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A HIGHER TURNDOWN FLEXIBILITY ON AE64.3A GAS TURBINE: DESIGN AND OPERATING EXPERIENCE

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ABSTRACT

Italian power generation market is living today a period of substantial changes due to the liberalization process, climate issues, natural gas price fluctuation and the uncertain future of nuclear and coal. In this framework, many gas turbine power plants, originally designed to operate mainly at base load, feel the necessity to be flexibly and profitably operated into the dispatch and ancillary energy service market. In particular, many operators ask for the possibility to operate their gas turbines intermittently, frequently cycling and quickly ramping up and down to satisfy energy demand. Such using drafts new trade off between profitability and maintenance cost. From this point of view it's not unusual to shut down the engine when the power demand is low if the unit cannot be cost effectively parked at a suitable low load and then quickly ramped up to base load when the power demand is higher.

The main barrier against lowering the minimum load of the gas turbines is the increase of the CO emission. When the engine operates close to its turndown load the compressor airflow is such that the heat released by the flame cannot properly support the conversion of CO into CO_2. In such a condition, the power plant will not comply with the environmental legislation and must be operated at a higher load or, worse, shut down. An operating strategy has been devised to face up such problem. It is based on the adjustment of compressor IGV (Inlet Guide Vanes) and the optimisation of cooling air consumption in order to keep the proper amount of combustion air close to the turndown load.

This paper shows the feasibility check, the installation and final field tests of the low load turndown upgrade on a AE64.3A gas turbine which allowed to operate the unit in a more cost effective way even when the power demand is low.

1. INTRODUCTION

The gas turbine on which has been installed the lower turndown load package is part of Edison fleet and, in particular, belongs to Terni power plant.

Terni power plant was erected in the 90's when its mission was to operate exclusively at base load. The power plant was erected when a special legislation, called CIP6, was active. Such regulation established a special price for the supply of electricity produced by renewable energy sources or cogeneration power plants. Since Terni power plant was designed to work as a cogeneration power plant, it has been able to access these special prices for the supply of electricity into the national grid.

The figure below shows a current overview of Terni power plant.

Figure #1. Terni power plant

The power plant is constituted by one AE64.3A gas turbine in combined cycle configuration.

A sketch representing the main components of the gas turbine is reported.

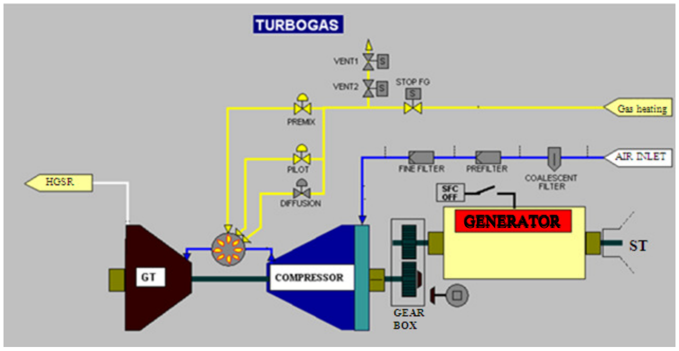

Figure #2. Gas turbine power block

The engine is a 67 MW rated gas turbine in simple cycle. Because the gas turbine has been aerodynamically speed-scaled downward from a larger engine operating at lower speed, a gearbox has been used to synchronize the power shaft of the gas turbine to the generator. The steam turbine power shaft can be coupled to the generator by means of a special component called "clutch". The clutch is a special toothed disc which allows the synchronization of the speed of both shafts and hence their engagement.
The power plant, which is part of a chemical pole which produces polyolefin, can operate in dual mode: as a cogeneration power plant and as a conventional combined cycle. In the first operating mode, a certain amount of the steam produced in the HGSR is extracted for cogeneration purpose. The steam extraction is made from three different points of the power plant. The first extraction is made directly from the HGSR, the second one from the medium pressure steam turbine and the last one from the low pressure one.
In the second operating mode the entire amount of steam produced in the HGSR is fed to the steam turbine thus maximizing the power production into the grid. The steam feeding the chemical process is produced by means of an auxiliary steam generator. This operating mode is usually called "full power" configuration.

The gas turbine is equipped with single fuel, natural gas lean premix combustion system. The engine is fed by two particular kind of natural gas: National gas and Algerian one. The molar composition, as well as the thermo chemical and reactive properties of these fuels, differs greatly each other resulting in different combustion behaviour of the engine both from emission and stability point of view. In the table below the typical composition of both National and Algerian gas is reported.

	National gas	**Algerian gas**
CH_4 [% vol.]	99.4	87.4
C_2H_6 [% vol.]	0.02	7.5
C_3H_8 [% vol.]	<0.01	1.5
N_2 [% vol.]	0.5	1.6
CO_2 [% vol.]	0.07	1.6
Others [% vol.]	<0.01	0.4
Density [kg/Sm^3]	0.721	0.777
LHV [kcal/Sm^3]	8079	8609

Table #1. Fuel properties of both National and Algerian natural gas

Before the pre major overhaul shut down of the engine, the combustion system were characterized by a very low degree of efficiency. The useful injection area of the nozzles was considerably obstructed by the deposition of the condensable residuals contained into the fuel thus affecting the proper mixing of the fuel with the combustion air. In this situation the turn down load of the plant was approximately 75 MW with an operating range of only 10 MW between the lowest and highest load. Moreover, in order to maintain the lowest load, a frequent backflow of the premix nozzles was mandatory to remove as much as possible the condensed deposition. This operation forced the engine to be stopped with catastrophic losses from the profitability point of view.
Before starting the upgrade activity, a pre major overhaul performance test has been carried out at the base load in order to evaluate the performance of the gas turbine itself.

2.0 LOWER TURNDOWN DESIGN

The whole activity was aimed to lower the turndown load of the power plant while maintaining the emissions lower than 50 mg/Nm^3 in the whole operating range of the engine. Moreover it was necessary to confirm at least the same performance of the gas turbine at the base load than the major overhaul. Despite the high grade of flexibility of the plant, a great effort was spent in lowering the turndown of gas turbine. The reduction of the turndown load allows the engine to be parked at a more convenient load when the power demand is low or not economically convenient. In this way the customer lowers the operative cost connected with the fuel consumption which is no more justified from the low price of the power. A possible alternative could be the shut down of the power plant. However, to park the gas turbine at the lowest load possible is preferable. This is mainly due to the time required for restarting the power plant. Another negative effect connected to the restart of the engine is the increase of the equivalent operating hours (EOH) of the gas turbine which lowers the time between two overhauls.
As well known it is possible to further reduce the minimum power output of a gas turbine by reducing the compressor airflow. In order to achieve a stable and environmental friendly combustion process, the fuel must be properly mixed with thw surrounding combustion air with an appropriate air to fuel ratio.

While tuning the fuel flow involves directly the combustion process, adjusting the air mass flow delivered by the compressor can have a significant impact on the whole engine, in particular on the behaviour of the compressor itself, turbine and cooling system; thus several mechanical and fluidynamic checks are required.
The AE64.3A compressor is equipped with a first stationary vane row (named Inlet Guide Vanes, IGV) which could be properly adjusted. IGV vanes pitch can be adjusted by means of a cinematic chain involving different components.
As mentioned before, modification of IGV position affects the behaviour of both the compressor and the secondary air system. Thus, the main boundary condition for the lower turndown upgrade program was the check of the performance and the integrity of the compressor, the efficiency of the turbine blade cooling and the sealing system. The target of these verifications was to allow the engine to be operated at the same reliability level of the previous configuration and to retrofit such newest operating condition to the former design. The ability to retrofit, in fact, allows the lower turndown package to be applied to the other AE64.3A gas turbines of the fleet. For this reason, the reduction of the minimum IGV opening was performed by maintaining the same IGV actuators as well as the entire cinematic chain; likewise, a fine-tuning of the secondary air system control parameters allowed the safe operating of cooling system close to the turndown load without modification of the cooling valves.
Among the several verifications to be done in order to properly apply the lower turndown package, the most significant are described in the next paragraphs and in particular:

- Compressor operating conditions: surge margin and boundary conditions for secondary air system;
- Secondary air system: cooling and sealing flows;
- Compressor pressure rise line and secondary air system: rotor axial thrust and thrust bearing verifications.

2.1 Compressor verification

In the AE64.3A axial flow compressor, the IGV setting modifies both inlet mass flow and stage-wise loading distribution. By closing the IGV, the front stage load decreases while the rear stage load increases and the same loading redistribution trend is produced by low ambient temperature operation. Therefore reducing the minimum IGV position the new stage-wise loading distribution has to be checked, with particular emphasis at low ambient temperature.
Considering the lower turndown package, the upgrade gives severe off-design conditions especially for IGV and first rotor blades; traditional throughflow approach could be not enough to evaluate the complex flow structures inside the engine. Several 3D Navier-Stokes calculations of the entire 17-stages axial compressor was used to evaluate different levels of ultra-low IGV opening, starting from the former one and closing IGV step by step, up to the lowest value matching with the standard actuator. Inlet mass flow, pressure rise line and maximum blade loading were evaluated, in order to select the minimum acceptable value for IGV opening and to give the correct boundary condition for secondary air system and axial thrust assessment.
In all conditions, a fluid network model of the secondary air system was used to verify if the pressure level was sufficient for both:

- cooling and sealing of turbine blades and vanes;
- thrust piston for reduction of axial bearing load.

2.2 Secondary air system (SAS) verification

Figure 3 shows a section of the AE64.3A gas turbine and the complex flow paths of secondary air system are highlighted.
Both turbine blades and vanes are cooled by a combination of film and convection cooling. Four extractions for compressed air are visible in the compressor section: three are led through extraction pipe lines connected to the outer casing; the inner one provides cooling air to the rotor blades.
The cooling air for the turbine blades of stages 2 and 3 and for the firtree of the 4th bucket, is extracted upstream of the 15th compressor stage and led through a rotating passages between the tie-rod and the center hollow shaft. The stationary rows of 4th and 3rd stages are supplied by the outer extractions, located upstream of the 6th and 11th compressor stage respectively. Bleed point for the 2nd stage vanes is downstream the 14th stage rotor. The same secondary air path as the one for vane cooling air provides the sealing air of clearances between rotor and stator.
The cooling air for the first stage vanes and blades is directly extracted at the compressor exit. For the turbine vanes either it is led to the tip of vanes (through the diffuser), or led to the root of vanes (through the filter pipes located downstream the outlet guide vanes, OGV, at the compressor exit).
Note that the first external bleed, which supplies the 4th stage vanes and the sealing air of the turbine bearing, ensures the proper pressure level of the thrust piston. It consists of the chamber between the rear hollow shaft and the bearing casing. The piston makes up for the rotor thrust relieving the bearing of part of the axial load.

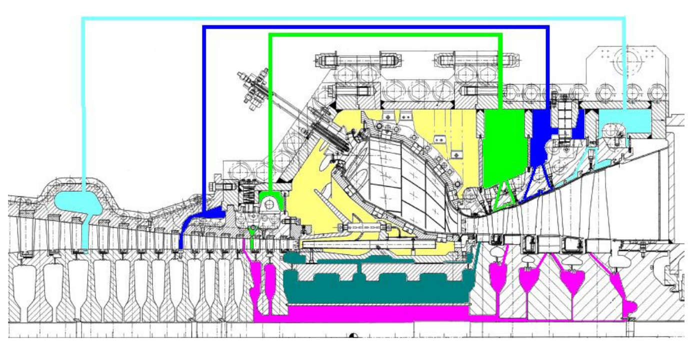

Figure #3. Flow path of cooling/sealing air in the AE64.3A GT

As well known, critical operating points of secondary air system are when bleed pressure is low compared with compressor end pressure. In the standard design, the operating points listed in Table 2 are identified as critical for temperature level and/or for a sufficient difference between tap pressure and turbine pressure.

From the point of view of the lower turndown upgrade, reduction of IGV opening makes decrease the pressure levels at the extraction points of second and third rotor (TB2, TB3) and third vane (TV3), in particular at low ambient temperature. Thus, the pressure margins were checked for condition B of Table 2.

Figures 4 summarises compressor calculations used for bleed pressure verification. In these calculations, set-points of cooling valves have been maintained at the design value. Operating condition with both IGV opening below the original fully-closed position (often called ultra-low IGV opening) and low ambient temperature gives a pressure level at the extraction point of the 2nd and 3rd blade of 68.5% (in per cent of compressor end pressure) in contrast with the 61% pressure limit.

The 3rd vane is more critical, since depletion of compressor line is higher from 9th to 12th compressor stage; however calculations gives a pressure margin of 5.5% with respect to the limit.

Figure 5 shows the trends of axial bearing load in function of the compressor end pressure. As well known, rotor thrust is proportional to the turbine pressure level and load. With closed IGV, in load engine condition, pressure at the thrust piston decreases and this effect is higher with low ambient temperature.

From calculations, in the new fully-closed position of IGV at the lowest ambient temperature of critical points for SAS design (Table 2), the calculated axial thrust does not exceed the 210 kN capacity bearing. During the field validation, monitored temperatures of axial bearing remained in the acceptable range (minus than 90°).

-	Ambient temp. [°C]	IGV [%]	Critical for
A	+15	100% (load)	SAS optimisation
B	-15	Closed (load)	3rd Vane,2nd Blade
C	+30	100% (load)	Bearing, casings
D	+30	Closed (idle)	Rotor

Table #2 – Critical operating points for SAS design

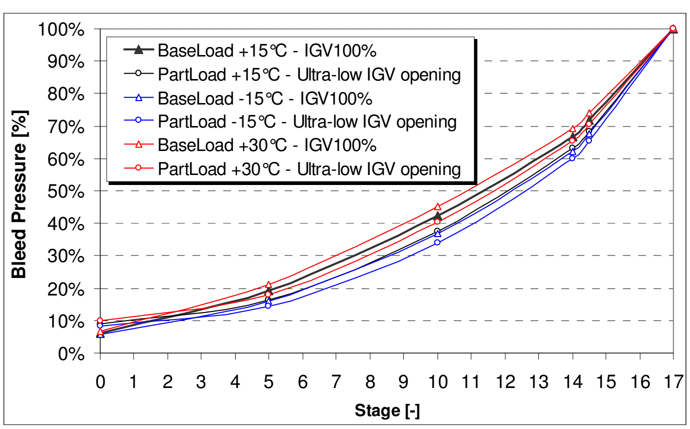

Figure #4. Bleed pressure levels at extraction points

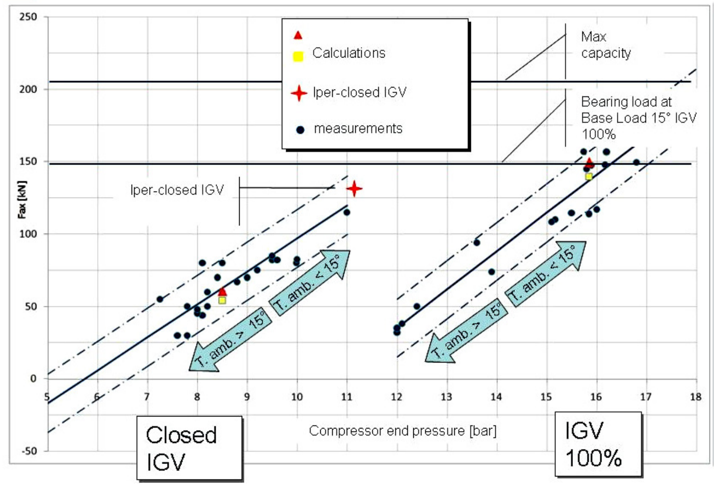

Figure #5. Axial bearing load

3.0 LOWER TURNDOWN PACKAGE INSTALLATION

In order to get the lowest turndown while maintaining the best performance it is important to assure that the hardware installed onto the gas turbine is perfectly aligned with all technical requirements. The first step performed was to wash and clean the burners. Once the cleaning was completed, all the burners were flowed in order to check the compliance with the applicable specification and to understand how effective the flushing procedure was.

In order to allow a uniform distribution of the fuel among the burners, all components were mounted onto the combustion chamber according to a defined arrangement procedure.

Such procedure, developed within Ansaldo for the larger engine and then applied even to the other gas turbines of the fleet, gives the guidelines for the arrangement of the burners onto a gas turbine. The procedure is aimed to reach the following objectives:

- to uniform as best as possible the fuel among the burners;
- to avoid the raising of harmful combustion instabilities which could limit the operation of the gas turbine.

In the figure below an example of burners arrangement is shown.

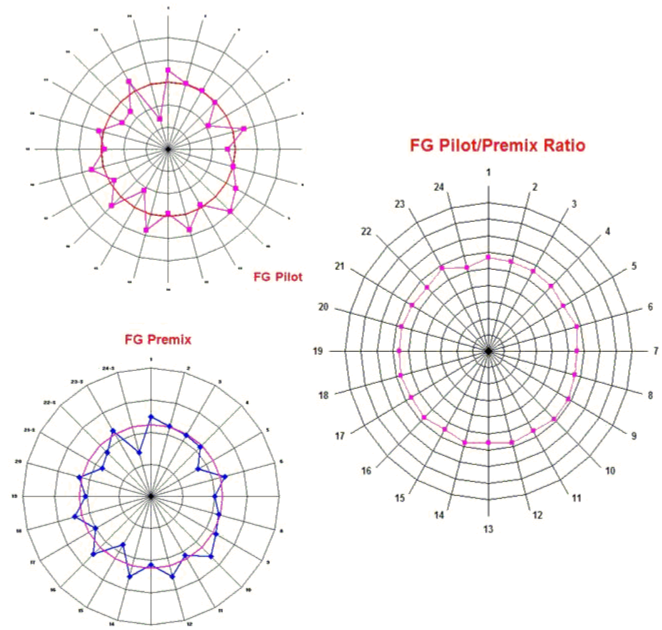

Figure #6. Arrangement of the burners onto the gas turbine

The figure shows, on the left side, the flushing results for both pilot and premix nozzles of each burner. The flushing results are given as reduced volumetric mass flow. On the right side, the ratio, for each position onto the combustion chamber, between pilot to premix reduced volumetric mass flow is shown.
Both pilot and premix reduced volumetric mass flow must be within a defined values as well as the ratio between pilot and premix one.

4.0 ON FIELD VALIDATION

Before the tests got started, the setup of the monitoring system was performed. When performing the on site testing it is important to know the response of the gas turbine when the main process parameters change. In particular it is mandatory to understand the relationship between dynamics and the slow changing parameters of the engine such as IGV, pilot and premix valves opening, outlet turbine temperature and ambient conditions. To do this, a portable FFT analyzer was used. This device allowed the acquisition of the raw signal of the dynamic pressure into the combustion air plenum and the elaboration of the FFT spectrum. Only three significant ranges of the FFT elaboration was monitored in the whole operative range.

4.1 Ignition and start up

The first step to be checked was the capability of the gas turbine to be ignited in different ambient conditions and for various gas turbine start up conditions (warm – cold start up).
Here below an instance of a typical cold start up is shown.

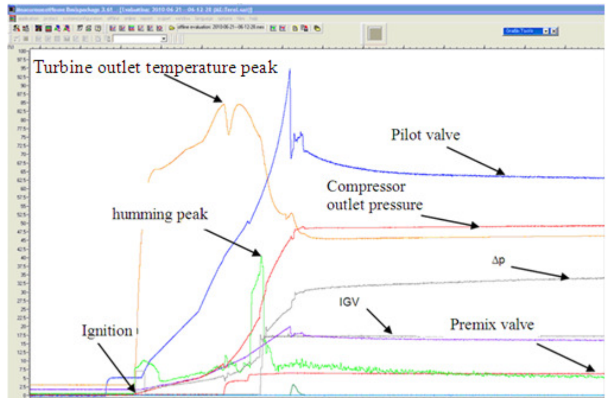

Figure #7. Cold start up

In order to fully validate the start up of the engine the distribution of the turbine outlet temperature was verified. This information gives a feedback on the state of the burners and, in particular, whether they all are correctly ignited.
Here below an instance of this check made at FSNL. The blue circle represents the actual exhaust temperature of each burner whilst the red one is the mean exhaust temperature of all 24 thermocouples.

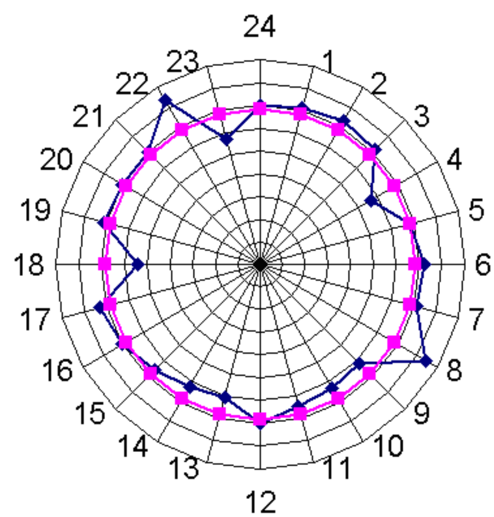

Figure #8. Turbine outlet temperature distribution at FSNL

As it is possible to note from the figure, the difference between the maximum and the minimum value is widely limited below the applicable threshold.

4.2 Turndown capability

At the beginning of the test campaign the characterization of the gas turbine in open cycle was performed. This was necessary in order to correlate the power output from the gas turbine to the power output of the whole cycle when the steam turbine is engaged to the generator shaft. During the characterization phase the power output from the gas turbine was correlated with the premix valve opening request, through the use of a special parameter called ISO Low Value Gate.

The following table summarizes the correlation between the gas turbine power output and ISO LVG at approximately 18 °C of ambient temperature.

GT power	LVG ISO
FSNL	15.8
10 MW	24.3
20 MW	29
30 MW	34.9
32 MW	37
35 MW	38.4
40 MW	44.5
45 MW	48
50 MW	51.2
55 MW	55
57 MW	57
59 MW	59.1
61 MW	61.6

Table #3. GT power output vs. LVG ISO

Another preliminary information necessary to fully understand the behaviour of the gas turbine was the difference between the power output from the gas turbine both in cogeneration mode and in "full power" mode. In order to make this evaluation in the best way, a switch of plant asset was performed maintaining the power output from the whole cycle constant.
It was possible to evaluate that, at approximately 83 MW, the difference between the power output from the gas turbine itself was about 3 ÷ 4 MW.
The turndown capability was then checked both in cogeneration and in "full power" production mode.

"Full power" production mode
Tests were performed starting from approximately 58 MW and lowering the power output down to 47 MW.

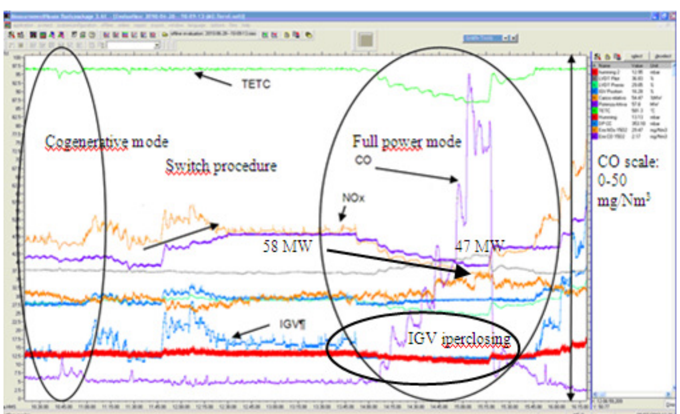

Figure #9. CO increasing in full power production mode

As it is possible to note from the figure, as the power produced decreases, the carbon monoxide increases as the consequence of the flame quenching. During the ramp down of the gas turbine, at approximately 47 MW the peak of CO emission was very close to 50 mg/Nm^3 which is the current limitation due to the ambient legislation.

From the table 3 it was possible to find the correlation between the power output from the whole power train and the power of the gas turbine. At 47 MW the ISO LVG parameter was approximately 34 and the relevant power produced from the gas turbine about 29 MW, equivalent to 49% of the base load at 18 °C.
During the test, the IGV position reached its minimum position and afterward the turbine outlet temperature went under its regulation level, reaching its minimum value of about 523 °C.

Cogeneration mode
Tests in this plant configuration were performed paying much more attention than in the "full power" mode. The need to supply a certain amount of steam to the bottom chemical production cycle implied to proceed with the test allowing the cycle to work continuously and safely avoiding unexpected trip of the gas turbine. Moreover it was necessary to maintain both a proper degree of attemperation to the HGSR and a minimum steam mass flow for the safe operation of the low pressure steam turbine. For these reasons it was not possible to reduce the load until the exponential increase of CO emission. The lowest load investigated in this configuration was approximately 55 MW.
These tests were preformed both with National and Algerian gas .
Concerning National gas it was possible to check that at 55 MW the CO emission was widely compliant with the ambient regulation limit.
It is necessary to note that, feeding the gas turbine with National gas rather than Algerian one, CO emission increased whilst NOx emission decreased on the whole operative range of the gas turbine. In order to manage at the best the variability in the fuel composition a new logic was implemented into the control system. This new logic modifies the opening of the pilot valve as function of the lower heating value of the fuel. At higher loads the pilot valve opens of about +1.5% when the engine is fuelled by Algerian gas, whilst at lower loads the logic doesn't act to modify the position of the pilot valve. At medium loads the opening of the pilot valve varies linearly between 0 and +1.5%.

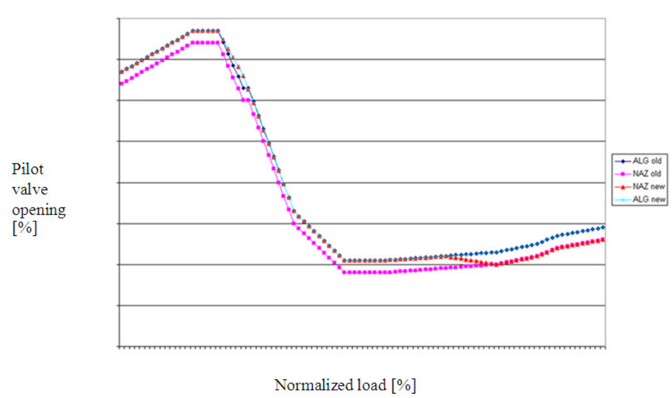

Figure #10. New logic of managing the fuel composition variability

From the table 2 it was possible to find the correlation between the power output from the whole power train and that of the gas turbine. At 55 MW the ISO LVG parameter was approximately 41.4 and the power produced from the gas turbine is about 37 MW, equivalent to 58% of the base load.
During the test the IGV position did not reach its minimum position and the turbine outlet temperature remained under IGV control.

Concerning Algerian gas it was possible to perform tests down to 50 MW. During this test the IGV position reached its minimum, iperclosed position and consequently the turbine outlet temperature went under IGV control level. CO emission remained under 4 – 5 mg/Nm^3 showing that a wide margin was yet available.
At this load level the measured temperature pattern at the outlet of the gas turbine was evaluated. Such analysis showed a slight connection with the ambient temperature and, in particular, the temperature pattern improves as the ambient temperature increases. In the figure below the dependence of the variation of the turbine outlet temperature with the ambient temperature at 50 MW is shown.

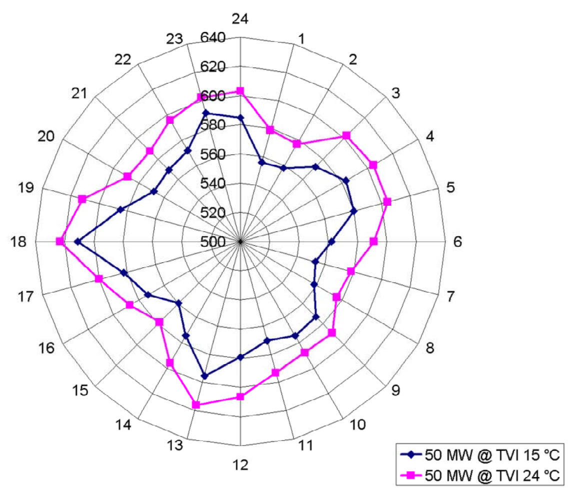

Figure #11. Turbine outlet temperature dependence with the ambient temperature at 50 MW

As it is possible to note from the above figure, as the ambient temperature (in the picture called "TVI") increases from 15 up to 24 °C, the difference between the maximum and the minimum value decreases from approximately 58 °C down to 46 °C. To evaluate the distortion of the exhaust temperature pattern, it was possible to make use of the "distortion index" which relates the difference between the maximum and the minimum exhaust temperature values and the mean value on all the 24 thermocouples. For the previous case the distortion index decreases from approximately 10% down to 7% as the ambient temperature increases from 15 to 24 °C.
From the operative point of view it is important to maintain the distortion index below a given threshold for two main reasons. The first one deals with the necessity to avoid the generation of harmful combustion instabilities while the second one deals with the necessity to have the most uniform temperature pattern as possible on the first turbine vane.
The following figure shows the temperature pattern at the outlet of the gas turbine at 55 MW for two ambient temperature, 15 and 29 °C.

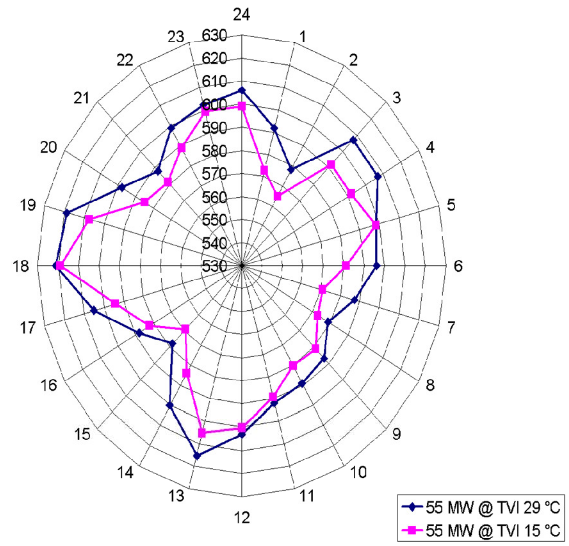

Figure #12. Turbine outlet temperature dependence with the ambient temperature at 55 MW

The temperature pattern at the outlet of the gas turbine decreases from approximately 54 °C down to 43 °C.

4.3 Global performance at higher loads

Similarly to what performed at lowest load a sensitivity analysis of the main combustion parameters was performed at the highest load too.
Here below the optimization of the maximum turbine outlet temperature at the base load is shown.

Figure #13. Maximum turbine outlet temperature optimization at the base load

Finally, the global performance of the engine was validated from the lowest to the highest load. Such validation was performed through the use of some fast gradient ramps from the parking load to the base load during a typical day of commercial operation. The figure below shows the global performance of the gas turbine during the optimization of the ramping gradient.

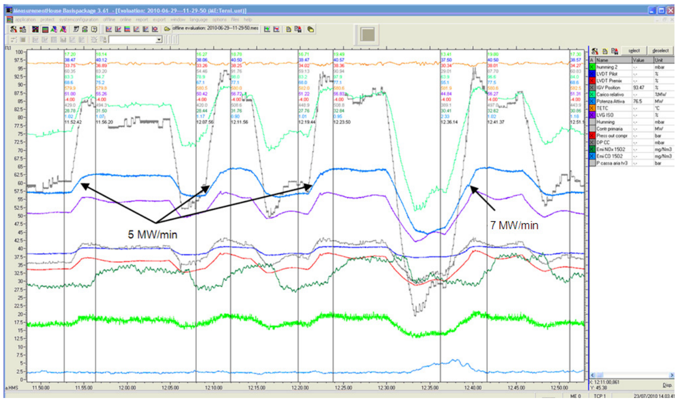

Figure #14. Ramping of the gas turbine during commercial operation

The tests reported into the picture above shows a series of tests performed at two different gradients and, in particular, at 5 and 7 MW/min, the latter being the highest loading gradient currently allowed by the thermo mechanical stresses of the engine.

4.4 Load Rejection

Finally a load rejection was performed in order to check that the gas turbine is able to comply with the grid regulation.
Such test was performed from a load level of approximately 30 MW with the gas turbine in simple cycle configuration. This test, performed from low load, was important in order to verify the ability of the control system to reset the IGV position from iperclosed to normal position. The necessity to quick resynchronize the engine with the national grid and then to produce steam for the bottom chemical process obliged to perform the test from a very low power level. Due to the particular operation of the whole power plant, the load rejection test from higher loads is yet to be performed as this test must match the production needs of the customer.
Below the load rejection test is reported.

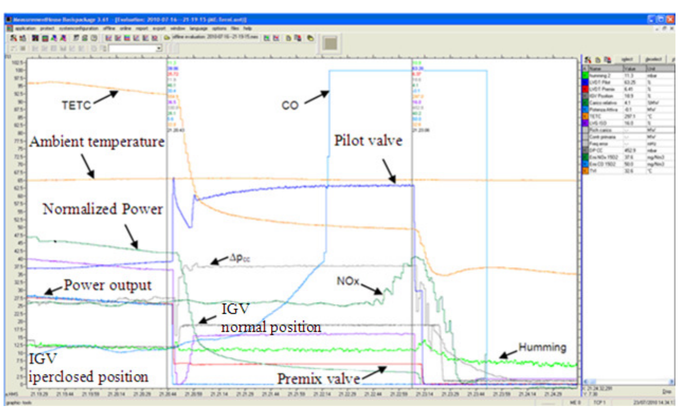

Figure #15. Load rejection test

Downstream the load rejection signal, the control system correctly reset the opening of the IGV from the current iperclosed position up to the normal closed position. From the fuel system point of view the main premix valve closed at its minimum position and the flame was well sustained only by pilot.
No humming anomaly was detected during the transient. The analysis performed on the exhaust temperature pattern showed that the difference between the maximum and minimum temperature was contained within 12 °C indicating that no burner was switched off.

7.0 CONCLUSION

In order to allow the customer to operate the AE64.3A gas turbine in the most cost effective way, a lower turndown package was designed and installed. Such upgrade dealt with three main items. The first one allowed the gas turbine to work with less air through a new, iperclosed position of IGV. The second one dealt with a new, optimized arrangement of the burners according with Ansaldo Energia specification. The third one dealt with the possibility to manage the air flow to the combustion chamber by adjusting the cooling air to the first vane of the gas turbine itself.
Before the installation of this upgrade the power plant operated with a very narrow range between the parking load and the base load. The widest variation of the power output between the minimum and the maximum load was approximately 10 MW.
On site tests showed that the new burner arrangement was very effective since no humming issue arose and the temperature pattern at the outlet of the engine always showed a uniform distribution. Moreover the combustion system allowed to manage flexibly the variability in the composition of the fuel.
The coupled effect of both the iperclosing of the IGV and the adjustment of the first turbine vane cooling air resulted in a further reduction of the parking load of about 2 MW of the combined cycle in “full power” mode at ambient temperature of about 30 °C.
The global effect of the lower turndown brought very good results. In particular it was possible to lower the parking load in all the power plant assets. In cogeneration mode the current parking load is set at approximately 55 MW (about 68% with respect to the whole power plant base load) equivalent to 37 MW of the only gas turbine (about 63% with respect to the only gas turbine base load).
In “full power” mode the current parking load is set at approximately 58 MW (about 69% with respect to the whole power plant base load) equivalent to 37 MW of the only gas turbine (about 63% with respect to the only gas turbine base load).
Basically, at the end of the activity, it was possible to reduce the turndown load of about 27% with respect of the parking load at the beginning of the activity.

The performance of the gas turbine was widely checked on its whole operating range. The gas turbine is today able to ramp up and down with the maximum gradient allowable and, in particular, at 7 MW/min without any combustion instabilities.
Finally a load rejection test was performed. Such test was made from 30 MW with the gas turbine in open cycle configuration and IGV in iperclosed position. The test showed that the gas turbine is able to support the load rejection by correctly resetting the IGV position from iperclosed to normal position safely.