Commission of the European Communities

WIND-DIESEL AND WIND AUTONOMOUS ENERGY SYSTEMS

Edited by
H. NACFAIRE

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Proceedings of a contractors' meeting on wind demonstration projects, organised by the Commission of the European Communities, Directorate-General for Energy, held in Mykonos, Greece, 25–26 April 1988

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PREFACE

The present publication gives an overview of Community Demonstration projects on "Autonomous and wind-diesel systems" presented during a meeting organised on Mykonos Island, Greece, on 25 and 26 April 1988 for the contractors involved in demonstration projects supported by the Commission of the European Communities ("CEC").

The meeting was held with the collaboration of the Public Power Corporation ("PPC"). It was attended by 55 participants from 9 member states, including representatives of most public utilities of the European Community.

The objectives of the meeting were to:

- assess the state of advancement of the projects, aiming at wind-diesel systems (including projects where wind turbines are connected to a diesel-based grid) and autonomous systems;
- share the experience gained by contractors;
- favorise a possible cooperation between manufacturers;
- inform the utilities of the state of the art;
- stimulate the replication of successful projects;
- visit the wind turbine in Mykonos.

The meeting was opened by Mr A Kravaritis (Deputy Director General of PPC) who referred to the existing plans to install 18 MW of various size WTs within the European Community programmes. Dr M Davis, Director in the Directorate-General for Energy, CEC, welcomed the participants on behalf of the Commission.

Presentations were made on 17 projects. Besides the papers presented on the projects, interesting information was presented on the establishment of wind/diesel plants other than those of CEC projects. There were also presentations by three invited speakers.

The first speaker, Professor N H Lipman, presented a paper on "Overview of wind-diesel activities" The second speaker, Dr G Cramer, presented a paper on "Control and load management systems on wind power plants connected to diesel based grids" and the third speaker, Mr S.E. Andreasen, described the experience gained from the realisation of a wind diesel project in China (a project financed by the Directorate-General for Development of the CEC.

Throughout the meeting, particular attention was given to successful cooperations between utilities, manufacturers and users. The audience's interest was proven by lively discussions with useful exchanges of ideas.

Many valuable and useful conclusions have been drawn, most of which are mentioned at the end of this publication.

I take this opportunity to thank all participants and the Greek organisations for their support and their contributions to the success of this meeting.

H. NACFAIRE
Coordinator for Wind Energy
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OVERVIEW OF WIND/DIESEL SYSTEMS

N.H. Lipman
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SUMMARY

This overview is made up of three main elements:

1) A look at the main design questions for wind/diesel systems. The criteria affecting design choices for the diesel sets, wind turbines and energy stores are looked at briefly.

2) Examples of current Research and Development and Demonstration projects are given, ranging from small supplies of a few kW to large systems up to 1MW.

3) There is a separate discussion of the largest systems (multi-megawatt) which include a number of diesel sets on an isolated grid, and which permit "multiple-diesel strategies" to be operated.

1. INTRODUCTION

I wish to thank Mr Michael Davis and members of the DGXVII directorate for inviting me to speak at the seminar on "Autonomous Wind/Diesel Systems". My instructions have been very clear and rather daunting: "cover a wide range of systems and scenarios and try to highlight the advantages and disadvantages of each one". Well I'm not sure that I can achieve this ambitious requirement, but I will attempt to cover a fair part of the field and will try to bring out some of the more important arguments.

The first thing that became apparent as I started to address this task is that there is a very extensive world-wide activity in this area. At the EWEA's 1986 Conference "EWEC 86 "(part sponsored by the CEC) there were some 20 papers on wind/diesel R & D. Two recent workshops on the subject took place in May and June 1987, at Dartmouth College near Boston, USA and at Rutherford Appleton Laboratory (RAL) near Oxford, UK, respectively. (The RAL workshop report which contains 15 papers is now available from BWEA). I have drawn on the papers from these 3 events and on the experience of my own research unit in preparing this report.

Let me start by putting the many types of W/D projects into a number of main categories. Even this is a difficult exercise as some projects may combine several different control and operation principles. For example there are projects containing both load control and flywheel storage. Others include "multiple diesel" strategies plus battery storage. Nonetheless, I will define a number of strategic principles. The fact that a "strategy" is required arises from the highly fluctuating nature of the wind; also from rapid changes in power requirements within small electricity networks. Thus a wind power station may be fully supplying an "autonomous" load at one moment and may be in considerable power deficit only seconds later. Hence the need for some magic formula such as wind and diesel. We now know that a simple diesel back-up may not suffice!

Some of the strategies that are being tried out in pilot studies in many parts of the world are listed below in table 1.

Table 1 Wind/diesel strategies

Main Strategy	Subset	Comments	Example
1) Load control	a)At domestic level	a)Frequency Switches	Lundy Isle,UK
	b)Major loads switched	b)Water pumps	Cape Verde(CWD)
	c)Desalination	c)Part day requirement	Fura Ventura (new proposal)
2) Long term store	a)battery	a)allow diesel start/stop	Cape Clear,Eire
	b)pumped hydro	b)allow diesel start/stop	Foula,Scotland
	c)battery/cylic diesel	c)Diesel cycles at max load	Canada
3) Short term store	a)Hydraulic/ pneumatic	a)5 mins for turbulence	Reading Univ,UK
	b)Flywheel	b)Few mins for turbulence	Imp College/RAL,UK
4) Hybrid systems	a)Load control/ flywheel	a)reduces cycling of load control	Fair Isle,Scotland
	b)Battery store/ flywheel store	b)flywheel for rapid diesel starts	Cape Verde (RISO)
5) Multiple diesel	a)Large Island grids	a)Can optimise loading of diesels	Shetland,Scotland
	b)with storage	b)Improve loading optimisation	Kythnos,Greece

In section 3 I will look at examples of several of these strategies in a little more detail. It should be noted that no two projects are exactly the same. Hence there are very many different strategies being tried out, world-wide, if we choose to look in a little more detail.

2. GENERAL CONSIDERATIONS

Before looking at the specifics of any one strategy I would like to ask some more general questions about what one is trying to achieve in setting up demonstration autonomous wind systems. What are the underlying principles in the design of such systems, and where may we hope to improve on this first cycle of studies and projects.

2.1 Diesel Power Systems, Single or Multiple Diesel

When we talk about "autonomous wind/diesel systems" we may be talking about anything from a 10kW wind turbine operated in conjunction with a 5kW diesel electric set, up to several 1MW single wind turbines being introduced into a 30MW island grid. The problems at these two extremes are so very very different that it is difficult to cover both in one short (30 minutes) paper. The larger systems have several advantages as far as ease of operating strategy is concerned, with respect to very small wind/diesel systems:

a) A large system will have a multiplicity of diesel generating sets, and hence running strategies can be adjusted (stopping or starting diesels) to minimise fuel consumption and to maximise the benefits from the wind power. (however there are limits to this flexibility as large supercharged diesels cannot be started and stopped too frequently or too rapidly.

b) Large loads representing 100's or 1000's of households vary in a much smoother way than very small loads.

c) In the case of multi-megawatt grids we are likely to be introducing a number of wind turbines. If these are geographically separated then they will provide a useful smoothing of wind power fluctuations when compared to a single wind turbine. In short time periods of seconds up to minutes (depending in the degree of separation) the reduction in power fluctuations will go as $\sqrt{N}$, where N is the number of wind turbines (W.T.'s)

For the reasons stated above we need to treat large autonomous diesel grids in a very different manner from the small systems, on which many of us are working.

I define a small system as lying in the size range from 10kW to about 200kW of diesel power. Such a system will probably have only 1 or 2 diesel electric sets and we will be introducing only 1 or 2 W.T.'s into the system. For most of the paper I will be dealing with these smaller systems which have a small number of generating components. The interesting and exciting challenge which we must meet with regard to such systems is how can we devise schemes that can provide very substantial diesel fuel saving (e.g. 30% to 60%), and yet must at the same time be both technically simple and reliable and economically viable. It is interesting at this moment, to stand back a little to examine the merits and demerits of the many schemes that, are currently being tried out in a wide range of imaginative projects.

2.2 The sizing of Diesel Generators

Frequently when we talk about autonomous wind power systems we are dealing with the introduction of wind power to an existing diesel grid. Our first calculations will show how much diesel fuel can be saved when compared to the fuel being burnt in the existing system.

I believe that WE MUST BE VERY CAREFUL here. The original diesel generator may be very much oversized, as is frequently the case. Small diesel systems (e.g. 10kW to 200 kW) are likely to be faced with highly variable and spiky loads. For example the peak load may be as high as 5 times the average load (see Bass and Twidell, 1986). It is not uncommon for the designers of the systems to have chosen a diesel with a capacity of 2 times the peak load (see Dure, 1985), to provide a safely margin and room for future expansion of the load. Such a diesel operation on its own (without wind power) will produce extremely costly electricity. This is apparent if we look at a typical small diesel efficiency curve, as in figure 1. Note that at zero load the diesel still burns about 1/3 of maximum fuel. Furthermore it is not recommended to run diesels for any length of time at small loads and normally a minimum loading of 30% is suggested to avoid bore glazing, oiling up of the silencer and other problems. If this advice is taken seriously and we operated a remote diesel power station at a strict minimum load of 30%, then it would be necessary to incorporate a controllable dump load in the system. Studies (Harrap, 1987) examining the economics of small diesel power supplies suggest electricity costs of the order of 90c/kWh for the situation described above.

Evidently, we would wish to avoid such an extreme situation. Yet in the real world it is not uncommon to find single grossly oversized diesels as in the case above. The practical reality is that there would be no computer controlled dump load, but the operators would probably run the diesel for less than the whole 24 hours, and would endeavour to switch on sufficient loads, whether actually required or not, to give the diesel a reasonable loading.

It is very difficult to quantify the true benefits of a new wind/diesel system which is added (e.g. by way of a "Demonstration Programme") onto a very unsatisfactory diesel network as described above. Yet such unsatisfactory diesel operation is very common in isolated applications around the world.

Now along comes the wind energy engineer with a wind turbine, a storage medium and a micro-processor controller. Recognising that the original diesel generator was grossly oversized he now introduces a smaller diesel which will work in tandem with the wind turbine and the store, to meet the load. Such a situation with and without wind energy has been examined by Harrap (1). He considers a wind/diesel system with battery storage. Whereas, the original diesel is sized at 10x average load, he now replaces this with a diesel sized at 2x average load. One option that he examines is to ignore the wind power and to use the battery/inverter system to improve diesel efficiency. In this way the load demand pattern assumed in the study is met without ever running the original (oversized) diesel generator. The results of this study suggest the cost of electricity produced by the diesel-battery system is likely to be 40% lower than that produced by the diesel-only system. In fact such systems, working along similar lines, are sold commercially in Canada, Australia and elsewhere. They may be referred to as "cyclic charging systems". Usually the diesel is run at full output to recharge the batteries and is then turned off. An alternative mode in which the batteries would be used for peak lopping might also be of interest.

The point that I wish to make here is that the wind/diesel engineer is making a useful contribution to the "isolated community" in devising improved strategies for the operation of the local diesel network. I suggest that he should examine carefully the relative benefits that are achieved by intelligent control strategy of the diesel network and those that are provided by the inclusion of the wind power.

I am not suggesting that the windpower cannot provide considerable economic benefit in its own right. I am sure that it can. But in fairness to the customer we should examine the two stage process:

a) The benefits provided by a newly optimised diesel network with intelligent control.

b) Additional benefits provided by wind power.

2.3 Wind turbine choices and sizing

There are a number of tricky decisions to be made with regard to the design choices for the wind turbine. These include some of the following:

a) Size relative to the diesel set(s) and relative to the load. For high penetration of wind power (e.g. 50%) the wind turbine rating may typically be twice the diesel rating, given that a typical W.T. load factor would be about 30%.

b) Some workers argue in favour of several smaller wind turbines (e.g. 30kW) rather than one larger wind turbine (e.g. 150kW) in a single installation, to make use of the short timescale smoothing effect (see Cramer, 1987).

c) There are arguments both ways in favour of a synchronous generator or induction generator on the wind turbine. The induction generator has the difficulty that it requires an external source of reactive power. On the other hand synchronisation to the diesel grid is much simpler, and dynamic interactions with the grid are less of a problem. The synchronous generator has the advantage of being self-energising, on the other hand it represents a "stiffer" source of AC power and synchronisation and stability problems can be encountered. A majority of projects use induction generators in conjunction with a continually spinning synchronous generator on the A.C. line to provide reactive power. This is usually the generator on one of the diesel sets which disconnects (via a clutch link) from the diesel, when this is stopped.

I would point out that the price that we must pay for adopting such a scheme will be the continuous spinning losses of the synchronous generator, which are quite large, e.g. 700 watts for a 7kW generator (Bleijs, private communication).

d) Finally there is the question of power shedding. If there is excess wind power and the storage is full then wind power must be shed in some way. There are several approaches to this problem.

(i) Some groups make use of a dump load; e.g. the Imperial College/RAL team (see Coonick et al, 1987).

(ii) Another approach is to permit the W.T. to overspeed thus activating a passive pitch control mechanism (see de Bonte and Costa, 1987)

(iii) A third approach is to have a rapid action pitch control on the W.T. This is the method used by Cramer et al. (see Cramer, 1987).

It is not possible to say which of these 3 methods will be most cost effective, without careful examination of the details of each project. Active pitch control tends to be expensive and is not usually favoured for small machines for this reason. Passive pitch control is quite common and well accepted. The power limiting approach of de Bonte and Costa requires additional equipment, namely an AC-DC-AC link, which is also expensive. Yet this scheme does include an additional benefit that some of the excess wind power is converted into additional kinetic energy in the W.T. rotor (which overspeeds). This represents a few seconds of stored energy which is helpful in dealing with short term downward fluctuations of wind power. The dump load approach of Imperial College/RAL also has its advantages and disadvantages. A dump load can be costly, although the design adopted by Imperial/RAL has cut this cost quite a lot. An advantage is that power dumping leads to quite a simple control strategy, and it can also be used to provide a minimum loading of the diesel. This "dumping control philosophy" also permits some of the excess wind power to be used, in practice, in auxiliary loads such as water heaters, etc, as local conditions permit.

2.4 Choice of energy store

There are very many complex issues relating to the several choices of energy storage listed in table 1. I will not attempt to discuss these in any detail in this section, but some points will come up as I discuss individual projects in the final section. Very briefly some of the questions that we must ask are as follows:-

1) Is the energy store providing only a strategic benefit or can it also save on fuel usage in its own right.

2) What is the efficiency of the store (in/out losses), and are the losses dependant on the rate of power flow.

3) Does the store have a continuous standing loss (e.g. continuously spinning machinery).

4) Does the store have a finite lifetime (e.g. batteries will take a certain number of charge/discharge cycles).

5) Does the store have a limit on the charge/discharge rates (e.g. batteries).

6) What are the likely maintenance requirements and costs.

7) Is the system of a complexity that can be handled in very remote areas.

8) Finally and most important, what is the cost of the store including all associated equipment.

Let me make one general remark on storage, as it relates to wind energy, before I go on to the third section of this paper. It is important that we consider the time structure of wind turbine output. If we look at a spectral analysis of wind speed, as presented by Van der Hoven in 1957 (see fig. 2) we see that wind turbulence comes in two main frequency domains. There is a high frequency turbulence (10 to 1000 cycles/hour) which causes us great difficulty in maintaining a short term steadiness of electricity supply. Secondly there is a turbulence in times from about 5 hours to 200 hours, corresponding to movements of weather fronts. This latter is less trouble to us, as it requires only relatively slow control decisions with regard to the operation of the various components of the autonomous electricity system. Those projects that opt for a short term store (e.g. flywheel, hydraulics, etc) are tackling the problem of the high frequency turbulence and are accepting the principle that there will need to be a fair amount of supply switching (wind or diesel, etc) in times of hours. The longer term stores may carry additional benefits of fuel saving, if they can bridge between periods of high and low wind. However, to achieve these benefits the costs must be acceptable and in/out efficiencies sufficiently high. I would be interested to see an analysis showing whether it is cost effective to go to these much longer storage times.

In fairness, I must also challenge the short term storage strategies. These provide the benefit of cutting down start/stop cycling of the diesel to less than once per hour. They also provide bridging power whilst the diesel is being restarted (see Coonick et al, 1987, Slack and Musgrove, 1987 and Bullock and Musgrove, 1987). What remains to be proven is that such systems will be reliable and can be built at a cost which does not spoil the economics of wind/diesel. I believe that the answer to these questions is in the positive, but it is still too early to say, as all of these short term storage projects are still at an early development and demonstration stage.

3. EXAMPLES OF SPECIFIC PROJECTS

In the time available it will not be possible to discuss in detail all of the different types of strategy listed in Table 1. Nor will I be able to do justice to the many excellent projects currently underway in each general category. Nonetheless, I will try to give an impression, if fairly brief, of some of the major initiatives in the wind/diesel area.

3.1.1 Load Control Schemes - Domestic Level

An early approach to autonomous wind diesel strategy was made by Mr Murray Sommerville (see Sommerville and Stevenson, 1984 and 1986) who worked for International Research and Development, and is now a Director of Wind Harvester. He has set up 3 systems, on off-shore islands of U.K and Ireland, in the years 1980 to 1982. These systems on Fair Isle, Lundy and Inis Oirr, differ in some details but are all designed to certain underlying principles.

A diagram of the Fair Isle system is shown in figure 3. A 55kW windmatic design wind turbine is combined with diesels of 50kW and 20kW into a small island electricity network. The basic control strategy is to go for load switching. Mr Sommerville's scheme has 3 priorities of load.

i) The top priority load which is made up of "high quality" domestic loads including lighting and electrical equipment (T.V., radios, hi-fi, etc).

ii) Load group 2 which would be a lower quality uses of electricity, including water heating and storage heaters.

iii) Load group 3 which is essentially a dump load, but can include low priority requirements such as swimming pool heating, etc.

The loads 2 and 3 can be brought-in in a graduated manner, this being accomplished by frequency sensing switches. These switches are installed into every house and are set at a range of different thresholds. The sizing of the wind turbine was such that for much of the time its output was well in excess of the priority load (load 1). Load 2 and possibly load 3 will then take up the excess wind power; the diesel generators being stopped for much of the time. The wind turbine speeds up or slows down slightly as input wind power increases/decreases, the frequency switches bringing loads in or out very rapidly. If the wind power drops too low to meet the priority load (load 1) then one of the diesels is brought on and takes over this load. The supply of the priority load was only guaranteed for 2 periods each day (e.g. 7am to 9am and 4pm to 11pm) although the scheduling may have changed by now. A tariff structure was adopted to encourage the use of wind electricity (when available). As reported in 1983 (see Infield and Puddy, 1983) the tariff structure for Lundy was 7p, 3p and 2p for diesel, wind priority 1, and wind priority 2, respectively.

Progress reports from these projects indicate that they have run very successfully and that wind power has supplied more than 75% of the loads. Let me give a view on the advantages and disadvantages of such an approach, as I have been asked to do.

Advantages	Possible disadvantages
-A simple and robust scheme	-Does frequent switching damage appliances
-No storage medium required	-Tailoring to each specific island may prove too costly in engineers time
-Most of W.T. output utilised	-Not all islands may have sufficient number of low priority loads
-Diesel running greatly reduced	-The low priority loads use electricity to a much lower worth
-Users get a better service than ever before	

3.1.2 Load Control Schemes - Switching of Major Loads

I will look very briefly at the other approach to load control, namely that of using several large lumped loads. Such a scheme has been built by the Dutch CWD group (Consulting Services Wind Energy Developing Countries) at Terefal on Cape Verde and was reported on at the RAL wind/diesel workshop (see de Bonte and Costa, 1987)

A schematic diagram of the system is shown in figure 4 a windturbine has been added to a grid that was originally supplied by a 175kW diesel electric set. This was grossly oversized, as the maximum load was some 45 kW. Electricity supply was provided for two short periods each day as is shown in the load diagram of figure 4b. The original diesel would have been running very inefficiently.

In the CWD scheme a new 70kW diesel generator set was brought in to replace the original oversized set. The wind turbine in the new system is described as "conservatively sized" and is rated at 30kW. Studies at CWD had shown that there was little benefit to having a larger wind turbine, as a diesel start/stop strategy was not to be adopted in this initial pilot project (see fig 4b).

In addition to the original island load, there were 3 additional loads of 11kW each coming from 3 large water pumping stations, each of which had to be run for about 8 hours per day. A much improved load profile is achieved in the new scheme by incorporating the 3 pumps into the island load, as in fig 4d, rather than having them running, rather inefficiently, each on its own diesel (as had been the case previously).

The authors estimated that there would be a saving of just under 1/3 in fuel (i.e. 30,000 litres per year), ignoring load strategies with the water pumps, but this saving becomes some 70,000 litres per year including the water pumps in the operating strategy.

My own conclusion would be that we see again the benefits of load management and a sensible re-optimisation of a remote diesel grid. It would seem to me that the wind energy engineers are having their main impact in achieving this. The benefits from the wind energy, itself. are probably quite small and may not even be economic.

Advantages

-A simple approach with real benefits
-Control strategy simple to execute
-Lumped secondary loads used to good effect

Disadvantages/Uncertainties

-Continuous running of diesel implies minimum impact of wind power
-Wind energy contribution probably about 10%
-Would it be simpler to ignore the wind power altogether and concentrate on load management?

3.2 Long Term Storage

Here I will take the case of battery storage in small to medium sized systems. There are many such projects in Europe and around the world. Groups active in the field include Linders et al (1987) at Chalmers University, Sweden, and Lundsager et al (1987) at the Riso test station. Gunther Cramer, who collaborates with Thomas Schott at the DEVLR Test Station in Germany, gave an excellent review of this type of system at the 1987 RAL workshop (see Cramer, 1987 and also Schott et al, 1987). A schematic diagram of the systems that the latter collaboration built and installed on the Irish Island of Cape Clear is shown in figure 5.

A completely new system has been installed including a 72kW diesel electric set, two 30kW wind turbines and a battery store of 100kWh, plus associated two way inverter (120kW). Starting from scratch, and ignoring the old generating system, it has been possible to design a well optimised system. The battery has two purposes:

a) To back up the wind turbines when the diesel is stopped.

b) For peak lopping when the diesel is running on its own and a load power spike in the load exceeds the diesel rated output.

Cramer in his 1987 paper does not indicate what level of fuel savings are to be expected with this newly installed system. However, I would comment that in my judgement the component sizes are well matched. I would expect a possible fuel saving of about 30%. Let me make a few technical comments.

a) This collaboration generally favours two smaller W.T's rather than one larger machine, because of the smoothing effect that can be achieved.

b) They favour active pitch control on the W.T's as a way of controlling output power; hence reducing the need for rapid action dump loads.

c) The diesel set and its synchronous generator can be decoupled by way of a clutch. The generator is kept spinning when the diesel is stopped in order to provide reactive power to the rest of the system. However, this does imply fairly large standing losses. (Most wind/diesel & battery schemes incorporate a similar rotating condenser arrangement.)

d) I note that the battery storage is unusually small (compared to most similar projects) with only 30 minutes of storage at maximum invertor rating. This surprises me as most lead-acid batteries have their lifetime shortened and their storage capacity greatly reduced when charge/discharge times are much shorter than 10 hours (Lucas batteries, private communication, 1988). Perhaps the average power flow in the system is much lower at about 30 kW, in which case the battery storage would correspond to 2 hours (which is still short for lead acid batteries).

Finally I note that elsewhere the authors talk about "rugged and low cost invertors" and of "special batteries". Both of these factors could be very significant, as otherwise the capital cost of a battery invertor system would seem to me to be potentially very high, and might make such systems too expensive for wind/diesel projects, other than those funded by demonstration programmes!

Several years ago in a joint paper with Reading University, we estimated an in/out storage cost for batteries (because of their finite lifetime) of 5p/kWh stored! More recently Michael Harrap has provided me with a figure from his work of 8p/kWh stored. These figures do not include the costs of buying or operating the invertors. Hence I deduce that if a substantial part of the wind power had to be processed in the battery then the cost of "wind electricity" is likely to exceed 10p/kWh.

I have indicated some possible uncertainties, mainly economic, with regard to the battery-inverter approach to wind/diesel systems. I will finish by giving a list of advantages and disadvantages.

Advantages

- Batteries & invertors are a well proven technology
- Additional benefit of peak lopping for diesel operation
- Larger battery systems can bridge between windy and less windy periods

Disadvantages/Uncertainties

- battery & invertor costs may be very high
- batteries have finite lifetime & need some care and maintenance
- Invertors can give harmonic distortion to electricity supply
- some types of invertor can fail in catastrophic manner
- standing losses from "rotating condenser"

3.3 Short term stores

In this area I know of two main activities. The first is work on a hydraulic- pneumatic store which is being carried out by Dr Peter Musgrove team at Reading University. The second is work on flywheel stores, where several teams are active, but where probably the most extensive such programme involves my own team (RAL) working in conjunction with Imperial College and two UK companies (Laing ETE and Hawker Siddeley Power Plant).

3.3.1 The hydraulic-pneumatic store

Two papers at the RAL workshop described this work (Bullock and Musgrove 1987, Slack and Musgrove, 1987). A schematic of the system is shown in figure 6a. This diagram does not show a back-up diesel generator, but there would normally be one in the system. A hydraulic pump/motor is coupled to the electrical power line by way of its own synchronous generator. This is spinning all of the time and may be decoupled from the hydraulic pump/motor at times when this is not in use. The synchronous generator does represent a standing loss, but it can be used as a rotating condenser if an induction generator type W.T. is in the system. Energy storage is in one or several hydraulic-pneumatic accumulators. These devices contain compressed nitrogen gas which acts up on the hydraulic fluid in a separation bladder. Several minutes of storage can be achieved in such systems at an acceptable cost. The storage units available commercially are limited in size (approximately 10-15KW/min) including the back-up storage bottle so that it will often be necessary to stack several in parallel for larger wind/diesel systems. Similarly the pneumatic pump/motors are only available up to a size of 100kW, so again it may be necessary to stack several units in parallel. Hence it would seem to me most likely that this approach will find its best application for the smaller sizes of wind diesel systems, perhaps up to 100kW diesel generator size.

Musgrove and his team have shown that there is considerable benefit to be had from the application of such a short term energy store (see figs 6b and 6c). We see in fig 6b that such a store will bring diesel start/stop cycles down to acceptable levels of about 10 per day. Fuel saving is considerably improved compared to a system with no storage, as we see in figure 6c, graph (a). In fact fuel savings of 50% or 60% are not out of the question for good windy sites. Let me now list the pros and cons as I see them:

Advantages

- -hydraulics is a well established technology
- -short term store can produce desired benefits
- -costs are likely to be acceptable
- -application looks good for small systems
- -possible use for peak lopping when only diesel is running!

Disadvantages

- -hydraulics can be troublesome
- -question of maintenance on remote sites
- -standing losses from synchronous generator and also from hydraulic motor when running
- -in/out losses fairly high e.g. 35% to 60%

Let me finish my remarking that in-out losses are probably not very important for a short term storage strategy as not much of the wind energy is cycled through the energy store.

3.3.2 Flywheel energy store

The flywheel is much older than the steam engine and is used in many applications including the motor car. Two UK companies, Laing ETE, and British Petroleum have been developing higher technology high energy density flywheel stores for special applications. My own experience is with the Laing ETE flywheel which I will discuss in a little more detail. The application to wind/diesel systems is an ongoing programme involving the Energy Research Unit at RAL, the Power Engineering Group under Dr Leon Freris, at Imperial College, and two UK companies, Laing ETE and Hawker Siddeley Power Plant. Apart from a considerable amount of theoretical work, on both system stability and optimisation of logistic control, we also have an experimental programme on a fully operating wind/diesel/flywheel rig. The system is shown schematically in figure 7a and 7b and a photograph of the rig is shown in figure 8.

This system has been operated successfully in a fully autonomous mode since October 1987. A considerable amount of experimental work has been carried out to investigate possible modes of instability and to monitor fuel saving and start/stop cycling. The companies involved are now working on the design of a commercial version of the diesel/flywheel rig which it is hoped can be coupled electrically as an add-on package, to a wide variety of commercial wind turbines.

Our theoretical work leads us to very similar conclusions to those of Musgrove et al. For example our estimates of annual fuel saving are shown in figure 9. We find, as Musgrove does, that fuel savings of 50% to 60% per annum can be achieved, for energy storage of just a few minutes. Our theoretical predictions on start/stop rates are very similar to Musgrove's. (for more details see Coonick et al, 1987 and Lipman et al, 1986).

An important consideration here, as in all cases, must be the standing losses, as the flywheel plus generator are rotating all of the time! In fact the diesel and the flywheel share the one synchronous generator, which minimises losses from this component. (i.e. the generator would be turning anyway when the diesel is running). When the diesel is stopped, the synchronous generator, whilst spinning with the flywheel, will serve a second purpose of acting as a rotating condenser for those cases where the wind turbine has an induction generator. In this respect we will be in a similar situation as regards losses to practically all of the projects discussed in this review paper.

It follows that the only additional standing loss singular to this storage approach will be the losses of the flywheel itself from windage, bearings and gearbox. Windage is very small as the flywheel operates in an evacuated chamber. Bearing and gearbox losses are expected to be small compared to the losses in the synchronous generator.

Finally, it would be fair to comment that although the approach looks very promising, and is likely to be cost effective, flywheels with many kilowatt-hours of storage are not in common use and will need great care in design and manufacture if they are to be reliable over many years of operation. Let me summarise the pros and cons.

Advantages	Disadvantages/Queries
-A simple and robust scheme	
-Flywheels are a well known and well tried technology	-killowatt hours of storage not yet well proven
-Short term store can produce desired benefits	-question of maintenance in very remote areas?
-Costs look very promising	-standing losses from continuously spinning synch. generator (but as in most other projects)
-Applications over a wide range of sizes (kW to Mw)	
-Possible use for peak lopping with respect to diesel	-simple scheme of fig 7 requires network frequency excursions of ±5Hz
-Standing losses of flywheel not high	
-in/out efficiency high	

3.4 Hybrid Systems

In this section I will be very brief, simply highlighting the fact that combinations of several of the principles discussed above are now being tried.

3.4.1 Battery storage and flywheel

Per Lundsager has described an advanced wind diesel system which a Danish consortium including Bonus and Riso Laboratory are currently constructing at Santa Caterina on the Cape Verde Islands (see Lundsager, 1987). The outline is quite similar to the German/Irish project on Cape Clear. The battery storage is 66kWh as against the diesel size of 40kW and wind turbine size of 55kW. This means that the batteries provide about some 2 hours storage at typical loads. (still quite a short storage time