Proven Upgrade of Siemens SGT5-4000F (V94.3A) at Mainz-Wiesbaden

Hans Maghon
Olaf Kreyenberg

Siemens Power Generation (PG), Germany

Olaf Thun
Kraftwerke Mainz-Wiesbaden
Germany

Milan, 2005
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.

SGT5-4000F

The SGT5-4000F gas turbine concept builds on more than 40 years’ experience with heavy duty gas turbines at Siemens. Since its market introduction in 1996, the fleet of SGT5-4000F and its three smaller sister models SGT6-4000F, SGT5-3000E and SGT 1000F (formerly known as 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.

The evaluation of the reliability and availability statistic 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 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 that 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.

Upgrade at Mainz-Wiesbaden

The first firing of the new Plant KMW3 took place in May 2000 with final handover to the customer KMW (Kraftwerke Mainz-Wiesbaden) in July 2001. The project is based on a V94.3A gas turbine fired on natural gas with distillate back-up driving a 330 MVA hydrogen-cooled generator. The plant further includes a 140 MW 3-cylinder extraction condensing steam turbine SST5-6000, formerly known as HMN, in a 1 + 1 multi-shaft configuration driving a 200 MVA air-cooled generator. The heat recovery steam generator is a triple-pressure reheat, natural circulation unit, producing steam at 278 tons per hour at 110 bar, 550/560ºC with an exhaust flue gas temperature of 90ºC. Designed for base load or part-load operation, the new cogeneration plant entered full commercial service in 2001.

Although the new plant was handed over, Siemens continued to work on-site in close partnership with KMW, effectively using this latest installation of the largest gas turbines in its range as a demonstration engine for a series of innovative engineering modifications. Implemented and tested on-line under actual commercial operating conditions at the Mainz-Wiesbaden cogeneration plant over a two-year period between 2002 and 2004, the modified components and new systems are now being installed as standard on all new SGT5-4000F frame heavy-duty gas turbines in production, as well as being available for retrofit on existing machines.

The new gas turbine upgrade technologies include:

- Slightly re-designed compressor blades and vanes on Stages 1 and 2 and inlet guide vanes for increased mass-flow.
- Row 4 turbine blades re-staggered to reduce aerodynamic losses at increased mass flow.
- Re-design of improved Ceramic Heat Shields (CHS) Material to reduce service cost by lowering the fallout rate.
• Changes to operating parameters to stay in premix mode at turndown below 50% base load 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 slots in the rotor discs. Thus, the new blades and vanes are fully retrofittable. They could easily be implemented in Mainz-Wiesbaden 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 restaggered by 1.5°. That 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 requalification 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 for high component efficiencies. However, under any operating condition a minimized 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, at base load once the engine is fully heated, the clearances are bigger than they need to be. 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.

© Siemens AG 2005. All rights reserved.
The HCO uses this potential by shifting the rotor in the compressor direction after the engine is fully heated and thus, reducing the radial clearances by about one millimeter. It could 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

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 inspect 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 – BerührungsloseSchaufelSchwingungsMessung), not only at 50Hz 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 were 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 308MW 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.

With the increased mass flow, the old released load limit of 281MW could be enhanced even though winters are rather mild at 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 could be directly observed that the power increased while the fuel mass flow remained unchanged. GT power was increased by about 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 to demonstrate 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 could be 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 at 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 do not show negative findings. The piston surfaces were in excellent condition and no deformation or cracking of any part could be seen.
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 the 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 4000EOH. 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.
Conclusion

The mature product SGT5-4000F was upgraded by evolutionary steps while keeping the proven design and technology. All features were intensively tested and validated in a lead engine made possible by a 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 inspections and showed the proper function and excellent condition of the new parts. Further improvements could be derived from operating experience for the HCO and have meanwhile also been demonstrated successfully.

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 the proven design features.