Review of conversion systems used in autonomous wind energy systems

REVIEW OF CONVERSION SYSTEMS USED IN AUTONOMOUS WIND ENERGY SYSTEMS

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Wind Energy Group, Department of Physics, Eindhoven University
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Group Electromechanics and Power Electronics,
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TABLE OF CONTENTS

1. INTRODUCTION

During the last ten years wind energy has become more and more suitable for practical applications, specially for supplying electric energy to the utility grid. However, in those areas where a utility grid is not available, the demand for wind energy systems, that can operate without utility grid, and/or in parallel with a small diesel generator set increases. These systems are often referred to as autonomous systems and in this report they are defined as:
Autonomous systems are hybrid wind-fuel power plants, in which the installed wind power is larger or of the same order as the installed fuel power; the frequency and voltage of the AC grid (autonomous grid) are nearly constant.
A lot of research has been and is being done all over the world, to develop autonomous systems. It has resulted or will result in a number of different solutions. This report tries to give a review of these solutions. However, the author realizes that it is nearly impossible to make a complete summary of all the developed systems, because it is very difficult to get information and the received information is often concise. That is also the reason why only a brief description of the known systems is given, without much comment.

In this report the autonomous systems are divided into three groups:

a. The electrical energy is only supplied by a wind turbine.

b. The electrical energy can be supplied by a wind turbine and/or a fuel (diesel) generator with an installed power of the same order as the installed power of the wind turbine.

c. The electrical energy can be supplied by a wind turbine and/or a fuel (diesel) generator with a much larger installed power than the wind turbine.

According to the definition of autonomous systems the last group (c) is not an autonomous system. But to complete this report a very brief summary of these systems is given in chapter 4.
The systems which belong to the first group (a) are systems without an auxiliary fuel engine. The speed of the wind turbine is regulated by load or by blade-pitch control. However, the admissable load of the

autonomous grid depends on the wind speed: when there is no wind, no energy is available. A summary of these systems is given in chapter 2.
In chapter 3 a summary of the second group (b) is given. In contrast to the first group the second group tries to guarantee a constant energy supply, independent of the wind speed.
In chapter 5 systems are mentioned of which it is unknown to which group they belong, or that don't belong to any group.
In chapter 6 a brief summary is given of combined DC-AC systems with battery systems. Although these systems belong to the autonomous systems, only a brief description is given because the capacity of these systems is small (maximal up to 5 kW) and these systems are rather expensive. So the applications are limited. For the sake of completeness a brief summary of battery storage DC systems is given in chapter 6.
Although these systems don't belong to the autonomous systems, they can be extended to an autonomous system (like the systems described in paragraph 6.1) by means of an voltage source inverter.
I also want to call attention to the work that is being done under auspices of professor N.H. Lipman at the Rutherford and Appleton Laboratories, Oxfordshire, U.K. and the Reading University, U.K.
Here general research is done on wind/diesel integration for electricity supply to isolated communities. This research is described in L1, L2 and L3.

2. AUTONOMOUS SYSTEMS WITHOUT AN AUXILIARY FUEL ENGINE

In these systems a synchronous generator is driven by a wind turbine. There are two possibilities to control the frequency of the autonomous grid:

- by blade-pitch control
- by load control.

Because there is no auxiliary fuel engine the energy supply depends on the wind speed.

2.1 Blade-pitch control

Blade-pitch control is used by Aerowatt. A wind turbine with a diameter of 9.2 m drives a 4 kVA synchronous generator with voltage control. The angular speed (and the frequency) is kept constant above wind speeds of 7 m/s by blade-pitch control, activated by centrifugal weights. The behaviour of this system is nearly the same as the Aeroman system, described later.

Manufacturer: Aerowatt, Paris, France.

2.2 Blade-pitch control, combined with load control

This method for speed control is used in the Aeroman wind turbine. The pitch of the rotor blades is controlled by a centrifugal controller via a hydraulic system, in such a way that the speed of the synchronous generator is kept constant, as long as the demanded power is less than the maximal power of the wind turbine (at the optimal blade pitch; at a certain wind speed). When the demanded power exceeds the maximal power of the wind turbine, the load is switched off step by step (priority switching) until the maximal power of the wind turbine is more than the demanded power (fig. 2.1). The maximal frequency deviation is less than 2% (data of the manufacturer).
The diameter of the wind turbine is 11 m and the generator capacity is between 5 and 20 kVA. This wind turbine can also be coupled to a utility grid or diesel generator. For this purpose a special synchronisation set is necessary.

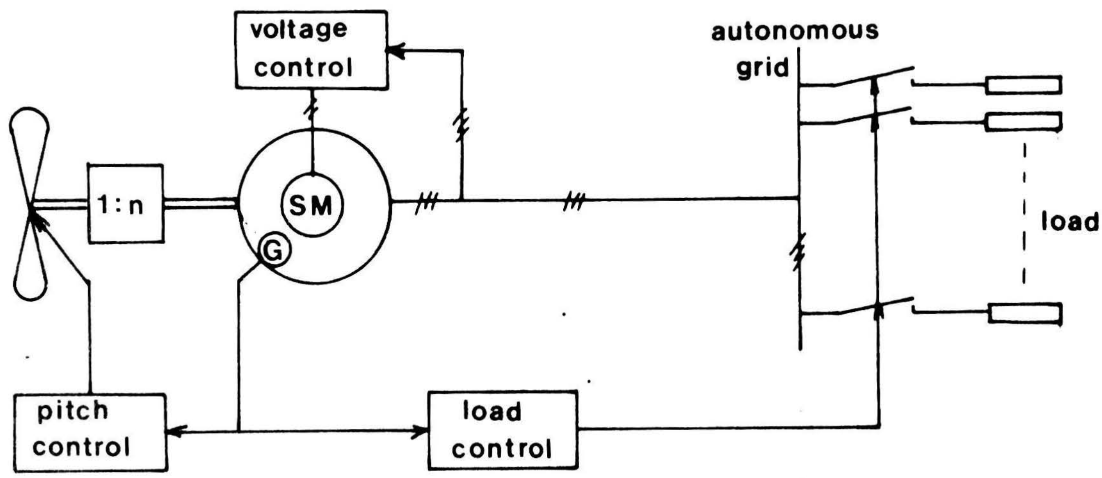


Fig. 2.1 The Aeroman system

The manufacturer of this system is: Maschinenfabrik Augsburg-Nürnberg, Germany.

Literature: 14

2.3 Load control

Load control is used in the MPI-200 wind turbine system. The frequency is controlled by load modulation (fig. 2.2). The rotor blades are of a fixed pitch, incorporating blade tip drag flaps which are automatically activated to stop the rotor under conditions of excessive wind speed, vibration or any system malfunctioning. The diameter of the wind turbine is 24 m and the generator capacity is 200 kVA. The frequency deviation is less than 5% (data of the manufacturer). This wind turbine can also be coupled to a utility grid or a diesel generator set. For this purpose a special synchronisation set is necessary.

At the moment this system is tested on the Block Islands (USA) in co-operation with 5 diesel generator sets (the largest set is 150 kW). Also a dump load is used to control the power flow for the minimum load of the grid is about 30 kW.

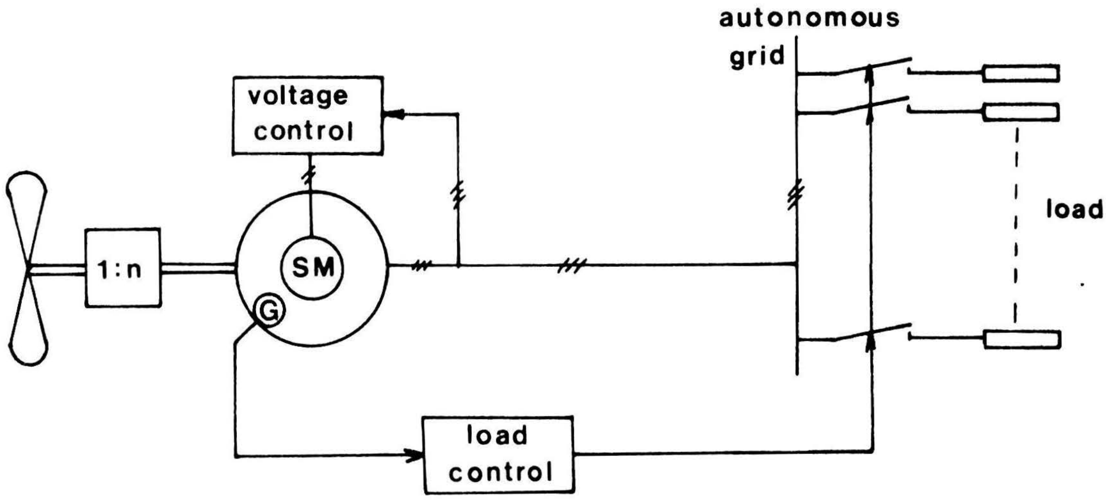


Fig. 2.2 The WTG system

The manufacturer of this system is: WTG Energy Systems Inc., New York USA

Literature: L5

3. AUTONOMOUS SYSTEMS WITH A FUEL ENGINE HAVING AN INSTALLED POWER OF THE SAME ORDER AS THE INSTALLED POWER OF THE WIND TURBINE

3.1 Introduction

In contrast to the systems described in the last chapter, these systems offer a constant supply of energy, independent of the wind speed.
When operating these systems three different situations may occur:

- The demand of power is less than the maximal power which can be supplied by the wind turbine (of course this depends on the momentary wind speed). If this situation exists during a certain time, the fuel engine can be switched off: the demanded power is supplied by the wind turbine only.
- The demand of power is more than the momentary maximal power which can be supplied by the wind turbine. In this situation the difference between the demanded power and the power supplied by the wind turbine has to be supplied by the fuel engine (parallel operation of the wind turbine and the fuel engine).
- There is no wind power available; the demanded power has to be supplied by the fuel engine only.

These three situations are typical of all the systems described in this chapter, although the final designs are different.
There are four types:

- electrical frequency control with an optimally loaded wind turbine (these systems are described in paragraph 3.2)
- mechanical frequency control with an optimally loaded wind turbine (these systems are described in paragraph 3.3)
- electrical frequency control with a non-optimally loaded wind turbine (these systems are described in paragraph 3.4)
- mechanical frequency control with a non-optimally loaded wind turbine (these systems are described in paragraph 3.5).

When the wind turbine is loaded optimally the rotor speed must be proportional to the wind speed, for (see L6):

$$P_{opt} = C_1 V^3 = C_2 n^3 \qquad (1)$$

where: P_{opt} is the optimal power (W)

C_1, C_2 are constants

V is the wind speed (m/s)

n is the rotor speed (r.p.m.)

To get a constant frequency of the autonomous grid a speed, resp. a frequency converter (mechanical resp. electrical) is necessary. There must also be an extra (controllable) load to absorb the difference of the power supplied by the wind turbine and the power demanded by the load. This extra load can be used for all kinds of power consumers which do not need a constant energy supply, e.g. cooling, heating, water pumping and so on.
In the next paragraphs the conversion systems of the four types of autonomous systems are described with a fuel engine with an installed power of the same order as the installed power of the wind turbine.

3.2 Electrical frequency control with an optimally loaded wind turbine

A. The system of the Eindhoven University of Technology in the Netherlands

The electrical system of the wind turbine is based on a synchronous machine (brushless) with an AC/DC/AC converter (fig. 3.1), so the frequency (and speed) of the synchronous generator driven by the wind turbine is independent of the frequency of the autonomous grid. By means of controlling the field current of the synchronous generator the wind turbine can be loaded optimally in a speed range of 50-150% of the synchronous speed of the generator. If the gearbox and the generator are well chosen, it is even possible that the wind turbine is loaded nearly optimally at a constant field current, in a great part of the operating area.
The operation of the Eindhoven system will be explained on the basis of the power balance of the system outline in fig. 3.1.
The power balance of this configuration is (the losses are neglected):

$$P_{diesel} + P_{wind} = P_{extra} + P_{load} + I\,\omega\,\frac{d\omega}{dt} \qquad (2)$$

where: P_{diesel} : power supplied by the diesel engine

P_{wind} : power supplied by the AC/DC/AC converter

P_{load} : power needed by the autonomous grid

P_{extra} : power fed into the extra controllable load

I : moment of inertia of the synchronous machine SM 2

ω : angular velocity of the synchronous machine SM 2 (in rad/s)

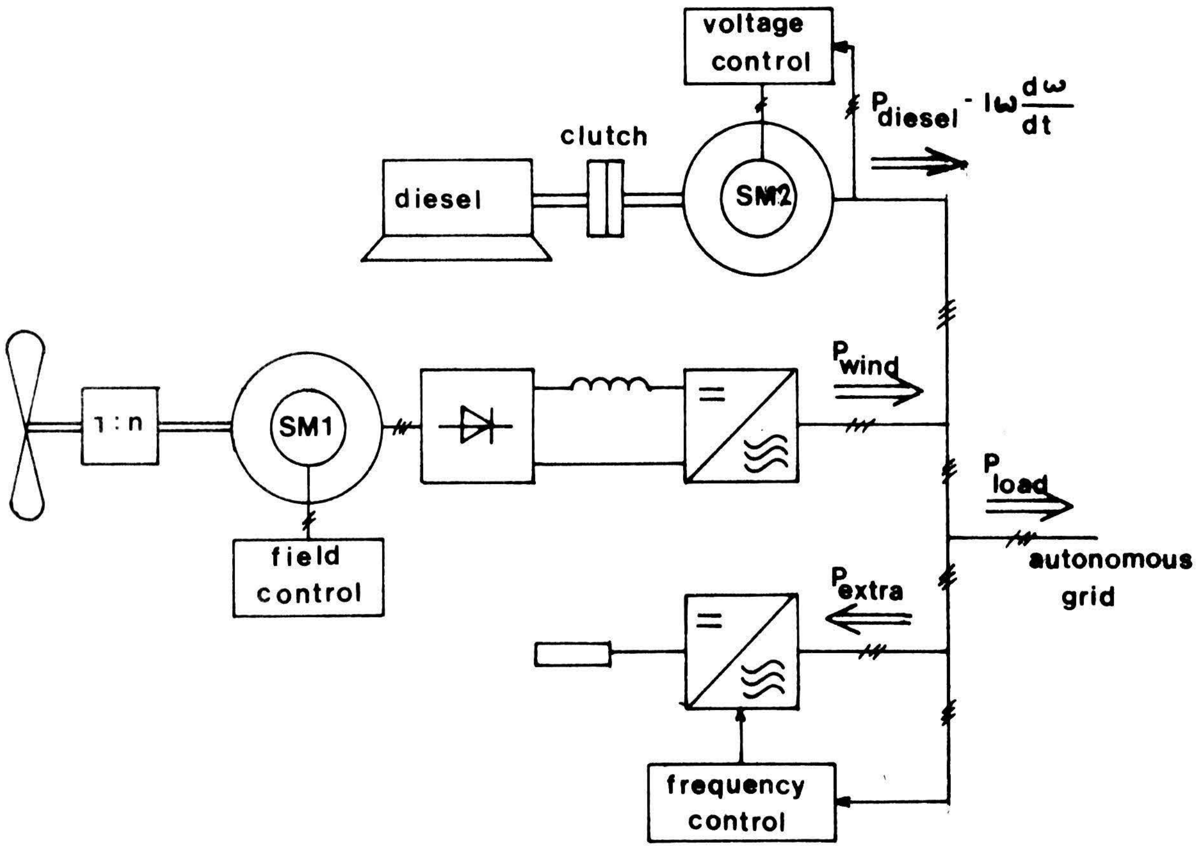


Fig. 3.1 The Eindhoven system

One of the advantages of the chosen system is the ability to stop the diesel engine whenever the wind turbine supplies all the demanded power. It is supposed here that at any time $P_{wind} > P_{load}$. In this case the coupling between the synchronous machine (SM 2) and the diesel engine is disengaged.

(P_{diesel} = 0.) The wind is now the only energy source for the autonomous grid. The rotating synchronous machine (SM 2) still remains an essential part of the system. The machine acts as the voltage source for the three phase grid and takes care of commutation in the inverter and the sinusoïdal wave shape of the grid voltage. The reactive power needed by the grid load and the inverter is supplied by the synchronous machine. The synchronous machine acts as a synchronous condensor. The grid's voltage is maintained at a fixed value by means of the field control of the synchronous machine (SM 2).

All surplus power is fed into the additional load. Formula (2) shows that the control of this load allows command of the power flow.
Thus the rotational speed of the synchronous machine (SM 2), which determines the frequency of the autonomous grid, can be influenced.
When $P_{wind} < P_{load}$, parallel operation of the wind turbine and the diesel engine is necessary to guarantee the power supply. The diesel engine has to supply the difference between the demanded power and the power supplied by the wind turbine. Now the frequency is controlled by the speed control of the diesel engine.
This system has been developed by the group Electromechanics and Power Electronics of the Eindhoven University of Technology in the Netherlands.
It has been tested in the laboratory and at this moment a demonstration set is being built up at the test site of the Netherlands Energy Research Foundation (ECN) in Petten (in co-operation with the Steering Committee Wind Energy Developing Countries (SWD) and the ECN).
Literature: L7, L8.

B. The system of the Napier College, UK

The electrical system of the wind turbine is based on a so-called static Scherbius drive (fig. 3.2).

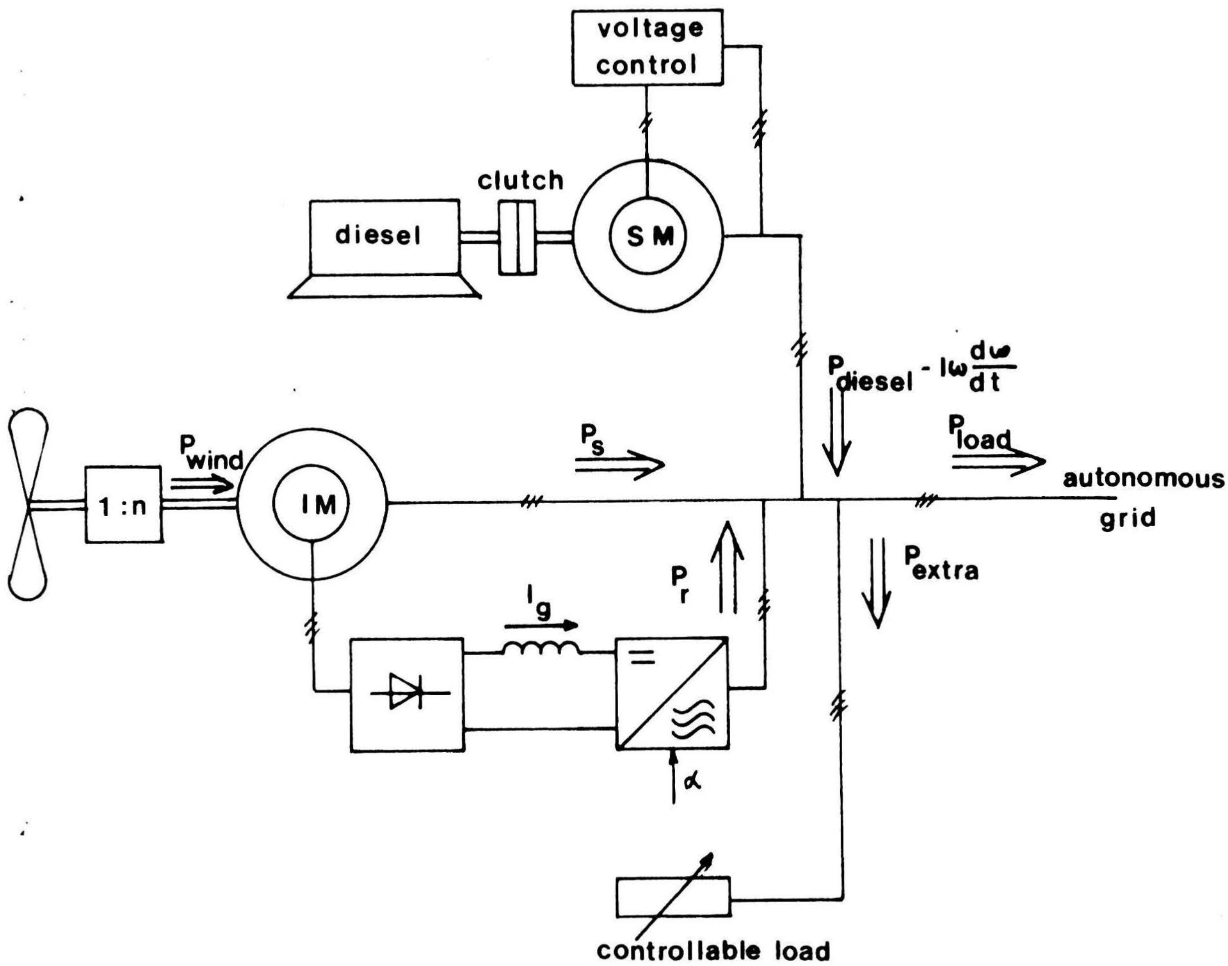


Fig. 3.2 The Napier system

The rotor slip power of a standard type of 3-phase wound rotor induction motor (IM) (slipring machine) is recovered and fed back to the mains by the AC/DC/AC convertor. When a static Scherbius drive is coupled to a grid, and the losses in the machine are neglected, then

$$\frac{P_r}{P_{wind}} = \frac{s}{s-1} = \frac{n-n_s}{n}$$

where:

P_{wind} is the supplied power by the wind turbine

s is the slip of the asynchronous machine well

n_s is the synchronous speed (proportional to the grid frequency)

n is the rotor speed

P_r is the rotor slip power

At a certain wind speed, P_{wind} is a function of the angular speed (L6) and the angular speed is a function of the slip. By controlling P_r (by means of the firing angle α of the line commutated inverter) the slip can be controlled in such a way that the supplied power by the wind turbine is optimal in a speed range of 100-200% of the synchronous speed of the generator. When the supplied power is more than the demanded power the frequency can be controlled by load modulation. The power balance for this configuration is (losses are neglected; when the diesel engine isn't coupled to the synchronous machine $P_{diesel} = 0$):

$$P_{wind} = P_s + P_r = P_{extra} + P_{load} + I\,\omega\,\frac{d\omega}{dt} \qquad (4)$$

where:

P_s the supplied power by the stator of the induction machine

P_r the rotor slip energy of the induction machine

I the moment of inertia of the synchronous machine

angular velocity of the synchronous machine

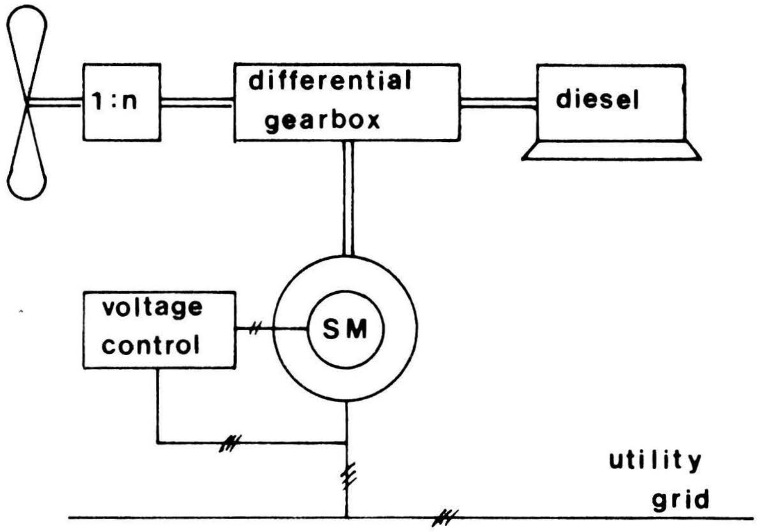
P_{load} power needed by the autonomous grid

P_{extra} power fed into the controllable load

The behaviour of this system is nearly the same as the Eindhoven system. For a further description see paragraph 3.2.A.
This system has been developed by the Napier College (UK) and is now in laboratory stage.
Literature: L9.

3.3 Mechanical frequency control with an optimally loaded wind turbine

In this Italian system a vertical axis wind turbine is coupled with an auxiliary diesel engine by means of a car gearbox, which is connected via the transmission shaft (usually connected to the car engine), to the synchronous generator (fig. 3.3a).
As the differential gearbox is a summing device of angular speeds, it is possible with this system to vary rotational speed of the wind turbine. This variation will be offset by properly changing the auxiliary motor speed, so as to keep the speed of the shaft drive to the synchronous generator constant. A proper control system of the auxiliary motor speed and power can keep the wind turbine at it's optimal speed according to the wind speed, so as to get maximum power from the wind at every wind speed.
This system is developed in the first place to be connected to the utility grid, which can keep the frequency constant and can absorb the surplus of power. It is also possible to use this system as an autonomous system by adding an extra controllable load (fig. 3.3b).



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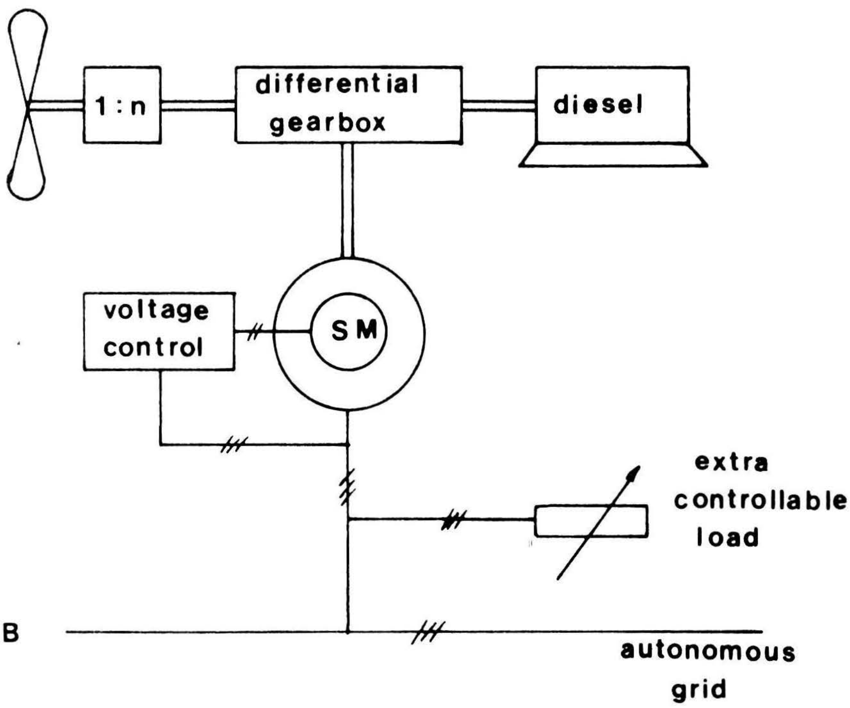


B

Fig. 3.3 The Italian system

a. coupled to the utility grid
b. as an autonomous system

This system has been developed by: Tema, Bologna in co-operation with Snam Progettie, Milano, Italy

Literature: L10.

3.4 Electrical frequency control with a non-optimally loaded wind turbine

A. The Iniss Oirr wind generator project

This system is based on a 63 kW wind turbine with a synchronous generator (fixed speed) and a 12 kW diesel engine, which drives a synchronous machine, as "peak lopper" (fig. 3.4). This "package" is not designed for parallel operation with the existing diesel plant (44 + 26 kW) and no storage is provided.

The wind turbine (Windmatic) disposes of excess output into a stepped resistive air-cooled load (18 elements) in order to maintain voltage and frequency. When the frequency falls, the resistive load is shed and if the frequency then cannot be maintained, the 12 kW diesel is automatically started, synchronized and switched in for at least 15 minutes. A minimum load of 3 kW is applied to the 12 kW diesel when the diesel is in operation, if necessary by the dump load, partly to reduce damage(which kind of damage is unknown to the author) caused by idling, and also to permit fast pick-up of frequency if the grid load suddenly increases. Subsequent rapid frequency control is provided by the diesel's governor. If the wind generator "package" cannot maintain frequency the existing diesel is automatically started and run up, the "package" disconnected and the 44 kW diesel switched on.

The change-over period during which all power is lost on the island on which this autonomous system is used, is 3/1000 second. The larger diesel then runs for at least 30 minutes and any power generated by the "package" is dumped.

All controls of the system are conventional electro-mechanical or solid state devices and indeed all the equipment installed is commercially available.

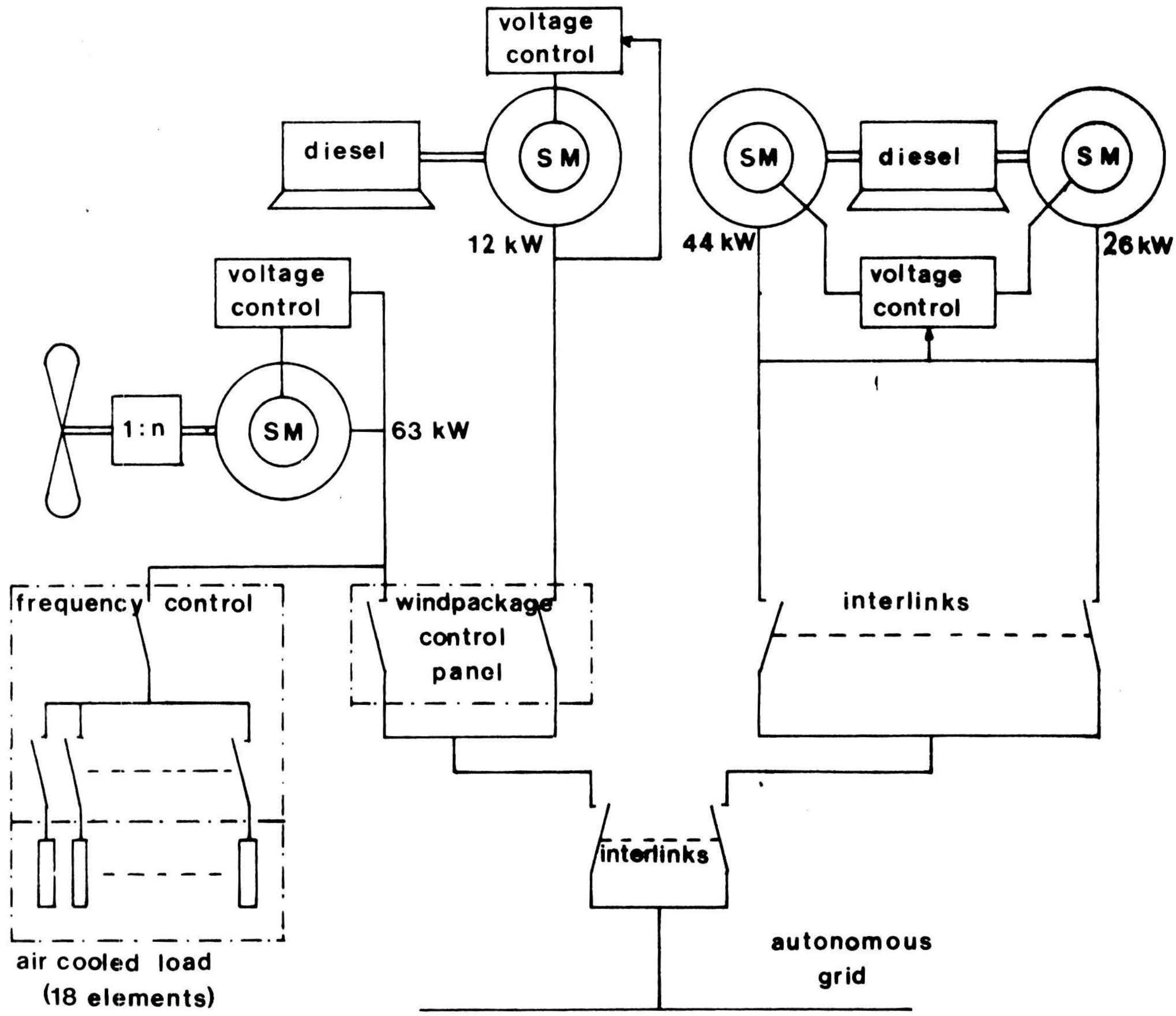


Fig. 3.4 The Iniss Oirr wind generator project.
This system has been developed by the Department of Industry and Energy, Dublin, Ireland.

Literature: L11.

B. The Dornier system

This system is based on a 20 kW vertical axis wind turbine which drives a brushless synchronous generator (fixed speed). The speed of the wind turbine can be controlled by the controllable brake resistances (fig. 3.5). When there is enough wind ($P_{wind} > P_{load}$) the wind turbine can supply the power independently. When the wind speed falls or the load increases ($P_{wind} < P_{load}$) the break resistances are shed and if the frequency then cannot be maintained, the diesel is started automatically. After synchronization the diesel generator can be connected to the grid. Now the diesel's governor takes care of the frequency control.
A prototype of this system is presently under design. The development of the system is dominated by three main problem areas:

- the synchronization of the two generators
- the potential oscillations of the paralleled generator excited by wind
- the control of the system.

It is assumed that by the end of 1982 the field test of the system can be started.

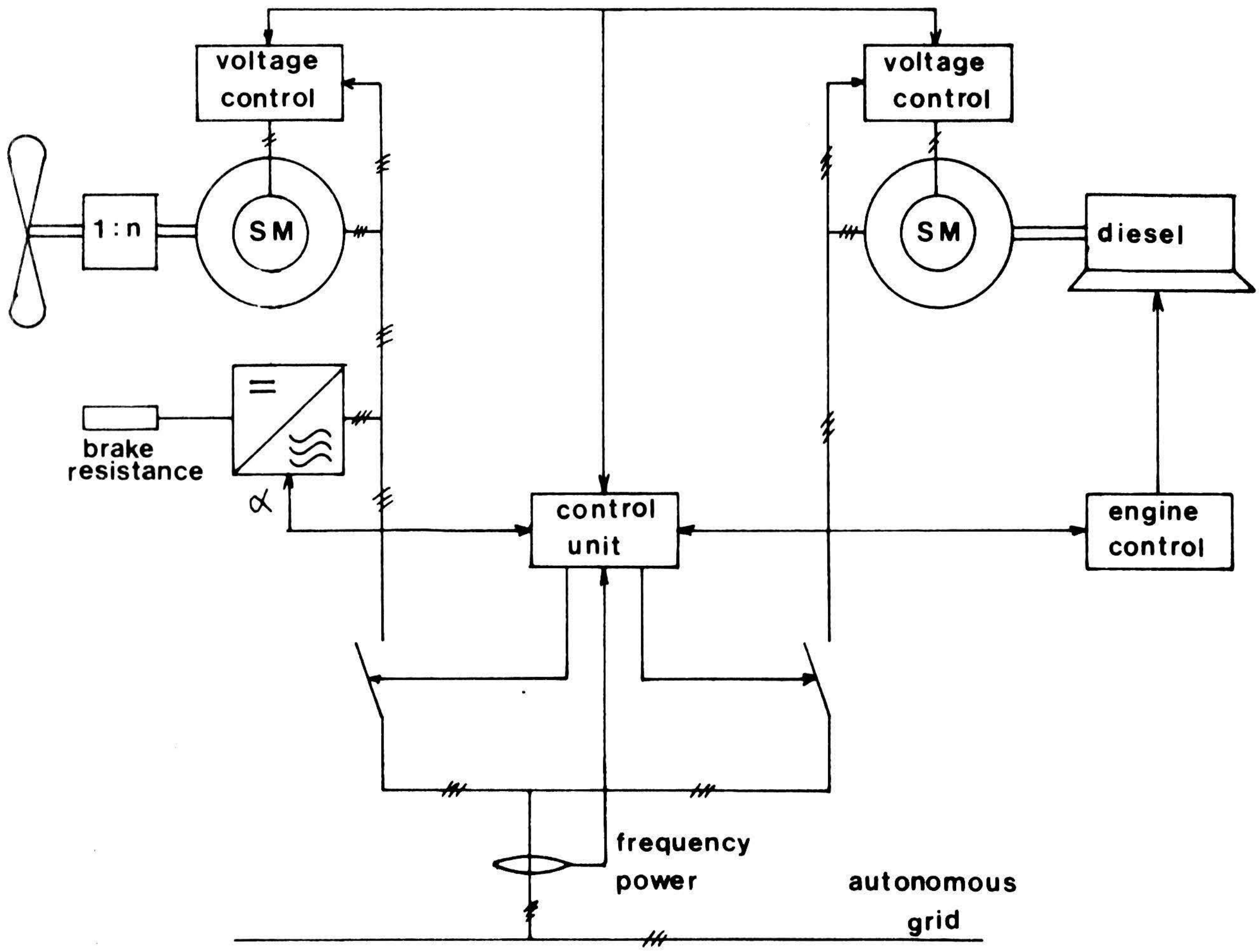


Fig. 3.5 The Dornier system

This system has been developed by: Dornier System G.m.b.H.
Friedrichshafen,
West Germany

Literature: L12.

Diesel: A small high-speed diesel alternator is incorporated in the system as a stand-by in case of emergencies. If the battery storage falls below a pre-determined minimum and the household demands power, the diesel will start in the DC mode and recharge the batteries. If the batteries or inverters should fail, or the system becomes incapable of supplying AC power to the house the diesel will start in AC mode and supply 240 volts AC directly to the house, by-passing the solar array, wind generator, batteries and inverters.
On the basis of the manufacturer's data, most of which were mentioned above, the tentative block diagram of fig. 3.6 was drafted.

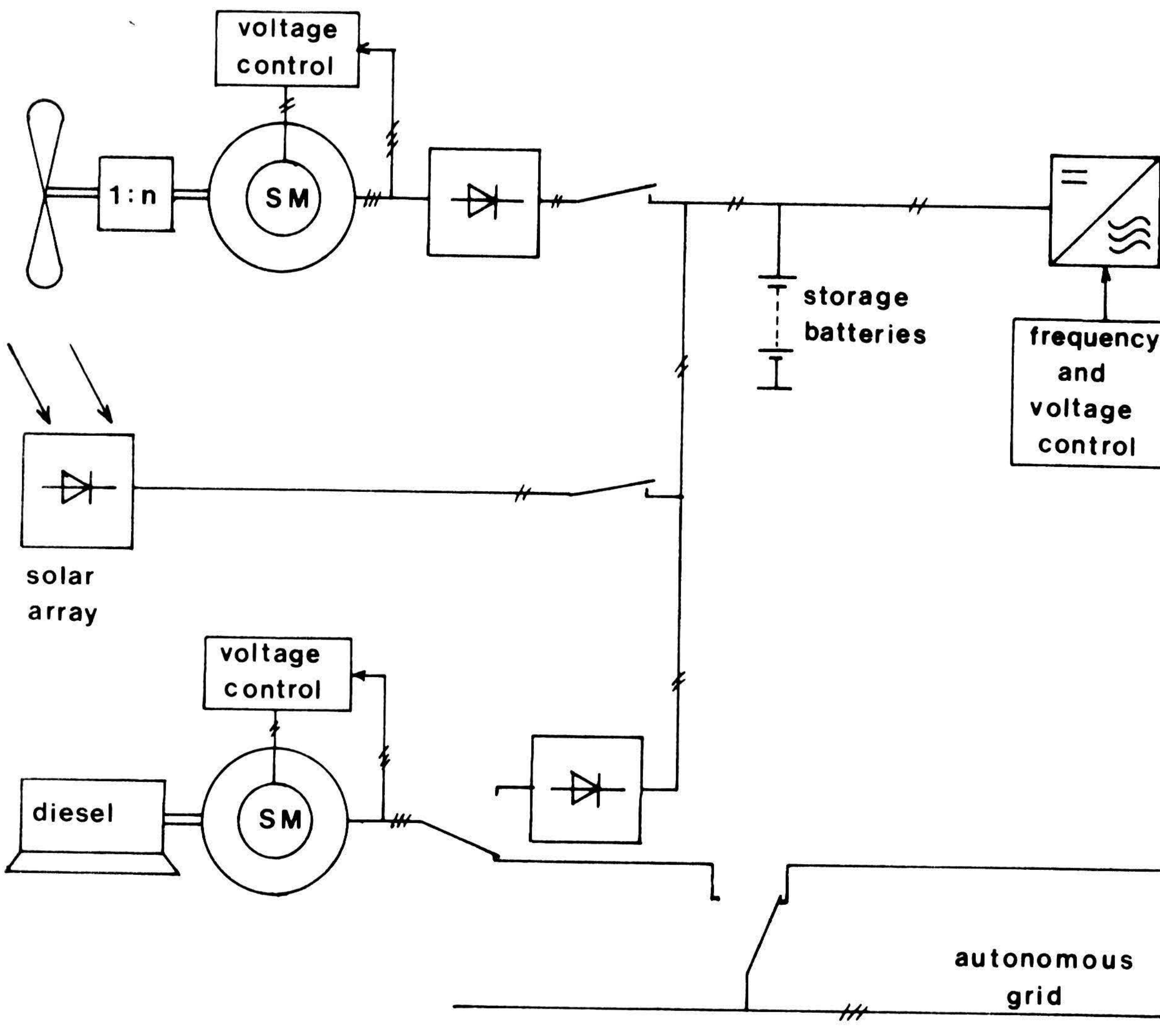


Fig. 3.6 The Dunlite system
This system has been developed by: Dunlite-Australia.

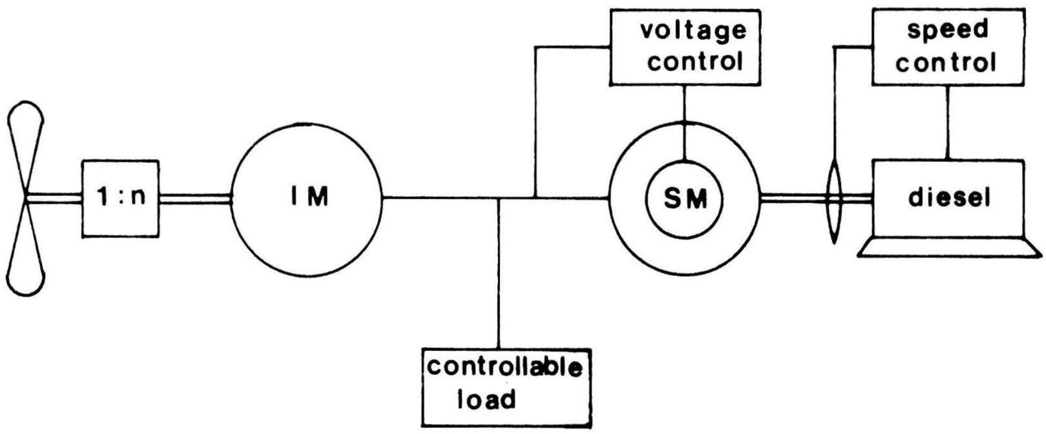
Literature: Documentation of the manufacturer.

D. The DAF Indal system

As a first step in demonstrating the technical feasibility of wind turbine assisted diesel generator, a system comprised of a 12 kW diesel generator (60 Hz, 240 V, single phase) coupled to a 10 kW rated vertical axis wind turbine (9.1 m x 6.1 m rotor) was tested by DAF Indal Ltd. at the Toronto Island Airport in 1977 and 1978. The system, shown in fig. 3.7 was designed to operate in both an electrical load sharing and a mechanical load sharing configuration.

From the test results seems that the efficiency of the mechanical load sharing configuration was higher than the electrical load sharing configuration because of the bad efficiency of the single phase induction machine. It was concluded, however, that for much larger systems, the advantage of the mechanical mode would be lessened because of the much higher efficiencies of three phase induction generators compared to single phase generators.

Based on the 12 kW system test results, DAF Indal developed an approach to the design of larger scale wind turbine assisted diesel generator systems in the mechanical assist mode. Design of a prototype 100 kW mechanically coupled wind turbine diesel generator system was completed in August, 1981. Continuous fully automatic operation of the plant for a six month period will begin in January, 1982, on an exposed hilltop site near Sudubry, Ontario, Canada.



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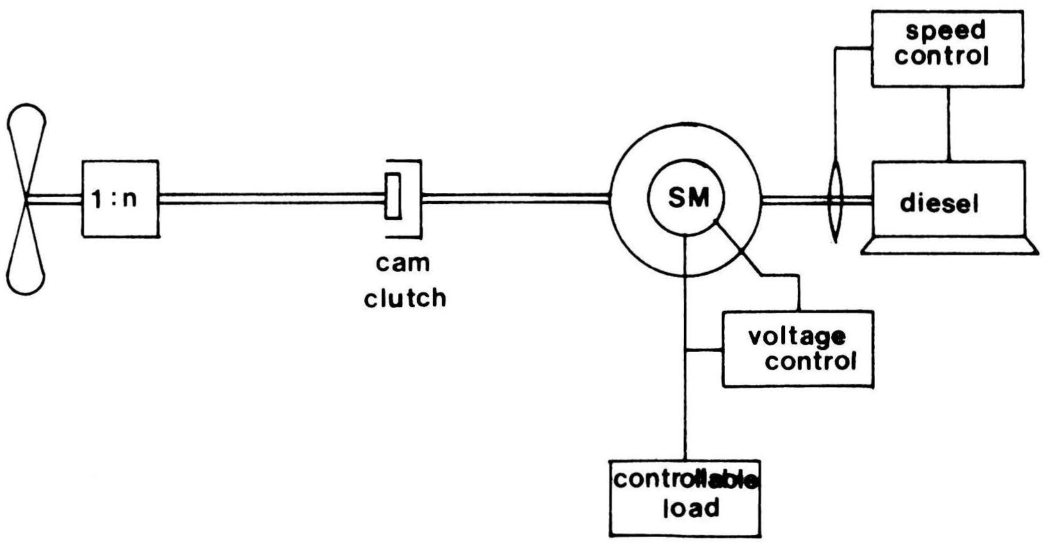

B

Fig. 3.7 The DAF Indal system a: the electrical mode
b: the mechanical mode

This system has been developed by: DAF Indal Ltd.
3570 Hawkestone Road
Mississauga, Ontario, Canada

Literature L18

3.5 Mechanical frequency control with a non-optimally loaded wind turbine: the Goppel system

This system is based on a stepless controllable speed variator (transmatic). This variator converts a speed of 750-3000 r.p.m. of the primary shaft into a constant speed of 1500 r.p.m. of the secundary shaft. When the wind turbine is coupled to the primary shaft the speed of the wind turbine (and hereby the supplied power) can be controlled in such a way that the speed of the secundary shaft is kept constant at 1500 r.p.m. (fig. 3.8), so the frequency of the isolated grid is kept constant.

When the wind speed falls or the load increases so that the speed of the primary shaft of the transmatic becomes less than 750 r.p.m. the frequency of the isolated grid falls. At that moment (or just before that moment) the diesel engine has to be started. When the speed of the synchronous generator becomes less than the speed of the diesel engine the freewheel clutch will switch in and parallel operation is realized. Then the frequency is controlled by the diesel's governor. How the transmatic is controlled in this situation is not known. (A possibility of controlling the transmatic in this situation could be controlling by means of the different frequency drops of both frequency controllers.)

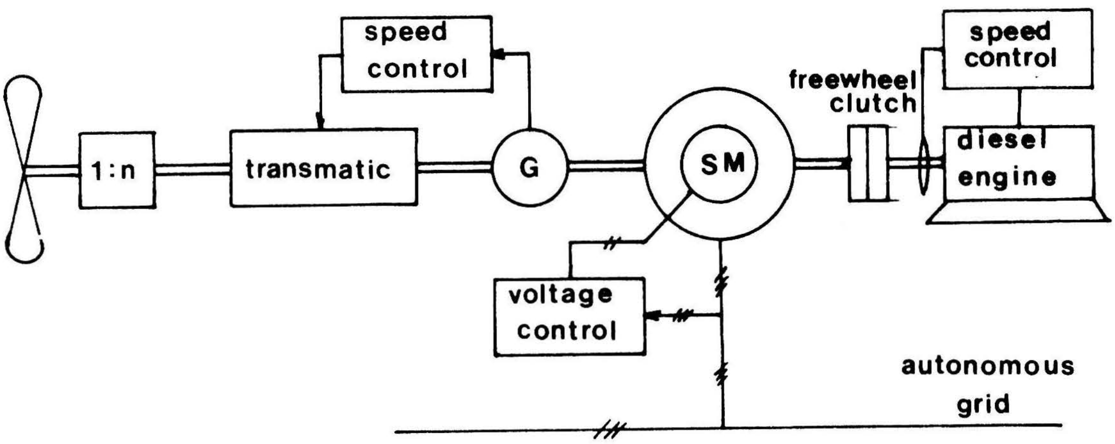

Fig. 3.8 The Goppel system

This system has been developed by: Goppel Electro-aggregaten b.v. Rijnsburg, Netherlands

At the moment the developing of this system has been stopped.

Literature: L13 and Internal notitions of the Netherlands Energy Research Foundation (ECN) in Petten (not published).

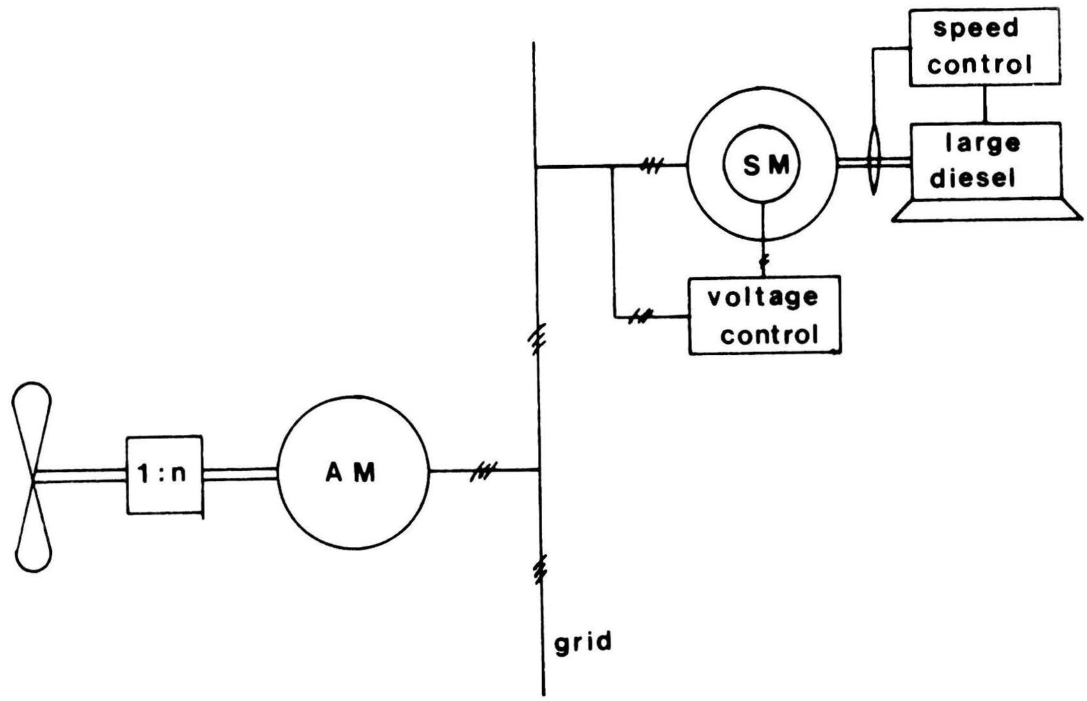

Fig. 4.1 Wind turbine coupled to a large diesel power plant

4. AC SYSTEMS WITH A FUEL ENGINE OF A MUCH LARGER INSTALLED POWER THAN THE WIND TURBINE

These systems (fig. 4.1) are not really autonomous systems, because in this case the grid is comparable with a strong utility grid; the demanded power is nearly always greater than the power supplied by the wind turbine, so there is no need for an extra load to control the power balance. The frequency is in all cases controlled by the diesel's governor. In nearly all known systems the wind turbine drives an asynchronous generator.

Because this system is not an autonomous system I will confine to mention some places where a system of this type is used:

France	: EDF (Electricité de France) : a system was tested in 1980 on l'Ile d'Ouessant.
France	: Bureau d'Etudes et de Recherces en Energies Naturelles Verneuil sur Seine: a system in preparation.
Scotland	: a system is being tested in the North of Scotland, by the Hydro Board, Edinbourgh
The Netherlands	: a system was tested by the PZEM, Middelburg on the artificial island Neeltje Jans: - installed wind power 60 kVA - installed diesel power 2400 kVA
The Netherlands	: a system is in preparation by the PEB, Leeuwarden, for the island Vlieland (the electrical system of the wind turbine(s) is not yet chosen) wind power : 100 - 150 kVA diesel power : 2000 kVA
USA	: - a system was (is?) tested on the Cuttyhunk Island (here the wind turbine drives a synchronous generator which is synchronized with the diesel grid)
Greece	: 5 Aeroman wind turbines (10-20 kW each) are coupled to a 280 kW diesel power plant (the Kythnos Island)
Tristan da Cunha (British crown-colony)	: a 45 kW Windmatic wind turbine is coupled to a 420 kVA diesel grid (3x 140 kVA). Also a resistive load dump is installed to guarantee a minimum load.
Australia	: two wind turbines (50 kW and 20 kW) are coupled to a 700 kVA diesel grid on the Rottness Islands.
Indonesia	: a 5.7 m VAT is coupled through a DC generator and a line commulated inverter to a diesel grid.

5. OTHER AC SYSTEMS

In this chapter some AC systems are mentioned of which it is unknown to which type they belong or which don't belong to any of the types described before:

Antarctica : A wind-diesel power plant is in preparation. The only known is that a wind turbine will be coupled to a diesel generator; probably variable frequency.

Denmark : Investigation of problems associated with the combined operation of a wind turbine and a diesel generator, and the development of control systems are done by the Risø National Laboratory, Roskilde, in co-operation with manufacturers.
Start of the project: 1982
Duration of the project: 2 years
Project plans:
- Negotiations with manufacturers
- Development of components
- Testing
- Evaluation and report

Japan : By Nippon Electric Industry Co., Tokyo, a system with a 4 m Darrieus wind turbine and a diesel generator has been tested.

6. BATTERY STORAGE SYSTEMS

6.1 Combined DC-AC systems

There are a lot of small DC systems (up to 5 kW, combined with an inverter to get AC systems. These systems are composed of the following major sub-elements (fig. 5.1):

- a wind turbine with a DC generator or an AC generator (permanent magnet synchronous) with a rectifier
- a storage battery
- a voltage source inverter.

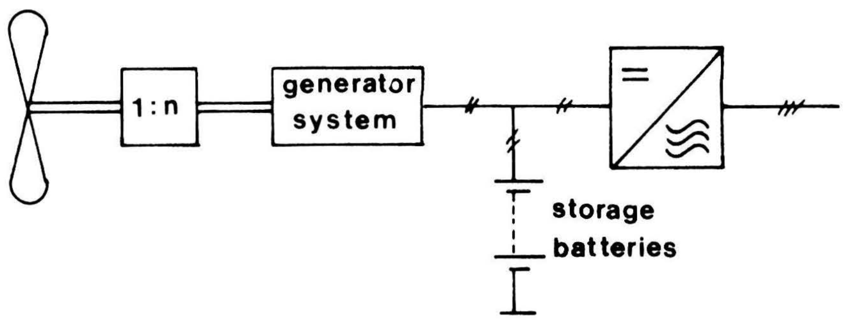

Fig. 6.1 Combined DC-AC system

These systems are only suitable for a small capacity (up to 5 kW). Here we restrict ourselves to mention some usable wind turbines and manufacturers of inverters (see also paragraph 3.4 C).

Wind turbine	rated power	generator type
Dunlite (Australia)	3000 W	AC
Kedco (USA)	1200 - 3000 W	AC
Sky Hawk (USA)	4000 W	DC
Elektro (Switzerland)	50 - 6000 W	AC
North Wind Power (USA)	2000 - 4000 W	DC
Haavecost (NL)	180 - 1000 W	DC
Wesp (SWD 1000 EL) (NL)	5 W	AC
Gramman (USA)	3000 - 5000 W	DC
DAF (Canada)	3000 - 6000 W	DC

Inverters

Emhiser Rand Industries	USA
Danamote corporation	USA
Topaz electronics	USA
Siemens	West Germany
BBC	Switzerland
Delatron	USA
Brinkman en Germeraad	The Netherlands
Alopex	The Netherlands
Blessing Electronics	The Netherlands

Literature: L14, L15.

6.2 DC system without an inverter

For the sake of completeness a very short description is given in this paragraph of some wind driven DC systems.

A. The Aerosolec system

The Aerosolec plant is composed of the following major sub-assemblies (fig. 6.2):

- a solar generator G1, based on photo-electric cells
- an aerogenerator G2
- a storage battery (energy reserve)
- stand-by equipment (second storage battery, dry cells, generating set)
- auxiliary fittings for the control of the system.

Power supplies are within the range of powers required by most micro-wave stations: from tens of watts to several kilowatts steady supply.

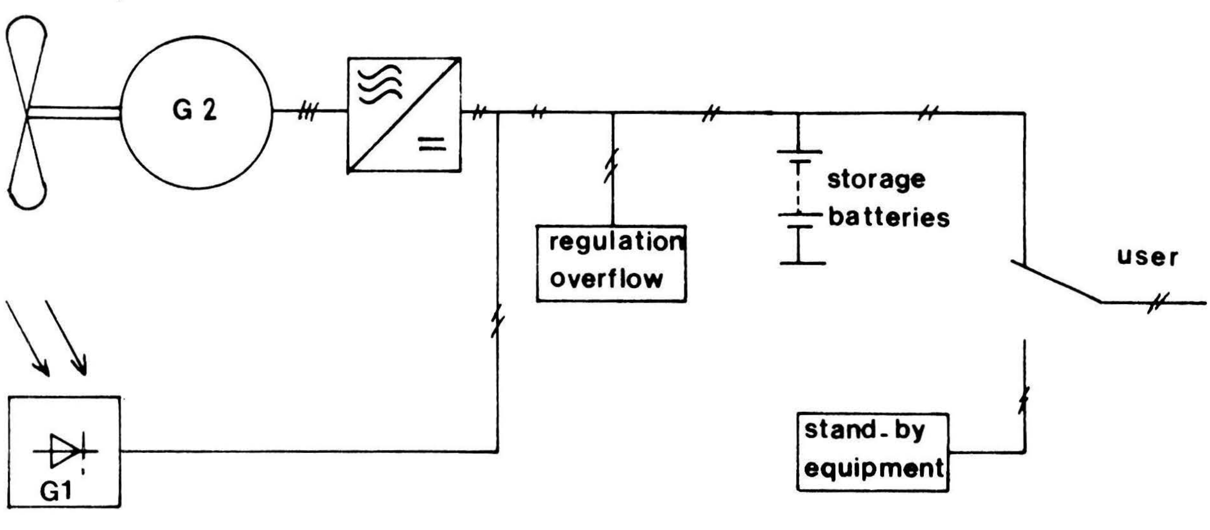

Fig. 6.2 The Aerosolec system
This system has been developed by: Centre National d'études des Télécommunications
Issy les Moulineaux, France

Literature: L16; documentation from the manufacturer.

B. The system of the Imperial college

This system is composed of the following major sub-assemblies (fig. 6.3).

- Permanent Magnet generator: three types have been tested on different wind turbines:
  . 2,4 kW, 300 r.p.m. (without gearbox)
  . 10 kW, 150 r.p.m. (without gearbox)
  . 7 kW, 1500 r.p.m. (with gearbox)
- Rectifier: a half controllable bridge rectifier (3 diodes, 3 thyristors) is used by which optimal load control of the wind turbine is possible in a wide range of speeds.
- Controllable load to control the power balance and the voltage of the grid. The dissipated power is used for heating.

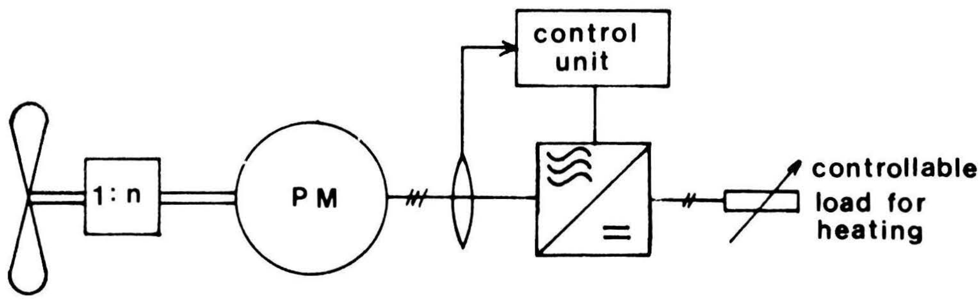

Fig. 6.3 The system of the Imperial college

This system has been developed by: The Imperial College
London, U.K.

Literature: L17.

Undoubtedly there are some more systems like these, but it is not the meaning of this report to describe this type of systems; only to give an illustration of the possibilities.

7. CONCLUSIONS

Most of the systems described here are still in the stage of development, so it is difficult to derive conclusions on the suitability of these systems. However, some general remarks as regards to the AC systems of chapter 2 and 3 can be made:

- The systems with a non-optimally loaded wind turbine make a bad use of the available wind energy and of the system.
- Most of the systems with a mechanical frequency control will have a bad efficiency.
- The systems with a fixed speed wind turbine will probably have problems with the great fluctuations in torque and current.
- Some systems (like the Goppel and Dornier system) will probably have problems with the controlling of the system.
- The systems with a hydraulic pitch control (Aeroman) will have an expensive wind turbine.
- The systems in which inverters are used will probably have some problems with distorsion of the grid voltage (for some purposes where this is not allowed, filters have to be used).

At this moment real autonomous systems are not commercially available (only systems with battery storage) and much research and field testing is needed to come to useful autonomous systems.

LIST OF LITERATURE

L1 N.H. Lipman, P.D. Dunn, P.J. Musgrove, B.E. Sexon, G. Slack
Wind/diesel integration for electricity supply to isolated communities.
Publication of the Rutherford and Appleton Laboratories, Oxfordshire, U.K.
and the Reading University, U.K., 1980.

L2 G. Slack, N.H. Lipman, P.J. Musgrove
The integration of small wind turbines with diesel engines and battery storage
Proceedings of the BHRA congress, Cranfield, 1982.

L3 N.H. Lipman, P.D. Dunn, P.J. Musgrove, B.E. Sexon, G. Slack
The integration and economic viability of SWECS
Proceedingsof the BHRA congress, Cranfield, 1982.

L4 K. Kaiba, D. Künz
Beschreibung des Windenergiekonverters Aeroman
München, 1979
EO-DOK, nr. ERA 41/79.

L5 Documentation of WTG Energy Systems Inc.
Wind turbine generators
Manufacturing, erecting, consulting
New York, 1975
(address: 251, Elm Street, Buffalo, New York 14203, tel. (716) 856-1620)

L6 E.W. Golding
The generation of electricity by wind power
E&FN Spon Ltd., London, 1976
ISBN 0470 11 0704

L7 M.J. Hoeijmakers, L.J.J. Offringa, W.J. de Zeeuw
A wind turbine driven electric power conversion system
Proceedings of the second international power conversion conference,
München, 1980.

L8 J.A.N. de Bonte, M.J. Hoeijmakers
Windturbine systeem met variabel toerental
PT Elektrotechniek/Elektronica, 37, nr. 8, 1982

L9 W.S. Bannister, S. Gair
Wind turbine research at Napier College
Proceedingsof the 3th BWEA Conference
Cranfield, 1981.

L10 V. Gervasio, A. Rossi, P. Verrecchia
Coupling of a vertical axis wind turbine with an auxiliary motor,
to give a constant AC output
Proceedings of the 4th BWEA Conference
Cranfield, 1982.

L11 Outline description of the Inis Oirr wind generator project, by the Department of Industry and Energy, Dublin, Ireland.

L12 A. Fritzsche, W. Müller
Bivalent wind-diesel power station
Proceedingsof the international colloquium on wind energy
Brighton, 1981.

L13 N.W. Langendijk
Nederlandse onderneming levert bijdrage aan ontwikkeling windenergie
Electra nr. 12, 1980.

L14 R. Merril, T. Gage
Energy primer
Dell publishing Co., Inc., New York, 1978
ISBN 0-440-52311-7

L15 Wind power digest, Winter 1978
by Michael Evans, 54468 CR 31 Bristol IN 46507

L16 G.R. Watson
Wind-solar systems for telecommunications and remote duties
Proceedings of the 4th BWEA conference
Cranfield, 1982.

L17 L.L. Freris, H. Bolton, I.K. Buehring, V.C. Nicodemou
A low cost wind energy system for heating of domestic premises.
Proceedings of the IEE conference on future energy concepts.
London 1979.

L18 Wind turbine assisted diesel generator systems by DAF Indal Ltd, Canada
(address: 3570 Hawkestone Road, Mississauga, Ontario, Canada, tel.: (416) 275-5300, tlx 06-961482).