1 ABB MT100 microturbine combined heat and power unit

Microturbines: speeding the shift to distributed heat and power

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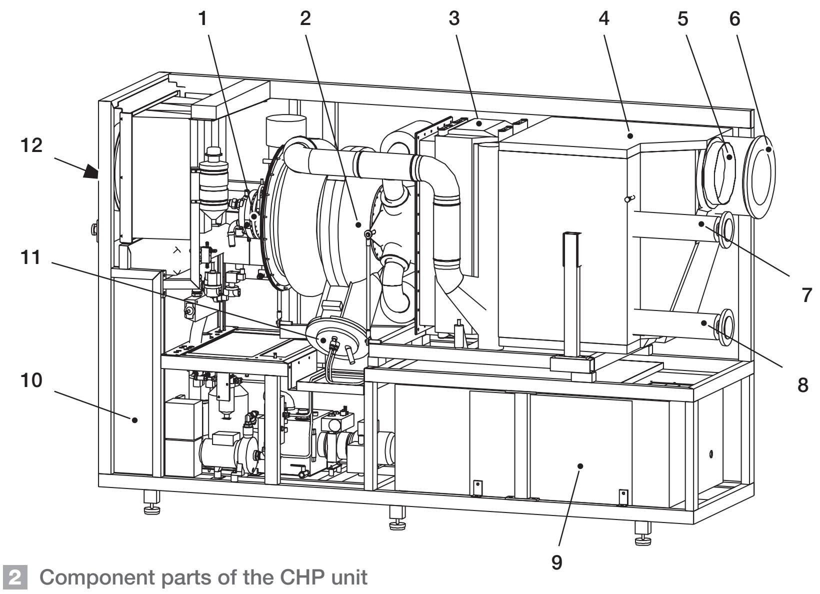
Fewer large power plants and overhead power lines, more efficient use of natural resources, and cheaper electricity – this scenario is within reach thanks to a brand new concept for distributed power generation. Key to its success is the microturbine – a small, highly efficient turbine that can be run on natural gas or biogas. Able to generate even more heat than electricity, the microturbine is eminently well suited as a power source for facilities ranging from hospitals and hotels to shopping malls and factories. With the help of telecommunications systems, such power plants can be linked together to create network solutions that will revolutionize how power is generated and delivered in the future.

As part of its business strategy, ABB Distributed Power Generation in 1998 set up a 50/50 joint venture with Volvo Aero Corporation to develop a new generation of microturbines. The partnership draws on Volvo's experience with gas-turbine-driven hybrid electric vehicles as well as ABB's experience in high-frequency power generation and conversion [1, 2].

The first product to come out of this new company, called Turbec AB, is the ABB MT100 Microturbine Combined Heat and Power unit 1. Run on natural gas, the ABB MT100 generates 100 kW of electricity and 167 kW of thermal energy.

At the heart of the ABB MT100 is a small gas turbine, mounted together with a compressor on a single shaft and integrated with a new high-speed generator, the HISEM 110/70.



2 **Component parts of the CHP unit**

1 *Generator,* 2 *Gas turbine engine,* 3 *Recuperator,* 4 *Exhaust-gas heat-exchanger,* 5 *Ventilation air outlet,* 6 *Exhaust outlet,* 7 *Water inlet,* 8 *Hot-water outlet,* 9 *Power electronics,* 10 *Control system,* 11 *Combustion chamber,* 12 *Air inlet*

A 'hot' new product with a string of benefits

Still a relatively new technology, microturbines have the potential to become a 'hot' product as the market grows and commercialization drives costs downwards. Features likely to speed up this development include:

- Compliance with the latest emissions standards
- Compact and lightweight, passes through a standard door
- Low noise level
- Minimal maintenance
- Remote control for unsupervised operation
- Low upfront investment due to series manufacture and simple design
- Fuel flexibility
- High efficiency

Designed for a new era of distributed power generation

The ABB MT100 microturbine is a combined heat and power (CHP) unit, ie it produces electricity and thermal energy. It is mounted in a small cabinet 2 and runs on natural gas. A compressor may be necessary, depending on the natural gas pressure. The ABB MT100 is designed for indoor installation and takes air from an outside intake. Its main parts are:

- Gas turbine engine and recuperator
- Electrical generator
- Electrical system
- Exhaust-gas heat-exchanger
- Supervision and control system

The technical data of the CHP unit are given in *Table 1*.

Table 1: ABB MT100 CHP unit - main characteristics

Property	Data
Dimensions	
Width	840 mm
Height	1900 mm
Length	2900 mm
Weight	2000 kg
Noise level	70 dB (A) at 1 meter
Performance[1)]	
Net electrical output	100 kW
Net electrical efficiency	30%
Net thermal output (hot water)	167 kW
Net total efficiency	80%
Volumetric exhaust gas emissions (15% O_2 and 100% load)	
NO_x	<15 ppm v
CO	<15 ppm v
UHC	<10 ppm v
Ambient inlet	
Air temperature	– 25°C to +40°C
Air inlet humidity	0-100%
Gas pressure min/max	6/9.5 bar (a)
Wobbe index	43–55 MJ/m^3
Mass flow, at 100 kW load (39 MJ/kg)	31 Nm^3/hour
Surrounding air	
Temperature	0°C to +40°C
Surrounding humidity	0–80%
Exhaust-gas flow	0.79 kg/s
Exhaust-gas temperature	55° C
Water inlet temperature	50° C
Water outlet temperature	70° C

[1)] Based on ISO conditions and taking into account power consumption and losses for all auxiliaries, including the gas compressor.

Design and operation

In the microturbine, a turbine wheel drives a compressor wheel mounted on the same shaft 3. The compressor feeds process air into the combustion chamber, where fuel is added and continuous combustion takes place.

The hot gas stream is expanded in the turbine, causing a large part of the thermal energy to be converted into mechanical energy, which drives the compressor and the load. In conventional power plants the load is either a two-pole or four-pole generator, driven via a gearbox. The generator speed is fixed, since it is synchronized with the frequency of an electric network. In the ABB MT100 microturbine the high-speed generator is coupled directly to the turbine shaft and a static frequency converter adjusts the speed electronically.

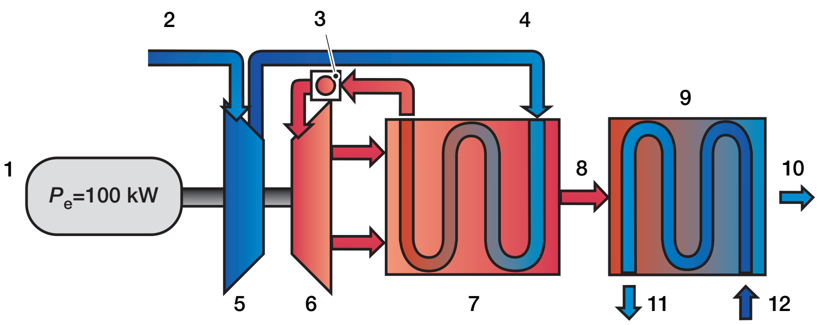
The remaining thermal energy can be dissipated through the stack, but such a gas turbine will suffer from poor efficiency unless several compressor and turbine stages are added. The ABB MT100 overcomes this problem with a recuperator, which recovers the exhaust heat and uses it to preheat the compressed air before it enters the combustion chamber. Less fuel is therefore required to reach the desired operating temperature. Another heat-exchanger, after the recuperator, heats the water in the external circuit.

Gas turbine emissions are very low as the continuous combustion can be carefully controlled. The external combustion chamber can also be optimized for low emissions.

Gas turbines often feature what is

3 ABB MT100: thermodynamic processes

1 *Generator,* 2 *Inlet air,* 3 *Combustion chamber,* 4 *Air to recuperator,* 5 *Compressor,* 6 *Turbine,* 7 *Recuperator,* 8 *Exhaust gases,* 9 *Exhaust-gas heat-exchanger,* 10 *Exhaust-gas outlet,* 11 *Hot-water outlet,* 12 *Water inlet*



known as 'variable geometry'; adjustable guide vanes control how the gas flows towards the turbine and compressor, allowing the operating point of the gas turbine to be controlled. Here too, the designers of the ABB MT100 took a different approach. The electric power generation system with the frequency converter permits variable-speed operation, which allows the power to be controlled by adjusting the turbine speed within a wide range. A simpler turbine concept can therefore be chosen, keeping product costs down. Details of the microturbine and a description of gas turbines in general can be found in [3] and [4], respectively .

Gas turbine engine

The gas turbine is a single-shaft engine with the following main components:

- Housing
- Compressor
- Recuperator
- Combustion chamber
- Turbine

Housing: The electrical generator and the rotating components of the gas turbine are mounted on the same shaft. The engine parts and the shaft are located in the same housing.

Compressor: In the ABB MT100, a radial centrifugal compressor is used to compress the ambient air. The pressure ratio is about 4.5:1. The compressor is

Microturbines: the 'upside' of downsizing

Following ABB's transformation into a knowledge company, ABB Distributed Power Generation was established as a new business unit to serve the changing power market.

Instead of selling hardware, the business of the new unit is to sell energy service solutions to customers in need of power, heating and/or cooling.

Selling service rather than equipment calls for a combination of technology and financing. ABB Distributed Power Generation installs, on the customer's premises, a compact generating unit which it owns, operates remotely and maintains as necessary. Customers pay only for the output, freeing up capital which they can invest in their core business.

How else does the customer benefit? By gaining a cost advantage over competitors in the marketplace. We are able to offer locally generated energy services at a lower price than with conventional solutions by avoiding the transmission and distribution costs, with heat provided as a useful by-product.

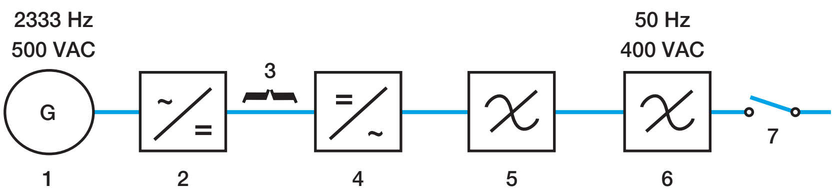
The second, and perhaps even more important, advantage to the customer lies in the power quality and safety areas. Although no longer so common, power outages still do occur occasionally. And each one poses a severe risk to the customer's processes, and by extension to his revenues. Installing a microturbine unit, combined with connection to the public grid, makes power outages extremely unlikely, thereby securing reliable operation for processes and computer systems, as well as an uninterrupted revenue stream.

Summing up: ABB is able to offer an energy service which costs less and offers more than competing solutions, and which requires no upfront investment by the customer. Typical application areas are office buildings, shopping centers, greenhouses, regions with a weak grid connection, hospitals, leisure centers, etc.

Transmission and distribution systems in some areas tend to be overloaded, and environmental or other legislation may make expanding them a long and tedious process. Using state of the art information technology, such as the Internet, a large number of microturbines and other distributed power generation resources can be linked and controlled by an operator who is in charge of what is, in effect, a large 'virtual' utility.

4 Schematic of the electric power generation

1 *Generator,* 2 *Rectifier/start-up converter,* 3 *DC bus,* 4 *Converter,* 5 *Line filter,* 6 *EMC filter,* 7 *Main circuit-breaker*



mounted on the same shaft as the turbine and the electrical generator.

Recuperator: The recuperator is a gas-to-air heat-exchanger attached to the microturbine. It increases the efficiency of the gas turbine by transferring the heat from the hot exhaust gases to the compressed air fed to the combustion chamber.

Combustion chamber: The preheated compressed air is mixed with the natural gas, and an electrical igniter in the combustion chamber ignites the mixture. The combustion chamber is of the lean pre-mix emission type, guaranteeing low emissions of NO_x, CO and unburned hydrocarbons in the exhaust gases.

Turbine: The radial turbine drives the compressor and the generator at a nominal speed of 70,000 rev/min. On leaving the combustion chamber the combustion gases have a temperature of approximately 950°C and are at a pressure of about 4.5 bar. As the gases expand through the turbine the pressure decreases to close to atmospheric and the heat drops to approximately 650°C.

Exhaust-gas heat-exchanger: The exhaust-gas heat-exchanger is of the gas/water counter-current flow type. It transfers the thermal energy contained in the exhaust gases, which enter the heat-exchanger at a temperature of approximately 270°C, to the hot-water system. The outlet water temperature depends on the incoming water conditions, ie its temperature and mass flow. The exhaust gases leaving the heat-exchanger pass through an exhaust pipe to the stack.

Supervision and control system

The ABB MT100 is controlled and supervised automatically by the Power Module Controller (PMC), so that in normal use the CHP unit can be left unsupervised. If a critical fault should occur, the PMC initiates either a normal stop or an emergency shutdown, whichever is necessary. A fault code is recorded by the PMC and shown on the display on the control panel.

The gas turbine and the electric power generation system are operated and controlled automatically by the PMC. Values from a number of sensors are needed by the PMC for this:

- Heat demand
- Electric power demand
- Gas pressure
- Oil temperature
- Vibrations
- Speed

High-speed electric power generation system

Small gas turbines benefit in particular when the gearbox that reduces the turbine shaft speed to the speed of conventional electrical machines is eliminated. The result is a more efficient, compact and reliable machine. With such a system, the shaft speed is normally above 30,000 rev/min and may exceed 100,000 rev/min.

High-energy permanent magnets and high yield-strength materials are state of the art, and have proved very suitable for high-speed electrical machines. For example, the use of neodymium-iron-boron (NdBFe) magnets reduces the generator rotor losses.

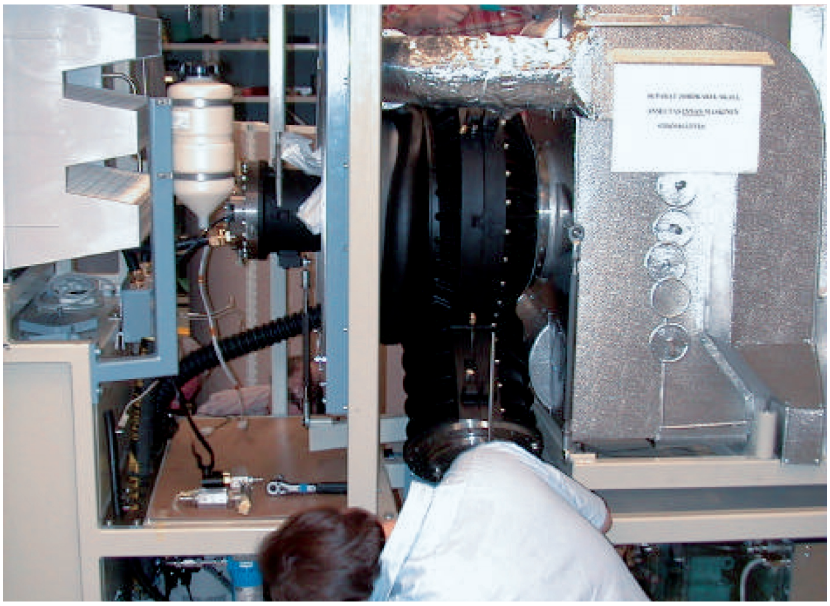
A prerequisite for direct mechanical coupling is highly efficient frequency conversion. Insulated gate bipolar transistors (IGBTs) not only provide this good efficiency, they can also be switched at an appropriately high frequency. Machines based on these devices are tailor-made for certain high-speed applications.

An advantage of the high-speed generator is that the size of the machine decreases almost in direct proportion to the increase in speed, leading to a very small unit that can be integrated with the gas turbine.

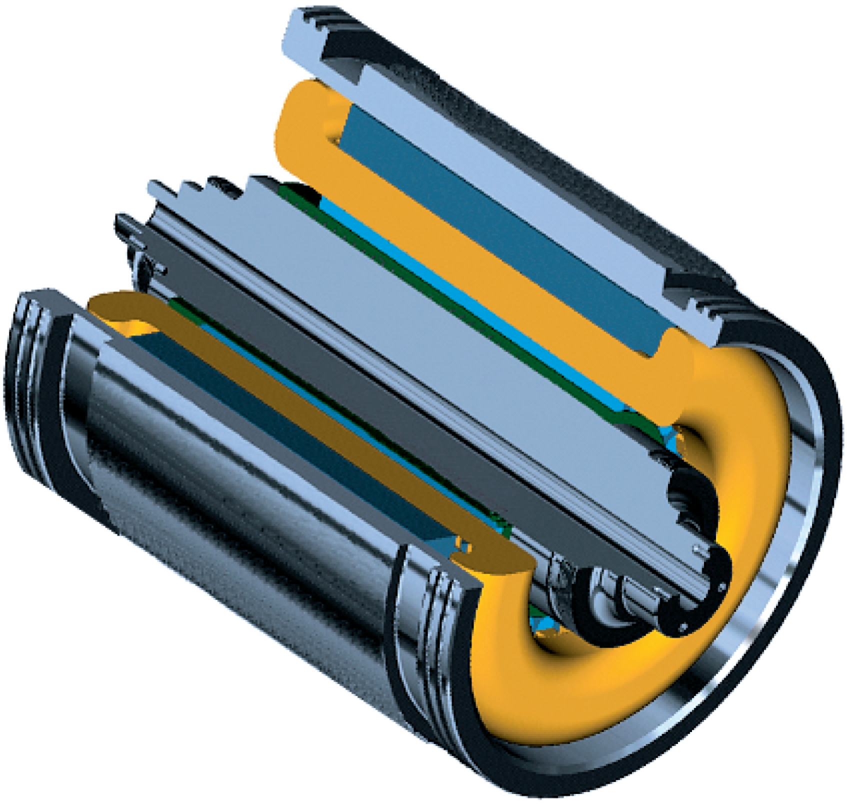
Electrical system

Before the generated power can be sent to the grid, it has to be converted to the grid frequency **4**. The AC of the generator is first rectified to DC and then

5 HISEM 110/70 generator and turbine being set up for testing



6 Cutaway view of the HISEM 110/70 generator



converted to three-phase AC. An inductor stabilizes the AC output, while an EMC filter protects the grid against generated interference. The electrical system can also be used as a power supply for starting the gas turbine.

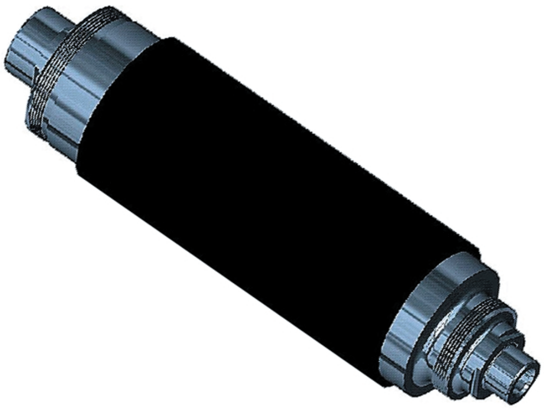
High-speed generator

The electric power is generated by an HISEM 110/70 high-speed permanent magnet synchronous generator, which is integrated with the microturbine 5. The rotor is suspended by one bearing on each side of the permanent magnet rotor; there are no additional bearings on the turbine shaft. The output frequency of the generator is high, being up to 2.3 kHz. The generator – acting as an electric starter for the gas turbine – also starts the CHP unit.

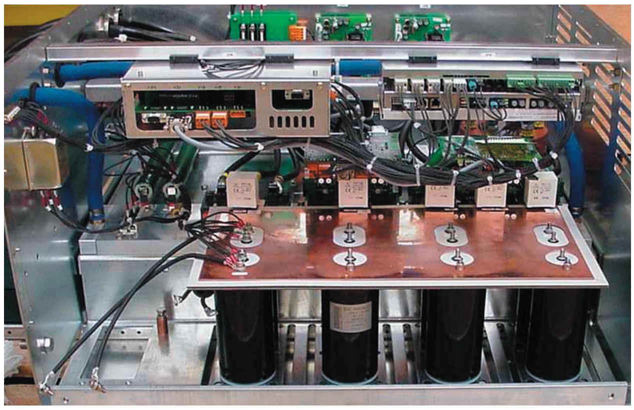
Generator design: The generator design is derived from the HSG100 generator [5], developed for use in hybrid vehicles. Experience gained from microturbine applications and the need to take account of some new requirements, have led to several major improvements, especially with regard to reliability and production costs. Also of benefit was ABB Motors' experience with high-volume production, which could also be incorporated in the design.

The generator stator can be seen in 6. Its core consists of thin laminations of low-loss electrical steel and the winding is made with litz wire to achieve good high-frequency characteristics. The four-pole arrangement contributes to short end-windings, making it possible to

7 Generator rotor



8 Frequency converter



keep the distance between the bearings short. Water-cooling is used to keep the temperature low in the winding. This feature, plus the vacuum pressure impregnation and extra insulation, ensures a long lifetime for the winding.

The rotor 7 consists of a magnetic steel body with surface-mounted permanent magnets. A carbon-fiber bandage holds the magnets firmly in place, even at 70,000 rev/min. As the operating conditions differ considerably from those for conventional machines, ordinary analytical programs are not enough for the electrical machine design. One hugely influential factor is the high fundamental frequency of 2.3 kHz at 70,000 rev/min, which makes the parameters of conventional design programs – parameters empirically determined over years of conventional machine design – invalid. A design strategy was therefore chosen that combines analytical calculations with finite element analysis.

The rotor radius is selected according to mechanical design criteria, and is a trade-off between an optimum bending stiffness and the largest magnet thickness that can be retained by a reasonably thin bandage. Using the rotor radius as a basis, the stator core radius and the axial length are determined in an iterative process. The discrete nature of the stator winding, with its very limited number of turns, is a key constraint.

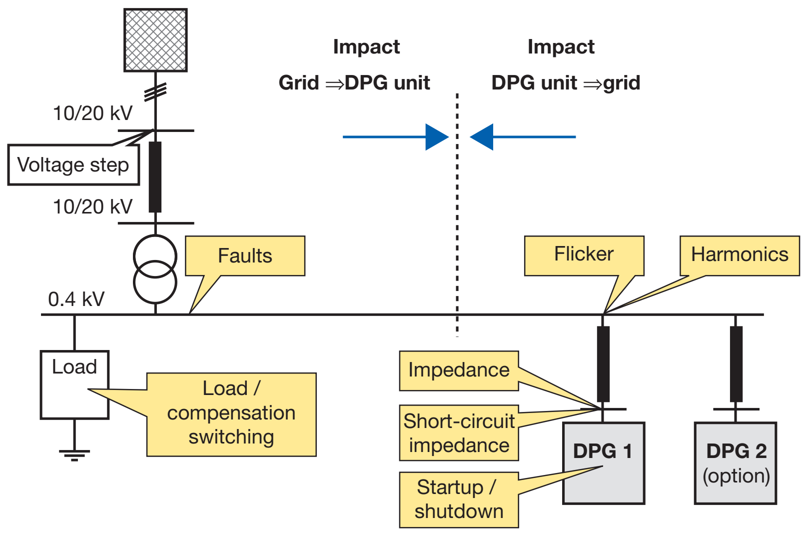
It is important to make sure that the rotor never reaches a temperature that would de-magnetize the magnet. This is ensured both by reducing the rotor losses and providing efficient cooling in the air-gap. Two factors, air friction and asynchronous mmf waves in the air-gap, are the main cause of temperature rise in the rotor. The latter is mainly due to harmonics in the stator current. Because the high speed causes high friction losses and the carbon-fiber bandage acts as a thermal insulator, the rotor is more sensitive to current harmonics than the rotor in a conventional machine. A current harmonics limit was therefore defined which is based on the acceptable rotor losses.

Frequency converter

The factors that provided the biggest challenge to the designers of the frequency converter were the high input frequency of 2300 Hz and the product cost target. The microturbine converter is derived from the ACS 600 converter platform, while the grid-side functions were available in the ACA 635 Inverter Supply Module. However, extensive application programming was needed to implement the interface and control functions required for the microturbine application.

The generator input stage, including the start-up converter, is based on hardware from the ACS 600, but a new control board had to be developed to regulate the speed of the turbine and control starting. In the start mode, the rectifier is used as an inverter to accelerate the turbine to 30,000 rev/min, the speed from which the turbine starts to produce net power for further acceleration to the operating range of 50,000 to 70,000 rev/min. The start-up converter acts as a rectifier and supplies electric power to the DC bus, from where

9 Grid interface problems having an impact on DPG units



the grid converter transfers it to the utility network.

The ACS 600 series converters are designed to operate in an industrial environment, while in the microturbine application they have to meet the requirements for residential area installations. Although distributed power generation applications are still a 'gray zone' with respect to grid regulations, it was decided to adapt the converter to comply with EN50081.

While the source of the functional hardware is the ACS 600 series, the mechanical installation has been tailored for the microturbine application 8. An important feature here is the use of water-cooling.

System analysis

In a typical microturbine application it is likely that the grid topology will not be known, so that controlling the system stability can be a challenging task. In cases where distributed power generation units have to be coordinated, the risk of grid instability may be very pronounced. Since there is more than one controller, even internal oscillations may appear all of a sudden, as tests on the pre-prototype CHP unit [7] at ABB Corporate Research in Dättwil, Switzerland, showed.

To avoid this kind of instability, different simulation models have been established. These were derived from previous work on the hybrid bus [6], from the topology of the CHP system and from measurements. Some of the models are time-domain-based and are used to understand and study the entire system as well as the different interfaces between the sub-systems. Possible problems are shown in 9. It goes without saying that ABB MT100 must be able to handle all of these without damage being caused to itself or to equipment outside of the microturbine system.

Other models are frequency-domain-based [8], allowing a more straightforward analysis and identifying possible locations of instabilities in the system, mainly towards the grid. This work is based on experience with railway systems, where a shutdown due to such instabilities occurred some years ago [9]. Such models are defined by generating a frequency spectrum of every component involved in the system, eg the inverter or a special type of grid topology. By combining these spectra and analyzing them, instabilities in the system can be rapidly located. This analysis results in the components – mainly the controllers – being designed such that stable interoperability of the entire system and its neighbors is ensured.

Maintenance concept

A key property of the ABB MT100 CHP unit is that it requires only very little maintenance. Preventive, ie scheduled, maintenance is divided into inspections and overhauls (see *Table 2*). Due to the

Table 2: Maintenance intervals

Type	*Interval (h)*	*Outage (h)*
Inspection	6,000	24
Overhaul	30,000	48

Table 3: Maintenance

Inspection	*Overhaul*
General checks	Same procedure as under 'Inspection'
Inspection of combustion chamber and replacement of fuel nozzle	Replacement of entire combustion chamber
Replacement of consumables, oil and water refill (if necessary)	Engine refurbishment
General visual check	New bearings for lubrication oil pump, ventilation fan and buffer air pump
Fuel gas compressor inspection, oil refill and change of oil filter	
New air filters	
Cleaning of cooling-water strainer	
New lubrication oil filter	

small number of moving parts, maintenance can be limited to the work shown in *Table 3*.

Outlook

The potential market for distributed power resources is a large and challenging one. To be successful in this market, a standard unit is required that is affordable, reliable and environmentally benign. The ABB MT100 microturbine meets these requirements with subsystems that have been derived from vanguard ABB technologies. Combined with IT functionality that provides safe, unsupervised operation, the ABB MT100 microturbine points the way to a whole new era in distributed power generation.

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