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International Energy Agency IEA

Implementing Agreement for a Programme of Research and Development on Wind Energy Conversion Systems – Annex XI

21th Meeting of Experts – Electrical Systems for Wind Turbines with Constant and Variable Speed

Göteborg, October 7-8, 1991

Organized by:
Project Management for Biology, Energy, Ecology (BEO)
Research Centre Jülich (KFA)

On behalf of the
Federal Minister of Research and Technology,
The Fluid Mechanics Department
of the Technical University of Denmark

Scientific Coordination:
M. Pedersen (Techn. Univ. of Denmark)
R. Windheim (BEO-KFA Jülich)

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Introductory note on electrical systems for wind turbines with constant or variable speed

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Wind turbines for electrical power production have been built during several decades but have developed into industrial design and production in the last 10-15 years. Traditional wind turbines operate with constant speed operation and some research machines and prototypes have been built for variable speed operation.
Today one of the most interesting question is which type of operation, constant or variable speed, that should be used. This question has a mechanical and an electrical point of view but the most important is what the design of a wind turbine system has to gain or lose with a system design throughout for a variable contra constant speed operation.
The electrical system in a wind turbine should meet different types of requirements such as:

- High efficiency
- High power factor
- Environmental factors such as isolation, cooling, temperature
- Possibility to generator and motor drive systems (motoring)
- Protection against short-circuits in the generator or grid or other failures
- System communication with the control system of the wind turbine
- Low prices

Further more if the wind turbine should operate with variable speed the convertor system gives some extra benefits and drawbacks such as:

- Operation at C_p-l optimal
- Decrease noise emission
- A large speed range
- Torque control of the drive train
- Possibility to damp resonances in the drive train
- Harmonic contents in currents and voltage in the generator
- Torque pulsations on the generator shaft
- Harmonic contents in currents and voltage supplied into the grid

The generator for a wind turbine with constant speed can be of a synchronous or induction type and should be equipped for soft connection to the grid. The electrical system for a wind turbine with variable speed can be designed in many ways, e.g. for synchronous generators with rectifiers and thyristor inverters or induction generators with forced-commutated convertors.
Suggestions for discussion about electrical systems for wind turbines with constant or variable speed can be divided in the following subjects :

- Generators
- Electrical convertors
- Systems with generators and convertors
- The electrical system in a windfarm
- Control of the electrical system
- Economics

As a conclusion of these subjects the advantages and drawbacks of systems with variable contra constant speed ought to be discussed.

Investigation of Load Reduction Controllers for Wind Turbine Systems with Different Electrical Conversion Systems ‡

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Abstract

In this paper the implications are investigated of controllers on the dynamic loads occuring in wind turbine sytems under full load operating conditions. Both fixed speed wind turbine systems and variable speed wind turbine systems are studied. The integrated dynamic models describing the various wind turbine configurations are implemented in DUWECS . For each wind turbine the controller is designed using the Optimal Control design techniques. The simulations clearly show that it it possible to reduce the loads for an optimal controlled variable speed wind turbine.

Keywords: wind turbine systems, optimal control, dynamic models, load reduction

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1 Introduction

In general a wind turbine system is operating satisfactory if two objectives are met:

a) the dynamic loads under operating conditions are minimal.
b) the electrical energy production is optimal;

- in partial load as much energy as possible
- in full load a constant amount of energy

These objectives are conflicting, hence a trade-off has to be made between the amount of acceptable dynamic loads and the desired energy production. Every designed controller will imply a compromise between these objectives.

In what way such an optimum between the two objectives can be achieved depends strongly on the applied type of wind turbine system.

For every wind turbine design a specific choice of the subsystems have to be made. In this paper we will focus on the choice of the electrical conversion system and the implications for the complete wind turbine behaviour. Two main type of wind turbine systems are compared:

1. **fixed speed wind turbine:** the generator is an asynchronuous generator directly coupled to the grid.

2. **variable speed wind turbine:** the generator is a synchronuous generator coupled by a thyristor rectifier to a DC-link, which is coupled by an invertor to the grid.

The fixed speed wind turbine is the cheapest configuration, the active pitch controlled variable speed wind turbine the most expensive one.

In Section 2 the integrated dynamic models of the two wind turbine systems are discussed. These models are implemented in the DUWECS package [2] which is used to obtain linear models and to simulate the non-linear dynamic behaviour. The control systems are designed using the LQ Control Theory [1, 11]. This implies that the controllers are designed on a linear state-space description of the non–linear wind turbine model. Because each wind turbine configuration has different control possibilities in Section 3 different control systems for each type of wind turbine system are designed. In Section 4 the dynamic models of Section 2 controlled by the controllers of Section 3 are used in the DUWECS program to obtain dynamic responses of the different controlled wind turbine configurations. Conclusions of this paper are given in Section 5.

2 Wind turbine configurations

The behaviour of a variable speed wind turbine and a fixed speed wind turbine are studied in this paper. The fixed speed wind turbine has an asynchronous generator directly coupled to the public grid and allows an active pitch control. The variable speed turbine has a synchronous generator coupled with a direct current link to the public grid. Both wind turbine configurations fit into the integrated dynamic model model description of flexible wind turbines [3]. The mathematical models describing each of the wind turbines are implemented in DUWECS [2].

A wind turbine, schematically depicted in Fig. 1, can be seen as a set of interacting submodels. Therefore only interaction between the submodels is allowed through the depicted interaction variables. For both wind turbines the rotor, tower and

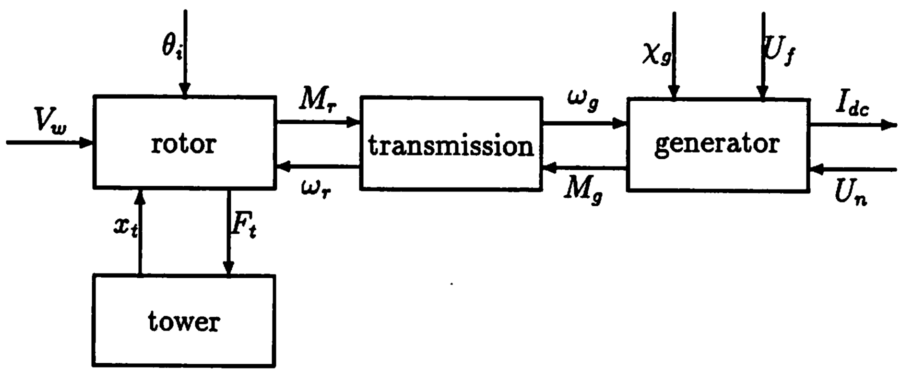

Fig. 1: modular structure of a wind turbine

transmission subsystems are the same:

rotor A two bladed rigid rotor with pitch, yaw and tilt freedom. The equations of motion are derived by using the method of Kane [9]. Each blade is divided into 10 sections with section dependend 2D blade profile characteristics, corde, mass and twist. A simple model of dynamic inflow and wind shear is assumed. The dynamics of the blade pitch adjustment mechanism is described as a torsion mode with a pitch moment as input.

tower The tower is described by the lowest bending mode.

transmission The lowest torsion mode is used to describe the transmission.

2.1 electrical conversion system

variable speed wind turbine For this type of wind turbine one electrical energy conversion system is chosen which allows large speed variations. The electrical conversion system consists of a synchronous machine coupled by a thyristor rectifier to a DC-link. This DC-link is coupled by an invertor to the public grid. In this setup it is possible to connect more wind turbines to the same DC-link. The excitation voltage and the delay angle of the rectifier can be used for control of the individual wind turbine. A mathematical model of this energy conversion system can be found in [7, 8, 14].

fixed speed wind turbine For this type of wind turbine one electrical energy conversion system is chosen which allows almost no speed variations. The electrical conversion system consists of an asynchronous generator directly coupled to the grid. A mathematical description of this energy conversion system can be found in [13, 10].

3 Controller design

In this section the control design method will be discussed. The (non–linear) integrated dynamic model (Section 2) of each wind turbine can be written as:

$$\begin{aligned} \dot{x} &= \mathcal{F}(x, u, v, t) \\ y &= \mathcal{H}_y(x, u, v, t) \\ z &= \mathcal{H}_z(x, u, v, t) \end{aligned} \qquad (1)$$

with $\mathcal{F}, \mathcal{H}_y, \mathcal{H}_z$ non–linear functions, x state vector and v the wind speed. In (1) y are the measurable outputs such as produced current I_g and rotor shaft angular velocity ω_r. The controllable inputs u are dependend on the wind turbine configuration and given in Table 1. The observed signals z: lead-lag blade root moment M_l, flap moment M_f and rotor shaft torque M_{shaft} are measured to judge the effectiveness of the controllers but not used for control purposes.

In this paper we will use a linear quadratic control design method, therefore the non–linear model (1) is linearized in an operating condition w, with w representing the steady–state condition ($\mathcal{F}(x, u, v, t) = 0$) of (1):

$$\begin{aligned} \delta\dot{x} &= A_l\delta x + B_l\delta u + G_l\delta v \\ \delta y &= C_l\delta x \\ \delta z &= H_l\delta x \end{aligned} \qquad (2)$$

with $A_l = \frac{\partial \mathcal{F}}{\partial x} |_w$ etc. Motivated by reasons of flexibility and allowing more complexity the controllers are implemented in digital hardware. Therefore the continuous time

wind turbine	inputs	outputs
fixed speed	blade pitch angle	produced current
variable speed	blade pitch angle	produced current
	delay angle	rotor speed

Table 1: input/output signals for different wind turbines

equations (2) are discretized, and one step time-delay to account for computation time is added:

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + Gv_k \\ y_k &= Cx_k \\ z_k &= Hx_k \end{aligned} \tag{3}$$

The linear system description lacks periodic information about the wind shear, tower shadow and gravity. Therefore it is assumed that a ficticious wind signal v_k can be chosen such that it is representative for the periodic effects. All these effects are described by:

$$\begin{aligned} x^w_{k+1} &= A_w x^w_k + B_w e_k \\ v_k &= C_w x^w_k \end{aligned} \tag{4}$$

with e_k white noise. A general linear dynamic controller can also be written in state–space form:

$$\begin{aligned} c_{k+1} &= A_c c_k + B_c y_k \\ u_k &= C_c c_k + D_c y_k \end{aligned} \tag{5}$$

The state–space descriptions of wind turbine (3), wind signal (4) and controller (5) can be written in one state–space form:

$$\begin{aligned} x^e_{k+1} &= A^e x^e_k + B^e u_k + G^e e_k \\ y^e_k &= C^e x^e_k \\ z^e_k &= H^e x^e_k \end{aligned} \tag{6}$$

The LQ control design method [1, 11] aims at minimizing:

$$J = \lim_{N\to\infty} \sum_{k=0}^{N} \{x^{eT}_k Q x^e_k + u^T_k R u_k\} \tag{7}$$

This means that the elements of the matrices (A_c, B_c, C_c, D_c) are chosen such that (7) is minimal. The influence of the wind velocity can be written as an initial condition:

$x_0^e x_0^{eT} = G^e G^{eT}$, the mechanical loads as $Q = H^{eT} H^e$ and the magnitude of the allowable input signals can be influenced by R.

The mathematical resctrictions on (4), (3), (6),(7) such that a stabilizing controller in the form of (5) exists is given in [1, 6, 5, 11].

The **fixed speed wind turbine** allows only single input single output (SISO) control (Table 1). A second order controller is designed, which can be seen as a sort of sophisticated tuned PID controller.

The **variable speed wind turbine** allows the application of multivariable controllers. Single loop controllers are also considered in [4] Using a multivariable controller the interaction between blade pitch control and generator control can be exploited to obtain a better overall performance. For computational convenience the order of the multivariable controller equals the order of the wind turbine model, which implies that there exists an explicite solution to (7) [1]. The resulting controller is called the LQG controller. The order of the SISO controller is restricted, which implies that the solution to (7) has to be found iteratively [11]. The resulting controller is called LQ output feedback. Both controller design methods are implemented at the Delft University of Technology using MATLAB [12].

4 Simulations

In this section some simulation results are given for four wind turbine configurations. The labels in the figures correspond with the list below:

1) **uncontrolled SM+DC** The uncontrolled variable speed wind turbine.
2) **controlled SM+DC** The variable speed wind turbine is controlled by the multivariable LQG controller.
3) **uncontrolled AM** The uncontrolled fixed speed wind turbine
4) **controlled AM** The fixed speed wind turbine is controlled by the single loop LQ output feedback controller.

All simulations are performed using DUWECS [2], assumed is an effective wind speed at rotor shaft height according to Fig. 2. The rotor blades experience a wind shear of +5% at the highest point and -7% at the lowest point.

The time history of the produced electrical power is given in Fig. 3.

It can be seen in Fig. 3 that the generated power can be kept almost constant for the controlled variable speed wind turbine. By applying the designed controller at the fixed speed wind turbine, the power variations can be reduced by almost 70%.

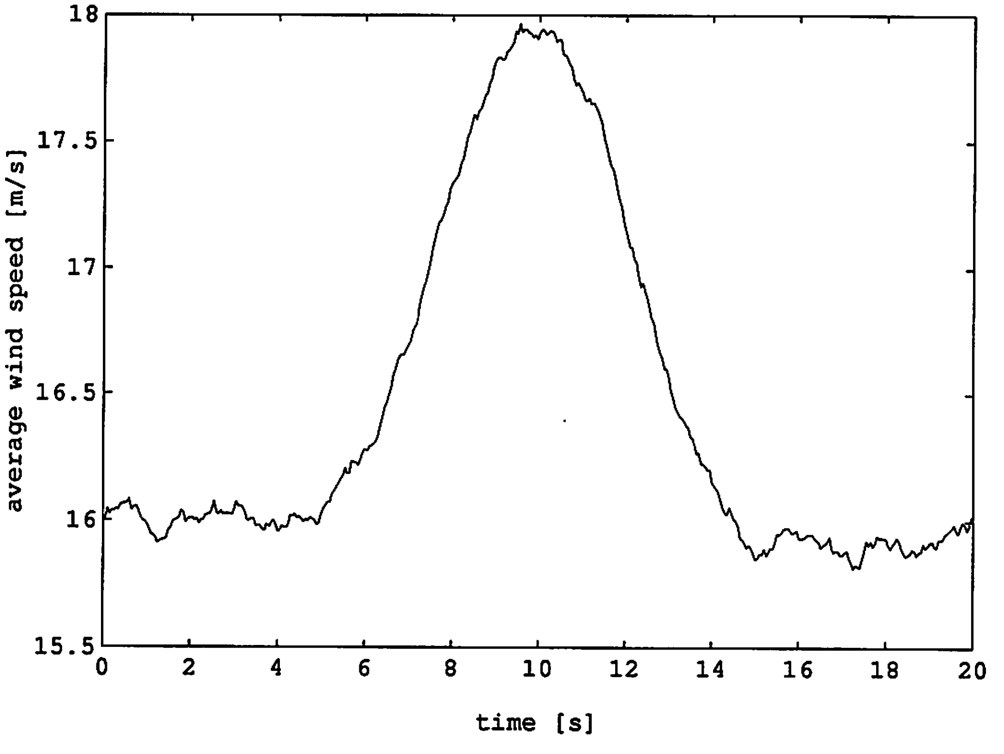

Fig. 2: wind speed at rotor shaft height

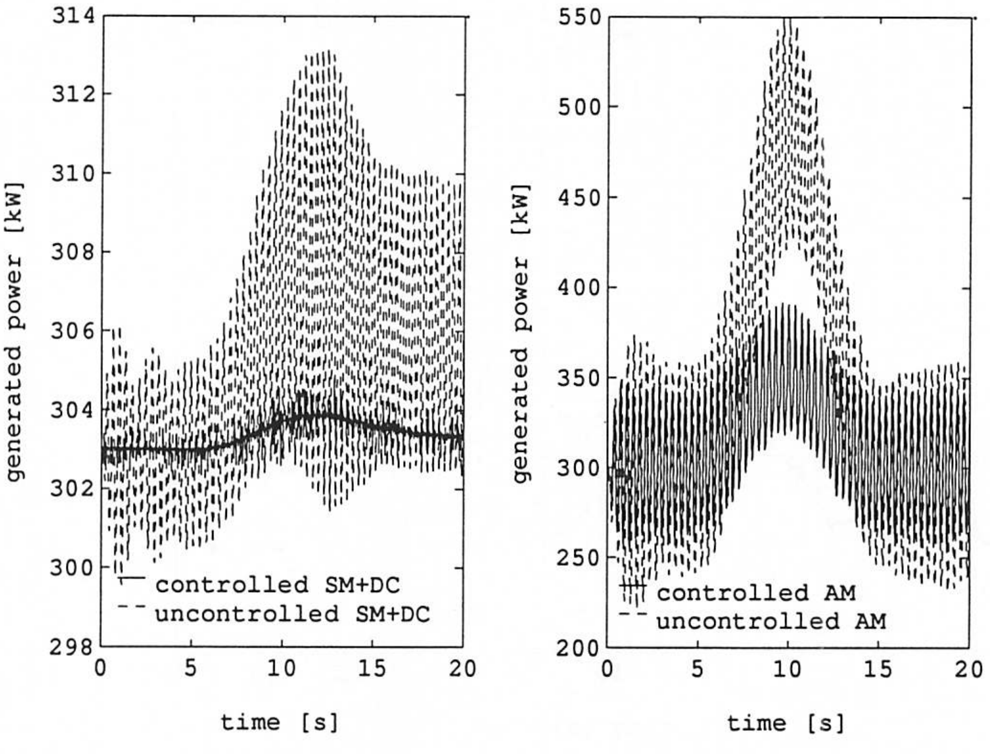

Fig. 3: produced electrical power

For both type of wind turbine configurations it is possible to reduce the rotor shaft

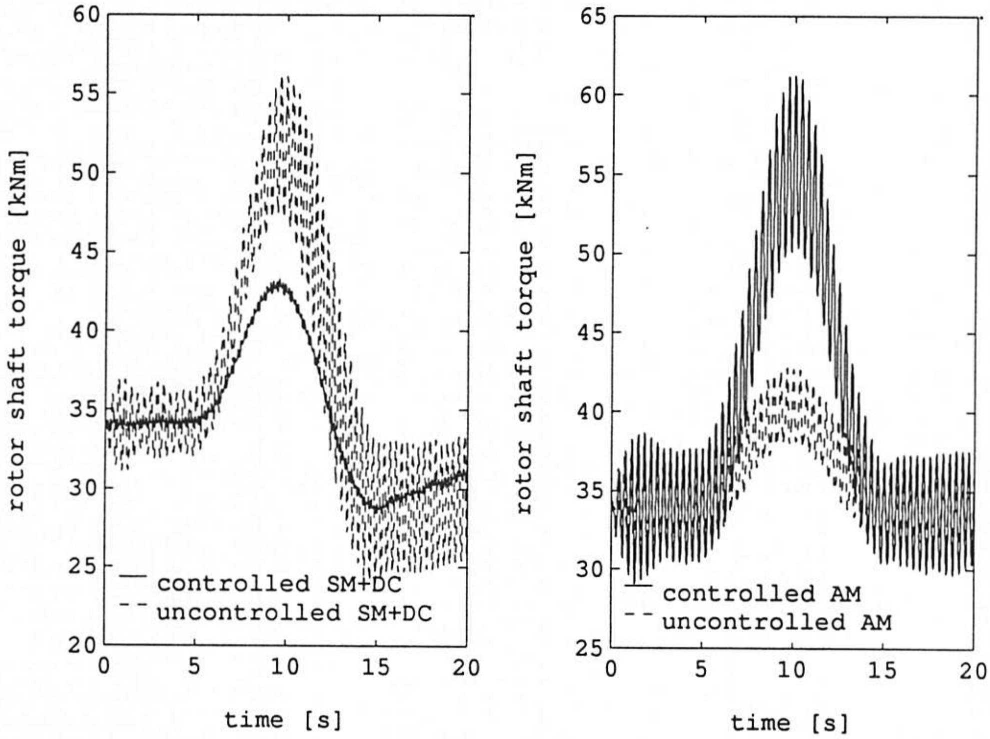

Fig. 4: rotor shaft torque

torque (see Fig. 4) significantly by applying the designed controllers. It can be seen that the LQG controlled variable speed wind turbine experience the smallest torque variations. Althought the torque variations of the controlled fixed speed wind turbine are reduced significantly they are in the same range as the uncontrolled variable speed wind turbine.

Based on these time histories the spectra of the "measured " signals are calculated. In Fig. 5 the spectrum of the rotor shaft torque is given. Comparing the time response of Fig. 4 with the frequency response of Fig. 5 for the variable speed wind turbine the above conclusions on load reduction are still valid.

In Fig. 6 the blade root bending moment in flap direction is given.

It can be seen in Fig. 6 that for the variable speed wind turbine the 1P oscilation of the blade root flap moment remains unchanged under the application of a controller. The controlled fixed speed wind turbine has higher loads than the uncontrolled wind turbine. Oscilations with 2P [1] and 4P occur

[1] An oscilation at 2P means an oscilation with a frequency of two times the rotor speed. For example an unbalance in a two-bladed rotor causes a 2P excitation on the rotor shaft.

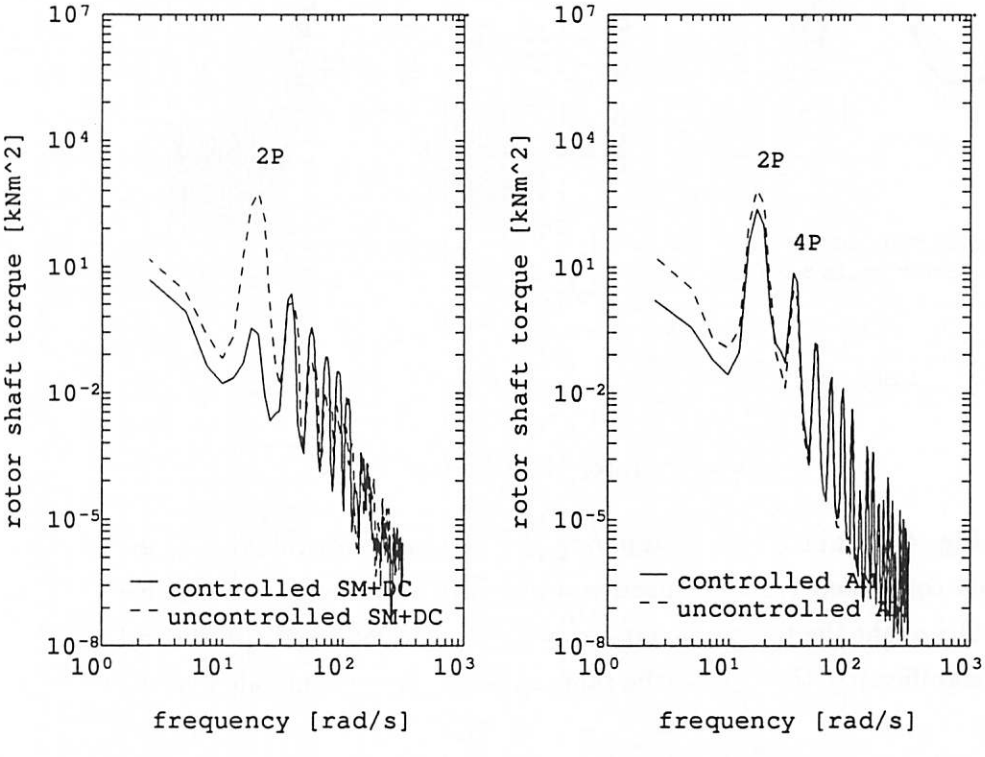

Fig. 5: rotor shaft torque

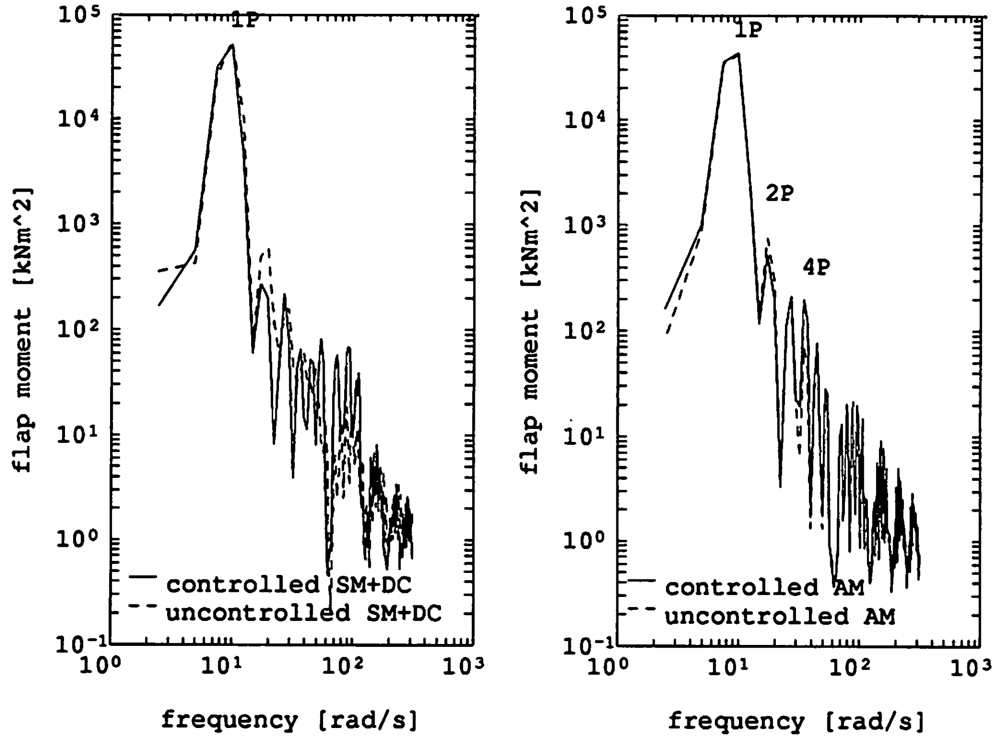

Fig. 6: Blade root flap moment

By applying a controller for fixed speed wind turbines it is possible to reduce the loads in the rotor shaft and reduce the variations in produced electrical power. However that is done at the expense of increasing blade root moments. Application of controllers for variable speed wind turbines will lead to reduction of variations in produced electrical energy as well as the reduction of loads.

5 Conclusions

Although the simulation results of the previous section are obtained with specific wind turbine configurations (rated power, rotor diameter, wind shear, etc.) the conclusions can be extended to the more general difference between fixed speed wind turbines and variable speed wind turbines, single loop control or multivariable control.

Using a fixed speed wind turbine it is possible to reduce the variations in produced power and rotor shaft loads at the expense of increasing blade loads.

Using a more expensive variable speed wind turbine it is possible to keep the produced electrical energy constant and simultaniously reduce the mechanical loads significantly more than using a fixed speed wind turbine.

It is not possible to give statements about fatigue reduction in the blades because the connection between a load spectrum and the load sequence is not yet transparant, which is a topic of further research.

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Electrical Systems for Wind Turbines with Constant or Variable Speed

Directly Coupled, Slow Speed Wind Turbine Alternators

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This summary is a record of the contribution made at the meeting and together with some details of the work undertaken in the UK on Directly Coupled, Slow Speed Alternators. The work was supported under an R&D contract, let by ETSU on behalf of the UK Department of Energy and carried out by NEI International Research and Development Ltd, further details are available on request.

The objectives for the work were as follows:-

1) To produce practical designs of directly coupled, slow speed, electrical alternators for use on horizontal and vertical axis wind turbines from which cost estimates can be derived.

2) To assess the comparative economic benefits that could be made from the use of directly coupled, slow speed, alternators on wind turbines.

3) To assess the scheme proposed by Dr Hylander et al of Chalmers University, Goteborg, Sweden, for the design of directly coupled, slow speed, alternators.

For economic reasons it was agreed at an early stage that this work should be limited to one power rating. A 1MW rating was selected. Additionally the outside diameter of the generator should be constrained to differ as little as possible from conventional WECS technology and has therefore concentrated on generator dimensions compatible with the present nacelle design of a HAWT or the tower design of a VAWT. For the same reasons the project was constrained to differ little from conventional generator design and manufacturing practice.

A pilot study [2] assessed the types of generator that could be utilized for this application and recommended further work on synchronous machines. The effect of a number of machine variables, specifically diameter and pole number, on cost and weight were examined within this work.

The research contractor , NEI International Research and Development, Newcastle-Upon-Tyne, was encouraged to have early discussions with the UK wind turbine manufacturers and thereby limit the design choices. In practice it was not possible to set too many design constraints and these were limited to the following,

- rated turbine rotational speed,

- overall size constraints, i.e. nacelle dimensions for the HAWT design and tower diameter for the VAWT design.

The work is fully reported by NEI International Research and Development Ltd [1].

Summary

Figure 1 shows the Schematic Arrangement of Generator and Wind Turbine it is possible to see the method of cooling the stator. The system suggested features a cylindrical plenum chamber, fabricated to the underside of the stator winding, supplied with air from a cooling fan. The air flows through the stator cores, figure 2, and is emitted into the rotor chamber. The cooling air passages are roughened at points along their length to give improved cooling characteristics.
The stator windings are fairly conventional and the general arrangement is shown in figure 3 along with a section through the cooling channels described above.

The rotor construction, Figure 4, shows how the pole pairs would be supported. Bolted onto a yoke, the pole windings are constructed using 'flat on edge' conductors which, at regular intervals, are widened to extend beyond the winding bundle to assist cooling. Centrifugal forces are small because of the slow running speed of the machine, 13 rpm. This allows for a number unconventional choices to be made for supporting the field windings shown at figure 5.

Financial constraints for this work concentrated the majority of effort toward vertical axis machines, however horizontal axis machines were considered, figure 6 and figure 7 give a parameter breakdowns for both a 1MW rating.

Results from this study indicate that smaller and lighter generator designs with improved output coefficients can be achieved, from the use of an enhanced cooling scheme and more detailed approach to the thermal analysis.

From the study, for a generator of 1MW rating, the following estimates of manufacturing weight and cost have been drawn:-

- vertical axis, total estimated weight of 82 tonnes at a cost of £348,100, 32 pole, 5 metre diameter, 13 rpm;

- horizontal axis, total estimated weight of 42.2 tonnes at a cost of £200,000, 20 pole, 2.7 metre diameter, 33 rpm;

- an estimated additional cost of £80,000/machine is required for the power conversion equipment necessary to interface the generator to the electrical network.

These figures indicate that a directly coupled, slow speed alternator would be more than twice the weight and cost of a conventional induction generator gearbox combination.

The work of J. Hylander et al [3], indicated that the weight and cost of slow speed, direct drive synchronous generators could be reduced by having a large generator diameter, short active length and high pole number. This could not be substantiated. The proposition that minimum active weight implies large diameter and large pole number is true, but account must be taken of the inactive weight (which tends to rise significantly with diameter) and the cost (which rises significantly with pole number).

Due to disappointing results, in terms of high cost and weight, no further work has been commissioned on wound rotor direct drive generators. However the need for frequency conversion with low speed generators may make them more cost effective for variable speed operation. Applications for this type of machine for use at variable speeds may be considered in the future.

A scheme to develop a direct drive generator using permanent magnets shows some promise with initial estimates of a machine of 300Kw being possible at a diameter of 1.7m, a length 1.5m and a total weight of 4 tonnes. The preliminary studies for this machine will last 2 years and report in late 1993.

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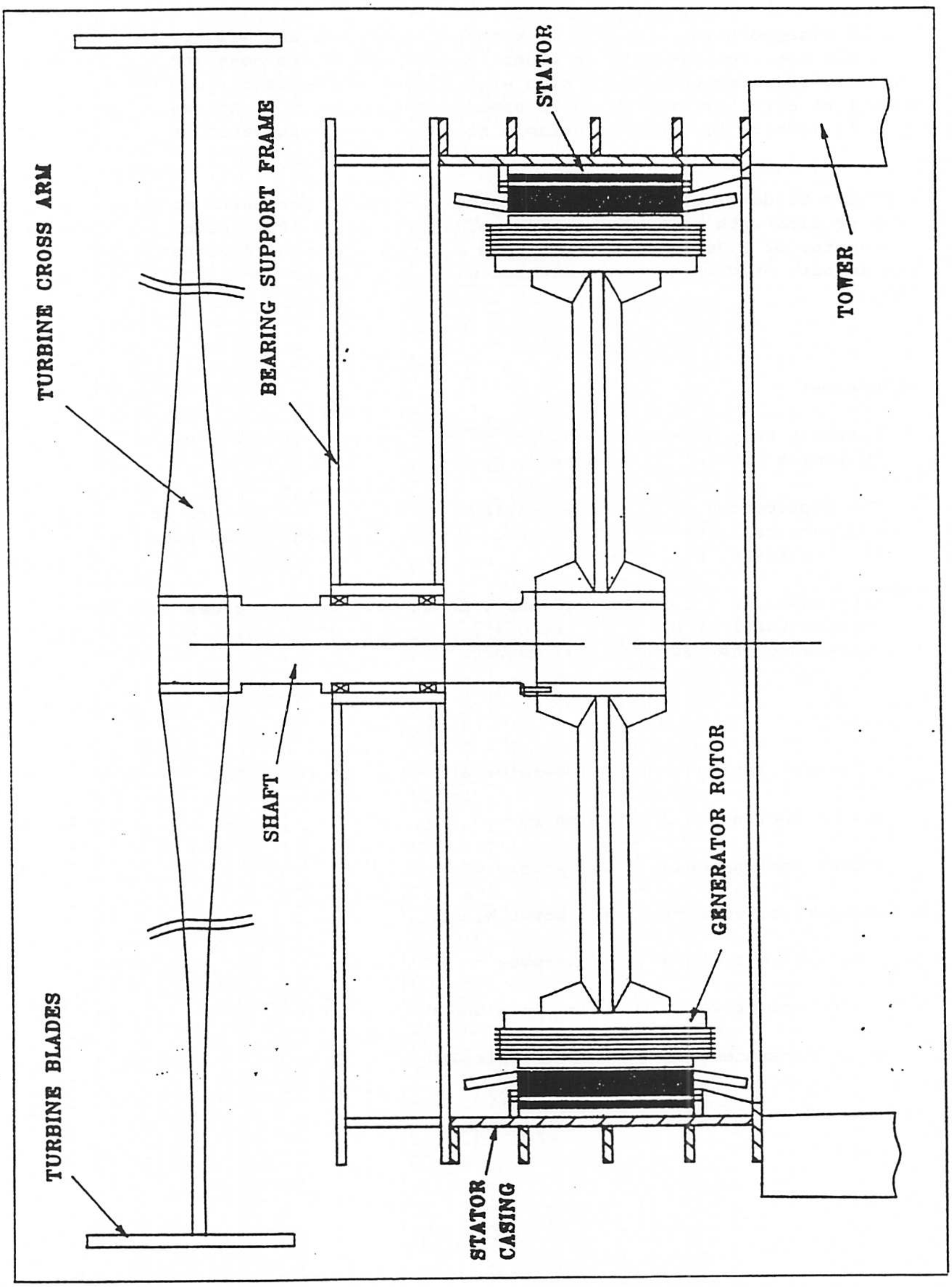
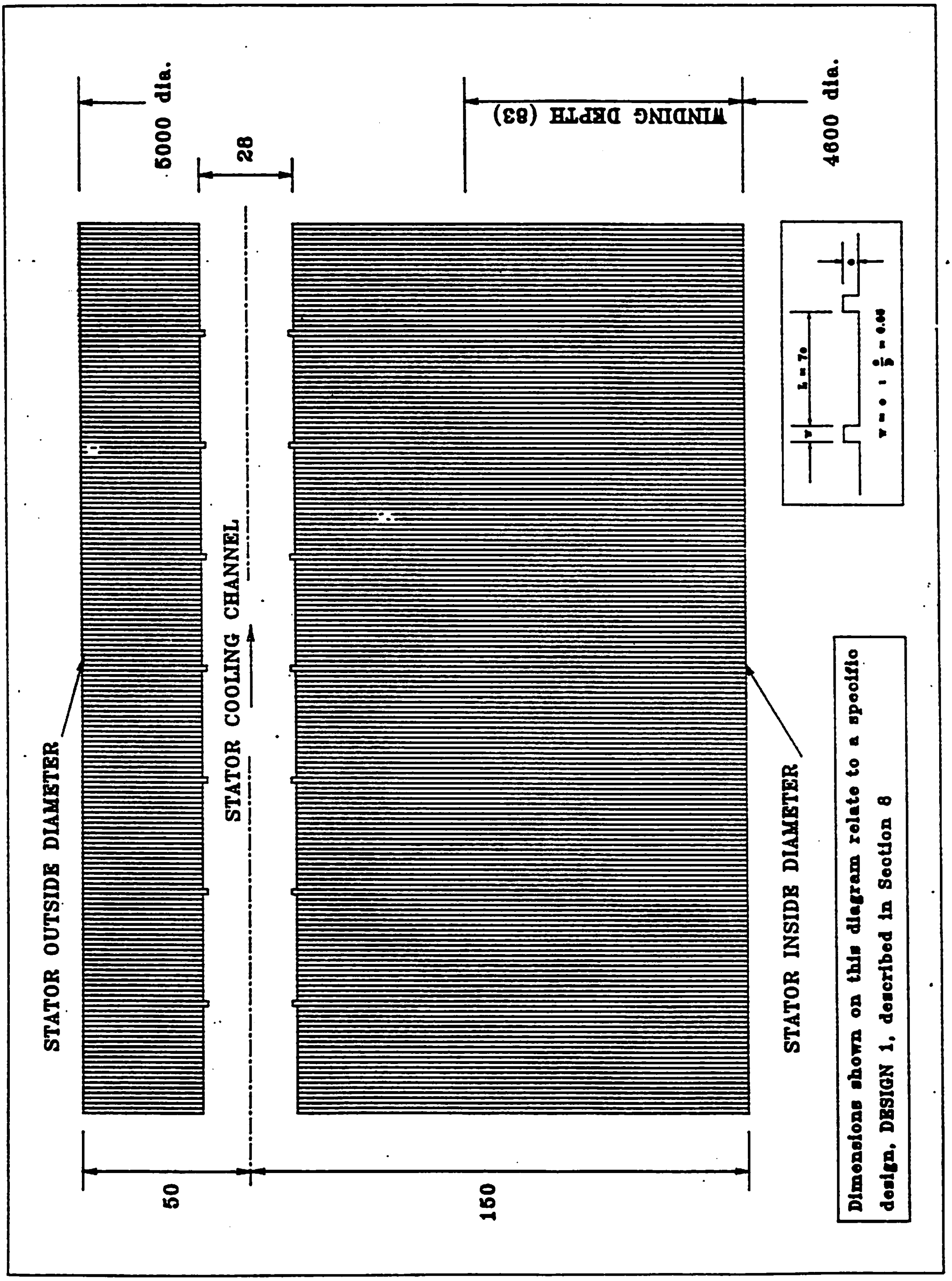
Figures



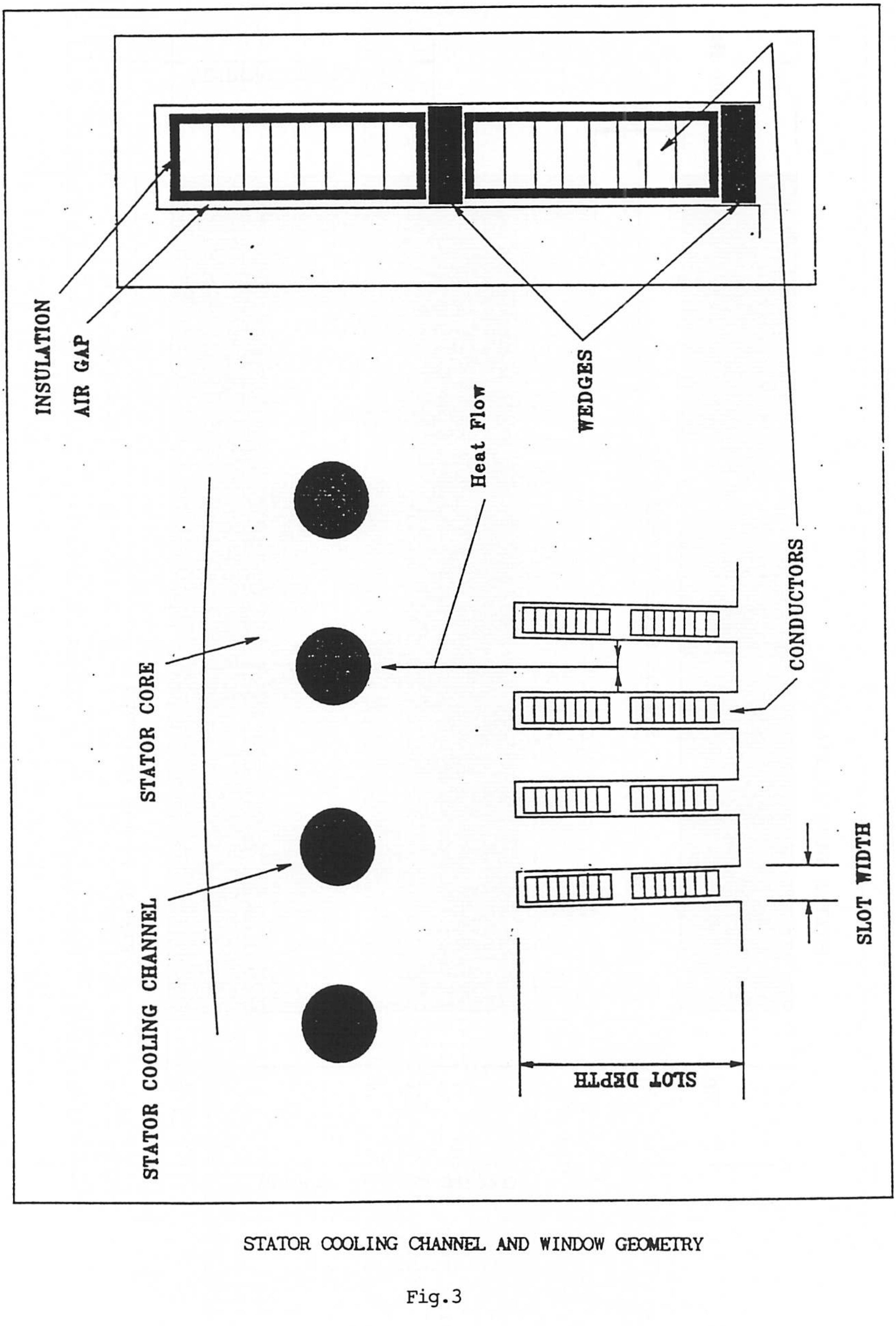
SCHEMATIC ARRANGEMENT OF GENERATOR AND WIND TURBINE

Fig.1



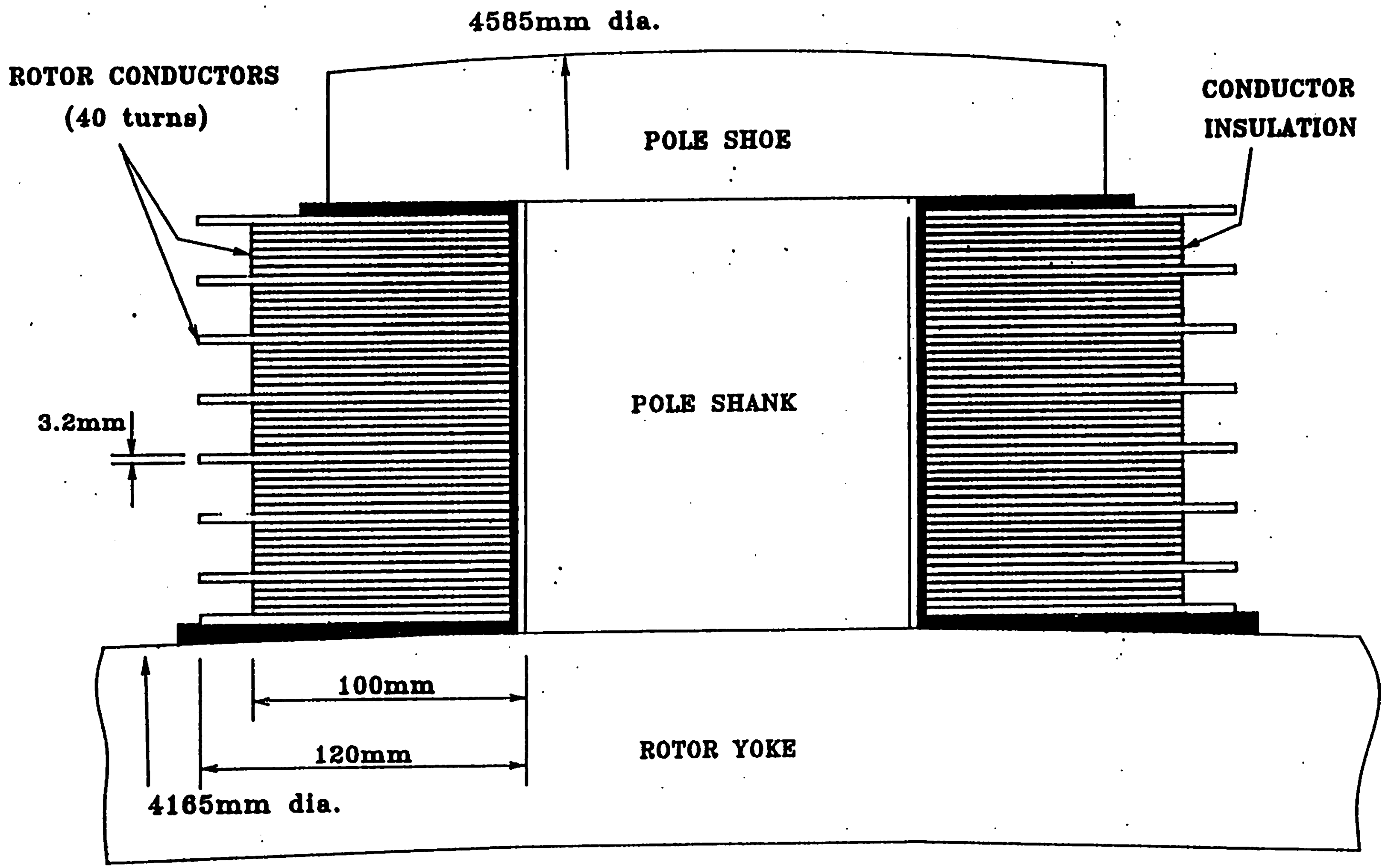
STATOR COOLING CHANNEL GEOMETRY

Fig. 2



STATOR COOLING CHANNEL AND WINDOW GEOMETRY

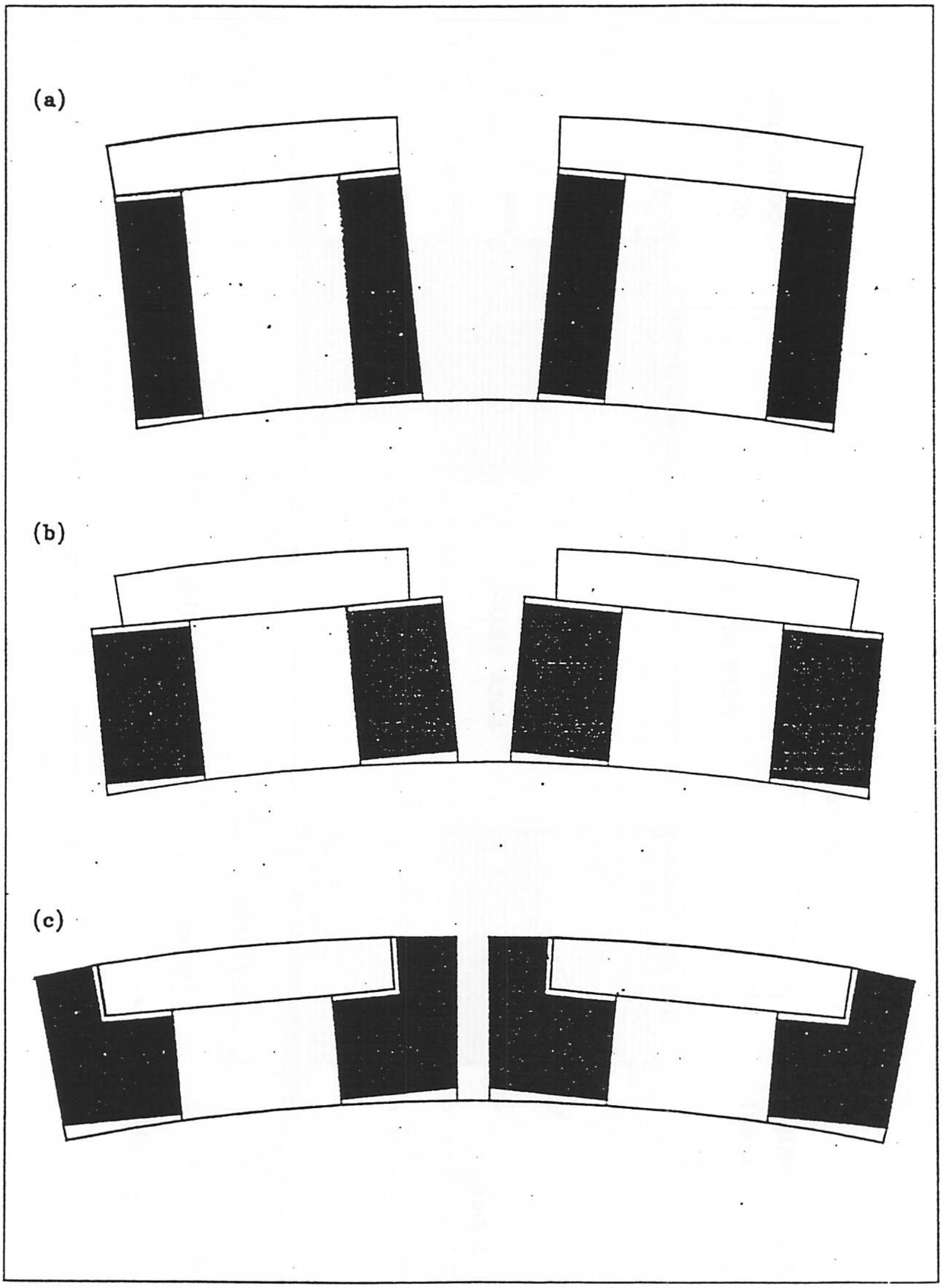
Fig.3



SECTIONAL PLAN VIEW

GEOMETRY OF POLE PIECE AND ROTOR WINDING

Fig.4



ALTERNATIVE FIELD WINDING SCHEMES

Fig.5

MAJOR PARAMETERS OF 'LOW COST' VERTICAL AXIS GENERATOR DESIGNS

	DESIGN 1	DESIGN 2	DESIGN 3
Power (kW)	1000	1000	1000
Speed (rpm)	13	13	13
No of poles	32	56	56
Frequency (Hz)	3.5	6.0	6.0
Power factor	0.85	0.85	0.85
Line and phase current (A)	206/206	206/206	206/206
Line and phase voltage (V)	3300/1905	3300/1905	3300/1905
Stator Electric loading (kA/m)	52	46	50
Stator core OD (mm)	5000	5000	6000
Stator core ID (mm)	4600	4600	5500
Stator Core length (mm)	950	1050	750
No of slots	456	504	576
Slots/pole/phase	4.75	3	3.43
Slot depth (mm)	83	67	103
Slot width (mm)	16.5	16.5	16
No of parallel paths	2	2	2
No of turns in series/phase	608	588	768
No of conductors per slot	16	14	16
Conductor width x depth (mm)	12.8x4.0	12.8x3.5	12.3x5.0
Length of mean stator turn (mm)	3474	3240	2852
Stator current density (A/mm^2)	2.06	2.33	1.72
Stator phase resistance 75 degC (ohm)	0.46	0.47	0.39
Air gap radial length (mm)	7.5	5.0	5.0
Pole shoe width (mm)	300	170	230
Pole shoe height (mm)	50	30	35
Pole shank width (mm)	160	90	115
Pole shank height (mm)	160	120	128
Yoke radial thickness (mm)	132	100	82
Yoke ID (mm)	3900	4090	5000
Field conductor width x depth (mm)	100x3.2	54x3.2	82x3.2
No of turns/pole	40	31	31
Field current (A)	345	298	322
Field current density (A/mm^2)	1.08	1.72	1.23
Length of mean rotor turn (mm)	2394	2397	1904
Excitation voltage (V)	70	152	86
Active weights (tonnes):			
Stator iron	16.3	19.1	20.3
Stator copper	6.2	5.0	7.7
Rotor iron (yoke and poles)	23.2	18.6	14.6
Rotor copper	8.7	6.4	7.7
Total active weight (tonnes)	54.4	49.1	50.3
Estimated weight of inactive structure (stator case, rotor disc, hub & webs)	27.6	29.4	36.5
Estimated total weight (tonnes)	82.0	78.5	86.8

Note that Design 1 is depicted in detail on the engineering layout drawings, Figs 5.3 to 5.5.

Fig. 6

MAJOR PARAMETERS OF 'LOW COST' HORIZONTAL AXIS GENERATOR DESIGN

Power	1000 kW
Speed	33 rpm
No of poles	20
Frequency	5.5
Power factor	0.8 lag
Line/phase currents	208A/208A
Line/phase voltages	3.46 kV/2.0 kV
Stator electric loading	64.1 kA/m
Stator core length	1340 mm
Stator core OD	2700 mm
Stator core ID	2360 mm
No of slots	285
Slots/pole/phase	4 3/4
Slot depth	93.5 mm
Slot width	14.2 mm
No of parallel paths	1
No of turns in series per phase	380
No of conductors per slot	8
No of subconductors in conductor width	1
No of subconductors in conductor depth	3
Subconductor width x depth	11 mm x 3 mm
Length of mean stator turn	3540 mm
Stator current density	2.1 A/mm^2
Stator phase resistance	0.030 pu
Air-gap radial length	5.0 mm
Pole shoe width	266 mm
Pole shoe height	45 mm
Pole shank width	165 mm
Pole shank height	165 mm
Yoke radial thickness	107 mm
Yoke ID	1716 mm
Field winding: no of turns per pole	40
Field conductor width x depth	48 mm x 4.0 mm
Field current	312 A
Field current density	1.62 A/mm^2
Length of mean rotor turn	3360 mm

Field winding transport loss as a function of shank height and winding width i.e. for various design variants:-

	(A)	(B)	(C)	(D)
Shank height (mm)	165	165	200	200
Field winding width (mm)	48	63	48	55
Excitation Loss per pole (w)	1490	1150	1230	1080
Inefficiency [1000 kW = 100%]	3.0%	2.3%	2.5%	2.2%
Excitation voltage (V)	96	74	79	70

Active weights for the above design variants:-

Stator iron (kg)	9,870	9,870	9,870	9,870
Stator copper (kg)	3,690	3,690	3,690	3,690
Rotor iron (kg)	13,950	13,950	14,990	14,990
Rotor copper (kg)	4,640	6,180	5,650	6,510
Total	32,150	33,690	34,200	35,060

Fig.7

MEETING ON ELECTRICAL SYSTEMS FOR WIND TURBINES WITH CONSTANT OR VARIABLE SPEED

POWER QUALITY

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1. SCOPE

This document discusses "power quality" and wind turbines. Power quality is concerned with the effect of wind turbines and wind farms on the external electrical systems, and covers two areas:

- Flicker (voltage fluctuations)
- Harmonics

For each of these cases, a brief description is given of the technical background and the relevant standards. The ways by which wind turbines, both constant and variable-speed, can cause these effects is discussed.

2. FLICKER

2.1 Technical Background

Voltage fluctuations can cause annoyance to electricity consumers. The major effect is on standard incandescent light bulbs, which appear to flicker (hence the name given to this phenomenon). Standards are therefore based not on the amplitude of the voltage fluctuations, but on their effect on the general public through lighting. The response of the light bulb and of the human eye and brain are taken into account.

Flicker can be caused by the starting of large motors, by arc furnaces, by welding equipment, by other fluctuating loads and of course by wind turbines. All these produce power (and reactive power) fluctuations which, because of supply system impedance, produce voltage fluctuations on the network.

The flicker level is therefore dependent on the amplitude of the voltage fluctuations, their frequency, and the shape of the waveform. Square waves create worse flicker than sine waves of the same amplitude and frequency (Fig. 1).

The flicker level at the source of the voltage fluctuations is not necessarily of interest. Instead the "point of common coupling" is defined (pcc), which is the point on the network where other consumers are (or could be) connected. Generally the pcc will be the boundary of the wind farm.

2.2 Standards and regulations

The International Union for Electroheat (UIE) has produced several publications on this issue, of which Ref. 1 is the most useful. Based on this work, IEC Standard 868 defines a standard for "flickermeters", devices to measure existing flicker.

IEC 555-3 is a standard for flicker from domestic and small equipment (below 16 Amps), which is not relevant for wind turbines.

IEC 555-5 covers flicker for industrial installations, i.e. wind turbines, but is only a recommendation. It is up to individual supply authorities to develop their own guidelines based on IEC 555-5. In the UK, this is covered by Engineering Recommendation P28 (Ref. 2). Some other countries have produced similar documents: others rely on Ref. 1.

These are only recommendations: supply authorities can vary them at their discretion.

There is a general principle that if the flicker at the pcc predicted for a new installation (such as a wind farm) is below a certain level, it is acceptable and no further studies are necessary. The level is determined by local or national guidelines, or by reference to Ref. 1. Above the level, the existing flicker is measured, and it may be calculated that the combination of the two is still acceptable.

In the UK, the 'first come, first served' principle is used. Ref. 1, on the other hand, recommends that some note is taken of the declared supply capacity of the customer when determining permissible flicker.

2.3 Wind Turbine and Flicker

Wind turbines cause flicker in the following cases:

- startup (inrush current)
- shutdown
- normal operation

2.3.1 Startup and Shutdown

These are easily calculable, knowing the characteristics of the induction generator, the fault level S_{cc} at the point of interest on the network, and the expected frequency of starts. The flicker level can then be estimated using the procedures in the relevant standard. If a problem is foreseen, a current-limiting soft-start unit can be fitted. The situation is similar but less severe when the turbine shuts down. The problem will be less significant for a wind farm, because it is inconceivable that more than one or two turbines will start or stop at exactly the same moment, unless grid voltage or frequency are out of limits.

2.3.2 Normal Operation

Power fluctuations from turbines, and hence flicker, are caused by turbulence in the wind, mechanical resonances in the turbine (negligible for well-designed turbines), and the effect of wind shear and yaw error, which produce sinusoidal power fluctuations at 2P or 3P (for two or three bladed turbines). Two-bladed turbines produce greater power fluctuations due to wind shear and yaw error than three-bladed turbines.

For stall-regulated turbines, the worst case will be at just below rated power, i.e. on the steepest part of the power curve, where a change in windspeed will produce the greatest change in power. For pitch-regulated turbines, the effect should be worst above rated power, because the pitch control mechanism will be unable to respond fast enough to filter sharp gusts. For this reason, it is expected that pitch-regulated turbines will produce worse flicker than stall-regulated, though I am not aware of any studies that prove this.

As can be seen from Fig. 2 the frequency range that is of most importance for flicker is above 2Hz. For turbines of size 300kW - 1MW, the 2P or 3P frequency is (very approximately).

	300kW	1MW
two bladed (2P)	1.5Hz	0.8
three bladed (3P)	2Hz	1Hz

These frequencies are below the most important frequencies. However, there is a still a significant component of turbulence in this region. Turbulence is expected to be a major cause of flicker, for single turbines.

Variable-speed turbines of course produce lower power fluctuations and therefore less flicker. Better power control was one of the original reasons for interest in variable-speed. However, in wind farms this may not be a significant benefit (see 2.5).

2.4 Determination of flicker from wind turbines

Flicker caused by a particular source can be calculated or measured.

2.4.1 Calculation

Techniques for calculation are presented in the standards discussed in 2.2. For a single turbine, the worst-case power and reactive power fluctuations have to be determined: either by estimation, or by measurement on a sample turbine (see 2.4.2). Even then, some estimate must be made of the effect of the difference in turbulence intensity between the measurement conditions and the proposed site.

For a wind farm, the situation is more complex, because of the averaging effect of the wind farm. This has been approached theoretically (see 2.5) but I am not aware of any published studies that validate the theoretical approach or provide methods for estimation of the effect. This will be covered in a project about to start in the UK.

2.4.2 Measurement

Measurements of the power fluctuations and voltage fluctuations caused by turbines or wind farms have been made, but no direct measurements of flicker, using a flicker meter. This also will be covered by the project mentioned above.

2.5 Is flicker a problem?

Danish experience appears to show that so far flicker is not a problem. This is on the basis that few complaints have been received: there do not appear to have been any published studies or measurements of flicker. Danish utility practice at present (Ref. 3) is to limit steady-state voltage rise due to a wind farm to 1% at the pcc. This therefore limits flicker to a low level, which perhaps explains why there have been no problems.

In the UK, there are as yet no operating wind farms. Potential UK sites often have low fault levels, and grid reinforcement is very expensive, but it is not yet clear whether flicker will prove to be a significant factor limiting the size of wind farm for a particular site. UK utilities may allow 3% steady-state voltage change (i.e. greater than the Danish limit), in which case flicker may become important.

An important factor will be the "averaging" effect of a wind farm. High frequency fluctuations contribute more to flicker than low-frequency fluctuations, but are not correlated across a wind farm and so do not appear in the output of the wind farm. Low-frequency fluctuations are correlated across the wind farm, but contribute little to flicker. As a complicating factor, turbulence within wind farms is higher than in the free-stream wind (up to 25%), and the turbulence spectrum is expected to be different (Fig. 3).

The conclusions at present are:

- flicker may be a problem for single turbines on a low fault level
- it is expected that the problem will reduce for wind farms
- measurements to validate a theoretical approach are necessary

3. HARMONICS

3.1 Technical Background

Harmonics are generated by fixed-speed wind turbines for a few seconds when the soft-start unit is in use. They are generated continuously by variable-speed turbines.

3.2 Standards

The situation is very similar to that for flicker. IEC 555-2 covers small equipment. IEC 555-4 covers industrial installations such as wind farms, but is only a recommendation. Individual countries or supply authorities can develop their own guidelines. In the UK, this is Engineering Recommendation G5/3 (Ref. 5).

Again, local or national guidelines can accept installations with a predicted harmonic contribution below a certain level without further study. If the predicted level is exceeded, further calculation and measurements of existing levels may still allow the installation to be accepted.

In the UK, "short-duration" harmonics (less than 2 seconds duration) can be ignored, which would appear to allow soft-start units.

3.3 Wind turbines and harmonics

Unlike flicker, calculation methods exist which can be easily applied to wind turbine variable speed drives.

On low fault levels, harmonic generation may become a problem, and it is possible that harmonic limits will reduce the available sites for wind farms of variable-speed turbines to some extent. There are methods to reduce the overall harmonic contribution from a wind farm: 12-pulse or PWM converters, or using transformers with different phase relationships.

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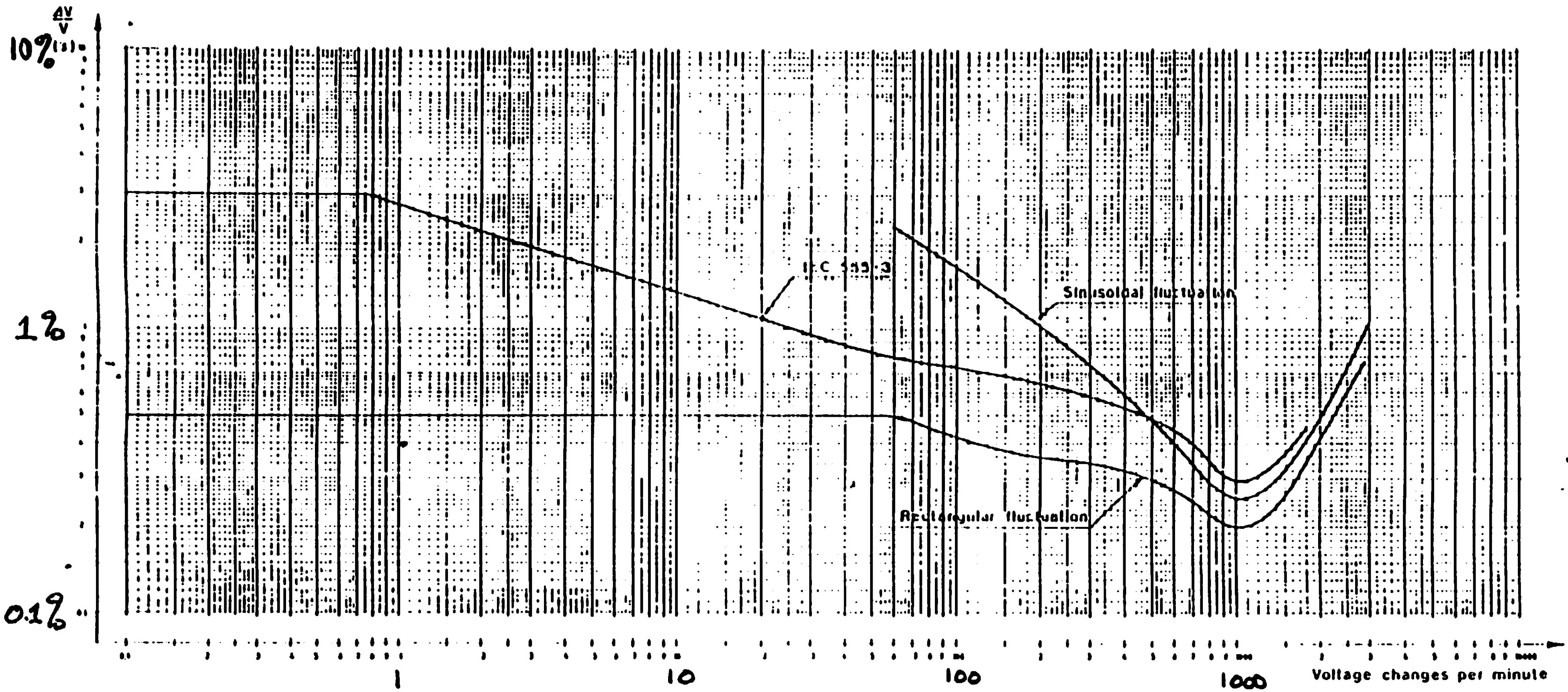

FIG. 1 - Perceptibility threshold for sinusoidal and rectangular voltage fluctuations versus frequency given by the UIE flickermeter - IEC limit curve for rectangular voltage fluctuations (a single domestic appliance on a reference impedance) is shown for comparison

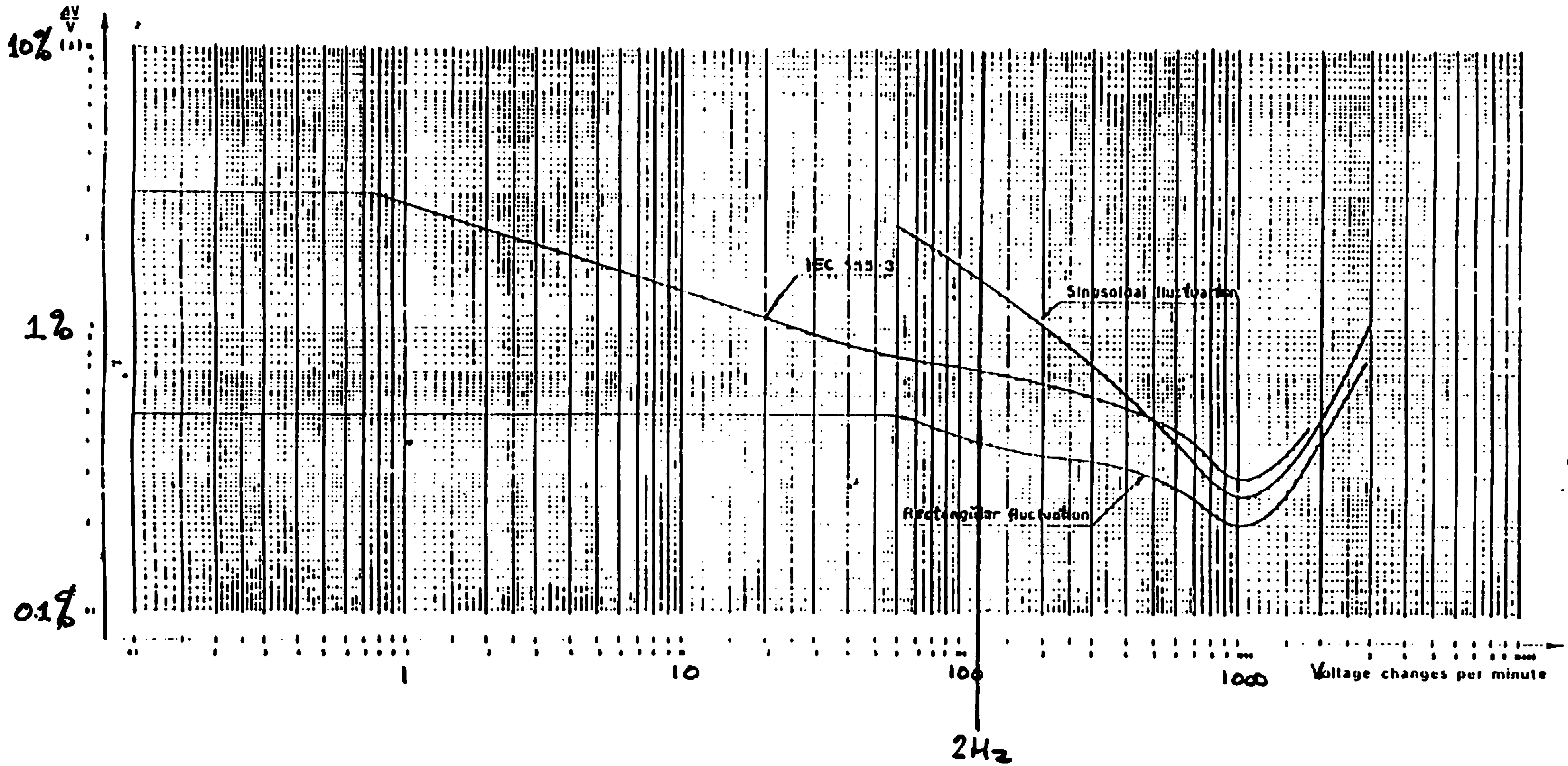

FIG. 2 - Perceptibility threshold for sinusoidal and rectangular voltage fluctuations versus frequency given by the UIE flickermeter - IEC limit curve for rectangular voltage fluctuations (a single domestic appliance on a reference impedance) is shown for comparison

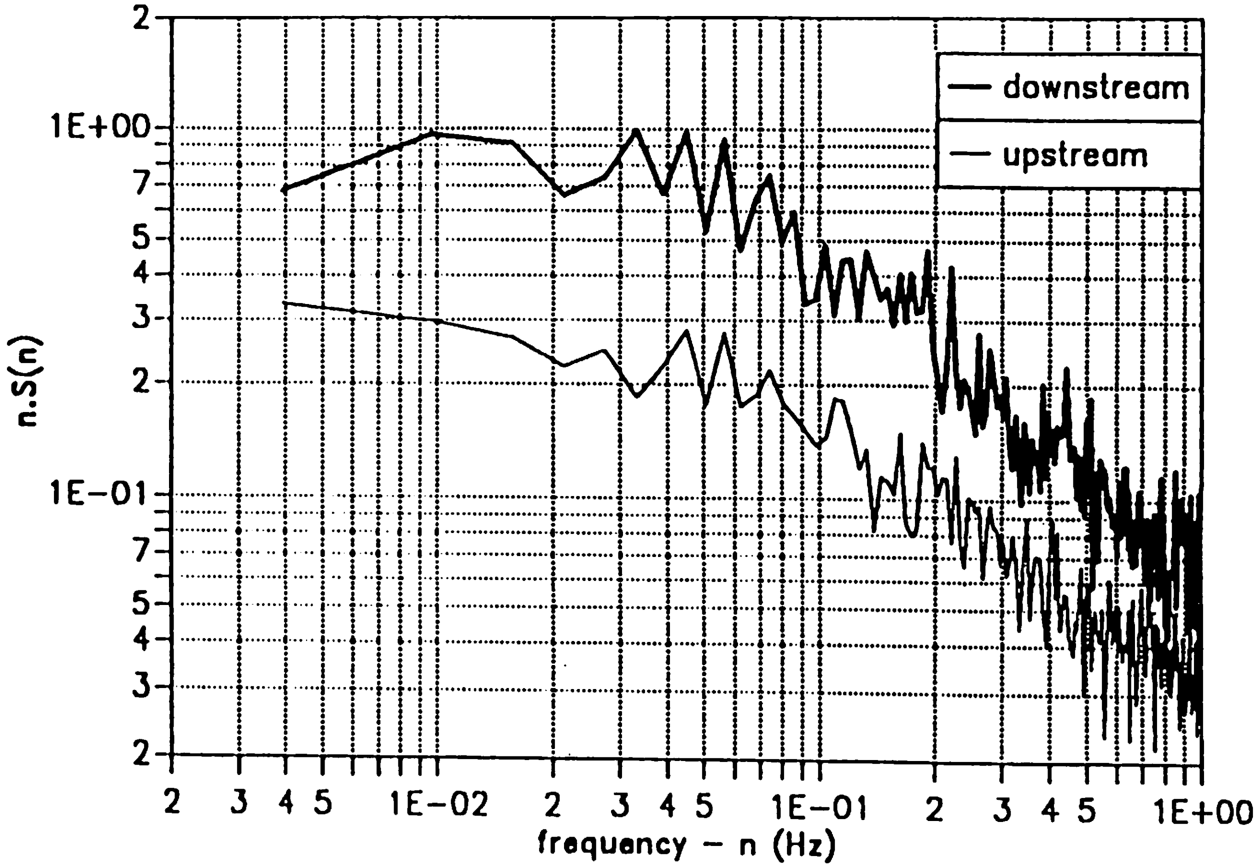

FIGURE 3 POWER SPECTRA OF TURBULENCE AT 56 METRES HEIGHT 100 METRES UP- AND DOWNWIND OF THE ROTOR

FROM REF. 4

Grid influence by wind energy converters

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Abstract

In coastal regions and on islands new perspectives for the supply of electricity could be enlarged, if the weather-dependent supply of wind power were to be integrated successfully into already existing supply structures and those which are to be developed. Besides the energy supply, the influences on grids as well as on the consumers of electricity are becoming more and more important.

For wind energy utilization only those plants for the generation of energy are of relevance whose performance is essentially determined by their electro-technical conception. Hereby the energy conversion from mechanical to electrical together with a suitable grid connection and plant control plays an important part. In this paper the configurations of the various functional structures of converter systems like

- wind turbine with active power control by
    - blade pitch variation with
    - asynchronous generator and
    - direct grid coupling as well as

- wind turbine with passive power control by
    - stall with
    - synchronous generator with dc interconnecting circuit and
    - inverter coupling to the grid

are reflected with regard to their

- grid influences. Hereby
    - power fluctuations
    - grid voltage harmonics and
    - grid resonances

are very important. On the basis of the measured results from "Windpark Westküste" the relevant characteristics will be outlined and the two existing conceptions will be discussed and compared.

1 Introduction

Energy absorption of wind energy is caused by a slowing down of the available airstream. The resulting power is transported by a gear to the rotor of the generator and is supplied to the consumers in the form of electrical energy either directly or via storage-batteries, connecting links like power lines, transformers and the mains.

Figure 1 shows the most important components of the system and their connections, and the different type of energy concerned at a particular stage. Furthermore ways of influencing by control and operation are also indicated. Here, the central position of the generator becomes obvious in such a supply structure.

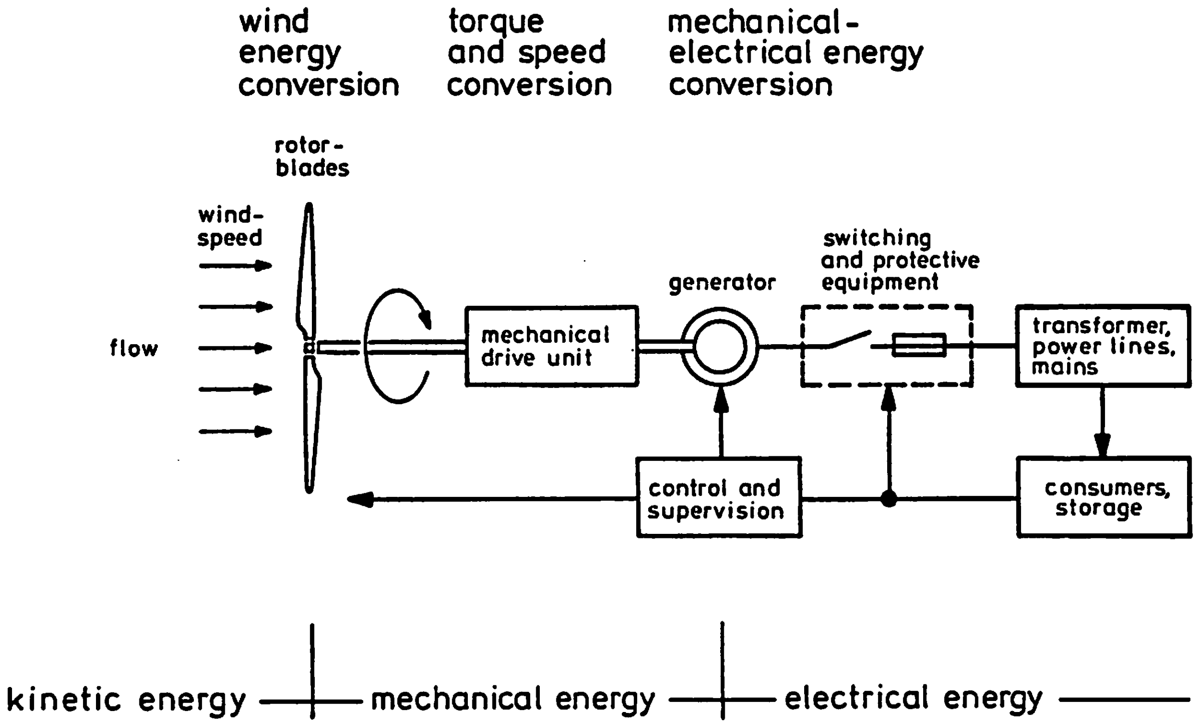


Figure 1: Power transfer of a wind energy converter

A large number of components make up the electrical system of a wind energy plant including the mains connecting point, the generator, control, supervision and technical arrangements for the safety and illumination of the nacelle. The chosen conceptions for the control and performance limit of the turbine as well as the energy conversion (mechanical to electrical) are important for the behaviour of a wind energy converter, and are important for possible influences on the mains and consumers etc. Therefore, this paper will explain these two system components.

2 Power limit and plant control

Energy supply of electrical supply systems can usually be adapted to a higher or lower power requirement. However, wind energy converters, whose power output is governed by the wind velocity, only allow operations with a lower power conversion.

When considering the control and supervision of wind energy converters one has to distinguish between an isolated power supply, a hybrid or mains power supply. In isolated configurations plant specific designs have to be taken into account. These factors determine how far it is possible to satisfy consumer demands. Besides, the locally given conditions for the mains supply have to be fulfilled according to the "Technische Anschlußbedingungen" (Technical conditions of connections) in order to generate current in parallel operation to the grid. Interconnected supply can only happen with big grids on a national and international level or with isolated island grids.

Influence of power inputs by the wind is possible by changing the pitch of rotor blades e.g. by hydraulics, or mechanic-electrical impulses, or so forth. For plant control and power limit, most of all wind energy converters larger than 200 kW, and some of the smaller converters work on this principle.

The majority of all American, Danish, Dutch and, in growing numbers, also German producers, use the principle of the so-called stall control (up to the capacity of ca. 300 kW) to limit the converter power for the small and medium sized plants. In standard operation there is gliding air flow across the rotor blades. This results in higher efficiency and favourable aerodynamic values. If the wind speed approaches the point at which the generator reaches its maximum running performance, and it is necessary to prevent a further increase in rotating speed, the air flow across the blade profiles will get close to stall operation. The torque drops and the drag rises, so that the performance generating factor decreases. This procedure usually happens without movable parts and consequently without delay.

By using the simple structures of figure 2a, b both the way of working and the functional relations of the main components of wind energy converters using either blade pitch control or stall control can be characterized, and also the differences in their behaviour can be demonstrated.

Controlled operation of the turbine is possible by changing the blade pitch (figure 2a) in a way so that the torque of the wind wheel and the power input are decreased. Such controlled actions can be made in all operational fields. When the wind power is high enough, the rotating speed of the rotor and the generator frequency which are determined by the torque of wind wheel in combination with the torque of generator can be influenced in all performance ranges. In power plants which have the above mentioned conception the essential premise for running in all ranges of load is achieved by regular of control operational handling.

Generally, a rotating speed control, which is a necessary regulation for limiting the turbine power, is applied in such a way as to lead the plant in starting-up and shutting-down, in synchronizing its various functions, and in case of grid failure and switch-off.

Plants without blade variation have to be held and kept at their speed by the load momentum of the generator. At a wind higher than the nominal range, the blades get into stalling. Through stalling at the blades the power input of the turbine will be limited by the type of construction. According to diagram 2b operations on the turbine can only be done retroactively by the braking torque of the generator via the complete mechanical drive elements.

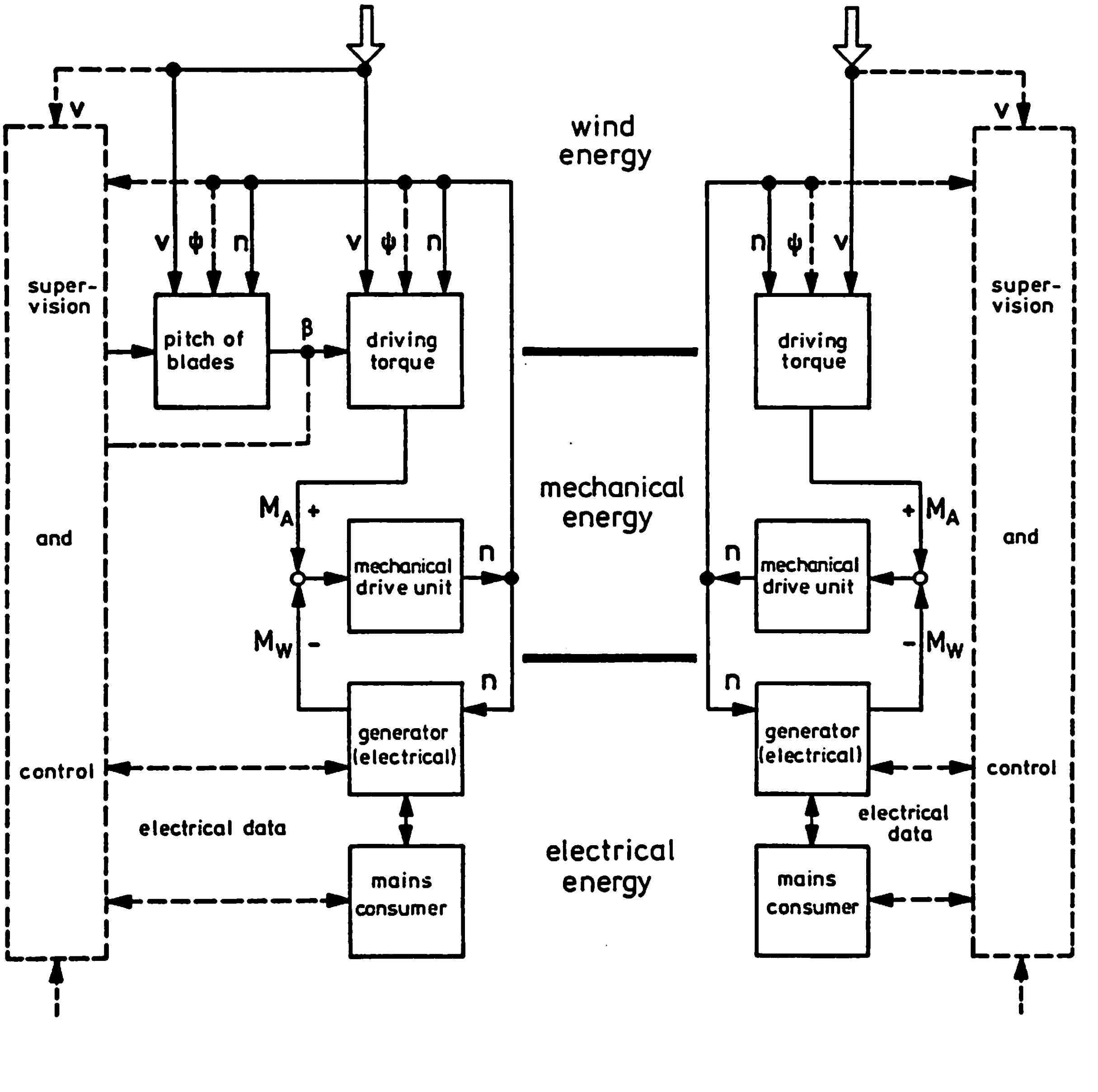


Figure 2: Functional structure of wind energy converters

- M_A driving torque of wind turbine
- M_W braking torque of generator
- ψ position of rotor blades
- n rotation speed
- v wind speed (velocity)
- β pitch of rotor blades

Influencing the turbine for reasons of the consumer are not easy to accomplish at plants with stall operation. As controlled speeding up of the turbine at such plants is not possible, the start-up has to be done mechanically by the generator. In contrast to plants with blade pitch control, plants with turbines with stall operation generally need generators with a considerably higher power to guarantee a strong speed coupling with the grid. The generator has an important influence on the operational behaviour of a wind energy converter.

3 Generators

For mechanic-electrical energy conversion of wind energy converters, three phase machines are used because of their stable construction. These generators (figure 3) are prinicipally differentiated into

- asynchronous and
- synchronous generators

with

- direct grid connection as well as
- current converter coupling

for supplies with

- three phase current and
- direct current.

Furthermore, asynchronous generators can be classified as

- cage rotor and
- slip ring machines.

Finally, synchronous machines can be divided up into generators with

- excitation unit with
    - self-excited, brushless or
    - slip ring input version or with
- permanent magnet excitation.

The power suppliers demand close tolerance limits relating to frequency, voltage and harmonics that can be achieved by different measures depending on the model version.

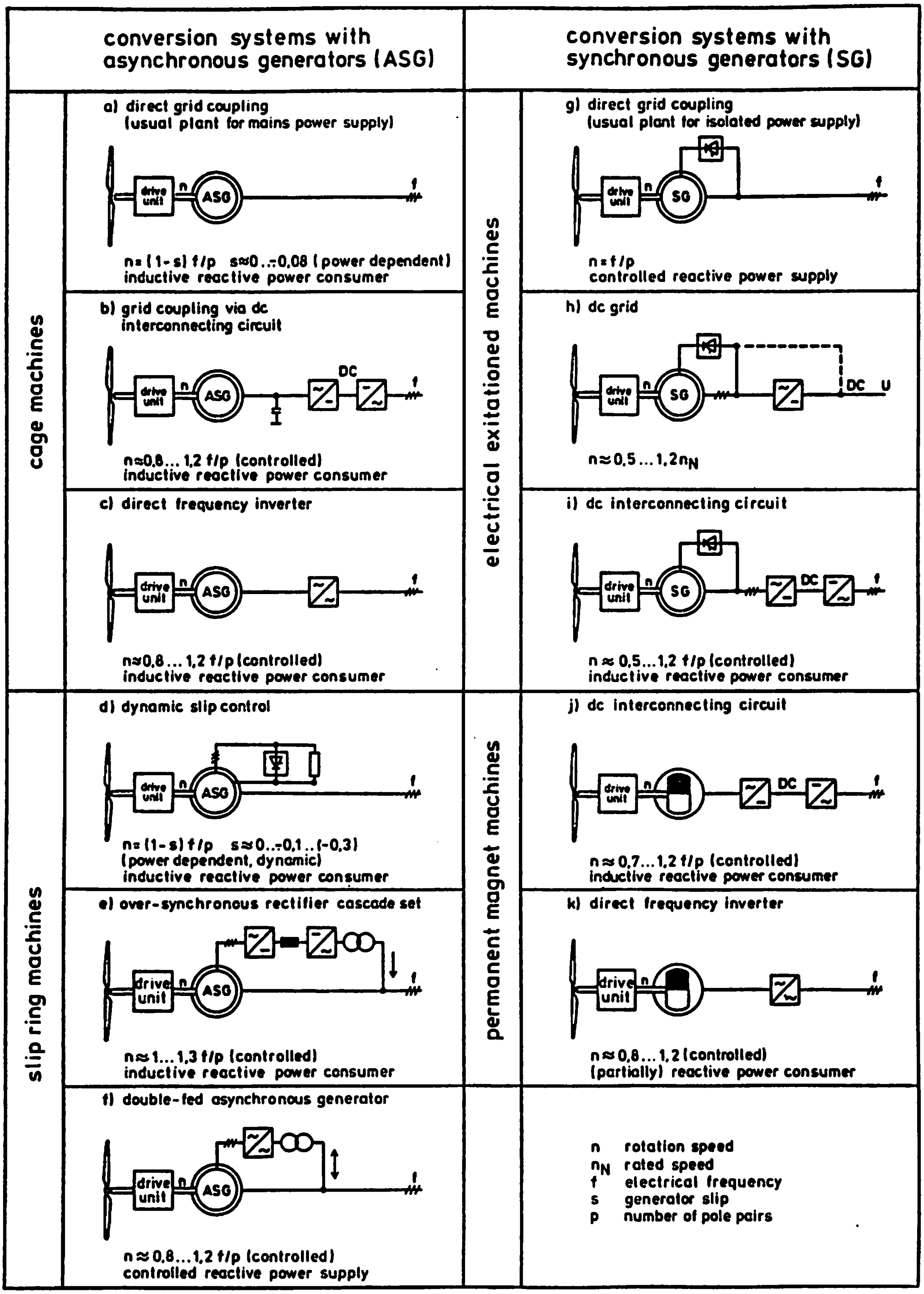


Figure 3: Converter Systems

4 Conceptional differences and their effects on the operational behaviour in grid operation

Public mains have to be protected from disturbing influences of feeding in electrical energy from wind energy converters. Protection against short circuits and protection for the generator have to be present. The mains has to be disconnected in the very moment when voltage and frequency limits are exceeded. Motor operation of the wind energy converter may only be used for a short time. The reactive performance requirement has to be held in grid specific power factor limits. The switch-on current of the generator should be kept as low as possible to protect on the one hand, the components of the wind energy converter such as the electrical switchgear, the mechanical drive unit and the wind wheel from the high impulse loads, and, on the other hand, to avoid mains voltage failure.

For mechanic-electrical energy conversion at wind plants - as already mentioned above - synchronous and asynchronous generators are used. To avoid overloading, the power input of the turbine has to be limited actively by blade pitch control or passively by using a construction for stalling. Concerning the mains connection, power-up devices as well as synchronization equipment is used.

Synchronous and asynchronous generators with direct grid connection are largely fixed grid couplings (see fig. 3a, g). So far asynchronous generators have been used for wind energy plants in the 10 to 1000 kW range with direct grid coupling due to their simple construction, their stability and their power speed flexibility at the lower end of the range. Synchronous generators have only been used in a few special cases at big plants with direct grid connection.

Besides the varying wind speeds and gusts, considerable air flow disturbances (e.g., near the tower) have a strong effect on the rotating blades. These result in periodical and non-periodical turbine power fluctuations.

In spite of the quick reaction of the control equipment and the blades to these performance changes, the power fluctuations of the wind wheel (e.g., caused by the tower shadow) cannot be corrected. Both the fixed speed couplings of synchronous generators and the low speed variations which are due to small slip values at big asynchronous generators consequently cause rather considerable power variations. Accordingly, the load on the mechanical and electrical components is big. Asynchronous generators of the usual type only generate approx. 2 % rated slip at 20 kW rated power. Larger machines have lower slip values (200 kW approx. 1 %).

However, by employing asynchronous generators with a higher rated slip, fluctuations of the electrical output power can be markedly decreased. Yet, this results in bigger losses in operation. But through power smoothing the stress on plant components can be decreased.

When there is a fixed mechanical coupling between the wind wheel and the generator, speed changing operation at the mains input is made possible by using a frequency converter. Besides, it is possible to convert the electrical energy total (see fig. 3c, h, i, j and k), or partly (e.g. 20 %), according to e and f, and it can be fed into the mains, or, according to version d, it can be led away in the form of losses. The systems b, e and f were only built in special cases and have been successfully tested.

Because of the development in current converter technology, systems with a synchronous generator, rectifier, dc-intermediate circuit and inverter (figure 3i) have turned out to be successful in the 20 to 1000 kW range and have shown excellent test results in the last few years. Apart from the advantages of smoothing the output power, and besides the relief of the energy transfer process, both the power optimal operation ranges can be run and the blade pitch processes can be reduced by using different speeds. Furthermore, these speed variations mean that the wind wheel performance of stall operated plants can be controlled, and, thus, parallel operation of wind plants is facilitated.

By using speed variable couplings between wind wheel and electrical consumer (grid) a lot of advantages can be attained in comparison to a nearly fixed coupling (e.g., asynchronous machine with low slip or synchronous generator). These advantages include:

- smoothing of the electrical output by short term storage of energy in kinetic form (using the rotating masses like a fly wheel storage)
- adjustment of the rotor speed favourably for the power gain
- relief of the mechanical power transfer by decreasing the dynamic loads (change to higher speed in gusts)
- by using speed variations the number and speed of blade pitch processes and thus the mechanical stresses can be kept low, and favourable torque-speed-characteristics can be achieved
- facilitation of parallel operation of wind energy converters by decoupling the dynamic processes on the electrical side of energy converter systems.

The integration of wind energy converters in the electrical mains produces a number of notable interactions. Concerning this the following points have to be observed:

- general compatibility,
- possible changes of short circuit power in relation to the optimal power,
- voltage variations with possible flicker effects,
- voltage asymmetries,
- harmonics,
- intermediate harmonics,
- disturbance emission.

4.1 Power fluctuations

Measurements from "Windpark Westküste" have demonstrated that a combination of several plants with considerably different power output variations will result in power smoothing when the number of plants is increased. Fig. 4c and d show that the smoothing effects of the total power of all plants operating at either a fixed or variable rotational speed is dependent on the number of plants. In both cases the power output was measured at the corresponding transformers.

Further tests have demonstrated that big power fluctuations are to be found especially

- below the rated operation, mostly in
- rows of plants positioned down-wind.

However, in both the lower partial load range and in the rated load range only small power variations occur. By adding together the synchronically measured individual performances in such a way as in fig. 5 below, the sums of the individual performances may be shown on the x-axis, the wind velocity on the y-axis and the power on the z-axis. During a test timing of one minute, the graph shows

- fluctuation ranges with
  - maximum and miminum values as a total range, with
  - standard divergence characterized by the dotted fields and with the
- average values characterized by a thick line in the interior field.

Figure 5 shows the strong smoothing effects of the output power, particularly in high speed wind ranges. Furthermore, it can be seen clearly that with an interconnection of 5 wind energy converters only a slight power fluctuation is to be expected. Therefore voltage variations, voltage asymmetries and disturbance emissions will be less significant.

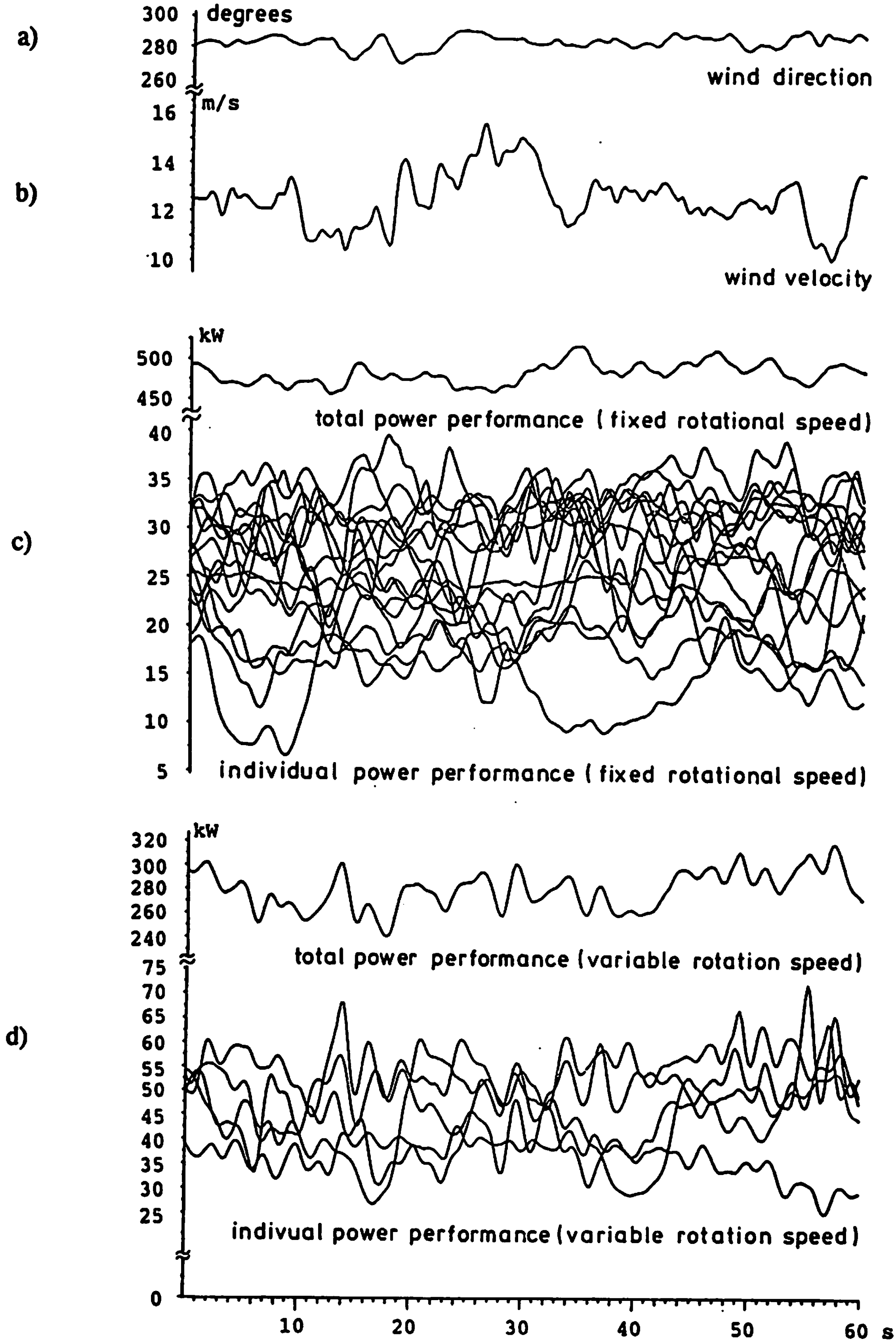


Figure 4: Measurements from the Windpark Westküste.
a) wind direction
b) wind velocity
c) total and individual power performance with a fixed rotational speed
d) total and individual power performance with variable rotational speed

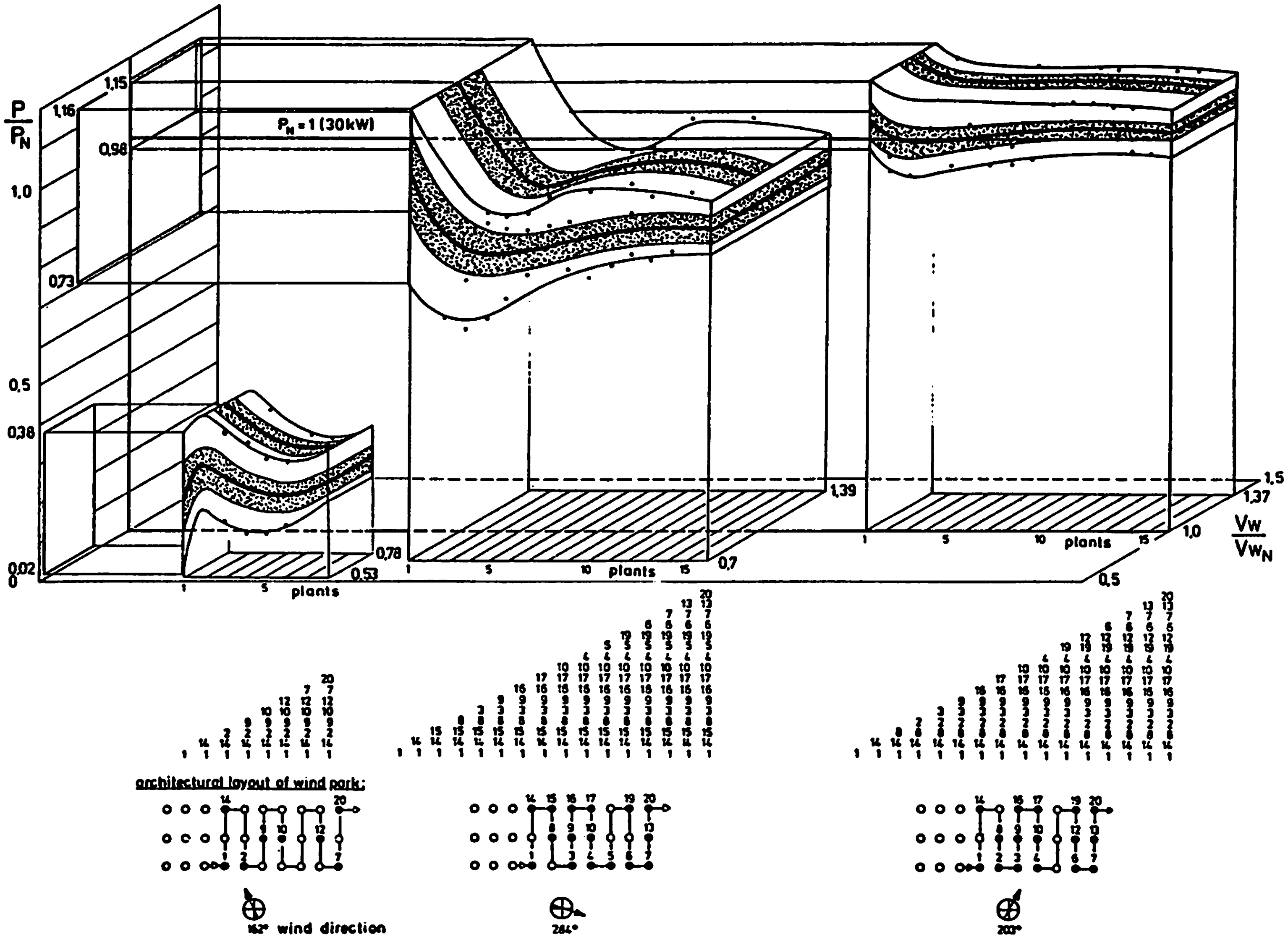
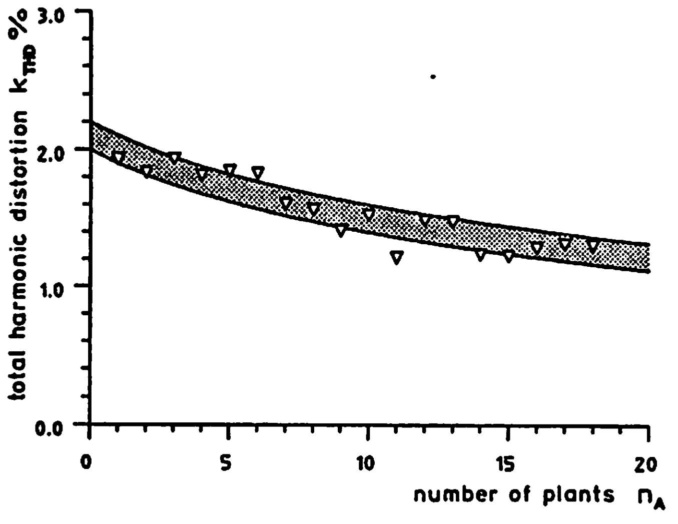


Figure 5: Power smoothing with maximum and minimum values, standard divergence and average values in different wind speed ranges with power summed up line by line in Windpark Westküste

4.2 Harmonics

However, harmonics and intermediate harmonics generate big variations with different converter systems. These are shown by means of the distortion factor in figure 6.

a)



b)

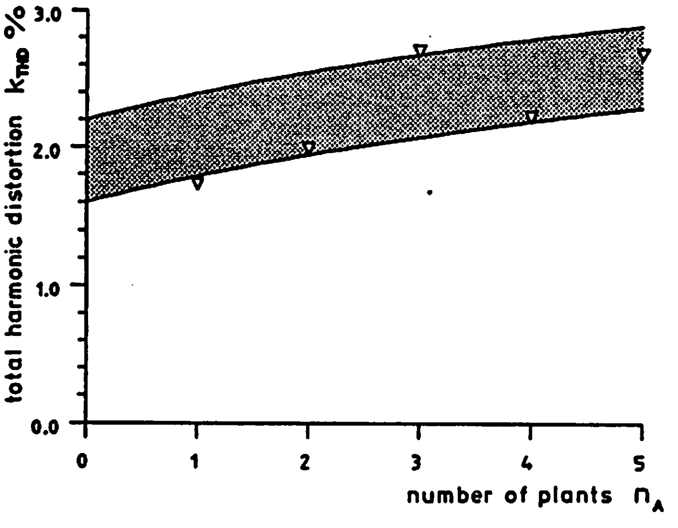


Figure 6: Total Harmonic Distortion k_{THD} dependent on the number of wind energy converters n_A at

a) asynchronous generators directly connected to the grid
b) synchronous generators connected to the grid via rectifier, dc circuit and inverter.

Asynchronous generators which are directly connected to the grid hardly produce grid influences (see figure 6a) even if their number is increased. Harmonics and intermediate harmonics will even be partially damped down.

In contrast figure 6b demonstrates quite clearly that the grid influences increase when the number of plants which feed into the grid via an inverter increases too.

Because of the increased short circuit power significantly lower grid influences will result from the combination of wind energy converters that feed (via inverters) into the grid with turbines that have asynchronous generators directly coupled to the grid.

In grids with weak power and high wind energy input particularly big grid influences are to be expected. However, practical tests have shown that wind energy inputs are possible even up to 100 % of the input by using special constructions of the grid and its components. Grid influences can be avoided by taking suitable measures to influence the grid characteristics by using phase shifters, battery storages with inverters, grid filters, compensation units and grid controllers.

4.3 Grid resonances

If the grid is considered from the connecting point of a wind park, the total impedance of the configuration is decisive for the behaviour when feeding in. The total impedance results from the combination of ohmic resistors, inductances and capacities at the input, the distribution and consumer system. Depending on the number of single elements, their connection and the size of their impedances, resonant frequencies occur in the part of the grid under consideration. When the resonant frequency is excited this may cause current and voltage overloads in the connected components.

By means of an equivalent circuit, the impedance graph for the connecting point of the harmonic sources can be calculated and reproduced for relevant harmonics. A comparison of the measurements has shown that the results correspond very well. Figure 7 shows the simulation of the network impedance in Windpark Westküste with a varying number of grid connected plants.

This diagram displays impedance variations and resonance shiftings with a varying number of grid-connected plants. Such tests enable us at an early stage in the design to identify critical conditions which are caused by current or voltage resonances. Thus, by chosing the right grid connection or by taking measures when the grid is working at full capacity, a safe operation of wind energy plants can be guaranteed without major grid disturbances.

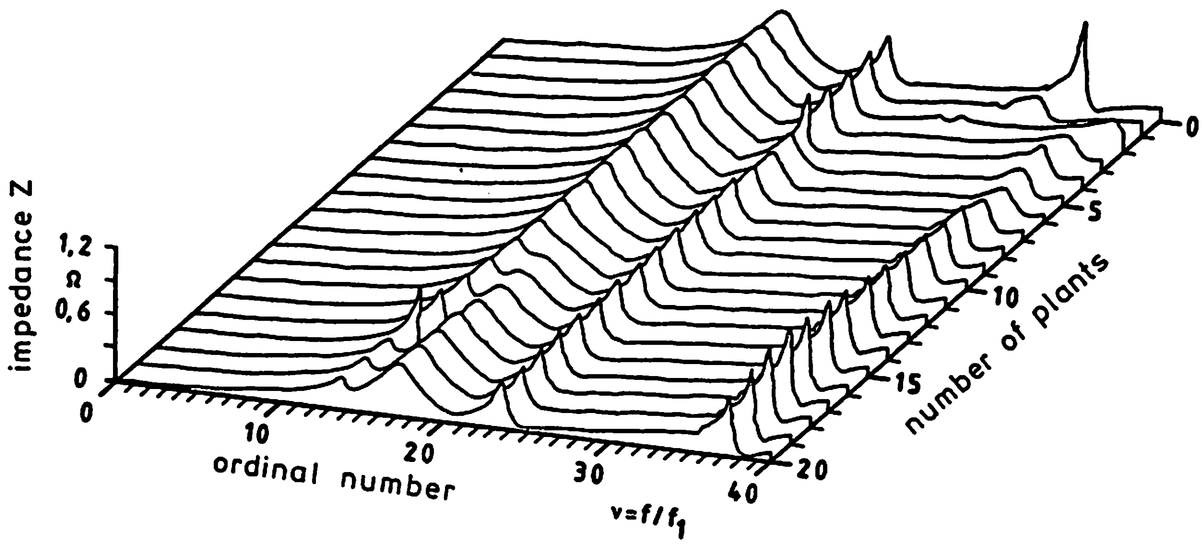


Figure 7: Simulation of the network impedance in Windpark Westküste depending on the ordinal number ν, and the number of plants (0 to 20 plants each at 30 kW)

SYNCHRONOUS MACHINE WITH RECTIFIER FOR WIND TURBINES

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Delft University of Technology

SUMMARY

Before going into recent developments with respect to the synchronous machine with rectifier for wind-energy conversion systems, a short explanation is given of the choice for a variable or a constant-speed system and of the choice for a synchronous machine with rectifier in particular.

The research in the Netherlands was initially directed towards the steady-state behaviour of the synchronous machine with rectifier: its theoretical description and the first experiments with this system in a small wind turbine (30 kW) have run parallel to each other and have been completed succesfully.

However, in these experiments (using a diode rectifier) instabilities sometimes occurred, for which a practical solution was found. Because this solution is only proper for smaller systems and since the cause of the phenomenon was not clear yet, research was further directed towards dynamic behaviour, first using network simulations with a detailed model. However, this model demands much computer-time and it is not very suitable for an integrated model of a complete wind turbine.

The simple model developed later on, which is also suitable for a thyristor rectifier, meets these difficulties, but can not be used for the calculation of very quick phenomena. However, simulations with this model have yielded important results with respect to stability and control behaviour. In order to determine the machine parameters which are necessary for this model a practical measuring method has been developed.

The present investigation within the research group is directed towards the modelling of the brushless exciter and the extension of the simple model with saturation.

INTRODUCTION

A constant or a variable speed

Before going into recent developments with respect to the synchronous machine with rectifier for wind-energy conversion systems, it may be useful to explain briefly the choice of the system which converts the mechanical (rotating shaft) into electrical energy. A choice can be made between systems with a (nearly) constant and systems with a variable speed.

On the average, a variable-speed system will be more complex and more expensive than a constant-speed system. On the other hand, the important advantages of the variable-speed system are that the wind turbine can be optimally loaded (for energy output), that torque shocks (particularly those resulting from disturbances of the utility-grid) in the mechanical transmission can be limited by a good torque control (cheaper and lighter transmission, and yet a long life) and that it is possible to store kinetic energy in the rotor, which reduces short-term fluctuations (resulting from wind-speed variations) in the shaft torque and in the electrical power. Moreover, in some places it can be important to make the wind turbine work at a reduced speed at night, in view of noise pollution. Finally, the natural smooth switch-on behaviour of most variable-speed systems may be mentioned as an advantage.

The synchronous machine with a dc link as variable-speed system

Once the choice has been made for a variable-speed system, the choice of systems still remains large. The Electromechanics and Power Electronics group of the Eindhoven University of Technology has chosen for a synchronous machine with dc link already at an early stage [1]. This electromechanical conversion system is a cascade connection of a synchronous machine, a rectifier, a choke and an inverter, as indicated in figure 1.
Furthermore, synchronous machines are usually made brushless, which means that there are no sliprings (or commutator) and no brushes. Since brush-slipring combinations require relatively much maintenance and since their functioning largely depends on atmospheric circumstances, this is an important fact for the choice of a variable-speed system for wind turbines.

An important advantage of this system compared to other variable-speed systems is its very high efficiency. In practice, however, it appeared that the use of synchronous machines in wind turbines also has an unexpected disadvantage. In

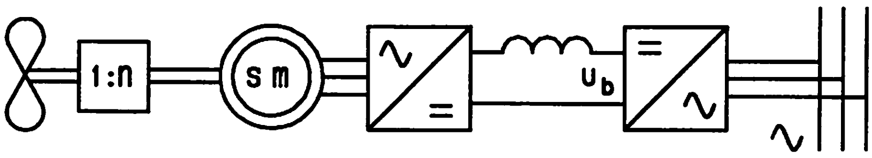

Figure 1 The synchronous machine with dc link in a wind-energy conversion system

view of the very quick ageing of the insulation (mainly by moisture), its quality has to comply with very strict requirements. Consideration must even be given to use only closed (expensive) machines in wind turbines.

In this contribution, a review is given of the recent developments (more or less chronologically) and the current views in the Netherlands with respect to the synchronous machine with rectifier.

THE STEADY-STATE BEHAVIOUR

The first plans for a system with a synchronous machine (30kVA) with rectifier were still based on a rather simple, steady-state model of the synchronous machine, in which for example the losses were neglected. It appeared from a comparison of the characteristics calculated with this simple model with the characteristics measured during the experiments carried out in the laboratory in Eindhoven in 1982, that this model is quite satisfactory for this small system. Furthermore, it appeared from the test of the system in a wind turbine on the test field of the Netherlands Energy Research Foundation (ECN) in Petten, that with a changing of the wind speed the conversion system continued to follow the steady-state characteristic: apparently, the electrical transients pass off rather quickly compared to the mechanical.

From this, the conclusion could be drawn that for this small system the simple steady-state model could be used. Apart from that, it appeared from tests on the test field that the system came up to the expectations.

Later on, a more extensive calculating method for the steady-state behaviour of the synchronous machine with rectifier was developed [2]. With this, it is possible to calculate for example voltage and current curves in detail. Once these are known, the extra losses that occur at the loading of a synchronous machine with rectifier, can be further determined. From this kind of loss determinations it has appeared that with the right machine and a slight overdimensioning (10 %)

the extra losses should not cause any problems.

THE DYNAMIC BEHAVIOUR

The first problems

In 1982, it already appeared that the examination of the steady- state behaviour of the system only, was insufficient. It was found in laboratory tests that the system was sometimes unstable: it started oscillating spontaneously. Although at first this phenomenon was not understood, a solution was yet found: by supplying the excitation winding from a current source instead of a voltage source, the order of the system could be lowered by one. This made the unstable behaviour disappear.

Through literature search it was discovered that the phenomenon was already known and that Auinger and Nagel had tried to explain it [3]. At a later stage, Ernst wrote about these problems as well [4].

A synchronous machine without damper windings

The solution that had been found (a current source instead of a voltage source excitation) can - for practical reasons - only be applied in smaller machines. This meant that for example another solution had to be found for the synchronous machines with rectifiers for the SEP wind-park in the Province of Friesland. Since the phenomenon was still not fully understood, this was not simple. The idea was suggested then to make the synchronous machine without the usual damper windings. This would slow down the commutation in the rectifier, which, in turn, would have a favourable effect on its stability.

Since in such big machines (300 kW) the behaviour can not be determined by simple experiment, it was further examined by means of simulation. To this end, a network-model was made of the system, which was then used in a network simulation programme.

It appeared from these simulations that the power supply of the excitation winding of the machine without damper windings would have to satisfy unfeasably high requirements. Partly because of the pressure of time a choice was made for a slightly more expensive thyristor instead of a diode rectifier for the SEP wind-park, which makes the system better controllable. Looking back, this seems a very good choice.

A detailed model

The developments in the field of the machine without damper windings have not really contributed to the understanding of - and with that may be a solution for - the instabilities. In order to be able to explain the behaviour of the system further, research was first directed towards the finding of a suitable model of the system.

The development of a new equivalent circuit of the synchronous machine has played a very important part in this. With this circuit a network model can simply be made of the synchronous machine (with damper windings) with rectifier, which is suitable for detailed simulations by means of a network simulation programme [5]. With this, one can for example also examine the states of the rectifier, which is important in case of disturbances.

A simple model

Disadvantages of the detailed network model are that simulations with it are very time-consuming, and that it is not directly suitable for the designing of control systems: it is practically unusable for an integrated model of a complete wind turbine. Therefore, a simple model of the synchronous machine with rectifier - based on the forementioned new equivalent circuit of the synchronous machine - has been developed, which does not have these disadvantages. However, this model can not be used for the calculation of very fast transients (some milli seconds).

In case a diode-bridge rectifier is used, the calculation results with the simple model have been compared to the results with the detailed model [6]. Their identity, apart from the very quick phenomena (like the ripple on the direct current) appeared to be good.

A description of the simple model, in case a controllable thyristor rectifier is used, is given in [7] and [8].

Some results

With the simple model, the first experiences with the dynamic behaviour of the synchronous machine with rectifier (diode bridge) can be simply simulated. The results of such a simulation can be found in figure 2. The synchronous machine was here driven by a direct current motor, which made its speed rather constant. If the system is excited by a slight voltage drop (U_b: -2.5 %) in the direct current circuit (see figure 1 and figure 2a) we can observe that the system is susceptible to oscillations (figure 2b). At a somewhat lower excitation voltage (U_F=0.7V instead of U_F=1V) the system appears to get even unstable (figure 2c). If the resistance of the excitation winding is now increased by means of an external resistance by a factor 100 with a simultaneous increase of the excitation voltage by the same factor (U_F=70V and R_F=0.46Ω instead of U_F=0.7V and R_F=4.6mΩ), the steady-state excitation current remains the same, but the system gets much more quiet (figure 2d). The power supply of the excitation winding has now got a current source character.

In the machine which was used during the first experiments, it was possible to realize a current character by means of the brushless exciter; however, this can not be done with all brushless synchronous machines. Yet if the diode bridge is replaced by a thyristor bridge which is controlled by a (not yet optimized, proportional) current regulator, excellent results can be obtained (figure 2e).

With bigger systems it is different. As an example a wind-turbine system with a synchronous machine of 375 KVA is used here according to [7]. Moreover, it is supposed that the mechanical transmission between the turbine itself and the generator is infinitely stiff. The simulations were based on excitation by means of a drop in dc voltage by 2.5 % (figure 3a). The system is again susceptible to oscillations, but it is stable (figure 3b). If the excitation winding is now supplied from a current-source-like power supply, the oscillation will disappear, but the response at the small voltage drop is relatively violent (figure 3c). Generally, this phenomenon is stronger in bigger machines than in smaller, because the time constants of the damper windings in bigger machines are usually greater than in smaller ones. This implicates that in bigger systems one has to turn soon to a thyristor rectifier with control system (figure 3d).

For brevity, the simulation results for the generator shaft torque have not been described. Anyway, these are very much the same as those for the direct current.

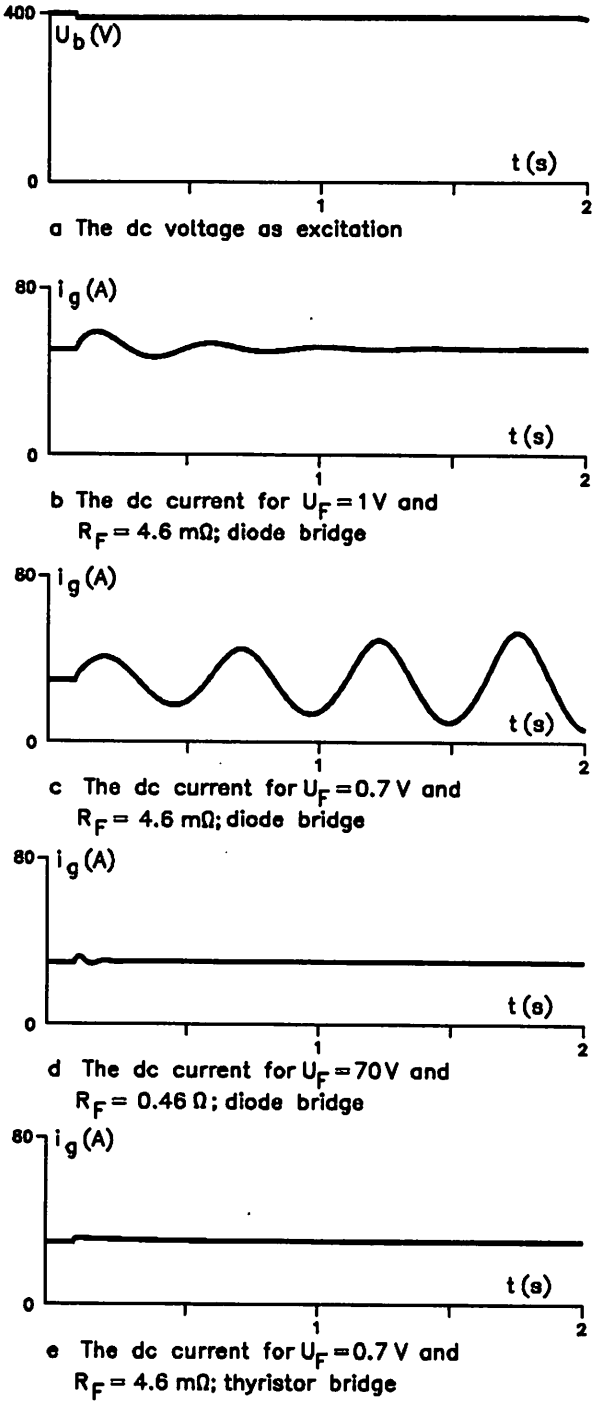

Figure 2 The synchronous machine (30 kVA) driven by a direct current machine

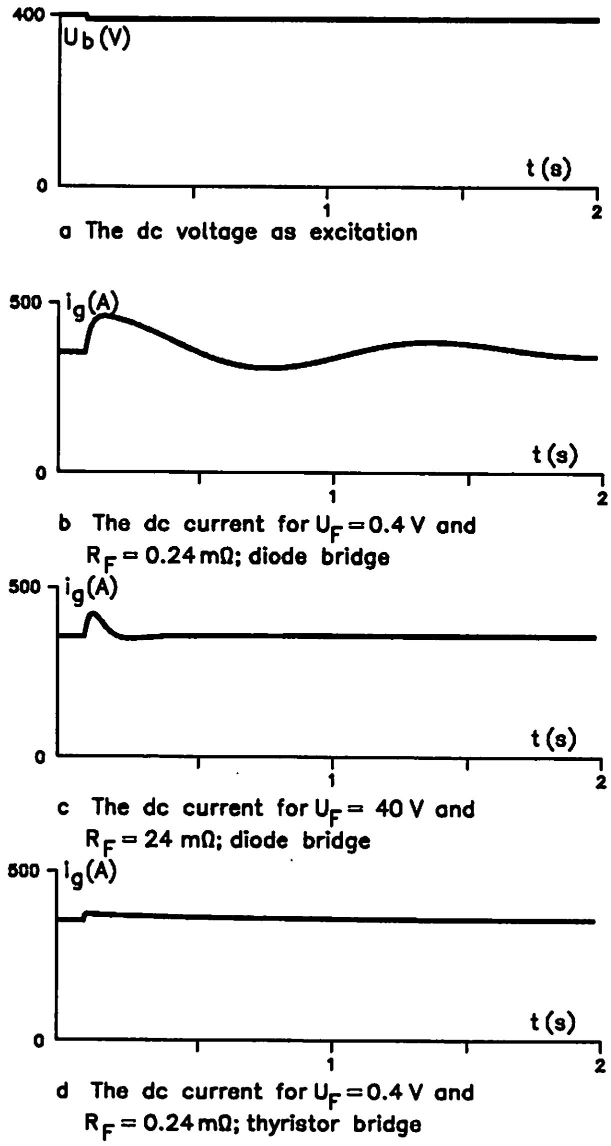

Figure 3 The synchronous machine (375 kVA) in a wind turbine

The experimental verification of the simple model

Before the simple model could be verified experimentally, its parameters had to be known. However, very little was yet known about the determination of the parameters of a synchronous machine which is loaded with a rectifier in particular. That is why a determination method has been developed which is easy to use in practice and is based on modern parameter estimation techniques.

This has been done first for the quadrature axis of the machine [9] and later for the direct axis [10,11]. With the latter, the problem occurred that the usual modelling with one damper winding was inadequate for the machine used in the experiments. This problem has been solved by adding one extra damper winding to the simple model. After that, the verification experiments have gone successfully [11].

Present and future research

The present research is directed towards the extension of the simple model with saturation [12] and the modelling of the brushless exciter. Then the thus created complete model is verified as part of the IRFLET project. This verification will take place at the Netherlands Energy Research Foundation (ECN). Moreover, the control of the complete wind-energy conversion system is also worked upon in the IRFLET project.

CONCLUSION

A verified simple model of the synchronous machine with rectifier is available and a practical estimation technique for the machine parameters has been developed. The model, which has been based on a new equivalent circuit of the synchronous machine, is very useful for control purposes.

It appears from the simulation results shown that in many cases a controllable thyristor rectifier should be preferred to a non-controllable diode rectifier.

Furthermore, it has appeared that a practically realizable system of 300 kW (375kVA) can be stable, which is not in line with the expectations in [3], and that in general the use of steady-state torque speed characteristics of the synchronous machine with rectifier for examination of the mechanical part of the wind turbine is not useful [7].

Thanks to the adequate dynamic and the adequate steady-state behaviour of the synchronous machine with (controllable) rectifier, this system is very suitable for the use in wind turbines. Attention must however be paid to the insulation of the machine.

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Summary of contribution by N. Jenkins, Wind Energy Group Ltd, UK

Electrical Variable Speed Operation of Horizontal Axis Wind Turbine Generators.

Experience gained in operating the WEG MS-1 prototype 20 metre diameter, 250 kW rated wind turbine in variable speed mode was reviewed [1]. The electrical variable speed equipment consisted of a synchronous generator, rectifier, d.c. link and 6 pulse line commutated inverter. The electrical control schematic is shown in Figure 1. A pre-determined power/rotor speed characteristic was held in the controller and used to maintain optimum tip speed ratio up to the maximum speed of the rotor. Although all equipment worked correctly the resulting overall performance of the wind turbine was disappointing in variable speed mode when compared with fixed speed operation e.g.:-

- A power factor of 0.72 compared with 0.97 for fixed speed operation
- Significant losses in the power conditioning equipment
- A power curve below that of fixed speed operation for windspeeds greater than 10 m/s (see Figure 2)
- Harmonic disturbance of the public telephone network.

Following this experiment a study [2] was undertaken to attempt to establish the cost effectiveness of wind turbines designed to use electrical variable speed equipment. Benefits which were quantified were:-

- increased energy capture due to higher average aerodynamic efficiency and lower cut in windspeed.

- reduction in gearbox cost due to reduced torque fluctuations.

Disadvantages which were quantified included:-

- increased losses due to frequency conversion equipment
- changes in structural cost due to any increase in maximum rotor speed
- capital cost of the variable speed electrical equipment.

A number of additional benefits and disadvantages were discussed but not quantified. These included:-

- reduced noise at low wind speeds
- the possibility of using the same wind turbine design effectively at sites with rather different mean wind speeds
- a possible reduction in reliability due to increased complexity
- generation of undesirable harmonics.

The study considered two cases of 250 kW and 2.4 MW rating and showed that the break even cost for the additional equipment for electrical variable speed operation was approximately 10% of the total installed cost of the wind turbine.

This encouraging result stimulated a further study to address the engineering issues of constructing a cost effective electrical variable speed wind turbine. This work is now in progress with attention, at present, focusing on the type of variable speed drive equipment to be used.

A particular problem for the application of electrical variable speed wind turbines to UK windfarms is that the electrical networks to which they will be connected have low fault levels. Therefore, the inevitable characteristic harmonic currents created by line commutated inverters will create significant, possibly unacceptable, harmonic voltages. Additional filtering equipment is likely to be required to ensure compliance with national standards of voltage quality. To avoid this problem and to allow control of the power factor advanced synthesised sine wave inverters are being considered for the connection of the wind turbines to the network.

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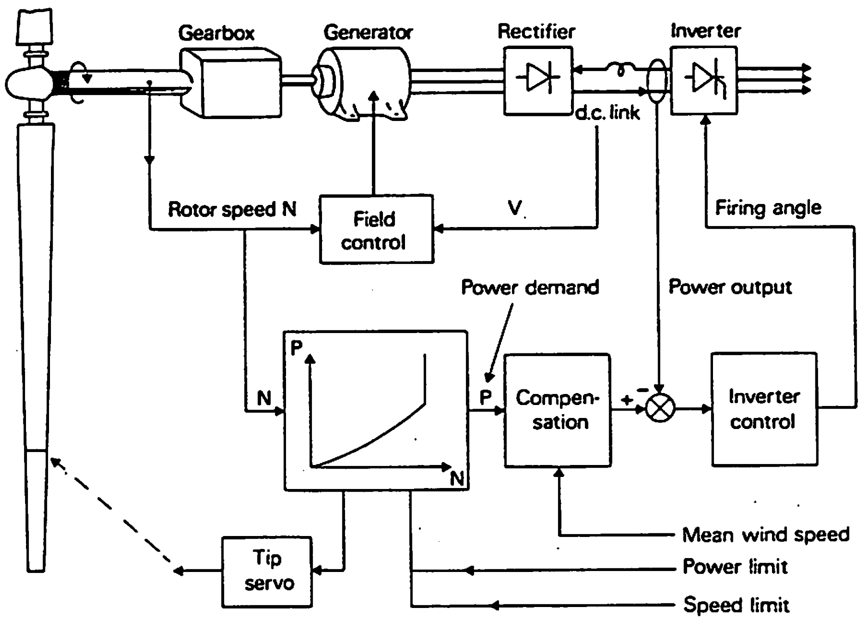


Figure 1 WEG MS-1 Control Scheme (Variable Speed)

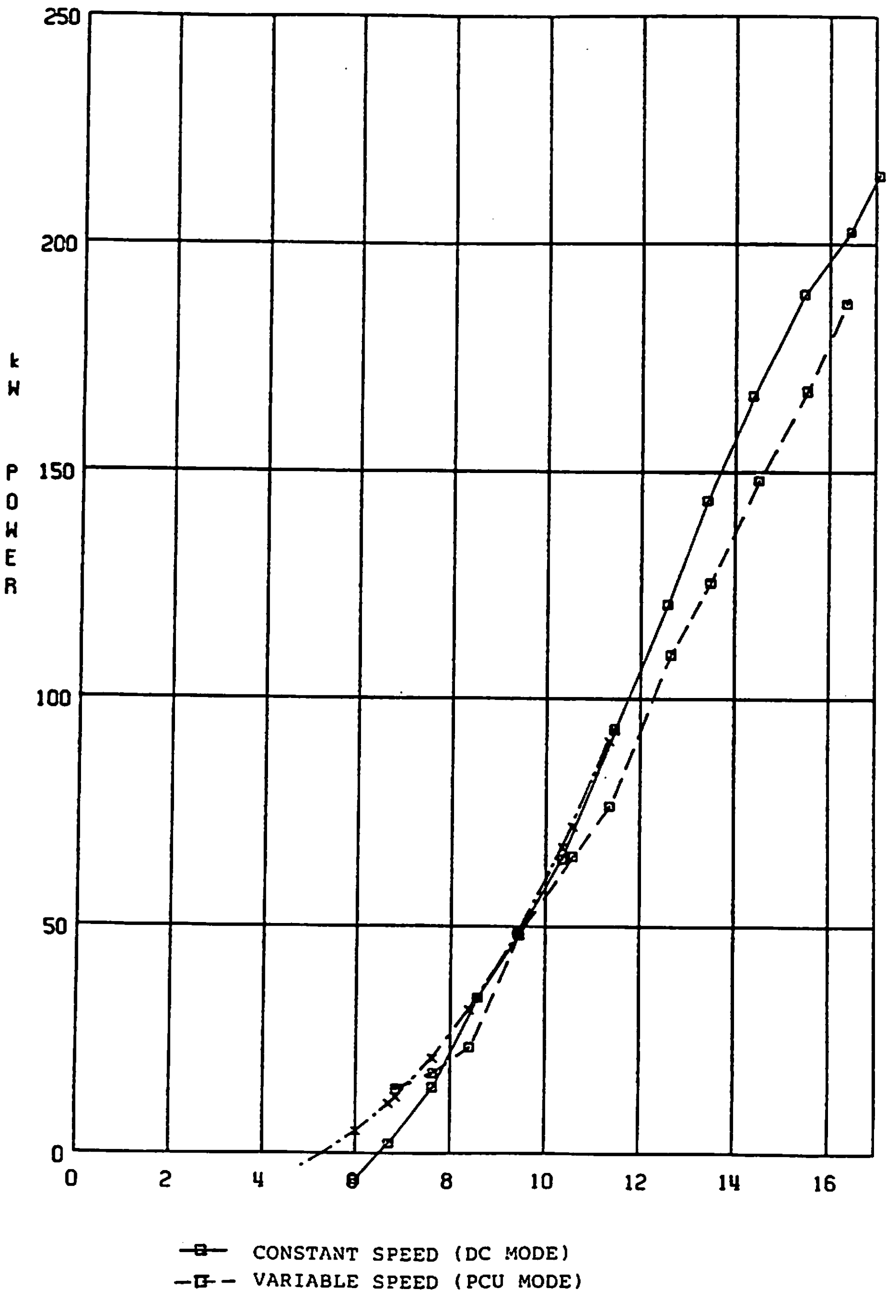


Figure 2 WEG MS-1 Power Curves

A VARIABLE SPEED SYSTEM WITH INTEGRAL CONTROL FOR WIND TURBINES (IRFLET): Design of the test-rig.

J.T.G. Pierik [1] M.J. Hoeijmakers [2] J.M. Vleeshouwers [2]
T.G. van Engelen [1] C.W.A. Baltus [1] A.T. Veltman [1]
A. Warmenhoven [1]

ABSTRACT

Previous research has shown that a variable speed electrical system with a brushless synchronous generator and a DC-link is a promising option for large and more advanced flexible wind turbines. It has also been shown that vibrations in the mechanical transmission, which are often observed in variable speed wind turbines, can be reduced by the use of a well designed controller. Prior to applying this new controller, the model used for the controller design has to be verified and the controller has to be tested in practice. Therefore a test-rig of the system has been designed and realized, using a DC-motor to simulate the wind turbine. A flywheel and a flexible shaft are part of the test-rig to obtain the same oscillatory behaviour as in the actual wind turbine. The controller is implemented on a process computer in a shell programme which performs all control and safeguard actions necessary in wind turbines.

This contribution contains the description of the test-rig and the integral controller. Implementation of grid faults and firing failure of the thyristors will also be discussed. This project is funded by the Netherlands Foundation for Energy and the Environment (NOVEM).

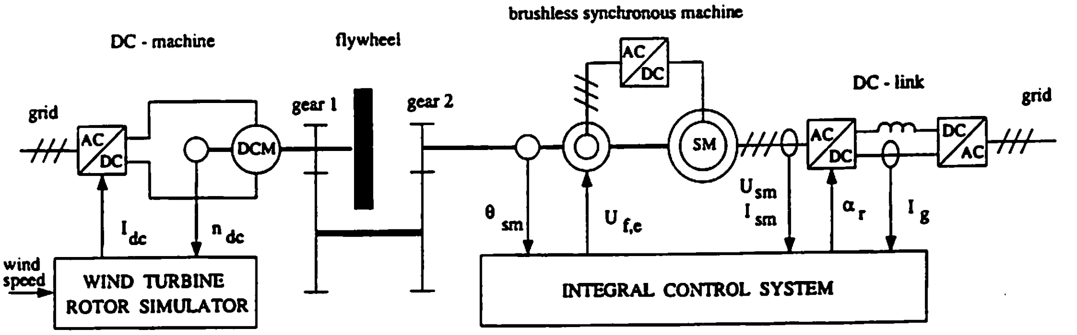
1 INTRODUCTION

The Netherlands Energy Research Foundation (ECN) and Stork Product Engineering (SPE) are executing a research programme named FLEXHAT which aims at the development of components for the next generation of megawatt-scale wind turbines [1]. One of the characteristics of the chosen turbine is power limitation through passive tip control activated by speed variations of the rotor. The variable speed electrical system for the FLEXHAT turbine is designed and tested in a separate project named IRFLET. Based on previous research a brushless synchronous generator with a DC-link was chosen [2]. This system has good control possibilities and the potential of further improvements, for instance the use of self-commutated convertors and a permanent magnet machine.

Variable speed operation of a wind turbine has a number of advantages: the reduction of electric power fluctuations by changes in kinetic energy of the rotor, the potential reduction of fatigue loads on the blades and the mechanical transmission, the possibility to tune the turbine to local conditions by adjusting the control parameters (for instance operation at reduced speed at night) and the relative ease of switching onto the grid. However there are some disadvantages too. The system is more expensive and due to the looser grid connection mechanical vibrations are observed. These vibrations result from excitation of the system at the eigenfrequency of the mechanical system.

The IRFLET project aims at the development of an advanced control system consisting of a process-computer, the controller software, the measurement and interfacing equipment and the control algorithm. The controller will reduce the vibrations by adjusting the torque of the synchronous machine. The control also will protect the system against damage that may occur as a result from grid faults. Furthermore the control of the electrical system aims at maximum energy capture and low control effort. In the near future the control system will be extended to include all control and safeguarding actions for the wind turbine. In the first phase of the IRFLET project a 30 kW laboratory system has been designed and built to test the control system. The controller software has been designed and implemented. In the second phase of the project multivariable feedback loops (the control algorithm) will be designed by the Delft University of Technology (DUT), using a model of the electrical system developed at the Eindhoven University of Technology (EUT) [3]. The model and the controller design will be verified on the test-rig. The design of the test-rig and of the integral control software will now be described.

[1] ECN, P.O.Box 1, 1755 ZG Petten
[2] EUT, P.O. Box 513, 5600 MB Eindhoven



Rotor shaft driving facility

Variable speed system with integral control

Figure 1: The test–rig for the IRFLET variable speed electrical system.

2 DESIGN REQUIREMENTS OF THE INTEGRAL CONTROL SYSTEM AND THE TEST-RIG

Objectives of the integral control are:

- damping of mechanical oscillations;
- optimal tip speed ratio below rated windspeed;
- protection against grid faults or faults in the firing of the line commutated convertor;
- realisation of a low value of the firing angle of the rectifier without loss of control margin;
- relatively low control effort.

The test-rig has been built to meet the following requirements:

- the unloaded mechanical system exhibits an eigenfrequency of about 5 Hz;
- the torque control of the DC-motor is able to simulate the steady state aerodynamic behaviour of a wind turbine;
- measurement equipment is able to detect mechanical oscillation, determine generated electrical power, grid faults or failure of the firing of the line commutated convertor.

3 TEST-RIG COMPONENTS

A schematic representation of the test-rig is given in figure 1. On the right hand side the electrical system with a brushless synchronous generator and a DC-link is shown, together with the integral control system. Of the three possible control parameters two are used: for fast control the firing angle of the rectifier is chosen and slower control is realised by the field voltage of the exciter. The left hand side represents the rotor shaft drive facility consisting of a controlled DC-motor. The DC-motor drives the variable speed system through a gearbox, a flexible shaft and a second gearbox. On the shaft of the DC-motor a flywheel is placed to represent the inertia of the rotor blades. The torsion shaft is designed to give the system an eigenfrequency of about 5 Hz. Measurement showed a frequency of about 3 Hz. The difference is probably due to interaction with the synchronous machine, at the moment of measurement the stator currents had not yet decreased to zero.

4 ROTOR SIMULATOR

The rotor simulator calculates the aerodynamic torque of a chosen wind turbine, using power coefficient data of the turbine. If no hardware flywheel is included in the system to represent the rotor inertia, it can be included in the simulation model. Input to the programme is the measured speed of the test-rig (see figure 2) and a file with a windspeed time series. For passive pitching the pitch angle is calculated from the rotor speed. The output torque is the setpoint for the controller of the DC-machine. The DC-current is controlled by adjusting the firing angle of the rectifier. The field current remains constant so the current control is equivalent to torque control. The programme that calculates the torque setpoint operates on interrupts to be able to synchronise to the time steps on the windspeed file. It includes a controlled start-up procedure for the DC-machine.

5 MEASUREMENTS AND INTERFACE TO PROCESS-COMPUTER

Figure 3 gives an outline of the interface that converts the measurements to inputs for the process-computer and output signals of the computer to control inputs for the system. The measured variables are the rotor position of the synchronous machine, the stator currents and voltages and the

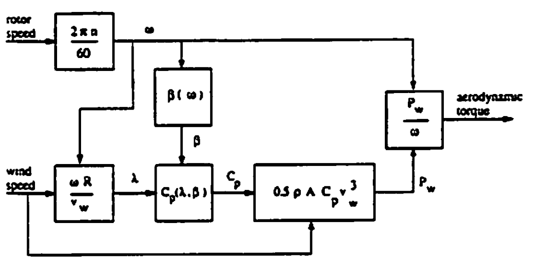


Figure 2: Wind turbine rotor simulator.

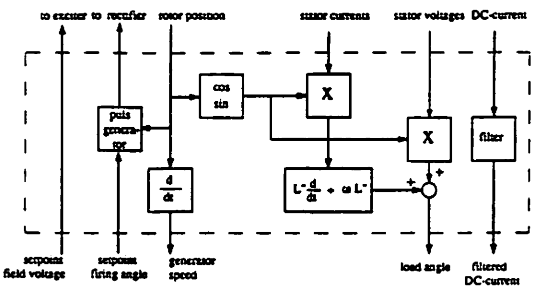


Figure 3: The interface between measurement and control hardware and the process–computer.

DC-current. The outputs of the interface to the process-computer are the angular speed of the synchronous machine, its load angle and the filtered DC-current. The speed measurement has to be highly accurate (about 0.5 % relative error) to detect the mechanical vibrations in the system. It is determined by analogue means from the measured rotor frequency. The load angle of the machine is determined from the rotor angle and the measured stator current and voltage. In the first step the stator currents and voltages are transformed to a reference frame fixed to the rotor. Next the voltage behind the subtransient inductance L" is reconstructed. The internal load angle then equals the angle between this voltage and the quadrature axis of the synchronous machine. The process-computer needs the load angle to calculate the firing angle of the rectifier with respect to the measured rotor position. To find the operating point of the system, the electrical power is determined from the DC-current, which is filtered to eliminate the ripple due to the switching of the thyristors. For protection agains grid failures the value of the DC-current is also passed to the control computer directly. The control algorithm in the process-computer calculates the firing angle and the field voltage of the exciter.

6 INTEGRAL CONTROL SYSTEM

The objectives of the integral control system, as mentioned in section 2, require control actions on different time scales:

- the turbine rotor speed should be adapted to windspeed variations of about 1 Hz for maximum energy capture; this requires periodic control actions with a frequency of 5 up to 10 Hz;
- the control system must act upon torsional vibrations in the order of 5 Hz; this requires periodic control actions with a frequency of 50 up to 100 Hz;
- the inductance of the choke is such that grid faults may result in generator current raising rates of its nominal value per 10 ms; this requires periodic generator current monitoring and safeguarding actions in case of fast current raising with a frequency of 500 up to 1000 Hz.

The application of the control system on a test-rig requires that it must be easy to change control algorithms for different experiments, and that it must be possible to load different controller sets during an experiment and change controller setpoints interactively.

Given these requirements on the integral control system, the main features of the process-computer system are:

- modular hardware, enabling parallel processing;
- user adaptable software, consisting of a fixed shell program and easy changeable, mathematical formulae like, user program modules.

The computer hardware is VME-bus based and consists of I/O-modules for measurement scanning and control signal emission, two parallel operating CPU-boards, a logging terminal (console) and a terminal for on-line user commands. Figure 4 gives the lay-out of the process-computer hard- and software.

On one CPU-board a more or less independently running program is allocated. This program takes care of 1000 Hz data I/O with the test-rig and safeguarding for the effect of grid failure. On the other CPU-board the shell program with embedded user modules is allocated. This program takes care of 100 Hz control and 10 Hz setpoint generation (maximum energy capture) and controller parameter set selection (operating point dependent linear control). Measurement and control signals are exchanged between the two CPU-boards. Setpoints and controller selection parameters are exchanged between the 100 Hz and 10 Hz running program parts on the second CPU-board.

The embedded user modules contain the experiment specific algorithms for 100 Hz control and 10 Hz control mastering. In the 10 Hz module, callable functions are available for operating point dependent controller parameter set selection and data storage on file, while in the 100 Hz module there are functions for execution of linear multivariable controller calculations and also data storage on file.

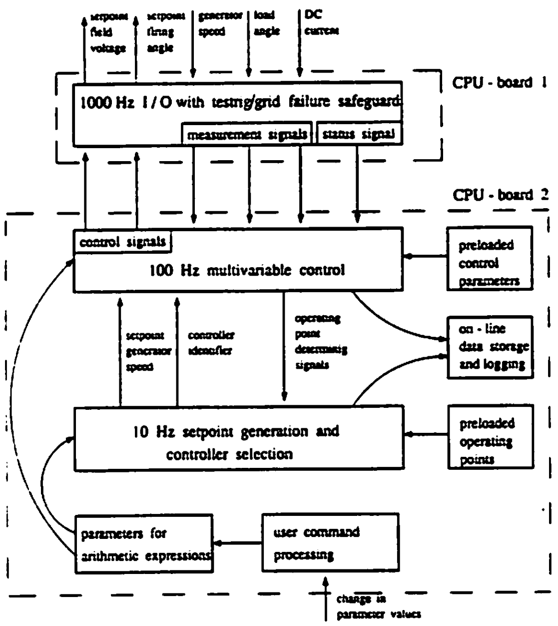


Figure 4: Lay–out of the process–computer hardware and software.

7 GRID FAULTS AND FAILURE OF THE FIRING OF THE THYRISTORS

Recently an inventory of grid voltage fluctuations occurring in a part of the Netherlands energy distribution grid has been made [4], based on a measurement period of 2 years on two locations simultaneously. From these measurements a "typical voltage fluctuation" occurring in a part of the Dutch grid can be defined as:

Δ U/U = -30%, Δ t = 180 ms, frequency = 5/year,

which figures however bear little statistical significance due to the small number of occurrences of fluctuations in the grid.

For measurements of the behaviour of the IRFLET test-rig and of the control system there are two ways of implementing the voltage disturbances: one possibility is by changing of the firing angle of the line commutated DC/AC converter, which causes effects comparable to a three phase voltage fluctuation on the mains grid. This way of control gives the possibility to generate considerable fluctuations in an easy way. Small fluctuations, in random phases on the other hand, can be generated by locally weakening of the grid by means of series inductances and by loading this grid by resistances of high power using a circuit breaker.

A complete grid failure can be caused by short circuiting of the AC side of the line commutated inverter, which also causes the blowing of the grid fuses. Another type of failure is the complete disconnection from the grid. This however is similar to a short circuit situation due to the magnetic energy in the DC-coil causing at least one of the thyristors to fire by the dv/dt induced gate current and so causing a short circuit in the inverter. The integral control system is designed to limit the effect of these failures, as will be verified by experiments.

8 CONCLUSION

A test-rig has been built to implement and test an integral controller for a variable speed electrical system for wind turbines. The software of a two-processor process-computer has been designed and implemented. In the second phase of the project the multivariable control algorithm will be designed and tested on the rig. Experiments to validate the model and the parameters of the electrical system will also be executed.

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A variable speed system with integral control for flexible wind turbines (IRFLET): Design of the test-rig and first results

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M.J. Hoeijmakers, P.M.M. Bongers (TUD)
J.M. Vleeshouwers (TUE)

Contracted by the Netherlands Agency for Energy and the Environment (NOVEM)

- Design of the integral control system for the variable speed electrical system of the FLEXHAT turbine;

- The E-system consists of a synchronous machine and DC-link;

- Control objectives:
  damping of mechanical oscillations in the drive train and reduction of torque fluctuations resulting from electrical faults ;

- Evaluation of the control system on a test-rig for the electrical system;

- Verification of the dynamic model of the system.

COMPONENTS OF THE TEST-RIG:

- Computer controlled DC-machine;

- Mechanical system with two gearboxes, a flexible shaft and a flywheel;

- Brushless synchronous machine with controlled rectifier, choke and grid commutated invertor;

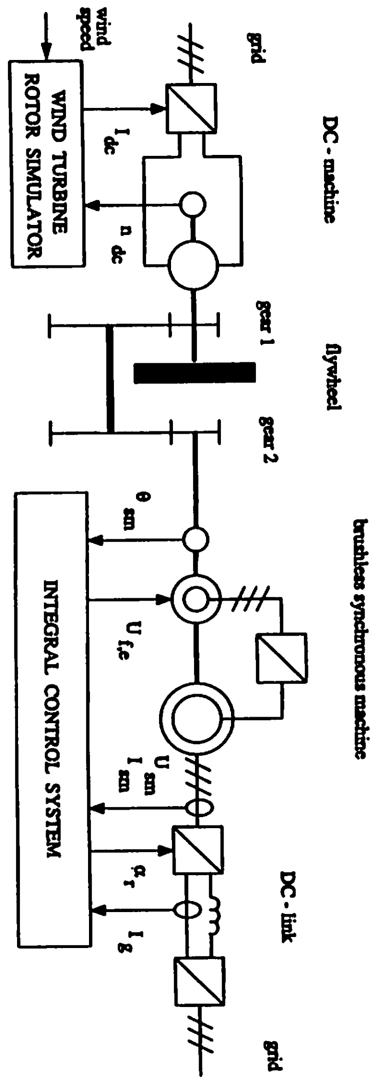
- Measurement equipment for rotor position of synchronous machine, stator voltage and current, DC voltage and current;

- Interfaces between measurements and process computer for determination of speed and load angle of synchronous machine;

- Process computer for 100 Hz control and 1000 Hz safeguard actions and 10 Hz control parameter adjustment;

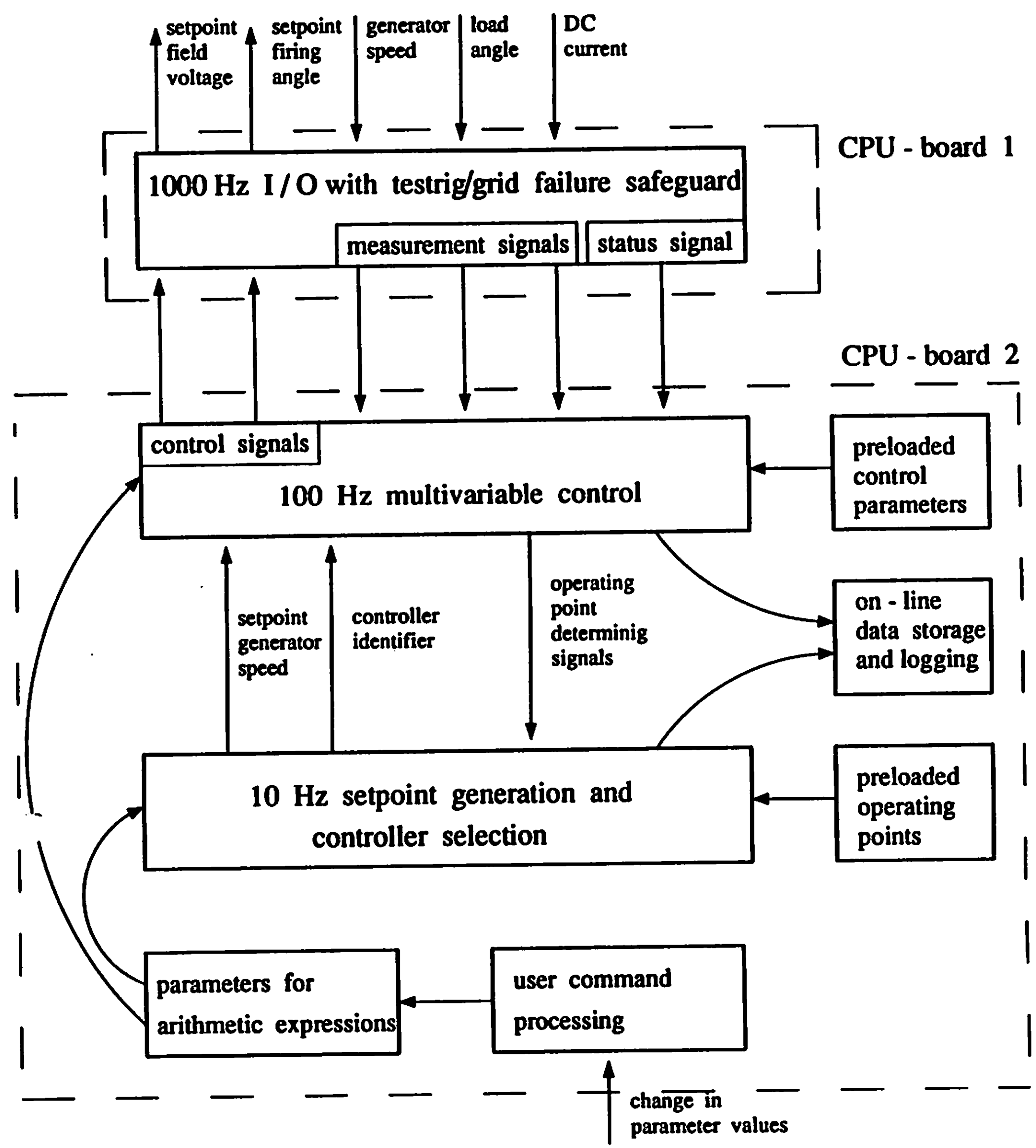
- PC's for:

  1) data-aquisition
  2) simulation of the quasi-steady state behaviour of the turbine rotor with passive pitch control.



Rotor shaft driving facility

Variable speed system with integral control



PROCESS COMPUTER AND CONTROLLER:

- CompControl computer with two CPU's for separate 10-100 Hz and 1000 Hz processing;

- Realised in a shell program (language C) for signal processing and flexible implementation of the multivariable control algorithm;

- Additionally the shell program is used for fast data acquisition at 100 Hz;

- Control algorithm (2x2) and constants will be designed by TU Delft, using the model and/or estimated transfer functions;

Inputs:	speed of the synchronous machine
	DC current
	DC voltage
Outputs:	exciter field voltage
	firing angle of the rectifier

LIST OF MEASURED SIGNALS :

** In the PC for data aquisition at 32 Hz:

- DC voltage and DC current;
- Exciter voltage;
- Field current of the main machine;
- Synchronous machine speed;
- Synchronous machine shaft torque;
- Stator voltage (in rotating coordinate system);
- Stator current (in rotating coordinate system);
- Rectifier firing angle (related to rotor position);
- Wind speed (simulated in PC);
- Aerodynamic torque (simulated in PC);
- Rotor pitch angle (simulated in PC).

** In the CompControl computer at 100 Hz (for identification purpose):

- Exciter voltage;
- Rectifier firing angle (related to stator voltages);
- DC current;
- Synchronous machine speed;
- Synchronous machine shaft torque.

** In the CompControl computer at about 1000 Hz (conversion from rotor position to stator voltages):

- Stator voltage (in rotating coordinate system);
- Stator currents (in rotating coordinate system);
- Calculated load angle.

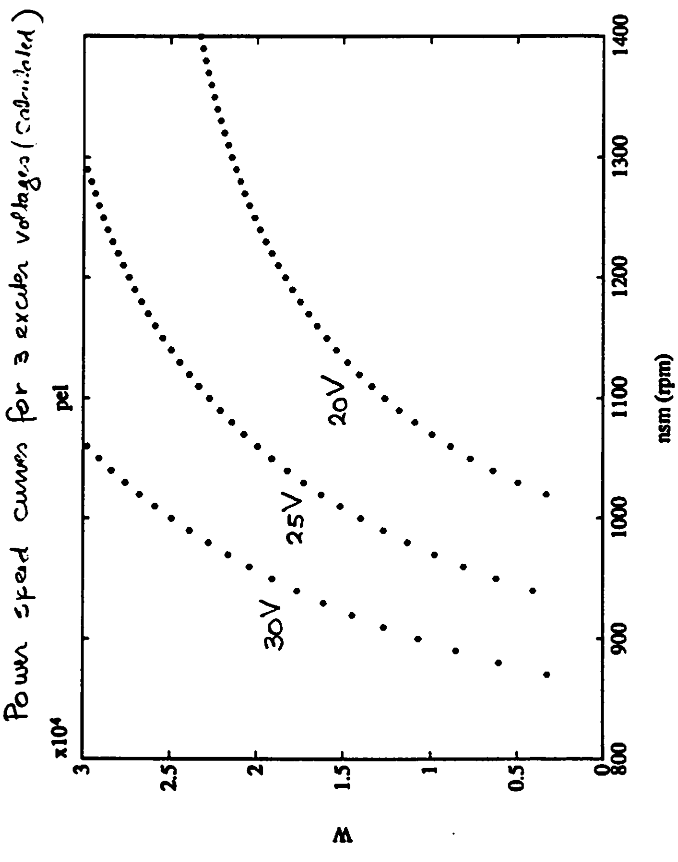
FIRST MEASUREMENT RESULTS:
(system without controller)

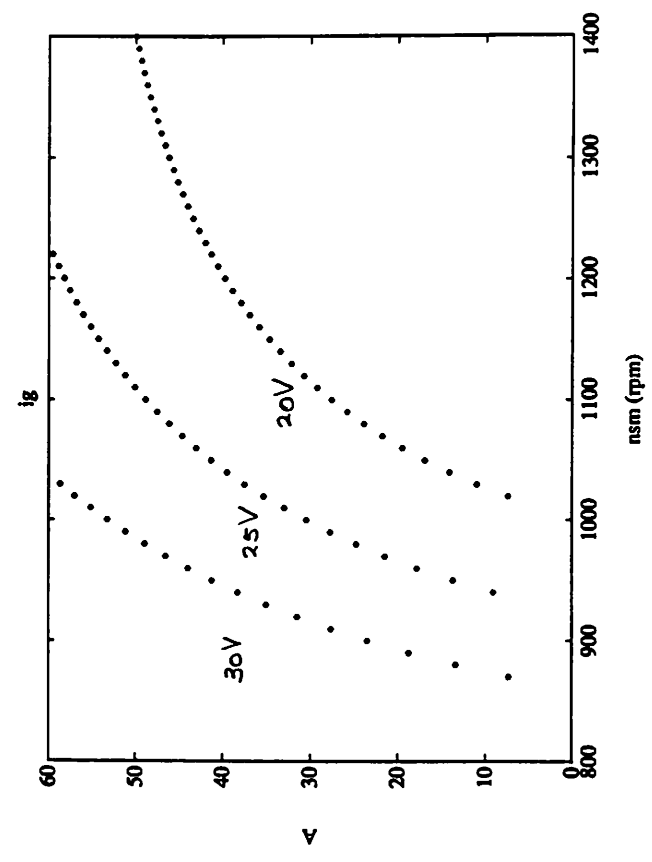
Steady state Power-speed curves at different values of:

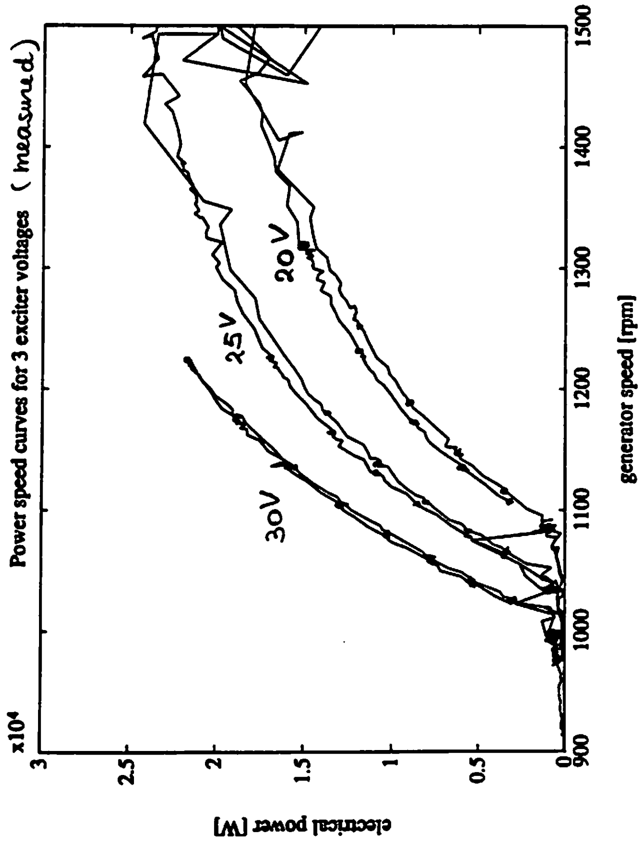
- the exciter voltage (20, 25 and 30 V);
- the firing angle of the rectifier (0.2, 0.4 and 0.7 rad).

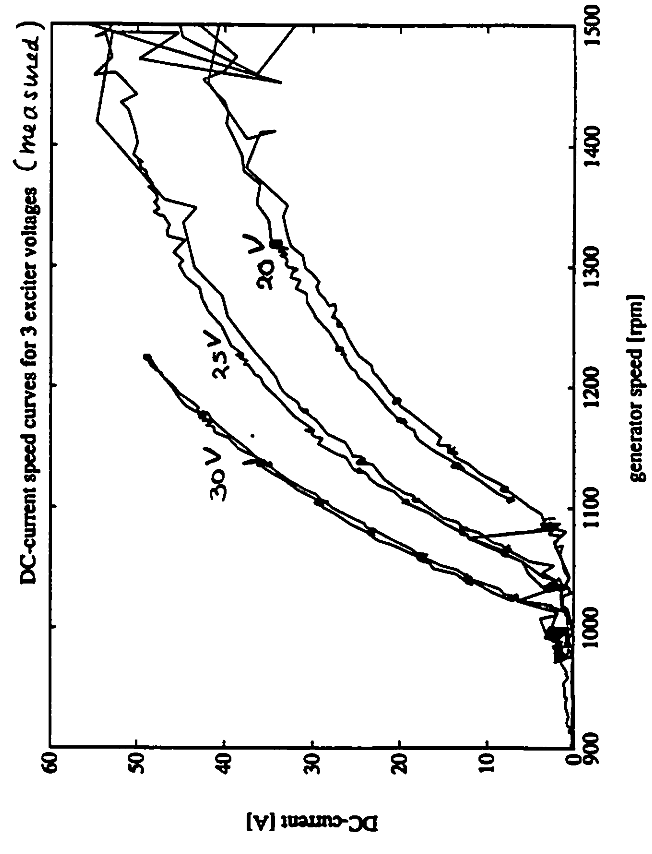
Determined for slowly increasing shaft torque.

To identify the operating range of the control signals (find unstable operating points) and to compare to modelling results.


Power speed curves for 3 exciter voltages (calculated)
pel
x10^4
W
nsm (rpm)
30V
25V
20V


ig
A
nsm (rpm)
30V
25V
20V


Power speed curves for 3 exciter voltages (measured)
x10^4
electrical power [W]
generator speed [rpm]
30V
25V
20V


DC-current speed curves for 3 exciter voltages (measured)
DC-current [A]
generator speed [rpm]
30V
25V
20V

FIRST MEASUREMENT RESULTS (continued):
(system without controller)

Dynamic behaviour of the system:

- using Pseudo Random Binary Sequence (PRBS) input signal on exciter voltage and firing angle.

- at two operating points:

  A) at part load (vwind = 10 m/s, ufe = 19 V, alpha = 0.2 rad)

  B) at full load with passive pitch control (vwind = 12 m/s, ufe = 19 V, alpha = 0.2 rad)

To detemine the eigenfrequencies of the system and the transfer functions from system inputs to outputs.

TU Delft elaborates these experiments to identify parametric transfer functions for controller design.

FIRST SIMULATION RESULTS:
(system without controller)

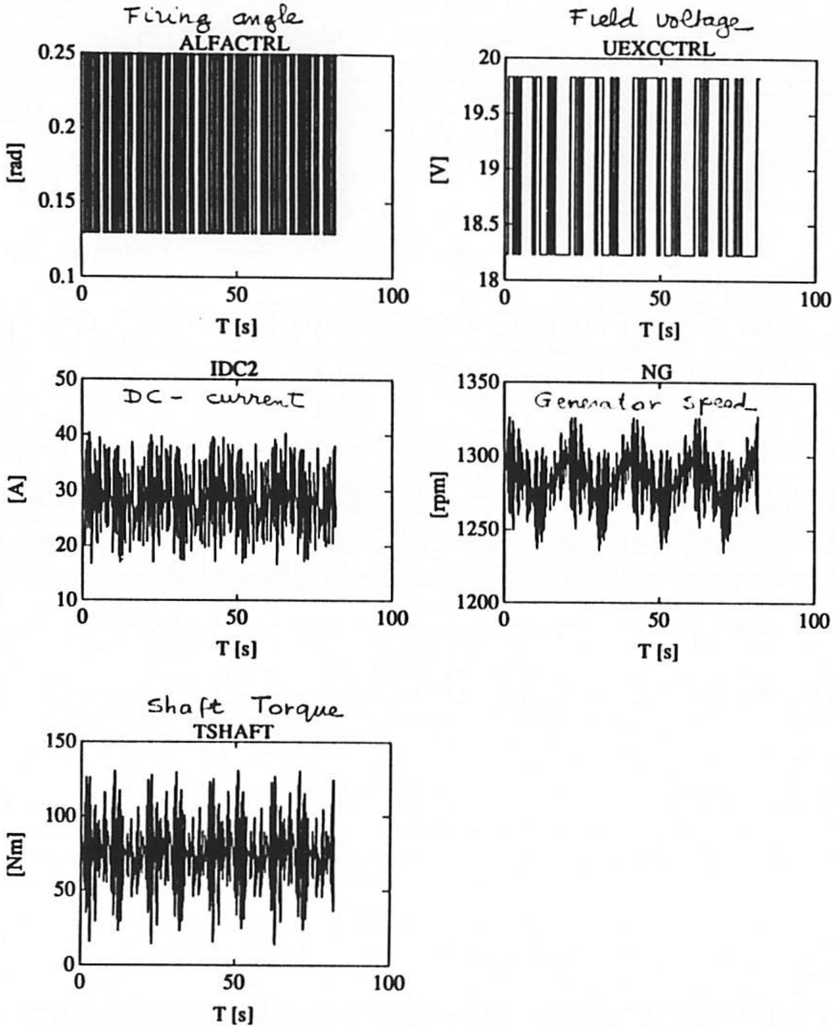
** Steady state Power-speed curves at different values of:

- the exciter voltage (20, 25 and 30 V);

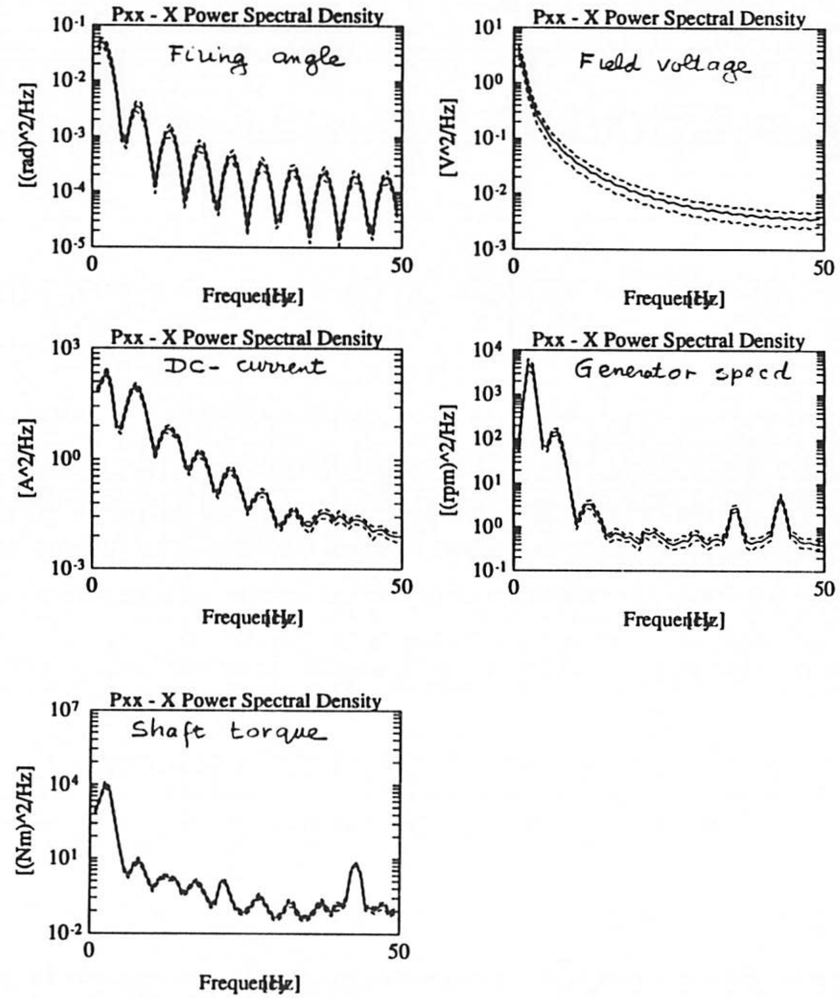
** Dynamic behaviour of the model:

- Pseudo Random Binary Sequence (PRBS) input signal at part load (vwind = 10 m/s, ufe = 19 V, alpha = 0.2 rad) The model calculates unstable operation;

Measurements



Calculated from measurements



CONCLUSIONS AND ITEMS FOR FURTHER RESEARCH:

1) The first measurements show uncontrolled stable operation for exciter voltages from 20-30 V and firing angles of 0.2-0.5 rad for the speed range between 1000-1400 rpm.;

2) At higher speed unstable uncontrolled operation occurs. The cause still has to be examined.

3) Measurements and simulations still show somewhat different results. The model is currently validated by experiments on a simular machine at TU Eindhoven;

4) Controller design based identification experiments (estimation of parametric transfer functions) by TU Delft;

5) Evaluation of different controller designs by experiments on the testrig;

CRITERIA FOR THE CHOICE OF A VARIABLE SPEED STRATEGY IN THE DESIGN OF A SINGLE BLADED WIND TURBINE

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E. Dalpane
Riva Calzoni SpA, Bologna, Italy

1 INTRODUCTION

Since a few years the discussion on constant speed and variable speed operation strategy rose up. The question is wether the advantages of the variable speed strategy can justify the investment increase or not.

One part of the new WTs, mainly of large scale, are now operating with a variable speed generator system. Some new and specific aspects of single bladed WTs on this item will be presented in this paper.

2 CRITERIA FOR STRATEGY SELECTION

Between a large number of parameters which will influence the choice of the operation strategy; 3 of particular interest will be discussed in the following chapters.

2.1 AERODYNAMIC NOISE

It is known, that the background noise depends on the wind speed. This dependency exits, more or less strong in function of the control strategy, also for the aerodynamic noise emission of WTs. In the following a new method of graphic presentation of the relative aerodynamic noise will be shown.

The aerodynamic noise has a particular importance in case of single bladed WTs. This because of the higher tip speeds and of lower mechanical noise of the gear box.

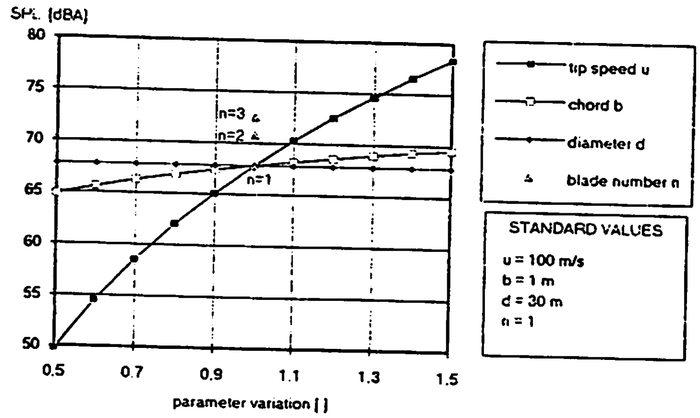

Figure 1: Aerodynamic noise - sensibility analysis

The aerodynamic noise can be calculated according the semi-empirical method of Keast and Potter [1]. The source sound pressure level can be obtained by the formula

$$L_w = 10 \cdot \log(n \cdot U^6 \cdot b \cdot d) - 15 \text{ dB} \quad (1)$$

The noise level in the reference point, defined by the IEA recommendation [2] at a distance downwind equal to the sum of rotor radius plus hub height, can be found with the formula

$$L_p = L_w - 10 \cdot \log(2\pi \cdot (h^2 + (h + d/2)^2)) \quad (2)$$

With the assumption, that the hub height is equal to the rotor diameter and equation (1) we get

$$L_p = 10 \cdot \log((n \cdot U^6 \cdot b)/(2\pi \cdot 3.25 \cdot d)) - 15 \text{dB} \quad (3)$$

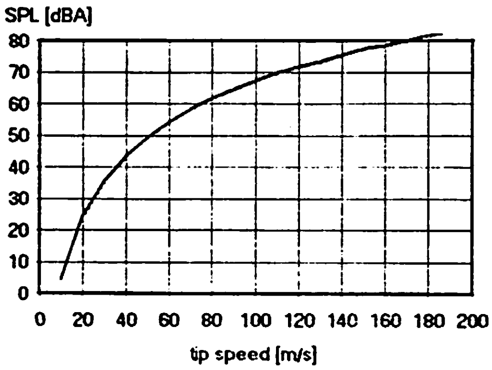

Figure 2: Noise versus tip speed

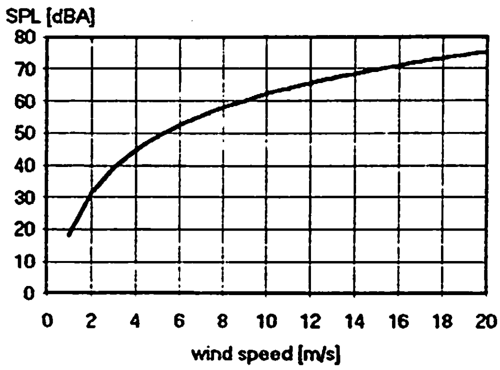

Figure 3: Background noise versus wind speed

Figure 1 shows the tip speed predominance with respect to the other parameters, which will be neglected in the following analysis. The diameter variation has no influence on the noise level because a constant chord-diameter ratio was assumed.

For the geometric data of Riva Calzoni's M30S WT results the noise versus tip speed curve presented in figure 2. The background noise depends strongly on the surrounding and it is also a wind speed function.
Results from swedish background noise measurements [3] for a site with high trees are shown in figure 3. The information contents of figure 2 and 3 can be plotted in a single graph in form of a delta sound pressure level versus tip speed in dependence on the wind speed. The result shown in figure 5 permits to design the "equivalent-noise" curve in the power tip speed diagram. In figure 4 the +5dBA curve is shown with the indication how to construct by means of figure 5. The different control strategies can be analyzed plotting them in the same figure.

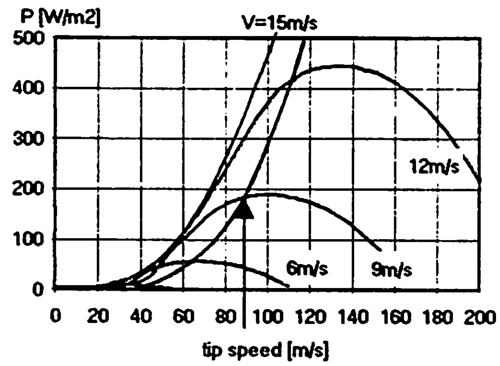

Figure 4: Equivalent-noise curves in the power - tip speed diagram

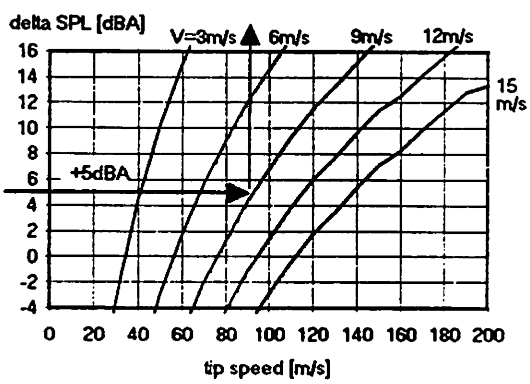

Figure 5: Curves of constant windspeed in the delta SPL tip speed diagram

2.2 TORQUE FLUCTUATION

The time and spatial variation in wind speed together with the dynamic behavior of the WT will determine the torque fluctuations. On one hand this fluctuations will be important for the fatigue life of the WT and on the other they are a criteria for the power quality evaluation. The larger the WT the more important get these aspects.

Beside the blade number and the hub type the drive train characteristic will mainly influence on the fluctuation magnitude.

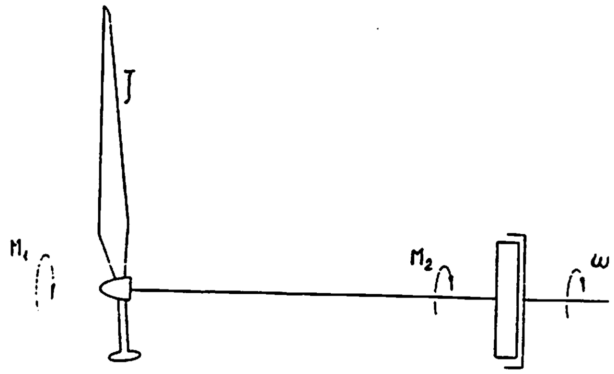

Figure 6: Dynamic model for torque fluctuation transmission analysis

A good approximation of the dynamic drive train behavior can be found analyzing the simple 1 degree of freedom model shown in figure 6. The damping coefficient for a generator is there defined as

$$c = d(P/\omega)/(d\omega) \qquad (4)$$

and the generator characteristic in case of an induction generator is

$$P = P_{rat} * (\omega - \omega_{syn})/(s * \omega_{syn}) \qquad (5)$$

From these two equations we get

$$c = P_{rat}/(s * \omega_{rat}^2) \qquad (6)$$

and in consequence the time constant of the model as

$$\tau = J/c = (s * J * \omega_{rat}^2)/P_{rat}. \qquad (7)$$

From a scaling analysis of this equation we can see that τ is proportional to the slip and to the radius of similar WTs.

The excitation moment and the response moment can be described with the formulas

$$M_1 = M_{10} * \sin(\Omega t) \qquad (8)$$

and

$$M_2 = M_{20} * \sin(\Omega t - \alpha). \qquad (9)$$

The filtering capacity of the upper described system is shown in figures 7.

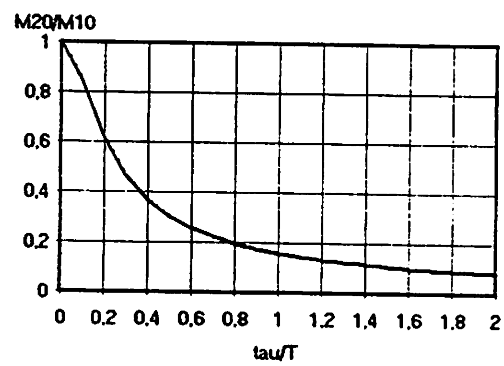

Figure 7: Drive train filtering capacity

2.2.1 1P TORQUE FLUCTUATION

The most important excitation factor for the 1P torque fluctuation is the wind shear. To simplify the equation it can be assumed that the wind speed increases linearly with a level increase above ground. The wind speed seen by the blade depends on the mean value defined at the hub height, the wind gradient and on the azimuth position of the blade.

Because the flapping rotor is a simple oscillator with an eigenfrequency of 1P the wind excitation must be equal to zero (see figure 8). This is fulfilled for the condition

$$U = V_m + dV/dh * (1-a_m) * r * \cos\varphi - r * d\beta/dt = V_m \qquad (10)$$

and with

$$\beta = \beta_0 * \sin\varphi \qquad (11)$$

we obtain

$$\beta_0 = \Delta V(1-am)/Vm * 1/2\lambda. \qquad (12)$$

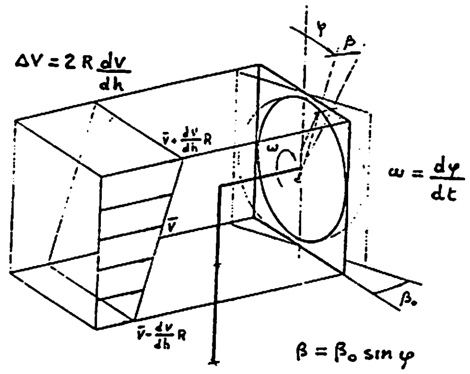

Figure 8: Model of 1P excitation by wind shear

The magnitude of the flap angle oscillation is independent on the WT size. In case of a single bladed WT excitation moments are mainly related to Coriolis forces which are defined as

$$M_C = 2^*\omega^*J^*\beta^*d\beta/dt \quad (13)$$

with a mean value of the flap angle (equivalent to the cone angle)

$$\beta = \rho^*R^5/J * \pi/2 * c_{MF}(\lambda)/\lambda^2. \quad (14)$$

With equation 13 and the definition of the mean torque

$$M = 1/2 * \rho^* c_{ML}(\lambda)^*\pi^*R^3 * V^2 \quad (15)$$

it is possible to describe the non dimensional input torque fluctuations as

$$M_c/M = \Delta V/V * c_{MF}/c_P. \quad (16)$$

This means that the input torque fluctuations are independent on the WT size.

Assuming a constant tip speed the excitation period is proportional to the radius and in consequence to the considerations made on equation (7) we see that the damping coefficient τ/T depends only on the generator slip. The normalized torque fluctuation versus slip is plotted in figure 9.

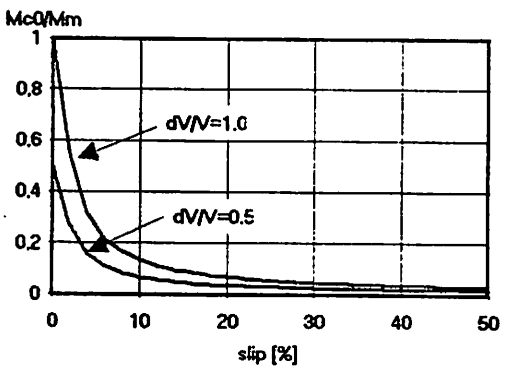

Figure 9: Normalized torque versus slip

2.2.2 Random Torque Fluctuation

Beside the WT characteristic the excitation frequency determines the transmission of the torque fluctuations. A typical non dimensional wind speed spectrum is given in figure 10. From figure 11, it can be seen that only large size WT with variable speed concept, with a time constant $\tau > 10$ s, can filter the fluctuations caused by wind turbulence. Typical values for τ reported in the figure are: 0.35s - M30, 2.0s - M55 with slip power recovery and 10.0s - M55 with variable speed concept.

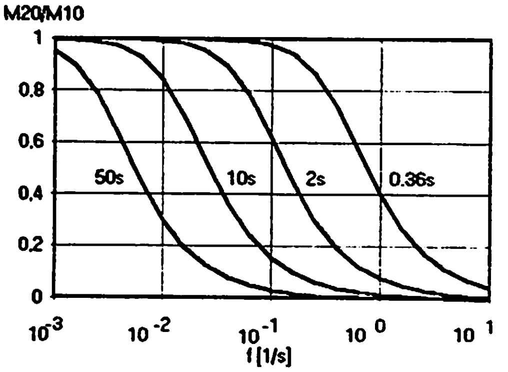

Figure 10: Filtering capacity in dependence on WT time constant

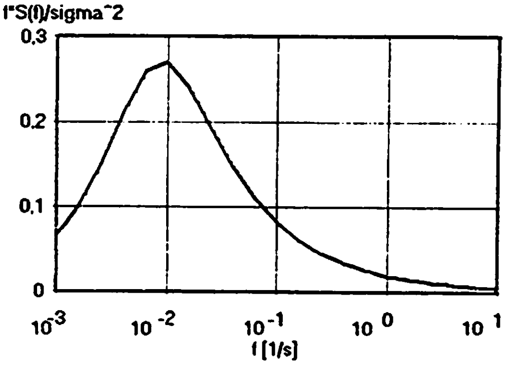

Figure 11: Wind turbulence power spectrum

2.3 DRIVE TRAIN EFFICIENCY

The power losses in the drive train are generally a function of the rotational speed and of the power. This relationship can be assumed as a linear function for both and we get the equation

$$P_{diss} = (M_{t0} + P_1 * K_p/\Omega_{rat}) * \Omega \quad (17)$$

with K_p a non dimensional constant and M_{t0} the residual torque. This equation can be expressed also in a non dimensional manner

$$\eta = 1 - (K_0/P_1^* + K_p) * \Omega^* \quad (18)$$

with

$$K_0 = M_{t0}*\Omega_{rat}/P_{1rat} \quad (19)$$

$$K_p = 1 - \eta_{rat} - K_0. \quad (20)$$

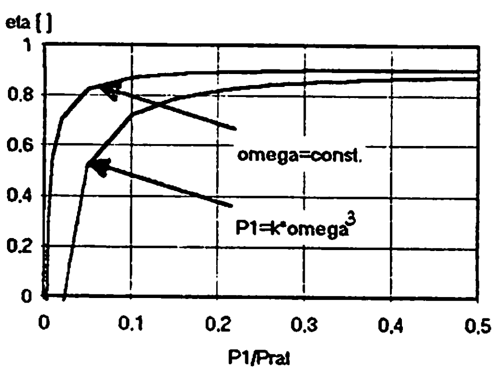

Figure 12: Drive train efficiency

The η - P_1^* curves shown in figure 12 are calculated with equation (18) for the cases Ω^* = constant (fixed speed) and $\Omega^* = (P_1^*)^{1/3}$ (variable speed operation). This considerations show that high losses at low power of the variable speed operation can be partially compensated.

3 CONCLUSION

In the present paper, it was tried to discuss very briefly 3 items which can influence the choice of the operation strategy. The graphic method for the aerodynamic noise evaluating could be very helpful for the WT layout because it is possible to compare different operation strategies. The second part, concerning aeroelastic aspects, is more specific for single bladed WTs, but in some cases, analog considerations can be carried out also for other WT types. Furthermore some equations for semi empirical efficiency modelling are presented in the last part of the paper. This formulas were then applied on constant speed and variable speed strategy without looking into the details of electric efficiency of the variable speed concept.

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[2] S. Ljunggren, A. Gustafsson (Editors) — Recommended practices for wind turbine testing and evaluation
4. Acoustics measurement of noise emission from wind energy conversion systems
1. Edition 1984

[3] S. Ljunggren, S. Engstrom — A swedish solution to the noise problem:
Wind turbine with variable RPM

NOMENCLATURE

a	- factor for induced velocity	[ ]
b	- chord length at 70% radius	[m]
c	- coefficient	
d	- rotor diameter	[m]
h	- hub height	[m]
J	- momentum of inertia	[kgm^2]
K	- constant	
L_w	- source sound pressure level	[dBA]
L_p	- sound pressure level	[dBA]
M	- moment	
n	- number of blades	[ ]
P	- mechanical power	[W]
s	- nominal slip	[ ]
U	- circumferential speed at 70% radius	[m/s]
V	- wind speed	[m/s]
Δ	- difference	
η	- efficiency	[ ]
τ	- time constant	[s]
ω	- rotational speed (low speed shaft)	[rad/s]
cor	- Coriolis	
d	- damping	
m	- mean value	
MF	- flap moment	
p	- power	
rat	- rated point	
syn	- synchronous point	
t0	- residual torque	
0	- residual	
1	- input	
2	- output	

Power Control of a Fixed-Pitch Variable Speed Wind Turbine

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1.Introduction

Usually pitch control has been used to reduce the output power from a variable speed windmill at winds above the rated. Some tests have also been performed with yaw control and stall control. Most small and medium size fixed-speed windmills have fixed pitch. Is it possible to introduce variable speed on these fixed frequency windmills ?
The purpose of this work was to shed some light upon the difficulties with stall regulation and to show that it is possible to operate a variable speed windmill with stall control. This paper starts with a presentation of the system and some unavoidable theory and the control strategy. It continues with static and dynamic performances and ends with a result discussion. The windmill and the system used in this work were earlier a stand-alone wind-diesel plant. The system could also in this work oparete as a standalone system.

2.Summary

Stall control of a fixed-pitch variable speed system was investigated on a system consisting of one windmill which could operate in a broad speed range, from 3-38 rpm, and produce any desired output from the rated (20 kW) to no-load, providing there was wind enough. The electrical system consists of two self-commutated convertors which makes the system very flexible. The windmill can be driven both grid-connected or as a stand-alone system. If there is too little wind, there is a diesel engine which can supply the autonomous grid. The self-commutated grid inverter has a switching frequency of 1500 Hz which gives a possibility to substantionally reduce harmonics on the grid.
The system operates well but large torque and power peaks are formed when the windmill is operating at the maximal rotational speed. The power peaks have the following origin: In order to increase the energy output from the turbine the windmill is operated at a higher rotational speed than its stall-speed for medium winds. But the system is here unprotected against gusts. A gust which increases the wind speed from 8 to 11 m/s raises the power from 20 to 32 kW. The torque and power ripple will also increase if the rotational speed change is increased.

3.System presentation

The windmill is a 55/11 kW bonus with a rated speed of 45/30 rpm. A 22 kW induction generator has replaced the 11 kW generator. The 22 kW generator is connected to the grid via two PWM-convertors. A large battery is connected to the DC-link between the convertors. The rotational speed can vary between 3 and 38 rpm. The system can provide any power from 0-20 kW providing there is wind enough. The rated power of the system is 20 kW and the rated wind speed 8 m/s.

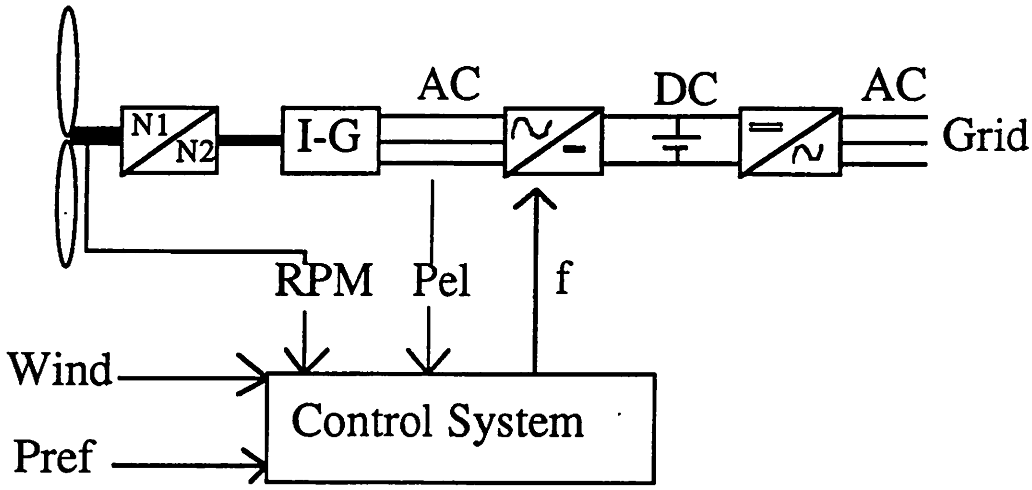


Figure 1: The windmill and the electrical system.

4.Theory

Some of the available energy in the wind is converted into mechanical power on the shaft and then into electrical power according to Eq.1-3.

$$P_{mek} = Cp(\lambda)\, k\, w^3 = \frac{Cp(\lambda)\, k\, \omega_t^3\, r^3}{\lambda^3} \qquad (1)$$

$$\lambda = \frac{\omega_t\, r}{w} \qquad (2)$$

$$P_{el} = \eta\, P_{mek} \qquad (3)$$

Where: λ is the tip speed ratio, r the radius of the blades, w the wind velocity, ω_t the rotational speed of the turbine, k a constant including the turbine area and the air density , Cp the power coefficient and η the efficiency of the generator and gear-box.

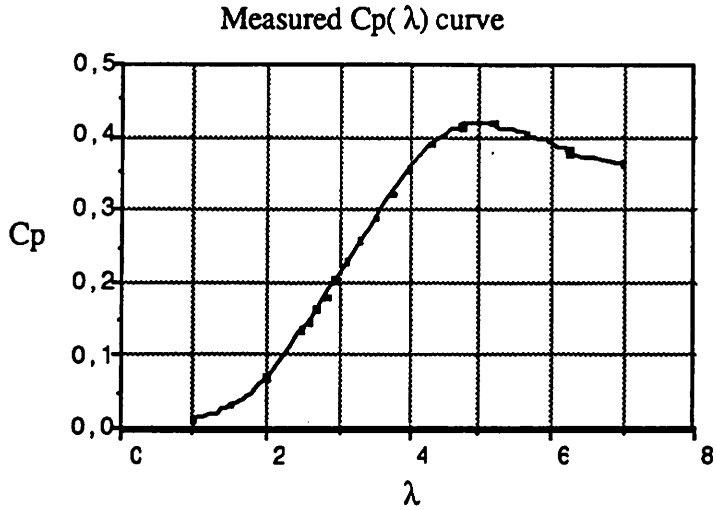


Figure 2: The measured power coefficient (Cp) curve of the windmill.

The output power does not only origin from the wind, there will also be an extra power contribution (Pi, inertia power) from the system during a deceleration or acceleration of the turbine due to the change of rotational energy (W) in the turbine.ω_t is the rotational speed of the turbine and T the sampling interval.

$$W=\frac{J\,\omega_t^2}{2} \qquad (4)$$

Differention of Eq (4) gives:

$$Pi=\frac{dW}{dt}=\frac{\Delta W}{\Delta t}\;\frac{J\,(\omega_t(T-1)^2-\omega_t(T)^2)}{2\,\Delta t} \qquad (5)$$

5.Control

The main control idea is to correct a power error as rapid as possible. When it is possible, the system operates with a dead-beat control strategy, i.e it corrects a power error in one sample interval. Usually this is not possible due to the inertia effect (Eq.5).
The windmill and the electrical system are far from a linear system, so to calculate the ideal change the operating point must be known. When the operating point is known, the dead-beat control parameter Allan can be calculated. (n is the gear ratio and p is the pole-pair number)

$$\frac{dP_{el}}{d\omega_{el}}=\frac{dCp(\lambda)}{d\lambda}\,\frac{\eta\;k\;w^2\;r}{n\;p}=\underline{Allan} \qquad (6)$$

The power measured is compared with a given reference power and after compensating for the inertia effect (Pi), the power error will be determined. The ideal change in supplying frequency in order to correct the power error in one sample interval is calculated with the nonlinear control parameter Allan. But in most cases the frequency change must be reduced otherwise the inertia effect will be too large.

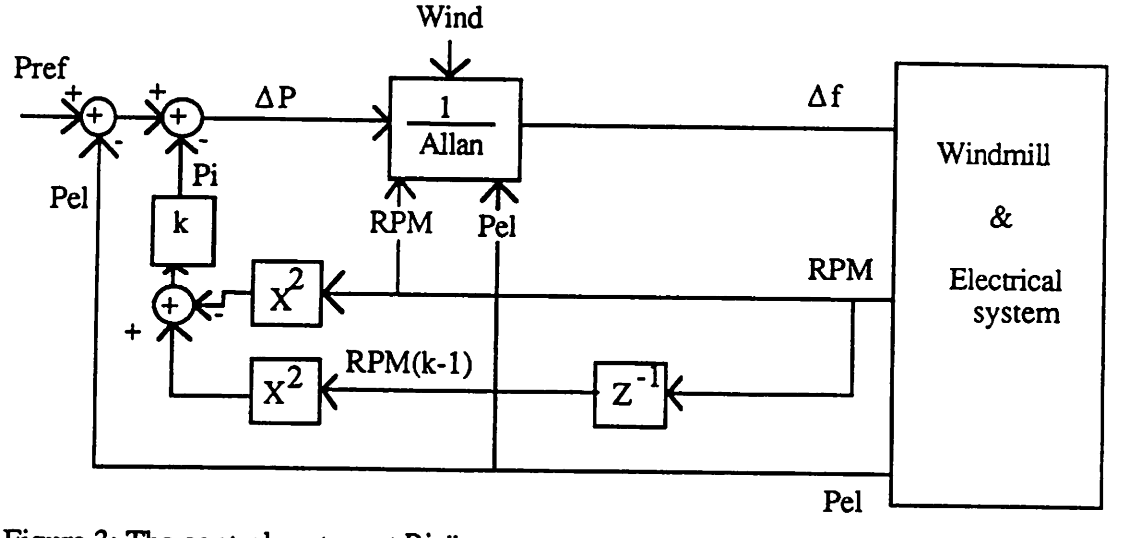


Figure 3: The control system at Risö.

The wind measurement is a problem. If the anemometer is situated behind the windmill, it will give too a low value. It will also sense a different turbulence than the windmill.
But it is possible to use the windmill as a wind measurer if the turbine is not operating in the stall region. From Eq 1 Eq 7 can be derived.

$$\frac{P_{mek}}{k\,\omega_t^3\,r^3} = \frac{P_{el}}{\eta\,k\,\omega_t^3\,r^3} = \frac{Cp(\lambda)}{\lambda^3} \qquad (7)$$

During each sample interval the electrical power and the rotational speed are measured and $\frac{Cp(\lambda)}{\lambda^3}$ is calculated. If the result is a value lower than 0,008, it will be possible to determine the tip-speed ratio λ as shown in the figure below. When λ is known, the wind can be determined by Eq.2.

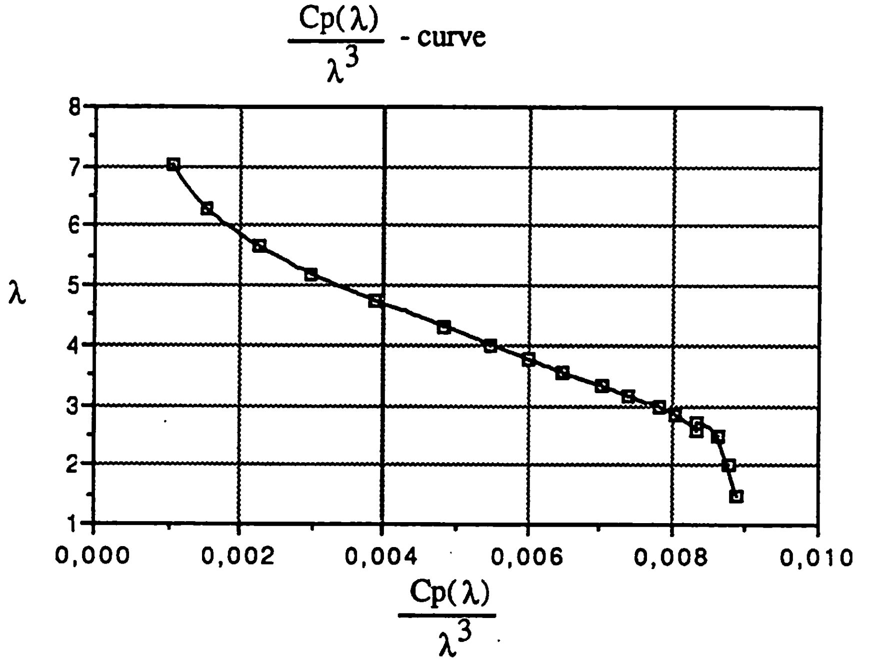
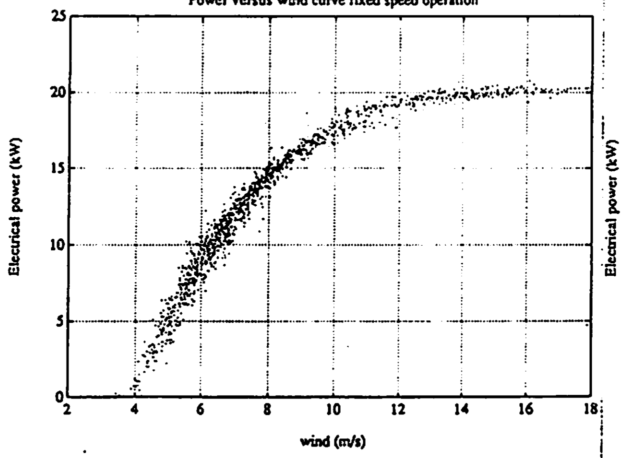


Figure 4: $\frac{Cp(\lambda)}{\lambda^3}$ versus λ, measured values.

6.Static Performance

Measurements were made on the windmill in April, May and August 1991. Figures 5.a, 5.b and 5.c compare the fixed speed operation with the variable speed operation during a measurement period of 68 hours. The dots in Figures 5.a and 5.b are 60 sec average values. In Figure 5.c the binned values are compared.



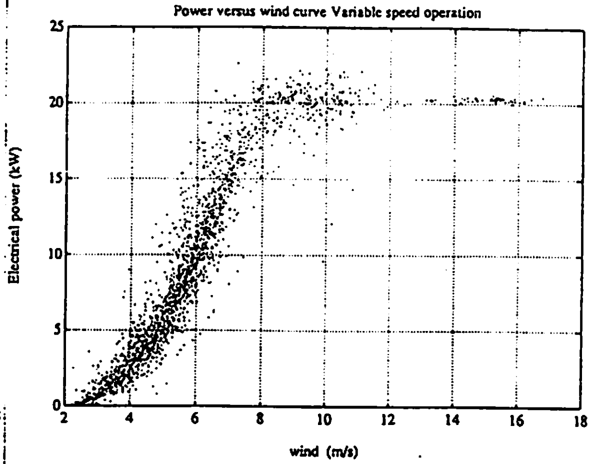


Figure 5.a and 5.b: Comparison between fixed frequency and variable speed operation.

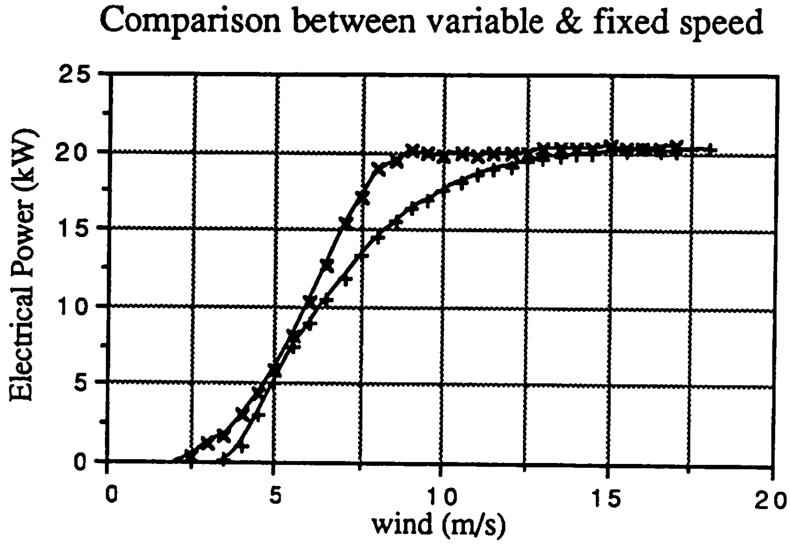


Figure 5.c. Comparison of the binned values for fixed and variable frequency operation.

It should be pointed out that the windmill is operated via the inverters also in the fixed frequency operation with a fixed frequency of 52 HZ. If a true energy comparison was to be performed, these losses should in the fixed frequency case have been accounted for. The result of the measurement, performed in the variable frequency case is also presented in a Lawson-Tancred nomogram (L-T nomogram).

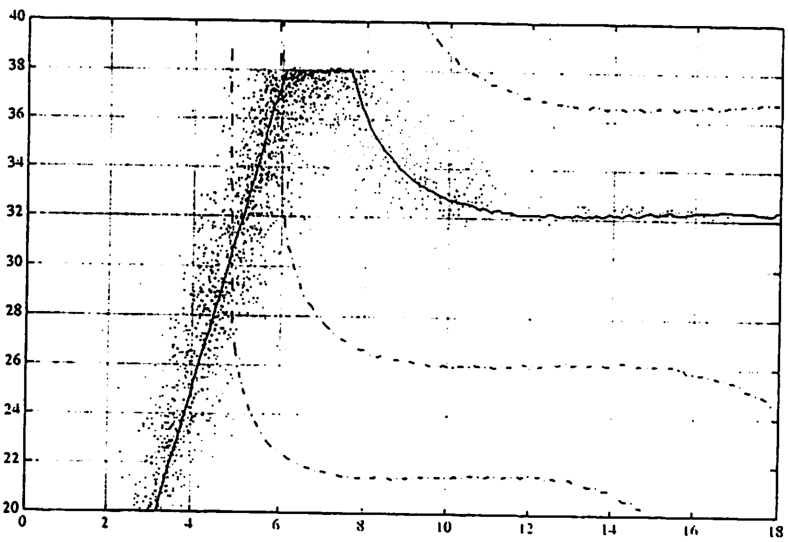


Figure 6: L-T nomogram.

The dashed curves are constant power curves. The dots are 60 sec average values. The windmill operates nicely along the optimal Cp(λ) curve until it reaches the top speed limitation. Above 8 m/s the system starts to reduce the speed in order to keep the power constant.

7.Dynamic performance

The speed of the control loop is 2 HZ. This is due to the control computer. The true name of this section should therefore have been quasi-stationaery conditions. The most critical point is when operating at 38 rpm and the wind is blowing with a strength of 8 m/s. A gust will unavoidably lead to an over-power situation.

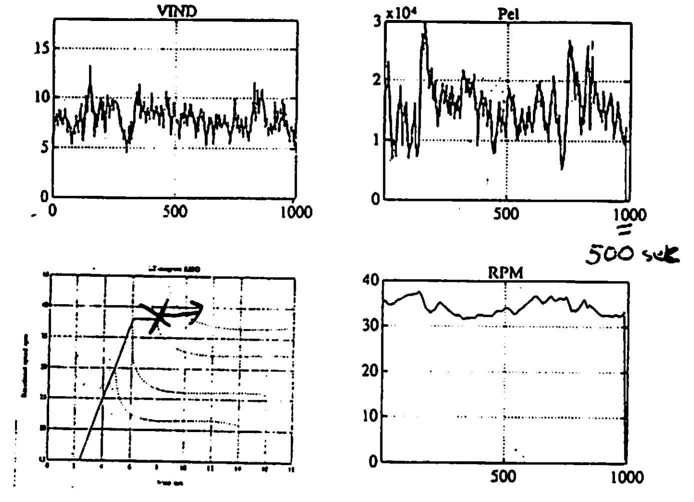


Figure 7: An increase in the wind from 8 to 11 m/s.

When the gust comes the power will increase from 9 to 26 kW. The control system detects the power error and starts to decrease the speed. According to Eq 3 this leads to an extra power contribution of 2 kW during the deceleration, which is the maximum Pi allowed. If Pi is allowed to have a larger value, the torque ripple will increase and the system will be more rapid. In the optimal Cp(λ) operation this change will also give some more energy because the system will deviate less from the optimal Cp(λ) point. After 10 sec the power error has been corrected. In the stall region the control situation is more favourable as shown in Figure 8 below.

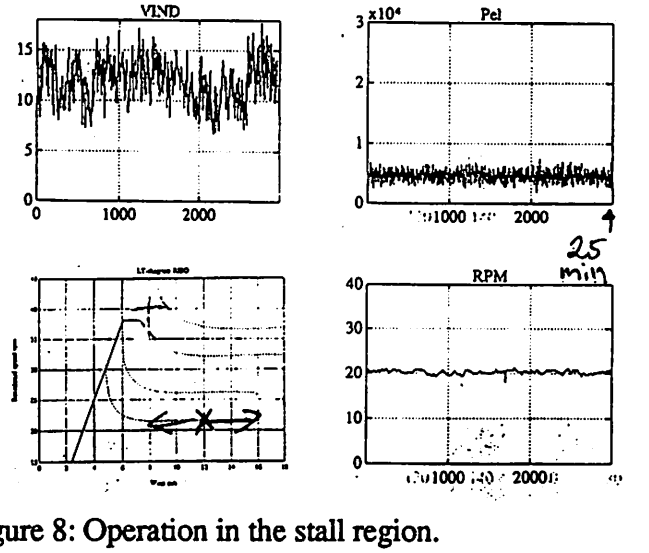


Figure 8: Operation in the stall region.

As can be observed in the L-T-nomogram above an increase of the wind does not effect the electrical power much.
It is impossible to avoid power peaks in the region when operating at maximum power and maximum speed. The only powerful solution is to reduce the speed earlier but in this way we will unfortunately lose energy.

8.Conclusion

It is possible to operate the system with any power from rated power to no-load, if there is wind enough. The wind turbine can be used as a wind measurer providing that the Cp(λ)-curve is known. The system operates with a dead-beat control strategy when possible High energy capture and fast control lead to an increase in power peaks. With a smaller turbine inertia the allowed change in rotational speed can be increased. With a faster computer an over-power situation can be detected earlier and the decrease in the rotational speed can begin earlier.

AN ELECTRICAL SYSTEM FOR VARIABLE SPEED OPERATION OF WIND TURBINES WITH INDUCTION GENERATORS

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ABSTRACT

Traditionally most of the wind turbines are working with constant rotation speed. However, this constant speed is not especially satisfactory as to the energy production and mechanical stress. Therefore, it is definitely a development to proceed to a system which allows a rotation speed depending on the wind.
This paper describes an electrical system which enables operation with variable speed and a control of the torque. This system, together with a suitable automatic control system, makes the wind turbine work with an optimal rotation speed up to the rated speed and for speeds higher than the rated one with a maximum torque.
The electrical system consists of one induction generator, two AC/DC convertors and one DC/DC convertor.
A transient model has been made to describe the electrical system. The results from the calculations have been compared with the results from the laboratory tests.

INTRODUCTION

Converting the kinetic wind energy into mechanical rotation energy and further processing to electric energy has had and will have many stages of development. Traditionally most of the wind turbines, in Denmark and in the U.S.A., are working with constant rotation speed. However, this constant speed is not especially satisfactory as to the energy production and mechanical stress. Therefore, it is definitely a development to proceed to a system which allows a rotation speed depending on the wind.
The electrical system for a constant speed wind turbine is usually an induction generator connected to the grid. If it is necessary to avoid inrush currents, a soft starter is often connected between the generator and the grid. The soft starter is equipped with thyristors. A wind turbine which operates with variable speed operates in a narrow speed range, ±10 % of the rated speed, or in a wide speed range, 30-120 % of the rated speed of the turbine. The system for the narrow speed range can be a slip-recovery system consisting of a wound rotor induction generator with a convertor connected to the rotor [1]. For the wider speed range a synchronous generator with a rectifier and a line-commutated inverter can be used. In this system no motoring is possible due to the rectifier, and the inverter consumes reactive power from the grid. There is also another electrical system for the wide speed range consisting of one induction generator, two AC/DC convertors and one DC/DC convertor. This system is described in the paper.
This electrical system enables operation with variable speed and a control of the torque in motor as well as in generator operation. Together with a suitable automatic control system it makes the wind turbine work with an optimal rotation speed up to the rated speed and for speeds higher than the rated one with a maximum torque.
A wind turbine can control the maximum power extracted from the wind in several ways e g by pitch- or yaw control [2, 3], or in the most common way by stall control. Up till now nearly all stall-controlled wind turbines operate with constant speed. During this fall tests with variable speed operation and stall control are to be started at Chalmers test station for wind turbines. The wind turbine has a rated power of 40 kW, two blades and a teeter hinge.

THE ELECTRICAL SYSTEM

The electrical system consists of one induction generator and three convertor units and is designed to manage 40 kW power.
The left part of the convertor block in Figure 1 shows the ac-dc convertor with power transistors as current valves [4]. With this convertor it is possible to have a full control of the torque in the speed range of 0.1-1.5 times the nominal frequency. The convertor is controlled by the PWM (Pulse Width Modulation) in such a way that the lower harmonics, which can be difficult for the generator, are cancelled. Reactive current to the generator is provided by the parallel capacitor Ce.

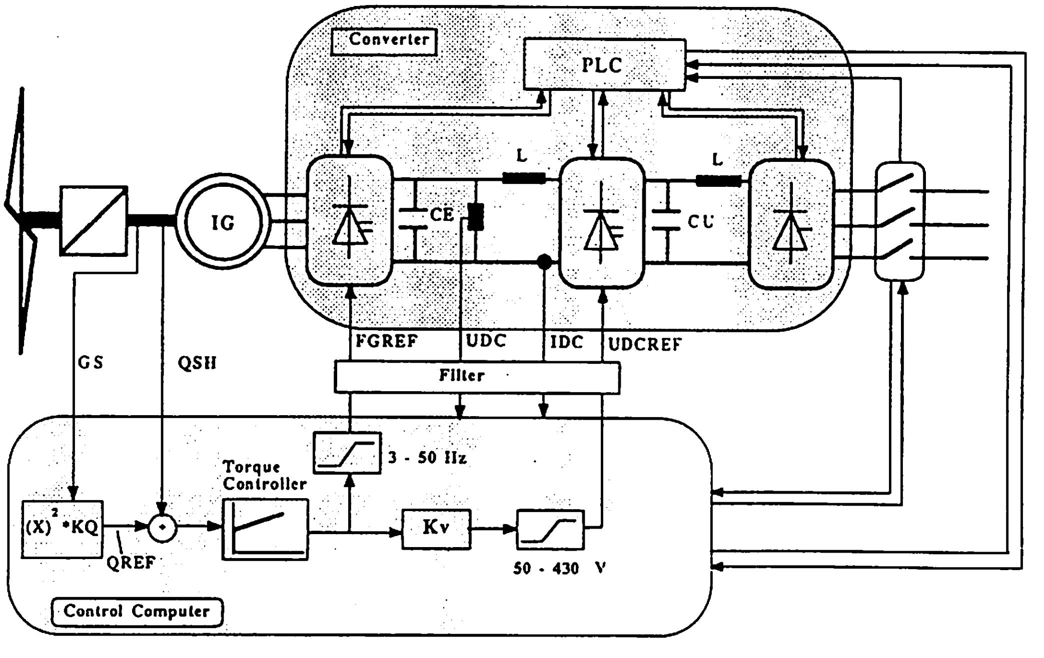

Figure 1: BLOCK DIAGRAM OF THE ELECTRICAL SYSTEM.

Figure 2 shows the generator phase-current wave form and the corresponding harmonic spectrum. The fundamental of the current is 40 Hz and the amplitude is 50 A. The lowest harmonic is of the 17th and 19th order. The 5th, 7th, 11th, and 13th harmonics are reduced.

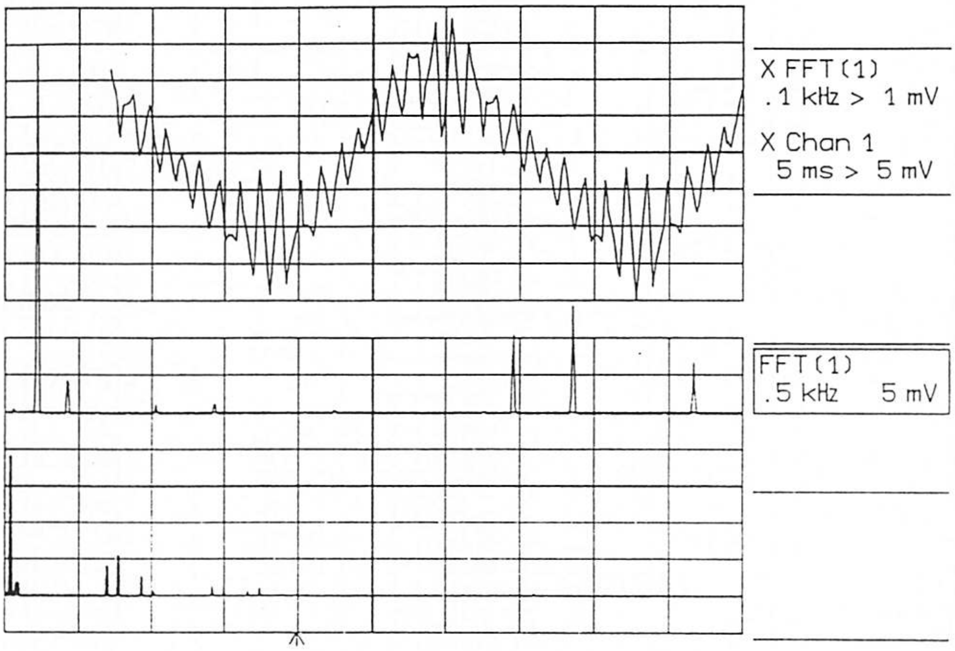

Figure 2: GENERATOR PHASE-CURRENT WITH HARMONIC SPECTRUM.

The middle one of the convertor units is a two-quadrant dc-dc convertor, which means that the power flow is bi-directional, based on a dead-beat control strategy [5]. The aim of the dc-dc convertor is to provide a regulated value of the voltage UDC by controlling the inductor current, IDC, so that the value of UDC keeps proportional to the frequency of the generator. Figure 3 shows the change in the current IDC in response to a current step. As can be seen, the response time is very short, 0.1 ms.

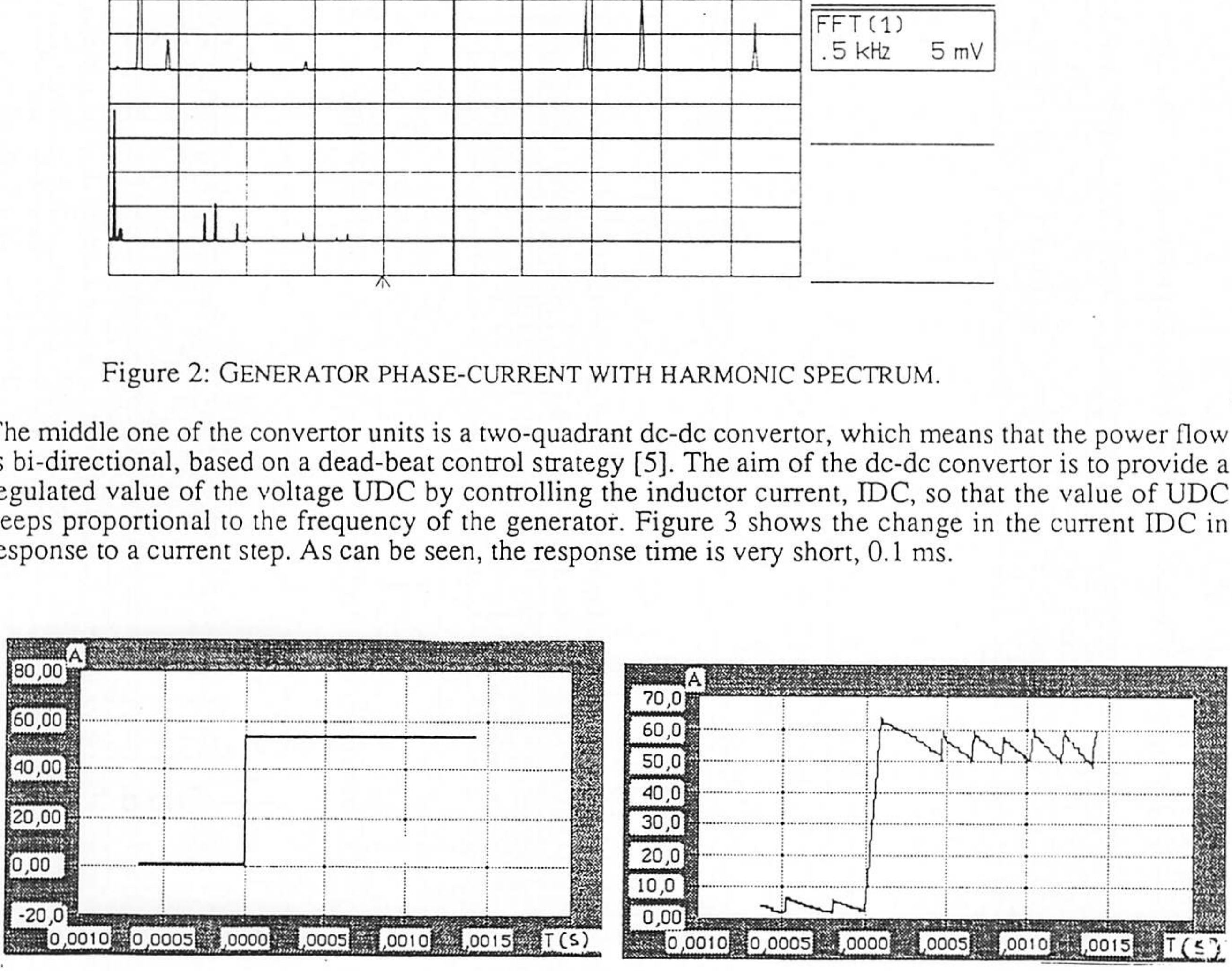

Figure 3: STEP RESPONSE IN THE DC-DC CONVERTOR.

The output convertor unit converts the dc power to ac for interconnection to the utility grid. This unit is actually a double thyristor line-commutated convertor. This type of convertor requires reactive power and causes current harmonics to the power line, see Figure 4. These harmonics can be eliminated by filters. The power factor for the electrical system is 0.9. This thyristor unit can be substituted with a PWM-controlled convertor in order to eliminate these disadvantages.

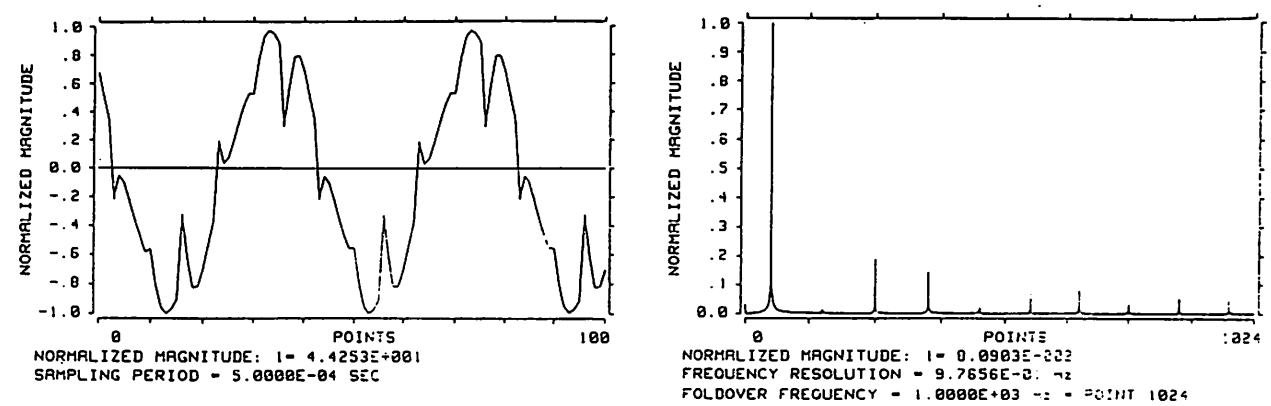

Figure 4: GRID PHASE CURRENT WITH HARMONIC SPECTRUM.

Control of the system

The torque control of a wind turbine has three major problems to solve.

- Operation at optimal tip-speed ratio by controlling the torque reference (QREF). This will only be done when there is a significant change in wind speed with a time constant of seconds.
  In the optimal control the speed of the turbine is measured (RS), squared and multiplied by a constant (KQ). This constant KQ is determined by the turbine. By this operation the aerodynamic torque is calculated. The difference between this torque and the measured torque in the primary shaft (Q) is calculated and gives the input to the PI-controller, see Figure 5. The output from the PI-controller controls the frequency of the generator (FGREF) via the electrical convertor which changes the turbine speed. JT and JG are the inertia of the turbine and of the generator. If it is difficult to measure the torque on the shaft, this torque can be calculated via the electrical power (Pel) and the speed of the turbine (Q=Pel/RS). The losses in the electrical system have to be taken into account.

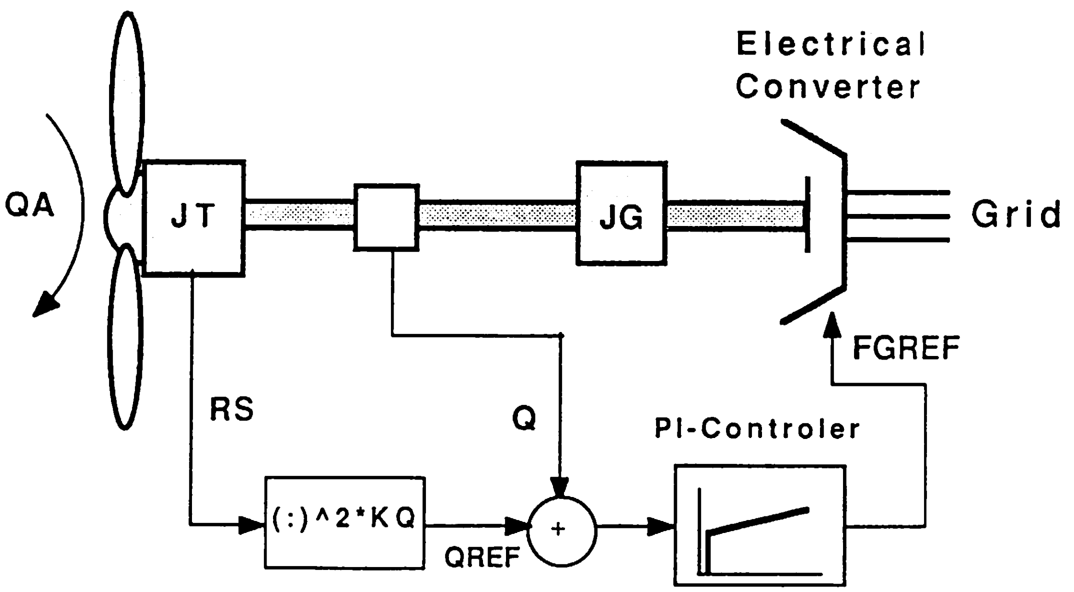

Figure 5: CONTROL OF THE SYSTEM.

This problem has been simulated in a computer with the program SANDYS (Simulation and ANalyse of DYnamic Systems). The model of the electrical machine is valid for dynamic conditions [7].
The operation of the optimal mode is simulated and shown in Figure 6. The aerodynamic torque, QA, varies with two frequencies 0.5 Hz and 6 Hz. The speed of the turbine rises when QA increases. The speed will also change the value of QREF, according to Figure 5, and thereby the torque Q. As appears from the simulations, Q and QREF follow each other with a differens in amplitude due to the acceleration of the turbine. (The torque has motor references and operates in generator mode, therefore the negative sign of the torques.)

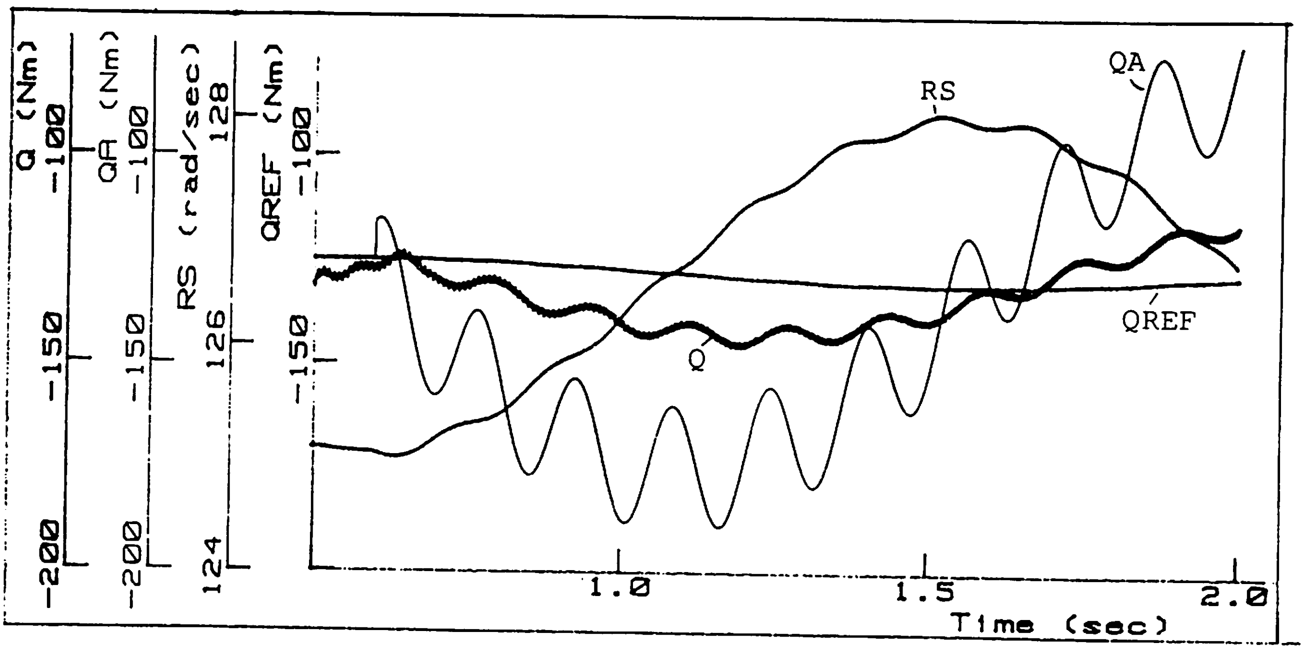

Figure 6: TORQUE CONTROL IN OPTIMAL MODE.

- Prevent as much as possible torque disturbances from the wind turbine to influence the torque in the drive train. If the generator torque is constant the disturbances will mainly accelerate the turbine and the torque on the shaft will depend on the inertia of the generator compared with the inertia of the turbine. However, the electrical torque depends on acceleration (depending on the integration of control).
In the simulations shown in Figure 7 QREF is constant and a step is applied to the aerodynamic torque, QA. The electrodynamic torque in the generator is equal to the QA before the step is applied. When the step is applied the generator starts to accelerate, and the torque of the generator only increases with a 1/4 of the step. This control minimizes the torque fluctuations in the drive train of the wind turbine.

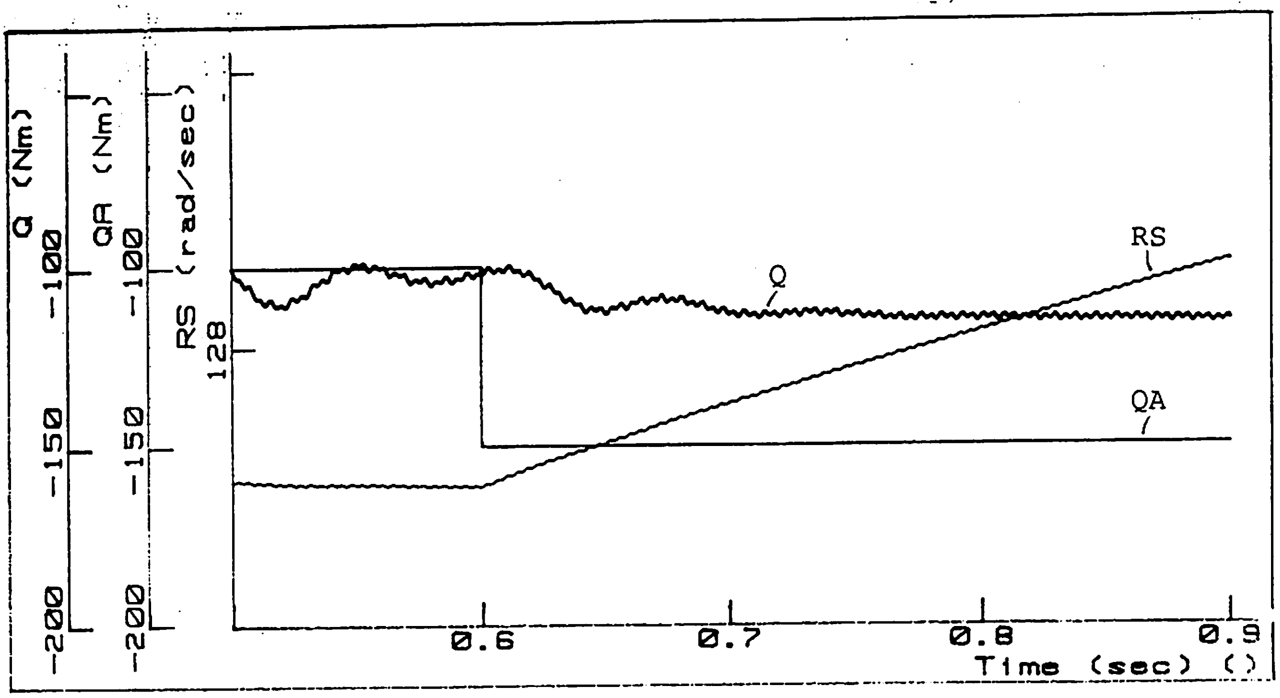

Figure 7: STEP RESPONSE IN THE TORQUE.

- Get a damping of the resonance frequency mainly caused by the inertia of the generator and the spring action of the drive shaft.

LOSSES OF THE SYSTEM

In order to define the losses of the system and further on to compare the variable and constant speed operations, both data calculations and measurements in the laboratory have been performed.
Figure 8 shows the instalment in the laboratory, how to define the efficiency in operation with variable speed. The generator load is shown in the following equation: $Q = W^2 \cdot kQ$ where Q is the moment of the generator shaft, W is the speed of the generator and kQ is a constant.

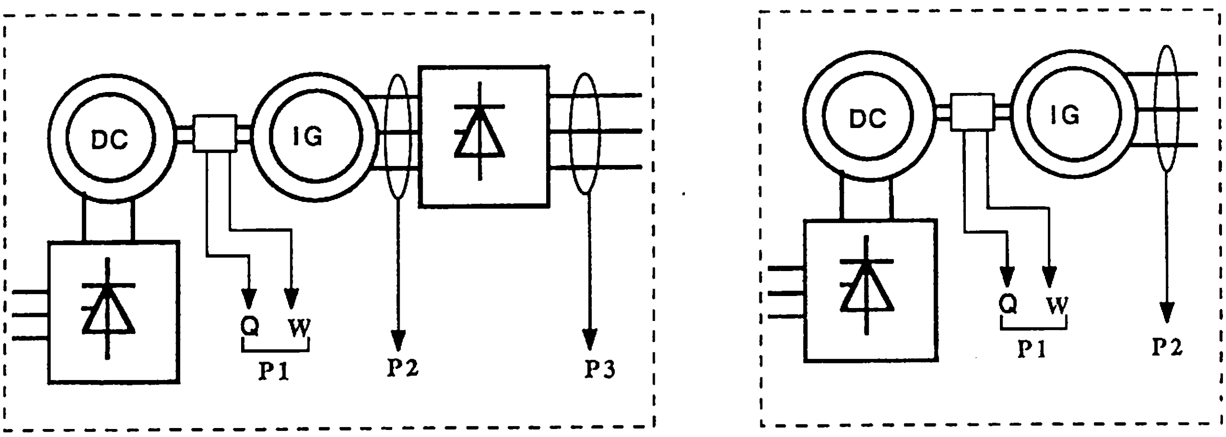

Figure 8: MEASUREMENTS OF THE LOSSES IN THE SYSTEMS.

When constant speed is used, the generator has been connected straight to the net and loaded in the same way as in the case with a more variable speed. In Figure 9 both losses in operation with more constant speed (the losses in the generator) and the losses in the whole system (incl. the generator) are shown. With loads up to 20 % of the rated load the losses in operation are higher with more constant speed than when a variable speed is used. The reason for this is that the friction and ventilation losses in the generator are greatly reduced concurrently with reduced speed.
With loads higher than 20 % rating load the losses are higher in operation with variable speed due to increasing losses in the convertor package.

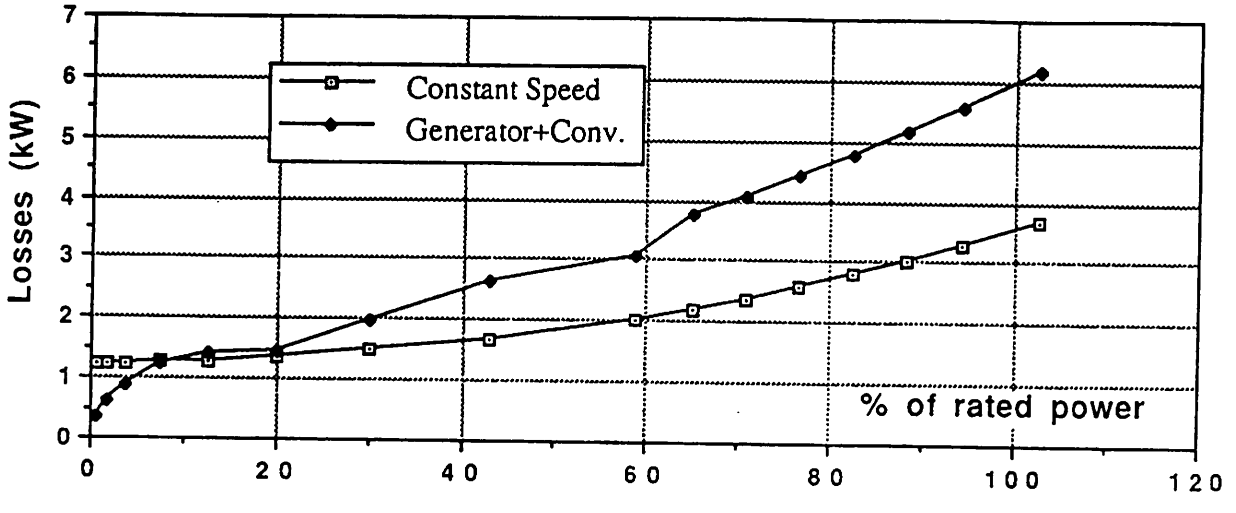

Figure 9: LOSSES IN THE SYSTEMS.

It is important to note that only losses in the electrical system are defined. It is well known that losses in the turbine are much higher during constant speed than the difference between the two systems presented here.

CONTROL OF THE WIND TURBINE

<u>The wind turbine</u>
During 1991 Chalmers test wind turbine has been reconstructed to a two-blade turbine with a teeter hinge and a variable speed drive system. The mechanical description is as follows:

Two blades, diameter 13.5 meter, profile NACA 63200,
exchangeable blade tips, manual adjustable blade pitch +- 1.5 degrees.
Manual adjustable cone angel 0, 2.5, 5 degrees.
Teeter hinge with rubber dampers; can also be set stiff.

There are two separate break systems in the wind turbine, one on the primary shaft and the other one on the secondary shaft. They are both released by the hydraulic system.
The yaw motor is hydraulic and the yaw speed is controllable from 0-7 degrees/second. The damping in the yaw system is controlled by two hydraulic valves.

The wind turbine is also equipped with a measuring system. Measurements are carried out on the rotor, in the nacelle and in the tower. The electrical output power is 40 kW.

The control

The control of the wind turbine is carried out with an industrial control computer. There are three different control modes during the operation. In the start/stop mode the turbine starts to rotate by the motoring of the induction machine, if the wind speed is over 4 m/s. The turbine is stopped by the mechanical brake, if the speed is too low. In optimal mode the turbine operates at optimal tip-speed ratio by the control of the speed [1, 6]. At 10 m/s the rated power of the wind turbine is reached and the turbine starts to stall. In the stall mode the speed is controlled via the electrical torque in the drive train so that the maximum power or speed never will be exceeded.

CONCLUSION

An electrical system with an induction generator and a frequency convertor has been designed, built and tested in the laboratory. This system makes it possible to operate the wind turbine with variable speed and to control the torque in the drive train. Laboratory tests and computer simulations show the possibility to prevent torque disturbances from the turbine to influence on the torque in the drive train. Measurements show that the efficiency of a variable speed system is higher in low wind conditions but lower in high wind conditions compared with a constant speed system.

ACKNOWLEDGEMENT

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Electric efficiency of a variable speed generator system.

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Summary

A theoretical study shows that a variable speed generator system can have a higher mean electric efficiency than a generator at constant speed. In low-wind sites, v_{median}= 5.6 m/s, the electric efficiency can be up to 7% higher than that of a grid-connected generator. In medium-wind sites, v_{median}=7 m/s, the efficiency can be 2 % higher and in high-wind sites, v_{median}=8.4 m/s, the efficiency can be the same for both systems. **The variable speed system, controlled in a proper way, must not have extra electric energy losses! If the generator control is optimized for high efficiency, the energy losses can actually be lower.** To achieve these low losses the frequency converter must allow the voltage of the generator to be lowered a lot at low output power. These results are valid for systems of ≈50-200 kW.

General

All the calculations are made with relative values (per-unit, p.u.),because the results can then be translated into different sizes of generators and into different rated wind speeds of the turbine. The energy calculations are based on the statistical information of the wind distribution curves. No time step simulations or time integrals have been used. This makes the calculation uncertain when it comes to energy capture but it has less effect on the calculated electric efficiency.

The speed of the generator is assumed to be proportional to the wind speed, in order to keep constant tip speed ratio. It is also allowed to be higher at variable speed operation than the rated speed at 50 Hz operation, 1800 rpm compared to 1500 rpm.

The higher turbine energy production is not included in the resulting electric efficiency and must, therefore, be added to show how much more mean output power the windmill is producing at variable speed.

The losses in the gearbox are also reduced by variable speed operation but that is not calculated on here.

The Cp(lambda) curve used is taken from a three-bladed pitch-regulated 12 m turbine.

Generator and converter losses

The most important part of the electrical system, when it comes to losses, is the generator. It normally has an efficiency of about 92-96% at rated power and speed, but at lower output and rated speed its efficiency can often be less than 85%. The losses in the generator are of a few different types. When comparing variable speed operation with constant speed the most important losses in the stator are the iron losses, friction losses and copper losses. The iron losses are proportional to the flux in square and proportional to the speed of the generator. Flux times speed is the voltage. A generator is designed for a specific flux, which can not be much exceeded. The voltage must be low, if the speed is low. The friction losses are both bearing friction and fan losses. The characteristics of these losses depend on the type of bearings and fan but they are roughly proportional to the generator speed in square. Finally, the copper losses are proportional to the generator current in square and independent of the speed. If the voltage is reduced, the copper losses will increase at fixed output power.

At grid-connected operation the iron losses and friction losses are constant because the generator has to operate at constant voltage and constant speed. However, the copper losses are reduced significantly with lower input power. All in all this means that the losses will be reduced when the output is reduced but they will not be zero at low input power. Therefore, the efficiency will fall rapidly, when the input power goes below 20% of the rated power. Actually the generator can not even work with less input power than 2-5% of the rated power, since the iron losses and the friction losses are so large.

There are two different ways in which to control the variable speed generator. The first and the most often way used is to keep the airgap flux constant. At variable speed operation the most obvious advantage is the reduced friction losses. Also the iron losses will be reduced, proportional to the speed, because, if the flux is kept constant, they will produce a constant braking torque. The copper losses will also be reduced, when the output power is reduced but not as much as at constant speed operation. That the copper losses are higher in the variable speed generator depends on the lower generator voltage. In this case the voltage is proportional to the speed. To use constant flux in the generator is common, because it means that a maximal torque can be produced. This is often important in motor drive systems but in a windmill there is no need for a constant torque. Instead the torque should be reduced by the square of the speed if optimal tip speed ratio is to be maintained. The flux can then actually be decreased as much as the square of the speed. This is the second way in which to control the variable speed generator.

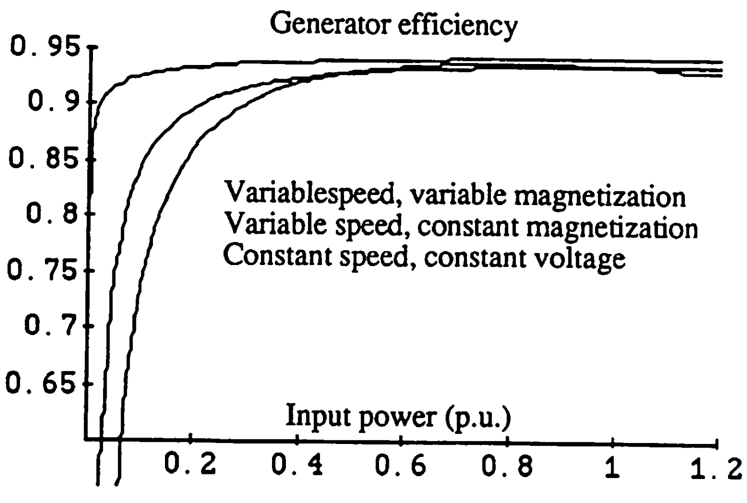


Figure 1:Efficiency of a generator with different control strategies.

To reduce the flux actually makes a significant difference to the generator efficiency. Even though the price for low flux is higher copper losses, the total losses in the generator will be lower when the flux is reduced. In Figure 1 the efficiency of the generator is plotted versus input power, when controlled in different ways. The values shown are those for a synchronous generator with a rated efficiency of about 93.5 %.

The converter losses depend a lot on the type of converter. In these calculations a diode/thyristor converter with a 98% rated efficiency is assumed. The losses for this type of converter are effected by the voltage of the generator. In Figure 2 the losses of the converter are plotted versus the input power. It shows that the converter unlike the generator has the lowest losses, if the voltage is constant at rated value. It has higher losses if it is fed by a generator with constant flux and variable speed and the losses are even higher if it is fed by a variable speed-reduced flux generator. However, it can be seen that the difference in losses is in the order of 0.5% which is much lower than the difference in generator losses. Therefore, the control is designed to minimize the generator losses not the converter losses.

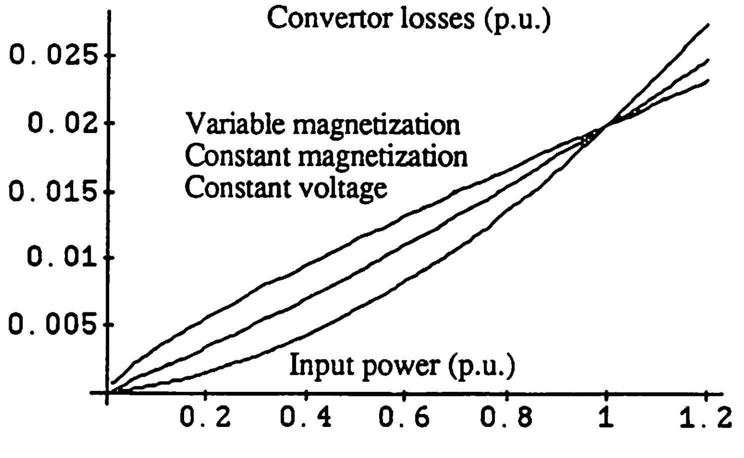


Figure 2: Losses in the frequency converter.

Energy losses

The objective in the design of a windmill generator system is not to maximize the rated efficiency but to minimize the annual electric energy loss i.e.to maximize the mean electric efficiency. The importance of efficiency at different input power depends on the wind distribution of the site of the windmill.

In Figure 3 it can bee seen that the electric losses of the variable speed system can be lower than those of a constant speed system up to wind speeds of about 70% of the rated wind speed. In Figure 4 the probability of different wind speeds at three different sites is plotted, namely the wind probability curves for a low-wind a medium-wind and a high-wind site. The area under each curve shows how often the wind speed is below a certain value. For all the three sites the turbine runs more often below than above 70 % of the rated wind speed. From this simple comparison it can be seen that the lower efficiency at rated power is not especially important compared to the efficiency of the system at less then 70 % of its rated wind speed (= less than 35% of its rated power).

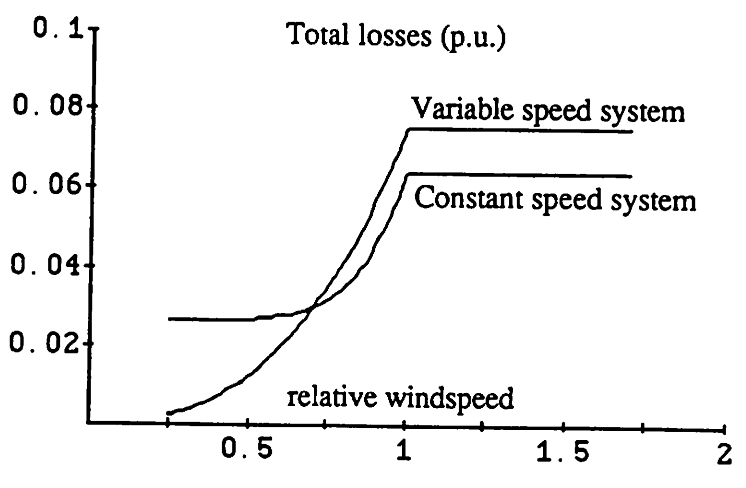


Figure 3. Electric losses at different wind speeds for a variable speed and a constant speed system.

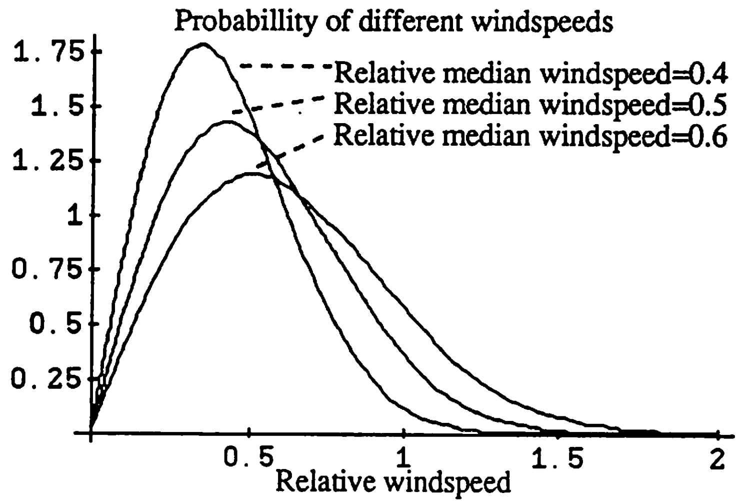


Figure 4. Wind probability curves for different median-wind speeds.

Calculations

Index "CS" stands for Constant Speed and "VS" for Variable Speed.
U= generator voltage
n = generator speed
v = wind speed
P1 = input power of the generator

The calculations can be made in 7 different steps:

1 Calculation of wind distribution:

$w(v)$ = weibull distribution

(with $c = 2$ in these calculations)

2 Determining C_{PVS}, $C_P(v)$ and C_{Pmax} :

For this turbine C_{Pmax} is here 0.46 and C_{PVS} (= mean C_p for the variable speed turbine) is assumed to be 0.44 on an average which will be achieved if the tip speed ratio can be kept within ±30% of its optimal value. $C_P(v)$ is C_p as a function of the wind speed for the constant speed turbine. This function varies for the different median wind speeds in order to optimize the energy capture.

3 Calculation of input power distribution:

The input power of the generator varies for constant speed operation and variable speed operation due to the different turbine efficiency. The value of C_P is divided by C_{Pmax} in order to get a relative value of P1; v and w(v) are already normalized.

$$P1_{CS}(v) = v^3\, C_P(v) \,/\, C_{Pmax}$$
$$P1_{VS}(v) = v^3\, C_{PVS} \,/\, C_{Pmax}$$

4 Calculation of energy capture:

$$E_{CS} = \int P1_{CS}(v)\; w(v)\; dv$$
$$E_{VS} = \int P1_{VS}(v)\; w(v)\; dv$$

5 Definition of generator and convertor losses:

$L_G(P1,U,n)$ $\qquad$ $L_C(P1,U)$

6 Calculation of electric energy loss:

The interval of the integrals is not the same in constant speed operation as in variable speed operation.

$$E_{LCS} = \int [L_G(P1_{VS},1,1)]\; w(v)\; dv \qquad \{\ U=1 \text{ and } n=1\ \}$$
$$E_{LVS} = \int [L_G(P1_{VS},U,n)+L_C(P1_{VS},U)]\; w(v)\; dv$$

7 Calculation of mean electric efficiency:

$$\eta_{el.VS} = 1 - \frac{E_{LVS}}{E_{VS}} \qquad \eta_{el.CS} = 1 - \frac{E_{LCS}}{E_{CS}}$$

The extra generator losses due to current harmonics are not included in the above calculation Since they are difficult to calculate they are instead included as an extra efficiency loss of 1% at all different input powers. The value1% comes from measurements on a 50 kW generator.

Results

The results of the calculations are presented as the mean electrical efficiency for three different median wind speeds. The wind speed is then related to the rated wind speed. However, to get a better comparison the relative wind speeds are also translated into m/s for a windmill with a rated wind speed of 14 m/s.

The mean electric efficiency is calculated as 1 minus the annual electric energy loss divided by the annual turbine energy capture. This means that also the energy capture has been calculated, and the values are also presented in Table 1. Too much attention should not be paid to these values, because it is uncertain how large the error will be when the energy capture is calculated from 10 min. average wind distributions. The error in the calculation of the energy capture does, however, not effect the electric efficiency much. Instead it is much more dependent on how the losses are distributed among the different generators.

Relative median wind speed	Variable speed		Constant speed	
	Electric efficiency	Capacity factor	Electric efficiency	Capacity factor
0.4 (5.6 m/s)	88%	0.142	81%	0.132
0.5 (7.0 m/s)	89%	0.248	87%	0.238
0.6 (8.4 m/s)	90%	0.355	90%	0.347

Table 1. The electric mean efficiency on different wind conditions.

Compared to the constant speed generator, high efficiency can only be achieved with a high efficiancy converter. In a few variable speed systems with low efficiency converters the total mean efficiency may even be lower with optimized control than that of a constant speed generator. To design a high efficient system is no problem today, since many converters have a rated efficiency of 98-99 %.

On a comparison between variable speed and constant speed the generator has been assumed to be the same, i.e. a synchronous generator. This might seem strange, since almost all constant speed windmills have asynchronous generators. The type of generator is not important for the calculations. Instead it is important how large the different types of losses are. These do not differ especially much between these two types of generators so the result has significance even when comparing an asynchronous generator with a synchronous one.

Even though there are some uncertanties about the usual distribution of losses in a 100 kW generator these results show that there is a lot of energy to win in controlling the variable speed system in the most efficient way.

Contribution to the proceedings

Electrical systems for wind turbines with constant or variable speed

Eskil Ulen, The Aeronautical Research Institute of Sweden

VARIABLE SPEED

BROAD RANGE

- OPERATION AT NEAR OPTIMAL TIP SPEED RATIO

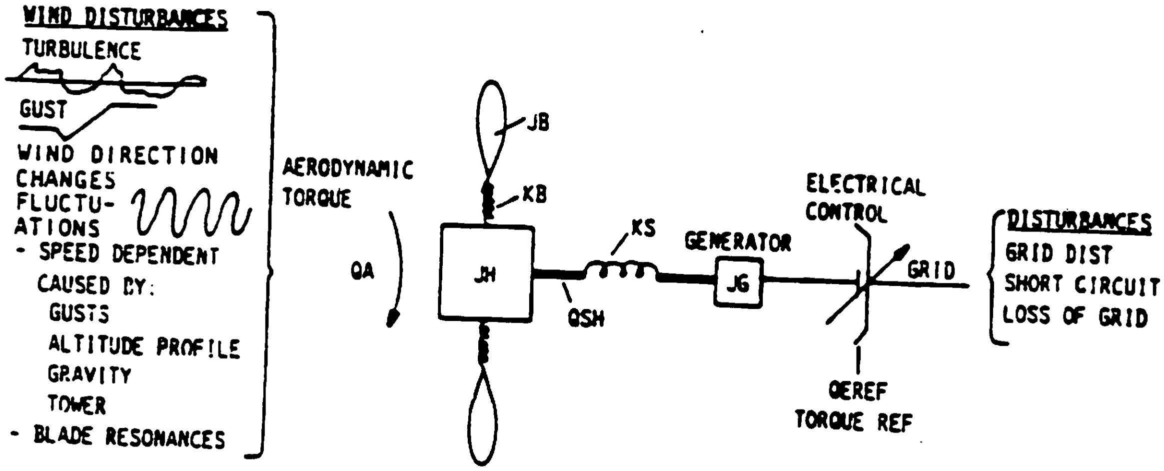
- INCREASED ENERGY PRODUCTION

- REDUCED MECHANICAL STRESSES

- REDUCED ACOUSTIC NOISE

- FAST CONTROL OF ELECTRICAL TORQUE

The following figure shows a simplified scheme (reduced to the turbin side of the gear).



QA= aerodynamique torque
JT= JH+2JB=turbin inertia
KS= drive shaft spring constant

JG = generator inertia
QSH= shaft torque
QE = electrical torque

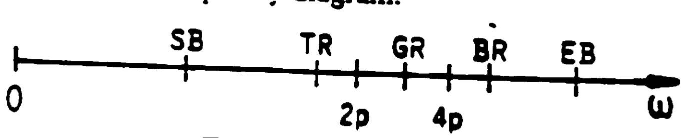
Fig. 2.4

Mainly the following resonances are of interest for control of the torsional dynamics:

GR (generator resonance) $\omega \sim \sqrt{KS/JG}$; supposed $JG \ll JT$
BR (blade resonance) blade structure edgewise
TR tower resonance (axial, lateral)

Also the flapwise movement and the thrust is of interest:

Tycical frequency diagram:



Bandwidth:
SB speed control
EB electrical control

Fig. 2.5

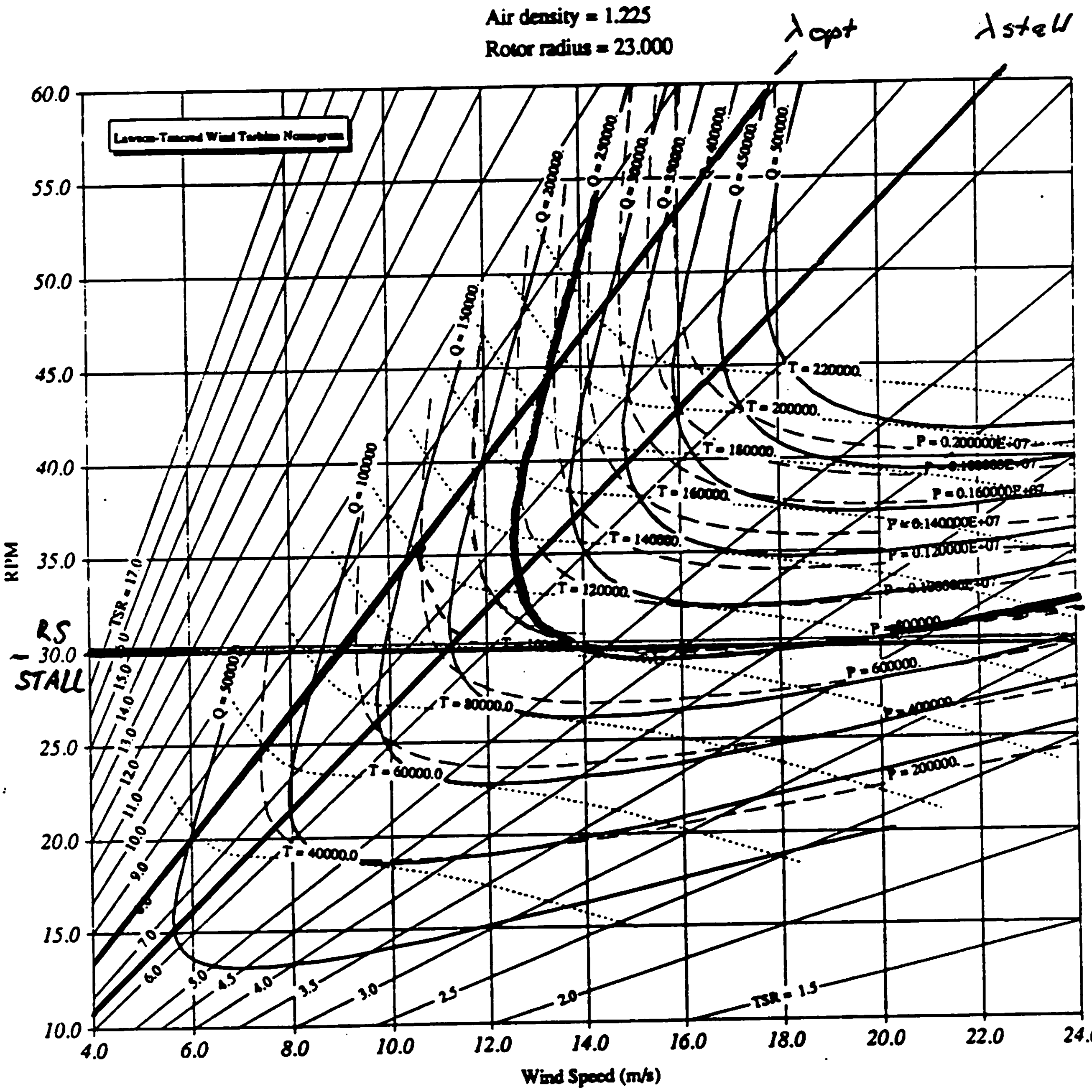
LOW FREQUENCIES (ω<BR,GR)

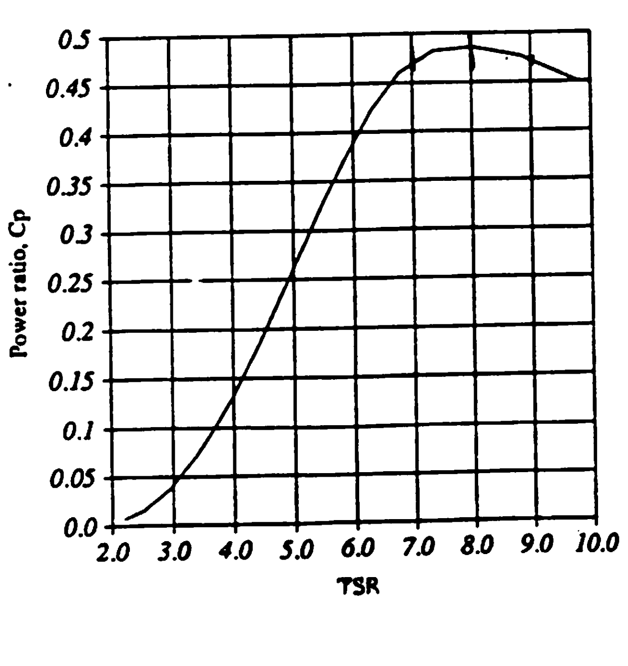
From the figure:

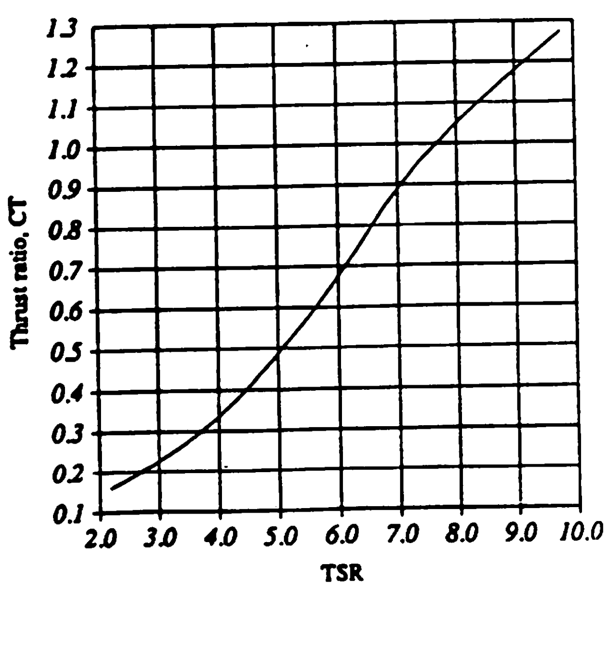
$$QSH = QE + \frac{JG}{JG + JT} \times QA$$

From control point of view JT,JT/JG and the bandwidth of the torque control loop should be as high as possible.

X_800 (Pitch = -4 deg)





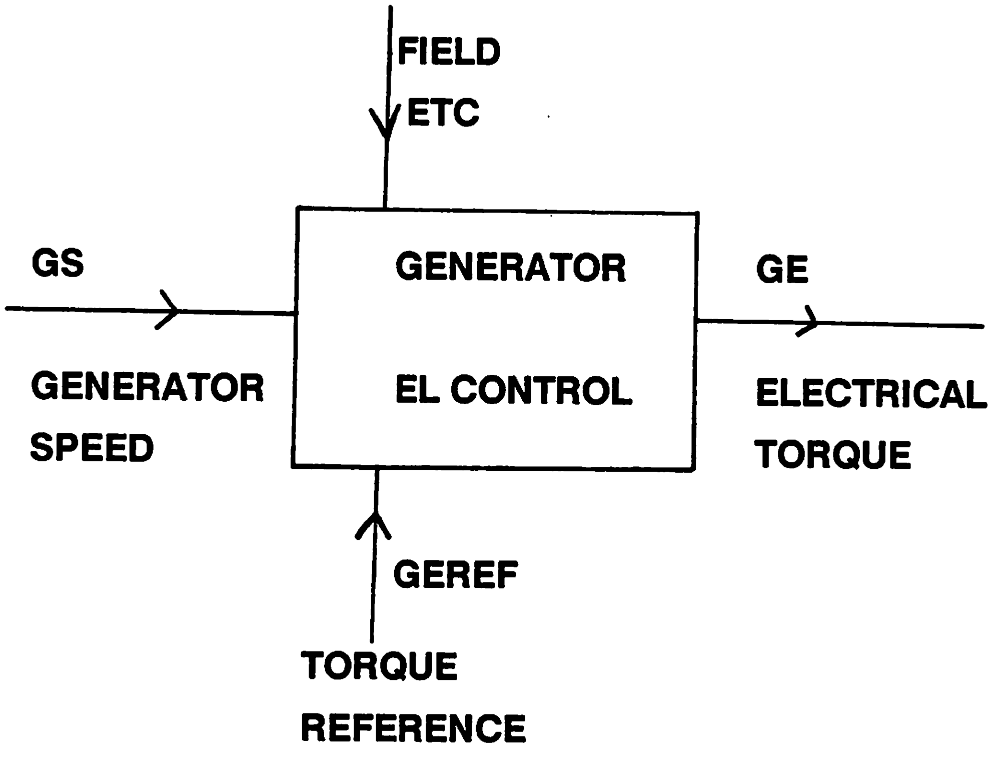


ELECTRICAL CONTROL

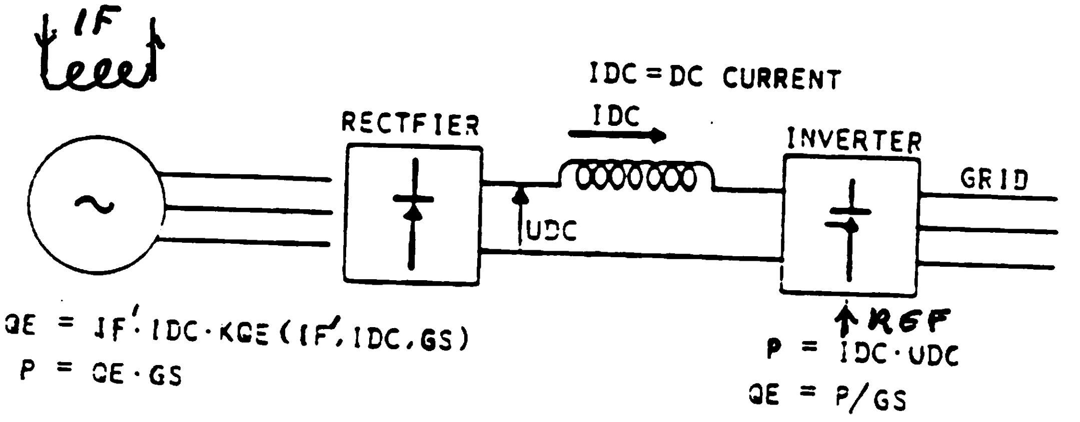
ACCURACY

BAND WIDTH

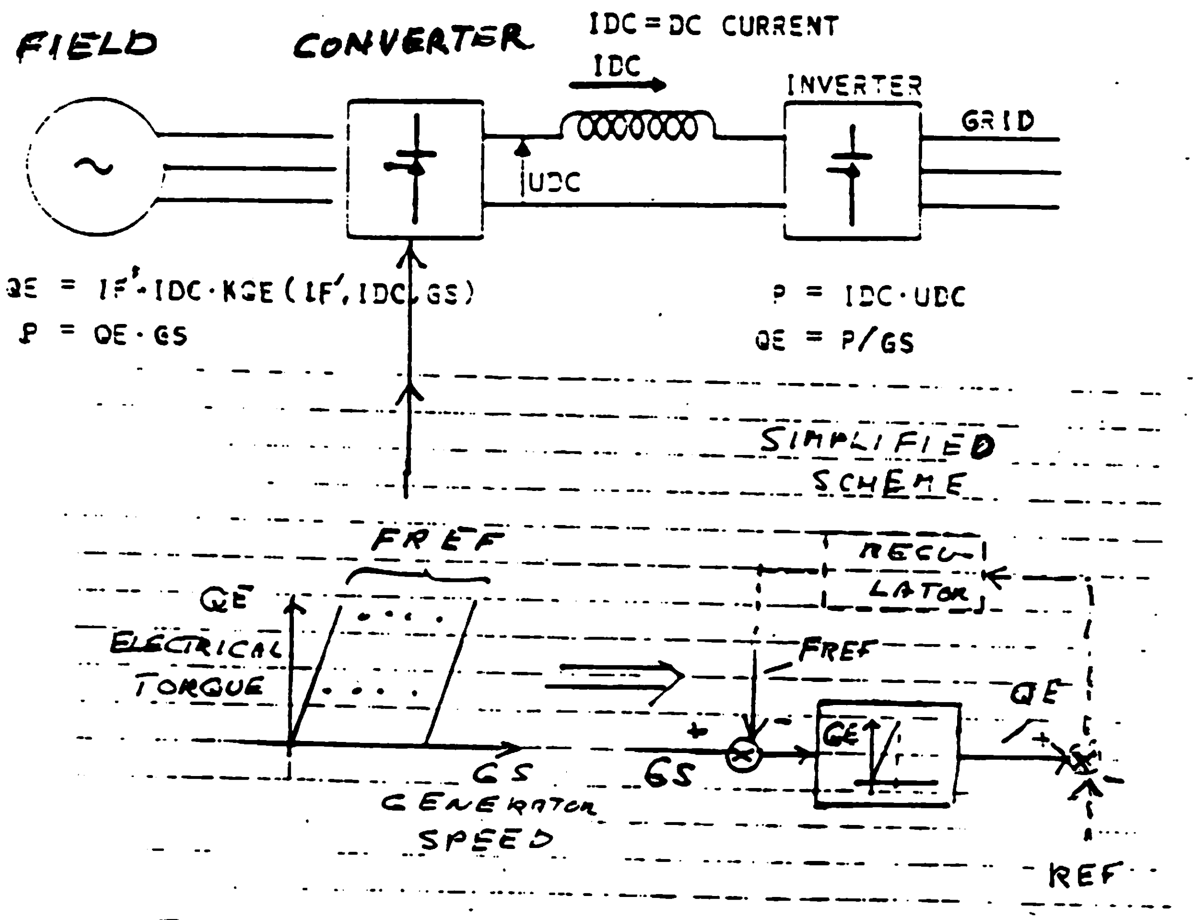
GS DEPENDANCE SMALL



SYNCHRONOUS GENERATOR



INDUCTION GENERATOR



MULTIVARIABLE -

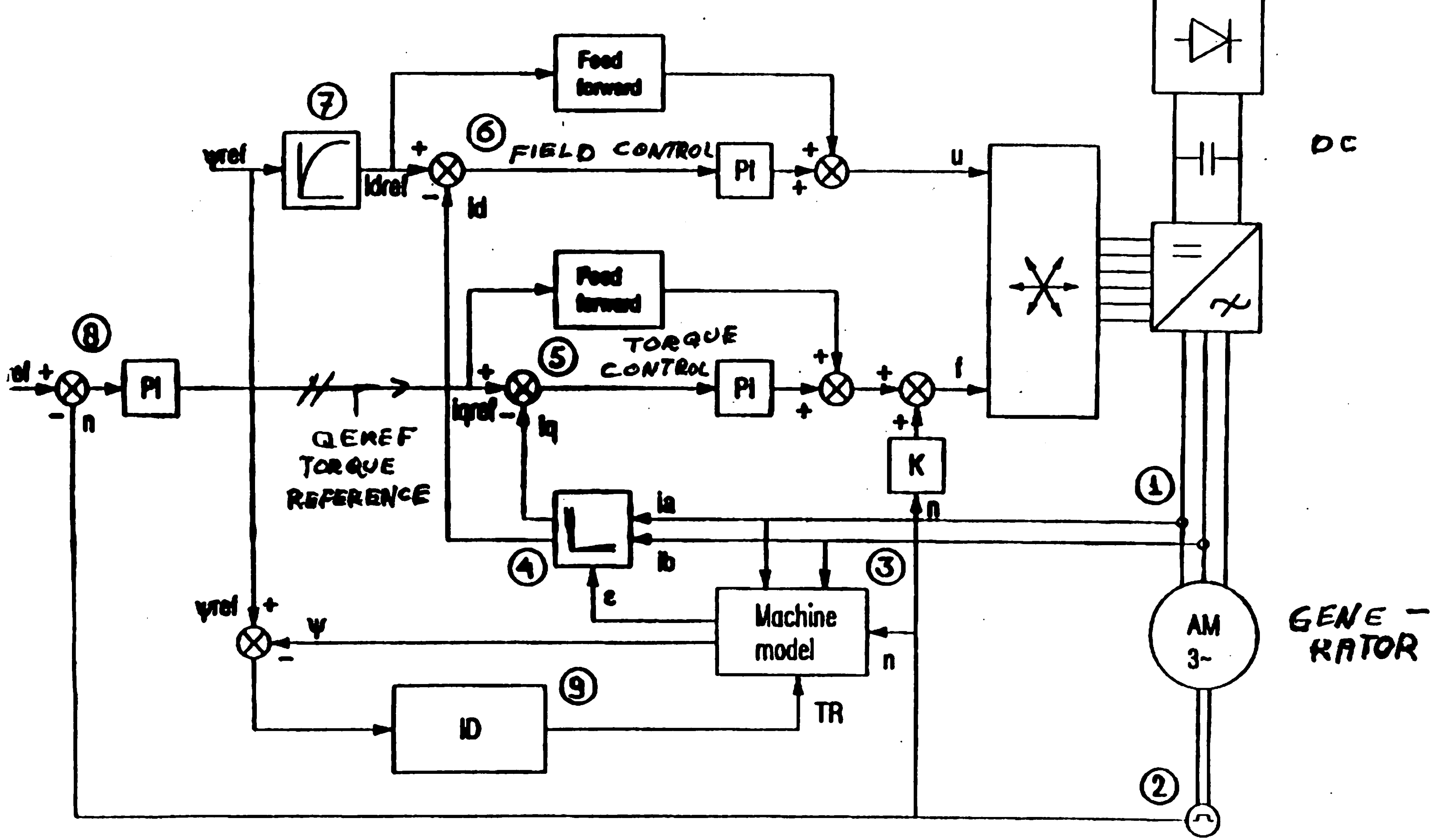
BUY FROM A SUPPLIER

THEY NORMALLY HAVE SOME MEANS OF CONTROL (TORQUE AND FIELD) INCLUDED IN THEIR DESIGN. FROM SEVERAL POINTS OF VIEW IT COULD BE ADVANTAGEOUS IN A PROJECT TO USE THIS.

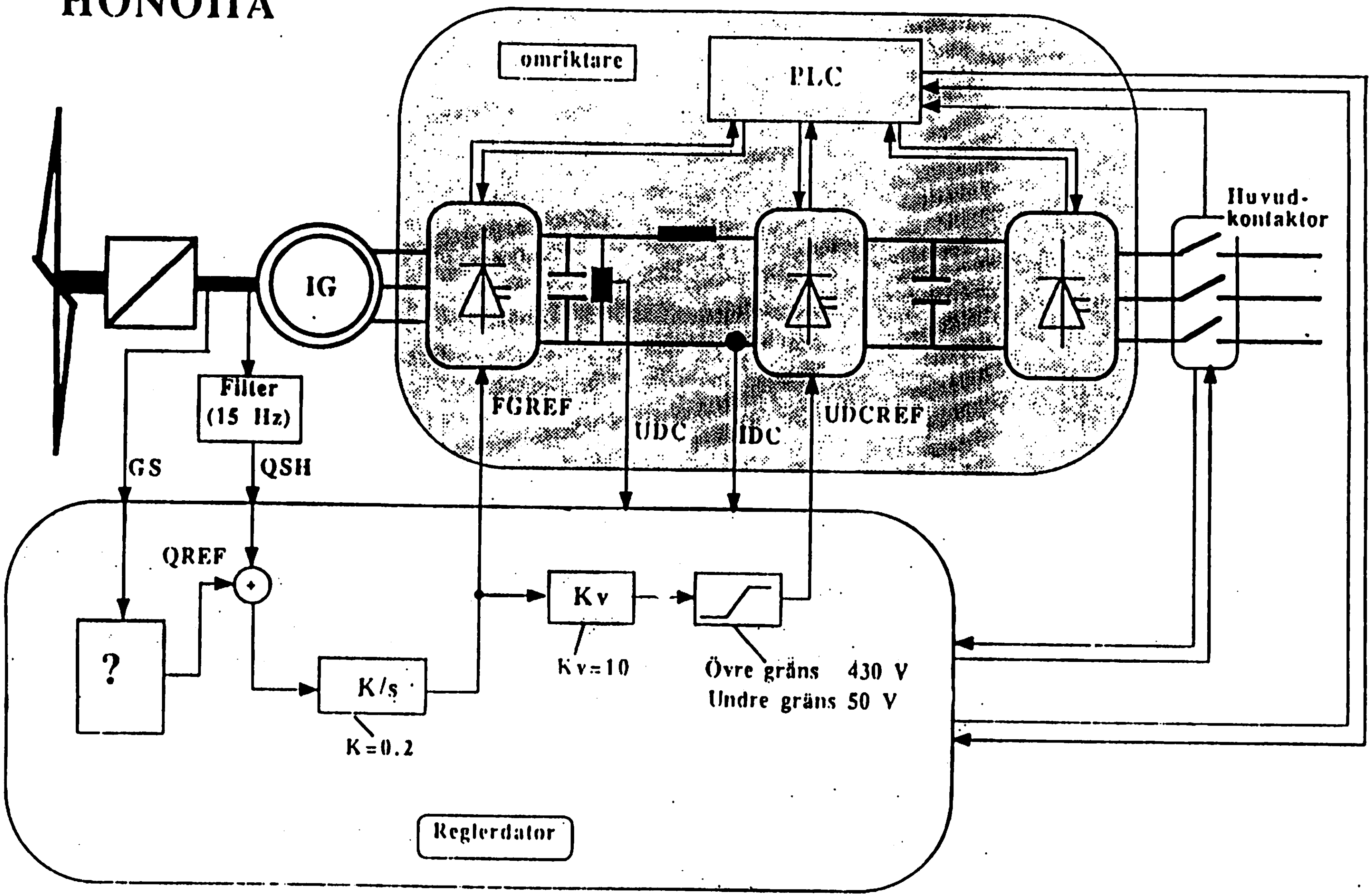
HOW CAN IT BE MODELLED?

CAN IT BE CHANGED TO BETTER SUITE OUR PURPOSE?

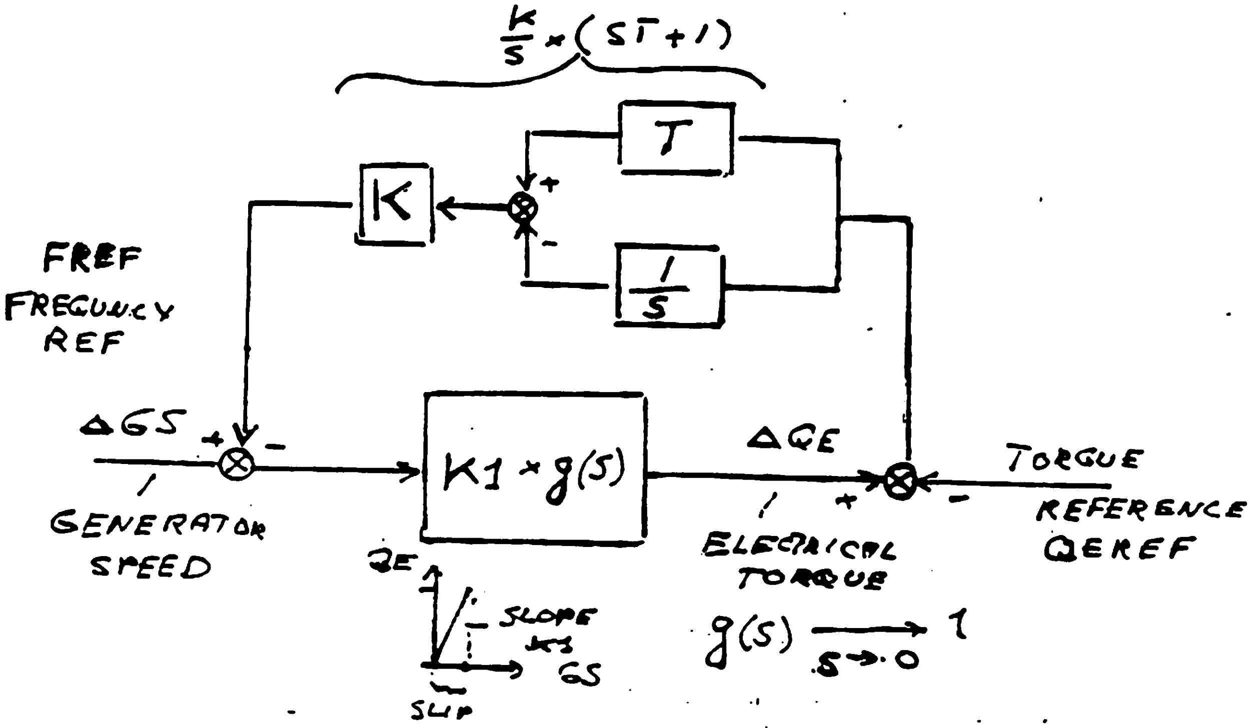
FIGURE 1
VECTOR CONTROL



HÖNÖIIA


omriktare
PLC
Huvud-
kontaktor
IG
Filter
(15 Hz)
FGREF
UDC
IDC
UDCREF
GS
QSH
QREF
?
K/s
K=0.2
Kv
Kv=10
Övre gräns 430 V
Undre gräns 50 V
Reglerdator

SUPPOSE THE FOLLOWING SIMPLE MODEL FOR THE TORQUE CONTROL



THE TRANSFER FUNCTION $\frac{\Delta QE}{\Delta GS}$ IS OF INTEREST

If the loop gain is high this transfer function will approximately be the inverse of the feedback operator for frequences lower than the bandwith.We therefore have:

$$\frac{\Delta QE}{\Delta \dot{G}S} \sim \frac{1}{K} \times \frac{1}{S \cdot T + 1}$$

This means an added inertia on the generator side equal to

$$JGE = \frac{1}{K} \times \frac{1}{S \cdot T + 1}$$

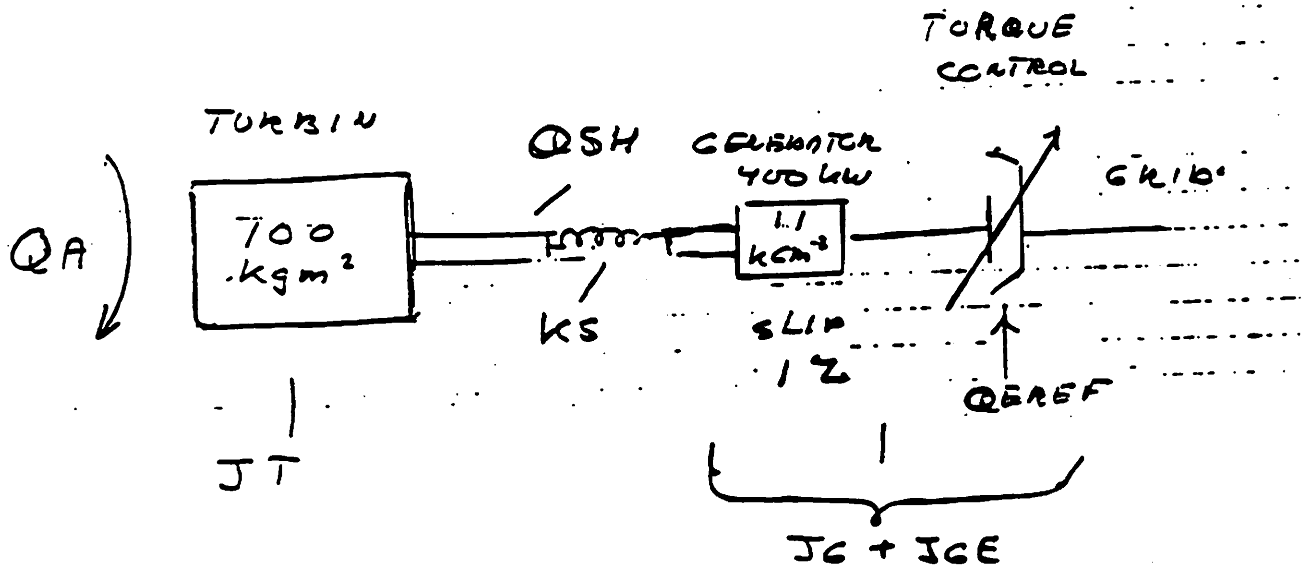
The values of K and T is therefor of interest.

SUPPOSE $K \times K1 = 50 \frac{1}{SEC}$

$$K = 0{,}02 \frac{RAD/SEC}{Nm\,SEC}$$

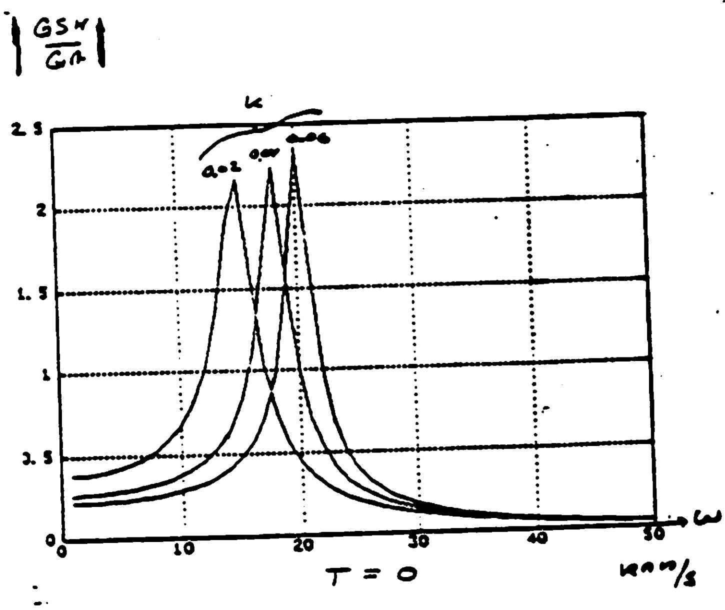
$$K1 = 2500 \frac{Nm}{RAD/SEC}$$

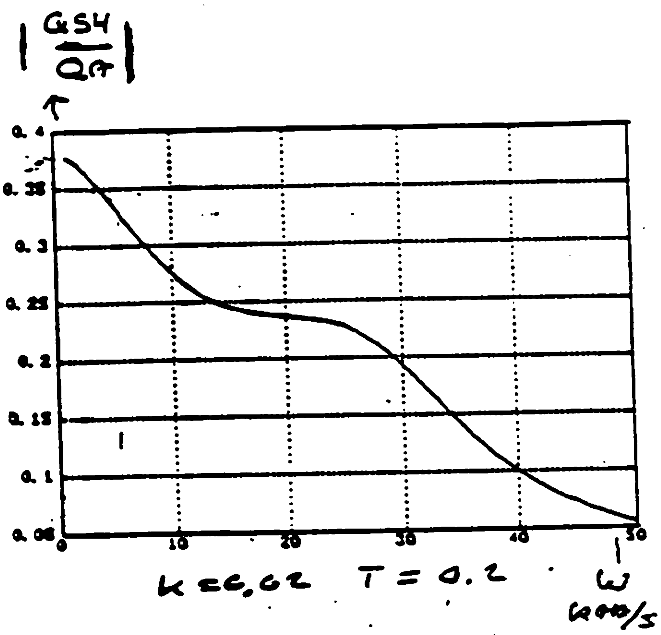
GENERATOR SLIP 1 %



For low frequences $\frac{QSH}{QA} \sim \frac{JG + JGE}{JT + JG + JGE}$

Simulations shows that the value of T is important for the damping of the resonance in the drive train.The following figures shows some simulations(BODE-diagram).

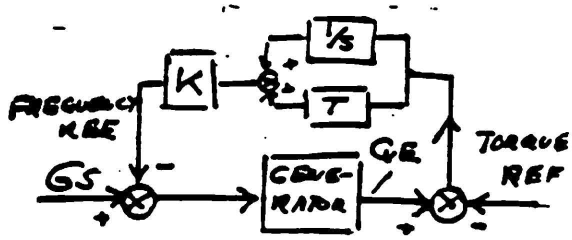


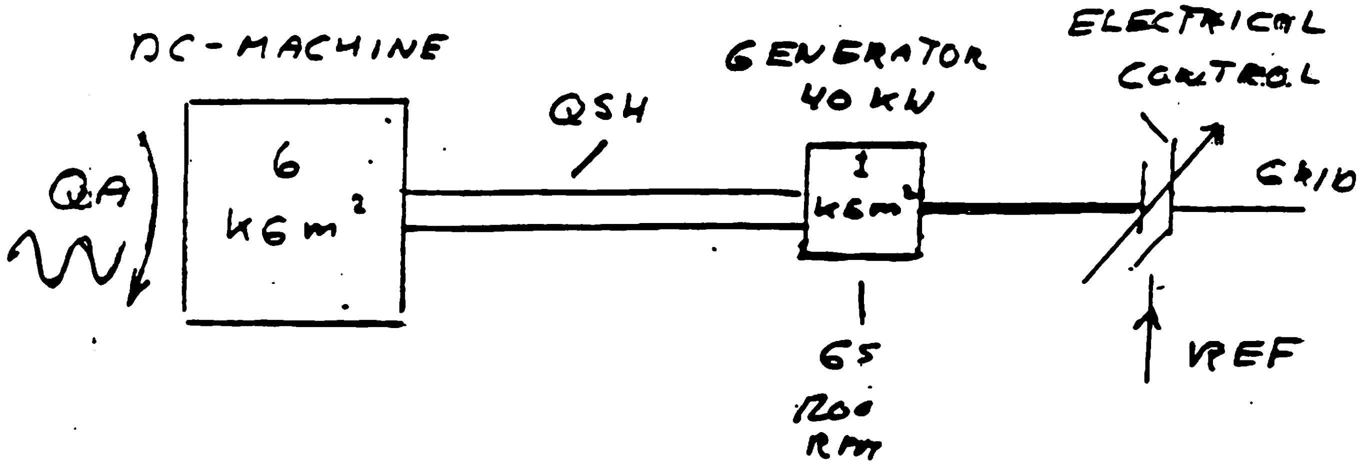


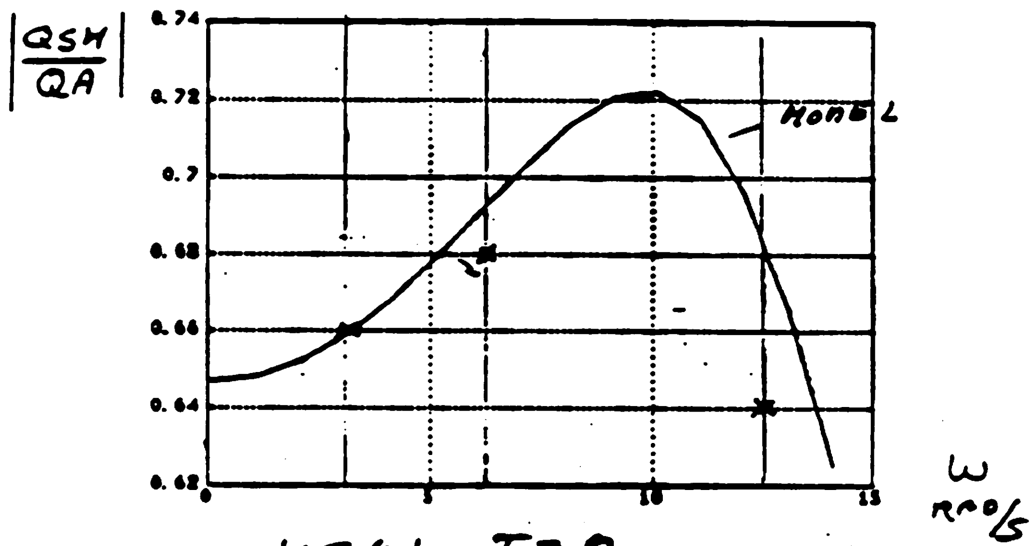
$JGE = \frac{1}{k} = 50$ For $k = 0{,}02$ $\qquad JGE = 50 \cdot \frac{1}{s \cdot 0{,}2 + 1}$

Our conclusion is that we need the parameters K and T of the PI-regulator

MEASURMENTS AT CHALMERS UNIVERSITY OF TECHNOLOY

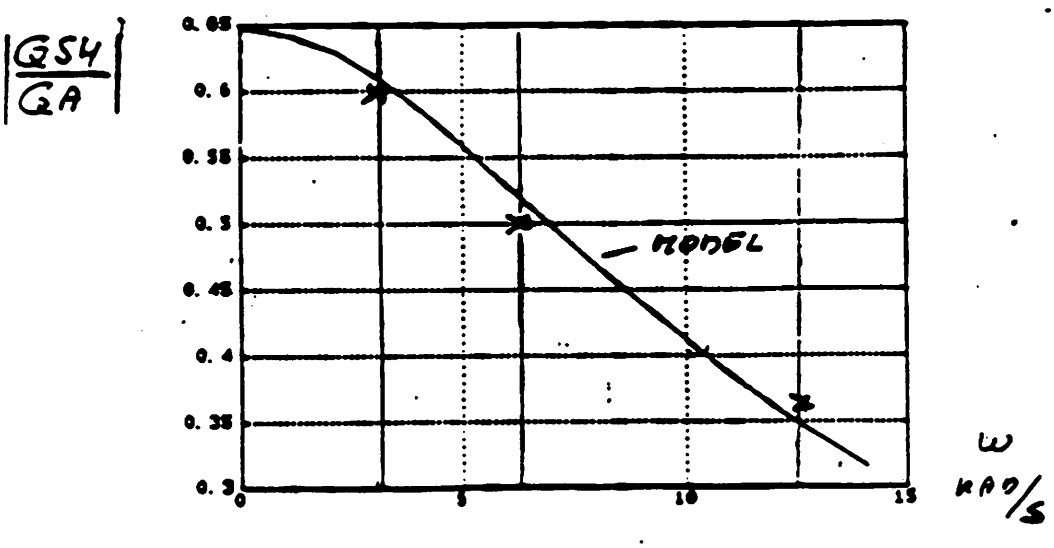






K = 0.1 T = 0

× MEASURED VALUES



FEED FORWARD POSSIBILITIES

MEASUREMENTS

RS - GS

$\dot{GS}$

QSH

THE SHAFT TORQUE CAN BE MEASURED AT THE GEAR MOUNTING

OBSERVER OR KALMAN FILTER

INTERESTING CASE:

ESTIMATING QSH USING

RS AND QE

RS = ROTOR SPEDD
GS = GENERATOR SPEED
$\dot{GS}$ = GENERATOR ACCELERATION
QSH = SHAFT TORQUE

VARIABLE-SPEED WIND TURBINE GENERATOR WITH LOW LINE INTERACTIONS

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1 Introduction

As well as giving lower torque pulsations on the drive train of a wind turbine a variable speed generator system causes a smoother electrical power output than a fixed speed system. Simultaneous measurements of power output at the north Germany windfarm "Westküste" are shown in Fig. 1 [1]. The higher frequency fluctuations of power output are much reduced, although those of lower frequency remain. When using a variable speed turbine power electronics are required, and often harmonics and reactive components of power are fed into the local network. Depending on the size of grid impedance and the type of inverter these line interactions may cause disturbances on the consumer side and in the network ripple control system. Therefore a careful comparison between the several possible generator systems has to be carried out.

2. Doubly-Fed AC Machine

Studies have shown, that a speed range of about 30% is sufficient for maximising the energy output [2], and a suitable control strategy can heavily reduce the mechanical stresses without a significant drop in efficiency. A wound-rotor ac machine with doubly-fed circuitry (Fig. 2) is a favourable solution because of the reduced size of the power converter. In addition it has the desirable electrical properties of a synchronous machine. As shown in Fig. 3 the generator may be operated above or below synchronous speed and its reactive power can be controlled to be positive, negative or zero as required. In the past cycloconverter have been used in the rotor circuit (GROWIAN, MOD 5) [3], with the disadvantage that considerable harmonics were caused. Nowadays, the declining cost of power electronics permit the use of a dc link voltage-source PWM converter, consisting of two GTO- or transistor inverters, one on the machine side and one on the grid side (Fig. 4). With a switching frequency of more than 1 kHz the currents are nearly sinusoidal, and the interaction between the generator and the line is minimized. This is because the low order rotor and grid current harmonics are strongly suppressed, and the higher order harmonics appear with constant frequencies in the grid current and so can easily be filtered out.

2.1 Control System

In order to realize a decoupled speed-independent control of active and reactive power a mathematical model of a generator which is suitable for field-oriented control [5] was developed [4]. The inputs to the model (Fig. 5) are the three impressed rotor currents, the RMS-value of the stator voltage U_S, and the angular velocity of the grid voltage vector ω_0 and the load torque m_L. The outputs are the mechanical angular velocity ω, the active stator power P_S and the reactive stator power Q_S. The d-q components of the rotor currents are directly related to reactive and active power respectively, and this leads to the field-oriented control scheme of a doubly-fed machine illustrated in Fig. 6. The two-stage control scheme, consisting of two controllers each for power and rotor current, is implemented in a DSP (TMS 32020), and the controllers use a synchronously rotating set of field coordinates.

The control of the line-side GTO inverter takes place in coordinates moving synchronously with the grid voltage, with all quantities being dc values in steady-state. The control scheme consists of dc-link voltage- and grid current-controllers and is implemented in the same DSP [2].

2.2 Experimental Results

The proposed control scheme was tested on a four-pole 22 kW wound-rotor induction generator with two GTO-PWM inverters. The behaviour of the rotor and drive-train of a large (MW-scale) wind turbine was simulated by a 64 kW dc motor with torque- and speed-control.

Fig. 7 demonstrates the excellent decoupling of stator active and reactive power flows. The fast step in active power has no effect on the reactive power and vice versa.

As a result of the near-sinusoidal rotor currents there are only negligible harmonics in the stator currents which are induced over the air gap. Fig. 8 shows a measured spectrum of stator current with a GTO inverter (1 kHz switching frequency) in the rotor circuit. If the rotor power flow were less then 100 kVA then a transistor inverter would be more suitable because the higher switching frequency then possible would almost completely eliminate all harmonics.

2.3 Efficiency of Doubly-Fed AC Generator

Fig. 9 shows the measured efficiency curves of a 22 kW ac generator used firstly as a squirrel cage machine and then as a doubly-fed machine supplied by a dc-link voltage-source PWM converter.

Above 20% of rated power the machine efficiencies are the same because the currents in the doubly-fed machine remain nearly sinusoidal and cause no additional copper and core losses. In measurements taken from the doubly-fed machine with a speed range of 30% ($0.85\ n_0 < n < 1.15\ n_0$) the converter power amounted to only 15% of the total power. Hence the overall efficiency was at most 2% less than that of the single squirrel-cage machine.

Acknowledgements

This work was supported by a grant from the German Federal Ministry for Research and Technology, Bonn.

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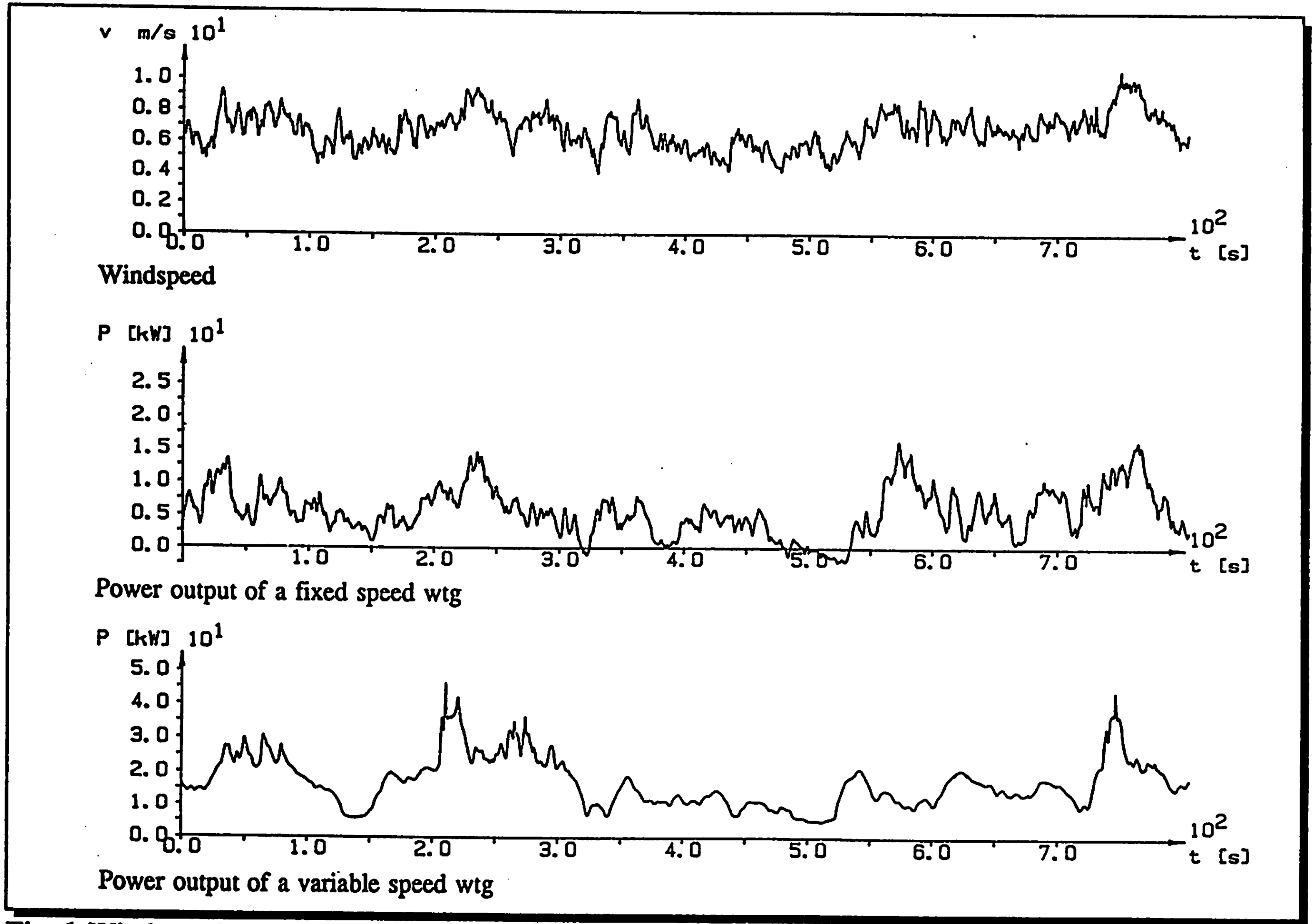

Fig. 1 Windspeed and power outputs of fixed and variable speed wind turbine generator

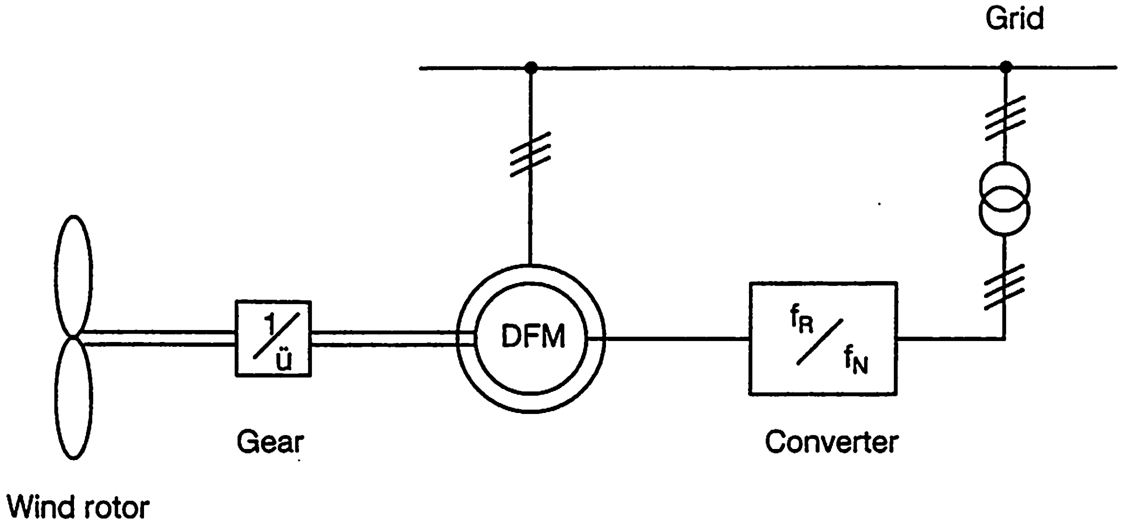

Fig.2: Doubly-Fed AC Generator System

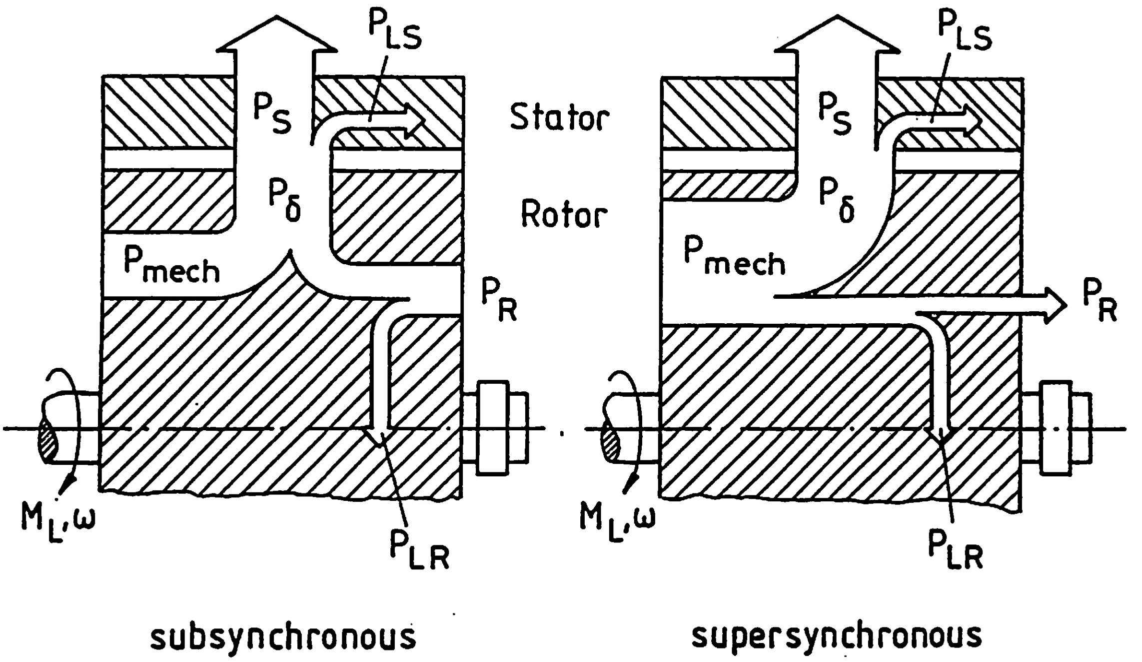

Fig.3: Power Flow of a Doubly-Fed AC Generator

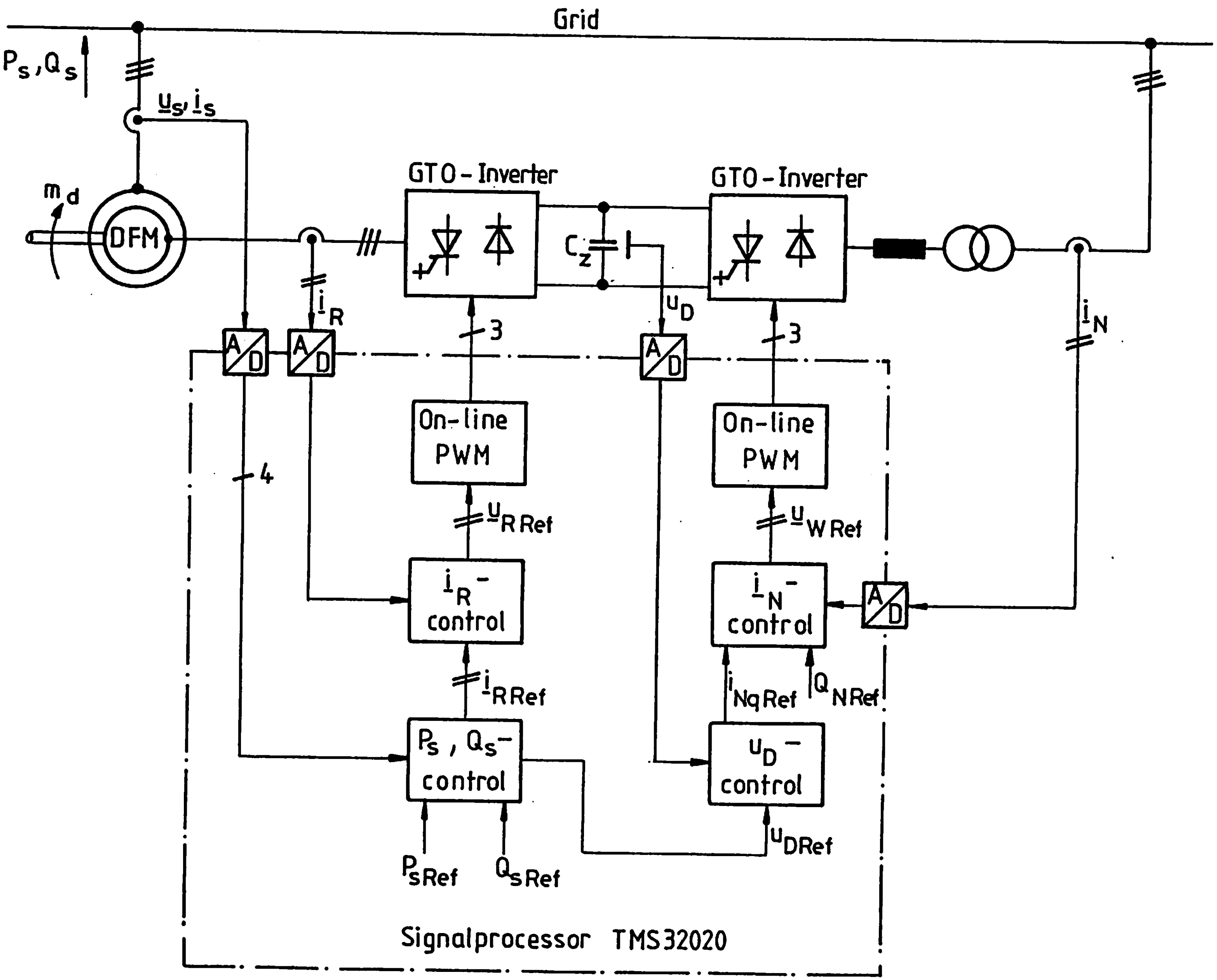

Fig. 4: Doubly-Fed AC-Machine with a Voltage Source GTO Converter

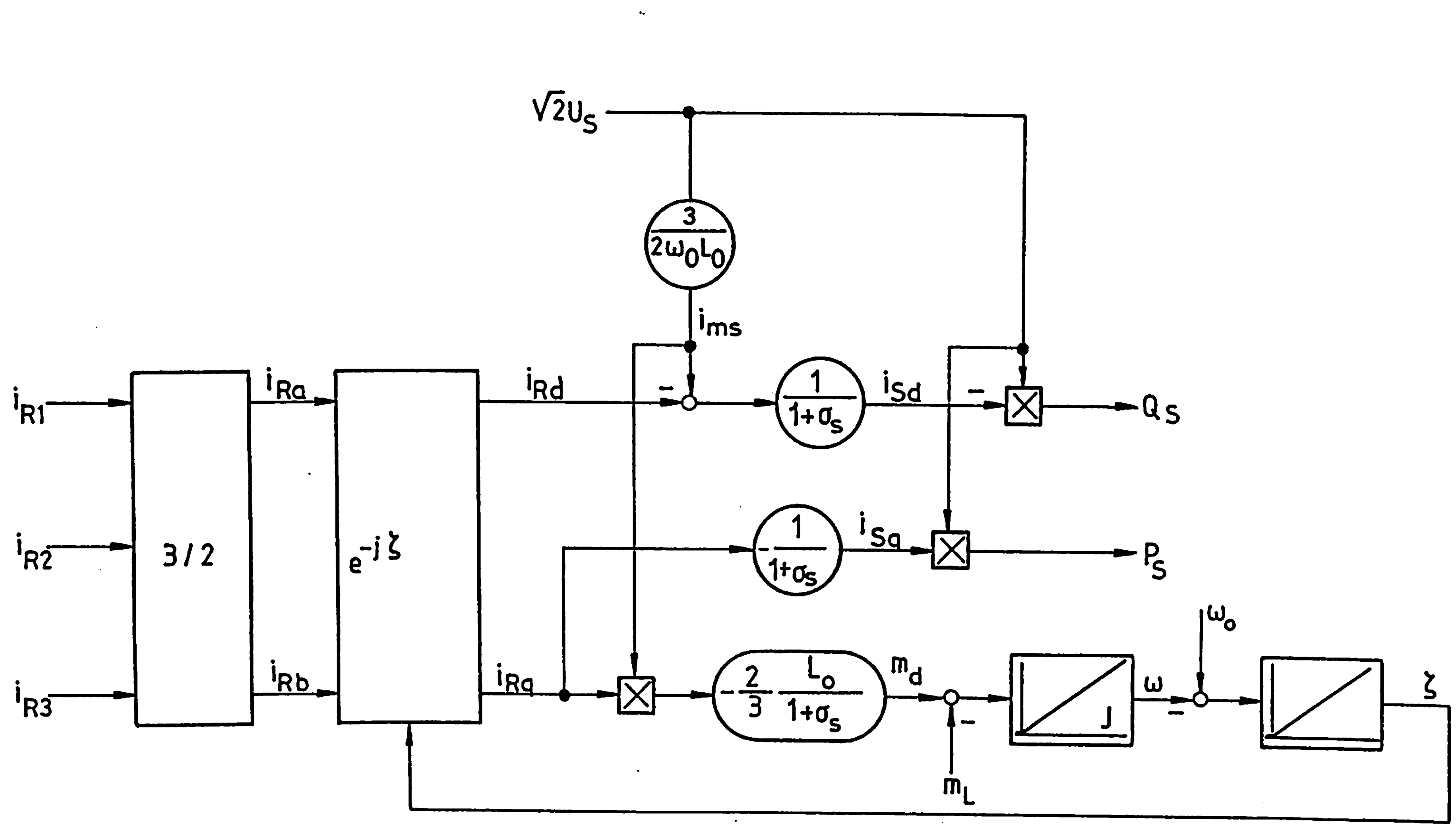

Fig.5: Block Diagram of a Doubly-Fed Machine

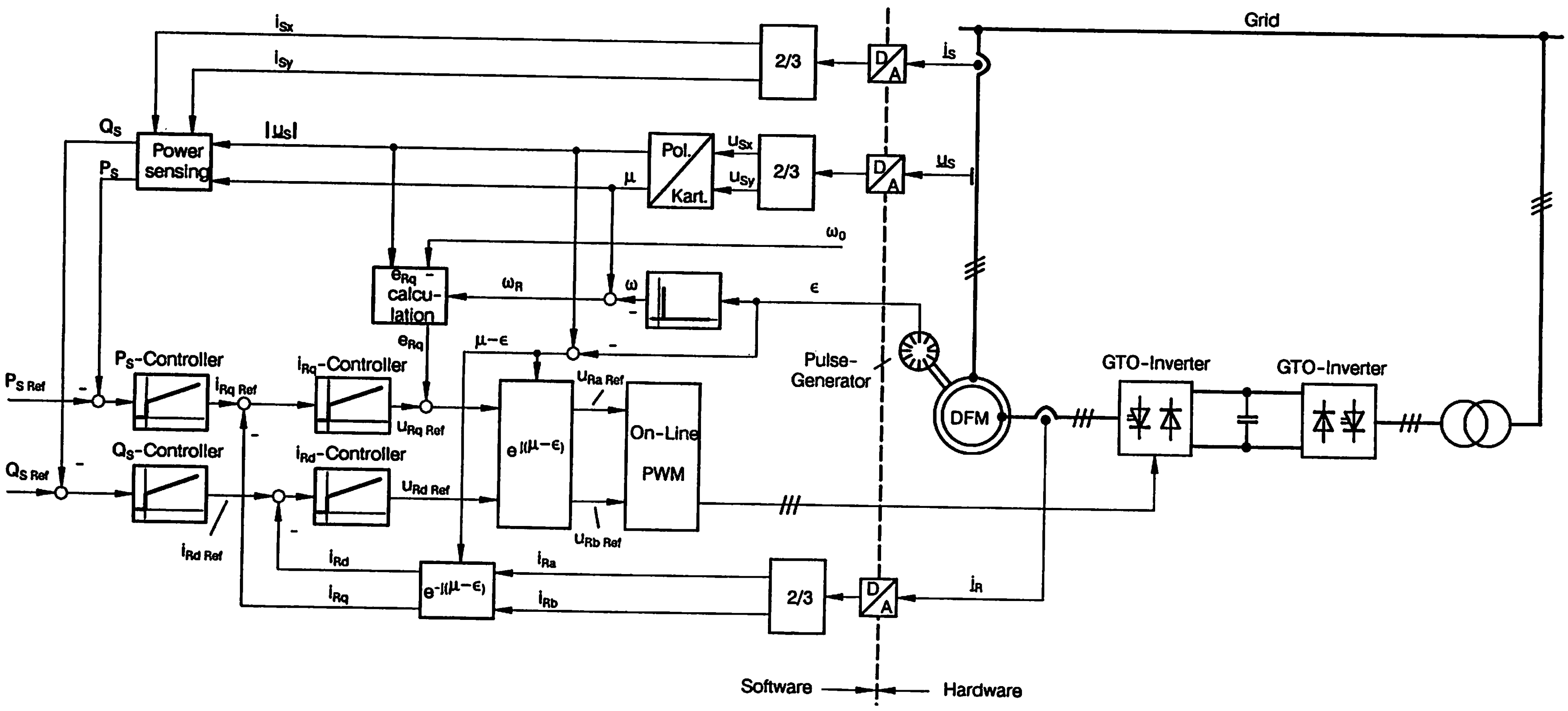

Fig. 6 : Power Control of a Doubly–Fed AC Generator

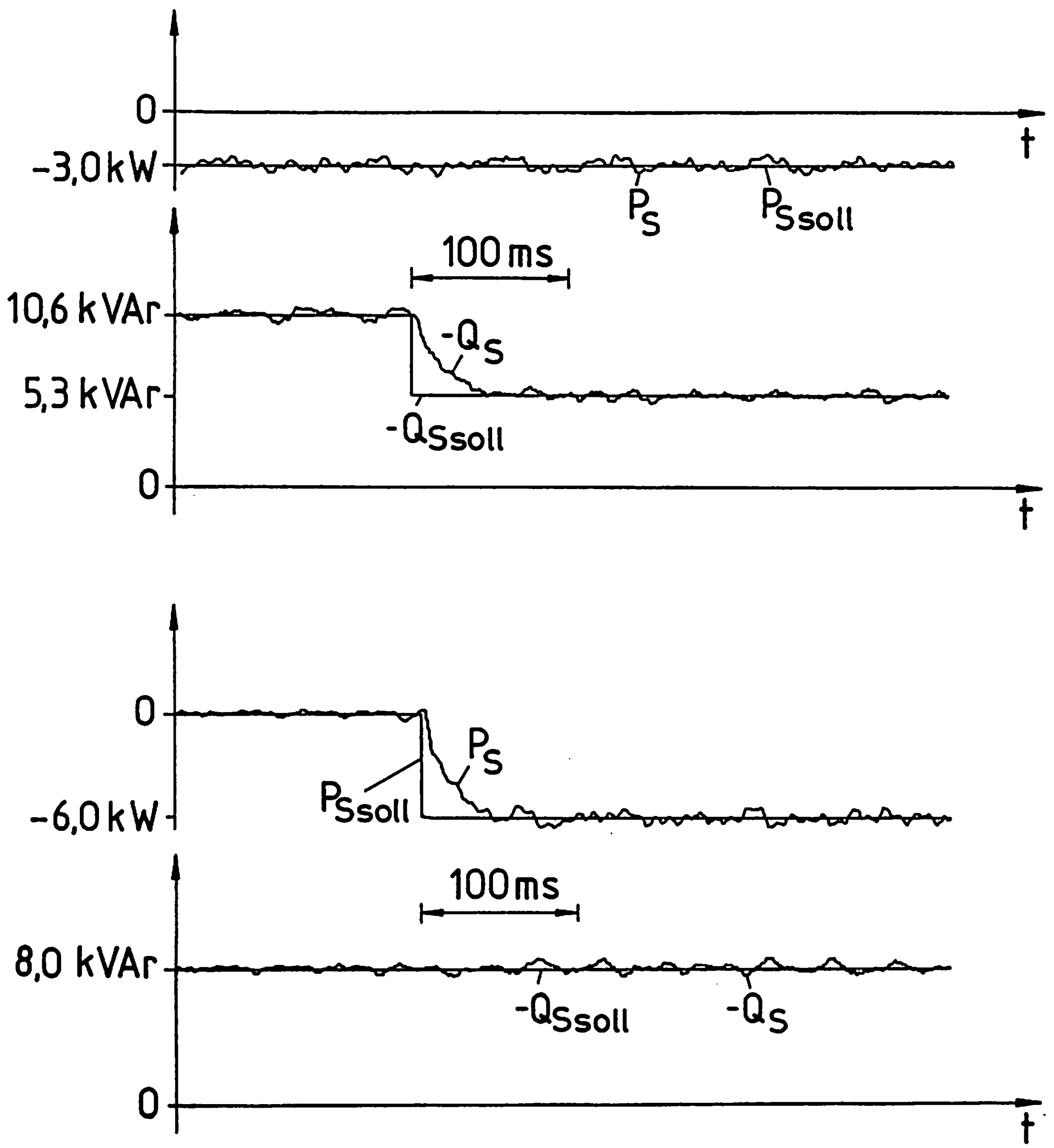

Fig. 7: Step Response of Active and Reactive Power (s=7%)

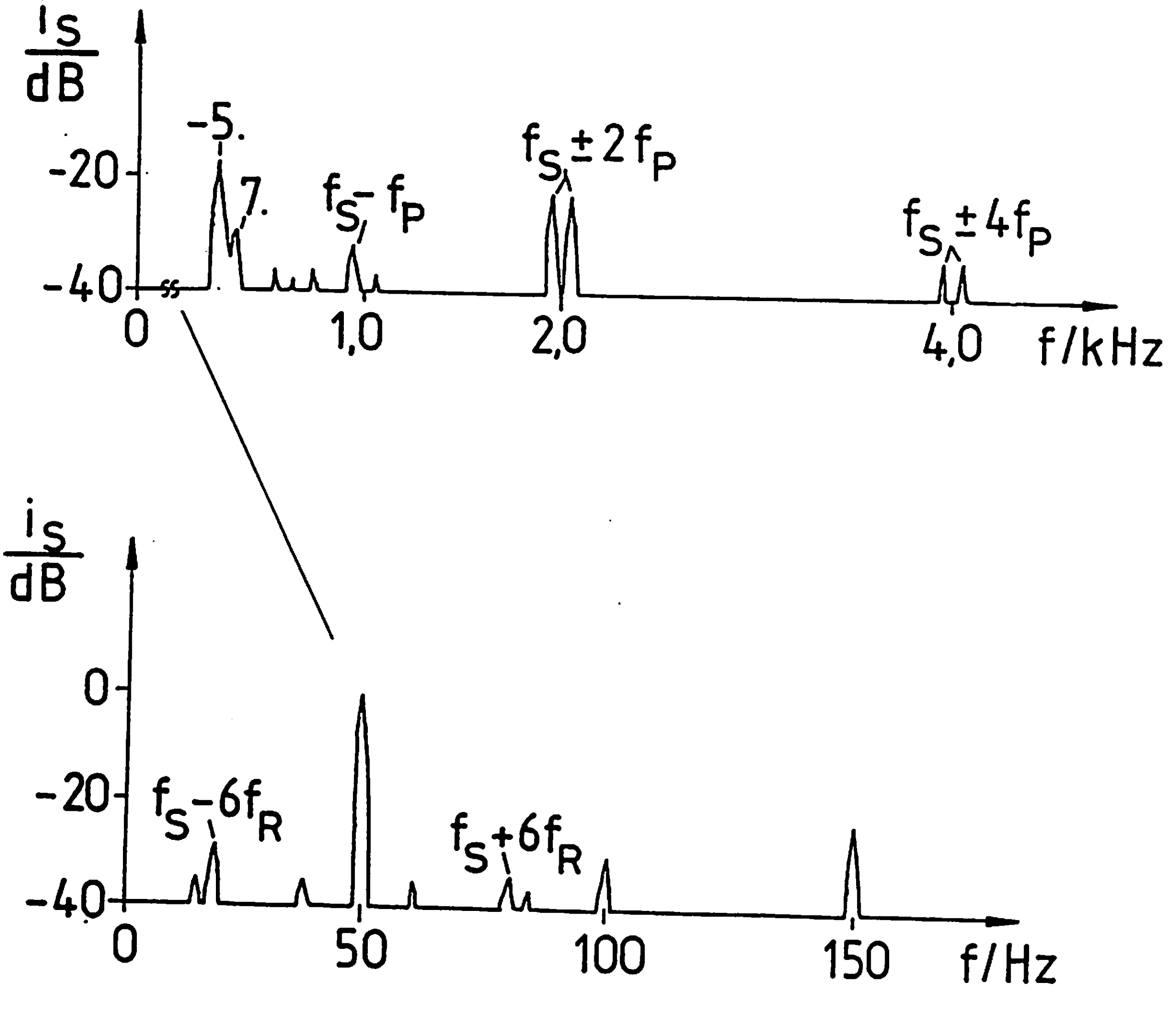

Fig.8: Spectrum of Stator Current

$s = 10\%$ $P_S = -6\,kW$ $Q_S = -6\,kVAr$

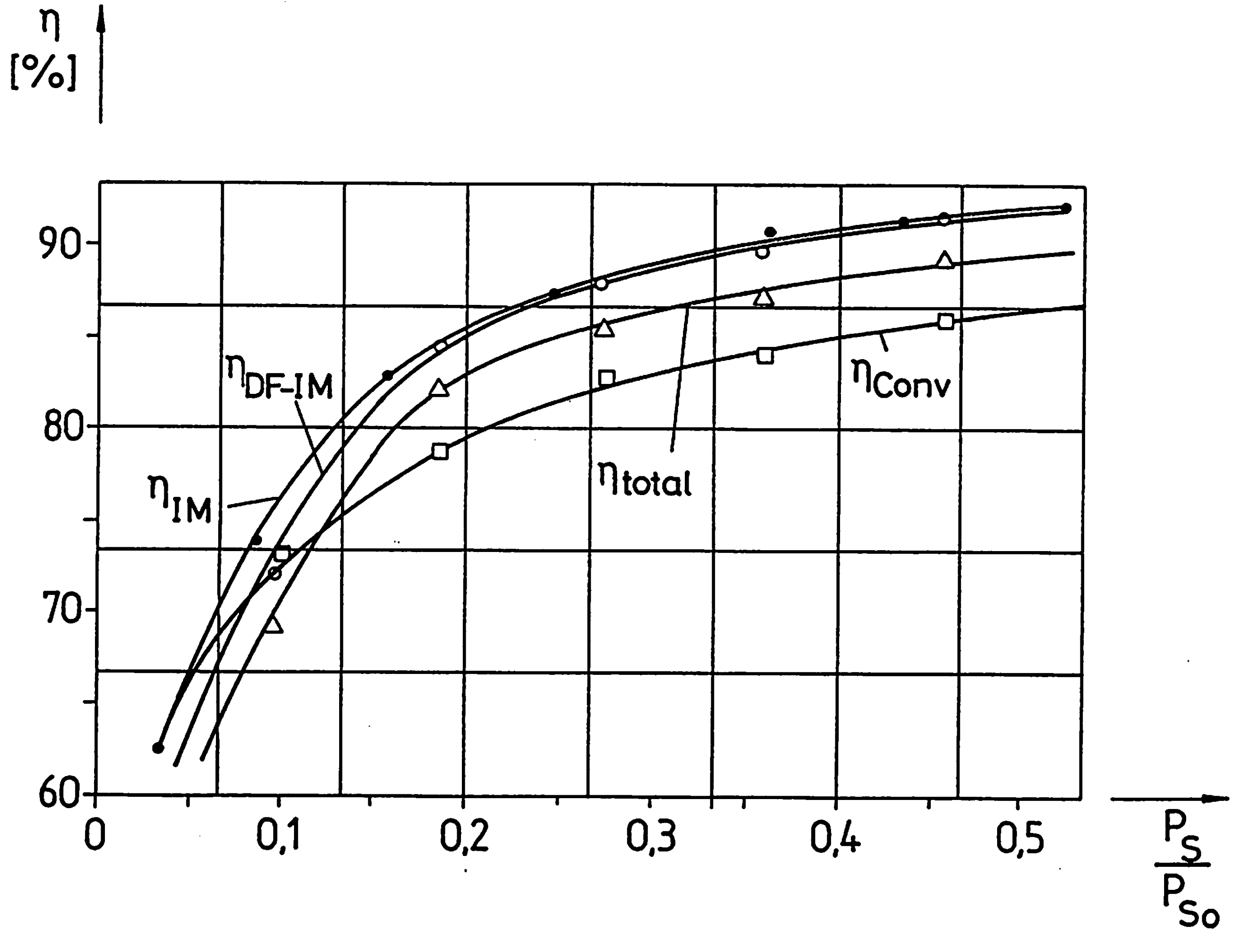

Fig. 9 : Measured Efficiency Curves of a AC Generator

- • Squirrel Cage Machine
- ○ Doubly-Fed Machine
- □ DC Link Voltage-Source PWM Converter
- △ Overall Efficiency of a Doubly-Fed AC Generator System

A CONVERTER SYSTEM FOR THE GAMMA 60 VARIABLE SPEED WIND TURBINE. MAIN FEATURES AND EXPECTED PERFORMANCES

P. Zanotti[1]

1. Introduction

A special design for medium-large size wind turbine generators to be connected to the electrical grid is required in order to solve the problems related to maximum conversion efficiency, cost and reliability of the machinery.

To the purpose an operation of the electrical machine driven by a variable speed wind turbine at a frequency different than that of the electrical network may be achieved by using an electronic power converter.

Such a system has been chosen in the overall design of the GAMMA 60 wind turbine generator, developed for ENEL by an Italian industries consortium led by Alenia-WEST.

Hereafter the GAMMA 60 main technical features of the electrical conversion system, with reference both to control aspects and grid interfacing, are shown. Due to the experimental interest of this plant a suitable test program of the electrical power equipment was also performed before its installation on the plant in order to verify the subsystem performances. A short report of these tests is also given in the paper.

2. Duty Requirements of the Conversion System

The design and basic operation of the GAMMA 60 wind turbine have been already described in previous papers [1,2]. Here the typical 'modes of operation' of the GAMMA 60 generator, each one at different wind speed range, are recalled:

a) Starting of the machine as a motor (with the turbine not aligned with the wind)

b) Running at constant power coefficient Cp (peak value) for wind speeds betweeen 5 and 12.5 m/s

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ITALY

c) Running at constant torque (rated value) for wind speeds between 12.5 and 13.5 m/s

d) Running at constant power output (rated value) for wind speeds between 13.5 and 27 m/s.

The range of the rotor speed for the above duty goes from about 15 up to 44 rpm. The choice of a wide range of speeds for the turbine is intended to get the highest energy rate together with a simple design of the generating unit (with fixed pitch blades).

The basic idea was that the rotor speed variation could be obtained without a torque choking except when exceeding the torque rated value [2].

The rotor speed can be controlled through a proper modulation of the load torque, in this case the electrical generator one.

For each generator power output there is a 'best' rotor speed which is taken as a reference point in the rotor speed control loop and then causes a reference torque in a load torque inner control loop.

An adjustable speed drive has been selected to match the above requirements, thus permitting the maximum energy capture and to comply with the needs of the electrical network.

The action of the drive is a smooth regulation of the load torque both with the electrical machine running as a generator and as a motor.

3 The GAMMA 60 Electrical Conversion System

On the basis of the abovementioned requirements the design of the electrical system configuration, which links the wind turbine to the distribution electrical grid, has been made.

A number of technical solutions were taken into account, all of them including an electronic power convertor. In the end two of them were found both quite acceptable.

The first was basically a squirrel cage converter-fed asynchronous machine. The frequency converter, a current-source type, consisted in a line-side line-commutated converter with a d.c. link between it and the machine-side self-commutated converter.

In the second solution a high speed (1800 rpm) synchronous machine with coaxial brushless-type exciter was fed by a convertor quite similar to the previous described, apart from the fact that both rectifier and inverter were line-commutated.

Finally the converter-fed, synchronous machine solution was preferred, not only due to the good efficiency and reliability of its power electronics but also because of the more favourable cost/rated power ratio, at least for a drive of the GAMMA 60 rating.

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2 This last situation is typical of d) operation mode, where a constant (rated) output power is mantained through yaw control of the wind turbine.

4 The Electrical System Layout

The electrical layout of the wind turbine generator GAMMA 60 is shown in Fig. 1, where the main power components of the conversion system are included:

a) A brushless-type synchronous generator

b) A variable frequency drive, with intermediate d.c. link

c) A static exciter

d) A step-up transformer (line side)

e) A power factor correction/harmonic compensation filter.

All of them, apart from the filter which will be discussed later, are shortly presented hereafter.

4.1 The Synchronous Generator

In order to satisfy all of the service conditions a 4 poles, 60 hZ, 2225 kVA cosφ=0.9 synchronous generator was chosen. It's a self-ventilated, enclosed machine, with a constant torque operating range between 1200 and 1800 rpm.

Through a special brushless exciter the field in the machine can be produced also when the rotor is locked, thus allowing the motor starting of the wind turbine.

A particular care to the rated voltage of the machine was paid. In fact the project value (1200 V) has been selected with regard to the convertor rating to get the best overall design of the conversion system.

4.2 The Frequency Convertor

4.2.1 General Features

The frequency convertor is basically set up as two six pulse line-commutated thyristor bridges linked through a smoothing reactor.

Thanks to the choice of the 1200 V value of the synchronous generator, for each arm of the converter bridges a single large-size thyristor (today easily available on the semiconductors market) is enough to insure the necessary degree of reliability for the converter and lately, to the system.

Here are some of the typical data for each bridge:

Thyristors:	VDRM/VRRM	5200 V
	Silicon Diameter	82 mm
	Cooling	forced air, open-circuit

Line-to-line Voltage (Uvo) valve side	1450 V ± 10%
D.C. Rated Current (Idn)	1325 A (30% overload for 1 min. every 30 min.)

4.2.2 Convertor Protection and Control

A double-level protection criterium is active in the convertor:

* On-line monitoring of the main electrical parameters and of special service conditions. This function is typical of the convertor control system
* High-level inherent safety components on the bridges, together with suitable protective devices.

The convertor control system (Fig. 2) has the following basic tasks:

- Setting of the current at a value which agrees with the demanded resistent/motor torque
- Running of the generator at practically costant power factor, thus mantaining a torque proportional to the current.

These actions take place in co-ordination with the static exciter control, which is demanded to keep a constant V/hZ ratio over the whole range of speeds of the wind turbine generator.

The convertor control system also allows the so-called 'pulsed operation' of the convertor during the starting of the wind turbine. In this mode of operation the flux of the synchronous machine is reversed and the latter works as a motor.

Lastly, the convertor control system acts as a protection system for the bridges during abnormal conditions (both inner and external to the convertor) by stopping the regular firing pulse sequence.

In the second protection level can be especially included:

- Zinc-oxide arresters on the low voltage windings of the transformer (phase-to-phase)
- VBO self-firing (emergency only) of the thyristors at a voltage value greater than 80% VDRM
- The thyristor Fault Suppression Capability.

No fuse was installed because of the above actions.

4.3 The Static Exciter

The exciter is a 20 kVA, 380 V machine, equipped with 1600 V thyristors. The brushless device is fed through a particular electronic convertor which consists in 3 pairs (one for each line) of back-to-back coupled thyristors.

4.4 The Step-up Transformer

An isolation transformer has been provided between the frequency converter and the ENEL 15 kV network. Between the two windinds of the 15/1,45 ±10%kV, 2715 kVA machine an electrostatic shield has been set. The transformer is an outdoor ONAN cooled type.

5 The Drive Test Program

Two different series of tests were performed on the GAMMA 60 electrical conversion subsystem:

- At single power component level, type and routine tests (shop tests). These tests have been especially done on the frequency converter, in agreement with the existing Standards, where possible
- Operational tests of the whole drive train at the bench, including the line-side transformer and the actual control system of the convertor.

The expected behaviour of each power component at the specific duties was verified since the first series of tests.

However, due to the peculiarity of the application, the need of further investigation in order to check the correct operation, both steady-state and transient, of the whole drive was deemed necessary.

The drive test bench, set up at the manufacturer's factory, is shown in Fig. 3. It can be seen that the wind turbine action was replaced by a d.c. machine driving the synchronous generator.

In the test schedule the following principal tests and checks were included:

* Load test
* Temperature rise test
* Starting of the drive (pulsed operation)
* Commutation from motor to generator operation
* System response to a sudden torque variation

* Transfer of a switching/ligthning impulse between the transformer windings
* Measurements of system efficiency and power factor
* Measurements of the harmonic currents
* Checking of correct VBO intervention.

The test results showed a correct operation of the drive in each load situation. A short report on the measured efficiency of the frequency converter and of the overall electrical conversion system is given in Table I.

During the bench testing a resetting and implementation of the logics of the supervision system (which has the task of insuring a correct and safe operation of the drive in every duty condition) was also possible, thus saving a heavier job on the installation site.

6 Effects of the Connection of the Wind Turbine Generator to the ENEL Network

The GAMMA 60 wind turbine generator will be connected to the ENEL 15 kV network through a 11 km line coming from the Porto Torres 150/15 kV substation.

No other user will be supplied from this link, apart from the emergency services required for the Fiume Santo thermal power plant, which is in the vicinity.

The line is therefore a dedicated one, what takes into account the prototypical character of the new wind turbine generator. A study was done in ENEL to analyze the impact of the wind turbine unit on the distribution network.

6.1 Reactive Power Consumption and Harmonic Emission of the Convertor

As already reported, the generator runs at constant V/hZ ratio on its whole range of operation (which means a constant flux in the machine). The rotor speed is therefore linear with the supplied voltage/frequency.

In this condition there is also a linearity between the generator output current and its torque.

In chapter 2 the 'modes of operation' were defined for the wind turbine generator.

Starting from mode c) towards mode b) a constant torque operation is active at first, where the reactive power absorbed in the line-side converter increases with the reduction of the rotor speed.

A further speed reduction switches the convertor in mode b), in which the torque is strongly decreasing. As a consequence, a reactive power absorption reduction on the network, even in presence of a lower and lower power factor, is given.

Table II shows the calculated power (both active and reactive) exchanged with the network for a number of operating points.

In Table III the expected 'typical' (q=6) harmonic currents on the convertor, injected at full load (1500 kW) on the 15 kV ENEL line, are shown.

6.2 Voltage Variation

The value of the short circuit power at the Porto Torres 15 kV bus (the substation at the end of the medium voltage line supplying the wind turbine conversion system) is about 40 MVA.

Considering the above short circuit power and the rate of exchanged active and reactive power between the GAMMA 60 conversion system and the network (see previous chapter 6.1) a 15kV±5% steady state voltage variation should be expected on the bus, the effect of the wind turbine generator being included too.

Therefore ENEL didn't decide to install any power factor correction device, except the filters for the convertor harmonic emission.

6.3 Harmonic Control & Filter Rating

The maximum voltage distortion, both as individual harmonic and THD, for the GAMMA 60 generating group was chosen on the base of criteria suggested by CIGRE papers (at the moment nothing was available as a national or IEC existing Standards).

The fact that the GAMMA 60 feeder was long enough and a dedicated one brought about the decision to fix a double distortion level:

- a low level for all kind of loads at the Porto Torres bus
- a higher level, quite similar to the one usually accepted for industrial users, at the GAMMA 60 connection point.

At the substation 15 kV bus the existing distortion level was measured and hence considered, sharing a 60% of the left permissible margin on the wind turbine group.

The results of the above procedure are shown in Table IV.

As a conclusion a tuned filter (between the 4th and 5th harmonic), to be installed near the GAMMA 60 at the 15 kV side of the isolation transformer, was deemed satisfactory.

In the filter design possible grid resonances were taken into account.

The filter, which has a quality factor Q=30, should generate 1.5 MVAr.

7 Final Remarks

A broad-variable speed wind turbine machine like GAMMA 60 should offer, with respect to the traditional systems, good inherent quality project together with a competitive energy/cost ratio.

From the point of view of the electrical conversion system the choice of a variable speed drive like the converter-fed synchronous machine, well known in a number of industrial applications in its motor basic configuration, should assure both a good reliability and the design expected performances.

In this second sense special care was paid in each step of the works progress to verify not only the convertor ratings but also the overall drive behaviour before its installation on site and to assess the consequences of the presence of the electronic power convertor in terms of reactive power absorption and harmonic currents emission on the ENEL network.

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2. S. Avolio, C. Calò, U. Foli, L. Rubbi, C. Casale, E. Sesto, "GAMMA 60 1.5 MW Wind Turbine Generator", Proceedings of the European Community Wind Energy Conference and Exhibition, Madrid, Spain, September 1990.

TABLE I - SUMMARY OF THE GAMMA 60 ELECTRICAL DRIVE EFFICIENCIES AT VARIOUS LOADS, MEASURED AT THE TEST BENCH

Generator Speed [R.P.M.]	Power at the shaft [kW]	Convertor Efficiency p.u.	Drive Efficiency p.u.	Output Power at the 15 kV network [kW]
493	121.3	0.865	0.672	81.5
660	266	0.94	0.795	211.5
862	598	0.97	0.86	514.2
1100	1132	0.976	0.871	986
1202	1426	0.983	0.881	1256.3
1304	1496	0.976	0.876	1310.5
1488	1680	0.980	0.885	1487

TABLE II - ACTIVE POWER FED INTO AND REACTIVE POWER ABSORBED FROM THE GRID BY THE GAMMA 60 WIND TURBINE GENERATOR

SYNCHRONOUS GENERATOR		MARGIN ANGLE OF THE FREQUENCY CONVERTER	15 KV GRID BUS	
SPEED (rpm)	OUTPUT POWER (kW)	γ (°)	ACTIVE POWER (kW)	REACTIVE POWER (kVAr)
1800	2000	34.1	1927	1577
1350	1500	50.6	1438	2023
1200	1324	55.4	1265	2122
1000	650	63.7	605	1334
495	86.4	78.1	75	375

TABLE III - GAMMA 60 PROJECT
HARMONIC CURRENTS EMITTED BY THE CONVERTOR

HARMONIC	WIDTH
5th	19 A
7th	13 A
11th	7 A
13th	6 A
17th	3 A
19th	2.5 A

TABLE IV - GAMMA 60 PROJECT
ADMITTED VOLTAGE DISTORTION LIMITS

HARMONIC	INDIVIDUAL HARMONIC DISTORTION	
	PORTO TORRES	GAMMA 60
3rd	2.5-3.%	6%
5th	2.5-3.%	8%
7th	2.5%	7%
11th	1.5%	5%
13th	1.3%	4.5%
TOTAL HARMONIC DISTORTION (THD)	4%	10%

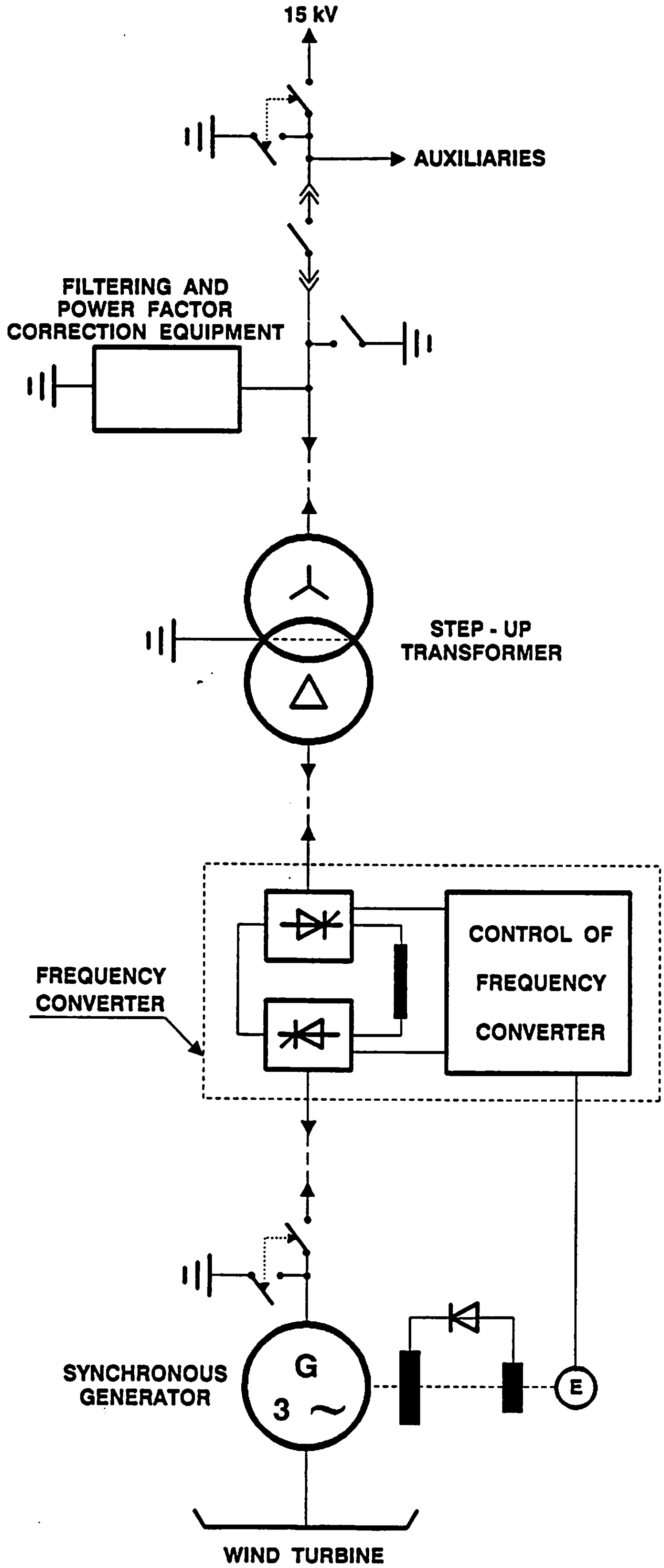


FIG.1 GENERAL DIAGRAM OF THE POWER CIRCUITS OF THE GAMMA 60 WIND TURBINE GENERATOR

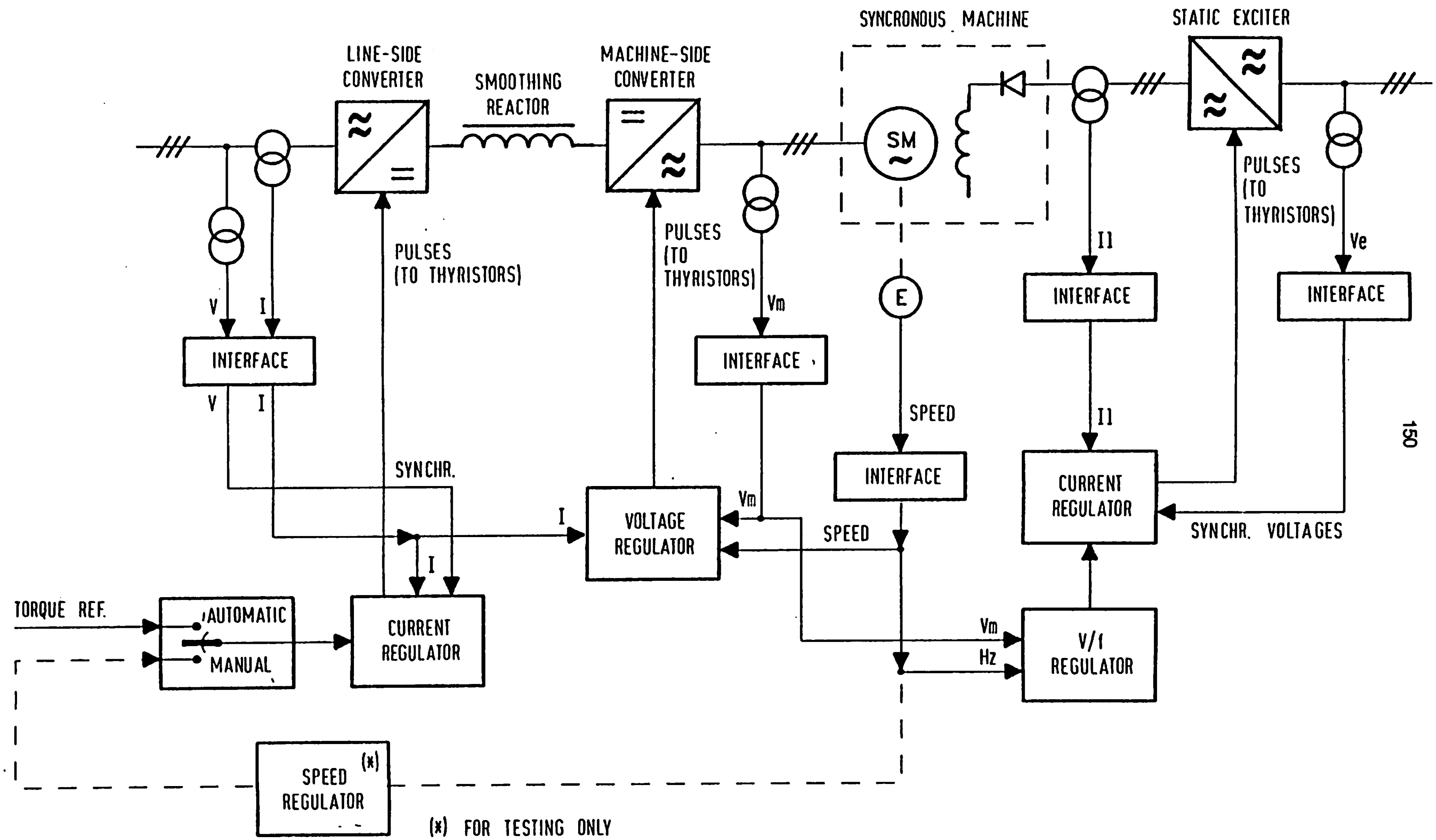
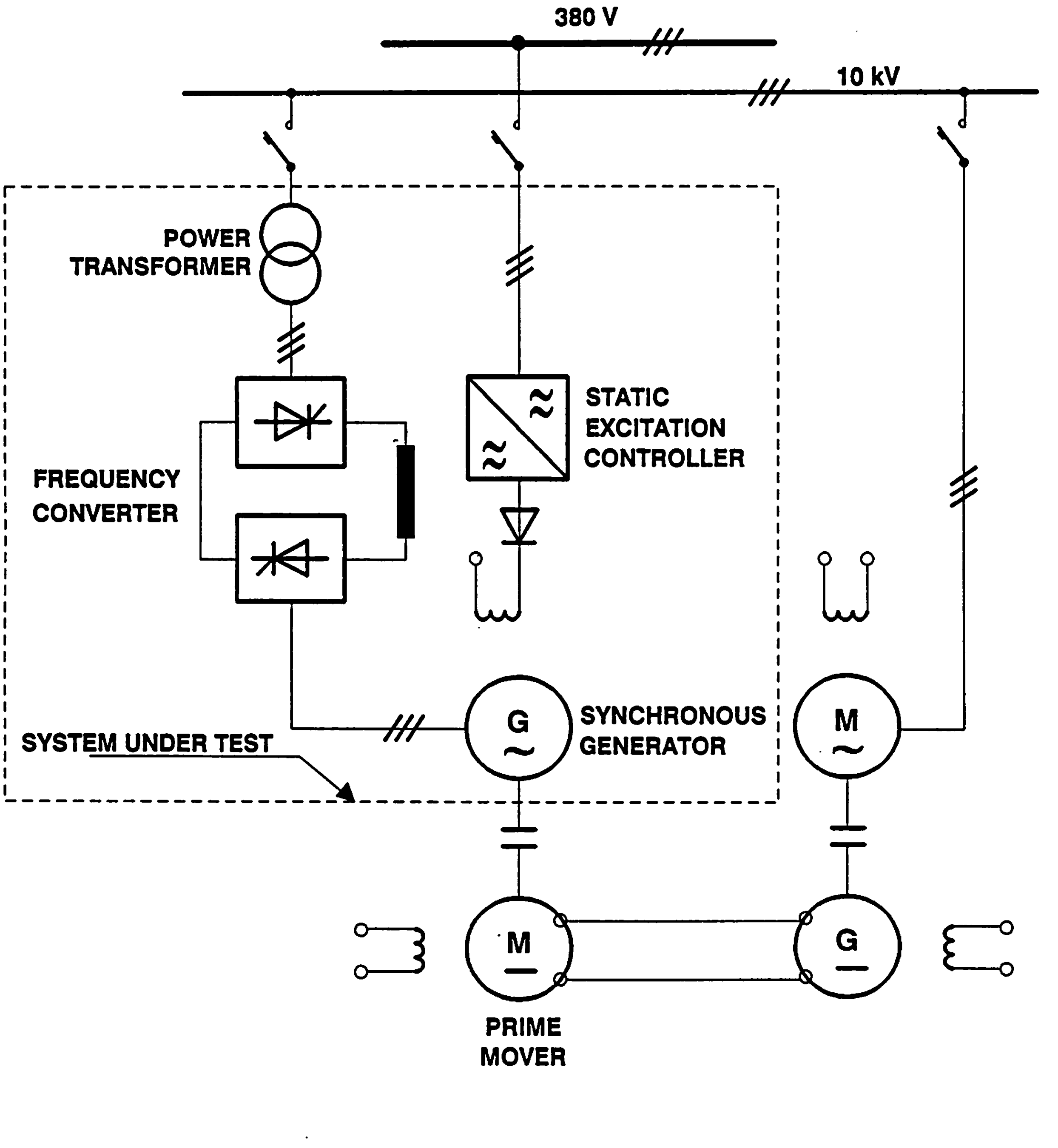


Fig. 2- GAMMA 60 wind turbine generator - Schematic of the static converter control system



7IG.3 LAYOUT OF MACHINERY DURING SHOP TESTS ON THE ELECTRICAL SYSTEM OF THE GAMMA 60 WIND TURBINE GENERATOR

IEA Meeting at Chalmers University Gothenburg
7-8 October 1991

NOTES ON FINAL DISCUSSION

The session commenced with a discussion of the possible areas of application of wound rotor doubly fed induction machines.

It was suggested that with the advent of high power transistors and a restricted speed range, this type of equipment might be applicable for turbine ratings from several hundred kilowatts up to 1 MW. To date, wound rotor doubly fed induction machines have only been used on a small number of multimegawatt machines. Concern was expressed over the maintenance requirements of the slip rings and it was noted that the Grovian had a separate slip ring compartment.

Attention then focused on whether an induction or synchronous generator was more suitable for application with stator connected power conversion equipment. Although no clear consensus emerged, it was felt that induction machines might be more suitable at lower (< 300kW?) power levels while synchronous machines in spite of their additional complexity, were more cost effective for large installations.

The discussion then moved to whether an enclosed induction generator was being compared to a ventilated synchronous machine. It was pointed out that most medium sized wind turbines presently being built used enclosed induction generators. The costs of enclosing a large synchronous machine might tip the balance back in favour of induction machines.

Subsequent discussion centred on the implications for the external electrical system of the variable speed drive type. Newer converter technologies can allow great reductions in harmonics. However, to date, line-commutated inverters have been used extensively, e.g. the Gamma 60 1.5 MW turbine uses a 6-pulse line-commutated converter. It was generally considered that for windfarm machines greater attention needs to be paid to this issue. It may be better to pay for an advanced converter than to add filters.

The next topic to be discussed was the comparison between pitch and stall regulation for variable speed. It was agreed that provided knowledge of stall behaviour was sufficient to be used with confidence for design, variable speed stall-regulation was feasible. However, concern was expressed that the control action of maintaining stall may introduce higher than expected blade loads.

The final discussion considered whether electrical variable speed operation was appropriate for wind turbines. It was generally agreed that in the long run, lighter, more flexible turbines were likely to give a lower cost of energy and these would require electrical variable speed operation. Therefore continuing research in this area is essential.

However, it is at present not clear whether variable speed operation can show benefits when applied to medium and large size turbines of conventional architecture (i.e. not designed for great flexibility). An example of this was given by the decision in Sweden to use two-speed operation for the new 3 MW Nassudden II turbine, whereas the Aeolus II in Germany, using the same rotor and nacelle, will use a variable speed drive.

It was generally agreed that the additional energy capture provided by variable speed operation gave only modest benefit, but there could be significant cost savings associated with the reduction on loads or mechanical components. It was also emphasised that standard industrial or marine variable speed drives were not optimised for wind energy applications and that cost reductions may be possible if low speed is associated with low torque, and reduced generator flux.

The final conclusions were that existing work on flexible variable speed wind turbines should be continued but further study was required before a firm view could be established on the desirability of electrical variable speed equipment for the existing generation of turbines. However, it was felt that more attention needed to be paid to the interactions of large variable speed turbines with the network and that further work was also needed to provide optimal designs of the power electronic systems for wind turbine application.

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IEA-EXPERT MEETING
7 - 8 OCT 1991, GÖTEBORG, SWEDEN
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IEA-Implement Agreement R+D WECS - Annex XI
Topical 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. Reliabiltiy 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 Atomospheric 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. Noise Generationg Mechanisms for Wind Turbines, Petten, November 27-28, 1989
19. Wind Turbine Control Systems, Strategy and Problems, London, May 3-4, 1990
20. Wind characteristics of Relevance for Wind Turbine Design, Stockholm, March 7-8, 1991
21. Elektrical Systems for Wind Turbines with Constant or Variable Speed, Göteborg, October 7-8, 1991

22. Effects of Environment on Wind Turbine Safety and Performance, Wilhelmshafen, June 16 - 17, 1992