DEVELOPMENT OF MEDIUM-SIZED GAS TURBINES FOR LNG APPLICATIONS

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ABSTRACT

Plant profitability, fuel flexibility and low environmental impact are of key importance for LNG plant operators. This paper describes recent developments of Siemens stationary gas turbines to meet these criteria. Key contributors to plant profitability are gas turbine reliability and availability. Current Reliability Factors for Siemens medium-sized gas turbines are above 99%. Optimized reliability is achieved by a systematic approach during product development and product improvements through systematic feedback of fleet experience. Optimized availability is achieved through an efficient service organization in combination with fast core-engine exchange. Furthermore, the availability is improved by an extended time between overhauls. A simple, robust and fuel-flexible dry low emission (DLE) system is the key to both profitability and a low environmental impact. In the case of the LNG process maximum profitability is achieved if the gas turbine can operate directly on the end flash gas without using expensive and complex N2 removal or fuel-treatment systems. It is commonly believed that DLE combustion systems require fuel treatment to avoid combustion instability. Siemens DLE systems have recently proven in full-scale engine tests their capability to burn fuel gas with up to 50 Vol% of nitrogen without affecting the combustion stability. In the tests rapid change from nitrogen-rich fuel to standard natural gas was also demonstrated at full load. Furthermore, the DLE systems can handle fuel gas with high content of heavy hydrocarbons.
NOMENCLATURE

AF  Availability Factor
DLE Dry Low Emissions
FOH Forced Outage Hours, the time the equipment is out of operation including service activities during a forced outage.
KPI Key Performance Indicator
LFP Low Frequency Pulsation
MTPA Million Tons Per Annum
NRU Nitrogen Rejection Unit
PH Period Hours, hours in the period under consideration, e.g. one year 8760 hours
POH\text{rev} Planned Outage Hours for revision according to maintenance plan
POH\text{maintenance} Planned Outage Hours due to maintenance such as filter exchange, compressor wash
POH\text{other} Planned Outage Hours due to implementation of modification & uprates etc
RF Reliability Factor in %
Vol\% Volume %

INTRODUCTION

The requirements on gas turbines for LNG applications are becoming more demanding as the requirement for profitability and low environmental impact increases. The basic requirement for plant profitability is high reliability and availability since every hour the gas turbine is out of operation results in loss of production for the plant owner. Furthermore, a reliable power source for either compression or power generation gives the operator more time to focus on optimization of the plant production rate instead of working with fault resolution and repair of gas turbines.

Fuel-flexible gas turbines can also improve plant profitability. A fuel-flexible gas turbine operating on flare gas can increase plant profitability and lower environmental impact. One example is if flaring can be avoided by operating the gas turbine on the end flash gas. There are two major cases to consider operating a gas turbine on the end flash gas, either to operate directly on the end flash gas or to use fuel treatment. Using untreated fuel is of course the preferable option as fuel-treatment systems can be complex and expensive both to purchase and to operate. A complex fuel-treatment system will definitely have a negative impact on the plant reliability.

Low environmental impact is achieved by designing high efficiency plants to minimize CO$_2$ in combination with low-NO$_x$ emission combustion systems. One market perception is that DLE combustion systems are less reliable than conventional combustion systems. Furthermore, the DLE combustion systems are also considered to be less fuel flexible. Siemens DLE system has proven over 6 million operating hours to have the same reliability as conventional combustion systems. The Siemens DLE system has also recently proved in full-scale engine tests the capability to burn fuel gas with up to 50 Vol\% of nitrogen without affecting the combustion stability.

The complete Siemens gas turbine program ranges from 5 MW to 375 MW in size and can be
used both in mechanical drive and power generation applications (Figure 1). The equipment is supplied to a variety of solutions such as pipelines, LNG power generation or mechanical drive, combined heat and power, combined cycle power plants or marine propulsion in onshore and offshore applications.

![Output in MW @ ISO conditions](image)

**Figure 1. Siemens complete gas turbine range from 5 to 375 MW**

This paper focuses on the medium-sized gas turbines SGT-600 [1], SGT-700 [2] and SGT-800 [3], their reliability, availability and DLE performance, including operational stability and fuel flexibility.

**OPTIMIZED RELIABILITY**

Optimized gas turbine reliability is the key to profitability for both customer and supplier but it requires structured approach from both parties to get there. The optimization of reliability is an excellent example of a win–win relationship between customer and supplier. From a customer perspective reliability means a predictable profit due to a minimum amount of unplanned disturbance in the production. Furthermore, the focus can be on optimization of the production process rather than fault-resolution of equipment in the plant. From a supplier point of view an optimized reliability means a satisfied customer and a good reputation on the market. Furthermore, the effort for fault and guarantee handling decreases and more time can be spent on product optimization and development instead of unplanned service activities and fault resolution.

Optimization of reliability requires a systematic approach and this chapter gives an overview of the main processes and measures used at Siemens. The definition of reliability factor is, according to ISO 3977-9, the probability that the equipment will not be in a forced outage condition.

\[
RF = \left(1 - \frac{FOH}{PH}\right) \times 100
\]

The main measures used to improve reliability at Siemens are:

- Design for reliability during product development
• Product improvements by systematic feedback of fleet experience and fault resolution
• Continuous development of maintenance concepts through systematic feedback of fleet experience
• Continuous dialog with the customer and informing about daily and long-term measures for an optimized reliability by issuing Product Improvement Bulletins.
• Elimination of unnecessary trip signals
• Implementation of auxiliary-system redundancy
• Use of 2 out of 3 voting for instrumentation to avoid instrument-related trips

Some aspects of reliability improvements are discussed in the following text and finally the result of product management at Siemens is described.

**Design for reliability**

The first step towards a reliable product is made during the product development. Siemens has therefore together with a controlled Product Development Process introduced a methodology to consider reliability also in the development phase [4]. By using this reliability methodology the critical systems affecting the gas turbine reliability are identified as early as the development phase and special attention can be devoted to these systems to design them so as to optimize the reliability. So reliability and availability are treated in the same way as other Key Performance Indicators (KPI) such as power, efficiency and emissions already during the product development phase.

The reliability model uses mainly the concept of fault-tree analysis and takes the analysis one step further than classical Failure Mode and Effect Analysis (FMEA) (Figure 2). An FMEA will identify potential risks, their probability and effects but does not quantify the potential statistical unreliability. Fault trees can be used to model independent failures and repairs of components. If other circumstances are valid other statistical tools are used to model the reliability of the systems. Input data for standard components like transmitters, pumps etc are gathered from existing reliability databases like OREDA [5], Eireda [6] and Siemens Norm SN 29500 [7]. Other important data sources are internal Siemens databases containing reliability information from the gas turbine fleet.

![Figure 2. Top level reliability model for a gas turbine with package expressed in a fault tree](image)


Fault correction process

The fault correction process used at Siemens consists of three major processes namely description, classification and resolution of the faults. All processes are critical for improved reliability and they need careful process management.

The collection and description of faults are done both by the supply organization during manufacturing and commissioning as well as the maintenance organization during maintenance and repair. The description of the fault is entered into a central fault-report system.

Once the fault has been described it has to be classified. The classification of the fault is made with the aim to decide on the severity of the fault as well as identifying who is responsible for the fault resolution. The faults are prioritized and the highest priority is given to those with a major impact on safety, i.e. if there is an actual or potential risk of personnel injury due to the fault. The highest priority faults are dealt with immediately and resources are allocated to solve the problem. Lower priority faults are dealt with during monthly product-support team-meetings where resources are allocated.

After prioritization and resource allocation the fault resolution process is started. The process contains eight major steps and four management approval gates as shown in Figure 3. The management approval gates are:

1) Issue approval gate where scope, project manager, resources and financing are defined
2) Root-cause approval gate where the root cause analysis is approved
3) Solution and implementation gate where the proposed solution is approved for implementation and finally
4) Problem-closure gate where the solution to the fault is approved as a standard solution for the whole fleet.

![Figure 3. Siemens’ eight-step Product Integrity Process is used for fault resolution](image)

Result of product management

In 2003 a systematic approach was introduced for product management at Siemens. The fault report systems and fleet feedback processes were already in place. The new dimension was the formation of dedicated product-support teams for each product with a clear responsibility for fault resolution and product Key Performance Indicators such as Availability Factor and Reliability Factor. The product-support teams with representatives from research and development, operations and maintenance departments have regular meetings on a monthly basis. The
product-support team communicates the product reliability status with metrics to key functions in the organization. Improvement areas are identified and prioritized and then the product-support team uses the processes described above for fault resolution to implement improvements. The result is a focus from the whole organization on resolution of the most important product-improvement areas. Finally, the improvements are implemented as a new standard for production and offered to existing customers in Product Improvements Bulletins.

The result of the systematic approach to product-fault resolution was substantial. During the period January 2003 to December 2007 the Reliability Factor for SGT-600 increased from 95.4% to 99.1%, a best-in-class number. At the same time the focus of both the research and development and the maintenance department was moved from short-term troubleshooting and fire-fighting towards long-term development and product optimization. Current Reliability Factors for SGT-600, SGT-700 and SGT-800 are above 99% for the complete package, i.e. auxiliaries and gas turbine. Siemens is making continuous efforts both in product development and product management to keep the reliability at this high level or even improve the numbers.

OPTIMIZED AVAILABILITY

High availability of the installed machinery is one key to continuous production and maximized plant output. In this section successive developments for increased availability of the SGT-600, SGT-700 and SGT-800 are described.

The Availability Factor is defined according to ISO 3977-9 as the probability that the equipment will be available for the customer to operate during a certain period of time.

\[
AF = \left(1 - \frac{FOH + POH}{PH}\right) \times 100
\]

The planned outage hours can be defined as

\[POH = POH_{rev} + POH_{maintenance} + POH_{other}\]

Further on, focus is on the planned outage due to revisions as this is the major part of the total planned outage.

Maintenance Plan Interval Extensions

A maintenance plan is a recommendation for the preventive maintenance schedule during the gas turbines life-cycle which includes parts replacement schemes and activities at different levels. It is designed to optimize cost and availability during the lifetime of the gas turbine. Inspection intervals are based on EOH (Equivalent Operating Hours) which are dependant on component lifetimes and the operating profile.

The basic maintenance plan for the SGT-600/700 with corresponding inspections for the gas generator is shown in Figure 4. The program contains 6 Level A (borescope), 3 Level B (hot section) and 2 Level C (overhaul). Various other activities such as power turbine maintenance, generator or compressor maintenance are included in the different levels. A full maintenance period is reached after 120 000 EOH, i.e. approximately 15 years of continuous operation.
Analysis of extensive field feedback data, material tests and advanced calculations have formed the basis for the extended intervals maintenance plan shown in Figure 5. The intervals between hot-section inspections are extended to 30 000 EOH and the number and levels of inspections for the gas generator are: 8 Level A, 2 Level B, 1 Level C. With the extended intervals maintenance plan, the number of B- and C-inspections are reduced from 5 to 3. This development was performed for the SGT-600/SGT-700 as well as for the SGT-800 [8]. This results in an improvement of AF by 0.7% over a maintenance period of 120 000 EOH of operation or approximately 35 days of additional production.

Further development has been carried out in order to fulfill the O&G industry requirements. The package of the SGT-600/700 is improved and made available for both onshore and offshore installation, the latter is especially suited for floating LNG applications. With 2 x 12 hour working shifts per day, 6 days a week the availability of the gas generator is further increased by around 0.6 %, or approximately 30 days of additional production.

An option in the O&G maintenance plan to further reduce downtime is the gas-generator (GG) exchange with accompanying workshop maintenance as illustrated in Figure 6. The exchange gas generators are either owned by the customer or leased from Siemens for the time of the workshop maintenance or purchased from Siemens on return of the customer’s own gas generator. Including the GG exchange option into the O&G maintenance plan increases the availability by around 0.6% or approximately 30 days’ additional production.
Figure 6. SGT-600 gas generator exchange

The individual contributions for the availability improvement related to the planned outage hours for revisions are summarized in Table 1. Calculating overall availability for the case with gas-generator exchange with actual field-feedback data for reliability and including planned outages other than for revisions results in a value above 98%.

### Table 1. Summary of availability improvements

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Availability increase (%)</th>
<th>Production increase (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended intervals</td>
<td>~0.7</td>
<td>~35</td>
</tr>
<tr>
<td>O&amp;G maintenance plan</td>
<td>~0.6</td>
<td>~30</td>
</tr>
<tr>
<td>O&amp;G maintenance plan with GG exchange</td>
<td>~0.6</td>
<td>~30</td>
</tr>
<tr>
<td><strong>Sum of all improvements</strong></td>
<td>~1.9</td>
<td>~95</td>
</tr>
</tbody>
</table>

**Part-load operation increases time between overhauls**

Certain applications designed for redundancy and thus running at part load for most of the time benefit in terms of availability by increased maintenance intervals. This is due to the fact that the SGT-600/700 are two-shaft engines, where the load is controlled by firing temperature. Decreasing firing temperature in part load results in increased lifetime of hot components. This fact is reflected by the load factor included in the calculation of Equivalent Operating Hours (EOH). The load factor is 1 at base load, i.e. 1 operating hour (OH) equals to 1 EOH. For loads above base load the load factor is larger than 1 and for loads below base load the load factor is smaller than 1. In the latter case 1 OH generates only a fraction of one EOH. The EOH’s are accumulated at a rate lower than OH and thus inspection intervals are stretched out in time.

Figure 7 shows lines of EOH above calendar time together with inspection occasions for a base-load case and 80% part load. As can be seen for a given year fewer inspections are performed for the case with part-load operation. In this example the gain in availability for a maintenance cycle would be 0.4% or approximately 20 days of additional production.
With the latest maintenance plan developments the SGT-600/700 are best-in-class in terms of overall availability for O&G applications. Similar development has already been performed for the SGT-100 through SGT-400 and is under way for the SGT-800 [9]. The increased availability will be translated into economic benefit in the chapter about plant profitability.

FUEL FLEXIBILITY AND OPERATION STABILITY

Siemens industrial gas turbines with DLE combustion systems can be operated on process gases available in a LNG process over a wide load range. Typically such process gas, depending on their origin in the LNG process, can have a high content of nitrogen and possibly also a high content of heavy hydrocarbons. A key gaseous-fuel parameter from the gas turbine perspective is the Wobbe Index (WI) which includes the heating value and the density of the fuel. More precisely, the heating value is divided by a relative density being the fuel density divided by the density of air:

$$WI = \frac{LHV}{\rho_{\text{gas}}^n / \rho_{\text{air}}^n}$$

There is a strong decrease in WI as the nitrogen content in the fuel increases and at about 40 Vol% nitrogen, the WI is halved. The fuel flow to the gas turbine increase accordingly and for a standard engine this is handled by increased pressure in the fuel-feeding system. Increasing the heavy hydrocarbon content in the fuel leads to an increasing WI since heavy hydrocarbons are very energetic.

Typically for DLE combustion, fuel is burnt with the double amount of air than what is needed
for stoichiometric combustion. The low flame temperature reduces emissions of nitrous oxides but on the other hand increases the risk of incomplete combustion. This results in higher contents of for instance CO as illustrated in Figure 8.

![Figure 8. Typical behavior of NOx and CO versus flame temperature.](image)

In the Siemens 3rd generation DLE burner robust operation is secured by the pilot flames during for instance, changes in fuel composition as well as during transients in engine operation such as rapid load changes. Several pilot flames on the tip of the burner support the main flame at the burner outlet, as shown in Figure 9. The penalty for this stability is a slight increase in NOx emissions.

The SGT-700 operation on natural gas with increasing nitrogen content was tested in August 2008. An “artificial” LNG process gas was simulated by feeding nitrogen from a separate tank into the natural gas. During the test the engine was operated on stable load as nitrogen content was increased. The blue line in Figure 10 shows the volume percentages of nitrogen during a test at 20 MW load. The nitrogen is increased in steps every five minutes, reaching 40 % after about 35 minutes. After the test it was concluded that even higher nitrogen contents can be allowed with maintained combustion stability.

The Low Frequency Pulsations (LFP), indicating combustion stability as well as NOx emissions, are shown in Figure 10. During the test the pilot-to-fuel ratio was kept at a high level as a precaution and thus the NOx emissions start at about 35 ppm. It should be noted that efforts to minimize the NOx emissions were not the focus of the test. When the nitrogen content in the gas is increased the NOx emissions are reduced to about 20 ppm. The nitrogen feed to the fuel was stopped after about 43 minutes, leading to an increase in WI from 24 MJ/nm3 to the double in about two minutes. The change in gas composition is handled by the pilots resulting in temporarily increased NOx emissions. No combustion dynamics are induced during this transient, as can be seen from the LFP. When the gas composition stabilizes, the pilot is reduced and the NOx emissions lower towards the expected 15 ppm at 15% O2.

![Figure 9. The 3rd generation burner used in the annular combustors of SGT-700 and SGT-800.](image)
Figure 10. Nitrogen content in the natural gas Vol-% and NOx emissions in ppm (left axis) and load and LFP (right axis) versus time during SGT-700 engine test at 20 MW.

A similar full-scale engine test was performed during summer 2009 on the SGT-800 where it was demonstrated that up to 50 Vol-% N2 can be handled with a standard fuel system. The SGT-700 [2] and the SGT-800 [8] DLE gas turbines have 15 ppm NOx emissions at 15% O2 over a wide operating range.

PLANT PROFITABILITY

The key to LNG plant profitability, once commissioning is complete, is to keep the plant running. High plant availability equates to high levels of LNG production, which equates to a high revenue stream. The gas turbines on an LNG plant are recognized as one of the major sources of unavailability, either planned or unplanned, and the measures outlined above all contribute to improving their availability. Thus the reduced time spent maintaining the gas turbine can be converted into extra operation and hence revenue.

An improvement of the availability factor by 1% is equivalent to an increase of 50 days of operation for a 120 000 EOH maintenance cycle. These extra days can be equated to LNG production and hence increased revenue by assuming typical industry factors as follows:

- Process availability without GT influence is 355 days (8 500 hours) running per year, thus an improvement in availability of 1% results in 3,55 days of additional operation per year
- Each MTPA LNG requires 37.5 MW of refrigeration compressor power,
- LNG is valued at a modest 250 USD per ton
- The average ambient temperature is 30°C
The benefits due to optimized availability for the SGT-700 new maintenance plan developments compared to the previous standard maintenance plan are shown in Table 2. The sum of the maintenance plan improvements results in a 1.9% increase of the availability relative to the previous standard. The additional revenue of 3.5 MUSD per year is calculated using the typical industry factors as given above.

Table 2. Benefits due to SGT-700 optimized availability

<table>
<thead>
<tr>
<th>Power @ 30°C (MW)</th>
<th>Equivalent LNG (MTPA)</th>
<th>Extra running (Days)</th>
<th>Extra Production (Tons/year)</th>
<th>Additional revenue @ 250 USD/ton LNG (MUSD/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.7</td>
<td>0.74</td>
<td>6.7</td>
<td>14000</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The benefits due to higher availability of the SGT-700 compared to the industry standard are shown in Table 3. The average availability factor for gas turbines between 20-49 MW for the period 2004-2008 is 92.63 % [10]. The expected availability of > 98 % for the SGT-700 is thus an improvement of at least 5 % over the industry standard. The additional revenue of 9.25 MUSD per year is calculated using the typical industry factors as given above.

Table 3. Benefits of SGT-700 optimized availability compared to industry standard availability

<table>
<thead>
<tr>
<th>Power @ 30°C (MW)</th>
<th>Equivalent LNG (MTPA)</th>
<th>Extra running (Days)</th>
<th>Extra Production (Tons/year)</th>
<th>Additional revenue @ 250 USD/ton LNG (MUSD/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.7</td>
<td>0.74</td>
<td>17.75</td>
<td>37000</td>
<td>9.25</td>
</tr>
</tbody>
</table>

In addition there can be further improvements of the availability at part load operation since EOH’s determine the time between overhauls. This is less easy to present in a general way as the result will be site specific and will differ between mechanical drive and power generation.

When we consider the light industrial gas turbines, like Siemens SGT-600, 700 and 800 ability to run on high N2 content fuels this benefits plant profitability by reducing CAPEX and OPEX when compared to gas turbines that cannot run with such high levels of N2 in the fuel. This is again going to be site-specific and will be a function of the N2 in the feed gas. Without the ability to run on high N2 fuel for fields with more than 1-2% N2 in the feed gas, additional fuel processing is required typically in a nitrogen-rejection unit. The CAPEX for an NRU is going to be dependant on the feed gas composition and the individual gas turbine capabilities but when required is typically in the range of 10-50 MUSD. Additionally this extra process needs maintenance and will contribute to either the overall unavailability, if an alternative source of fuel is not available, or to a higher environmental impact due to increased CO2 emissions. For cases where the fuel gas is high in N2 content, the ability to burn the fuel directly will have a very positive impact on the overall plant profitability.

CONCLUSIONS

Siemens is continuously working to improve our products to maximize the customer’s profitability. The main focus is to improve reliability and availability and decrease the environmental impact through development of new products as well as improving the existing
The reliability of Siemens SGT-600, SGT-700 and SGT-800 gas turbines is well above 99%. The improvement in reliability is made through a systematic approach both during product development and fleet management. During product development the reliability is given the same focus as any other KPI. The product reliability numbers are predicted using a reliability model that utilizes data from public databases as well as in-house statistics gathered from fleet experience. In fleet management the product support teams are monitoring the product KPI’s and correct upcoming problems with the eight-step Siemens Product Integrity Process. Major improvements have been made in product reliability since this process and methodology of working was introduced.

Siemens gas turbines have an availability factor above 98%. The product availability is determined by the reliability and the downtime during planned maintenance. During recent years, Siemens has focused on two initiatives to increase availability. One initiative is to extend the interval between and decrease the number of maintenance events during the product life time. This leads to decreased time for maintenance and increased availability. The second initiative is to decrease the time for the maintenance events. The most recent development is the 24h gas generator exchange that will limit the downtime at each maintenance event to 24 hours. The availability with this concept is expected to be above 98%.

For end flash gas applications the DLE system can handle at least up to 50 Vol% nitrogen in the fuel gas. Siemens is striving to decrease emissions through development of products and solutions with high efficiency for a low carbon-dioxide footprint. Furthermore, DLE combustion systems are developed for low emissions of NOx. The Siemens DLE system has proven, during its evolution of 6 million operating hours, to have the same reliability as conventional combustion systems. Furthermore the operational stability over the whole operating range and fuel flexibility of the DLE system is excellent.

It has also been shown that all these improvements implemented in the Siemens product range will significantly enhance plant profitability beyond current industry standards.

REFERENCES

1. Detailed Hot Section Mapping of Siemens SGT-600, Sundberg J. and Blomstedt M., PowerGen Asia, October 21-23, Kuala Lumpur, Malaysia.


7. SN 29500, Siemens Norm, Siemens AG, Munich (2008).


10. Emissions reduction and cooling improvements due to the introduction of passive acoustic damping in an existing SGT-800 combustor, D. Lörstad, J. Pettersson and A. Lindholm, ASME Turbo Expo 2009, June 8-12, Orlando, FL, USA.