CONTINUED ENHANCEMENT OF SGT-600 GAS TURBINE DESIGN AND MAINTENANCE

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ABSTRACT

Current Power Generation and Oil & Gas markets are dynamic with continuously growing requirement to gas turbines toward high reliability and availability and low emissions and life cycle cost. In order to meet these growing requirements to the gas turbines, the OEM should sustain continued product improvement and employment of innovative solutions and technologies in the area of design, operation and maintenance. This paper describes the successful development and operation experiences of Siemens’ medium size 25 MW gas turbine SGT-600.

The SGT-600 entered the market in 1986 as a 22 MW gas turbine (originally known as GT10A). In 1991 the SGT-600 was up-rated to 24.8 MW@34.2 % electrical efficiency (originally known as GT10B). A unique Dry Low Emission (DLE) combustion system was introduced at that time as well.

Since then (up to 2007) more then 230 units have been sold. The current fleet has demonstrated a high reliability and availability. Total accumulated operating experience (up to 2007) is about 5 million Equivalent Operating Hours (EOH), and the fleet leader has more than 130 000 EOH.

High reliability and availability of the SGT-600 gas turbine were provided by further improvements and modifications of the gas turbine components design.

All these modifications have made it possible for Siemens to increase the Life Cycle of the engine beyond 120 000 EOH and to extend the maintenance intervals from 20 000 EOH to 30 000 EOH.

The Life Cycle and the maintenance intervals extension in combination with extended scope of components reconditioning and repair mean additional opportunity for users and Siemens to substantially reduce the SGT-600 Life Cycle Cost.

DEVELOPMENT HISTORY

The development of this engine originally started in 1977 by the Swiss company Sulzer Escher Wyss. In 1986 the test engine was started and the first commercial unit was in operation in 1988. The rating at that time was 22MW and was considered as an introductory rating.

In 1990 a transfer of this engine from Sulzer Escher Wyss to the Swedish company ABB Stal (now Siemens Industrial Turbomachinery AB) took place and the first modification to be introduced was the DLE burner (25 ppm NOx dry @15% O2 on gas). This DLE-burner is the standard equipment today (where conventional equipment can be delivered on request).

In 1992 a new (mature) rating was launched. The turbine inlet temperature was increased by 50°C (TIT= 1115 °C) and by that the rating was increased to 24.5 MW. Coating of the compressor turbines blades and vanes was introduced at that time as well.

The rating has almost been the same since then: a minor increase of output (0.5MW) was introduced later (in 1997) by a minor optimization (increase) of air flow through the engine.
Three major steps have been taken regarding the package and the auxiliary equipment. The first rearranged equipment was installed in 1994. This was performed in order to better suit the market requirements:

- shorter inlet,
- new lube oil system arrangement and some other features.

The second rearrangement has been in operation since 1998. The main purpose with this installation was to better suit the Mechanical Drive (MD) market and this is the standard installation today:

- more narrow package (4 meters width),
- single lift (with the lube oil tank integrated in the skid),
- workshop pre-tested of the core engine and auxiliary equipment for short installation time on site.

The third arrangement is an option for a floating installation with rolls and pitch requirements (Floating Production Storage and Offloading (FPSO) vessels application), which has been available to the market since 2006.

**SGT-600 LATEST DESIGN FEATURES**

The SGT-600 is a twin shaft engine with free standing Power turbine and is identical in Mechanical Drive (MD) and Power Generation (PG) installations (see Figure 1).

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**Compressor design features**

- welded compressor rotor,
- 10 stages axial compressor (pressure ratio 14),
- two bleeds after stage 2 and 5,
- two variable guide vanes,
- all blades and vanes (exclude titanium blade1) have corrosion resistant coating,
- stator rings above the blades are made from material with low heat expansion coefficient and are coated with abradable coating to provide smooth rubbing and minimum radial clearance.

Reconditioning and repair processes are developed for the following compressor components:

- blades and vanes - recoating,
- stator rings above blades – recoating with abradable coating to restore the compressor performance,
- repair of the rotor seals,
- repair of the compressor rotors, including exchange of the compressor discs.

Compressor components repair is done based on components conditions.

**Combustor design features**

The simple and robust SGT-600 DLE combustor is based on the aero-derivative film-cooled concept. The combustor is coated with a normal aero-combustor Thermal Barrier Coating (TBC).

The 18 burners are welded on to the combustor back wall and 18 fuel rods are mounted to the burners from the outside (see Figure 2).

Pilot gas and main gas are supplied through these fuel rods. For dual fuel engines, oil is also supplied through the fuel rods. Water can be added to the oil in the fuel rods as an emulsion.

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**Figure 1: SGT-600 Gas Turbine Cross-section**

**Figure 2: SGT-600 DLE combustor system**

The technology used is lean, pre-mixed fuel in a two-slotted cone/burner (see Figure 3). The pilot gas (stage 1) enters in the tip of the burner and creates a stabilizing flame at part loads. The main gas (stage 2) enters the burner slots and mixes well with the high amount of burner air before combustion, thus creating low flame temperature and low NOx. The liquid fuel enters in the burner tip and burns in a similar way to the pilot gas flame.
The technology of the combustor is simple, as it has no moving parts and just two control valves for pilot gas and main gas. No staging is used for the combustion. No mapping is required over time since there are no parameters in the control that are drifting over time[1].

To achieve lower CO emissions at part load, a combustor bypass system is available as an option. The bypass system is integrated into the turbine casing (see Figure 4). The system consists of 6 valves controlled by one actuator. Opening of the bypass valves means that the airflow to the burners decreases, the flame temperature increases and the CO emissions decrease. The bypass system keeps the flame temperature and the emission levels constant at 70 to 100% load.

The combustion stability and emissions are kept at low levels over the load range by only two parameters, namely Pilot Fuel Ratio (PFR) and bypass opening (see Figure 5).

Reconditioning and repair processes for the Combustion chamber are developed and are included in to standard maintenance program. The following repair capabilities of combustion chamber are available:
- local weld repair,
- exchange of outer and inner liners,
- weld repairs of the burners,
- recoating of the combustor with TBC.

Compressor Turbine design features:
The SGT-600 compressor turbine has two stages (see Figure 6). All blades and vanes are cooled and are coated with oxidation resistant coating. Blades on the first and second stages have aerodynamic shrouds to provide high efficiency. Blades/disc attachments on first and second stages have the same design and geometry (assembly and cost reduction reasons). To minimize the leakages on the first row vanes are combined into segments, each segment consists of two vanes.

Reconditioning and repair processes for the Compressor Turbine components have been developed and are included in to standard maintenance program. The following repair capabilities of the gas turbine components are available:
- weld repair of blade 1,
- recoating of blade 1,
- weld repair of vane 1 & 2,
- recoating of vane 1 & 2,
- repairs of Heat shields above blade 1 & 2 – brazing of new honeycomb.

Power Turbine design features
The SGT-600 power turbine is a free standing, two stages turbine (see Figure 7). Blades on the first and second stages are shrouded to provide high efficiency and reliability. Originally blades were not shrouded and were equipped with lasing-wire. Blades/disc attachments on first and second stages have the same design and geometry (assembly and cost reduction reasons).

Guide vanes in the first stage have variable capability to provide power turbine matching to hot ambient conditions.
Vaness in the second stages have a segmented design – 4 vanes are combined into one segment. Blades and vanes are not coated. Power turbine rotor has welded design.

**Figure 7: SGT-600 Compressor Turbine**

**OPERATING EXPERIENCE AND STATISTIC**

The operating statistics shows good and mature records: the average Reliability Factor is 99.2%, Availability Factor is 97.0%. Mean Time Between Failures (MTBF) is more then 1700 hours defined in accordance with ISO 3977-9.

**LATEST ENGINE EXTENDED TEST VALIDATION**

In order to validated the latest design of SGT-600 hot gas path components the engine mapping, including measurements and thermal and lifing analyses were initiated in December 2004. The aim of the work was to confirm long-term reliability and to enhance our knowledge in the area of components loading and lifing.

The results of this extended R&D program and testing was and is the basis for:

- calibration of hot gas path components models,
- further improvement of SGT-600 life counter (in terms of Equivalent Operating Hours and Equivalent Operating Cycles),
- enhancement of the prognostic models and algorithms for Condition Based Maintenance,
- gas turbine operation and performance optimization,
- further increase of components robustness and reliability,
- possibility to extend the time between overhauls,
- extension of Life Cycle beyond 120 000 EOH.

**Scope of components lifing analysis**

All tests and investigations have been done for standard SGT-600 with DLE combustor running on gas fuel. The analyses have been concentrated on the most critical hot gas path components:
- Combustor,
- Compressor Turbine blade and vanes,
- Power Turbine blades and vanes.

The following issues and damage mechanisms have been investigated and utilized during the lifing modelling and analysis:

- computational lifing and damage modelling:
  - Thermo Mechanical Fatigue, TMF (>500°C),
  - Low Cycle Fatigue, LCF
  - creep
  - oxidation
- state of the art instrumentation & measurements technologies to calibrate the models,
- component’s operational experience.

The TMF lifing analysis is the most delicate and novel one of the tasks above. In order to perform TMF lifing analyses it is crucial to catch, both, accurate temperature gradients and transients in the components. The temperature gradients are captured mainly within the steady state test, described below, and the temperature transients are given by the transient test, also described below.

In addition, there are other important factors and issues that have a significant influence on lifetime consumption and modelling:

- load cases (start-full load-normal stop cycle, start-full load-trip cycle, start-part loads-normal stop cycles),
- ambient temperature,
- Power Turbine matching,
- stochastic variation of Material properties (like creep strain at rupture, creep rate, plastic yield level, aging)
- variation of engine parameters (temperature, pressure, gas mass flow, cooling air mass flow).

In order to take into account stochastic variation of variable analysis parameters a probabilistic approach was used for lifing modeling (see Figure 8).

Methodologically the lifing modeling process included the following steps and State of the art features (see Figure 9):

- Thermo-Crystal technique for full load steady state temperature measurements,
- transient hot gas and metal temperature measurements,
- Finite Element sub-modelling technique,
- Thermo Mechanical Fatigue related lifing analyses,
- probability based assessment of lifing.
Figure 8: Probability based assessment of lifing

Figure 9: Lifing prediction process

Steady state full load test

The test has aimed at mapping the steady state full load temperature gradients in the turbine blades and vanes and hot gas path temperature field. Thermo-crystal technique has been used. The turbine blades and vanes of the test engine (see Figure 10) have been instrumented with:

- 295 crystals for gas path temperature measurements and
- 1446 crystals for turbine blades and vanes metal temperature measurements.

The following loading profile has been used for this test:

- normal start-up sequence followed by
- about 15 minutes on full load, during which the instrumentation, i.e. the actual thermo crystals are exposed to the present temperature level, finishing with a
- normal stop sequence.

During the test complementary instrumentation like thermal paint, thermo couples and pressure probes have been used, in order to be able to correlate this test with the transient test, described below.

Transient test

The transient test has covered the hot gas, cooling air and material temperature transients in the areas of the combustion chamber, the compressor turbine discs, turbine blades and vanes and gas path. Several transient load cases have been run:

- start-full load-normal stop,
- start-part load-normal stop,
- start-full load-trip,
- start-part load-trip.

Pioneering work regarding measurements of the exhaust temperature variations has also been performed during the transient test. The objective of this part of the measurements has been to check the normal state of circumferential irregularity of the hot gas distribution, together with simulating the effect of uneven burners by reducing the fuel flow of one burner.

To follow up transient response of the hot gas path components the test engine has been instrumented with:

- 96 measurement points on rotating parts like compressor turbine blade #1 and #2 and compressor turbine discs,
- 687 measurement points on static parts, comprising both thermo couples and pressure gauges.

Figure 10: Instrumentation with Thermo-crystal

Figure 11: Instrumentation with thermo couples
SGT-600 LIFE CYCLE AND MAINTENANCE IMPROVEMENTS

As shown in the previous chapters continuous improvement of SGT-600 performance and reliability has been provided by significant R&D investments. During the last two years the SGT-600 R&D portfolio has been extended by additional few projects dedicated to maintainability improvement, down time reduction and Life Cycle extension.

In addition to achieved high reliability and availability the latest design modifications enabled Siemens to extend the Life Cycle of the engine beyond 120 000 EOH and to extend the maintenance intervals from 20 000 EOH to 30 000 EOH.

The Life Cycle and the maintenance intervals extension in combination with extended scope of components reconditioning and repair mean additional opportunity for users and Siemens to substantially reduce the SGT-600 Life Cycle cost.

The extension of the SGT-600 Life Cycle beyond 120 000 EOH has been driven by market demands and aging fleet. Significant amount of the engines in the fleet are approaching their design life time of 120 000 EOH. The accumulated positive operating experience of the whole SGT-600 fleet in combination with further components improvements enables Siemens to consider further extension of the life cycle. In the Summer 2007 the Life Cycle of one of the SGT-600 installations has been extended from 120 000 EOH to 160 000 EOH. The unit is now in continuous commercial operation.

Life Cycle extension

Life Cycle extension is not a simple and highly standardized solution that could be applied in the same manner for all SGT-600 installations at 120 000 EOH. The scope of the life extension is strongly dependent of the unit and their components condition at 120 000 EOH. The unit and their components’ condition are determined by the unit operation profile, operation history and performed maintenance. In order to keep the Life Cycle extension product predictable, planned, controlled and profitable it is necessary to know the unit’s history and its components’ condition before the 120 000 EOH, especially for the components that have long lead time.

Therefore, Siemens recommends two major activities within the Life Cycle extension process:

- major inspection, that determines the general state of the engine - Life Time Assessment (LTA) and
- actual Life Time Extension (LTE) event.

These two events should be carried out separately in time. In order to minimize the unit’s down time the LTA should be combined with one of the standard inspections. The most suitable standard inspection for the SGT-600 is the C-level inspection at 80 000 EOH.

The LTA will enable Siemens to identify the replacement needs for components especially those with long lead time and could be considered as the qualification for another 40 000 EOH.

The targets for Life Cycle extension of SGT-600 have been:

- Life Cycle extension for the whole installation,
- Life Cycle cost reduction,
- utilization of the SGT-600 standard Maintenance Plan (MP) with some extension:
  - Life Time Assessment of the gas turbine components,
  - Life Time Extension of the whole installation by means of extension of the life time of the Rotors and Casings,
- replacement package, tailored for customer based upon results from LTA.

The standard SGT-600 Maintenance Schedule with added LTA and LTE milestones is presented in the Figure 12.

The outcome of the LTA is a tailored scope of reconditioning/replacement during the LTE.

The scope of inspections and activities at the LTA are as follows:

- inspections according to Level-E (compressor blades and vanes, turbine blades and vanes, fuel rods, couplings and gears, auxiliary systems)
- inspections to determine status of major components includes non-destructive and destructive tests
  - non-destructive (compressor rotor, flanges/bolts connections, casings positions, roundness measurements, exhaust parts)
  - destructive (Power Turbine Vanes 3 and 4, Power Turbine Blade 4).

The scope of inspections and activities at the LTE are as follows:

- the Level-C activities performed, with some add-ons
- replacements based upon LTA as agreed with customer
- add-on sales as agreed with customer

Figure12: SGT-600 Maintenance schedule with LTA & LTE

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- the Level-C activities performed, with some add-ons
- replacements based upon LTA as agreed with customer
- add-on sales as agreed with customer
The purpose with the LTE is that the Gas turbine shell be fit for another 40,000 + EOH, but still with a potential for further life extensions.

Extension of the maintenance intervals

A Maintenance Plan (MP) with minimized down time is strongly requested by all users and in particular by Oil & Gas industry for both Mechanical Drive and Power Generations applications for on- and offshore installations. The target for SGT-600 down time reduction has been to establish a new Maintenance Plan with increased availability due to Planned Outage Hours reduction:

- extension of the maintenance intervals from 20,000 EOH to 30,000 EOH,
- reduction of the current inspections and site activities down time:
  - extension of shifts work,
  - reduction of the Level-A inspection from 3 days to 1 day,
  - improvement of the maintenance processes and tools.

The developed MP with maintenance intervals of 30,000 EOH will initially be implemented on the SGT-600 installations with base load operation profile and with latest component design and features:

- DLE combustors (for both liquid and gas fuel) and
- latest components design:
  - Compressor Guide vane 2,
  - Combustor design and combustor governing system
  - Compressor Turbine Blade 1 & 2,
  - Compressor Turbine Guide vane 1 & 2,
  - Power Turbine blade 3
  - Diffuser

The extension of the maintenance intervals from 20,000 to 30,000 EOH enables Siemens to reduce the number of overhauls from 5 to 3 and as a result of this modification the availability of the SGT-600 will be increased by about 1%. The current MP and the MP with extended maintenance intervals are presented in Figures 13 and 14.

The scopes of different inspections levels are as follows:

**Level A:**
- Borescope inspection:
  - Compressor stage 4 and 10,
  - Combustion chamber,
  - Turbine blades & Vanes

**Level B:**
- Borescope inspection:
  - Compressor stage 4 and 10,

**Level C:**
- Visual inspection:
  - Compressor blades & vanes
  - Turbine blades & Vanes

**Level D:**
- Borescope inspection:
  - Compressor stage 4 and 10,

**Level E:**
- NDT of:
  - Compressor blades & vanes
  - Turbine blades & Vanes
- Visual inspection:
  - Couplings and gears
  - Auxiliary systems
  - Electric generator

- Level E inspection is excluded. Furthermore, the duration of
the remaining inspections has been reduced. Totally Planned Outage Hours have been reduced by more then 50%.

CONCLUSIONS

- High reliability and availability of the SGT-600 gas turbine have been achieved due to continued improvements and modifications of the gas turbine components design.
- All these modifications have made it possible for Siemens to increase the Life Cycle of the engine beyond 120 000 EOH and to extend the maintenance intervals from 20 000 to 30 000 EOH.
- The Life Cycle and the maintenance intervals extension in combination with extended scope of components reconditioning and repair mean additional opportunity for users and Siemens to substantially reduce the SGT-600 Life Cycle Cost.

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