Successful Power Limit Increase of SGT-2000E Gas Turbines on the Basis of Si3D Blading

Russia Power 2013, Moscow, Russia
March 05-06, 2013

Authors:
Simon Kliesch
Christoph Sorgenfrey
Martin Stapper

Siemens AG
Energy Sector
# Table of Contents

1 Summary ................................................................................................................ 3

2 Introduction ............................................................................................................ 4

3 Measurement campaign.......................................................................................... 7

4 Summary .............................................................................................................. 13

5 Outlook................................................................................................................. 14

6 Acknowledgements .............................................................................................. 14

7 Nomenclature ....................................................................................................... 15

8 Disclaimer ............................................................................................................ 16
1 Summary

One of the most innovative solutions for making SGTx-2000E gas turbines more competitive and more cost-effective is the Si3D upgrade product. Si3D stands for "Siemens innovative 3D" optimized turbine blades and vanes and has been developed for all four stages of the turbine section. The profile of the Si3D blades and vanes has been aerodynamically optimized, significantly improving output and efficiency.

The Si3D upgrade has been introduced onto the market step by step. While the earlier turbine blading upgrades comprised only retrofitting stages 1 and 2 with Si3D, the full Si3D package for stages 1 to 4 has been available since 2008. The major output improvement achievable with the full Si3D package made further studies necessary, because the present-day power limit of 173 MW is quickly achieved. Depending on the turbine configuration, the power output may be constrained as ambient temperatures decline below 10°C.

To verify and validate new products, Siemens relies on customers volunteering their plants for a product first time application. In 2011/2012 an opportunity arose in Finland to carry out an extensive program of measurements for testing and validating how the power limit can be increased in parallel with the blading upgrade. The essential feature of this campaign was a non-intrusive measurement of blade vibration by means of optical probes. The campaign has now been successfully completed and the Finnish customer is able, by optimizing winter operation, to take advantage of the improved output and efficiency potential of the upgraded turbines even at low ambient temperatures. On the basis of these encouraging results, Siemens is currently preparing the fleet release for a power limit increase of all SGT5-2000E gas turbines with Si3D airfoils in stages 1 to 4 from 173 MW to 185 MW (the scope of the modernization required can vary, so a check will still need to be performed for each specific plant).

This publication gives an account of operating experience and the fleet penetration of the Si3D upgrade product to date and draws a balance after more than 600,000 accrued operating hours. It also describes details of the tests and the technical conversions needed to increase the power limit of the SGT5-2000E fleet.
2 Introduction

Siemens' innovative 3D turbine blades and vanes (Si3D) are one of Siemens Energy's latest modernization and upgrade products for gas turbines that achieve an enormous improvement in power output and efficiency. 3D stands for 3-dimensional, aerodynamically optimized design of turbine blades and vanes. This blading generation also features enhanced materials and coating, an improved cooling air path, and optimized cooling air demand.

Retrofitting Si3D turbine blades enables achievement of the following power output and efficiency improvements:

**Turbine stages 1 and 2:**
- gas turbine power output increased by 5 MW * or more
- gas turbine efficiency improved by 0.8% points* or more

**Turbine stages 3 and 4:**
- gas turbine power output increased by 2.5 MW * or more
- gas turbine efficiency improved by 0.5% points* or more

*Actual results may vary depending on local site conditions.

The Si3D turbine upgrade reduces life cycle costs and is compatible with all other upgrade products such as the Siemens 41,000 EOH maintenance concept upgrade. Si3D blading is state of the art for new SGT5-2000E gas turbines.

Since the new blading design was first introduced in 2006, more than 50 new-apparatus and service gas turbines have been equipped with Si3D blades and vanes in stages 1 and 2. In all, this upgrade has by now clocked up over 600,000 equivalent operating hours (EOH) and over 12,000 starts.
Furthermore, six gas turbines with the full Si3D turbine upgrade package (stages 1 to 4) have already been successfully commissioned since 2008.

![3D CAD model of the SGT5-2000E with its characteristic silo combustion chambers](image)

**Fig. 1: 3D CAD model of the SGT5-2000E with its characteristic silo combustion chambers**

This turbine upgrade is also available for the 60 Hz market. In 2009 Siemens was able to implement the first set of Si3D blades and vanes in stages 1 and 2 of a SGT6-2000E in the USA. Currently five engines have already been upgraded with Si3D stages 1 and 2. In the next years, Si3D (stages 1 to 4) is scheduled for implementation in further gas turbines of this type.

Thanks to the Si3D cooling air design without film cooling holes, the blades are also suitable for special fueling operation, e.g. crude-oil, heavy-fuel-oil etc. More than 25 SGT6-2000E gas turbines capable of running on these types of fuel are currently being fitted with Si3D in stages 1 and 2.

Experience with this upgrade within the Siemens service fleet shows that, with the full Si3D package, the gas turbines quickly come reach the current power limit of 173 MW, especially on cold days (even < 10°C, depending on the configuration). From this point on the pitch angle of the compressor inlet guide vanes is reduced. The gas turbine goes into part-load operation, preventing any higher power output (\(P_{eL, max} = \text{constant} = 173 \text{ MW}\)).
Keeping the turbine exhaust temperature constant also has a negative impact on district heat extraction, because it prevents a higher energy yield here, too.

For this reason Siemens has performed further studies with a view to increasing the power limit across the entire SGT5-2000E fleet. The Si3D turbine blades and vanes were designed according to the Siemens Design Philosophy. Although potential operational risks are already minimized at the engineering stage, this guideline calls for not only theoretical release of the blades and vanes but also real-time measurement on a turbine in the field. To validate operation at a higher power limit, especially with regard to vibration aspects, an extensive program of measurements was developed and carried out on an SGT5-2000E in Finland. This measurement campaign and its results are discussed in the following.
3 Measurement campaign

The method

The non-intrusive stress measurement system (NSMS), often also referred to as a blade-tip timing system, was used to monitor the vibration of the turbine blades in operation. This system uses stationary external probes to detect vibration-induced stresses and frequencies in rotating parts (in this in particular case, optical probes were used). This technology is used for example by the US corporation Agilis Group, Inc., which assisted Siemens in this campaign.

The basic principle of NSMS measurement is outlined below without going into the detailed physics of the method. NSMS is based on the principle that the time taken by a vibrating blade to cover a given rotational distance will differ from that taken by a theoretical, non-vibrating blade. The blades are said to have different arrival times. The time taken by a theoretical non-vibrating blade to complete one rotation can be calculated from the rotor speed and the circumferential distance traveled per rotation. Comparing the theoretical and the actual (as measured by NSMS) arrival times of a blade makes it possible to calculate the blade frequency and the associated amplitude when running, i.e. one obtains a precise indication of the magnitude of the blade deflection. As the NSMS measurement is performed in real time, action can be taken immediately (e.g. load reduction, turbine trip) if the defined maximum permissible deflection of the blade is reached or exceeded.

According to the Nyquist stability criterion, the minimum sampling frequency for monitoring of a given maximum frequency $f_{\text{max}}$ is $2 \times f_{\text{max}}$. 
To increase the blade vibration sampling rate, 8 NSMS probes were used in each turbine stage monitored.

![Distribution of NSMS probes using turbine stage 3 as an example](image)

**Fig. 3: Distribution of NSMS probes using turbine stage 3 as an example**

The best probe locations for the measurement were defined by Agilis Group, Inc. taking the following parameters into account:

- Turbine stages 2, 3 and 4 were to be instrumented. Measurement at turbine stage 1 was not necessary, as these blades are engineered according to the Siemens Design Philosophy to afford adequate safety margins in terms of vibration.
- 8 vibration probes (NSMS) were to be used per stage.
- All probes of a stage should lie in the same axial plane.
- Within each stage, the probe locations should be asymmetrically distributed over the circumference to detect as many vibration modes as possible.

The green curve in Figure 4 below shows an example of a vibration signal measured over one rotation. Superimposing the NSMS probe distribution at turbine stage 3 shown in Figure 3 gives an impression of the intervals of the vibration signal captured by the probes. Interval 0 to $\pi$ defines the rotation of the blade starting at the horizontal joint in the upper part of the gas turbine, interval $\pi$ to 2 $\pi$, similarly, rotation in the lower part.
Fig. 4: Example showing a vibration signal at turbine stage 3

The high resolution of the data thanks to the number of probes makes it possible to isolate the original signals from the measured frequency (see Figure 5). The blue curve in Figure 5 represents the rotor frequency at 50Hz and the red curve the frequency to be analyzed.

Fig. 5: Example showing the original signals isolated from the vibration signal at turbine stage 3 (see Figure 4)
To be able to correlate the vibration data and amplitudes with a certain blade, the precise location of each individual blade around the circumference must be known. This information is provided by a key phase sensor which recognizes the marked zero position on the rotor and thus records each rotation individually.

Another factor essential for precise analysis of the measured data is the axial position of the rotor and thus also of the blade. This may shift slightly during operation, causing an error that needs to be corrected. The precise axial position of the rotor relative to the casing is recorded by a second pick-up. An eddy-current sensor installed in the turbine-end bearing registers any change in the rotor position relative to the bearing housing, no matter how small.

![Image](image_url)

*Fig. 6: Turbine bearing housing: An eddy-current sensor measures the axial shift of the rotor relative to the casing*

Thanks to the key phase sensor and measurement of the axial rotor position, both the precise axial and the precise circumferential position of each individual blade at all times during the measurement were known.

**The instrumentation**

To perform the NSMS measurement described above, a way had to be found to install the NSMS probes in the machine. This first made it necessary to design a suitable holder for the probes. Of course, calculation of the optimum probe locations had to make allowance for the available space above and below the gas turbine. This space was further limited by piping and support structures outside the gas turbine. And finally, for strength reasons, not every possible probe location within the gas turbine was suitable.
Once the final probe locations had been defined, the 24 holes for the 24 NSMS probes were drilled in the machine. The holes went through the center casing and the vane carrier. As this mechanical work could not be performed on the assembled turbine, extreme precision was required to ensure the correct seating of each holder and the precise positioning of each probe relative to the tips of the rotor blades when the turbine was re-assembled.

Fig. 7: Left: A laser measuring device is used to survey the precise inside contour of the turbine vane carrier; Right: Once the precise location has been determined, a hole for the NSMS probe is drilled in the vane carrier

Holes were made by Electrical Discharge Machining (EDM) of the outer shrouds of the vanes concerned. The optical probes were able to precisely monitor the trailing edges of the rotor blade tips through these holes.

Fig. 8: Turbine vane carrier with some vanes in the stages 2, 3 and 4 after EDM
The holes were then extended outward by adapters welded to the outer casing of the turbine. The adapters served to accommodate and fix the probe holders.

**The test phases**

To avoid extended outages and to optimize the test runs performed during commercial operation, Siemens agreed with the customer to carry out the NSMS campaign in two phases. The first phase was accomplished in August 2011 in the context of re-commissioning after a scheduled major outage. The measurements performed that summer focused on identifying the natural frequencies of turbine blade vibration. To investigate the influence of blade excitation and natural frequency, the test turbine was run through a rotor speed range of +/- 5% around the nominal frequency of 50Hz. By contrast, the focus of the winter measurements in February 2012 was on identifying the widest amplitude of the vibration of the blade tips at maximum engine power output. For this purpose, three test runs were performed at a significantly higher power limit, which was only possible at low ambient temperatures.

The probes were cooled with nitrogen gas to protect the sensitive optical units. Figure 9 conveys an impression of what the turbine looked like during these measurements.

![Fig. 9: View of the test turbine; 12 of the 24 NSMS probes can be seen here; with hoses connected for nitrogen cooling.](image)
To achieve the highest possible new power limit for the SGT5-2000E fleet as a whole, the results obtained from this one turbine need to be reproducible across the entire fleet. This means making allowance for thermodynamic safety factors that can be derived from significant distinguishing features within the Siemens gas turbine fleet, such as:

- different machine configurations,
- the average ambient temperature at the specific site,
- the power output contributions of the various blading stages,
- frequency fluctuations in the grid, etc.

The test turbine had to be run at the maximum possible power output to optimize the results of this campaign despite the aforesaid deductions. The favorably cold ambient temperatures during the winter measurement campaign and the associated higher air density made it possible to achieve a significant increase in the compressor air mass flow. This in turn enabled running the gas turbine at a high electrical output with high load on the turbine blading.

Installation and removal of the instrumentation within the two phases was planned in close consultation with the customer to keep the downtimes short and outage costs low.

4 Summary

Following the successful conclusion of the two-stage measurement program, a detailed analysis and assessment of the NSMS results confirmed that SGT5-2000E gas turbines with the new Si3D blading achieve and exceed the expected power output and efficiency improvements. This enabled giving the go-ahead for a series release of the Si3D turbine upgrade.

Preparations are currently underway for releasing an increase in the power limit for all SGT5-2000E gas turbines fitted with Si3D blading in stages 1 to 4 from 173 MW to 185 MW.
5 Outlook

Now that Si3D verification and validation of the SGT5-2000E gas turbines at the higher power limit has been successfully completed, a similar measurement campaign for the 60 Hz fleet is planned for 2013.

At the same time, a measurement campaign for increasing the power limit of SGT6-2000E gas turbines is planned in the context of the first time implementation of Si3D in stages 1 to 4 of this turbine design. This will likewise center on complex NSMS monitoring of the turbine blades. However, pressure and temperature measurements will also be performed on the new 60 Hz Si3D blading.

6 Acknowledgements

We would like express our special appreciation to our Finnish customer Helsingin Energia, whose kind cooperation and professional competence made it possible for us to perform this test. We also thank our colleagues at the Test Center and Field Service in Berlin and our On-site Machining colleagues in Mülheim/Ruhr for their assistance.
## 7 Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD</td>
<td>computer-aided design</td>
</tr>
<tr>
<td>EDM</td>
<td>electrical discharge machining</td>
</tr>
<tr>
<td>EOH</td>
<td>equivalent operating hours</td>
</tr>
<tr>
<td>f, fmax</td>
<td>frequency, maximum frequency</td>
</tr>
<tr>
<td>Hz</td>
<td>frequency unit Hertz</td>
</tr>
<tr>
<td>MW</td>
<td>power unit megawatt</td>
</tr>
<tr>
<td>NSMS</td>
<td>Non-Intrusive Stress Measurement System (for non-intrusive measurement of blade vibration)</td>
</tr>
<tr>
<td>( P_{el}, P_{el,\text{max}} )</td>
<td>electrical power output, maximum electrical power output</td>
</tr>
<tr>
<td>SGTx-2000E,</td>
<td>( S = ) Siemens, GT = gas turbine, ( x = 5 ) for 50Hz and ( 6 ) for 60Hz, ( 2000 ) = rating class identifier, ( E ) = efficiency class identifier; old designation Vx4.2</td>
</tr>
<tr>
<td>Si3D</td>
<td>Siemens innovative 3D, the new Generation of turbine blades and vanes for the SGTx-2000E</td>
</tr>
<tr>
<td>3D</td>
<td>three-dimensional</td>
</tr>
</tbody>
</table>
8 Disclaimer

These documents contain forward-looking statements and information – that is, statements related to future, not past, events. These statements may be identified either orally or in writing by words as “expects”, “anticipates”, “intends”, “plans”, “believes”, “seeks”, “estimates”, “will” or words of similar meaning. Such statements are based on our current expectations and certain assumptions, and are, therefore, subject to certain risks and uncertainties. A variety of factors, many of which are beyond Siemens’ control, affect its operations, performance, business strategy and results and could cause the actual results, performance or achievements of Siemens worldwide to be materially different from any future results, performance or achievements that may be expressed or implied by such forward-looking statements. For us, particular uncertainties arise, among others, from changes in general economic and business conditions, changes in currency exchange rates and interest rates, introduction of competing products or technologies by other companies, lack of acceptance of new products or services by customers targeted by Siemens worldwide, changes in business strategy and various other factors. More detailed information about certain of these factors is contained in Siemens’ filings with the SEC, which are available on the Siemens website, www.siemens.com and on the SEC’s website, www.sec.gov. Should one or more of these risks or uncertainties materialize, or should underlying assumptions prove incorrect, actual results may vary materially from those described in the relevant forward-looking statement as anticipated, believed, estimated, expected, intended, planned or projected. Siemens does not intend or assume any obligation to update or revise these forward-looking statements in light of developments which differ from those anticipated. Trademarks mentioned in these documents are the property of Siemens AG, its affiliates or their respective owners.