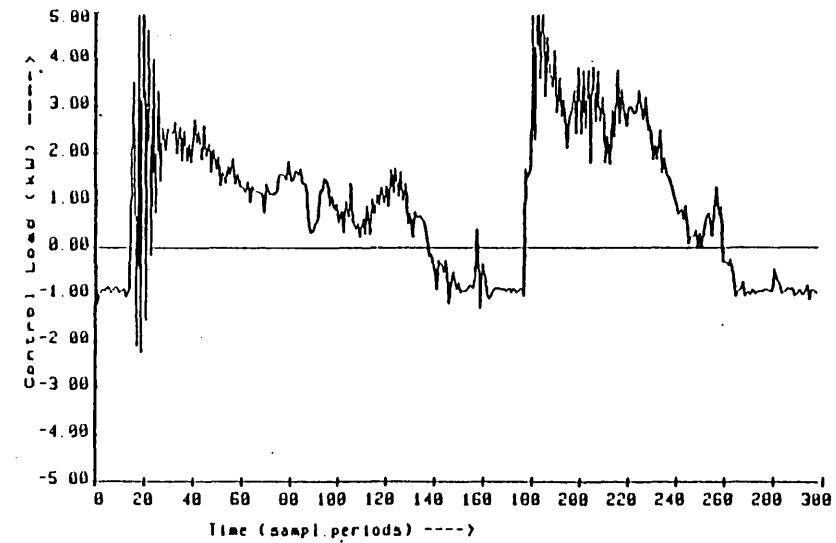
a. M.v. Control Frequency Error



b. P-controller Frequency Error



c. M.v. Control Power Signal



d. P-controller Control Power Signal

Fig. 5.8 P-controller and m.v. adaptive controller
Performance comparison with frequency feedback and power feedforward
Power balance as in Fig. 5.6 a

In this case the disturbance prediction $\hat{v}(t+1|t)$ has been calculated and the $x(t)$ determined in order to make $\hat{w}(t+1|t)$, which is a function of $\hat{v}(t+1|t)$, equal to zero. The results are presented in Fig. 5.8a-d.

The performance of the m.v. control is again better although the improvement is not so pronounced as in the previous case.

Noticable is the filtering of the 1Hz eigenfrequency which has been measured in the system (Ch. 4) only within a few cycles after it appears.

The performance of the m.v. controller is comparable to the deterministic one during the very sharp transition periods of the WECS from motoring to generating state. This indicates the possibility of improvement if the predictor parameters and order are reinitialized to some empirically determined and stored values each time a transition like the one described is detected. In other words that the predictor is designed to 'forget' all previous information, which is of no value, when the operational state has radically changed.

5.4 Comments

Two possible applications for adaptive control in wind/diesel system, the diesel switching decision process and adaptive frequency control, and some elements of the theory of prediction and minimal variance control associated with these problems, were discussed in this chapter.

Two examples of predictive algorithm implementation have been considered, involving data recorded for the wind/diesel system tested at RAL. Short term prediction of wind speed or wind power is not very accurate in absolute terms with the algorithm implemented. The prediction confidence limits which are computed in the prediction seem nevertheless to provide a relatively reliable criterion for the diesel switching.

A thorough investigation of the frequency of disruptive incidents (that is unacceptable frequency excursions) due to prediction failure and the correlation between wind speed statistics, prediction confidence limits and diesel fuel savings is needed in order to assess the advantages of stochastic prediction methods in comparison to the simple persistency criteria used up to now.

The simple frequency control example given shows in this case a definite advantage of adaptive over deterministic control. It should be emphasized that the results presented, for the application examples given, serve only to illustrate the method of approach and are by no means conclusive on the practical applicability or the superiority of stochastic algorithms.

Nevertheless the author believes that future developments in the wind power utilization will be very much concerned with applications of adaptive control on wind energy converters, which after all are systems of inherently stochastic nature.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

a) The realisation of a high wind power penetration level without energy supply quality deterioration is of capital importance for the economic viability of WECS integration in small isolated networks supplied by diesel sets.

In this thesis it is shown (Ch. 2) that, even under very unfavourable economic assumptions i.e. high interest/discount rates, stable fuel prizes, relatively high WECS cost, no capacity credit for WECS and modest wind regimes (5-7 m/s), generation of electricity from the wind is competitive with generation from diesel sets. Significant fuel and overall cost savings are therefore feasible for better wind regimes and when the economic conditions are realistically relaxed.

It was also shown that there are optimal values of total WECS capacity and WECS design wind speed which, for a certain network, maximize the net present benefit expected from the investment. Such optimal values depend on the prevailing wind regime but also significantly on the load demand pattern of the isolated grid.

The application of wind power allocation optimization program to the complex of the isolated small networks on the Greek islands indicates very good prospects for wind energy exploitation in this region.

b) The realisation of high penetration level imposes severe requirements on the dynamic performance and the control system of the integrated WECS/Diesel network.

The detailed dynamic performance simulation of a system with one diesel and one WECS equipped with induction generator indicates that a stable power supply of acceptable quality is achievable with minor modifications in the generating equipment viz. (i) clutch between diesel generator and diesel engine, (ii) enhanced diesel voltage regulator and diesel engine starter, (iii) provision of a controllable fast reacting dump load and (iv) some capacitive compensation.

The control system can be digitally optimized for maximum wind power yield in steady state and designed to operate suboptimally under transient conditions using straightforward control schemes. Besides the time domain simulation, analytical tools, e.g. the participation matrix technique, can be used to assist the frequency domain approach in stability estimation and in the approximate location of system components which introduce weakly damped or unstable oscillation modes.

c) Special design features in WECS with synchronous generators as found in the MP-9 model are shown to reduce significantly the complexity of the system and to enhance the dynamic behaviour of the WECS.

Appropriate parameter identification techniques were used to achieve a system model which simulates the real system behaviour with a good degree of accuracy. Some test results provide evidence

that the simulation techniques are reliable. The dynamic performance of the combined WECS/Diesel system at RAL is expected to be satisfactory.

d) The inherently stochastic nature of the wind speed and the time variance of the WECS parameters in a way which makes their deterministic estimation very difficult, seem to invite a stochastic approach to state estimation, prediction and control problems associated with WECS in general and wind/diesel systems in particular. Two such problems, the diesel switching decision problem and minimal variance frequency control in the WECS stand alone operation mode have been presented in Ch. 5.

Wind or power prediction algorithms can provide a quantitative criterion for the assessment of the failure risk. This would enable generation cost optimization methods to be incorporated in the control system which take into account quantifiable system stability constraints.

Minimal variance frequency control is shown, for an extremely simplified system model, to achieve better performance than control with deterministic time invariant parameters.

A thorough investigation of these questions is expected to be proven valuable for the better understanding and solution of dynamic stability and economic optimization problems associated with the wind/diesel systems.

In conclusion, the results from this thesis indicate that integrated WECS/Diesel systems for isolated networks can be economically viable, their dynamic performance can be predicted with a good

degree of accuracy and control policies can be developed to optimize the energy yield without deterioration in the quality of supply.

6.2 Original contributions

The author believes that the following contributions are original:

1. Development of a generalized statistical method for optimal WECS integration into small networks supplied by diesel sets, taking into account load demand statistics and relevant cost factors in addition to the wind statistics.
2. Comprehensive assessment of the wind power potential on all the Greek islands not interconnected to the mainland grid of the Public Power Corporation and establishment of survey and investment priorities.
3. Simulation of the dynamics of a complete isolated WECS/diesel system with induction generator; establishment of a method for steady state wind power yield optimization for this system and simulation of a suitable suboptimal system for dynamic control.

4. Application of the participation matrix technique for eigenvalue analysis and location of system components causing weakly damped or unstable oscillation modes in a WECS/diesel system.
5. Application of parametric identification techniques for WECS and diesel generator modelling .
6. Simulation of the complete dynamics of a WECS with synchronous generator and free-wheeling clutch and comparison of the results with measurements on site for the RAL system.
7. Application of stochastic prediction techniques as a first approach to the development of stochastic control techniques for WECS/diesel systems.

6.3 Suggestions for further work

1. Development of the optimization program for wind power allocation to incorporate:
 - a. Cross correlation between load demand and wind speed.
 - b. Various WECS types with different characteristics.
 - c. Optimization of diesel engine sizes if required.
 - d. Assessment of the loss of load probability for the optimized system as a function of load demand, wind speed and diesel availability.
2. Development of analogue computer programs for WECS/Diesel simulation and control system optimization
3. Extension of the digital simulation programs to incorporate various types of short-term energy storage e.g. flywheels and batteries.
4. Development and testing of control algorithms incorporating the voltage regulation system and wind speed feedforward signal(s).
5. Development of on-line stochastic identification and control techniques for WECS/Diesel systems and implementation on the system under development at RAL.

Appendix 2.1

Optimal wind power allocation tables

Legend

CFACT : Economic Factor
 LF : Load Factor
 DMIN : Normalized Minimum Diesel Power (Basis: Peak Load Demand)
 K : Weibull Shape Factor
 WM : Average Wind Speed. (m/s)
 CW : Weibull Scale Factor (m/s)
 EVALU : Number of Cost Function Evaluations in optimization
 POPT : Optimal Normalized Wind Power (Basis: Peak Load Demand)
 WOPT : Optimal normalized Rated Wind Speed (Basis: Average Wind Speed)
 COST : Total Normalized Cost (Basis: Peak Load x 1 hour Cost)
 SERV : Normalized WECS O+M+Capital Cost (Basis: as above)
 DCST : Normalized Diesel only Cost (Basis: as above)
 SAVE : Cost Difference DCST-COST (Absolute and in % of DCST)
 PMIN/PMAX : Lower/Upper Power Limit for Savings within 1% of Optimum
 WMIN/WMAX : As above for Rated Wind Speed
 Load Demand Distribution: Triangular

Tables for K=2.0

LF=0.2-0.6 ,step 0.1

DMIN=0.0-0.20 ,step 0.05

WM=4-10 m/s ,step 1 m/s

Table A2.1.1

Economic Factor= 100.

OPTIMAL WIND POWER ALLOCATION

CFACT	LF	DMIN	K	WM	CW	EVALU	POPT	WOPT	COST	SERV	DCST	SAVE	PHIN	FMAX	WMIN	WMAX	
100.	.20	0.00	2.0	5.0	6.8	34	.81	2.23	.19	.03	.20	.01	7.	.54	.92	1.93	2.25
100.	.20	0.00	2.0	7.0	7.9	44	1.04	1.88	.17	.05	.20	.03	17.	.80	1.12	1.69	1.97
100.	.20	0.00	2.0	8.0	9.0	40	1.00	1.55	.15	.05	.20	.05	25.	.90	1.17	1.50	1.63
100.	.20	0.00	2.0	9.0	10.2	53	1.02	1.57	.13	.04	.20	.07	33.	.89	1.29	1.39	1.63
100.	.20	0.00	2.0	10.0	11.3	54	1.11	1.38	.12	.04	.20	.08	39.	.90	1.28	1.34	1.55
100.	.20	.05	2.0	6.0	6.8	39	.53	2.13	.22	.03	.23	.01	5.	.42	.62	1.91	2.26
100.	.20	.05	2.0	7.0	7.9	29	.92	1.95	.20	.04	.21	.03	12.	.64	1.04	1.68	1.95
100.	.20	.05	2.0	8.0	9.0	46	.80	1.69	.19	.03	.23	.04	19.	.70	.80	1.52	1.99
100.	.20	.05	2.0	9.0	10.2	55	1.16	1.68	.17	.03	.23	.06	25.	.76	1.16	1.39	1.78
100.	.20	.05	2.0	10.0	11.3	58	.94	1.38	.16	.04	.23	.07	30.	.83	.94	1.35	1.40
100.	.20	.10	2.0	6.0	6.8	31	.60	2.26	.25	.02	.26	.01	3.	.54	.85	1.90	2.46
100.	.20	.10	2.0	7.0	7.9	42	.81	1.90	.24	.03	.26	.02	9.	.63	.91	1.82	2.01
100.	.20	.10	2.0	8.0	9.0	46	.80	1.69	.22	.03	.26	.04	14.	.70	.92	1.53	1.77
100.	.20	.10	2.0	9.0	10.2	41	.80	1.59	.21	.03	.26	.05	19.	.80	1.27	1.59	1.71
100.	.20	.10	2.0	10.0	11.3	48	.92	1.53	.20	.03	.26	.06	23.	.75	1.34	1.33	1.59
100.	.20	.15	2.0	6.0	6.8	31	.60	2.26	.29	.02	.29	.01	2.	.35	.60	1.94	2.46
100.	.20	.15	2.0	7.0	7.9	28	1.03	1.92	.28	.04	.29	.02	6.	.78	1.04	1.69	1.92
100.	.20	.15	2.0	8.0	9.0	45	.80	1.69	.26	.03	.29	.03	11.	.72	.95	1.67	1.90
100.	.20	.15	2.0	9.0	10.2	36	.80	1.69	.25	.02	.29	.04	14.	.77	1.16	1.64	1.85
100.	.20	.15	2.0	10.0	11.3	54	.82	1.41	.24	.03	.29	.05	18.	.75	.94	1.38	1.91
100.	.20	.20	2.0	6.0	6.8	30	.40	2.26	.32	.02	.33	.00	1.	.32	.60	1.92	2.26
100.	.20	.20	2.0	7.0	7.9	29	.60	2.26	.31	.02	.33	.01	4.	.53	1.08	2.22	2.47
100.	.20	.20	2.0	8.0	9.0	34	.80	1.69	.30	.03	.33	.03	8.	.60	1.04	1.68	1.88
100.	.20	.20	2.0	9.0	10.2	49	.74	1.60	.29	.02	.33	.04	11.	.67	.87	1.52	1.69
100.	.20	.20	2.0	10.0	11.3	43	.85	1.41	.28	.03	.33	.04	13.	.67	.85	1.34	1.59
100.	.30	0.00	2.0	5.0	5.6	36	.70	2.11	.39	.06	.30	.01	5.	.44	.83	1.97	2.26
100.	.30	0.00	2.0	6.0	6.8	43	.93	1.92	.35	.06	.30	.05	15.	.93	1.06	1.83	1.96
100.	.30	0.00	2.0	7.0	7.9	47	.88	1.92	.32	.07	.30	.08	25.	.86	1.00	1.49	1.55
100.	.30	0.00	2.0	8.0	9.0	62	1.11	1.56	.20	.06	.30	.10	34.	.87	1.13	1.45	1.58
100.	.30	0.00	2.0	9.0	10.2	56	1.13	1.40	.18	.06	.30	.12	41.	1.03	1.18	1.33	1.44
100.	.30	0.00	2.0	10.0	11.3	51	1.14	1.34	.16	.05	.30	.14	47.	1.14	1.43	1.27	1.41
100.	.30	.05	2.0	5.0	5.6	19	.60	2.26	.31	.04	.33	.01	3.	.40	.60	2.06	2.26
100.	.30	.05	2.0	6.0	6.8	62	.81	1.90	.29	.05	.33	.04	12.	.74	.95	1.78	1.92
100.	.30	.05	2.0	7.0	7.9	59	.88	1.67	.25	.06	.33	.07	21.	.82	.97	1.59	1.74
100.	.30	.05	2.0	8.0	9.0	63	1.03	1.56	.23	.05	.33	.09	28.	.85	1.03	1.43	1.56
100.	.30	.05	2.0	9.0	10.2	63	1.00	1.39	.21	.05	.33	.11	34.	.88	1.13	1.32	1.49
100.	.30	.05	2.0	10.0	11.3	57	.96	1.34	.20	.05	.33	.12	38.	.90	1.09	1.21	1.43
100.	.30	.10	2.0	5.0	5.6	30	.60	2.26	.34	.04	.34	.01	2.	.31	.60	2.04	2.26
100.	.30	.10	2.0	6.0	6.8	42	.73	1.86	.31	.05	.34	.03	10.	.58	.83	1.81	2.08
100.	.30	.10	2.0	7.0	7.9	53	.80	1.69	.29	.05	.34	.06	17.	.79	.96	1.39	1.82
100.	.30	.10	2.0	8.0	9.0	58	.81	1.55	.27	.04	.34	.08	22.	.81	1.08	1.41	1.55
100.	.30	.10	2.0	9.0	10.2	64	.90	1.39	.25	.05	.34	.09	28.	.85	1.02	1.35	1.48
100.	.30	.10	2.0	10.0	11.3	44	.92	1.26	.23	.05	.34	.11	32.	.82	1.07	1.25	1.34
100.	.30	.15	2.0	5.0	5.6	29	.40	2.26	.36	.03	.37	.01	1.	.30	.57	2.10	2.33
100.	.30	.15	2.0	6.0	6.8	46	.73	1.88	.34	.05	.37	.03	7.	.57	.76	1.82	2.09
100.	.30	.15	2.0	7.0	7.9	47	.80	1.69	.32	.05	.37	.05	13.	.67	.83	1.63	1.82
100.	.30	.15	2.0	8.0	9.0	46	.75	1.47	.30	.05	.37	.07	18.	.75	1.08	1.44	1.65
100.	.30	.15	2.0	9.0	10.2	67	.91	1.47	.28	.04	.37	.08	22.	.80	.99	1.43	1.54
100.	.30	.15	2.0	10.0	11.3	47	.79	1.27	.27	.04	.37	.09	26.	.79	1.27	1.27	1.48
100.	.30	.20	2.0	5.0	5.6	30	.40	2.26	.39	.03	.39	.00	1.	.17	.44	2.04	2.56
100.	.30	.20	2.0	6.0	6.8	46	.63	1.98	.37	.04	.39	.02	5.	.51	.68	1.83	1.98
100.	.30	.20	2.0	7.0	7.9	40	.80	1.69	.35	.05	.39	.04	10.	.62	.80	1.67	1.87
100.	.30	.20	2.0	8.0	9.0	50	.85	1.60	.34	.04	.39	.06	14.	.70	.91	1.59	1.71
100.	.30	.20	2.0	9.0	10.2	61	.75	1.37	.32	.04	.39	.07	18.	.69	.77	1.34	1.43
100.	.30	.20	2.0	10.0	11.3	51	1.03	1.43	.31	.04	.39	.08	21.	.78	1.17	1.34	1.47
100.	.40	0.00	2.0	4.0	4.5	12	.02	2.34	.40	.00	.40	.00	0.	0.00	.70	1.13	2.85
100.	.40	0.00	2.0	5.0	5.6	60	.77	2.03	.36	.07	.40	.04	10.	.72	.90	1.92	2.10
100.	.40	0.00	2.0	6.0	6.8	59	.88	1.70	.31	.08	.40	.09	22.	.88	1.01	1.64	1.81
100.	.40	0.00	2.0	7.0	7.9	73	1.02	1.53	.27	.08	.40	.13	33.	.97	1.11	1.46	1.59
100.	.40	0.00	2.0	8.0	9.0	54	1.20	1.53	.24	.07	.40	.16	39.	.97	1.38	1.33	1.53
100.	.40	0.00	2.0	9.0	10.2	46	1.14	1.34	.22	.06	.40	.18	46.	.97	1.22	1.26	1.38
100.	.40	0.00	2.0	10.0	11.3	70	1.24	1.27	.20	.06	.40	.20	51.	1.04	1.24	1.20	1.27
100.	.40	.05	2.0	5.0	5.6	49	.75	2.01	.38	.07	.41	.03	8.	.60	.86	1.90	2.14
100.	.40	.05	2.0	6.0	6.8	66	.80	1.69	.34	.08	.41	.08	18.	.76	.91	1.82	1.69
100.	.40	.05	2.0	7.0	7.9	65	.87	1.41	.30	.09	.41	.11	27.	.86	.94	1.39	1.43
100.	.40	.05	2.0	8.0	9.0	62	1.01	1.38	.27	.07	.41	.14	34.	.88	1.01	1.34	1.41
100.	.40	.05	2.0	9.0	10.2	58	1.07	1.29	.25	.07	.41	.16	40.	.93	1.14	1.26	1.30
100.	.40	.05	2.0	10.0	11.3	61	1.23	1.27	.23	.06	.41	.18	44.	.97	1.32	1.19	1.34
100.	.40	.10	2.0	5.0	5.6	36	.74	2.00	.40	.07	.42	.03	6.	.54	.81	2.00	2.23
100.	.40	.10	2.0	6.0	6.8	50	.80	1.69	.36	.08	.42	.06	15.	.70	.84	1.64	1.84
100.	.40	.10	2.0	7.0	7.9	51	1.03	1.57	.33	.09	.42	.09	22.	.81	1.09	1.44	1.60
100.	.40	.10	2.0	8.0	9.0	56	.91	1.40	.30	.06	.42	.12	29.	.93	1.04	1.37	1.53
100.	.40	.10	2.0	9.0	10.2	54	.89	1.28	.28	.06	.42	.14	34.	.86	1.13	1.27	1.33
100.	.40	.10	2.0	10.0	11.3	41	1.06	1.35	.26	.04	.42	.16	38.	.85	1.29	1.18	1.42
100.	.40	.15	2.0	5.0	5.6	53	.65	2.11	.42	.06	.44	.02	5.	.55	.75	1.94	2.11
100.	.40	.15	2.0	6.0	6.8	34	.68	1.73	.39	.06	.44	.05	13.	.66	.98	1.69	1.92
100.	.40	.15	2.0	7.0	7.9	51	.80	1.67	.36	.05	.44	.08	18.	.70	.95	1.57	1.74
100.	.40	.15	2.0	8.0	9.0	76	.86	1.48	.33	.05	.44	.11	24.	.75	.87	1.38	1.48
100.	.40	.15	2.0	9.0	10.2	51	.82	1.25	.32	.06	.44	.12	28.	.77	1.10	1.24	1.43
100.	.40	.15	2.0	10.0	11.3	65	1.04	1.28	.30	.05	.44	.14	32.	.91	1.25	1.28	1.38
100.	.40	.20	2.0	5.0	5.6	37	.54	2.13	.44	.04	.46	.02	3.	.54	.71	2.13	2.34
100.	.40	.20	2.0	6.0	6.8	44	.81	1.90	.41	.05	.46	.04	10.	.60	.82	1.84	1.96
100.	.40	.20	2.0	7.0	7.9	48	.80	1.69	.39	.05	.46	.07	15.	.68	.82	1.61	1.74
100.	.40	.20	2.0	8.0	9.0	64	.79	1.44	.37	.05	.46	.09	20.	.72	.93	1.43	1.50
100.	.40	.20	2.0	9.0	10.2	55	.96										

Table A2.1.1 (cont.)

OPTIMAL WIND POWER ALLOCATION

CFACT	LF	DMIN	K	WM	CW	EVALU	POPT	WOPT	COST	SERV	DCST	SAVE	PHIN	PMAX	WMIN	WMAX	
100.	.50	0.00	2.0	4.0	4.5	33	.40	2.26	.49	.05	.50	.01	2.	.40	.63	2.04	2.46
100.	.50	0.00	3.0	5.0	5.6	43	.81	1.82	.43	.11	.50	.07	15.	.77	.93	1.82	1.91
100.	.50	0.00	4.0	6.0	6.8	62	.93	1.61	.37	.10	.50	.13	27.	.91	1.07	1.57	1.66
100.	.50	0.00	5.0	7.0	7.9	67	1.09	1.46	.32	.10	.50	.18	36.	.94	1.09	1.38	1.46
100.	.50	0.00	6.0	8.0	9.0	58	1.22	1.38	.28	.09	.50	.22	44.	1.04	1.22	1.27	1.39
100.	.50	0.00	7.0	9.0	10.2	69	1.12	1.24	.25	.08	.50	.25	50.	1.06	1.32	1.23	1.35
100.	.50	0.00	8.0	10.0	11.3	61	1.45	1.27	.23	.07	.50	.27	54.	1.18	1.56	1.20	1.31
100.	.50	.05	2.0	4.0	4.5	38	.40	2.26	.49	.05	.50	.01	2.	.27	.51	2.16	2.43
100.	.50	.05	3.0	5.0	5.6	49	.81	1.90	.44	.09	.50	.06	13.	.70	.81	1.80	1.90
100.	.50	.05	4.0	6.0	6.8	50	.82	1.53	.39	.09	.50	.11	33.	.73	1.03	1.53	1.64
100.	.50	.05	5.0	7.0	7.9	82	.92	1.42	.34	.09	.50	.16	32.	.70	1.09	1.38	1.51
100.	.50	.05	6.0	8.0	9.0	54	1.11	1.35	.31	.09	.50	.19	38.	.89	1.11	1.38	1.58
100.	.50	.05	7.0	9.0	10.2	38	1.06	1.35	.28	.06	.50	.22	44.	.94	1.38	1.18	1.43
100.	.50	.05	8.0	10.0	11.3	58	1.24	1.23	.26	.07	.50	.24	48.	1.25	1.44	1.21	1.31
100.	.50	.10	2.0	4.0	4.5	33	.31	2.38	.50	.04	.51	.00	1.	.25	.47	2.23	2.56
100.	.50	.10	3.0	5.0	5.6	44	.62	1.86	.45	.08	.51	.05	10.	.62	.94	1.86	2.06
100.	.50	.10	4.0	6.0	6.8	53	.80	1.65	.41	.08	.51	.10	20.	.74	1.01	1.65	1.79
100.	.50	.10	5.0	7.0	7.9	64	.99	1.48	.37	.09	.51	.14	27.	.85	1.09	1.42	1.59
100.	.50	.10	6.0	8.0	9.0	72	.98	1.39	.34	.07	.51	.17	34.	.98	1.13	1.34	1.46
100.	.50	.10	7.0	9.0	10.2	69	1.05	1.33	.31	.06	.51	.19	38.	.89	1.13	1.23	1.33
100.	.50	.10	8.0	10.0	11.3	67	1.09	1.19	.29	.06	.51	.21	42.	1.04	1.13	1.18	1.27
100.	.50	.15	2.0	4.0	4.5	36	.24	2.25	.51	.03	.51	.00	0.	.14	.40	2.18	2.54
100.	.50	.15	3.0	5.0	5.6	60	.67	1.98	.47	.07	.51	.04	8.	.58	.78	1.86	2.10
100.	.50	.15	4.0	6.0	6.8	49	.81	1.68	.43	.08	.51	.08	17.	.76	.91	1.59	1.78
100.	.50	.15	5.0	7.0	7.9	60	.89	1.43	.39	.09	.51	.12	23.	.73	.90	1.43	1.62
100.	.50	.15	6.0	8.0	9.0	61	.87	1.33	.36	.07	.51	.15	29.	.84	.99	1.33	1.42
100.	.50	.15	7.0	9.0	10.2	61	1.03	1.35	.34	.06	.51	.17	33.	.89	1.17	1.26	1.36
100.	.50	.15	8.0	10.0	11.3	75	.91	1.25	.32	.05	.51	.19	37.	.91	1.06	1.25	1.35
100.	.50	.20	2.0	4.0	4.5	12	.02	2.34	.52	.00	.52	.00	0.	0.00	.20	1.13	2.85
100.	.50	.20	3.0	5.0	5.6	46	.52	1.74	.49	.06	.52	.03	6.	.52	.77	1.74	2.20
100.	.50	.20	4.0	6.0	6.8	52	.75	1.76	.45	.06	.52	.07	14.	.67	.81	1.61	1.76
100.	.50	.20	5.0	7.0	7.9	56	.76	1.55	.42	.06	.52	.10	20.	.71	.89	1.47	1.60
100.	.50	.20	6.0	8.0	9.0	67	.74	1.37	.39	.06	.52	.13	24.	.72	.91	1.30	1.37
100.	.50	.20	7.0	9.0	10.2	58	1.01	1.35	.37	.06	.52	.15	28.	.79	1.02	1.26	1.36
100.	.50	.20	8.0	10.0	11.3	54	1.09	1.30	.36	.05	.52	.16	31.	.98	1.20	1.24	1.37
100.	.60	0.00	2.0	4.0	4.5	36	.71	2.07	.57	.12	.60	.03	4.	.51	.71	2.06	2.34
100.	.60	0.00	3.0	5.0	5.6	53	.73	1.73	.49	.14	.60	.11	18.	.86	1.02	1.73	1.88
100.	.60	0.00	4.0	6.0	6.8	58	.99	1.50	.42	.14	.60	.18	30.	.97	1.15	1.49	1.59
100.	.60	0.00	5.0	7.0	7.9	67	1.02	1.42	.37	.10	.60	.23	39.	.95	1.14	1.32	1.49
100.	.60	0.00	6.0	8.0	9.0	49	1.17	1.39	.32	.09	.60	.28	46.	1.00	1.27	1.33	1.43
100.	.60	0.00	7.0	9.0	10.2	59	1.37	1.28	.29	.09	.60	.31	52.	1.24	1.43	1.21	1.32
100.	.60	0.00	8.0	10.0	11.3	56	1.42	1.21	.26	.08	.60	.34	56.	1.35	1.54	1.21	1.27
100.	.60	.05	2.0	4.0	4.5	39	.60	2.26	.58	.08	.60	.02	4.	.49	.75	2.12	2.37
100.	.60	.05	3.0	5.0	5.6	49	.83	1.77	.50	.12	.60	.10	16.	.81	.96	1.77	1.89
100.	.60	.05	4.0	6.0	6.8	63	.97	1.53	.44	.13	.60	.16	27.	.85	.99	1.48	1.54
100.	.60	.05	5.0	7.0	7.9	71	1.04	1.42	.37	.11	.60	.21	36.	.91	1.04	1.37	1.43
100.	.60	.05	6.0	8.0	9.0	71	1.04	1.28	.35	.10	.60	.25	42.	.96	1.10	1.28	1.36
100.	.60	.05	7.0	9.0	10.2	70	1.19	1.22	.32	.09	.60	.28	47.	1.12	1.34	1.21	1.31
100.	.60	.05	8.0	10.0	11.3	59	1.18	1.24	.29	.06	.60	.31	51.	1.05	1.19	1.17	1.24
100.	.60	.10	2.0	4.0	4.5	47	.60	2.26	.58	.08	.60	.02	3.	.48	.66	2.07	2.26
100.	.60	.10	3.0	5.0	5.6	40	.92	1.83	.52	.12	.60	.08	14.	.68	.78	1.73	1.96
100.	.60	.10	4.0	6.0	6.8	64	.85	1.58	.46	.10	.60	.14	24.	.83	.90	1.58	1.63
100.	.60	.10	5.0	7.0	7.9	74	.90	1.40	.41	.10	.60	.19	32.	.90	1.06	1.40	1.49
100.	.60	.10	6.0	8.0	9.0	53	1.00	1.27	.37	.10	.60	.23	38.	1.00	1.21	1.27	1.36
100.	.60	.10	7.0	9.0	10.2	60	1.01	1.22	.34	.08	.60	.26	43.	.97	1.23	1.19	1.36
100.	.60	.10	8.0	10.0	11.3	63	1.23	1.24	.32	.06	.60	.28	46.	1.10	1.46	1.16	1.27
100.	.60	.15	2.0	4.0	4.5	33	.40	2.26	.59	.05	.60	.01	2.	.39	.60	2.04	2.26
100.	.60	.15	3.0	5.0	5.6	52	.70	1.82	.53	.09	.60	.07	12.	.70	.86	1.80	1.92
100.	.60	.15	4.0	6.0	6.8	63	.89	1.66	.47	.09	.60	.13	21.	.77	.95	1.61	1.70
100.	.60	.15	5.0	7.0	7.9	69	.80	1.44	.43	.08	.60	.17	28.	.80	.95	1.44	1.55
100.	.60	.15	6.0	8.0	9.0	64	.76	1.37	.40	.07	.60	.20	34.	.82	.99	1.28	1.37
100.	.60	.15	7.0	9.0	10.2	49	.89	1.25	.37	.06	.60	.23	38.	.85	1.06	1.19	1.35
100.	.60	.15	8.0	10.0	11.3	67	1.11	1.25	.35	.06	.60	.25	41.	.95	1.13	1.17	1.26
100.	.60	.20	2.0	4.0	4.5	33	.40	2.26	.59	.05	.60	.01	2.	.38	.53	2.12	2.42
100.	.60	.20	3.0	5.0	5.6	62	.68	1.84	.54	.09	.60	.06	10.	.62	.78	1.77	1.89
100.	.60	.20	4.0	6.0	6.8	51	.80	1.69	.49	.08	.60	.11	19.	.69	.91	1.61	1.74
100.	.60	.20	5.0	7.0	7.9	73	.61	1.45	.45	.08	.60	.15	24.	.80	.88	1.42	1.51
100.	.60	.20	6.0	8.0	9.0	59	.88	1.36	.42	.07	.60	.18	29.	.80	.94	1.31	1.41
100.	.60	.20	7.0	9.0	10.2	61	1.00	1.32	.40	.06	.60	.20	33.	.81	1.00	1.22	1.32
100.	.60	.20	8.0	10.0	11.3	67	.99	1.21	.38	.06	.60	.22	36.	.91	1.13	1.20	1.27

Table A2.1.2

Economic Factor= 200.

OPTIMAL WIND POWER ALLOCATION

CFACT	LF	DMIN	K	WM	CW	EVALU	POPT	WOPT	COST	SERV	DCST	SAVE	PMIN	PMAX	WMIN	WMAX	
200.	.20	0.00	2.0	7.0	7.9	33	.60	2.26	.19	.03	.20	.01	3.	.39	.60	2.08	2.47
200.	.20	0.00	3.0	8.0	9.0	39	.64	1.85	.19	.04	.20	.02	10.	.64	.83	1.85	2.19
200.	.20	0.00	4.0	9.0	10.2	40	1.04	1.88	.16	.04	.20	.04	18.	.80	1.09	1.64	1.96
200.	.20	0.00	5.0	10.0	11.3	35	.81	1.54	.15	.04	.20	.05	25.	.80	1.17	1.51	1.69
200.	.20	.05	2.0	7.0	7.9	29	.40	2.26	.33	.02	.23	.00	2.	.40	.73	1.79	2.49
200.	.20	.05	3.0	8.0	9.0	30	.60	2.26	.32	.02	.23	.01	6.	.60	1.08	2.26	2.47
200.	.20	.05	4.0	9.0	10.2	32	.93	1.83	.20	.04	.23	.03	13.	.68	1.04	1.69	1.96
200.	.20	.05	5.0	10.0	11.3	46	.78	1.63	.19	.04	.23	.04	19.	.73	.85	1.54	1.74
200.	.20	.10	2.0	7.0	7.9	31	.40	2.26	.36	.02	.26	.00	1.	.23	.60	2.17	2.56
200.	.20	.10	3.0	8.0	9.0	32	.74	2.00	.25	.04	.26	.01	5.	.54	.86	1.86	2.23
200.	.20	.10	4.0	9.0	10.2	43	.81	1.70	.24	.03	.26	.03	10.	.74	.99	1.75	1.93
200.	.20	.10	5.0	10.0	11.3	51	.80	1.69	.23	.03	.26	.04	14.	.69	.81	1.59	1.75
200.	.20	.15	2.0	7.0	7.9	28	.31	2.38	.29	.01	.29	.00	1.	.31	.52	2.23	2.73
200.	.20	.15	3.0	8.0	9.0	34	.58	1.73	.28	.03	.29	.01	4.	.40	.66	1.90	2.30
200.	.20	.15	4.0	9.0	10.2	27	.93	1.83	.27	.04	.29	.02	7.	.80	1.19	1.69	2.19
200.	.20	.15	5.0	10.0	11.3	46	.80	1.69	.26	.03	.29	.03	11.	.69	.81	1.61	1.76
200.	.20	.20	2.0	7.0	7.9	11	.06	2.32	.33	.00	.33	.00	0.	0.00	.40	1.13	2.85
200.	.20	.20	3.0	8.0	9.0	31	.60	2.26	.32	.02	.33	.01	2.	.42	.82	1.83	2.42
200.	.20	.20	4.0	9.0	10.2	47	.70	1.89	.31	.03	.33	.02	5.	.50	.70	1.71	1.95
200.	.20	.20	5.0	10.0	11.3	30	.68	1.73	.30	.03	.33	.03	8.	.61	.93	1.59	1.83
200.	.30	0.00	2.0	6.0	6.8	30	.60	2.26	.29	.05	.30	.01	3.	.31	.60	2.04	2.26
200.	.30	0.00	3.0	7.0	7.9	42	.87	1.95	.27	.07	.30	.03	11.	.66	.72	1.84	2.03
200.	.30	0.00	4.0	8.0	9.0	42	.91	1.68	.24	.07	.30	.06	19.	.75	.89	1.66	1.84
200.	.30	0.00	5.0	9.0	10.2	55	.71	1.57	.22	.07	.30	.08	27.	.88	1.08	1.57	1.70
200.	.30	0.00	6.0	10.0	11.3	63	1.05	1.46	.20	.07	.30	.10	34.	.98	1.05	1.38	1.50
200.	.30	.05	2.0	6.0	6.8	33	.40	2.26	.32	.03	.32	.01	2.	.31	.51	2.10	2.46
200.	.30	.05	3.0	7.0	7.9	30	.70	2.43	.30	.04	.32	.02	7.	.50	1.08	2.26	2.47
200.	.30	.05	4.0	8.0	9.0	49	.93	1.84	.27	.06	.32	.05	15.	.77	1.04	1.69	1.90
200.	.30	.05	5.0	9.0	10.2	48	.81	1.56	.25	.06	.32	.07	22.	.79	1.03	1.54	1.66
200.	.30	.05	6.0	10.0	11.3	55	.77	1.45	.23	.06	.32	.09	27.	.84	1.05	1.39	1.46
200.	.30	.10	2.0	6.0	6.8	33	.40	2.26	.34	.03	.34	.00	1.	.20	.44	2.01	2.39
200.	.30	.10	3.0	7.0	7.9	36	.60	2.13	.32	.04	.34	.02	5.	.60	.75	1.77	2.30
200.	.30	.10	4.0	8.0	9.0	32	.93	1.83	.30	.06	.34	.04	12.	.66	1.01	1.69	1.92
200.	.30	.10	5.0	9.0	10.2	54	.92	1.70	.28	.05	.34	.06	18.	.75	.76	1.63	1.74
200.	.30	.10	6.0	10.0	11.3	61	.90	1.55	.27	.05	.34	.08	22.	.86	1.00	1.45	1.62
200.	.30	.15	2.0	6.0	6.8	11	.40	2.26	.37	.03	.37	.00	0.	0.00	.40	1.13	2.85
200.	.30	.15	3.0	7.0	7.9	40	.60	2.18	.35	.03	.37	.02	4.	.43	.60	1.91	2.26
200.	.30	.15	4.0	8.0	9.0	44	.81	1.90	.33	.05	.37	.03	9.	.65	.91	1.77	1.96
200.	.30	.15	5.0	9.0	10.2	53	.80	1.69	.32	.05	.37	.05	14.	.71	.85	1.55	1.75
200.	.30	.15	6.0	10.0	11.3	41	.81	1.44	.30	.05	.37	.06	18.	.74	1.16	1.44	1.74
200.	.30	.20	2.0	6.0	6.8	12	.02	2.34	.39	.00	.39	.00	0.	0.00	.20	1.13	2.85
200.	.30	.20	3.0	7.0	7.9	40	.48	2.16	.38	.03	.39	.01	3.	.45	.72	2.16	2.34
200.	.30	.20	4.0	8.0	9.0	29	.81	1.72	.37	.06	.39	.02	6.	.61	1.03	1.59	1.92
200.	.30	.20	5.0	9.0	10.2	42	.80	1.69	.35	.05	.39	.04	11.	.63	.80	1.56	1.80
200.	.30	.20	6.0	10.0	11.3	52	.68	1.55	.34	.04	.39	.06	14.	.65	.82	1.55	1.74
200.	.40	0.00	2.0	6.0	6.8	39	.81	2.23	.37	.07	.40	.03	7.	.54	.81	1.93	2.25
200.	.40	0.00	3.0	7.0	7.9	59	.92	1.84	.33	.09	.40	.07	17.	.81	1.04	1.72	1.88
200.	.40	0.00	4.0	8.0	9.0	56	.95	1.60	.30	.09	.40	.10	26.	.93	1.07	1.56	1.67
200.	.40	0.00	5.0	9.0	10.2	67	.94	1.47	.27	.08	.40	.13	33.	.90	1.10	1.47	1.59
200.	.40	0.00	6.0	10.0	11.3	61	1.11	1.38	.24	.09	.40	.16	39.	.90	1.11	1.33	1.46
200.	.40	.03	2.0	6.0	6.8	52	.71	2.15	.39	.07	.41	.02	6.	.64	.79	2.13	2.29
200.	.40	.03	3.0	7.0	7.9	39	.75	1.80	.35	.07	.41	.04	14.	.75	1.01	1.80	1.97
200.	.40	.05	2.0	8.0	9.0	59	.88	1.67	.32	.07	.41	.09	22.	.82	.97	1.59	1.74
200.	.40	.05	3.0	9.0	10.2	75	.76	1.59	.30	.07	.41	.12	29.	.84	.96	1.44	1.57
200.	.40	.05	4.0	10.0	11.3	62	.94	1.38	.27	.07	.41	.14	34.	.91	1.04	1.35	1.41
200.	.40	.10	2.0	6.0	6.8	44	.56	2.14	.41	.05	.42	.02	4.	.47	.69	2.03	2.34
200.	.40	.10	3.0	7.0	7.9	51	.81	1.70	.38	.07	.42	.05	11.	.72	.91	1.89	2.00
200.	.40	.10	4.0	8.0	9.0	53	.80	1.69	.35	.06	.42	.08	18.	.79	.96	1.69	1.82
200.	.40	.10	5.0	9.0	10.2	62	.89	1.60	.32	.06	.42	.10	24.	.84	1.12	1.60	1.66
200.	.40	.10	6.0	10.0	11.3	63	.84	1.41	.30	.06	.42	.12	29.	.84	1.17	1.41	1.55
200.	.40	.15	2.0	6.0	6.8	36	.60	2.26	.43	.05	.44	.01	3.	.37	.60	2.02	2.38
200.	.40	.15	3.0	7.0	7.9	61	.73	1.90	.40	.06	.44	.04	9.	.73	.88	1.83	2.02
200.	.40	.15	4.0	8.0	9.0	56	.80	1.69	.37	.06	.44	.06	15.	.70	.80	1.63	1.73
200.	.40	.15	5.0	9.0	10.2	54	.90	1.57	.35	.06	.44	.09	20.	.77	.97	1.46	1.65
200.	.40	.15	6.0	10.0	11.3	60	.82	1.41	.33	.06	.44	.10	24.	.76	.97	1.38	1.49
200.	.40	.20	2.0	6.0	6.8	35	.40	2.26	.45	.03	.46	.01	2.	.31	.60	1.97	2.36
200.	.40	.20	3.0	7.0	7.9	37	.60	2.26	.43	.03	.46	.03	6.	.53	.81	2.22	2.42
200.	.40	.20	4.0	8.0	9.0	41	.80	1.69	.40	.06	.46	.05	12.	.62	.83	1.67	1.87
200.	.40	.20	5.0	9.0	10.2	50	.74	1.60	.38	.05	.46	.07	16.	.68	.88	1.52	1.69
200.	.40	.20	6.0	10.0	11.3	47	.85	1.41	.37	.06	.46	.09	19.	.69	.88	1.34	1.58

Table A2.1.2 (cont.)

OPTIMAL WIND POWER ALLOCATION

CFACT	LF	UMIN	K	WH	CW	EVALU	POPT	WOPT	COST	SERV	DCST	SAVE	PHIN	PMAX	WMIN	WMAX	
200.	.50	0.00	2.0	5.0	5.6	31	.40	2.26	.49	.06	.50	.01	2.	.37	.60	2.12	2.26
200.	.50	0.00	3.0	6.0	6.8	56	.90	2.00	.44	.10	.50	.06	12.	.77	.91	1.88	2.00
200.	.50	0.00	4.0	7.0	7.9	55	.99	1.82	.39	.09	.50	.11	22.	.80	.99	1.69	1.82
200.	.50	0.00	5.0	8.0	9.0	48	.99	1.50	.35	.11	.50	.15	30.	.91	1.15	1.49	1.60
200.	.50	0.00	6.0	9.0	10.2	74	.99	1.43	.31	.09	.50	.19	38.	.95	1.10	1.39	1.45
200.	.50	0.00	7.0	10.0	11.3	51	1.07	1.29	.29	.10	.50	.22	43.	.96	1.07	1.26	1.41
200.	.50	.05	8.0	5.0	5.6	39	.41	2.30	.49	.05	.50	.01	1.	.25	.48	2.26	2.45
200.	.50	.05	9.0	6.0	6.8	57	.79	2.01	.45	.09	.50	.05	10.	.66	.79	1.90	2.09
200.	.50	.05	10.0	7.0	7.9	57	.88	1.73	.41	.10	.50	.09	19.	.80	.95	1.68	1.73
200.	.50	.05	11.0	8.0	9.0	55	.74	1.65	.37	.08	.50	.13	26.	.85	1.16	1.60	1.66
200.	.50	.05	12.0	9.0	10.2	45	1.00	1.50	.34	.08	.50	.16	33.	.98	1.19	1.50	1.55
200.	.50	.05	13.0	10.0	11.3	50	1.08	1.33	.31	.09	.50	.19	38.	.89	1.11	1.28	1.38
200.	.50	.10	14.0	5.0	5.6	30	.17	2.31	.50	.02	.51	.00	1.	.14	.44	2.08	2.49
200.	.50	.10	15.0	6.0	6.8	49	.34	2.04	.47	.07	.51	.04	9.	.63	.84	1.88	2.14
200.	.50	.10	16.0	7.0	7.9	58	.86	1.75	.43	.09	.51	.08	16.	.73	.90	1.68	1.80
200.	.50	.10	17.0	8.0	9.0	59	.84	1.53	.39	.09	.51	.11	23.	.79	.93	1.51	1.55
200.	.50	.10	18.0	9.0	10.2	74	.77	1.44	.36	.09	.51	.14	28.	.81	1.06	1.41	1.51
200.	.50	.10	19.0	10.0	11.3	71	1.00	1.37	.34	.07	.51	.17	33.	.89	1.00	1.36	1.43
200.	.50	.15	20.0	5.0	5.6	12	.20	2.85	.51	.01	.51	.00	0.	0.00	.20	1.13	2.85
200.	.50	.15	21.0	6.0	6.8	34	.78	2.07	.48	.08	.51	.03	6.	.54	.81	2.00	2.24
200.	.50	.15	22.0	7.0	7.9	40	.69	1.72	.45	.08	.51	.07	13.	.68	.87	1.72	1.74
200.	.50	.15	23.0	8.0	9.0	54	.83	1.60	.41	.08	.51	.10	19.	.77	.93	1.60	1.72
200.	.50	.15	24.0	9.0	10.2	73	.95	1.48	.39	.07	.51	.12	24.	.76	.93	1.41	1.51
200.	.50	.15	25.0	10.0	11.3	58	1.09	1.47	.37	.07	.51	.15	29.	.97	1.14	1.35	1.51
200.	.50	.20	26.0	5.0	5.6	46	.60	1.79	.50	.07	.52	.02	5.	.55	.73	1.93	2.27
200.	.50	.20	27.0	6.0	6.8	51	.73	1.85	.47	.07	.52	.05	10.	.68	.81	1.73	1.93
200.	.50	.20	28.0	7.0	7.9	49	.80	1.69	.44	.06	.52	.08	16.	.71	.90	1.54	1.73
200.	.50	.20	29.0	8.0	9.0	57	.73	1.49	.41	.06	.52	.11	20.	.71	.87	1.41	1.63
200.	.50	.20	30.0	9.0	10.2	72	.83	1.35	.39	.07	.52	.13	24.	.74	.88	1.32	1.37
200.	.60	0.00	3.0	5.0	5.6	47	.62	2.11	.58	.11	.60	.02	4.	.52	.73	2.11	2.29
200.	.60	0.00	4.0	6.0	6.8	62	.92	1.88	.51	.13	.60	.07	15.	.81	.95	1.81	1.74
200.	.60	0.00	5.0	7.0	7.9	57	.77	1.85	.45	.13	.60	.15	25.	.91	1.08	1.57	1.86
200.	.60	0.00	6.0	8.0	9.0	71	.98	1.50	.40	.11	.60	.20	33.	.97	1.12	1.47	1.54
200.	.60	0.00	7.0	9.0	10.2	58	1.05	1.41	.36	.10	.60	.24	40.	1.05	1.29	1.33	1.45
200.	.60	0.00	8.0	10.0	11.3	63	1.13	1.33	.32	.10	.60	.28	46.	1.06	1.21	1.29	1.37
200.	.60	.05	9.0	5.0	5.6	49	.60	2.36	.58	.08	.60	.02	3.	.54	.74	2.19	2.36
200.	.60	.05	10.0	6.0	6.8	60	.70	1.94	.52	.11	.60	.08	13.	.76	.95	1.90	2.00
200.	.60	.05	11.0	7.0	7.9	50	.77	1.54	.47	.12	.60	.13	22.	.75	.80	1.54	1.69
200.	.60	.05	12.0	8.0	9.0	81	1.02	1.52	.42	.11	.60	.18	30.	.92	1.12	1.45	1.54
200.	.60	.05	13.0	9.0	10.2	60	1.01	1.41	.38	.10	.60	.22	37.	.90	1.11	1.34	1.45
200.	.60	.05	14.0	10.0	11.3	71	1.07	1.30	.35	.10	.60	.25	42.	.96	1.07	1.25	1.32
200.	.60	.10	15.0	5.0	5.6	36	.60	2.26	.58	.08	.60	.02	3.	.41	.60	2.06	2.40
200.	.60	.10	16.0	6.0	6.8	56	.80	1.90	.53	.11	.60	.07	12.	.75	.97	1.86	1.98
200.	.60	.10	17.0	7.0	7.9	63	.81	1.60	.48	.12	.60	.12	20.	.77	.92	1.59	1.69
200.	.60	.10	18.0	8.0	9.0	71	.96	1.51	.44	.11	.60	.15	27.	.81	1.02	1.46	1.58
200.	.60	.10	19.0	9.0	10.2	72	.87	1.35	.40	.10	.60	.20	33.	.87	1.09	1.35	1.48
200.	.60	.10	20.0	10.0	11.3	45	1.00	1.27	.38	.10	.60	.22	37.	.86	1.21	1.27	1.36
200.	.60	.15	21.0	5.0	5.6	42	.40	2.26	.59	.06	.60	.01	2.	.33	.44	2.06	2.26
200.	.60	.15	22.0	6.0	6.8	61	.70	1.86	.54	.10	.60	.06	10.	.62	.70	1.80	1.92
200.	.60	.15	23.0	7.0	7.9	58	.80	1.69	.50	.10	.60	.10	17.	.78	.98	1.69	1.77
200.	.60	.15	24.0	8.0	9.0	59	.83	1.56	.46	.08	.60	.14	24.	.77	1.00	1.44	1.63
200.	.60	.15	25.0	9.0	10.2	72	.79	1.38	.43	.08	.60	.17	29.	.79	.84	1.32	1.41
200.	.60	.15	26.0	10.0	11.3	56	.93	1.33	.40	.08	.60	.20	33.	.93	1.09	1.29	1.40
200.	.60	.20	27.0	5.0	5.6	47	.40	2.26	.59	.06	.60	.01	1.	.40	.52	2.24	2.44
200.	.60	.20	28.0	6.0	6.8	64	.66	1.98	.55	.08	.60	.05	8.	.61	.76	1.86	2.04
200.	.60	.20	29.0	7.0	7.9	54	.78	1.71	.51	.09	.60	.09	15.	.67	.83	1.69	1.77
200.	.60	.20	30.0	8.0	9.0	63	.76	1.51	.48	.09	.60	.12	20.	.76	.88	1.48	1.55
200.	.60	.20	31.0	9.0	10.2	55	.76	1.38	.45	.08	.60	.15	25.	.73	.94	1.37	1.49
200.	.60	.20	32.0	10.0	11.3	57	.87	1.36	.43	.07	.60	.17	29.	.87	1.05	1.36	1.44

Table A2.1.3

Economic Factor= 300.

OPTIMAL WIND POWER ALLOCATION

CFACT	LF	QMIN	K	WM	CW	EVALU	POPT	WOPT	COST	SERV	DCST	SAVE	FMIN	PMAX	WMIN	WMAX	
300.	.20	0.00	2.0	9.0	9.0	35	.60	2.26	.19	.03	.20	.01	3.	.40	.75	2.00	.32
300.	.20	0.00	2.0	9.0	10.2	48	.76	2.03	.18	.04	.20	.02	10.	.58	.76	1.95	2.09
300.	.20	0.00	2.0	10.0	11.3	31	.93	1.93	.17	.05	.20	.03	16.	.73	1.04	1.69	1.96
300.	.20	.05	2.0	8.0	9.0	28	.40	2.26	.23	.02	.23	.00	2.	.40	.73	1.99	2.49
300.	.20	.05	2.0	9.0	10.2	43	.94	2.22	.22	.04	.23	.01	6.	.82	1.00	2.09	2.37
300.	.20	.05	2.0	10.0	11.3	43	.80	1.81	.20	.04	.23	.03	12.	.71	.96	1.73	2.00
300.	.20	.10	2.0	8.0	9.0	31	.40	2.26	.26	.02	.26	.00	1.	.23	.60	2.17	2.56
300.	.20	.10	2.0	9.0	10.2	32	.56	1.92	.25	.03	.26	.01	5.	.56	.90	1.89	2.26
300.	.20	.10	2.0	10.0	11.3	39	.87	1.98	.24	.03	.26	.02	7.	.68	.91	1.91	2.11
300.	.20	.15	2.0	8.0	9.0	28	.31	2.38	.29	.01	.29	.00	1.	.31	.52	2.23	2.73
300.	.20	.15	2.0	9.0	10.2	37	.60	2.26	.29	.02	.29	.01	3.	.44	.82	1.93	2.39
300.	.20	.15	2.0	10.0	11.3	18	1.03	1.92	.28	.04	.29	.02	5.	.60	1.08	1.69	2.47
300.	.20	.20	2.0	8.0	9.0	11	.06	2.32	.33	.00	.33	.00	0.	0.00	.40	1.13	2.85
300.	.20	.20	2.0	9.0	10.2	29	.60	2.26	.32	.02	.33	.01	2.	.35	.60	1.94	2.38
300.	.20	.20	2.0	10.0	11.3	47	.66	1.99	.31	.03	.33	.01	5.	.50	.66	1.80	2.16
300.	.30	0.00	2.0	7.0	7.9	36	.60	2.26	.29	.05	.30	.01	3.	.39	.60	2.07	2.26
300.	.30	0.00	2.0	8.0	9.0	39	.64	1.85	.27	.06	.30	.03	10.	.54	.83	1.85	2.19
300.	.30	0.00	2.0	9.0	10.2	43	1.04	1.88	.25	.06	.30	.05	18.	.80	1.09	1.69	1.96
300.	.30	0.00	2.0	10.0	11.3	45	.81	1.54	.23	.07	.30	.07	25.	.81	1.00	1.51	1.55
300.	.30	.05	2.0	7.0	7.9	37	.40	2.26	.31	.03	.32	.01	2.	.40	.60	2.02	2.37
300.	.30	.05	2.0	8.0	9.0	30	.60	2.26	.30	.03	.32	.02	7.	.60	1.08	2.26	2.47
300.	.30	.05	2.0	9.0	10.2	35	.93	1.83	.27	.06	.32	.05	14.	.70	1.04	1.69	1.96
300.	.30	.05	2.0	10.0	11.3	49	.78	1.63	.26	.05	.32	.06	20.	.77	.85	1.56	1.74
300.	.30	.10	2.0	7.0	7.9	34	.40	2.26	.34	.03	.34	.00	1.	.23	.52	2.17	2.56
300.	.30	.10	2.0	8.0	9.0	41	.75	2.12	.32	.05	.34	.02	6.	.60	.81	1.95	2.23
300.	.30	.10	2.0	9.0	10.2	46	.81	1.90	.30	.05	.34	.04	11.	.66	.93	1.75	1.90
300.	.30	.10	2.0	10.0	11.3	55	.80	1.69	.29	.05	.34	.06	16.	.78	.87	1.59	1.75
300.	.30	.15	2.0	7.0	7.9	32	.31	2.38	.36	.02	.37	.00	1.	.25	.47	2.16	2.43
300.	.30	.15	2.0	8.0	9.0	36	.58	1.93	.35	.05	.37	.02	4.	.40	.66	1.90	2.30
300.	.30	.15	2.0	9.0	10.2	45	.71	1.79	.33	.05	.37	.03	7.	.69	.84	1.78	2.01
300.	.30	.15	2.0	10.0	11.3	46	.80	1.69	.32	.05	.37	.05	13.	.69	.81	1.61	1.76
300.	.30	.20	2.0	7.0	7.9	11	.06	2.32	.39	.00	.39	.00	0.	0.00	.40	1.13	2.85
300.	.30	.20	2.0	8.0	9.0	41	.54	2.05	.38	.04	.39	.01	3.	.44	.71	2.03	2.26
300.	.30	.20	2.0	9.0	10.2	51	.70	1.89	.37	.04	.39	.03	7.	.57	.81	1.84	2.04
300.	.30	.20	2.0	10.0	11.3	53	.68	1.73	.35	.04	.39	.04	10.	.66	.93	1.63	1.83
300.	.40	0.00	2.0	6.0	6.8	41	.40	2.26	.40	.05	.40	.00	1.	.23	.41	2.07	2.43
300.	.40	0.00	2.0	7.0	7.9	43	.83	2.13	.37	.08	.40	.03	8.	.69	.88	1.93	2.21
300.	.40	0.00	2.0	8.0	9.0	52	.84	1.83	.33	.08	.40	.07	17.	.81	1.04	1.70	1.94
300.	.40	0.00	2.0	9.0	10.2	50	.84	1.67	.30	.08	.40	.10	24.	.83	1.12	1.56	1.80
300.	.40	0.00	2.0	10.0	11.3	61	1.05	1.57	.28	.09	.40	.12	31.	.94	1.20	1.45	1.60
300.	.40	.05	2.0	6.0	6.8	29	.22	2.17	.41	.03	.41	.00	1.	.22	.42	2.14	2.60
300.	.40	.05	2.0	7.0	7.9	42	.68	2.00	.38	.07	.41	.03	7.	.54	.81	1.93	2.23
300.	.40	.05	2.0	8.0	9.0	43	.80	1.81	.35	.09	.41	.04	14.	.79	.93	1.81	1.95
300.	.40	.05	2.0	9.0	10.2	59	.85	1.64	.33	.08	.41	.08	21.	.84	1.01	1.64	1.75
300.	.40	.05	2.0	10.0	11.3	53	.88	1.40	.31	.10	.41	.11	26.	.78	1.18	1.40	1.55
300.	.40	.10	2.0	6.0	6.8	12	.20	2.85	.42	.01	.42	.00	0.	0.00	.20	1.13	2.85
300.	.40	.10	2.0	7.0	7.9	50	.61	2.20	.40	.05	.42	.02	5.	.60	.82	2.15	2.29
300.	.40	.10	2.0	8.0	9.0	50	.81	1.90	.38	.07	.42	.05	11.	.81	.93	1.86	1.99
300.	.40	.10	2.0	9.0	10.2	48	.83	1.71	.35	.07	.42	.07	17.	.77	.94	1.66	1.82
300.	.40	.10	2.0	10.0	11.3	42	1.03	1.57	.33	.08	.42	.09	22.	.80	1.16	1.44	1.74
300.	.40	.15	2.0	7.0	7.9	40	.53	2.06	.42	.06	.44	.02	4.	.40	.68	2.02	2.27
300.	.40	.15	2.0	8.0	9.0	61	.73	1.90	.40	.06	.44	.04	7.	.73	.88	1.83	2.02
300.	.40	.15	2.0	9.0	10.2	47	.80	1.69	.38	.07	.44	.06	14.	.67	.95	1.63	1.80
300.	.40	.15	2.0	10.0	11.3	66	.84	1.59	.36	.06	.44	.08	19.	.78	.99	1.58	1.70
300.	.40	.20	2.0	7.0	7.9	35	.60	2.26	.44	.05	.46	.01	2.	.35	.60	1.94	2.26
300.	.40	.20	2.0	8.0	9.0	47	.74	1.98	.43	.06	.46	.03	7.	.74	.92	1.89	2.14
300.	.40	.20	2.0	9.0	10.2	38	.68	1.73	.41	.05	.46	.05	11.	.65	.85	1.63	1.83
300.	.40	.20	2.0	10.0	11.3	48	.80	1.69	.39	.05	.46	.07	15.	.69	.88	1.61	1.74

Table A2.1.3 (cont.)

OPTIMAL WIND POWER ALLOCATION

CFACT	LF	DMIN	K	WM	CW	EVALU	POPT	WOPT	COST	SERV	DCST	SAVE	PHIN	PMAX	WMIN	WMAX	
300.	.50	0.00	2.0	6.0	6.6	41	.60	2.26	.48	.07	.50	.02	4.	.46	.71	2.07	2.34
300.	.50	0.00	3.0	7.0	7.9	45	.73	1.37	.43	.10	.50	.07	13.	.73	.93	1.97	2.05
300.	.50	0.00	4.0	9.0	9.0	66	1.00	1.75	.39	.11	.50	.11	22.	.83	1.00	1.65	1.76
300.	.50	0.00	5.0	9.0	10.2	85	.74	1.53	.35	.11	.50	.15	29.	.94	1.07	1.51	1.58
300.	.50	0.00	6.0	10.0	11.3	73	1.06	1.42	.32	.10	.50	.18	36.	.92	1.06	1.39	1.47
300.	.50	.05	6.0	6.0	6.8	59	.60	2.26	.49	.07	.50	.02	3.	.39	.67	2.15	2.35
300.	.50	.05	7.0	7.0	7.9	47	.80	1.99	.45	.09	.50	.05	11.	.68	.80	1.86	2.03
300.	.50	.05	8.0	9.0	9.0	51	.87	1.80	.41	.09	.50	.09	18.	.76	.89	1.66	1.80
300.	.50	.05	9.0	10.0	10.2	67	.77	1.60	.37	.10	.50	.13	25.	.88	1.00	1.50	1.60
300.	.50	.05	10.0	11.0	11.3	73	.94	1.46	.34	.09	.50	.16	31.	.87	1.02	1.42	1.54
300.	.50	.10	6.0	6.0	6.8	33	.40	2.26	.49	.05	.51	.01	2.	.32	.60	2.06	2.27
300.	.50	.10	7.0	7.0	7.9	51	.67	1.98	.46	.07	.51	.04	9.	.63	.77	1.93	2.13
300.	.50	.10	8.0	9.0	9.0	58	.84	1.74	.43	.09	.51	.08	16.	.73	.89	1.66	1.88
300.	.50	.10	9.0	10.0	10.2	52	.81	1.54	.40	.09	.51	.11	22.	.76	.93	1.52	1.59
300.	.50	.10	10.0	11.0	11.3	58	.84	1.43	.37	.09	.51	.14	27.	.78	.77	1.39	1.45
300.	.50	.15	6.0	6.0	6.8	43	.40	2.26	.50	.05	.51	.01	1.	.30	.51	2.11	2.44
300.	.50	.15	7.0	7.0	7.9	35	.60	2.13	.48	.05	.51	.03	7.	.60	.91	1.91	2.25
300.	.50	.15	8.0	9.0	9.0	40	.69	1.72	.45	.08	.51	.07	13.	.68	.87	1.72	1.94
300.	.50	.15	9.0	10.0	10.2	46	.80	1.69	.42	.07	.51	.09	18.	.72	.83	1.63	1.74
300.	.50	.15	10.0	11.0	11.3	69	.86	1.49	.39	.08	.51	.12	23.	.86	.98	1.48	1.58
300.	.50	.20	6.0	6.0	6.8	28	.40	2.26	.52	.05	.52	.00	1.	.14	.44	2.08	2.49
300.	.50	.20	7.0	7.0	7.9	38	.60	2.26	.49	.05	.52	.03	5.	.49	.82	1.90	2.35
300.	.50	.20	8.0	9.0	9.0	56	.73	1.85	.47	.07	.52	.05	10.	.69	.81	1.93	1.93
300.	.50	.20	9.0	10.0	10.2	55	.77	1.67	.44	.07	.52	.08	15.	.73	.90	1.63	1.73
300.	.50	.20	10.0	11.0	11.3	64	.84	1.54	.42	.07	.52	.10	19.	.74	.96	1.54	1.61
300.	.60	0.00	6.0	6.0	6.8	50	.68	2.03	.56	.11	.60	.04	6.	.68	.90	2.01	2.26
300.	.60	0.00	7.0	7.0	7.9	60	.87	1.79	.50	.13	.60	.10	16.	.82	1.03	1.74	1.90
300.	.60	0.00	8.0	9.0	9.0	57	.97	1.65	.45	.13	.60	.15	25.	.91	1.08	1.57	1.66
300.	.60	0.00	9.0	10.0	10.2	74	1.03	1.51	.41	.12	.60	.19	32.	.96	1.08	1.46	1.56
300.	.60	0.00	10.0	11.0	11.3	65	1.23	1.48	.37	.11	.60	.23	39.	.94	1.24	1.33	1.48
300.	.60	.05	6.0	6.0	6.8	36	.60	2.12	.57	.09	.60	.03	6.	.57	.82	1.97	2.12
300.	.60	.05	7.0	7.0	7.9	55	.89	1.90	.51	.11	.60	.09	14.	.77	.93	1.85	1.95
300.	.60	.05	8.0	9.0	9.0	50	.77	1.54	.47	.12	.60	.13	22.	.75	.80	1.54	1.69
300.	.60	.05	9.0	10.0	10.2	81	.93	1.51	.42	.11	.60	.18	29.	.88	.95	1.45	1.55
300.	.60	.05	10.0	11.0	11.3	63	1.06	1.43	.39	.11	.60	.21	35.	.90	1.06	1.35	1.43
300.	.60	.10	6.0	6.0	6.8	37	.51	2.08	.57	.08	.60	.03	5.	.47	.61	1.97	2.30
300.	.60	.10	7.0	7.0	7.9	50	.81	1.70	.52	.10	.60	.08	13.	.71	.85	1.76	1.90
300.	.60	.10	8.0	9.0	9.0	70	.82	1.67	.48	.10	.60	.12	20.	.78	.76	1.60	1.76
300.	.60	.10	9.0	10.0	10.2	64	.70	1.55	.44	.10	.60	.16	26.	.86	1.00	1.49	1.62
300.	.60	.10	10.0	11.0	11.3	61	1.00	1.50	.41	.09	.60	.19	31.	.83	1.12	1.41	1.52
300.	.60	.15	6.0	6.0	6.8	43	.60	2.26	.58	.07	.60	.02	4.	.40	.60	2.02	2.26
300.	.60	.15	7.0	7.0	7.9	60	.75	1.76	.54	.09	.60	.06	11.	.75	.87	1.88	2.00
300.	.60	.15	8.0	9.0	9.0	56	.80	1.69	.50	.10	.60	.10	17.	.73	.86	1.69	1.77
300.	.60	.15	9.0	10.0	10.2	49	.72	1.50	.46	.09	.60	.14	23.	.72	1.03	1.44	1.69
300.	.60	.15	10.0	11.0	11.3	80	.85	1.43	.43	.09	.60	.17	28.	.85	.93	1.38	1.45
300.	.60	.20	6.0	6.0	6.8	41	.42	2.21	.58	.05	.60	.02	3.	.37	.60	2.04	2.26
300.	.60	.20	7.0	7.0	7.9	65	.67	1.92	.55	.08	.60	.05	9.	.58	.77	1.86	1.98
300.	.60	.20	8.0	9.0	9.0	57	.78	1.71	.51	.09	.60	.09	14.	.67	.83	1.66	1.77
300.	.60	.20	9.0	10.0	10.2	68	.80	1.57	.48	.09	.60	.12	20.	.77	.88	1.57	1.66
300.	.60	.20	10.0	11.0	11.3	72	.81	1.46	.46	.08	.60	.14	24.	.74	.87	1.39	1.52

Appendix 2.2

Optimal wind power allocation on the Greek Islands
with autonomous grid

Table A2.2.1

Minimum Diesel Station Load= 30% of smallest set rated power

OPTIMAL WIND POWER ALLOCATION PROGRAM

DISCOUNT RATE 10.0/0
 MAINTENANCE COST 3.0 0/0
 LIFE YEARS 20
 SPEC. TURB. COST 150. POUNDS/M2 SWEEP AREA
 AIR DENSITY 1.225 KG/M3
 RATED POWER COEF. .40
 RATED GENER. EFF. .75
 REL. CUT-IN SPEED .40
 REL. FURL. SPEED 2.00
 HUB HEIGHT 10.0 M

LOCATION	PEAK KW	LOAD FACT	FUEL COST P/KWH	U AVER. M/S	PARAM. K	MIN. POWER KW	POPT KW	VOPT M/S	FUEL SAVE 0/0	NET SAVE 0/0	PAY-BACK YEARS
SKYROS	970.	.43	5.50	5.2	1.40	180.	258.	13.5	10.7	4.8	7.1
SAMOTHRAKI	530.	.32	6.34	4.5	1.60	54.	0.	3.2	0.0	0.0	0.0
KEFALLINIA	9400.	.40	2.86	5.0	1.50	150.	0.	3.2	0.0	0.0	0.0
ZAKYNTHOS	7500.	.35	5.58	6.6	1.50	75.	3362.	14.6	22.0	12.3	5.6
PAXI	720.	.32	5.97	4.0	1.50	24.	0.	3.2	0.0	0.0	0.0
OTTHONI	58.	.32	8.64	4.0	1.50	12.	0.	3.2	0.0	0.0	0.0
ERIKOUSA	84.	.21	7.55	4.9	1.50	12.	0.	3.2	0.0	0.0	0.0
RODOS	33434.	.50	3.34	5.7	1.60	6687.	0.	15.5	15.2	7.2	0.0
KASSOS	235.	.34	6.24	5.6	1.50	26.	74.	14.6	15.1	7.5	7.4
KARPATHOS	1400.	.36	5.47	6.6	1.50	180.	419.	14.6	12.2	3.0	7.5
MEGISTI	70.	.35	9.30	5.7	1.50	5.	28.	12.6	16.7	8.8	6.6
SYMI	507.	.30	7.35	5.7	2.00	21.	185.	12.9	15.1	5.1	14.2
TILOS	94.	.33	7.70	6.0	2.00	12.	31.	13.5	11.3	4.2	12.1
HALONI	72.	.29	8.58	6.0	2.00	8.	25.	13.5	12.2	3.1	10.2
KALYMNOS	11300.	.45	2.65	6.4	2.00	678.	0.	15.5	15.4	4.4	0.0
ASTYPALIA	235.	.34	5.71	7.0	1.80	26.	121.	15.7	16.7	3.1	7.7
LIPSI	135.	.26	7.93	6.0	2.00	9.	49.	13.5	14.0	5.2	12.2
NISYROS	170.	.34	7.40	6.0	2.00	24.	52.	13.5	11.5	4.2	12.6
PATHOS	760.	.35	6.47	6.0	2.00	75.	378.	13.5	13.2	4.9	12.4
LESBOS	17300.	.46	2.53	5.7	1.60	750.	0.	3.2	0.0	0.0	0.0
HIOS	13900.	.42	3.64	5.7	1.60	240.	0.	3.2	0.0	0.0	0.0
PSARA	240.	.25	9.70	6.5	1.80	24.	105.	12.0	20.1	8.0	11.1
SAMOS	7900.	.35	3.57	5.6	2.00	300.	0.	3.2	0.0	0.0	0.0
IKARIA	1380.	.36	5.71	6.0	2.00	48.	538.	13.5	17.0	7.4	7.5
FOURNI	210.	.32	7.14	5.8	2.00	24.	47.	13.1	9.8	3.3	11.9
SYROS	10000.	.44	2.62	6.6	1.80	240.	2511.	14.8	11.2	2.6	24.4
AMORGOS	250.	.31	7.89	6.6	1.70	30.	89.	14.8	13.4	8.0	4.9
THIRA	2450.	.33	5.15	6.6	1.50	210.	290.	14.6	15.5	6.4	10.4
IOS	850.	.28	6.78	6.6	2.00	24.	264.	11.7	23.5	10.4	9.1
MYKONOS	3450.	.37	5.50	7.0	2.00	120.	1942.	12.0	34.5	16.1	8.4
PAROS-NAXOS	6700.	.38	2.58	7.0	2.00	225.	2412.	15.8	15.2	3.1	28.8
SIKINOS	95.	.27	7.64	6.6	2.00	12.	37.	14.7	11.8	5.3	9.1
FOLEGANDROS	125.	.24	7.54	6.6	1.50	30.	32.	17.8	3.6	1.3	12.4
ANAFI	49.	.31	10.78	6.6	1.50	12.	14.	14.6	7.3	4.3	5.2
AG. EFSTR.	36.	.26	8.38	7.0	1.70	12.	50.	15.7	11.6	6.9	5.0
AGISTRI	285.	.24	6.01	7.0	1.70	26.	85.	15.7	11.5	5.6	6.5
ANDROS	5400.	.38	2.65	6.2	1.80	600.	0.	3.2	0.0	0.0	0.0
KEA	640.	.33	6.67	5.2	1.50	45.	134.	14.1	16.9	5.9	12.8
SYTHNOS	525.	.26	10.30	6.8	1.50	45.	172.	15.1	15.2	5.7	9.7
LIMNOS	3400.	.37	5.56	5.0	1.50	300.	636.	13.5	5.9	1.4	24.2
MILOS	2050.	.33	5.24	6.6	1.50	150.	320.	14.0	17.7	7.0	11.1
SERIFOS	440.	.33	5.72	6.6	1.60	24.	132.	14.1	14.5	5.5	7.0
SIFNOS	720.	.29	6.30	6.6	1.60	15.	116.	14.7	17.1	3.0	7.4
ARITI	110536.	.56	3.96	7.0	1.50	22172.	56667.	15.5	15.6	7.4	8.0

Table A2.2.2

Minimum Diesel Station Load= 0

OPTIMAL WIND POWER ALLOCATION PROGRAM

DISCOUNT RATE 10.0/0
 MAINTENANCE COST 3.0 0/0
 LIFE YEARS 20
 SPEC. FUEL COST 150. POUNDS/M2 SWEET AREA
 AIR DENSITY 1.225 KG/M3
 RATED POWER COEF. 40
 RATED GENER. EFF. .75
 REL. CUT-IN SPEED 4.0
 REL. FURL. SPEED 2.00
 HUB HEIGHT 10.0 M

LOCATION	PEAK	LOAD FACT	FUEL COST	U AVER.	PARAM. K	MIN. POWER	POPT	VOPT	FUEL SAVE	NET SAVE	PAY-BACK
	KW	-	P/KWH	M/S		-KW	-KW	-M/S	0/0	0/0	YEARS
SKYROS	270	.43	5.50	3.2	1.40	0.	582.	13.6	25.1	12.0	8.0
SAMOTHRAKI	530.	.33	6.34	4.5	1.60	0.	0.	3.2	0.0	0.0	0.0
KEFALLINIA	3400.	.40	6.36	3.0	1.30	0.	0.	3.2	0.0	0.0	0.0
ZAKYNTHOS	7500.	.35	6.58	5.5	1.50	0.	4500.	14.6	25.8	13.1	7.1
PAXI	720.	.32	5.97	4.0	1.50	0.	0.	3.2	0.0	0.0	0.0
OTHOINI	56.	.32	6.64	4.0	1.50	0.	0.	3.2	0.0	0.0	0.0
ERIKOUSIA	84.	.21	7.55	4.0	1.50	0.	0.	3.2	0.0	0.0	0.0
RODOS	33434.	.50	3.34	5.7	1.60	0.	10431.	16.5	6.8	1.5	27.1
KASSOS	235.	.34	6.24	5.5	1.50	0.	129.	12.7	30.6	14.4	9.2
KARFATHOS	1400.	.36	5.47	5.5	1.50	0.	940.	14.6	25.8	13.1	7.1
MEGISTI	70.	.35	9.20	5.7	1.50	0.	38.	11.0	39.5	13.9	8.7
SYMI	507.	.30	7.35	5.7	2.00	0.	185.	12.7	17.5	7.4	10.0
FILOS	81.	.33	7.70	5.0	2.00	0.	30.	10.3	28.6	11.7	10.2
HALKI	72.	.27	8.58	5.0	2.00	0.	26.	13.5	18.9	11.4	4.9
KALYMNOS	11500.	.46	3.65	5.4	2.00	0.	1877.	14.4	7.3	1.3	34.6
ASTYNOLEA	235.	.34	6.71	7.0	1.80	0.	116.	12.5	33.2	16.3	7.5
LIPSI	135.	.36	7.93	5.0	2.00	0.	53.	13.5	19.6	10.7	8.3
NISSYROS	170.	.34	7.40	5.0	2.00	0.	51.	10.3	28.4	11.5	10.6
PATMOS	760.	.33	6.47	5.0	2.00	0.	325.	11.1	28.8	10.7	12.3
LESBOS	17300.	.46	2.53	5.7	1.60	0.	0.	3.2	0.0	0.0	0.0
HTOS	13800.	.42	2.64	5.7	1.60	0.	0.	3.2	0.0	0.0	0.0
PSARA	240.	.25	9.70	5.5	1.80	0.	119.	11.6	33.2	16.4	7.3
SAMOS	7800.	.53	3.57	5.6	2.00	0.	0.	15.4	1.1	0.1	0.0
INARIA	1280.	.36	4.91	6.0	2.00	0.	538.	10.7	28.5	9.1	15.7
FOURNI	210.	.32	7.14	5.9	2.00	0.	32.	13.1	18.6	8.8	9.2
SYROS	10000.	.44	2.82	5.5	1.80	0.	2511.	14.8	11.6	3.0	21.2
ANDROS	250.	.31	7.87	6.5	1.70	0.	124.	11.8	33.1	17.0	7.0
THIRA	2450.	.35	5.15	5.6	1.50	0.	1159.	14.6	22.9	12.0	5.6
IOS	850.	.28	5.78	5.6	2.00	0.	305.	11.4	38.5	11.7	10.4
MYKONOS	3450.	.39	5.50	7.0	2.00	0.	1812.	12.0	38.9	18.7	7.1
PAROS-NAXOS	6700.	.38	2.58	7.0	2.00	0.	1604.	15.8	11.9	3.2	15.0
SEINIOS	95.	.27	7.64	6.6	2.00	0.	44.	11.2	35.0	14.2	10.7
SOLEAGANDROS	125.	.34	7.54	5.5	1.30	0.	59.	14.6	35.0	12.1	5.5
ANAFI	48.	.31	10.78	6.6	1.30	0.	30.	11.2	19.4	11.7	8.0
AG. EFESTO.	95.	.26	8.29	7.0	1.70	0.	44.	13.8	30.5	18.3	4.9
AGISTRI	195.	.24	6.01	7.0	1.20	0.	130.	13.9	26.5	11.1	10.1
ANDROS	5400.	.38	2.65	5.2	1.30	0.	0.	17.0	6.	0.6	0.0
KEA	540.	.33	6.67	5.2	1.50	0.	200.	12.2	14.8	4.6	16.0
KYTHNOS	525.	.26	5.95	5.8	1.50	0.	205.	12.1	20.7	10.9	6.5
LIKNOS	3400.	.39	5.56	5.9	1.30	0.	489.	13.5	7.4	2.7	13.1
MILOS	2050.	.33	4.24	5.5	1.50	0.	1230.	14.6	25.9	11.5	7.2
SERTIOS	440.	.23	5.72	5.5	1.60	0.	176.	14.7	20.4	10.1	7.4
TIFNOS	770.	.29	6.30	5.6	1.60	0.	311.	13.2	24.4	12.3	7.1
KRITI	110535.	.55	3.95	7.0	1.50	0.	26605.	13.7	31.9	13.7	9.3

Table A2.2.3

Minimum Diesel Station Load= 30% of smallest set rated power

OPTIMAL WIND POWER ALLOCATION PROGRAM

DISCOUNT RATE 10.0/0
 MAINTENANCE COST 3.0 0/0
 LIFE YEARS 20
 SPEC. TURB. COST 250. POUNDS/M2 SWEPT AREA
 AIR DENSITY 1.225 KG/MS
 RATED POWER COEF. .40
 RATED GENER. EFF. .75
 REL. CUT-IN SPEED .40
 REL. FURL. SPEED 2.00
 HUB HEIGHT 30.0 M

LOCATION	PEAK	LOAD FACT	FUEL COST	V. AVER.	PARAM. K	MIN. POWER	POP	VOPT	FUEL SAVE	NET SAVE	PAY-BACK
	KW		P/KWH	M/S		KW	KW	M/S	0/0	0/0	YEARS
SKYROS	970.	.43	5.50	7.3	1.40	180.	394.	15.9	10.9	4.4	10.8
SARATHRAKI	530.	.32	6.34	5.3	1.60	54.	0.	3.2	0.0	0.0	0.0
KEFALLINIA	9400.	.40	3.84	5.8	1.50	150.	0.	3.2	0.0	0.0	0.0
ZAKYNTHOS	7500.	.38	5.88	7.7	1.50	75.	4500.	17.1	25.3	12.9	8.1
PAXI	720.	.35	6.77	4.7	1.50	24.	0.	3.2	0.0	0.0	0.0
OTHOI	56.	.32	10.64	4.7	1.50	12.	0.	3.2	0.0	0.0	0.0
ERIKOUSA	84.	.21	7.55	4.7	1.50	12.	0.	3.2	0.0	0.0	0.0
RODOS	33434.	.50	3.34	5.7	1.50	5687.	0.	3.2	0.0	0.0	0.0
NASOS	235.	.34	6.24	7.7	1.50	36.	94.	17.1	14.9	7.0	8.2
KARPATHOS	1400.	.36	5.47	7.7	1.50	180.	560.	17.1	14.2	5.7	11.1
MEGISTI	70.	.35	9.20	6.7	1.50	6.	26.	14.8	16.0	0.3	6.9
SYMI	507.	.30	7.55	5.7	2.00	21.	203.	14.3	18.0	1.8	19.9
TILOS	84.	.35	7.79	7.0	2.00	12.	31.	15.8	11.2	3.9	14.0
HALKI	72.	.29	8.58	7.0	2.00	8.	25.	15.8	12.0	4.6	11.6
KALYMNOS	11300.	.45	5.25	7.5	2.00	678.	0.	20.6	2.2	0.0	0.0
ASTYPALEA	235.	.34	5.71	8.2	1.80	26.	74.	18.4	14.7	7.7	6.6
LIPSI	135.	.26	7.93	7.0	2.00	9.	49.	15.8	13.7	4.8	14.0
NISYROS	170.	.34	7.40	7.0	2.00	24.	52.	15.8	11.4	3.9	14.2
PATMOS	760.	.38	6.47	7.0	2.00	75.	278.	15.8	13.2	4.0	14.0
LESROS	17300.	.46	5.63	6.7	1.60	750.	0.	3.2	0.0	0.0	0.0
HIOS	13800.	.43	6.64	6.7	1.50	340.	0.	3.2	0.0	0.0	0.0
FOARA	240.	.25	9.70	7.6	1.80	24.	96.	17.1	13.8	7.5	6.1
SAMOS	7800.	.55	5.57	6.6	2.00	300.	0.	3.2	0.0	0.0	0.0
IKARIA	1380.	.26	6.91	7.0	2.00	48.	505.	15.8	16.1	6.8	10.1
FOURNI	210.	.32	7.14	6.8	2.00	24.	77.	15.8	12.1	3.9	35.9
SYROS	10000.	.44	2.62	7.7	1.80	240.	3120.	19.6	17.9	7.0	16.1
AMORGOS	250.	.31	7.89	7.7	1.70	30.	38.	17.3	13.3	7.7	5.4
THIRA	2450.	.35	6.15	7.7	1.50	210.	904.	17.1	15.8	6.0	9.4
IOS	850.	.25	6.78	7.7	2.00	24.	365.	14.3	25.9	9.9	12.2
HYDROS	3450.	.39	5.50	8.2	2.00	120.	1566.	14.1	31.5	15.2	7.9
PAROS-NAXOS	6700.	.38	5.58	8.2	2.00	225.	1455.	17.5	11.5	1.6	25.1
SIRINOS	95.	.27	7.94	7.7	2.00	12.	19.	17.4	8.4	4.3	5.3
FOLEGANDROS	125.	.24	7.54	7.7	1.50	30.	25.	20.9	3.1	1.2	11.0
ANAFI	48.	.31	10.78	7.7	1.50	12.	14.	17.1	7.2	1.1	10.0
AG. EFSTR.	96.	.26	6.89	8.2	1.70	12.	30.	18.4	11.4	3.6	3.4
AGISTRI	285.	.24	6.01	8.2	1.70	26.	95.	18.4	11.4	3.0	9.9
ANDROS	5400.	.38	2.65	7.3	1.80	600.	0.	3.2	0.0	0.0	0.0
REA	540.	.33	6.67	6.1	1.50	45.	134.	16.4	6.8	1.1	14.9
KYTHNOS	525.	.26	5.85	9.0	1.50	45.	197.	17.6	13.8	5.0	11.7
LIKHOS	3400.	.39	5.56	5.8	1.50	300.	636.	19.7	9.0	1.1	31.7
MILOS	2050.	.35	7.24	7.7	1.50	150.	673.	17.1	14.5	3.3	9.0
SERIFOS	440.	.25	7.92	7.7	1.60	24.	132.	17.2	13.3	3.0	9.0
SIFNOS	720.	.35	6.30	7.7	1.60	45.	316.	17.2	15.9	7.9	9.0
KRITI	110536.	.55	3.96	8.2	1.50	22172.	51513.	19.1	11.7	7.0	8.0

Table A2.2.4

Minimum Diesel Station Load= 0

OPTIMAL WIND POWER ALLOCATION PROGRAM

DISCOUNT RATE 10.0/0
 MAINTENANCE COST 3.0 0/0
 LIFE YEARS 20
 SPEC. TURB. COST 250. POUNDS/H2 SWEEP AREA
 AIR DENSITY 1.225 KG/M3
 RATED POWER COEF. .40
 RATED GEAR. EFF. .75
 REL. CUT-IN SPEED .40
 REL. FURL. SPEED 3.00
 HUB HEIGHT 30.0 M

LOCATION	FEED	LOAD FACT	FUEL COST	W AVER.	PARAM. K	MIN. POWER	POPT	VOPT	FUEL SAVE	NET SAVE	PAY-BACK
	KW		P/KWH	M/S		ΔW	KW	M/S	0/0	0/0	YEARS
SKYROS	970.	.43	5.50	7.3	1.40	0.	512.	15.9	23.6	11.3	7.7
SAMOTHRAKI	530.	.32	6.34	5.3	1.50	0.	0.	3.2	0.0	0.0	0.0
KEFALLINIA	8400.	.40	2.86	3.8	1.50	0.	0.	3.2	0.0	0.0	0.0
SAKYNTHOS	7500.	.35	5.98	7.7	1.50	0.	3362.	17.1	22.5	12.7	5.8
PAXI	720.	.32	5.97	4.7	1.50	0.	0.	3.2	0.0	0.0	0.0
OTIMONI	56.	.32	3.34	4.7	1.50	0.	0.	3.2	0.0	0.0	0.0
ERIKOUSA	34.	.21	7.55	4.2	1.50	0.	0.	3.2	0.0	0.0	0.0
RBOS	33434.	.50	3.34	6.7	1.40	0.	9561.	17.8	7.7	1.2	41.6
KASOS	235.	.34	6.24	7.7	1.50	0.	112.	17.1	23.3	13.7	5.2
KARPATHOS	1400.	.36	5.47	7.7	1.50	0.	755.	17.4	23.1	12.6	5.0
HEGISTRI	70.	.35	9.20	6.7	1.50	0.	42.	14.4	17.0	13.5	7.3
SYMI	507.	.30	7.35	6.7	2.00	0.	185.	15.0	17.7	11.1	11.5
TILOS	84.	.33	7.73	7.0	2.00	0.	30.	15.7	19.2	11.3	5.1
HALKI	72.	.29	8.58	7.0	2.00	0.	26.	13.5	24.2	11.5	3.1
KALYMNOS	11300.	.45	2.65	7.5	2.00	0.	3526.	18.0	10.5	.8	33.2
ASTYPALFA	235.	.34	5.71	8.2	1.80	0.	109.	13.8	34.7	15.2	9.4
LIPSI	135.	.26	7.93	7.0	2.00	0.	41.	15.8	16.1	8.1	7.2
NISSYROS	170.	.34	7.40	7.0	2.00	0.	41.	15.7	19.1	11.2	5.2
PATHOS	760.	.35	6.47	7.0	2.00	0.	325.	13.0	38.6	9.8	14.0
LESBOS	17300.	.46	2.53	6.7	1.40	0.	0.	0.	0.0	0.0	0.0
HIOS	13800.	.42	2.64	6.7	1.50	0.	0.	0.	0.0	0.0	0.0
PSARA	240.	.25	9.70	7.6	1.30	0.	111.	13.9	34.7	15.2	9.3
SAMOS	7800.	.53	3.57	6.6	2.00	0.	0.	0.	0.0	0.0	0.0
IKARIA	1380.	.36	5.91	7.0	2.00	0.	466.	13.4	23.0	8.8	11.8
FOURNI	210.	.32	7.14	6.8	2.00	0.	64.	15.3	16.2	9.1	7.7
SYROS	10000.	.44	2.62	7.7	1.80	0.	3483.	17.4	14.7	2.4	37.8
AMORGOS	250.	.31	7.89	7.7	1.70	0.	116.	13.2	33.7	16.0	9.1
ITHRA	2450.	.35	3.15	7.7	1.50	0.	1470.	17.1	25.8	11.5	12.2
IGS	350.	.28	8.78	7.7	2.00	0.	305.	17.3	19.2	11.2	5.3
MYKONOS	3450.	.39	5.30	8.2	2.00	0.	1783.	14.1	36.4	17.8	7.7
SAROS-NAXOS	6700.	.38	3.50	8.2	2.00	0.	1891.	18.5	13.2	3.4	21.5
SIKINOS	95.	.27	7.34	7.7	2.00	0.	45.	15.7	26.5	13.7	5.5
FOLEGANDROS	125.	.24	7.54	7.7	1.50	0.	50.	17.1	21.1	11.3	5.0
ANAFI	48.	.31	10.78	7.7	1.50	0.	20.	14.9	23.8	21.3	1.9
AG. EFSTR.	86.	.26	8.23	8.2	1.70	0.	43.	14.4	23.9	17.2	7.1
AGISTRI	285.	.24	8.01	8.2	1.70	0.	138.	16.5	26.7	10.6	11.1
ANDROS	5400.	.38	2.55	7.3	1.80	0.	0.	0.	0.0	0.0	0.0
KEA	340.	.33	6.67	6.1	1.50	0.	164.	16.4	2.5	3.9	10.7
KYTHNOS	525.	.26	5.95	8.0	1.50	0.	170.	17.6	19.7	10.3	6.7
LIMNOS	3400.	.39	5.26	5.8	1.50	0.	714.	15.8	7.7	2.4	16.4
MILOS	2050.	.33	5.24	7.7	1.50	0.	902.	13.1	20.7	10.9	8.6
SERIFOS	440.	.33	5.92	7.7	1.60	0.	175.	15.7	20.2	9.5	8.6
SIFNOS	790.	.32	6.30	7.7	1.60	0.	141.	17.0	21.6	11.6	6.6
NAITI	110538.	.35	3.95	8.2	1.50	0.	79190.	19.6	22.4	12.7	6.6

APPENDIX 3.1

System parameter values used in the simulation examplesDiesel engine

Rated power : 100 kW

Governor set point : 75% of rated power

Maximum output point: 110% rated power

Rated speed: 1500 rpm

Droop: 4% of rated speed

Governor dead band: 0.3% of rated speed

Control and fueling time constant: 50 ms

Combustion system time constant : 400 ms

Inertia : 12 Nms^2

Friction losses : 5% of rated power at rated speed

Shaft torsional stiffness 300 kNm/rad

Synchronous diesel generator

Rated power : 125 kVa

Rated power factor : 0.8 lag

Minimum output power : 50% of rated real power

Maximum output power : 110% of rated real power

Minimum reactive power output : -50 kVar

Maximum reactive power output : 80 kVar

Armature resistance : 0.02 p.u.

Direct-axis synchronous reactance : 1.0 p.u.

Quadrature-axis synchronous reactance : 0.65

Direct-axis transient reactance : 0.35 p.u.

Direct-axis open circuit transient time constant : 1.0 sec.

Maximum instantaneous current : 2.5 p.u.

Inertia time constant : 400 ms

Friction, windage and core losses : 3% of rated real power

Number of poles : 4

Excitation system

Minimum excitation voltage : 0.3 p.u.

Maximum excitation voltage : 50 p.u.

Voltage regulator time constant : 10 ms

Amplifier gain : 200

Amplifier time constant : 20 ms

Exciter gain : 1

Exciter time constant : 1.3 sec.

Stabilizer gain : 0.03

Stabilizer time constant : 1 sec

Induction generator

Rated real power : 125 kW

Stator resistance : 0.02 p.u.

Stator reactance : 0.12 p.u.

Magnetizing reactance : 30 p.u.

Rotor resistance : 0.03 p.u.

Rotor reactance : 0.12 p.u.

Inertia time constant : 0.4 sec

Friction, windage and core losses : 3% of rated power

Shaft torsional stiffness : 302.7 KNm/rad

Number of poles : 8

Static capacitor

Rated reactive power/phase in Δ : 17.5 kVAr

TCR and dump load

TCR transformer rated power : 50 kVa

Transformer reactance : 0.10 p.u.

Transformer ratio : 415:240 Volts

Dump load resistance : 2.03 Ohms

Gear box

Transmission ratio : 19.32

First stage inertia : 140 Nms²

Second stage inertia : 0.375 Nms²

First stage friction constant: 107 Nm/rads⁻¹

Second stage friction constant : 0.29 Nm/rads⁻¹

Wind turbine

Diameter : 38 m

Inertia (rotor + hub) : 128 kNms²

Friction constant : 215 Nm/rads⁻¹

Shaft torsional stiffness : 22600 kNm/rad

Minimum pitch angle : 0 degrees

Maximum pitch angle : 40 degrees

Rated speed : 40 rpm

Base values

Base power : 125 kVA

Base voltage : 415 V

Base frequency : 50 Hz

Operational limits

Voltage : $\pm 10\%$

Frequency : 48-52 Hz

Accuracies

Voltage : 0.05%

Frequency : 0.05%

Power : 0.05%

Angle : 0.5 degrees

APPENDIX 3.2

Description of routines in the simulation program DYTEST

The routine STEADY in the main body checks first if the steady state windspeed is in the operational region of the WECS (above cut-in and below furling speed. If it is not, calls the subroutine DIESST which determines the steady state with only the diesel set in operation and the WECS off. If the WECS is operational, the maximum real power available from the WECS for the given wind speed is calculated. If it is sufficient to cover the load demand plus losses, the subroutine WECSST is called which determines the steady state with the WECS supplying all real power and the diesel generator operated as synchronous capacitor with the diesel engine off. If the WECS maximum output for the given wind speed is not sufficient to cover the load demand plus losses or if the subroutine WECSST fails to locate an operational point not violating operation constraints, the subroutine PARAST is called which determines the steady state optimal operation with the WECS and the diesel set supplying the load demand in parallel.

In the case where the real load steady state conditions imposed cannot be met by the system (an obvious case being the real load demand exceeding the diesel set plus WECS capacity), the routine exits with failure message. If other constraints are violated (e.g. voltage limits) the routine still calculates the operational point meeting the constraints as far as possible and exits with a warning that steady state operational limits are violated.

A flow chart diagram for STEADY is shown in Fig A3.1

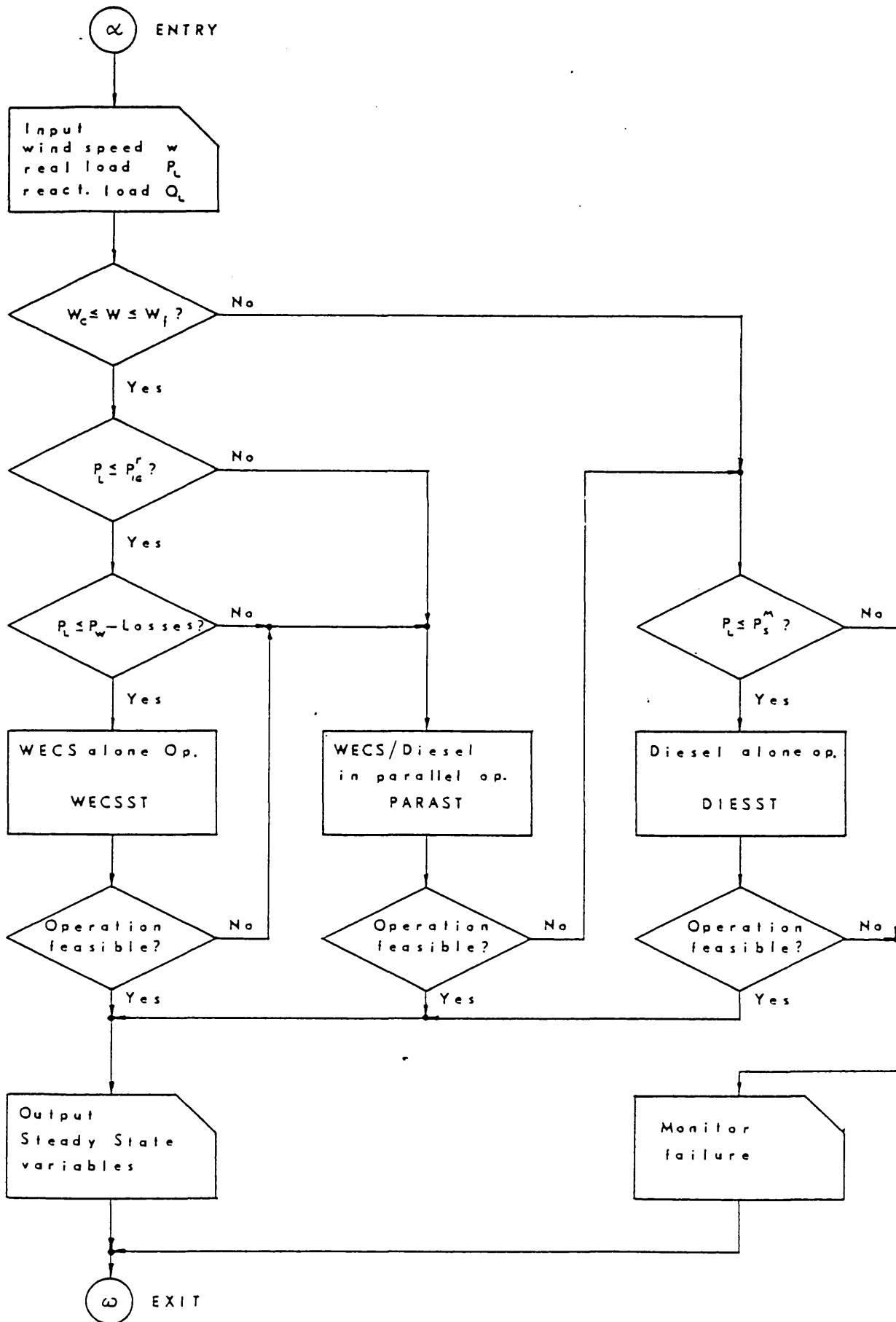


Fig. A3.1 Subroutine STEADY (WECS/Diesel Steady State Optimization)
Flow Chart

The subroutine DYNAM checks at the end of each integration step for emergency conditions defined in separate logical functions by the user in order to initiate switching operations which are:

- a. Wind turbine start up/shut down
- b. Diesel engine clutching/declutching
- c. Static capacitance switch up/switch down

If there are any switching operations the electrical network equations are solved for the new conditions (the state variables are of course kept constant).

The integration routine must be supplied with a subroutine (FCN) calculating the derivatives of the state variables, which are functions of the state variables themselves (either explicitly or implicitly through the electrical network equations) and time. The electrical network must be solved at the end of each internal step before calculating the derivatives to be used for prediction/correction to the next step.

If the user wishes, a subroutine calculating the Jacobian matrix of the system can be supplied otherwise the elements of the Jacobian are calculated numerically. In the present program the explicit calculation of the Jacobian has been omitted as cumbersome and prone to analytical errors. Care must be taken for the change of structure in the system of D.E. in FCN when the system transfers from one operational mode to the other after switching actions in DYNAM.

A flow chart diagram for DYNAM is shown in Fig. A5.2.

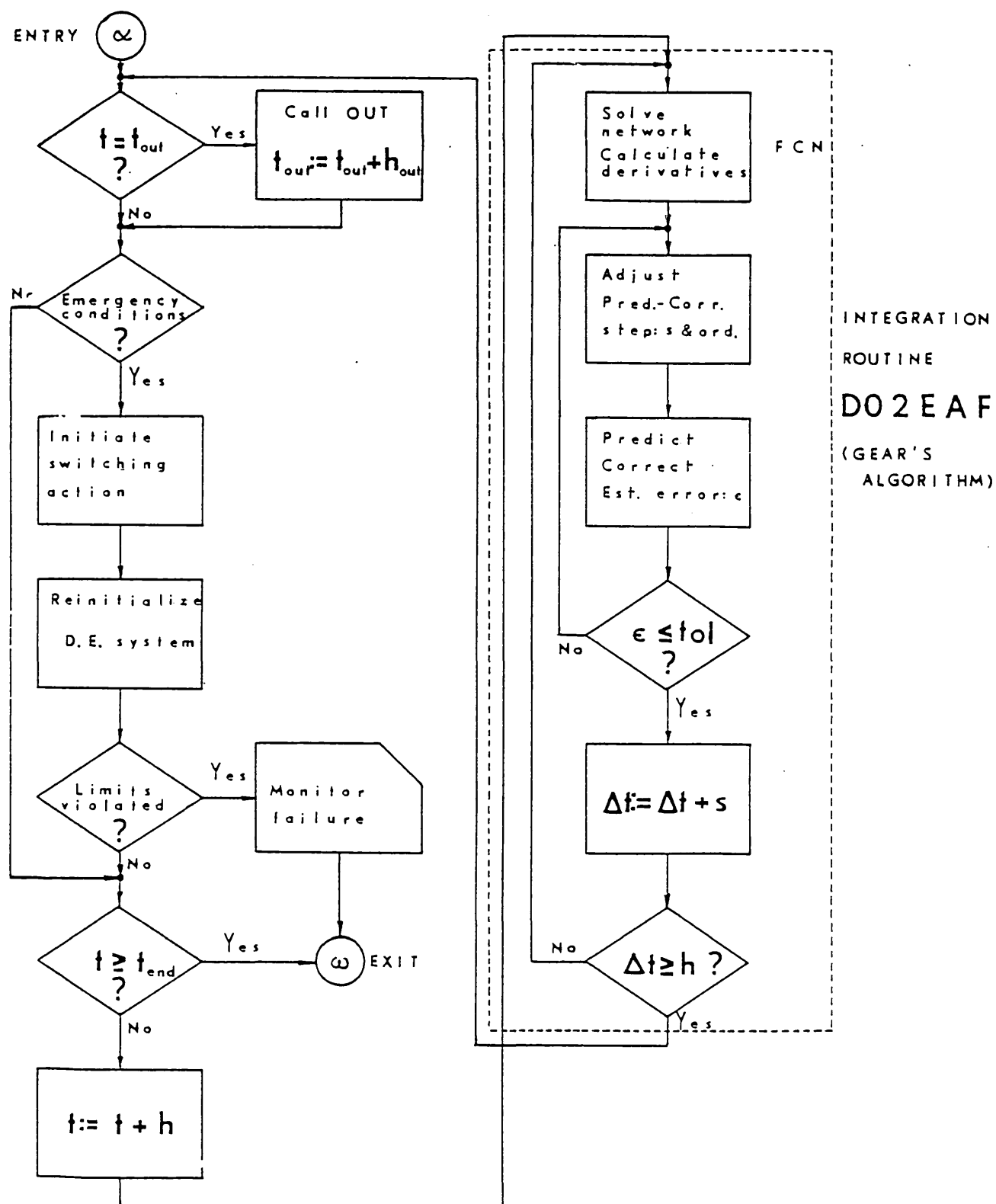


Fig. A3.2 Subroutine DYNAM (WECS/Diesel Dynamics Simulation)
 Flow Chart

APPENDIX 3.3

Eigenvalue and participation matrix tables

In all cases the the eigenvalue table on the left refers to the controlled system and the table on the right to the uncontrolled system.

State variables index in the participation matrix

1. Turbine speed
2. Turbine shaft angle
3. Gear box speed
4. Gear box angle
5. Induction generator speed
6. Induction generator shaft angle
7. Induction generator transient voltage (real part)
8. Induction generator transient voltage (imag. part)
9. Synchronous speed
10. Synchronuous generator shaft angle
11. Transient excitation voltage
12. Voltage regulator output
13. Excitation amplifier output
14. Field voltage
15. Exciter stabilizer output
16. Diesel machine speed
17. Diesel machine shaft angle
18. Diesel machine power
19. Diesel machine speed governor output

20.(16.) TCR firing angle

21.(17.) Blade pitch angle

In the case of WECS alone operation where the systems order is reduced by the four state variables 16-19 referring to the diesel engine, the control state variables 20-21 are referred to with the order number 16-17 respectively.

Table A3.3.3

1STEADY STATE

REAL LOAD= .800 PU
 REACTIVE LOAD= .300 PU
 WIND SPEED= 13.0 M/S

WECS SUPPLIES ALONE ALL REAL LOAD
 DIESEL GENERATOR OPERATED AS SYNCHRONOUS CAPACITOR

PARAMETER VALUES

REAL LOAD= .799 PU
 REACTIVE LOAD= .399 PU
 VOLTAGE= .999 PU
 FREQUENCY= 1.0000 PU
 DIESEL REAL POWER= -.042 PU
 DIESEL REACTIVE POWER= .731 PU
 EXCITATION VOLTAGE= 1.731 PU
 POWER ANGLE= -2. DEGREES
 REAL DUMP LOAD= .073 PU
 REACTIVE DUMP LOAD= .159 PU
 SCR FIRING ANGLE= 33. DEGREES
 INDUCTION GENERATOR REAL POWER= .915 P.U.
 INDUCTION GENERATOR REACTIVE POWER= -.562 P.U.
 CAPACITOR SWITCH FACTOR= 2.0
 STATIC CAPACITIVE POWER= .359 PU
 WIND SPEED= 13.0 M/S
 WIND TURBINE POWER= 1.059 PU
 BLADE PITCH ANGLE= 14. DEGREES
 NUMBER OF ITERATIONS FOR LAST CASE= 233

MATRIX EIGENVALUES ARE:

	REAL PART	IMAG. PART	MAGNITUDE	REAL PART	IMAG. PART	MAGNITUDE
1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2	-0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	-0.12232	0.00000	0.12232	-0.12232	0.00000	0.12232
4	-0.29713	0.00000	0.29713	-0.31905	0.00000	0.31905
5	-0.35967	1.29569	1.45395	-0.39609	0.00000	0.39609
6	-0.35967	-1.29569	1.45395	-0.39609	0.00000	0.39609
7	-7.03033	0.00000	7.03033	-27.66050	0.00000	27.66050
8	-22.46134	0.00000	22.46134	-44.31329	0.00000	44.31329
9	-31.60527	0.00000	31.60527	-32.11806	31.73763	45.15330
10	-44.31329	0.00000	44.31329	-32.11806	-31.73763	45.15330
11	-1.38488	46.38813	46.38813	-15.03290	46.18217	48.56729
12	-1.38488	-46.38813	46.38813	-15.03290	-46.18217	48.56729
13	-32.24015	37.38482	49.74623	-100.00000	0.00000	100.00000
14	-32.24015	-37.38482	49.74623	-94.554	707.04733	707.04796
15	-100.00000	0.00000	100.00000	-94.554	-707.04733	707.04796
16	-0.77275	707.05102	707.05144			
17	-0.77275	-707.05102	707.05144			

MAGNITUDE OF PARTICIPATION MATRIX

	1	2	3	4	5	6	7	8	9	10	11	13	15	16
1	0.00	0.00	0.00	0.00	.54	0.00	0.00	0.00	0.00	0.00	.04	.02	0.00	0.00
2	0.00	0.00	0.00	0.00	.50	0.00	0.00	0.00	0.00	0.00	.04	.02	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.48
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.48
5	0.00	0.00	0.00	0.00	.27	0.00	.02	.08	0.00	.34	.23	0.00	.02	
6	0.00	1.00	0.00	0.00	.51	0.00	.07	.07	0.00	.46	.27	0.00	.02	
7	0.00	0.00	0.00	0.00	0.00	0.00	.30	.51	0.00	.01	.11	0.00	0.00	
8	0.00	0.00	0.00	0.00	0.00	0.00	.02	.05	0.00	.12	.70	0.00	0.00	
9	0.00	0.00	0.00	0.00	.14	0.00	.09	.13	0.00	.34	.72	0.00	0.00	
10	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
11	0.00	0.00	0.00	.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	
13	0.00	0.00	0.00	0.00	0.00	.15	0.00	0.00	1.14	0.00	0.00	0.00	0.00	
14	0.00	0.00	.39	0.00	0.00	.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
15	0.00	0.00	.10	0.00	0.00	1.04	0.00	0.00	.14	0.00	0.00	0.00	0.00	
16	0.00	0.00	0.00	0.00	.01	0.00	.34	.23	0.00	.24	.09	0.00	0.00	
17	0.00	0.00	0.00	.01	.50	0.00	.01	0.00	0.00	.01	0.00	0.00	0.00	

APPENDIX 5.1

Rectangular window, 'extended matrix', recursive, univariate, estimation/
prediction algorithm

Definitions and assumptions:

Window width N samples

Model order n ($n < N$)

Prediction for k steps

State vector sequence $\{\bar{x}(t)\}$

Innovations (error) sequence $\{\varepsilon(t)\}$

Model parameter vector $\bar{\theta}$

Inverse covariance matrix sequence $\{P(t)\}$

Gain vector sequence $\{\bar{K}(t)\}$

Output sequence $\{y(t)\}$

For the predictive algorithm with input sequence only white noise
the process model assumed is:

$$y(t) = \frac{C(q^{-1})}{A(q^{-1})} \varepsilon(t)$$

with

$$C(q^{-1}) = 1 + c_1 q^{-1} + \dots + c_n q^{-n}$$

$$A(q^{-1}) = 1 + a_1 q^{-1} + \dots + a_n q^{-n}$$

or

$$y(t) = \bar{x}^T(t) \cdot \bar{\theta} + \varepsilon(t)$$

with

$$\bar{x}^T(t) = [-y(t-1), \dots, -y(t-n), \varepsilon(t.1), \dots, \varepsilon(t.n)]$$

$$\bar{\theta}^T = [a_1, \dots, a_n, c_1, \dots, c_n].$$

In the following $\hat{v}$ means estimated value of the variable v .

Algorithm description:

A. Initialization

1. Set initial output sequence $\{y(-1), y(-2), \dots, y(-N-n)\}$
2. Set initial estimated error sequence $\{\hat{\varepsilon}(-1), \hat{\varepsilon}(-2), \dots, \hat{\varepsilon}(-N-n)\}$
3. Set initial estimated parameter vector $\hat{\theta}(0)$
4. Set initial inverse covariance matrix $P(0)$
5. Set $\hat{x}^T(i) = [y(i-1), \dots, y(i-n), \hat{\varepsilon}(i-1), \dots, \hat{\varepsilon}(i-n)]$ ($i=0, -1, \dots, -N$)
6. Set initial estimated error variance $\hat{\sigma}^2(0) = \sum_{i=1}^N [\hat{\varepsilon}(-i)]^2 / N$

B. Recursive estimation updating

7. Read observation $y(t)$
8. Update estimated error

$$\hat{\varepsilon}(t) = y(t) - \hat{x}^T(t) \cdot \hat{\theta}(t)$$

9. Update estimated state vector

$$\hat{x}^T(t+1) = [y(t), \dots, y(t-n+1), \hat{\varepsilon}(t), \dots, \hat{\varepsilon}(t-n+1)]$$

10. Calculate $\bar{r} = P(t) \hat{x}(t+1)$

$$s = 1 + \hat{x}^T(t+1) \bar{r}$$

11. Update gain vector

$$\bar{K}(t+1) = \bar{r}/s$$

12. Update inverse covariance matrix

$$P(t+1) = (I - \frac{\bar{r}x^T(t+1)}{s})P(t)$$

13. Update estimated parameter vector

$$\hat{\theta}(t+1) = \hat{\theta}(t) + \bar{K}(t+1)\hat{\epsilon}(t)$$

14. Update estimated error variance

$$\hat{\sigma}^2(t+1) = \hat{\sigma}^2(t) + [\hat{\epsilon}(t)]^2$$

C. Prediction

15. Calculate coefficients f_m ($m=1, \dots, k-1$; $f_0 = 1$) recursively

$$f_m = \hat{c}_m - \sum_{i=1}^{m-1} \hat{a}_{m-i} f_i$$

16. Calculate coefficients $g_{p,r}$ ($p = 0, \dots, n-1$; $r = 1, \dots, k$)

$$g_{p,r} = \hat{c}_{r+p} - \sum_{i=0}^{r-1} \hat{a}_{r+p-i} f_i$$

with $\hat{c}_{n+j} = \hat{a}_{n+j} = 0$ for $j > 0$

17. Calculate predicted values $\hat{y}(t+r|t)$ ($r = 1, \dots, k$)

$$\hat{y}(t+r|t) = - \sum_{i=1}^n \hat{c}_i \hat{y}(t+r-i|t-i) + \sum_{i=0}^{n-1} g_{i,r} y(t-i)$$

18. Calculate prediction error variance $v(t+r|t)$ ($r = 1, \dots, k$) recursively

$$v(t+r|t) = v(t+r-1|t) + \hat{\sigma}^2(t) \cdot f_{r-1}^2$$

with $v(t|t) = 0, \quad f_0 = 1.$

- D. Calculate adjustment; Rejection of oldest stored value

19. Calculate $\bar{h} = P(t+1)\hat{x}(t-N)$

$$m = 1 - \hat{x}^T(t-N)\bar{h}$$

20. Assign $\bar{K}(t+1) = \bar{h}/m$

$$\text{Assign } P(t+1) \Leftarrow (I + \bar{h}\hat{x}^T(t-N)/m) \cdot P(t+1)$$

$$\text{Assign } \hat{\theta}(t+1) \Leftarrow \hat{\theta}(t+1) - \bar{K}(t+1)[y(t-N) - \hat{x}^T(t-N)\hat{\theta}(t+1)]$$

$$\text{Assign } \hat{\sigma}^2(t+1) \Leftarrow \hat{\sigma}^2(t) - [\hat{\epsilon}(t-N)]^2$$

21. Assign $t \Leftarrow t+1$

Go to step 7.

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