

TNO-report

**Power output fluctuations from wind farms
due to wind variations - a numerical model**

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Author
Ir. H. van Oort

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Intended for
SEP
Ir. P. van der Ploeg
Afdeling Planning & Onderzoek
Energie- & Milieutechnologie
Postbus 575
6800 AN Arnhem

Summary

One of the main problems of large-scale wind energy integration is the maintenance of high quality of supplied electric energy. The variability of the power output from wind energy systems 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.

This report describes a first set-up of a model which can calculate the time dependent power output from wind farms. First, an outline is given of relevant factors in relation to the time dependent behaviour of wind farms. Second, the developed model is described. Third, an example calculation is given which illustrates the time dependent behaviour of a wind farm in 'bad weather' conditions. The report closes with suggestions for further developments of the model in relation to possible applications. Those suggestions include a validation of the model against experimental data.

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1 Introduction

When large scale application of wind energy was considered for the first time, the importance of the impact of the fluctuating nature of the wind on the quality of the total power output of a wind turbine cluster was recognized. As a result of the variability of the wind and the consequent fluctuating power output of the cluster itself, large voltage fluctuations in the public grid may occur with time scales varying from hundreds of seconds to several days. This is an issue of prime importance to electricity companies when considering large scale integration of wind energy systems, because continuous supply of electric energy of high quality is a main task of these companies.

Turbine power output fluctuations with small time scales (e.g. due to blade-tower passages) are usually hardly correlated within a cluster, and cause therefore relatively small voltage variations. With increasing time scales the correlation of turbine power output fluctuations normally increases, resulting in larger voltage changes.

Low frequency fluctuations, with time scales larger than about 1 minute, may be minimized by using cluster control systems. To that end however, these low frequency power output fluctuations must be determined beforehand.

Up till now, most research on low frequency power output fluctuations has been performed as feasibility studies on introducing large scale integration, using (reduced) statistical data from meteorological measurements. These methods however are rather inaccurate. Since the actual development of wind turbine clusters in the Netherlands is going ahead, a more precise prediction of the expected power output fluctuations from these clusters is required.

To that end, a simulation model has been developed, describing the time dependent behaviour of the power output of wind turbine clusters, with respect to the low frequency fluctuations. This model can be seen as a first set-up for a dynamic wind turbine cluster model and is an extension of already existent 'steady-state' models.

Such a model can be used for several applications:

- Determination of power output 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 output fluctuations.
- Application as a design tool; with a dynamic cluster model, the effects of various strategies for individual wind turbines as well for the complete wind turbine 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 output 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.

An analysis of the prediction of the fluctuations in power output from wind turbine clusters is given in chapter 2. The analysis is restricted to low frequency fluctuations and does not deal with 'generator induced' fluctuations like higher harmonic currents. In this analysis the relevance of all factors to be incorporated in the simulation model has been considered.

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In chapter 3 a description of the developed simulation model is given, together with assumptions and neglected factors.

With this model an example calculation has been carried out, which is described in chapter 4.

Finally the conclusions are given in chapter 5.

2 Analysis of the prediction of power output fluctuations

There are several factors affecting the time dependent behaviour of a wind turbine cluster. In figure 1 these factors are given schematically. These factors and their relevance are separately described below.

2.1 Wind input

The most important factor is without any doubt the fluctuating wind input. Fluctuations in wind input may cause large fluctuations in the power output of a turbine clusters. There is however a strong relation between the time scales of the wind input fluctuations and the power output fluctuations of the turbine cluster. The division of the wind speed fluctuations on the various time scales can be shown in the power spectrum, which is given in figure 2. This figure is based on information about this in the relative literature hereon.

With respect to the integration of a wind turbine cluster, a clear distinction can be made between fluctuations with time scales larger than about one hour and fluctuations with time scales less than about one hour. The two regions in time scales can be clearly recognized in figure 2.

These regions can be characterized as follows:

1. 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; this means that the wind speed is equal over the cluster, but is variable in time. Hence, the impact of these fluctuations on the time dependent power output can be obtained by quasi-steady calculations;
 - time scales of the wind fluctuations more than a few days are not relevant to wind energy integration, because for larger time scales the changes are so slow that they can be compensated by conventional power stations.
2. 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 roll-vortices (a description of these weather systems is given in [1] and [2]). Although these fluctuations themselves carry little energy (as can be seen in the power spectrum, figure 2), they are of major importance for the power fluctuations of wind turbine clusters.

In summarizing the meso-scale weather systems described in [1], the following features are of importance to cluster power fluctuations:

- 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 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 over this in the literature, is that the correlation between wind turbines perpendicular to the wind direction may be neglected, so the power output fluctuations of the cluster as a whole are smoothed. 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 the individual wind turbine response, due to the dynamic response of the wind turbines (e.g. the mass inertia of the rotor blades). This portion ranges between one and ten minutes approximately.

2.2 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, which is normally given in the power characteristic. Usually, the power characteristic is based on 10 minutes averaged wind data [3]. 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.

2.3 Wake effects

The wake effects on the cluster power fluctuations arise as a consequence of the variations in rotor drag, which on its turn are due to wind speed fluctuations. Consequently, downwind positioned wind turbines may experience stronger or weaker wind speed fluctuations.

At IMET-TNO several studies about the wake effects have been carried out. Based on the results of these studies, a semi-empirical wake model has been developed [7]. This model is based on the assumptions that:

- the wake growth downstream of an individual wind turbine is a function of local conditions i.e.:
 - local mean velocity,
 - local tip speed ratio,
 - local thrust coefficient;
- the local velocity within the cluster can be found by adding linearly the local velocity defects, generated by all upstream turbines, and subtracting the total defect from the undisturbed wind speed.

These assumptions are analysed in ref. [5].

2.4 Cluster control systems

Mostly it is assumed that the control system for a single turbine can also be used within wind turbine clusters. This means that each individual turbine maintains its own control system. Due to the wake effects in a turbine cluster it is not necessarily true that the optimal control system for each individual turbine is equal to the optimal cluster control system.

Various cluster control systems have been described in the literature, e.g. [3]. These control systems may be used to optimize the power output as well as to limit the power fluctuations e.g. a gradual disconnection of turbines on the basis of a storm forecast.

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

2.5 Summary of relevant factors

With respect to the fluctuating wind input it can be concluded that for wind input fluctuations more than a few hours the time dependent power output can be obtained by quasi-steady calculations. Simulation models for these calculations are already available [4], [5], [6], [7].

For fluctuations with time scales around one hour, a quasi-steady approximation is not possible. These fluctuations are of major importance for the power fluctuations of wind turbine clusters. In many cases these fluctuations belong to meso-scale weather systems for which mostly a two-dimensional description of the wind field is possible.

For small scale fluctuations, 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.

The impact of deviations from the standard power-curves due to the dynamic effects present in the total system, the control system characteristics (start-stop procedures) and yaw angle variations should be incorporated in the simulation model.

The wake effects can be modelled using the semi-empirical wake modelling described in ref [7], a rather accurate 'easy-to-use' model.

The impact of the control system on the power output fluctuations is in principle a model application.

3 Model description

In chapter 2 an analysis has been given of the relevance of factors to be incorporated in the simulation model. In paragraph 3.1 the mathematical formulation of the simulation model is given based on this analysis.

In paragraph 3.2 the general structure of the simulation model is given.

3.1 Mathematical modelling

The considerations in chapter 2.5 form the foundation for the basic assumptions of the simulation model.

The space and time dependent behaviour of the wind flow field is related to the features of meso-scale weather systems, described in chapter 2.1. It is assumed that (see figure 3):

- the wind speed, wind direction and turbulence intensity are constant in regions (the ‘front regions’) between straight line contours in the surroundings of the cluster;
- these straight line contours are parallel and have a fixed angle α with the axis of the turbine cluster;
- The velocity of each straight line contour is equal to the velocity of the ‘wind front’, and hence not necessary equal to the wind speed in the ‘front regions’;
- the ‘wind front’ moves in a direction perpendicular to the straight line contours.

These assumptions are analysed in [8].

It can be concluded from statistical information that the correlation of the wind field fluctuations perpendicular to the wind direction of the wind front is not perfect. So, the described modelling of a wind front can be considered as a ‘worst case’.

With respect to the turbine response it is assumed that:

The turbine response on the (stepwise) changes in wind velocity is approximated by a first order system with time constant τ .

For velocities lower than the cut-in wind speed or higher than the furling wind speed the power delivered by the turbine is zero; in this way the start-stop procedure is approximated.

The yawing procedure is approximated in the following way:

- for yaw angles $\phi < \phi_{\text{critical}}$ the turbine power output is multiplied by a factor $\cos^3(\phi)$;
- for yaw angles $\phi \geq \phi_{\text{critical}}$ the turbine starts yawing with a yawing speed ψ , until the turbine is aligned with local wind direction.

With respect to the wake effects the semi-empirical wake modelling described in chapter 2.3 is used in the simulation model.

Besides that it is assumed that 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 according to the C_p - λ curve.

The modelling of the turbine response, the start-stop procedure and the yawing procedure is rather simple. Hence, the model can be considered as a first set-up of a simulation model which calculates the (low frequency) fluctuating power output from wind turbine clusters.

3.2 General description

The developed model is called INSTA.

Input data for the INSTA model are needed on:

- the position of the wind turbines in the cluster (coordinates);
- the wind turbine characteristics for each turbine (power curve, turbine height, rotor diameter, etc.);
- atmospheric conditions (the 'wind front' characteristics, surface roughness, etc.);
- turbine response characteristics (time constant, critical yaw angle, cut-in wind speed, etc.).

On account of the assumption that the wind flow field in a front region is constant, the wake evolution within a front region is the same as for a steady situation. Hence, when moving with a front region through the wind farm, there is no difference with a calculation using a constant wind flow field input.

A certain turbine however, finds itself only during a certain time interval in a certain front region. Consequently, each turbine finds itself in the successive front regions during certain successive time intervals. In figure 3 the situation for two turbines at a certain time instant is drawn for a fictitious schematized wind front. The supposed wind velocities and 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.

The calculation starts for the situation just before the wind front has arrived the wind turbine cluster, and ends for the situation just after the passage of the wind front. It is assumed that the wind flow field before the arrival of the wind front is uniform and that the situation after the passage of the wind front is uniform again (but not necessary equal to the situation before the arrival of the wind front).

For each front region, the power outputs of all turbines are calculated as if the situation is constant, using the undisturbed wind flow field in that front region. Due to the fact that the turbine response on wind speed changes is approximated as a first order system, the total cluster power output is not constant during that time interval. The total power output of the wind turbine cluster at a certain time instant can be calculated by simply adding the different power outputs of all turbines at that time instant.

4 Example calculation

An example calculation with the INSTA model has been performed for a fictitious wind farm, similar to the wind farm at Sexbierum [9], under the influence of a 'bad weather' situation in the Netherlands. This 'bad weather' situation is based on measurements performed by the Royal Netherlands Meteorological Institute (KNMI). The characteristics of this wind front are given in figure 4.

The wind front is divided into 16 regions, each with a width of 30 sec. (= 480 m). It is assumed that the wind flow field before the arrival of the wind front ($t < 0$ sec.) is uniform, and that the wind flow field after the passage of the wind front ($t > 523$ sec.) is uniform.

The lay-out of the fictitious wind farm is given in figure 5. All turbines (18) have the same rotor diameter (30 m), hubheight (35 m) and turbine characteristics. The influence of turbine and wind farm control systems and the impact of the yawing procedure has not been taken into account in this example calculation.

The results of the calculation are given in figure 6. The total power output of the wind farm is given as percentage of the (constant) power output of the wind farm before the arrival of the wind front. This example shows that large power output fluctuations can be expected due to weather systems.

It should be kept in mind however that the INSTA model is not yet validated.

5 Conclusions

A first set-up for a dynamic cluster model for the calculation of the power output fluctuations has been developed, called INSTA. This model deals only with low frequency fluctuations caused by meteorological circumstances. The turbine response, start-stop procedure and yawing procedure are modelled in a simple way. With this model an example calculation has been carried out. The result shows that large power output fluctuations can be expected due to weather systems. In this calculation the turbine control strategies were not taken into account. The INSTA model is not yet validated against experimental results. The next step in the development of the model will be the validation. Also a more accurate modelling of the turbine response, the start-stop procedure and the yawing procedure may be possible.

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7 Authentication

Name and address of the principal

SEP

Postbus 575

6800 AN Arnhem

Names and functions of the cooperators

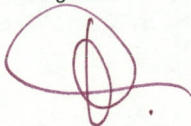
Ir. H. van Oort - research engineer

Names of establishments to which part of the research was put out to contract

1 januari 1987 until 1 september 1993

Date upon which, or period in which, the research took place

Signature



Ir. H. van Oort
research engineer

Approved by



Ir. N.J. Duijm
section manager
wind engineer

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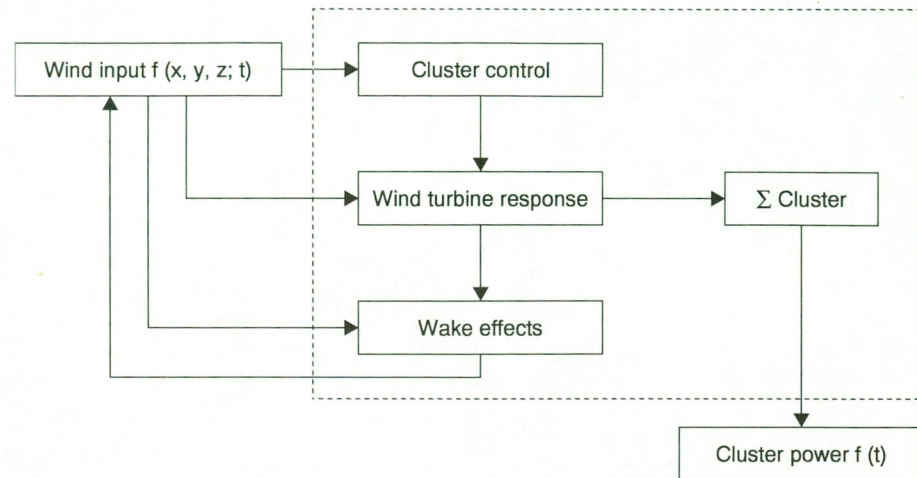


Figure 1 Relevant factors for time dependent behaviour of a wind turbine cluster

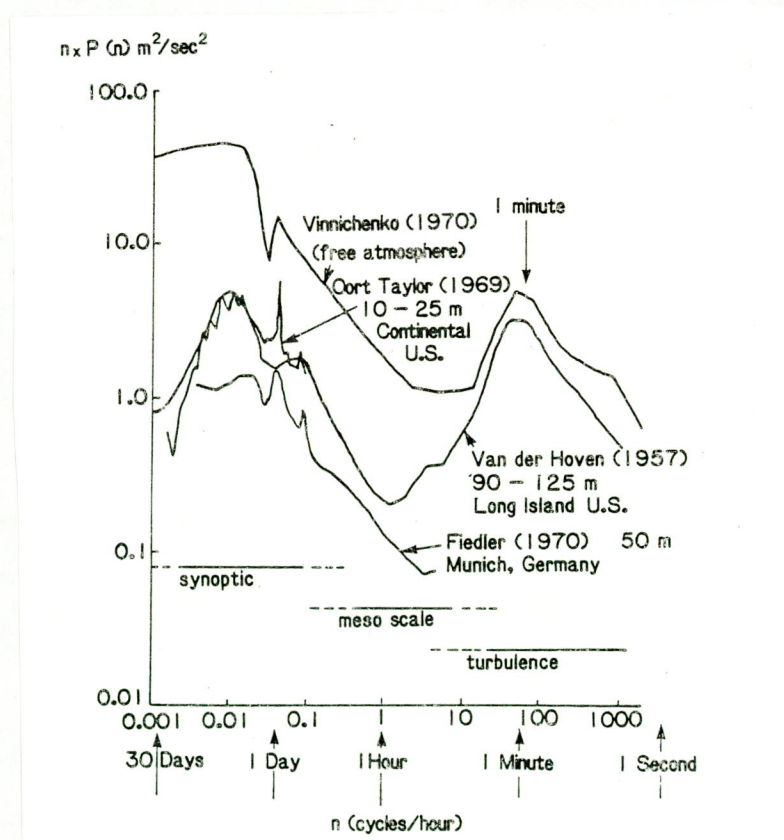


Figure 2 Power spectrum of the fluctuating wind speed



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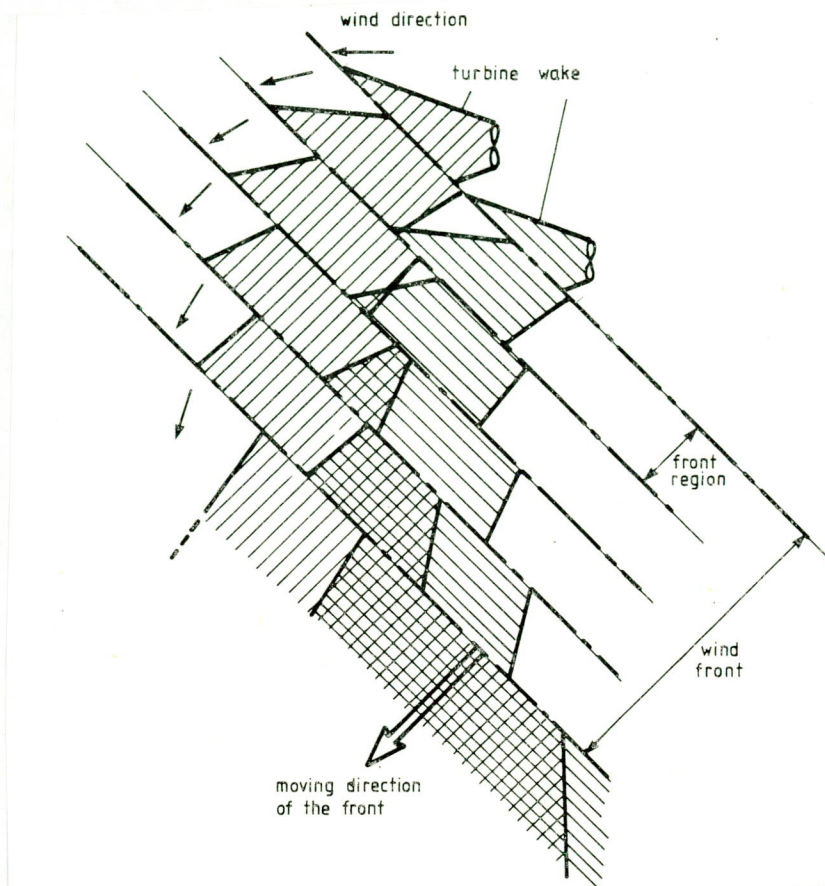


Figure 3 Schematic wind front and wake evolution

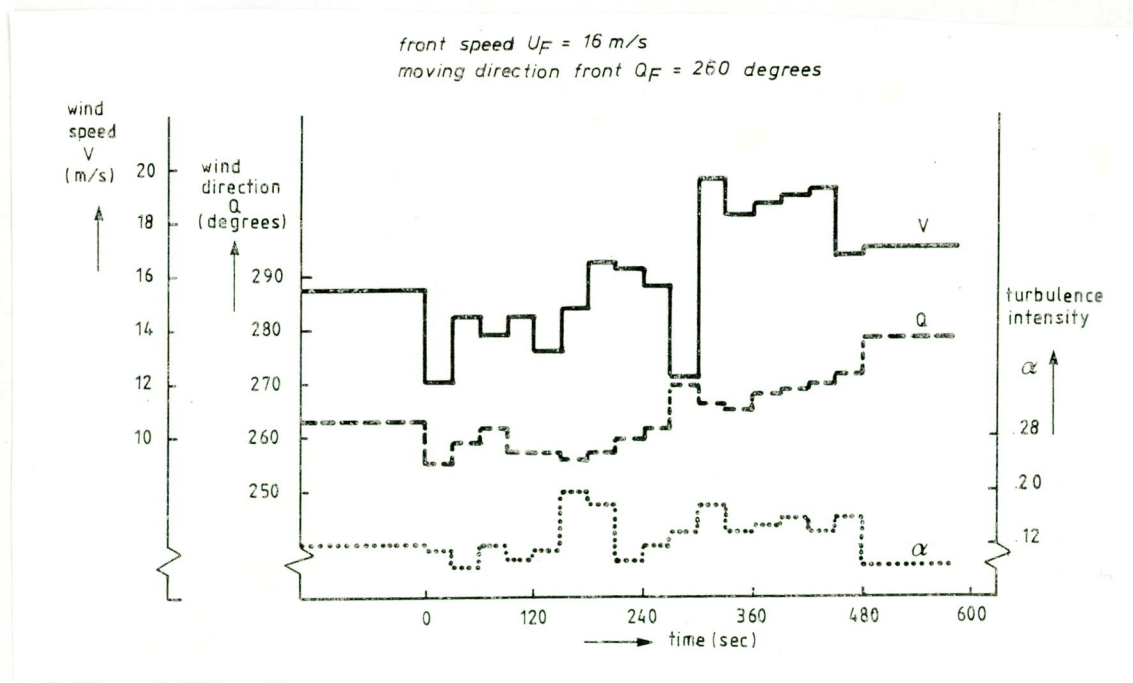
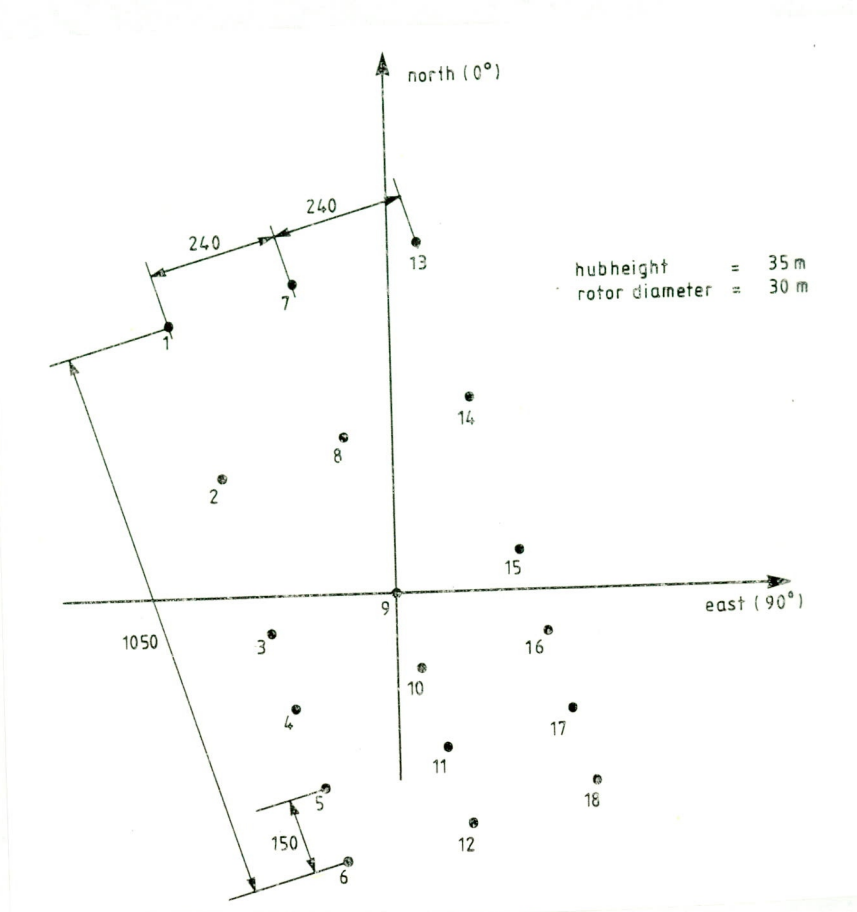
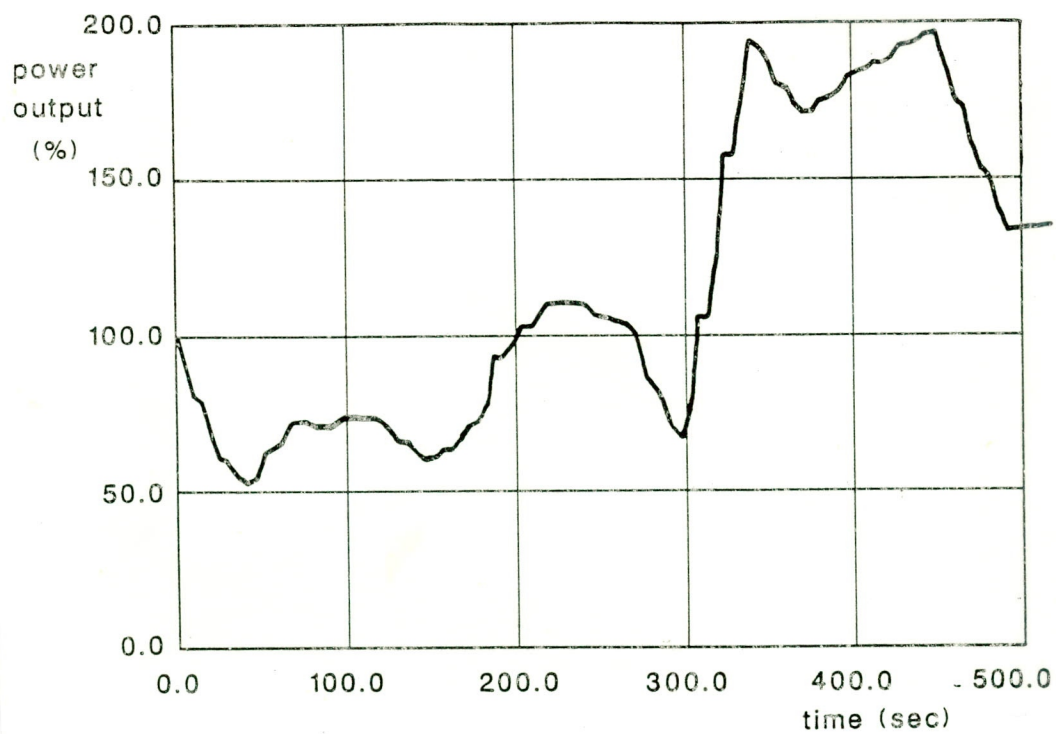


Figure 4 'Bad weather' front

Power output fluctuations from wind farms due to wind variations - a numerical model*Figure 5 Lay-out of the fictitious wind farm**Figure 6 Time dependent power output*