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A PROCEDURE FOR COMMISSIONING A MICROTURBINE ELECTRIC ENERGY GENERATING POWER PLANT

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Abstract. Microturbine power plant performance procedures have been developed for commissioning purposes. When someone buys a plant, its start up can only be made when the measured performance matches the manufacturer values. Most procedures try to specify the test conditions, so that the measured values can be extrapolated for other conditions, including longterm ones. The following parameters are normally measured : power, gas consumption, emission values, electric energy quality (including harmonic distortion and frequency). Usually, the frequency of data acquisition is specified, so that the results be representative of equipment average behavior. However, no information is required as far as the stability of the test conditions is concerned. Also, the procedures usually specify the uncertainty of measuring instruments, without paying attention to the overall uncertainty of calculated parameters. In this paper, a methodology is presented to calculate the uncertainty of the main parameters, which are representative of the micoturbine performance, together with the analysis of the measuring instrument uncertainty that are required to achieve an overall parameter uncertainty as required for commissioning purposes.

Keywords: ***Microturbine, Commissioning, Distributed energy source***

1. Introduction

1.1 Testing guideline

The U.S. Environmental Protection Agency´s Office of Research and Development (EPA-ORD) operates the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative technologies through performance verification and information verification. Its goal is to further environmental protection by substantially accelerating the acceptance and use of improved and innovative environmental technologies. It is believed that there are many viable environmental technologies that are not being used for the lack of credible third-party performance data. With performance data developed under this program, technology buyers, financiers, and permitters in U.S.A. and abroad will be better equipped to make informed decisions regarding environmental technology purchase and use.

Under this program, a guideline for testing natural gas-fired microturbine electrical generators, used as a distributed energy source, was prepared (GHG-SRI-GD-03, 2002), which is the basis for this work. Distributed generation refers to power generation equipment, typically ranging from 5 to 1000 kW, that provide electric power at a site closer to customers than central station generation. A distributed power unit can be connected directly to the customer or to a utility´s transmission and distribution system. It can provide customers one or more of the following services : (a) Stand-by generation (emergency backup power), (b) Peak shaving capability (generation during high demand periods), (c) Baseload generation (constant generation), or, (d) Cogeneration (combined heat and power generation).

1.2 Overview of the microturbine technology

According to (GHG-SRI-GD-03, 2002), most microturbines operate on natural gas at a fuel pressure ranging from 3,5 to 8,5 bar (gauge), depending on manufacturer specifications. Those units requiring pressurized gas are offered with optional booster compressors that allow low pressure natural gas supply to be pressurized to the required operating condition. Specific design characteristics among different microturbines vary, but each type is comprise of four main sections : a compressor, a recuperator, a combustor, and a power generator. In the compressor section, combustion air is drawn into the microturbine and compressed. Normally, the compressed air is passed through a recuperator where the air is pre-heated using exhaust gas from the combustor. Use of recuperator results in significantly improved electrical efficiency. In applications where high temperature exhaust gases are desirable (cogeneration), the recuperator can be removed or bypassed. The compressed and pre-heated air is then mixed with with fuel in the combustor, and this mixture is burned under constant pressure conditions. The resulting hot gas is allowed to expand through the turbine section to perform work, rotating the turbine blades to run a generator that produces electric energy. On most microturbines, the compressor is mounted on the shaft as the electric generator, and consists of only one rotating part. Other units have a dual shaft design.

Because of the inverter-based electronics inherent to these systems, the generator can operate at high speed and frequencies, and the need of a gear box and associated moving parts is eliminated. On some systems, the high speed rotating part is supported by air-foil bearings and does not require lubrification, although some designs do use oil-lubricating bearings. The exhaust gas exiting the recuperator passes through a muffler before being discarded to the atmosphere. The exhaust from these units using a recuperator typically contain sufficient thermal energy for heating purposes , making a microturbine a good candidate for a co-generation application.

The permanent magnet generators supplied with microturbines produce high frequency alternating current which is rectified, inverted , and filtered by the the line power unit into conditioned alternating current at various voltage levels, depending on manufacturer. The output can be converted to the voltage level required by the facility, using either an internal transformer or external transformer for distribution, offered by most suppliers. Most units are equipped with sophisticated control systems that allow for automatic and unattended operation. Normally, all operations including startup, synchronization with the grid, dispatch, and shutdown, can be performed manually or remotely using these control systems.

1.3 Overview of the verification strategy for testing microturbines

In developing the verification strategy for testing microturbines, (GHG-SRI-GD-03, 2002) has applied existing standards for large gasfired turbines, engineering judgement, and technical input from industry experts. Performance testing guidelines (ASME-PTC22, 1997) have been adopted to evaluate electric power production and energy conversion efficiency performance. Some variations in the PTC-22 requirements were made to reflect the small scale of the microturbine. Exhaust stack emissions from stationary gas turbines, described in (EPA-40CFR60, 1999), have been adopted for criteria pollutant emissions testing. Power quality standards used for the verifications are based on (IEEE-519, 1993).

Using these reference materials, already used strategies and procedures, a site-specific approach was developed, as outline in four steps.

- Identification of verification parameters applicable to the unit being evaluated and its installation specifics.
    - Power production performance
    - Electrical efficiency
    - Electrical power quality performance
    - Operacional performance
    - Emissions performance
    - Estimated emission reduction
- Identification of detailed measurement requirements including instrumentation and test procedure.
- Development of a site-specific test plan that addresses each of the verification parameters based on the reference materials described above and guidelines presented here.
- Fiel evaluation of a test unit, data analysis and interpretation, and results reporting

Finally, the methodology was tested for a commercial supermarket (GHG-SRI-QAP-27, 2002)

1.4 Contribution of this work

All the procedures, as detailed by (GHG-SRI-GD-03, 2002) , together with the related equations, were followed in this analysis. However, due to the fact that the uncertainty analysis was not detailed, a procedure was developed to estimate the uncertainty analysis of each parameter, from literature and from measuring instrumentation specification, based on the respective equations and (ISO GUM, 1995), thus complementing the reference procedure. Then, the calculated uncertainty was used to analyze the measured data (GHG-SRI-QAP-27, 2002).

2. Testing procedures

Following is brief discussion of each verification parameter and their method of determination. Uncertainty parameters (95,45 % confidence level) are calculated in addition to the procedures.

2.1 Power production performance

The power production performance evaluation reports electrical power output and efficiency at selected loads and total energy generated.

2.1.1 Electrical Power output and efficiency at selected loads

Four load points are selected for verification : 50%, 75%, 90% and 100% of rated capacity. Electrical power output is determined with the use of a power meter, and fuel consumption rates are measured using a gas meter. Both meters are programmed to measured 1 (one) minute average readings that can be used to satisfy (ASME-PTC22, 1997) requirements. Fuel heating value is determined using local gas quality reported by the distribution company (CEG).

Efficiency determinations must be performed for continuous time periods in which maximum variability in key operational parameters do not exceed specified levels, Tab. (1). Testing of each of the four loads are conducted in triplicate over a 30 minute period.

Table 1. Maximum Permissible Variation in key operating conditions

Measured Parameter	Maximum Permissible Variation
Power output	± 2 %
Power factor	± 2 %
Fuel flow	± 2 %
Barometric pressure	± 0,5 %
Ambient air temperature	± 0,2 ^{o}C

Average electrical power output (P), in kW, is computed as the a average of 1-minute average reading (P_i) over the sampling period (N), in minutes (30).

$$P = \frac{\sum_{i=1}^{N} P_i}{N} \tag{1}$$

Repeatability (u_r) and uncertainty of power measurement (U_P) are calculated from power meter uncertainty (U_m).

$$u_r^2 = \frac{\sum_{i=1}^{N} \left(P - P_i\right)^2}{N-1} \tag{2}$$

$$u_m = \frac{U_m}{2} \tag{3}$$

$$u_P = \left(u_r^2 + u_m^2\right)^{1/2} \tag{4}$$

$$U_P = 2{,}09 \;.\; u_P \tag{5}$$

The average heat input (Q) over the same period, in kW, is determined by measuring the amount of consumed gas (G_i), in kg / s, and the Low Heating Value (LHV) of the natural gas, in kJ / kg.

$$Q = G.LHV \tag{6}$$

Repeatability (u_r) and uncertainty of gas measurement (U_G) are calculated from power meter uncertainty (U_m).

$$G = \frac{\sum_{i=1}^{N} G_i}{N} \tag{7}$$

$$u_r^2 = \frac{\sum_{i=1}^{N} \left(G - G_i\right)^2}{N-1} \tag{8}$$

$$u_m = \frac{U_m}{2} \tag{9}$$

$$u_G = \left(u_r^2 + u_m^2\right)^{1/2} \tag{10}$$

U_G=2,09 . u_G
(11)

Uncertainty of input energy measurement (U_Q) can be calculated from LHV uncertainty (U_{LHV}) and gas uncertainty (U_G), Eq. (11)

$$u_Q = Q.\left[\left(\frac{u_G}{G}\right)^2 + \left(\frac{u_{LHV}}{LHV}\right)^2\right]^{1/2} \tag{12}$$

$$U_Q = 2.\ u_Q \tag{13}$$

$$u_{LHV} = \frac{U_{LHV}}{2} \tag{14}$$

$$u_G = \frac{U_G}{2} \tag{15}$$

Electrical efficiency (η) at selected loads is calculated as :

$$\eta = \frac{P}{Q} \tag{16}$$

Efficiency uncertainty (U_η) is calculated from power uncertainty (U_P), Eq. (5), and heat input uncertainty (u_Q), Eq. (12) :

$$u_P = \frac{U_P}{2} \tag{17}$$

$$u_\eta = \eta.\left[\left(\frac{u_P}{P}\right)^2 + \left(\frac{u_Q}{Q}\right)^2\right]^{1/2} \tag{18}$$

$$U_\eta = 2.u_\eta \tag{19}$$

2.1.2 Total Electric Energy Generated

For 1-minute readings, the total testing period (T), in hours, is :

$$T = \frac{N}{60} \tag{20}$$

The total electric energy generated (E), in kWh, is

$$E = P.T \tag{21}$$

If the total electric energy generated (E) is measured continuously over the testing period, the uncertainty of measurement is equal to the power meter uncertainty. If it is calculated as a sum of N 1-minute reading, the total electric energy uncertainty (U_E) is equal to the power meter uncertainty multiplied by $\sqrt{N}$.

2.2 Power Quality Performance

All measurements were taken during a 30 minute testing period, for a 1-minute reading.

2.2.1 Electrical Frequency Output

The average frequency (F), in Herz, can be calculated as the average of all 1-minute readings (F_i)

$$F = \frac{\sum_{i=1}^{N} F_i}{N} \tag{22}$$

Repeatability (u_r) and uncertainty of frequency measurement (U_F) are calculated from frequency meter uncertainty (U_m).

$$u_r^2 = \frac{\sum_{i=1}^{N} \left(F - F_i\right)^2}{N-1} \tag{23}$$

$$u_m = \frac{U_m}{2} \tag{24}$$

$$u_F = \left(u_r^2 + u_m^2\right)^{1/2} \tag{25}$$

$$U_F = 2{,}09 \; . \; u_F \tag{26}$$

2.2.2 Voltage output and transient

Traditionally, it is accepted that voltage output can vary within ± 10 % of the standard voltage without causing significant disturbances to the operation of most end-use equipment. Deviations from this range are often used to quantify voltage sags and surges. All voltages were measured as root mean square, as usual for AC voltages. As for frequency, the following parameters can be calculated :

The average Voltage (V), in V, which includes sags and surges, can be calculated as the average of all 1-minute readings (V_i)

$$V = \frac{\sum_{i=1}^{N} V_i}{N} \tag{27}$$

Repeatability (u_r) and uncertainty of voltage measurement (U_V) are calculated from frequency meter uncertainty (U_m).

$$u_r^2 = \frac{\sum_{i=1}^{N} \left(V - V_i\right)^2}{N-1} \tag{28}$$

$$u_m = \frac{U_m}{2} \tag{29}$$

$$u_V = \left(u_r^2 + u_m^2\right)^{1/2} \tag{30}$$

U_V=2,09 . u_V (31)

Besides, the following parameters should be registered :

- Total number of voltage disturbances exceeding ± 10%
- Maximum, minimum, average, and standard deviation of voltage exceeding ± 10 %
- Maximum and minimum duration of incidents exceeding ± 10 %.

2.2.3 Voltage and Current Total Harmonic Distortion (THD)

Based on (IEEE-519,2002), microturbine manufacturers have specified a value of 5 % for the maximum total harmonic voltage and current distortion. For the verification, up to 63 th harmonic should be recorded. One (1) minute average should be used.

Voltage and Current THD can defined as the ratio between the sum of all harmonic intensities (up to 63 th harmonic) and the fundamental one.

2.2.4 Power factor

Power factor is the phase relationship between current and voltage in AC electrical distribution systems.

Most microturbines can be manually specified to deliver varying power factors. Continuous monitoring of power factor during test should be made.

2.3 Operational Performance

Microturbine start time is useful in knowing the time required to reach full power when backup power is needed, or when electrical power is needed during peak demand periods. It varies with temperature.

Availability is defined as the percentage of time the machine is unavailable due only to unscheduled downtimes.

2.4 Emissions performance

Exhaust gas emissions testing is conducted to determine emission rates for criteria pollutant (O_2, NO_x, CO, THC, CO_2 and CH_4). Stack emission measurements should be conducted in conjunction with the electrical power output and efficiency measurements in the controlled test periods, following the U.S. Environmental Protection Agency Standards of Performance of Stationary Gas Turbine (EPA-40CFR60, 1999). Tests should be conducted at four points, 50%, 75%, 90% and 100% full load capacity. The microturbine should be allowed to stabilize for 15 to 30 minutes before starting tests. Three (3) replicate test runs (each approximately 30 minutes) should be conducted for each parameter at each load selected. Tab. (2) presents the measurement EPA reference methods, principle of detection , typical analytical range and accuracy for each air pollutant.

Table 2 :Summary of emission testing methods

Air Pollutant	EPA Method	Principle of Detection	Range	Accuracy
O_2	3A	Paramagnetic or fuel cell	0 to 25%	± 5%
CO_2	3A	NDIR	0 to 10%	± 5%
NO_x	20	Chemiluminescence	0 to 25 ppmvd	± 2%
CO	10	NDIR-Gas Filter Correlation	0 to 25 ppmvd	± 5%
CH_4	18	Gas Chromatograph/FID	0 to 25 ppmvd	± 10%
THC	25A	Flame Ionization	0 to 25 ppmvd	± 5%

2.5 Electricity offsets and estimation of emission reduction

The electric energy generated by a microturbine will offset the electricity supplied by the grid whether the unit is operated in stand-alone mode or interconnected to the grid . Consequently, the reduction in electricity demand from the grid caused by this offset can result in changes of, primarily, CO_2 emissions associated with producing an equivalent amount of electricity at a central power plant, which must be estimated (GHG-SRI-GD-03, 2002).

3. Uncertainty calculations

The aim of this work is to estimate the largest uncertainty of each performance parameter, using ::

- Maximum Permissible Variation in key operating conditions, Tab. (1), type B uncertainty. It can be smaller, depending on the fluction during test.
- Measurement goal accuracy, Tab. (3), (GHG-SRI-GD-03, 2002), type A uncertainty. It can be smaller, depending on used meter uncertainty.

3.1 Measurement goal uncertainty

Table 3 : Measurement goal accuracy (GHG-SRI-GD-03, 2002)

Type of measurement	Measurement variable	Instrument range	Goal accuracy
Microturbine Output	Power	0 to 75 kW	± 0,2% of reading
	Voltage	0 to 480 V (3-phase)	± 0,1% of reading
	Voltage transient	600 to 8000 V	Not defined
	Frequency	49 to 61 Hz	± 0,01% of reading
	Current	0 to 200 A	± 0,1% of reading
	Voltage THD	0 to 100%	± 1% FS
	Current THD	0 to 100%	± 1% FS
	Power Factor	0 to 100%	± 0,5% FS
Booster compressor	Power	0 to 75 kW	± 0,25% of reading
Fuel Input	Gas flow rate	0 to 35 Nm^3/h	± 1% of reading
	Gas pressure	0 to 140 kPa (gauge)	± 0,75% FS
	Gas temperature	-50 to 400 ^oC	± 0,1% of reading
	Low Heating Value	0 to 100% CH_4	± 0,2% for CH_4 conc.
			± 0,2% for LHV
Ambient conditions	Temperature	10 to 50 ^oC	± 0,1 ^oC
	Pressure	500 to 1100 mbar	± 0,1% FS
	Relative humidity	0 to 100% RH	± 2% RH (<90%RH)
			± 3% RH (>90%RH)
Exhaust stack emission	NO_x	0 to 100 ppmvd	± 2% FS
	CO	0 to 1000 ppmvd	± 5% FS
	THC	0 to 100 ppmvd	± 5% FS
	CO_2	0 to 20%	± 5% FS
	CH_4	0 to 100 ppmvd	± 10% FS
	O_2	0 to 25%	± 5% FS
	H_2O	0 to 50%	± 5% FS

3.2 Low Heating Value (LHV) Uncertainty

The low heating value (LHV) uncertainty of the natural gas was estimated using data available for gas and liquid phase thermochemistry data (NIST,2004). The literature has a compilation of the available experimental data from different researchers, together with the estimated uncertainty, for each natural gas component. By calculating the maximum and the minimum values of the LHV, as indicated by the researchers, a range was determined to include all available data. The midpoint of this range was considered the average value of the LHV. The type B uncertainty was estimated as half this range.

The composition of the natural gas was obtained from the gas utility company data, considered as typical. It was obtained from chromatograph analysis, and its uncertainty was estimated in ± 1%, apparently, the lower limit of what some Brazilian laboratories have been estimating (± 1 to 2% range). Tab. (4) presents the data used to estimate the LHV uncertainty, for a typical natural gas composition.

The Low Heating Value of the natural gas (LHV) can be calculated from the composition (x_i) and Low Heating Value (LHV_i) of each component.

$$LHV = \sum_{i=1}^{N} x_i . LHV_i \tag{32}$$

The uncertainty of the Low Heating Value (LHV) can be calculated by propagating each uncertainty (ISO GUM, 1995).

$$u_{LHV} = \left[\sum_{i=1}^{N} (LHV_i . u_{x_i})^2 + \sum_{i=1}^{N} (x_i . u_{LHV_i})^2 \right]^{1/2} \quad (33)$$

$$u_{x_i} = \frac{U_{x_i}}{2} \quad (34)$$

$$u_{LHV_i} = \frac{U_{LHV_i}}{\sqrt{3}} \quad (35)$$

$$U_{LHV} = 2.u_{LHV_i} \quad (36)$$

Table 4 : Composition, LHV and uncertainties for a typical natural gas composition in Rio de Janeiro

Component	Composition (%)	Low Heating Value (kJ/mol)	
	x_i	LHV_i	$U_{LHV,i}$
CO_2	0,472	-393,51	± 0,13
CH_4	88,232	-73,73	± 1,43
C_2H_6	8,904	-84,33	± 0,83
C_3H_8	1,591	-104,21	± 1,00
iC_4H_{10}	0,064	-134,86	± 1,29
nC_4H_{10}	0,0891	-126,35	± 1,42
iC_5H_{12}	0,0091	-146,92	± 1,19
nC_5H_{12}	0,0076	-154,23	± 1,12
C_8H_{18}	0,0038	-224,10	± 1,30
H_2O	-	-241,83	± 0,04
		-76,3	± 1,6

Thus, the Low Heating Value of natural gas is (-76,3 ± 1,6) kJ/mol, or ± 2,1 %, well above of what is required as a goal in TAB. (3) (± 0,2 %). Probably, if one wishes to reduce uncertainty, a direct measurement of the Low Heating Value should be made. That will reduce its value to probably ± 0,5 %.

3.3 Uncertainty of performance parameters

Using as a type B uncertainty the maximum permissible variation in key operating conditions, Tab. (1), rather than the actual fluctuation (type A uncertainty), the standard uncertainty can be calculated by dividing this value by $\sqrt{3}$. Using goal accuracy in Tab. (3), and dividing Eq. (4) by P, and Eq. (10) by Q, the following uncertainties can be calculated, Tab. (5).

Table 5 : Maximum uncertainty of measured parameters and performance parameters (relative uncertainty with respect to the value of the parameter)

Parameter	Repeatability (%)		Meter Measurement (%)		Uncertainty
	Expanded	Standard	Expanded	Standard	(%)
	U_r	u_r	U_m	u_m	U
Power output	2	1,15	0,2	0,1	2,3
Fuel flow	2	1,15	1,0	0,5	2,5
LHV	-	-	-	-	2,1
Input Energy	-	-	-	-	3,3
Efficiency					4,0
Electric Energy			0,2	0,2	0,2

It can be seen that the most important factor for parameter measurement is the repeatability, not the meter itself. Therefore, if one wants to reduce uncertainty, the system must be as stable as possible.

3.4 Acceptance criterium

When commissioning a microturbine, one must know :

- Manufacturer performance data, for parameter, P
- Manufacturer uncertainty data, for same parameter, U_P
- Measured performance data, M
- Estimated performance uncertainty, U_M

The two average difference test can be applied, resulting in the combined uncertainty U, for one measurement.

$$U = \left(U_P^2 + U_M^2\right) \tag{37}$$

If a 5% significance level is accepted, the performance is considered acceptable, if the absolute value between manufacturer and measured data (D) is :

$$D \leq U \tag{38}$$

4. Conclusions

Based on the Greenhouse Gas Technology Center (GHG), a methodology was developed and critically examined for estimating the uncertainty of parameters in microturbine electric energy generation.

The Low Heating Value was calculated from natural gas composition and low heating value of each component, resulting in an uncertainty well above of what it is required in their methodology. Maybe, a direct measurement of the Low Heating Value would result in a rediction by a factor of 4.

The most important factor for performance measurement is the stability of the system. If a maximum permissible variation is allowed, following the values as indicated by GHC, uncertainties values for Power Output, Fuel Flow, Input Energy and Efficiency in the 2 to 4% range can be obtained, thus not being feasible for the purpose. In that case, the meter uncertainty can be larger, resulting in instrumentation cost reduction. Thus, it is recommended the the system be as stable as possible

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