Recent developments of the OP16 gas turbine to meet the requirements for flexible CHP applications

Lars-Uno Axelsson, Sebastian Papst and Thijs Bouten

OPRA Turbines, the Netherlands

The trend towards more decentralized power generation in Europe has made small gas turbines an attractive complement to the large power plants. This trend, together with the increasing amount of renewable power feeding the grids, has led to additional challenges for the traditional power generation equipment. This includes more part-load operation, weaker electric grids, changing fuel compositions and new fuel sources. While facing these challenges the equipment still need to meet the stricter emission limits and the requirement for high efficiency. The OP16 gas turbine, rated at 1.85 MW electric power, is in operation at several industrial plants throughout Europe and more units will be commissioned during the coming years.

Due to the new challenges, the grid owners are implementing stricter regulations for the power generating equipment. One example is Germany, where the grid owners require the equipment to fulfill the guidelines from BDEW (Bundesverband der Energie- und Wasserwirtschaft e.V) covering the generating plants' connection to and parallel operation with the medium-voltage network. As part of this requirement the units need to complete and pass an extensive test campaign. Of particular importance during this test is to examine the so-called LVRT capability, i.e., the passing through voltage dips and simultaneous dynamic grid support for defined periods of time, as well as the active and reactive controls functional capabilities and accuracy.

As the first gas turbine, the OP16 successfully passed all the required tests in 2015. This paper will discuss the BDEW requirements and the associated challenges. Data from the testing of the OP16 will be used to exemplify the requirements.

1. Introduction

Combined heat and power (CHP) or cogeneration is the simultaneous generation of useful thermal and electrical/mechanical energy from one prime mover. The prime mover is typically a gas turbine or a reciprocating engine. By utilizing both the mechanical/electrical energy and the thermal energy high overall fuel utilization can be achieved. Depending on the prime mover and application the overall fuel efficiency can be between 70-90%. The exhaust heat can be used in many different ways including:

- Direct drying in industrial applications
- Steam generation for industrial applications
- District heating and cooling
- Electrical energy using (organic) Rankine cycles

The power generated by CHP installations has steadily increased in Europe from the early 90's up to today. Although Europe has a relatively large portion of CHP installations there is a huge variation between the countries. Today, about 20% of the total installed capacity of the conventional power plants in Europe is based on CHP [1]. However, only 11 of the 28 countries included in this statistics makes up for more than 85% of the total CHP capacity.

During the recent years small gas turbines have gained increasing popularity in CHP applications for small and medium size industrial applications. This trend, together with the increasing amount of renewable power feeding the grids, has led to additional challenges for the traditional power generation equipment. This includes more part-load operation, weaker electric grids, changing fuel compositions and new fuel sources. While facing these challenges the end users still need to meet the stricter emission limits and the requirement for high efficiency. In order to promote the development of energy efficient power solutions, certain countries within the European Union (e.g. Germany) have implemented subsidy schemes for "high efficiency" CHP installation. Such schemes have been proven to help smaller and medium sized industries to transit to more efficient and environmentally friendly power production by using combined heat and power solutions. With the increasing diversity of power generating equipment feeding to the electrical networks the owners/operators have found it necessary to enforce stricter requirements for these equipment. Germany is one example where the stricter grid regulations has added additional challenges for the OEM's and end-users.

The OP16 gas turbine, rated at 1.85 MW electric power, is in operation at several industrial plants throughout Europe with several units installed in Germany. With the new grid regulations in Germany the OP16 gas turbine has been required to undergo a detailed test program to obtain the certification. This paper will start with an introduction of the OP16 gen-set followed by a discussion of the grid requirements in Germany and the associated challenges. Data from the testing of the OP16 will be used to exemplify the requirements.

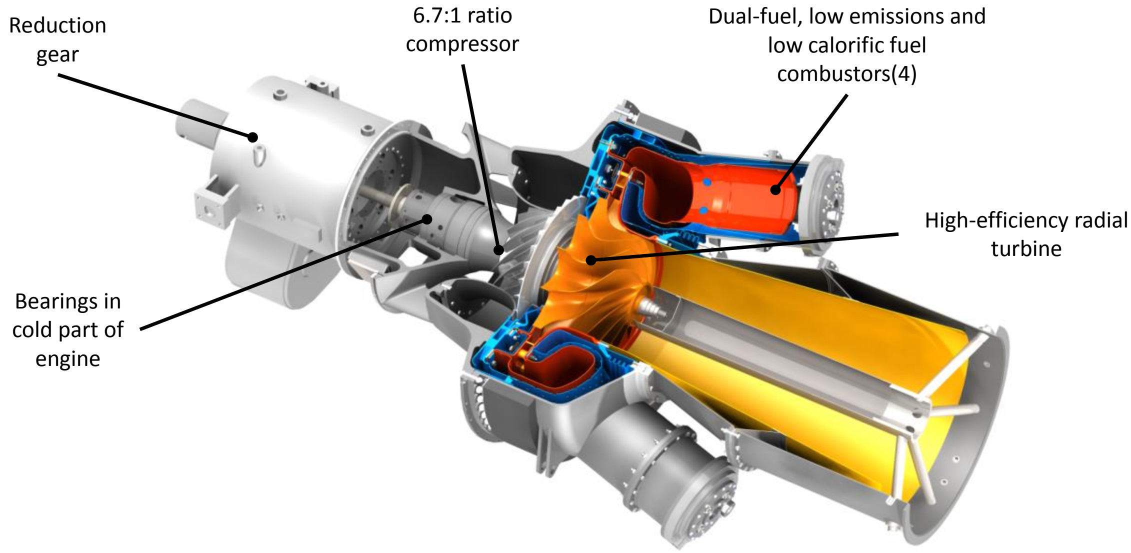

Figure 1 – The OP16 gas turbine

2. The OP16 gas turbine generator set

OPRA Turbines develops, manufacturers, markets and maintains gas turbine generator sets. The generator sets are powered by the robust and efficient OP16 gas turbine, which is rated at 1.85 MWe. The generator package is a containerized solution that includes the OP16 gas turbine, fuel systems, generator, control system, air intake and ventilation system. The generator sets can be provided in a variety of configurations to meet specific customer requirements. These sets can be installed as single or multiple units, covering installation requirements from 1.5 to 10 MW.

The OP16 (Figure 1) is a single-shaft all-radial gas turbine for industrial, commercial, marine and oil & gas applications. Since its market introduction in 2005 many generator sets based on the OP16 gas turbine have been delivered worldwide and the fleet has accumulated 2 million operating hours. The OP16 gas turbine features a single stage centrifugal compressor with a nominal pressure ratio of 6.7:1. The moderate pressure ratio reduces the need for gas compression prior to introducing the fuel into the gas turbine. The radial turbine wheel, which is mounted back-to back with the compressor, has been aerodynamically optimized to achieve a high efficiency. The compact compressor/turbine configuration permits the use of an overhung rotor assembly where the bearings are located on the cold side only. The all-radial configuration makes the OP16 robust and insensitive to foreign object damages and fuel contaminants. The combustion system consists of four can combustors mounted in a reverse flow direction. This is convenient for the maintenance as well as to provide uniform temperature and flow distribution into the turbine.

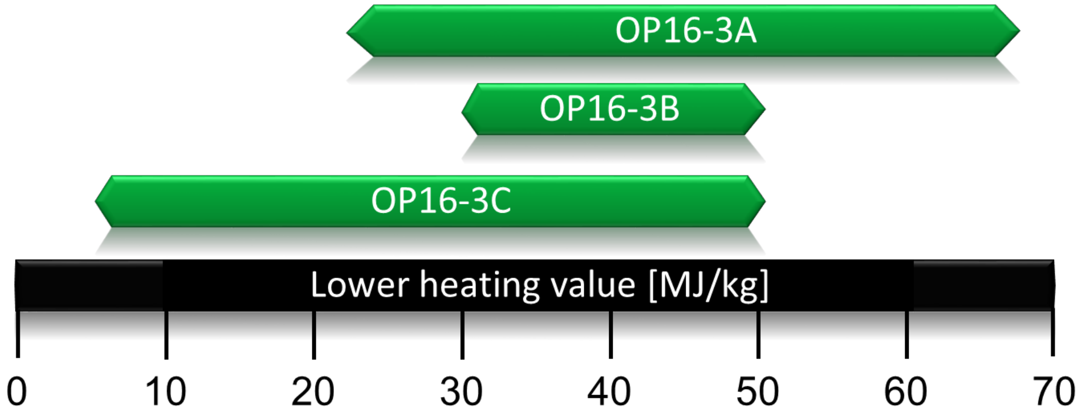

Figure 2. The lower heating value range (indication) for the OP16 product line.

The OP16 product line consists of three different configurations. All configurations have the same engine core and differ only by the combustion system. The OP16-3A has a conventional combustor operating with a diffusion flame. It was introduced in 2005 and can handle a wide range of gaseous fuels including natural gas, biogas, hydrogen rich gas and syngas. The OP16-3A has dual-fuel capability and can operate on both liquid and gaseous fuels including switch-over at full load operation. The OP16-3B configuration was introduced in 2007 to meet the more stringent emission requirements in Europe and globally. It features a low-emission combustor operating with a lean pre-mixed flame. Although it is intended for natural gas operation it can also operate on liquid fuel as a back-up fuel (diffusion flame). The third configuration is the OP16-3C, which was introduced in 2014. This configuration has been developed to meet the increasing demand to utilize (ultra) low-calorific gaseous and liquid fuels including waste gas, syngas, biogas, ethanol and pyrolysis oil. A summary of the typical lower heating value range for the different configurations are provided in Figure 2. For more information about the operation on alternative fuels and the fuel flexibility capabilities of the OP16 the reader is referred to *Axelsson and Beran* [2], *Beran and Axelsson* [3] and *Bouten et.al.* [4].

The OP16 gen-set consists of two 20-feet containers (Figure 3). The lower module houses the gas turbine and generator as well as the auxiliary equipment including oil system, electro-hydraulic starting system, gas and/or liquid fuel system. The upper module is the filtration and ventilation module. The gas turbine gen-set has been designed in a modular way to enable easy and fast adaptation of the product based on the customer requirements. This is essential in order to minimize the lead time as well as the commissioning time on site. The complete gas turbine train and associated equipment mounted on the skid are protected by a weatherproof, insulated and sound attenuated enclosure. The doors on the enclosure walls are designed to enable easy access to all equipment in the enclosure and to enable removal of the engine and generator from either side of the package. The weatherproof ventilation and air intake system is directly mounted on the top of the main enclosure.

Figure 3. The OP16 modular package.

The OP16 gen-set have certain features making it well-suited for the demand from the market for increased flexibility. The simple and robust all-radial configuration permits fast start-up of the unit as well as the possibility to handle large load steps and load sheds. The capability to handle large load sheds is becoming increasingly important as the electric grids are becoming weaker and grid failures are more likely to occur. However, if there is a grid failure and the breaker opens the OP16 gas turbine control system will ensure that the engine will stop in a safe way and the direct re-starting capability enables the operator to re-synchronize quickly and be back online very shortly. Furthermore, by having the bearings located only in the cold section there is virtually no lube oil consumption. An additional benefit of having the bearings in the cold section is that the exhaust is free of oil, which might not be the case if bearings are located in the hot section as the oil might leak into the exhaust. Having a clean exhaust is very important for CHP application where the heat is used for food processing applications, as well as for safety reasons.

To reduce the commissioning time on site it is important to be able to test as much as possible of the unit before shipment. In order to address this, OPRA has invested in test facilities to be able to test the complete gen-set prior to shipment. This test cycle includes I/O checking, control system functionality and load testing.

3. Grid requirement compliance in Germany

Due to the new challenges, the grid owners are implementing stricter regulations for the power generating equipment. One example is Germany, where the grid owners require the equipment to fulfil the guidelines from BDEW (Bundesverband der Energie- und Wasserwirtschaft e.V) covering the generating plants' connection to and parallel operation with the medium-voltage network [5]. As part of this requirement the units need to complete and pass an extensive test campaign. In the case of the OP16 gas turbine, and other smaller gas turbines, the guideline for generating plants' connection to and parallel operation with the medium-voltage network need to be fulfilled. Similar to the high and extra-high voltage level, generating plants supplying medium-voltage networks will have to contribute to the network support in the future. This means that in the event of failures the generating plants must not be immediately disconnected from the network. In addition, they have to contribute to the voltage stability in the network during normal operation. All of this is to ensure security and reliability in the power supply. As part of this certification, power generating units need to undergo a significant test campaign where the following power generation characteristics need to be tested and verified:

- Active and reactive power generation in normal operation
- Network disturbances
- Performance in case of grid and system failures
- Verification of the grid connection conditions
- Disconnection functions

4. BDEW certification testing of the OP16 gas turbine

The testing of the grid compliance requirements were performed in the summer of 2015 in Aachen, Germany. For these tests OPRA partnered with Windtest Grevenbroich GmbH for the measurements. The measurements was performed at the Institute for High Voltage Technology at RWTH Achen. This test site is operated by P3 Energy and Storage GmbH. This chapter will provide an overview of the most significant tests conducted, namely the active power dynamic response, reactive power dynamic response, grid failure performance and network disturbances.

4.1. Active power dynamic response

For the OP16 gas turbine the control of the active power output is done within the PLC controller. The active power can be provided in three ways; remote control with an external interface, via the human machine interface (HMI) or with an analog signal. Of importance for the certification is the accuracy of the active power with respect to the set-point value. BDEW requires a maximum tolerance of 5% from the set-point. Figure 4 shows the active power output (black) and the active power set-point signal (red) during load changes. The highest deviation was found to be about 1.25%, which is significantly lower than the requirement of 5%. Note also the full load step from 0-100% performed at the end of the test. It shall also be noted that no disconnection from the grid took place during this testing and the gen-set is capable to operate continuously between 0-100% load range.

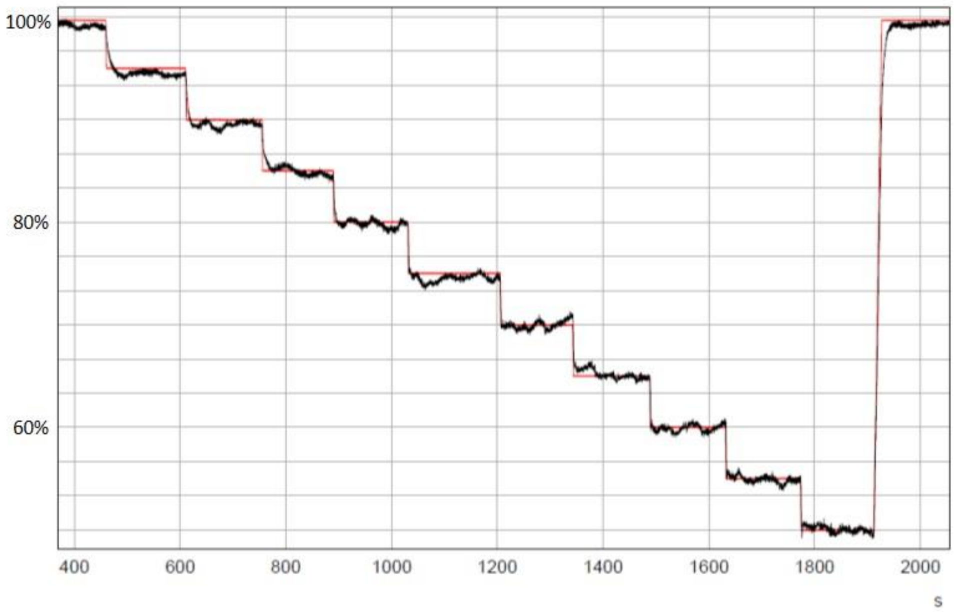

Figure 4. Active power output as a function of time. Black curve shows the 200 ms averaged active power and the red curve shows the active power-set point signal.

For the grid compliance it is important to ensure that the power generating unit is able to quickly respond to load changes. Figure 5 shows the measurement of active power for a 50% load drop. The settling time is defined as the time from the new set-point has been set till the power has reached within 5% of the set power, as indicated by the blue horizontal lines in the graph. Based on this, the settling time for this measurement was just below 10s corresponding to gradient of 75 kW per second. This means 5% of the nominal load per second, which is well above the required 66% of the nominal load per minute. During the testing compliance with the requirements for active power reduction during over frequency events was successfully demonstrated, as well as active power reduction upon the grid operator demands.

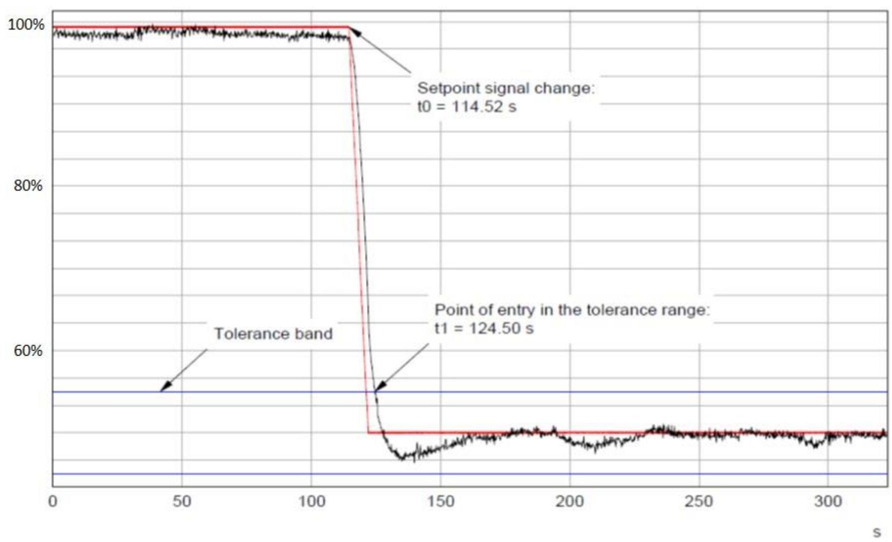

Figure 5. Step change of the set-point value from 100% active power to 50% active power.

4.2 Reactive power dynamic response

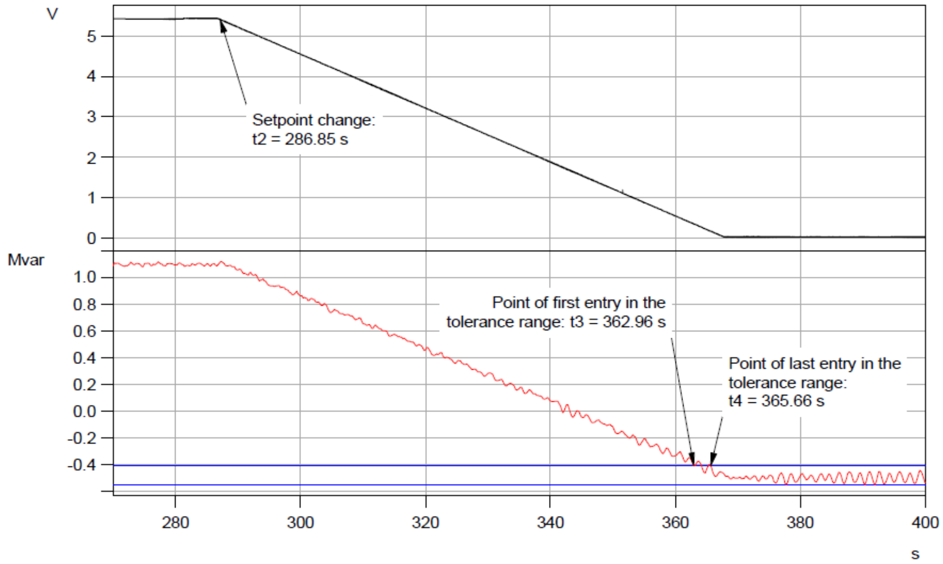

Figure 6. Reactive power step response from maximum over-excited to maximum under-excited at full load. Black: Set-point signal voltage; Red: Reactive power (Mvar); Blue: Tolerance band.

Next to the requirements for active power control also all requirements for the reactive power control have been successfully demonstrated. Four steps with different set-points (Q_{sp} = 0; Q_{sp}= $Q_{max,\ over\text{-}excited}$; Q_{sp}= $Q_{max,\ under\text{-}excited}$; Q_{sp} = 0) for the reactive power have been applied at 6 different power levels between 50-100% load. It was found that the maximum deviation of the reactive power was less than 2% of the nominal power, which is well within the criterion of 5%. Another important criterion is the reactive power settling time. Figure 6 shows an example from the testing where the reactive power step response is evaluated at full load. The black curve is the set-point signal, the red curve is the reactive and the blue curve is the tolerance band.

4.3 Performance in case of grid and system failures

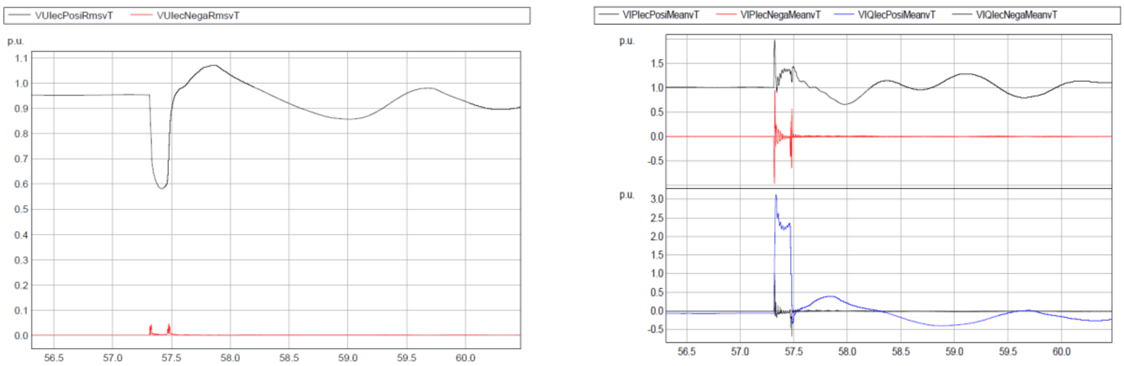

Figure 7. Characteristics of the voltage (left) and the active and reactive power (right) at a symmetrical voltage dip to 33.43% of the nominal voltage as a function of time (s).

The OP16 has demonstrated that it is fully capable of passing through a grid fault without disconnecting from the network. This is mainly due to the electrodynamic properties of the synchronous machine. In case of voltage dips the generator automatically overexcites and supports the network voltage during the fault by feeding reactive current into the network. The high initial active power peak, encountered during a grid fault, is absorbed by the high rotating inertia of the gas turbine. In total 28 tests have been performed to verify the low-voltage ride through (LVRT) capability of the OP16. Verification of the low-voltage ride through capabilities has been performed with test configurations resulting in voltages of 30-35% of the nominal voltage (U_n), 45 – 55% of U_n and 70 – 80% of $U_{n.}$ Voltage dips where invoked symmetrically on all three phases of the grid, as well as asymmetrically on 2 phases of the grid. Whereas the LVRT tests on 30-35% of U_n are most challenging for the mechanical train and the excitation system of the generator, the dips to 70-80% of Un are more challenging for the controller to keep the turbine in a controlled state. The difference in demands is mainly caused by the duration of the low voltage events.

Figure 7 shows the test results for a voltage dip to 33.43% of the nominal voltage, which was the most extreme case. The left graphs show the voltage in symmetrical components, where the red line is for the negative sequence and the black line is for the positive sequence. The right graph shows the corresponding active and reactive current for the same test. The two curves shown at the top of the right figure are the active current as positive sequence (black) and active current as negative sequence (red). The corresponding curves in the bottom portion of the right figure are the reactive current in positive sequence (black) and reactive current in negative sequence (blue). The duration of the voltage dip is 160 ms. By these tests it was concluded that the OP16 are fully able to meet the BDEW requirements regarding the LVRT capability.

4.4 Network disturbances

There are different types of network disturbances. Flicker caused by voltage variation is a common source of network disturbance. During generator start-up and generator switching, there will be inrush currents which will cause line voltages to dip or flicker. The effect of the flicker depends on several factors including its magnitude, frequency and stability of the grid. Flicker is typically encountered when operating wind turbines, due to their intermittent characteristics and the so-called tower shading. Also, reciprocating engines can encounter flickering due to misfiring leading to a decrease in power output momentarily. However, gas turbines, such as the OP16, that can operate at a fixed load with continuous combustion does not cause this issue. Nevertheless, the OP16 underwent a test to demonstrate the flicker characteristics as part of the test campaign.

5. Conclusions

The benefits of CHP solutions have been recognized by many end-users in Europe as well as globally. In particular, smaller industries with a demand for heat or steam in their process have discovered the benefits of simultaneously producing electricity and heat/steam. Most often the requirements for steam/heat are the primary selection criterion when choosing the gas turbine model and the electricity demand is secondary. With the increasing diversity of power generating equipment feeding to the electrical networks the owners/operators have found it necessary to enforce stricter requirements for these equipment. Germany is one example where the stricter grid regulations has added additional challenges for the OEM's and end-users.

During the recent years OPRA Turbines has seen an increasing number of requests from smaller industries in Europe, and particularly in Germany, to utilize the gas turbine in CHP applications. As a result the number of units installed is growing rapidly. The OP16 gas turbine combines high overall fuel efficiency with robustness and low operating costs. With its advanced combustion technology the OP16 gas turbine meets the current and future emission regulations.

During 2015 the OP16 gas turbine has been certified according to the requirements by BDEW (Bundesverband der Energie- und Wasserwirtschaft e.V) covering the generating plants' connection to and parallel operation with the medium-voltage network. As part of this certification the OP16 gas turbine has been subject to a rigorous test campaign. The tests were successfully conducted and the OP16, as the first gas turbine, passed all the required tests. This included the ability to stay connected to the grid in case of a significant voltage dip.

Nomenclature

P	Active power	[W]
S	Apparent power	[VA]
Q	Reactive power	[VAr]
t	Time	[s]
U	Voltage	[V]

Abbreviations

BDEW	Bundesverband der Energie- und Wasserwirtschaft e.V
CHP	Combined heat and power
HMI	Human machine interface
PLC	Programmable logic controller
LVRT	Low-voltage ride through

Subscripts

n	Nominal
sp	Set-point

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