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WIND FARMS IN COMPLEX TERRAIN

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	Page
89-233/R.24/MST	2
TABLE OF CONTENTS	
SYMBOLS	3
SUMMARY	4
1. INTRODUCTION	5
2. POWER OUTPUT OF WIND FARMS IN COMPLEX TERRAIN	7
2.1 Introduction	7
2.2 Mathematical modelling	8
2.3 Second order effects	10
2.4 Validation of the model	12
2.5 Conclusions	13
3. POWER OUTPUT FLUCTUATIONS	14
3.1 Introduction	14
3.2 Relevant factors	14
3.3 Mathematical modelling	17
3.4 Conclusions	19
4. INTEGRATION OF WIND ENERGY INTO WEAK DISTRIBUTION GRIDS	20
4.1 Introduction	20
4.2 Discussion of the technical thresholds	21
4.3 Rules of thumb for integrating wind power	28
4.4 A handmethod to determine the wind power which can be integrated freely	31
4.5 Conclusions	33
5. CONCLUSIONS	34
6. RECOMMENDATIONS FOR FURTHER RESEARCH	35
7. REFERENCES	37
8. AUTHENTICATION	40

Tables: 2

SYMBOLS

A_c	conductor cross-section of cable part
C_m	53.7 for copper conductors 32.4 for aluminium conductors
C_p	power coefficient
C_t	thrust coefficient
DV	second order effect
I_{max}	maximum current
L_c	length of cable part
$P_{current}$	wind power which can be integrated according to the maximum current criterion
$P_{voltage}$	wind power which can be integrated according to the maximum voltage criterion
S_{short}	short-circuit power at the feeding point
U	local mean velocity
U_o	undisturbed local velocity
U_g	voltage connected
V	local velocity
ΔU_i	local velocity defect
λ	tip speed ratio

SUMMARY

Wind energy is considered to be a promising renewable energy source particularly for remote areas, like islands and mountainous regions.

Two engineering methods have been developed for the design of wind farms in such remote locations.

The application of the first method, the numerical COMPL model, is the optimization of the lay-out of wind turbine clusters in topographically complex terrain with respect to the total power output.

The application of the second method is the determination of the maximum amount of wind power which can be integrated in a weak electricity grid, taking into account connection conditions, standards and instructions, and management.

Besides these two methods, a first set-up of a dynamic wind farm model (INSTA-model) has been developed. The application of this INSTA-model is the prediction of power output fluctuations of wind farms.

1. INTRODUCTION

Wind energy is considered to be a promising renewable energy source particularly for remote areas, like islands and mountainous regions. The features of such regions generally differ from cultivated regions at flat terrain.

One of the characteristic features is that the topography of the terrain influences the local wind flow. Consequently each individual wind turbine will be subject to a different wind flow. Moreover, wake interaction will also be dependent of the topography.

Another specific problem at remote locations is the extent of the power network, as far as available.

In most cases the local grid will be weak. Therefore, the extent of the local power grid will generally limit the integration of wind power. The maximum wind power will also be dependent of the siting of the individual wind turbines relative to the existing transformer and generation stations.

Initially all engineering methods to optimize, with respect to total power output, the lay-out of wind turbine clusters are intended for use in flat terrain [1,2]. When wind farms are planned in remote regions, these methods are of limited value due to the above-mentioned features. The objective of the project described in this report is to develop engineering methods to optimize the lay-out of wind turbine clusters in typical remote locations, i.e. in topographically complex terrain and with an existing weak power grid, with respect to total power output and the amount of wind energy which can be integrated in the grid.

The research work is divided into three parts.

The first part, described in chapter 2, is the development of a mathematical model to predict the power production of a wind farm in topographically complex terrain. This part is carried out by MT-TNO and UPM (Spain) and has been described by van Oort et al [3].

The second part, described in chapter 3 and 4, is the development of a method to assess the maximum wind power to be integrated in a given weak power grid. The part is carried out by MT-TNO and CE (The Netherlands) and has been described by van Oort [4] and van Gemert [5]. In chapter 3

the development of a dynamic wind farm model has been described. At the start of this project it was expected to use this model for dynamic load flow calculations, in order to develop a method to determine the maximum wind power to be integrated in weak electricity grids. Due to lack of data however, validation of this dynamic model was not possible. Therefore, this dynamic model has not been used in the development of the maximum wind power integration method. This method has been described in chapter 4.

In the third part, described in this report, both models are evaluated and reported.

In chapter 5 the conclusions are summarized.

In chapter 6 recommendations for further research are given.

2. POWER OUTPUT OF WIND FARMS IN TOPOGRAPHICALLY COMPLEX TERRAIN

2.1 Introduction

Wind turbines are used to extract energy from the wind. The amount of extracted energy is dependent of the local wind input.

In a wind turbine cluster the local wind input is influenced by meteorological conditions, the presence of obstacles, the complexity of the terrain and the wakes of upstream positioned turbines.

Meteorological conditions are time-dependent and are dealt with in chapter 3.

Obstacle effects are outside the scope of this project, but subject of a separate project within the concerted action "wake effects" [6].

Terrain effects will result in a 3-dimensional space-dependent wind flow field, due to acceleration of the airflow over hills, recirculations behind ridges, wind deflection around peaks and a range of combinations of these effects.

Besides this space-dependent wind flow field, knowledge of the disturbing effect of the wakes of upstream turbines is necessary for the determination of the local wind input. Using the local wind input, the power production of a wind farm can be determined by adding the output of the individual turbines.

The 3-dimensional space-dependent wind flow field can be obtained by measurements at the actual site, wind tunnel test or numerical modeling. Hence, when it is possible to model the disturbing effect of the wakes, the local wind flow can be obtained and the power production of a wind turbine cluster, located in the particular terrain can be determined.

In this chapter the influence of the complexity of the terrain and the wakes of upstream positioned turbines are considered. A model has been described which calculates the power production of wind farms in topographically complex terrain.

2.2 Mathematical modelling

Computer models for the prediction of the power output of wind farms in flat terrain already exist. At MT-TNO the semi-empirical MILLY- and FARMS-codes [1, 2, 7, 8] have been developed, in which the wake evolution and wake interaction in wind turbine arrays in flat terrain are modelled. These codes calculate the power output from wind farms with different lay-outs. At the Universidad Politecnica de Madrid (UPM) a similar but more advanced code has been developed [9], in which the turbulence effects at each wind turbine are described by the boundary layer approximation of the Navier-Stokes equations.

For the development of a computer model for calculating the power production of wind farms in complex terrain, use has been made of the existing FARMS-code.

The basic assumptions of the FARMS-model, with respect to the wake evolution and wake interference are [7]:

- a. The wake growth downstream of each individual wind turbine can be calculated with the semi-empirical wake model developed in [10]. This model is a modified version of the earlier Lissaman model [11].
- b. The wake of an individual wind turbine is a function of local conditions i.e.:
 - local mean velocity U ;
 - local tip speed ratio λ ;
 - local thrust coefficient C_t .
- c. The local velocity V within the cluster is found by adding linearly the local velocity defects (ΔU_i), generated by all upstream wind turbines and subtracting the total defect from the undisturbed wind speed U_0 , i.e.: $V = U_0 - \sum \Delta U_i$.
- d. The power delivered by an individual wind turbine is proportional to the local power flux, averaged over the rotor area, times a power coefficient. The power coefficient depends only on the tip speed ratio and the $C_p - \lambda$ curve.

These assumptions, analysed in [7], are useful for the modelling of the wake evolution and the wake interference in complex terrain.

As yet, no literature is available about the evolution of wakes in a non-uniform wind field. Therefore, the following assumptions have been made:

1. The height differences in the terrain have only an indirect effect (by way of wind speed, wind direction and turbulence intensity) on the evolution of the wake. Hence, mathematically the terrain can be modelled as a flat terrain on which (spatial) variations in wind velocity, wind direction and turbulence intensity occur. In other words: the curved coordinated along the ground plane are transformed to straight coordinates, assuming that the wake and its image wake are not influenced by this transformation.
2. The wind field is known only in a number of points in the total area. This wind field can be obtained by:
 - extensive measurements at the actual site;
 - wind tunnel tests;
 - numerical methods with various degrees of complexity.The output of these models will be an input for the described model. This means that in a number of points in the area the value of the wind speed, wind direction and, if possible, the turbulence intensity must be given, together with the location (coordinates) of that points.
3. The undisturbed local conditions of a turbine are the same as that of the nearest "point" where the wind conditions are known. This assumption will give second order effects which are believed to be small when a sufficient number of points are given equally spread over the total area and when the differences in local conditions between neighbouring "points" are small.
4. The vertical component of the wind speed does not influence the power output of a turbine and the wake evolution. Hence, the value of the velocity must be the horizontal component of the velocity vector.
5. The velocity defect in a wake is not influenced by changes in wind speed, wind direction and turbulence intensities. This means that the velocity defects behind a wind turbine are calculated as if the wind field is uniform downstream of that turbine. This will give small errors when the changes in wind speed and direction are small over relatively small distances, which is generally the case in complex terrain. Larger changes in wind speed and direction can occur over relatively larger distances. In that case, however, the wake effects are negligible.

Using these assumptions, the FARMS-model has been modified. This modified computer model has been called COMPL. Application of the assumptions will result in second order effects, what has been studied and described in chapter 2.3.

A description of the general structure of the COMPL-model and an example calculation are given by van Oort et al [3].

2.3 Second order effects

Application of the assumptions, mentioned in chapter 2.2., may result in second order deviations. These second order deviations are studied numerically, as it is impossible to calculate these analytically.

The assumptions 1 and 5 state that the velocity defects in the wake are in complex terrain conditions the same as in flat terrain when the turbine input and wind flow input are equal.

The effect of assumption 2 is beyond the scope of this project, but should be studied in the framework of the accuracy of windtunnel studies, numerical methods and measuring techniques.

Second order effects, due to assumption 3, are dependent on the windflow field at the actual site, the number of wind turbines and "points", where the wind conditions are given and the distances between the turbines and these points. These second order effects will be small when a sufficient number of points are given, equally spread over the total area and when the differences in local conditions between neighbouring points are small.

In principle the vertical component of the wind speed influences the power output of a wind turbine (assumption 4). Investigation of this influence, however, is beyond the scope of this project, but should be studied in the framework of aerodynamics of wind turbines.

The effect of assumption 1 and 5 have been studied by using the PHOENICS-model, a product of CHAM ltd. (U.K.). PHOENICS is a computer code, which simulates fluid flow, heat-transfer, chemical reaction and related phenomena. In fluid flow problems, the Navier-Stokes equations are solved, using a finite volume technique.

More details about the PHOENICS modelling and the Q1 program to introduce the model in PHOENICS are given by van Oort et al [3].

The second order effects are calculated for a characteristic complex terrain obstacle (figure 1). This is a triangular hill of which the basis is twice its height (an isosceles triangle). The turbine, of which the height and the rotor diameter are equal to the height of the hill, is placed at 5 separate positions relative to the characteristic obstacle (figure 2):

- turbine 3D before the hill;
- turbine 0D before the hill;
- turbine on top of the hill;
- turbine 0D behind the hill;
- turbine 3D behind the hill.

In order to calculate the second order effects the following equation has been used:

$$DV = \frac{V_{d, \text{comp}} - V_{d, \text{flat}}}{\frac{1}{2} \cdot (V_{d, \text{comp}} + V_{d, \text{flat}})} * 100\%$$

in which: $V_{d, \text{comp}}$ = velocity defects due to turbine wake over complex terrain;

$V_{d, \text{flat}}$ = velocity defects due to turbine wake over flat terrain;

DV = second order effect; deviation of velocity defects in complex terrain from velocity defects in flat terrain.

In the figures 3 to 7 the lines of constant DV are shown for the five positions of the turbine. Positive values of DV mean that the velocity defects in complex terrain are larger than those in flat terrain and the opposite happens for negative values of DV. The limiting values of DV are - 200% and 200%, which correspond to zero velocity defect in complex terrain and in flat terrain, respectively. When the turbine is either at the apex or upstream of it (figures 3 to 5) the values of DV are in general negative close to the ground and positive in the upper part.

This is due to two opposite influences: the hill causes the turbulence level to increase and consequently the turbulent diffusion effects are larger, while on the other hand the hill concentrates the streamlines, causing the velocity defects to be enhanced.

The first effect dominates near the ground and the other one above the hill. When the turbine is downstream of the hill (figures 6 and 7) those tendencies of the results are not so clear; also, the second order effects are less important. As expected, the larger values of the second order effects happen close to the hill.

It can be concluded that the second order effects can be large in the proximity of large changes in the terrain topography.

These second order effects can be positive and negative.

2.4 Validation of the model

At the start of this project it was expected to use the extensive data available from the Kythnos wind farm in Greece. However, it appeared that the observed differences in local wind input at the separate wind turbine locations were primarily the result of local complex terrain effects. Due to the relatively large spacings between the various turbines, wake effects will be very small.

As an alternative, validation data have been used of the wind farm of Ampurdam, located in Gerona, Cataluna, in the North East of Spain. These data appeared to be the most suitable for the validation. The amount of data however is limited, while the terrain is rather smooth. The lay-out of the Ampurdam wind farm is given in figure 8. The five turbines have a rotor diameter of 10 m, a hubheight of 12 m and turn at 75 rpm.

The ground roughness is taken as .1 m, corresponding to a terrain with few trees, short grass and some bushes. The validation data consist of the wind speed, measured at three measuring stations (at the first turbine, the last turbine and at the meteorological tower), the wind direction, measured at the meteorological tower and the power production of the wind farm.

For a number of cases with wake interference between the turbines the power production of the wind farm calculated by COMPL and by FARMS are

compared with the measured power production. The results are given in table 1. This comparison shows that the COMPL model gives better results with respect to the measurements than the FARMS model.

More details about the validation of COMPL are given by van Oort et al. [3].

2.5 Conclusion

A model has been developed which predicts the power production of wind farms in topographically complex terrain. This model, called COMPL, is based on the existing FARMS model. The mathematical modelling of the wake evolution in the FARMS model has been adjusted to complex terrain circumstances. To that end, assumptions with respect to the wake evolution in complex terrain were necessary.

Due to the assumptions, with respect to the wake evolution in complex terrain, second order effects occur. These second order effects can be large (up to about 50% in velocity deficit) in the surroundings of large changes in the terrain topography.

Validation of the COMPL model, using data from the wind farm of Ampurdam (North-East of Spain) shows better agreement of the COMPL model with experimental data than the FARMS model. The validation however is limited, due to the limited amount of data and the rather smooth terrain topography of the Ampurdam wind farm. More data from wind farms in complex terrain are therefore necessary for the validation of the COMPL model.

3. POWER OUTPUT FLUCTUATIONS

3.1 Introductions

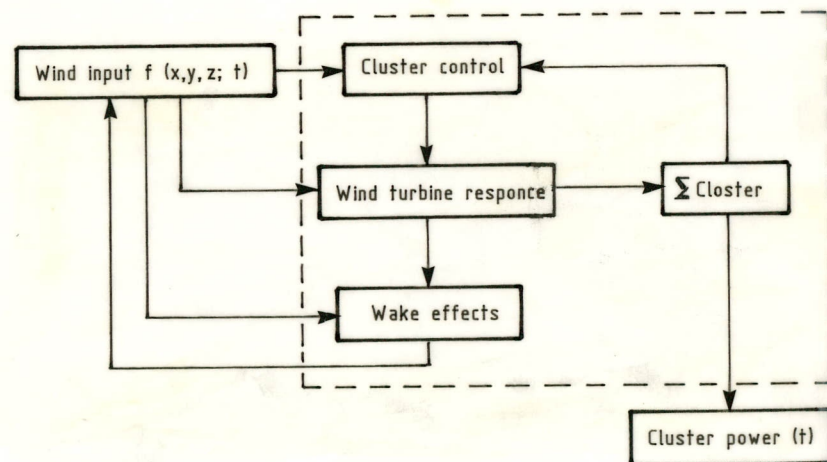
One of the main problems of large-scale wind energy integration is the maintenance of high quality of supplied electric energy, due to the variability of the power output from wind energy systems, which may lead to large frequency and voltage fluctuations in the grid.

To control this problem, knowledge is required about power output fluctuations of wind energy systems. Hence there is a strong need for an accurate prediction of these fluctuations.

In this chapter a model has been described with which the time dependent power production of wind farms can be calculated.

3.2 Relevant factors

The relevant factors affecting the time dependent behaviour of a wind turbine cluster are given schematically in the figure below [12].



Windinput

The most important factor is the fluctuating wind input.

The problem of wind power fluctuations, caused by the stochastic character of wind fluctuations, is strongly related to the different time scales of these fluctuations.

In general, the timescales of the wind fluctuations relevant to wind energy integration, are less than a few days.

With respect to the integration of a wind turbine cluster however, a clear distinction can be made between fluctuations with time scale larger than about one hour and with time scales of less than about one hour.

These regions can be characterized as follows:

a. Fluctuations with time scales larger than "one hour":

- are caused by macro-scale weather systems (e.g. depressions) and are therefore in some degree predictable;
- are correlated within the cluster; hence, the impact of these fluctuations on the time dependent power output from wind farms can be obtained by quasi-steady calculations.

b. Fluctuations with time scales smaller than "one hour":

- are due to atmospheric turbulence and small elements of weather systems and are therefore hardly predictable;
- are weakly correlated within the cluster; hence, a quasi-steady approximation is not possible.

In between the two distinct regions there is the so called "spectral gap" around the one hour time scale. In this spectral gap region, a number of synoptic and meso-scale weather systems cause wind fluctuations around the entire spectral gap region itself, lasting several minutes to several hours. For example, these weather systems are cold fronts, thunderstorms and rollvortices. Although these fluctuations themselves carry little energy, they are of major importance for the power fluctuations from wind turbine clusters. It appears that "turbulence" and "meso-scale processes" coincide in the frequency range about several minutes.

In summarizing the meso-scale weather systems, the following features are of importance to cluster power fluctuations [12]:

- The life-cycles of these systems are much larger than the passage time through the cluster. Consequently they may be considered as "coherent" structures passing the cluster with an "overall" transit speed.
- The length scale perpendicular to the transit direction is larger than or equal to the cluster size. This leads to the feasibility of a two dimensional approximation in most cases.
- Fluctuations in wind direction also occur.

- Generally, the characteristic behaviour of wind speed and wind direction can be recognized. Due to the various forms of behaviour however, a quantitative description is difficult to determine.

In the matter of turbulent fluctuations, the major conclusion drawn from statistical information disclosed in the literature is that the correlation between wind turbines perpendicular to the wind direction may be neglected.

As a result, the turbulent velocity contributions to be applied in a cluster simulation model can be reduced to a time series of the velocity fluctuations correlated only in longitudinal direction. It also appears that only a part of the total spectrum is of importance to wind turbine cluster response. This portion ranges between one and ten minutes approximately.

Consequently, simplified turbulence modelling may be applied by using simulated time series based on this part of the spectrum only. These time series can be "moved through" the cluster with a fixed convection speed according to Taylor's "frozen turbulence" concept.

Wind turbine response

An essential part of a cluster model is the relation between the power production of each individual wind turbine and the local instantaneous wind speed, i.e. the power characteristic. Usually, the power characteristic is based on 10 minutes averaged wind data [13]. For a dynamic cluster model however, the relevant time scale should be about 30 to 60 seconds. Consequently, deviations from standard power-curves may occur due to the dynamic effects present in the total system, the control system characteristics (start/stop procedures) and yaw angle variations. Wind shear is expected to have minor effects on the power production.

Wake effects

As a result of recent studies at MT-TNO, two different wake effects on cluster power fluctuations can be distinguished.

First, variation in wind direction may cause substantial power reductions. The extent of these reductions is strongly dependent on the cluster lay-out.

Another wake effect may occur as a result of variations in rotor drag due to wind speed fluctuations. Hence, the velocity defect within the wake may change. Consequently, downwind positioned wind turbines may experience stronger or weaker wind speed fluctuations.

Cluster control systeem

Various cluster control systems have been described in the literature, e.g. [14]. These control systems may be used to optimize the power output as well as to limit the power fluctuations.

The effect of the actual cluster control system on the time dependent behaviour of the cluster itself can be extensive.

3.3 Mathematical modeling

The model structure is based on the semi-empirical MILLY- and FARMS-codes [4], [5], which have been developed at MT-TNO. These codes calculate the total power output from wind farms for a uniform wind flow field.

The FARMS-code has been modified in order to calculate the time dependent power output from wind farms. This modified model is called INSTA.

The basic assumptions of the INSTA-model with respect to the wake evolution and wake interference are [7], [8]:

- a. The wake growth downstream of each individual wind turbine can be calculated with the semi-empirical wake model developed in ref. 10. This model is a modified version of the earlier Lissaman model [11].
- b. The wake of an individual wind turbine is a function of local conditions i.e.:
 - local mean velocity U
 - local tip speed ratio λ
 - local thrust coefficient C_t
- c. The local velocity V within the cluster is found by adding linearly the local velocity defects (ΔU_i), generated by all upstream turbines, and subtracting the total defect from the undisturbed wind speed U_0 , i.e.:

$$V = U_0 - \sum \Delta U_i$$

d. The power delivered by an individual wind turbine is proportional to the local power flux, averaged over the rotor area, times a power coefficient C_p . This power coefficient depends only on the tip speed ratio and the C_p - λ curve.

These assumptions are the same as in the MILLY- and FARMS-codes, and are critically analysed in ref. 7.

The basic assumptions of the INSTA-code with respect to the space and time dependent behaviour of the wind flow field are (see figure 9):

- e. The wind velocity, wind direction and turbulence intensity are constant in regions (the "front regions") between straight line contours in the surroundings of the cluster. This means that the wind speed, wind direction and turbulence intensity change step-wise from one "front region" to another.
- f. The straight line contours, which are the dividing-lines between adjacent front regions, are parallel.
- g. The straight line contours move with the velocity of the "wind front", which may differ from the wind velocity in the front regions.
- h. The "wind front" moves in a direction at right angles to the straight line contours.

These assumptions are analysed in ref. 15.

It can be concluded from statistical information that the correlation of the wind front is not perfect. So, the described modelling of a wind front can be considered as a "worst case".

In this INSTA model, no allowance is made for the turbine and cluster control systems and for the yawing procedure. Hence, the model can be considered as a first set-up for a simulation model which calculates the fluctuating power output from wind turbine clusters.

In figure 9 the situation at a certain time instant is drawn for a fictitious schematized wind front, for two wind turbines. The supposed wind directions in each front region are drawn in this figure. The figure illustrates clearly the curvature of the wakes due to the variation of the wind direction.

A description of the general structure of the INSTA-model and an example calculation are given by van Oort [4].

3.4 Conclusions

A first set-up for a dynamic wind farm model has been developed, which has been called INSTA.

At the moment no data are available for the validation of the INSTA-model. These data may come available from the experimental wind farm at Sexbierum, the Netherlands [16] or other wind farms in Europe in the framework of the JOULE-programme.

The next step in the development of the INSTA model will be the development of models for calculating the impact of control strategies as the wind turbine and cluster control systems and the yawing procedure. The detail of these modules is dependent on the desired application.

4. INTEGRATION OF WIND ENERGY INTO WEAK DISTRIBUTION GRIDS

4.1 Introduction

Due to the fluctuating nature of the wind and the consequent whimsical supply of wind energy, the connection of wind turbines to the electricity grid will run up against problems. Moreover, the wind energy is sometimes fed-in at weaker locations in the grid.

Another problem which is attended by the integrations of wind energy are the costs for the connection of wind turbines to the electricity grid. Laying out a complete electrical infrastructure will lead to high investments. When planning wind plants one can profit from the possibilities of the existing distribution grid - the medium voltage grids in particular-, which will cause the costs of grid connection to remain relatively low.

At the moment, now the actual development of wind turbines is proceeding, more knowledge is required about the consequences of the integration of windenergy. In this chapter these consequences are studied by discussing the various technical threshold which are relevant for the integration of windpower into the distribution grid. Based on this discussion, rules of thumb are deduced for the wind power which can be integrated freely.

By "windpower which can be integrated freely" is meant in this chapter: The maximum power which, when taking into account the connection conditions, the standards and instructions and the management, can be connected to the distribution grid at a given place, without causing extra hindrance to the other consumers or generators connected.

"Taking into account" will in this case be explained in such a way that the standards under normal conditions (so the conditions for which the standards are valid) will not be overstepped by wind energy and that the management of the distribution grid will be adapted optimally to the introduction of wind energy.

4.2 Discussion of the technical thresholds

In managing the distribution grid the electricity company uses a number of guidelines which have often been laid down in standards and instructions. Most of the time the guidelines are adjusted to international standards.

On the one hand they have the intention to reach a standardisation of such frequent items as (over-) voltages and (short-circuit) currents. On the other hand they provide rules on how to act in certain or specific situations and of course they have to guarantee personal safety.

When new developments are being employed "unusual" situations will arise.

Decentral generators are causing new phenomena in the distribution grid too, which ask for an adaption of the usual managerial methods.

Every country has its own thoughts about what extra kinds of adaption should be made obligatory for grid-connected generators. There are a lot of varieties for example with regard to the values at which these generators have to respond and with regard to the time lapses after which the safeguards have to respond.

In this section the potential interferences for the integration of wind energy into the distribution grid are discussed with respect to the various technical thresholds. More details are given by van Gemert [5].

The height of the grid voltage

The distribution grid is made up out of grids with different voltage levels which are connected by way of transformers. For these voltage levels different preference values are being given. It is furthermore customary in standard management not to diverge more than a certain percentage from the standard voltage.

If now decentralized electricity is being generated the voltage loss will decrease. When more is being generated locally than consumed even a voltage increase might occur. Because the voltage is already high under zero load, it might overstep the maximum value in the case of high electricity production and a simultaneous low demand.

Deviations from the voltage level can be partly compensated for by regulating the voltage at medium voltage level as a function of the magnitude and the phase displacement of the mains current. Such a combined voltage regulation (compound regulation) is found in traditional excitors.

With a well-adjusted compound-regulation it is basically possible to draw up a generating-power in a supply area equal to the nominal load, without endangering the voltage management.

An adapted compound-regulation for the voltage at medium voltage level is not always being applied. Sometimes they desired (setpoint)voltage at medium voltage level is fixed for the entire supply area, just as the compounding factor.

The voltage changes in the grid

Through changes in the load and/or generating variations may occur in the amplitude of the ground harmonic voltage. These voltage variations are noticeable particularly in lightbulbs, because these have a strong voltage dependent light-production. Partly for this reason an international standard has been drawn up.

This standard gives, taking into account the perception of the human eye, a maximum repeat frequency for a certain step-by-step voltage change (the so-called flicker-curve).

Wind turbines can cause voltage dips because of the passage of a blade past the tower and the a-symmetry of the turbine. The effect depends upon the turbine lay-out and should have to be tackled just there.

Whether the voltage changes which are caused by wind electricity should be tested with the help of the present-day flicker-curve is an item of research which is getting attention in an international context.

The magnitude of the voltage changes is among others determined by the strength of the local grid. A measure for the strength is the so-called short-circuit power. The local short-circuit power depends strongly upon the distance to the distribution transformer (the length of the feeder line) and is not coupled to the connection value of a consumer.

The higher harmonic currents

The subscribers of the distribution grid are as a rule offered sine-shaped voltage. The appliance the subscribers are connecting operate more and more at a different supply voltage (most Direct Current voltage). In general static convertors are being used here.

A static convertor takes in a non-sine-shaped current from the grid. This current (with the help of fourier analysis) can be splitted into harmonic components. Every higher harmonic component will cause a harmonic voltage over the impedance in the grid, and one could therefore speak of voltage distortion (grid pollution).

Voltage distortion is furthermore being caused by the power electronics of wind turbines too. Two or sometimes all three voltage phases are being connected together periodically which causes peaks in the voltage (so-called commutation-peaks). In order to reduce hindrance to fellow-subscribers each apparatus is allowed to cause a restricted amount of harmonic voltages only. A generator which is connected to the grid using an invertor, supplies a considerable amount of higher harmonic (watt-) currents (background report). The resulting grid-harmonic is being obtained by dividing the generator current and the consumer current into harmonic components and adding them up per harmonic.

The voltage distortion in the grid depends among others on the "resistance" in the grid and on the connected loads. The lower this "resistance" is, the easier the harmonic currents find their way back. Resonance in some parts of the grid may force a harmonic current to take a different route (with higher grid resistance), which will cause "voltage oscillations".

Generators, just as motors can play a purifying role in the low voltage grid.

The wattless power consumption and the feeder capacity

The magnetization current, like the watt current, is in general supplied by the distribution grid. The distribution grid has been laid out to a maximum power. This nominal current value depends upon the dissipation in the feeder cable resistance, so upon the type of cable and the diameter thereof. The normative criterion in this respect is the maximum current which is allowed continuously.

When wind electricity is being supplied to the grid the watt component of the absorbed current will be negative (The $\cos\phi$ component is smaller than zero). The absorbed wattless current component ($\sin\phi$) can, dependent upon the type of generator, be both positive or negative (inductive respectively capacitive "load").

If relatively a lot of watt power is being supplied decentrally by synchronic generators the phase angle of the resulting grid current will become increasingly large. The grid current supplies a lot less energy to the consumer but still causes grid losses.

The wattless current can be compensated for by over excited synchronic machines ("synchronic capacitor") or normal capacitors. Nevertheless, compensation also has its disadvantages.

If the $\cos\phi$ of the exciter is larger than 0,85 inductively, the resulting grid current will consequently decrease in the grid section concerned and so the transformer is always relieved somewhat. The grid losses up to the location concerned therefore always decrease with regard to the original situation.

The short-circuit currents

The various elements of the distribution grid are protected against short-circuit damage by way of safety fuses and current breaker switches. A current breaker is a device which has been constructed especially to interrupt high short-circuit currents.

The lay-out of a security system is such that in case of a shortcircuit in the grid only the failing part is being disconnected.

An increasing number of decentralized generators might cause various problems:

- The selectivity between the safeguards will be lost. A fuse can not detect in which direction the short-circuit current is flowing (decentral generators jointly feed a short-circuit at a higher level).

- The surge short-circuit current increase above the standardized value of the installation, which causes mechanical overload. The installation will have to be reinforced then.
- The short-circuit current is too large for the security devices and is not interrupted. This will cause a shower of sparks.
The current breaker or fuse will have to be replaced by a type of a higher nominal break-off current.

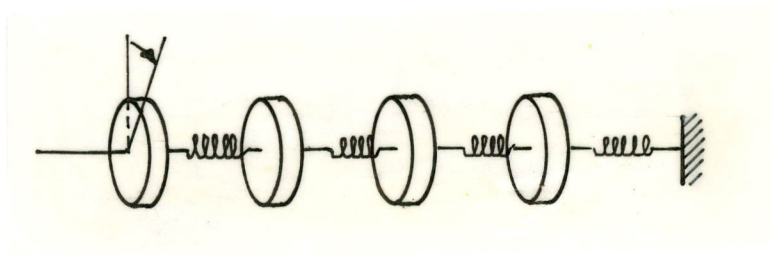
A generator which is connected to the grid by power electronics will be switched off rather quickly because of its own fuses, and will therefore not contribute to the abovementioned problems.

The stability of the distribution grid

The distribution grid can become unstable in various ways. If several generators start to exchange power of a certain frequency among each other (haunting) the power oscillation can, in the case of insufficient subdueing, become so large the safeguards will become operational (f.i. over-current). If a short-circuit at a higher level has occurred generators can trip before the grid voltage is being restored.

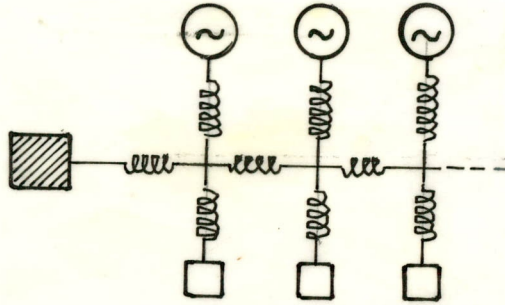
Reciprocating-frequencies emerge because various rotating machines, which are connected through the grid, behave like a linked mass-spring system. Two situations are roughly possible [5]:

- a. Several machines of the same oscillate as a group with another group of machines (see figure below).



The mass inertiae per group may be added up globally to estimate the reciprocation frequency which will therefore be relatively low (0,1 - 1 Hz).

- b. Different machines of a group oscillate among each others. The reciprocation frequency will be somewhere in the neighbourhood of the resonance frequencies of the generators/load concerned (see figure below).



The mutual coupling in the mass-spring system is the local grid voltage. The power oscillations are accompanied by voltage changes. In both cases the oscillation is being evened out by load, in so far as it is present locally and is voltage-dependent and/or by a voltage stabilizer.

In case a, the largest voltage changes occur at the ends of the groups and the largest currents at the joining of the groups (the sub-station). If both groups are evened out insufficiently, a power reciprocation could still be limited by wattless current control.

In case b, the voltage change and therefore the subduing is considerably lower. The reciprocation frequency is somewhere in the neighbourhood of the system frequencies and will have to be subdued with the same means as with which the possible system-resonances in the wind turbine will be subdued as well.

Failure susceptibility

The use of wind energy should in principle not affect the reliability. This means among other things that a local failure may not lead to a failure for other consumers. The selectivity of various safety devices will have to be maintained. This goes for both the security devices on transformers (where the direction of the short-circuit currents might turn around) as well as for the safeguarding of generators against feeding in on a short-circuit.

The safety/earthing

Because of the arrival of decentrally generated power a change of management is taking place. A considerable danger for the utility is the fact that parts of the distribution grid which need to be worked on (without voltage) nevertheless remain live.

This situation may occur when both the watt power balance (the frequency) and the wattless power balance (the voltage) are being disturbed so little that the security devices do not respond. In theory should therefore both a frequency regulator and a voltage regulator have to be operative.

In practice it turns out that the connected load itself has a strongly positively regulating character. As a rule the consumption increases when the frequency and/or the voltage increases. Often the wattless current balance also proves to be regulating itself, if enough capacity is connected. In this case island operation sometimes occurs, despite the absence of an active frequency and voltage regulator.

The most simple solution to this problem is to take care the local wattless current balance is disturbed in advance.

This means that less wattless current has to be compensated locally than would be optimal from the point of view of minimalizing grid losses.

A second problem in the case of wattless current compensation is the fact that when one of the three phases breaks down so little voltage difference occurs that the a-symmetrical security devices often do not respond.

In the interest of the safety of the executive technicians agreements and guidelines will have to be formulated with regard to the use and securing of capacitor batteries.

For the earthing of low-voltage appliances at consumers' places guidelines have most of the time been laid down. It is often not allowed to include a switch or a separator in an earthing an earthing cable/-wire.

4.3 Rules of thumb for integrating wind power

In this section rules-of-thumb will be proposed for the different technical problems to estimate the wind power which can be integrated freely.

First the amount of wind power will be derived which can maximally be connected at a certain point to the grid, while the magnitude of the voltage stays within acceptable limits.

Because the distribution grid behaves differently for harmonic currents than for the basic current the local harmonic voltage is less useful as a criterion.

A link has been made therefore between the local short-circuit current and the possible harmonic current.

The height of the grid voltage

The standards and instructions concerning the grid voltage always apply to the maximally permissible deviations from the nominal voltage level. The maximum voltage level therefore is not allowed to increase and the generator safe guards are set at this maximum value. Starting point is that the wind power equals the average load and that the capacity of the average load equals 5% of the short-circuit capacity. When nevertheless over-voltages in the grid occur, although this instruction has been regarded, the electricity company will adjust the voltage.

This means for example for The Netherlands (where the nominal voltage is 220 Volts) that the utility will do its best to supply no more than 231 Volts and that the over-voltage relays are adjusted to 242 Volts.

The voltage changes in the grid

A reoccurring problem with wind turbines is the frequent switch-on and switch-off of the electrical system around the cut-in windspeed. Particularly in the case of squirrel-cage motors a short magnetisation current is running for a short while each time, and/or a supercharge current for wattless current compensation (capacitors). Such problems can be prevented by limiting the switching frequency or by connecting "softly" to the grid [5].

Wind supply variations are non-periodical and non step-by-step and do not need to be judged by the flicker curve system power fluctuations (as a result of blade-tower passages) on the other hand will have to be limited, in order to comply with the flicker curve.

Departing from a voltage increase of 5% this means maximum dips of around 10% of the nominal power.

The higher harmonic currents

The higher harmonic currents in the distribution grid increase constantly merely because of the growth in the use of power electronics controlled drives. Directly connected decentral generators can take care of these currents very close to the source. Harmonic currents in the grid will also increase when decentralized generators with invertors are being used.

In reference [5] it is shown that the greatest restriction is being imposed by the fifth harmonic, namely a reduction of respectively up to 65% for an inverter with a large choke and up to 50% for an inverter without a choke. Through the employment of a filter for the 5th harmonic or the employment of a 12 pulse inverter power up to the full 100% can be integrated.

The wattless power consumption and the feeder capacity

The maximally permissible power in the grid depends upon the dissipation in the feeder cable resistance, so upon the type of cable and the diameter thereof.

In tabel 2 a number of values are given for the maximally permissible current for different types of cable.

Short-circuit currents

The generator principally contributes to a short-circuit current in the grid. In the case of a squirrel-cage motor the same current will flow as if it were motor operated. This does not lead to other security methods than when motor operated with regard to the dynamic surge current.

When a short-circuit occurs at the generator itself, its own security devices should be the first to take care of a switch-off.

These security devices will have to be at least one step more sensitive than those in the grid, even if the type of cable is similar to the grid type. Should this not be possible because of the nominal generator current one might consider connecting the generator to the transformer station by way of a separate cable, or connecting the generator to the transformer station by way of a soft starter and a lower step than is possible with regard to the switch-on current.

Only if the exciter is contributing to the stationary short-circuit current (in fact only in the case of synchronic generators) unnecessary switch-off of the generator concerned will occur, in the case of short-circuits in the grid near the generator.

Installing generators in the grid can lead to an increase of the dynamic (short-circuit) currents in the installation in the case of a short-circuit.

It is not easy to give generally valid rules for the increase. The short-circuit currents will be dependent upon the grid lay-out (the impedances) and integrating extra wind generators can in some cases indeed lead to an increase of the dynamic short-circuit currents and in other cases hardly.

Stability

Instabilities could occur when the grid has an insufficiently subduing effect and when at the same time the stability of the individual turbine is low. This situation could occur when a group of less stable turbines is connected to the public grid by way of a relatively weak connection, and when the local consumption is low on top of that. Especially in the case of more wind turbines with a combined step-up transformer one has to be apprehensive for this.

With regard to the international experience up to now reciprocating motions among/between turbines do not seem very likely on the one hand, but can not be excluded on the other if impedances between the turbines and the transformer are too high.

Failures, safety and earthing

Two points of attention are island operation and earthing: by island operation is meant the fact that an isolated part of the grid remains live. The most reliable solution against undesired island operation is to take care and avoid circumstances under which island operation might occur. This means that parallel operation without a connection to the public grid should not be possible.

The conclusion here is that the electricity supplied by the wind turbine definitely has to depend upon the public grid. This can be realized simply by consistently obtaining the excitation current from the public grid, in other words by not (or limitedly) installing decentralized capacitors. One should be able to disconnect the capacitors which have been installed by the electricity company by way of a frequency relay.

In general wind turbines have an electrical conversion system which is connected to the grid by a delta connection. No neutral wire is then present in the conversion system that could be used as earth connection. The security earthing of the metal parts of the conversion system is mostly carried out by connecting it to the reinforcement of the foundation.

4.4 A handmethod to determine the wind power which can be integrated freely

There are several potential technical problems that might show up when wind turbines are being connected to the grid, which have been discussed in section 4.2. The two main limitations of the grid appeared to be the maximum current and the maximum voltage change. The other problems have to be solved by adapting the system itself. When a lot of wind turbines are being installed a number of typical phenomena will damp out, such as switch-on, switch-off, dynamic power overshoot, system vibrations etc.

The two limitations, which have been mentioned above, are no new criteria. They play a role in the planning of normal distribution grids too, when the amount of power consumed is deciding for the grid dimensions.

The criteria (maximum current and maximum voltage change) can also be applied to the practice of planning wind-farms in the following way.

Maximum Current

For a given type cable or overheadline with specified cross-section and material of conductor there will be a specific maximum current (also depending more or less on ambient temperature, see table 2. The maximum current in the grid is calculated by the sum of generators feeding into the grid and will occur only between the generators and the nearest consumers. Part of the current consists of the needed reactive power to be indicated by the power factor ($\cos\phi$).

When the minimum value of the power-factor is considered to have a minimum value of 0.85, there is a simple relationship between the (real) power and the maximum current [5]:

$$P_{\text{current}} = \sqrt{3} \cdot U_g \cdot I_{\text{max}} \cdot 0.85 \quad (4.1)$$

When the windpower is generated by several turbines it is unlikely that they all deliver their maximum power at the same moment, so the assumption that the maximum power is $P = \sqrt{3} \cdot U_g \cdot I_{\text{max}} \cdot 0.85$ seems a reasonable and safe estimation for the maximum wind farm power limited by the maximum current.

Maximum voltage rise

In most cases the distance to the sub-station is so large that the voltage increase is normative. A measure for the strength of the grid is the short-circuit power (short-circuit impedance) that can give a measure for the maximum power than can be connected to the grid without causing a voltage increase of more than 5% (see section 4.3). In such cases the wind power which can be integrated freely equals one-twentieth of the local short-circuit power. The short-circuit power depends upon the nominal grid voltage and the cumulative grid impedance. The grid impedance in this case roughly equals the cumulative Ohmic grid resistance. The Ohmic resistance of various cable lengths/cable parts can be approached simply by the type, diameter and length of the length of cable concerned. At a given voltage level the windpower which can be integrated maximally can be estimated simply:

89-233/R.24/MST

33

$$P_{\text{voltage}} = \frac{0.05 * U_g^2}{\frac{U_g^2}{S_{\text{short}}} + \sum \frac{L_c}{A_c * C_m}} \quad (4.2)$$

in which the short-circuit power is represented as the sum of the cable-resistance and the (reactive) transformer impedance. As the impedance is lower in reality, the short-circuit power will be higher. This will therefore cause a pessimistic estimation.

The short-circuit impedance of the transformer, which is mainly reactive, is added algebraically to the mainly ohmic cable-impedance instead of complex vector addition which yields an impedance which is too big, causing a pessimistic estimation.

The wind power which can be integrated freely is the lowest value of P_{current} (4.1) and P_{voltage} (4.2).

4.5 Conclusions

A method has been developed which determines the maximum amount of wind power to be integrated freely.

This method makes it easy to give an estimation of the total potential of windpower which can be connected in an area. When the substations are given, it is possible to calculate the maximum wind power from the cables and their maximum current inside a certain radius. Beyond this distance the voltage-criterion will become limiting which will also give a fast result either by using the grid short-circuit information, or by simple hand-calculation using the given formula. In this way one can make a map showing not only the wind-potential but also the wind power that can be integrated cheaply by using the existing grid.

5. CONCLUSIONS

Two engineering methods have been developed for the utilization of wind energy in remote locations.

The application of the first method, a numerical model, is the optimization of the lay-out of wind turbine clusters in topographically complex terrain with respect to the total power output.

It appears that the second order effects, due to the assumptions with respect to the wake evolution in complex terrain, can be large in the surroundings of large changes in the terrain topography.

Validation of this numerical model (COMPL-model) shows however better agreement of the COMPL-model with experimental data than comparable models intended for use in flat terrain conditions. The validation however is limited due to the limited amount of available data.

The application of the second method is the determination of the maximum amount of wind power which can be integrated in a weak electricity grid, taking into account connection conditions, standards and instructions and management.

Several technical problems show up when wind turbines are connected to the grid. The two main limitations of the grid appeared to be the maximum current and the maximum voltage change. Formula for the determination of these limitations and the resulting maximum amount of wind power have been deduced. The other problems have to be solved by adapting the system itself. Possible adaptations are given.

Both methods can be used in combination, by making a map which shows both the wind potential and the wind power that can be integrated using the existing grid.

Besides these two methods, a first set-up of a dynamic wind farm model (INSTA-model) has been developed. The application of this INSTA-model is the prediction of power output fluctuations of wind farms. At the moment however, no data are available for the validation of this model.

6. RECOMMENDATIONS FOR FURTHER RESEARCH

At the moment the amount of useful validation data for the COMPL-model is limited. As a consequence the validation of the developed COMPL-model was limited. In the near future however a number of wind farms are planned in complex terrain conditions (e.g. in the U.K. and Spain) for which extensive measuring campaigns are planned.

It is expected that this will result in useful and sufficient data for the validation of the COMPL model and other wind farm models.

It is therefore recommended to use data from such wind farms for an more extensive validation of the COMPL-code.

In the first set-up of the INSTA, only the wind input and wake interaction effects are taken into account. Other relevant factors, such as the wind turbine response and the control systems are left out of consideration. These factors however, do have a severe influence on the time-dependent behaviour of wind turbine clusters.

Moreover, the INSTA model has not been validated, due to lack of data.

Extension of the INSTA model by taking into account the wind turbine response and control system effects and validation of the model is considered to be necessary to arrive at a reliable tool with several applications like:

- Determination of power fluctuations as a part of wind power integration studies; this application may range from "worst case" estimates to the determination of a complete probability distribution of the power fluctuations.
- Application as a design tool; with a dynamic cluster model, the effects of various control strategies for individual wind turbines as well as for the complete cluster can be studied. Moreover, cluster lay-outs can be optimized in more detail than by applying a quasi-steady approximation.

- Application as a part of the overall control system; in order to maximize the power output as well as to minimize the power fluctuations, a dynamic cluster model may be applied for "real-time" control. In connection with local wind forecasting or an on-line wind measurement system, a real-time simulation model can even be applied as a strategic part of the power grid control system. This is of particularly interest for remote areas, as in most cases the local grid, as far as available, will be weak. As a consequence the power grid will be sensitive to power fluctuations. Forecasting the power output fluctuations will therefore increase the quality of the supplied electric energy and the amount of the maximum to be integrated wind energy.

The use of the INSTA model in these applications may lead to an increase of the quality of the supplied electric energy, a considerable amount of saved "fuel" energy and an increase of the maximum amount of wind energy to be integrated in the electricity grid.

A proposal for the extension and validation of the INSTA model has been submitted to the CEC in the framework of the R&D JOULE programme.

89-233/R.24/MST

37

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89-233/R.24/MST

40

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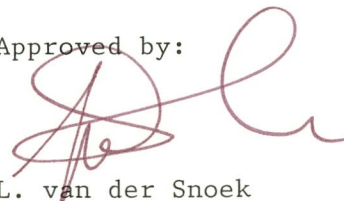
January 1987 - June 1989

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supervisor wind energy

Table 1 Measured and COMPL-calculated power production of the Ampurdam wind farm

Case	Wind speed ¹⁾ [m/s]	Wind direction ¹⁾ [degrees]	Power production		Difference ²⁾ (COMPL) [%]	Power production		Difference ²⁾ (FARMS) [%]	Best results by
			Measured [kW]	Calculated (COMPL) [kW]		Measured [kW]	Calculated (FARMS) [kW]		
1	8.1	19	40.8	41.3	1	40.8	41.2	1	-
2	7.5	337	37.4	39.2	5	37.4	33.2	-11	COMPL
3	7.7	2	33.9	33.8	0	33.1	33.9	- 2	COMPL
4	8.1	20	43.5	43.6	0	43.5	41.3	- 5	COMPL
5	8.7	335	45.4	47.5	5	45.4	47.5	5	-
6	7.5	41	41.2	40.9	-1	41.2	34.2	-17	COMPL
7	8.2	2	36.0	38.2	6	36.0	38.4	7	COMPL
8	8.4	343	41.3	43.8	6	41.3	43.1	4	FARMS
9	8.2	2	37.2	37.4	1	37.2	38.4	3	COMPL
10	8.3	343	42.3	42.2	0	42.3	41.9	-1	COMPL
11	7.2	19	29.3	31.3	7	29.3	30.3	3	FARMS
12	7.8	4	34.8	33.6	-3	34.8	34.4	-1	FARMS
13	8.9	2	43.9	43.4	-1	43.9	45.3	3	COMPL
14	7.5	20	36.8	36.5	-1	36.8	33.9	-8	COMPL
15	7.9	342	32.9	36.6	12	32.8	37.5	14	COMPL
16	8.6	2	40.4	40.7	1	40.4	42.3	5	COMPL

¹⁾ measured at the meteorological tower

²⁾ difference = $\frac{\text{calc. power prod.} - \text{meas. power prod.}}{\text{meas. power prod.}} \cdot 100\%$

Table 2 Feeder capacity [kW] of different types of cable at
low-voltage (l.v., 220 V) and medium voltage (m.v., 10 kV).

Diameter in mm ²	Copper		Aluminium	
	l.v.	m.v.	l.v.	m.v.
10	36	960	22	590
16	48	1.250	36	960
25	62	1.620	45	1.180
35	76	1.990	56	1.470
50	93	2.430	79	2.060
70	112	2.940	93	2.430
95	135	3.530	112	2.940
120	157	4.120	123	3.240
150	180	4.710	140	3.680
240	236	6.180	182	4.780

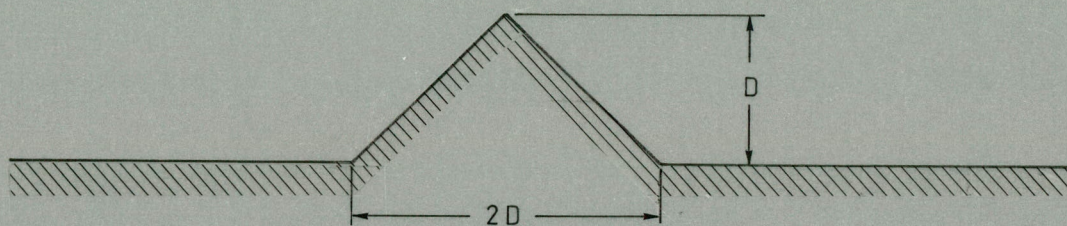


Fig.1 Characteristic obstacle ; D = turbinediameter

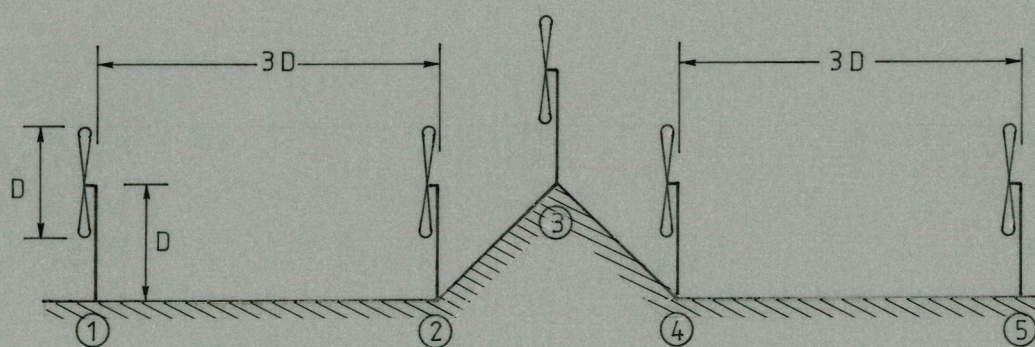


Fig.2 Five situations ; hubheight = diameter = D

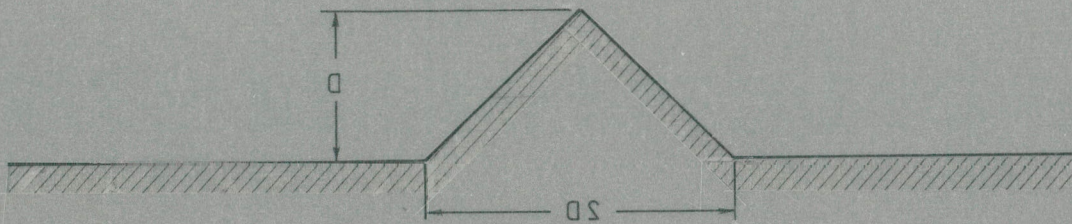


Fig. 1 Characteristic obstacle ; D = turbine diameter

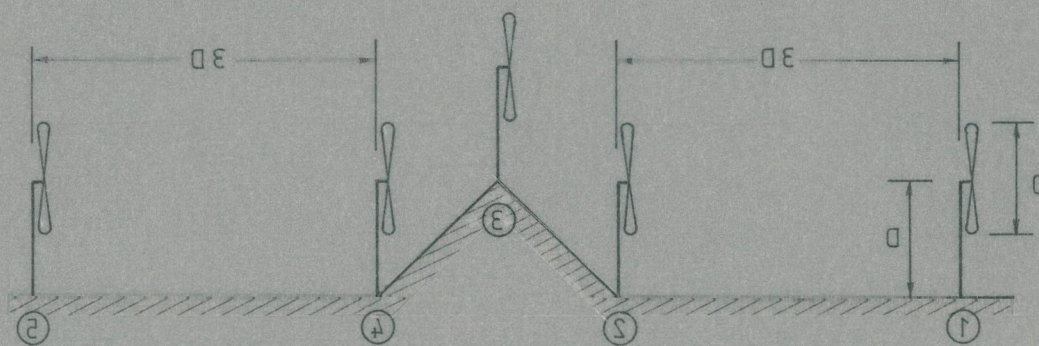
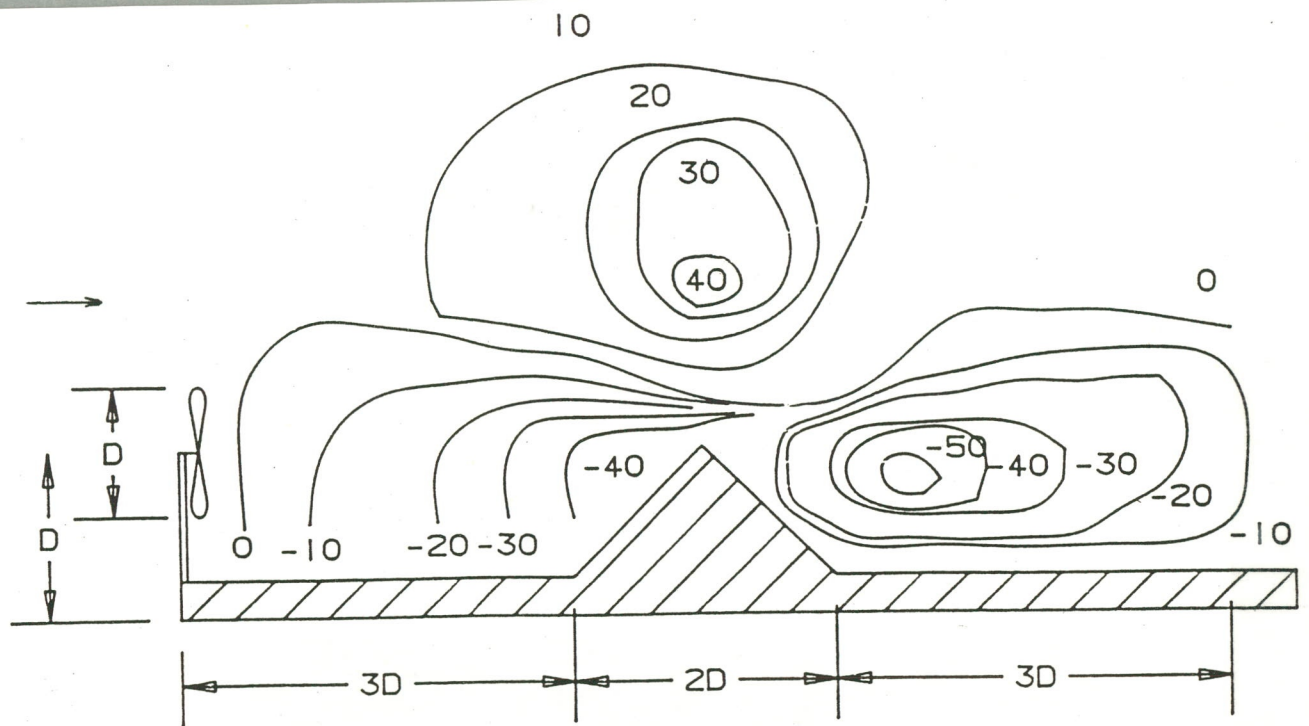
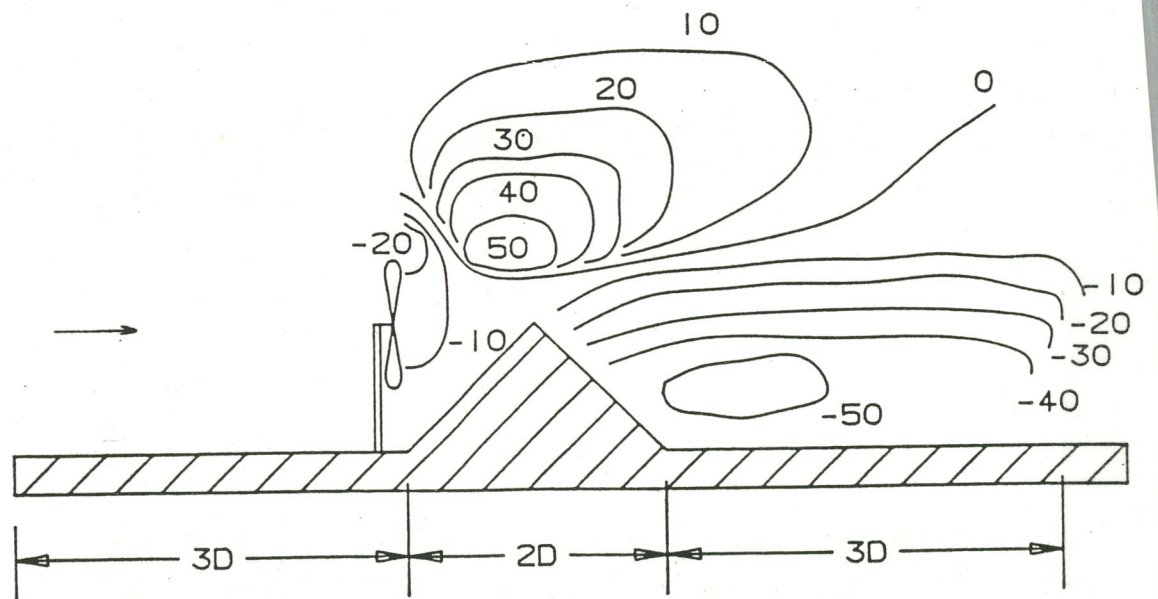


Fig. 2 Five situations ; hubheight = diameter = D



LINES OF CONSTANT DEVIATION

Fig.3 Turbine position 1



LINES OF CONSTANT DEVIATION

Fig.4 Turbine position 2

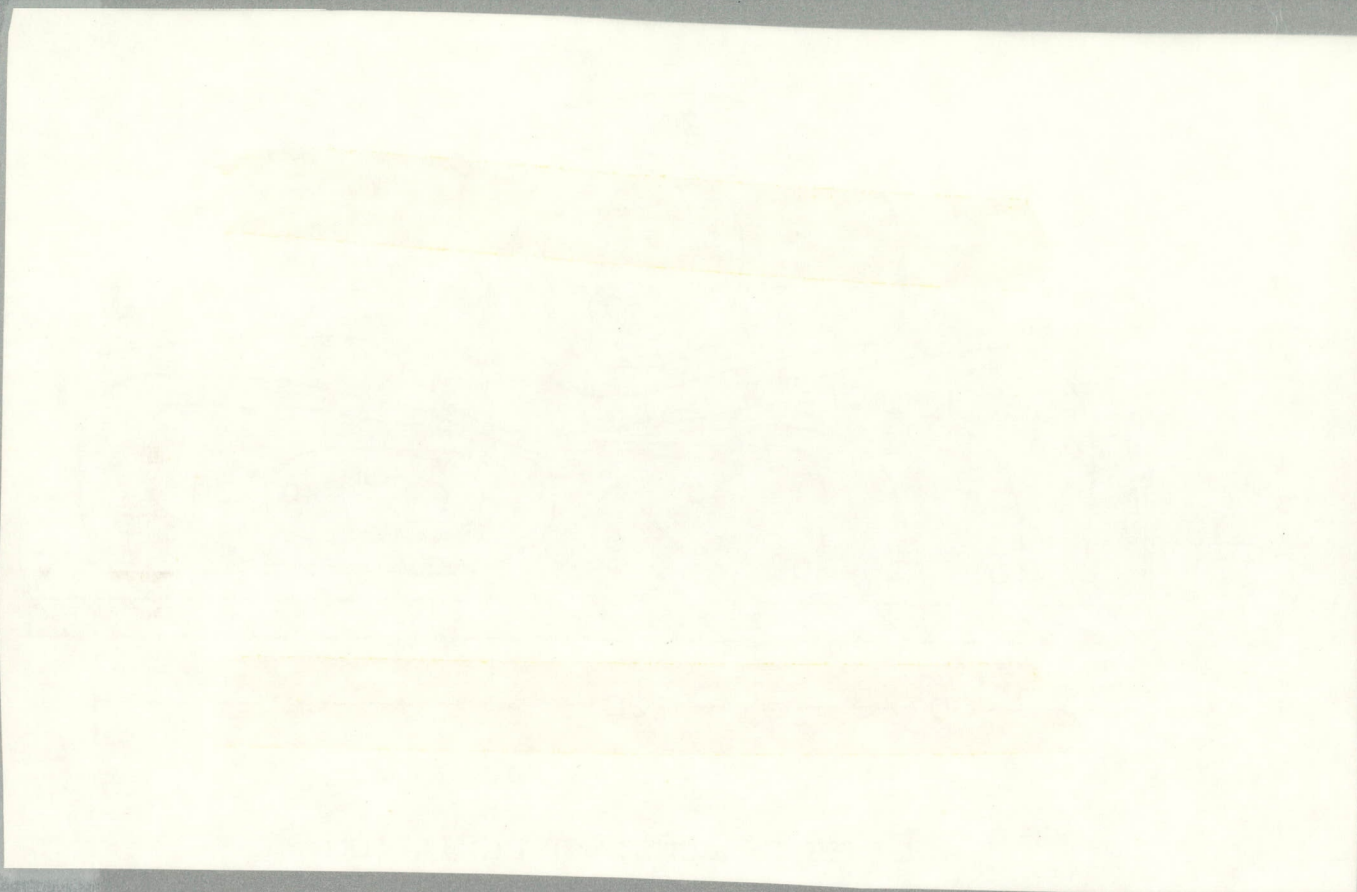


Fig. 3 Turbine position 1

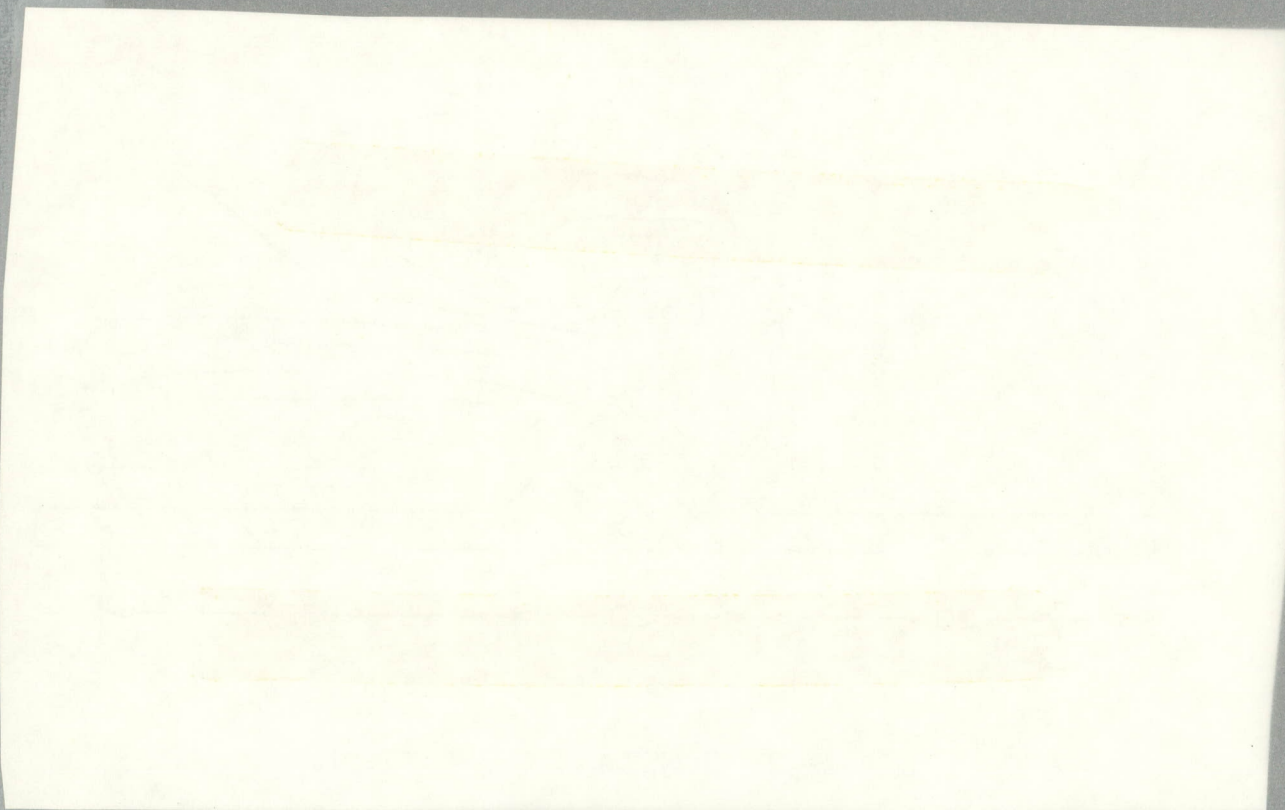
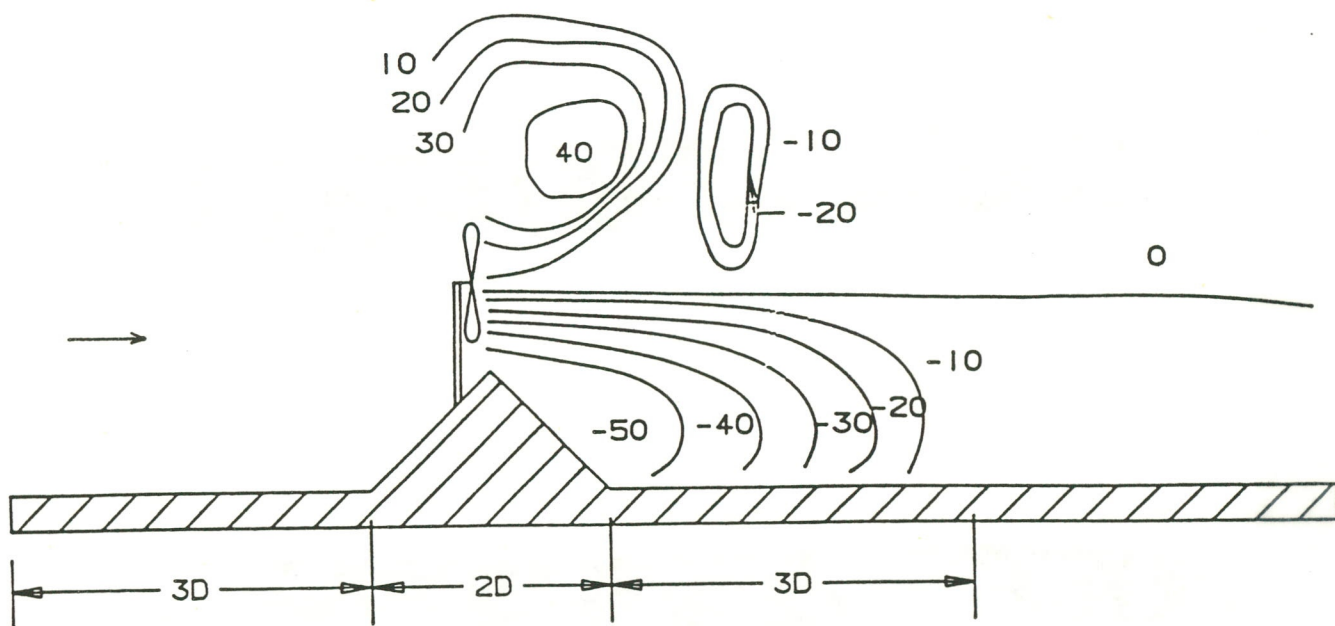
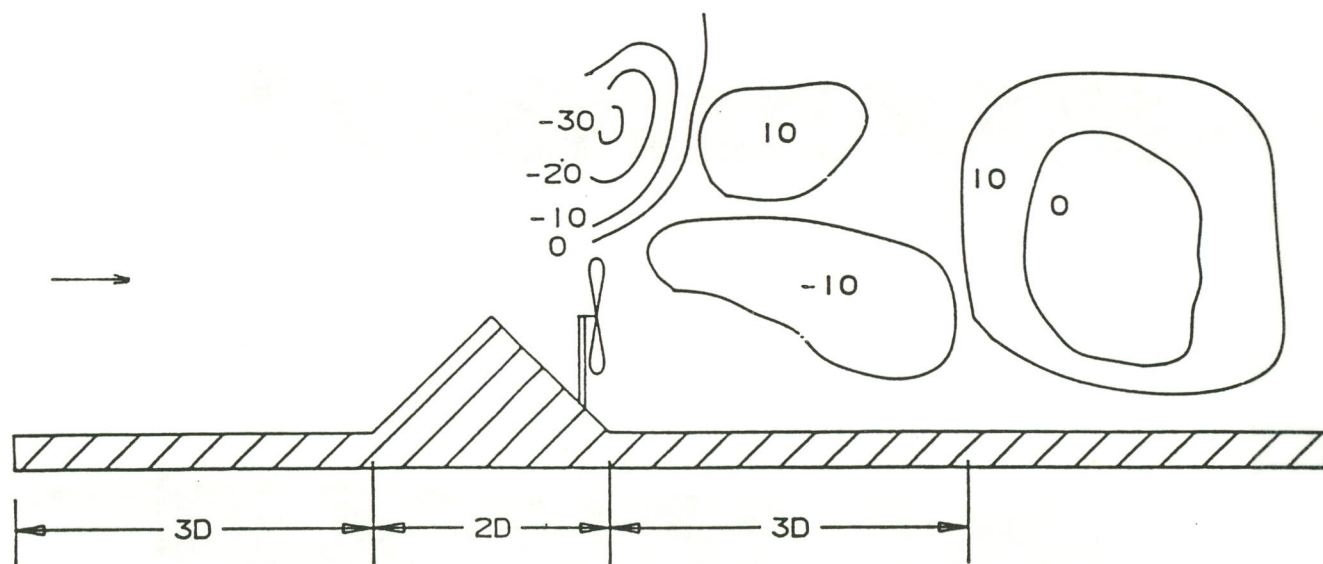


Fig. 4 Turbine position 2



LINES OF CONSTANT DEVIATION

Fig.5 Turbine position 3



LINES OF CONSTANT DEVIATION

Fig.6 Turbine position 4

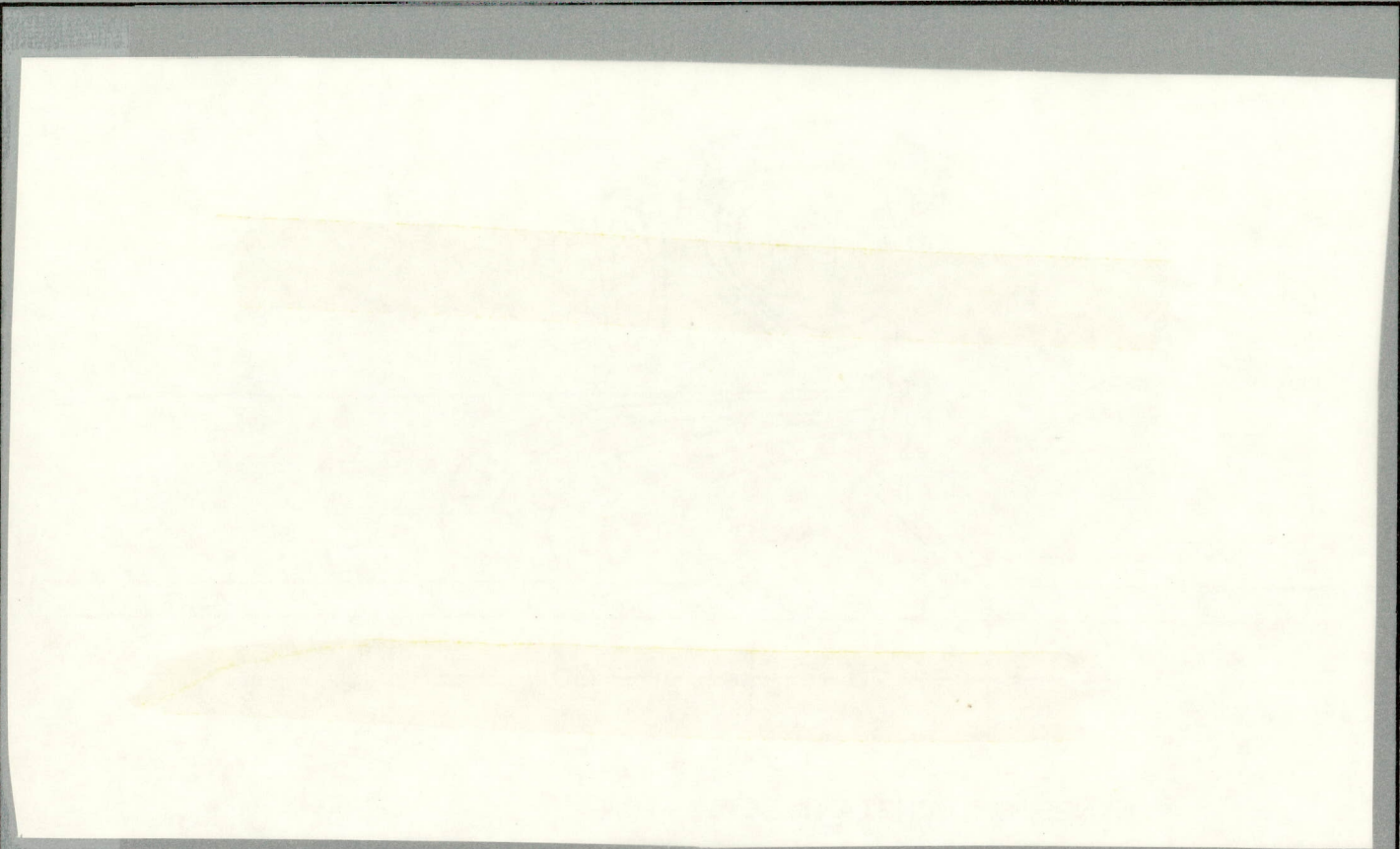


Fig. 2 Turbine position 3

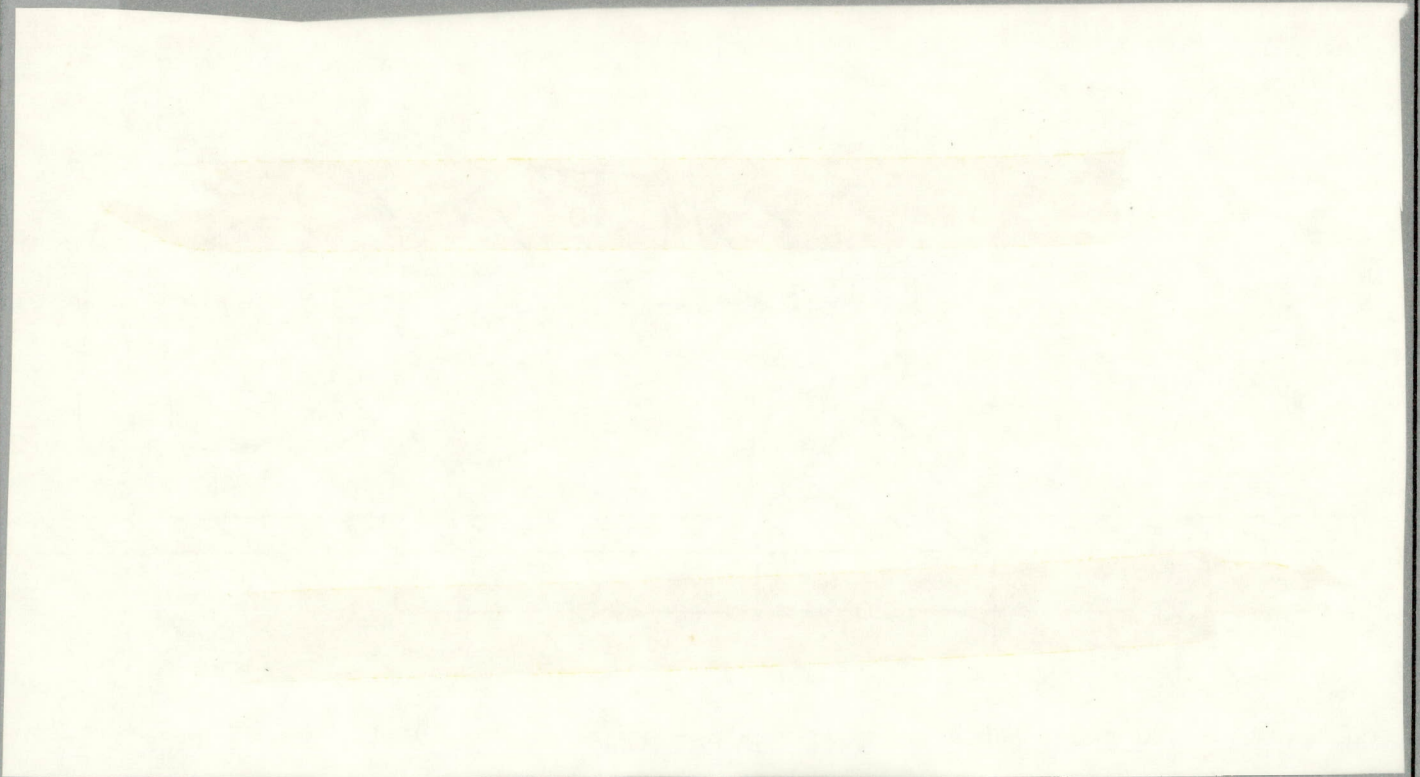
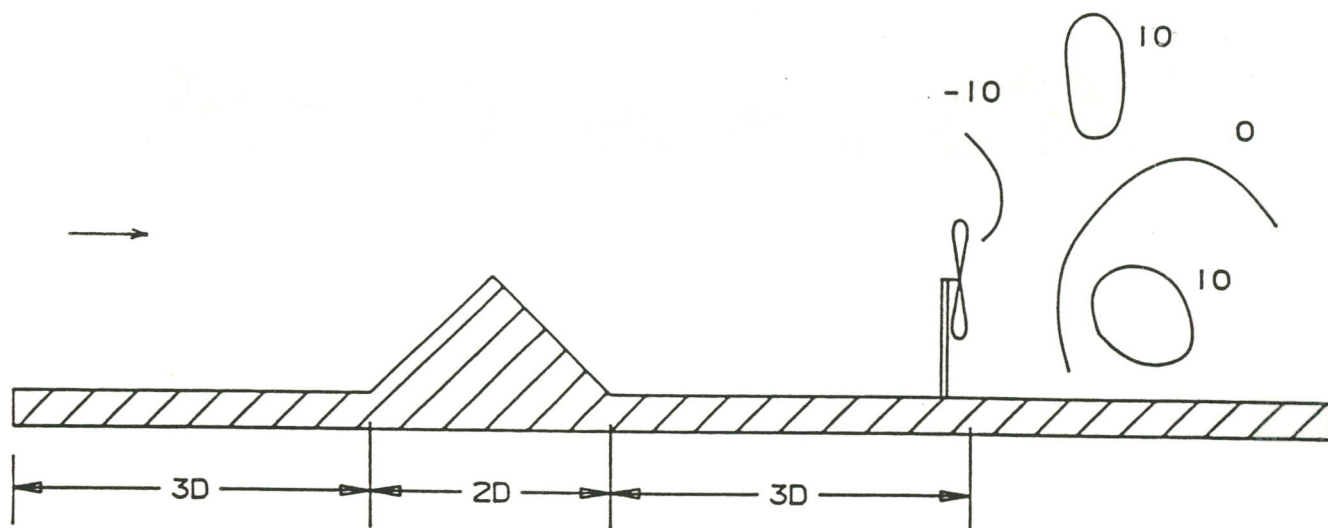
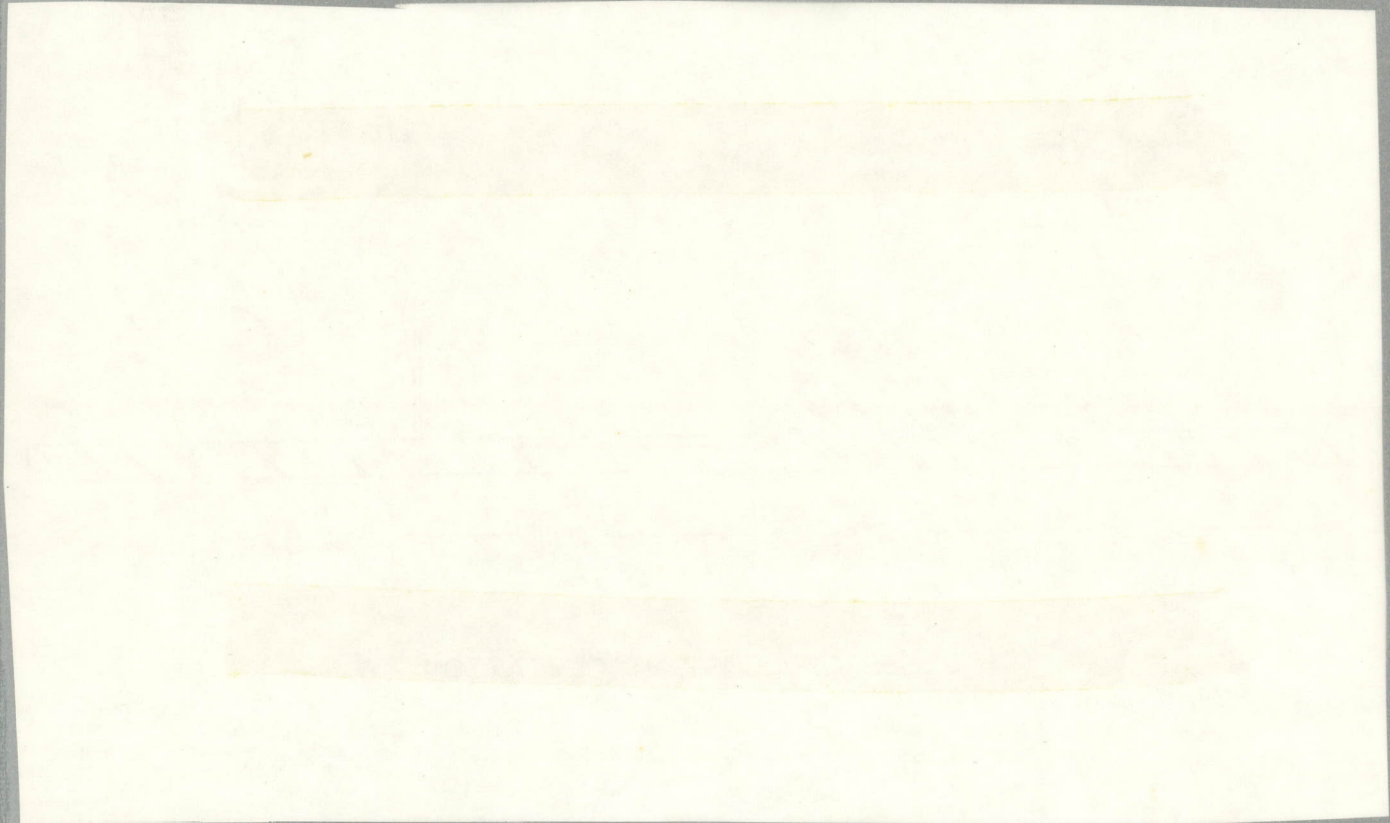


Fig. 6 Turbine position 4

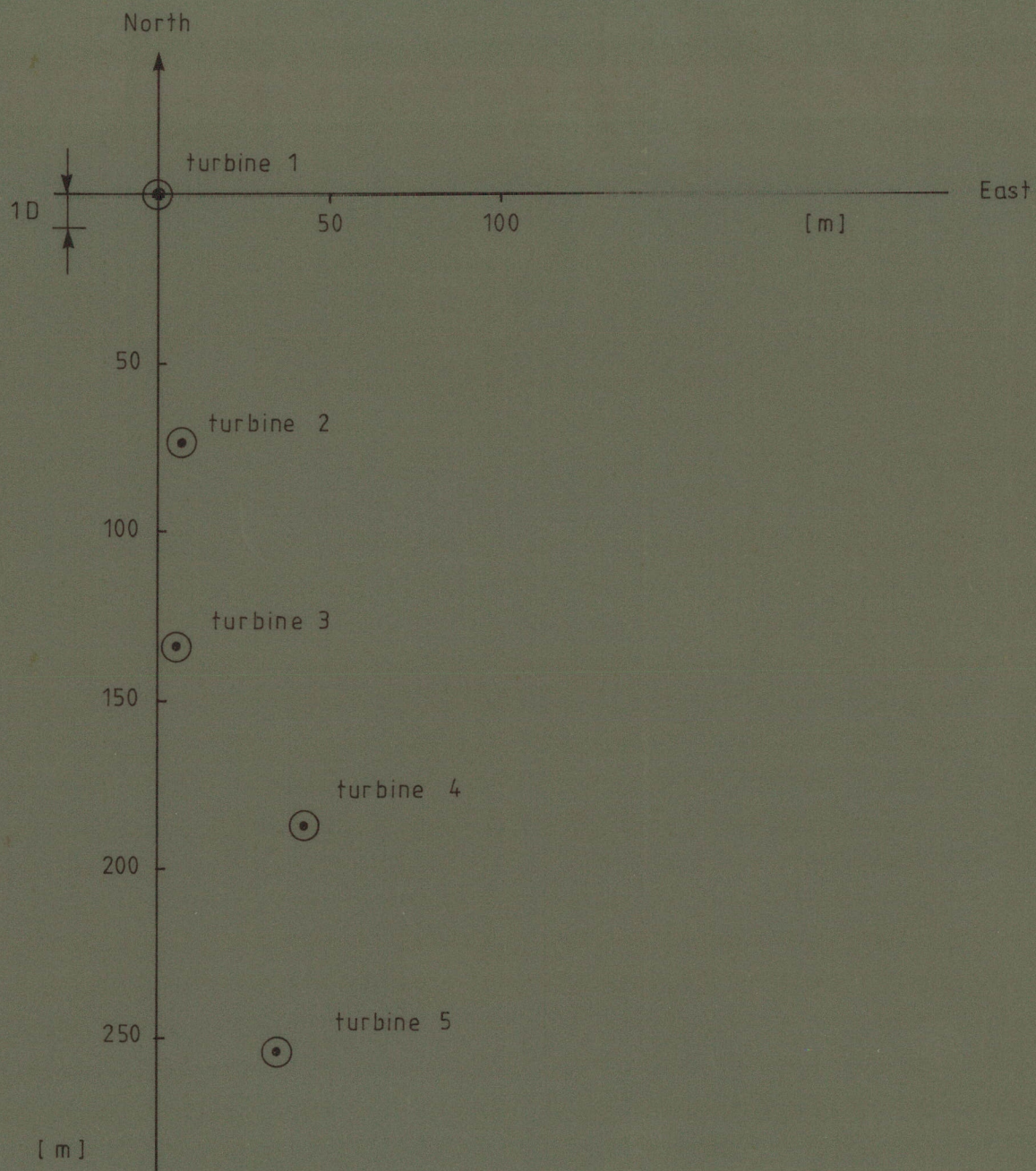


LINES OF CONSTANT DEVIATION

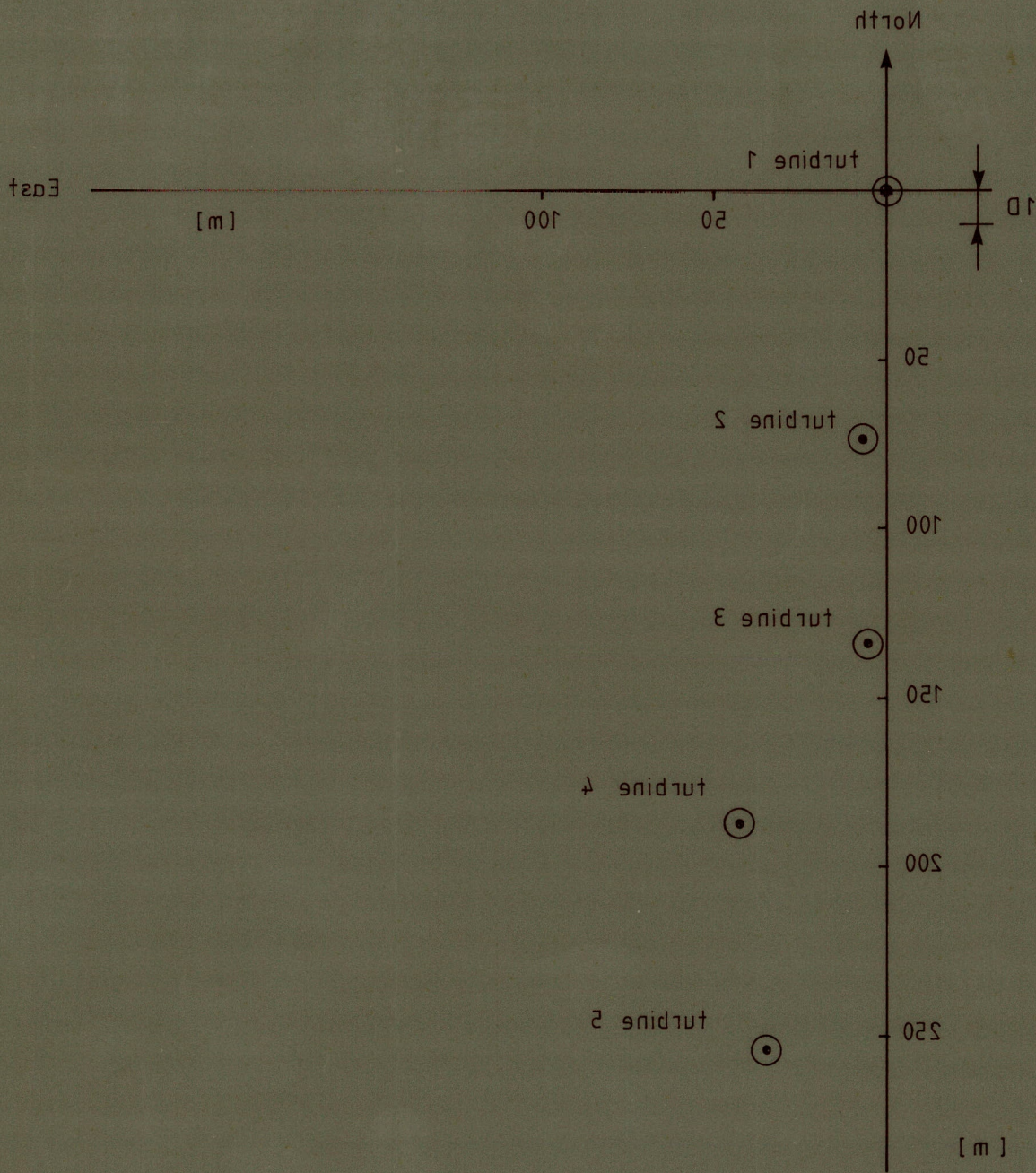


Turbine position 2

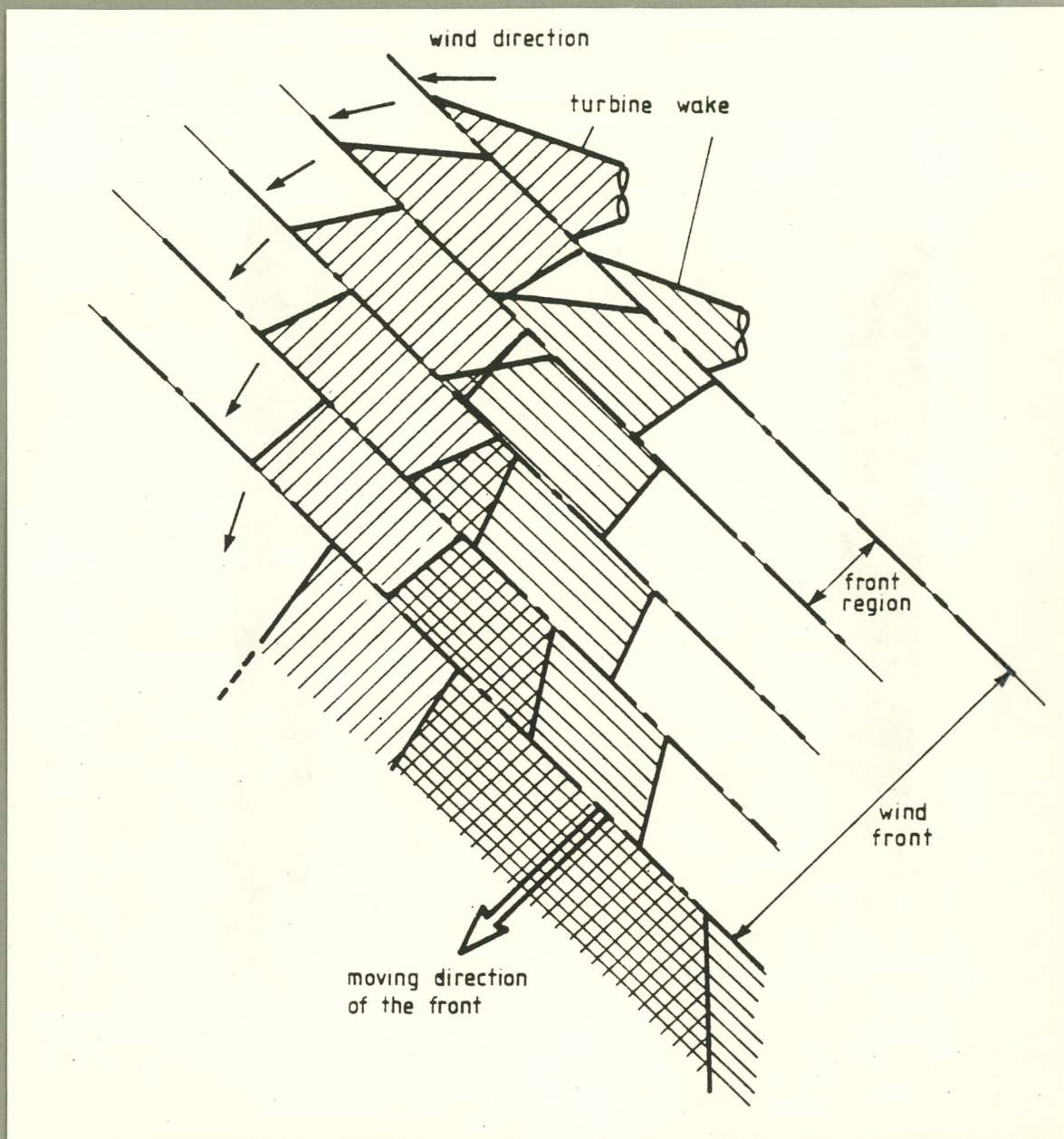
Fig. 7
89-233
MT-TNO



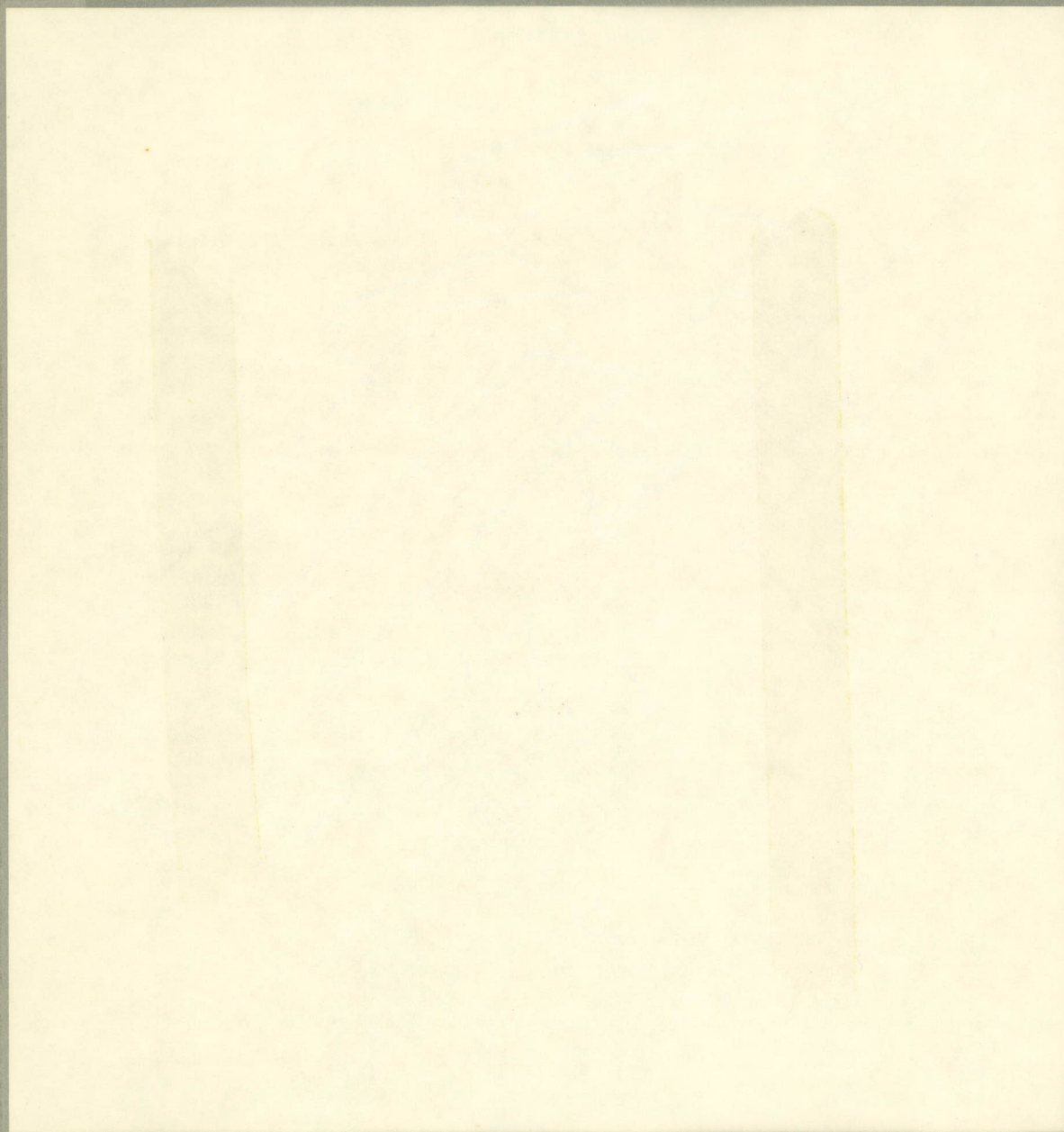
Lay_out of the ampurdan wind farm



Layout of the onshore wind farm



Schematic wind front and wake evolution.



Schematic wind front and wake evolution.

Fig. 9
89-233
MT-TM