50-Hz Heavy Duty Gas Turbines – Experience and Evolution

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Introduction

Permanently increasing market requirements for combined cycle power plants, in terms of performance, efficiency, emissions, operational flexibility and life cycle cost, are driving forces in the power industry demanding a continuous development process. Especially the gas turbine, as the core component of a combined cycle power plant, is affected by this requirement.

This paper describes the latest evolutionary step of the largest Siemens gas turbine – the SGT5-4000F, formerly known as V94.3A – along with the associated commercial operating experience. Adhering to its proven and mature design, the performance characteristics of the SGT5-4000F have been enhanced, resulting in higher component efficiencies due to better compressor and turbine aerodynamics and in greater gas turbine output.

Incremental improvements of the combustion aerodynamics reflect the potential towards lower emissions, higher operational flexibility and even further enhanced performance. The paper will conclude with a review of the latest SGT5-4000F operating experience, including demonstrated customer benefits from the further refinement of the combustion system.

The evolutionary approach is not only used to further increase the performance of existing products like the SGT5-4000F, but is also utilized to create new products to meet specific market requirements. This will be shown in the example of the SGT5-3000E (formerly known as V94.2A).

Derived from the larger F-class model, the lower rated SGT5-3000E is tailored to meet the intermediate output market requirements. This machine is characterized by the same technical platform and the same proven concept as the SGT5-4000F. Targeting the same high reliability and even better availability, the SGT5-3000E is optimized for simple cycle and combined applications in the 190 MW / 550 MW classes, respectively.

SGT5-4000F

The SGT5-4000F gas turbine concept builds on more than forty years’ experience with heavy duty gas turbines at Siemens. Since its market introduction in 1996, the SGT5-4000F fleet and its three smaller sister models SGT6-4000F, SGT5-3000E and SGT 1000F (formerly V84.3A, V94.2A and V64.3A) have accumulated over 2.7 million Equivalent Operating Hours (EOH) with 120 units in service. With more than 47 engines on order, this fleet is still growing at a rapid pace.

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The evaluation of the reliability and availability statistics reveals the excellent operating experience of this GT type. The data is based on statistical evaluation of customer feedback via GEB (Gasturbinen-Erfahrungs-Bericht), a customer self-analysis of key operational data reported to Siemens monthly, typically provided by about 60 to 70% of the fleet. The reliability level of the SGT5-4000F engines has been above 99% for five consecutive years. Comparing this record with other mature frames, such as the SGT5-2000E (formerly known as V94.2), which was introduced in the early 80’s, shows that the SGT5-4000F engine can clearly be considered a mature product based on proven technology. Availability levels are typically above 94%, depending on the percentage of engines that have a major revision in the period. These numbers also reflect the maturity and high service friendliness of this GT type, meeting planned outage intervals and short outage durations. It should be noted that the above numbers do not only represent the top percentage of the fleet but the fleet average of all engines with sufficient GEB feedback.

**SGT5-4000F Latest Upgrade**

The mature SGT5-4000F has been continuously improved and upgraded over the past years since its market introduction 1996. These improvements and upgrades have followed an evolutionary path, which means that they are based on rather small design changes, while keeping proven features and technologies. They are typically based on positive field experience showing additional potential for higher loading of components or utilizing already built-in design margins, as well as additional improvements that can be found with more sophisticated design tools or new but already validated and tested technologies.

Modified parts and design features are thoroughly examined in test rigs and/or a test bed engine. Even though these tests provide good confidence that the parts will meet their design intent, they typically lack long-term experience, which can be a significant market introduction hurdle. Therefore, a number of measures were selected and bundled to be used in a long-term demonstration run at a selected customer site to gain additional long term experience.

These latest gas turbine upgrade measures include:

- Slightly re-designed compressor blades and vanes on Stages 1 and 2 and inlet guide vanes for increased massflow.
• Row 4 turbine blades re-staggered to reduce aerodynamic losses at increased mass flow.
• Re-design of improved Ceramic Heat Shield (CHS) material to reduce service cost by lowering the fallout rate.
• Changes to operating parameters to operate in premix mode even at turndown below 50% base load and within required emissions limits.
• World-first installation of a Hydraulic Clearance Optimization (HCO) system to control turbine blade-tip clearances, resulting in increased power and efficiency.

The aerodynamic characteristics of the first two compressor stages and the inlet guide vane were modified to increase compressor inlet mass flow associated with an increase in efficiency. The airfoil geometry was adapted to the existing flow channel and the rotor disc slots. Thus, the new blades and vanes are fully retrofittable. They were easily implemented in Mainz-Wiesbaden, the site selected for the long term demonstration run, and are also available as a service upgrade for other existing engines.

To also adapt the turbine to the higher flow, the last stage blade was re-staggered by 1.5°. This was achieved by a simple casting change by turning the existing airfoil on the existing blade root. With this measure, aerodynamic losses could be reduced without major re-qualification efforts for the modified casting and without significant changes to blade vibration behavior.

Tight radial clearances in both the compressor and the turbine section is one key to high component efficiencies. However, under any operating condition, some radial clearance must be maintained in order to avoid contact between rotating and stationary parts. The solution lies in striking a favorable balance between the warm-up and cool-down behavior of the casing and rotor components. The rotor, which typically has the slower thermal response, can be heated and cooled quickly by internal secondary airflows.

The conical flow path in the turbine casing of the Siemens frames gives another opportunity to introduce clearance control by combining axial and radial growth. It facilitates active clearance control by shifting the rotor against the flow direction and consequently reducing the radial gaps above the turbine blade tips.

Even though the SGT5-4000F already has a very good thermal balance allowing for tight clearances, once the engine is fully heated and running at base load, the clearances are larger.
than required. This is because the clearances are designed for hot restart conditions, which is the most critical operation mode. Furthermore, clearances need to be large enough to account for casing ovalization during heat up. These two effects, hot restart capability and casing ovalization, lead to the fact that turbine clearances can be reduced after the engine is fully heated.

The HCO uses this potential by shifting the rotor in the compressor direction after the engine is fully heated and thus, reduces the radial clearances by about one millimeter. It can be shown that the efficiency gain in the turbine of about 0.35% points is far larger than the loss in the compressor section of about 0.15% points due to slightly increased clearances.

The design of the HCO allows for only two positions. HCO is either switched on or off and the positioning is ensured by mechanical stops in the hydraulic cylinders. There is no need for a closed loop control circle with position measurement. Just by applying the oil pressure, the rotor moves automatically into the right position. As the axial thrust of the gas turbine is directed in the turbine direction, the system is even fail safe. In the unlikely event of a pressure loss, the axial thrust would move the rotor back into the “safe” position.

Operating Experience at Mainz-Wiesbaden with the Upgraded SGT5-4000F

All of these optimization measures were implemented at the Mainz-Wiesbaden power plant between 2002 and 2004. The gas turbine’s output was increased by eight megawatts and its efficiency boosted by 0.3 percentage points. However, this enhancement is “bought” at the expense of an exhaust temperature that is about four to five degrees Kelvin lower. Depending on the design of the boiler, the benefit for the entire combined cycle is 0.1 to 0.2 percent points. These measures have now been in place for over 11,000 operating hours, and it has since become field-proven technology that is also recognized by insurance companies. Through the increase in mass flow rate, combined-cycle output increases in total by between 11 and 12 megawatts. Extrapolated for a new power plant (under the same boundary conditions as in Mainz), an efficiency of over 58.5 percent in combined-cycle duty would result, given the multifaceted improvements implemented at the Mainz-Wiesbaden power plant. For Siemens PG and the customer KMW, the intensive cooperation that has developed is a win-win situation: KMW has, at its disposal, a power plant that represents the latest state of the art, while Siemens has the opportunity to test and assess the iterative steps of new developments in the power plant in real-life operation.
In the two one-year demonstration periods, as agreed between KMW and Siemens, the upgrade features were implemented and tested:

   Phase 1 from summer 2002 to summer 2003 focusing on hot gas path improvements.
   Phase 2 from summer 2003 to summer 2004 implementing the mass flow increase, HCO and turndown.

In addition to an extensive measurement program, both test phases included a sequence of planned inspections to visually examine the new parts. These inspections were scheduled in close cooperation between Siemens and KMW to achieve all required testing and inspection results while minimizing the commercial impact for the customer.

The new compressor design was validated by numerous measurements for blade vibration to confirm dynamic behavior and mechanical integrity as well as pressure and temperature measurements to verify the aero-dynamic design intent.

Blade vibrations were monitored by strain gages on the airfoils and laser probes for non-contact vibration measurement (BSSM – Berührunglosenschaufelschwingungsmessung), not only at 50-Hz grid frequency but also at over and under speed during several Full-Speed No-Load (FSNL) runs without being synchronized to the grid.

It was verified that the required blade frequencies were met with sufficient margin to the harmonics of engine speed and that the measured vibrations were well below the allowable ranges.

With more than one year of operation, a wide variety of ambient conditions have been seen, from about –8°C to +35°C, and the upgraded compressor met and exceeded expectations.

As expected after such a successful design validation, the visual inspections showed no negative findings on the blading.

Even though the engine is designed for a 308 MW mechanical load limit, only 281 had been demonstrated before the KMW testing series due to lack of tests at very low ambient conditions. It is Siemens’ design philosophy to release only the maximum power that has been previously demonstrated in an engine equipped with BSSM on Turbine Blade 4 to validate that no blade flutter might occur and that blade vibrations are within the allowable limit.

The new re-staggered Blade 4 had been BSSM tested in Mainz-Wiesbaden and showed no significantly different vibration behavior compared to the previous design. That confirmed the expectation, as the design change was very minor.

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With the increased mass flow, the old released load limit of 281 MW could be enhanced even though winters are rather mild in Mainz-Wiesbaden. During a test run at an ambient temperature of minus 8°C, the power was successfully increased to 301 MW.

A special focus was given to the validation of the HCO, as this was the first application to a commercial engine after a successful run in the test bed engine in Berlin in 2001.

During commissioning after implementation in summer 2003, the operation and control settings were optimized.

The validation of upgrade features usually has the difficulty that the features are implemented together with other changes to the engine, and improvements have to be calculated by comparison of test runs before and after the implementation. However, the testing with HCO was different as this feature can be switched on and off during operation even at full base load. This way, HCO benefit can be directly measured. In one test run, the fuel mass flow and the compressor inlet mass flow were held constant. Then, HCO was switched on and it was directly observed that the power increased while the fuel mass flow remained unchanged. GT power was increased by about 1.5 MW at constant fuel consumption. This reflects a GT efficiency increase of about 0.3 percentage points. As the additional power is actually taken out of the exhaust energy, the impact on the combined cycle performance is slightly lower but still close to 1 MW more power and about 0.1 to 0.2 percent points on efficiency, depending on the boiler characteristics.

An online clearance measurement monitored the rotor movement and was also helpful in demonstrating the potential for clearance reduction when a hot restart was performed. When HCO is switched on, the clearances are not smaller than during a hot restart. In the fleet, numerous hot restarts have been demonstrated over the past years without any rubbing issues. During the one year testing period, the HCO was always functional and no GT trip was caused by the system. After some weeks of operation, it was observed that the hydraulic pumps that generate the static pressure started to switch on more frequently to build up the pressure that is maintained by a pressure accumulator, which indicated a very slight oil leakage. The full functionality of the HCO was maintained during the whole one-year period without risk, as the pumps are designed to run full time.

In parallel, the root cause was identified as a combination of a slightly higher than specified temperature of the hydraulic pistons in combination with the turbine oil specification. Jointly with the seal manufacturer, a different type of seal ring material was selected and implemented after one year of test operation. Since then, no further oil leakage has occurred. On the contrary, the seals proved to be so tight that the switching procedure needed to be
revised to avoid overpressure warnings during filling of the cylinders on one side of the thrust bearing while cylinders on the other side are drained.

The inspection further showed that all other parts of the bearing had no negative findings. The piston surfaces were in excellent condition and no deformation or cracking of any part could be seen.

SGT5-4000F - Next Steps

In Phase 1, the engine was already prepared for higher temperatures in the future by improving hot gas parts based on operating experience from the large and continuously growing fleet.

Actually, the engine was even run most of the time with an increased ISO turbine inlet temperature of up to 20K above standard rating.

The key to achieving this is twofold. On the one hand, combustor cooling air consumption needs to be reduced to keep flame temperature constant to avoid increase of NO\textsubscript{x} emissions. On the other hand, the burner needs to be improved towards higher stable loads.

Reduction of combustor cooling air consumption can be achieved by applying a new type of holder for the ceramic tiles. In the current design, the tile holders are cooled from the back in the area of the tile holder neck and that cooling air also works as seal air to protect the tile holder heads from hot gas ingestion. The new design is slightly modified so that the impingement jet directly cools the tile holder head, which is the most critical position. With the so-called Impingement Cooled Tile Holder (ICTH), a reduction of cooling air consumption of about 2 % compressor inlet mass flow is envisioned. A limited number of ICTHs have already been installed in the combustor since summer 2004 and have shown very good results for more than 4000 EOH. Consequently, the next steps will be to equip the whole combustor with that new design.

On the burner side, Siemens has taken several different approaches to improve not only combustion stability but also to reduce NO\textsubscript{x} emissions and to allow for operation with heated fuel.

Incremental improvements of the combustion aerodynamics reflect the potential towards lower emissions, higher operational flexibility and even further enhanced performance.

The burner version now implemented in Mainz-Wiesbaden, allows for higher flame temperatures leading to increased power and efficiency. Also, the fuel gas preheat temperature could be increased to boost efficiency by approximately 0.3 percentage points.
A further refinement of the burner design is ongoing. The combination of the achievements of Mainz-Wiesbaden with other improvements that were tested at other sites will finally lead to a new burner version with even further performance enhancements.

**SGT5-3000E – The Derated Daughter**

The SGT5-3000E development started at the end of 2002. It is designed to cover the 150 to 200 MW power range in the 50-Hz market. Utilizing the excellent reliability and availability of the SGT5-4000F, the 3000E was derived from this engine by decreasing the compressor mass flow and the turbine inlet temperature. Following a common parts concept, as many components as possible of the SGT5-4000F were left unchanged. To achieve compressor mass flow reduction, the compressor vanes were re-staggered and adjusted. To increase the surge margin especially for high ambient temperatures, the first stage blade row was slightly modified, but the stagger angle was maintained. To improve turbine efficiency, the row one vane was slightly re-staggered. The casting tolerances of this vane are such that a re-qualification of the casting process was unnecessary. Because all other hot gas path components remained unchanged and the turbine inlet temperature was reduced, the service intervals between major overhauls could be extended to 33000 EOH for the higher power output and 41000 EOH for the lower power output, leading to an increase in availability and a reduction in service cost. Much attention was given to cooling air savings for further NOx emission reduction.

The first gas turbines were introduced at BASF in Ludwigshafen. The combined heat and power plant (CHP) contains two gas turbines with a heat recovery steam generator and a back pressure steam turbine. The gas turbines deliver 185 MW each and the steam turbine 80 MW. Besides power production, the main objective of the power plant is to supply 181 kg/s process steam for BASF’s chemical plant. The steam is tapped from three different pressure and temperature levels.

During commissioning, one prototype engine was equipped with measurement instrumentation. The aim was to guarantee safe operation and verify the design targets. Low load of the compressor blading during start up and shut down as well as during speed variations between 94% - 108% of rated speed and up to 108% of rated mass flow were demonstrated. Due to cooling air optimization of vane rows two and three, additional cooling air savings and therefore, efficiency improvements and emission reduction were achieved.

The first gas turbine in Ludwigshafen had first fire at the beginning of December 2004 and the second followed at the middle of the month. All measurements were carried out during
commissioning. No problems were experienced during commissioning, and the gas turbine performance with respect to power output, efficiency and NOx emissions exceeded expectations. The plant was handed over to BASF at the end of April 2005.

Due to the common parts concept, any modification and improvement developed for the SGT5-4000F as well as experience gained can be implemented one by one into the SGT5-3000E, thus saving time and cost. In case a future power increase is required by the customer, the SGT5-3000E can easily be upgraded to an SGT5-4000F.

**Conclusion**

Siemens’ mature product, the SGT5-4000F, was upgraded by evolutionary steps while maintaining the proven design and technology. All features were intensively tested and validated in a lead engine made possible by successful cooperation with the customer Kraftwerke Mainz-Wiesbaden.

The project became a clear win-win situation for both parties. Siemens benefited from the testing opportunity, while KMW benefited from the performance enhancements of its engine. Measurements confirmed that the design intent was fully met and, in several regards, even overachieved. Planned inspections were used for visual examinations and showed the proper function and excellent condition of the new parts. Further improvements were derived from operating experience for the HCO and have, meanwhile, also been successfully demonstrated.

The upgraded design has become standard for newly built SGT5-4000F gas turbines. Further evolutionary improvements, especially in the field of combustor and burner technology, are on their way and will be introduced in similar scenarios leading to even higher customer benefit while keeping proven design features.

The evolutionary development approach was also very successfully used to derive the SGT5-3000E from the proven and mature SGT5-4000F using about 95% common parts. The design goals were achieved or even overachieved while using proven design features and technologies of the SGT5-4000F. This leads to a very attractive product which will have the same high reliability and even better availability due to longer maintenance intervals.