1 MW ADAPTABLE WIND TURBINE

H. Stiesdal, M. Winther-Jensen

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Abstract

The Joule project "1 MW Adaptable Wind Turbine", Contract JOR3-CT95-0050 was carried out in a partnership between Bonus Energy A/S of Denmark, Risø National Laboratory of Denmark, and ABB Industry OY of Finland. The project period was from 1 January 1996 to 28 February 1999.

A 1 MW turbine was developed early in the project, and in the summer of 1996 the prototype turbine was erected at Tjæreborg near Esbjerg, Denmark. The so-called CombiStall adaptive stall regulation system was developed as a simple version of the adaptive part of the project. The serial version of the turbine is fitted with this system.

In relation to the machine learning techniques suitable sensor technologies were investigated and the optimum sensor type was selected. A control unit based on machine learning techniques was developed, using a neuro-fuzzy algorithm, combining the benefits of the neural network in the learning process with the robustness of the fuzzy regulator in the control process. The adaptive regulator was provided with operating "experience" by combination with a typical aeroelastic code used for structural load calculations in the turbine design.

The potential benefits of full-blown adaptive regulation were found to be somewhat disappointing. This was confirmed by practical experiments. The conclusion was that the benefits of adaptive regulation were unlikely to outweigh the disadvantages of the additional complexity.

For the variable speed necessary in the adaptive regulation a competitive industrial drive was developed, using the latest higher-voltage IGBT and filter technologies. The resulting drive system would be generally available on the market for both wind turbines and other industrial use. The variable speed drive is now part of ABB's standard program for large frequency converters.

Since the full-blown adaptive regulation did not provide the benefits looked for, the serial production 1 MW turbine has constant-speed operation, not using the variable speed drive.

For the investigation of less visually obtrusive wind turbines Risø developed a successful technology for the manufacturing of translucent rotor blades. However, field experiments showed that while the transparency worked well under some conditions, it was giving higher visibility under other conditions. Consequently, the idea was abandoned. A more successful result was achieved with a new type of surface coating, leading to a better adaptation to the background lights and hues than the present-day light grey colour.

Project Partners

The project had the following partners:

Coordinator
Bonus Energy A/S
Fabriksvej 4
7330 Brande
Denmark

Phone +45 97 18 11 22
Fax +45 97 18 30 86

Contact person: Henrik Stiesdal, hst@bonus.dk

Partner
The Test Station for Wind Turbines
Risø National Laboratories
4000 Roskilde
Denmark

Phone +45 46 77 46 77
Fax +45 42 37 29 65

Contact person: Martin Winther-Jensen, martin.winther@risoe.dk

Partner
ABB Industry OY
P.O. Box 184
00381 Helsinki
Finland

Phone +358 10 22 22656
Fax +358 10 22 23065

Contact person: Tommi Kasteenpohja, tommi.kasteenpohja@fidri.mail.abb.com

Objectives

The general scope of the project was to extend the development a large wind turbine with the following main objectives:

- To improve the economy
- To make the turbine adaptive to a specific local wind, turbulence and grid regime
- To reduce the environmental impact

The following works and sub-projects would meet these objectives:

1. The modification of the existing turbine design for a larger rotor and for higher generator rating;
2. The development of machine learning techniques suitable for the automatic optimisation of turbine operation with respect to performance, loads, grid behaviour and noise characteristics;
3. The development of a competitive variable speed drive based on the newest IGBT technology; and
4. The development of translucent rotor blades and the identification of the optimum surface coating of tubular towers

Technical Content

The project had four work packages, representing the four specific objectives.

1. Modification of Existing Design to Higher rating

Past experiences had shown that the most significant economical improvements had often been associated with moderate up scaling of existing turbine designs, rather than with entirely new designs. In the past history of Bonus the 150 kW turbine was based on a 95 kW design, increasing the rotor diameter from 19 to 23 m with no significant changes in the turbine structure and achieving a 25 percent improvement in turbine economy (partly due to improved aerodynamics). The 600 kW turbine with 41 m rotor diameter was the most economic machine at the time of the project proposal, having grown from our 450 kW Mk I turbine with 35 m rotor diameter with no significant changes in the turbine structure. Like the 150 kW predecessor the 600 kW turbine had led to a further improvement in turbine economy by some 25 percent. Similar cases had been experienced in the product ranges of other manufacturers, often associated with very simple changes, such as the introduction of hub extenders.

When such up-scaling was at all possible it would be because the original turbine design would tend to be a structural "overkill", with significant safety margins. This could hardly be avoided, since the turbine designer would have very legitimate need to ensure that the structure would be adequate. However, once the machine was in production and structural measurements could be performed with good statistical significance, the reserves of the design could be determined and could be exploited. The notable exception would be the tower. This part of the structure is very straightforward from a design point of view and the loads and stresses are predicted with good precision, so it would normally be necessary to upgrade this part when upgrading the turbine.

It was intended to go through the above process in the upscaling of the 750 kW turbine. Design calculations performed in association with the Danish type approval had shown that the machine had some further extension potentials. When combined with the expected benefits of the adaptive control technology the project group expected to be able to stretch the machine significantly.

Aiming at the largest possible recycling of the 750 kW machine design and including the prototype experiences and the experiences from the most recent production turbines the 1 MW machine design would be developed. The fatigue loading input would be determined with a modified aeroelastic calculation program, taking into account the assumed efficiency of the adaptive regulation system. The result of the work would be the production basis (parts lists, drawings, QC instructions, etc.) for the 1 MW turbine exclusive of the blades, actuation system, variable speed system, controller and tower coating.

The actuation systems of the 750 kW blade pitch arrangement would have to be uprated in order to allow for the rapid and precise regulation expected to be required by the adaptive regulator. It was anticipated that the new actuation system would mainly require the development of high-reliability position and movement control.

The prototype 1 MW turbine would be manufactured at BONUS and would be erected on a suitable location.

2. Adaptive Regulation

The second work package would aim at the development of machine learning techniques suitable for the automatic optimisation of turbine operation to a specific local wind, turbulence and grid regime.

For the individual machine the adaptive regulator should be provided with the optimum starting point for the adaptation of the turbine to a specific environment. This starting point could be based on experience from adaptation of an analytical turbine model. Such a model could simply be a typical aeroelastic code used for structural load calculations in the turbine design, extended with interactive facilities to respond to the regulation response. The result would be a "teacher" consisting of the standard aeroelastic code used by BONUS (the TURBINE pc-program family), modified to provide load conversion to suitable measurement points in the turbine and to respond to the interactive input from the regulator.

The overall problem complex should be described and the regulation requirements should be defined. The algorithms currently available for adaptive regulation should be considered. At least four different machine learning paradigms should be reviewed:

- Inductive learning (learning from examples, concept formation, etc.)
- Statistical evaluation
- Generic algorithms (and classifier systems)
- Connectionist learning systems (neural networks)

Based on the problem complex to be solved and the expected level of expert knowledge the turbine controller could be provided with prior to installation the most suitable learning algorithm would be selected.

The controller software for the selected algorithm should be developed. The deliverable of this work section would be software in a format suitable for installation in an industrial controller.

The necessary input to the adaptive regulation would be an adequate continuous description of the ambient conditions, the turbine performance and the structural loads.

The ambient conditions would be described by meteorological parameters. The automatic measurement of temperature, pressure, wind speeds and wind direction, etc., was a well established technology and no further work would be required here.

The continuous description of the structural loads would be the real challenge in the sensor development part of the project. Structural loads would normally be monitored by strain gauge technology and accelerometers. While this type of equipment had an acceptable reliability for scientific measurements,

it did not in normal applications have the high reliability required from a controlling parameter for unmanned operation.

The state-of-the-art in monitoring technology would be reviewed, and the most suitable sensor systems would be selected and, if necessary, further developed for the application in the turbine. The deliverable of this work section would be the specification of the complete sensor equipment to be used as input for the adaptive regulation.

The adaptive controller would built in a suitable hardware environment (preferably the standard turbine controller, if possible) and would be tested in the laboratory using the "teacher". It would then be installed in the turbine, commissioned and monitored.

3. Variable Speed Drive

A variable speed drive would be necessary to give the flexibility required for the adaptive regulation. The blade pitch angle is one of the two primary tools; the rotor speed is the other.

A number of different variable speed systems would be considered. Typical variable speed systems used on wind turbines at the time of the project proposal were full-range, with a power rating of the frequency converter equal to or greater than the rated turbine power. The different options would be considered with respect to the newest technology, e.g. higher IGBT voltage ratings.

A high-reliability version of the most cost-efficient converter system would be developed. The development would be based on experiences and other ongoing development in the ABB Industrial Drive Section and in the ABB Traction Section. Reference would be made to the newest technology on ABB railway engine drives.

A combination of the higher IGBT voltage rating and the application of a new filter topology on both the generator and the main side would achieve higher efficiency. This new filter concept would provide both improved converter efficiency, improved grid distortion, and simpler converter protection.

A variable speed controller would be developed on the basis of ABB's new VECON chip, thereby introducing high-performance state-of-the-art modular control technology in the variable speed system.

Finally, a prototype of the new system would be built, tested in the laboratory, installed on the prototype turbine, and tested and adjusted under field conditions.

4. Environmental Impact

The fourth work package would aim at the development of stealth technologies. From the outset the work would concentrate on transparent blades and new tower coatings.

A comprehensive review of the available fibreglass materials would be performed. It was expected that

suitable transparent polyester/epoxy resins and transparency-enhancing coatings of glass fibres would be readily available as commercial products, but also that it would be necessary with test laminates in order to verify the translucency and hue. When the materials had been selected a number of realistic blade skin sections would be manufactured and subjected to static and dynamic tests. The replacement of normal sandwich laminate with thicker, transparent GRP material would be dimensioned. The possible sacrifices of structural strength relative to normal blade materials would be estimated. Specifications for possible changes in the normal blade laminate would be determined. The deliverables of this work section would be the specifications of suitable materials for translucent rotor blades.

A number of studies had been performed on tower colours and on the effects of various surface characteristics. In this project the available material would be reviewed, and the selection criteria for the optimum coating would be determined. The work was expected to include considerations on colour, change of colour with height, mattness, and advanced surface coatings. The result would be the specifications of suitable materials for an optimised tower coating.

The prototype blade set would be built in a standard mould using the selected materials with possible structural upgrading as necessary. The prototype tower would be coated with the selected coating type. The deliverables of this work section would be a set of prototype blades and a prototype tower.

Results

1. Modification of Existing Design to Higher rating

This part of the project was the first to be completed, and in the summer of 1996 the prototype turbine was erected at Tjæreborg near Esbjerg, Denmark. Commissioning with passive stall regulation took place in August 1996.

The overall design of the 1 MW machine is in accordance with what is often called the "Danish Concept". It has a three-bladed upwind rotor with stall regulation and constant rotor speed, an asynchronous generator coupled directly to the grid, and fail-safe safety systems with automatic air brakes and hydraulic disc brakes.

The rotor is a three blade cantilevered construction, mounted upwind of the tower. The blades are made of fibreglass reinforced polyester. Their aerodynamic design was developed as part of the previous project, under the Second Framework, Project No. JOU2-CT92-0171, by LM Glasfiber of Denmark. The blades are mounted on pitch bearings and can be feathered 90 degrees for shutdown purposes. Each blade has its own independent failsafe pitching mechanism capable of feathering the blade under any operating condition. The rotor hub is cast in nodular cast iron and is fitted to the main shaft with a flange connection.

The main shaft is in construction steel. The shaft is hollow for the transfer of power and signals to the blade pitching system. The upwind main bearing absorbs the rotor thrust and reaction forces from gravity and bending moments. It is a self-aligning double spherical roller bearing shrunk onto the main shaft. The bearing housing is bolted directly onto the nacelle bedplate. There is no downwind bearing; instead, the gearbox absorbs reaction forces from gravity and bending moments. The gearbox is a custom-built 3-stage planetary- helical design. As for the blades this component was developed under the Second Framework, Project No. JOU2-CT92-0171, by Flender of Germany. The first, high torque stage is a helical planetary design, providing a compact high-performance construction. The intermediary and high-speed stages are helical, providing the lowest possible noise level. The gearbox is splash lubricated and is cooled with a separate oil cooler. The gearbox is mounted on the nacelle with flexible rubber bushings, thereby reducing structural noise transfer.

The coupling between the gearbox and the generator is a universal coupling with two flexible elements. The generator is a fully enclosed asynchronous generator. The generator rotor construction and stator windings are specially designed for high efficiency at partial loads. The generator is fitted with a separate thermostat-controlled ventilation arrangement.

The mechanical brake is fitted to the gearbox high-speed shaft. It is failsafe and has two spring-loaded hydraulic calipers. The brake application system has two stages; one for normal shutdowns and the other for emergency shutdown in case of malfunctioning pitch systems.

The nacelle bedplate is a massive steel construction without welding. It is cut out of a 200-mm steel

plate. The topside has machined surfaces for the bearing and the gearbox supports, and the bottom side has similar surfaces for the yaw bearing.

The yaw bearing is an externally geared ring with a friction bearing. Four electrical planetary gear motors drive the yawing. The yaw brake is passive and is based on the friction of the yaw bearing.

The turbine controller is a microprocessor-based industrial controller; similar to the type used in other Bonus wind turbines. The controller is complete with switchgear, protection devices, etc.

The turbine is mounted on a tapered tubular steel tower. The tower has internal ascent and direct access to the yaw system and nacelle.

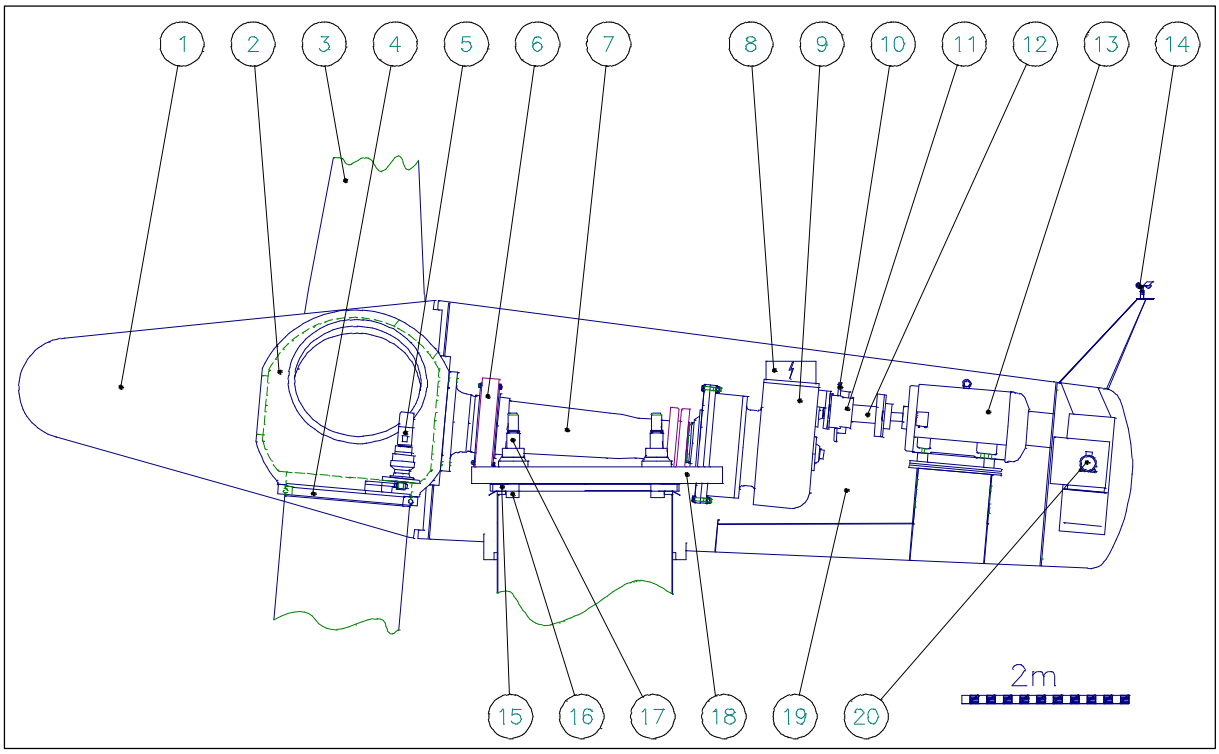

Fig. 1: Bonus 1 MW nacelle layout

The figure has the following legend:

1. Spinner
2. Rotor hub
3. Blade
4. Pitch bearing
5. Pitch actuator
6. Main bearing
7. Main shaft
8. Controller top
9. Gearbox
10. Brake disc
11. Brake caliper
12. Coupling
13. Generator
14. Met instr.
15. Yaw ring
16. Yaw bearing
17. Yaw gearbox
18. Bedplate
19. Canopy
20. Cooling

At an early stage in the project it became clear that the prototype turbine was well suited for experiments with a “discount” version of the adaptive regulation.

Power regulation is a necessary feature of all wind turbines. Regulation is required to limit the output at high wind conditions. The two traditional methods for power limitation are stall regulation and pitch regulation.

A turbine with normal passive stall regulation has blades mounted in a fixed position on the rotor hub. The blade pitch setting is adjusted once and for all during erection and running in. The blades are designed so the airflow separates from the downwind side at high wind speeds, causing lower lift forces on the blade, and higher drag. Thereby the efficiency of the blade is reduced at high winds, and the power output is limited at a roughly constant level. Due to the entirely passive use of the aerodynamic characteristics of the blades, stall regulation is simple and reliable under all conditions. No advanced pitching system is necessary. At high wind speeds the output is insensitive to wind speed variations, and under turbulent conditions the power output has only moderate variations.

It is a disadvantage of conventional stall regulation that the maximum power output depends on the air density and the surface roughness of the blades. Therefore, changes in the maximum power output may occur from summer to winter or if the blade surface is rough from insects or dirt.

A turbine with normal pitch regulation has blades mounted to bearings on the rotor hub. The blades can be turned around their axis for pitch setting adjustment. At high wind speeds the blade pitch is continuously adjusted to match changes in wind speed with changes in pitch angle. The direction of pitching at increasing wind speed is towards more positive pitch angles, away from stall. Due to the continuous adjustment the maximum power output can be kept constant at high wind speeds, irrespective of the conditions. Variations in air density and surface roughness are automatically compensated. The regulation range can be extended to lower wind speeds, causing a small increase in aerodynamic efficiency at partial load.

On the other hand, it is a significant disadvantage of normal pitch regulation that the output is very sensitive to small changes in the wind speed. This causes substantial variations of the power output under turbulent conditions. Therefore, the pitch adjustment system has to be fast reacting and quite complicated. Furthermore, to prevent large power peaks it is usually necessary to use some kind of variable speed in the generator arrangement.

The adaptive stall regulation system developed for the 1 MW prototype is a combination of the two traditional methods for power regulation.

At high wind speeds the blade pitch is continuously adjusted to match changes in wind speed with changes in pitch angle. However, contrary to normal pitch regulation the direction of pitching at increasing wind speed is towards stall. Therefore, the power limitation as such takes place by stalling, and the blade adjustment is merely a fine-tuning of the stall process.

Regulation by adaptive stall has the same advantages as pitch regulation. The maximum power output can be kept constant at high wind speeds, irrespective of the conditions, and variations in air density are automatically compensated. A small increase in aerodynamic efficiency can be achieved at partial load. Since the adaptive regulation involves stall, it retains most of the advantages of normal stall

regulation. Due to the insensitivity to wind speed variations the power output has only moderate variations under turbulent conditions. The adaptive stall system shares the disadvantage with pitch regulation that a pitching system is necessary. However, since the pitch adjustment is here merely a fine-tuning of the stall process, the requirements to the pitching system are much smaller, and it can be made vary simple and rugged.

The operational results with the 1 MW prototype have been satisfactory.

The power curve has been measured. It has been found to match the calculated power curve very well.

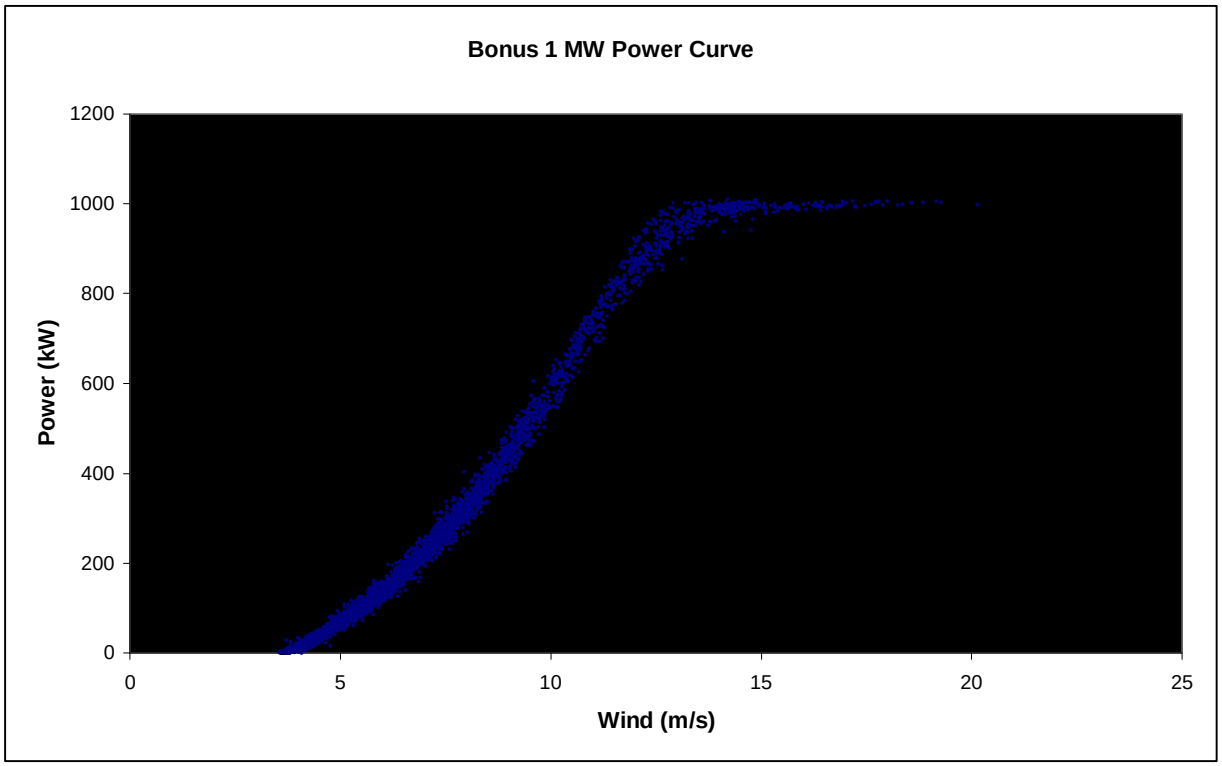

Fig.2. Measured power curve of prototype turbine

The noise behaviour has been measured. It has been found to be satisfactory, with a low noise level for this size of machine.

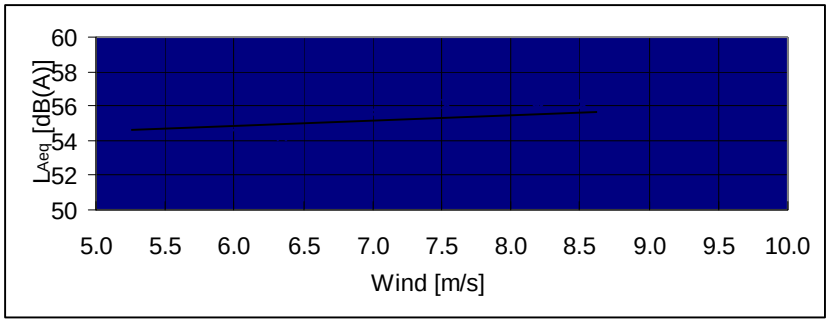

Fig.3. Measurement of sound pressure at reference point

The sound power level can be determined from the measured sound pressure at the reference point. The sound power level is 99.6 dB (A), measured at 8 m/s in 10 m height.

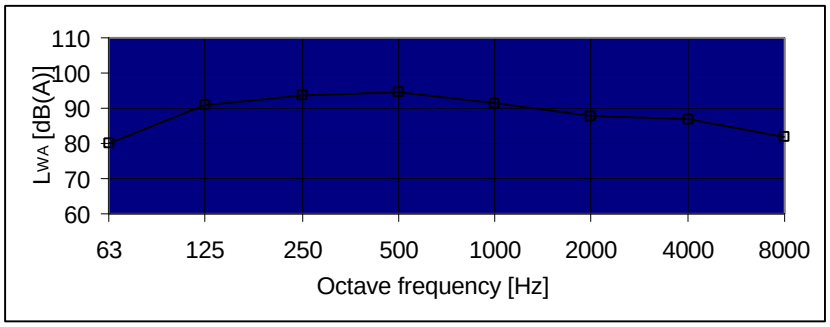

Fig.4. Octave band spectrum

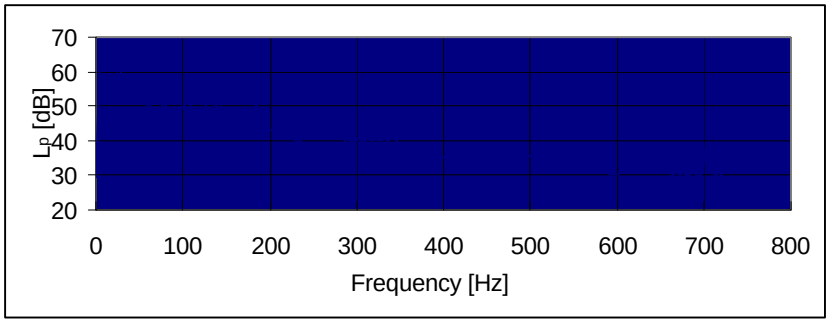

Fig.5. Narrow band spectrum

The narrow band spectrum shows an acceptable tonal content. No pure tone penalties would be applied under most European tonal assessment rules.

Due to the good technical results with the prototype turbine and the demonstrated advantages of the adaptive stall regulation Bonus decided to introduce the turbine commercially already during the project period.

A 0-series of four turbines was installed in the last quarter of 1997. Compared with the prototype the 0-series turbines had a less sophisticated pitch actuation system, reflecting the more moderate needs of adaptive stall regulation compared with the “full-blown” adaptive regulation. Since the adaptive stall regulation was implemented with constant-speed operation, a two-speed generator replaced the single-speed generator of the prototype in order to enhance energy capture at low wind speeds.

Serial production of the 1 MW turbine commenced in 1998. The annual production figures have been as follows:

1996 1
1997 4
1998 40
1999 ..... > 150

2. Adaptive Regulation

The machine learning techniques and the associated sensor technology were developed largely as planned.

It was expected that the sensor technology study could lead to improvements in the technology available for monitoring of loads. At the end, the preferred solution was quite conventional, consisting of strain gauges pre-mounted in a suitable frame.

For reasons of internal priority ABB could not carry out the adaptive regulation work package as planned. Consequently, this activity was subcontracted, with good results.

The machine learning algorithm was expected to be a connectionist learning system, a neural network, or a combination of these. The studies resulted in the selection of a more robust alternative, the neuro-fuzzy algorithm in which the neural network plays a role in the learning process only, not in the actual execution in the machine.

The algorithm was developed as planned, but the results achieved in simulation and measurement did not meet the objectives of the project. It was anticipated that the adaptive turbine would be able to improve the energy efficiency, the noise behaviour, the grid behaviour, and the loading response. As it turns out, the possible benefits are considerably smaller than anticipated.

For both the energy efficiency and the noise, the problem is the frame of reference. The commercial Bonus 1 MW turbine with CombiStall already has fairly high efficiency and a low noise level. An optimised pitch setting below rated power as a function of the wind speed has been implemented in the CombiStall system at a very small effort and no additional cost. In energy output terms this feature combined with the two-speed operation of the standard turbine is a good approximation to the continuously variable speed and pitch angle of the adaptive turbine. At wind speeds above those where maximum rotor efficiency is achieved at nominal rotor speed (typically 8-9 m/s) the rotor can not be allowed to follow an increasing wind speed with a corresponding increase in rotor speed, since this would lead to unacceptable levels for the blade tip speed. All these factors in combination lead to a situation where the potential energy benefit from the “full blown” adaptive control is on the order of some percent only when compared with the “discount” adaptive control of the CombiStall feature. When on top of that the variable speed is achieved with a frequency converter having a few percent losses, the realistic net gain in energy output from adaptive control is reduced to something close to zero.

For similar reasons it turns out that the noise behaviour can not be much improved. With the simple adaptive control systems of CombiStall the standard turbine has a noise control very close to that achieved by the adaptive controller with a lot of training. A reduction in noise level can actually be measured, but the difference to the standard turbine is within the normal measurement tolerances, and the results can not be said to be statistically significant.

Concerning the grid behaviour this is governed exclusively by the frequency converter, when a full-range converter system is applied, as it is in this case. The grid behaviour is actually quite satisfactory, but this is more due to a good IGBT control algorithm of the converter, rather than due to any adaptive regulation.

Finally, concerning the loading, both simulations and measurements show that the everyday turbulence loads can not realistically be modified to any significant degree by adaptive regulation. The reason is that the turbulence loads are so significantly influenced by the turbine dynamics. The 'tools' of the adaptive regulation, the rotor speed and the pitch setting, both have much longer time constants than the periods of the dynamic vibrations. The most rapid tool, the pitch setting, can at most be regulated with a frequency on the order of 1 Hz. In comparison, the main load types (blade root and shaft bending moments) have first fundamental frequencies in the range of 1.5-3 Hz, effectively making active control impossible.

Contrary to this, certain special loads can actually be significantly modified with adaptive regulation. These loads generally show dominant 1-p variations. At a rotor speed of 22 rpm the load fluctuations occur at 0.3 Hz, too slow to excite the fundamental dynamic frequencies of the structure and sufficiently slow to be followed efficiently by a pitch drive. However, here the adaptive regulator runs into the problem of occasionally 'missing the beat', actually making the 1-p loading worse for a brief period until the adaptive controller restores proper synchronisation. This situation can consume in a limited time all the fatigue life saved over a long period with a system functioning as intended.

3. Variable Speed

In terms of technology the variable speed drive was developed largely as planned. In terms of schedule, however, significant delays were encountered. These delays were of such magnitude that an extension of the overall project became necessary. The Commission granted a half-year extension. Ultimately the variable speed drive was supplied as planned in the updated schedule.

Since Bonus found it necessary to carry out field measurements in reasonable time before the project termination, an off-the-shelf variable speed drive was acquired prior to the termination of the original deadline of the project. Even though this standard equipment did not meet the requirements for reliability, grid behaviour, etc. of the drive developed as part of the project, it provided the necessary variable speed operation for the adaptive regulation. Consequently, field tests of the adaptive regulation with variable speed were carried out at the same time as the benchmark testing of the ABB drive. This parallel arrangement offered the possibility of both optimising and extensive testing of the converter while at the same time not jeopardising the timing of the field measurements.

Part of the variable speed work package was the selection of an optimum generator / converter arrangement. A normal squirrel cage generator and a full-range converter were selected. It was anticipated that the selected arrangement would indeed represent a good commercial choice. As it turned out, this arrangement is unlikely to be commercially attractive due to less than expected cost reductions in converter systems. Therefore, no continued commercial use of the full range

converter is expected.

On the other hand, Bonus and ABB have recently entered an agreement with respect to the exploitation of a special version of the variable speed drive for a partial speed range. Therefore, a commercial product will ultimately emerge from the project.

4. Stealth Technology

The stealth technology was developed as planned. However, certain difficulties arose in implementation.

The idea of transparent blades did not work well in real life. It was possible to make quite transparent glass fibre laminates but certain opacity seemed unavoidable. The term “translucent” used in the project proposal was actually quite suitable. However, even though wind turbine blades fabricated from the tested materials would be transparent to light to a certain degree, they would be far from invisible. Under certain light conditions internal reflections in the opaque blades will cause the blade to appear very bright against the background, almost certainly leading to a visual effect that is more intrusive than normal blades. Consequently, the transparent blades do not seem to be an option for commercial turbines, at least not with the material technology currently available.

It was anticipated that a high-gloss tower coating could provide good stealth effects. This turned out not to be the case. On the other hand, a new type of coating was developed that turned out to be significantly more stealthy than the normal grey colour. It is anticipated that this coating will be implemented commercially on towers, nacelles and blades.

Summary of Conclusions

Generally the results of the Joule project are found to be satisfactory, having resulted in a competitive commercial turbine.

More specific:

- The first main objective was cost efficiency improvement of more than 10 percent relative to the 750 kW turbine under any wind conditions. The 750 kW turbine never reached a commercial stage but when corrected for inflation the 1 MW turbine improved the cost efficiency of the 600 kW turbine contemporary with the 750 kW prototype by 20 percent.
- The second main objective was an adaptive regulation capable of reducing the wind induced operational blade and rotor loads by at least 10 percent relative to comprehensive designs of similar size and concept. This goal was not reached and the project conclusion is a question as to whether this goal is actually attainable when the few serious “missed beats” are taken into consideration. It turned out to be difficult to improve on a modern turbine by replacing steel and fibreglass with silicon and active systems. However, the “discount” type of adaptive regulation represented by active stall is very successful.

- The third main objective was the development of a variable speed drive with higher reliability (MTBF target: 200,000 h), reduced costs (Cost target: 20,000 ECU/MW) and high efficiency (Converter efficiency target: 0.98). The MTBF target appears possible by calculations but for obvious reasons the sustaining evidence is still sparse. The cost target was not reached for the prototype but it is likely that it can be reached following optimisation over some years' time. The efficiency was about 0.97.
- The fourth main objective was a visual impact, which would be significantly reduced relative to conventional designs. This goal was reached with the new surface coating. However, the blade transparency idea did not work well in full scale.

Exploitation Plans

The exploitation of the results centres on the marketing of the Bonus 1 MW turbine and larger turbines derived from this structure. The turbine has the simplified version of the adaptive regulation was developed and was implemented in the 1 MW and larger Bonus turbines. This regulation principle was generally new compared with the two main groups of regulation at that time, pitch regulation and fixed-pitch stall regulation.

The benefits of the new turbine are substantial; including an inflation-corrected cost reduction of wind energy of more then 20 percent compared with market standards at the time of the project proposal.

The competitive variable speed drive developed by ABB would be exploited by ABB in their normal marketing of variable speed drives.

Risø developed transparent composite laminates that would form part of their composite technology know how exploited in Risø consultancy.

A new tower coating was developed. This coating has new properties compared with the state of the art of surface coating of large structures. It would be exploited by Bonus for specific projects.