PREDICTION OF GAS TURBINE PERFORMANCE GE 7FA

Alysson Ramos Carvalho, alyssonrcarvalho@hotmail.com
Elviro Pereira Barbosa Júnior, elviro.junior@sga.pucminas.br
Felipe Raul Ponce Arrieta, felipe.ponce@pucminas.br
Kevin Schleiss, kevinschleiss@hotmail.com
Núbia Nale Alves da Silveira, nubianale2@hotmail.com
Pedro Henrique de Gregório Dias, pedro2201@hotmail.com
Pontifícia Universidade Católica de Minas Gerais, Avenida Dom José Gaspar 500, Belo Horizonte, MG, Brasil

Abstract. *With the intention of subsidizing information to fulfill the diagnostic of the thermodynamic condition of an industrial gas turbine, to get the performance equation curves that predict the change of the generated power, of the specific heat consumption (heat rate), exhaust gas flow and exhaust gas energy caused by the environmental conditions variation, the fuel composition and the pressure drop at the compressor inlet and the turbine outlet were the objective of the performance prediction of the gas turbine GE 7FA. To develop the performance equation curves, the modeling of the gas turbine cycle was created using the "Gate Cycle" software. The developed model allowed parametric studies to verify the changes of the generated power, of the specific heat consumption (heat rate), exhaust gas flow and exhaust gas energy caused by the environmental conditions variation (environment temperature, relative humidity, atmospheric pressure), the fuel composition and the pressure drop at the compressor inlet and the turbine outlet. With the numerical data obtained in the parametrical studies, it was possible to find polynomial equations that made possible the calculation of the generated power correction factor of the specific consumption heat (heat rate), exhaust gas flow and exhaust gas energy, based on previous environmental conditions variation, the fuel composition and so on. And from the calculated correction factors, to obtain the corrected values from the development parameters to the real operation conditions. The polynomial equations for the calculation of the correction factors were obtained in the EES (Engineering Equation Solver). It is smaller than 0.5%, the error average for all the output variables calculated with the polynomial equations. In the error test that was done, it was observed a maximum error, inferior to 1% to 95% and 89% from the exhaust flow and the exhaustion energy, respectively, calculation simulations. The performance equations obtained for the gas turbine GE 7FA performance prediction allow, with a maximum deflection of 1.8% verified in the exhaust energy, permit to corrected performance parameters for the real operation conditions. From the input variable considered it was corroborated that the most influent between all of them is the environment temperature, and its raise has the tendency to decrease the power and the exhaust energy, whereas the specific heat consumption increases.*

Keywords*: gas turbines; gas turbine performance; gas turbine performance prediction; performance simulation.*

1. INTRODUCTION

With a total of 130 thermal power plants in operation, the electricity generation from natural gas has an installed capacity of 13,025 GW, which represents 10,68% of the electric energy of Brazil (ANEEL, 2011). However it has been decreased in 53,7%, the electricity generation from natural gas in 2009, due to the international crisis that has affected Brazil, there was an enlargement of the gas natural supplying infrastructure, with a warranty of an offer of that crosses 60 million of m³/day (EPE, 2010). As per the actual decennial plan of energy expansion, the predominance of natural gas as the main fossil source of electricity generation must remain until 2019 (MME & EPE, 2010). The electricity generation from natural gas in Brazil happens preferably with gas turbines operating in simple cycle or in combined cycles.

The gas turbines were already used for electricity generation since the 1940's (Maslak and Tomilson, 1996). The technology development of the gas turbines in the last four decades of the XX century allows us today to have in our disposal machines with electricity generation capacity between 50 MW and 380 MW, which can produce energy with high thermal efficiency if they are operated in combined cycle (Chase and Rehoe, 2000). During the 1960´s and beginning of the 1970´s, the continuous headways in the efficiency of the gas turbine, in the availability and reliableness, propitiated to the gas turbines a big scale of applications. With the increase in the operation hours of the gas turbine, the cost of the fuel began to have a bigger importance in the optimization of the machine project. And due to the fast increase of the fuel prices in consequence of the petrol crisis in the 1970´s, the matter of this factor increased a lot more (GEBHARDT, 2000). As the fuel cost became of vital matter in the gas turbine economy, the technological development was focused in the improvement of the thermal efficiency, mainly through the increase of the burning temperature. The bigger headways are focused mainly to the compressors aerodynamic and the increase of the maximum temperature of the gas turbine cycle, with the purpose to guarantee a bigger useful life of the equipment (BOYCE, 2002). The highlighted article has as its target to obtain the polynomial equations that allow foreseeing the performance of the GE 7FA gas turbine in off-design, when the variation of some boundary parameters (for example, ambient temperature, atmospheric pressure or fuel composition) happens.

2. METHODOLOGY

The flow of information between the softwares utilized in the acquisition of the results is showed in the figure 1, where initially, it is elaborated in the software GateCycle a model that shows the same performance characteristics of the equipment operating in the reference conditions. Through a supplement called CycleLink, Excel tool is used to supply to the model input data for the simulation and to carry out the results. These results are converted in correction factors and are introduced into EES (Engineering Equation Solver), to find the polynomials coefficients. The polynomials equations are introduced into the Excel tool where the validation tests are carry out, and the results are achieved.

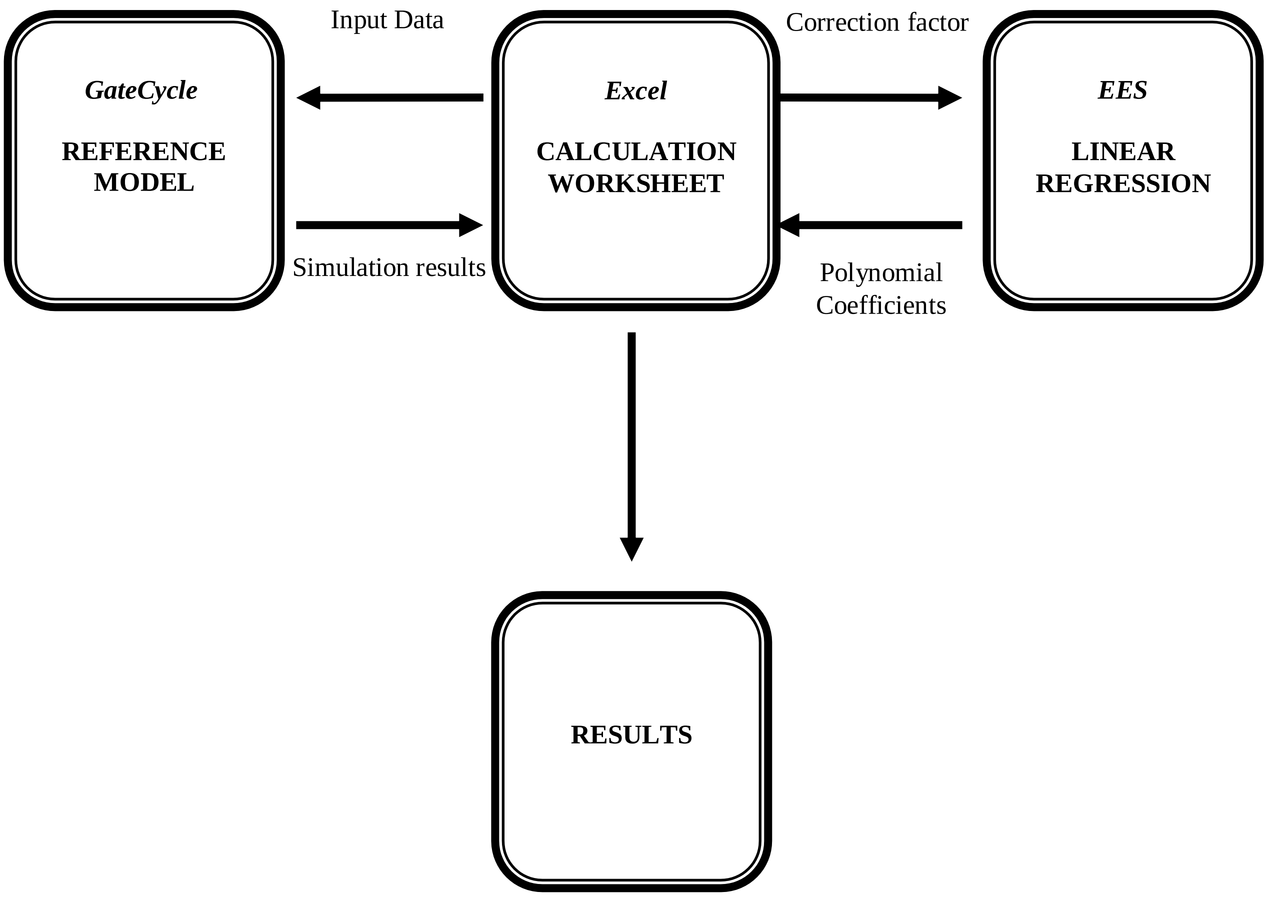

Figure 1. Diagram of the process for achieving the results

2.1. Reference Model

The process of attainment the correction factors that will predict the GE 7FA gas turbine performance began with the definition of a reference model (also called on-site condition). The software GateCycle™ version 6.0 was used to the model elaboration. This software has a large commercial gas turbines library. For the reference model was selected in the GateCycle library the GE 7FA gas turbine model, and inserted the value of the input variables at the reference condition shown in table 1.

The reference values of the ambient parameters are typical of Belo Horizonte metropolitan area, where the work was developed. The composition of the natural gas adopted is quite frequent to be found in the natural gas supplied by GASMIG (GASMIG, 2011). The values of the pressure drop at the compressor inlet and gas turbine exhaust were adopted from the software used in the calculations (GateCycle, 2010). The pressure of natural gas supplying is considered needed for the turbine.

With the definition of the equipments and the ambient conditions it was realized the simulation which results are showed in the figure 2. After the complete validation of the reference model was selected the mode off-design in the GateCycle software for new simulations that supplied the necessary information to get the performance curves. The variables showed in the table 2 were chosen as on-site condition and used for the determination of the gas turbine performance curves.

Table 1. Input variables to the calculation for the reference condition

Input Variables	***Value***	***Unit***
Ambient Temperature	22	C
Ambient Pressure	91.84	kPa
Ambient Relative Humidity	0.67	fraction
HRSG Press. Loss	2.9890670	kPa
Inlet Press. Loss	0.6220995	kPa
Fuel Inlet Temperature	30	C
Fuel Inlet Pressure	2500	kPa
Fuel Gas CH_4 Mole Fraction	0.8950	fraction
Fuel Gas CO_2 Mole Fraction	0.0048	fraction
Fuel Gas C_2H_6 Mole Fraction	0.0690	fraction
Fuel Gas Iso-Butane C_4H_{10} Mole Fraction	0.0016	fraction
Fuel Gas Iso-Pentane C_5H_{12} Mole Fraction	0.0004	fraction
Fuel Gas N_2 Mole Fraction	0.0074	fraction
Fuel Gas n-Butane C_4H_{10} Mole Fraction	0.0025	fraction
Fuel Gas n-Pentane C_5H_{12} Mole Fraction	0.0004	fraction
Fuel Gas Propane C_3H_8 Mole Fraction	0.0189	fraction
Fuel Gas LHV	48334	kJ/kg

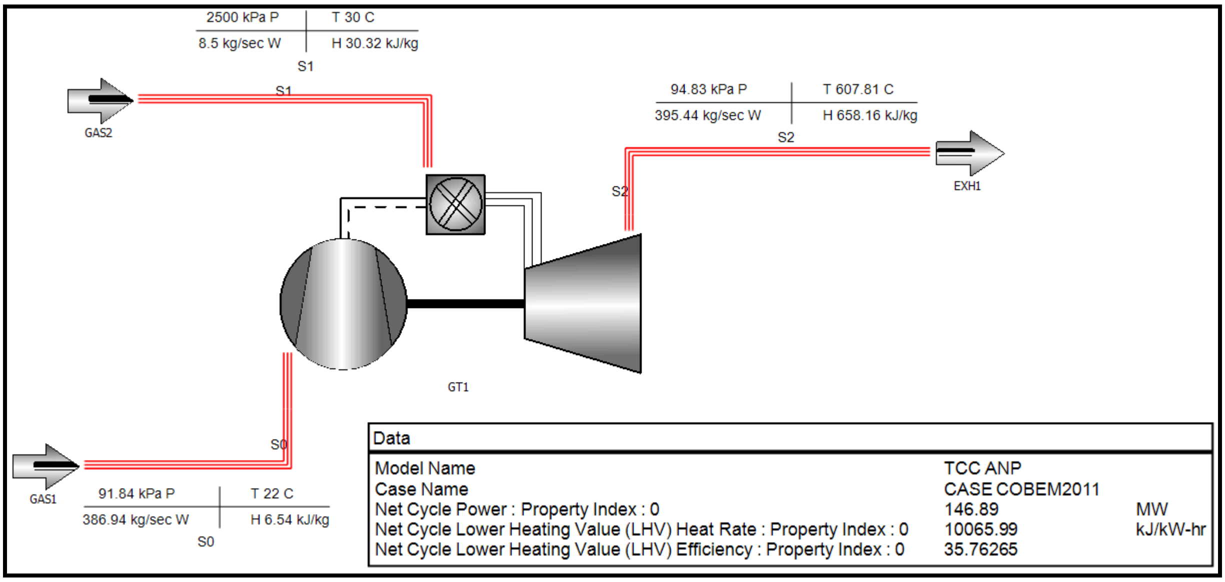

Figure 2. Reference model results.

Table 2. Monitored output variables and their values in the on-site condition

Performance Variables	***Value (V_{ref})****	***Unit***
Net Cycle Power	146.89	MW
Net Cycle LHV Heat Rate	10065.99	kJ/kW-h
Exhaust Gas Outlet Flow	395.44	kg/sec
Exhaust Energy	260262.79	kW

*See equation (1).

2.2. Acquisition of the performance curves

For the acquisition of the performance curves, variation ranges were defined to the input variables showed in the tables 3 and 4. From the input variables showed in the table 3, the first three are environmental variables. They are ambient temperature, atmospheric pressure and ambient relative humidity, and the other two are variables which refer to the compressor inlet pressure drop and turbine exhaust pressure drop. The table 4 presents the natural gas composition used in the simulations, which are representatives of the natural gas composition observed in different regions of Brazil (GASNET, 2011). The simulations in the variable ranges showed in the tables 3 and 4, with their respective complements were accomplished through CycleLink, a GateCycle supplement to Microsoft Excel, which makes possible the realization of the parametric studies. With the results of the parametric studies were calculated the correction factors, these ones are based on the relative difference between the reference value of the variable and the calculated value in the simulation. As an example of the obtained results, the figure 3 shows the behavior of the output variables based on the ambient temperature variation. In this graphic it is highlighted that the generated power by the turbine is a bigger change target with the ambient temperature variation.

Table 3. Variation range of the input variables

Input Variables	*Value*	*Increment*	*Unit*
Ambient Temperature	10 to 35	1	°C
Ambient Pressure	90 to 100	0.4	kPa
Ambient Relative Humidity	0.2 to 1	0.02	fraction
HRSG Press. Loss	1.24 to 3.98	0.1245	kPa
Inlet Press. Loss	0.24 to 1.49	0.0498	kPa

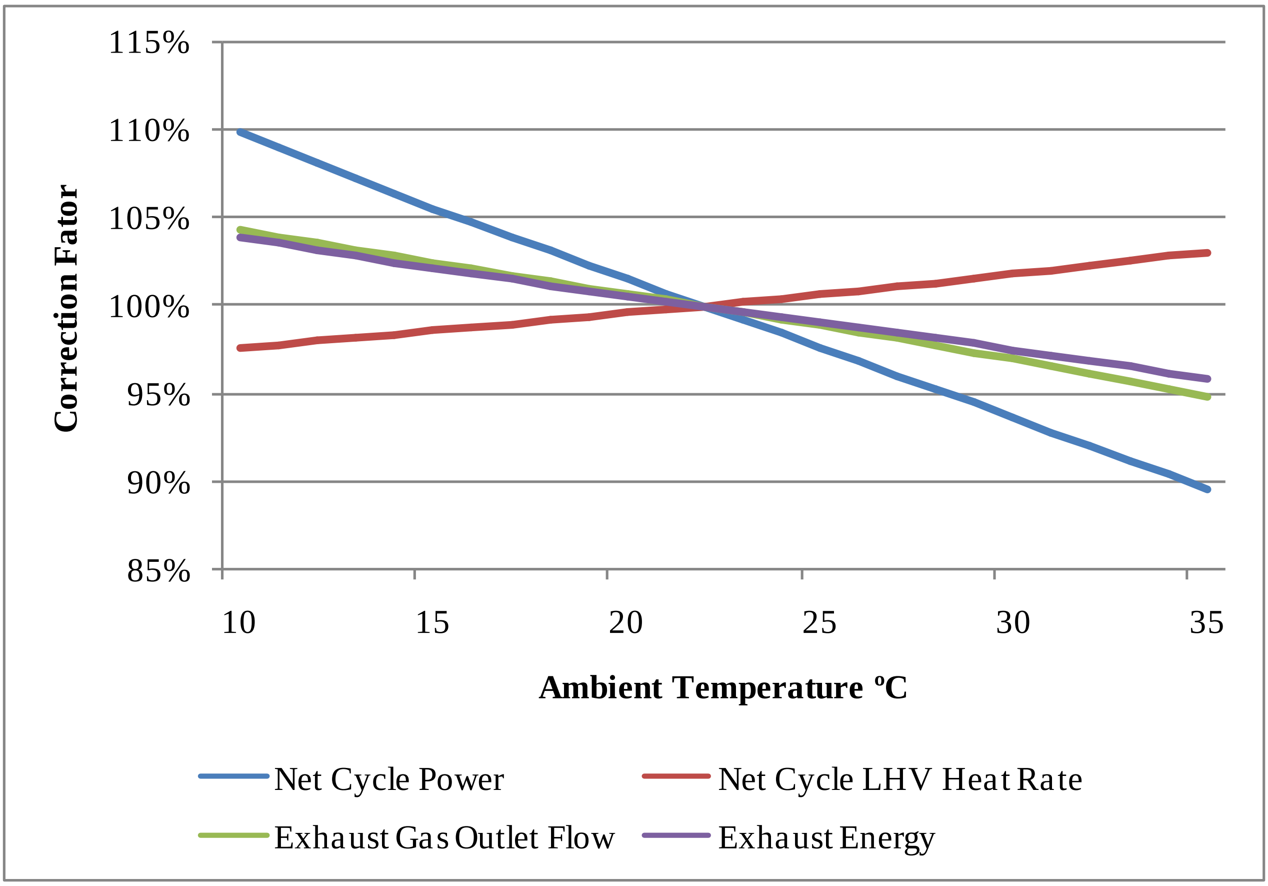

Figure 3. Behavior of the output variables based on the ambient temperature calculated with GateCycle

Table 4. Fuel compositions adopted in the simulations

Fuel Composition	***I****	***II***	***III***	***IV***	***V***
Fuel Gas CH_4 Mole Fraction	0.895	0.8673	0.843	0.893	0.8729
Fuel Gas CO_2 Mole Fraction	0.0048	0.0056	0.0312	0.0132	0.007
Fuel Gas C_2H_6 Mole Fraction	0.069	0.0966	0.1076	0.0726	0.0987
Fuel Gas Iso-Butane C_4H_{10} Mole Fraction	0.0016	0.0003	0	0.0002	0
Fuel Gas Iso-Pentane C_5H_{12} Mole Fraction	0.0004	0	0	0	0
Fuel Gas N_2 Mole Fraction	0.0074	0.0129	0.0157	0.0174	0.017
Fuel Gas n-Butane C_4H_{10} Mole Fraction	0.0025	0.0006	0	0.0002	0
Fuel Gas n-Pentane C_5H_{12} Mole Fraction	0.0004	0	0	0	0
Fuel Gas Propane C_3H_8 Mole Fraction	0.0189	0.0167	0.0025	0.0038	0.0044
Fuel Gas LHV (kj/kg)	48334	47801	44721	46675	47392

*Standard composition.

3. RESULTS AND ANALYSIS

3.1. Characteristic polynomials

The characteristic polynomials of the performance curves were obtained through a Linear Regression Tool of the software called EES (Engineering Equation Solver, 2009). In the figure 4 it is showed, as an example, the result of the linear regression for the liquid power variation based on the ambient temperature variation. To obtain the polynomials, firstly the tables of the values of the correction calculated at Excel with GateCycle are inserted, as it is possible to observe in the window Lookup Table in the example of the figure 4, where the column AT represents the variation of the ambient temperature and the columns W, HR, EF and EE represent the values of the corrections factors for power, heat rate, exhaust flow and the exhaust energy, respectively. In the window Linear Regression are defined the dependent and the independent variables, and also the order of the polynomial that is proper. In the window Linear Regression Coefficients are shown the results of the polynomial equation coefficients and different statistical parameters which represent the error size associated to the equation.

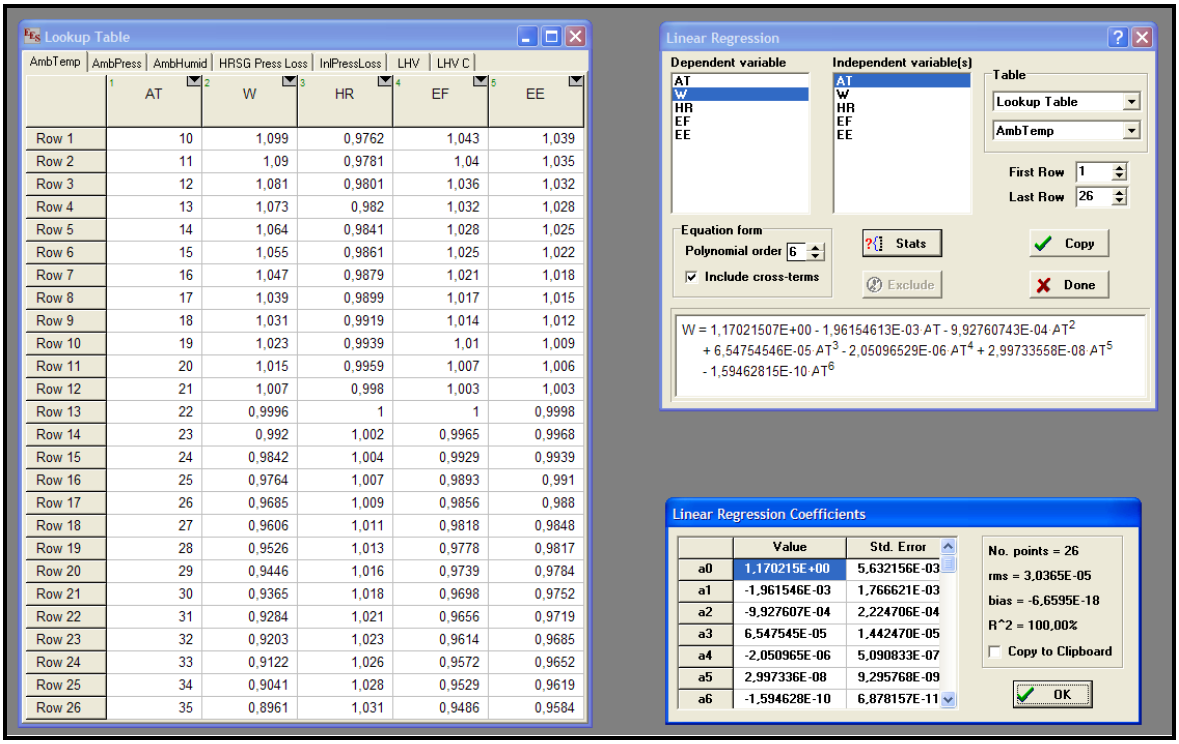

Figure 4. Result of the linear regression in the EES for the variation of liquid power based on the ambient temperature

In the table 5 all the coefficients of the calculated polynomials are presented. By the observation of the table 5 it is possible to appreciate that all the polynomials are closed to a first degree polynomial or, in other words, the variations of the development parameters obey to a bend.

Table 5. Coefficients of the polynomials obtained from the performance curves

Coefficients	*Net Cycle Power*	*Net Cycle LHV Heat Rate*	*Exhaust Gas Outlet Flow*	*Exhaust Energy*
Ambient Temperature (FC_1)				
a_0	1.170215	0.9553245	1.037661	1.060145
a_1	-0.001961546	0.002333366	0.008272426	0.003475216
a_2	-0.000992761	-4.66274E-05	-0.001480262	-0.000952045
a_3	6.54755E-05	3.32369E-06	9.09496E-05	6.0076E-05
a_4	-2.05097E-06	-1.50044E-07	-2.8648E-06	-1.90288E-06
a_5	2.99734E-08	3.92235E-09	4.46857E-08	2.8965E-08
a_6	-1.59463E-10	-3.94716E-11	-2.73545E-10	-1.67823E-10
Ambient Pressure (FC_2)				
a_0	-1310.358	214.876	-24.11454	-945.5234
a_1	59.69637	-9.970577	1.106703	43.16043
a_2	-0.9605572	0.1687484	-0.01755358	-0.6972363
a_3	0.004885907	-0.001047456	8.74997E-05	0.003608736
a_4	2.9477E-05	-2.20302E-06	5.66329E-07	2.04298E-05
a_5	-4.11148E-07	5.35088E-08	-7.68461E-09	-2.92436E-07
a_6	1.22527E-09	-1.71636E-10	2.27831E-11	8.75583E-10
Ambient Relative Humidity (FC_3)				
a_0	0.9877492	1.000044	0.9997396	0.9883542
a_1	0.06861843	-0.02612397	0.000884011	0.02394351
a_2	-0.2902908	0.1535184	-0.002765092	-0.03732046
a_3	0.744121	-0.4020948	0.006842845	0.09750669
a_4	-1.021321	0.5622831	-0.009102145	-0.1403871
a_5	0.716195	-0.4009534	0.00620644	0.1042037
a_6	-0.2015063	0.1144498	-0.001704775	-0.03096485
HRSG Pressure Loss (FC_4)				
a_0	1.004543	0.9848314	0.9997479	0.9823029
a_1	0.01504406	-0.000471057	0.000323156	0.01276618
a_2	-0.004626622	0.000384826	-9.34548E-05	-0.003592299
a_3	0.000625215	-3.18158E-05	1.30661E-05	0.000518336
a_4	-4.6271E-05	9.90986E-07	-9.97021E-07	-4.07027E-05
a_5	1.78245E-06	9.87895E-09	3.9455E-08	1.65202E-06
a_6	-2.79666E-08	-8.41092E-10	-6.33894E-10	-2.71341E-08
Inlet Pressure Loss (FC_5)				
a_0	1.01431	0.9963665	1.006902	1.007602
a_1	-0.007782492	0.000605054	-0.002826906	-0.004527636
a_2	0.002266544	0.001040077	7.30623E-05	0.001766344
a_3	-0.001153973	-0.000455889	-3.58308E-05	-0.000878821
a_4	0.000311569	9.92126E-05	9.17306E-06	0.000225951
a_5	-4.20446E-05	-1.01828E-05	-1.16934E-06	-2.87737E-05
a_6	2.22123E-06	3.83416E-07	5.84462E-08	1.43249E-06
Fuel Gas LHV (FC_6)				
a_0	3836.876	-1726.254	45.71084	1092.812
a_1	-0.7640308	0.3438401	-0.008903438	-0.2177528
a_2	5.70503E-05	-2.56599E-05	6.64903E-07	1.62812E-05
a_3	-1.89274E-09	8.50817E-10	-2.20667E-11	-5.40881E-10
a_4	2.35411E-14	-1.05759E-14	2.74572E-16	6.73631E-15

In off-design conditions, the calculation of the corrected value of the performance parameter in issue is accomplished by using the equations 1 and 2, which are showed in the sequence below:

$$V_{cor} = \prod_{j=1}^{6} FC_j \cdot V_{ref} \quad (1)$$

$$FC_j = \sum_{i=0}^{6} a_i . (V_{actual})_j^i \quad (2)$$

Where, in the previous equations:

V_{cor} Corrected value of the performance parameter for the real conditions of operation;
V_{ref} Reference value of the performance parameter;
FC_j Value of the calculated correction factor, which refers to the output *j*;
a_i Value of the coefficient *i* of the polynomial equation;
$V_{actaul\ j}$ Value of the input variable *j* in the real condition of operation.

3.2. Polynomials Test

The polynomials generated from the linear regression, accomplished in the EES, and the performance curves were tested. The test was achieved through the random variations of the input variables respecting the limits of the performance curves, in a total of 200 combinations. The figure 5 shows the values of the ambient temperature for each one of the 200 combinations. It can be noted that the random values were distributed in a big quantity in a track of temperatures between 10°C and 35°C as was showed in table 3. The other random values of the other input variables also showed the same characteristic, what made possible a big diversity of situations in which the polynomials were submitted to a test. These combinations were simulated in the polynomials and in the GateCycle for the results comparison.

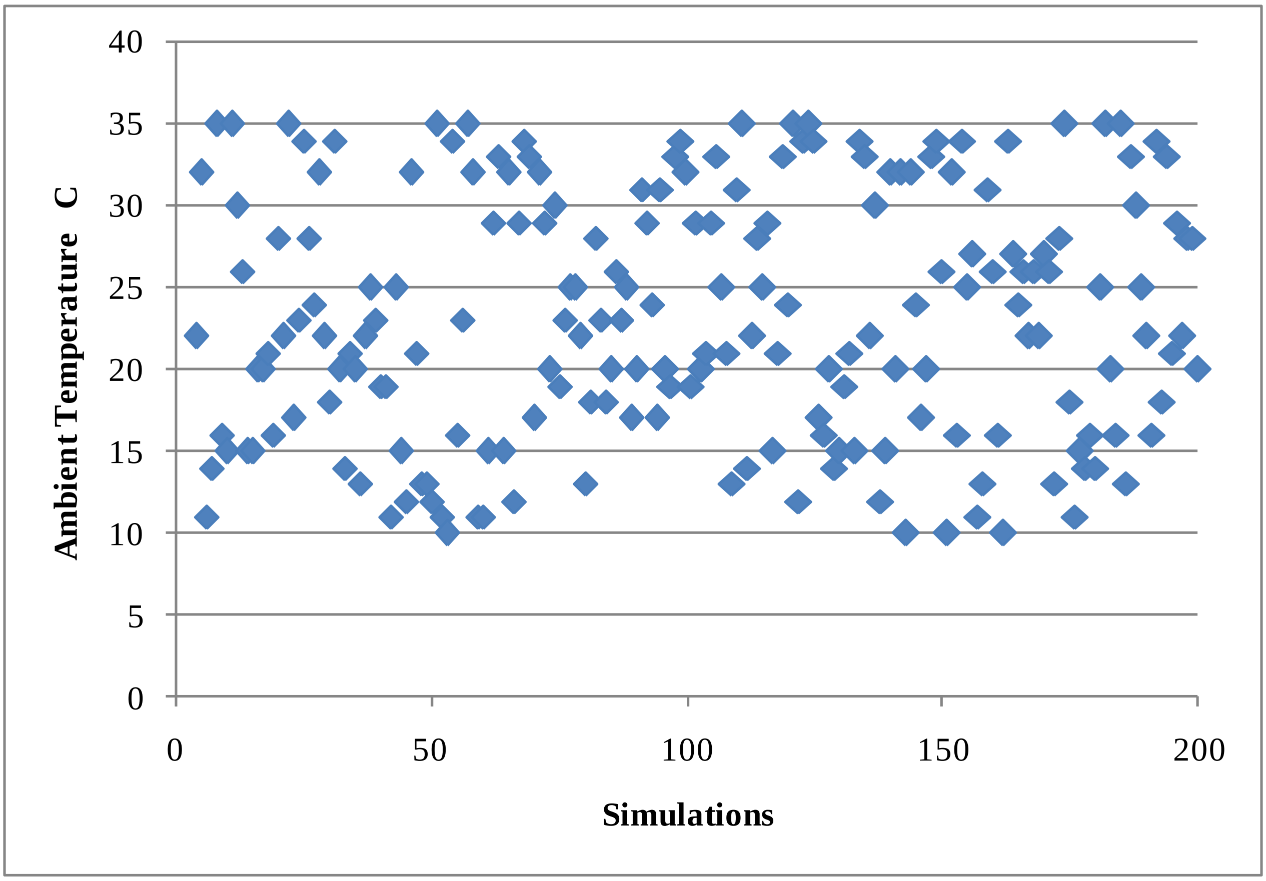

Figure 5. Random distribution of the temperatures for the test of polynomials

The values obtained in the tests of polynomials were compared with the values calculated by the GateCycle. The calculation of exhaust energy is the parameter where was verified the simulation with the biggest error (1,8%). The detailed analysis of this simulation shown that this error occurred in extreme situations with not easy incidence. The error average of the simulations for all output variables are under 0,5% (table 6). For 95% and 89% of the simulations that were done for both, exhaust flow and the exhaust energy respectively, shown an error less than 1%, which reveals a satisfactory result.

Table 6. Verified errors in the obtained values with the polynomials for each output variable concerning the GateCycle values

Performance Variables	***Minimum***	***Average***	***Internal Average (20%)***	***Maximum***
Net Cycle Power	0.001%	0.211%	0.201%	0.707%
Net Cycle LHV Heat Rate	0.061%	0.252%	0.251%	0.457%
Exhaust Gas Outlet Flow	0.002%	0.402%	0.375%	1.070%
Exhaust Energy	0.000%	0.456%	0.402%	1.839%

The figure 6 shows a comparison between the values of the parameters calculated by GateCycle and the ones calculated by the polynomials based on the ambient temperature. It is observed that there is an absolute coincidence between the values, as it can be observed in the position of the performance curves, which it is also observed for the other input variables studied. So, it can be affirmed that the obtained polynomials can be utilized to estimate the gas turbine GE 7FA performance from the project conditions which were predefined.

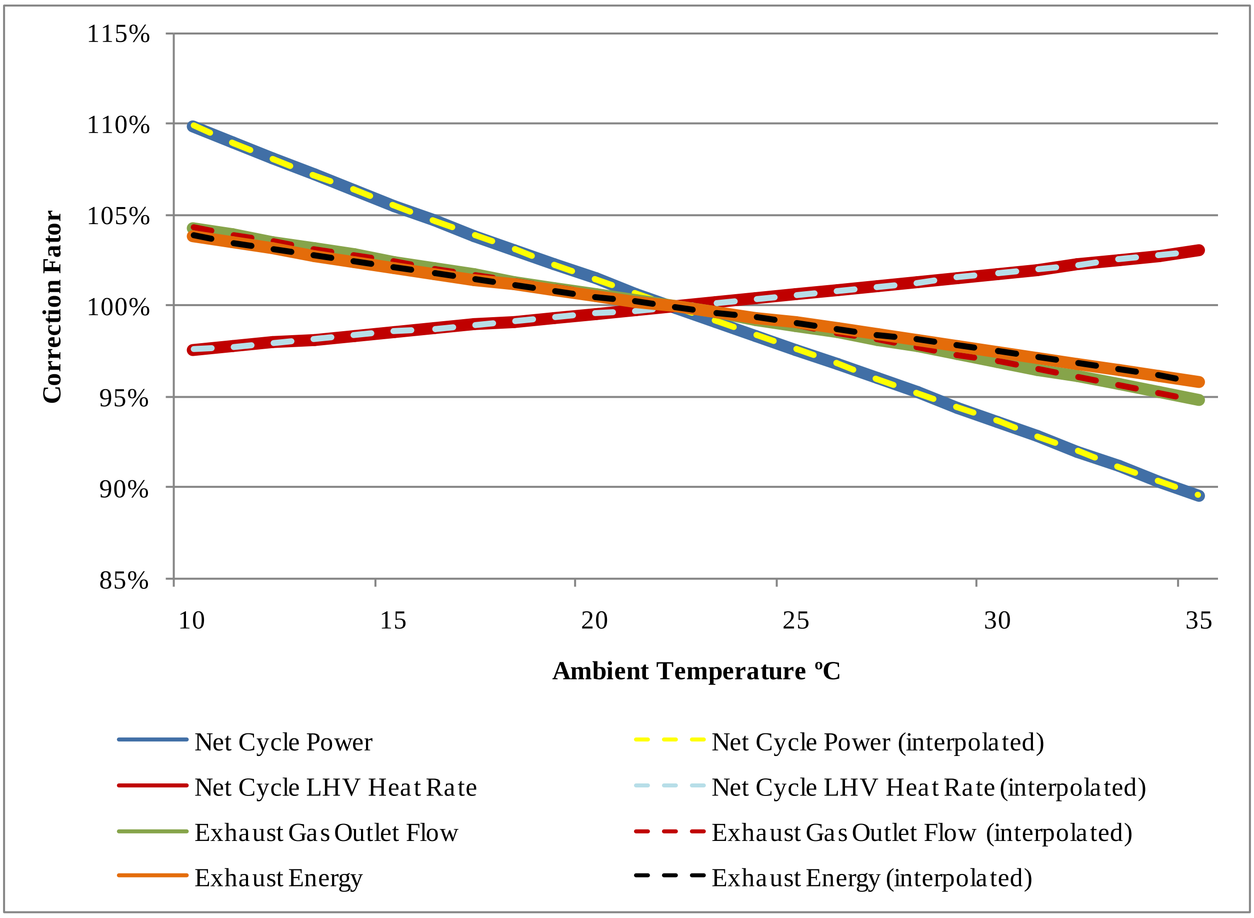

Figure 6. Comparison of the behavior of the performance output variables, based on the ambient temperature calculated, with the GateCycle and with the polynomials

4. CONCLUSIONS

The study realized regarding the gas turbine GE 7FA performance prevision allows us to establish the following conclusions:

- The error averages for all the output variables of the gas turbine GE 7FA performance prevision calculated with the obtained polynomial equations are below 0,5%;
- It was observed that, for 95% and 89% of the simulations that were done for both, exhaust flow and the exhaust energy respectively, shown an error less than 1%, which reveals a satisfactory result;
- The mathematics functions obtained for the prevision of the gas turbine GE 7FA performance allow us, with a maximum deflection of 1,8% verified in the exhaust energy, determine the corrected value of the performance parameters for the real condition operation;
- With the polynomial equations obtained for the gas turbine GE 7FA performance prevision, there will be possible to correct the effect of the environmental conditions variation, the fuel composition and the pressure drop at the compressor inlet and turbine outlet. From the considered input variable it was corroborated that the most influent between all the researched ones is the ambient temperature, considering that its raise tends to decrease the power and the energy of the gases in the output, whereas increases the heat specific consumption.

Finally, we would like to emphasize that the estimation of the gas turbine performance in off-design conditions is a complex process, and the presented equations are satisfactory for this purpose, but for greater accuracy and guaranty must be used the performance curves provided by the gas turbine's manufacturer. This paper was developed as part of a research project supported by FAPEMIG (Foundation for Research Support of Minas Gerais). The project aims to develop a computer interface in Microsoft Excel for Windows to diagnose the causes of degradation of thermal performance in industrial gas turbines for electricity generation from the simulation of operating conditions on performance tests, typical performance curves and the actual and reference conditions obtained from the simulation of thermal scheme of the gas turbine thermodynamic cycle. The project expects to be finished in December of 2011.

5. ACKNOWLEDGMENTS

We would like to thank the Pontifical Catholic University of Minas Gerais, Ibiritermo S/A and FAPEMIG (Foundation for Research Support of Minas Gerais) for the support given to the development and the elaboration of this paper, and to Marcus Vinicius de Macedo for the support with the English language.

6. REFERENCES

ANEEL, 2011. "Matriz energética – Empreendimentos em operação". Agencia Nacional de Energia Elétrica - ANEEL. Atualizado em 15/02/2011. 15 Feb. 2011. <http://www.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.asp.>.

Boyce, Meherwan P., 2002. "Gas Turbine Engineering Handbook". 2. ed. Gulf Professional Publishing an imprimint of Butterworth-Heinemann, 2002. 799 p.

Chase, D .L. and Rehoe, P. T., 2000. "GE Combined-Cycle Product Line and Performance". GE Power System. GER-35746. 2000.

Engineering Equation Solver, 2009. Engineering Equation Solver for Windows Professional Version 8 479-3D: 12/04/2009 Copyright© 1992-2009 S.A. Klein.

EPE, 2010, "Balanço Energético Nacional 2010: Ano base 2009", Empresa de Pesquisa Energética – EPE, Rio de Janeiro, Brasil, 276 p.

GASNET, 2011. "Gás natural". 15 Feb. 2011.<http://www.gasnet.com.br/novo_gasnatural/gas_completo.asp#gas12>.

GASMIG, 2011. "Composição do gás natural". 15 Feb. 2011.< http://www.gasmig.com.br/Gas/Composicao.aspx>.

GateCycle, 2010. Gate Cycle for Windows Version 6: Copyright© 1989-2010. The General Electric Company. All rights reserved. 2010. 1 CD-ROM.

Gebhardt, Eric., 2010. "GER 3950C - The F Technology Experience Story". GE Power Systems. Atlanta, GA. 2000. 26 Mar. 2010: <http://www.gepower.com/prod_serv/products/tech_docs/en/downloads/ger3950c.pdf>.

Maslak, C. E. and Tomilnson, L. O., 1996. "GE combined cycle experience". 39th GE Turbine State-Of-The-Art Technology Seminar. GER-3651E. USA. August. 1996.

MME and EPE, 2010, "Plano Decenal de Expansão de Energia 2019", Ministério de Minas e Energia – MME, Empresa de Pesquisa Energética – EPE, Vol. 1, Brasília, Brazil, 332 p.

6. RESPONSABILITY ADVICE

The authors are the responsible ones for the printed material included in this document.