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STUDY OF AN INDUSTRIAL GAS TURBINE WITH TURBINE STATORS VARIABLE GEOMETRY

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Abstract. *The Brazilian electrical power generation market will move towards the use of gas turbine as prime movers, running on natural gas. The industrial gas turbines presently available in the market are of fixed turbine geometry. To cope with varying load, several options for the turbine efficiency improvement are available, among then the variable-area nozzle guide vanes. To predict off-design performance characteristics and nozzle angle schedules that result in maximal settings, it has been studied the adaptation of variable nozzle guide vanes to the engine LM6000. This paper reports the engine new characteristics in comparison with the production bare engine.*

Keywords*: gas turbines, turbine, performance, variable geometry*

1. Introduction

It was already shown (Bringhenti and Barbosa, 2001), (Bringhenti, Barbosa and Carneiro, 2001) that variable geometry can be used to improve the performance of general gas turbines. Four turbines configurations were studied (Bringhenti and Barbosa, 2002). The study concluded that the variable geometry free turbine was the most suitable.

In this work the technique developed to produce the turbine performance characteristics to match literature data was used. Despite the published data (GTW Performance Specs) are not 100% suitable for the study, once the maker does not disclosed the conditions in that the published data were obtained, the results of the study correlates with other published data.

For a more precise study, it would be required to measure locally the pressures and temperatures of the installed turbine, for different load conditions. This would allow better compressor and turbine maps calibration for the engine model (Barbosa and Bringhenti, 1999 and 2000).

Although variable geometry could be incorporated to the compressor, to the turbine and to the nozzle, in this work it will be studied the variable geometry is incorporated to the turbine. Walsh and Fletcher (1998) in his Gas Turbine Performance book describe that variable area NGVs (Nozzle Guide Vanes) are occasionally employed on LP or power turbines for recuperated cycles to maintain high turbines gas path temperatures, and hence heat recovery, at part load. The operating mechanism to pivot the NGVs is expensive and complex being in a far higher temperature environment than compressor VIGVs (Variable Inlet Guide Vanes) or VSVs (Variable Stator Vanes). They are not practical for HP turbines due to the extreme temperatures and extensive cooling requirements. It must be emphasized that each NGV angle represents a unique geometry and hence has its own turbine map.

To minimize part load SFC (Specific Fuel Consumption), automotive gas turbine development programmes have always used a recuperated cycle with variable power turbine nozzle guide vanes. An intercooled recuperated cycle would provide further improvements, but the weight, volume and cost incurred by an intercooler are prohibitive at this engine size.

The results shown in this work was obtained by the GTAnalysis computer program, written in FORTRAN (Bringhenti, 1999). It is able to simulate the steady state, variable NGV, design and off-design behavior of almost all gas turbines existent in the market.

The model gas turbine considered in this work is based on an LM6000 model. LM6000 is derived from GE's CF6 high bypass turbofan aircraft engine, industry standard for high-thrust engines. There are a variety of options of LM6000, whose configurations depend on the application requirements. In this work it will be considered the twin shaft, free power turbine engine. Complete details and specifications the reader will find in the Gas Turbine World Performance Specs quoted in the references.

Table (1) shows the design point data. Many of them were obtained using GTAnalysis for adjustment of values. In this table are summarized all important parameters for design point. It is important to observe that cycle efficiency for these turbines surpasses 40% what it can be observed in GE marine & Industrial Engines folder.

2. Gas turbine and numerical model

This work aims to study an industrial gas turbine with variable geometry incorporated to the power turbine. An exiting gas turbine based GE Marine & Industrial (LM6000-PC), 44.088 MW ISA power output, was chosen as a basis to provide the relevant cycle parameters. This particular engine was selected because there are many of them in use nowadays. GE engine is not equipped with variable NGV.

Table (1) shows the main design point parameters chosen for this study, obtained from cycle simulation as performed by Gratz (2000), for example, based on a scarce set of data available in the open literature, as already mentioned.

Table 1. Gas turbine design point characteristics

Mass Flow (kg/s)	130.092
Overall Compressor Pressure Ratio	29.4 : 1
LPC – Low Pressure Compressor Pressure Ratio	3 : 1
HPC – High Pressure Compressor Pressure Ratio	9.8 : 1
Maximum Cycle Temperature (K)	1530
Shaft Power Output (MW)	44.088
Isentropic Efficiency of Low Pressure Compressor	0.88
Isentropic Efficiency of High Pressure Compressor	0.88
Surge Margin of Low Pressure Compressor	0.15
Surge Margin of High Pressure Compressor	0.15
Combustor Chamber Pressure Loss	0.04
Combustion Efficiency	0.99
Isentropic Efficiency of Low Pressure Turbine	0.89
Isentropic Efficiency of High Pressure Turbine	0.89
Isentropic Efficiency of Free Power Turbine	0.89
Mechanical Efficiency of Low Pressure Turbine Shaft	0.99
Mechanical Efficiency of High Pressure Turbine Shaft	0.99
Mechanical Efficiency of Free Power Turbine Shaft	0.99
Pressure Loss – Intake	0.0
Pressure Loss – Exhaust	0.0
Bleed – Percentage of total mass flow (kg/s)	8%
Pressure Loss – Bleed	0.04
Fuel Flow (kg/s)	2.45237
SFC – Specific Fuel Consumption (kg/s)(fuel)/kW	0.05562×10^{6}
Exhaust Gas Temperature (K)	720
Exhaust Gas Temperature of High Pressure Turbine (K)	1122
Exhaust Gas Temperature of Low Pressure Turbine (K)	1018
Exhaust Gas Temperature of Free Power Turbine (K)	720
Inlet Pressure (Pa)	101325
Inlet Total Temperature (K)	288.15
Angle of NGVat design Point (degree) - Free Power Turbine	0.
Cycle efficiency	0.4181

A computer program that simulates numerically the steady state performance of complex gas turbines with NGV variable area was used (Barbosa and Bringhenti, 1999). Several runs provided the data for a number of NGV stagger settings, in the range of -15° to +15°, that is, closing and opening the NGV blade throat area. For each run all thermodynamic parameters were calculated, from which a selection of appropriate data was taken to produce the graphs shown before.

The gas turbine model for this study was modeled as show in Fig. (1), represented by blocks. There are two shafts running independently. The most external N1 (corrected speed) is coupled to the low pressure compressor and low pressure turbine. The other N2 (corrected speed) , is coupled to the high pressure compressor and high pressure turbine. The blocks used are: ambient, intake, LPC (low pressure compressor), HPC (high pressure compressor), bleed, combustion chamber, mixer, HPT (high pressure turbine), LPT (low pressure turbine), free power turbine. The load is carried by the free turbine, at constant speed of 3600 rpm (60Hz).

Stations numbers are shown in Fig. (1), corresponding to the component inlet and outlet stations.

The flow is divided in two at station 4. The two flows, station 5 (core) and 12 (secondary), are directed to the combustion chamber and to the blade cooling system respectively. These two flows are mixed again at station 7 before entering the HP turbine. Cooling air is necessary because the turbine inlet temperature exceeds 1250K at design point. Actual mixture of the flows is more complex, since air mixes with the main flow at different locations at the NGV an HPT rotor passage.

In the context of this study, the assumption is acceptable, as it would be also if the mixing stations would be station 8 instead.

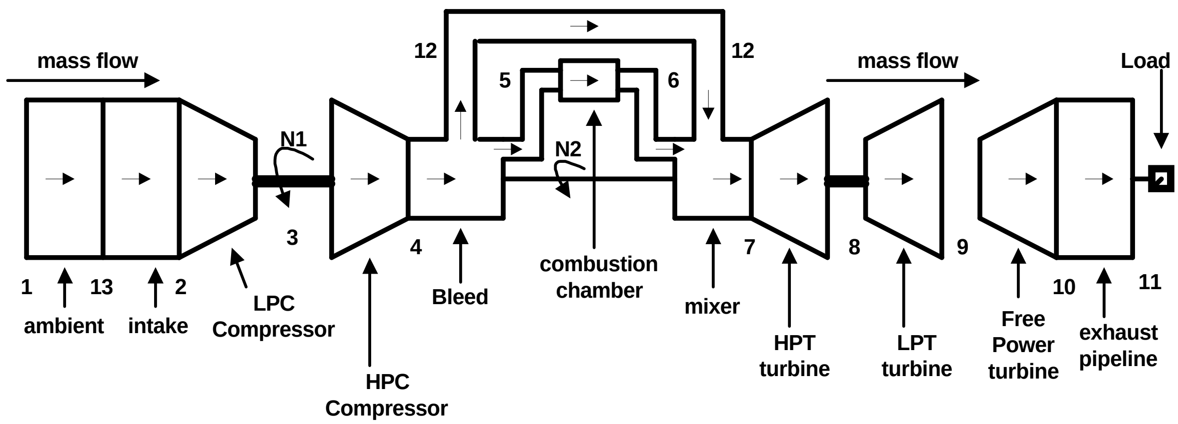

Figure 1. Free turbine (twin shaft gas generator)

Table (2) is the content of the input file used in this study. It has a title section to characterize the engine under study (ended by line "fim titulo"). It follows the blocks description and their input data. Show are the blocks:

1) ambie 1. Represents the ambient at which the engine is running.
2) intake 2. Represents inlet air duct (admission).
3) compr 3. Low pressure compressor.
4) compr 4. High pressure compressor.
5) divma 5. Bleed.
6) camar 6. Combustion chamber.
7) mixpa 7. Mixer.
8) turbi 8. High pressure turbine.
9) turbi 9. Low pressure turbine.
10) turbi 10. Free power turbine.
11) escap 11. Exhaust duct.
12) desem. Performance.
13) teixo. Indicates a turboshaft engine.

The engine description ends with line "fimmo". If ODP (off-design point) calculations are requested then a new section will begin with line "odp" followed by title lines to identify the requested runs, ending with line "fimmo". Following there are lines with ODP runs, as many as required for the study, ending by line "99.   0.   0.".

There are three entries at each line. The first entry refers to the engine block; the other two parameters that will be fixed at the ODP run. Only a few cases of ODP runs are indicated on Tab. (2)

The initials on Tab. (1) have the following meanings:

1) nc, component number.
2) ee, station number of inlet
3) es, station number of outlet
4) mach, mach number
5) alt, altitude
6) dtisa, ISA desviation
7) Empuxo_Requerido, Thrust required at design point for aircraft power
8) Power_requerida, Power output required at design point for shaft power output
9) etadims, isentropic efficiency at inlet duct
10) etac, isentropic efficiency of compressor
11) rc, compressor pressure ratio
12) nmapc, compressor map number, necessary for off-design calculation
13) es2, number of outlet station when more than one outlet is considered, such that bleed
14) pctm, percentage mass flow that are not bleed
15) pctp2, pressure loss considered at core outlet or main outlet

16) pctp3, pressure loss considered at secondary outlet or bleed
17) ibypass, one if bypass is one variable, zero if bypass is not one variable
18) etacomb, combustion efficiency
19) delp, pressure loss in combustion chamber
20) Ttscc, maximum cycle temperature
21) etat, isentropic efficiency of turbine
22) etamec, mechanical efficiency
23) nmapt, turbine map number necessary for off-design calculation, at design if variable NGV is considered nmpat=6
24) tipo, type of turbine. For example free power turbine, linked turbine
25) poteixo, auxiliary power
26) Dptab, pressure loss
27) Totcomplig, how many compressor are driven by that turbine
28) ncomplig, compressors driven by that turbine.

Table 2. Input data for Two Shaft – Free Power Turbine

```
                         CENTRO  TECNICO  AEROESPACIAL
                   INSTITUTO  TECNOLÓGICO DE AERONÁUTICA
                DIVISAO DE ENGENHARIA MECÂNICA AERONÁUTICA
                         DEPARTAMENTO DE ENERGIA
                    Turboeixo com turbina livre - Two Shaft
                             Gas Turbine Model
          ===================================================
fim titulo
ambie      1
1 1 13 0 0 0 0 44.088            nc, ee, es, mach, alt, dtisa, Empuxo_Requerido, Power_requerida (MW)
admis      2
1 13 2 1.0                       nc, ee, es, etadmiss
compr      3
1 2 3 0.88  3.00 1               nc, ee, es, etac, rc, nmapc
compr      4
2 3 4 0.88  9.80 1               nc, ee, es, etac, rc, nmapc
divma      5
1 4 5 12 0.92 0.00 0.04 0.       nc, ee, es, es2, pctm, pctp2, pctp3, ibypass
camar      6
1 5 6 0.99 0.04 1530.            nc, ee, es, etacomb, delp, Ttscc
mixpa      7
1 6 12 7                         nc, ee, ee2, es
turbi      8
1 7 8 0.89 0.99 1 1 0. 0. 1 2    nc,ee,es,etat,etamec,nmapt,tipo,poteixo,DPtab,Totcomplig,(ncomplig,=1,Totcomplig)
turbi      9
2 8 9 0.89 0.99 1 1 0. 0. 1 1    nc,ee,es,etat,etamec,nmapt,tipo,poteixo,DPtab,Totcomplig,(ncomplig,=1,Totcomplig)
turbi     10
3 9 10 0.89 0.99 6 4 0. 0.01 0  0   nc,ee,es,etat,etamec,nmapt,tipo,poteixo,DPtab,Totcomplig,(ncomplig,=1,Totcomplig)
escap     11
1 10 11 0.00                     nc, ee, es, delp
Desem
Teixo
Fimmo
Odp
      turboeixo com turbina livre - Two Shaft
fim titulo  -    BEGIN ODP CALCULATION
   10.00000      0.00000      0.0000
    3.00000      0.00000        1.00
    3.00000      0.00000        0.95
    3.00000      0.00000        0.90
    3.00000      0.00000        0.85
    3.00000      0.00000        0.80
    3.00000      0.00000        0.75
```

Table 3. Output data at design point

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DIVISAO DE ENGENHARIA MECÂNICA AERONÁUTICA
DEPARTAMENTO DE ENERGIA
Two Shaft – Free Power Turbine

e	block	f	mass	P	Pt	T	Tt	V	A
1	ambie	0.00000	130.092	101325.	101325.	288.15	288.15	0.00	0.000000
13	ambie	0.00000	130.092	101325.	101325.	288.15	288.15	0.00	0.000000
2	admis	0.00000	130.092	0.	101325.	0.00	288.15	0.00	0.000000
3	compr	0.00000	130.092	0.	303975.	0.00	408.46	0.00	0.000000
4	compr	0.00000	130.092	0.	2978954.	0.00	810.93	0.00	0.000000
5	divma	0.00000	119.685	0.	2978954.	0.00	810.93	0.00	0.000000
12	divma	0.00000	10.407	0.	2859796.	0.00	810.93	0.00	0.000000
6	camar	0.02049	122.137	0.	2859796.	0.00	1530.00	0.00	0.000000
7	mixpa	0.01885	132.545	0.	2859796.	0.00	1475.79	0.00	0.000000
8	turbi	0.01885	132.545	0.	779743.	0.00	1122.24	0.00	0.000000
9	turbi	0.01885	132.545	0.	500730.	0.00	1018.29	0.00	0.000000
10	turbi	0.01885	132.545	0.	106391.	0.00	720.11	0.00	0.000000
11	escap	0.01885	132.545	101325.	106391.	710.85	720.11	141.47	1.886374

Altitude = 0.0 m - - - - - - - - - - - - 0.0 ft
Flight Mach N. = 0.0000
Power = 44.0880 MW - - - - - - - - - - - - 58472.15 hp
fuel flow = 2.45237 kg/s(fuel) - - - - - - - - 5.40645 lb/s
sfc = 0.05562 *10^6 kg/s(fuel)/kW
Specific Power = 338.898 kW/(kg/s(air))
Air mass flow = 130.0922 kg/s - - - - - - - - - - - 286.7994 lb/s
by-pass ratio = 0.0000
compressor N = 100.0000 100.0000
turbine N = 100.0000 100.0000 100.0000
PR / etac / sm = 3.0000 0.8800 0.1500 9.8000 0.8800 0.1500
Ttmax / etat = 1530.0000 0.8900 0.0000 0.8900 0.0000 0.8900
NGV Angle (Deg) = 0.0000 0.0000 0.0000

The DP output data is shown in Tab. (3). The entries are:

1) e, outlet station number
2) block, block name representing each component of turbine
3) f, fuel air ratio
4) mass, mass flow
5) P, estatic pressure
6) Pt, total pressure
7) T, static temperature
8) Tt, total temperature
9) V, velocity
10) A, area
11) sfc, specific fuel consumption
12) pr, compressor pressure ratio
13) etac, compressor isentropic efficiency
14) sm, surge margin
15) Ttmax, maximum cycle temperature
16) etat, turbine isentropic efficiency

3. Results

The engine simulated in this work is a free power turbine, working at constant speed and NGV. Table (3) contains the DP calculated values. Similar tables are obtained for each ODP run, to produce the data to locate one operating point shown in Fig. (2) to Fig. (6).

Simulations were carried out for NGV settings in the range of -15° to +15°, in steps of 2°, the output powers indicated in the inserts on Fig. (2) to Fig. (6). Output shaft speed was kept constant at 100% of design speed.

Monitored were: turbine maximum temperature and surge margin. The former because the engine life would be compromised if the gas temperature exceeds a given limit, the latter because engine stability would be not achieved if surge margin decrease below certain value.

Operating points of maximum efficiency were researched for every power output considered. N1 is adjusted according to the power settings.

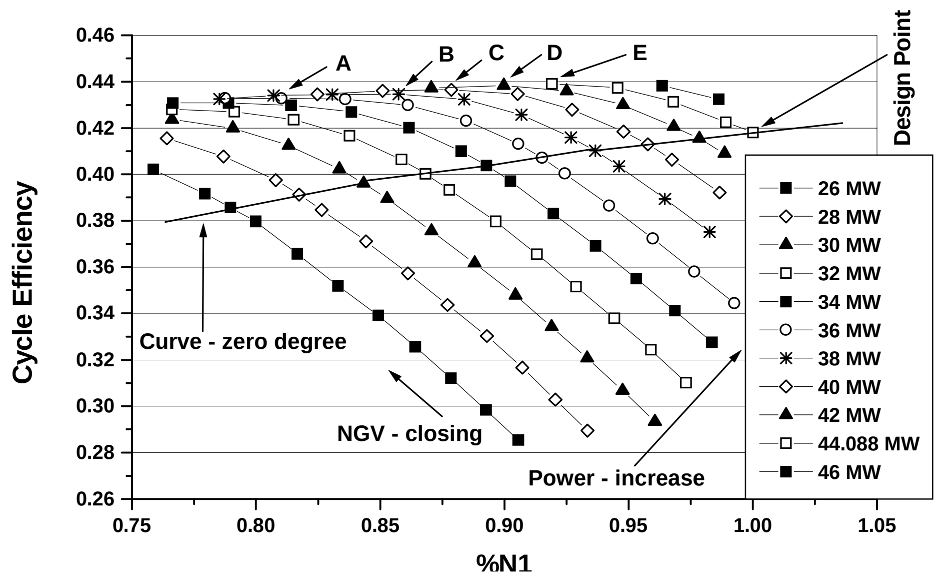

Figure 2. Cycle Efficiency versus corrected speed (low pressure compressor)

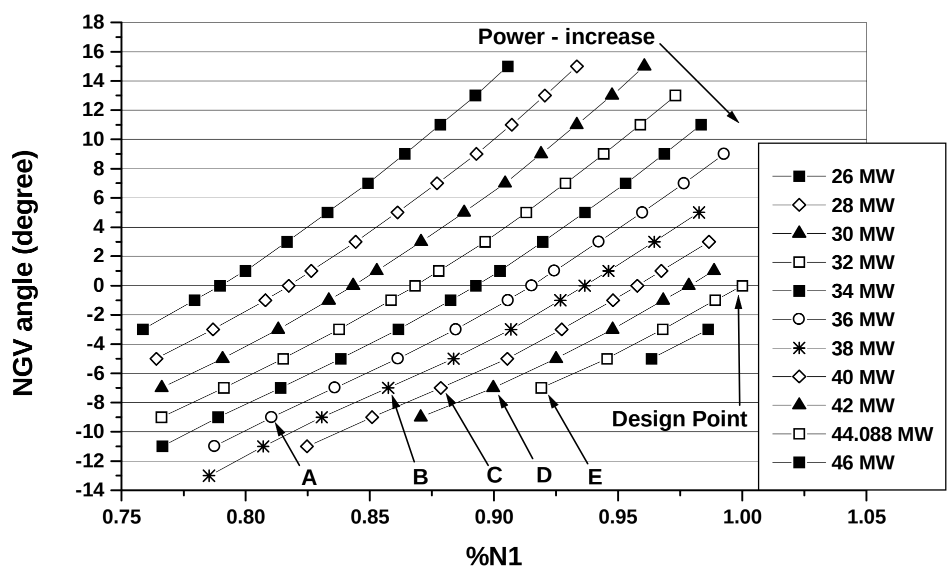

Figure 3. NGV angle versus corrected speed (low pressure compressor)

In Fig. (2) to (6) capital letters indicate the maximum cycle efficiency for different power settings. At the power output setting of 44.088 MW two points are indicated: the DP and the one corresponding to minimum fuel consumption. This inconsistency is apparent: the maximum cycle temperature was limited by 1550K, a value higher than the DP temperature (1530K).

Figure (2) shows curves of cycle efficiency for fixed power output and varying NGV settings. Closing the NGVs gives rise to increase in efficiency, although reduction in N1 is required. Eventually a maximum (efficiency) is attained. The peak efficiencies (indicated by capital letters A, B, C, D and E) may then be obtained and a control schedule is derived, as Fig. (7). For the least fuel consumption the user will want to run his engine according this control constraint.

Figure (3) shows the NGV angle schedule for different power outputs. Peak efficiencies (indicated also by capital letters A, B, C, D and E) are indicated.

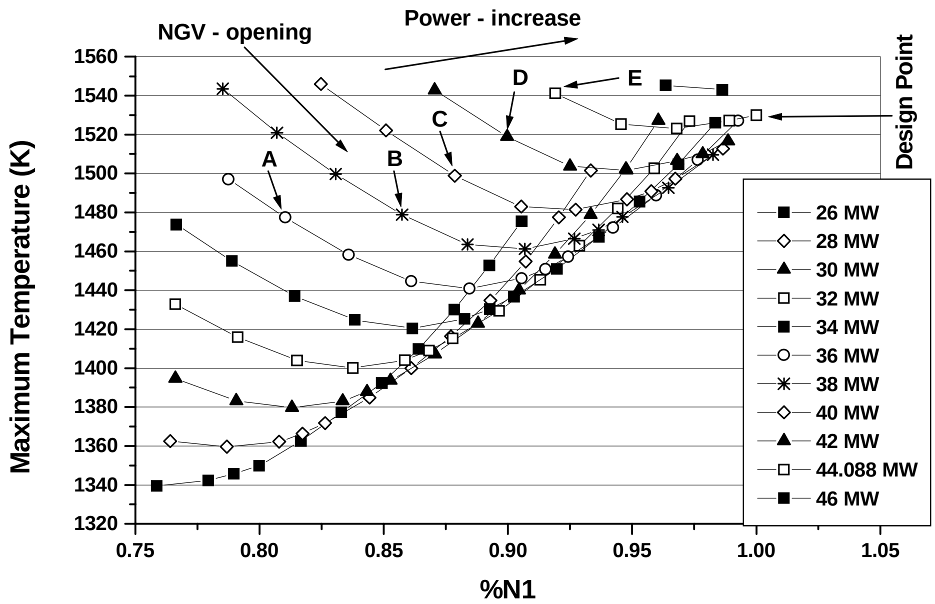

Figure 4. Maximum Cycle Temperature versus corrected speed (low pressure compressor)

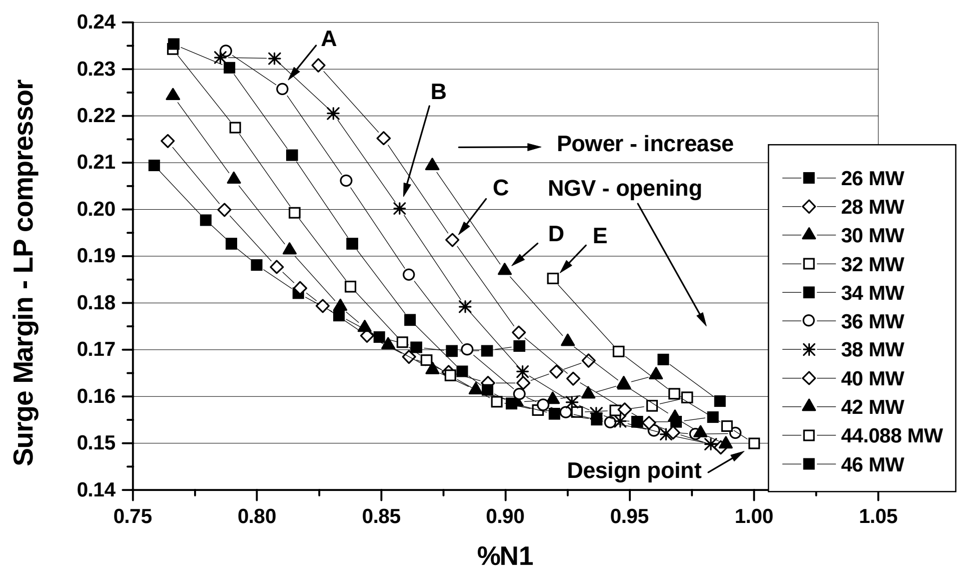

Figure 5. Surge margin low pressure compressor versus corrected speed (low pressure compressor)

Figure (4) shows cycle temperature versus N1. For a given power output the points associated with the capital letters show the attainable maximum cycle efficiency.

For the sake of engine operating stability, the LP compressor does not impose any problems, as indicated by Fig. (5).

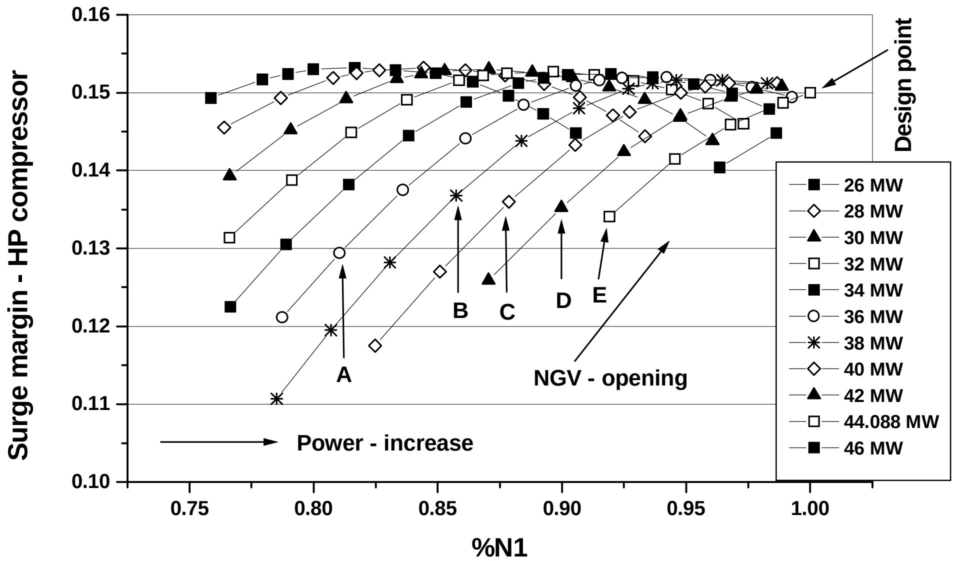

Figure 6. Surge margin high pressure compressor versus corrected speed (low pressure compressor)

Nevertheless, the HP compressor is driven towards surge at partial load. This may represent an intransponible obstacle since fast load response would reduce even more the surge margin at the transients. Figure (6) shows the surge margin at which the engine would be require operating at its best efficiencies. Surge margin down to 13% (Point A on Fig. (6)) may be observed at steady state operation. Closing the NGV will reduce surge margin.

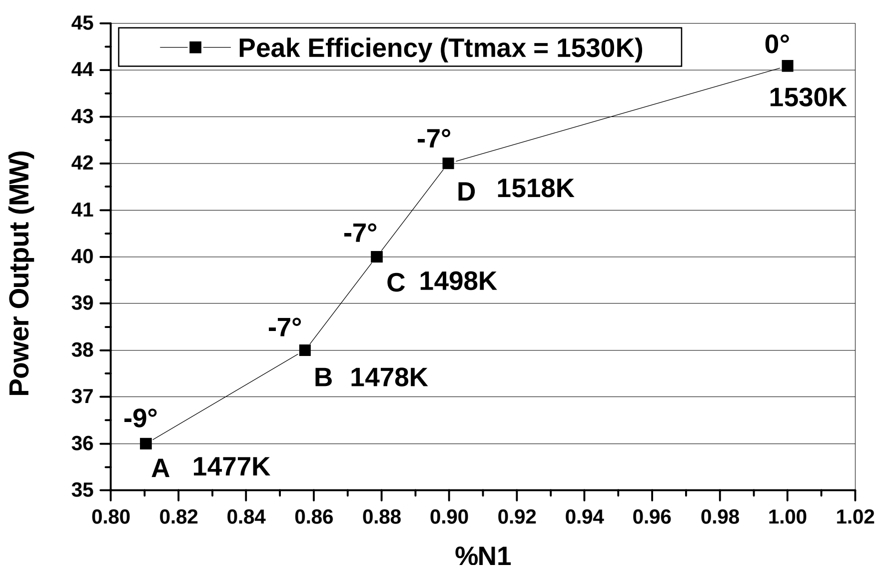

Figure 7. Power Output versus corrected speed (low pressure compressor)

Saravanamuttoo (1996), in his Gas Turbine Theory book, describes methods to overcome surge problem. To overcome the problem it is necessary to lower the running line locally in dangerous regions of operation. One common method of achieving this is blow-off, where air is bleed from some intermediate stage of the compressor or raise the surge line using variable stators in the compressor. Surge margin problems and methods to overcome this problem is not in the scope of this work, but is being studied.

4. Comments and conclusions

An existing turbine with several applications as prime movers for electric power stations was modeled and its performance evaluated when modified to be equipped with VNGV. Efficiency improvement at part load was demonstrated, although surge margin may decrease to unacceptable values, since the HP compressor is driven towards surge if load is reduced and NGV area decreased. This possible problem may be overcome through variable compressor geometry.

Since this study is based on a more accurate model of variable geometry nozzle guide vane (Bringhenti and Barbosa, 2001, 2002), a more realistic simulation has been possible. Usually the simulations are carried out for different NGV blade openings, keeping constant the turbine efficiency.

It was possible to derive the engine control schedule Fig. (7), in which the user may require his engine to operate, for minimum fuel consumption, a constraint that is usually among the ones of an electric power plant operating with gas turbines.

Indications to continue the research, including VG (variable geometry) compressor, supports the on-going research on compressor.

5. Acknowledgement

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