Testing and Commissioning of Lillgrund Wind Farm

Lillgrund Pilot Project

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PREFACE

Vattenfall's Lillgrund project has been granted financial support from the Swedish Energy Agency and Vattenfall will therefore report and publish experiences and lessons learned from the project. This report is compiled in a series of open reports describing the experiences gained from the different aspects of the Lillgrund Wind Farm project, for example construction, installation, operation as well as environmental, public acceptance and legal issues.
The majority of the report authors have been directly involved in the Lillgrund project implementation. The reports have been reviewed and commented by a reference group consisting of the Vattenfall representatives Sven-Erik Thor (chairman), Ingegerd Bills, Jan Norling, Göran Loman, Jimmy Hansson and Thomas Davy.

The experiences from the Lillgrund project have been presented at two seminars held in Malmö (4th of June 2008 and 3rd of June 2009). In addition to those, Vattenfall has presented various topics from the Lillgrund project at different wind energy conferences in Sweden and throughout Europe.

All reports are available on www.vattenfall.se/lillgrund. In addition to these background reports, a summary book has been published in Swedish in June 2009. An English version of the book is foreseen and is due late 2009. The Lillgrund book can be obtained by contacting Sven-Erik Thor at sven-erik.thor@vattenfall.com.

Although the Lillgrund reports may tend to focus on problems and challenges, one should bear in mind that, as a whole, the planning and execution of the Lillgrund project has been a great success. The project was delivered on time and within budget and has, since December 2007, been providing 60 000 households with their yearly electricity demand.

Sven-Erik Thor,
Project Sponsor, Vattenfall Vindkraft AB
September 2009

DISCLAIMER

Testing and Commissioning of Lillgrund Wind Farm

SUMMARY

This report gives an overview of the tests carried out in the Lillgrund project. The report covers factory tests, site tests and the performance tests, which can be carried out during the defects liability period. The report describes tests relevant for the wind turbine generators, the electrical system and the foundations.

On the whole, the Lillgrund test results have been satisfactory. One of the more problematic issues experienced were when the foundation interface verification showed that the bolts were not meeting the height requirements. Since this shortcoming was detected relatively early in the project life, it was possible to correct the misalignment and keep the additional costs to a minimum. From a management point of view, this highlighted the importance of clear and unambiguous interface specifications and to make sure that the project has a proper interface management function.

According to the Contract, Vattenfall has the right to verify a number of performance parameters during the 5-year defect liability period. The performance tests include availability, power curve, electrical system losses and acoustic noise levels. The contract specifies the test criteria, the test methods and procedures and the penalty if the tests result in undesirable levels. In some cases, there is a financial incentive for the supplier if the tests show that the wind farm is performing better than stipulated in the contract. Lillgrund has performed very well thus far and Vattenfall has determined that the contractual performance requirements are being met. Vattenfall has, therefore, not requested to carry out any of these elective Performance Tests.

SAMMANFATTNING

I denna rapport presenteras en översikt av test- och provningsaktiviteter som utförts i Lillgrund-projektet. Rapporten behandlar fabrikstester, anläggningsplatstester och prestandaprover. Rapporten innefattar test av vindkraftverk, elsystem och fundament.

På det hela taget har test och provning av Lillgrund varit framgångsrika. Ett relativt komplicerat problem upptäcktes dock under kontroll och verifieringen av fundamentbultarna i vilka tornet monteras. Det visade sig att bultarna ej uppfyllde aktuella höjdkrav. Då problemet upptäcktes i ett relativt tidigt projektskede kunde det åtgärdas till en förhållandevis begränsad merkostnad. Från ett byggherre-perspektiv belyser det uppkomna problemet vikten av att ha klara och otvetydiga gränssnittsspecifikationer och att säkerställa erforderliga projektresurser för hantering av leveransgränssnitt.

Lillgrund-kontraktet ger Vattenfall möjlighet att utföra ett antal prestandaprover under anläggningens femåriga garantiperiod. Prestandaproverna omfattar tillgänglighet, vind-effektkurva, elsystemförluster och ljud. I kontraktet specificeras testkriterier, testmetoder samt ersättning om utfallet av aktuellt prestandaprov ej är i enlighet med kontrakt. I vissa fall kan det utgå ersättning till leverantören om prestandaprovet visar att anläggningen har bättre prestanda jämfört med kontrakt. Lillgrund har hittills uppvisat en mycket god prestanda och Vattenfalls bedömning är att de kontraktsmässiga prestandakraven är uppfyllda. Vattenfall har därför ej begärt att något prestandaprov ska utföras.

TABLE OF CONTENTS

1 INTRODUCTION

The purpose of this report is to give an overview of the tests carried out in the Lillgrund project. The report covers factory tests, site tests and the performance tests, which might be carried out during the defects liability period.

2 WIND TURBINE GENERATOR (WTG) TEST

2.1 Factory Acceptance Tests

The Contract [1] defines a number of Factory Acceptance Tests (FAT), which shall be performed during manufacturing of the WTG's. These tests are listed in three different categories relevant for the WTG,

- Tower
- Electrical parts
- Nacelle

FAT on **Tower** includes
- Mill certificate for steel plates
- Dimensional inspection report
- NDT (Non Destructive Test) report
- Coating inspection report
- Non-conformance reports and
- Inspection certificate from a certifying body

FAT on **Electrical Parts** includes
- Generator
- WTG transformer
- Converter system and
- Controller

FAT on **Nacelle** includes
- Gear box including lubrication system
- Main shaft installation
- Yaw drives and system
- Blade pitch system
- Cooling system and
- Major castings

Vattenfall participated in a selection of the above tests and only on one or two batches of each system. The general impression is that the FAT were performed professionally and satisfactory.

FAT of the turbine generator, in which Vattenfall participated, showed that two generators had some defects and the test had to be cancelled. Based on this experience, Vattenfall requested to observe the Generator Type Test.

2.2 Site Acceptance Tests

The Lillgrund Contract defines no Site Acceptance Tests (SAT) specific for the WTG's.

2.3 Commissioning Tests (CT)

Commissioning Tests on WTG's is required in order to demonstrate that each WTG is safe and capable of continuous automatic operation. The Commissioning Tests were performed after the Final Adjustments of the WTG's, and most of the tests were included in the manufacturer's standard commissioning procedures.

The Commissioning Test includes the following:

- 6 hour test run with the generator connected to the grid
- Demonstration of WTG vibration level below acceptable level
- Test of trip function when WTG is generating and grid loss occurs
- Test of over speed trip of each WTG
- Test of yaw drives
- Test of Power Measurement System
- Verification of settings for electrical protection relays

CT's were satisfactorally performed for all WTG's except for the grid loss trip function that was postponed to a later routine test of the wind farm. This test is not a standard test performed by wind turbine manufacturers and the test should not be performed unnecessarily since it causes high loads on the machine. Furthermore, due to delay in delivery of WTG Power Measurement System, this test was not performed as part of the CT.

2.4 Test on Completion (ToC)

Before Test on Completion could be initiated, the Commissioning Tests needed to be finalised and approved by Vattenfall.

Test on Completion were divided into two different tests:

- ToC for individual WTG
- ToC for complete Wind Power Plant (WPP)

ToC for individual WTG

This test required that each WTG should be in operation continuously for 240 hours, of which at least 150 hours should be generator time (generator producing power to the grid).

Conditions for approved test-runs were that no more that 3 faults caused by the WTG are allowed during the complete test period and that no faults are allowed within the last 100 operation hours. Each fault could not exceed being repeated twice.

Faults not caused by the WTG were defined in the Contract. This could be grid loss, high wind, lightning, manual stop by Vattenfall, grid faults, etc.

ToC for individual WTG was started on October 11, 2007 and was completed for the last WTG on February 5, 2008.

Each WTG test was recorded by the manufacturer and presented to Vattenfall for approval.

ToC for Wind Power Plant (WPP)

This test required that the complete WPP should be in operation continuously for 200 hours, of which at least 150 hours should be generator time (WPP producing power to the grid). During the test, the main transformer temperatures were measured during a high load period.

The condition for approved WPP test-runs were that the availability was at least 85% for the WPP during the test-run period.

ToC for WPP was started on February 8, 2008 and ended on February 17, 2008.

The test was recorded by the manufacturers SCADA system and presented to Vattenfall for approval.

2.5 Performance Tests

The Contract defines four different Performance Guarantees together with procedures for verification.

- Availability
- Power Curve
- Electrical System
- Acoustic Noise

Availability

The WTG manufacturer warrants Availability for the Wind Power Plant during the Defect Liability Period.

Availability for a WTG is defined in the Contract as the relationship between the time where the WTG has been available for producing power to the grid and the time where the grid has been available to receive energy from the WTG's. This performance test will run during the 5 years Defect Liability Period.

Power Curve

Vattenfall is entitled to request a verification of the Power Curve based on two WTG's (C-08 and D-08) at any time within the Defect Liability Period. The selection of these two turbines is due to their proximity to the existing Met-mast in the wind farm. The Met-mast is used as a reference for wind measurements in case of Power Curve verification.

If a power curve verification is requested, this shall be performed according to:

- IEC 61400-12:1998.
- Wind Turbine Power Performance Testing, Danish Energy Agency, March 7, 2000
- Measnet POWER PERFORMANCE MEASUREMENT PROCEDURE and
- Measnet CUP ANEMOMETER CALIBRATION PROCEDURE version 1, Sept. 1997

The WTG power will be measured on the low voltage side of the WTG transformer.

Based on the WTG's own Power Curve measurements (recorded by the WTG controller and displayed in the SCADA system), it will be evaluated if a Power Curve has to be verified. If the WTG Power Curves seems to be realistic the measurement verification will not serve any purpose.

Electrical system

Performance test of the electrical system is described in chapter 4.5.

Acoustic Noise

Vattenfall is entitled to request measurement verifications of the acoustic noise levels of the Lillgrund WTG's. The guaranteed sound power level for each WTG is 106,5 dB(A) at 8 m/s in 10 m height, as measured according to IEC 61400-11(1998).

Verification of acoustic noise levels will only be performed in case Contractual requirements are potentially not being met.

3 SCADA TEST

The only test performed on the SCADA systems was the Site Acceptance Tests (SAT).

3.1 SCADA SAT

The SCADA system for Lillgrund Wind Power Plant is divided into two independent systems.

The WPS SCADA covers SCADA for the wind turbines and meteorological system and SICAM PASS SCADA covers the sub station and electrical grid system.

After installation and commissioning of the wind turbines and electrical system, a combined SCADA Site Acceptance Test was performed.

The SCADA SAT was split into five main topics:

1. Online Communication Functions including tests on:

- Turbines
- Met station
- EON Grid Station
- Time sync.
- Offline data storage and replication
- Automatic switchover

2. WPS SCADA including function tests on:

- WPS Server
- WEB WPS History Section
- WEB WPS Online Section
- WEB WPS Utility
- WEB WPS Documentation
- WPS Park Pilot

3. SICAM Specific test procedure including test on disturbance fault recordings

4. Site specific tests including test on:

- E.ON Grid Station
- OPC Communication
- IEC104 Communication
- Beckhoff Module
- Watchdog
- UPS
- Aviation Lights
- Energy Metering

5. Special features including test on:

- SNMP Supervision
- Status Server

The SCADA SAT was performed during three different sessions during a period of four months due to parts of the systems malfunctioning during the initial SAT. Also, part of the SCADA system was not implemented in a timely manner for the planned SAT.

4 TESTS ON ELECTRICAL SYSTEM

4.1 Factory Acceptance Tests (FAT)

The Contract [1] defines a number of FAT that should be performed during manufacturing of the electrical system. FAT on the electrical system includes

- Main transformer
- Auxiliary transformer
- Diesel generator
- Onshore and offshore cables

Vattenfall participated in all of the above tests except for tests run on the diesel generator. Vattenfall was not invited to this FAT due to some kind of misunderstanding. The Contractor compensated Vattenfall by performing an extended Site Acceptance Test (SAT). The general impression of the FAT was that they were performed professionally and satisfactory.

4.2 Site Acceptance Tests (SAT)

The Contract does not define specific SAT's for the electrical system.

4.3 Commissioning Tests (CT)

CT's are required in order to demonstrate that the electrical system is safe and ready for operation. The Commissioning Tests were performed after the Final Adjustments and most of the tests were included in the manufacturer's standard commissioning procedures.

The CT for the electrical system include the following:

- Demonstration of satisfactory operation of power measurement equipment.
- Function tests of the relay protection and verification of settings.
- Demonstration of satisfactory operation of control equipment (Siemens Sicam control equipment).
- Demonstration of satisfactory operation of 33 kV cubicles.
- Demonstration of satisfactory operation of the diesel generator.
- Demonstration of satisfactory operation of the transformer cooling equipment.
- 24 hours voltage test on the cables.

All CT's were satisfactorally performed for the electrical system, except for the demonstration of satisfactory operation of the power measurements equipment. Installation of the power measurement equipment in the individual wind turbines was delayed and had to be completed later on in the project. Demonstration of satisfactory operation of transformer cooling equipment is part of the ToC described in chapter 4.4.

4.4 Test on Completion (ToC)

ToC of the electrical system was a part of the ToC for the complete WPP. This test required that the complete WPP should be in operation for continuously 200 hours of which at least 150 hours should be generator time (i.e. WPP producing power to the grid). During the test the main transformer temperatures were measured for 12 continuous hours, with a load of >85% power output (i.e. 85% of rated WPP capacity).

The purpose of these measurements was to verify that the main transformer and its cooling equipment operate normally on the offshore platform. The temperature measurements at high load were approved separately.

4.5 Performance Test

The Contractor guarantees that power losses occurring in the main transformer, WTG transformers, HV cables and the MV cables shall not exceed the maximum loss values stated in the Contract.

The losses of concern in this section of the Contract are no-load losses, load losses and also cool equipment loss for the transformers. The losses shall be determined by preapproved measurements (factory tests) where Vattenfall shall be given the opportunity to attend.

The Contract states that in the case the sum of the measured losses subtracted by the stated maximum losses are positive, Vattenfall is entitled to financial compensation. In case of a negative sum, the Contractor is entitled to an incentive payment of 30% of the compensation. The compensation is based on capitalised cost for the losses stated above.

5 TESTS ON FOUNDATIONS

5.1 Factory Acceptance Tests (FAT)

The Contract [2] defines that the following testing and inspections must be done:

- Factory testing of foundations including NDT (non-destructive test) of welding and test of concrete samples
- Other relevant tests to obtain a statement of compliance for the fabrication phase
- Test to obtain type certificate from classification entities
- Test of individual offshore foundations after installation

In order to facilitate the above following test were done.

Testing and inspection in connection with Concrete Manufacturing

All normal concrete manufacturing test are included, such as certification of cement quality, aggregate quality, calibration of mixing equipment etc. Curing is monitored using temperature sensors etc.

Cured concrete

Verification of the concrete hardening process was required in the contract, in appliance with the used design code.

Steel items

Verification of the steel, including welding and surface treatment was done following applied code and applicable standards.

Interface verification

The main interface that needed to be taken into consideration was the tower bolts. They had to be correct both in plane and in height.

The positions and heights above the concrete surface of the tower bolts were thoroughly tested. A template was used on site for the positioning of the bolts prior to casting, a photogrametric method was also applied but there still were some misaligned bolts on a few of the foundations. For these foundations, special tower flanges were made. These flanges were brought to, and tested on the foundations prior to welding it on the wind turbine tower.

Unfortunately, the specification of the height above the concrete surface was poorly defined and last minute adjustments were needed on those foundations. Each bolt was locally fulfilling the height requirement but did not fulfil the height requirement on an overall level since the concrete surface at the top of the foundation was not horizontal.

5.2 Site Acceptance Tests (SAT)

Several under water tests and inspections had to be documented and video recorded to verify that the stiffness of the foundation and the rock fill, ballast, armour rock and J-tubes were correctly placed. Without these individual verifications, the system as a whole could not be trusted.

Dredging

Position and height of the trenches, as well as the occasional high spots and boulders were documented. High spots and boulders were to be avoided to make sure that good alignment of the foundation and correct soil stiffness was achieved.

CPT investigations

Soil investigations were made to verify geotechnical design assumptions at every foundation position.

Stone bed

After placement of the stone bed the theoretical centre and surface tolerances were verified.

Placing of foundation

After placement of the foundation, its position and inclination was measured in order to make sure they are within tolerances.

Ballasting

Ballasting of cells in the foundation below water was monitored by the Contractor's divers and verified using video. Ballast fill height in the shaft was measured and documented.

Armour rock and scour protection

Thicknesses and position of armour rock and scour protection was verified with video monitoring.

J-tubes

Visual inspection and video documentation showing that the cable wire was connected, flange bolts tightened, marker buoy connected and that the J-tube being free of sand.

Anodes

After mounting and connecting the anodes to the foundation, they were tested with transition resistance between the concrete reinforcement bars and the surrounding sea. The corrosion potential between the concrete reinforcement bars in the foundation and a temporary reference electrode was also measured.

5.3 Commissioning Tests (CT)

Conductivity testing of the concrete's reinforcement was done together with the cast in mechanical connections to make sure that the expected function was achieved and personnel safety could be ensured after completion at site.

This was, in practice, done with measurement of the resistance between specific reinforcement bars and the grounding mesh set in the concrete bottom slab before casting. The connection between the flanges and the reinforcement at the concrete deck of the foundations were also measured in order to ensure proper grounding of the cable connections.

5.4 Test on Completion (ToC)

Geotechnical data was transferred back to the wind turbine supplier. They used the data to calculate the overall stiffness of the underground foundation and turbine, and to verify the Eigen frequency of the system.

5.5 Performance Test

No performance test was done on the foundations themselves, but the hydraulically-controlled boat landings were tested to satisfaction.

6 COMMENTS AND CONCLUSIONS

The test and validation phase is a crucial part of a wind farm delivery. Those testing offshore wind farms face extra challenges since site work is weather dependent and costly. It is, therefore, of great importance to find a proper balance between factory and site tests. It is recommended to perform as many tests on shore as possible although it is recognised that certain tests must be carried out when the plant is installed on the site.

The Lillgrund procurement was conducted under two contracts. The trend in the offshore wind industry is to split the supply into smaller packages, i.e. more contracts. From a management point of view, having more contracts may be less desirable as this will require a more extensive and structured testing program.

On the whole, the Lillgrund test results have been satisfactory. One of the more problematic issues experienced were when the foundation interface verification showed that the bolts were not meeting the height requirements. Since this defect was detected relatively early in the project life, it was possible to correct the misalignment and keep additional costs to a minimum. From a management point of view, this highlighted the importance of clear and unambiguous interface specifications and to make sure that the project has a proper interface management function.

Lillgrund has performed very well thus far and Vattenfall has determined that the contractual performance requirements are being met. Vattenfall has, therefore, not requested any of the elective Performance Tests that are stipulated in the Contract.

7 REFERENCES

[1] CONTRACT AGREEMENT WIND TURBINE AND ELECTRICAL SYSTEM SUPPLY AND INSTALLATION, CONTRACT PV-2004_168, LILLGRUND

[2] CONTRACT AGREEMENT FOUNDATIONS AND SEABED PREPARATIONS , CONTRACT PV-2004_169, LILLGRUND