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

17th Meeting of Experts – Integrating Wind Turbines into Utility Power Systems

Herndon, Virginia, USA, April 11 - 12, 1989

Organized by:
Project Management for Biology, Energy, Ecology (BEO)
of the
Research Centre Jülich (KFA) on behalf of the
Federal Minister of Research and Technology,
the Fluid Mechanics Department
of the Technical University of Denmark

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M. Pedersen (Techn. Univ. of Denmark)
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INTRODUCTORY NOTE

INTEGRATING WIND TURBINES INTO UTILITY POWER SYSTEMS

Dan Ancona

Connecting wind turbines with existing utility power systems has been successfully accomplished in a variety of applications and configurations. However, concern exists that as the size and number of wind plants increases, power quality, voltage profiles, controls, system protection, operating strategies, and personnel safety could be adversely affected. There are a number of studies and wind plant field tests underway around the world from which data are being collected to address technical questions and further refine theoretical projections of effects of interconnection of variable power sources such as wind turbines with a utility power system.

It is the purpose of this meeting to determine areas where additional research is needed and to establish facts and document previous operational experience which can reduce concerns in the utility community about using wind generated power. The primary emphasis of this meeting and the planned research will be on issues relating to interconnecting wind power plants with existing electric utility systems. Two areas to be addressed are: (1) macro-scale issues involving controls, interconnection and operation with high penetration, and large numbers of wind turbines interconnected with large area networks; and (2) micro-scale issues relating to interface and control of individual or small clusters of wind turbines interfacing with local area networks. Emphasis will be on technical rather than economic issues.

Micro-scale issues involves determining the impacts of wind turbines, which are intermittent generating sources. At low penetration levels (ratio of operating wind plant capacity to overall system load), the operating problems should be small. However, the potential impacts on substation and other equipment increase with penetration. Portions of the subtransmission and distribution networks may be subject to overloading or counter flows which can result in reliability and voltage regulation problems. VAR support for the network could be an additional requirement. Such needs could be strongly influenced by the type of generators used in the wind turbines, the interconnection between systems, and the control equipment.

Macro-scale issues include large area control and system stability problems which may result from large penetrations. A primary concern is that individual wind turbines or wind turbine arrays will lack sufficient control to prevent the power they inject into the utility network from causing operational problems and significant deviations in crucial system variables such as frequency and voltage. Consequently, the burden of regulating frequency, voltage and line loading deviations produced by wind turbines will fall on conventional power generation regulating units. Moreover, if existing system operating constraints and power quality standards are to be maintained, the range of control adjustments which can be made by conventional procedures needs to be examined to determine limits on penetration of wind generation.

Degraded operating performance can be avoided by: limiting wind turbine penetration; or, at moderate penetration levels, modifying the utility's unit commitment program to schedule additional conventional regulating units which increases the ramp rate of control capability. These regulating units are more expensive to operate than the intermediate units they would displace. As operating problems become more acute this will require the development of more sophisticated operating control systems. In addition, large penetrations of wind generation could require additional spinning reserve and/or load curtailment agreements to account for the loss of wind generation in the event of a fault, storm front or sustained lull. The cost of resolving operating problems at the higher levels of wind turbine penetration will be weighed against the value of wind generation.

Specific discussion topics suggested for the expert meeting are:

1. Utility power quality criteria - with and without wind turbines.

2. Definitions of terms such as "penetration," "availability," and "spinning reserve."

3. Impact of wind generation on utility requirements for spinning reserve, unloadable generation, and regulating unit ramp rate.

4. Alternative strategies to mitigate the impact of wind generation on power systems, including:

   o Wind power system control strategies
   o New wind turbine generator designs
   o Short term storage
   o Integrated customer load control
   o Adoptive unit commitment strategy

GRID INTEGRATION OF DANISH WIND TURBINES

Poul Nielsen

1. Introduction.

In the recent years, there has been a rapid growth in the number of wind turbines connected to the Danish electricity supply system. As of 1st January 1989, the total number of all grid-connected wind turbines in Denmark was 2.050 units. The total electrical capacity was 190 MW. In 1988, the power production was about 290 GWh, and this corresponds to about 1.0% of the country's electricity consumption. As of 1st January 1988, the total number of grid-connected small-scale wind turbines in Denmark was 1630 units, and the total electrical capacity was 110 MW.

As a by-product of this technological advancement, a valuable collection of experiences has provided insight into many potential problems of linking wind turbines to electric utility systems. In some respects the Danish experience is similar to that of other countries regarding power quality problems, for instance. A more specific Danish problem would appear to be a topic such as how to handle "surplus power", and also one involving load-frequency control at high levels of wind power penetration. Therefore, an extensive study project on power grid integration was undertaken some years ago.

Some of the Danish wind turbines, e.g. the multi-bladed windroses, are not grid-connected. They are mainly used for heating or water pumping. Wind-diesel installations are not in common use, but some initial experimental units have been installed.

2. The Danish Electricity Supply System.

The Danish electricity supply is based almost completely on fossil-fuel thermal steam power stations. Many of these are combined heat and power stations producing heat for urban district heating and electricity for the public grid. The predominant fuel is coal in contrast to the years before the energy crises when it was oil.

Figure 1 shows the location of the various Danish power stations. The map also shows the interconnection lines to Norway, Sweden and West Germany. Through these transmission lines and cables the two Danish power systems are linked to the Norwegian and Swedish systems. There is no electrical connection across the Great Belt.

The Great Belt thus divides the country into two supply areas. In the western area seven power production companies collaborate within the utility association ELSAM. In the eastern area three power production companies collaborate within ELKRAFT Power Company Ltd. A total of 120 electric utilities are responsible for the electricity distribution in Denmark. 54 of these are owned and operated by municipalities, 54 are cooperatives or partnerships, 10 are private foundations and 2 are joint-stock companies.

The integration of the Scandinavian power grid into one interconnected grid is of great value in matching electricity production with demand. Short-term discrepencies between demand and production in Denmark are balanced out by the Norwegian and Swedish hydro power stations because hydro power responds quickly to load variations. Remaining discrepencies between demand and electricity production are corrected from Danish load dispatching centres by ordering the power stations to change their production rate. In this context in must be borne in mind that coal-fired steam power stations are relatively slow acting compared with oil-fired stations.

Table I summarizes the types of publicly owned generating plants in Denmark as of 1st January 1989. Privately owned wind turbines are not included.

Table I. Types of generating plants.

Type	Capacity	%
Steam	7.507 MW	95.6
Gasturbines	245 MW	3.1
Diesel	63 MW	0.8
Hydro	8 MW	0.1
Wind	28 MW	0.4
Total	7.851 MW	100.0

Several types of fuel can be used in the Danish power stations. Thus 79% of the production capacity can be fuelled either by coal or oil, 9% either by natural gas or coal/oil, 11% only by oil and 1% only by coal. (The figures refer to estimated installed capacity). Coal covered 94%, oil 4%, and natural gas the remaining 2% of the fuel used in 1988.

In Denmark heat and power are commonly produced in a combined process. Table II summarizes the key figures for production and consumption of electricity and district heating from power stations in 1988.

Tabel II. Production and Consumption.

Total continous electrical capacity	7.851 MW
Maximum net demand	5.789 MW
Net production of electricity	24.297 GWh
Net import from abroad	5.425 GWh
Purchase from autoproducers	298 GWh
Sales to consumers	27.963 GWh
Production of district heating	52.913 TJ
Total coal, oil and gas consumption	259.300 TJ

The district heating supply from power stations contributes up to about 50% of the total supply of district heating and about 20% of the total heating requirements in Denmark. Purchase from autoproducers by utilities includes about 248 GWh generated by private wind power plants.

According to 1988-prices, the fuel costs for typical conventional power stations were approximately 11 øre per kWh for both coal and heavy fuel oil (12 kr./GJ , 9 GJ/MWh).

Excluding taxation, the average electricity price as of 1st January 1989 for a Danish low-voltage customer consuming 3000 kWh per year was 43 øre per kWh, and the average subscription charge was 392 kr. per installation. The average production costs, respectively distribution costs, were 31.5 and 11.5 øre per kWh.

Note:

All calculations in this paper are performed in Danish kroners = 100 øre. At the time of writing, the exchange rate was: 1 US $ = 7.25 Danish kroners.

3. Accounting Rules for Wind Power Generation.

The first accounting rules for sales of electricity from grid-connected wind turbines to local electric utilities were set up in 1976 by the Association of Danish Electic Utilities. As of 1st October 1984 completely new rules with an agreed continuance of ten years came into force. Since then, the agreement has been currently revised, and the rates have also been updated. All prices quoted in this section are valid from January 1989.

According to the latest agreement between the electric utilities and the Danish Wind Power Association, the electric utilities buy wind-generated electricity at rates as specified in the following two cases, also illustrated in Figure 2 (single and joint ownership):

1. The surplus production from wind turbines placed as an internal component of the owner's installation is bought by the electric utility at a rate of 70% of the utility's net selling price to ordinary domestic consumers. (For installations prior to 1986. For later installations, the rules are more complicated).

2. Within a certain limit, all electricity produced by wind turbines connected to the public grid with a separate installation, and with all owners belonging to the same municipality, or living within a distance of 10 km from the wind turbine, is bought by the utility at a rate of 85% of the utility's net selling price to ordinary domestic consumers.

In both cases VAT and a special electricity tax are excluded, and the same applies to the administrative and metering costs (1.9 øre per kWh). With these items left out, the net selling price is 43 - 1.9 = 41.1 øre per kWh taken as an average for all Danish utilities. The buying rate is higher in case 2 than in case 1, because the utility in case 2 receives the revenue of a normal sale of electricity to the wind turbine owners.

The electricity tax is 32.5 øre per kWh on all electricity consumed domestically. Electricity generated by renewable energy sources is exempted from this taxation - whether or not it is temporarily "stored" in the public grid system. The exemption from the electricity tax is administrated by adding the value of the tax to the payment that owners of wind turbines receive for supplying wind-generated electricity to the grid.

Although this is the main principle, the "pay-back rate" of electricity tax is at present restricted to 23 ør per kWh. In both cases the VAT of the electricity tax is also added to the price of wind-generated electricity. (This applies to private installations. For mixed private/commercial installations, the rules are more complicated).

Disregarding the complicated cases, results of the above-mentioned accounting rules are as summarized below, and all prices they are average Danish utility prices.

Purchase (P) from local utility = selling price (production + distribution) + electricity tax + 22% VAT of preceeding items = 43 + 32.5 + (9.5 + 7.2) = 92.2 øre per kWh.

Sale (S) to local utility (single ownership) = selling price - administrative costs) x 70% + electricity tax + 22% VAT of electricty tax = (43 - 1.9) x 0.7 + 23 + 5.1 = 56.9 øre per kWh.

Sale (S) to local utility (joint ownership) = (selling price - administrative costs) x 85% + electricity tax + 22% VAT of electricity tax = (43 - 1.9) x 0.85 + 23 + 5.1 = 63.0 øre per kWh.

Electricity produced by wind turbines owned by electric utilities is not exempted from taxation, neither will electric utilities in the future receive any government subsidy for their installation. The same applies to municipalities. Private owners of wind turbines receive at present time a 10% government installation subsidy, and 35% of the grid-connection costs are reimbursed by the electric utilities with 377 kr per kW as an upper limit.

The government has further recommended that the electric utilites reject grid-connection of private wind turbines in cases where these are not eligible for the government installation subsidy.

4. Grid-Connection of Wind Turbines.

4.1. General Guidelines.

In 1976 the Association of Danish Electric Utilities (DEF) published a set of general guidelines for the connection of small-scale wind turbines to the utility grid system. The main conditions were as follows:

- Connection of private power-generating equipment must be reported to the local electric utility by an electrical contractor who is authorized to do so by the utility.

- The equipment must be designed in such a way that the wind turbine is automatically disconnected from the grid in cases of malfunctions, either on the utility grid or in the equipment itself.

- Permission to connect a wind turbine to the power grid is granted under the condition that no disturbance in the voltage of the power grid is caused by the equipment.

- A person must be assigned as responsible for the operation of the equipment. An agreement between this operator and the local electric utility must establish rules for the operation of the grid interface equipment.

- Members of the technical staff of the local electric utility may disconnect the power-generating equipment from the utility grid at any time, for instance, when maintenance or repair work on the grid is being carried out.

4.2. Power Quality Standards.

These guidelines have been followed up by more information from the Research Association of Danish Electric Utilities (DEFU), for instance regarding quality of power.

The effect of wind turbines on the distribution system (10 kV and below) depends on the deployment strategy, see Figure 3. Wind farms connected to 10 kV feeder lines or at substations affect the system in another way than small machines dispersed throughout the electric system. The effect may be voltage variations, fluctuations etc.

With few exceptions, Danish wind turbines are equipped with induction generators that are simple and reliable. The generator is connceted to the grid at the synchronous speed when the wind velocity is high enough. It is automatically disconnected when the power meter for some time has indicated that power is being absorbed from the grid.

In the early days, many on-off operations occured, but the present widespread use of dual-generator systems - and now also the introduction of pitch controlled wind turbines - has reduced the number of on-off operations to a more tolerable level. This is among other things done by introducing a hysteresis between the windspeeds at cut-in and cut-out.

When an induction generator is connected directly to the grid a high in-rush current occurs because an induction generator draws a magnetising current 5-8 times maximum continous rating. This may cause intolerable voltage changes. Figure 4 shows the present Danish power quality standard for the low-voltage level. For voltage changes between 10 and 100 changes per hour, the curve is identical with a well-known international power quality standard. For changes between 1 and 10 per hour, there is no international standard so the depicted curve is only a Danish standard.

Good voltage quality can be established in two ways - or in a combination. The first is to use thyristor inter-connection equipment which is capable of limiting the in-rush to the normal level at full power. In fact this equipment is now mandatory on all small-scale wind turbines in Denmark. The other solution is to reinforce the local utility network in order to reduce the system impedance.

In a distribution system with only a small number of dispersed grid-connected units, the influence of these on the 10 kV and low voltage systems can be neglected. If many units are deployed in a given area and connected to the same 10 kV feeder line, for instance sited in a windfarm, they may cause voltage disturbances both on the feeder line and the low voltage mains connected to the line. If the 10 kV voltage level is increased by more than 1%, it is normally necessary to increase the capacity of the 10 kV line in order to maintain the required voltage quality in the low voltage system. In the same way, the voltage increase in the low voltage mains from a wind turbine to the 10/0.4 kV substation should in general not be more than 2.5% (6 V). Otherwise, a reinforcement of the network would be required.

Wind farms may offset the voltage control system in 60/10 kV substations. This occurs if the voltage control system compensates for the voltage drop in the distribution system by using the current through the 60/10 kV transformer as an indication of the load level. This current measurement is, however, misleading if a wind farm is supplying power to the grid. In this case the output current from the farm should, therefore, be subtracted from the first mentioned current measurement.

The question of reactive power compensation also calls for attention. One way out of the problem is to install a capacitor battery in each wind turbine and to design and operate it in such a way that islanding situations would be of short duration and not accompanied by over-voltages. As a crude rule of thomb, each wind turbine in a wind farm should be provided with a capacitor battery dimensioned to compensate for the reactive power consumption at zero load. In addition, an adjustable capacitor battery can be connected to the common output lines from the windfarm and used for final compensation if the wind farm is connected to a separate feeder line.

4.3. Protection and Safety Requirements.

The main concern for the utilities is to avoid supply of power from a wind turbine to a portion of the system which is disconnected from the main system (islanding). This could lead to both personnel and material damage.

To avoid this risk of islanding, a frequency detection relay should disconnect the wind turbine from the grid if the frequency is outside the range of 47-51 Hz for more than 0.2

second. A voltage detection relay should disconnect the wind turbine if the voltage is outside the range of 207-242 volt for more than 1 minute, and within 0.5 second if the voltage exceeds 250 volt. Three phase measurements are presupposed.

If reactive power compensation is used harmfull overvoltages may quickly occur in islanding situations. Supposing 100% compensation at zero load, the capacitor battery should be switched off within 0.2 second if the voltage reaches 250 volt or the frequency is outside the range of 47-51 Hz. The turbine will be disconnected from the grid according to the above mentioned criteria.

As a general rule, automatic reclosing is normally allowed on distribution systems (10 kV lines) with a high percentage of temporary faults. (Automatic reclosing means that the 10 kV line is disconnected from the busbar for about 0.3 second). Danish grid interface equipment is usually designed in such a way that an automatic reclosing event automatically disconnects adjacent wind turbines from the grid due to lack of power supply to the relay system. Until recently, a manual reset action was needed to restart the turbines but today automatic equipment is provided so restart automatically follows after a time delay of approximately 15 minutes.

5. Power Integration Study.

As mentioned above, the existing Danish power generation system is characterized by a high degree of combined heat and power production. This sets limits on the possibilities of stopping co-production units; for instance during night hours in winter when the demand for heat is high while the demand for electricity is low. The amount of wind-generated electricity which cannot be absorbed by the power system, so-called "surplus energy", increases rapidly with the installed wind power capacity.

For this reason a simulation study was carried out in 1983, the aim of which was to identify the problems encountered at high levels of wind power penetration. A computer programme simulated the operation of the conventional power system supplemented with unpredictable elements of power production from an increasing number of wind turbines. The simulation programme calculated savings in operating costs and fuel expenses as well as the "surplus energy" generated by the wind power plants.

Calculations for the ELSAM-area (Jutland and Funen) at the expected 1987 stage showed that a wind energy contribution of, for example, 10% of the total electricity production would lead to an amount of "surplus energy" close to 15% of the total production of wind-generated electricity. The figures for the ELKRAFT-area (Zealand) were rather similar to these. The situation is anticipated to be more or less the same in 1995.

The simulation study also showed that even at low levels of wind power penetration "surplus energy" is to be anticipated on certain occasions. If this happens, either some wind turbines must be stopped or the electricity must be used for other purposes, for instance electrical heating. This solution presents no technical problems, only economic disadvantages.

Some Danish power stations have heat storage facilities, e.g. large water tanks with hot water to be used for district heating during peak load hours. By increasing the size of these storage facilities the amount of wind-generated "surplus energy" can be reduced. Again, the economy of such a scheme must be considered.

If Denmark had a considerable supply of hydro power from high dams, the problem of energy storage would be easier to solve as the water behind the dams effectively stores energy. The storage problem together with any problem of matching the production with the electricity demand may find its solution by keeping some quick-acting oil-fired power stations running. Alternatively, the present Scandinavian collaboration on electricity supply might be extended to take the existence of Danish wind power plants into account.

At present, a special study project addressing the control problem is in progress. The first step is to undertake a series of measurements of the short-term variations in the output power from wind farms. The aim is to determine to which degree these short-term variations are equalized when added together on the common grid system.

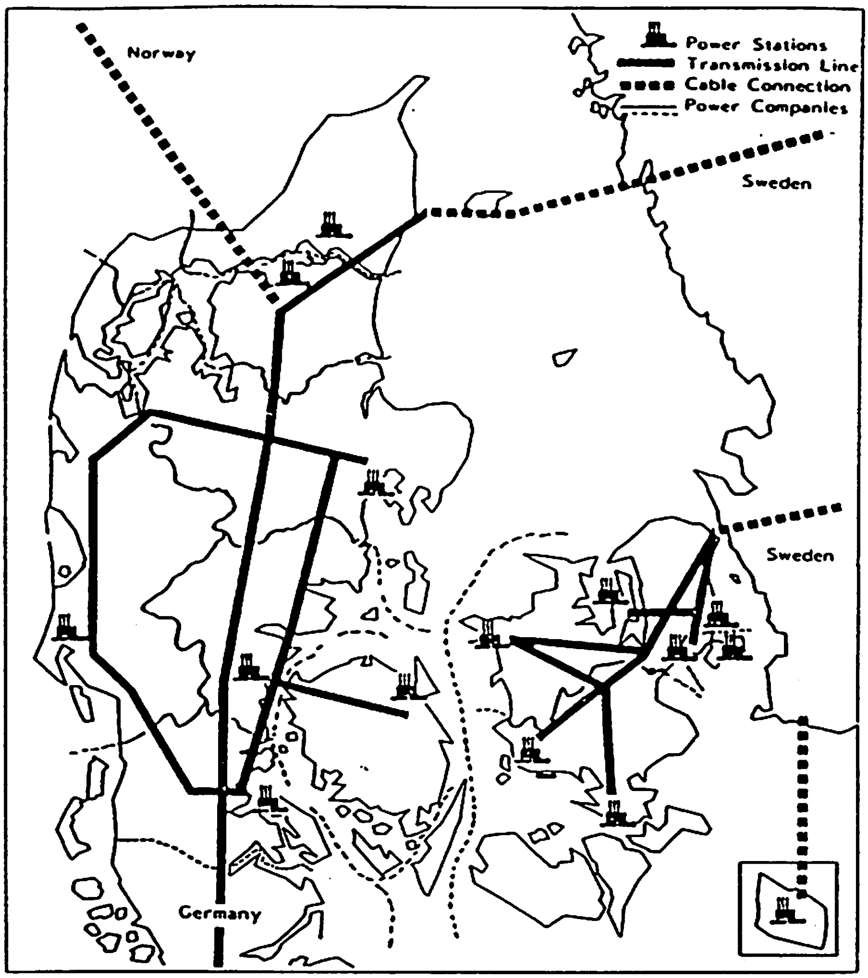
6. Wind-Diesel Project.

The electricity supply system on the small Danish island of Anholt is based exclusively on power from 3 diesel-generator units with an aggregate electrical capacity of 565 kW. Maximum demand in 1985 was close to 400 kW and total annual consumption about 1000 MWh. As of April 1986, the consumer price was 132.5 øre per kWh excluding electricity tax and VAT, and 197.6 øre per kWh including these two items.

A study project carred out in 1986 showed that a wind turbine with a capacity of 45 kW could supply 100 MWh to the grid per year, and thus annually substitute 20.000 l light fuel oil, without affecting the voltage quality on the island provided that proper interconnection equipment was installed.

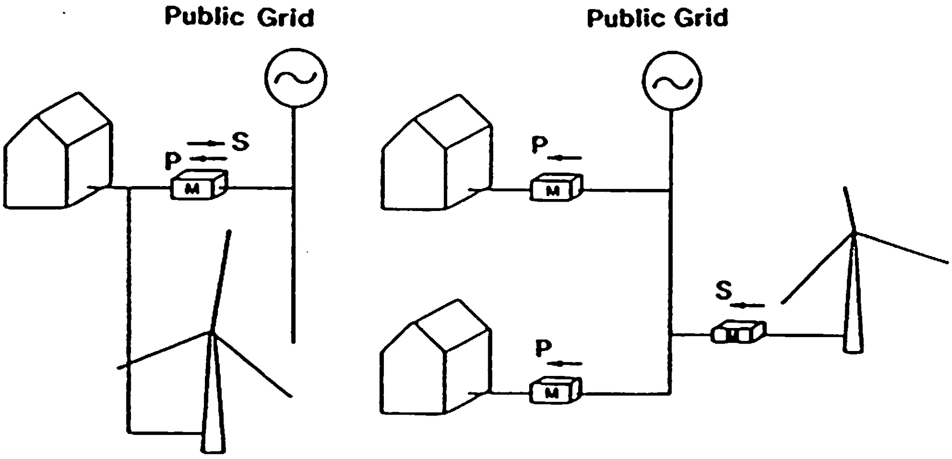
To avoid load-frequency problems, the actual output power from the wind turbine should never exceed about 50% of the total consumer demand. Otherwise, the diesel engines might not be able to control the grid frequency. On certain occasions this condition might have the effect that the wind turbine must be stopped even when wind speed allows it to generate eletricity. Without this restriction the wind turbine could, presumably, produce about 140 MWh per year.

The decision to proceed with the project, e.g. to install a wind turbine and implement an adequate measurement programme, has since 1986 been delayed for several reasons. The wind turbine was, however, installed in the beginning of 1989. The operational experience and the results of the measurements are now awaited.



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

Fig. 1. Main grid system in Denmark.



P : Purchase from Local Utility.
S : Sale to Local Utility.

Fig. 2. Single and joint ownership

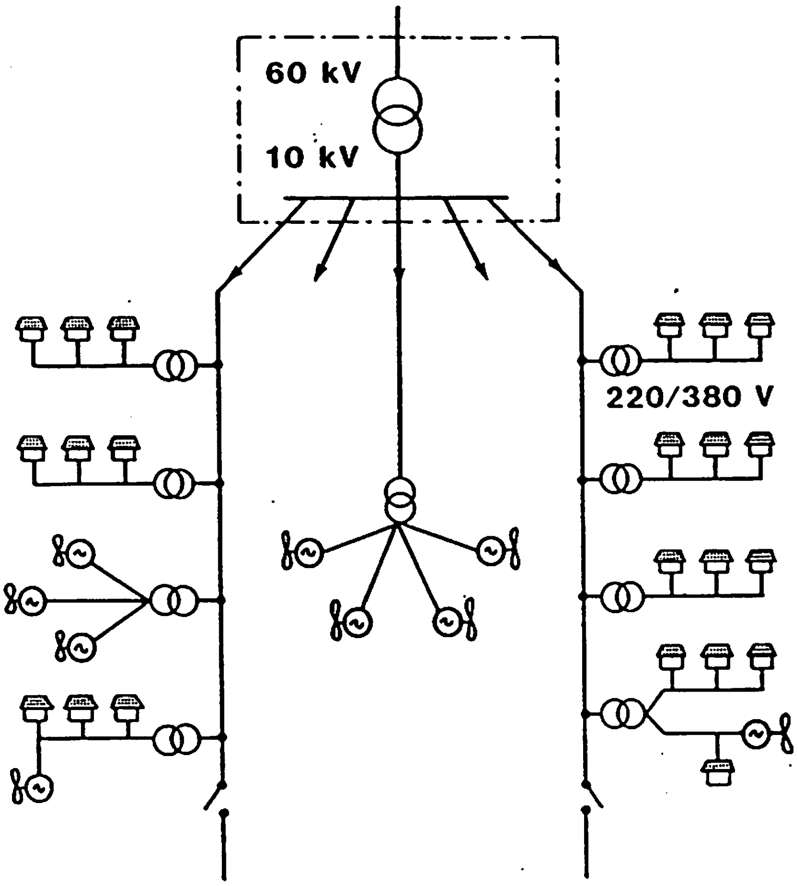


Fig. 3. 60/10 kV substation and distribution system with dispersed units and a wind farm.

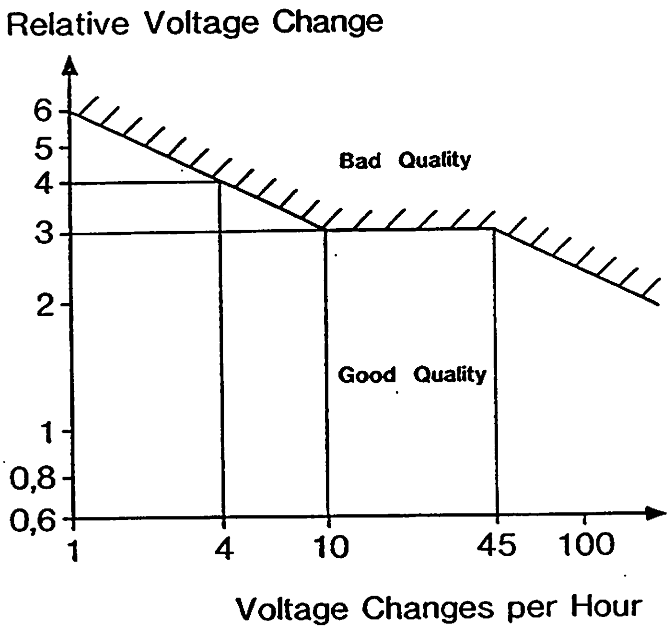


Figure 4. Power quality standard for the low voltage level.

INTEGRATION OF WIND POWER INTO EXISTING POWER SYSTEM

Trond Toftevaag

Rune Malmo

1. INTRODUCTION

The Norwegian power production system has an installed capacity of about 25 000 MW, 99,2% of which represent hydro plants. Average yearly hydro production is about 100 TWh. Total thermal capacity is approx. 200 MW. Wind- and wave-power is being developed in som areas, mainly for investigation and demonstration purposes. The contribution from these renewable resources will in the foreseeable future remain marginal.

The National Wind Energy Programme is run by the Norwegian Water Resources and Energy Administration (NVE). NVE is responsible for the national energy administration, and for advising the Norwegian government in energy policy questions. The annual budget for the programme has for the last four years been close to $ 1 mill.

The participants in this national programme are at present Institute for Energy Technology (IFE), Soer-Troendelag Kraftselskap, EB Energi (member of the ABB group), and the Norwegian Research Institute of Electricity Supply A/S (EFI). The main fields of activity are: wind measurements and site assessment methods, small-scale integration of wind turbines (WT) into the distribution network, and development of wind/diesel plants (autonomous systems).

2. THE NORWEGIAN APPROACH. A SURVEY.

Wind power, from a general point of view, has to be considered as a supplement to other electricity supply.

The contribution from wind, will be in the nature of casual generation, and this contribution will always substitute supply from the most expensive production plants otherwise in operation.

2.1 PROFITABILITY

The profitability of wind power development, is given by a cost/benefit analysis over the expected depreciation period for the plants. The costs are usually dominated by the purchase cost of the wind turbine itself. When calculated in spesific units (e.g. $/kW), this cost show a falling trend.

Due to technological improvements, which lead to plants with better availability and with progressively better aerodynamic characteristics, a move towards an increasing energy benefit of the investments in new wind power plants, can be seen.

These features of the cost/benefit picture, contribute to make wind power a potentially interesting power source.

The economics of a certain wind power application, will strongly be influenced by the price level of oil, coal, and possibly gas and nuclear, since wind power in many cases will have a running utilitarian value which is connected to the productions costs of the "balancing" fuel based plant(s) in the system.

2.2 INTEGRATION

From the Norwegian viewpoint, the exploitation of wind power can be of interest in three main connections:

- as a supplement to the power supply of isolated areas
- as a micro-scale supplement in the distribution networks
- as a macro-scale supplement in the power system.

2.2.1 POWER SUPPLY OF ISOLATED AREAS

Local and isolated exploitation of small or medium-scale wind power plants, operating in parallel with diesel plants, can be of interest in two main connections from a Norwegian viewpoint:

- As a potentially economic alternative of energy supply for a lot of isolated , rural areas and islands along the Norwegian coast. For areas which at present have diesel/electric plants as the only energy supply, substitution of a part of the expensive diesel oil by wind power, could show to be economic.

- As a basis for industrial development of wind/diesel plants, in the intention of creating new markets, both national and international, for Norwegian industry.

In a current collaboration project between EB Energi and EFI, a wind/diesel prototyp rated ~100 kW, has been developed, and the final evaluation is to be carried out in the spring of 1989.

2.2.2 MICRO-SCALE INTEGRATION OF WIND TURBINES

In certain coastal areas of Norway, with extended, loss-making main distribution and retail distribution grids, and with favourable wind conditions, integration of medium-scale wind turbines into the existing distribution system on certain places, can show to be interesting, both technical and economic. There are three main reasons for this:

* Wind conditions resulting in a high production during the winter season, when the power demand and unit price is at the highest level

* Extended and often weak distribution grids, which in the heavy load periods give considerable marginal losses when supplied from the central power production system.

* Cost favourable and robust medium-scale wind turbines (100~500 kW). Such wind turbines can be mounted without special requirements to the infrastructure on the potential site.

2.2.3 MACRO-SCALE INTEGRATION INTO THE POWER SYSTEM

The long-term marginal cost for firm power in Norway, will in the 90th be in the range of 3-5 US cents/kWh. With adaption between power supply capacity and the power demand, the current short-time marginal cost in the energy market will be within the same range. This cost is a measure of the marginal benefit of the wind generation.

The energy cost resulting from macro-scale wind power development is supposed to be at a higher level than this "benefit-value" stated above. Thus, macro-scale development of wind power today seems to be a not very interesting perspective for the Norwegian electricity industry.

3. AREAS OF FURTHER WORK IN NORWAY

Until now, preliminary studies of technical and economic aspects of small-scale integration of wind power has been carried out by EFI, within the National Wind Energy Programme. Cost/benefit analyses show promising results concerning profitability for integration of medium-scale plants (200 - 500 kW) into the distribution grid in some windy, rural areas along the Norwegian coast.

A demonstration plant, backed by the Government and rated 55 kW, was put into operation in November 1986, as the first, modern wind power plant in Norway. A new plant, rated ~400 kW, will be erected in June 1989, with the intention of analysing cost/benefit relations, and gathering further operational experience with wind power plants. In this connection theoretical investigations and practical measurements will be performed, as a preliminary project concerning the general impacts of connecting wind turbines to a distribution system. Both wind turbines are operated by Soer-Troendelag Kraftselskap.

The national long-term project for wind power development, formulated by NVE for the period 1987-95, gives the framework for further work in this field in Norway.

According to this project, micro-scale integration into the distribution system will be a main activity, and the aim is development of 3-4 MW of wind power, based on medium-scale , "cost optimum" wind turbines.

It is expected that the National Wind Energy Programme also will assure the financing of further studies on the technical and economic aspects of such integration, with the intention of developing a thorough base of knowledge and perhaps national guidelines.

4. AREAS OF ADDITIONAL RESEARCH AND DEVELOPMENT

The following areas are recognized to be of interest concerning further work and additional R & D in this context:

- basic criteria (economics, power quality)
- economic analyses (cost/benefit)
- electrical analyses (voltage, stability, losses, thermal, (frequency)).

Power quality questions should be related to already existing publications and recommendations from, and work done by internationally acknowledged institutions, e.g. IEC, UNIPEDE, EPRI.

A lot of work is being done internationally on this field, to specify limit values as a basis for assessing quality of power.

The main irregularities that may affect the voltage wave are as follows:

- slow voltage variations
- sudden changes in the RMS value of the voltage
- voltage dips
- rapid fluctuations in voltage
- unbalance of three-phase voltages
- harmonic voltage distortion
- frequency variation.

Definitions of and information regarding characteristics of these irregularities, are normally given in national or international standards.

Integration of wind power, can result in all types of the above mentioned irregularities.

Concerning economic analyses, characteristics of the power system, operational constraints, spinning reserve, installed capacity, type of power production plants, penetration level, size and cost of wind turbines or arrays of WT generators, quality of wind-speed and load data, system models etc., will be aspects/variables of interest.

Electrical analyses can comprise computer based load flow analyses, stability and transient simulations, etc. The quality of the output, e.g. for power quality assessment purposes, depend strongly on the quality of component and system models, of time base for wind speed and load data, etc.

It is suggested, on the basis of the foregoing, that emphasis in this planned IEA Annex, will be on both technical and economic issues.

5. ACKNOWLEDGMENT

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REQUIREMENTS AND EXPERIENCES WITH INTERCONNECTING WIND POWER PLANTS TO PG&E'S POWER SYSTEM

William J. Steely

INTRODUCTION

The largest collection of wind driven electric turbines in the world is in the PG&E service area. In 1987, the Altamont Pass wind power plants delivered 875,000,000 kWh to PG&E. This amounts to nearly half of the world's wind energy production of 1,885,000,000 kWh for that year. (See Figure 1, World Wind Electric Generation.)

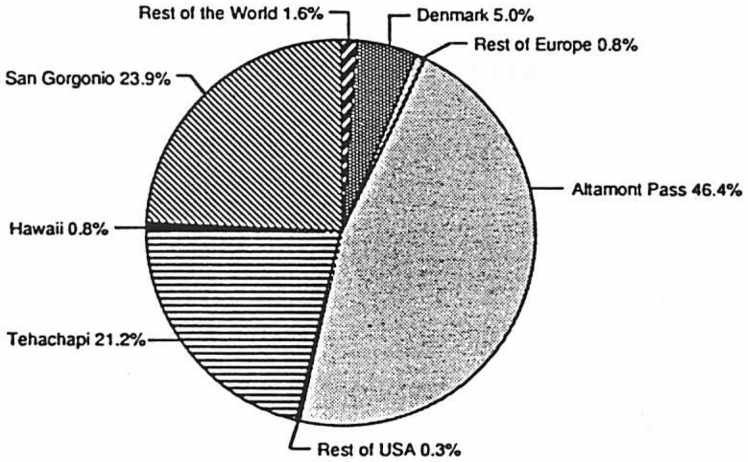

Figure 1. World Wind Electric Generation

Since 1981, when the first wind turbine developers connected to PG&E's transmission system, PG&E has developed a handbook entitled "Power Producers' Interconnection Handbook." This handbook was compiled by PG&E to serve as a guide for wind power plants to follow in interconnecting generation projects with the PG&E transmission and distribution system. It describes the interconnection process from the planning of a project to the operational phase.

The purpose of this paper is to describe PG&E's requirements and some of the experiences we have gained with interconnecting wind power plants to our system.

PROJECT REQUIREMENTS

PG&E has established operating, metering, and equipment protection requirements for wind power plants and other power producers to be interconnected with its system. The requirements vary according to the name-plate rating of the generator, unless otherwise indicated. Table 1 summarizes these requirements.

	10 kW or Less	11 kW to 40 kW	41 kW to 100 kW	101 kW to 400 kW	401 kW to 1 mw	1 mw to 10 mw	Over 10 mw
Dedicated Transformer		X	X	X	X	X	X
Disconnect Device	X	X	X	X	X	X	X
Generator Circuit Breaker	X	X	X	X	X	X	X
Overvoltage Protection	X	X	X	X	X	X	X
Undervoltage Protection	X[2]	X[2]	X	X	X	X	X
Over/Underfrequency Protection	X	X	X	X	X	X	X
Ground Fault Protection			X[5]	X	X	X	X
Overcurrent Relay With Voltage Restraint					X	X	X
Manual Synchronization With Generator Synchronizing Relay Supervision	X	X	X	X	X	X	X
Voltage and Power Factor Regulation			X	X	X	X	X
Utility Grade Relays[3]						X	X
Telemetering[4]							X
Time-of-Day Metering[4]				X	X	X	X
Graphic Recorder[4]						X	X
Direct Phone Service	X	X	X	X	X	X	X
30 Fault Interrupting Device				X	X	X	X

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[1] All requirements are based on generator nameplate, unless otherwise indicated.

[2] This requirement can be met by the contactor undervoltage release.

[3] Utility grade relays are required for any transmission voltage (60 kV and above) interconnection, regardless of generator output.

[4] Requirement is based on deliveries to PGandE, not necessarily generator nameplate.

[5] For generators 41 kW to 100 kW, ground fault detection requirements will be reviewed on a case-by-case basis.

Table 1 Summary of Interconnection Requirements[1]

The wind power plant is responsible for the design, installation, operation and maintenance of all necessary equipment for connection to the PG&E system, unless otherwise stated in a contractual agreement. It is also the wind power plant's responsibility to submit specifications and detailed plans for the installation of the control and protective devices to PG&E for review and written approval prior to parallel operation. PG&E's requirements are designed to protect PG&E facilities and not designed to protect the customer's generator from internal faults.

INTERCONNECTION PROCEDURE

In order to efficiently coordinate all interconnection requests in a timely manner, PG&E has defined a sequence of steps for all wind power plants to try to follow. This is illustrated in Figure 2, Interconnection Flowchart.

UTILITY SERVICES - ELECTRIC and GAS

Depending on the specific project, electric and gas services available from PG&E may be required. If so, regular, supplemental or standby power requirements can be supplied under PG&E's authorized rates and tariffs.

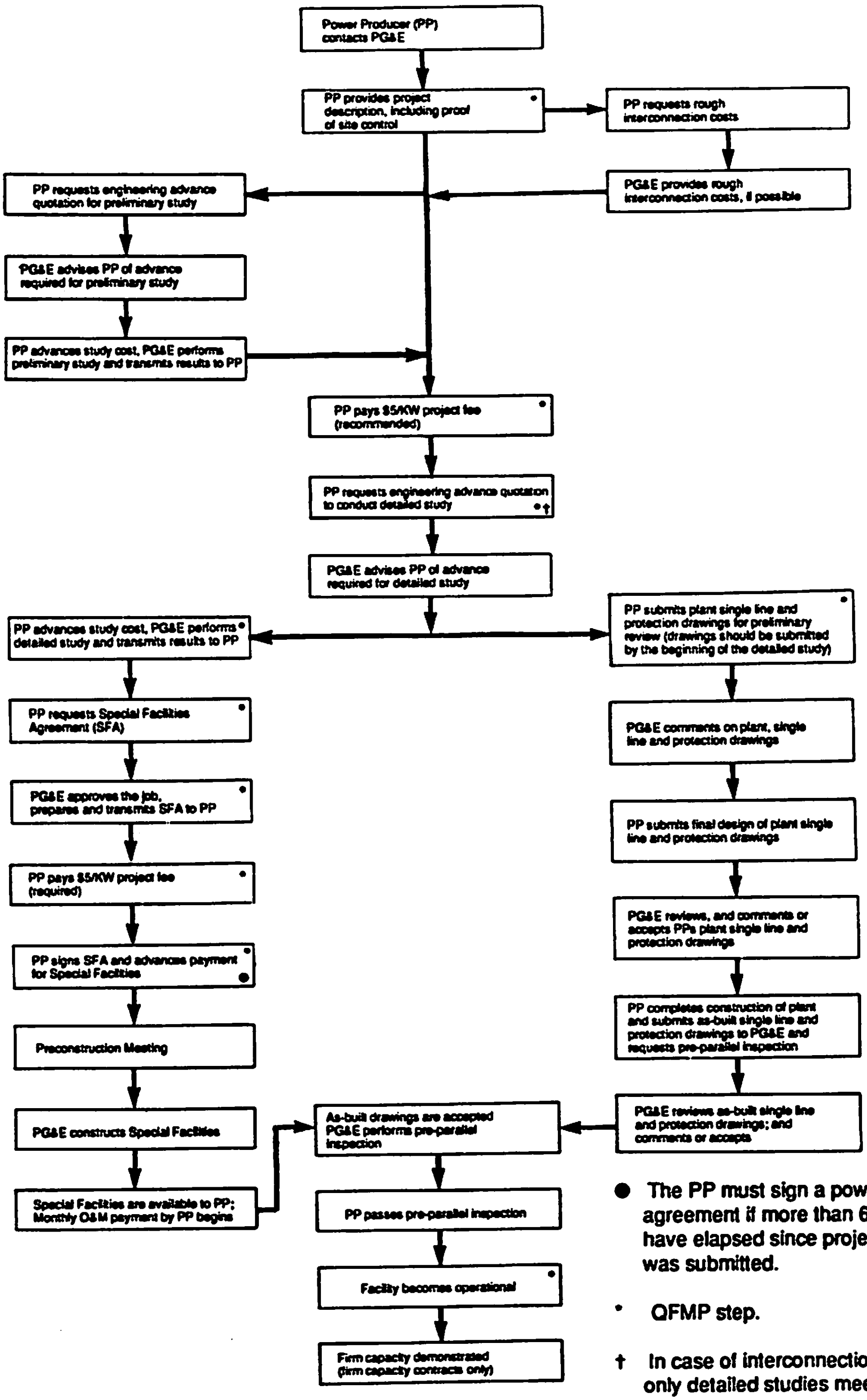
POWER PURCHASE AGREEMENTS

PG&E has developed standard forms of agreement, including prices, terms and conditions under which PG&E offers to purchase power. These agreements have been approved by the California Public Utility Commission (CPUC). The standard offers currently in effect are:

Standard Offer No. 1	Power Purchase Agreement for As-Delivered Capacity and Energy
Standard Offer No. 3	Power Purchase Agreement for As-Delivered Capacity and Energy from Facilities of 100 kW or less

Two other standard offers have been suspended by the CPUC and are not currently available:

Standard Offer No. 2	Power Purchase Agreement for Firm Capacity and Energy
Standard Offer No. 4	Power Purchase Agreement for Long-Term Energy and Capacity



● The PP must sign a power purchase agreement if more than 6 months have elapsed since project description was submitted.

• QFMP step.

† In case of interconnection studies, only detailed studies meet QFMP requirements.

Figure 2. Interconnection Flowchart

CONSTRUCTION

There are two components to the construction process. One is the construction of the wind power plant's generation and interconnection facilities. The other is the construction of PG&E special facilities, if required, which may be financed by PG&E.

The special facilities are those additions and reinforcements to the PG&E system which are needed to accept delivery of energy and capacity from the power producer. Also, they are those parts of the interconnection facilities which are owned and maintained by PG&E at the wind power plant's request.

The design and construction of the wind power plant's generation and interconnection facilities are the responsibility of the wind power plant. At the wind power plant's option, certain of these interconnection facilities may be installed by PG&E under contract as special facilities. Monthly cost of ownership charges begin when PG&E special facilities are available for use by the wind power plant.

APPROVAL TO OPERATE

The wind power plant must meet several requirements before obtaining the approval to operate which are the following:

(1) A Power Purchase Agreement must be in effect.
(2) The special facilities must be complete enough to accommodate the wind power plant's power deliveries.
(3) The wind power plant's generation and interconnection facilities must be ready for operation, with all required permits executed.
(4) The required insurance coverage as defined in the power purchase agreement must be furnished to PG&E.
(5) The Standard Operating Agreement for Facilities of 40 kW and Larger must be executed and complied with.
(6) The facility must pass a preparallel inspection by PG&E (see Appendix I).

OPERATION

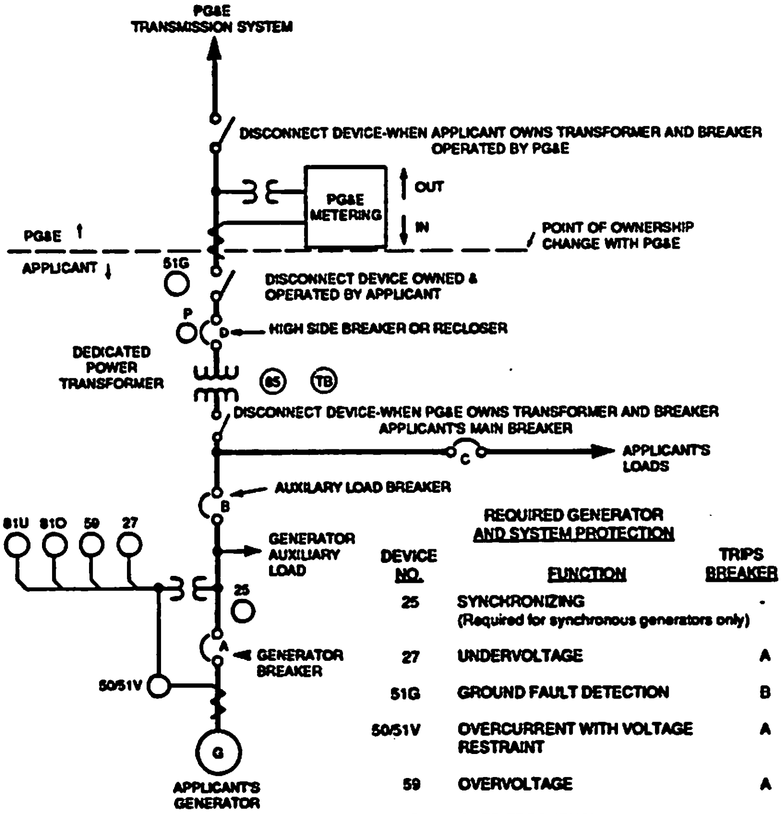
The wind power plant must notify PG&E of any unusual or emergency conditions or of any change in the wind power plant's mode of operation including separating from or paralleling with the system. PG&E also expects capacity and energy reports for all projects with deliveries greater than 1,000 kW when direct telemetering is not available. The frequency of reporting (i.e., daily) is specified in the power purchase agreement.

The wind power plant must maintain a daily operations log which is available to PG&E. It should have a record of all communications between the power producer and the designated PG&E switching station and note all unusual occurrences. For further details see Appendix II.

ELECTRIC METERING REQUIREMENTS

Metering requirements for the delivery of power to PG&E fall under two general classifications:

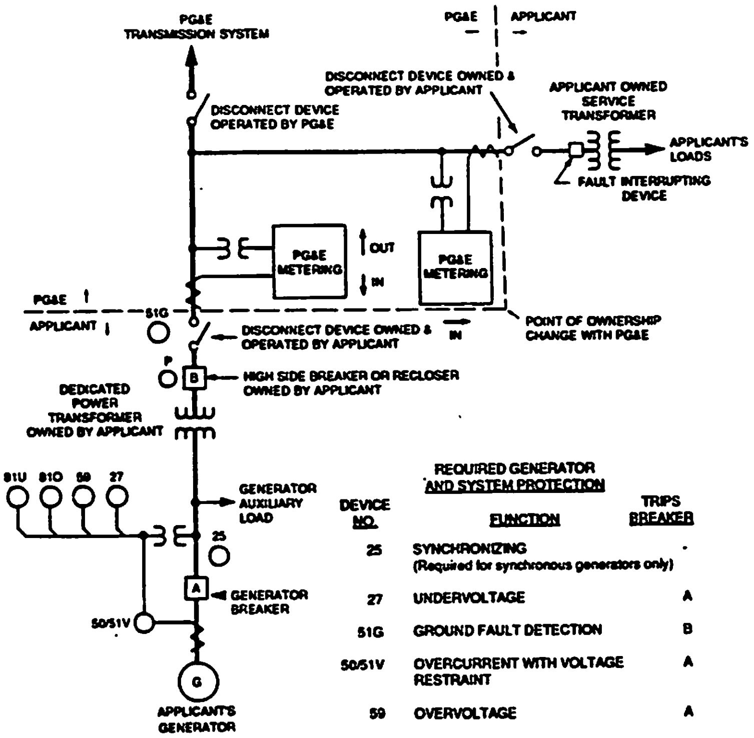
- Surplus Sale - The wind power plant's gross output in kWh, less station use, any other use by wind power plant, and transformation and transmission losses, is delivered to the PG&E system (see Figure 3).
- Simultaneous Purchase and Sale - The wind power plant's gross output in kWh, less station use and transformation and transmission losses, is delivered to PG&E. The above output is metered independently from the wind power plant's own electric load that is served by PG&E (see Figure 4).



REQUIRED GENERATOR
AND SYSTEM PROTECTION

DEVICE NO.	FUNCTION	TRIPS BREAKER
25	SYNCHRONIZING (Required for synchronous generators only)	-
27	UNDERVOLTAGE	A
51G	GROUND FAULT DETECTION	B
50/51V	OVERCURRENT WITH VOLTAGE RESTRAINT	A
59	OVERVOLTAGE	A
81O	OVER FREQUENCY	A
81U	UNDER FREQUENCY	A
P	LINE PROTECTION	B
TB	TRANSFORMER OVERCURRENT	B
85	TRANSFER TRIP MAY BE REQUIRED	A OR B

Figure 3. Transmission Interconnection-Typical Protection and Metering Installation for Generators Greater than 1000 KW for Sale of Surplus Energy to PG&E



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59	OVERVOLTAGE	A
81O	OVER FREQUENCY	A
81U	UNDER FREQUENCY	A
P	LINE PROTECTION	B

Figure 4. Transmission Interconnection-Typical Protection and Metering Installation for Generators Greater than 1000 KW for <u>Simultaneous Purchase and Sale</u>

PROTECTIVE RELAYS

The main safety requirement for generators interconnected to the PG&E system is that the unit must go off the line immediately if a fault is detected or the utility's power is disconnected from the line into which the unit is generating. Some protection requirements can be standardized, but most of the line relaying depends on generator size, line characteristics (voltage, impedance, ampacity) and existing system protection requirements in the interconnection area. The basic protective devices are shown in Table 1.

A test report for all relays is required prior to paralleling and every three years thereafter. Circuit breakers must be tested every six years after the preparallel inspection.

MANUAL DISCONNECTS

A PG&E operated disconnect device must be provided as a means of electrically isolating the PG&E system from the wind power station and to establish a visually open working clearance for maintenance and repair work. The disconnect device must be located at the point of interconnection (ownership change) with PG&E for interconnections 2.4 kV and above.

REACTIVE AND VOLTAGE REQUIREMENTS

GENERAL

Most wind power plants are concerned with the delivery of real power (watts) into the PG&E grid because this is the basis on which purchase payments are made. However, reactive power (vars) is also a vital component of the PG&E system load. It is therefore essential that PG&E receive both real and reactive power from wind power plants. Where the wind power plant is unable to furnish reactive power support--because of interconnection limitations, type of generator or the generator loading--PG&E will charge for the installation of equivalent reactive support.

INDUCTION GENERATORS

An induction generator absorbs vars and therefore requires reactive power support from PG&E's system. For facilities greater than 40 kW, PG&E requires a power factor controller as well. Power factor controllers or capacitors will be installed either by the wind power plant or as special facilities by PG&E. Care should be exercised in connecting capacitors directly to the generator terminals because of the possibility of self-excitation. Switched capacitors supplied by the wind power plant must be switched on and off at the request of PG&E to satisfy system operating requirements.

In many cases, where the generator is located at a remote location on an existing distribution line, severe circuit voltage regulation problems may result if all the capacitors are located at the generator terminals. In these cases, the generator can be operated at a power factor less than unity (absorbing vars) with part of the generator reactive supply furnished from capacitors located elsewhere on the PG&E system.

Induction Projects 40 kW and Less

Switched capacitors may be required in areas where severe reactive limitations exist.

Induction Projects Greater Than 40 kW and Less Than or Equal to 1,000 kW

Under electric Rule No. 21 the wind power plant is required to provide reactive supply equivalent to operating at unity power factor at full load. When either the wind power plant or PG&E determines that it is not practicable for the wind power plant to provide this level of reactive support, the wind power plant will be charged the equivalent cost to install capacitors on the PG&E system as special facilities to correct to unity power factor.

Induction Projects Greater Than 1,000 kW

The wind power plant must provide reactive support equivalent to operating a synchronous generator anywhere within the range from 95 percent leading power factor (absorbing vars) to 90 percent lagging power factor (producing vars) at full load, as directed by PG&E's system dispatcher. When either the wind power plant or PG&E determines that it is not practicable for the wind power plant to provide this level of reactive support, the wind power plant will be charged the equivalent cost to install capacitors on the PG&E system as special facilities to correct to 90 percent lagging power factor.

STATISTICS and PROJECT EXPERIENCES

The wind power plants in the Altamont are connected to one of the largest substations on the PG&E system. The rest of the paper is dedicated to showing some of the statistics of the wind power plants in the Altamont as a composite plant and to sharing some of the experiences we at PG&E have had with them connected to our system.

Figure 5 shows the quarterly output of all the wind power plants in the Altamont. There is a good seasonal fit to PG&E needs, as the wind power plants produce most of their output during the second and third quarter of the year, when PG&E's loads are greatest.

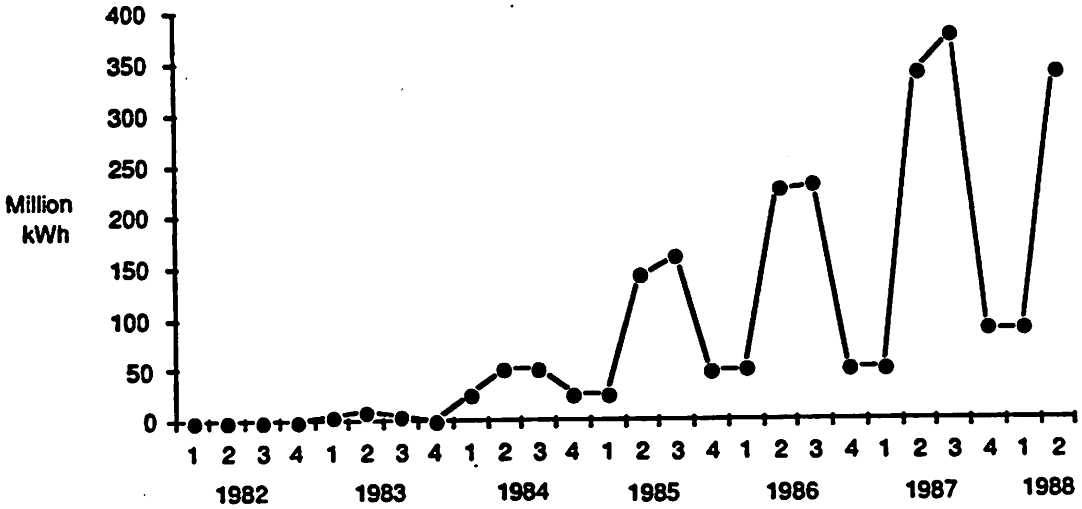


Figure 5. Quarterly Altamont Pass Area Wind Power Plant Output

As of late 1988, there were 7,650 wind turbines installed in the Altamont Pass with a total rated capacity of 750 kW. In 1987, 750 turbines were installed compared to 2,100 during the peak tax credit year of 1984 (see Figure 6).

In 1987, the 875,000,000 kWh produced by the power plants in Altamont Pass represented 1.1% of PG&E system deliveries of 79,149,007,000 kWh of electric energy. At times during late summer evenings, the wind power plants were supplying nearly 6% of the system load. During peak load hours, the wind power plants occasionally supplied close to 4% of the system load. To our knowledge there have been no system stability problems from the wind power plants.

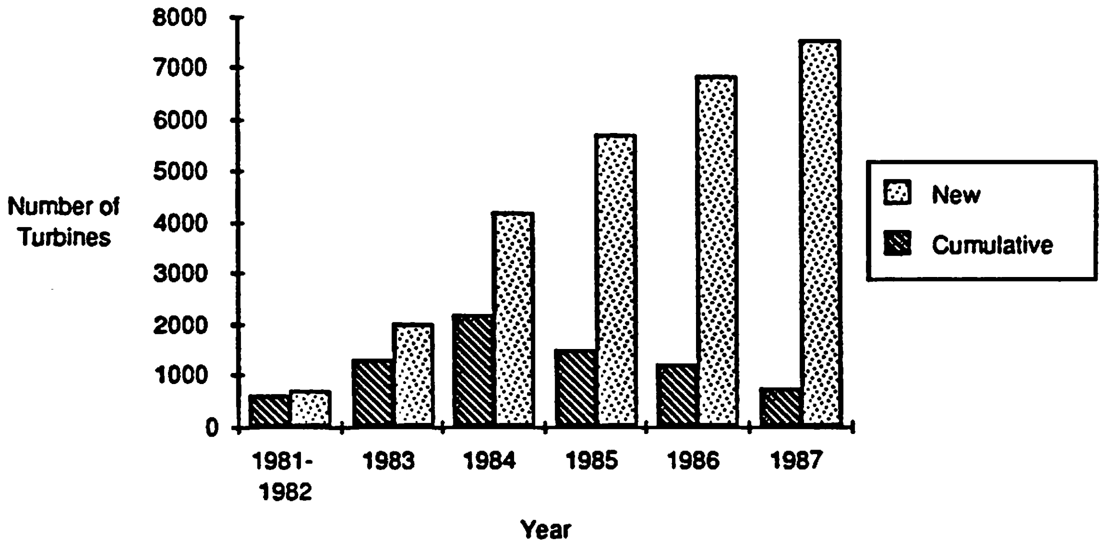


Figure 6. Number of Turbines in Altamont, New and Cumulative

The average total output for all of the Altamont Pass wind power plants has been compiled for every hour of 1987. Figure 7 shows the average hourly wind power plant output during a summer month (July) and a winter month (January). In July the lowest average output was at noon (PDT) and the highest was at 11:00 p.m. At the hour of maximum PG&E annual needs, summer afternoons from 3:00 to 4:00 p.m. (PDT), the average total wind power plant output was 190 MW. This compares with the 1987 average Altamont output of 100 MW, and the maximum summer output of 377 MW. In January, the average output showed no clear connection with time of day, and was very small.

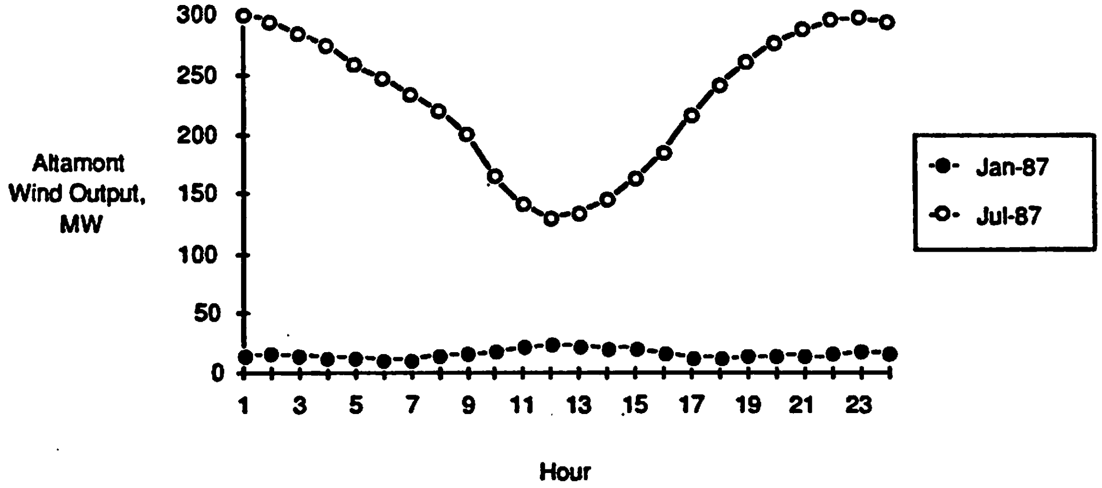


Figure 7. Total Altamont Output by Time of Day

An examination was made of wind power plant output on the day of the 1987 PG&E peak system load, which was during the hour from 3:00 to 4:00 p.m. (PDT) on July 15, 1987, and results are shown in Figure 8.

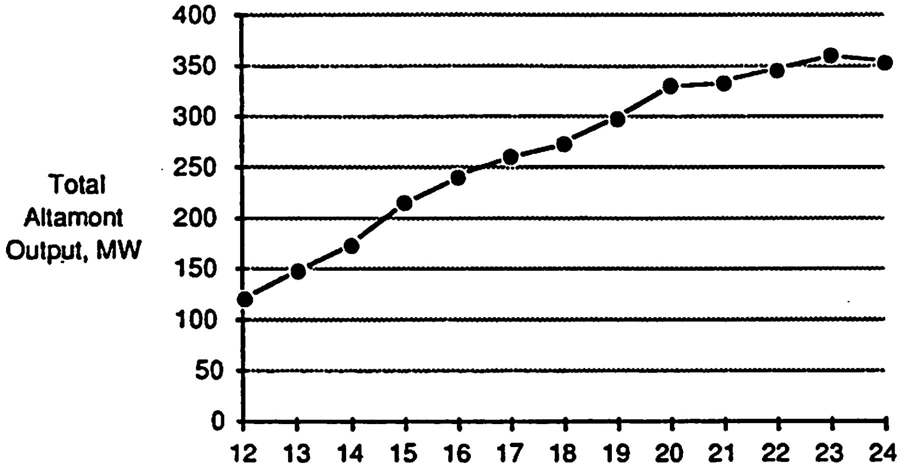


Figure 8. July 15, 1987 Altamont Wind Power Plant Output

At the time of the peak 1987 PG&E system load, the wind power plants were producing 243 MW, which is 2.4 times their average 1987 output. This output is also 37% of the total Altamont rated capacity at that time of 660 MW, and 64% of the maximum 1987 Altamont output of 377 MW.

Three wind power plants are connected to the Tesla-Trust 115 kV transmission line which is connected directly to the 115 kV bus at Tesla Substation. From this we have been able to monitor real and reactive power flows over the years. These are shown in Table 2. Negative MW or MV values indicate that the direction of the power flow is into Tesla Substation from the wind power plants. Positive MW or MV values indicate that the direction of the power flow is from Tesla Substation into the wind power plants.

Table 2

Tesla - Trust 115 kV T/L Loading History

Date	Amps	MW	MV	P.F.	Bus Volt	Time
3/1/89	700	-140	50	0.94 lead	117	0000
3/1/89	120	-25	-3	0.99 lag	118	0600
7/31/88	420	-92	53	0.87 lead	116	0600
7/31/88	860	-140	70	0.89 lead	116	1800
7/31/88	880	-140	75	0.88 lead	117	2000
3/1/88	200	-35	25	0.81 lead	117	0600
3/1/88	560	-95	65	0.83 lead	114	1600
7/29/87	880	-152	111	0.81 lead	115.5	0600
7/29/87	780	-135	95	0.82 lead	115	1600
7/29/87	820	-130	90	0.82 lead	116.5	2000

Of special interest is the power factor which has steadily improved as a result of the wind power plant developer's effort to comply with utility reactive and voltage requirements. The Tesla substation operators like to operate the 115 kV bus between 117 kV and 120 kV; otherwise, they receive complaints from customers with voltage sensitive equipment such as computers. PG&E operators reported that before adequate power factor correction was installed by the wind power plants, they have seen the 115 kV bus voltage pulled down from 119 kV to 114 kV when the wind plants came on line (see Table 2).

In general, PG&E operators have no severe complaints and in fact are pleased overall with the cooperation they are receiving from the wind power plants. However, some of the areas that could be improved are the following:

(1) Communications - Sometimes wind power plants don't say when they're going off-line. They are better about requesting when they want to come on-line (usually within the hour). Our substation operators need information on who's on-line to coordinate such activities as line maintenance or line switching operations.

(2) Different Objectives - Wind power plants have as their main objective to make money. As a result they are not always as willing to make changes (curtail power, supply vars, etc.) to assist PG&E system operation. However, they have met and will try to meet most of the requests from our operators.

(3) Personnel Training - Wind power plant operators lack training in some cases and don't know what to do when requests come from PG&E operators (i.e., How do you boost or buck the voltage?).

(4) Availability - Due to economic and other constraints, some wind power plant operators are just not available to handle requests from PG&E operators.

In conclusion, PG&E operators and wind power plant operators have been able to work together to both's satisfaction. Reactive power and system voltage support have improved from the wind power plants. The minor problems that remain should eventually be resolved as economic conditions stabilize in the wind industry so that the remaining wind power plants are able to fully comply with the standard operating procedures required by PG&E. Having Tesla Substation (one of the largest at PG&E) as the interconnection point for 95% of all the wind power plants on the PG&E system has diminished many of the problems with voltage and reactive support, frequency and stability constraints, and so forth that other utilities may experience with weak transmission and/or distribution systems.

Appendix I

PREPARALLEL INSPECTION

REVIEW OF REQUIREMENTS

Prior to scheduling the parallel inspection, the following items must be completed by the wind power plant:

- Sign a Power Purchase Agreement and Standard Operating Agreement.
- Sign a Special Facilities Agreement (if necessary).
- Sign any applicable regular service or standby service agreements.
- Receive written approval from PG&E of the wind power plant's "as built" protective relay/control schematic drawings including relay settings.
- Furnish proof of insurance to the manager of PG&E's Insurance Department as required in the Power Purchase Agreement.
- Provide complete relay test reports to PG&E.

PREPARALLEL INSPECTION

The following functional tests will be performed after the equipment has been energized but before the generator is paralleled with PG&E's system. PG&E test personnel must be present to observe all tests listed.

- Check that each protective relay trips the appropriate generator breaker and/or main breaker.
- When first energized, check that proper secondary potential is applied to all voltage and frequency relays.
- Check the synchronizing meter and equipment with the paralleling breaker closed and the generator off line. The equipment should show an "in-phase" condition.
- Check the generator phase rotation.

The following load tests may be done when the generator first picks up load.

- Check for correct load current in all relay current coils.
- Direction check all impedance and directional relays.

When the inspection is completed the PG&E inspector will complete and sign the Preparallel Inspection Form.

PERMISSION TO PARALLEL

The wind power plant's generation will be allowed to operate in parallel with the PG&E system after the following conditions have been met:

- PG&E has received and approved a copy of the wind power plant's preliminary tests.
- PG&E has received a final copy of the single-line meter-and-relay, and elementary diagrams that show "as built" changes made during construction.
- PG&E personnel have observed that the functional and load tests have been performed and the preparallel inspection form has been filled in and signed.
- The PG&E system dispatcher or designated switching center has been notified that the generator is ready for commercial operation.
- An Operating Agreement is signed by both the power producer and PG&E.

Appendix II

OPERATING PROCEDURES

JURISDICTION OF DISPATCHER

While operating in parallel with the PG&E system, the wind power station is at all times under the jurisdiction of PG&E's system dispatcher. The system dispatcher shall normally delegate such control to the designated local PG&E switching center. A signed Operating Agreement must be obtained between the wind power plant and PG&E prior to parallel operations.

COMMUNICATIONS

The wind power plant shall maintain telephone service from the local telephone company to the generator location. In the event such location is remote or unattended, telephone service shall be provided to the nearest building normally occupied by the generator operator. PG&E and the wind power plant shall maintain operating communications through the designated switching center.

The operating communications shall include system paralleling or separation, scheduled and unscheduled shutdowns, equipment clearances, levels of operating voltage or power factors and daily capacity and energy reports.

Daily Capacity and Energy Reports

If the wind power plant makes deliveries greater than one megawatt, a graphic recording device must be installed to measure and register power in kW and voltage in kV at a location within the facility.

If the wind power plant makes deliveries of greater than ten megawatts, he is required to telemeter the delivered capacity and energy information, including real power in kW, reactive power in kvar, and energy in kWh to PG&E. PG&E may also require telemetering of transmission kW, kvar, and kV data depending on the number of generators and transmission configuration.

If dispatchable capacity of greater than ten megawatts is provided pursuant to the Power Purchase Agreement, the wind power plant may be required to respond to system load frequency requirements on digital control from PG&E through additional equipment.

Paralleling to and Separating from PG&E

The wind power plant must notify the designated switching center prior to paralleling or separating from PG&E system. For unexpected separations from PG&E, the wind power plant must inform the designated switching center of the nature of the problem (i.e., overvoltage, underfrequency, ground fault, etc.) and report on relay target operations.

Clearances and Switching Requests

These requests will be handled through the designated switching center. Each power plant has installed an approved disconnect device for operation by PG&E personnel as a clearance point.

Unusual or Emergency Conditions

Unusual operating conditions or other factors that may affect the capability or the reliability of the wind power plant's generation should be reported to the designated switching center as soon as practicable.

Other Communications

These include:

- Notification whenever relays are changed or taken out of service.
- Three-year bench test reports on all relays.
- Six-year circuit breaker test reports.
- Report of relay operations and targets.

CURTAILMENTS, REACTIVE POWER SUPPORT and MAINTENANCE and SCHEDULING

It may be necessary for PG&E to request partial or total curtailment of energy and capacity deliveries from a wind power plant's facility. This notification will be through the designated switching center and in accordance with the Power Purchase Agreement.

The wind power plant will provide such reactive power support as required by PG&E to maintain system voltage level and power factor.

The wind power plant should follow recognized electrical industry standards for maintenance of protection and control equipment.

DAILY OPERATING LOG

The wind power plant shall keep a daily operating log for each generating unit which shall include information on unit availability, maintenance outages, circuit breaker trip operations requiring a manual reset, and any significant events related to the operation of the facility. PG&E reserves the right to review this log when analyzing system disturbances.

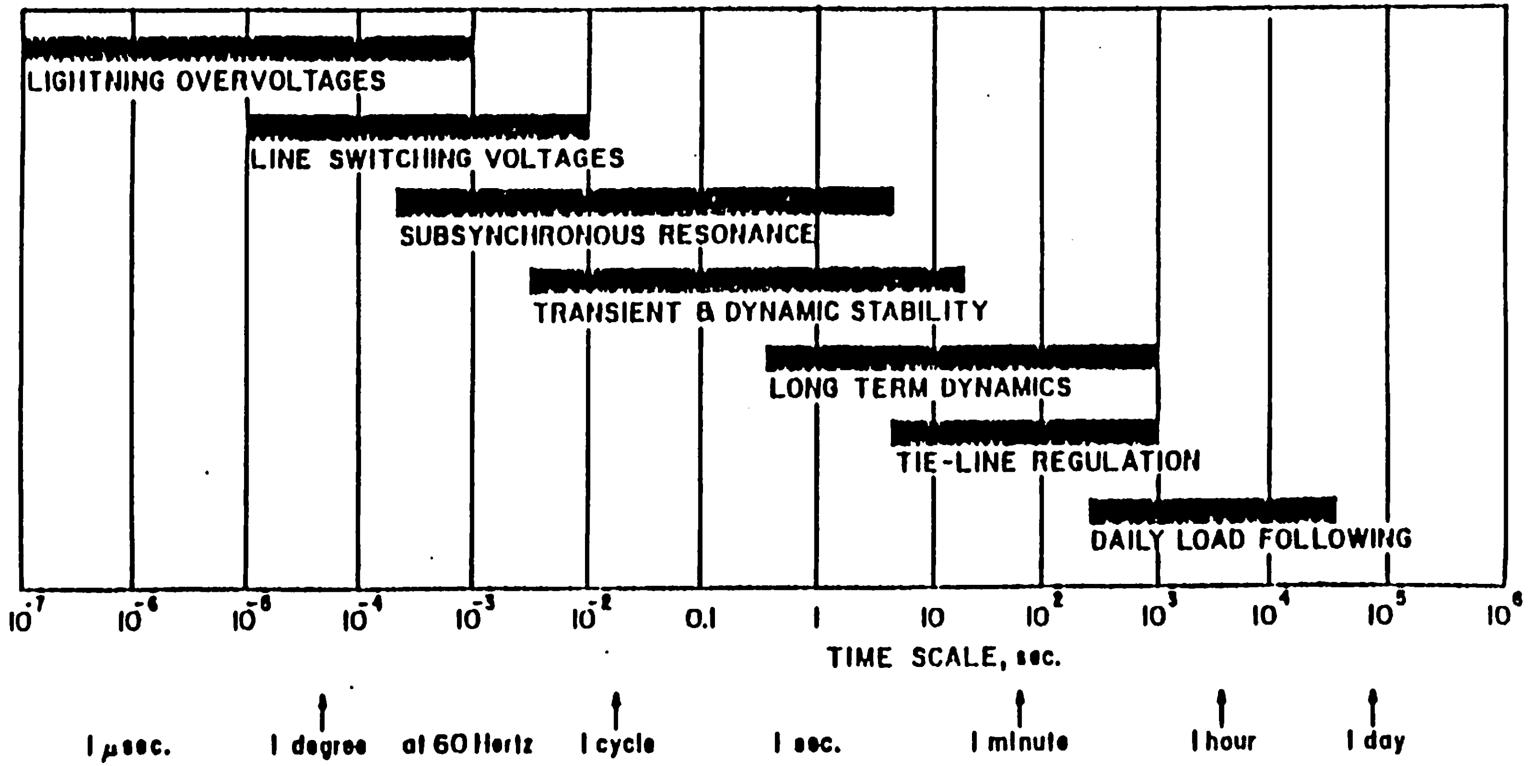
OPERATING AGREEMENT

An agreement between the wind power plant facility operator and PG&E will have to be signed by both parties prior to parallel operation.

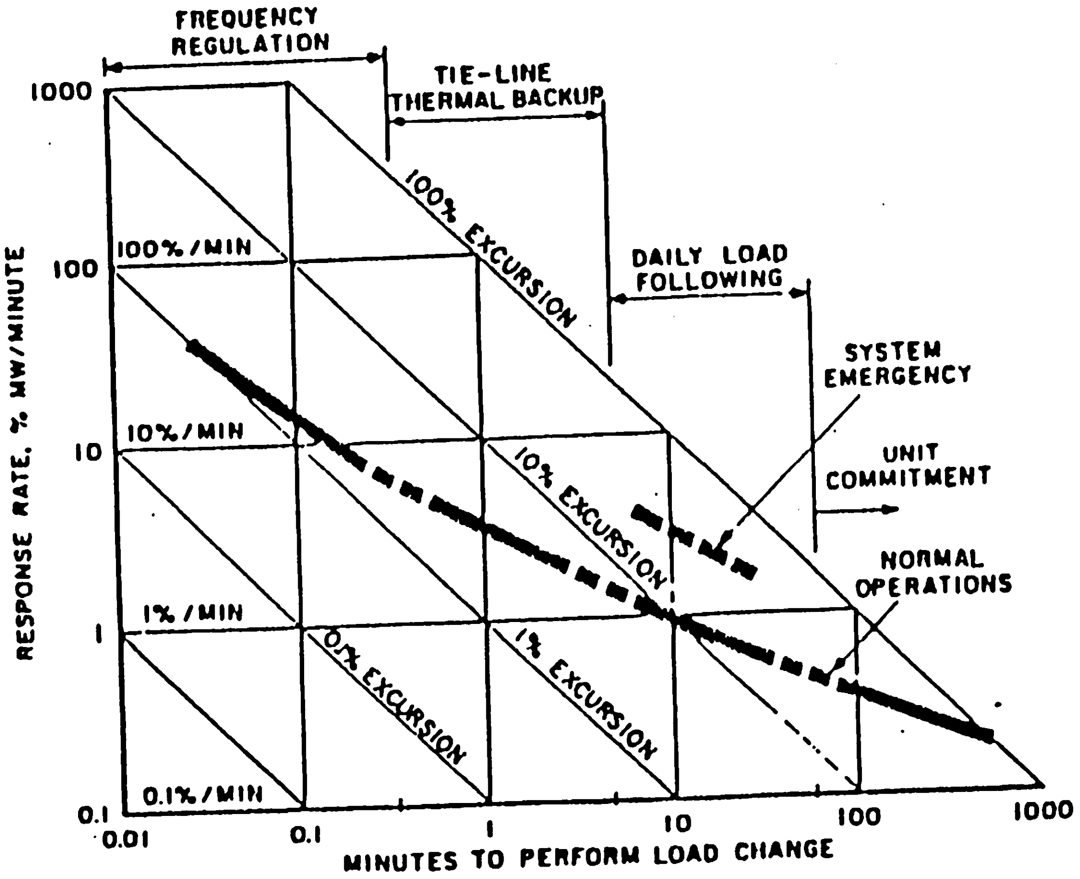
SELECTED UTILITY WIND INTEGRATION STUDIES

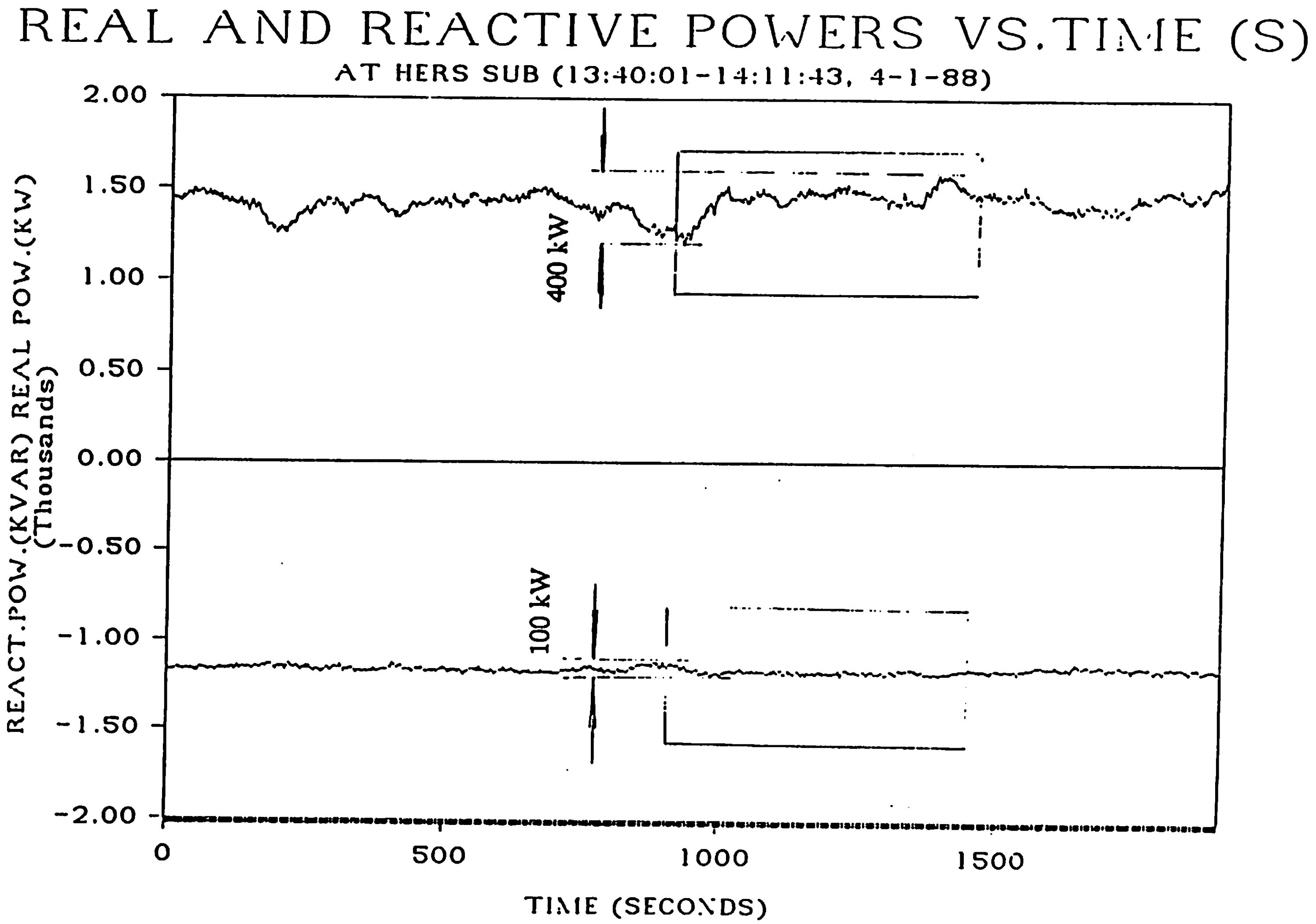
J. Charles Smith

SYSTEM DYNAMICS

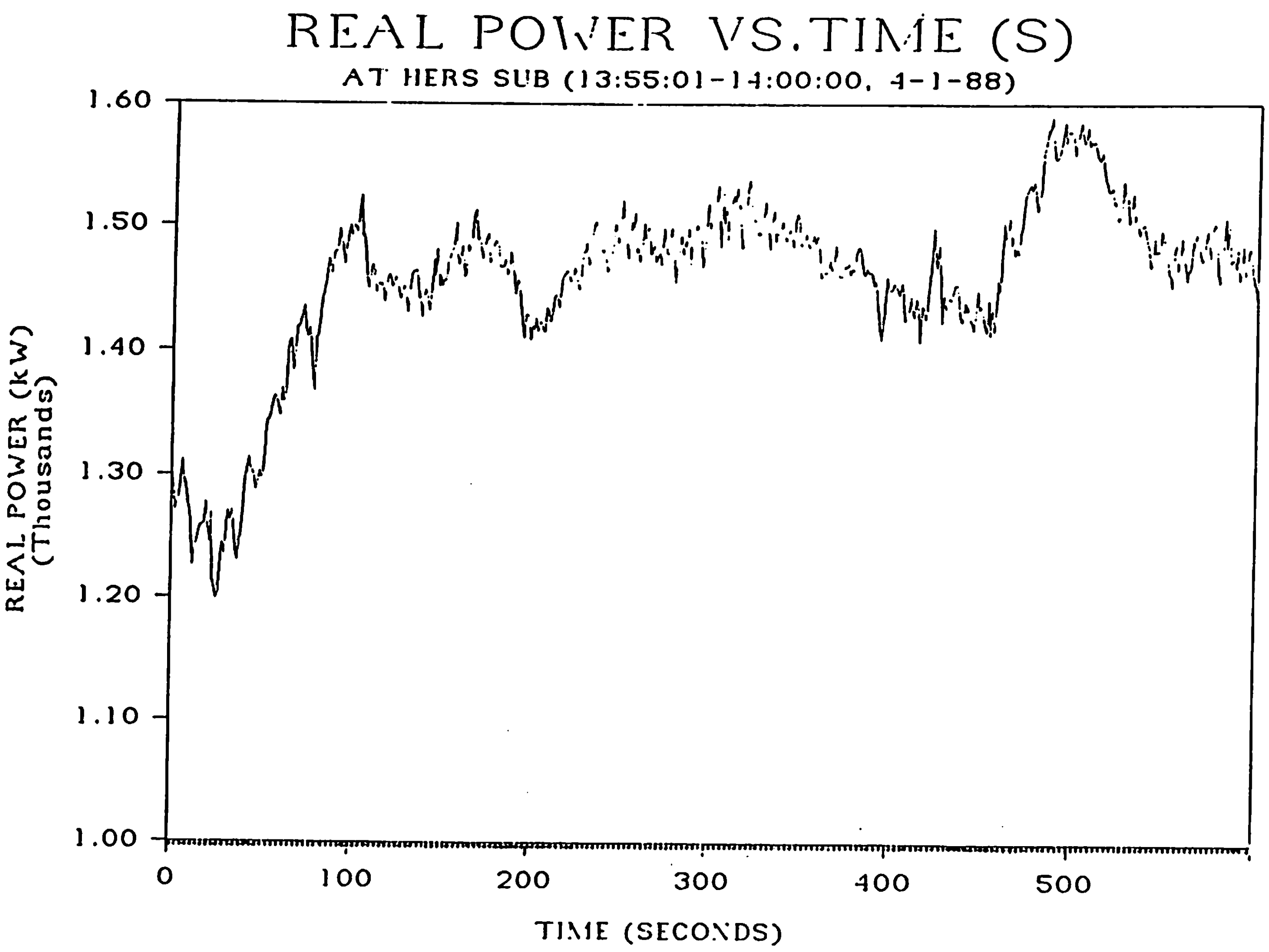


GENERATION RESPONSE REQUIREMENTS





Real and Reactive Powers in Second-to-Second Time Frame |



Close-up of Real Powers in Second-to-Second Time Frame I

TITLE: Wind Power Generation Dynamic Impacts on Electric Utility Systems

CONTRACTOR: Zaininger Engineering Company

FUNDING AGENCY: EPRI

DATE: 1980

SUMMARY:

- Deals with clusters of large wind turbines
- Dynamic Impacts Affect Wind Turbine Penetration Through System Operating Requirements
- Three classes of problems examined
    - short-term transient stability
    - system frequency excursions
    - minute-to-minute unit ramping limitations
- Simplified Models and Analyses showed adverse impacts at moderate penetrations

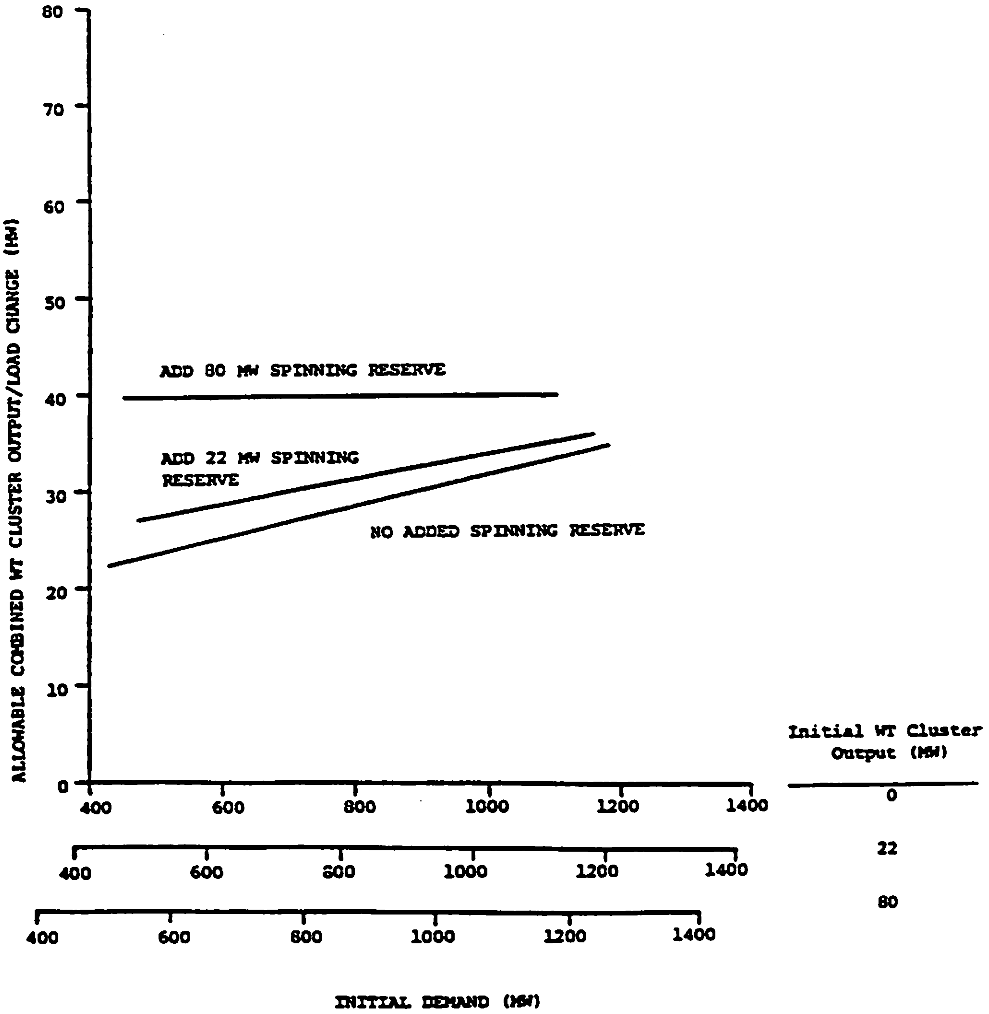


Figure S-1. Allowable Combined WT Cluster Output/Load Change Corresponding To A 0.1 Hz Frequency Excursion. A combined WT cluster output/ load change means an increase (or decrease) in WT cluster output and simultaneous decrease (or increase) in system demand.

TITLE: The Impact of Wind Power Generation on the Operation of An Electric Power System

CONTRACTOR: TVA

FUNDING AGENCY: DOE

DATE: 1982

SUMMARY:

- Investigate impact of 30% penetration of TVA installed capacity by wind generation on system operating requirement.
- Investigation included issues of:
    - operating reserves
    - unloadable generation
    - automatic generation control
- Wind generation treated as uncontrolled negative load with assumed loss of 20% of total capacity possible over 1 hour.
- Results showed WECS could be successfully integrated at levels up to 15% of system generating capacity.

TITLE: Methodology for Control and Operation of Wind Turbine Arrays in Utility Systems

CONTRACTOR: General Electric Company

FUNDING AGENCY: DOE

DATE: 1983

SUMMARY:

- Studied impact of high penetration on utility requirements for:
  - regulating units
  - load following capability
  - spinning reserve
  - unloadable generation
- Investigations included:
  - open loop control
  - feed forward control
  - feedback control
  - resulting operating requirements
- Hierarchical Control Strategies.
- Identified control methodologies suitable for integration into utility hierarchical control systems.

EXHIBIT 2.9-1 Block Diagram of the Negative Load Approach to Interconnecting Wind Plants to the Utility System

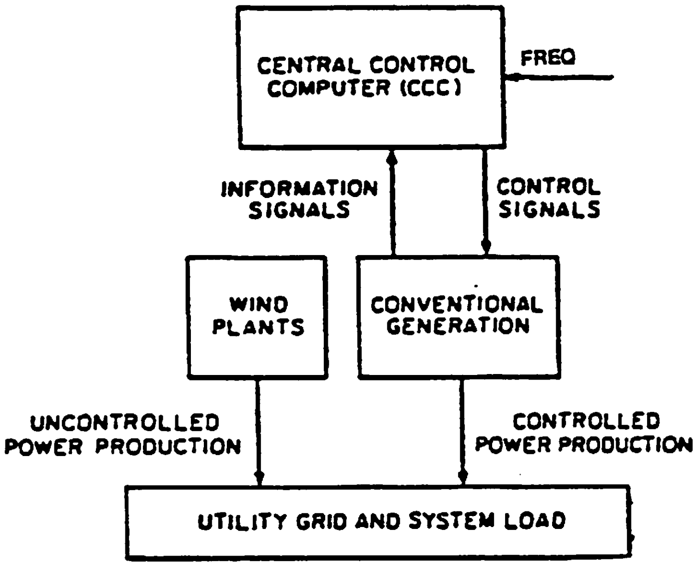


EXHIBIT 2.9-2 Block Diagram of the Open-Loop Control Concepts with Limits on Power Charge Rates (Trend Component)

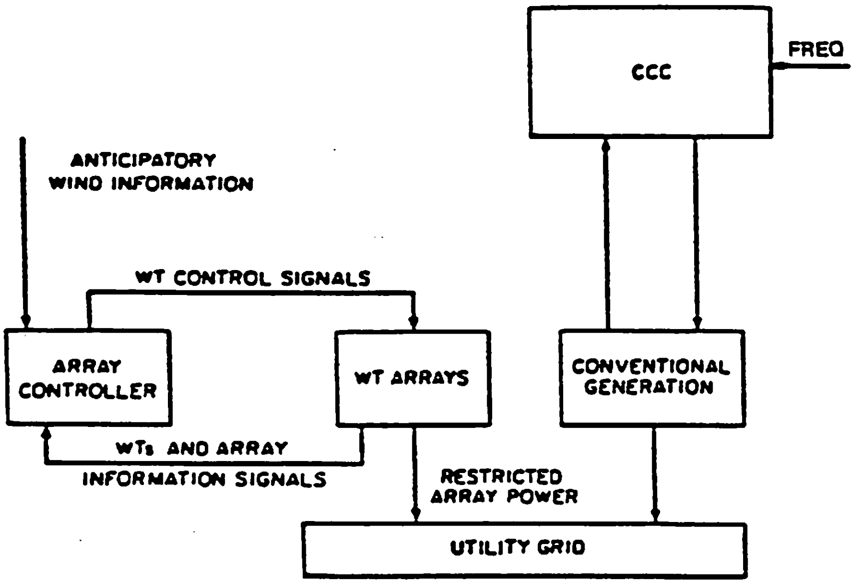


EXHIBIT 2.9-3 Block Diagram on the Open-Loop Feed Forward Control Concept

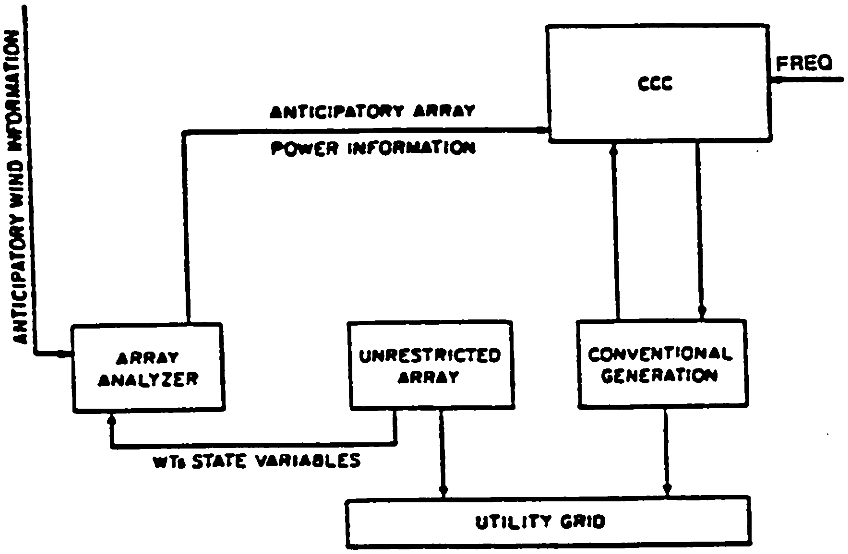
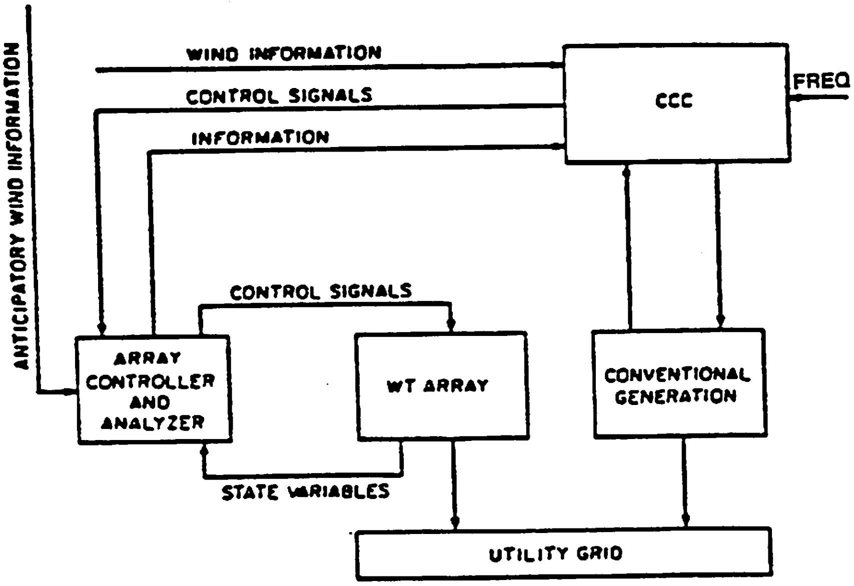


EXHIBIT 2.9-4 Block Diagram of a Closed-Loop Feedback Control Concept



TITLE: Modification of Power System Operation for Significant Wind Generation Penetration

CONTRACTOR: Michigan State University

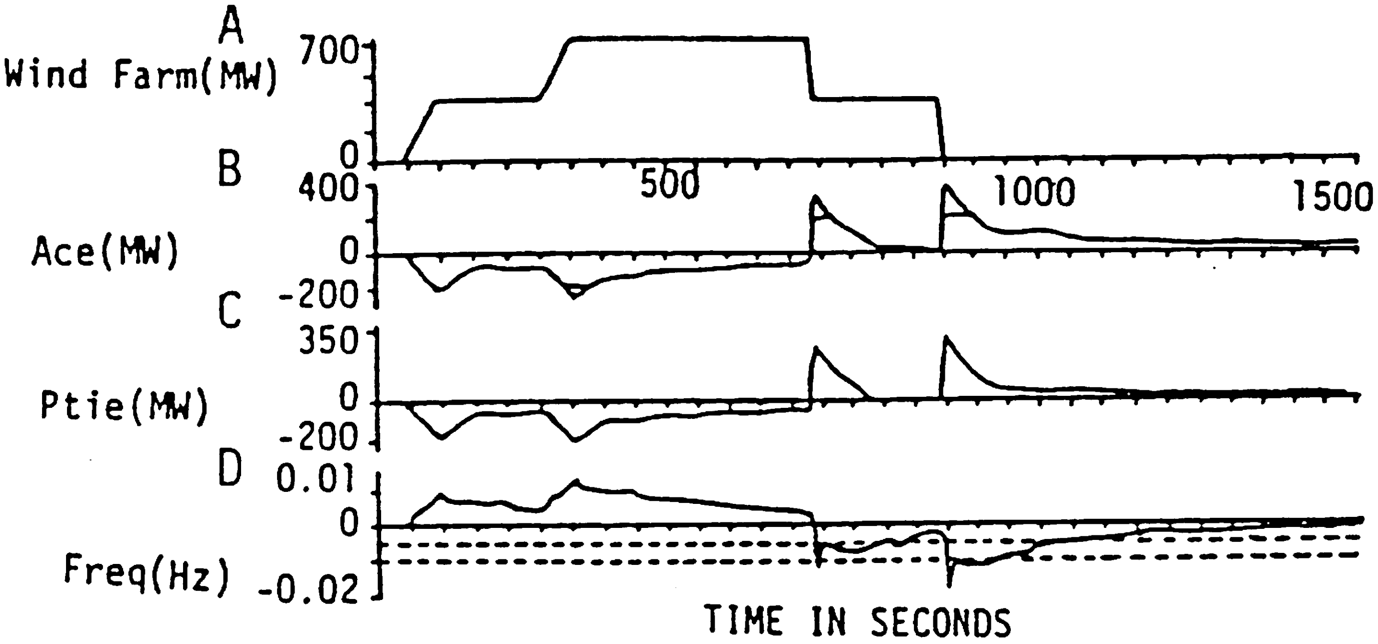
FUNDING AGENCY: DOE

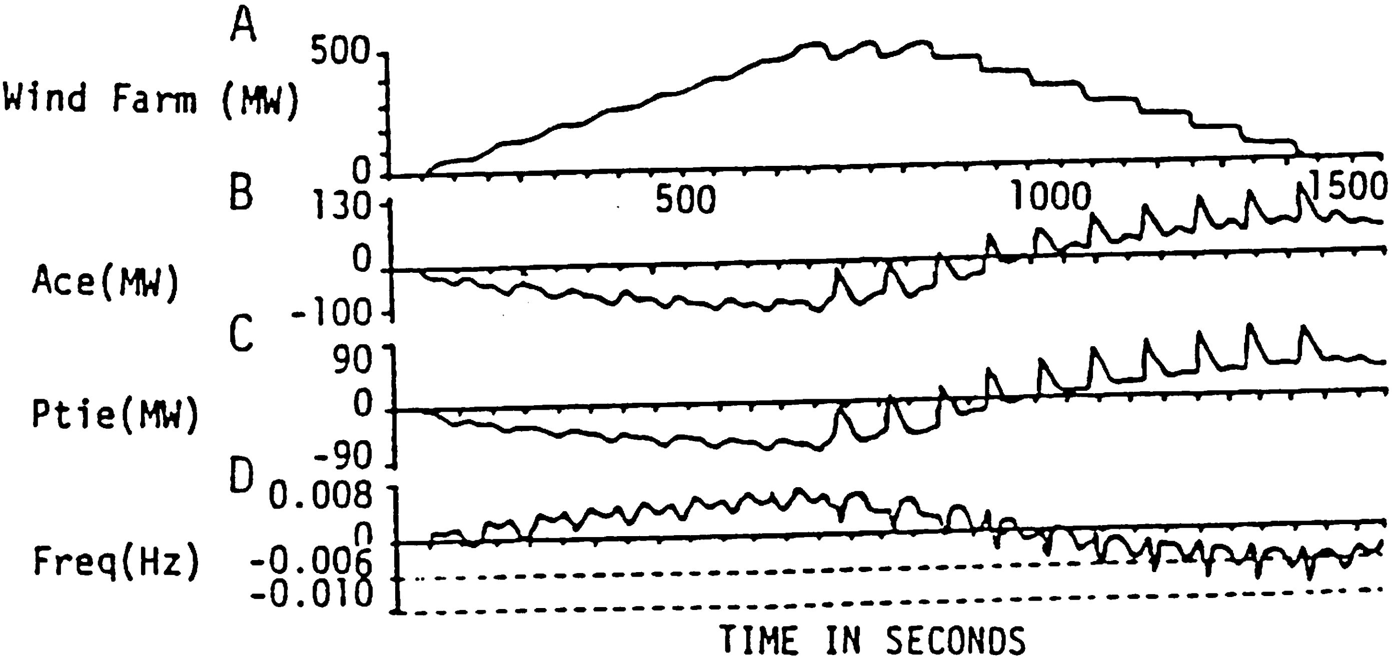
DATE: 1983

SUMMARY:

- Investigates methods to reduce WECS generation changes through:
  - selection of wind turbine characteristics for each site
  - selection of appropriate siting configuration
  - use of coordinated wind turbine controls
- Reduced WECS generation changes reduces the need for:
  - increased spinning reserve
  - increased unloadable generation
  - increased load following requirements
- Turbine parameters, siting, and coordinated blade pitch control can remove windfarm capacity as limiting design criterion from power system viewpoint.

EFFECT OF REDUCED SITING DENSITY AT A FIXED PENETRATION LEVEL





TITLE: An Integration Methodology for Large Wind Energy Conversion Systems

CONTRACTOR: Cornell University

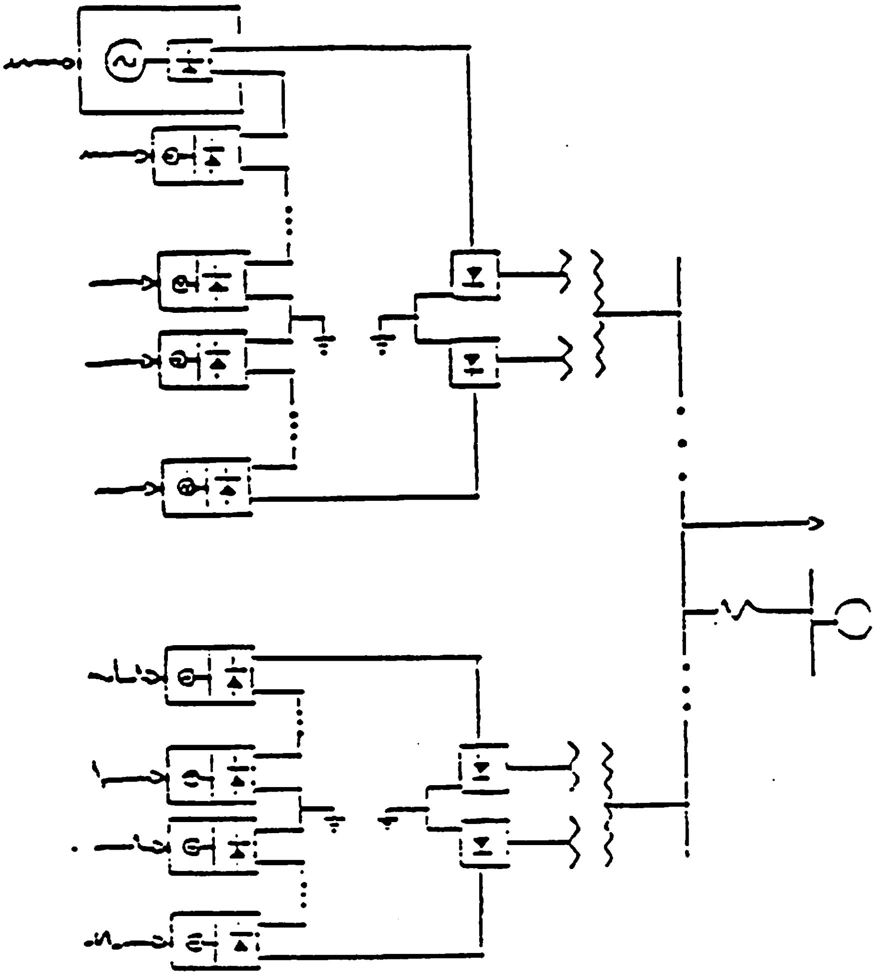
FUNDING AGENCY: DOE

DATE: 1985

SUMMARY:

- Developed synthetic wind data for large numbers of spatially correlated time functions.
- Investigated wind farm AC-DC-AC interface with variable speed wind turbine using controllable induction generator.
- Investigated economics, steady-state and dynamic control, and protection.
- Studied harmonic impacts, VAR requirements, damping system transient oscillations.
- Significant penetration can be achieved with no adverse impact.

Figure 9-1. AC/DC/AC Interface



TITLE: Status Report on Utility Interconnection Issues for Wind Power Generation

CONTRACTOR: ELECTROTEK Concepts, Inc.

FUNDING AGENCY: DOE

DATE: 1986

SUMMARY:

- Summarizes broad range of utility interface issues and R&D needs:
  - Wind Turbine Control Characteristics
  - Wind Power Station Dynamics and Control
  - Power System Planning Issues
  - Power System Operating Issues
- Operations Planning Requirements:
  - Load forecast and unit commitment 1 day to 1 week in advance
  - Accurately forecast hourly wind power values 24 hours in advance
  - Accurately forecast minute-to-minute variations 24 hours in advance.

- Real Time Operations Requirements:
  - Maintain system frequency, scheduled tie line flow, and economic dispatch
  - Increased penetrations possible with:

    Wind Power Station Control Strategies

    Adaptive Unit Commitment

    VSCF designs

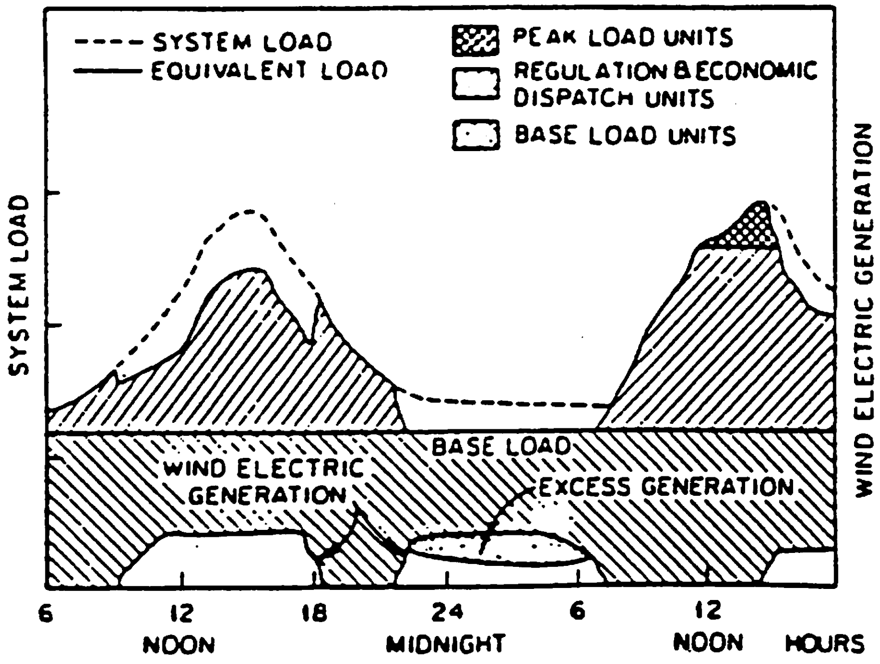
    Short-term storage

    Faster responding conventional units

    Integration with direct customer load control

Hypothetical Generation Dispatch with Wind Generation Against 48 Hours of Load Demand

EQUIVALENT SYSTEM LOAD PROFILE FOR A SIGNIFICANT AMOUNT OF WIND ELECTRIC GENERATION (PENETRATION DURING PEAK PERIOD IS 13.8%)



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2. Mod-2 Wind Turbine Farm Stability Study, PTI. DOE, 1980.
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NSHEB EXPERIENCE IN INTEGRATING WIND TURBINES WITH LARGE AND ISOLATED NETWORKS

W. G. Stevenson

ABSTRACT

Control schemes are described which are designed to optimise the power quality from a 250 kW and a 3 MW wind turbine generator installed on the island of Orkney in the north of Scotland (Fig 1). Until 1982 electricity supplies were provided by diesel generators. At that time a submarine cable connection was made to the mainland and therefore this site presents a unique facility to enable designs to be proved in both weak grid and stiff grid modes. Monitoring results are presented.

1 INTRODUCTION

The North of Scotland Hydro-Electric Board's area covers one quarter of the land area and contains about 2% of the population of Great Britain. It includes the most mountainous part of the mainland and a large number of offshore islands. Almost 99% of all potential consumers in the Board's area have been provided with a supply of electricity.

Since the oil crisis of 1973 the NSHEB has adopted a long term strategy for removing dependence on oil fuel used in making supplies available on its main island groups. The connection of these island groups to the mainland by submarine cable is the prime option. In the medium term, wind energy is considered to be the most likely viable alternative energy source for island groups to which it is currently uneconomic to provide a mainland cable link.

Following discussions with the UK Departments of Energy and Industry an agreement was reached in late 1981 to proceed with a 250 kW machine (MS1) (Ref 1) with Department of Industry support and a 3 MW machine (LS1) (Ref 2) with Department of Energy support, both to be sited on Burgar Hill, Orkney. Design concepts for the 3 MW machine to be incorporated in the 250 kW machine. Both machines were designed and constructed by the Wind Energy Group comprising Taylor Woodrow Construction Ltd, British Aerospace Dynamics Group and GEC Power Engineering Ltd.

2 ORKNEY PROJECT

The power transmission and associated control systems for the wind turbine generators MS1 and LS1, forming part of the UK wind energy programme, are discussed in this paper (Ref 3). The smaller turbine MS1 is rated at 250 kW with a rotor diameter of 20 m and was connected to the grid on Mainland Orkney in August 1983 (fig 2). MS1 is both a versatile research machine and a development prototype for the larger 3 MW, 60 m diameter machine LS1. The LS1 was first synchronised to the grid in February 1988. It is expected that post synchronisation tests will be complete by May 1989.

The electrical system on Orkney is basically an isolated grid fed by diesel generators with an installed capacity of 35 MW. Although the grid was connected to the main Scottish grid in 1982 by an undersea ac link, thus making it electrically stronger, LS1 and MS1 are required to meet the more arduous control conditions associated with providing adequate power quality to the isolated, electrically weak grid.

The variability of the wind also introduces control problems for wind turbines that do not apply to conventional generators, since for maximum economy wind turbines are required to supply electricity whenever the wind is available and without appreciable power-smoothing losses. In general, most turbulent fluctuations in the wind occur with time-scales in the range of 5 s to 10 min. On Orkney the wind speed can vary typically by 20% over 2 s. Since the power available is proportional to the cube of the wind speed, a wind speed variation of 20% corresponds to a variation of 70% in power. The situation is complicated by the rotation of the wind turbine rotor, which introduces additional fluctuations at the rotational frequency and its harmonics.

The quality of electrical power supplied to the grid system by the wind turbine generator is mainly determined by cyclic variations in output power, although power factor variations and harmonics also need to be taken into account. For a weak grid these variations affect the frequency and voltage of the grid system. For a given set of input wind conditions, output power fluctuations can be reduced by dumping or storing energy above a set power level. The Orkney wind turbines can dump energy by varying the pitch of part of the rotor blades to reduce the energy capture efficiency and can store energy in the rotational inertia of the rotor.

3 CONTROL SYSTEMS FOR THE 250 kW WIND TURBINE

The power transmission of the 250 kW, 20 m diameter wind turbine generator MS1 consists of a low-speed shaft which carries the wind turbine rotor and is mounted on two main bearings. The shaft carries a two-stage in-line gearbox, the high-speed output shaft of which is connected to a synchronous ac generator via a one-way clutch. A disc brake is mounted on the low-speed shaft between the bearing housing and the gearbox.

The power transmission is located at the top of the wind turbine tower in a rectangular nacelle, which is rotated to keep the wind turbine rotor pointing into the wind. The yaw control system is not discussed here.

All the functions of the machine are controlled by a mini-computer (Fig 3). The control system can be divided into two functions: (1) "Health" start/stop/run; (2) Regulatory.

The health control system scans sensors indicating a number of machine and external conditions - eg wind speed - and initiates procedures such as start-up, stop, yaw corrections and so on. The regulatory control system comes into action when the health system allows the machines to run.

MS1 may be operated in either fixed-speed or variable-speed mode. The variable-speed mode allows the optimisation of the aerodynamic efficiency of the rotor to different wind conditions. The variable-speed mode was included in the design in order to assess the increase in energy production achievable, particularly at lower wind speeds.

In the fixed-speed mode the turbine rotor is run up on a controlled-speed schedule to 88 rev/min and then synchronised to the grid. If the power demand is greater than that available in the wind, then the machine is essentially uncontrolled and the grid must accept all the power offered to it. Power fluctuations caused by the combination of wind turbulence, the variation of wind speed with height and the rotational speed of the turbine rotor are attenuated by the introduction of an element of resilience into the transmission system. This is accomplished by allowing the gearbox casing to rotate through a limited angle against restraining springs and dampers.

If the power demand is less than that available in the wind, or if a more constant power output is required, then the fast-acting variable-pitch tips forming the outer 20% of the blade radius are used to spill the energy captured by the blades. The tips are also used for start-up, and normal and emergency braking.

The control scheme for the fixed-speed mode is shown in fig 4. The basic control is on the basis of output power. An error between the actual and demanded output power is fed to the tip servos via the microprocessor controller. Gearbox case velocity and wind turbine rotor speed signals are used to compensate the control loop to give improved dynamic performance and reduce the variation in output power. For optimum operation the control system gain is automatically adjusted with respect to the mean wind speed.

Figures 5 to 10 illustrate records of generated power, reactive power and tip jack actuator position with power demands of 250 kW and 100 kW respectively ie unregulated and regulated in the fixed speed mode. The records were taken on 13.10.83. Note that, once the power demand was set to 100 kW, for the first 20 seconds the power was ramping down to the set level. Blade tip position is a (slightly non-linear) function of jack position, where 0 mm jack position corresponds to 9 degrees tip, and 300 mm corresponds to 90 degrees.

The plots well illustrate the effect on power quality of both the swung gearbox (the power peaks in unregulated running are rounded rather than spikey) and tip control.

In the variable-speed mode the output of the generator is fed to the grid through a rectifier-inverter system, as shown in fig 11. The speed is controlled to vary between 44 and 88 rev/min in such a way as to maximise the energy captured from the wind by optimizing the aerodynamic efficiency for the particular wind conditions. This entails keeping the ratio of the tip speed to the wind speed near a value of 8. At any given rotor speed the optimum power is selected from a look-up table within the controller, as indicated in fig 11. In addition, power quality is improved by allowing fluctuations to be absorbed in speed changes, and the gearbox case resilience is not normally required.

In this case the power is controlled by setting the firing angle of the inverter thyristors, with subsidiary control of the dc link voltage through the generator field. When the wind speed reaches a sufficiently high level, the wind turbine is constrained to the maximum rated speed of 88 rev/min and operation is no longer at the optimum tip-speed to wind-speed ratio. The blade tips are held constant at the maximum torque setting with increasing wind speed until the maximum rated power is achieved, when they operate to spill excess power.

Figures 12 to 17 illustrate sample records of rotor speed, generated power, generated current, reactive power, windspeed and grid voltages with the machine operating in variable speed mode (ie with Power Conditioning Unit in service) in the medium to high output range.

A Comparison was made between the fixed-speed and variable speed mode characteristics using data from the same day or two of operations. A correction term was added representing the losses in transmission and generation to obtain the rotor power. The rotor power thus calculated and averaged in bins of windspeed for each mode is shown in Fig 18. The variable speed mode power is seen to be the greater up to 8 metres/sec., but fixed speed mode power is greater in winds of 11 metres/sec or more. Analysis of power losses shows that no additional loss in variable speed mode is detectable up to 100 kW output, after which additional loss grows rapidly. It appears that at low power the losses in the Power Conditioning Unit (PCU) balance the reduced transmission losses associated with a lower speed but at higher powers the PCU losses become dominant.

The most striking result to have emerged from this investigation is that energy capture in the variable speed mode is if anything rather lower than at synchronous speed, whereas improved energy capture is commonly advanced as a benefit of variable speed running. From the machine power/windspeed curve and the windspeed distribution at the site the energy capture at 100% availability is estimated to be 10% higher in the fixed speed mode than in the variable speed mode.

In practice, the amount of running in PCU mode has been severely restricted by operational difficulties. Most of these can be attributed to the distorted 50 Hz wave form produced by the Thyristor invertor. This caused interference on the local telephone network and spurious tripping of the machine. Active consideration is being given to the replacement of the PCU equipment with more modern equipment (the original was designed in 1981) and incorporating harmonic filters.

Genuine overcurrent trips were experienced however due to the poor power factor. This problem prevented PCU mode operation in winds gusting above 18 metres/sec.

The operation of the PCU leads to a high level of reactive power as can be seen in Fig 19 where ten-minute mean values are plotted against those for direct power. This shows that the phase angle is stable at about 44°. The apparent intercept at about 3 kVAR may represent a zero error. By contrast in DC mode the phase angle typically varies between -15° and +15°. Thus in PCU mode, the power factor is about 70% whereas it is typically over 97% in DC mode.

The 250 kW 20 m diameter MS1 prototype unit now has a high availability and up to the end of February 1989 had operated for 18558 hours and generated 1674095 kW hrs

4 POWER TRANSMISSION AND CONTROL FOR THE 3 MW WIND TURBINE

It was decided to base the power transmission of the 3 MW,60 m diameter wind turbine generator LS1 on reaction-machine resilience, in which the reaction machine and differential gearbox are mounted on top of the main generator in the tower head.

The overall concept of LS1 is illustrated in fig 20 and the tower top equipment in fig 21 and is discussed further in reference 2. The main components of the drive train are shown in fig 22. The main shaft is supported by bearings within the casing of the primary gearbox, which consists of two parallel epicyclic stages followed by a bevel output stage. The disc brake operates on an extension of the secondstage output shaft and is designed to stop the machine from overspeed in an emergency, as well as to bring the machine to a final stop following normal operation of the tip-blade pitch-control system in the braking mode. This equipment is located in the nacelle.

The flexibly-mounted shaft transfers power from the nacelle through the secondary, differential gearbox to the generator mounted vertically in the tower top. A shear-pin assembly protects the gearbox against generator faults.

The four-pole, synchronous, reaction machine is fed from a standard four-quadrant variable-frequency inverter (GEC Industrial Controls' SYNCDRIVE). Reaction machine torque (and thus generator shaft torque and generator output power) is controlled as a function of reaction machine speed. Operation in the first and second quadrants caters for generating and motoring conditions. The system has characteristics similar to those for a Ward Leonard controlled dc machine.

Control philosophy

The power transmission system and the generator control and protection systems are designed to optimise the following features:-

(i) Quality of power output
(ii) Control flexibility
(iii) Availability and reliability
(iv) Personnel and plant protection under fault conditions

For the 3 MW wind turbine LS1 the turbine speed is permitted to vary cyclicly by up to ± 5% as a result of wind speed fluctuations, whilst the main generator remains synchronised to the grid. This gives considerable attenuation of cyclic torque fluctuations at the generator.

The control system is designed to ensure that cyclic power fluctuations are reduced and that the system will perform satisfactorily during large ramp or step changes in wind power. To this end the resilience and pitch-control systems are combined as a single system designed to minimise the frequency and rate of tip blade movement. (On the 3 MW wind turbine the blade tips are referred to as tip blades, because they sweep a larger area than the inner blades.)

Since the control laws for all these functions are generated as algorithms within a computer, adjustments and modifications can be made any any time, with suitable in-built security precautions. Automatic control of run-up, synchronisation, shut-down, and emergency shut-down sequences are included within the computer.

During start up, following release of the brake, acceleration of the rotor is controlled by adjustment of the tip blades pitch setting. This control is exercised by the supervisory control system (SCS), acting in conjunction with the closed loop controller (CLC). See fig 23. The SCS transmits a rising rotor speed demand to the CLC, and the CLC, fed with measured rotor speed, adjusts pitch setting to meet this demand. When rotor speed reaches 32.6 rpm, equating to a generator speed of 1438 rpm, the reaction machine, which is coupled to the main drive train via the third shaft of a differential gearbox, is enabled. The reaction machine is then accelerated to raise the generator speed to 1500 rpm and hold it there, while adjustment of tip blade pitch setting continues to maintain rotor speed close to 32.6 rpm. The SCS then enables the auto-synchroniser which, in conjunction with the SCS/CLC speed control, adjusts the generator speed further to permit synchronisation.

During operation, the LS1 rotor is free to teeter, uncoupling out of plane bending moments from the main shaft, primary gearbox, etc. Whilst stationary and during the initial stages of start up, full teeter restraint is imposed. During the course of start up this restraint is removed.

Figures 24 to 27 show records of measurements made during a particular start up sequence. More details are provided in reference 4.

These illustrate CLC combined control of reaction machine and pitch setting to achieve generator speed control - 170 to 185 secs with wind speed between 17 and 23 m/sec:

Figure 24:	Wind Speed
Figure 25:	Reaction machine speed
Figure 26:	Tip blade pitch setting
Figure 27:	Generator speed error.

It should be noted that all wind speed records reproduced here are from an anemometer mounted at the equivalent of 45 m hub height, on an 80 m high mast located some 300 m distant from the wind turbine.

Generation Below Power Demand

Following synchronisation the CLC switches to power control. This is exercised through torque control of the reaction machine as a function of turbine rotor speed and through pitch control of the tip blades. The higher frequency wind power variations (up to 0.2 Hz approx) are attenuated by permitting the turbine speed to vary over a limited range (±5%) at constant torque. The pitch control system enables the wind turbine to follow large low frequency wind power variations.

When the power available in the wind is less than demanded, the tip blades are held at fine pitch and power control is exercised solely by the reaction machine. Figures 28 to 32 show records of measurements of wind speed (at the 80 m mast), pitch setting, reaction machine speed, rotor speed and power output, made during operation when the wind speed was falling, and the reaction machine was accelerating in order to compensate for decreasing rotor speed. There is a corresponding modest reduction in mean power output, from 1.4 MW to 1.1 MW, as a result of the gradual slope of the speed/torque characteristic that governs CLC control of the reaction machine. The record of power output also displays fluctuations at blade passing frequency, as a result of gusting, tower shadow etc. The extent to which the fluctuations have been attenuated by the reaction machine is not clear from early records, such as these, although small perturbations in reaction machine speed are evident.

Generation With Power Limitation

Normally, power regulation by moving tip blade pitch setting away from fine pitch is only exercised when wind speed rises above the 17 m/sec level at which the turbine will generate at its 3 MW rated capacity. At any time, however, when limitation at a lower power level is required (such as during the initial stages of operation), a lower level can be set and power input is limited by the CLC system, exercising pitch control.

Figures 33 to 35 show measurements of wind speed, pitch setting and power output taken during operation with power output limited to 600 kW, when the mean wind speed was falling from 18.5 m/sec to 15.5 m/sec and corresponding available power therefore remained above 2.3 MW. As shown in figure 36, the reaction machine was in this instance constrained to hold a more or less constant speed.

Shutdown

Normal shutdown is controlled by the SCS/CLC. The tip blades are driven to coarse pitch at a rate of 10 degrees per second, the generator is de-synchronised and teeter restraint is applied, at first through switching in dampers, followed by application of full restraint.

Figures 37 to 40 show records of rotor rpm, tip blade pitch setting, teeter restraint and teeter excursions over a period of 160 secs during a shutdown when mean wind speed was 13 m/sec.

Summary

The essential function and operation of the reaction machine system, when operating within the constant torque band described earlier, are as follows:-

The function of the reaction machine system is to maintain a constant unidirectional torque on the third shaft of the differential gearbox, as set by the torque demand signal. The torque on the turbine output shaft and on the generator shaft (and therefore output power) is proportional to this "third shaft" or reaction machine output torque.

Synchronised to the grid, the generator speed remains constant and the wind turbine speed varies in line with the acceleration and deceleration produced by the difference between the constant shaft torque and the variable wind torque on the turbine blades.

Taking into account gearbox ratios, the reaction machine speed is constrained, through the differential gearbox, to be equal to the difference between the generator and wind turbine speed. Any variation in reaction machine torque has therefore only an indirect effect on reaction machine speed, caused by the resulting variation in wind turbine acceleration/deceleration torque.

In order to reduce reaction motor size and therefore minimise the destabilising effect of reaction motor inertia, the latter was designed to rotate in either direction (Motoring or regenerating) as required by the difference between generator speed (constant) and wind turbine speed.

The reaction machine is a 4 pole synchronous type fed from a static variable frequency converter. The gearbox ratios are such that a ±5% speed variation of the wind turbine from synchronous speed causes the reaction machine speed to vary between ±662 rpm.

At the higher reaction machine speeds the VF converter thyristors are controlled from the reaction machine back emf but at low speeds the latter is not sufficient and forced commutation is employed. The forced commutation operation band is termed Mode 1 and natural commutation, Mode 2. The changeover point in both directions of rotation is very approximately an average of 150 rpm but hysteresis is included to prevent hunting.

When setting to work of the system commenced and no closed loop torque control, it was found to be difficult to match the torque levels exactly between Mode 1 and Mode 2 for all conditions and output power levels. In addition, when changing from one mode to the other it was necessary to change the field control setting and this introduced significant torque pulses into the system.

In Mode 1 and during Mode 1 to Mode 2 changeover it is necessary during commutation of the thyristors to interrupt the current for about 7 milliseconds. This normally has little effect on the system but occasionally, during the setting up period, a commutation failure occurred which caused a more severe torque disturbance to the system.

During this initial stage of setting to work the torque variations were severe and were further amplified by the oscillatory nature of the system. As a result it was not possible to measure the actual system response and introduce the torque and CLC feedbacks designed to stabilise the system. A "chicken and egg" situation resulted.

By the end of 1988 the performance of the variable frequency converter had been greatly improved and as a result it was possible to set to work the high speed shaft torque feedback and also the CLC power feedback. The combined effect of these two feedback systems resulted in a very significant reduction in the amplitude of power transients and enabled further adjustment to the VF converter to be made. Fig 41 illustrates the power quality achieved in a specific test during which the reaction machine operation was forced from regeneration to motoring, back to regeneration and again to motoring with a total of 5 mode changes and 3 zero crossings. The mean wind speed during the test was 18 metres/sec. Generally the quality of the output is excellent with variations restricted within 4% of the mean level. On the other hand the transient disturbances that remain at syncdrive mode changes and zero crossings are as much as ± 14% of the mean. Such transient disturbances will occur much less frequently during normal operations than during the test described above. Due to other delays it has not been possible to complete the optimisation of the system and further improvement is envisaged when work can recommence.

While commissioning has been under way it became evident that harmonic currents are being injected into the 11 kV supply from the syncdrive system and causing interference on the local telephone network. Harmonic current levels were measured and recorded at various power levels while the wind turbine was generating. Harmonic filter equipment is being designed for installation in the base of the support tower.

The post synchronisation programme is continuing with the machine having run at its rated output of 3 MW. Total running time to end February 1989 was 270 hours with a cumulative output of 305000 kW hrs. A monitoring programme will continue until mid-1990.

5 VOLTAGE CONTROL ON ISOLATED SYSTEMS WITH WIND TURBINE GENERATION

Typical island systems will comprise a diesel power station located in close proximity to the main load centre. It is quite common to find the diesel generators feeding into the same 11 kV feeders supplying the same bulk of the island load as indicated in Figure 42. The remainder of the island load is supplied from a 33 kV grid system to which are connected 33/11 kV transformers providing supply to small local 11 kV networks. In normal operation, with no wind-generation, voltage control on the system will be achieved by having the 11 kV generator busbar voltage maintained by AVR action on the diesel generators. The 33 kV grid system voltage will be maintained by manual tap change control of the 33/11 kV transformers, and the small local 11 kV networks will be controlled by automatic tap change control on the local 33/11 kV transformers.

Synchronous wind turbine generators with machines in the range from a few hundred kW up to 1000kW or 2000kW generate at 11 kV and can conveniently be connected into one of the small local 11 kV networks. Introduction of a wind turbine generator with its fluctuating power output causes voltage fluctuations on the local network which in turn are reflected in the voltage seen by the consumers. There will also be a variation in voltage gradient across the 33 kV grid system due to the changes in power transfer across the system.

Two options are considered for control of the voltage on the local 11 kV system to which the wind turbine generator is connected. The first option is to have the local 33/11 kV transformer on fixed tap and to operate the wind turbine generator with normal AVR control to maintain constant 11 kV voltage. The second option is to operate with constant power-factor control on the wind turbine generator AVR and to have the 33/11 kV transformer on automatic tap change control. The choice of option will depend on a number of factors including a) consideration of the wind turbine generator kW capacity in relation to both the local 11 kV load and to the total island load, b) the projected load factor on the wind turbine generator, c) the reactive capability of the wind turbine generator in relation to the requirements of the local 11 kV network and the 33 kV grid system with changing wind turbine generator power output and system load, d) the strength of the 33 kV grid system between the wind turbine and the diesel power station.

Wind turbine generators rated in MWs will have a greater reactive MVAr capability but will also have a greater impact on the system voltage particularly at times of low system demand. Generators in the kW range will have very limited reactive capability but will have far less impact on system voltage. The load factor on the wind turbine generator will be a measure of the proportion of time it will be there to provide voltage support to the local 11 kV network, and the size of wind turbine generator will in general dictate the reactive capability. The strength of the

33 kV grid system, or the electrical impedance between the wind turbine generator and the diesel power station site, will dictate the voltage variation resulting from the fluctuating power output of the wind turbine generator.

It is considered that the most convenient mode of operations is to put the wind turbine generator AVR on constant power-factor control, and to use the 33/11 kV automatic tap changer to control the local 11 kV voltage. In this mode the variation in wind turbine generator output when combined with the local load appears to the local transformer as fluctuating power transfer and the tap changer voltage control can be selected to give the requisite 11 kV target voltage and dead band to minimise tap change operations.

ACKNOWLEDGEMENTS

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4 SIMPSON, BURTON, LINDLEY & TURNER. "First Performance Results of the LS1 3 MW Wind Turbine on Orkney". 10th BWEA Conference, London, UK, March 1988.

POWER STATIONS AND MAIN TRANSMISSION SYSTEM

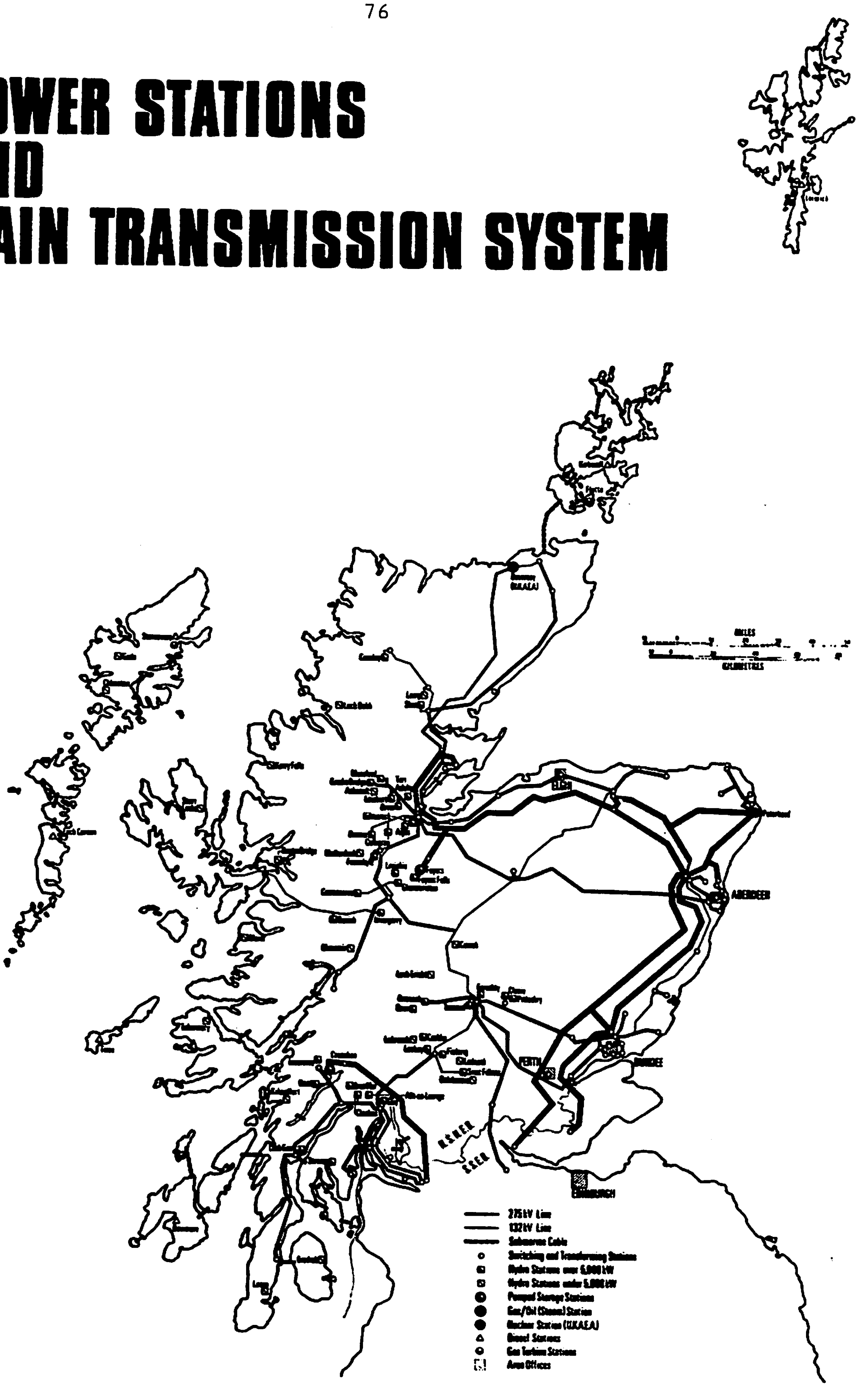


Fig. 1

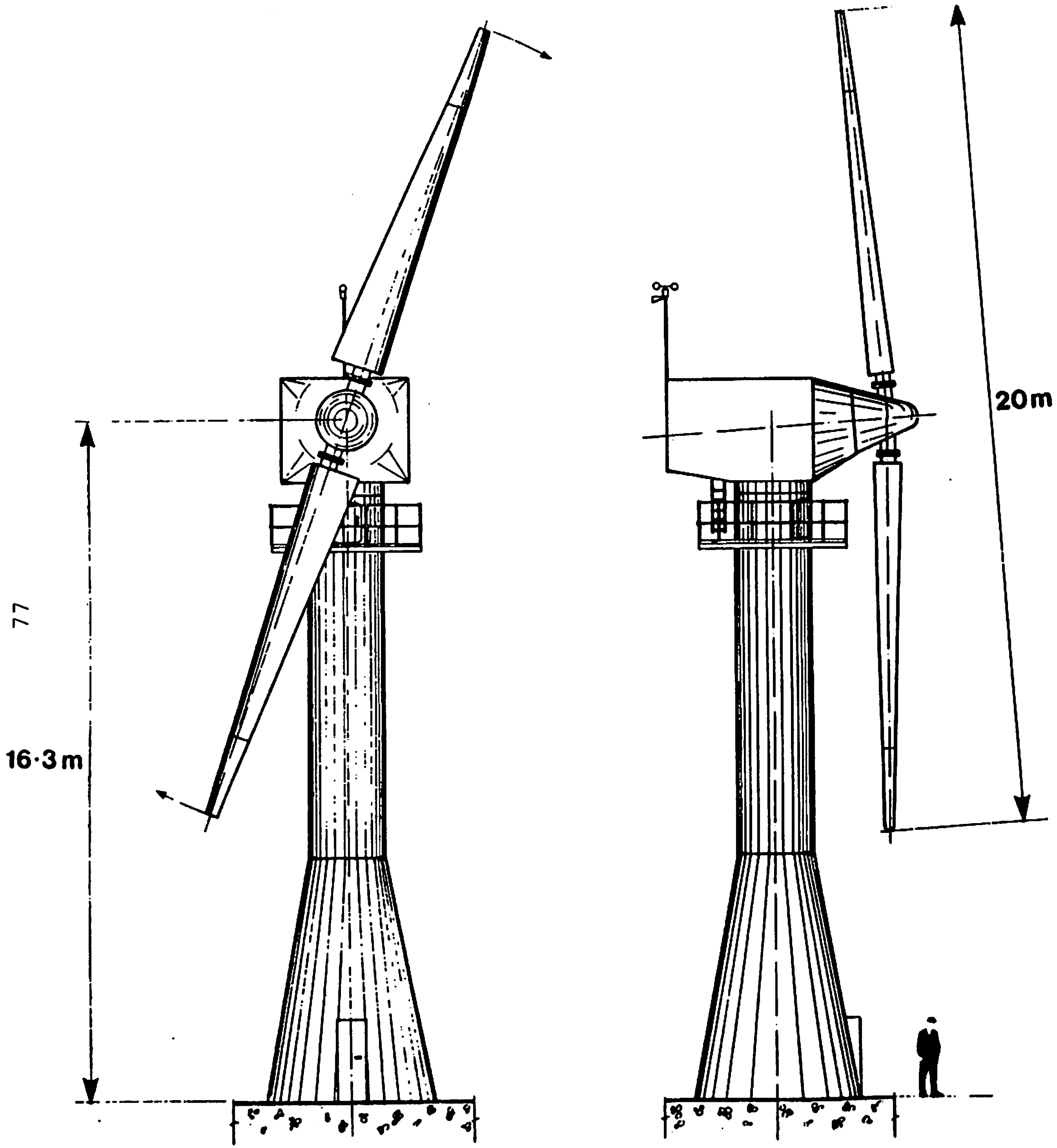


FIG.1 ORKNEY 20m W.T.G SPECIFICATION

DIAMETER	20m
RATED POWER	250kW
RATED WIND SPEED	17m/sec
ROTATIONAL SPEED	44–88 r.p.m.
BLADES	Fixed pitch, NACA 44xx series
CONTROL	Variable pitch tips
TRANSMISSION	2stage shaft mounted
GENERATOR	Synchronous, 440v. 3phase
ORIENTATION	Servo drive
TOWER	1·82m dia. steel
CONTROLLER	Microprocessor
ANNUAL ENERGY	700,000kWh at 10m/sec site

Fig. 2

ORKNEY 20m WTG INSTALLATION

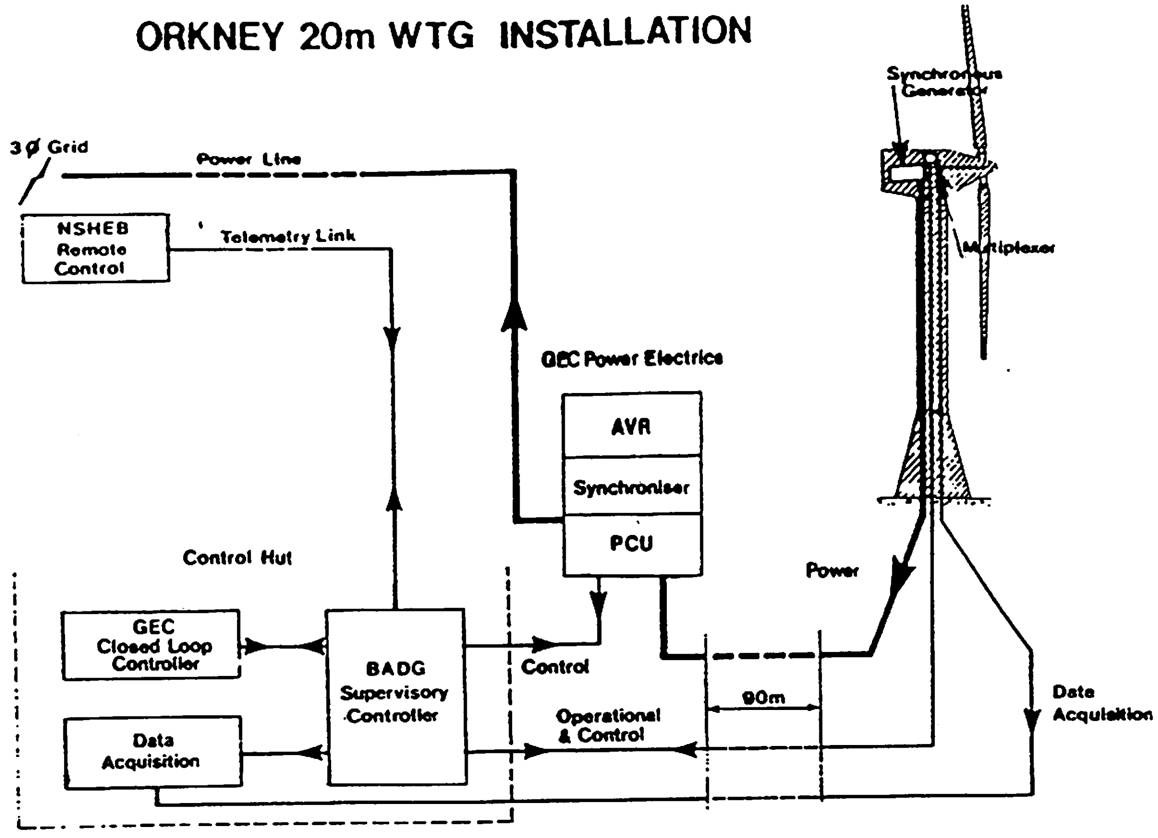


Fig. 3

CONTROL SYSTEM SCHEMATIC DIRECT CONNECTED MODE

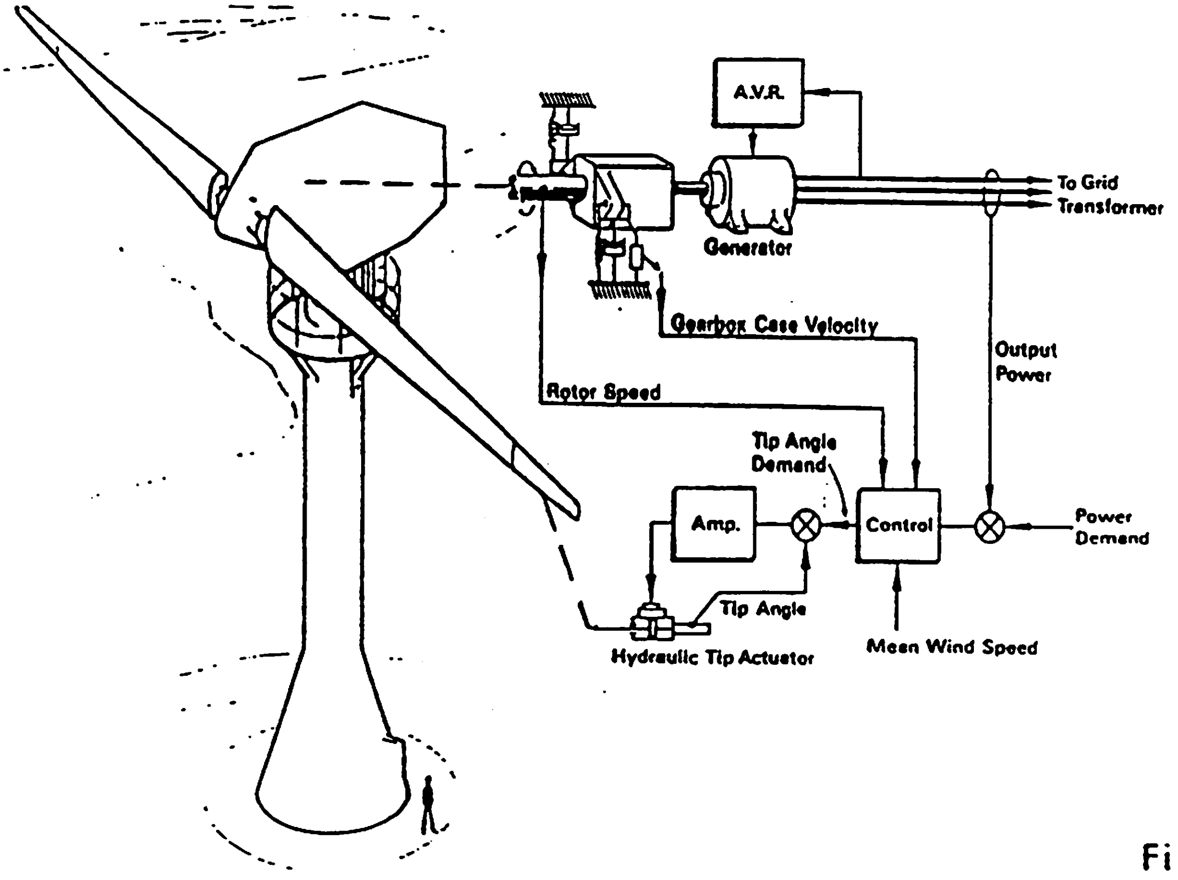
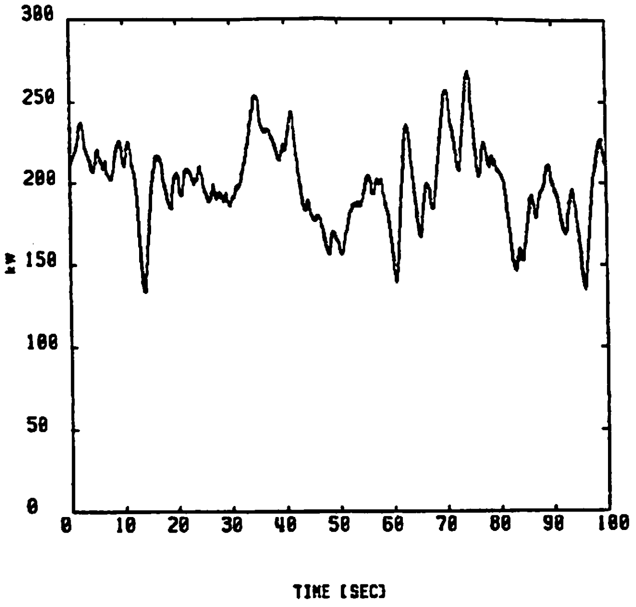


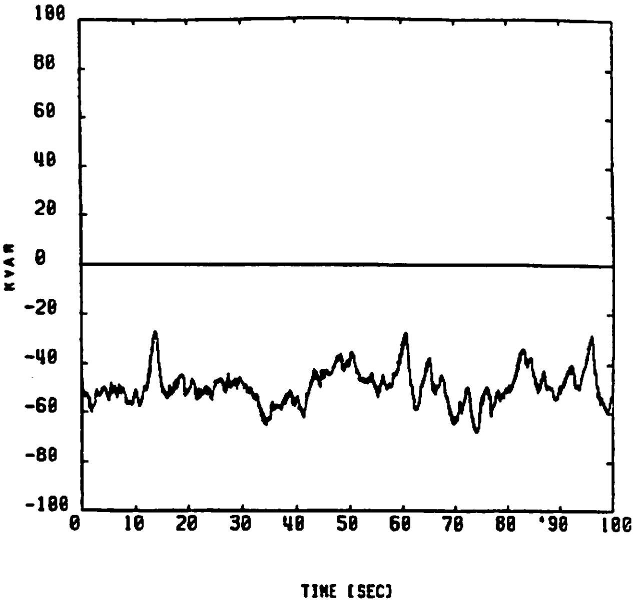
Fig. 4



250kW WTG

DC-MODE, UNREGULATED

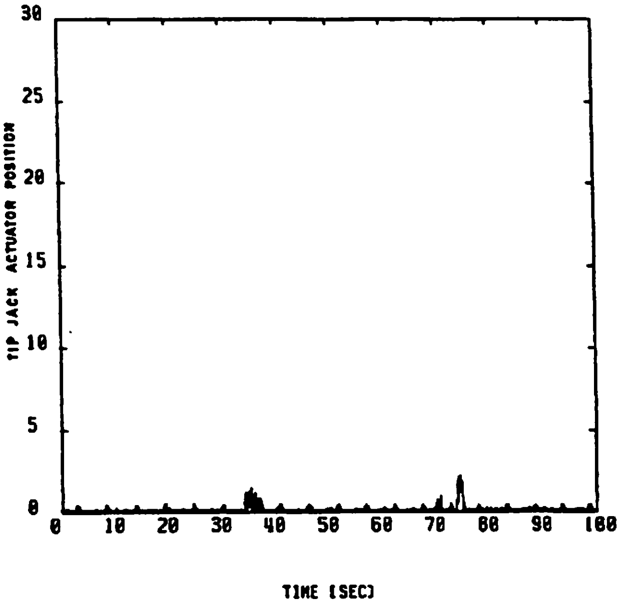
Fig. 5



250kW WTG

DC - MODE, UNREGULATED

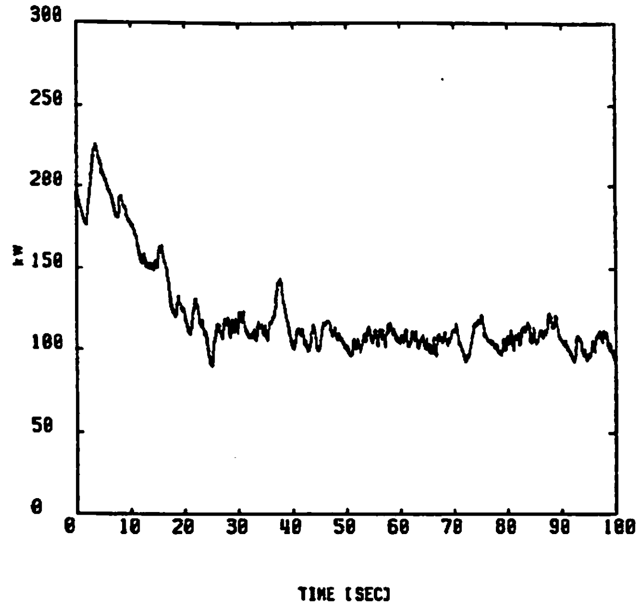
Fig. 6



250kW WTG

DC-MODE, UNREGULATED

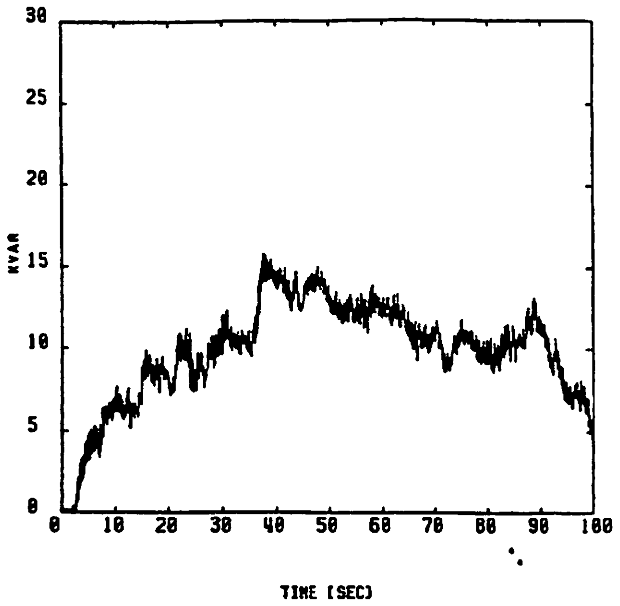
Fig. 7



250kW WTG

DC – MODE, POWER REGULATION

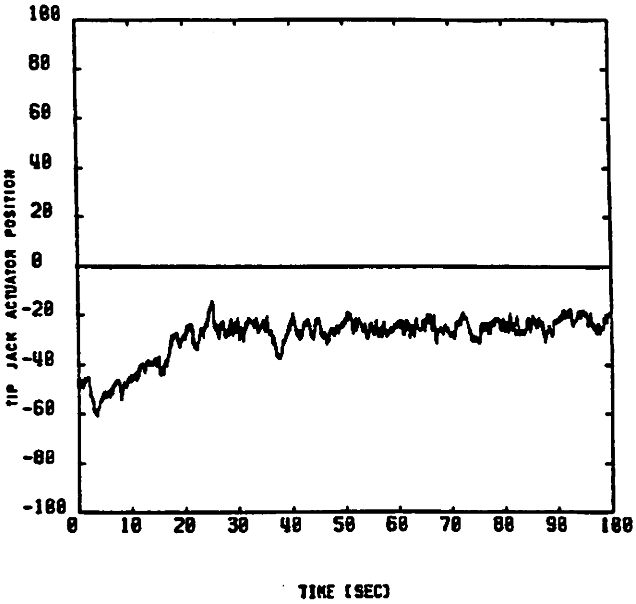
Fig.8



250kW WTG

DC – MODE, POWER REGULATION

Fig.9



250kW WTG

DC – MODE, POWER REGULATION

Fig.10

CONTROL SYSTEM SCHEMATIC P.C.U. MODE

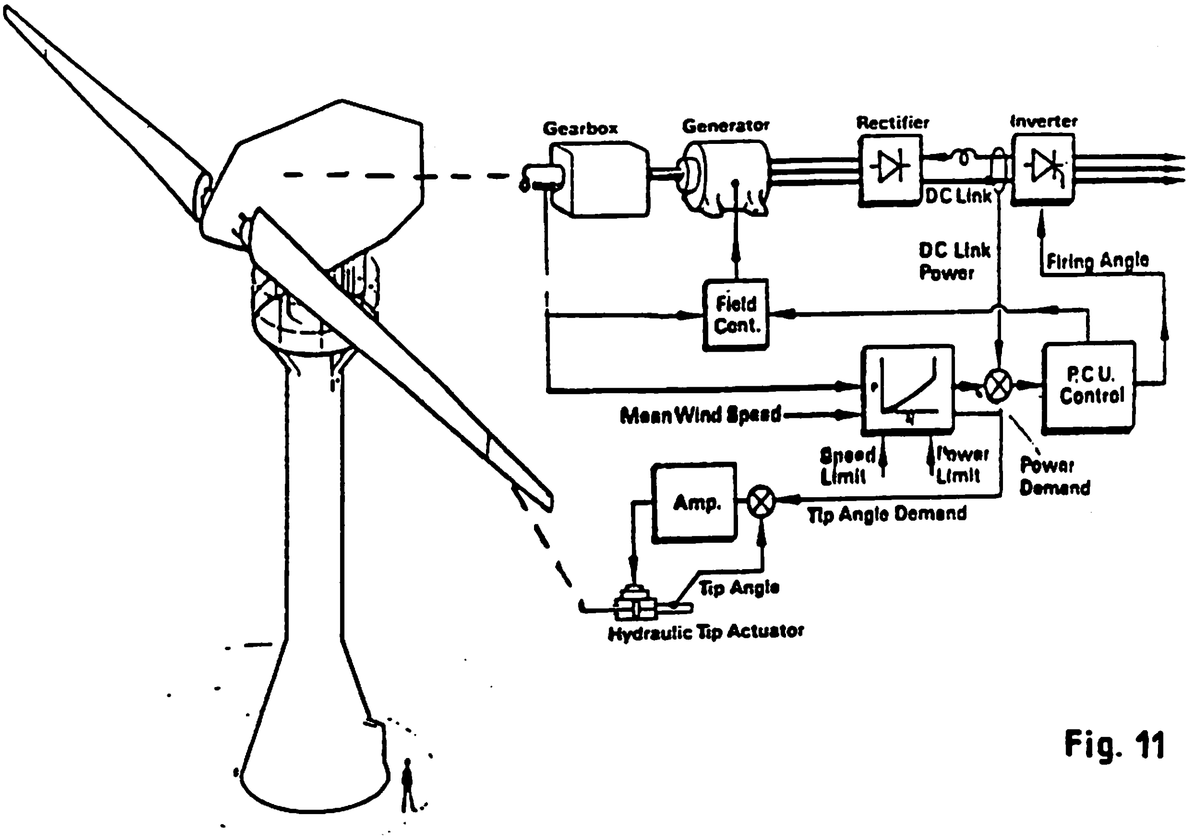
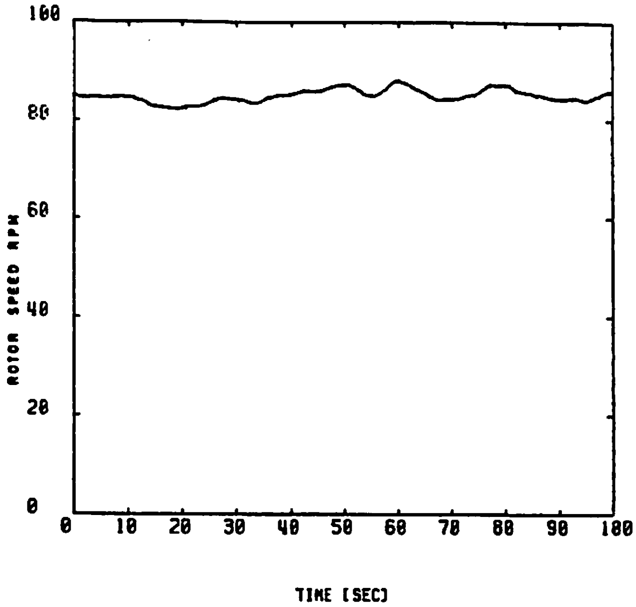
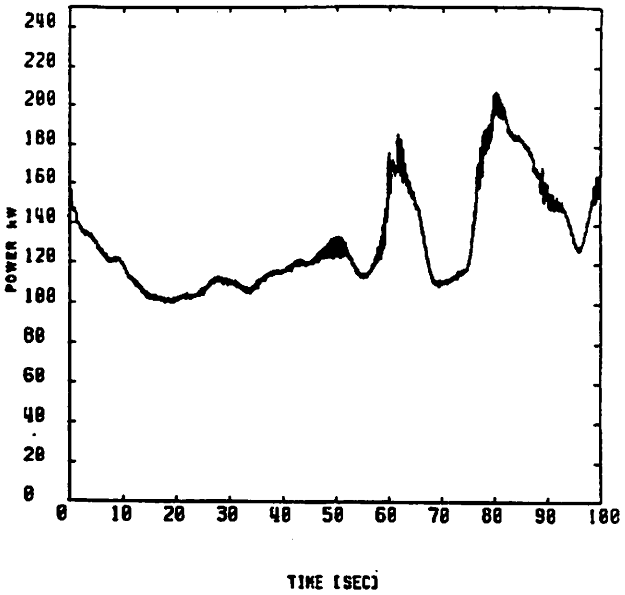


Fig. 11



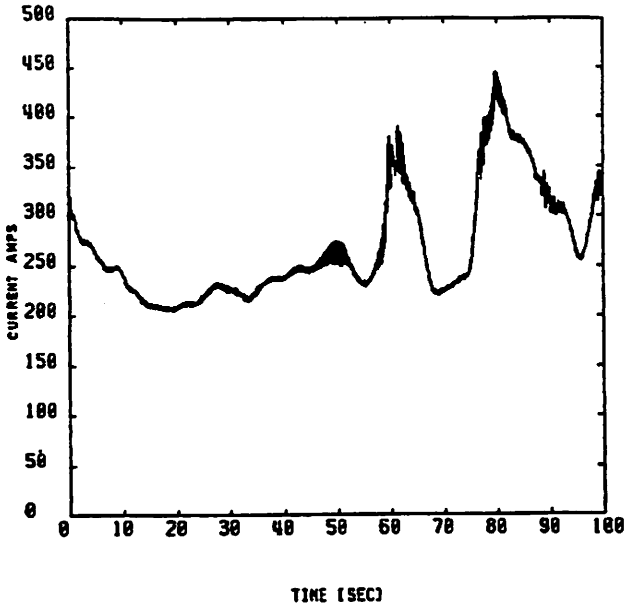
250kW WTG
PCU MODE

Fig. 12



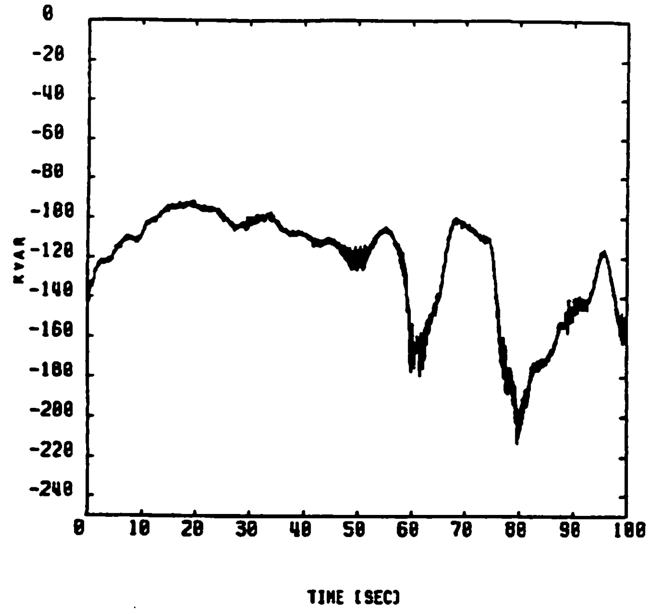
250kW WTG
PCU MODE

Fig. 13



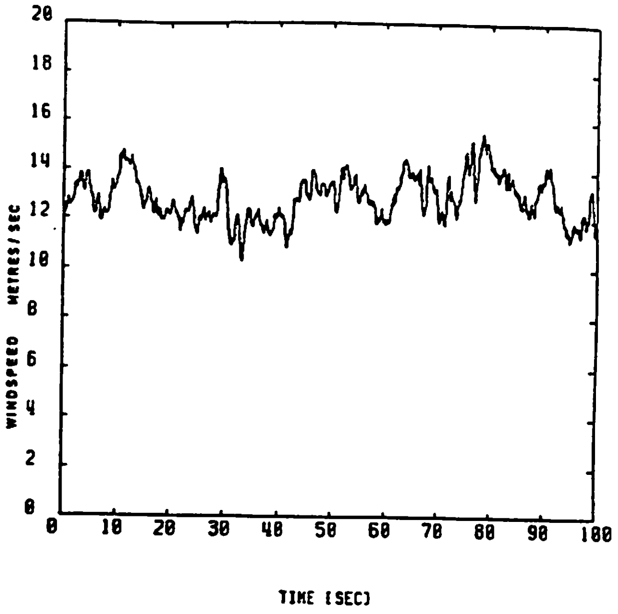
250kW WTG
PCU MODE

Fig. 14



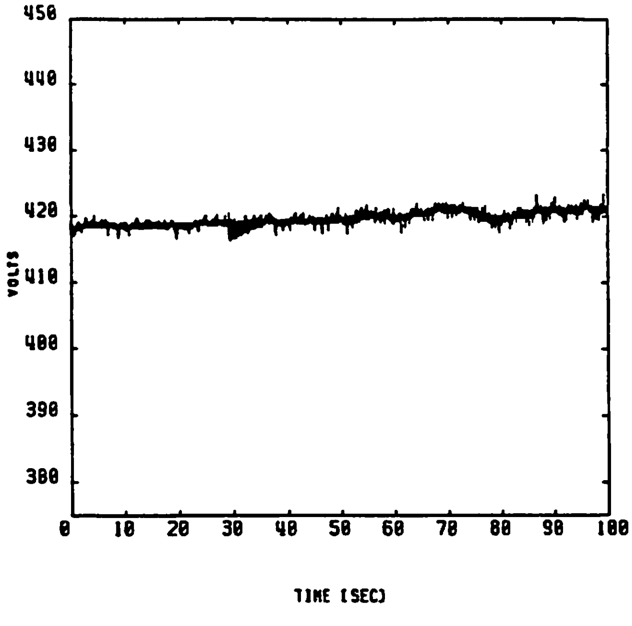
250 kW WTG
PCU MODE

Fig. 15



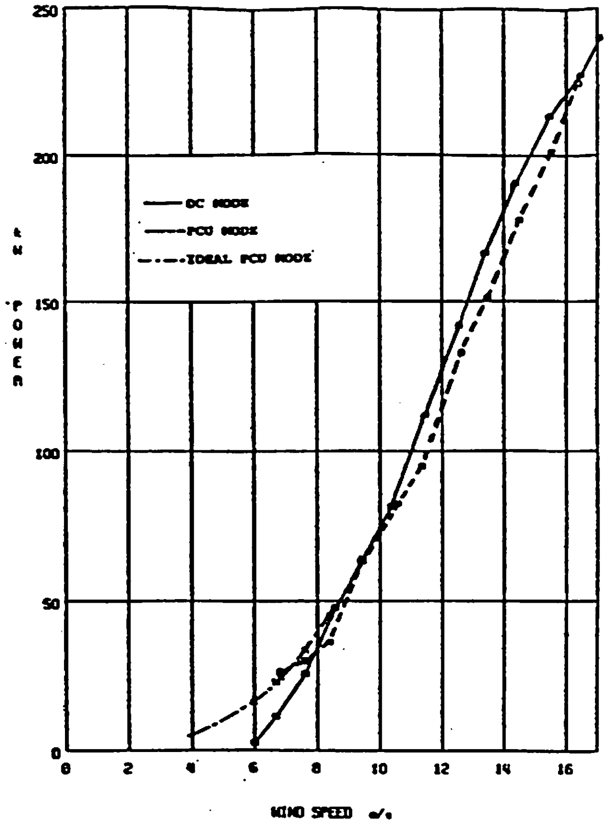
250 kW WTG
PCU MODE

Fig. 16



250 kW WTG
PCU MODE

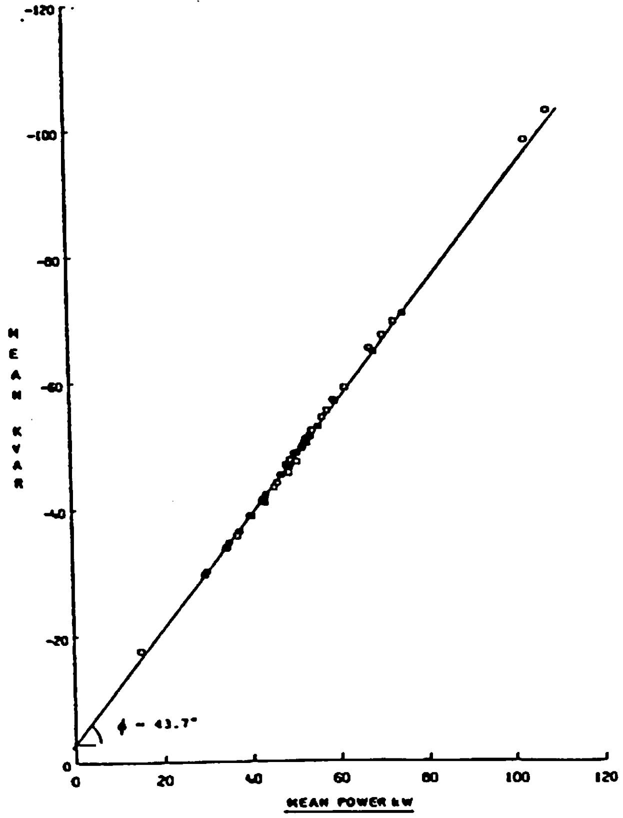
Fig. 17



250 kW WTG

POWER AT ROTOR IN TWO RUNNING MODES

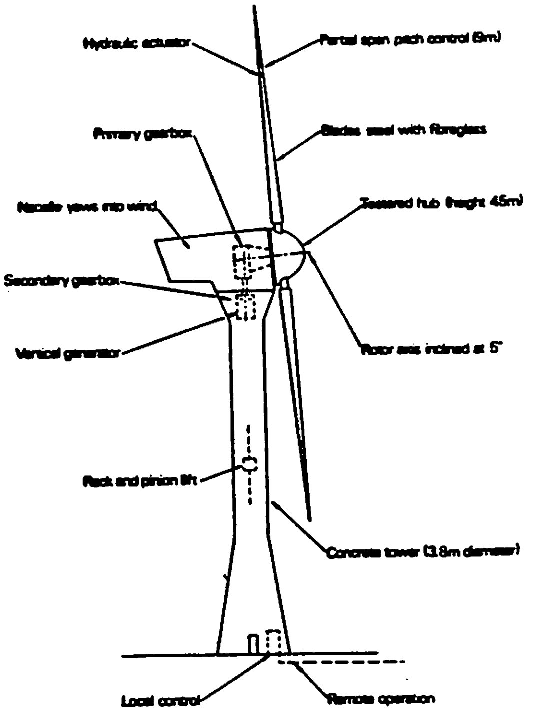
Fig.18



250 kW WTG

REACTIVE POWER IN PCU MODE

Fig. 19



The concept of the 3 MW, 60 m diameter wind turbine generator LS1 for Orkney

Fig. 20

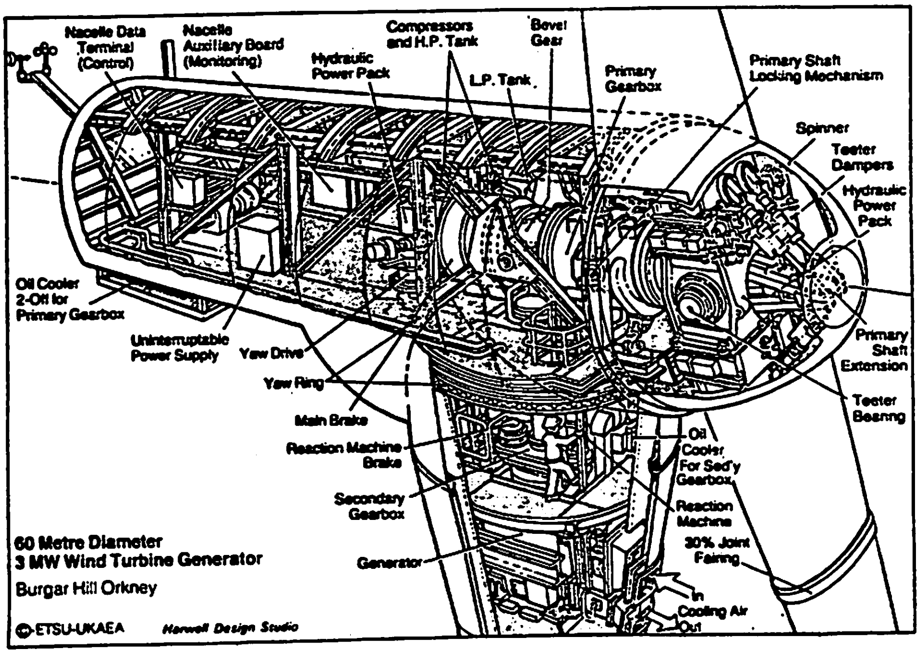
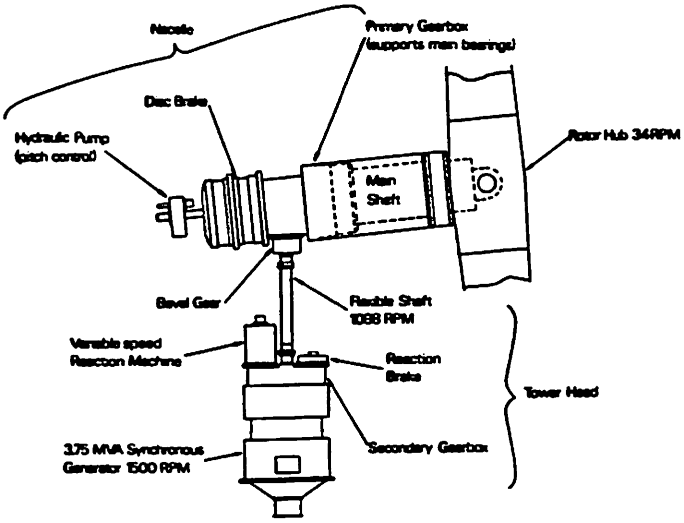
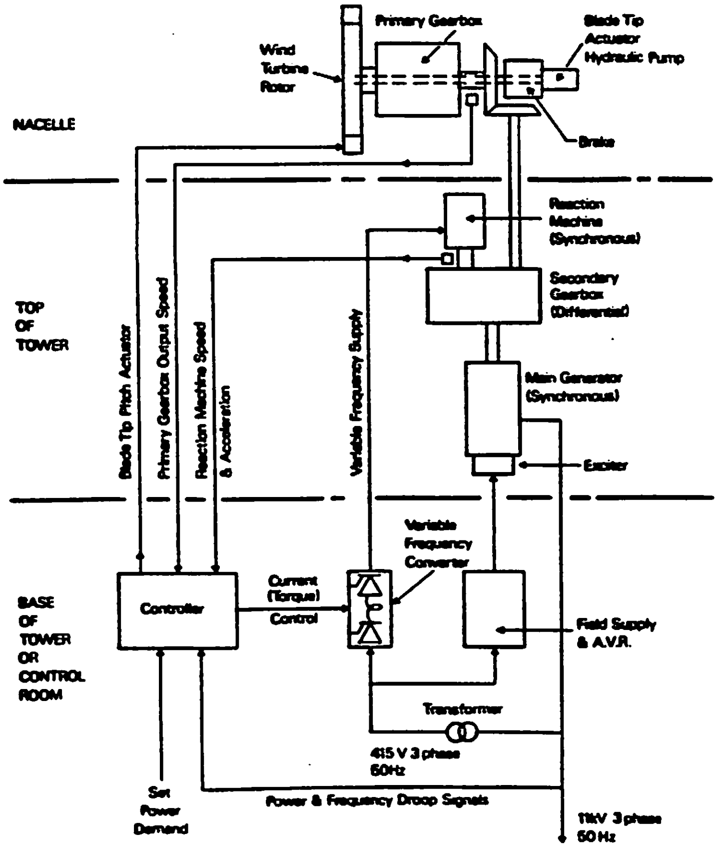


Fig. 21



Schematic arrangement of the power transmission for the 3 MW wind turbine generator LS1

Fig. 22



Block diagram of the closed loop control system for the 3 MW wind turbine generator LS1

Fig. 23

START UP

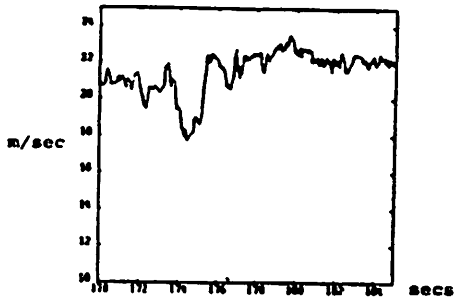


Fig 24 Wind Speed

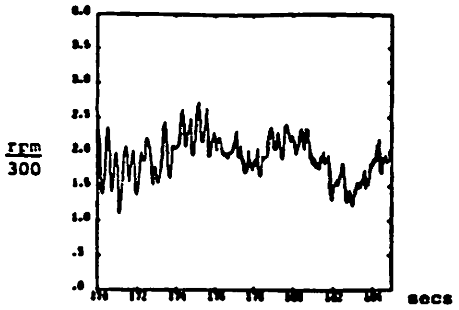


Fig 25 Reaction Machine Speed

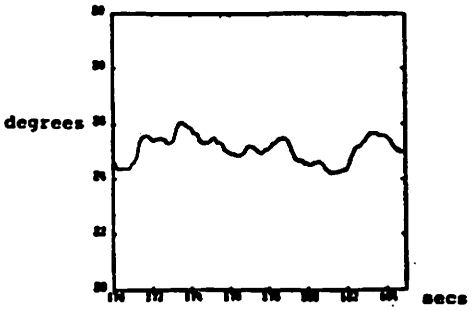


Fig 26 Tip Blade Pitch Setting

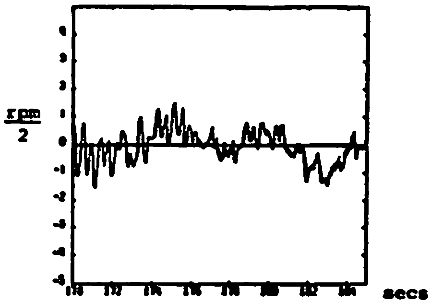


Fig 27 Generator Speed Error

GENERATION BELOW POWER DEMAND

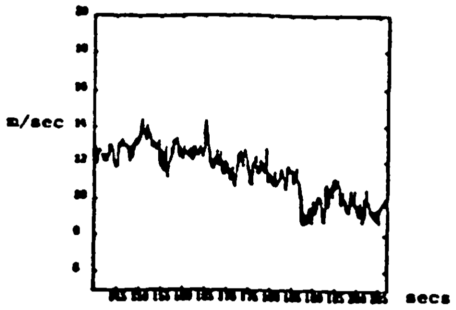


Fig 28 Wind Speed

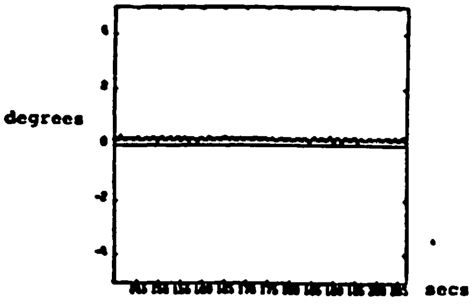


Fig 29 Tip Blade Pitch Setting

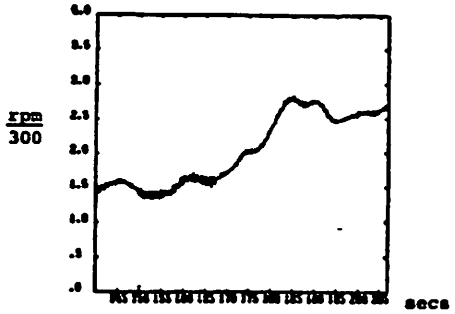


Fig 30 Reaction Machine Speed

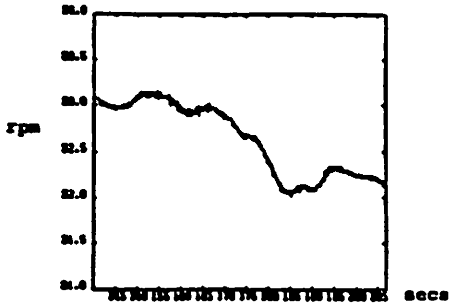


Fig 31 Rotor Speed

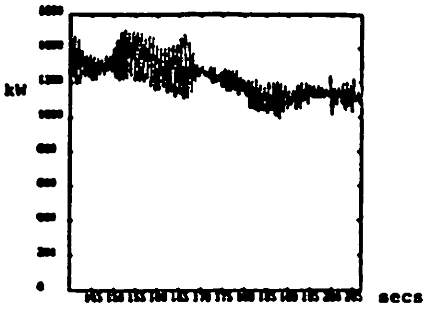


Fig 32 Power Output

GENERATION WITH POWER LIMITATION

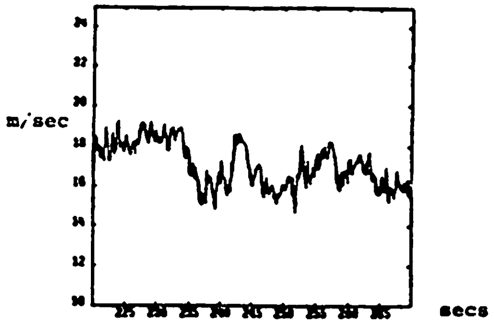


Fig 33 Wind Speed

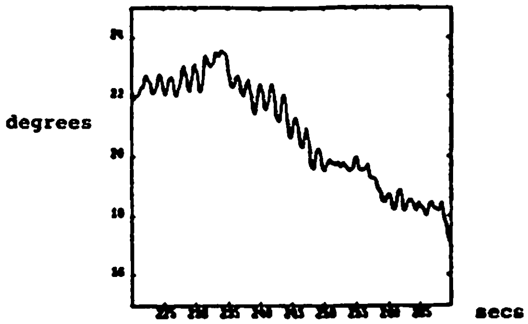


Fig 34 Tip Blade Pitch Setting

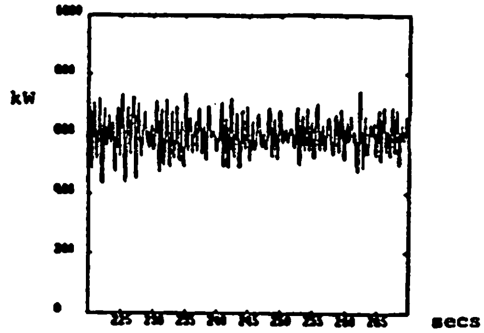


Fig 35 Power Output

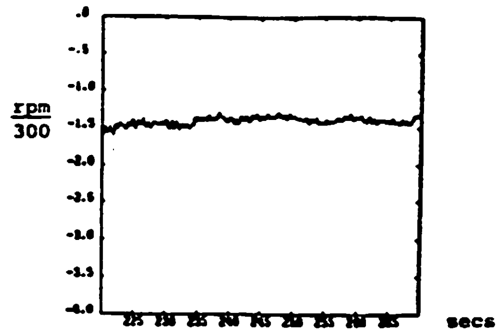


Fig 36 Reaction Machine Speed

SHUTDOWN

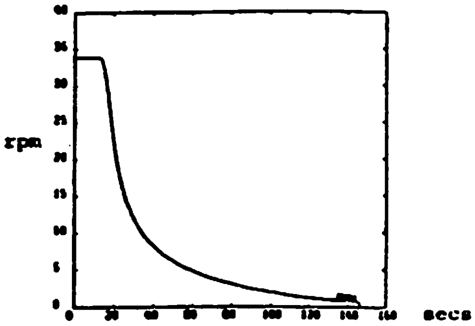


Fig 37 Rotor Speed

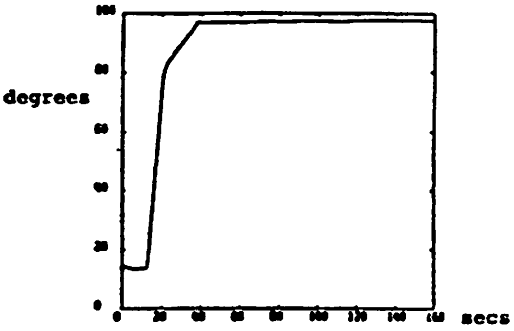


Fig 38 Tip Blade Pitch Setting

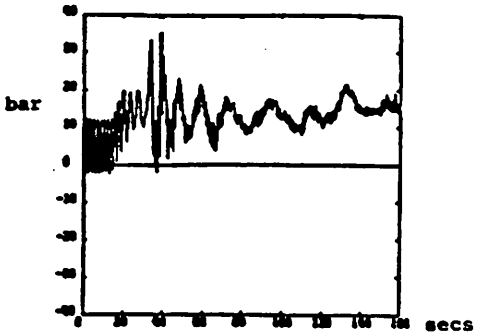


Fig 39 Teeter Restraint

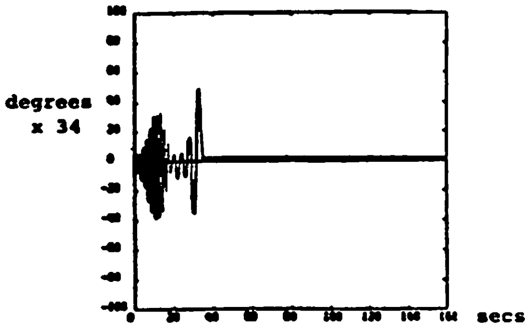
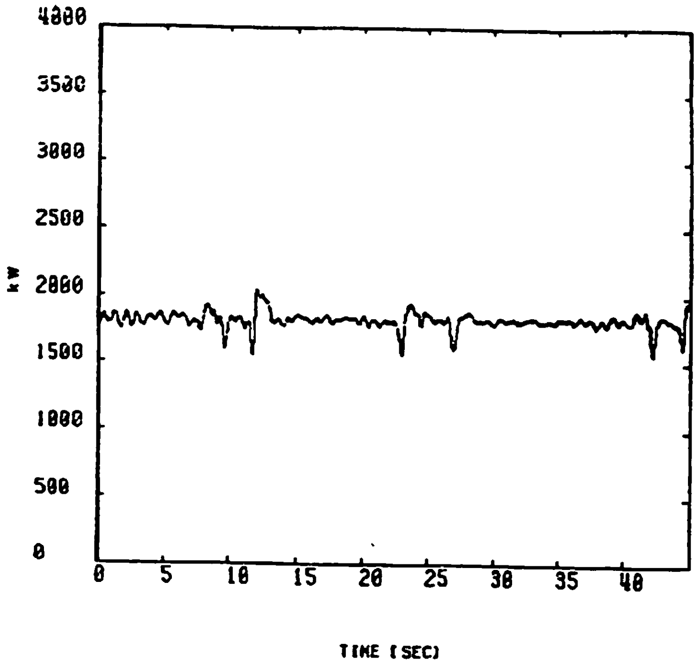
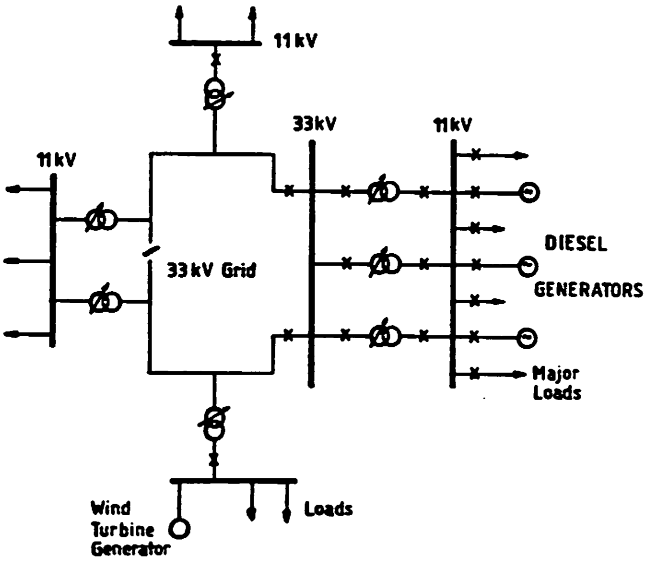


Fig 40 Teeter Excursion



3 MW WTG
REACTION MACHINE

Fig. 4.1



TYPICAL ISLAND ELECTRICITY SUPPLY SYSTEM

Fig. 4.2

WIND POWER INTEGRATION INTO HYDRO-THERMAL POWER SYSTEMS

Lennart Söder

Summary

The Swedish power industry performed a wind power integration study between 1979 and 1984. Wind energy replacement of 5-30 TWh in a system of total 145 TWh hydro-thermal production was studied. The hydro production was estimated to 45 % of the total. The wind power impact on power system was compared to an equal (energy/year) installation of coal condensing units. In this paper the result from this study is summarized.

With a large-scale introduction of wind power the system operation including keeping of spinning reserves will be influenced since extra uncertainties are introduced. To study this a more detailed analyze of system operation is required. Parameters such as wind speed forecast uncertainties, system load forecast uncertainties, ramp rates of thermal units, spinning reserves and economic optimal scheduling have to be considered.

Mathematical optimization techniques can be used to determine a detailed schedule of each wind, hydro or thermal unit for each hour in the planning period, e.g. 24 hours in the daily planning. The requirements of instantaneous, fast and slow reserves, depending on possible forced outages of thermal units and uncertain load and wind speed forecasts etc., can then be calculated as well as the available capacities of the corresponding reserve types. The result includes an estimation of whether there are deficit or excess of instantaneous, fast or slow reserves, during the hours of the planning period. A short description of the daily planning of a wind-hydro-thermal power system is included in this paper.

In Appendix 1 the state of the Swedish wind energy program is described. The appendix is written by Göran Svensson, Swedish State Power Board.

Source	TWh	%
Hydro power	68.8	48.7
Nuclear power	66.4	47.0
Cogeneration	5.6	3.9
Fos. condense, gasturb.	0.5	0.4
Total	141.3	100.0

Table 1: Production in the Swedish Power System, 1988

1. Introduction

1.1 Wind power in Sweden

Sweden is situated in the "belt of westerly winds" and thus has favourable wind conditions. Generally the winds are strongest along the coasts and at the great lakes. Figure 1 shows the wind conditions in the south part of Sweden and the until November 1988 installed wind power units with a capacity $\geq$ 15 kW. Total installed capacity is 7655 kW.

1.2 The Swedish Power System

Sweden Norway, Finland and eastern Denmark are synchronical interconnected in the Nordic power system, figure 2. In table 1 the production in the Swedish power system 1988 is shown.

The hydro power in Sweden is mainly located in the north part of the country while the load centers are concentrated to the south part. The hydro system includes several storage capabilities. The total storable amount of water corresponds to an energy production of 33.4 TWh.

The uncertainty of the total amount of rain during a future year is the most important criteria in the expansion planning. The available energy from the rain can be approximated to be Gaussian with a standard deviation of 9 TWh. The energy criteria is defined as the risk of a yearly energy deficit in the Swedish power system. A risk of 3 % i.e. energy deficit 1 year of 33, is found economically optimal. Energy deficit might occur mainly during a dry and cold year. The temperature during the winter is important since around 40 TWh of the annual energy consumption consists of electric space heating.

A loss of load probability (LOLP) of 0.1 % is accepted in the expansion planning. The energy criteria is the dimensioning criteria in most of the studied future power systems. This implies that if there are plants enough to meet the energy criteria the LOLP becomes lower than 0.1 %.

2. The Swedish Power Industry Wind Power Integration Study

Between 1979 and 1984 the Swedish power industry performed an integration study concerning wind power. The background for the investigation was energy policy decisions taken by the Swedish Parliament. According to these decisions the energy supply shall be directed towards renewable and domestic forms of energy.

Unit	Capacity (kW)	Manufacturer	Started	Owner
1 Maglarp	3 000	Karlskronavarvet	1982	Statens energiverk
2 Näsudden	2 000	Nohab KMW Turbin	1983	Statens energiverk
3 Tågarp	55	Vestas	1983	Lantbrukare Roland Bengtsson
4 Hönö	40	Berewoud	1983	Chalmers provstation
5 Näsudden	55	Vestas	1984	Vattenfall
6 Härnösand	55	Vestas	1984	Härnösands kommun
7 Åkeskär	18	Dansk Vind Teknik	1985	Vattenfall (vind-diesel)
8 Dalby	150	New Wind	1987	Skånska elverk
9 Bösarp	150	New Wind	1987	Konsult Bertil Alvetorp
10 Tomelilla	150	New Wind	1988	Tomelilla sommarland
11 Tomelilla	15	New Wind	1988	Tomelilla sommarland
12 Tomelilla	150	New Wind	1988	Lantbrukare Elis Fritsson
13 Lärbro	55	New Wind	1988	Lantbrukare Nils Gösta Wiberg
14 Helsingborg	180	Danwin	1988	Helsingborgs energiverk
15 Alsvik	4x180	Danwin	1988	Vattenfall (Gotland)
16 Risholmen	750	Howden	1988	Kraftföretagens vindkraft AB
17 Gärdet	100	Vestas	1988	Stockholm Energi (demonstration 2 år)
18 Laholm	100	Vestas	1988	Södra Hallands Kraft
19 Långalma	22	Vestas	1988	Lantbrukare Ragnar Jacobsson

Figure 1: Wind conditions in the south of Sweden at the height 100 m. Black areas have $\geq$ 4000 kWh/m^2, off-shore locations have depth of 6-30 m

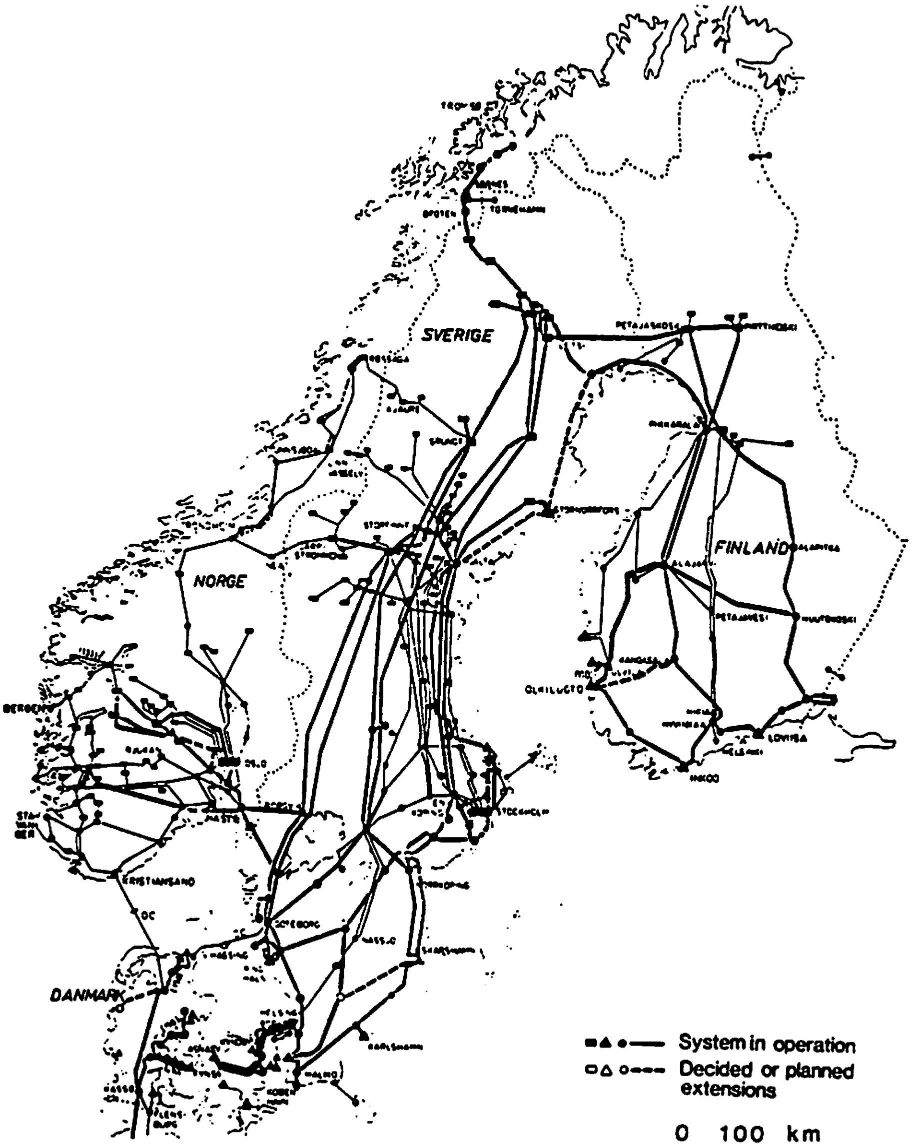


Figure 2: The Nordic power system

Energy source	Capacity	Energy per year	
		Available	Average
	MW	TWh	TWh
Hydro power	16 500	53-75	66.0
Cogeneration			
- Industrial	1 200	6.0	6.0
- Distict Heating	4 200	16.0	14.1
Condense power, oil	2 300	16.0	1.0
Condense power, coal	9 900	64.4	57.9
Gas turbines	1 000	2.0	0.0
Total	34 750	157-179	145.0

Table 2: Base power system for wind power integration

The investigation was sponsored by the National Energy Administration. The total cost was 3.8 miljon SEK corresponding to 570 000 US$.

The base alternative in the study was a future power system when nuclear power has been phased out and been replaced mainly by coal condensing power. According to a Parliament decision, nuclear power will not be used in Sweden after the year 2010. The composition of the base production alternative is shown in table 2. The energy consumption was judged to 145 TWh. Coal condensing power was then successively replaced by 5, 10, 20 and 30 TWh wind power.

Important data in the study were wind speed and wind speed variations in the time scales from seconds to several years. Such data was collected during several years on several locations on heights up to 100 meters. The characteristics of the 2 MW unit at Näsudden were used in the study. Existing simulation models were modified and developed for wind power.The wind power impact on power system regulation was divided into 5 parts.

2.1 Annual regulation

Wind energy replaces the corresponding coal condensing production, but wind power causes a slightly increase of more expensive thermal production. The explanation is that wind power production varies more than coal condensing production and this causes a more frequently use of more expensive thermal production.

2.2 Short term regulation

If wind power is introduced the variation of hydro power production within a week increases. A hydro power station is normally run on best efficiency. With larger variations in net load, the hydro stations are regulated more which causes more runs at lower efficiencies. Also the losses on the transmission lines from the hydro plants in northern Sweden to the load centers in the south of Sweden increase.

2.3 Power regulation and reserve margins

Thermal units have to be partly loaded to be able to meet unforecasted decrease of wind power generation. Partly loaded thermal units have lower efficiencies.

	Wind energy TWh/year			
	5	10	20	30
Wind power cap. MW	2 150	4 300	8 600	12 900
Decrease coal cond. MW	900	1 700	3 400	5 000
Annual regulation	0.00	0.00	0.02	0.04
Short term regulation	0.34	0.38	0.73	0.97
Power regulation	0.20	0.20	0.20	0.28
Wind power spillage	0.00	0.00	0.04	0.22
Additional grid costs	0.18	0.20	0.22	0.22
Total costs UScents/kWh	0.71	0.77	1.21	1.73

Table 3: Additional costs for wind power alternatives

2.4 Wind power spillage

With a high percentage of wind power in the power system it is not possible to always use the total installed capacity. Problems occure especially during low load - high wind situations. If spillage is unavoidable the spillage is probably performed with hydro units.

2.5 Grid costs

To be able to use hydro power in the north part of Sweden to balance wind power variations in the south part, a new transmission line has to be installed when wind power capacity is increased.

2.6 Total costs

The power industry investigation included an estimation of the total additional system costs caused by wind power in comparison to the coal condense alternative. All costs except grid costs referes to increased use of fuel and/or increased use of more expensive fuel in thermal plants. If e.g. the efficiency of a hydro plant or a thermal plant decreases more fuel has to be used to produce the same amount of energy.

In table 3 the estimated costs are shown for the studied systems. The investigation used a real discount rate of 4 %. The used rate of exchange is 1 US\$ = 6.5 SEK. The monetary value is from February 1989.

An additional conclusion from the investigation was that there is no need of extra reserve capacity in any of the studied wind power alternatives. This depends on the fact that the energy criteria is dimensioning in all studied alternatives.

2.7 New knowledge and assumptions

If the study was recalculated today some new knowledge and assumptions should replace the ones used in the above described study.

1) Today it is possible to perform better wind speed forecasts than the persistance forecast ("it will blow as much as now during the following hours") which was the best known forecast method, in the study.

2) During the last 8 years a negative correlation between available hydro power and wind power has been shown. If this can be verified to be generally valid, it means that there are better winds in dry years than during wet years. In the study above the available hydro energy and wind energy were considered independent.

3) The alternative to wind power is today not only coal condensing units. Imported natural gas from Denmark, Norway or Sovjet to be used for electric production is today another more accepted alternative.

4) The amount of electric space heating has increased during the last years. This cause the installed capacity to a more important factor, since the capacity demand during cold winter days is high. It is possible that the LOLP-criteria then becomes more important if the study is recalculated.

5) There are also some new transmission lines under construction. The impact of these lines might also have an impact on the integration of wind power.

3 Operation Planning of Wind-Hydro-Thermal Power System

3.1 Introduction

Wind power has mainly to be considered as an expansion alternative for the future Swedish electric power supply system. The simulation of system operation of a power system including wind power is therefore required to study wind power influence on power system reserve margins, need of extra reserves etc. It is also important to describe the short term operation planning of a wind-hydro-thermal power system.

In the following the operation planning model of a hydro-thermal power system is supplemented with a wind power model and a reserve model. This involves that wind speed and load forecasts are treated as uncertain. Possible forced outages of thermal plants are also considered.

3.2 Load model

The system load is in the operation planning forecasted for the planning period e.g. 24 hours for the daily planning. The load is here assumed to be reforecasted at each hour within the period since new information, e.g. weather forecasts, might change the forecast conditions. The forecast error can me modeled as a stochastic variable with a mean and a standard deviation, where the standard deviation of the load is included in the forecast. In figure 3 an example of uncertain load forecast is shown.

The uncertainty shown in figure 3 is the uncertainty for the forecasted hourly mean load. But there are also load variations *within* each hour . The load variations of interest are the unpredictable load variations within 15 minutes, since these changes must be met by the frequency reserve, chapter 3.6.1. Assume also that the slow reserve, chapter 3.6.3, has to be available in m hours. The slow normal operating reserve is used to release used fast normal operating reserve, chapter 3.6.2. This implies that unpredicted load variations occuring between 15 minutes ahead and m hours ahead have to be met with fast reserve. The fast reserve should also replace occupied frequency reserve within 15 minutes. The unpredicted load variations within m hours can be modeled as a stochastic variable with a mean and a standard deviation.

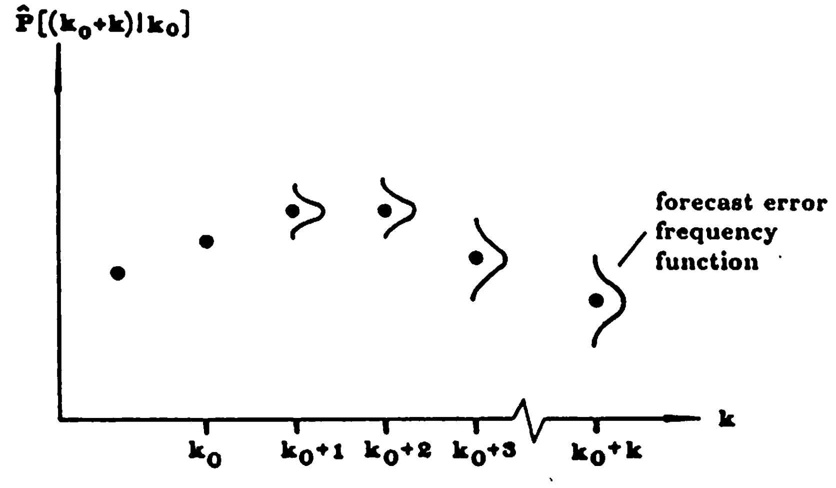


Figure 3: Load forecast with uncertainty

3.3 Thermal power model

For the operation planning the modeling of thermal units, such as nuclear units, fossil fueled condensing units, cogeneration units and gas turbines are important. The model has to take into account unit specifications such as

- minimum production of thermal units
- maximum production of thermal units
- ramprates i.e. maximum increase of production within a specified time interval
- time required for a cold start
- time required for a hot start
- number of hot hours after stop of unit

In figure 4 the model of an oil fueled condensing plant is shown. For nuclear power, cogeneration plants and gas turbines the model has to be modified to take into account the special features of these plants.

3.4 Hydro power model

Figure 5 shows the model of an interconnected hydro system. Hydro stations 1–4 and 8–10 have regulating capabilities, while stations 5–7 and 11–16 are run-of-the-river plants.

For each station and for each hour, a balance equation can be written.

$$\begin{aligned} x_i(k+1) &= x_i(k) - u_i(k) + \sum_{j \in i} u_j(k - \tau_{ji}) - s_i(k) + \\ &\quad + \sum_{j \in i} s_j(k - \tau_{ji}) + w_i(k) \end{aligned} \tag{1}$$

where

$x_i(k)$ = reservoir content, station i, end of hour k
($x_i(k) \equiv 0$ for run-of-the-river plants)

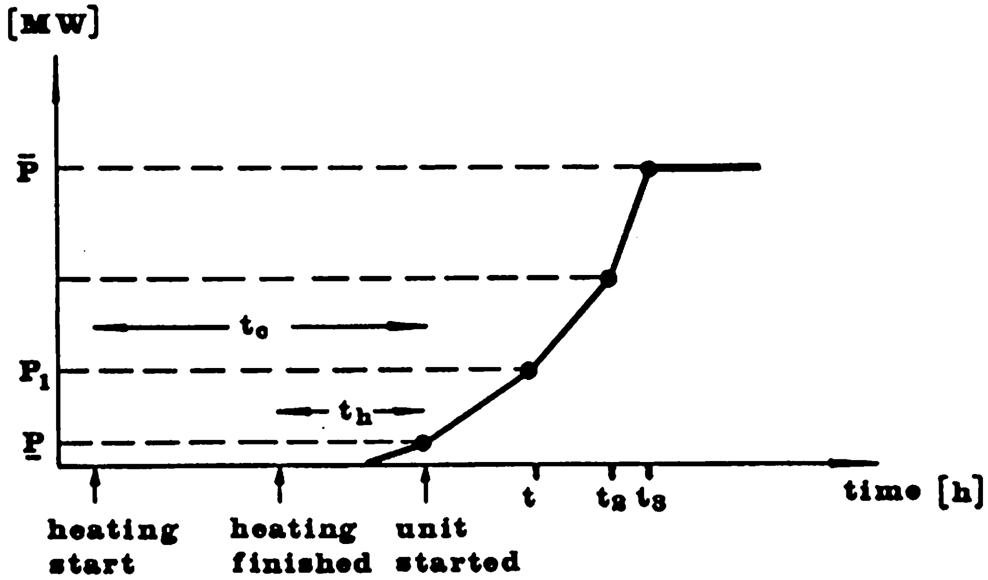


Figure 4: Start-up maximal ramp rates of oil fueled condensing unit

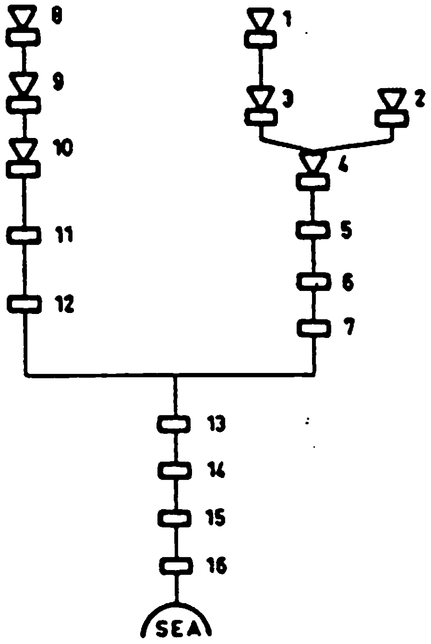


Figure 5: Lule river hydro system

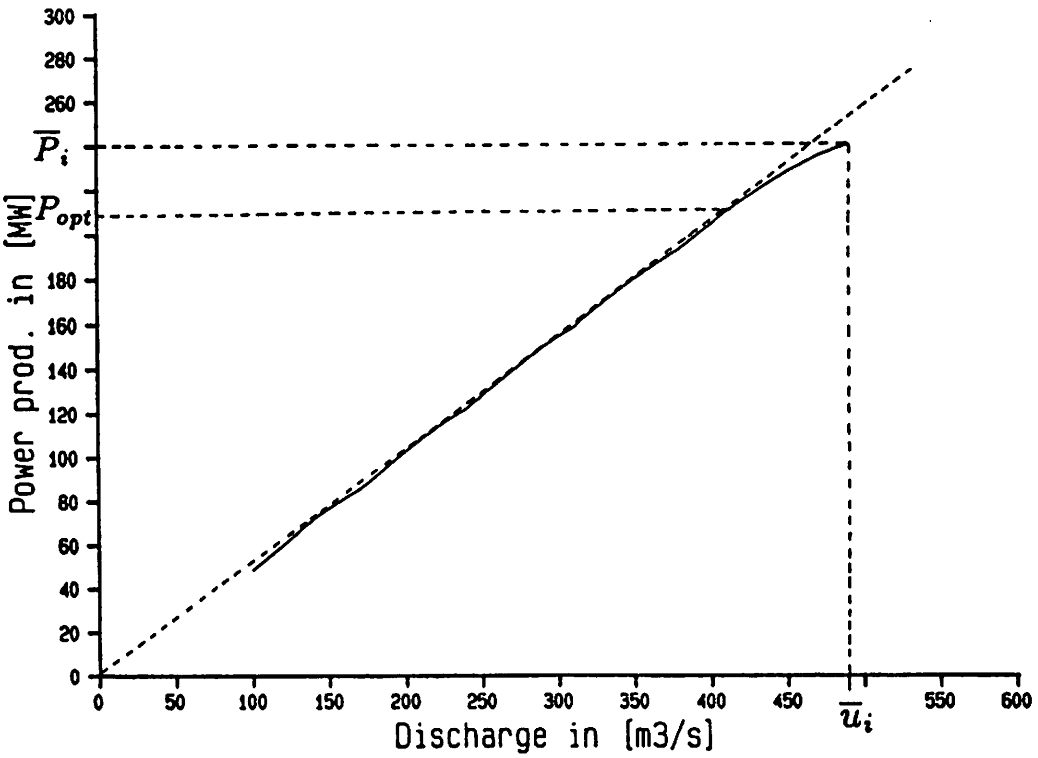


Figure 6: Hydro station characteristics at fixed head hight, Krångede power station

$u_i(k)$ water discharge, station i, hour k
$s_i(k)$ = water spillage, station i, hour k
$w_i(k)$ = natural inflow to reservoir i during hour k
τ_{ij} = water delay time between reservoir j and its downstreem neighbour i

The reservoir content has lower, $\underline{x}_i(k)$, and upper $\overline{x}_i(k)$ limits. Also the water discharge has a lower $\underline{u}_i(k)$, and an upper $\overline{u}_i(k)$, bound.

Power production of hydro plants is a nonlinear function of effective head and turbine discharge. Figure 6 shows an example of the power production of a hydro unit as function of discharge at fixed head hight. The figure shows that from start to production level P_{opt} the efficiency is variating between maximal efficiency (= the line of short dashes) and a lower value. This depends on the fact that Krångede power station has 6 turbines. At higher production the efficiency decreases.

A hydro power station is either synchronized or not synchronized, depending on the operation strategy. A hydro unit requires some time to speed up the turbine and generator from standstill to rated speed. When it is synchronized the rated power can be produced in some seconds. These features have to be taken into account in determination of hydro power reserve margins, chapter 3.7.

3.5 Wind power model

The wind speed at the sites with wind power units is assumed to be forecasted for the planning period. In figure 7 the forecast error of available wind speed forecast methods are shown. To obtain better predictions the wind speed is also assumed to be reforecasted for e.g. each hour.

The wind speed forecast error can be modeled as a stochastic variable with a mean and a standard deviation, where the standard deviation is included in the forecast. The uncertainty of this wind speed forecast is the uncertainty of the hourly mean wind speed. But as with the load there are also wind speed variations *within* each hour. As with the load, chapter 3.2, the unpredictable wind speed variations within 15 minutes are of interest since these changes must be met by the frequency reserve, chapter 3.6.1. These 15 minutes variations can be modeled as a stochastic variable including a mean and a standard deviation.

The unpredicted wind power variations between 15 minutes ahead and m hours ahead have to be met with fast reserve, chapter 3.6. The unpredicted wind speed variations within m hours can be modeled as a stochastic variable with a mean and a standard deviation.

As mentioned above the result of a wind speed forecast is an expected wind speed and an estimated standard deviation of the forecast error. Assume that the result of a wind speed forecast is the mean $\hat{v}$ and the standard deviation $\sigma_{V_{ki}}$ m/s. The forecast error of the wind speed can be represented with the density function. A corresponding frequency function is obtained for the *power* from one wind power unit. This is shown in figure 8 together with the wind speed–power transfer function of a wind power generator.

The total wind power forecast is the sum of the forecast of the individual productions of each unit. The total forecast error can be determined from the standard deviations from the forecast from each unit and the correlation between forecast errors for different units.

3.6 Power system reserve margins and requirements

Variations in the consumption of electricity must be met by an equivalent modification of the production. This implies that some of the capacity in the system must be saved for reserve purposes. Also in the case of disturbances which cause generation deficits in the system, reserve capacity must be available to restore the balance. The operating reserves in the Nordel network are coordinated and the system is in this respect operated as one system.

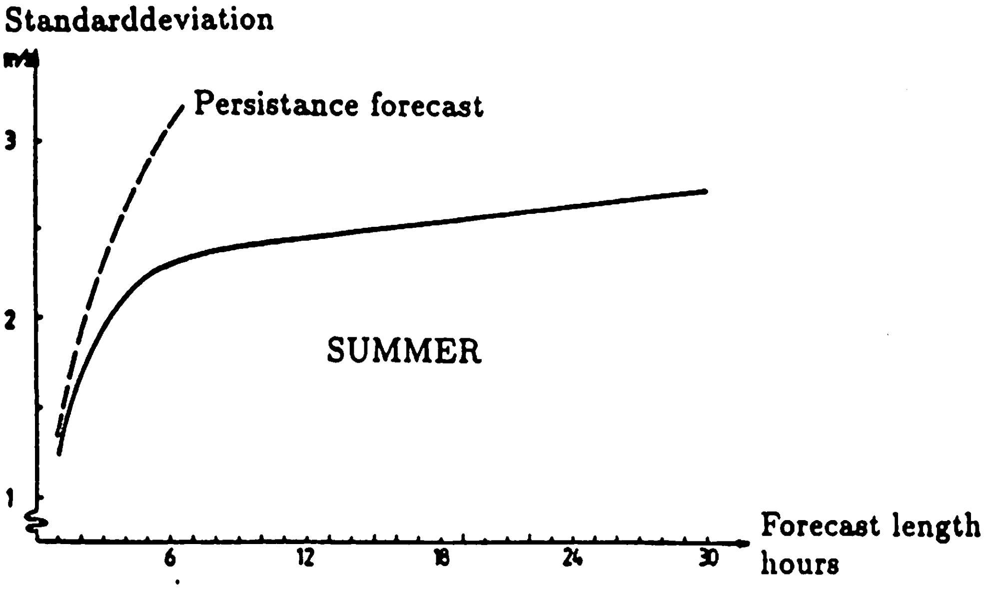
In the operation planning the reserve is divided into normal operation reserve and disturbance reserve, dependent on the cause of the reserve requirement. At operation of the system, the reserve is divided into different groups depending on how fast the reserve capacity is available. The groups are instantaneous, fast and slow reserve. An overview of system capacity is shown in figure 9.

Operating reserves are the total reserves necessary for the daily operation. The operating reserves consist of spinning reserve and units held in readiness.

Normal Operating Reserve

is the part of the operating reserve, which is used for normal frequency control and forecast errors. the normal operating reserve is divided into three parts according to its availability.

- Frequency Control Reserve



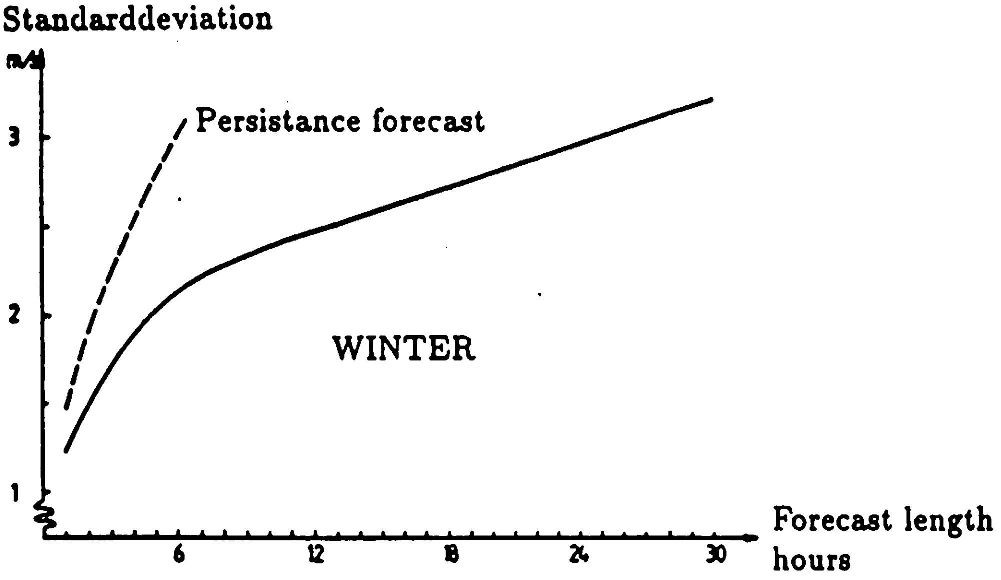


Figure 7: Wind speed forecast error as a function of forecast length

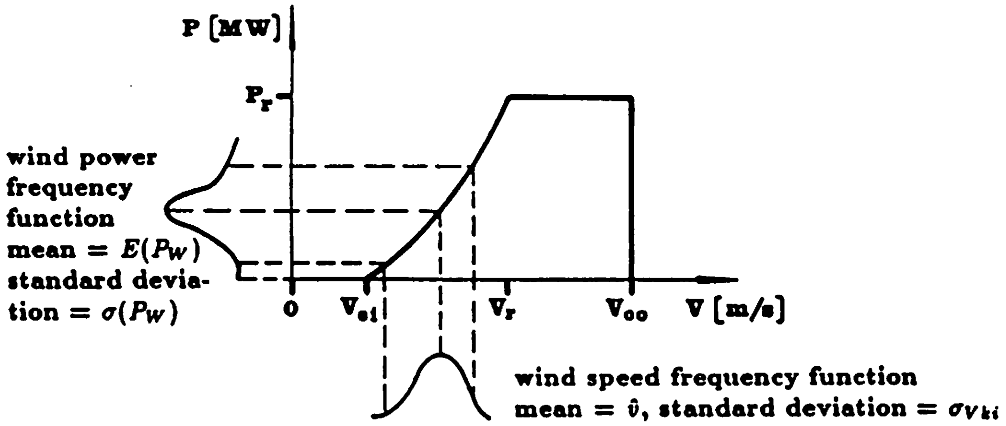


Figure 8: Wind speed and power frequency functions

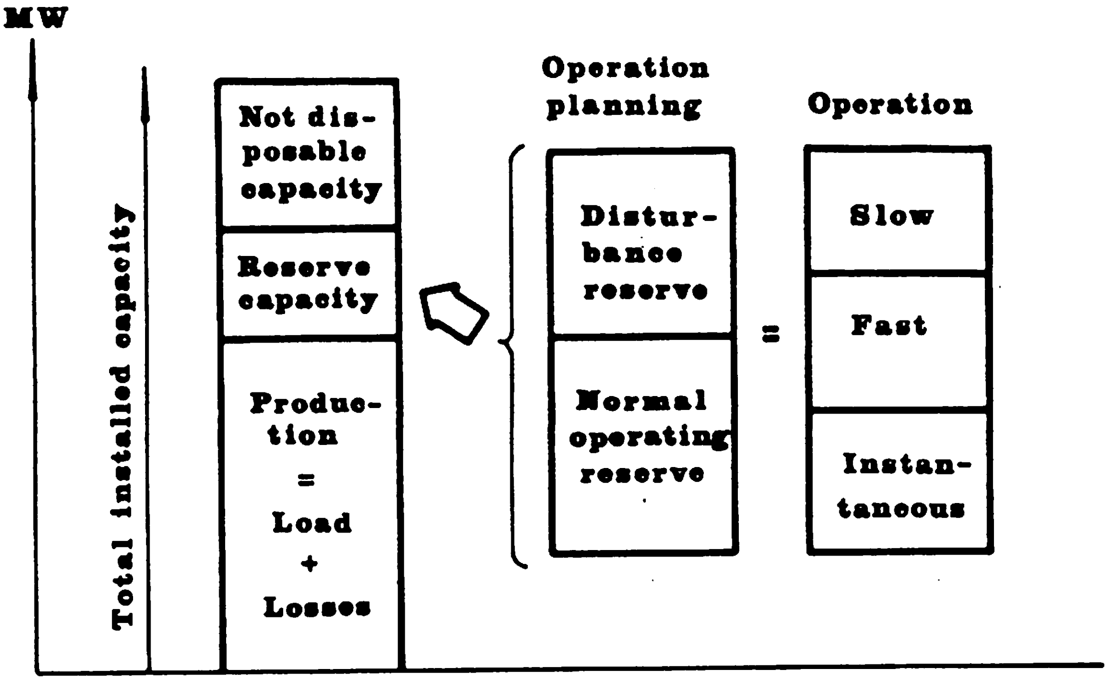


Figure 9: Overview : Use of system capacity

is the reserve necessary for keeping the frequency within the tolerances ± 0.1 Hz. The main part of this reserve consists in practice of momentary reserve, that is available within 30 sec. The Frequency Control Reserve is under primary control, that means controlled by the frequency.

- Fast Normal Operating Reserve
  is available within 15 min.
- Slow Normal Operating Reserve
  is available within 15 min. to 4 h

Disturbance Reserve

is the part of the operating reserve provided for use in case of 1) unit trip, 2) outage of part of the network with power excess, 3) change in load flow in case of overload or risk of loosing stability. The disturbance reserve is divided into three parts according to its availability.

- Momentary Disturbance Reserve
  is spinning active reserve controlled by fast governor actions (< 30 sec.), and available within 49.5 Hz.
- Fast Disturbance Reserve
  is active reserve available within 15 min.
- Slow Disturbance reserve
  is active reserve available within 15 min. to 4 h

3.6.1 Instantaneous reserve

The instantaneous reserve consists of the frequency control reserve and the momentary disturbance reserve. It means that it is reserve capacity that is available within 30 sec.

The frequency control reserve is used to keep the frequency within the tolerance ± 0.1 Hz. In figure 10 the strategy of load frequency control in presence of wind power is shown. The load and total wind power is forecasted and the non-wind power sources are planned to produce according to the net load (load minus wind power) forecast. The difference between forecasted net load and real net load is met with frequency control reserve.

Used frequency control reserve is after 15 minutes replaced by fast reserve. This implies that all unpredictable load + wind power variations within 15 minutes have to be met with frequency control reserve.

The frequency function of 15 minutes net load forecast error is assumed to be Gaussian, figure 11.

There are costs connected to the ambition to keep the frequency within the tolerance ± 0.1 Hz i.e. keep enough frequency control reserves. But there are also advantages in keeping a stable frequency. An analyze of these costs and benefits leads to a decision of how often one can accept that the frequency will pass outside the required interval. As shown in figure 11, a frequency control reserve of P_{LW15} MW will lead to lower frequency than -0.1 Hz in α_{15} % of all 15 minute periods.

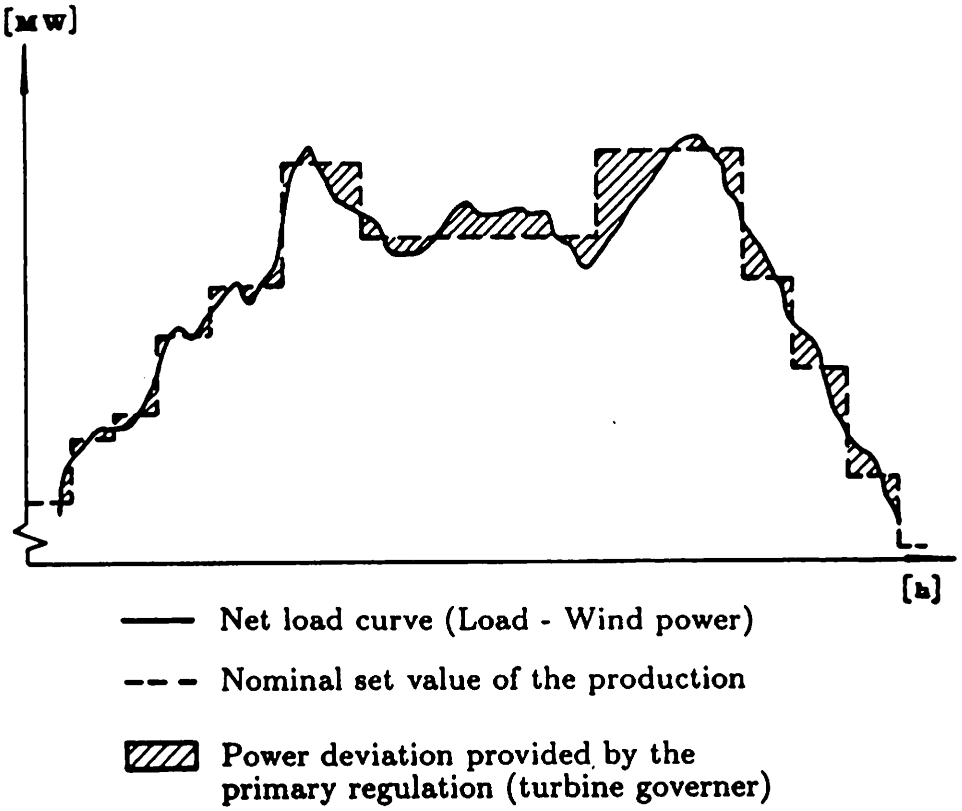


Figure 10: Load frequency control strategy

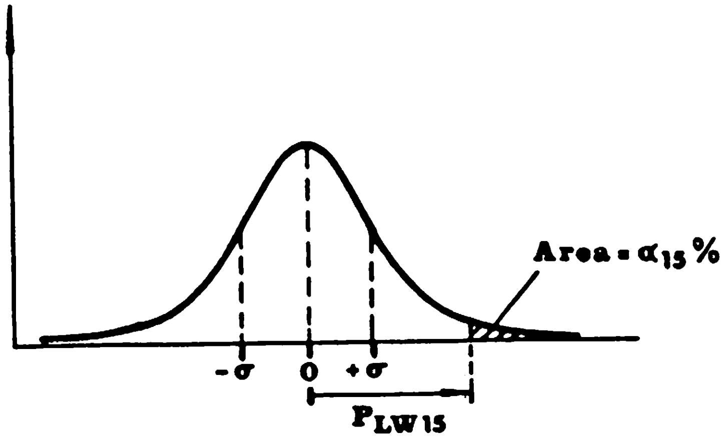


Figure 11: Frequency function of 15 minutes net load forecast error. Function assumed to be Gaussian depending on dominating Gaussian load forecast error

The momentary disturbance reserve should be available to replace the lost production of tripped units or outages of important transmission lines etc. After 15 minutes, used momentary disturbance reserve is replaced with fast disturbance reserve. This implies that there must be enough momentary disturbance reserve to meet possible outages within 15 minutes. In Sweden "possible outages" are defined as outages which has a possibility to occure at least as frequently as one time in three years.

In the Nordic countries (NORDEL) the momentary disturbance reserve requirement is 200 MW less than the decisive fault case. This depends on the frequency and voltage dependency of the consumption. The required reserve is then divided between the countries.

In order to be able to handle extremly severe disturbances in Sweden and the other countries within NORDEL, load-shedding programmes have been established. Thermal units are specified to stay in operation for frequencies above 47.5 Hz. The main objective is therefore to keep frequency above this level to avoid tripping, particulary of nuclear units, since the restarting time of these units are in the order of 6-24 hours. The load shedding programme involves about 50 % of the load in middle and south Sweden, subdivided in five steps. The programme is implemented with frequency relay equipment operating on a large number of breakers.

The frequency control reserve and momentary disturbance reserve have to be available in 30 sec. In Sweden only synchronized hydro units can increase the production that fast.

3.6.2 Fast reserve

The fast reserve consists for the fast normal operating reserve and the fast disturbance reserve. Hence it follows that it is reserve capacity that is available within 15 minutes.

The fast normal operating reserve is used to release the frequency control reserve. At greater deviation from the net load forecast, the normal operating reserve is used to restore the marginals in the frequency regulating units. Otherwise the system will be vulnerable for disturbances.

The fast reserve is after *m* hours replaced with slow reserve. Hence the fast normal operating reserve must meet possible unpredicted net load variations within *m* hours.

In the decision of required frequency control reserve the accepted times with too low frequency was estimated. Also with the fast normal operating reserve a cost-benefit analyze leads to a corresponding decision. The decision is the acceptable rate of how many percents of all possible net load changes within *m* hours, that will not be met with fast normal operating reserve.

When the momentary disturbance reserve is used at a disturbance, it has to be replaced with fast reserve, so the system is capable to meet a new disturbance. Within the Nordic countries there is no common used fast disturbance reserve, so each country has to have its own. The magnitude of the fast reserve has to be the same as the real decisive fault case.

The fast normal operating reserve and the fast disturbance reserve have to be available within 15 minutes. In Sweden synchronized and not synchronized hydro units, as well as gasturbines are available within this time period. Also partial loaded condensing units (not nuclear), can increase the power within 15 minutes if needed. Synchronized hydro units can be used both for instantaneous reserve and for fast reserve. This implies that excess of instantaneous reserve can be used as fast reserve.

3.6.3 Slow reserve

The slow reserve is the slow normal operating reserve and the slow disturbance reserve. The slow reserve has to be available within m hours, where m normally is 3-4 hours.

The slow normal operating reserve is used to release used fast normal operating reserve. It is sometimes also used at greater deviation from the net load forecast. AS with the instantaneous and the fast reserves a cost-benefit analyze leads to a decision of the acceptable rate of how many percents of all possible net load changes, that can not be met with slow normal operating reserve.

When the fast disturbance reserve is used after a disturbance, it has to be replaced with slow reserve, so the system is capable to meet a new disturbance. Within the Nordic countries each country have its own requirements of slow reserve. The magnitude of the slow disturbance reserve has to be the same as this decision.

The slow normal operating reserve and the slow disturbance reserve have to be available within m hours, where m is 3-4 hours. In Sweden manned oil condensing units and excess of fast reserve m hours ahead is used as slow reserve. The excess of fast reserve has to be reduced with the amount of partial loaded thermal power margins, since these margins otherwise is considered twice.

3.7 Solution of wind-hydro-thermal short term operation planning

One possibility to perform the operation planning of a wind-hydro-thermal power system is to formulate it as a mathematical problem. It can be shown that this formulation probably is unsolvable for a Swedish power system including wind power, mainly depending on the large number of integer varibles. These variables origin from the formulation of reserve margins. To solve the operation planning of a wind-hydro-thermal system the formulation therefor has to be modified.

A feasible methodology is to solve the operation planning problem *excluding* all reserve constraints and reserve cost functions. The reserve constraints are instead controlled in the obtained solution of this reduced problem.

In figure 12 a flow chart of the used methodology is shown. First the conventional hydro-thermal problem excluding reserve requirements and uncertainties is solved. The net load (= load - wind power) forecast is used instead of load forecast. This depends on the fact that wind power has neglectable incremental costs. *If* all available wind power can not be used spillage of wind power or hydro power has to be performed. The needed spillage will probably be perfomed in hydro stations instead of using the more complex methods of dispatching wind power units. The conclusion is that available wind power will always be used. Therefor wind power can be modeled as negative load. Solution methodologies for this problem are available. An example of the conditional operation plan is shown in figure 13.

The solution of the conventional hydro-thermal problem is a conditional optimal operation plan including schedules for all involved power units. The solution is "conditional optimal" since it is optimal only if all excluded reserve constraints are not binding. If these constraints are binding or not binding will now be controlled.

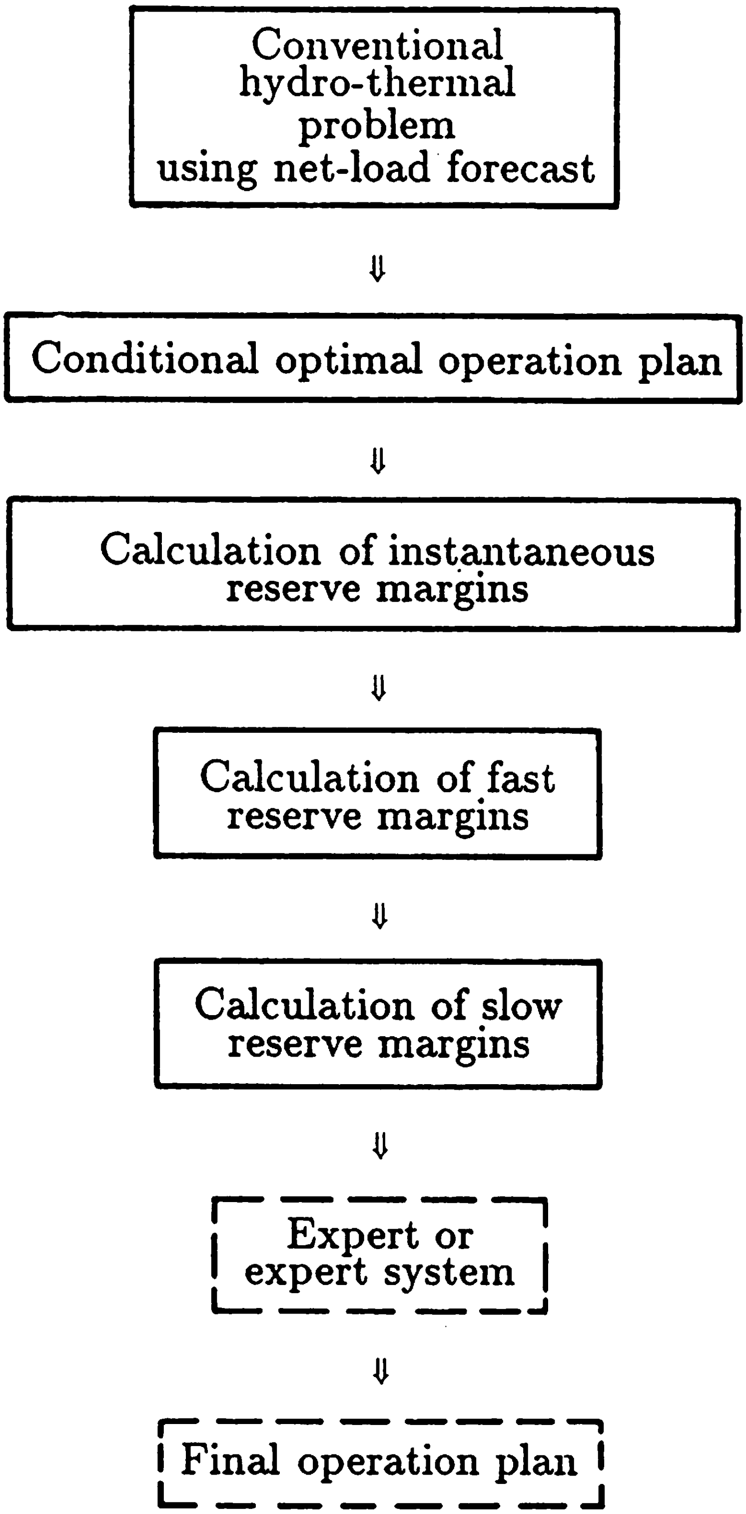


Figure 12: Solution methodology for operation planning of wind-hydro-thermal power system

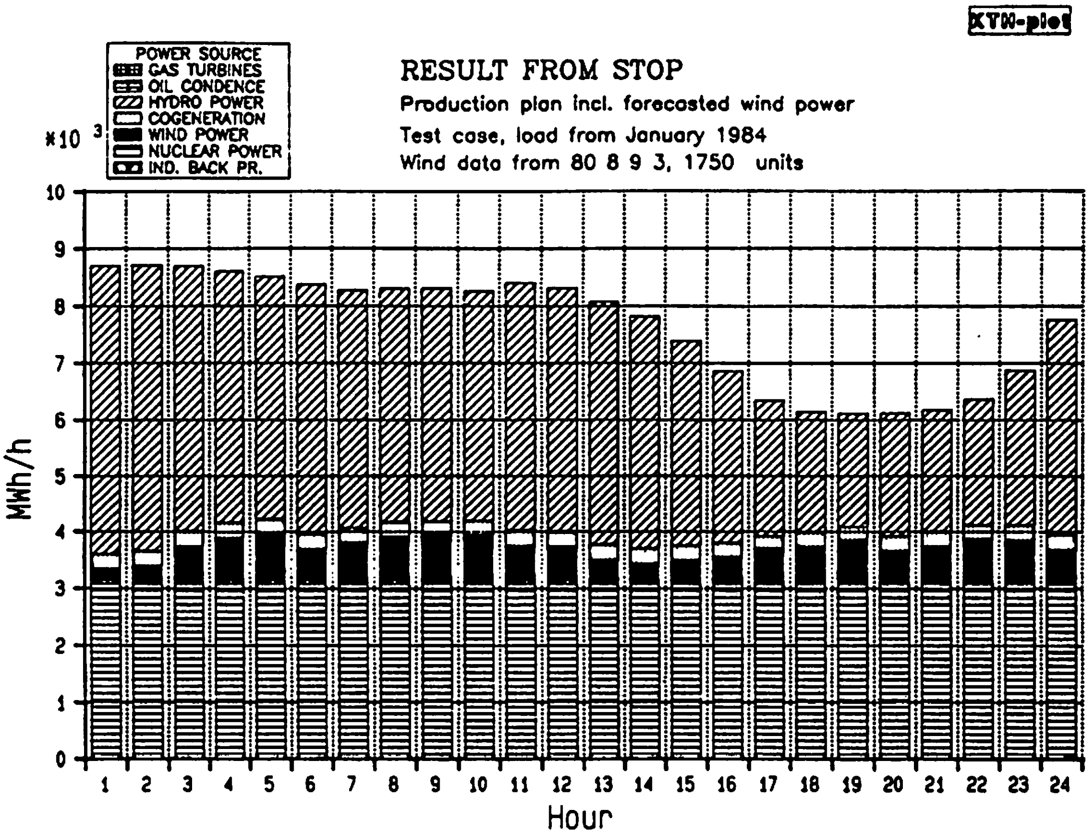


Figure 13: Conditional optimal wind-hydro-thermal scedule

From the conditional optimal operation plan the available reserves can be calculated and from load and wind power forecast uncertainties the reserve requirements are estimated. The instantaneous reserve margins are determined first followed by calculation of fast reserve margins, since excess of instantaneous reserve can be used as fast reserve. Finally the slow reserve margins including excess of fast reserve are determined. In figures 14-16 examples of available reserve margins are shown.

The result from these calculations include instantaneous, fast and slow reserve margins at each hour of the planning period. If there is no deficit of any type of reserves at any hour then the "conditional optimal" plan is also optimal.

If there are deficit of reserves at any hour of the planning period, i.e. some reserve constraints are binding, then the conditional optimal plan has to be modified. To obtain a final operation plan, an expert or expert system has to take into account subjects as

- the conditional optimal operation plan
- calculated reserve margins
- costs connected to use of reserves
- the accepted percentage of time with deficit of reserves
- the cost of reserve deficit depending on how soon it might occur
- requirements of unloadable generation
- local requirements of reserves

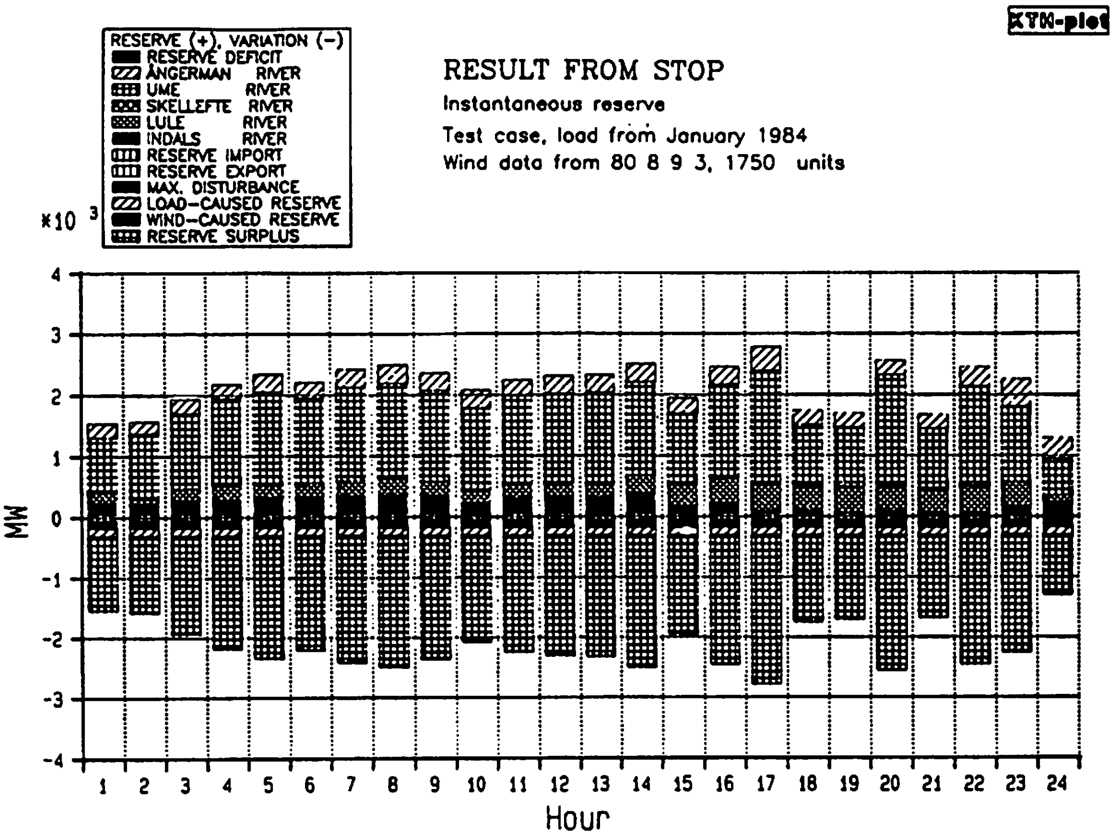


Figure 14: Instantaneous reserve margins

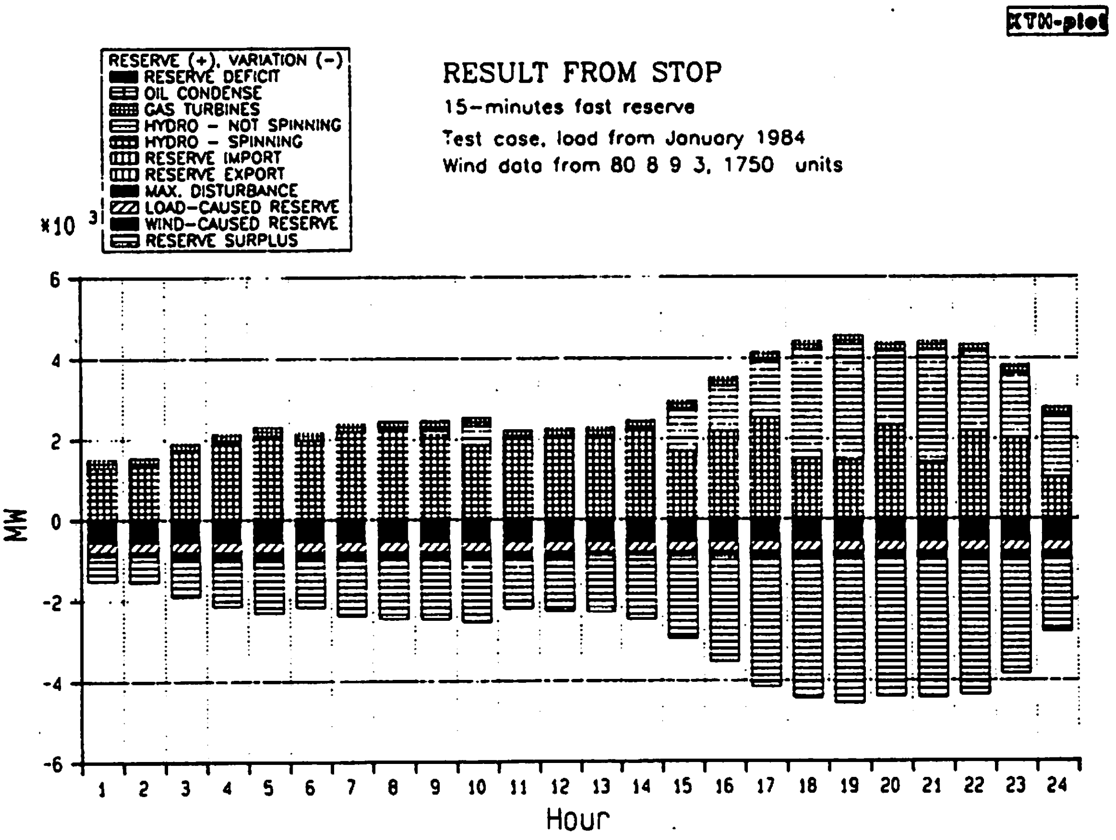


Figure 15: Fast reserve margins

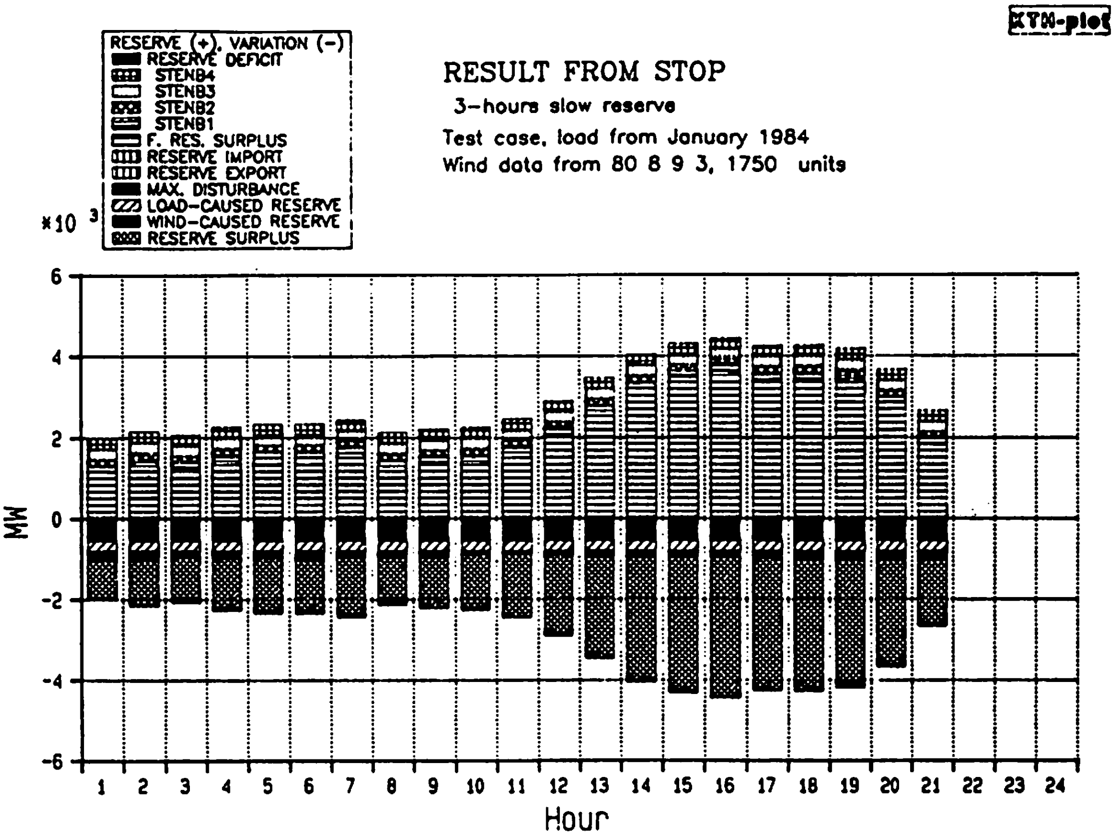


Figure 16: Slow reserve margins

In the example shown in figures 13-16 the conditional optimal plan is also optimal since there are excess of reserve capacity during all hours of the planning period.

A detailed presentation of the operation planning of a wind-hydro-thermal power system is found in *Benefit assessment of wind power in hydro-thermal power systems*, Lennart Söder, The Royal Institute of Technology, Stockholm 1988.

Appendix 1

Wind Energy in Sweden - A Summary

Göran Svensson, Swedish State Power Board March 1989

Background

As in most countries a national research programme on new energy sources started in Sweden around 1975. Wind energy was at that date regarded as one of the more realistic alternatives compared to many other "new" energy sources which were still in a fairly basic phase of the development. A 10-year programme was established to investigate the possibility for wind energy in the national grid.

The main activities inside this programme have been the building of the two large prototypes Nåsudden and Maglarp. Both are horizontal axis wind turbines with rotor diameters of 75m and 78m respectively. The generator ratings are 2 and 3 MW. Both were taken into operation in 1983. A lot of experience and knowledge have been gathered from these machines. As they are prototypes they can though not yet be regarded as technically or commercially mature but have both been operating for more than 11 000 hours each.

Due to the very low cost of electrical energy in Sweden there has been no market for smaller wind turbines as for example in Denmark. No subcidies have been available for private investments which means that there are a very few number of wind turbines in Sweden. Most projects are part of a research or demonstration programme.

In 1985 the Government evaluated the ten year wind energy programme. The total cost had been slightly less than 300 MSEK. The result of the evaluation was that technically wind energy can be part of a future production system but the cost was still too high to be competetive with other alternatives. Further research activities were called upon. The Government and also the Parliament transferred some of the responsibilities for the further development to the utilities.

Kraftföretagens Vindkraft AB (The Utilities Wind Power Company)

After discussions on how this responsibility was to be carried out a cost sharing programme was agreed upon. The main activities were:

The erection of a medium sized wind turbine with a rated power of 750 kW, purchased on commercial terms and with the aim to give practical experience from operation of a machine which was not a pure prototype. The wind turbine was bought in Scotland from James Howden & Co. Erection of the machine took place in the summer of 1988 on an island, Stora Risholmen, in Gothenburg. The commissioning of the unit has been delayed by some minor technical problems mainly in the control system. In February 1989 these problems seem to be solved and the operation of the machine has started. The evaluation of the project will be concentrated on the experience from operation & maintenance and the performance of the machine. An evaluation programme is planned to run until 1991.

The second activity was to make a technical and economical study for the next generation of the large wind turbines, with generator ratings 2-3 MW. The study should be based on the experience gained from the first two prototypes Maglarp and Nåsudden. In cooperation with the Swedish company Kvaerner Turbine AB, responsible for the Nåsudden unit, a commercial offer has been worked out and presented in the autumn of 1988. as a base for a decision if such a unit shall be erected. This so called Conceptual Design Study is performed together with West Germany to share the development cost and with the aim to build one machine in each country.

For these two activities the Swedish utilities have shared the financing with some help of governmental money. A separte company owned by the utilities has been formed for the two projects, Kraftföretagens Vindkraft AB (The Utilities Wind Power Company).

The Swedish State Power Board

The Swedish State Power Board has been operating the 2 MW prototype, Nåsudden, on contract from the National Energy Administration. The results from the Conceptual Design Study for the large machines mentioned above has been judged to be so interesting that the Board has decided to be responsible for the erection of one machine based on the results from the study. The expected remaining lifetime of the existing

Näsudden machine is limited and the evaluation programme is finalized. In this situation the Swedish State Power Board has decided to use the old tower for the new design and dismantle the old machinery.

The main characteristics of the new unit is summarized in the following table where the new design, Näsudden II is compared with the old one, Näsudden I.

Näsudden I		**Näsudden II**
2 MW	Rated power	3/1 MW
75 m	Rotor diameter	80 m
77 m	Tower height	77 m
25 rpm	Rotor speed	21/14 rpm
210 tons	Weight of machinery	105 tons
21 tons	Weight of one blade	6 tons
5.0 GWh	Annual energy	6.5 GWh

The new machine will be taken into operation in 1991. The project will get financial support from the Swedish Energy Development Cooperation and the National Energy Administration

As a next step in the development of the large wind turbines a wind park of 5 machines of the third generation is aimed at. These machines can be in operation earliest in 1995/96 depending on the experiences from Näsudden II.

The Swedish State Power Board has also erected a small wind farm of 4 units this winter. The site, Alsvik, is also on the island of Gotland close to the Näsudden site. The size of the machines is 180 kW each. The main pupose is to demonstrate wind energy in the landscape and get experience from the operation of the most mature technology available on the market. Experiences from the first months of operation has shown high availability. Measurments will be made at the wind farm to learn more about interaction between the different units.

The State Power Board will also investigate the possibilities for and consequences of building 300 MW of wind turbine generators which means 100 units of the new design. The results of this study will show economy and siting possibilities. Off-shore siting will also be looked into inside this study.

Siting investigations

An investigation of possible sites for a large penetration of wind energy in Sweden has been performed by the Government. When taking conflicting interests into account the result clearly indicates that on land the number of suitable sites are limited. The allowable distance between a wind turbine generator and the nearest building has a tremendous influence on the number of machines that can be installed. This is reflecting the structure of the Swedish landscape. Other conflicting interests are coming from the defence, the visual impact in the landscape, intrusion in farming areas e.t.c.

To get a large energy contribution from the wind it seems necessary to go for off-shore siting. The conflicting interests are less offshore although the commercial fishing is seeing a potential problem. The economy and the technical aspects on off-shore wind power is to a large extent still an open question.

To summarize the result of the investigation the estimated energy contribution from the wind, with todays knowledge, is 1.5 - 7 TWh/year for land based machines and roughly 20 TWh/year for off-shore wind power. It must though be stated that the economical aspects are not looked into deeply when the energy potential has been estimated. Todays electrical consumption in Sweden is slightly more than 130 TWh/year.

Off-shore Wind Power

As the energy potential seems to be much larger for off-shore wind power than land based a separate project has been initiated by the regional authorities in Blekinge in south of Sweden. The aim is to investigate the commercial prospects for an industrial group to develop the off-shore technology. A small experimental off-shore unit is planned inside the project. The work is done in cooperation with Sydkraft AB, the next largest utility in Sweden. Sydkraft is also responsible for the operation of the Maglarp unit.

The National Wind Energy Programme

In parallel to the activities inside the utilities the Government is responsible for a research programme. The aim is to increase the knowledge about the basics in wind engineering as a resource for the utilities and the industry. Some of the major areas inside the programme are:

Basic wind research
Modelling of wind turbine structures
Aerodynamics
Materials
Design- and safety aspects
Environmental aspects
Evaluation of physical machines

INTEGRATION OF WIND TURBINES INTO ENEL GRID: PRESENT PERCEPTIONS

A. Invernizzi

1. Introduction

In Italy utilization of wind energy is still in an experimental stage; the study of the technical problems of integrating wind turbines into an electric grid are presently considered from the point of view of planning.

In this phase one of the purpose of studies is to individuate the main problems rising when interfacing wind turbines and wind farms to the ENEL network. Obviously the particular Italian situation is taken into account that depends on the wind resources, on the orography of land, on the characteristics of the network and of those of the wind plants that can be installed in Italy.

The possible technical problems presently investigated, that could be caused by wind power fluctuations, are:

- stability of conventional units
- spinning reserve requirements
- load following capability requirements
- voltage regulation.

A detailed analysis of these particular aspects is strongly limited by the lack of wind farm production data recorded with a time resolution in the range of seconds or less. Nevertheless, the following aspects need to be stressed.

- The complex orography of the land in the windiest areas, population density, and constraints on the utilization of the land for wind farm installations will probably not permit a high wind farm concentration at any site in Italy. A realistic scenario could be the installation of wind farms with a limited maximum generating capacity (of the order of 10 MW) scattered over the windiest areas and connected to different HV/MV substations of the subtransmission network.

- The whole of Italy is covered by a fully interconnected transmission and subtransmission network, strongly meshed (save locally); this means that the effect of wind fluctuations needs to be analyzed in the context of the whole electric power system (except in a few cases where the effect of intermittence and of rapid wind variations at one site could be compensated for by the different wind conditions at other locations; therefore more data are needed on total energy production from whole large areas where several wind farms are installed.
- The penetration scenarios show high percentages of wind power, related to consumption in the windiest regions selected, but the percentages are markedly lower if related to total system consumption and the relevant influence on the dynamic behaviour of the system is lower too.

Bearing this in mind, the effect of wind fluctuations on the above said aspects of system operation are briefly analyzed and discussed in the sections that follow.

2. System stability

At the planning stage of an electric power system, the criteria applied are usually aimed at checking whether the network structure designed ensure that all the generators connected to the grid maintain synchronism, even in the event of infrequent but very severe disturbances falling in the short time (lower than 1 sec.); for example, a typical condition examined is that the generators of a power plant should maintain stability in the event of a 3 phase short-circuit near the plant with definitive loss of the faulted line.

In this connection, the question arises if, at least in theory, the rapid fluctuation of wind turbine power output could influence the transient stability of conventional electric generators connected to the grid: the effect depends very much on the amount of power output variations and on how rapid these variations are.The answer to the question therefore requires the availability of power production data from both single wind farms and from the combination of several wind farms connected to the network, with a very short time resolution (< 1 sec.) in order to detect the highest variation rates.

Nevertheless, as regards the Italian situation, the limited penetration of wind power, the small capacity installed in single wind farms and the fact that they will be distributed throughout the network (i.e., exposed to different wind regimes), leads to the assumption that rapid fluctuations in wind turbine production should not cause transient instability situations.

This assumption should be confirmed when the above-mentioned data becomes available.

3. Frequency control

Operation of an electric power system calls for a suitable amount of spinning reserve, ready to cope with random events such as the sudden loss of a large generating unit or a sudden load variation. If the spinning reserve is not enough to control the frequency transient, in particular the frequency decrease, in the ENEL network under frequency relays permit the automatic shedding of some of the load (for example up to about 30%) in order to avoid the frequency decrease that would automatically bring the thermal power plants to a halt.

The addition of wind turbines could affect the system frequency regulation in two different ways:

a) Wind turbine output fluctuations are further random events that the spinning reserve should to cope with.

b) Wind generators increase the part of the generating system that can not partecipate to the frequency control (such as thermal base units, run-of-river, etc.)

The carefull evaluation of these effects would call for data that show how total MW supplied from several scattered wind farms will change in times ranging from seconds to minutes, with a resolution of about 1 sec.

The high percentages of peak duty units of ENEL generating system (about 25%), the possibility to use a part of the generating capacity of part loaded thermal units and the characteristics, already mentioned, of wind power utilization, lead to the assumption that the total system has sufficient frequency regulating capability, and that the presence of wind turbines should only affect the dispatching of conventional units (for example, increasing their part loading).

This assumption might not be realistic in the case of local areas, weakly interconnected with the rest of the network, but with a high concentration of wind farms.

In Italy, this condition could occur on the island of Sardinia, whose wind characteristics are, indeed, favourable, while the electric network has undergone modest development in the past and is connected to the mainland network via a single d.c. link 412 km long, with a transmission capacity currently equal to 200 MW, but soon to be increased to 300 MW (see Fig. 1).

Preliminary calculations |1| were made on the Sardinia network, to determine the maximum wind production that can be integrated into the network in order to maintain adequate frequency control despite the intermittence and variability of the wind source.

Various frequency transients in the network have been considered, caused by the following events:

- **Sudden loss of all** wind production (due to sudden wind gusts that exceed cut-out velocity, for example), with all the conventional generating units available.
- The same event as before but with a **gradual diminuition** (down to zero in 4 seconds) in wind production.
- **Variable production,** depending on to wind availability (evaluated on the basis of the few data available for single wind turbine output).

The calculations were performed on the assumtpion of an outage of the dc link with the mainland (network thus isolated), under maximum and minimum load conditions and with various assumptions as to the composition of the spinning reserve.

The results show that, in the event of the sudden loss of all wind turbine output with all the other conventional generators available, the maximum acceptable wind production need to be less than the **11%** of the demand considered (1), in order to avoid load-shedding by under-frequency relays; this percentage rises to **12%** in the event of loss of wind production in 4 sec. and drops **to 10%** if the loss of wind generation occurs under night-time load conditions (1).

The maximum acceptable percentages of wind production should be lower than 10-12% in a further situation: sudden loss of the largest generator (240 MW), combined with the gradual diminuition (down to zero in 4 sec.) wind turbine output; the calculations so far performed do not permit evaluation of the new percentages. In considering the aforementioned results, it should be borne in mind that:

- The hypothesis of sudden drop to 0 of all the wind power output is hardly realistic, even if related to not a very large area, such as Sardinia island;

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(1) The preliminary calculation were made considering the present demand levels of Sardinia: about 1200 MW at peak and 600 MW at night time.

- The simultaneous occurrence of isolated network (dc link out of service) and the sudden loss of the largest generators combined with a rapid and substantial drop in wind turbine output is a very severe assumption, and, in any case, the probability of occurrence of this event needs to be evaluated.

From a balance of the above mentioned considerations the necessity arises of more refined investigations, should high penetration scenarios of wind power into the Sardinia electric sub-system be considered, just from the point of view of frequency control.

4. Load following capability

The daily load diagram of an electrical grid is highly modulated; thus, the maximum system load change rates (about 100 MW/min at the 1988 peak day) occur during the morning load rise and the night time fall-off, and a suitable loading variation capability (that is load following capability), from the generating system is required.

The fluctuation in wind turbine output (e.g., a drop during the morning load pick-up and a rise during the night-time fall) should reduce the ability of the system to follow load variations.

But bearing in mind once again that:

- For the ENEL system the percentage of peak units is high enough;
- The rated capacity installed at individual wind farms should be limited to few tens of MW (which means low wind-turbine concentration levels);
- The wind farms should be distributed throughout the network (which should compensate for output variations in wind farm installed in different areas);

then the load-following capabilities of the system should be sufficient to meet the additional requirements imposed by wind power utilization.

Only in the case of Sardinia, where, locally, wind penetration is to be higher, some penalties could occur (such as changes in load dispatching or limitation in wind turbine output) in the case of the highest penetration scenarios. These aspects shall be further examined when more data on the rapid variations of aggregated wind farms output will be available.

5. Voltage regulation

In Italy, the wind production should be supplied to the system through HV/MV (132-150/20 kV) substations. Such substations are normally equipped with HV/MV transformers, having on-load taps (± 18%) on the HV side.

Two cases are possible:

- For the high-medium size (10-20 MW) wind farms, the production will be directly connected to the HV busbar and then flowing to the system;
- For small wind farms, possibly intended to feed local isolated loads, the connection should be made, through MV lines, to the MV busbars. In this case the production exceeding the demand, as probably could occur during light load conditions during the night, will flow from the load point to the MV busbars. In such cases, the practice usually adopted in the voltage control at the distribution feeders level is to be re-examined. Infact the voltage regulators allocated on the HV/MV transformers and controlling the HV on load tap changer are presently setted on a MV reference value such as to allow suitable voltages on all the loads connected in cascade on the MV feeders. In the above said situations, new regulator settings (reference MV voltage) need to be determined and applied to the pertaining HV/MV substations.

Apart from the effect on the steady-state operation of the network, wind power should also bring transient disturbances, as is indicated by the following points:

- Fluctuations in wind turbins output could cause flicker, voltage dips and harmonics;
- In the case of asynchronous wind generators, the high transient magnetizing current absorbed at the starting-time could cause unacceptable voltage dips. This problem might make it necessary to stagger wind turbine start-up;
- The switching-off of a wind farm to isolate it from the system in the event of a fault on the distribution network could build up dangerous overvoltages.

However, it is likely that the above technical problems can be solved. The cost of solutions (i.e., additional VAR sources, appropriate selection of the HV/MV substation where the wind farms should be connected, suitable design of the line connection, etc.) should be low if compared with the total cost of the wind farm, and should not adversely affect the overall economic evaluation.

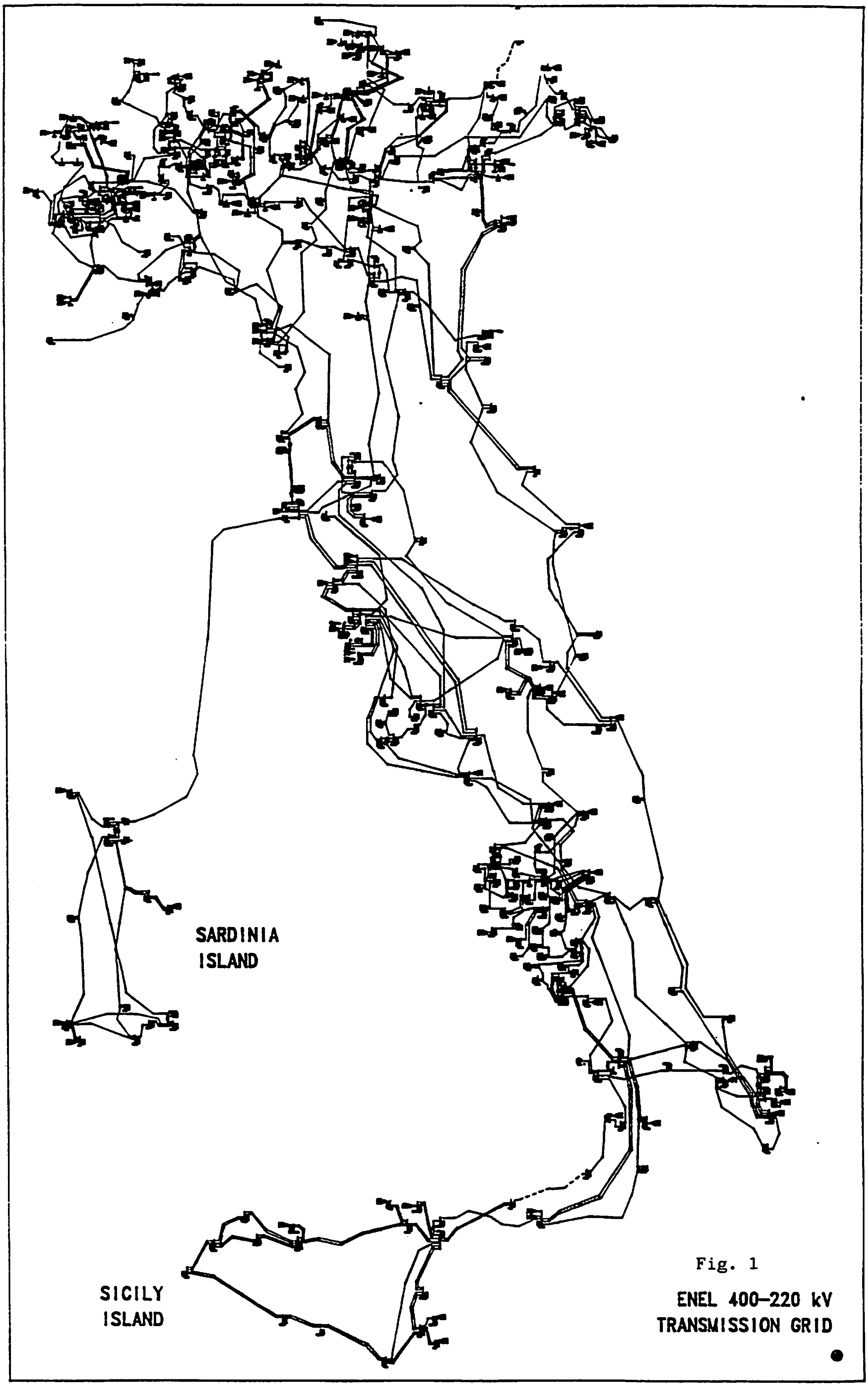

Fig. 1

ENEL 400-220 kV TRANSMISSION GRID

QUEBEC-HYDRO'S APPROACH TO INTEGRATE WIND TURBINES INTO DIESEL NETWORKS

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SUMMARY

The paper describes briefly the technico-economic justification leading to the Wind/diesel coupling as a means of reducing the high annual operating deficit of remote power systems.

With the no-storage high penetration scenario, at optimum penetration with the range of wind speed expected in Northern Quebec, 54 % to 76 % of the fuel used to produce electricity can be displaced by wind energy. In addition, a substantial quantity of fuel used for space and/or water heating can be displaced.

A program schedule for the implementation of such wind/diesel systems in HQ's remote networks is presented and discussed.

Results of the first two phases of this program are discussed. The first phase demonstrated the technical feasibility of wind energy in the far north.

The objective of the second phase of this program is to develop a regulation and control system that will allow wind turbines to supply all of the demand of the community, when sufficient wind is available, the diesel being shutdown, while maintaining and/or improving the quality of power .

The paper presents some preliminary analytical results demonstrating the transient response and stability of the high penetration no storage wind/diesel scenario.

• 1 INTRODUCTION

Due to the unpredictable nature of the wind, the utilisation of wind turbines as generating units in existing electrical power systems raises numerous questions as to their potential as a viable and economic adjunct to conventional electric power sources. Hydro-Quebec has been involved in research and development work in wind energy since 1975. Through research activities, many aspects of this technology have been looked at on both theoretical and experimental basis. A constant concern in this activity has been to improve the understanding of these complex machines so as to allow their economical integration in existing networks.

Approximately 800 remote diesel generator units supply electricity to 290 communities in Canada, for a total installed capacity of 350 MW. Hydro-Quebec operates 92 MW of diesels in 20 Power Plants. Electrical production costs are typically much higher in these communities than in the main networks of southern Canada. In general, since many of these sites are coastal, the wind regime is better than in the south. It is recognised that wind turbines will find their first economically viable applications in this type of environment.

• 2 JUSTIFICATION FOR WIND/DIESEL IMPLEMENTATION

Cost effectiveness and power supply quality are the two basic requirements for an effective integration of wind energy in any given community. A good control strategy should maximize the acceptance of wind energy by the network and apply the energy not required by the electrical network to serve other needs of the community (to heat buildings and/or water for example).

• 2.1 W/D COUPLING : TECHNICAL BACKGROUND

The integration of wind energy in a given community power system must take into account the characteristics of the major equipments involved, a few of which are given below:

- Demand and wind power output are both random. However, demand, being largely fashioned by community habits, follows more predictable patterns.
- A diesel generating plant has good load following capability but is an inefficient fuel to electrical energy converter. Also, as its load decreases, its specific fuel consumption increases. Operating and maintenance costs are high.
- Due to the random nature of wind, wind turbines are poor power producers. However, on a yearly basis, they are excellent energy producers. Reliable machines exist today that have very low Operating and Maintenance costs. For a given wind generator installed capacity, a group of machines will exhibit smoother power output than a single machine.
- Mismatch between wind and demand imposes increased load following burden on the diesel generating set. The net demand, as seen by the diesel is more random than the demand itself.
- Power and frequency stability call for a variable dump load for maintaining the energy balance in the system.

A detailed analysis of current operating practices of the all-diesel generating plant and their effect on the planning of a large penetration of wind energy into this network must also be taken into consideration for efficient W/D coupling and optimum economic penetration. Simulation programs that facilitate these economic choices are being developed [1,2].

• 2.2 W/D COUPLING :ECONOMIC JUSTIFICATION

As discussed in a previous paper[3], the most cost effective power production system in Northern Quebec communities is the no-storage, high penetration wind/diesel scenario schematically shown in Figure 1.

An economic analysis based on this scenario was done. The analysis assumed that the control and regulation system will allow wind energy to be used primarily to supply the electrical demand at a value equal to the cost of fuel for the diesel generator set, while the surplus will be used to supply part of the heating demand of the village at a value equal to the cost of fuel used for heating.

Before such a project is implemented, much more detailed calculations are needed. Each community will have to be considered separately for the choice of sites (wind regime), cost of fuel and electricity demand. Wind energy will be more profitable for those communities were the fuel price is high. Figure 2 and 3 show that in 1986, the optimum penetration for the communities where Hydro-Quebec bought fuel from the local COOP would have been 100 % for a wind speed of 6.8 m/s and 200 % for a wind speed of 7.8 m/s.

The financial aspect also deserves special attention. For example, even if Hydro-Quebec does not pay income taxes, advantage can be taken of the accelerated depreciation through Lease-Purchase (LP), the lessor absorbing the tax credits and leasing the installation to Hydro-Quebec, resulting in lower capital cost. This effect is also shown in figures 2 and 3 for the reference scenario and for COOP communities. For this latter case (COOP + LP), the optimum penetration becomes 150 % and more than 300 % for wind speeds of 6.8 and 7.8 m/s respectively.

The calculations were based on a typical 65 kW danish wind turbine. Recent developments show that larger wind turbines are more cost effective. For communities were the fuel cost, the winds and the electricity demand dictate a high wind turbine installed capacity, larger wind turbines might be a better choice, provided that enough turbines are installed for a given community to result in a relatively stable wind power and provided that those larger wind turbines can be erected and maintained without heavy lifting equipment which is generally not available in these communities.

According to reference 3, 54 % of the fuel used to produce electricity can be displaced by wind energy at a penetration of 100 % for a 6.8 m/s wind, whereas 76 % would be displaced at a penetration of 300 % for a wind speed of 7.8 m/s.

The Northern Quebec wind energy potential for the reference case and for the average wind speed of 6.8 m/s at the optimum penetration (100 %), calculated from reference 3, would be around 11 MW of wind turbines for a NPV of around 8 000 000 $.

For those economic calculations, the only source of income used to justify wind energy was the fuel saved. Other benefits would accrue from savings in maintenance on the diesels; the maintenance cost of a diesel is proportional to its running time. At a wind penetration of 100 %, the diesel running time would be reduced by 50 %, giving a 50 % reduction in its maintenance costs. For the same reason, the life of the diesels would be prolonged (life to retirement is specified in running hours), the capital cost would be decreased because the scheduled replacement of the diesels would be delayed.

• 2.3 WIND/DIESEL PROGRAM OBJECTIVES

The program objectives for the development of the W/D scenario for Hydro-Quebec's remote networks are the following:

- To develop a reliable Wind/diesel coupling system which will allow the optimal reduction of operating costs in remote networks. More specifically, a control and regulation system will be designed and developped in such a way that:

  -The penetration level (defined as the ratio of installed wind energy power to peak power demand of the local network) will be determined by economic criteria and not by current operational constraints which limit its contribution into diesel based network to a low percentage of the total diesel capacity.

  -Production priority will be given to wind energy to the extent that if wind power output is sufficient to supply the demand, the diesel(s) will be shut off.

The scenario we are pursuing stems from demonstration of W/D coupling made in 1977 by WTG on Cuttyhunk Island. This installation showed that, when the wind was strong enough, the diesel gensets could be shutt off and the demand supplied by wind power alone. Likewise, the results obtained in 1978 at IREQ on an horizontal axis wind turbine driving a synchronous generator will be useful to reach the objectives of the proposed project. The system was operated in an autonomous mode with a speed regulation loop that acted directly on the load. Research projects along similar schemes are pursued in Holland, in Denmark and in the UK.

• 3 GLOBAL SCHEDULE OF WIND/DIESEL COUPLING IMPLEMENTATION

To give some perspective towards the implementation of this Wind/diesel scenario in Quebec, Figure 4 gives a tentative schedule of the development and demonstration activities.

This global program covers a period of 9 years, from the Kuujjuaq demonstration project to full scale implementation.The schedule present an overview of the different phases that will lead to the full development of the W/D potential in Ungava region.

• 3.1 PHASE 1 KUUJJUAQ'S DEMONSTRATION PROJECT

The main goal of the Kuujjuaq's demonstration project was to demonstrate the technical feasibility of the installation and the operation of a wind turbine in a remote, northern diesel-electric network

Kuujjuaq was choosen for this demonstration project because it is easily accessible (daily flights from Montreal) and because it is the northern headquarter of Hydro-Quebec. Figure 5 shows the location of Kuujjuaq and of the other northern communities. The machine chosen was a well proven 65 kW horizontal axis wind turbine. The penetration level was low, of the order of 4 %.

After a two years monitoring program, the project has demonstrated that it is possible to install wind energy in the far north and that it can operate reliably.

• 3.2 PHASE 2 W/D CONTROL SYSTEM DEVELOPMENT

The installation of equipments in remote northern areas of Canada is always very expensive due to the high transportation costs and the investments in support logistic required. Obviously, the development of such a system in these area would be prohibitive both in terms of time and money.

Therefore, we are developping this system at IREQ where the technical resources and the scientific expertise is available. Once the feasibility of the scenario is validated, a full scale demonstration in a northern village will be possible with the best chances of success.

• *3.2.1 Modelisation of system dynamics*

In the following two sections, the letter "s" represents the Laplace's operator. The lowercase letters refer to normalised values, whereas uppercases letters refer to absolute engineering values. The system is represented on a per unit (p.u.) base, in relation to a chosen operating point "O". The reference values of this base are the nominal values of the given parameters at this point. Time is in seconds. Generally, "p" refers to a power and "ω" to a pulsation (rad/sec). Appendix 2 gives a more detailed nomenclature.

Figure 6a gives the detailed schematics of the wind diesel coupling, without dump load The asynchronous wind generator set is represented by a well established dynamic model[4,5]. The induction generator representation is included as the slope "γ" of the (adimensional) power output vs slip. Also, the electromechanical and aerodynamic phenomenas each act, through the high speed generator shaft, on the power output of the generator and on the aerodynamic power p_a, in proportion of the speed deviation ω_E.

• *3.2.2 PID control of the dump load*

In the high penetration, no-storage wind diesel scenario, quality of power and frequency in the network is maintained by insuring a fast elimination of unpredictable power fluctuations originating from the wind or the load.

A programmable dump load of an appropriate capacity, controlled by a Proportional Integral and Derivative (PID) regulator which absorbs excess wind power and provides a virtual power reserve in case of a sudden power demand from the consumer load (or a drop in wind power). The dump load controller is only an auxiliary for the conventional regulators of the diesel power units, but when the diesel is stopped, it becomes the primary frequency regulator for the network. This principle has already been demonstrated[6] with success, but its use has been so far restricted to test beds.

A. Auxiliary measuring and control devices

The principle of the correcting circuit calls for a measuring system (phase detector) and a controlling device (programmable load). Whatever way we choose to implement the first element, the phase comparator is by definition an integrator:

$$\omega_n(t) - \omega_s(t) = T_D \frac{d\theta(t)}{dt}$$

where $\theta(t)$ is the phase difference.

If we choose to bring the control voltage of the programmable load U_T to its maximum value U_{TM}, the regulating power activated p_{cm} is given by :

$$p_{cm} = \left(\frac{U_T}{U_{TM}} \cdot \frac{\Delta P_{eM}}{\eta_a P_0}\right) u_{cm}$$

ΔP_{eM} is the maximum power capacity of the programmable load; η_a is the alternator efficiency and u_{cm} is the relative value of the programmable load control voltage. In reality, the static switch relays of the programmable load will only apply power p_{cm} on the shafts at the next zero crossing of the network voltage, so as not to introduce harmonics. This corresponds to an absolute random time delay equal to half a period of the network frequency ($\tau_n/2$),

$$p_{cm} = \frac{K_{cm}}{1+T_{cm}s} \cdot u_{cm} = G_{cm}(s) \cdot u_{cm} ; \qquad T_{cm} = \frac{\tau_n}{4}$$

B. Detailed block diagrams of the regulation

Figures 6b and 6c present the regulating loops for the diesel/dump load and for the diesel/dump load/aerogenerator configurations. In the second configuration, it should be noted that, because the active power on the alternator shaft is never equal to the demand, p_{cm} has to be corrected by the factor Pdemo/Pao to keep the system in proportion with the alternator power adopted for reference. This factor is applied to the network demand to be coherent with that power base.

Similar considerations have led to rescale the power feedback of the asynchronous generator and to correct, in certain cases, the value of electrical sensitivities e_1, e_2 and e_3.

• *3.2.3 Numerical simulation of the system without dump load*

Figure 7a present some results obtained with the configuration described in figure 6a. The aerogenerator corresponds to the 50 kW VAWT installed at IREQ and the diesel genset data are those obtained from Garvey[7]. As there are no precise data on the voltage regulator of the alternator, we will suppose that it is identical to the one described by D. Angell [8]. The characteristics are given in Appendix 1. The electrical sensivities of the grid are those of Borel[9] .

A similar study made with a simpler model has been presented elsewhere[10] . Other researchers[11] have also proposed a nonlinear approach to the modelisation that permits to simulate almost all the operating modes of the coupled system and could point to certain instabilities in very strong winds. Unfortunately, classical methods do not lead to practical solutions for designing the corrective circuits necessary to improve the quality of electricity in that case.

Table 1 puts on the essential performance indices for three operating modes of the diesel/aerogenerator configuration, without dump load. These cases indicate that generally, the introduction of an aerogenerator in a given diesel network has the potential of contributing to satisfy power demand without creating instabilities in the system. However, if no corrective measures are taken to make the system more immune to power fluctuations,the quality of power can be significantly reduced.

Table 1. Performance Indices of the Wind/Diesel Coupling, Without Levelling Load Regulation at Different Wind Penetrations (0%, 20%, 100%).

Operating Mode	Response Time	Rise Time	Frequency Deviation	Gain Margin	Phase Margin
0% Penetration: Autonomous Diesel (240kw)	1 s	0.1 s	3.7%	3.16	66.3°
20% Penetration: 50kW Aerogenerator	2 s	0.1 s	3.2%	4.12	158.5°
100% Penetration: Five 50kW Aerogenerators	4 s	0.1 s	2.8%	8.31	136°

• *3.2.4 Validation of dynamic regulation of the dump load by PID control*

The simulations refer to the block diagrams of figure 6b and 6c. No simplification of the dynamic model is postulated. In all of the three simulation programs, written in *PC-MATLAB* language[12], the dynamic impact of the low-pass filter is ignored by setting $G_{fm}(s)$ to 1 . However, it is recognized that a more explicit characterisation of a filter that would smoothen the real signal sent to the control elements of the PID would be :

$$G_{fm}(s) = \frac{K_{fm}}{1+sT_{fm}}$$

In actual reality, a perfect derivative circuit is not implementable: the operation always introduce a time delay which should be as short as possible. Therefore the derivative part of the PID regulator has to be taken into account via an additional time constant $T_{vp}= T_v/D_p$, where D_p is a rather large value (10^3 to 10^6). The real transfer function of the regulator becomes:

$$G_R(s) = A\frac{(1+sT_n)\cdot(1+sT_v)}{sT_i\,(1+sT_{vp})}$$

All the auxiliary gain coefficients of the system are regrouped in a general gain coefficient of value K_{cm} =100. All the other gains can therefore be set to a constant value, $K_{fm} = K_\phi = A = 1$.

With the same parameters used in the previous system, Figures 7b and 7c give a sample of the typical time response of a step variation in the demand in the case of the second configuration, without and with the PID. It is clear that the PID regulator presents an improved behaviour for a similar perturbation, at 100% wind power penetration.

Table 2 shows the principal observations on the response and the stability of the regulation system for the different configurations. "System in open loop" designates the system operated without the dump load. Taking the autonomous Diesel in open loop as the reference case it is clear again that the addition of the PID regulator and its associated dump load leads to significant improvements in terms of power quality (lower frequency variations and quick recovery in time) in the case of significant load perturbations. The stability margins of the system are also wide. The narrowest stability margin belongs to the configuration where the diesel operates in a stand-alone mode with the dump load acting as an additional regulator.

Table 2. Performance Indices of the Wind/Diesel Coupling in its Different Operating Modes, With Levelling Load Regulation

	PID Regulators				Close Loop System			
Operating Mode	$T_S^{\clubsuit}$	$T_{pS}^{\clubsuit}$	T_i	$T_a=T_v$	Response Time	Max. Frequency Error	Gain Margin	phase Margin
Autonomous Diesel (240kw)	260ms	6.7ms	632µs	85.9ms	0.5s	0.3%	10	39°
Diesel + Aerogenerator (50kW)	408ms	13.4ms	206ms	141ms	1s	2.5%	∞	155°
Diésel + Aerogenerator (240kw)	877ms	13.1ms	90.5ms	138ms	1.2s	2%	∞	151°
Autonomous Aerogenerator (50kw)	9.24s	10.9ms	308µs	121ms	0.2s	0.12%	1482	179°
Autonomous Aerogenerator (240kw)	52.9s	2.43ms	4.5µs	52.8ms	0.1s	.02%	1010	167°

($^{\clubsuit}$)T_S,T_{pS}: Time constants of the plant reduced order dynamic model

• *3.2.5 Supervisory control for the High Penetration No-Storage Wind Diesel Scenario*

The optimal coupling of a wind farm to a diesel base power system consists of allocating in real-time the generating units of the site in such a way that the consumer demand is met at the minimum production cost. Continually, the number of aerogenerators and diesel units on line must be adapted to maximize wind power input, to minimize fuel consumption and operating costs, and to maintain the quality standards in energy delivery to the consumer (reliability, and frequency and voltage stability).

This kind of automation calls for an event manager whose role is to compensate for tendencies and important events that modify the operating point of the network. This supposes that the power systems themselves are already dynamically tuned in all operating modes and that they are able to adapt to the smaller perturbations that continuously come from the load and the wind. This part of the problem has been covered in the previous sections. This section addresses the coordination and the supervision aspects of the overall wind diesel power system.

The Wind/diesel system that we propose to develop will be designed and built according to the following strategy :

- Priority is given to wind energy production.
- diesel gensets are the standby units; if wind power is high enough to safely meet the load, diesels are shut off.
- Dissipative loads are used for absorbing the difference between the demand and the wind + diesel power output. Dissipative loads could be installed in community buildings. They could be of two types: variable by step(operated by addressable frequency

sensitive switches) and/or binary progression loads (zero crossing solid state relays controlled).

- The reference frequency of the regulation could come from an oscillator, the controlled parameter being the network frequency.
- The control system monitors the power consumed by the dissipative loads. If the level of power consumption reaches a predetermined low level setpoint,the control system commands the startup of one wind turbine or diesel genset . At the opposite, when a predetermined high level setpoint is reached, then one diesel or one wind turbine is closed.
- When the demand is met by the wind turbine only, the synchronous generator(s) of the diesel group(s) provides the reactive power to the asynchronous generator of the wind turbine.
- When the diesel is operating, it could provide the frequency reference of the network. It could also be operated at a fixed power production level, while the control system maintains the grid frequency.

The development of a real-time supervisory control program implementing this strategy is being initiated on a Masscomp RTU (Real-Time Unix) system. It emulates the case of a wind farm consisting of three aerogenerators and three diesel gensets, and includes the operating constraints of each power unit in its evaluation of the appropriate actions to take, namely the start or stop of any given unit. For example, these constraints include for each machine: the total number of hours of operation, the planned maintenance outage time, etc... The event manager has to maintain a database on the network operation statistics and should be able to handle the system monitoring, including communications with the operator of any given unit.

The resulting control system will then be translated into the appropriate programmable analog/numeric-input/output equipment.

This prototype program follows a first phase of the exercise which consisted in establishing the functional specification of the supervisory control functions with the help of concurrent communicating Petri Networks. This specification has been analysed only informally so far, since formal analysis tools for such a system are not available. The formal analysis of the specification will be carried in parallel with the fine tuning of the supervisory control program, a task that is presently complicated by the asynchronous aspects of the supervisor functions and to a lesser degree by the mastering of the graphical resources of the RTU.

When the model will have been fully validated by experimental work, it will be a valuable tool for sensitivity analysis of the proposed scenario for other W/D combination . This will minimize the margin of error for the design of regulation and control systems. Matching W/D equipments of different characteristics in any remote location,will be an easier task, thus ensuring a successful and cost effective application of wind/diesel systems in remote networks.

• *3.2.6 Experimental setup*

The experimental installation consists of IREQ' s 50 kW vertical axis wind turbine manufactured by Indal Technologies and a 30 kW Ford/Onan diesel generator set. A one-way clutch has been installed between the diesel and its generator to keep the alternator running when the diesel is shut down. A soft start system has been installed on the wind turbine to allow the diesel generator set to start it. A 30 kW resistive load simulates the demand whereas a 50 kW resistive load is used as a dump load, its capacity is sufficient to dissipate the energy generated by the wind turbine.

It should be noted that this experimental setup is actually a worst case situation for the W/D high penetration scenario since it consists of only one wind turbine, a Darrieus with its inherent torque ripple characteristics having a power capacity larger than that of the diesel genset alone. For implementation, we believe it would be preferable to install at least four (4) turbines, grouped in a small wind farm. This should reduce the peak-to-average-power of wind energy due to the dispersion of the machines, increasing the base wind power capacity, improving the fuel savings and reducing the number of diesel starts/stops.

• 3.3 PHASE 3 FULL SCALE DEMONSTRATION IN A VILLAGE

Once the feasibility of the high penetration no storage scenario will have been demonstrated at the experimental site, a full scale demonstration in a real site will be done. This demonstration will be done in two steps.

In phase 3a, a small wind farm of the order of 360 kW will be installed in a northern community having a peak demand of around 360 kW (penetration of around 100 %) or lower (penetration higher than 100 %) to allow a clear demonstration af the high penetration no storage scenario. The village choosen should also have a good wind regime for a proper demonstration of the potential for economies obtained from the reduced running time of the diesels. These economies would be ; reduced maintenance costs and lower capital costs for their replacement because of the prolonged life.

In this phase of the project, the wind turbines could be put in operation according to the negative load scenario in which the diesels have priority and the wind turbines are shut down whenever there is a conflict. For example, in normal practice, the diesels should not operate lower than 50 % of their nominal power.

In phase 3b, the systems necessary for the demonstration of the high penetration no storage wind/diesel scenario will be installed, these systems are :

- one or more dump loads,
- clutches (one way) between the existing diesels and their alternators,
- a regulation system. This regulation system is under development in phase 2, its function is to regulate the dump load in order to maintain the frequency at its nominal level,
- a command system. This system will monitor the level of power going to the dump load and decide when a diesel should be started or stopped or will dispatch power to heating loads,
- an automatisation system for the diesel power plant. Although their protection is fully automatic, the diesel power plants in northern Quebec are manually started.

• 3.4 PHASE 4 IMPLEMENTATION

After a period of succesful operation of the system installed during phase 3, the commercial implementation of the system could be undertaken for the other remote communities were a combination of winds and fuel costs makes it interesting.

•4 CONCLUSION

We believe that wind energy has a good economic potential in remote networks with the use of the no storage high penetration scenario.

Simulation results of the transient behaviour for the proposed scenario have been presented. In all operating states of the high penetration W/D system, taking a standard autonomous Diesel powered network as the reference case, the simulations show that the response of the system to significant load perturbations is improved by the addition of the PID regulator and its dump load. The result is a significant improvement in power quality, lower frequency variations and quicker recovery in time . The different simulation runs indicate wide stability margins.

Furthermore, the simulation shows that the wind turbine can be operated autonomously, without affecting the frequency stability of the network; therefore, the diesel can be shut down when the wind is sufficiently strong to meet the instantaneous demand.

A realistic program for the orderly development and implementation of this scenario was presented.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the participation of E, M & R in the financing of the Kuujjuaq demonstration project and for the R&D work described in Phase 2.

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APPENDIX 1

Tables A1 to A3 give the values of the parameters involved repeatedly in the simulations. The characteristic time constants of the mechanical inertias and the adimensional coefficients of static losses have been evaluated at the nominal operating point (Table A1). The coefficients of electrical sensitivity associated with the network are also evaluated at the nominal operating point and they correspond to those used by Borel[9] to caracterize a typical autonomous network (Table A3).

The synchronous alternator efficiency is constant at $\eta_a = 90\ \%$. This value is taken into account to calculate the no-load losses when it operates as a compensator. In that case, The coefficients e1, e2, e3 have to be corrected: the alternator power capacity being P_{a0} and its nominal power P_{an}, the actual values of the electrical sensitivity coefficients are:

$$e_1^0 = e_1 \frac{P_{an}}{P_{a0}} \; ; \quad e_2^0 = e_2 \frac{P_{an}}{P_{a0}} \; ; \quad e_3^0 = e_3$$

Table A-1. Mechanical Coefficients of Rotating Machines
(*Diesel*:240kw, 1800rpm; *Aerogenerator*:50kw, 79rpm)

Rotating Machine	Friction	Inertia (kg.m^2)	Caracteristic Time	Loss Coefficient
Diesel	D_D = 1e-3	$J_D = 8.3744$	$T_D = 1.2398$ s	α_D = 1.48e-4
Alternator	D_a = 1e-5	$J_a = 0.919$	$T_a = 0.136$ s	α_a = 1.48e-5
Aerogenerator	D_E = 1e-3	$J_E = 12003$	$T_E = 16.48$ s	α_E = 1.373e-3

Table A-2. Conventional Regulators Coefficients and Transfert Functions

$T_{av} = 1.667$ s	$T_{bv} = 0.33$ s	$T_{cv} = 6.667$ s	$T_{dv} = 0.083$ s	$T_{ev} = 0.01$ s
$T_{ag} = 0.303$ s	$T_{bg} = 0.05$ s	$T_{cg} = 0.013$ s	$T_{dg} = 0.01$ s	$T_{ev} = 0.01$ s
$T_A = 0.053$ s	$T_f = 0.5$ s	$T_{rMS} = 0.25$ s	$T_{tm} = 6.25$ ms	$G_g = -100$ et $G_v = 1.3$

$$G_{rv}(s) = G_{rvo}\frac{(1+sT_{av})(1+sT_{bv})}{(1+sT_{cv})(1+sT_{dv})(1+sT_{ev})} = \frac{v_{rv}(s)}{e(s)}.$$

$$G_A(s) = \frac{p_{aD}(s)}{v_A(s)} = \frac{e^{-T_{tm}}}{1+sT_A}.$$

$$G_f(s) = \frac{v_f(s)}{v_{rv}(s)} = \frac{1}{1+sT_f}.$$

$$G_{rMS}(s) = \frac{v_{tf}(s)}{v_f(s)} = \frac{1}{1+sT_{rMS}}.$$

$$G_{rg}(s) = \frac{G_{rgo}}{s}\frac{(1+sT_{ag})(1+sT_{bg})}{(1+sT_{cg})(1+sT_{dg})} = \frac{v_A(s)}{e(s)}.$$

Table A-3. Sensibility Coefficients at Nominal Point.

$t_s = .15$	$e_1 = 0.4$	$e_2 = 0.8$	$e_3 = 0.2$	$\gamma = 0.0182$

Appendix 2

List of Main Symbols and Abbreviations

g, p_{mas}	Asynchronous Generator Slip, Ouput Power
p_E	Wind Input Power
p_{dem}	Grid Load
p_{aD}	Diesel Governor output
p_{cm}	Levelling Power
v_t	Grid Voltage
t_e	Aerodynamic Sensibility
e	Frequency Deviation
ω_s, ω_E	Grid, Wind Frequency
$_O$ subscript	Value at Operating Point O
$_{E}$, $_{D}$, $_{mas}$ subscript	Wind, Diesel, Asynchronous Generator Variables
OM, PID, OCM	Sensor, Regulator, Transducer Block

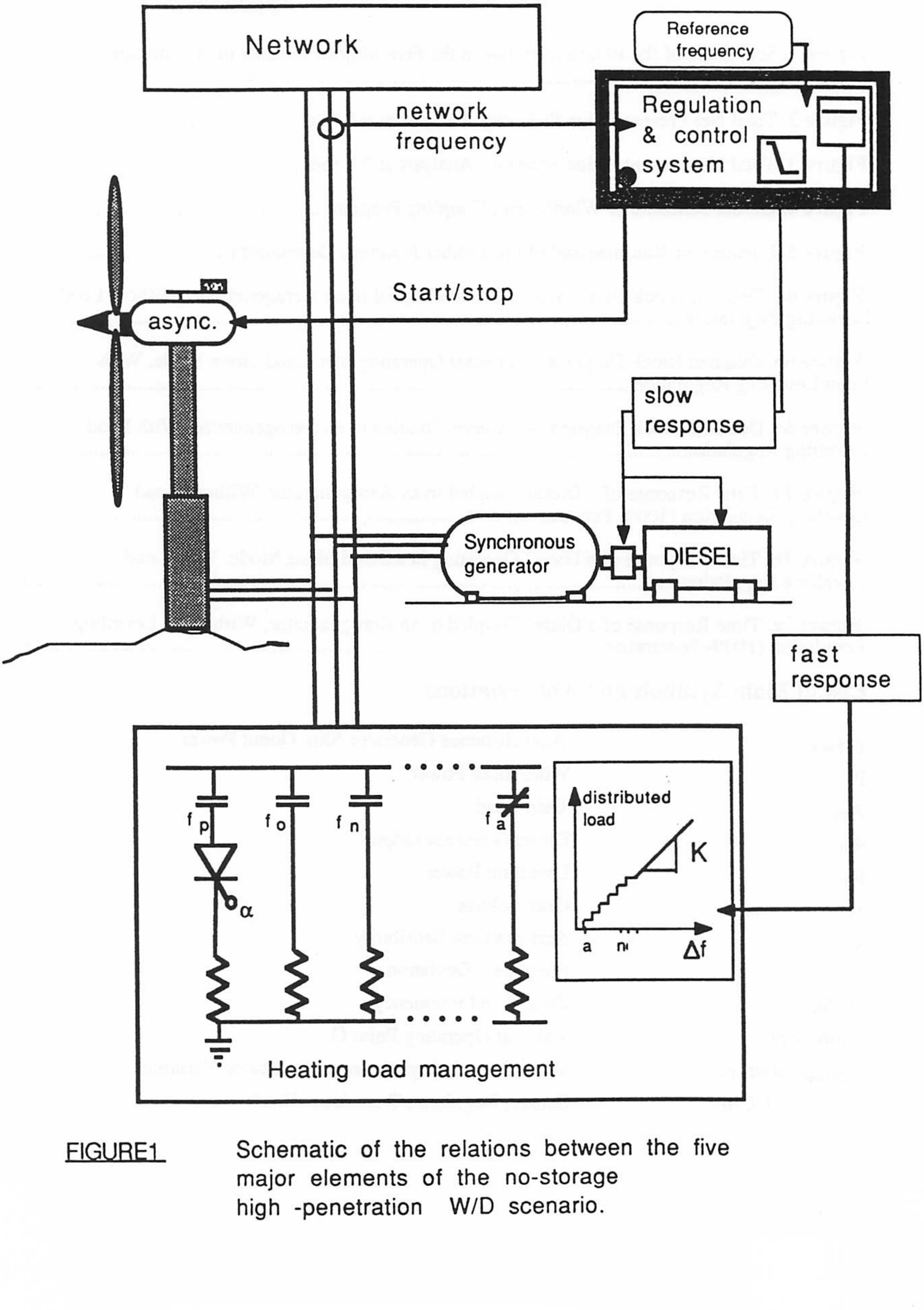


FIGURE1 Schematic of the relations between the five major elements of the no-storage high -penetration W/D scenario.

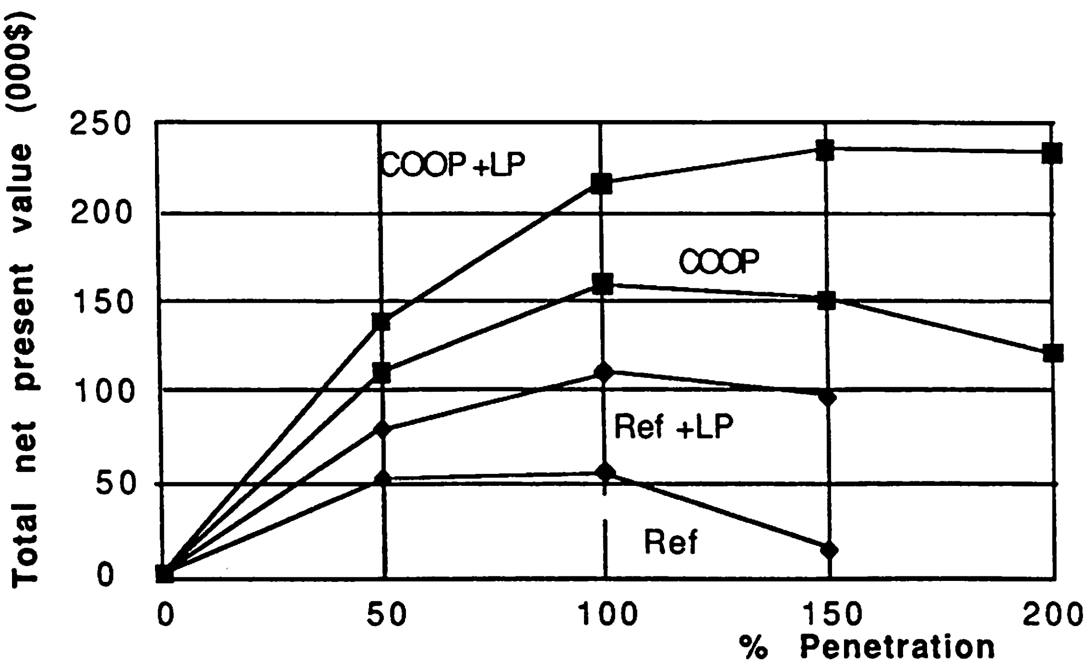


FIGURE 2 Total Net Present Value
Sensitivity analysis at Vm = 6.8 m/s

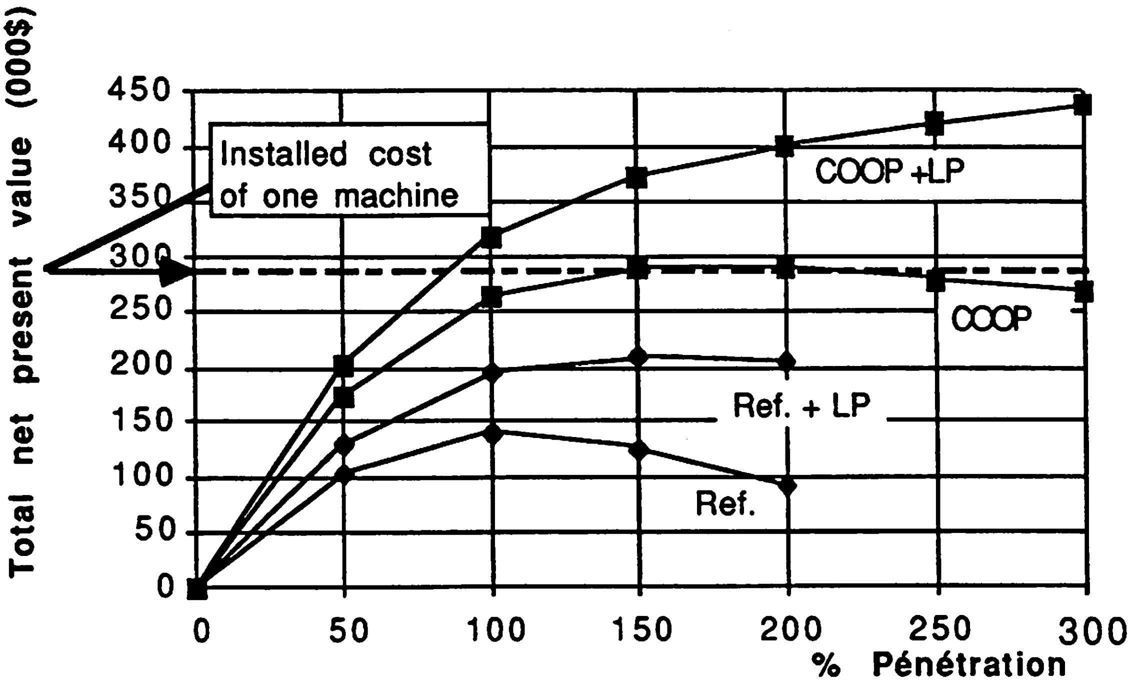
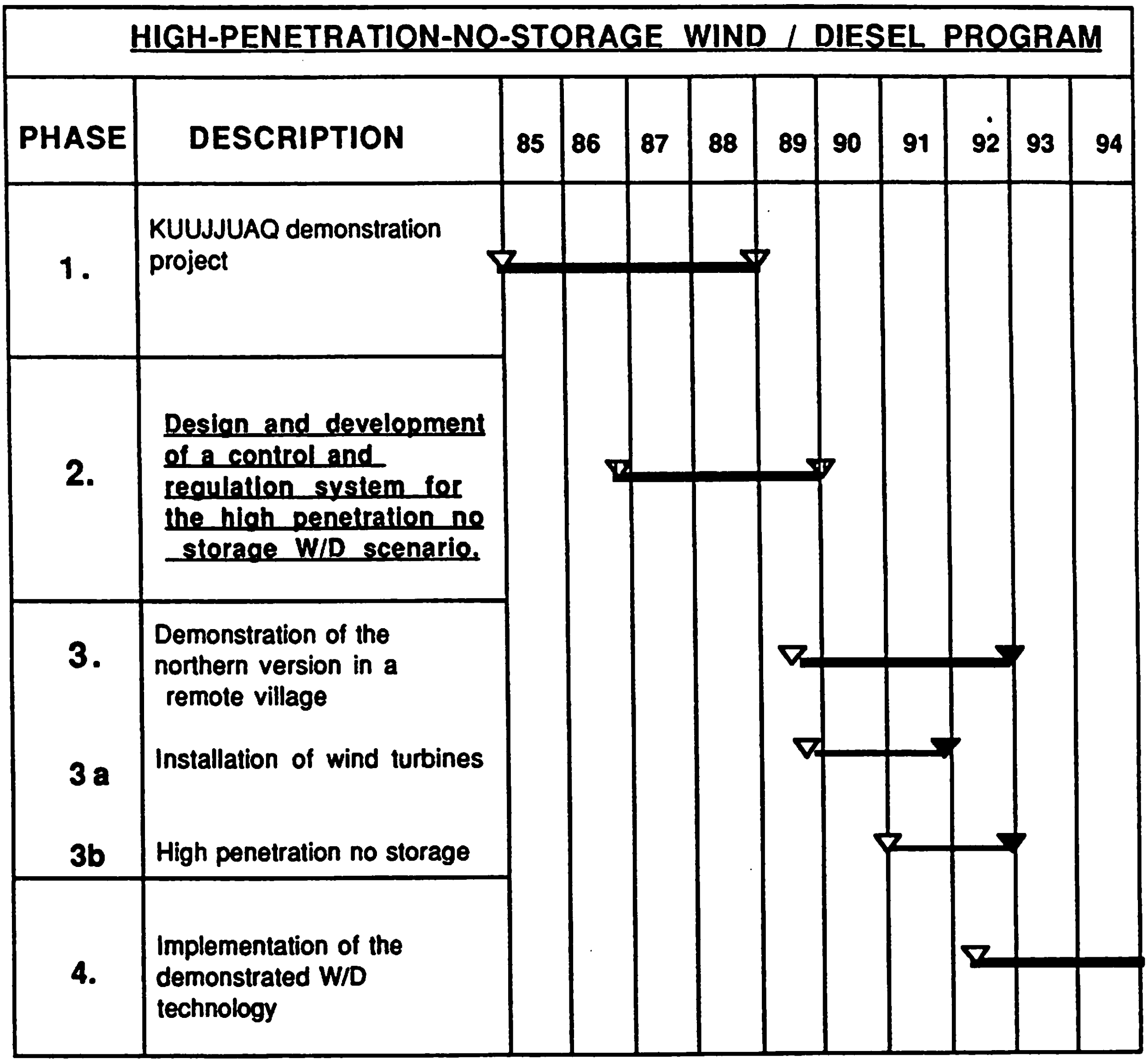


FIGURE 3 Total Net Present Value
Sensitivity analysis at Vm = 7.8 m/s

FIGURE 4

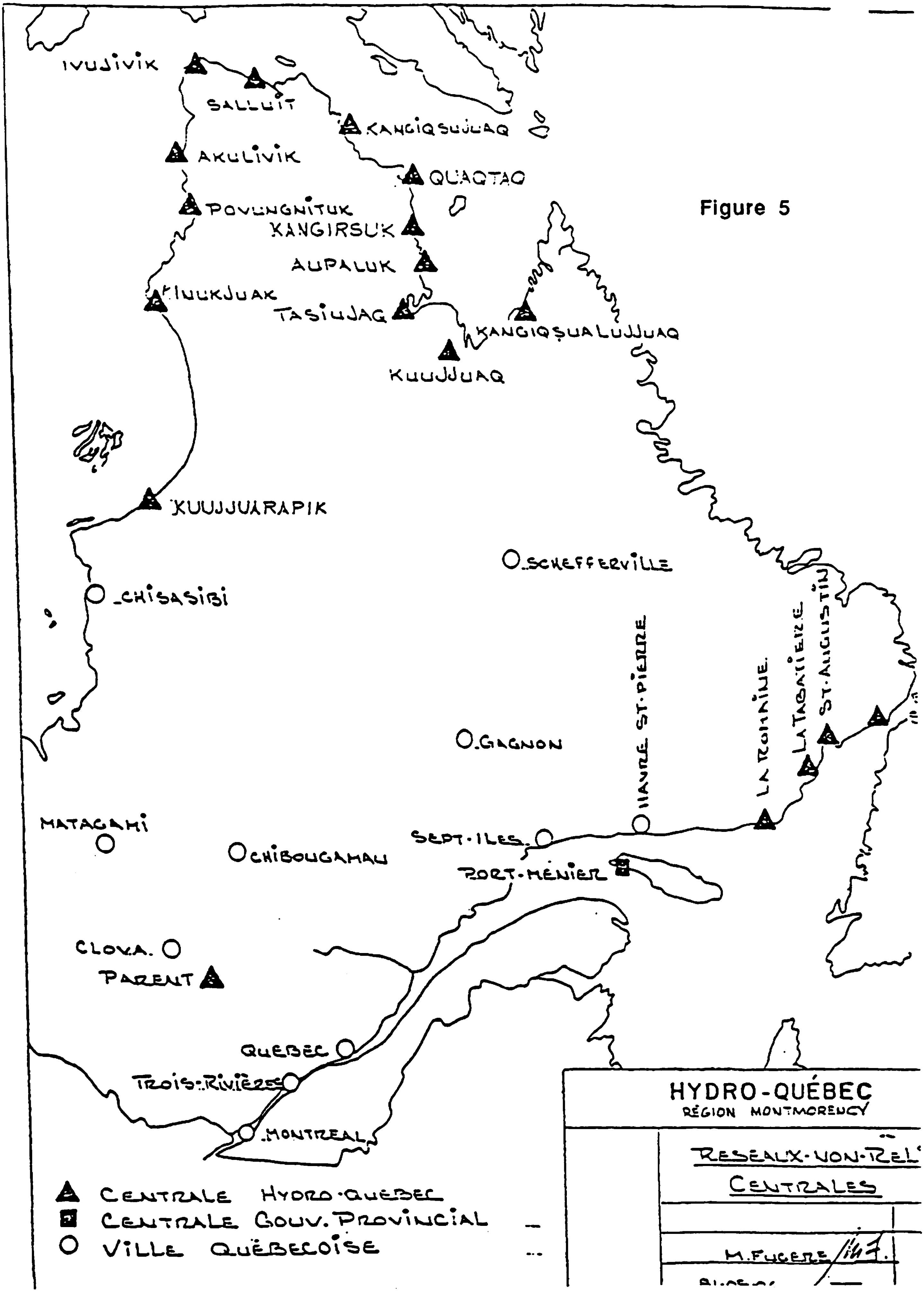
GLOBAL SCHEDULE OF WIND / DIESEL COUPLING PROGRAM



HIGH-PENETRATION-NO-STORAGE WIND / DIESEL PROGRAM

PHASE	DESCRIPTION
1.	KUUJJUAQ demonstration project
2.	Design and development of a control and regulation system for the high penetration no storage W/D scenario.
3.	Demonstration of the northern version in a remote village
3 a	Installation of wind turbines
3b	High penetration no storage
4.	Implementation of the demonstrated W/D technology

Figure 5


IVUJIVIK
SALLUIT
KANGIQSUJUAQ
AKULIVIK
QUAQTAQ
POVUNGNITUK
KANGIRSUK
AUPALUK
INUKJUAK
TASIUJAQ
KANGIQSUALUJJUAQ
KUUJJUAQ
KUUJJUARAPIK
SCHEFFERVILLE
CHISASIBI
HAVRE ST-PIERRE
LA ROMAINE
LA TABATIERE
ST-AUGUSTIN
GAGNON
MATAGAMI
SEPT-ILES
CHIBOUGAMAU
PORT-MÉNIER
CLOVA
PARENT
QUEBEC
TROIS-RIVIÈRES
MONTREAL
▲ CENTRALE HYDRO-QUEBEC
■ CENTRALE GOUV. PROVINCIAL
○ VILLE QUÉBECOISE
HYDRO-QUÉBEC
RÉGION MONTMORENCY
RESEAUX-NON-REL
CENTRALES
M.FUGERE

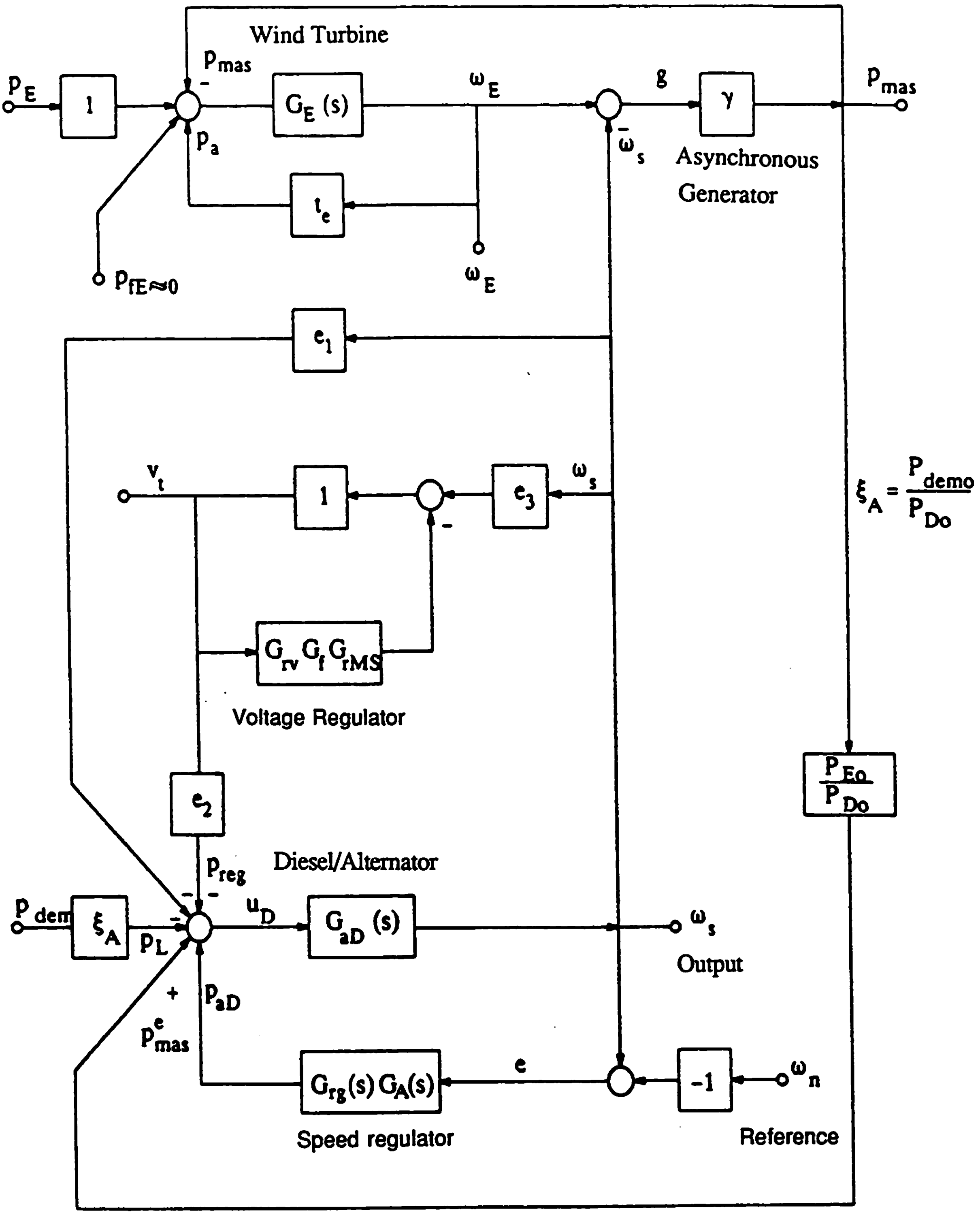


Figure 6a Detailed Block Diagram of a Diesel Coupled to an Aerogenerator, Without Load Levelling Regulation.

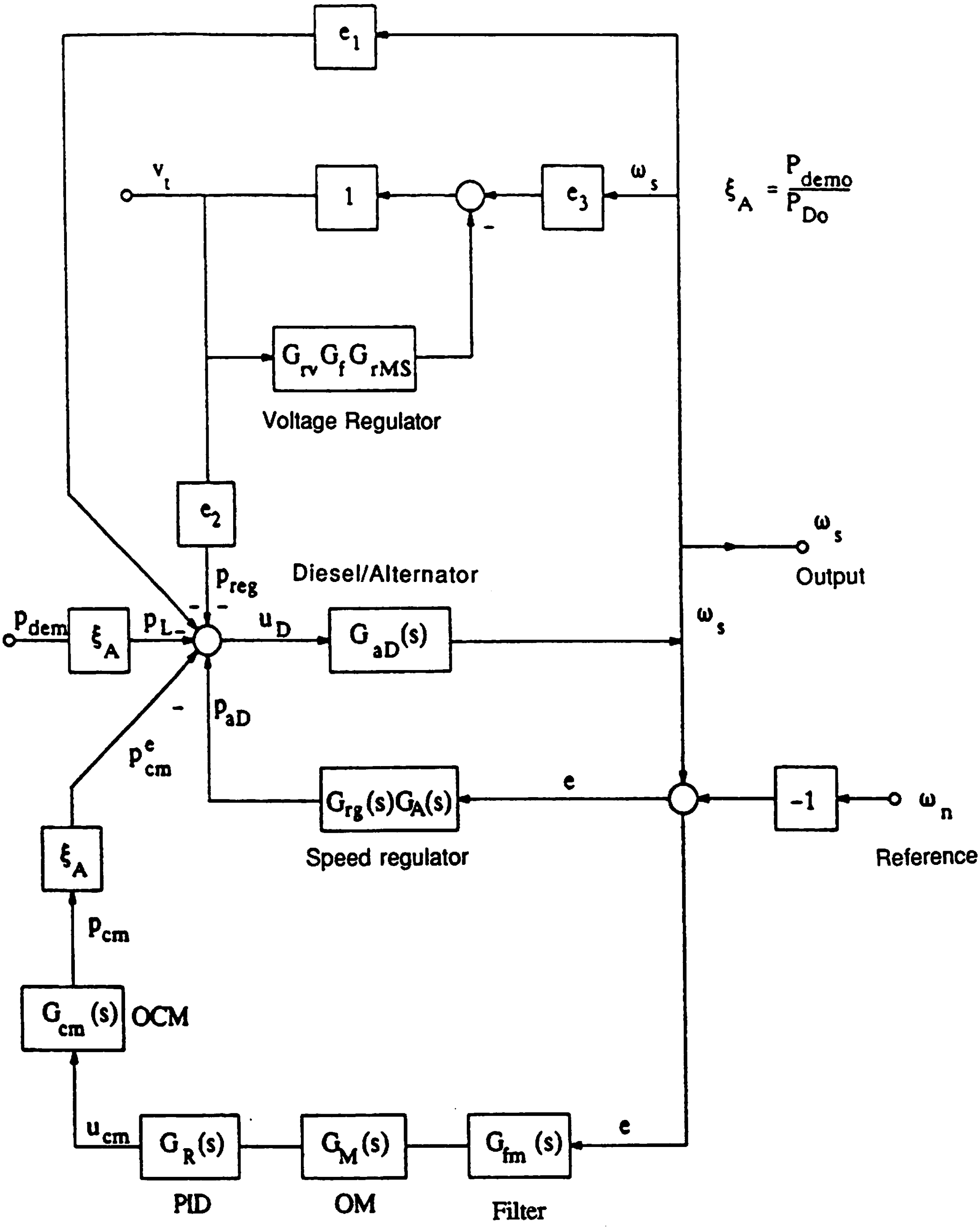


Figure 6b Detailed Block Diagram of a Diesel Operating in a Stand-alone Mode, With Load Levelling Regulation

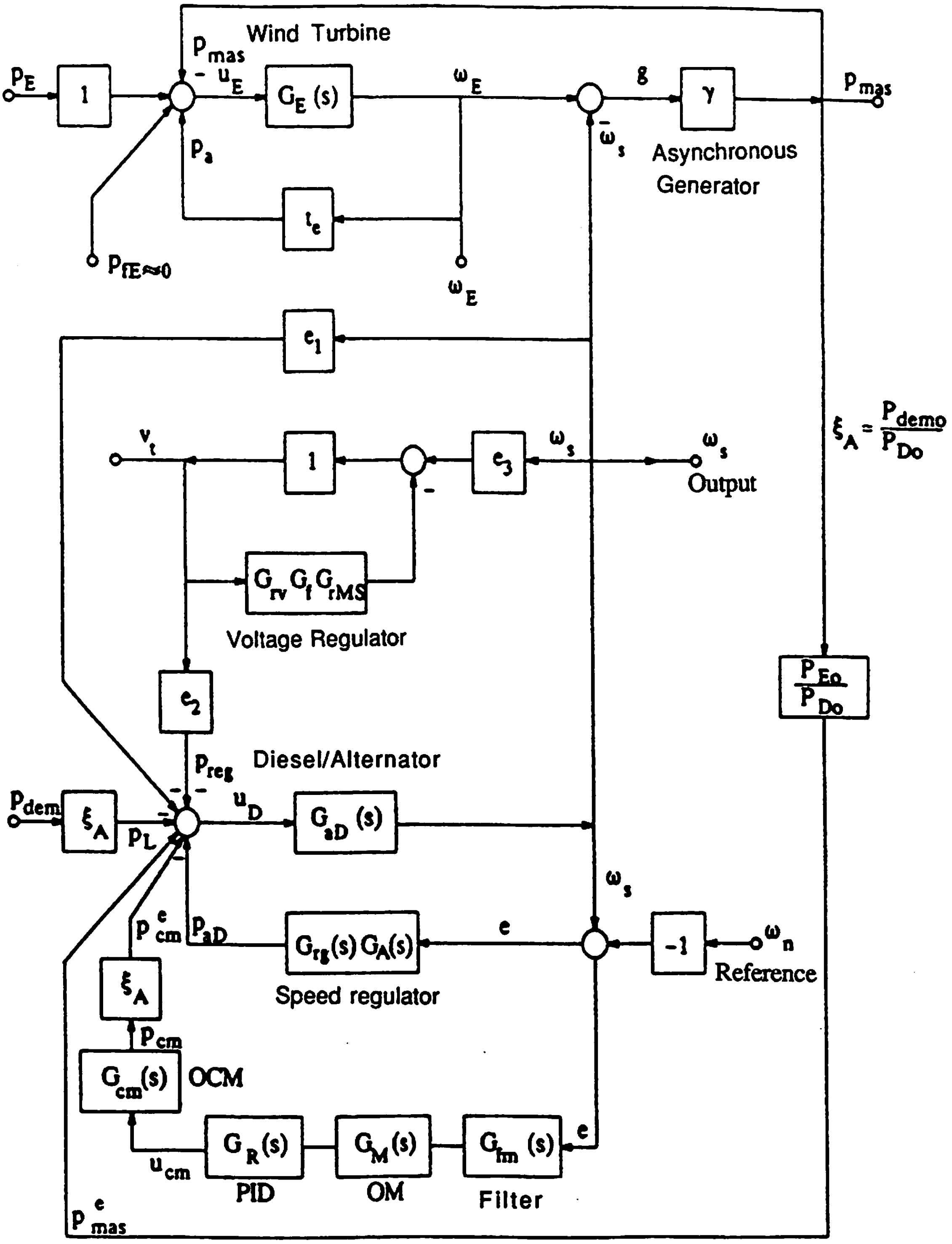


Figure 6c Detailed Block Diagram of a Diesel Coupled to an Aerogenerator, With Load Levelling Regulation.

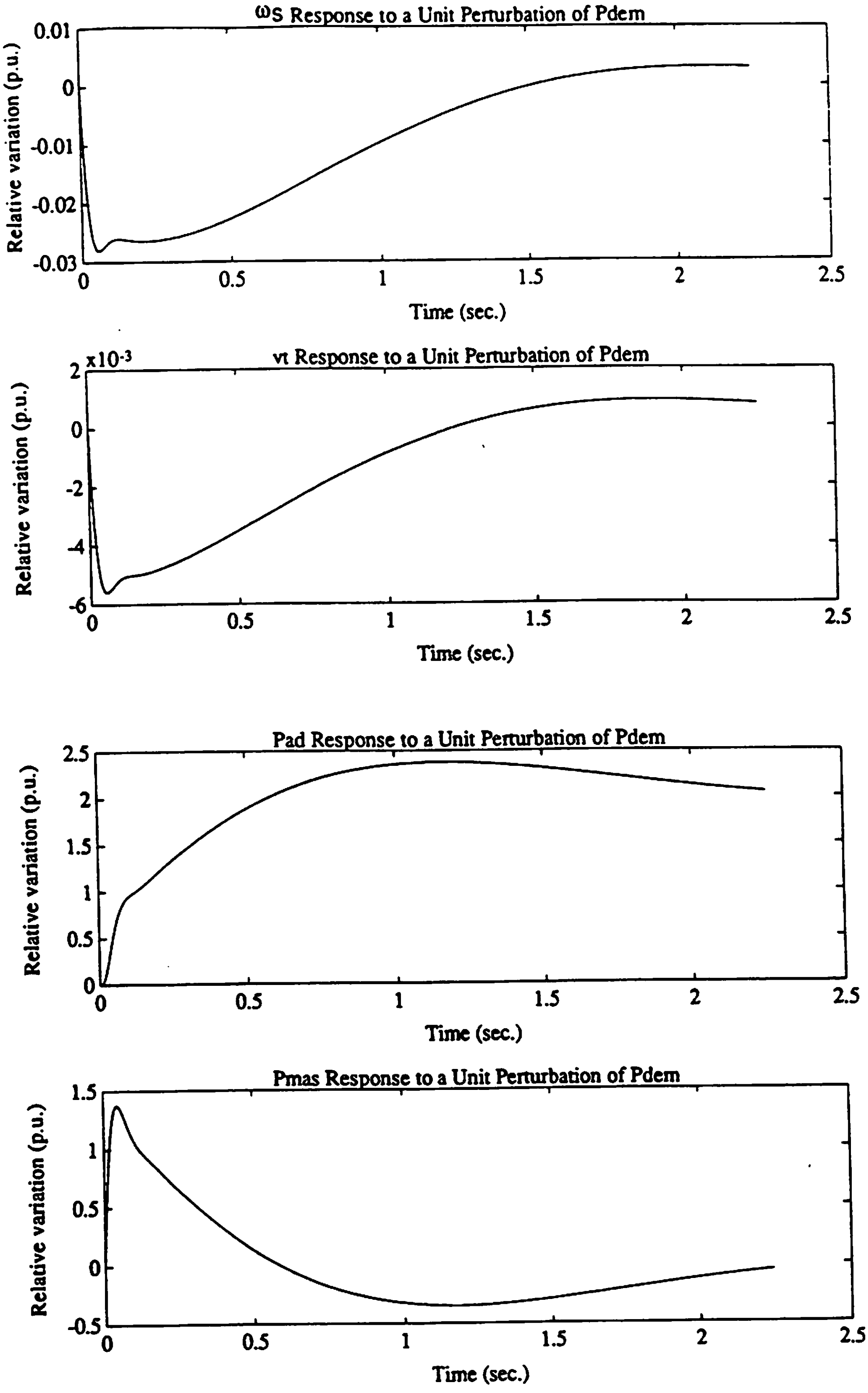


Figure 7a Time Response of a Diesel Coupled to an Aerogenerator, Without Load Levelling Regulation (100% penetration).

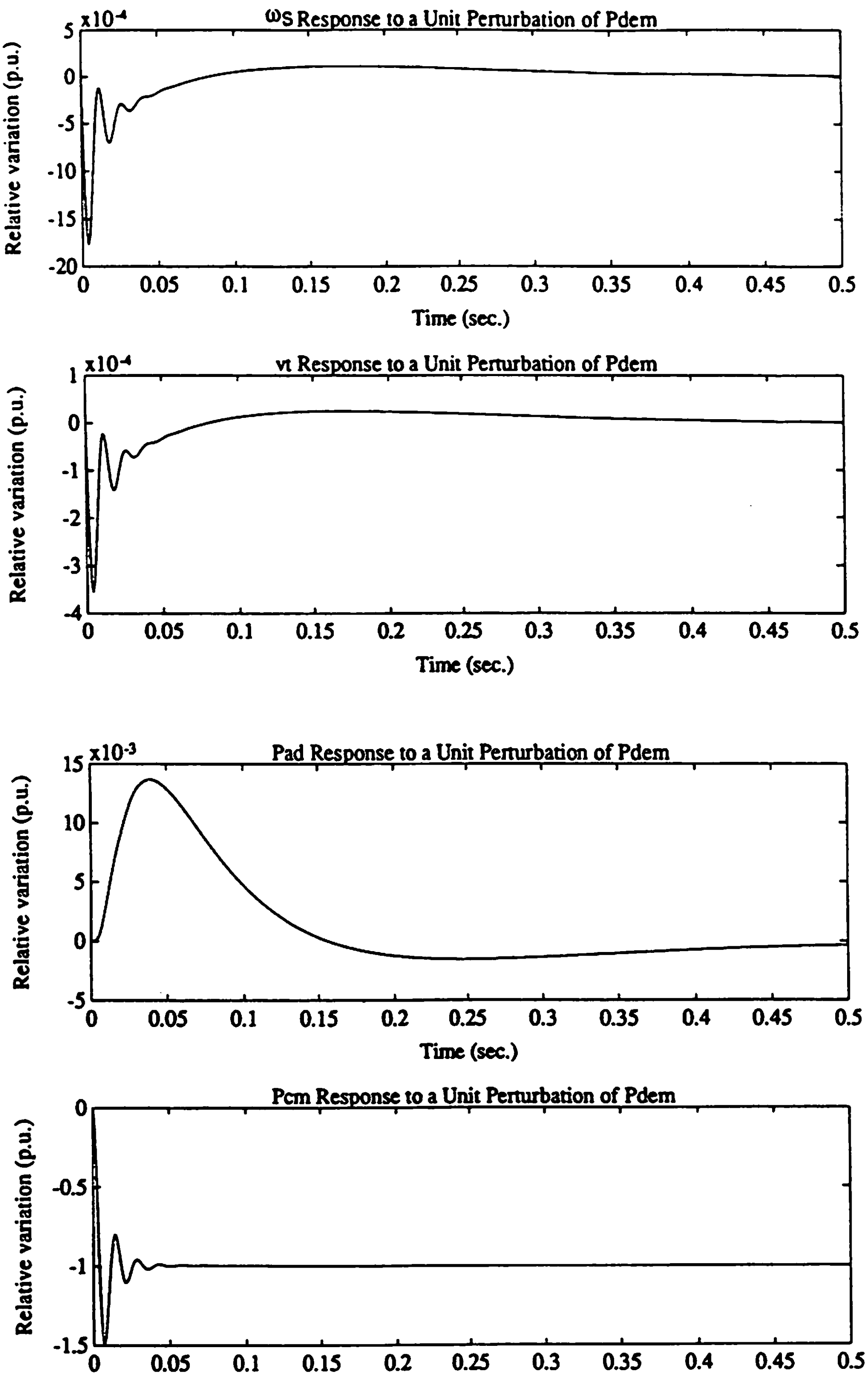
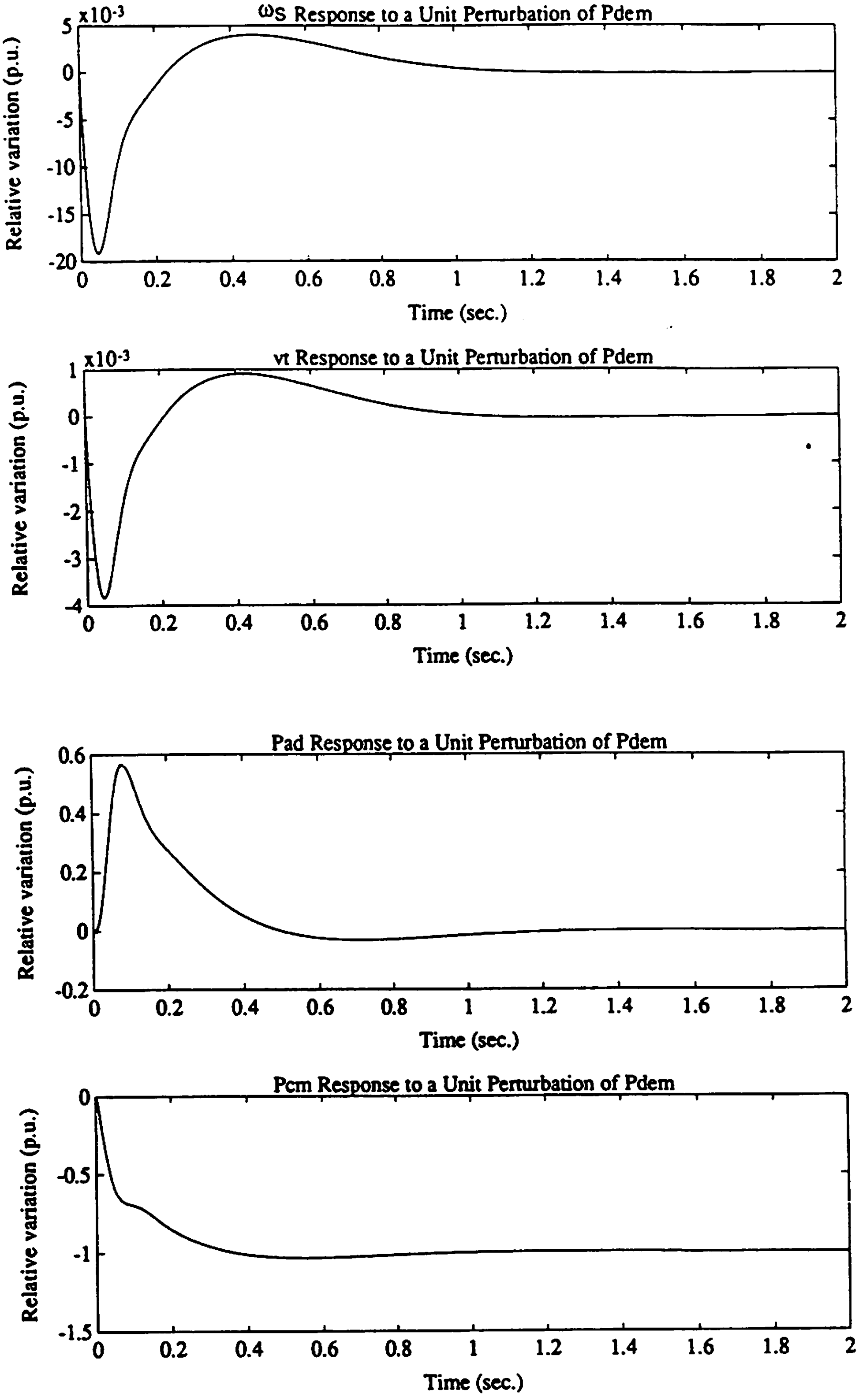


Figure 7b Time Response of a Diesel Operating in a Stand-alone Mode, With Load Levelling Regulation.


ωs Response to a Unit Perturbation of Pdem

vt Response to a Unit Perturbation of Pdem

Pad Response to a Unit Perturbation of Pdem

Pcm Response to a Unit Perturbation of Pdem

Figure 7c Time Response of a Diesel Coupled to an Aerogenerator, With Load Levelling Regulation (100% penetration).

CEC PENETRATION STUDIES

Bent Rasmussen

A. CEC Information, 1989

The pentration studies have been carried out for ten mainland grids and the French Islands possessions to estimate the contribution which wind energy could make, taking into account the special characteristics of each grid.

B. Viewgraphs of the Author

Wind Energy Penetration Europe 12 Guidelines for National Studies

Authors:	J. K. Vesterdal	
Contract number:	EN3W-0006-DK(b)	
Duration:	10 months	1 February 1986 - 30 November 1986
Total budget:	DKR 2.415.000	CEC contribution: DKR 2.415.000
Head of project:	Chief Engineer P. F. Bach, ELSAM Planning Department	
Contractor:	ELSAM Planning Department	
Address:	ELSAM DK 7000 Fredericia Denmark	

Summary

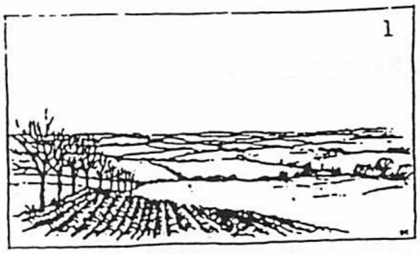
For CEC DGXII ELSAM has been engaged in preparing "Guidelines for System Studies under CEC Wind Power Penetration Study".
The intention with the Guidelines is to provide the different CEC-countries with a tool which - in the absence of national data - makes it possible for them to evaluate the extent to which wind power can technically and economically be fitted into the national power production systems, in order to

- Serve as background information in the energy political deliberation of the Community and the national governments
- Serve as background information for utilities
- Serve as guidance for wind turbine manufacturers' market analyses.

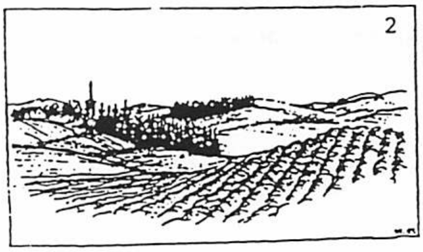
The guidelines consist of

- recommendations for technical and economic evaluations which form a background for harmonization of the studies in the different countries
- demonstration of the possibility to obtain the necessary wind turbine data and wind data where these are not available.

In obtaining the wind turbine data and the wind data ELSAM's Planning Department has been assisted by ELSAM's Power Station Engineering Division and RISØ National Laboratory.
As a result of discussions with utilities in the majority of the twelve CEC-countries during 1986 the Guidelines have been modified a number of times and are now available in the final edition.



1. Non-mountainous regions far away from mountains. Complications occur in the form of surface roughness inhomogeneities and sheltering effects. The theory of geostrophic drag law is applicable.



2. Non-mountainous regions as under (1) but with the additional complication of small-scale smooth hills and valleys. Typical horizontal dimensions are less than 1 km. The flow modifications introduced by the obstacles can be treated as potential flow with modification from turbulence and wind shear.

3. Larger scale hills and valleys. Horizontal dimensions larger than 1 km. On these scales buoyancy effects are almost always important and under stable stratifications mountain waves are often present.

4. High mountain massifs cut by deep valleys. Depending on the local geometry, the winds at the peak may be representative of the free atmospheric values. In the valleys thermally-induced mountain valley winds are dominant in the wind climate. Except for leeside foehn the winds are decoupled from free atmosphere winds.

5. Broad sloping foreland regions. The regions are characterized by some distinct mechanisms caused by processes like channelling, deflection, leeside descent, and low-level jet. These mechanisms are often well-known like:
   - Foehn (leeside descent caused by upstream blocking and large-scale mountain waves).
   - Bize (blocking and deflection of low-level cold air).
   - Bora (hydraulic intensification of cold air flow and channelling).
   - Mistral and Tremontane (combines channelling, leeside descent and hydraulic intensification).
   - Morning jet (low-level jet generated thermally by sloping terrain).

Terrain forms used in the CEC Wind Atlas to define the meaning of the terms "non-mountainous" and "mountainous" terrain.
The CEC Wind Atlas is the basis for the Wind Data which can be obtained in connection with the Wind Penetration Study, Europe 12.
Source: E. Lundtang Petersen, I. Troen, Department of Meteorology and Wind Energy, RISØ National Laboratory, DK-4000 Roskilde, Denmark

EC WIND POWER PENETRATION STUDY
ENEL CONTRIBUTION

Authors : G.BOTTA, A.INVERNIZZI, A.RIVOIRO, S.PANICHELLI, L.SALVADERI
Contract number : EN-3W-0053-I
Duration : 15 months 1 October 1987 - 31 December 1988
Total budget : ECU 61000 CEC contribution: ECU 61000
Head of project : A.Invernizzi, Electrical Research Center
Contractor : ENEL (Ente Nazionale per l'Energia Elettrica), Study and Research Department
Address : Via G.B.Martini 3
I - 00198 ROME
ITALY

Summary

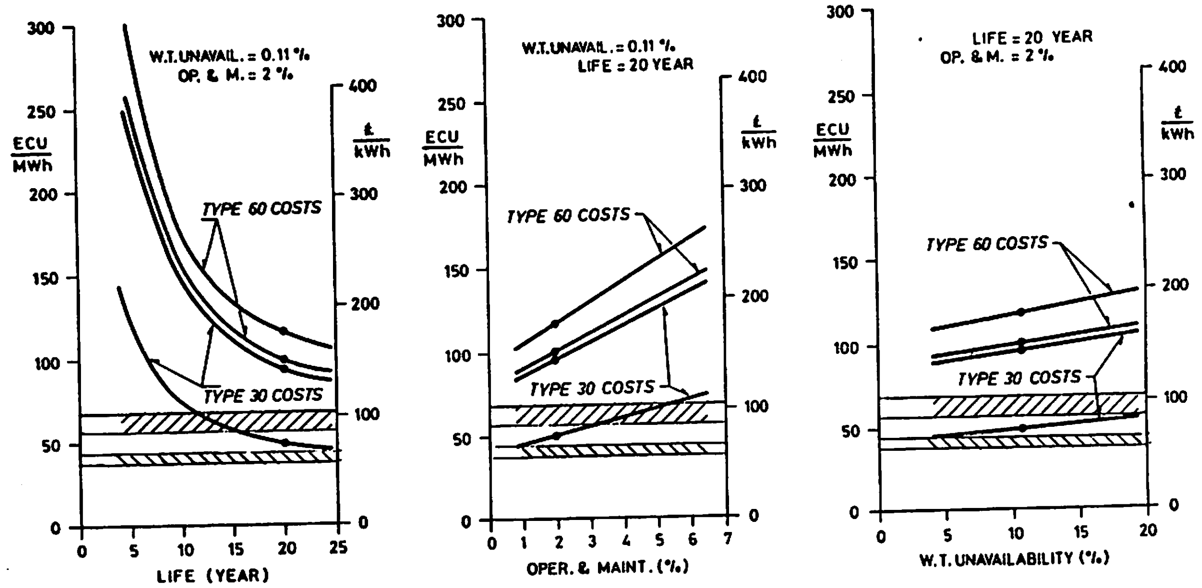
In the frame of the 1987 European Community Study, ENEL carried out investigations concerning on one side the availability of exploitable wind energy resources in Italy and on the other the quantitative evaluation of the related credits in a possible generation system structure for the year 2000.

Even if the methodology adopted in the evaluations is rigorous, it is to be underlined that the results produced are to be kept with caution: infact, many uncertainties affected the input data. First of all, at the beginning of the study the Italian National Energy Plan (PEN) was still to be formulated: only in the month of August 1988 it was issued by the Industry Ministry and up to now it has not jet been approved by the Parliament; this has an obious effect on generating system structure. Secondly, the cost projections of wind turbines are, on their side, also affected by incertitudes so as the fuel costs. Finally, in the cost of the wind sources the economic value of "land occupation" was not included: this factor, which is certainly high in a densely populated nations as Italy, could be of paramount importance in the operative decisions.

In this rather uncertain frame, the quantitative evaluations were carried out with reference to the "high" demand projection foreseable at the moment for the ENEL system in the year 2000, that is 285 TWh. Capacity and Energy credits of the wind source have been investigated. In doing this, various percentages of wind energy penetration have been considered, with a maximum of 1500 GWh presently foreseen by the Italian Energy Plan and corresponding to 0.5% of the yearly demand. Two hypothesis of fuel cost projections (high and low) have been considered, since the higher contribution to the wind credits stems from the energy credits. The effect on the turbine cost of parameters such as life, operation and maintenance cost, unavailability was also examined.

The results of the evaluation, in term of comparison "credits vs; cost" are not valid for any system but are peculiar of each system structure and characteristic. For the italian system they are resumed in the following three drawings: a necessary caution is to be exerted in "interpreting" them, for the existing above mentioned incertitudes concerning the input data.

Comparison of wind energy credits with costs as a function of: expected life of wind turbines, annual charges for operation and maintenance (as % of investment), wind turbines unavailability. The cost of wind energy does not include the cost for land occupation.



Type 30 wind turbines: 30 m rotor diameter
Type 60 wind turbines: 60 m rotor diameter

<u>Wind energy credits</u>

▨ Range of variation relevant to "HIGH" fuel cost forecast (oil 62.2 ECU/MWh, coal 33.7 ECU/MWh)

▧ Range of variation relevant to "LOW" fuel cost forecast (oil 43.4 ECU/MWh, coal 21.4 ECU/MWh)

<u>Wind turbines cost</u>

——— National manufacturers cost: 97 KECU (Type 30), 118 KECU (Type 60)

------ EC Guidelines cost: 51 KECU (Type 30), 101 KECU (Type 60)

INTEGRATION OF WIND POWER IN THE GREEK GENERATION SYSTEM

Authors : D.KANELLOPOULOS, M. TOMBROU (A.E.F)
E.P. KARIDOGIANNIS (P.D.)

Contract number : EN3W-0054-GR

Duration : 12 months 1st February 1988- 31 January 1989

Total budget : ECU 83000 CEC contribution: ECU 80000

Head of project : Dr. D. Kanellopoulos, PPC/ Alternative Energy Forms.

Contractor : PUBLIC POWER CORPORATION
Alternative Energy Forms and Planning Department.

Address : Public Power Corporation/Alternative Energy Forms
10, NAVARINOU Str., GR-106 80, ATHENS. GREECE

Summary

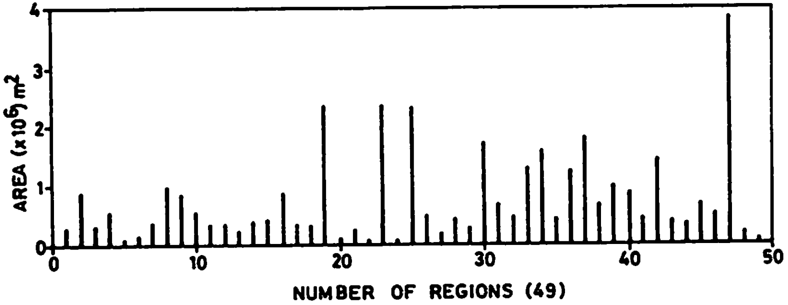
The scope of this work is to carry out a penetration study for wind energy in the generating system of Greece. This is carried out in accordance with the "Guidelines for System Studies under EC WIND POWER PENETRATION STUDY,January 1987". The wind power penetration senarios include 5%,10% and 15% penetration levels for the following cases: a) Wind Energy generated in Crete by 300 kW wind turbines (WT) with the power system of Crete operated in isolated mode. b) Wind Energy generated in Crete by 300 kW WT and 1000 kW WT in mainland Greece with a 600 MW interconnection DC link between mainland and Grete. The generated units in Crete are on cold reserve.
Because of the large potential of Wind Energy in the Greek islands of CYCLADES, PPC is planning to carry out an extra senario wich will incorporate the wind energy generated in Cyclades, Crete and mainland Greece as an interconnected System.
For the above senarios various matters are taken into consideration. To start with, emphasis was given to SITE selection with criteria the annual mean speed at 10m height, accessibility and wind farm configurations. A combination of experimental hourly values plus theoretical evaluations using a mass consistent algorithm were used in order to establish the time series for the power pool. Following the coise of the two types of WT, energy calculations of the total number of wind farms were prepared and used as input in the subsequent calculations. These include:energy demand projections for the year 2000, generation and production cost, energy displaced, annual production cost saving both for ENERGY GREDIT and CAPACITY GREDIT mode, wind power economic value with sensitivity analysis.

PPC-CRETE

THE AREA OF THE REGIONS SELECTED MEETING THE FOLLOWING CRITERIA

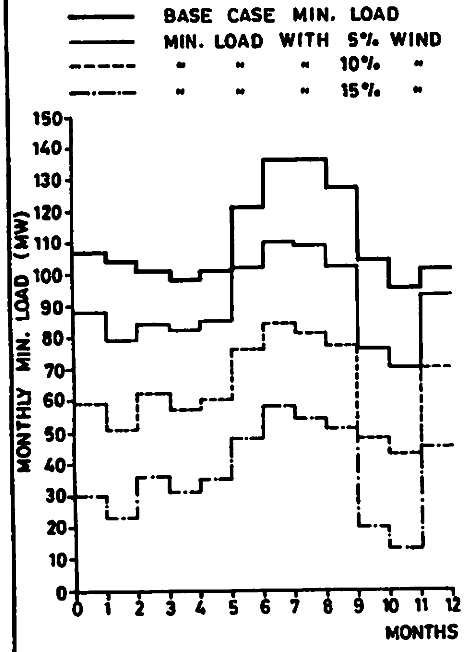
1	DISTANCE FROM EXISTING ROAD < 2 km
2	DISTANCE FROM TOWNS - VILLAGES > 1 km
3	GROUND SLOPES < 10 %
4	MEAN WIND SPEED AT 10 m HEIGHT AS GIVEN BY "EOLOUS" ≥ 6.0 m/s

TOTAL AREA
36.3625 sq.km



MIN. MONTHLY SYSTEM LOAD

YEAR 2000



WIND POWER PENETRATION

YEAR 2000

	5%	10%	15%
W.T. Type (kW)	300	300	300
Number of W.T.	108	218	329
Total W.T. Capacity (MW)	32.4	65.4	98.7
Wind Farm Production (GWh)	101.1	202.1	304.5

WIND POWER ECONOMIC VALUE

YEAR 2000

(Fuel Escalation Rate 2%)

Penetration %	WF. Cap. MW	Credit Mode	IRR %	Present Value (1986 ECU/kW		
				d=3%	d=5%	d=7%
5	32.4	Energy Capacity	16.7 20.2	1084.5 999.3	605.6 575.1	334.0 330.8
10	65.4	Energy Capacity	16.0 18.6	1020.2 944.1	565.0 536.8	307.8 303.8
15	98.7	Energy Capacity	15.6 17.7	976.5 938.6	537.4 529.6	290.0 296.5

CEC WIND ENERGY PENETRATION STUDY

Author : N. Halberg

Contract number : EN3W-0055-NL

Duration : 16 months 1 October 1987-31 January 1989

Total budget : 148000 ECU CEC contribution: 80000 ECU

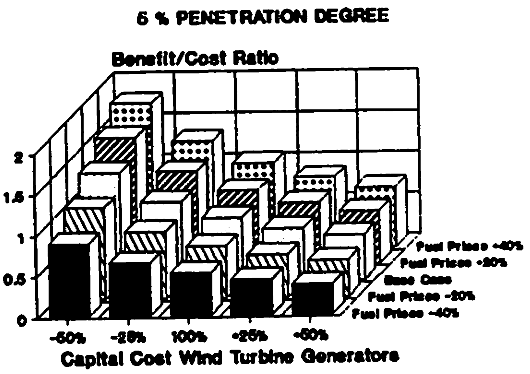
Head of project : N. Halberg, N.V. Sep

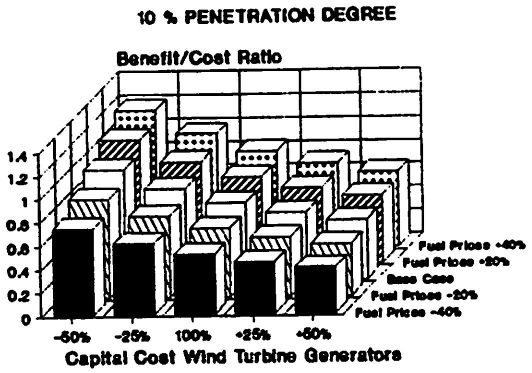
Contractor : N.V. Samenwerkende elektriciteits-produktiebedrijven

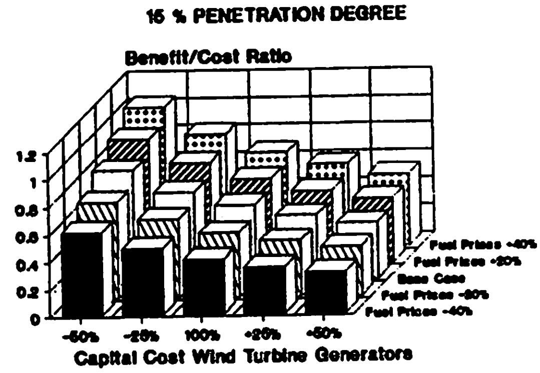
Address : Utrechtseweg 310
P.O. Box 575
NL-6800 AN ARNHEM

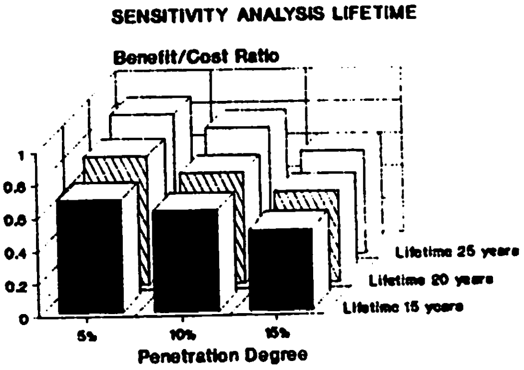
Summary

Operation of the Dutch electricity generating system has been examined with varying penetration degrees of Wind Energy Conversion Systems (WECS). The simulation has been carried out using wind data recorded at 6 sites spread across the area of interest in the Netherlands. The recorded wind data has been used in conjuction with a production costing model normally used by Sep for planning purposes. This model was modified to give a correct assessment of quantity and value of fuel savings by WECS.
System studies were carried out for the year 2000 and for three distinctive penetration degrees of WECS, namely 5%, 10% and 15%. After incorporation of WECS capacity, adjunstments were made to the basic plant mix to allow for the capacity credit of WECS. Separate production cost simulations were executed for each distinct WECS capacity factor.
Recent studies by Sep suggest that, up to about 1,000 MW to 1,600 MW installed WECS capacity, the aggregate power output of the wind systems could be absorbed into the generating system without recourse to storage and without significant wind energy losses. Previous results clearly demonstrate the potentially devastating effect of the load-following and spinning-reserve penalties on the economics of wind power for higher penetrations of WECS and no storage.
For the 10% and 15% cases an energy storage system was therefore included in the plant mix. Economic assessments were carried out using standard procedures. The results of this analysis are shown in the following figures.


5 % PENETRATION DEGREE


10 % PENETRATION DEGREE


15 % PENETRATION DEGREE


SENSITIVITY ANALYSIS LIFETIME

INTEGRATION OF WIND POWER IN THE PORTUGUESE GENERATION SYSTEM

Authors	: A.M.d'A. CARVALHO, F.A.P. DOMINGUES, H.C.R. MOREIRA, A.C.L. NUNES		
Contract number	: EN3W-0056-P(TT)		
Duration	: 18 months	1 October 1987 - 31 March 1989	
Total budget	: 322 000 ECU	CEC contribution :	80 000 ECU
Head of project	: A.M.d'A. Carvalho, EDP-DTA		
Contractor	: Electricidade de Portugal, EP		
Address	: Av. José Malhoa, Lote A/13 P-1000 LISBOA		

Summary

The study of the integration of wind power in the Portuguese generation system is part of the EC Wind Power Penetration Study that is intended to evaluate the extent to which wind power can technically and economically be fitted into the power production systems of the member countries.
It is also an aim of the project to identify relevant R&D projects that may facilitate the penetration of wind power in the existing generation systems. The results obtained are expected to serve as background information for the utilities and for energy policy by the Community and the national governments as well as to supply useful information for market studies by the wind turbine manufactures.
Several typical sites were selected as representative of regions with good wind power potencial and, after being duly characterized, wind speed and energy time series were obtained from the Danish Risoe National Laboratory. Preliminary calculations were carried out for a scenario with 5% wind energy penetration in the year 2000 compared to a reference scenario without wind energy using EDP's Valoragua model. Energy and capacity credits were estimated as well as the corresponding economic evaluation. Simulations for lower and higher penetration scenarios are currently being carried out.

Integration of Wind Power in the Danish Generation System

EC Renewable Energy R&D Programme

Authors : Uffe Steiner Jensen

Contract Number: EN3W-0057-DK (B)

Duration : 17 months, 1 October 1987 - 1 March 1989
Total Budget : 97.331 ECU CEC

Head of Project: Carl Hilger, ELSAM

Contractor : ELSAM, The Jutland-Funen Electricity Consortium

Address : ELSAM
The Planning Department
DK-7000 Fredericia

Summary

The purpose of the "Penetration Study" is to examine the extent to which it is feasible, technically and economically, to integrate wind power into the Danish power system maintaining the quality of the electricity supply at the usual level.

Scenarios with 5, 10 and 15 % wind energy have been analysed. The Elsam Expansion Plan for the year 2000 has been used as the reference scenario.

Different 5% scenarios have been analysed taking into account the following factors:

- added wind power capacity
- reduced conventional capacity
- added load control capacity
- added energy storage capacity

The preliminary results indicates that the wind power scenarios are unprofitable.

A number of operational difficulties e.g. load control and load gradients must be analysed in more detail in the future.

Scenario (Year 2000)	Reference	5%	5%	5%	5%	10%	15%
Scenario number	1	2.0	2.1	2.2	2.3	3.0	4.0
Installed Windpower (MWe)	55	700	700	700	700	1400	2100
Reduced Conventional Capacity (MWe)	0	0	340	740	600	0	0
Storage (MWe) and (h)	0	0	200-6	200-6	200-6	0	0
Gas Turbines (MWe)	0	0	0	400	400	0	0

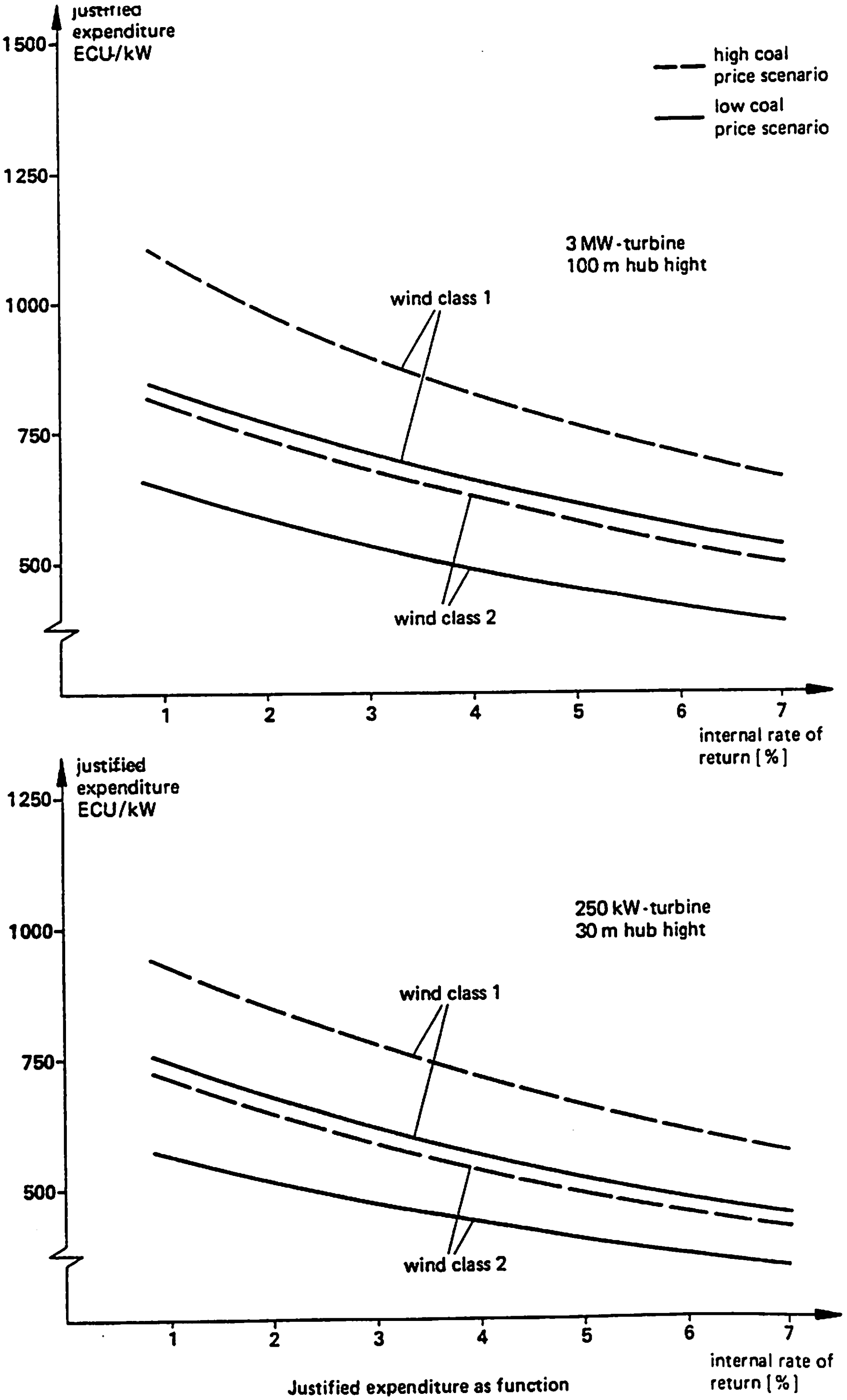
Scenarios

CEC WIND ENERGY PENETRATION STUDY

Author	: A. Elstermann		
Contract number	: EN3W-0059D		
Duration	: 16 months	November 1987 - February 1989	
Total budget	: 80,000 ECU	CEC contribution : 100%	
Head of project	: A. Elstermann, CONSULECTRA		
Contractor	: CONSULECTRA Unternehmensberatung GmbH		
Address	: Flotowstr. 41-43 D-2000 Hamburg 76		

Summary

The present study offers a better insight into the economical and technical problems arising with increasing wind penetration into an electricity system. The simulation models developed here have made it possible to depict a sequence of scenarios with different parameters. The influence of the internal rate of return, the future price development on the world coal market (it has been assumed here that wind energy will replace generating by coal-fired power plants), the influence of wind potential and operation and maintenance costs have been analysed. To calculate the cost-benefit ratio within different scenarios, the capacity credit of wind turbines (ratio of safe capacity share to installed capacity) has also been computed on a special model. The justified expenditure for 3 MW and 250 kW wind turbines in wind classes 1 and 2 for 2 different world coal price scenarios are shown depending on the internal rate of return (see attached chart). This justified expenditure can be directly compared with estimates from the wind turbine manufacturers, inasmuch as these include all investment costs per kW up to the transformer station.



Justified expenditure as function
of internal rate of return
wind scenario: North German coast
15 % capacity credit

EC WIND ENERGY PENETRATION STUDY

Authors : A. Cooke, C. Kelleher, H. Mangan, E. O'Dwyer.

Contract Number : EN3W-0060-IRL

Duration : 18 months from 1/December/1987.

Total Budget : ECU 157,000. CEC Contribution : ECU 80,000.

Project Leader : Edmond O'Dwyer.

Contractor : Electricity Supply Board.

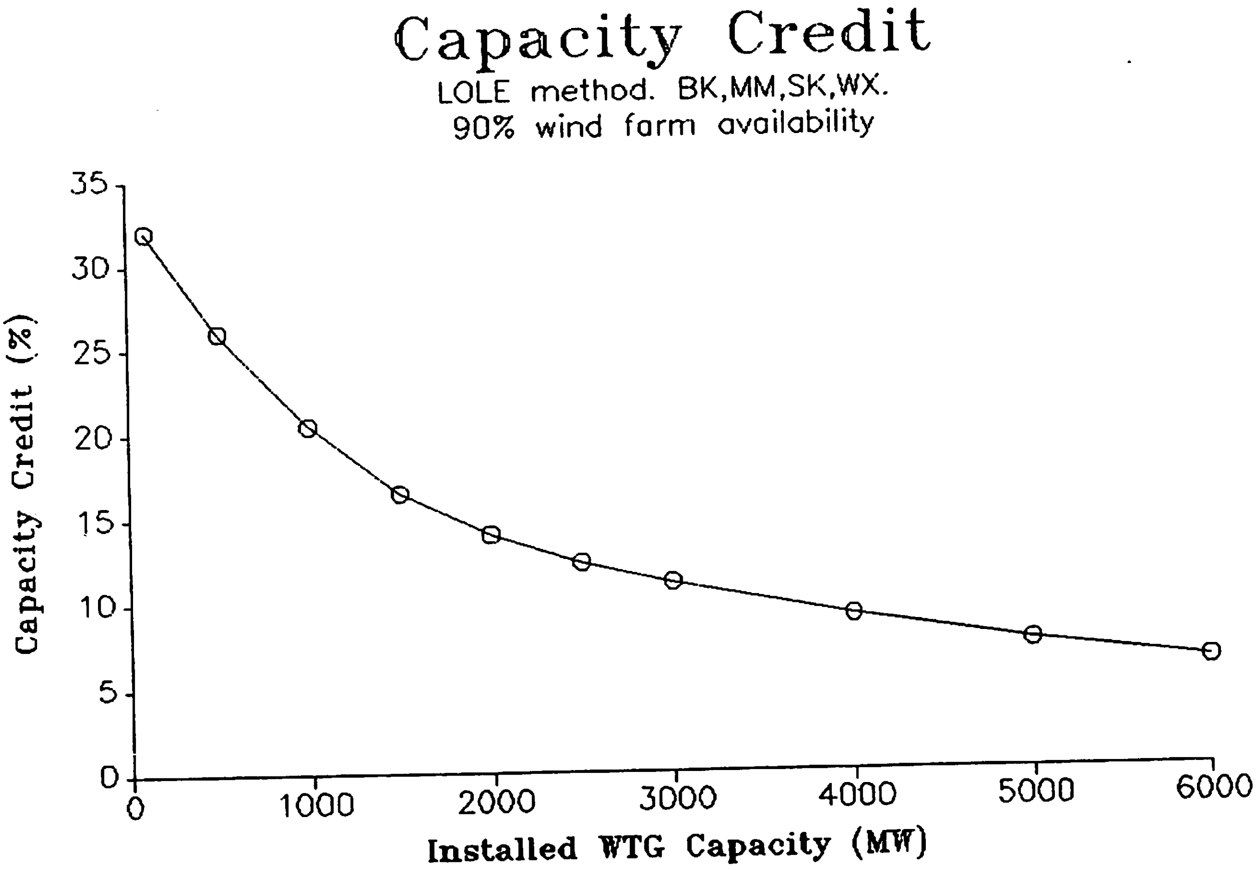
Address : Lower Fitzwilliam Street, Dublin 2, Ireland.

SUMMARY :

ESB, together with other European utilities, has been participating in this study.

The intention is to compare a reference system expansion plan without wind power for the year 2000, with three equivalent alternative expansion plans for that year having wind energy supplying 5, 10 and 15% of total primary energy required for electricity generation.

The economics of wind energy in 2000 in this context has been assessed, with wide-ranging parameter variation sensitivities. The issues of energy credit, capacity credit, environmental impact, system frequency control and other technical problems have been addressed.



Main System Planning Division,
Electricity Supply Board, Ireland.
10/Mar/1988. CAPCR/CAP.

THE EC WIND POWER PENETRATION STUDY

Contract number : EN3W 0061-E

Duration : 14 months 1 July 1987 - 1 September 1988

Total budget : 80.000 ECU CEC contribution: 80.000 ECU

Head of project : Julio Barceló

Contractor : ENHER

Address : Pº Gracia, 132
08008 Barcelona

Summary

A study about the possibilities of wind energy as a substitute of conventional energy sources has been carried out. The steps of the study have been: first of all, site selection, time series of wind data and wind data correlations; then, wind farm configuration and power production; finally economical evaluation. Four scenarios have been taken into account: 1,5, 5, 10 and 15% level of penetration for year 2000 scenario. 1,5% level is the optimal wind energy production for spanish energy balance mix. 5, 10 and 15% are kept in order to be comparable with other CEC regional studies. Preliminary conclusions show that would be interesting to have more accurate data in order to validate wind energy production data; preliminary economic calculations show that wind energy could reach, with great difficulties, break-even situations under favorable circumpstances.

WIND POWER PENETRATION STUDY : CASE OF THE FRENCH OVERSEAS DEPARTMENTS AND TERRITORIES.

Author	: E. NOGARET	
Contract number	: EN3W-0070F	
Duration	: 6 months	1st June 1988 - 30 November 1988
Total Budget	: 20.000 ECU	CEC contribution : 20.000 ECU
Head of Project	: E. NOGARET	
Contractor	: ARMINES, Centre d'Energétique.	
Address	: ARMINES, 60 Bd St Michel, 75006 PARIS	

Summary

This report is the french contribution to the Commission of the European Communities concerted action : "**Wind Power Penetration Study**".
The purpose is to perform an economic evaluation of investments in wind power in the electricity power pool of the French Overseas Departments and Territories.
The Guadeloupe island, in the carribbean sea, has been chosen due to its good wind potential. From different informations such as wind speed data at the chosen spot, power curve of the selected wind turbines, availability of the WT and effectiveness of the wind farm, it is shown that a 10 MW wind farm would produce 28 GWh per year.
A 50 GWh production from wind power in year 2000, i. e. a 5 % share of the overall production of 1000 GWh, would thus require a 18.6 MW capacity from 62 wind turbines rated at 300 kW.
Taking, for the year 2000, a fuel cost of 0.072 ECU per kwh for the diesel units, the 5% scenario of wind power would have an internal rate of return of 14 % in the case of energy credit only and 18 % in the case of energy and capacity credit ; the pay back times of the investment would be 9 years (first case) and 7 years (second case).
Concerning control problems, it is shown that precise studies should be done to evaluate the additionnal control equipment needed and the limits to wind power penetration at any moment.

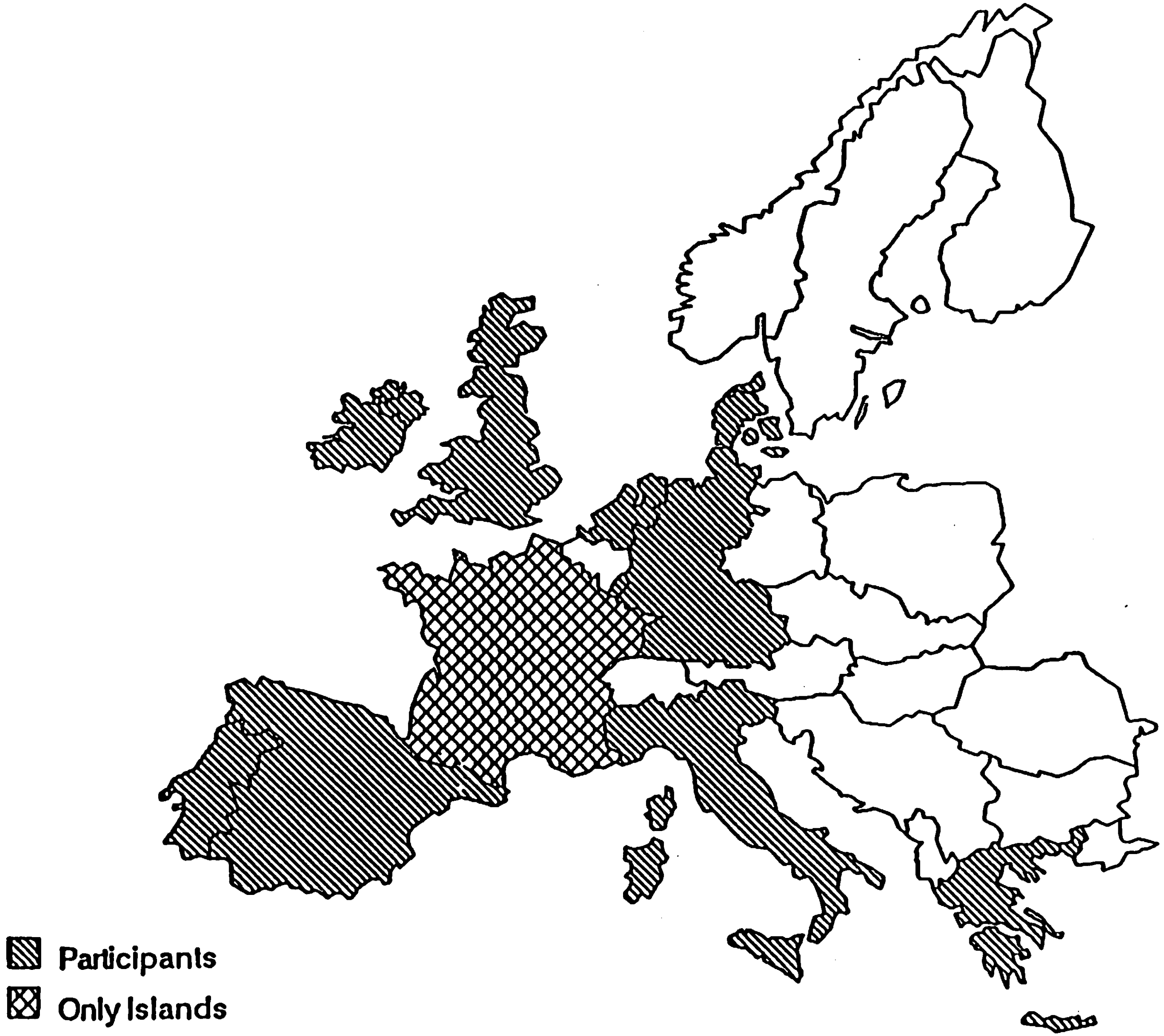
CEC Penetration Studies

Study 1: Autumn 1981 - June 1983

Study 2: Autumn 1987 - Spring 1990

Study 3: Autumn 1989 - Autumn 1991

CEC wind power penetration study



CEC wind power penetration study

Objective:

Generation Study.

- 5% wind energy

- 10% wind energy

- 15% wind energy

Specific Studies.

CEC wind power penetration study

Method:

Common Guidelines.

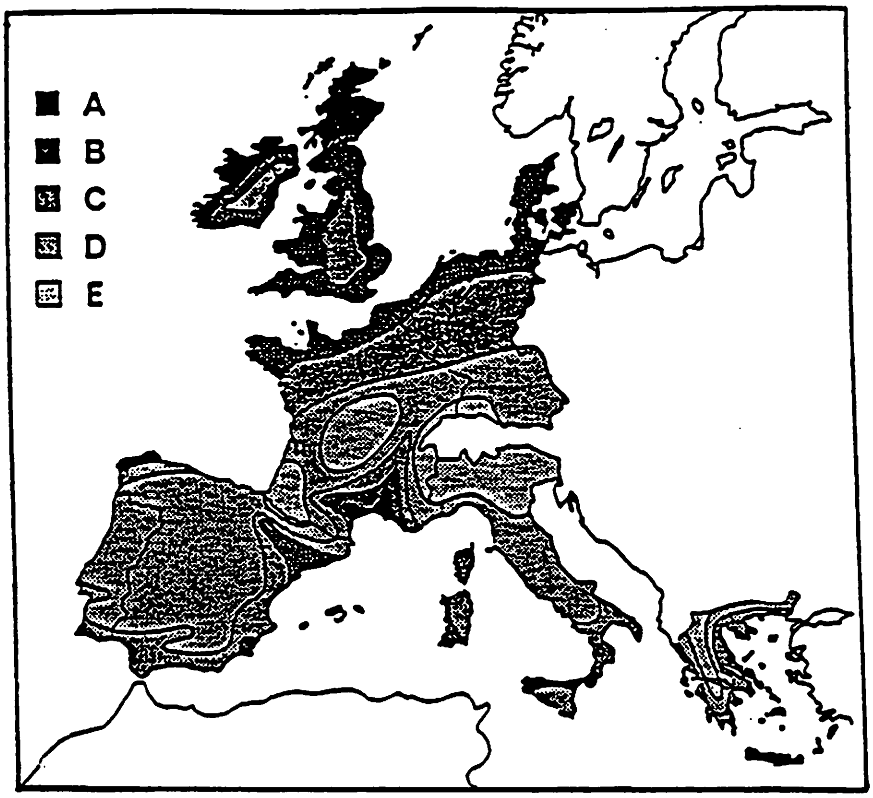
National or Regional
Simulation Models.

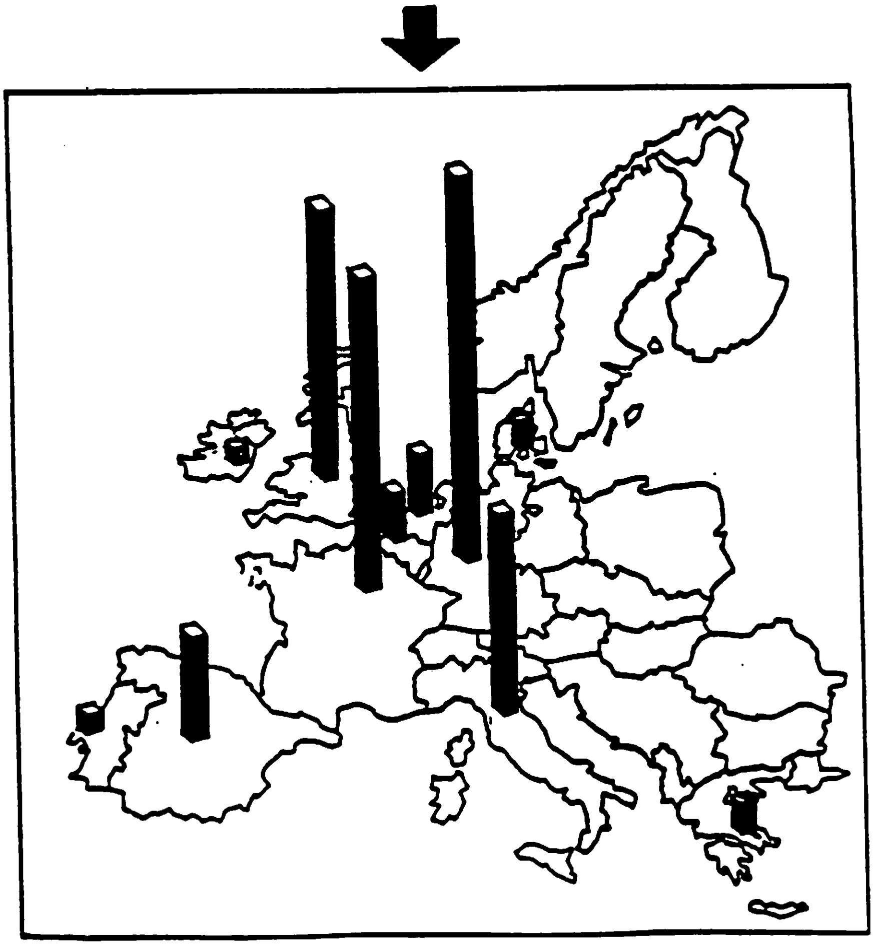
CEC wind power penetration study

Common basis:

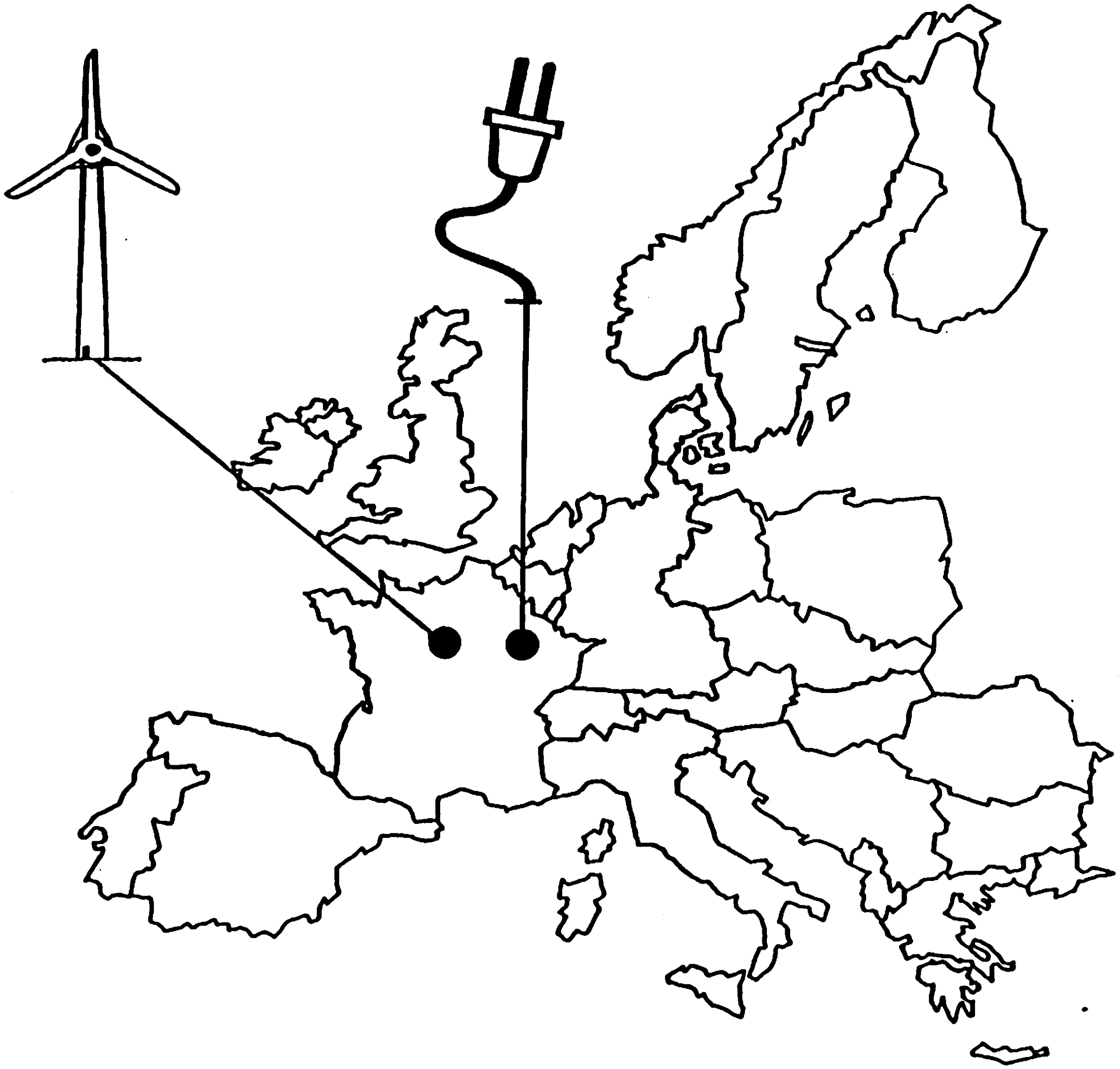
- Year 2000
- 0 - 5 - 10 - 15% scenarios.
- Same topics.
- Same economic calc.
  & parameters.
- Nearly same assumptions:
  - Wind resources.
  - Wind turbines.

CEC wind power penetration study

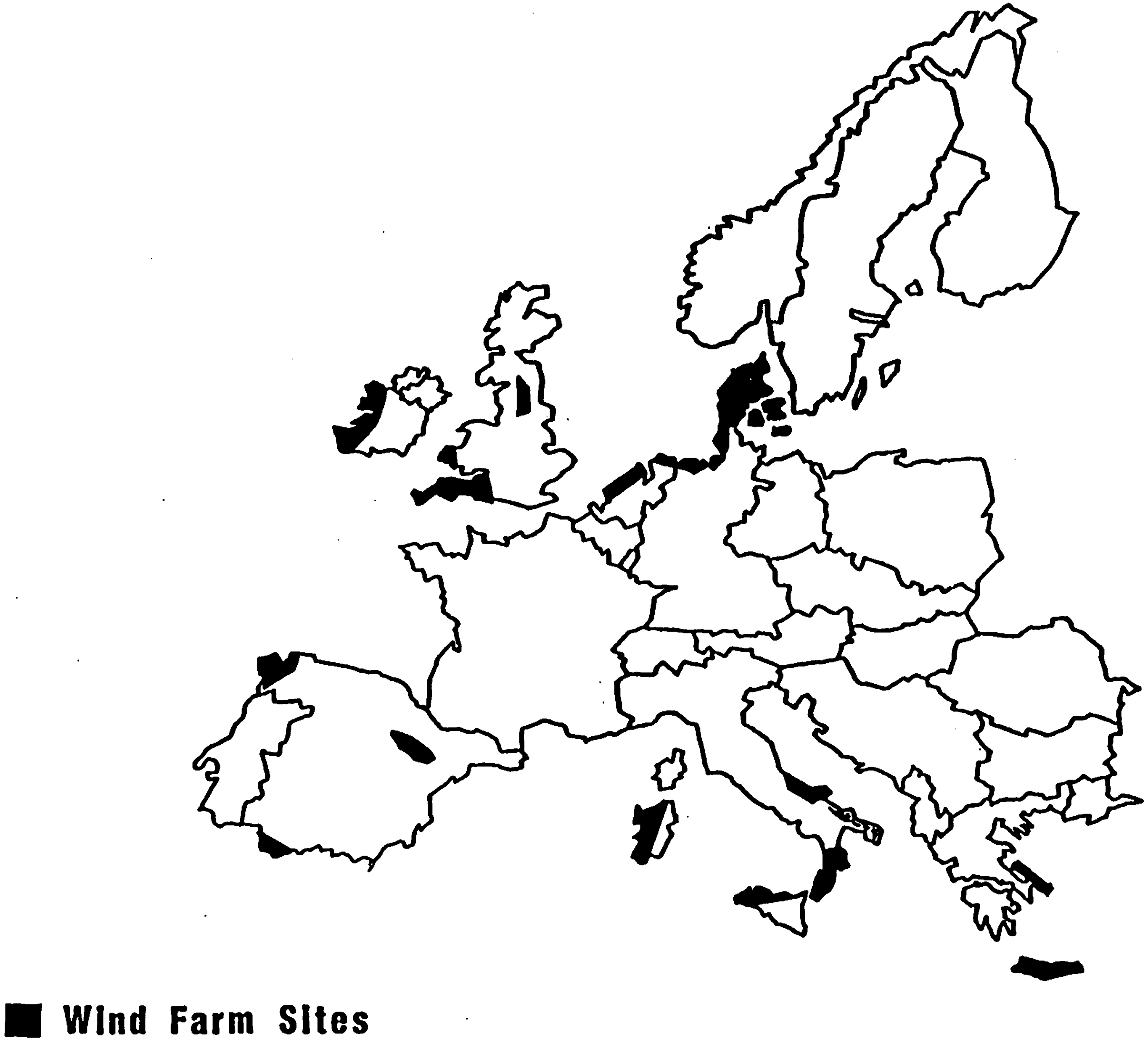




CEC wind power penetration study



CEC wind power penetration study



CEC wind power penetration study

Correlation
Wind / Power Supply

- Wind and electrical heating

- Diurnal variations in wind and in power load

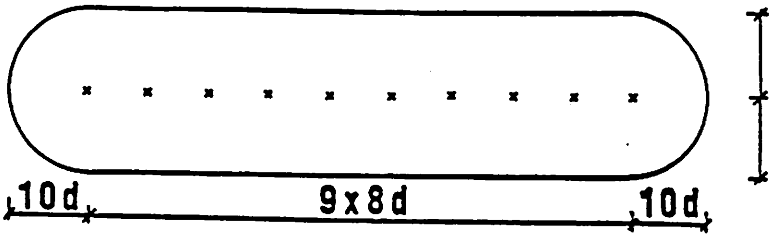
- Wind and hydro

CEC wind power penetration study

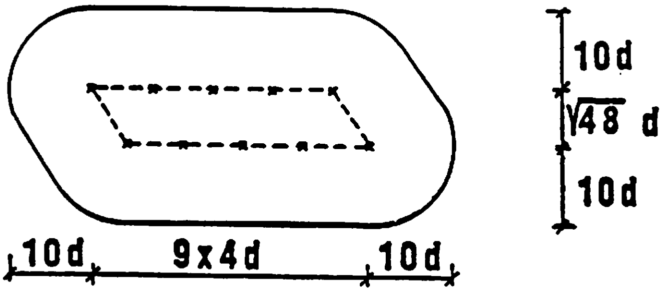
Wind Farm Configurations

4 different types of wind farms, each consisting of 10 turbines are shown below.

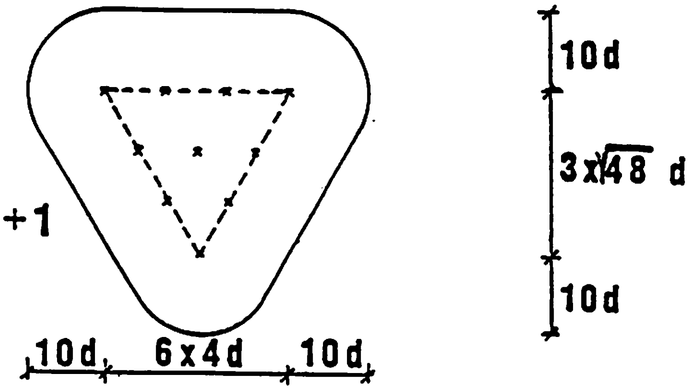
Farm type 10



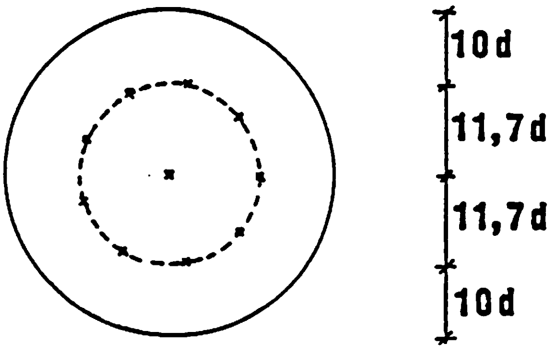
Farm type 5+5



Farm type 4+3+2+1

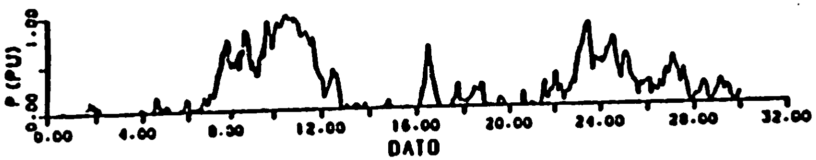


Farm type 1+09

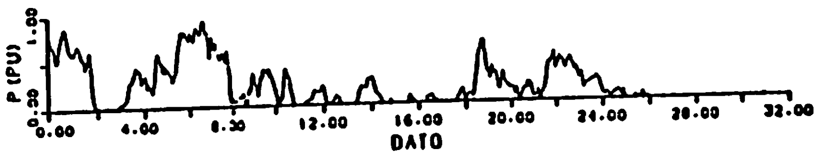


CEC wind power penetration study

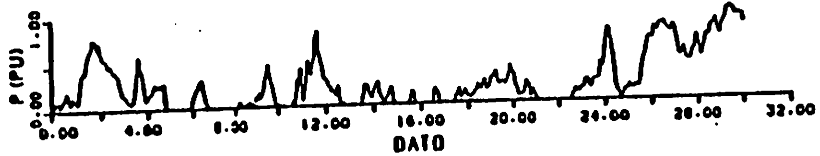
PRODUKTION JUNI



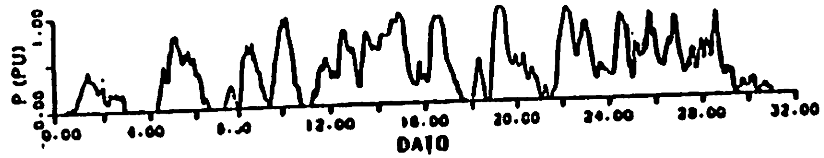
PRODUKTION MAJ



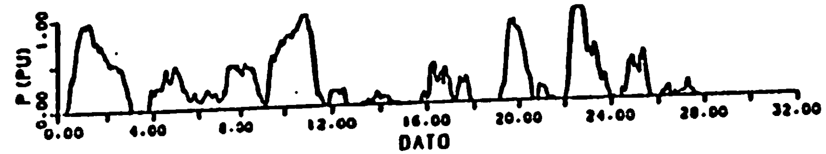
PRODUKTION APRIL



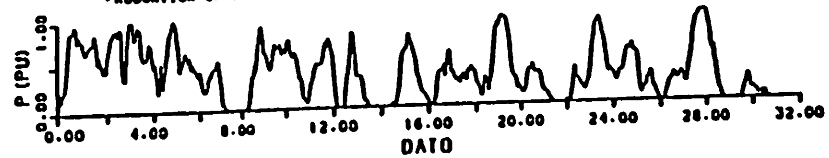
PRODUKTION MARTS



PRODUKTION FEBRUAR



PRODUKTION JANUAR



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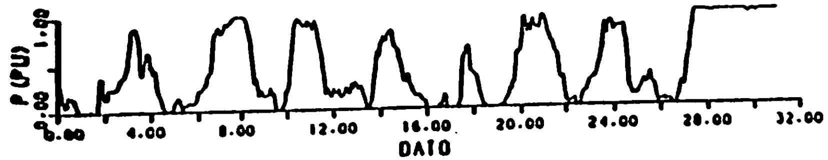

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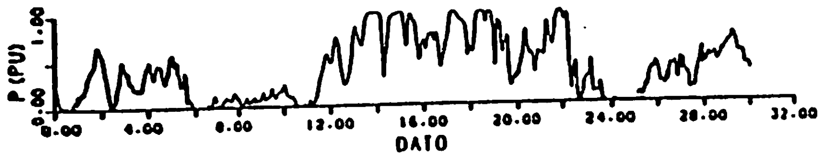
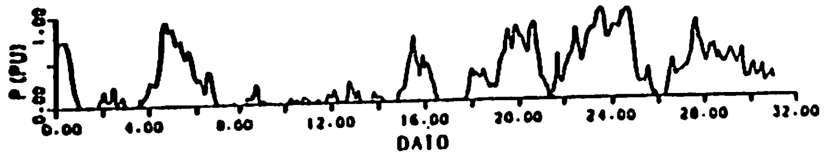


PRODUKTION OKTOBER



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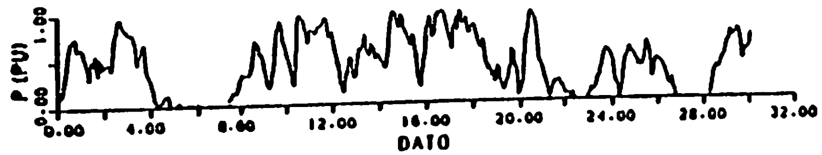
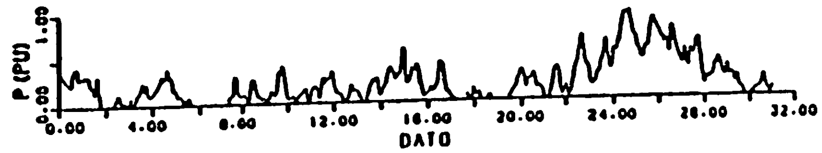
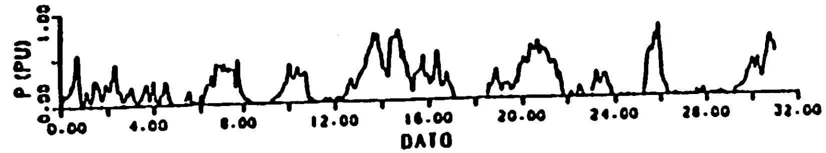


PRODUKTION AUGUST

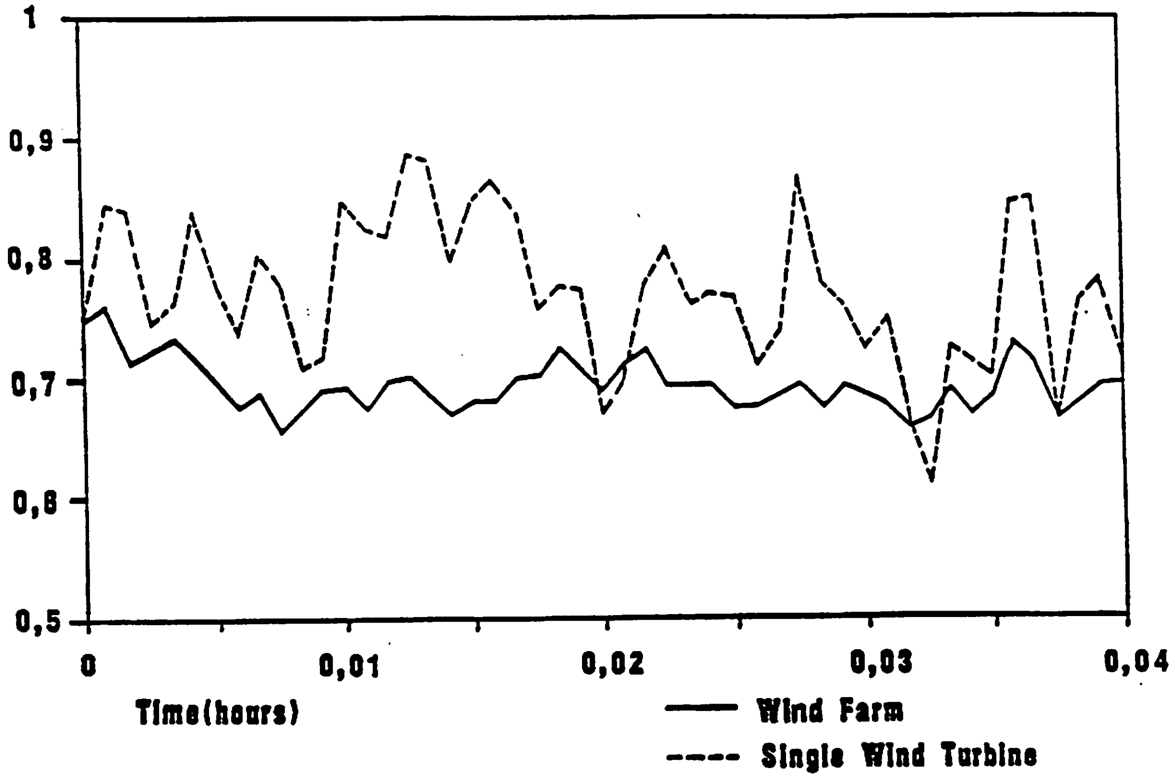


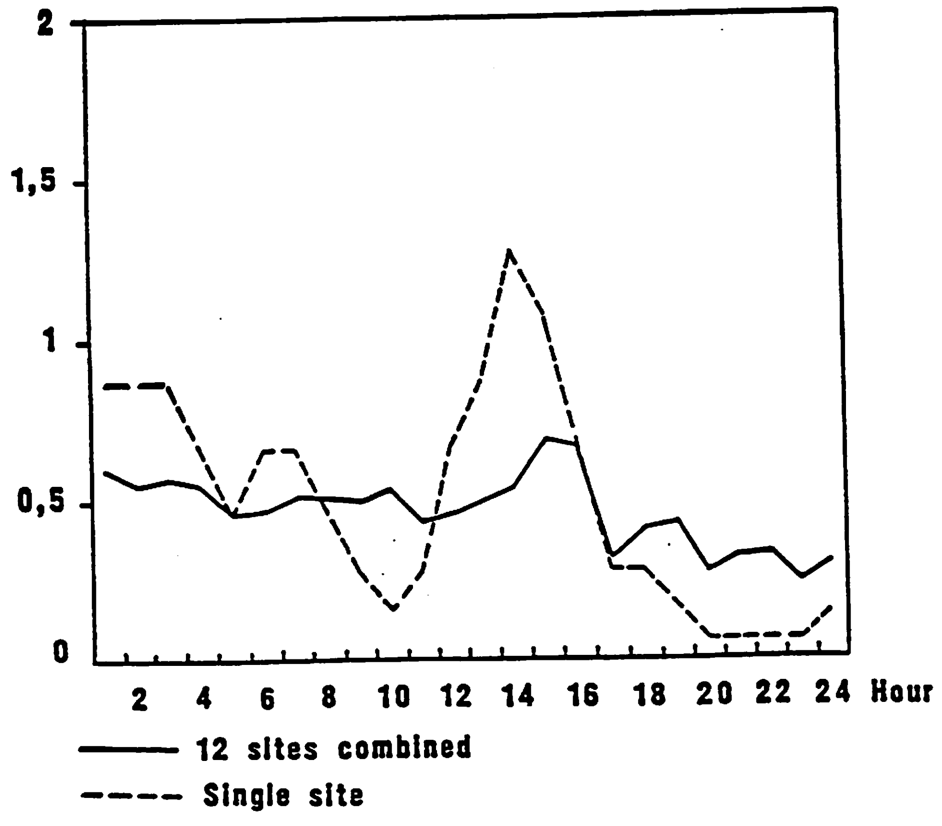
PRODUKTION JULI



CEC wind power penetration study

Windfarm power production



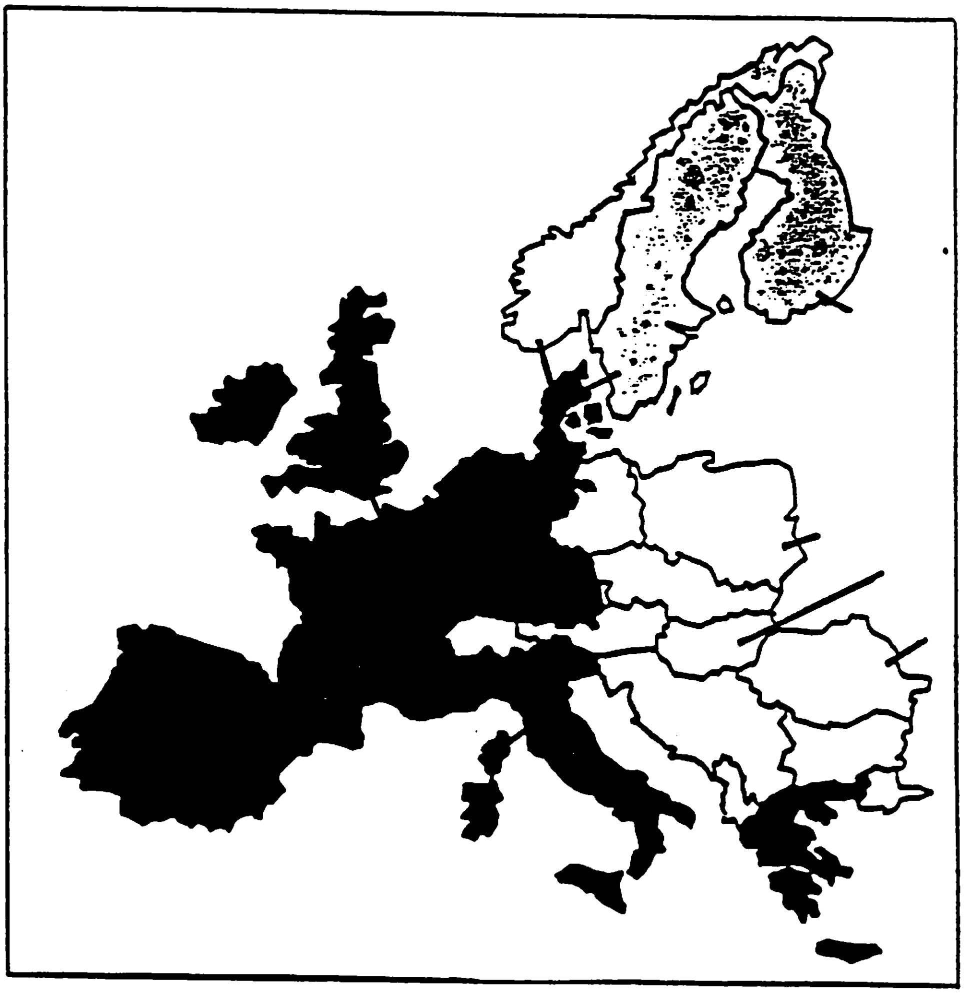


CEC wind power penetration study

Wind Predictability:

- Improved unit commitment schemes.
- Improved dispatch, reduced start up cost.
- Reduced control problems.

CEC wind power penetration study



Europe 12:

400,000 MW

1600 TWh/y.

Δ ~ 10,000 MW/y.

CEC wind power penetration study

Common topics:

- Energy Credit.
- Capacity Credit.
- Control Problems.
- Environmental impact.
- Voltage Control,
  Reactive Power,
  Primary Network.

CEC wind power penetration study

Energy credit:

75% of total credits.

- Fuel savings

- Savings in O.& M.

CEC wind power penetration study

Capacity credit:

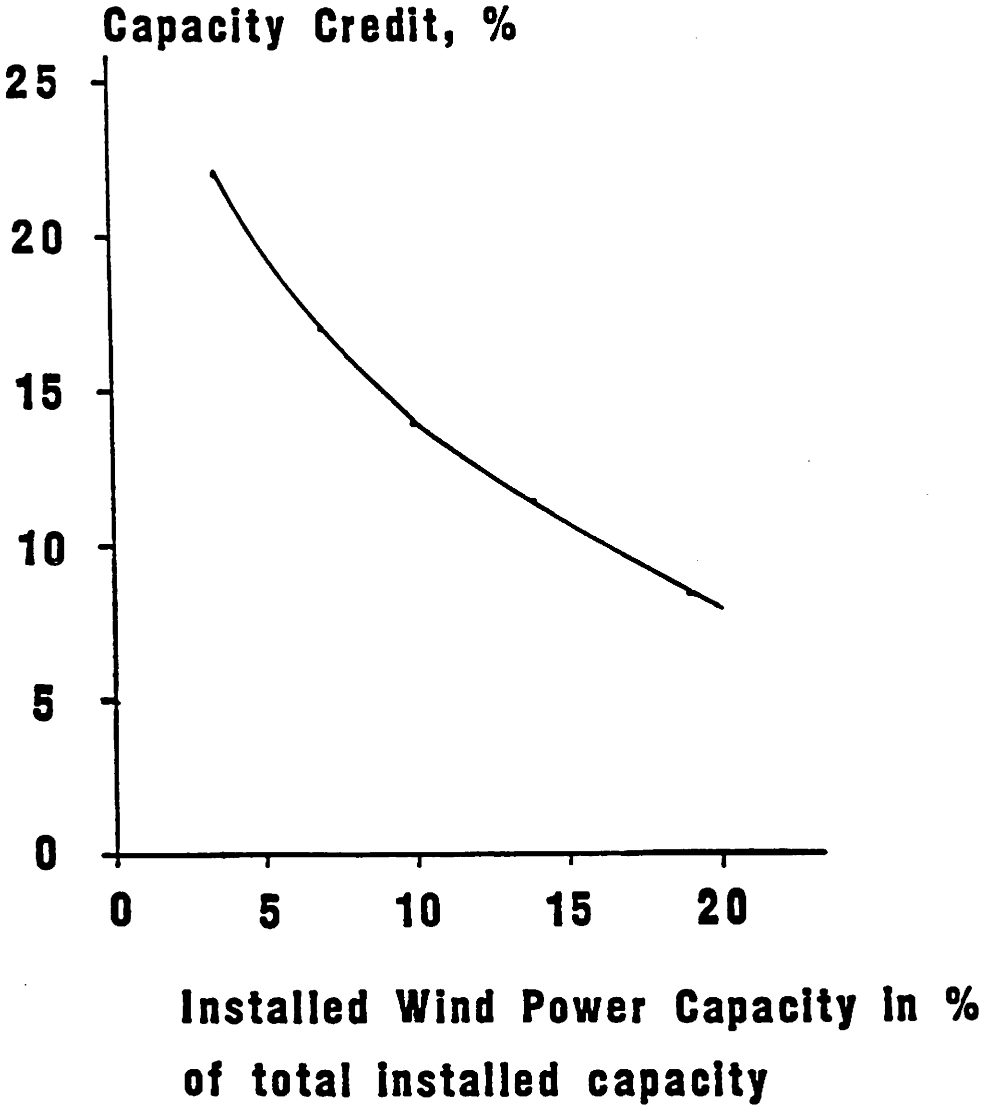
Unchanged:

- LOLP

- Power quality

CEC wind power penetration study

Capacity Credit of Wind Power



CEC wind power penetration study

Control problems:

- Ramping capacity
  (min. domain)

- Transients,
  stability etc.

CEC wind power penetration study

Island studies

- **Crete.**
- **Guadeloupe.**

CEC Wind Power Penetration Study

Sensitivity Analysis:

1. Parameter Variation (fuel cost, discount rates etc.)
2. Spider diagrams for benefit/cost ratio
3. Break-even ECU/kW wind

CEC Wind Power Penetration Study

Study 3

1. System Stability
2. Wind Predictability
3. Windfarm-Grid Interface
4. Windfarm Cost and Operation
5. Wind/Solar Cogeneration

SUMMARY

Areas Needing further Research on Wind Turbine/Utility Systems Interactions

These subtasks partition WT/utility system interaction issues into a number of major categories, as follows: Power System Operations, Wind Forecasting, Wind Power System Control Strategies, Electrical Interface Issues, Third Party Ownership, and Definition of Terms. The issues range from those associated with single WT's having local impacts, to large arrays of WT's having global impacts.

Subtask A: Power System Operations

An Electric utility considering the addition of wind turbines to its power generation mix must anticipate the problems which may be imposed on the utility's operating control system due to the intermittent nature of the wind energy source. Of primary concern is the possibility that the fluctuating power injected by the wind turbines may cause unacceptable deviations in critical operating performance variables such as frequency error and tie line power deviation. Maintaining operating performance within acceptable bounds, while accommodating wind power production, may require changes in system operation.

The exact nature and extent of the operating problems imposed on a utility by wind electric generation is utility specific, and can only be determined by a careful engineering evaluation. Important considerations in such a study are wind and wind turbine characteristics (particularly the time rate-of-change-of-wind generation), wind turbine penetration of utility system capacity, conventional generation mix and response rate, load characteristics, and utility operating philosophy. In addition to these factors, the compatibility of wind generation with system operation will be strongly influenced by the degree of predictability and control associated with the wind generation.

Subtask B: Wind Forecasting

Successful implementation of solutions to problems created by high penetrations of wind energy generators, in the operations planning and real time operations require the ability to forecast short-term (minute-by-minute over the period of an hour) and long-term (hourly over the next 24 hours) variations in the wind velocity. This is due to the fact that both the charge and the rate of charge of aggregate wind power output are important. To date, no acceptable method to accurately determine these parameters has evolved.

Subtask C: Wind Power System Control Strategies

It may be possible to reduce the ramping requirements placed on conventional units by wind generators through implementation of alternative control strategies, including (a) array ramp rate control, (b) feed forward control, and (c) closed loop feedback control. The array ramp rate control strategy limits the generation ramp rate of the wind turbine array and causes the output power to appear as a well behaved negative control. The feed forward approach provides the central control computer with advance information concerning array power changes. This provides the load following units with additional time to respond to the changes. The closed loop control can enhance the advantages of the other two concepts and dispatch the wind plant to an optimum power level. A detailed evaluation of the various control concepts is warranted.

Subtask D: Electrical Interface Issues

A number of electrical interface issues arise with the introduction of wind energy generators into the utility transmission and distribution system. The complexity and severity of these issues varies with the number of wind machines in question, their point of interconnection, and the type of electrical machine. These concerns include the following: overvoltage protection, protective relaying; reactive power compensation; harmonic resonance; capacitor switching transients; self-excitation and islanded or isolated operation; behavior during faulted conditions; ferroresonance; voltage regulation and transformer load tap-changer operation. Systematic evaluations of these issues are required. The ability of variable speed wind turbines to effect these problems should also be investigated.

Subtask E: Third Party Ownership

With the growing trend toward congeneration and third party producers, utilities no longer have total control over the design and operation of new facilities. Because of this, a process of negotiation is required to arrive at a suitable compromise between the utility and the third party. The implications of this process on personnel safety, ability to control the wind generator, and the economic impact of curtailment and control measures, needs to be investigated.

Subtask F: Definition of Terms

With the prospect of large scale application of wind generation on power systems, the need for a consistant set of terminology becomes more critical. Before any new definitions are proposed, existing standards organizations should be consulted for any current or conflicting usage of terms (e.g., CIGRE, IEC, IEE, IEEE, UNIPED, ANSI, EWEA, CANWEA, AWEA). Terms for which an agreed-upon definition is required include penetration, reliability, availability, and stability.

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IEA - Implementing Agreement LS WECS
Expert Meetings

1. Seminar on Structural Dynamics, Munich, October 12, 1978
2. Control of LS-WECS and Adaptation of Wind Electricity to the Network, Copenhagen, April 4, 1979
3. Data Acquisition and Analysis for LS-WECS, Blowing Rock, North Carolina, Sept. 26-27, 1979
4. Rotor Blade Technology with Special Respect to Fatigue Design Problems, Stockholm, April 21-22, 1980
5. Environmental and Safety Aspects of the Present LS WECS, Munich, September 25-26, 1980
6. Reliability and Maintenance Problems of LS WECS, Aalborg, April 29-30, 1981
7. Costings for Wind Turbines, Copenhagen, November 18-19, 1981
8. Safety Assurance and Quality Control of LS WECS during Assembly, Erection and Acceptance Testing, Stockholm, May 26-27, 1982
9. Structural Design Criteria for LS WECS, Greenford, March 7-8, 1983
10. Utility and Operational Experiences and Issues from Mayor Wind Installations, Palo Alto, October 12-14, 1983
11. General Environmental Aspects, Munich, May 7-9, 1984
12. Aerodynamic Calculational Methods for WECS, Copenhagen, October 29-30, 1984
13. Economic Aspects of Wind Turbines, Petten, May 30-31, 1985
14. Modelling of Atmospheric Turbulence for Use in WECS Rotor Loading Calculation, Stockholm, December 4-5, 1985
15. General Planning and Environmental Issues of LS WECS Installations, Hamburg, December 2, 1987
16. Requirements for Safety Systems for LS WECS, Rome, October 17-18, 1988
17. Integrating Wind Turbines into Utility Power Systems, Herndon (Virginia), April 11-12, 1989
18. Wind Turbine Noise, Petten (The Netherlands), November 27-28, 1989
19. Wind Turbine Control Systems, Strategy and Problems, London, May 3-4, 1990