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CHALLENGES IN THE DEVELOPMENT OF MICRO GAS TURBINES FOR CONCENTRATED SOLAR POWER SYSTEMS

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ABSTRACT

Parabolic solar dish systems have gained more interest recently as a reliable way for harnessing the solar power in form of electricity. Micro gas turbines can be used as engines in such system to convert the heat available from the solar collector o electricity. In this paper the technical challenges related to using micro gas turbines for utilising concentrated solar power will be addressed based on the experience gained from the EU funded project OMSoP (Optimised Microturbine Solar Power system) which aims to develop and demonstrate a micro gas turbine coupled to a parabolic dish for the power range of 5–10 kW. The technical challenges related to the turbomachinery design, rotordynamics and dynamic stability, control system, power electronics and thermal storage will be briefly reviewed. Techno economic considerations of the system will also be discussed.

NOMENCLATURE

CSP	Concentrated Solar Power
MGT	Micro Gas Turbine
TIT	Turbine Inlet Temperature
TET	Turbine Exit Temperature
DNI	Direct Normal Irradiation
SFD	Squeeze Film Damping
IGBT	Insulated-Gate Bipolar Transistor
HSG	High Speed Generator
EPCS	Electronic Power Conversion System
PE	Power Electronics

INTRODUCTION

Generating electricity from CSP can be accomplished in a number of alternative routes depending on the size of the unit required and the type of the system that converts the resulting thermal power to mechanical power. CSP systems use mirrors to focus the direct sunlight onto a focal point where the temperature of a working fluid rises. The working fluid then transfers its energy to the prime mover. From several solar concentrator types the parabolic dish and solar towers have the potential to increase the temperature of the working fluid in excess of 800°C which is needed for some prime movers such as gas turbines (Pavlovic *et al.,* 2012). However the solar towers are not suitable for low power range of few tens of kilo Watts (Buck *et al.*, 2002). A schematic of such system is shown in Figure 1. The first attempt to use the MGT in CSP system seems to be the work done by English at NASA during the 1980’s (English, 1980). However the work has not been continued and has not been progressed toward commercialisation. Six and Elkins (1981), among other works, have tried the idea by adopting turbochargers technology and more recently dedicated MGT engines was adopted to examine the performance of the CSP systems based on MGT (Dickey, 2011). Parabolic solar dish systems are a promising technology for harnessing solar power because it can offer inherent hybridisation with other fuels or thermal storage resulting a dispatchable system providing electricity around the clock from the same system. Most of the development effort in recent years focused on utilising Stirling Engines as a prime mover. Micro Gas Turbines (MGT) can provide a more reliable and robust alternative prime mover with more flexibility for hybridisation and coupling to thermal storage. In this paper the challenges that face micro gas turbine designers in adapting existing technology for solar applications are discussed and solutions are proposed. Generally, the main challenge facing the micro gas turbine industry is the capital cost per kWe of installed capacity. It has been argued that the use of turbocharger technology can cut the cost through utilising massively produced parts. However, this comes at the expense of reduced efficiency. For Concentrated Solar Power (CSP) systems, the MGT presents relatively small part of the overall capital cost compared to the solar dish (concentrator). Thus optimising the MGT for high efficiency and the related increase in production cost could be outweighed by the reduction in the dish size and thus overall cost of the system. Other challenges are associated with the variable solar insolation requiring the MGT to operate efficiently at a much wider range than conventional technology. The wide operating range also has a significant impact on the rotor-dynamic design of the shaft-bearing arrangement and mass distribution. In addition, the control strategy of the MGT needs to be adapted to the fact that the thermal input to the system cannot be used as a control parameter. Various challenges are also associated with the electrical and electronic components design and performance due to the more frequent need to alternate between motoring and generation modes of the High Speed motor/generator. The challenges related to the thermal storage for the MGT in the CSP plants will be discussed in the last section. The main challenge would be to provide high temperature output from thermal storage systems usually in excess of 800°C. There are technical challenges facing hybridisation of MGT-CSP systems mainly related to the combustor design in order to operate efficiently over a wide range of loading. Apart from providing continues power, the hybridisation of the system will improve the controllability of the MGT. Without co-firing for the pure solar system on the challenges is the controllability of the MGT.

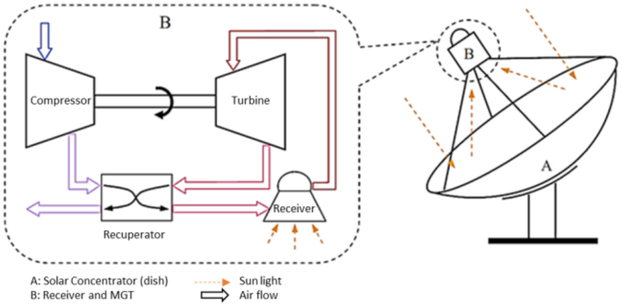

Figure 1: Schematic of MGT-based CSP plant (Courtesy of OMSoP project, 2016)

MGTS AND THEIR APPLICATION IN CSP

Gas turbines are used extensively in power generation as well as in aero-applications. Micro-gas turbines (MGTs) are a term loosely used for gas turbines producing power from several hundred Watts to about 1 MW. Nowadays, they are commercially available in the power range from 30 kW up to 1 MW. Small MGTs producing less than 10 kWe are not commercially available yet. However there is a growing interest in MGTs in this power range for various applications, including domestic combined heat and power (CHP), range extenders in hybrid vehicles, auxiliary power units in heavy vehicles, portable power generation, marine auxiliary power and standby power units and small unmanned air vehicles (UAVs). Compared with internal combustion reciprocating (IC) engines that currently dominate the market below 10 kW, MGTs offer the potential for lower emissions, superior fuel flexibility (including renewable fuels), higher reliability, longer engine life, lower noise and vibrations and, reduced maintenance costs. The focus of this paper is on MGT application for concentrated solar power generation systems.

Internal combustion engines are not a suitable contender for concentrated solar power applications because of their basic engine cycle and design principles. Stirling engines have been proposed as a possible choice. These are piston type reciprocating engines that operate with an external heat source, and thus they are suited for CSP. Stirling engines use hydrogen as the working fluid at high pressure. Mainly because of this feature they suffer from a number of technical problems affecting life and reliability, such as issues with cylinder seals, Hydrogen leakage, hot spots in the heater and difficulties with part-load control. Such problems lead to system complexity and increased costs. Some projects for Stirling engine based CSP failed mainly because the cost of the prime mover hardware was too high (Sinai *et al*., 2005).

In general Micro Gas Turbines can provide a more reliable and robust alternative prime mover with more flexibility for hybridisation and coupling to thermal storage. The nature of the MGT's cycle makes it easier and more practical to be hybridised and to be coupled with thermal storage. This potentially would result in non-interrupted power generation system from solar source.

COST CONSIDERATIONS

The main challenges facing the micro gas turbine industry are the capital cost per kW of installed capacity comparing to the other prime movers. Although there are technical superiority for MGT over other prime movers, the economic consideration will remain essential to compete with other renewable technologies. It has been argued that the use of turbocharger technology can cut the cost through utilising massively produced parts. However, this comes at the expense of reduced efficiency. For the Concentrated Solar Power systems, the MGT presents relatively small part of the overall capital cost compared to the solar dish. Thus optimising the turbine for maximum achievable efficiency and the related increase in production cost could be outweighed by the reduction in the dish size and thus overall cost of the system.

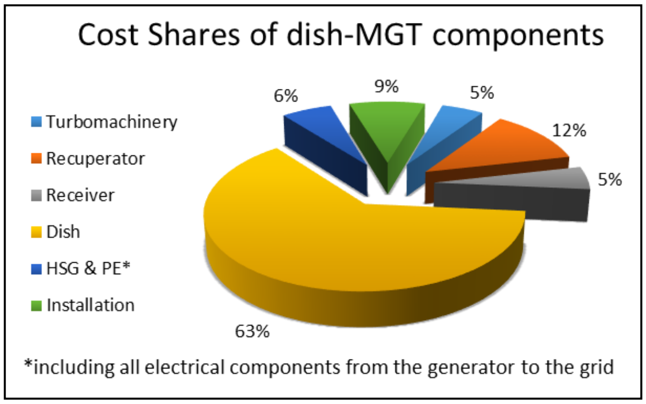

Figure 2: Components costs for initial design point, (Courtesy of OMSoP project, 2016)

A typical break down of the cost of the MGT-based CSP system is shown in Figure 2 for one specific level of TIT. The portion of the turbomachinery, recuperator and receiver will increase for higher TIT levels. It can be seen that the largest component cost is the one for the dish and its accessories, such as the dish control unit and sun tracking system, contributing about 63% of the total cost. Thus the careful consideration is needed to use the dish optimally and efficiently and to maximise the electricity production for a given dish. There should be a balance between increased cost of different components (apart from the dish) and the gain that can be achieved in term of overall efficiency and power generated.

The increased efficiency of the MGT over a wide range of operating conditions could lead to higher energy produced over a duty cycle and thus reduction in the cost of electricity. There should be an optimal value of the balance between increasing efficiency of the MGT and the associated increase in cost. It will reach at some stage diminishing returns and thus the cost curve will turn up again. To achieve higher efficiency in addition to better component efficiencies, which will be discussed later, innovative cycles could be considered to increase the efficiency of the cycle.

ROTORDYNAMICS AND DYNAMIC STABILITY

A challenge is associated with the variable solar insolation requiring the MGT to operate efficiently at a much wider range than conventional technology. The wide operating range also has a significant impact on the rotor-dynamic design of the shaft-bearing arrangement and mass distribution. At least three different mechanical arrangements can be considered for the MGT components (compressor, bearings, turbine and the electricity generator). These are cantilevered design, generator-in-middle design and coupled shaft design. Figure 3 shows a schematic for three different mechanical arrangements. The main advantages and disadvantages of these designs are summarised below:

Cantilever arrangement: This is the most common in small-scale micro gas turbines. In this arrangement, the assembly of the turbine-compressor is hanged from one end of the rotor. The main advantage of this design is that no major cooling is needed for the HSG. Practically the air intake, before the compressor, can act as cooling subsystem for the HSG. Although this could affect the efficiency of the MGT, it can reduce the size and cost of the accessories. Alternatively a separate cooling system can be integrated to the MGT for no excessive cooling requirement. The main disadvantage of this arrangement is that this design suffers from rotordynamic issues. For the range of power concerned in this article, it is not practical to have a stable cantilever design for a wide range of operating speed needed for the solar application.

Coupled Shaft arrangement: In this design two separate shafts are coupled, one contains the rotor and the HSG and the other shaft will contain the compressor and turbine impellers. The rotordynamics of this arrangement is improved compared to the cantilever design. This allows moving all bending modes out of the operating range and no excessive cooling is required for the HSG as it sits on a separate shaft and far from the turbine. However, this comes in expense of having more bearings and associated costs. Also this raises technical difficulties with the high speed coupling.

Generator-in-middle arrangement: The HSG rotor is located between of the compressor and turbine wheels in this design. It provides simpler mechanical design with improved dynamic stability. Similar to the coupled-shaft design, it is possible to move all bending modes out of the extended range of operation required for the solar application. However a more significant cooling is required for the HSG as it is sitting in vicinity of the turbine wheel, but it has also the advantage that the compressor, particularly its inlet, is far from the hot section. Although the cooling system can be integrated with the lubrication system of the bearings it would be considered as a disadvantage for this design.

A study was undertaken as part of OMSoP project showed that the generator-in-middle design could potentially fit better for the solar powered MGT (Arroyo *et al.*, 2016). The study has taken into account different factors such cost, reliability and losses. It was concluded that generator-in-middle arrangement could be more suitable for solar powered micro gas turbine.

Another aspect of the rotordynamic for MGT's is the choice of bearings. The rolling angular contact ball bearings, oil film bearings, floating ring bearings, magnetic bearings and air/foil bearings are different options for the MGT's. The ball bearings are the most common type particularly in smaller MGTs. The technology is well known, however, it requires an oil system. Recent advancement in the development of high-speed ball bearing makes this technology a viable option for the MGTs. For CSP-based MGTs some form of damping is required to reduce the vibrations caused by passing through or running close to the critical modes. Squeeze Film Damping (SFD) is a feasible option to be integrated with this type of bearing. Oil film bearings have been the most common type in automotive turbochargers. Despite their robustness, their high friction loss is a big disadvantage for MGT applications where the efficiency is critical issue. More work in larger engines was done on magnetic bearings; however, their development and implementation cost for MGTs prevented them from being used despite their advantage of oil free operation and the inherent ability to control vibrations. Foil air bearings have made significant progress recently due to their high reliability and their oil-free operation. However, there is still much work to be done for the smaller machines in the lower power range to make them a feasible option. The main technical challenges related to the bearing for CSP-based MGT is the robustness of the bearing and their ability to operate in a wide range of operation and more hostile environment that most conventional, both speed and loading, with high efficiency. They are also required to operate in a more hostile environment, as the most appropriate location is near the focal point of the dish, which typical MGTs would not operate efficiently.

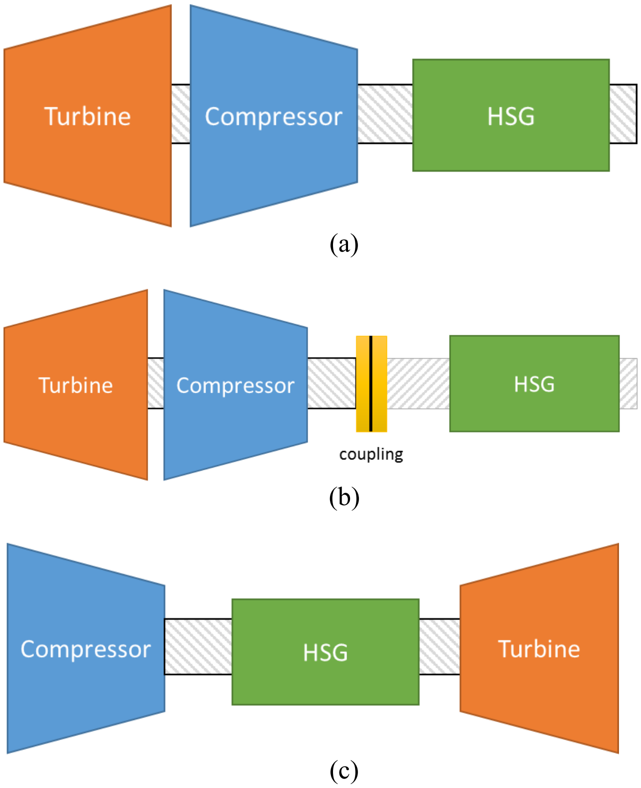

Figure 3: different mechanical arrangement of rotor assembly: (a) Cantilever design, (b) Coupled shaft design, (c) Generator-in-middle design

MGT TURBOMACHINERY DESIGN FOR SOLAR APPLICATION

CSP-based MGTs are required to operate in wide range of rotational speeds and loading due to the variation in the DNI. To keep the overall efficiency of the system close to its highest possible level for the wide operating range, it is necessary that the turbomachinery components (turbine and the compressor) operate at high efficiency for a wider range of condition, which is not typical in conventional designs. Typically the turbine and the compressor are designed in such a way that they have their maximum efficiency within a narrow range of operation dictated by the need to have the highest possible peak efficiency. For CSP applications however, it is more desirable to design these components in such a way that their off-design performance is high. This may require the added complication of variable geometry or sacrificing some of the peak efficiency or both.

Most of the current micro gas turbine designs use one centrifugal compressor and one radial turbine arrangement. An alternative approach is to use two-stage compressors and two-stage turbine in order to reduce the rotational speed and improve the dynamic behaviour of the micro gas turbine allowing, for example, to use ceramic components for the turbine (Vick *et al.*, 2009). Lower stage loading also benefits component's efficiencies although this may be compromised by the ducting losses. Research work has started recently at City University to explore the idea of introducing small features on the turbine impeller to increase the efficiency of the turbine beyond its current state, particularly. The idea is to reduce the effect of the secondary flows which are one of the main source of the losses in the turbine (Miao *et al.*, 2016). These could also be tailored to reduce the over-the-tip leakage losses.

The sealing of the rotor assembly is another technical challenge for the design of the turbomachinery components. In the CSP application oil contamination can cause degradation for the solar receiver especially in presence of optical components such glass. Usually for conventional MGTs small amount of oil contamination doesn't affect the system, as the oil will burn in the combustor eventually. Careful consideration should be taken during the design of the sealing mechanism for the CSP-based MGT in order to prevent the oil entering the air path, particularly upstream of the solar receiver.

CONTROL STRATEGIES FOR CSP BASED MGT

The control strategy of the MGT needs to be adapted to the fact that the thermal input to the system cannot be used as a control parameter. In a conventional MGT the fuel (or heat input for the external-fired MGTs) are used to control the MGT, namely the rotational speed, Turbine Inlet Temperature (TIT) and Turbine Exit Temperature (TET). For a CSP based MGTs this option is not possible as the incoming solar power to the receiver cannot be practically controlled. For example, controlling the dish position in order to adjust the amount of thermal input power would not be an option due to the much slower dynamic response of the dish movement mechanism than that of the MGT dynamic response that is orders of magnitude apart. A feasible option to control the MGT in such system is by adjusting the power taken (or given) to the HSG. This would result in controlling the TIT, TET and rotational speed.

A different Power electronic architecture can be considered for the CSP-based MGT. As mentioned before the power electronics would be responsible for controlling the MGT alongside its primary function to convert the power to and from the grid; this would happen in the Electronic Power Conversion System (EPCS). At least two different architectures can be considered for the power conversion system: single converter architecture and double converter architecture. All designs involve an active inverter to control the power output, as this is essential for solar-based MGT.

Single Convertor Architecture: By using electronic components such as IGBTs, the conversion system can act as bi-directional convertor. The Insulated-Gate Bipolar Transistor (IGBT) acts as passive rectifier during the generating mode while they will functions as variable frequency converter during the motoring mode. The later function controls the speed of the MGT during the start-up process. The MGT control unit will be integrated with this convertor. The technology is not commercially available for the power range of concern of this work. The main challenges are to design an efficient conversion system for higher speed as the speed will be higher for the lower power rage.

Double Convertor Architecture: A simple option is to have to separate convertors for the two modes of operation, motoring and generation modes. As shown in Figure 4 the conversion system will form of a passive rectifier during generation modes and a grid-tie inverter to feed the power into the grid. For the motoring mode another passive rectifier and variable frequency inverter are used to run the HSG as motor during the start-up. The design is less complex than the single convertor architecture but it increases the number of components in the system and subsequently the size. The need to alternating between the two separate circuits would also increase the electrical losses. Furthermore using the passive rectifier (basically a set of diodes) will introduce more power losses compared to IGBTs. Although using IGBTs will increase the complexity of both the conversion system and the control system but it will increase the robustness of the system and decreases the power losses in the power electronic circuits. Different component of the double converter architecture system are widely available commercially with more optimisation required for the lower power range where the speed is higher.

Another option is to adopt active rectifiers in the EPCS. An active rectifier can control the speed of the HSG (and subsequently the speed of the MGT) along with is primary function to convert the AC to DC. This potentially can act as controller for the speed of the MGT although the power output of the system still need to be controlled in order to keep the TIT and TET within the acceptable range. The main disadvantage for the active rectifier is the relatively higher losses compared to the passive rectifier. To have adequate control over the speed the switching frequency of the active rectifier could be as high as 50 kHz. The switching frequency in other components of the system is usually about 16 kHz.

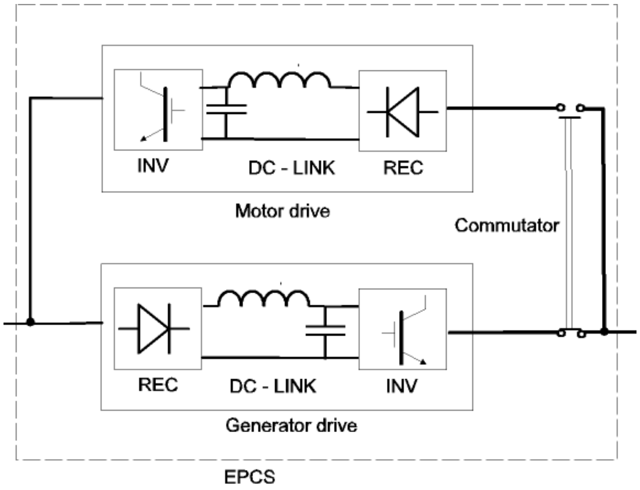

Figure 4: One possible EPCS architecture to connect the HSG to the grid which includes REC (passive rectifier), INV (active inverter), DC-Link and Commutator to alternate between the generation and motoring modes (Courtesy of OMSoP project, 2016)

Although power electronics and control technology are well-developed fields, the challenge is to provide a robust and cost effective design for the CSP-based MGT giving high rotational speed, wide range of rotational speed in generation mode and the need for more frequently alternating between the motoring and generation modes than in conventional MGTs. Other challenges are also associated with the electrical and electronic components design and performance due to the more frequent need to alternate between motoring and generation modes of the high speed motor/generator which require adequate addressing.

THERMAL STORAGE AND HYBRISATION

One of the advantages of the solar dish-MGT arrangement is the inherent potential to integrate thermal storage and hybridisation with conventional or bio-fuels. The pure solar power generation system, similar to most renewable energy systems, cannot provide continues source of power that might be considered as the main downside of this technology. As discussed before, the CSP systems with MGT as prime mover can be hybridised more efficiently compared to the other prime movers (Aichmayer *et al.*, 2013 and Fisher *et al*, 2014). The second source of energy, typically conventional combustor, can be integrated in the system both in serial and in parallel to the solar receiver. The serial arrangement would have the advantage that it can overtake the responsibility of controlling the MGT from the power electronic system. However this means that the combustor should be in operation all the time including the peak-DNI periods. One of the technical challenges for such a system is the combustion stability over a wide range of loading. There might be a dramatic change in the DNI in cloudy condition; in order to maintain the power output the relatively high fuel flow rate should be supplied to the combustor. In the normal operation conditions the air-to-fuel ratio is much higher compared to such conditions. This means that the combustor should be able to operate in wide range of air–to-fuel ratio which is quite a challenge for small scale combustors.

Thermal storage is another way to maintain the power output during the night, when no solar input is available, and during the cloudy condition, when the solar irradiation is interrupted for short periods. For both type of thermal storage the main technical challenge is to achieve high temperature output (in excess of 800°C) and to provide stable thermal source over long period of time (during the night). The balance between live power generation (feed to the grid) and thermal storage requires careful consideration and optimisation in order to maximise the overall plant efficiency while keeping the cost low (Ferrari *et al.*, 2014). Phase-changing thermal storage technology could provide a promising solution for MGT-CSP plants (Lee, 2010).

CONCLUSION

The advantages of using micro gas turbine as prime mover in the concentrated solar power system have been discussed. Some technical challenges related to the different aspects and components of the micro gas turbine s for such application have been addressed. The main technical challenges would be design and manufacturing of high-efficiency turbomachinery components that are able to perform in near peak efficiency for a quite wide range of operation. The control system needs proper integration with the power electronic system, as practically power electronics would be the only way of controlling the micro gas turbine in absence of conventional fuels. In order to have continues power generation system the thermal storage should be coupled with the MGT. The thermal storage system needs to be capable of providing high temperature in excess of 800°C to achieve the desired range of efficiencies. As the operational range of the MGT is varying with variation of the DNI, the mechanical arrangement of the MGT's components should be designed properly. A preliminary study showed that generator-in-middle arrangement has more potential to operate in wider range of speed, which is the case for the solar application.

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