DESIGN TOOL FOR THE PREDICTION OF FLICKER FROM WIND TURBINES
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ABSTRACT

The main aim of this project has been to produce a well validated and user friendly commercial quality software package which would enable wind turbine designers and manufacturers to evaluate the flicker implications of their machines at the design stage. This has been achieved by extending an existing commercially available package for wind turbine performance and loading calculations, ***Bladed for Windows***, to allow it to predict flicker effects during normal operation of the turbine.

The first step was to identify and test suitable electrical models of generators to replace the purely mechanical representations in the existing code. A series of generator models was developed for this purpose and incorporated, together with a standard flicker calculation algorithm, into ***Bladed***. The resulting code has been validated with very good agreement against measurements from two commercial MW-scale wind turbines.

Four generator models of increasing levels of precision were developed for fixed speed turbines and incorporated in the code. A model for variable speed generators was also incorporated. Since active and reactive power can rapidly be controlled with modern variable speed drives, a relatively simple model of the dynamics is sufficient in this case.

A simple network model has been incorporated into the software package, allowing the characteristics of the distribution network connecting the turbines on a wind farm to be specified as well as the connection to the wider network. A detailed dynamic load flow model was used to study the effect of various network configurations with embedded static and dynamic loads on the flicker effects of a wind turbine or wind farm. This has shown that the flicker effect is generally reduced by the presence of consumer loads. The reduction is small for static loads, and rather more significant in the case of dynamic loads. It is safe to ignore consumer loads as this will produce a conservative estimate of the flicker.

Flicker measurements on two commercial 1 MW turbines were undertaken, and then used to carry out a validation of the models. The results showed that the flicker generated by the turbines was well predicted, for a range of different network angles. Furthermore, it was found that the flicker during normal operation was dominated by relatively low frequency power variations, mainly at blade passing frequency, and that the more detailed dynamic models of the generator were little better than the simple models.

The wind turbine design tool, ***Bladed***, now extended to allow flicker evaluation at the design stage, is of particular value to wind turbine designers and manufacturers. However, the need was also recognised for a simpler software tool aimed at utilities and wind farm developers, which they can use to assess the flicker implications of installing one or more wind turbines with known flicker characteristics onto a particular network. This project has defined the scope of such a software tool, and developed this into a complete functional specification. The specification also includes provision for evaluating the effect of turbine starts and stops. Although the software itself was not written during the course of the project, the specification is sufficiently detailed, including all the necessary equations, to allow such a software package to be written.

1. PROJECT PARTICIPANTS

The project partners were as follows:

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2. OBJECTIVES OF THE PROJECT

The objectives of this project are:

- To develop a software tool capable of predicting flicker for any given wind turbine design and network parameters, in any specified wind condition;
- To validate the software against measurements on two representative wind turbines;
- To package the software with a user friendly, Windows based graphical user interface with the aim of producing a tool which could become the "industry standard" for wind turbine flicker calculations.

This software tool should enable the connection of large wind turbines to weak grids in the confidence that flicker problems will not be encountered, to help minimise the risk to utilities and manufacturers.

3. TECHNICAL DESCRIPTION

Any significant introduction of wind energy into the EU electricity network requires the co-operation of Europe's utilities. In areas where high levels of penetration have been achieved, some reaction is now being felt. This reaction has been strong in Germany where de-facto standards for "power quality" (including power fluctuations and flicker) produced by wind turbines have taken effect, supported by the electricity utilities in whose areas most wind turbines are installed. These documents set criteria which are in addition to the generic standards and pay particular attention to flicker. Flicker may, therefore, become a serious limitation to wind generation on weak systems.

Flicker is a term used to describe and quantify rapid fluctuations in voltage experienced by a consumer connected to an electricity distribution system. The term "flicker" is used because the most common symptom is perceptible variation in illumination from standard incandescent lighting, which causes annoyance and customer complaints. A method is outlined in standards such as IEC 868 [10] by which the voltage fluctuations over a given period can be quantified by a single figure, the flicker severity, which has been found to give a good estimate of the likelihood of customer complaints. Specific limits for flicker are currently set by utilities. A recent standard [13] provides target figures for utilities to achieve for their networks, which may in time become accepted across Europe.

Wind turbines operate in turbulent wind, and produce greater power fluctuations than other forms of generation. These fluctuations in power (and reactive power), in conjunction with the impedances of the local network, result in voltage fluctuations which are experienced as flicker by customers connected to the network, and can lead to customer complaints.

The problems are greater on weak electrical systems typical of the upland or rural areas often chosen for wind turbine sites. A previous Joule 2 project [1] considered the effect of large machines on weak grids. The work demonstrated that flicker is a major issue limiting such applications. It showed that, for a given generation capacity, the flicker produced by megawatt-scale fixed speed turbines would be worse than that from smaller (500 to 600 kW) turbines. Often the limiting factor on wind capacity on a network is the steady-state voltage range or the thermal rating of electrical plant or overhead lines, but the study showed that for large fixed-speed wind turbines on weak electricity networks, flicker can be the limiting factor on total wind turbine capacity. This finding is specific to wind energy.

Some means for predicting flicker for an individual machine type would therefore be valuable, to minimise the risks which a manufacturer has to take in the development of a new machine. Prediction techniques are required which allow flicker to be calculated for wind turbines in any combination of network conditions and wind conditions. This project aims to develop such methods, in a form which is readily accessible to the industry, and to validate them by comparison of the results against measurements on two existing megawatt scale wind turbines.

The work has been divided into six tasks, as follows:

1. Selection of generator models for fixed speed turbines
2. Selection of generator models for variable speed turbines
3. Field measurements on two existing turbines
4. Validation of models against field measurements
5. Investigation of different network models
6. Software engineering

These tasks are summarised in Sections 3.1 to 3.6.

3.1 Selection of generator models (fixed speed)

The aim of this task was to investigate and compare available models for simulation of the dynamic behaviour of an induction generator connected to a grid system of given impedance. In order to be useful for flicker prediction, the models needed to predict 3-phase voltages and currents as well as air-gap torque. The objective was to find models suitable for incorporation into a full dynamic simulation model of a wind turbine, driven by a realistic turbulent wind input.

Starting from an 8th order model, successive simplifications were investigated in an attempt to reduce the simulation time required without compromising the accuracy of predictions. The models were compared by running a short simulation in which the generator speed was prescribed as a series of steps. This avoided the need to model the wind turbine dynamics, allowing a direct comparison of the characteristics of the different models.

The 8th order model consisted of a d-q axis model of the generator, contributing the first four integration states, and four additional states to represent the dynamics of the grid impedance and the power factor correction capacitors. The next simplest model was of 4th order, and consisted of the same d-q axis model of the generator with a steady-state representation of the grid and power factor correction capacitors. A further simplification to a 2nd order model was achieved by ignoring stator flux transients in the generator. The first order model was derived by introducing first order lag dynamics with a time constant equal to the short circuit transient time constant into the relationship between slip speed and the rotor resistance in the equivalent-circuit representation of the generator. Finally, for completeness, a zero order model was included in which even the first order lag is ignored.

The simulation results indicated that the 8th order model is unnecessarily complex for this task. It is extremely slow to run, but gives no significant benefit in terms of accuracy compared to the 4th order model. The 4th order model is slow enough to have a significant impact on simulation speed of a full wind turbine simulation model, although if any high frequency structural dynamics are modelled, then these rather than the generator model may become the limiting factor on speed of simulation. The accuracy of the 2nd and 1st order models may be sufficient in some cases, especially on smaller machines, so it may be possible to take advantage of their faster running speeds. For this project, it was decided to keep the 1st, 2nd and 4th order models for detailed comparison in the validation exercise using the measured field data. The steady-state model was also kept for comparison purposes.

It is possible that the 8th order model would be more accurate for the simulation of switching transients. However this is considered to be outside the scope of this project. Although switching transients are potentially important for flicker, soft start systems are widely used to reduce inrush currents, so mitigating the flicker due to start-ups. Standard calculations of flicker due to start-ups are available as described in Section 3.6.

3.2 Selection of generator models (variable speed)

The purpose of this task is to identify dynamic models of variable speed drives, assumed to comprise the generator and the frequency converter, which are suitable for incorporation into a detailed wind turbine simulation model to allow it to be used for flicker evaluation.

The assumption has been made that modern state-of-the-art PWM drives are likely to be used, which deliver a rapid response to both the active and reactive power demands.

Three possible models were proposed initially. The most complex involved a very detailed representation of the variable speed drive and its control system, including the calculation of the PWM signals for the generator and network side bridges in response to the measured generator speed and position, the generator currents, the DC link voltage, and the network currents and voltages. The main outputs are the PWM signals to the generator and network bridges. The generator bridge is controlled to maintain a constant DC link voltage, up to some maximum current, power or torque limit set by mechanical components, generator or inverter rating. The network bridge controls the power output of the wind turbine. Such a model was considered far too detailed for the purpose of the project.

A simpler model which uses a voltage source converter model [16], and treats the variable speed drive as a system with two closed loop feedback controllers, was therefore developed. One of the controllers monitors the active power, and varies the converter phase angle to minimise the active power error (the difference between the active power and the demanded power). The second controller monitors the reactive power and varies the converter voltage to minimise the reactive power error. Good response to variations in active and reactive power demand was obtained with both controllers modelled as PI controllers. The controller gains were tuned by trial and error. Such a model is likely to give a good representation of the actual behaviour of a typical system, and would be feasible to implement, although it may not always be straightforward to obtain suitable gain values for the PI control loops.

The simplest model proposed by UMIST is a first order lag model, in which the closed loop response of the system incorporating these two feedback loops is approximated by a first order lag response from demanded to actual active or reactive power. A time constant of the order of 10 - 50 ms is likely to be appropriate.

In view of the short time constant, the simplest model is likely to be adequate for the intended purpose. Informal contacts with a drive manufacturer confirmed this choice.

3.3 Measurements

The measurement task consisted of undertaking a series of flicker measurements on two representative large grid-connected wind turbines. The measurements are of interest for their own sake, as they will provide flicker severity data for two representative megawatt-scale turbines connected to typical networks. However, a second reason for the measurements was to provide data sets suitable for validation of the computer models being developed as part of this project.

The measurement task was led by project partner WindTest KWK GmbH. WindTest were responsible for specifying the monitoring equipment, planning the measurement campaigns, undertaking the measurements and carrying out analysis of the data collected.

The results of a previous Joule project on power quality from wind turbines [14] were reviewed in order to make use of any relevant experience and measurements arising from that project.

3.3.1 The instrumented turbines

The two turbines used had some features in common: both were fixed speed turbines rated at 1 MW, and both had full-span pitching blades which were used for assisted stall regulation, i.e. the pitch is used to increase the angle of attack to induce stall rather than to reduce the angle of attack towards the zero lift point.

Turbine 1 was a prototype 2-bladed 1 MW turbine of about 50 m diameter. A significant feature of this turbine is that it used four 250 kW generators, and the number of generators in use is changed during operation depending on the power being generated. The use of small generators means that a relatively high rated slip of about 1.7% is achieved. Another result of this is that the flicker severity is increased during periods when generators are switching on or off.

Turbine 2 was a similarly-sized 3-bladed wind turbine employing a single 1 MW generator with a rated slip of about 0.7%.

3.3.2 Measurement details

The measurements consisted of one-minute time histories of current and voltage on all three phases, sampled at 1000 Hz at Turbine 1, and 900 Hz at Turbine 2. The date and time were also recorded. The power range was divided into 100 kW bins, and for each one-minute period the short-term flicker index P_{st} was calculated along with the mean, standard deviation, minimum and maximum of the active and reactive power. In each power bin, six complete one-minute time-histories were kept for later analysis, covering the range from the lowest to the highest flicker value in the bin. These time-histories were then subsequently used for the model validation part of the project. Concurrent measurements of wind speed and direction were also available.

3.3.3 Analysis of measurements

The measurements were analysed, and the detailed results were presented in the form of scatter plots showing mean, maximum and minimum active power, reactive power, and short term flicker severity (P_{st}) for a range of network angles.

3.4 Model validation

The measured data from these two turbines was used for validation of the wind turbine flicker prediction software developed as described in Sections 3.1 and 3.6

3.4.1 Validation strategy

The available measurements consisted of six one-minute campaigns consisting of time histories of current and voltage in each 100 kW power bin, spanning the entire range of flicker values in each bin from the highest to the lowest. Therefore it made sense to carry out a series of one-minute simulations in different wind speed conditions to compare with the measurements, the wind speed conditions being chosen to be comparable to those at the site.

As is usually the case with validation of wind turbine models, it is not possible to know the exact wind conditions prevailing at the turbine during each campaign, since (a) if the anemometer is sited close enough to the turbine, the wind field will be distorted by the presence of the turbine, and (b) the wind speed must be known over the whole swept area and not just at one point.

Therefore, a series of simulated 3-dimensional turbulent wind fields were created as inputs to the wind turbine simulations, with turbulence characteristics representative of the sites. Apart from the mean wind speed, the turbulence can be characterised by:

- the frequency spectra of the longitudinal, lateral and vertical components of turbulence,
- the spatial correlation between values of each component at points separated in space, represented by a frequency-dependent coherence function,
- the turbulence intensities for the three components of turbulence.

The quantity and quality of the measured wind data available was not sufficient to characterise the turbulence to this level of detail. Therefore a standard von Karman model of turbulence was used [3], which defines all these relationships as a function of the surface roughness length, given the height above ground and the geographical latitude of the site.

Since one minute is too short to be representative of the mean wind conditions prevailing at any time, five different realisations of simulated turbulence were generated at each wind speed, each with the same turbulence parameters but using a different random number seed to initialise the turbulence generator. Simulations were then carried out at a number of wind speeds, with the five different realisations of turbulence giving a certain amount of scatter in the results. The extent of the scatter could then be compared to the scatter in the measured data points. For each site, two different turbulence intensities were used. These were selected to be representative of the measured turbulence intensities.

The measured and simulated data were processed to allow a comparison of the flicker severity at a number of representative network impedance angles. Comparisons of active and reactive power using spectral analysis were also made.

3.4.2 Further processing of the measured data

Although the voltage was one of the signals measured, the wind turbine flicker cannot be calculated directly from this, since the voltage is subject to external disturbances, which means that the flicker calculated from it would include background flicker and not just the flicker produced by the wind turbine. Also the resulting flicker severity would be appropriate only for the particular network to which the turbine was connected, and flicker does depend significantly on the network characteristics.

Therefore the recommended method is to measure both the current and the voltage, from which it is possible to calculate what the voltage variation caused by the turbine would have been on any given network, in the absence of background flicker. The standard method for this, given in [4,5,6], was used by WindTest on this project. However, when this method was used on the simulation results, it became apparent that it produced significant errors. Investigation of the formula showed it to be an approximation. An exact calculation of the voltage is possible, and when this was used it showed that the approximate method resulted in a difference in the calculated flicker severity of as much as 20% in some cases, depending on the network parameters. The exact method was therefore incorporated into the software and used for whole of the validation exercise. The exact voltage U is obtained by solving a quadratic for U^2:

$$U^4 + U^2 (2(QX - PR) - U_0^2) + (QX - PR)^2 + (PX + QR)^2 = 0$$

where U_0 is the voltage at the infinite busbar, P and Q are the active and reactive power derived from the measurements, and R + jX is the network impedance. This is quoted in [7]. Although this gives two solutions for U, it is easy to eliminate one of them.

In order to calculate the voltage in this way, it was first necessary to process the 1000 Hz or 900 Hz current and voltage data to generate active and reactive power sampled every half cycle, i.e. at 100 Hz. This was done for each phase, and the three phases added together for comparison with simulation results (the simulation model assumes balanced phases).

3.4.3 The turbine models

Bladed models of the two turbines were built up from information supplied by the manufacturers. This included all the aerodynamic, mass, stiffness, power train and control data, along with the equivalent circuit parameters of the generators.

3.4.4 Comparison of measurements and simulation results

One-minute flicker P_{st} values were calculated for each of the simulations, for each of four network impedance angles (i.e. arctan(X/R)), and for a short circuit power level of 20 MVA. These were plotted against mean power. An example plot is shown in Figure 3.4.1. Note that the five realisations of turbulence result in one cluster of five points for each mean wind speed and turbulence intensity.

Since the raw measured data had to be reprocessed as described in Section 3.4.2 for an exact comparison with simulations, it was only possible to use the six datasets per 100 kW power bin which had been stored. These, by definition, included the highest and lowest flicker points of the in each bin. Thus the scatter of these six measured points therefore appears more pronounced than if all the points in each bin had been available, and also more pronounced than the scatter of the simulation results, but the mean values agree well between measurements and simulations.

To compare in more detail the dynamics of simulated and measured signals, spectra of simulated and measured active and reactive power were compared. An example is shown in Figure 3.4.2. This shows excellent agreement between measured and simulated data at low frequency at around the dominant peak at the blade passing frequency, around 1 Hz.

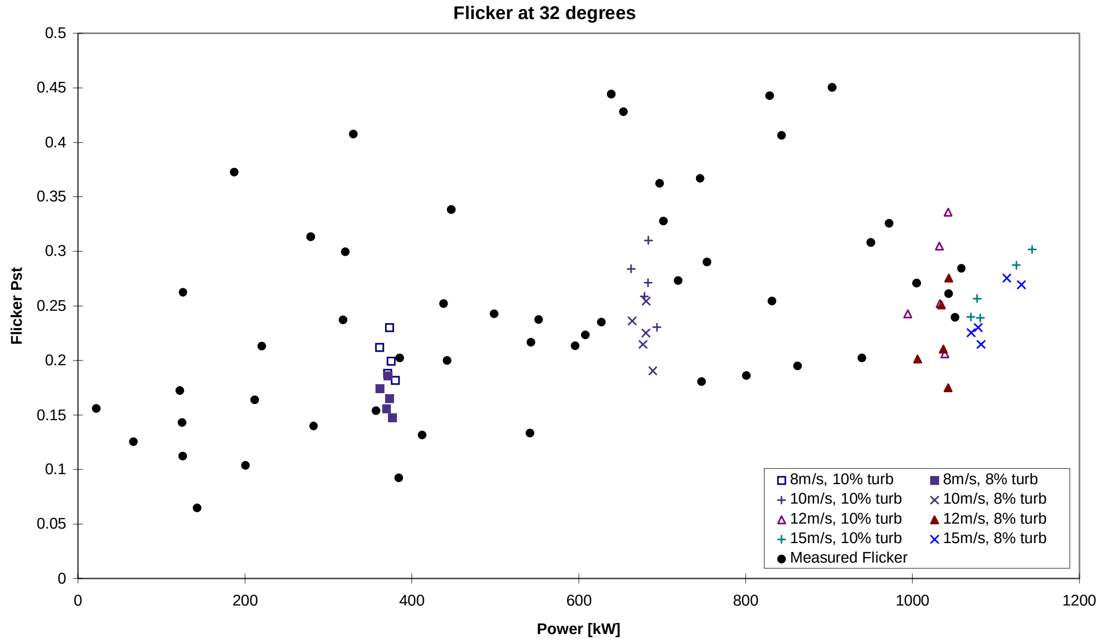


Figure 3.4.1: Measured and simulated flicker P_{st} values at 32° network angle: Turbine 2

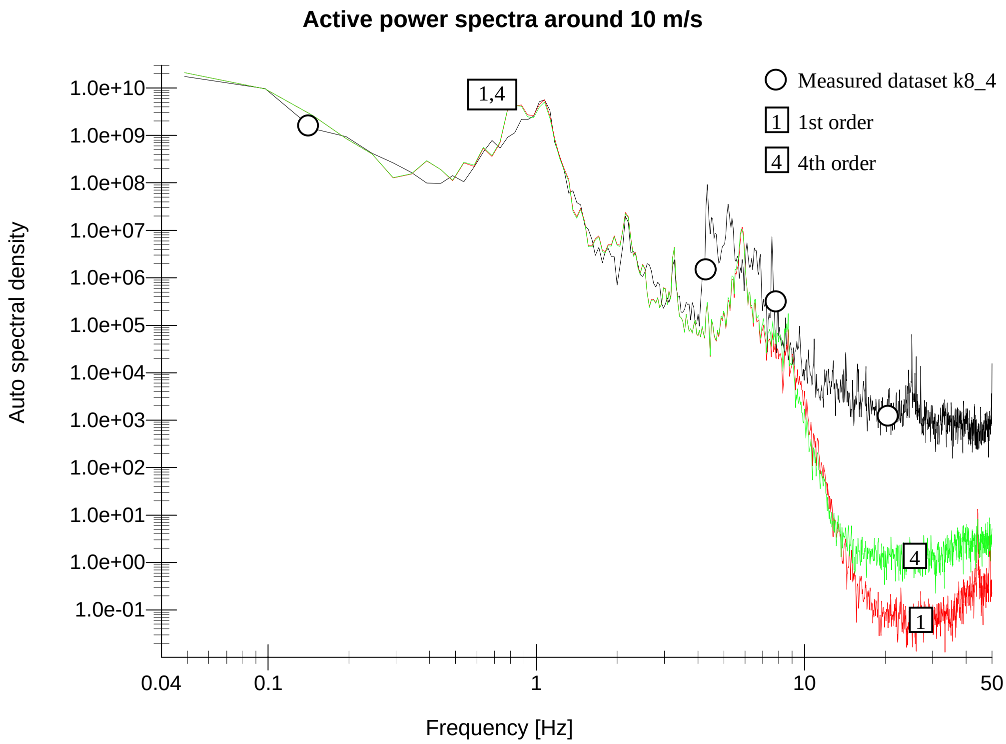


Figure 3.4.2: Spectra of active power around 10 m/s: Turbine 2

The measurements show some additional dynamic activity around 4-8 Hz. Although flicker is more sensitive to these frequencies than to frequencies around 1 Hz, the magnitude of the spectrum in the 4-8 Hz region is so much lower than at 1 Hz that these higher frequency dynamics contribute very little to the flicker. The simulated results also tail off faster at frequencies above 10 Hz, but again the effect on flicker is insignificant.

These results also show that the order of the generator model has a negligible effect on the results. The spectra for 1st, and 4th order models are virtually identical apart from a very small amount of ‘noise’ at the high frequency end.

3.5 Network models

The purpose of this task was to ascertain the type of network model and the appropriate level of complexity which would be suitable for the design tools which are being developed, bearing in mind the likely availability of data for particular networks.

A model was developed allowing a complex meshed representation of a network composed of busbars, transmission lines and transformers. It is essentially a classical transient stability program which allows various types of load to be connected and their effects on flicker to be examined. It also includes an induction machine model, which enables the investigation of the effects of generator dynamics on flicker. A flicker algorithm was also implemented, which calculates the value of the short term flicker severity parameter P_{st} for each of a set of 10-minute voltage time histories.

The dynamic loads included in the model are represented by induction motors, which are modelled using the second-order model described in Section 3.1. This was also used to represent the wind turbine generators. Three type of static load were considered:

- Constant power: active and reactive power independent of voltage.
- Constant current: active and reactive power proportional to voltage.
- Constant impedance: active and reactive power proportional to the square of the voltage.

The model was used to calculate the short term flicker parameter P_{st} at each busbar for various combinations of loads, using wind turbine inputs modelled both as a low frequency sinusoidal power variation and also as a variation derived from a real measured megawatt-scale wind turbine power signal sampled at 40 Hz. This power signal was used to represent the mechanical power at the turbine, feeding into the second order generator model referred to above.

Studies carried out have shown that the effects of network parameters (i.e. short circuit power level and X/R ratio) on flicker are significant. It has been shown that, depending on the X/R ratios of the circuits and the short circuit power levels of the network, the highest levels of flicker can sometimes be experienced at busbars away from the busbar where the wind turbines are connected.

The model has shown that flicker is generally reduced when the various loads are taken into account. The reduction is small for static loads, whether constant power, constant current or constant impedance. There is a more significant reduction in the case of dynamic loads, since the short circuit power is increased, causing voltage variations to decrease.

Because network loads vary over time and accurate data is unlikely to be available, a conservative assumption is to ignore loads.

3.6 Software engineering

The software engineering task consisted principally of developing the wind turbine flicker prediction algorithms developed during the course of the project into a validated software design tool with a user-friendly windows-based interface, making it suitable for commercial use by the industry. This tool should allow wind turbine designers to take account of flicker at the design stage.

A specification was also developed for a second software product aimed more at utilities and wind farm developers, allowing them to estimate the flicker effects of connecting one or more wind turbines of a given type, with known flicker characteristics, at a given point on a particular network. The specification gives details of the algorithms to be used, although the development of a marketable software tool for this purpose lies outside the scope of the project.

3.6.1 Development of the wind turbine flicker design tool

The wind turbine design tool should be capable of predicting the flicker produced by a given wind turbine design, taking into account the following information:

- Fixed or variable speed operation
- Physical and structural dynamics of the turbine, including mechanical resonances
- Aerodynamic forcing frequencies
- Realistic turbulent wind characteristics
- Generator electrical characteristics
- Network characteristics

In order to predict the flicker, it is necessary to perform dynamic simulations of the turbine behaviour when connected to a particular network and driven by a particular turbulent wind, so that the voltage variations at a point on the network can be predicted. The resulting voltage variations should then be used to calculate the flicker, both for the specified network and also for any other network impedances.

This requires a very complex piece of software, in order to model with sufficient accuracy the dynamics of the wind turbine in realistic conditions of turbulence. A clear route to achieving this goal was available by extending the existing commercial software package ***Bladed for Windows***, which was developed by Garrad Hassan in a previous Joule project [11] as a tool for wind turbine performance and loading calculations. The package, which already includes

- Rotor and tower vibration
- Yaw dynamics
- Drive train dynamics
- Control dynamics
- Turbulent wind input

has therefore been extended by adding modules for:

- the electrical dynamics of the generator,

- the network characteristics, and
- the calculation of flicker from simulated voltage variations, or from simulated active and reactive power time histories in combination with various network impedances.

Since the electrical model of the induction generator implies some electrical losses, a further modification was required to ***Bladed*** so that mechanical and electrical losses could be treated separately.

3.6.2 Algorithms for predicting windfarm flicker on a given network

A specification has been written for a further software package, much simpler than ***Bladed***, aimed at utilities and windfarm developers. This package would use a table of flicker data for a particular turbine, obtained either from ***Bladed*** or from measurements, and allow the user to calculate the flicker caused by such a turbine, or a whole windfarm of such turbines, on any particular network specified by its short circuit power level and network angle. The calculations would also take into account the flicker caused by inrush currents during turbine start-up events.

The input data which would be supplied by the user would consist of:

- Turbine flicker coefficient for standard network impedance values and wind conditions
- Network impedance
- Number of turbines
- Synchronism factor to specify the degree to which power variations are correlated between turbines
- Maximum number of starts and stops or speed changes per 10 minute interval
- Inrush current on switching (if available), defined by the current spike factor and shape factor
- Rated power, reactive power and "maximum continuous power", as defined in [4].
- Range of power factor correction capacitor values.

The software package will produce the following outputs:

- P_{st} and A_{st} for one wind turbine on the chosen network, for the full range of wind speeds for which the input data is available, presented as a graph and as a table. The package will also determine the "maximum credible flicker" to be expected from one wind turbine, as defined in [4], if sufficient input data is available.
- P_{st} and A_{st} for a wind farm of N wind turbines on the chosen network, for the full range of wind speeds for which data is available.
- P_{st} due to starts and stops, or the maximum inrush current allowable for switching operations, given a limiting $P_{st.}$
- Comparison of calculated values with the recommendations of [9].
- Steady state voltage changes

- The effect on steady state voltage levels of adding or removing power factor correction capacitors, or adjusting the power factor of variable speed machines.

All the equations needed to implement these calculations were defined as part of the project. It is anticipated that they will be incorporated into an existing wind farm design tool being developed commercially by Garrad Hassan.

3.6.3 Flicker reduction

This task aimed to investigate electrical methods for flicker reduction by means of power electronic devices connected, for example, at the wind farm. The investigation concluded that a Unified Power Conditioning Systems (UPCS) could be used. These are currently available in unit sizes of several hundred kW, and can be combined to give ratings of several MW. Since the rating of such a unit need only be a fraction of the windfarm rating to achieve significant improvements in power quality, such a device may be suitable for large windfarms of many MW rating.

4. RESULTS AND CONCLUSIONS

The principal conclusion of this project is that it has been possible to develop a validated software design tool, in a form immediately suitable for commercial application, which is capable of giving reliable estimates at the design stage of the flicker effects of wind turbines during normal operation. This has been achieved by incorporating the necessary features and calculation methods as additions to an existing mature commercial product, the very detailed wind turbine performance and loading code ***Bladed for Windows***.

A series of generator models have been developed to allow the electrical behaviour of a turbine to be simulated when connected to a particular network. These, together with a standard flicker calculation algorithm, have been incorporated into ***Bladed*** and the resulting code has been validated with very good agreement against measurements from two commercial MW-scale wind turbines.

Although four generator models of increasing levels of precision were developed for fixed speed turbines and incorporated in the code, the results demonstrated that the simpler models are likely to be adequate for flicker prediction, largely because flicker effects are dominated by variations at the (relatively low) blade passing frequency. For variable speed turbines a simple electrical model is sufficient, since a modern variable speed drive operates with very short time constants to produce controlled active and reactive power outputs.

A simple network model has been incorporated into the design tool. A study was made of the effect of various network configurations with embedded static and dynamic loads, to investigate the significance of these aspects. This showed that the flicker effect of an installation is generally reduced when these effects are taken into consideration. The reduction is small for all types of static loads, and somewhat more significant in the case of dynamic loads. Therefore it is safe to use the simple network model without embedded loads, as this will produce a conservative estimate of the flicker. In some circumstances, depending on the X/R ratios of the lines and the short circuit power, it is possible for the highest flicker severity to occur on a busbar away from the busbar where the wind turbines are connected.

Flicker measurements on two commercial 1 MW turbines have been carried out using standard procedures. The results have been presented in the form of scatter plots and tabulations showing mean active and reactive power levels and peak power levels, as well as Flicker P_{st} values for various network angles. A representative selection of campaign datasets were saved, and have been used for validation of the software developed during the project.

A discrepancy was identified between the flicker calculated from the measured data by standard methods, which involve a certain degree of approximation, and the flicker calculated using an exact method. Such approximations may be masked by data uncertainties and scatter when considering measured data, but comparisons with simulation results showed that the approximate method yielded errors in flicker P_{st} of up to 20% for some network angles. Since the exact method is actually not particularly onerous to implement, this method has been adopted in the software tool, and it is recommended for use also with measured data, in place of the approximate methods which are normally used at present.

Once the measured data were reprocessed using the exact method, excellent agreement was obtained between simulated and measured flicker P_{st} values for given network angles, as well as active and reactive power variations.

While the wind turbine design tool ***Bladed*** is of value to wind turbine designers and manufacturers, there is also a need for a simpler software tool aimed at utilities and wind farm developers, which they can use to assess the flicker implications of installing one or more wind turbines with known flicker characteristics onto a particular network. This project has defined the scope of such a software tool, and developed this into a complete functional specification. Although the software itself has not been written during the course of the project, the specification is sufficiently detailed, including all the necessary equations, to allow such a software package to be written.

Finally an investigation was undertaken of the feasibility of using Unified Power Conditioning Systems to assist in reducing the flicker effects of a windfarm. A UPCS has the capability to control voltage and power factor as well as harmonics, in addition to acting as an uninterruptible power supply if required. A UPCS rated at a fraction of the windfarm rating can achieve a very significant reduction in the flicker. Although quite expensive, this may in some cases be cheaper than strengthening the network connection. Also the relative cost of the installation will decrease as the number of turbines on the windfarm increases, because of the incoherence between turbines of the blade passing effects which tend to dominate the flicker.

5. EXPLOITATION PLANS AND ANTICIPATED BENEFITS

5.1 Wind turbine flicker predictor

This project has produced a well validated and user friendly commercial quality software tool which will enable wind turbine designers and manufacturers to evaluate the flicker implications of their machines at the design stage. This has been achieved by extending an existing commercially available package for wind turbine performance and loading calculations, ***Bladed for Windows***, to allow it to predict flicker effects during normal operation of the turbine. The intellectual property and copyright in ***Bladed*** is the property of Garrad Hassan.

It is undoubtedly the case that the incorporation of the flicker predictor in ***Bladed*** during the project reported here has strengthened the code and increased its usefulness to the industry.

Existing commercial users of the code will be provided with an upgrade which will include the flicker prediction module.

There is considerable uncertainty in estimating the size of the market for ***Bladed*** incorporating the flicker predictor. The market for the full commercial version of the software is amongst the wind turbine and major component manufacturers, engineering consultancies, certification agencies and test laboratories involved in the wind industry. Garrad Hassan has recently undertaken a review of the potential worldwide market for ***Bladed***, and concluded that there are approximately 70 organisations which should be considered as potential commercial users.

Based on research already conducted by Garrad Hassan, it is clear that there is a sizeable market for an educational version of ***Bladed***. The software is well suited for both teaching and academic research purposes and it is estimated that the number of sales could finally run into three figures. The educational version of the code will have restricted capabilities compared with the full commercial version but it is anticipated that it will retain the flicker predictor which will considerably enhance its sales potential.

5.2 Wind farm flicker predictor

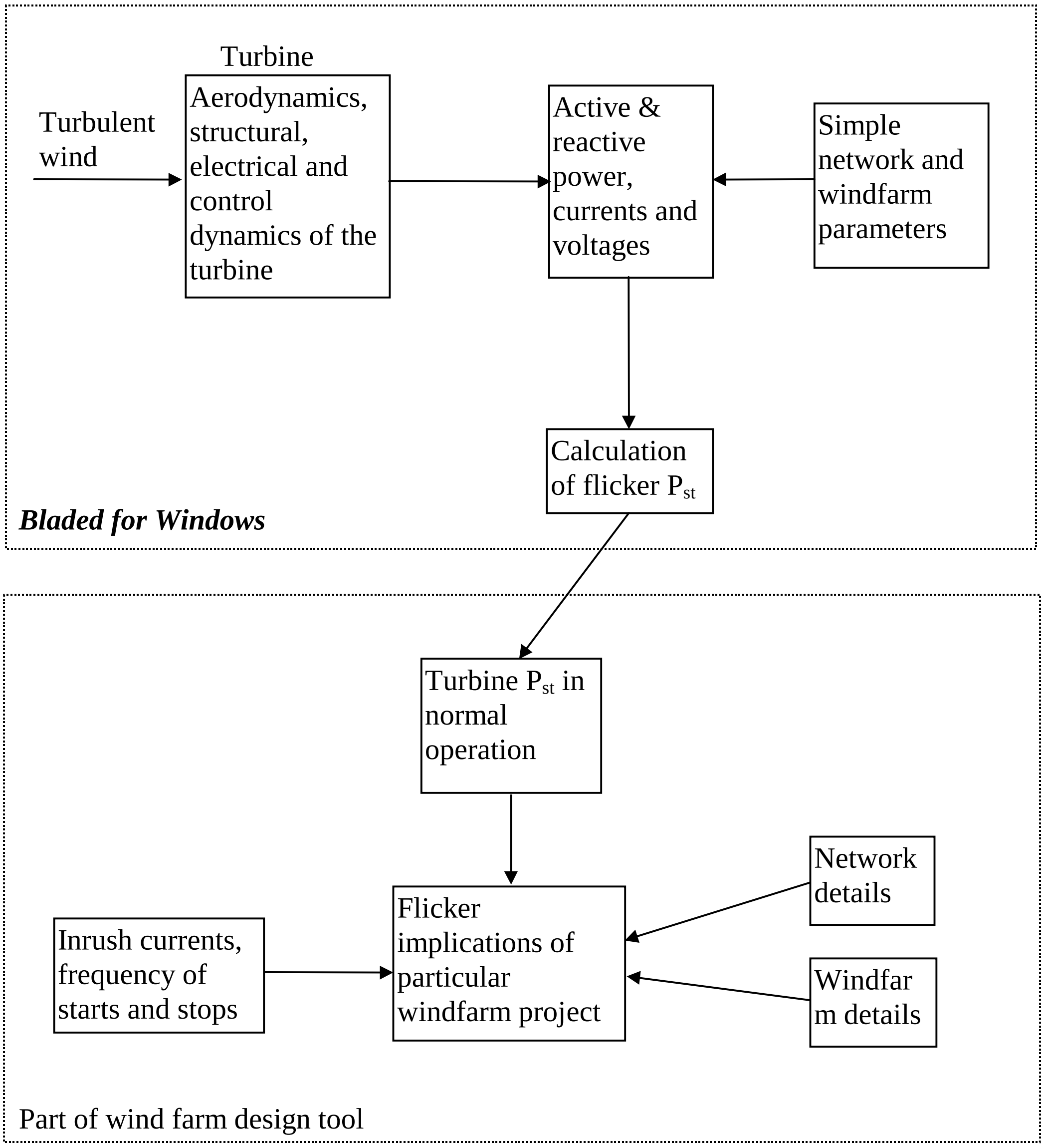
The wind turbine design tool ***Bladed***, extended to allow flicker evaluation at the design stage, is of particular value to those involved in wind turbine design, certification and/or manufacture. There is, however, also a need for a simpler software tool aimed at utilities and wind farm developers, which they can use to assess the flicker implications of installing a wind farm of one or more wind turbines with known flicker characteristics onto a particular network. The project reported in this document has defined the scope of such a software tool, and developed this into a complete functional specification. Although the software itself has not been written during the course of the project, the specification is sufficiently detailed, including all the necessary equations, to allow such a software package to be written. The specification also includes provision for evaluating the effect of turbine starts and stops.

Garrad Hassan are in the process of developing a wind farm design tool which will have the following features:

- Wind farm energy capture calculations.
- Optimisation of wind farm layout.
- Interface to WAsP to account for complex terrain.
- Sophisticated array wake loss model.
- Electrical infrastructure design and loss calculation.
- Wind farm noise calculation.
- Noise constrained turbine placement.
- Estimation of turbine loads.
- Interactive graphical user interface.
- Surfer/Autocad and Excel compatible.
- Library of turbines.

Following the work undertaken in this project, it is now planned that the wind farm design tool will be enhanced to include a wind farm flicker prediction module.

6. POTENTIAL APPLICATIONS OF THE PROJECT



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