II CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
II NATIONAL CONGRESS OF MECHANICAL ENGINEERING
12 a 16 de Agosto de 2002 - João Pessoa – PB

PERFORMANCE EVALUATION OF DIFFERENT TYPES OF GAS TURBINES FOR POWER GENERATION

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Abstract. *Since 1996 the Brazilian electric sector has undergone a major restructuring, mainly to reduce the State's participation and to induce the growth of private investments. In particular, it has created several opportunities for thermal power plant projects, leading to competition at the generation level. In this scenario of increased competition, the power plant efficiency becomes a key element for determining the feasibility and profitability of the project (Martins et al, 2000). Gas turbines are considered as prime movers, and as such it is important to analyze their performances based on their mechanical structures, that is, as a function of their internal mechanical arrangements single or multi-shaft, linked or free power turbine, to name just a few. For these constant speed applications, a single-shaft gas turbine will run at the same mechanical speed independently of the applied load. In the other hand, a free power turbine leaves the gas generator to run at different speeds. It is expected that their performances would be different, since the operating points travel in different areas on the compressor maps where efficiencies differ significantly. A numerical method for the simulation of gas turbines operating steady-state off-design is used to model and simulate turbines of same power but with different internal arrangements.*

Keywords: *Gas Turbines, Turbine, Variable Area, Performance.*

1. INTRODUCTION

Development of the gas turbine began not long before the World War II when increased the need for more advanced and efficient cycles for aeronautical propulsion. The need for more efficient cycles took researchers to look for more complex cycles. Many different cycles and arrangements were proposed, tested and are in operation today. The great technological progress in gas turbines was mainly due to the aeronautical propulsion.

In many countries the consumption of electric power is not possible to be accomplished by hydroelectric power generation. Gas turbines are then the main source of electric power generation. On these days most attention is placed on the development of gas turbines for power generation, not only to match the new resources demand but also to make then more efficient to respond to the increasing fuel costs.

The Brazilian short term needs for gas turbine based power plants is mainly due to the necessity based power plants. The generation capacity has been kept constant for many years while the power consumption has been increasing steadily. Several power plants are being considered so that in the near future many gas turbines will be continuously operating. Not always it is possible that the gas turbines operate at full load, conditions at which they are most efficient. At part load the efficiency is always lower so that a means to increase their part load performance would significantly contribute to lower the costs of electricity.

A quick look at what has been done to improve gas turbine performance reveals that variable geometry is not new. More than 50 years ago it was already utilized as a means of improving part load performance.

Rahnke (1969) reports the use of variable-geometry power turbine in the Ford 702 turbine engine, installed in a Ford TC800 series tilt-cab truck, in 1956. In this application, variable geometry, in the form of movable power turbine nozzle vanes, resulted in several engine-vehicle operating advantages, some of which are: increase in engine braking, improvement in part power fuel consumption, improvement in engine starting characteristics, an improvement in engine acceleration characteristics, over-speed protection for the power turbine, reduction in engine 'creep torque', additional flexibility in engine assembly by providing a 'trim' device to compensate for variations in component efficiency due to manufacturing tolerances. There were disadvantages too, and these included: added complexity in the engine and fuel control, added manufacturing cost, additional leakages introduced into the flow path. The relative importance of these advantages and disadvantages depends upon overall engine objectives and applications, as well as the aerodynamic performance of the variable-geometry power turbine stage.

Allely et al (1964) considered the design compromises that are imposed on a typical fixed-geometry engine with gas producer shaft power extraction, as well as a method of power management that uses a variable position power turbine nozzle, with particular emphasis on the selection of practical control parameters. The application of variable power turbine geometry to regenerative vehicular engines can provide several desirable operating characteristics, including improved load capabilities. By appropriate selection of control parameters, the variable nozzle can be exploited to optimize both steady state and transient performance characteristics of the engine.

Alves et al (2001) study the concept of introducing intercooling and reheat for gas turbines, using a model that includes losses from the turbomachinery and the need to cool the turbine blades in order to evaluate their effects on the engine performance. The objective of introducing intercooling and reheat is to increase specific power and thermal efficiency. Also examined is the choice of the position where intercooling or reheat is implemented which can have a large effect on the engine output. A comparison is made with the simple cycle and it is shown that these schemes show much promise. Some of the development difficulties are also outlined. Intercooling promises large improvements in efficiency over the simple cycle, especially at high-pressure ratios. Reheat on the other hand is much more suited to combined cycles.

Alves et al (2001) also studied part load performance of an industrial gas turbine with reheat. The part-load behavior of this kind of cycle was investigated considering several options to control the engine output, that is, varying turbine entry temperature, compressor and turbine geometry. The control through turbine entry temperature variation is usually considered, but variable geometry has become an important option in terms of efficiency. Reheating gas turbine, presents a further option, since the turbine entry temperature of both main and reheating combustors can be controlled. It also allows the geometry variation of the turbines before and after the reheating combustor. Comparison of simple and reheat cycles at part load operation was reported, concluding that the reheat cycle may produce great increase in power without high loss of efficiency when compared to the simple cycle. The most adequate control would be the control of fuel flow into the reheat combustor, that is, control of the reheat temperature. Additional advantage would be extracted due to the fact that the temperature decreases with load, what may result in life improvement of the turbine, although thermal cycles may result in operational limitations. On top of it, variable geometry NGV would increase further the gas turbine efficiency.

Cox et al (1995) describes the Westinghouse/Rolls-Royce WR-21 marine gas turbine with an intercooled, recuperated thermodynamic cycle utilizes exhaust heat to provide excellent efficiency not only at full power but also at part power. Vital to the success of the engine and the optimization of fuel consumption is the Variable Area Nozzle that is used to control turbine capacity across the power range. By continuously monitoring and controlling turbine capacity, the heat recovered by the recuperator is optimized across the power range. The efficiency of the power turbine variable stage at low power (low flow) and its ability to deliver full power (high flow) is vital to success of the engine. Success also requires precise control of the variable vane, easy maintenance and good reliability in a hot, mechanically hostile environment.

Rand et al (2000), unveils the Royal Navy in-service experience of both marinized industrial and aero derivative propulsion gas turbines since the late 1940s. Operating through a Memorandum of understanding between British, Dutch, French, and Belgian Navies the current in-service propulsion engines are marinized versions of the Rolls Royce Tyne, Olympus, and Spey aero engines. Future gas turbines engines, for the Royal Navy, are expected to be the WR-21 (24.5 MW), a 5 to 8 MW engine and a 1 to 2 MW engine in support of the All Electric Ship Project.

This work deals with the variable geometry of the turbine nozzle guide vanes at part load, searching new blade settings that would allow best flow matching between stators and rotors. The study was carried out also to analyse different gas turbine layouts. Among many possible configurations, four engines were chosen. They are sketched in Fig. (1) to Fig. (4), namely: single shaft direct drive and free power turbine; twin shaft direct drive and free power turbine. There are turbines whose responses to load variation may differ significantly.

This work aims also to study the effect of variable-area turbines stators over the important parameters that affect gas turbines performance. The methodology and information reported by Bringhenti and Barbosa (2002) is adopted. While that reference the basis for the NGV variable geometry is set out, this paper deals with an important application of the methodology, e.g. the engine layout most suitable for a specific application. An existing gas turbine was selected; its cycle parameters obtained either from the manufacturer’s published data or from thermodynamic cycle calculations to fit published data (Gratz, 2000). The basic cycle parameters were then imposed to the other engine configurations at design point, namely: cycle maximum temperature, compression system pressure ratio and efficiency, turbine system expansion ratio and efficiency, mechanical efficiency and extracted power.

Therefore, at the design point all four gas turbines have the same efficiency. For different power settings the engine performance was calculated varying the NGV stagger, both closing and opening the NGV. The computer program GTAnalysis (Bringhenti, 1999) was developed from the one already reported as part of a MSc. research study (Barbosa and Bringhenti, 1999). It is written in FORTRAN to simulate the steady state, variable NGV, design and off-design behavior of gas turbines. The results are plotted and for each power setting the maximum efficiency, maximum temperature and surge margin were marked (Fig (5) to Fig. (17)).

2. GAS TURBINE PARAMETERS AND NUMERICAL MODEL

For the study of the four different gas turbine layouts, one existing engine was chosen, for which the following data were obtained from GTW performance Specs and GTW magazines Tab. (1).

The variable geometry turbine capability, incorporated to the GTAnalysis program, with turbine maps generated using the Ainley-Mathieson loss model for axial turbines (Bringhenti et al, 2001), produced the information for this study.

The nomenclature adopted in Fig. (1) to Fig. (4) is: C = C1 = C2 = compressor, T = T1 = T2 = T3 = turbine, C.C = combustion chamber, Wtc = compressor work and Wtp = turbine work output.

Attention has been focused on the maximum cycle temperature, engine efficiency and surge margin only, despite information about all cycle parameters were available. Curves similar to the ones shown could be produced to support a better analysis but were no included for the sake of space.

Turbine maximum temperature and surge margin are parameters indicating the adequacy of the engine configuration. Cycle efficiency was the major parameter under investigation.

Table 1. Chosen design point characteristics

Mass Flow (kg/s)	47.8
Compressor Pressure Ratio	16.1 to 1
Maximum Cycle Temperature (K)	1335
Shaft Output (MW)	11.699
Heat Rate (kJ/kWh)	12345
Isentropic Efficiency of Compressor	0.85
Combustor Chamber Pressure Loss	0.04
Combustion Efficiency	0.99
Isentropic Efficiency of Gas Generator Turbine	0.87
Mechanical Efficiency Gas Generator Shaft	0.99
Exhaust Gas Temperature (K)	754
Isentropic Efficiency of Free Turbine	0.87
Mechanical Efficiency of Free Turbine Shaft	0.99

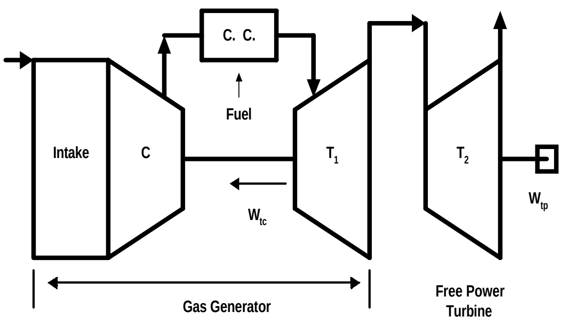

Figure 1. Free turbine unit

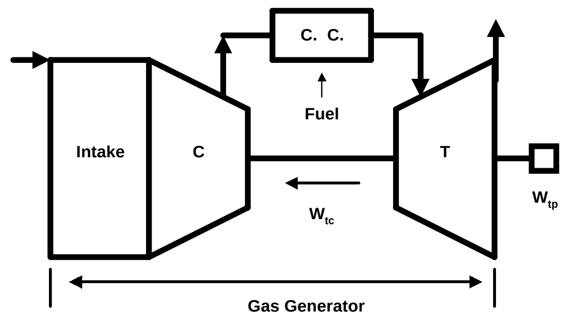

Figure 2. Single shaft power generator

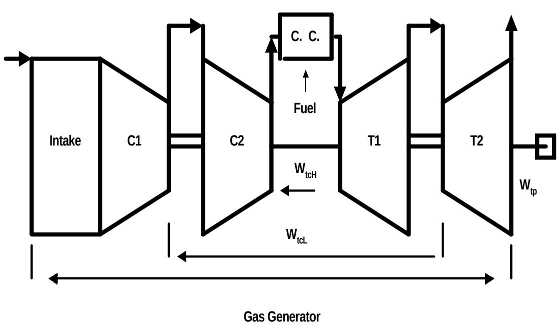

Figure 3. Twin shaft power generator

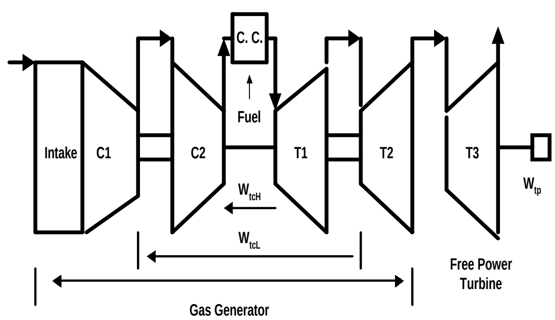

Figure 4. Free turbine (twin shaft gas generator)

Having in mind that the gas turbine will operate at part load, the calculations started from the design point (11.699MW) and arbitrarily the power settings of 11, 10, 9, 8, 7, 6, 5 MW were chosen. Additionally another setting of 12 MW was added to the scope of analysis, as an indication of a small degree of overload.

The NGV (Nozzle Guide Vanes) settings were identified as follows: 0 degree for the design NGV stagger. +1° to +15° the new NGV staggers in the direction of blade opening increase. -1° to -15° the new NGV staggers in the direction of blade opening decrease. Therefore a plus (+) sign indicates that the blade channel is being enlarged (increasing the flow) and a minus (-) sign that it is being closed (decreasing the flow).

The engine controls were as follows: for the direct drive layout (Fig. (2)) N1 is fixed and temperature varies; for Fig. (3), N1 is fixed and N2 varies. For the free power turbine layouts Fig. (1) and Fig. (4), the power turbine speed is fixed and N1 varies. N1 represents the corrected speed for compressor 1 (C1) and N2 the corrected speed for compressor 2 (C2).

The parameters analyzed in this work are: cycle efficiency, cycle maximum temperature and surge margin. The study aims at the analyses of feasible engine configurations that can be most efficient, therefore less fuel consumption. It follows the analysis of the chosen parameters.

2.1 The Efficiency Curves

For the engines without variable NGV's, the efficiencies are plotted on Fig. (5) to Fig. (8) as a solid line (zero degree). As was expected, the cycle efficiency decreases as load decreases. For the four particular engine configurations, the free power turbine models (Fig. (5) and Fig. (8)) would be the best engine configurations to be selected. If variable geometry is added, the search for maximum efficiency would indicate that the single shaft direct drive turbine would be the best option Fig. (6).

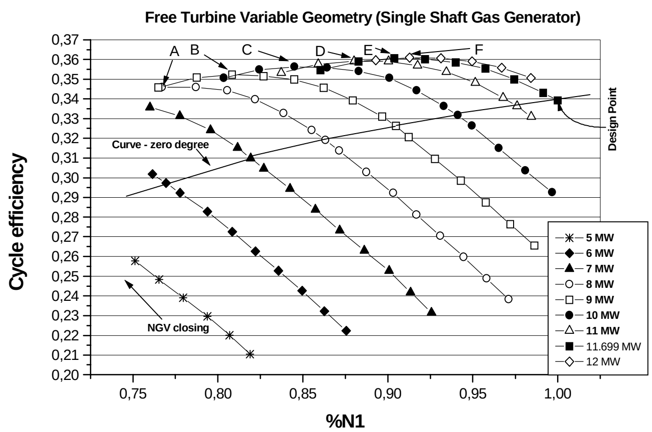

Figure 5. Cycle efficiency versus corrected speed

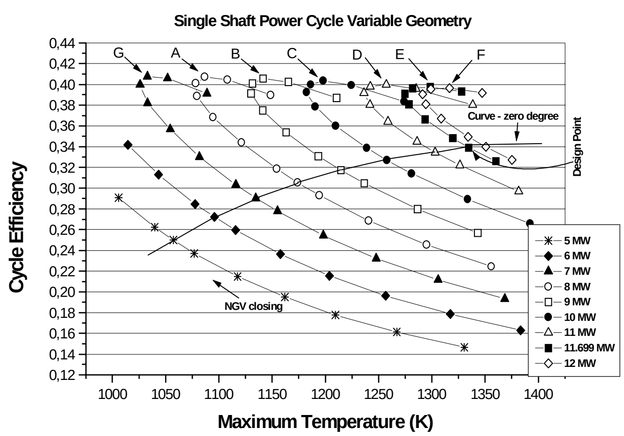

Figure 6. Cycle efficiency versus maximum cycle temperature

Besides higher efficiency, a larger increase in efficiency would be attractive when compared to the other engine types.

Also indicated on those figures are the points of maximum cycle efficiency for several power settings (A, B, C, D, E, F).

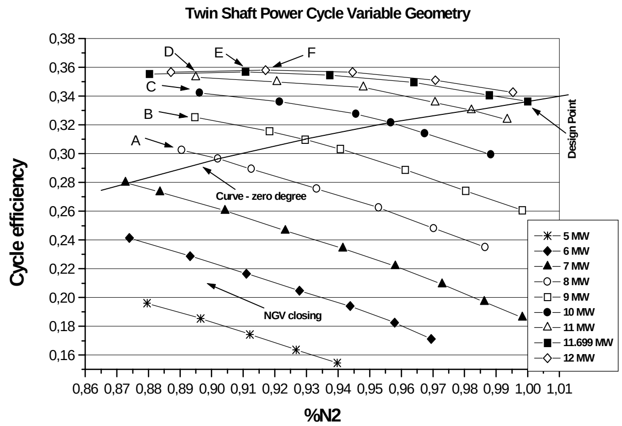

Figure 7. Cycle efficiency versus corrected speed

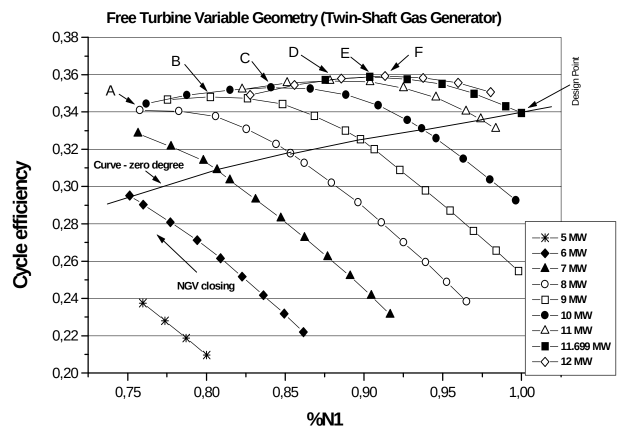

Figure 8. Cycle efficiency versus corrected speed

2.2 The Maximum Temperature Curves

Maximum cycle temperature is the one specified at design point (Tab. (1)), at the exit of the combustor chamber (or inlet to the HPT – High Pressure Turbine). Since material technology is compatible with fairly low metal temperatures due to the high levels of stress, it is required blade cooling of the NGV and/or HPT rotor. This is achieved usually with air bled from the compressor.

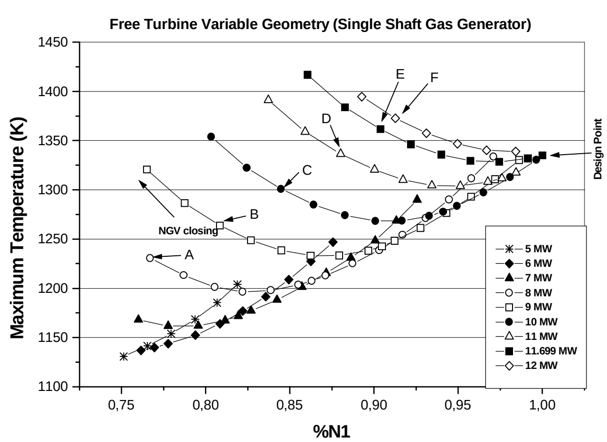

Figure 9. Maximum cycle temperature versus corrected speed

Figure (6), Fig. (9), Fig. (10) and Fig. (11) were produced from data obtained with an allowance for the maximum temperature to increase up to 1400K just for the sake of exploration of future material improvement need. Single shaft gas generator layout is the worst because it requires higher gas temperatures over the studied power range (Fig. (9)). The best option, as can be drawn from Fig. (6), would be the same chosen for best efficiency.

Having in mind those Figures and fixing the attention to the indicated points A, B, C, D and F, it may be concluded that:

a) for each of these points, the maximum efficiency is attained at the specified power output.
b) maximum cycle temperature will be greatest for the single shaft free power turbine engine.

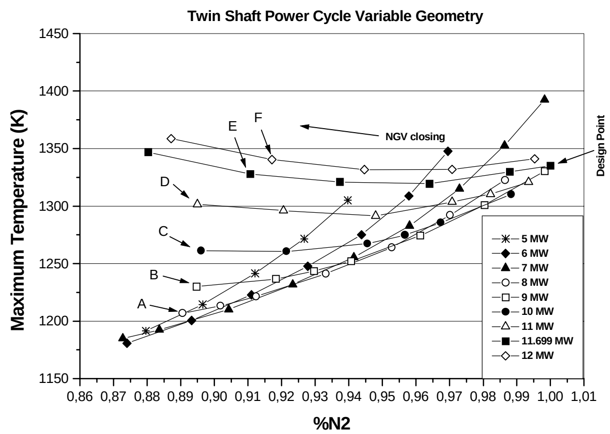

Figure 10. Maximum cycle temperature versus corrected speed

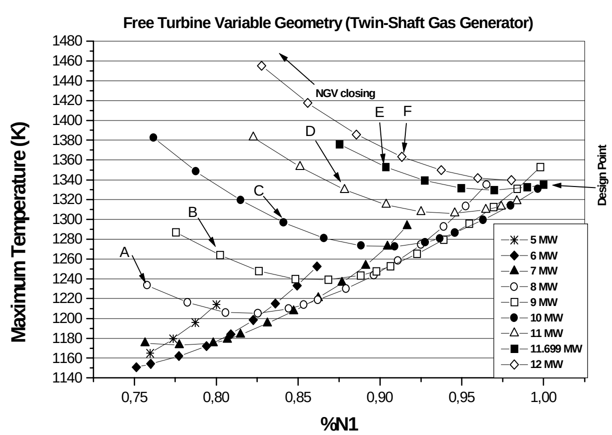

Figure 11. Maximum cycle temperature versus corrected speed

2.3 Surge Margin

This is a limiting parameter. Too low a value would result in compressor surge and/or impossibility of accepting variable load.

At design point the surge limit was set to 15% but it was considered acceptable a decrease of this value to 12 %, subject to future confirmation as far as power handling is concerned. From this point of view, the best option based on efficiency and maximum cycle temperature, direct drive layout would not be selected because the surge margin drops down to 7%, what is unacceptable (Fig. (13)). Two shaft engines surge margins are not also acceptable, as can be seen from Fig. (14), even the HPC will work towards the increase of their surge margin. Best options would be the free power turbine configurations, either single or twin shaft, Fig. (12), Fig. (16) and Fig. (17).

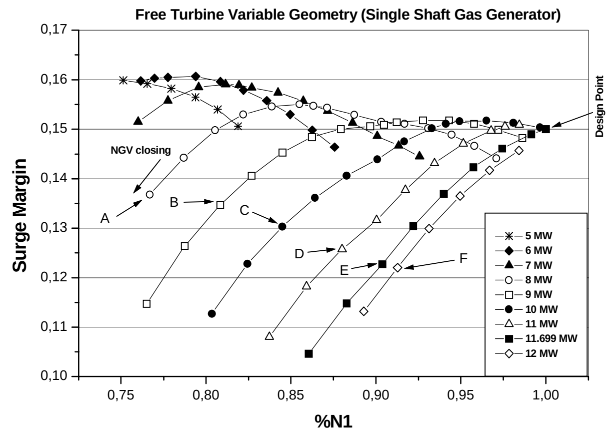

Figure 12. Surge margin versus corrected speed

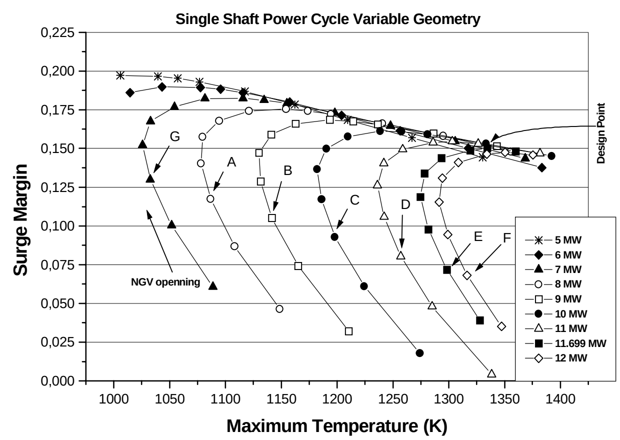

Figure 13. Surge margin versus maximum cycle temperature

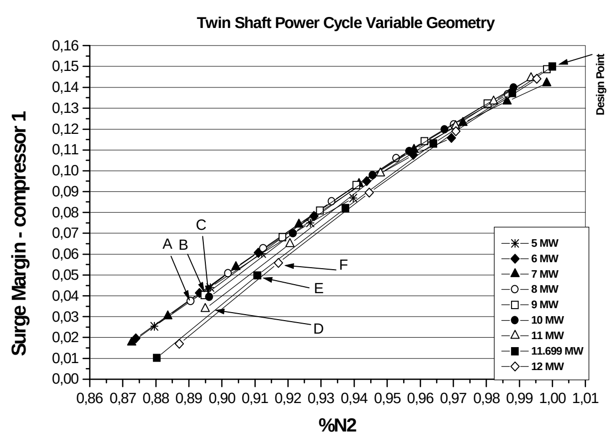

Figure 14. Surge margin versus corrected speed

Surge margin must be kept above a minimum figure for the sake of engine operating stability, otherwise compressor may surge. Surge is detrimental to engine operation and integrity. There are ways to overcome and/or avoid compressor surge but it is out of scope of this paper. Cycles that would require LPC (Low Pressure Compressor) compressor to operate at reduced surge margin would therefore require additional engine control analysis.

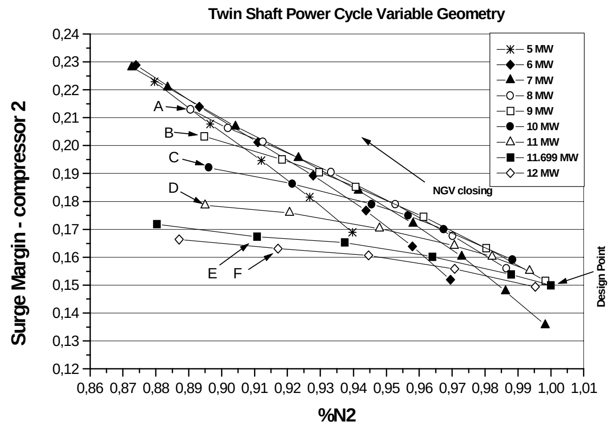

Figure 15. Surge margin versus corrected speed

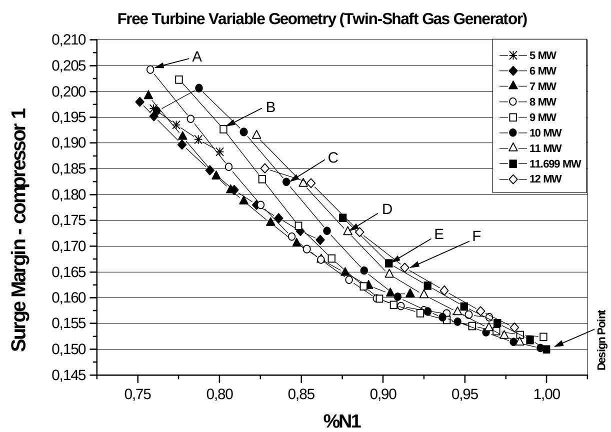

Figure 16. Surge margin versus corrected speed

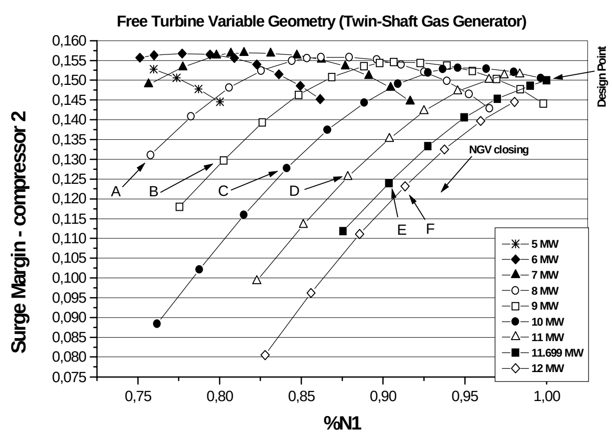

Figure 17. Surge margin versus corrected speed

Future work will contemplate means of surge control like compressor air blow-off and compressor variable stators. It may be stressed that engine configurations like the ones shown on Fig. (13) and Fig. (14) would certainly require blow-off and/or variable compressor stators.

3. CONCLUSIONS

Variable geometry NGV gas turbines were studied aiming at the selection of adequate layout for operation at part load. Free power turbine seems to better respond to the load variation as far as efficiency, maximum temperature and surge margin is concerned. It is not possible to point out whether a single or a twin shaft engine layout would be the best option for an application in an electricity power plant. It is required therefore further study and, of course, better information on the engine components (better data input).

When the maximum cycle temperature is fixed at the design point temperature, that is, 1335K, the conclusions are the same as far as the engine layout is concerned. Since previously there were temperatures above 1335K, the maximum efficiencies now achieved are lower, the maximum power is restricted to the design power (11.699MW) for the free power turbine but 12MW may be achieved with the direct drive counterparts, provided variable NGV is available.

4. ACKNOWLEDGEMENT

The authors wish to acknowledge the grant received from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the support of this research, under a Ph.D. scholarship.

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