Harmonic Distortion Analysis of a Micro Gas Turbine Interconnected to the Electricity Grid

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Abstract. Micro gas turbines have opened new opportunities for integrated energy systems using thermally activated technologies for waste heat recovery, improved overall efficiency and reduced emissions in commercial buildings and other small-scale polygeneration applications. However some issues are still unclear, such as the legal and technical issues regarding the electric grid interconnection. In this paper both issues will be addressed from the point of view of the electric system protections and the power quality supply with respect to harmonic distortion. The objective is to provide data and analyse the harmonic distortion of a low-pressure natural gas micro gas turbine of 28 kW_e interconnected to the grid. Additionally the main interconnection requirements and protection systems will be described.
The studied micro gas turbine cogeneration system is located in the Technological Innovation Centre CREVER at the University Rovira i Virgili in Tarragona (Spain).
The results obtained show that the harmonic distortion is clearly below the limits recommended by the existing international standards. Also the already built-in microturbine interconnection protections are enough to assure the correct operation and safety of the micro turbine system and the external grid. However increased communications and automation will be required to manage large amounts of distributed micro gas turbines generation systems connected to the grid.

Key words

Distributed generation, micro gas turbine, grid interconnection, harmonic distortion.

1. Introduction and objectives

Micro gas turbines have opened new opportunities for integrated energy systems using thermally activated technologies for waste heat recovery, improved overall efficiency and reduced emissions in commercial buildings and other small-scale polygeneration applications.
However some issues are still unclear, such as the legal and technical issues regarding the electric grid interconnection [1]. In this paper both issues will be addressed from the point of view of the electric system protections and the power quality supplied by microturbines. The measurement of harmonic distortion is an important issue in the power quality assessment for a given generator system [2]. Harmonic current and voltage distortion can cause overheating of rotating equipment, transformers, and current-carrying conductors, premature failure or operation of protective devices (such as fuses), deterioration of the electric power operation, and metering inaccuracies.
Power quality and grid safety are frequently the most limiting issues with respect to how much microturbine capacity can be accommodated without changes to the electrical distribution grid.

The objective of this paper is to provide data and analyse the harmonic distortion of a micro gas turbine of 28 kW_e interconnected to the grid. Additionally the main interconnection requirements and protection systems will be described.

2. Micro Gas Turbine Description

The studied micro gas turbine system is located in the Technological Innovation Centre CREVER at the University Rovira i Virgili in Tarragona (Spain). The components of this testing plant consist of a Capstone micro gas turbine, a heat recovery boiler and a heat dissipation system to simulate the heating load and a data acquisition system.

The micro gas turbine is a single shaft regenerative micro turbine that produces. three phase output of variable voltage proportional to speed and up to 480 V AC at 50 Hz. The microturbine produces 28 kW_e at full load and ISO conditions when is used with a low pressure natural gas supply and a gas compressor is required or 30 kW_e when it is used with a high pressure natural gas supply and a compressor is not necessary.
It uses a variable speed 2 Pole rare earth permanent magnet generator cooled by the air flow before entering the air compressor. The air is used as a motor during star-up and cooldown cycles.

The microturbine uses 3 fuel injectors and an igniter operated by spark exciter solenoid. The maximum rotation speed is around 96000 rpm, producing high-frequency (0 - 1600 Hz) AC power that is rectified to DC and finally converted to 50 Hz AC power by the power conditioning electronics of the digital power controller. Figure 1 shows a schematic of the complete electrical system. The exhaust gas is used to produce hot water at the selected temperature up to an operating temperature of 90ºC.

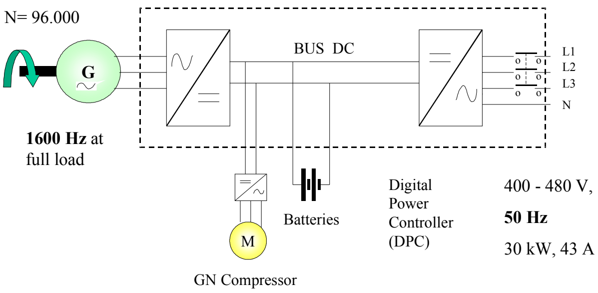

Figure 1. Diagram of the electrical system

The engine operation involves the following stages. Current is applied to the generator to rotate the shaft to draw air over the generator and to the compressor. The temperature of the compressed air is increased with the turbine exhaust heat as it passes through the recuperator. The fuel is metered to control combustion/temperature. The pressurised combustion gas is converted to shaft power as it passes through turbine wheel. The generator converts shaft power to electrical power, being the additional shaft power consumed by compressor. Turbine exhaust gas heats recuperator and remaining hot gas exits engine and enters the heat recovery boiler.

The starting process comprises the following steps:

1. Prepare to start: the microturbine checks all the connected systems and parameters.
2. Lift Off: the generator starts to rotate at 25000 rpm
3. Light Off: Combustion starts
4. Acceleration: the generator speed goes up to 45000 rpm Run: the temperatures increase in a idle condition.
5. Load: The seep is adjusted to the power demand.

A Schneider Electric CM4000 electric grid analyser is used to register voltage and current harmonics to study the dependency between the harmonic distortion and the electrical load. The measurements include the monitoring of voltage and current THD for each phase at different operating conditions.

The firsts results of the microturbine cogeneration plant operating as a stand-alone system were shown in [1]. Figure 2 shows a view of the microturbine test facility including the microturbine system (on the rightside of the picture) and the grid analyser enclosure (on the left side).

Figure 2. View of the micro gas turbine test facility in CREVER-URV (Tarragona).

3. Grid Interconnection of Microturbines

The objective to pursue with micro gas turbines and distributed generation systems in general is to take advantage of their benefits at the maximum level. This requires the extensive deployment of these technologies in commercial buildings and small industries. The basic problem is that most utility Electric Power Systems (EPS) were/are not designed to accommodate active generation and energy storage at the distribution level. Thus it is needed to develop technology and operational concepts that will enable realisation of micro gas turbine benefits while avoiding negative impacts on system reliability and safety.

The desirable features for the grid interconnection of distributed generation are [3, 4] :

- Interconnection costs must be minimal
- Interconnection equipment should be some fraction of the cost of the DER being connected.
- Utility involvement should be minimized
- Interconnection must be ‘simple’ so that it won’t discourage DER applications
- Interconnection apparatus should be ‘maintenance free’ as much as possible
- Interconnection operation should be ‘automatic’

The main difficulties are given by:

- Impact studies on the grid cost too much
- Some utilities use interconnection standards as a means of avoiding the deployment of small-scale distributed generation.

The IEEE is developing a standard (IEEE 1547) intended to address distributed generation without regard to prime mover (wind, fuel cell, etc) [5]. It attempts to address systems up to 10 Mw in size. The IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems was approved by the IEEE Standards Board in June 2003. It does not define the maximum Distributed generation capacity for a particular grid nor describes the self-protection requirements for distributed generation systems. This standard is divided in four documents:

a. IEEE P1547.1 Draft Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems. This standard specifies the type, production, and commissioning tests that shall be performed to demonstrate that the interconnection functions and equipment of a distributed resource (DR) conform to IEEE Standard 1547.

b. IEEE P1547.2 Draft Application Guide for IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems. This document facilitates the use of IEEE 1547 by characterising the various forms of distributed resource technologies and the associated interconnection issues. Additionally, the background and rationale of the technical requirements are discussed in terms of the operation of the distributed resource interconnection with the electric power system.

c. IEEE P1547.3 Draft Guide For Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems. This document facilitates the interoperability of one or more distributed resources interconnected with electric power systems. It describes functionality, parameters and methodologies for monitoring, information exchange and control for the interconnected distributed resources with or associated with electric power systems.

d. IEEE P1547.4 Draft Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems. This includes the ability to separate from and reconnect to part of the area EPS while providing power to the islanded local EPSs. The document is intended to provide an introduction, overview and address engineering concerns of DR island systems. It is relevant to the design, operation, and integration of DR island systems. Implementation of this guide will expand the benefits of using DR by targeting improved electric power system reliability

The micro turbine incorporates many of the grid and system protection features required for the interconnection to the grid, including the following built-in relay programmable functions:

- Under/over voltage
- Fast under/fast over voltage
- Over/under frequency
- Rate of change of frequency

The microturbine shutdown if any of the above parameters goes outside a specified value for a given set time. The inputs to the protection system provide protection system and equipment status, while the outputs provide interconnection functionality:

- Trip and close control
- Inadvertent utility energisation interlocks

The microturbine matches automatically grid frequency and voltage and requires an energised grid to operate and produce 400-480 V AC, 3 Phase, 50 Hz. This is important also for safety reasons because the personnel working on the distribution system must be protected from backfeed or accidental line energisation.
In the event of a grid failure the microturbine attempts to restart unless a user initiated shut down occurs.
Using an external power meter is possible to establish a reverse power protection in order not to export electricity, and also operate the turbine in the load following mode.
In dual mode the microturbine can be either grid connect or operate in standalone mode. Can run in grid connect and switch to standalone and switch back to grid connect. Switch over is automatic on grid failure. The dual mode controller accessory for this operation mode is not included in the basic microturbine package. Some or all the electrical loads can be protected by the microturbine in the case of grid failure as shown in the diagram of figure 3.
The system provides disturbance data capturing and sequential event reporting to easily trace faults.

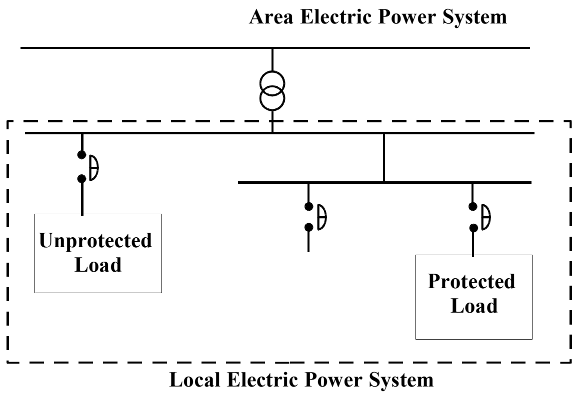

Figure 3. General connection diagram of a micro gas turbine with the electrical power system.

4. Harmonic Distortion Measurements

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate, termed the fundamental frequency; usually 50 o 60 Hz. Harmonics combine with the fundamental voltage or current, and produce waveform distortion. Harmonic distortion exists due to the non-linear characteristics of devices and loads on the power system. It is a growing concern for many users and for the overall power system due to the increasing application of power electronics equipment.

The voltage and current waveform for 28 kW_e and 24 kW_e are shown in figures 4 to 7. As it was concluded with the measurements with the microturbine working as a stand alone system [1] the waveform distortion is very low especially for the voltage waveform.

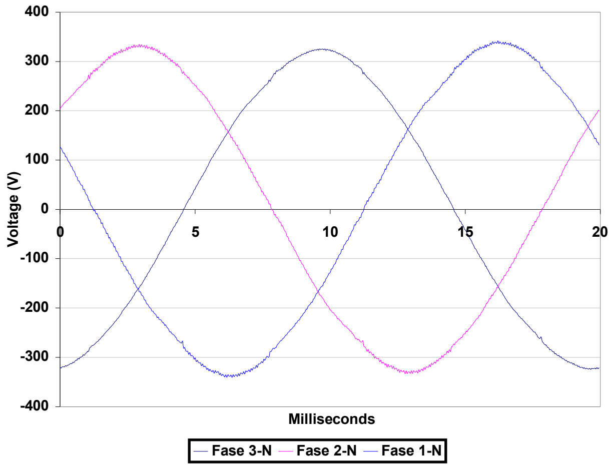

Figure 4. Voltage distortion at 24 kW_e.

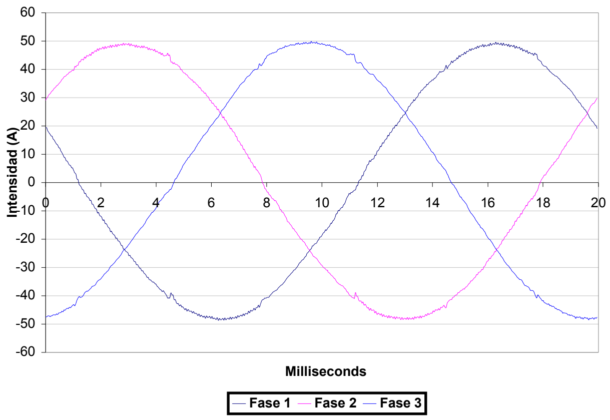

Figure 5. Current distortion at 24 kW_e.

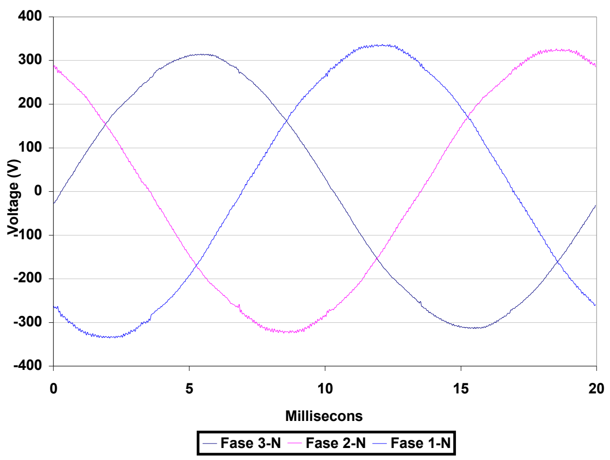

Figure 6. Voltage distortion at 28 kW_e.

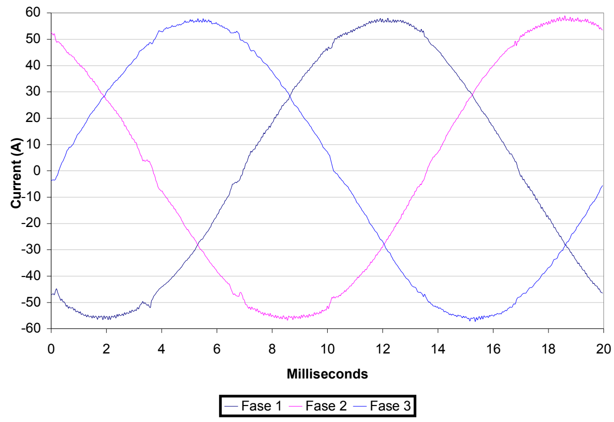

Figure 7. Current distortion at 28 kW_e.

Harmonic distortion can be characterised also by the complete harmonic spectrum with the magnitudes of each individual harmonic component. The harmonic spectrum obtained (figures 8 - 13) reveal that the voltage distortion is caused mainly by the 3rd, 5th, 7th and 9th order harmonics and for high-order harmonics the most significant are 210th and 214th. The largest low-order current harmonics are from the 2nd to the 7th, and for high-order are also harmonic 210th and 214th. This distribution holds for both microturbine electric loads measured. In figures 14 and 15 some values for the IEEE 519 [6], EN50160 [7], ER G5/3 and National Guideline (NL) are shown. The harmonic content of each individual harmonic is lower than the maximum values allowed for these international standards.
Additional measurements will be made to determine what level of background voltage and current distortion is preexisting on the system and how the harmonic distortion varies with unit start-up and shutdown.

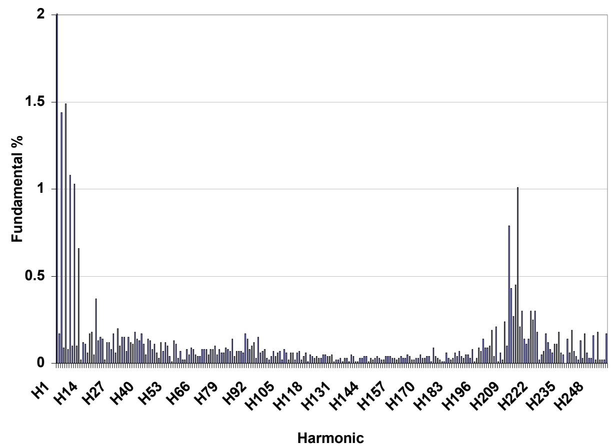

Figure 8. Voltage harmonic spectrum for 28 kW_e Phase 1-N

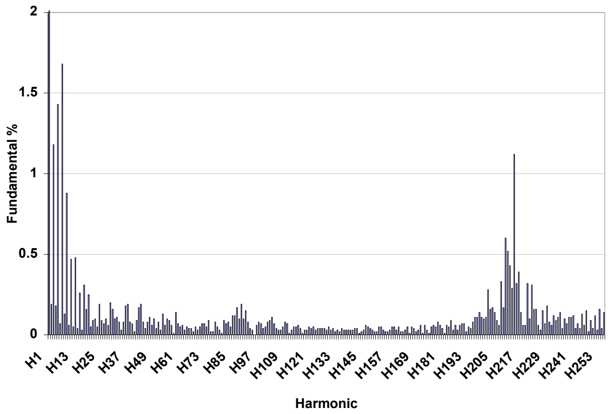

Figure 9. Voltage harmonic spectrum for 28 kW_e Phase 2-N

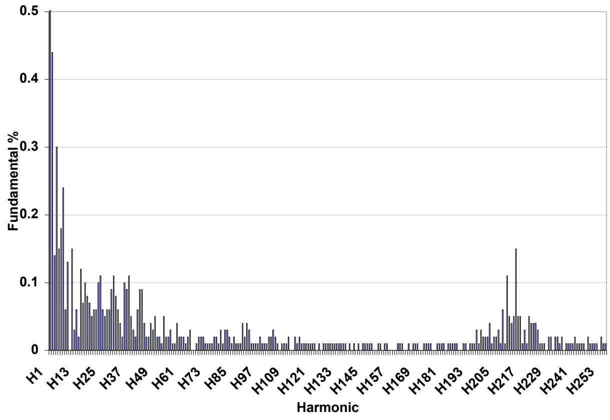

Figure 12. Current harmonic spectrum for 28 kW_e Phase 2-N

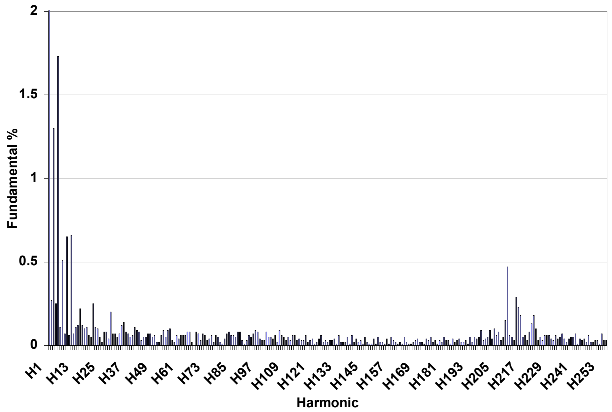

Figure 10. Voltage harmonic spectrum for 28 kW_e Phase 3-N

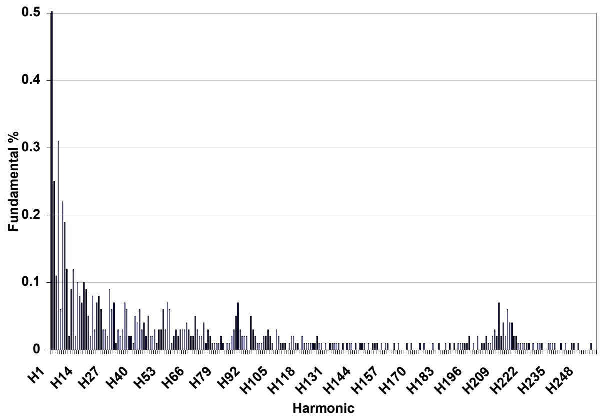

Figure 13. Current harmonic spectrum for 28 kW_e Phase 3-N

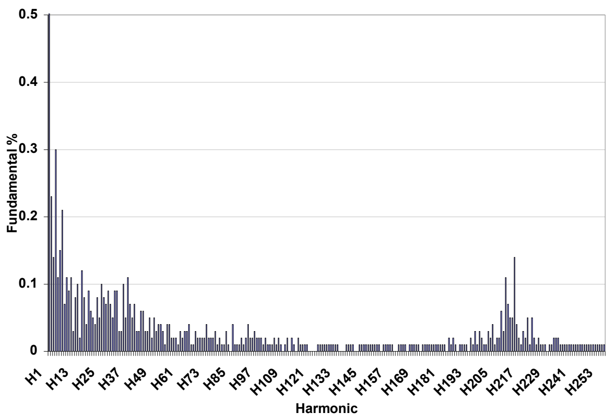

Figure 11. Current harmonic spectrum for 28 kW_e Phase 1-N

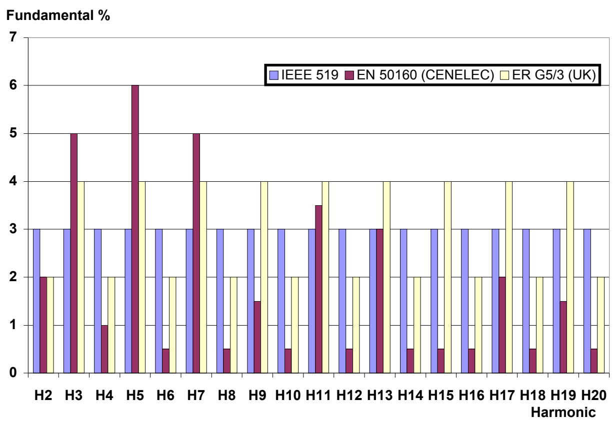

Figure 14. Some standards for voltage harmonics content.

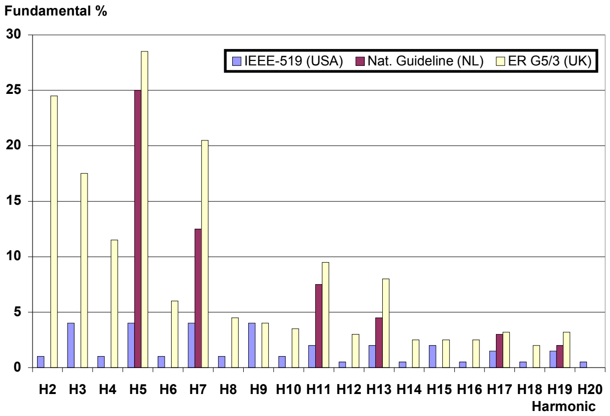

Figure 15. Some standards for current harmonics content.

The magnitude of the global harmonic distortion can be measured using a single quantity, the Total Harmonic Distortion (THD). Table 1 shows the obtained THD for 24 and 28 kW_e. In all the measured cases the average voltage Total Harmonic Distortion (THD) was lower than 2% (Table 1). The average current THD is higher than the voltage THD but it is also lower than 2% (Table 1). These results demonstrate that the microturbine power quality with respect to harmonic distortion complies with the existing international standards IEEE 519-1992 (IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems) and CENELEC EN50160-1999 (Voltage Characteristics of Electricity Supplied by Public Distribution Systems).

Table 1. Average THD for the tested micro gas turbine system.

	24 kW_e		28 kW_e	
	Voltage	**Current**	**Voltage**	**Current**
Phase 1-N	1.69	1.83	1.50	1.80
Phase 2-N	1.64	1.70	1.56	1.85
Phase 3-N	1.28	1.66	1.27	1.70

5. Conclusions

The deployment of micro gas turbines in large numbers can benefit the electric system reducing the electric peak demand, providing voltage regulation control and will contribute to alleviate the load of electrical transmission and distribution lines.

The results obtained show that the harmonic distortion of a micro turbine connected to a low voltage grid is clearly below the limits recommended by the existing international standards. Also the already built-in microturbine interconnection protections are enough to assure the correct operation and safety of the micro turbine system and the external grid. However increased communications and automation will be required to manage large amounts of distributed micro gas turbines generation systems connected to the grid.

Acknowledgement

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