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INNOVATIVE STARTING PROCEDURE OF SIEMENS SGT-600 IN COLD CLIMATE CONDITIONS

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ABSTRACT

A start-up of a gas turbine means that stress and forces are put on the machine. A start-up in cold climate conditions means that the forces are more critical since the material in the machine becomes more brittle. At a certain temperature the material is utilized to its limits (with appropriate margins applied) and for the SGT-600 ambient temperatures below -30°C (-22°F) become critical.

In earlier installations in an arctic climate, an electric pre-heater has been utilized to prevent the critical components from becoming too brittle. This additional hardware costs money, is consuming auxiliary power and may contribute to unavailability. Another way to solve this issue may be to install material that is less brittle, but this will also increase the cost of the installation.

Siemens is now applying an improved control logic during start-up, solving this issue in the software, without any additional hardware and avoiding unnecessary material changes. This new innovative start-up procedure is performing an automatic check of the stress levels before loading the machine, resulting in a safe and reliable start at temperatures below -30°C (-22°F).

NOMENCLATURE

SGT	-	Siemens Gas Turbine
ISO	-	International Standard Organization
rpm	-	Revolutions per minute
rms	-	Root Mean Square
TIT	-	Turbine InletTemperature
OEM	-	Original Equipment Manufacturer
GT	-	Gas Turbine
PT	-	Power Turbine
IGV	-	Inlet Guide Vane
DLE	-	Dry Low Emission

INTRODUCTION

The SGT-600 (25MW size gas turbine from Siemens, former name GT-10) is a proven twin-shaft, industrial design that have been on the market for almost 25 years, see figure 1.

The twin shaft design makes this unit suitable for both Power Generation, where the power turbine is operating at 7700 rpm and Mechanical Drive, where the operating speed can be between 50 and 105% of the nominal 7700rpm (3850 rpm to 8085 rpm). The absolute maximum speed of the gas generator is 10200 rpm, but at ISO conditions the speed is approximately 9700rpm.

At ISO-conditions, the airflow of the engine is 79kg/s with an exhaust gas temperature of 543°C (1009°F). The pressure ratio is 14:1 and the TIT 1115°C (2039°F). The unit comes with a DLE combustor as a standard.

This product has accumulated more than 7 million operating hours and some 250 units sold. This experience has been gained at a wide spread of ambient conditions from the heat of middle-east deserts to the cold temperatures of Siberia.

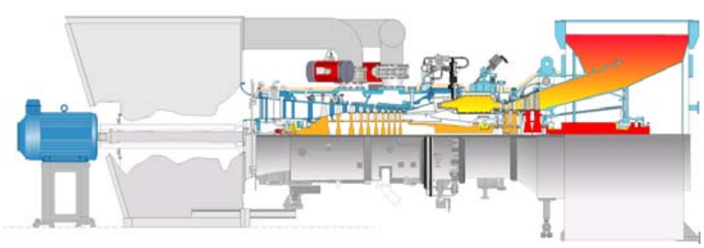

Figure 1: SGT-600 Gas Turbine cross section.

The availability of the unit at all conditions is of large importance for the customers. A key performance factor for an Original Equipment Manufacturer (OEM): it shall be able to start, operate and shut down in a safe and reliable way.

Depending on the type of installation, ambient conditions and operating regime different requirements will be put on the unit. However to avoid a large number of variants the design utilized is preferably the same in all applications.

DESIGN

Installation

The SGT-600 unit is installed inside an enclosure and/or a building. During normal conditions, the temperature inside the enclosure/building is always kept above +5°C (41°F) i.e. at cold climate installations the ventilation air is pre-heated to meet this temperature, see figure 2.

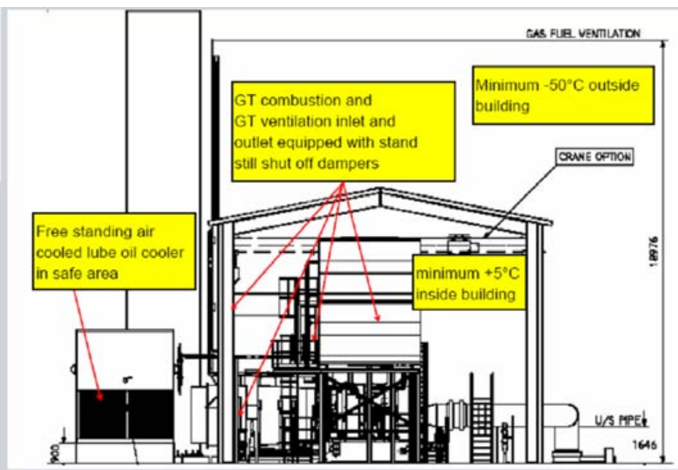

Figure 2: Layout of an installation in cold climate condition

During start-up, small electrical heaters are normally used, but when the unit comes into operation a bleed air system from the gas turbine will heat the ventilation air and the electrical heaters will be switched off.

At stand-still, the material of the gas turbine will have a temperature somewhere between the ambient temperature and the building temperature (depending on location of the hardware). Dampers are installed at the inlet and the outlet of the gas turbine in order to prevent circulation of cold air during stand still, which would cool down the engine further.

Core engine

An inventory of the gas turbine core components shows that most of the design and the material selection gives a proper installation for the cold climate conditions. However one item showed to be critical: the inner central casing including the struts. This part of the design is also holding the bearing #2 of the gas generator. No materials were identified to replace the existing one with properties suitable for cold climate installations. See figure 3.

The starting motor was moved from inside the plenum, to prevent the motor to face these extreme conditions. It was moved to be outside the inlet plenum, the shaft was extended and the motor placed in the heated auxiliary room in front of the plenum.

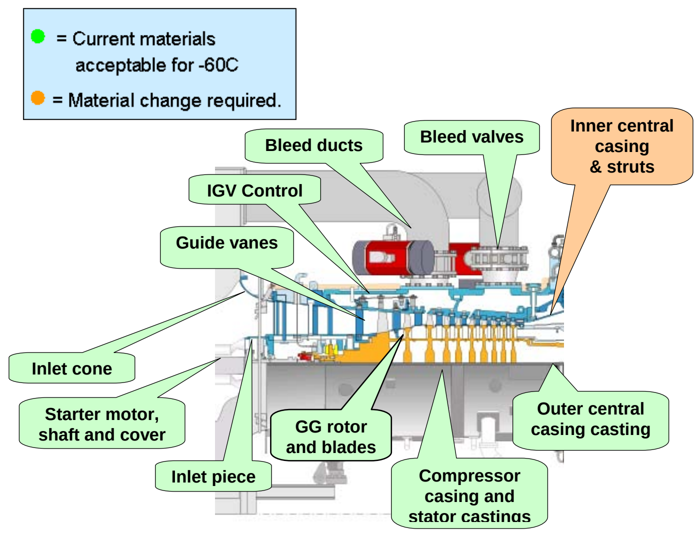

Figure 3: Core engine mapping of design acceptable in cold ambient conditions

Operation

The normal start-up procedure is shown in figure 4 below. The exact time for reaching "GT in operation" (PT received operating speed), and the shaft power required at that time, is unique for each installation and depending on the characteristic of the driven component. Additional time might be needed at this point depending on whether the driven component needs warming or other preparations before further loading of the GT can be executed. Purge time of the installation also depends on local regulations and needs to be considered.

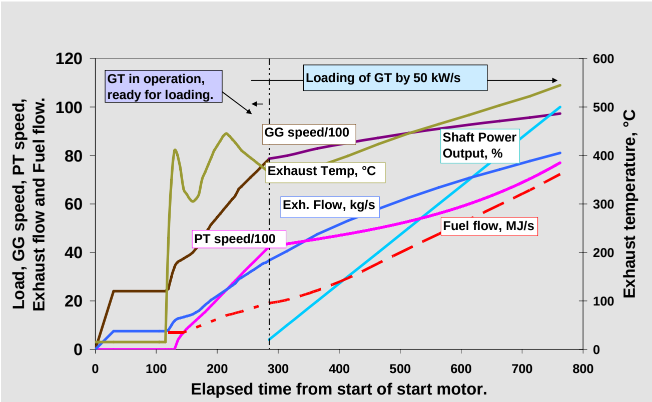

Figure 4: Normal start-up sequence (for a Mechanical Drive unit) vs time (seconds)

Regarding the operation in cold ambient conditions, the start-up of the unit is considered as the most critical sequence. This is due to two reasons:

- At start-up, the unit is *cold* and the material becomes brittle – during the first two to three minutes of the start sequence, some parts will actually be lowering the temperature due to the cooling effect of the air flow, before the speed, air flow and load is increasing and the unit will be heated and material becomes less brittle. See figure 5.
- At start-up, a *resonance* of the gas generator shaft is passed at approximately 3700 rpm. This resonance will increase the vibration levels and put extra forces and stress on the material.

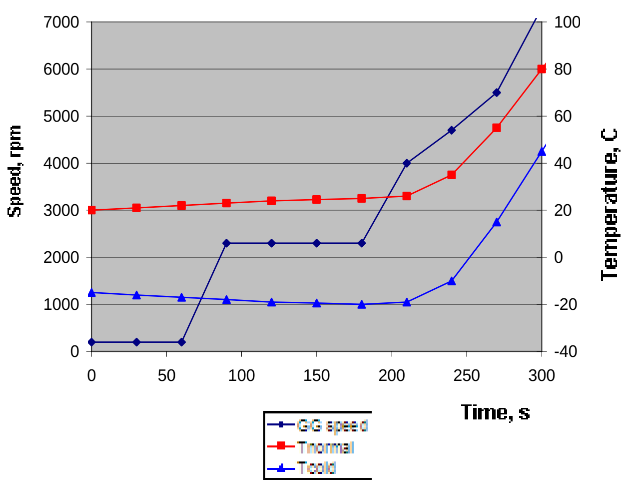

Figure 5: Example of struts metal temperatures from *cold* (-15°C (5°F) during a start-up at -60°C (-76°F) ambient) and *normal* (+20°C (68°F)) conditions versus time (seconds)

ORIGINAL INSTALLATION & OPERATION

The original, and probably most obvious, solution to avoid the brittleness is to install a pre-heater of the gas turbine inlet air flow, in order to ensure that the air and metal temperatures never will reach a critical level, where the material becomes too brittle.

This was the standard solution for the SGT-600 for a couple of years, for units installed in ambient conditions below -30°C (-22°F). For these installations, electrical heaters were installed. The heater was shut-off when the critical speed was passed and parts downstream in the metal temperature of the compressor had reached a certain level.

This solution is working in a proper way but the drawback is naturally that additional hardware is installed (electrical heater, switchgear and control equipment) that may cause unavailability and an additional cost is introduced (both first time cost as well as operational cost in terms of auxiliary power).

Siemens then initiated a development program in order to investigate if there could be any possible design solution that eliminated this additional hardware.

NEW STARTING PROCEDURE

Since the background for this issue is the combination of brittle material and the stresses put on the design, the first step was to map the stresses that are put on the design during normal (not cold) operating conditions.

Stresses put on the design

The maximum stresses to the material, specifically the rear compressor stator is expressed as increased vibration levels that may occur during the resonance at approximately 3700rpm. This stator is holding the rear bearing (#2) of the gas generator and the design (material MAT221656/MAT222403[1]) has not been adapted to the cold conditions due to lack of realistic alternatives.

Material data

The risk for brittle failure in a component increases with thickness, presence of defects such as in welds and decreasing temperature. The linear elastic stress intensity factor (K_I) in front of a crack can be expressed as

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[1] Material according to Siemens specification. MAT221656 corresponds to 13CrMo4-5 and MAT224303 to G17CrMo9-10.

$$K_I = f\sigma\sqrt{\pi a}$$

Eq. 1

where f is a geometrical factor, σ is the stress in front of the sharp crack and a is the crack depth. When the stress intensity factor reaches a critical value the specimen will break. This critical value, describing resistance of a component against flaws, is called the fracture toughness K_{IC}. A method for evaluation of the fracture toughness in the ductile to brittle transition range has been presented by Wallin, and is called the master curve method [1]. This method has been adopted for ferritic steels in the American testing and analysis standard ASTM E1921-97 and has been validated for a large number of materials.

$$K_{IC} = 20 + \left(11 + 77\,exp\left[0.019\cdot(T - T_0)\right]\right) \times \left(\frac{25}{B}\right)^{0.25} \times (-ln(1 - P_f))^{0.25}$$

Eq.2

where T is the testing temperature, T_0 the transition temperature corresponding to a medium fracture toughness of 100MPa√m, B the thickness of the specimen and P_f the cumulative failure probability. Charpy impact toughness testing provides a quick and simple method for the evaluation of fracture behavior at low temperature. The following correlation between impact and fracture toughness results has been verified by Wallin for 141 steels [2], with yield strengths between 300 and 1000 MPa.

$$T_0 = T_{28J} - 18$$

Eq.3

where T_{28J} is the transition temperature corresponding an impact energy of 28J and T_0 is the transition temperature corresponding to the temperature where K_{IC} is 100MPa√m.

Figure 5 below is showing the fracture toughness of the material used in the design. The requirements in the material specification for the purchase of the materials imply that $T_{28J} < +20°C$. Thus the lower curve provides a conservative prediction of the fracture toughness values. However, if the impact toughness in general is better than the requirements in the material specification, the values for fracture toughness will also be higher as illustrated by the upper curve in figure 5. In addition, the slope of the master curve will also increase and if relative differences in fracture toughness between different temperatures are considered (rather then the actual values of the fracture toughness) it is more conservative to consider curves for lower T_{28J} values, as the upper curve in figure 6.

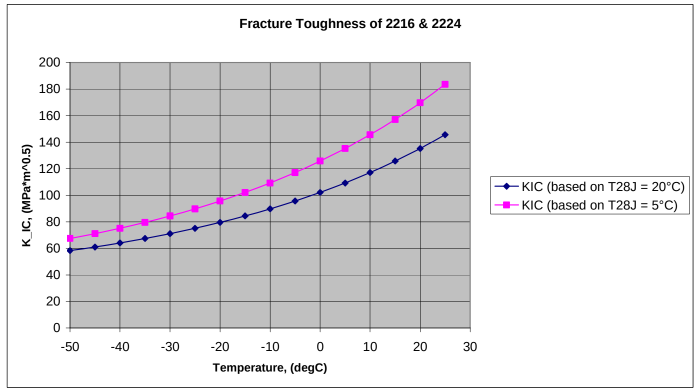

Figure 6: Material fracture toughness vs ambient temperature

The additional load from the temperature transient is considered as low since the expected temperature change is from -15°C (5°F) to -30°C (-22°F) during the start-up sequence, when the resonance is passed. Since the stator is not rotating there are no centrifugal forces added.

If the system is linear, the forces put on the stator will be proportional to the vibration levels. Since the experience is that unbalances are easy to eliminate by re-balancing demonstrating that the system actually is linear. A linear system also means that e.g. fouling will not affect the risk. An increased level of fouling may lead to increased stresses shown as vibrations. But the detected vibration levels are correlated linear to the stresses meaning that the defined trip levels will give the same stress levels as a new and clean installation.

The design of the SGT-600 accepts vibration levels of 18mm/s (trip level) measured at bearing #2 (accelerometer bearing casing type). This is the design criteria according to calculations which have also been proven by the vast experience gained throughout the years.

Rear compressor stator stress at -60°C (-76°F) (metal temperature -15°C (5°F))

Assume that the rear compressor stator has the same temperature as the last guide vane of the compressor at start-up. The guide vane is (according to Figure 3 above) cooled from -15°C (5°F) to -20°C (-4°F). That corresponds to a fracture toughness of 95 MPa*m^0,5 (see Figure 6).

Rear compressor stator stress at +20°C (68°F) (metal temperature +20°C)
Regarding the case with "normal" ambient conditions, the temperature of the stator will increase by 5°C (9°F) during the start-up sequence (from purge speed to the resonance speed): from +20°C (68°F) to +25°C (77°F). This corresponds to a fracture toughness of 180 MPa*m^0,5 (see Figure 6).

The running experience from this temperature range is extensive and naturally a number of units have experienced high vibration levels during the passing of the resonance and some units have even tripped (at 18 mm/s) where no defects on the engines have been found. This is confirming that the design is working as intended.

What is the correlation between the fracture toughness and vibration levels?
The ratio between the two cases is 1.9 (=180/95). This correlates to a vibration level of 9.5 mm/s (18 mm/s / 1.9) at the cold conditions, utilizing the properties of the material to the same extent.

Blade loss calculation
The design of the SGT-600 is intended to manage a blade loss at normal ambient conditions. Will this view of utilizing the material increase the risk at a blade loss – for which the unit is designed? The fracture toughness of this material is 180 MPa*m^0,5 at normal start-up conditions. The ratio between the excitation forces (acceleration) at the resonance speed versus the maximum speed (10200rpm) is 7.6 ($=(10200/3700)^2$).

The ratio between the fracture roughnesses is 1.9 (180/95) which means that the risk at a blade loss when passing the resonance in cold conditions is far less (1.9 compared to 7.6) than a blade loss at normal full load conditions – which the unit is designed for.

Conclusion
In other words: the stresses that are actually put on the engines today, tripping at 18mm/s at ambient temperature +20°C (68°F) will correspond to the stress level at vibration level of 9.5 mm/s at -60°C. If the limit is set to 8 mm/s an additional margin is introduced as well.

Implementation

Will a reduction of the vibration trip level affect the starting reliability? A normal machine behavior is to run at a vibration level of 2-3 mm/s during initial loading, see figure 7. In view of this the 8 mm/s is far above what could be expected and no affect on the reliability is foreseen – if the unit actually reaches the level of 8 mm/s it is considered as an abnormal case and not a normal, "healthy" unit, such unit is not considered as balanced.

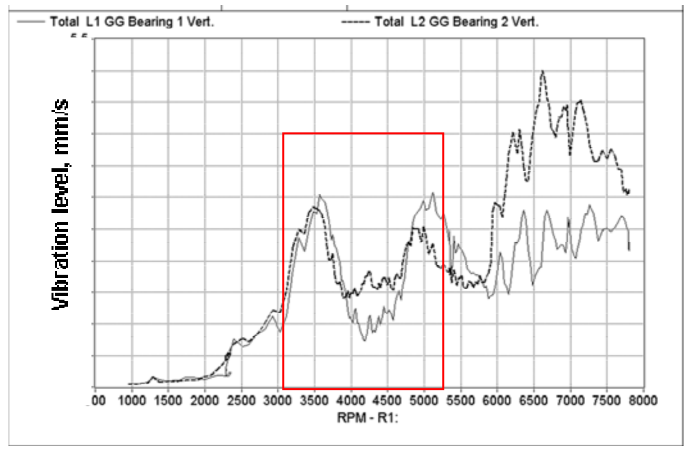

Figure 7: Typical start-up sequence with vibration shown vs rotating speed. Resonance at 3700 rpm visible. Range for changed vibration levels indicated

The starting sequence of the machine has now been up-dated to include a self check in order to determine the expected behavior of the machine: just before the engine has reached the resonance speed. The starting procedure is put on hold for approximately 5 seconds at 3000 rpm. During this period the control system is checking the vibration level – if it is 4 mm/s or below, the additional vibration due to passing the resonance speed will be summarized to a level below the trip level of 8 mm/s. An approval will be given in the control system to proceed the start-up sequence. Otherwise the start-up will be aborted.

The vibration levels are measured both filtered and unfiltered (rms). These values are normally similar since no un-synchronous vibrations are found in this type of engines. The trip levels are based on the rms values

Switch back to normal vibration monitoring
At the speed of 5400rpm the vibration levels for alarm and trip is reset to the original values (18mm/s for trip) where also a second resonance has been passed. At this point the critical parts have reached a metal temperature of at least -4°C (25°F). According to figure 6 the fracture toughness has now reached the level of 120 MPa*m^0,5.. The speed ratio 1.89 (10200 rpm / 5400 rpm) is applied to the fracture toughness in a similar way as before: the normal level of 180 MPa*m^0,5 may be divided by 1.89 giving the value 95 MPa*m^0,5 that is required as a material fracture toughness at this temperature and

rotating speed. The level in figure 6 of 120 MPa*m^0,5 gives that the operation at this vibration level is safe.

Experience

This new starting procedure has recently been implemented for six units (two different locations) in the northern part of Russia where the temperature can be as low as -50°C (-58°F). These units are equipped with the standard combustion chamber (DLE). Originally these units had the electrical pre-heaters installed for start-up but the change in the logics has shown that the units now can start without pre-heating in a safe way.

CONCLUSION

To run the machine below a reduced trip level of bearing number 2 vibration measurement is a safe way to solve the issue with the brittleness of compressor stator of the SGT-600 in cold conditions. Since the accepted vibration levels are lowered at these cold conditions the stress put on the hardware is not higher compared to a start at normal ambient conditions. The normally used pre-heating system can be eliminated. This argument can be put on all static parts in a unit if the risk for cracking due to brittleness is related to load at passing a resonance.

REFERENCES

[1] K. Wallin, The master curve method: a new concept for brittle fracture, Int. J. Prod. Tech., vol. 14 (1999), p. 342-354

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