Analysis of a gearless medium-voltage variable speed gas turbine

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Abstract

Analysis of a gas turbine system

Introduction

Over the last couple of years, renewable energy sources have attracted considerable interest. Besides photovoltaic systems, wind power is still showing elevated growth rates. Together with other regenerative sources like hydropower or biomass, these renewables already account for a substantial part of electricity production in several countries. In addition, market liberalisation, often combined with incentives to produce electricity whenever process heat is required, has steadily increased the number of small co-generation gas-fired power plants, also called combined heat and power (CHP) units. These CHP plants are using gas engines (power range 0.5 MWe up to 5 MW, or gas turbines (typical size above 5 MW) to convert gas into heat and electrical power. While the share of dispersed generation in power systems has notably increased and continues to grow even further, questions are being raised concerning power quality and grid stability. Apart from storage systems, such as pump-storage hydro power plants, electro-chemical, and compressed air energy storage systems, fluctuating electricity production of renewable power sources can also be compensated by coordinating the vast amount of small co-generation power generation units, because they are, in principle, capable of delivering power-on-demand within specified limits.

Although small CHP units may offer fast response times, their efficiency diminishes rapidly at part load conditions due to their operation at fixed speed. This loss of efficiency is noticeable especially in small, low-cost, high-speed, single-shaft gas turbines. Due to their long life, low maintenance and low investment costs these units would otherwise compete favourably against gas engines, even at power levels down to 1 MW.

Therefore, a MW-size variable speed gas turbine system for medium-voltage grids was analysed to evaluate its potentials in the CHP market. In contrast to conventional turbine systems, the considered turbine-generator system has no gearbox. Rather a power electronic converter is used to feed the variable frequency (between 400 up to 500 Hz) electric power of a high-speed generator in the grid and to control turbine speed. This reduced component count results not only in significantly lower weight, but may also lead to improved reliability. Additional benefits of this compact design are enhanced transportability and minimum installation effort. Furthermore, operating a gas turbine at variable speed could increase the thermal efficiency, leading to fuel savings, by applying maximum power point tracking algorithms.

State of the art versus modified topology

With regard to their power ratings, existing turbines for power generation purposes may be roughly classified in three groups: large steam turbines with electric power levels between 30 MW and 1 GW are being used for large-scale electricity production, e.g. in fossil fuel-fired or nuclear power plants. At the lower end of the scale, micro-turbines, having a rated power typically below 30 kW with rotational speeds up to 100,000 min⁻¹ have been developed for private homes and small business applications. Recently, interest in mini power systems (between 100 kW and 30 MW) for industrial applications, large buildings and city quarters has increased due to the incentive programmes of several EU governments to stimulate combined heat and power (CHP). Compared to gas engines, gas turbines have a higher power density and less NOₓ emissions, but suffer from lower part load efficiencies. As turbine speeds may easily reach 15,000 min⁻¹ and higher, conventional systems are usually equipped with gearboxes to adapt the high rotational speed of the turbine to the generator speed at 50 Hz or 60 Hz (equivalent to 3000 min⁻¹ or 3600 min⁻¹). The schematic of such a turbine system is shown in Figure 1(a).

Concerning the core component of the system, i.e. the turbine itself, two classes of gas turbines for electricity production can be distinguished, which are single and twin spool gas turbines.

Typically, a gas turbine is designed such that the highest efficiency is obtained in a small range around the design point, i.e. at a certain power level. Running the turbine under part
load conditions quickly lowers the efficiency as the compressor and the turbine are reaching regions with lower efficiency [1]. If it is possible to run the compressor independently of the spool speed, the resulting efficiency is higher. This is the reason why twin spool gas turbines achieve higher part load efficiencies than single spool gas turbines. This advantage of the twin spool turbine, however, comes at the expense of greater complexity and higher investment costs. Another option to raise part load efficiency would be to choose a full load operation point of the power turbine at an efficiency level below the original design maximum. By a sophisticated choice the part load operation curve passes through the region of best efficiencies. Therefore, higher part load efficiencies can be reached. Whether this “part load design” is reasonable depends on the particular application of the gas turbine.

Increased part load efficiency can also be obtained by implementing a variable geometry inside the turbine. If the guide vanes in the compressor can be turned, it is possible to adjust the mass flow rate through the gas turbine to the required part load value. The compressor map is then shifted to smaller mass flow rates. Thus, the efficiency remains nearly constant. However, similar to a twin spool gas turbine, the investment costs for a variable geometry are higher than for a simple single spool fixed-speed turbine.

The preceding discussion leads to the conclusion that variable-speed operation of a gas turbine could yield significant efficiency gains at part load. However, conventional system architectures (Figure 1(a)) do not permit any speed variation as the direct grid coupling of the generator enforces a fixed shaft speed of the turbine. To overcome this limitation, generator and grid have to be decoupled, which is accomplished by inserting a power electronic converter between compressor and turbine. This configuration is depicted in Figure 1(b).

Due to the high power level, the frequency converter has to work at voltage levels in the kV range (medium voltage). It basically comprises three main parts: the active rectifier is in charge of speed control of the generator, while the three-phase inverter feeds the electricity into the grid. The intermediate dc link acts as short-term energy storage and provides the desired decoupling of generator and grid frequency. Thus, shaft speed can, within limits, be continuously adapted to the required values, enabling maximum power point tracking for the turbine. This concept is, with substantially higher shaft speeds, similar to wind turbines with full converter solutions. It is also used for gas-fired micro-turbines and has been demonstrated for small steam turbines [2]. As the converter is able to transfer power in both directions the generator can also be driven as a motor during start-up of the turbine. Hence, no auxiliary starter/motor is required.

The conventional gas turbine system according to Figure 1(a) needs a gearbox to adapt the rotational speed of the turbine to the generator speed of 1500 min$^{-1}$ or 3000 min$^{-1}$ (for application in 50 Hz grids). In the variable speed solution the decoupling of generation unit and grid provides the opportunity to eliminate the bulky gearbox, which might be prone to maintenance and reliability problems. In addition, the removal of the gearbox also leads to a substantial reduction of volume and weight, which simplifies transport and installation of the turbine system. With its clear advantages over the fixed speed solution the gearless topology, however, has to meet demanding specifications for the generator as well as for the frequency converter. Due to the elimination of the gearbox the generator must rotate at the same speed as the gas turbine, i.e. up to 15,000 min$^{-1}$ and higher. Although electrical machines for much higher shaft speeds are commercially available, the power rating of these machines are significantly lower than those of the considered system. In the multi-megawatt range the construction of a high-speed generator represents a real challenge. Because of the high rotational speed, the rotor of the generator is subjected to extremely high centrifugal forces. Thus, for certain machine concepts, measures have to be taken to avoid damage of the generator caused by, e.g. flaking of coils or of permanent magnets in the rotor. Consequently, the given specifications require a unique and special electrical machine design.

Similarly, the high generator speed in conjunction with the power rating of several megawatts places high demands on the frequency converter design. Here, the main optimisation target is the reduction of power losses to maximise the efficiency. Generally, losses in power electronic conversion stages can be divided into losses in passive components (e.g. filter inductors and capacitors) and losses in semiconductor devices. Among the latter conduction losses and switching losses are to be distinguished. Conduction losses occur since power semiconductor devices represent in the on-state no perfect conductors, thus exhibit a voltage drop of approximately 1 to 3 V across the device in the on-state. Switching losses are caused by the overlapping of voltage and current waveforms during transitions from the
on-state to the off-state and vice versa. High-frequency pulse width modulation (PWM) switching is used to generate an output voltage waveform of which the fundamental frequency component is equal to the desired frequency of generator or grid.

Simplified characteristic waveforms of voltage and current during turn-on and turn-off are given in Figure 2(a). Here the losses per switching event are easily calculated by integrating the product of voltage and current over time. The higher the switching frequency, the higher become the losses. Clearly, the high rotational speed of the generator is worsening the situation. To control the generator, the motor-side converter has to operate at elevated switching frequencies, which, for the aforementioned reasons, inevitably may deteriorate the efficiency of the converter if no countermeasures are taken. A solution to cope with the problem of high switching losses is to use so-called soft-switching converter topologies. These power electronic circuits permit to turn-on or turn-off the semiconductor devices either at zero voltage (zero-voltage-switching, ZVS) or zero current (zero-current-switching, ZCS). Figure 2(b) illustrates simplified waveforms of voltage and current in a ZVS-enabling converter. As voltage and current during switching transitions do no longer overlap, corresponding losses may be considerably cut down. This principle of switching loss reduction was used for the analysis of the gas turbine system as explained below.

**System analysis**

**Gas turbine**

To assess potential efficiency gains of variable speed operation of a MW size gas turbine, the two configurations according to Figure 1(a) and (b) were subject of an analysis based on analytic calculation and numerical simulations. For the investigation, a simple and robust single-shaft gas turbine designed for a shaft power of 3 MW was considered. It could also be shown that the results obtained can be generalised for gas turbines in the range of 1 MW to 10 MW without significant loss of accuracy. To determine the point of maximum efficiency at different part load conditions, the turbine was simulated for a range of shaft speeds. Thus, it was possible to find the optimum rotational speed for each power level and to derive the curve of maximum efficiency over a certain load range. This variable speed efficiency was then compared to the efficiency curve of a turbine that was simulated at fixed speed over the entire load range. Furthermore, some additional gas turbine concepts were taken into consideration. Among others, these included a single spool gas turbine with variable geometry, as well as different twin spool configurations with variable and fixed shaft speed of the power turbine. The influence of the ambient temperature was evaluated based on the single spool configuration.

One of the main results is illustrated in Figure 3. Operation of a single spool gas turbine at optimum speed yields significant efficiency gains. For the considered turbine, an absolute increase of 3.0 % at 40 % load could be obtained. Compared to fixed spool speed efficiency, this corresponds to a relative augmentation of 12.8 %. To reach this improvement, the gas turbine is operating at 83 % of rated spool speed (cf. Figure 3). As expected, the effect of enhanced efficiency is even more pronounced the lower the ambient temperature is. In contrast, part load operation of a twin spool gas turbine with a variable speed generator only allows for an efficiency gain of 0.8 % (absolute). This lower increase could be expected as the gas generator already operates independently of the spool speed of the power turbine. Consequently, only the power turbine benefits from this configuration. Optimizing also the power turbine for part load operation by choosing a full load operation point below the maximum lowers the absolute efficiency gain to 0.3 %.

**Generator**

For the high-speed generator, several traditional design configurations were investigated within the scope of this study. Apart from generator concepts based on conventional synchronous or induction machines, also the switched reluctance machine was taken into consideration. Due to its simple and robust construction the machine seemed to be particularly well suited for the envisaged application. In a first step, a preliminary machine design and a calculation of the main dimensions for all generator types with power levels up to 20 MW and rotational speeds between 10,000 min⁻¹ and 20,000 min⁻¹ was carried out. To ensure that the rotor will be in a safe stress point of operation, the maximum speed limit was used to define an upper limit of the rotor diameter. Thus, the length-to-diameter ratio L/Dis and the length of the generators could be calculated. This relation between length and rotor diameter is desired to be within certain limits to avoid oscillations of the shaft [3]. As one of the specifications of this study was to design a compact generator, large L/Dis ratios were undesirable.

The squirrel-cage induction machine with solid-rotor (IG-SR) and the radial-flux buried permanent magnet synchronous machine (PMG) turned out to be two appropriate generator types.

Generator efficiencies were calculated for several power levels between 1 MVA and 10 MVA at stator voltages between 3 kV and 10 kV. To derive the variable speed efficiency for part load conditions the generator speed was set to the optimum shaft speed of the gas turbine for each considered power level. Of all analyzed concepts, the permanent magnet generator showed the lowest losses. The derived efficiency at different load conditions for a 10 MW PM generator (rated speed 15,000 min⁻¹) is shown in Figure 4 for both fixed speed and variable speed (maximum power point operation). As expected, variable speed operation yields higher generator efficiencies than fixed speed if the load drops below its rated value.

**Frequency Converter**

Two approaches are commonly used to obtain the needed high blocking capability of the medium-voltage converter. Either state-of-the-art series-connection of semiconductor devices is applied, or multi-level converter topologies are used instead of the conventional two-level circuit (Figure 5(a)). The latter is common in low-voltage applications. Possible realizations of a multi-level converter...
are, among others, the Neutral-Point-Clamped (NPC) converter [4] and the Flying-Capacitor (FLC) converter [5]. The equivalent circuit diagrams of these two configurations are shown in Figure 5 (b) and (c), respectively. In theory, the number of voltage levels is not limited and may be higher than three, allowing for either an improvement of the harmonic spectrum at the output of the converter or for a reduction of switching frequency, which in turn would raise converter efficiency. However, for reasons of dc voltage balancing and mechanical construction more than three (NPC) or four (FLC) levels are difficult to realize.

To identify a suitable converter topology with maximum efficiency, the conventional two-level circuit was compared against its three-level (NPC and FLC) and four-level (FLC) counterparts. All topologies may be converted into soft-switching configurations that employ the Auxiliary Resonant Commutated Pole (ARCP) principle [6] and thus enable ZVS of the main semiconductor switches. Consequently, hard- as well as soft-switching circuits were considered. For reasons of simplicity, equal voltages were assumed at both generator and grid side of the frequency converter. Converter losses were calculated with numerical simulations using datasheet values of available semiconductor devices. The loss characteristics of the semiconductors were fitted to measurement data of similar devices that had been characterized under hard- and soft-switching conditions in previous projects at the Institute for Power Electronics and Electrical Drives (ISEA) of RWTH Aachen University. With the aid of the simulation model, converter losses were determined for power ratings between 1 MV A and 10 MV A at voltage levels between 3 kV and 20 kV. Note that in all simulations the losses of passive components such as grid side harmonic filters or auxiliary inductors were neglected. The highest converter efficiency was obtained for a soft-switching three-level NPC. The efficiency of a 10 MV A topology (line voltage 10 kV, switching frequency 3 kHz) is shown in Figure 6. It can be concluded that the soft-switching principle permits efficiencies higher than 98 % even for high-power converters that operate with relatively high switching frequencies. This result could not be realised with conventional converter circuits.

Overall system efficiency
To assess the overall impact of variable speed operation on system efficiency the calculated values for the three main components turbine, generator, and power electronic converter were combined into a single efficiency curve. In addition, the efficiency of a standard medium-voltage distribution transformer was included. The comparison of fixed speed and variable speed system efficiency is summarized in Figure 7. Thus, to give an example, the efficiencies of 28 % (turbine), 98.5 % (generator), and 98.5 % (converter) yield an overall system efficiency of 27 % at 50 % load. Compared to the fixed speed efficiency of 24.5 % this represents an augmentation of 2.5 % (absolute).

Summary
The impact of variable speed operation on the part load efficiency of a gearless gas turbine system in the lower megawatt was analyzed with the aid of numerical simulations. The efficiencies of the single components were determined under different load conditions to derive an overall system efficiency curve. In conventional gas turbines used for power generation, the fixed spool speed of the generator (due to the direct coupling to the fixed-fre-
Frequency electrical grid) requires appropriate designs to enhance part load efficiency. Generally speaking, these modifications (variable geometry, second spool) imply higher investment costs. Implementation of a variable high-speed generator may avoid this added complexity. Furthermore, the efficiency gains related to variable speed operation exceed those of conventional design modifications. Consequently, the combination of a simple single spool gas turbine (without adjustable guide vanes) together with a variable-speed generator represents an optimum solution for maximized system efficiency. Concerning the generator, the ratio of rotor length to diameter has to be kept within certain limits to guarantee high efficiency and low mechanical stress. Considering traditional generator concepts, a squirrel-cage induction machine with solid-rotor and a radial-flux buried permanent-magnet synchronous machine are potentially appropriate generator types for the envisaged application.

With regard to the power electronic conversion system, it was found that high efficiencies can be realized even though the medium-voltage converter has to operate at elevated switching frequencies. Particularly soft-switching converter circuits offer important advantages over conventional hard-switching configurations since they show lower losses and therefore enable the higher switching frequencies of several kHz that are required for the gearless connection of generator and turbine.

Overall significant efficiency gains were found if a light-weight medium-size gas turbine system is designed for and operated at variable speed instead of fixed speed.

References

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