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A COMPARATIVE STUDY OF THE CONTROL STRATEGIES FOR PURE CONCENTRATED SOLAR POWER MICRO GAS TURBINES

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ABSTRACT

The concept of combining small micro gas turbines with solar dish concentrator is being developed by the EU funded project OMSoP [1] to benefit from the advantages of higher efficiency, power density and reliability. This paper focuses on small units which are only powered by the solar irradiation and aims to identify suitable means of control that would minimize power output variations and achieve maximum annual generated electricity. Three different strategies have been proposed and studied in this work: power regulation control which is based on variation of the load to achieve maximum permissible power for any particular value of insolation, recuperation control which is a novel idea to partially by-pass the recuperator and use it as an additional degree of freedom in the control scheme and a hybrid control strategy which combines the first two methods. The evaluation criteria of these strategies are based on the annual generated electricity, rated generated power, solar-to-electrical efficiency and practical considerations. The performance of a 5kWe system has been calculated and compared when each of the above control strategies are applied. Quantitative and qualitative comparisons show that the recuperation control and combined methods can provide constant power output for a wide range of solar irradiation, but at the expense of reduced overall performance and additional cost and complexity. The power regulation strategy provides maximum generated electricity, but it is not suitable when the generated power by the system requires to follow the variations of the load from the consumer side.

INTRODUCTION

In recent years, there has been increasing interest in research on micro gas turbines (MGT) powered by concentrated solar power (CSP) for electricity generation. The main focus has been on systems with the rated power above 100kWe for distributed power generation and large scale combined heat and power (CHP) applications [2] [3] [4], [5]. Most of such systems are powered by a heliostat field where the solar receiver is positioned at a high central tower and delivers the concentrated solar heat to the Brayton cycle at temperatures as high as 1000°C [6]. Parabolic dish systems achieve higher optical efficiencies in such elevated temperatures compared to other CSP technologies and may be used when the rated power of the dish-engine unit is below 25-30kWe, such that the size of the single dish doesn't exceed practical structural limits. While the dish-Stirling systems have demonstrated relatively higher efficiencies, the reliability, ease of maintenance and power density of dish-MGT systems have motivated several research in recent years [7], [8], [9]. The majority of work have focused on the hybrid systems where auxiliary combustion is used to compensate for the variations of solar irradiance [10], [11], [12]. Pure solar powered systems which are also called solar only systems completely replace the combustion in conventional MGTs with the solar receiver. Such systems are advantageous over the hybrid architecture particularly in terms being less complicated and hence lower in cost in addition to avoiding the environmental impacts and the technical difficulties pertaining to the combustion system [5] and [12]. However, performance of these systems is affected by the variable nature of solar irradiance received at the surface of the dish, because it directly determines the input heat to the system and consequently the output power of the system. Therefore, the exploitation of solar-only dish-MGT systems requires addressing such issues. In addition, they need to be integrated within a grid system that provides back up and feed in the grid when there is excess generation. Although as such, they would be competing with the much cheaper PV systems, they have the advantage much lower land utilization for the same power output and the potential of much higher overall efficiency through the use of the exhaust heat.

Several studies have been done on the simulation and investigating the performance of the dish-MGT systems. Most of these efforts have been done to optimize the dish-MGT system using the design point performance and application of a correlation for off-design conditions when the solar irradiance changes [2], [13]. Semprini et al. provided a comprehensive list of the research on the performance of solar powered gas turbine systems [14]. In most of these studies, the effect of the operation strategy of the micro gas turbine on the system performance has not been sufficiently investigated. Fixed speed operation strategy is very common in the gas turbines and is used as the main option for scale power generation systems. It is shown that the performance of a micro gas turbine can be improved by running the engine at a variable speed operation strategy compared to fixed speed operation [15]. However, these studies have been done for fueled micro gas turbines where the operation of the engine is controlled by the variation of the fuel flow rate. For a pure solar MGT this is obviously not possible and the input solar heat changes at any time independent of the system load. As a result, the generated power of these systems always varies with solar insolation.

In this paper, two methods for control of the pure solar dish-MGT systems are proposed and investigated. The first method, power regulation, is based on the assumption that the output power of the system is delivered to a large grid and therefore, variations of the generated power does not affect the consumers. The power regulation control strategy relies on finding the instantaneous rotational speed which allows for the production of maximum achievable power at any particular value of insolation. Such control strategy is technically viable through power electronics, which control the high speed alternator while the system is connected to the main grid. The second method, recuperation control, enables the system to match the variations of the power demand of the consumer whether it is on a large grid or not. The recuperation control strategy is based on partial diversion of the air flow from the compressor to the receiver directly instead of going through the recuperator.

The first section of the paper briefly introduces the performance model which is used to calculate the system performance when different operation strategies are applied by the control systems. Operation strategies which can be applied using the power regulation control in pure solar micro gas turbines are investigated and compared in the next section and in the third section the concept of the recuperation control and performance results of the system are presented. Comparison of the system performance under these two control strategies with the constant speed operation is then presented. Results of the combination of these control systems and a qualitative comparison among the proposed methods of control are then presented.

NOMENCLATURE

Abbreviations

CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
HSA	High Speed Alternator
IGBT	Insulated-Gate Bipolar Transistor
ISO	International Organization for Standardization
MGT	Micro Gas Turbine
MPP	Maximum Permissible Power
TET	Turbine Exit Temperature
TIT	Turbine Inlet Temperature
EPCS	Electronic Power Conversion System
PE	Power Electronics

Variables

E_{an}	Annual Generated Electricity
I	Electric Current
I_{max}	Maximum Allowable Current
N	Rotational Speed
N_{max}	Maximum Allowable Speed
PWe	Net Electric Output Power
t	Time
TET_{max}	Maximum Allowable TET
U	Voltage

THERMODYNAMIC MODEL

A schematic of the dish-MGT system is shown in figure 1. The micro gas turbine considered here is based on a recuperated Brayton cycle which is commonly used in small scale MGTs. The system is connected to a high speed alternator which is connected to the power grid via a generator/motor drive.

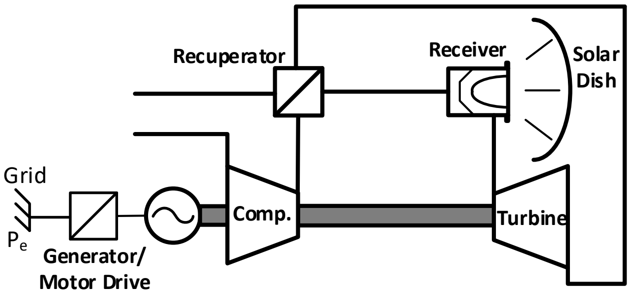

Figure 1) pure solar dish-MGT system

The thermodynamic model of the dish-MGT system uses component models or performance maps to calculate their performance characteristics. The governing equations of the dish-MGT system are arranged as set of nonlinear equations in general form of $\mathbf{F}(\mathbf{X}) = \mathbf{0}$. For any given input data, the solution to the equations, $\mathbf{X_0}$, represents the working point of the system for the particular conditions which are introduced by the input data and system characteristics.

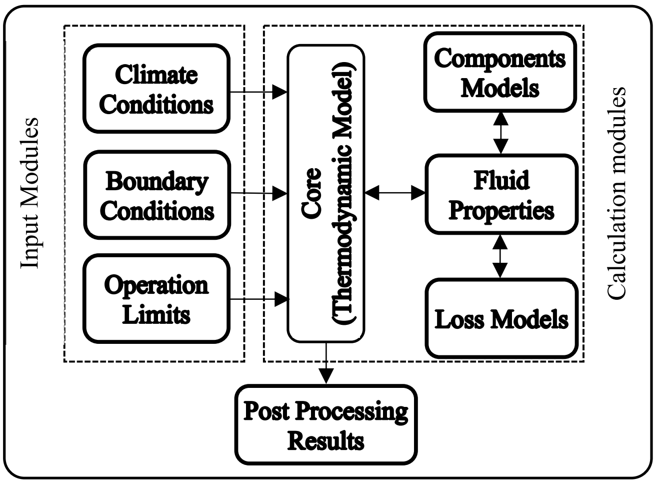

Figure 2) general structure of the computational model

Figure 2 represents the structure of the thermodynamic model. The input data are introduced to the computational model through three individual modules. The ambient conditions include the direct normal irradiance (DNI) value that determines the input heat to the system and also the ambient conditions that dictate the properties of the inlet air to the MGT. The boundary conditions define the load applied to the dish-MGT system. Loading of the system is generally done through the settings of the high speed alternator (HSA) and control system which is discussed in detail in the next section. The operation limits module defines the constraints for the operation of dish-MGT system. These limits are mostly determined by materials considerations, rotor dynamics stability and compressor operating envelop. The latter is accounted for in the performance simulation code by considering the margins from the surge and choke lines. Maximum turbine inlet temperature (TIT), turbine exit temperature (TET), rotational speed and maximum current in the winding of the HSA are the main limiting parameters.

The performance model is able to calculate the generated power for any particular DNI when other input data are known. The annual generated electricity over a time period is calculated using equation 1. The time interval Δt, is the minimum value in which the DNI is assumed constant and the system performance can be considered to be steady state. Figure 3 shows variations of the DNI for a sample day. The DNI values are presented in an hourly basis. Clearly, DNI data with higher resolution is required for more accurate calculation of the performance and the generated electricity.

$$E_{an} = \sum PW\Delta t \qquad (1)$$

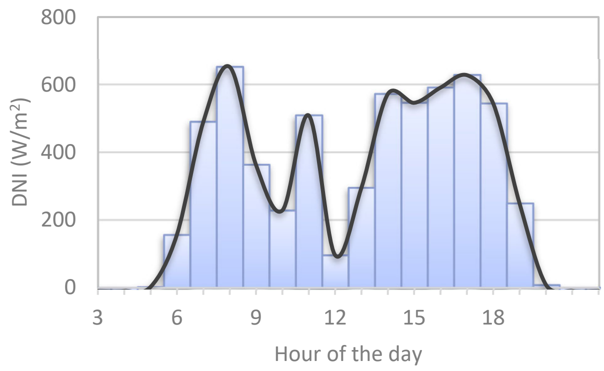

Figure 3) hourly variations of the DNI in a sample day in Rome, Italy.

To demonstrate and compare the performance of the dish-MGT system when different operation and control strategies studied in this paper are applied, a 5kWe micro gas turbine designed for Optimized Microturbine Solar Power system (OMSoP) project [16] is used as the case study here. Table 1 provides the main design point data of this system.

Table 1 also includes the maximum allowable limits of some system performance parameters which are defined as the operation limits in figure 2. TETmax is determined by the material used to build the recuperator. The data provided in table 1 is suggested for a recuperator made from Austenitic stainless steels such as AISI 321 [17]. The speed is mainly based on the limitations applied by the rotor dynamics [18] and also the limitations on the high speed alternator to run the system in the motoring mode during the start-up and shut down. Maximum TIT is equal to the design point value and is considered to be the upper limit allowable because of the solar receiver limitations.

Table 1) design point data for 5kWe dish-MGT

Parameter	value
DNI	800W/m^2
TIT	800°C
Speed (N)	130krpm
Pressure ratio (π)	3.0
TET	604°C
TET_{max}	650°C
N_{max}	150krpm
I_{max}	13A

OPERATION STRATEGIES FOR PURE SOLAR MGT

The main operation strategies that are applied to the conventional fueled micro gas turbines are devoted to keep one of the MGT parameters constant at part load conditions. These strategies are applied by the variation of the fuel flow as the controlling parameter. For a pure solar powered MGT, as the input energy is provided only by the solar radiation, the system performance for any operation strategy is studied for the variations of DNI.

The main parameter which is preferred to be constant is the rotational speed because it determines the generator speed and therefore, the output voltage. However, constant speed results in large reduction of the generated power at off design conditions and it is preferred that the control system be able to allow variable speed operation and achieve higher part load efficiencies [15] [19]. The common variable speed operation strategies that lead to considerable advantages over constant speed are the constant TIT and constant TET strategies. Constant TIT operation results in maximum power generation when it is set to the maximum allowable value for TIT [20]. For the recuperated cycles, constant TET operation may be preferred because it prevents the cyclic temperature variations in the recuperator.

Figure 4 shows the performance of a dish-MGT system with the variations of DNI when it is operated under any of the mentioned strategies. Clearly, the system would work at its design point only when the DNI is equal to the rated value as specified in table 1. For any other DNI value, the performance simulation code uses the components maps to calculate the performance. Other climate conditions are set to be equal to the International Organization for Standardization (ISO) conditions as 15°C, 1atm absolute and 0% relative humidity. The constant speed deemed to be an unsuitable option to operate the system because the generated power large reductions with DNI. Operation of the system with the turbine exit temperature fixed at 650°C as the maximum allowable limit is acceptable for low DNI values, but as the DNI increases, TIT exceeds its allowable limit. To operate the system with constant TET for the entire range of DNI variations, it should be set to values as low as 600°C which in turn results in lower generated power. Figure 4 shows that operating the MGT at the constant TIT of 800°C is not possible for low DNI values because the low rotational speed and consequently low expansion ratio result in TET values higher than the safe limit. Reduced TIT values allow to avoid this problem but at the expense of reduced generated power.

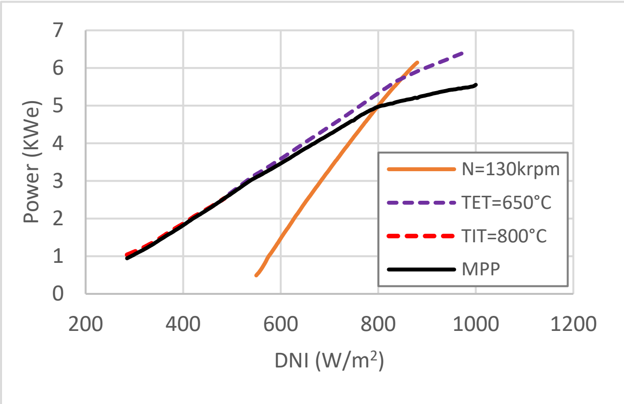

Figure 4) MGT performance with different operation strategies

Maximum Permissible Power strategy (MPP)

To keep the MGT working conditions within the safety limits and at the same time generate maximum power at any DNI value, MPP strategy is proposed here. This strategy is investigated by the running the performance simulation for any given DNI to find the rotational speed which results the maximum generated power. Safety limits of operation are applied in the form of constraints as mentioned before. As shown in figure 4, MPP strategy is practically very similar to TIT-constant strategy except for low DNIs where TET is exceeding their allowable values. To summarize this section, the MPP operation is more suitable compared to other strategies introduced here when the system is connected to a large grid and is not affected by variations of electrical load.

CONTROL STRATEGIES FOR PURE SOLAR MGT

It is important to distinguish between the operation and control strategies. Whereas the operation strategy determines how to operate the micro gas turbine, the control strategy is a way to design and use the control system to apply the operation strategy. The core of the control system used to apply MPP operation is shown in figure 5. There are four nested loops which are used in the control procedure. While the main objective is to keep TIT at its maximum value, it will be reduced if any of the controlled parameters exceeds a certain value. This is controlled by the Least Value Gate (LVG) operator in the control system.

Only the TIT control loop is equipped with a PID controller because it is the main control loop. PI controllers are technically adequate for the other loops as shown in figure 5.

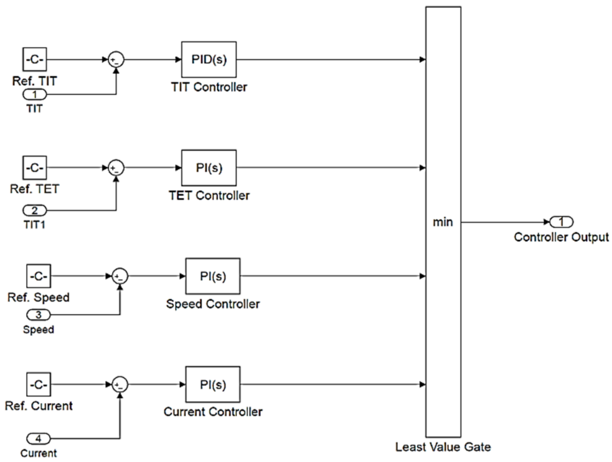

Figure 5) controller model for the pure solar MGT

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.

POWER REGULATION

A feasible option to control the MGT in such system is by adjusting the electrical power extracted by the HSA. This would result in controlling the TIT, TET and rotational speed. Different Power electronic architectures can be considered for the CSP-based MGT. 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 commercially for the power range in 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 6 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 HSA 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 optimization required for the lower power range where the speed is higher.

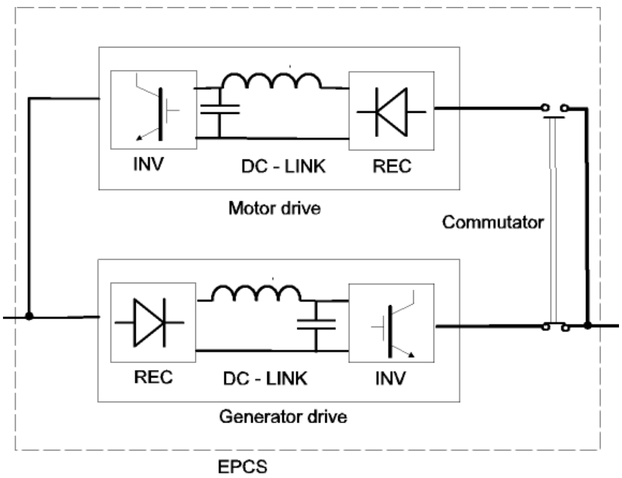

Figure 6) one possible EPCS architecture to connect the HSA to the grid which includes REC (passive rectifier), INV (active inverter), DC-Link and Commutator to alternate between the generation and motoring modes (Courtesy of OMSoP project, 2016)

Another option is to adopt active rectifiers in the EPCS. An active rectifier can control the speed of the HSA (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. Based on the range of frequency for typical MGTs in order to have adequate control over the speed, the switching frequency of the active rectifier should be as high as 50 kHz while the switching frequency in other components of the system is usually about 16 kHz.

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.

SENSITIVITY ANALYSIS FOR CONTROLLING PARAMETERS

Because the MPP operation strategy is based on the variations of system performance with DNI, selection of one of the above mentioned parameters (current, voltage and power) as a suitable controlling parameter directly depends on their sensitivity to DNI. The sensitivity is determined based on the variations of the controlling parameter with the DNI and the accuracy of the inverter as the controller when regulating that parameter. The rate of the variation and the accuracy allow calculating the minimum change in DNI for accurate regulation of each of the proposed controlling parameters. Typical data for an active inverter are given in table 2 as well as the rated values and the resultant value of the minimum readable value. The absolute accuracy is the product of accuracy percentage and the rated value.

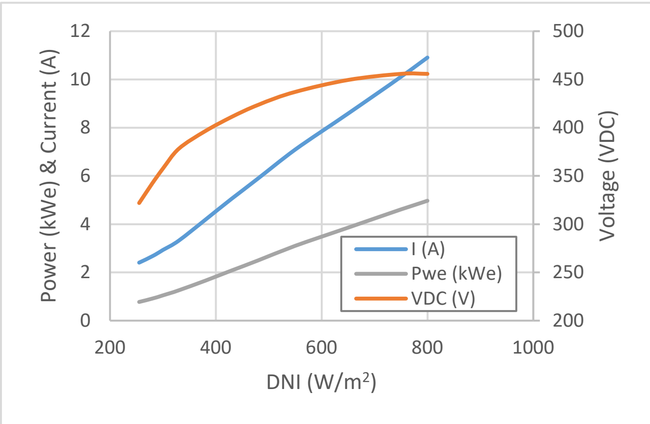

Figure 7) variations of proposed controlling parameters with DNI for MPP operation strategy

Table 2) absolute accuracy of the electrical parameters for a typical inverter rated at 5kWe

Parameter	Percentage of accuracy (err)	Rated value	Absolute accuracy (Err)
Current	0.4	13 (A)	0.052 (A)
Voltage	0.3	400 (V)	1.2 (V)
Power	1.5	5 (kW)	0.075 (kW)

Variations of the electric current, voltage and power with DNI are given by figure 7 when the MGT is operated under MPP strategy.

Table 3) values of the proposed controlling parameters at the minimum and maximum DNI

DNI (W/m2)	Current (A)	Voltage (V)	Power (kWe)
255	2.40	322	0.773
800	10.91	455	4.971

To calculate the rate of variation of each of these parameters with DNI, the numerical data for minimum and maximum DNI within the operation range are also given by table 3. An average rate of variation is calculated for each parameter and is given in table 4.

Table 4) gain factor (rate) of the controlling parameters

K_C [A/(W/m^2)]	K_V [V/(W/m^2)]	K_{PW} [kW/(W/m^2)]

0.0156	0.244	7.703 x 10^{-3}

Having the absolute accuracy of the controller and the variation rate for the controlling parameters, it is possible to calculate the minimum change of DNI which allows the rectifier to do a reliable measurement and regulation. For each parameter, the minimum value is given as below:

$$\Delta dni_I = \frac{Err_I}{k_I} = 3.33\, W/m^2 \quad (2)$$

$$\Delta dni_V = \frac{Err_V}{k_V} = 4.93\, W/m^2 \quad (3)$$

$$\Delta dni_{PW} = \frac{Err_{PW}}{k_{PW}} = 9.74\, W/m^2 \quad (4)$$

The results show that if the generator drive control the MGT by regulating the electrical current, it will be able to operate with minimum variations of DNI. This implies that the electrical current would make a suitable controlling parameter. However, as it can be seen in figure 7 and tables 3 and 4, the electrical current dramatically reduces in low DNIs. In comparison, the reduction in voltage is much less than the current. The weak electric current makes it unsuitable for controlling purposes compared to voltage because of the following points:

- Low current can be affected by the electrical noise
- The output voltage is mainly proportional to the rotational speed for an electric machine and it is always available regardless of the electric current value, but the opposite statement is not valid.

RECUPERATION CONTROL

The power regulation control strategy allows for controlling the dish-MGT system to operate in MPP strategy. However, the generated power of the system would be a direct function of DNI variations. As such, the power regulation strategy may apply MPP operation only if the dish-MGT unit is connected to a large power grid which is able to receive variable power. Although this is one of the main scenarios which have been considered in the study and design of the dish-MGT units ([21] and [5]), it is also possible that the dish-MGT unit is used in a direct connection to a smaller consumer with variable power demand. In such applications, the instantaneous generated power by the dish-MGT system needs to match the electric load at that time. Controlling the MGT for such load-oriented performance cannot be properly achieved by power regulation control because it has only one degree of freedom. As such the control system will not be able to cope with two variable conditions (DNI and load) at the same time.

A novel concept to address this issue and provide flexibility to the solar-only micro gas turbine is proposed and discussed in this paper, which is termed "Recuperation Control" and is depicted schematically in figure 8. A three way proportional valve, V1, by-passes part part of the compressed air flow to the recuperator by diverting it directly to the receiver. The diverted flow mixes with the hot air from the recuperator. The temperature of the inlet flow to the receiver is therefore controlled by the by-pass ratio of the diverted flow (x). The second diverting valve V2 is used to by-pass the turbine exit flow. For simplicity and to have equal mass flow rate in hot and cold sides of the recuperator, by-pass ratio of this valve is set to be equal to that of valve V1. The by-pass ratio and inlet temperature to the receiver are defined by equations 5 and 6.

$$x = \frac{\dot{m}_B}{\dot{m}_{AB}} \quad (5)$$

$$T_{RECV,i} = \frac{(1-x)h_5 + xh_2}{\left(C_p\right)_{RECV,i}} \quad (6)$$

$(Cp)_{RECV,i}$ is the specific heat of the inlet air to the receiver and h_5 and h_2 are total enthalpies of the recuperator and compressor outlets respectively.

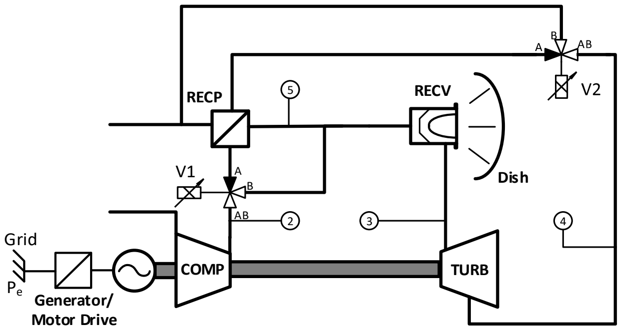

Figure 8) schematic of recuperation control for a simple recuperated cycle. Part of the flow is by-passed via port "B" of the three way diverting valves

With the recuperation control, it would be possible to control one additional performance parameter. An example is the variation of the rotational speed with DNI when it is operated in MPP and recuperation control strategies. While in the former there is no choice but to increase the speed, the latter allows changing the by-pass ratio and keeping a constant speed and hence the MGT would remain within the safe operation window.

An application of the recuperation control is to prevent overheating of the solar receiver for excessive DNI conditions. For a system operated using MPP, the rotational speed increases with DNI to balance the additional input heat with the increased mass flow rate and keep the TIT constant. However, this control is limited to the maximum allowable speed and cannot always be a reliable solution. Figures 9 and 10 show the system performance when the recuperation control is applied for DNI values above 900W/m^2. The by-pass ratio gradually increases from zero to keep TIT at 800°C. As a result, the rotational speed doesn't need to increase and therefore, the pressure ratio and mass flow rate will also remain constant. Below the recuperation control set point, MPP strategy is applied to achieve maximum generated power. As a direct consequence, the generated power doesn't change and the efficiency reduces because of the increase in the input heat. However, the efficiency penalty is not more than 1.4%.

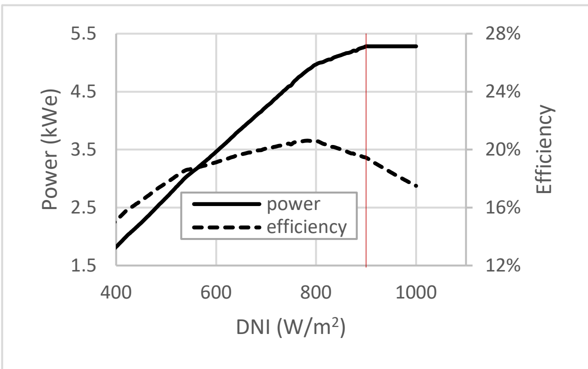

Figure9) performance of the dish-MGT system with the recuperation control strategy applied for DNIs above 900W/m^2

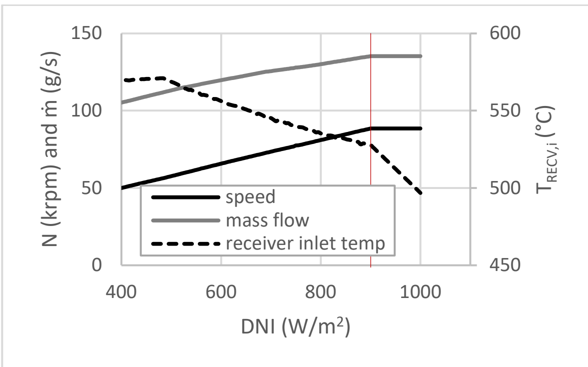

Figure 10) variations of speed, mass flow rate and inlet temperature of the receiver recuperation control applied for DNIs above 900W/m^2

Figures 9 and 10 show the performance results of the dish-MGT system for the case that recuperation control loop keeps TIT constant and the power regulation control loop assures constant rotational speed. It can be seen that as soon as the combined control starts, the generated power remains at a constant value. The reason obviously is that the TIT, compressor ratio and mass flow rate (because of the speed) have been already kept constant and therefore, increase in DNI will not change the working point of the system. However, the effect of by-passing the recuperator can be seen in the reduction of system efficiency because MGT generates same power while receives more heat. The additional heat received by the system results in increasing of the recuperator exhaust line. Figure 10 shows that the Recuperation control can be applied whenever the DNI reaches a certain value. Below that DNI value, the system would be controlled to operate in MPP strategy. When DNI exceeds the set point value, the recuperation control is activated. At the set point, the by-pass ratio is zero and as the DNI continues increasing, the control system opens the valves V1 and V2 to keep the TIT constant.

In general, any other objective for the control system may be defined when using recuperation control. For a load-oriented application, when the system has to follow the variations of power demand and DNI at the same time, the recuperation control is applicable from lower DNI values compared to what showed in figures 9 and 10. An additional control loop will be added to the control system logic (figure 5). The controlled parameter of the added loop will be the generated power. Whenever the required power changes, the by-pass ratio will be changed by the control system to adjust the power. The system performance when the recuperation control is applied from certain DNIs to keep the generated power constant is shown in figures 11 to 13.

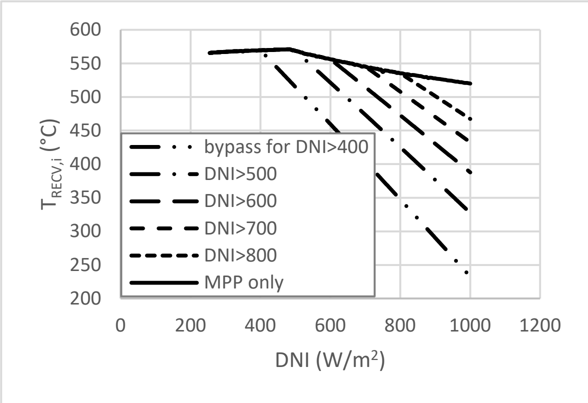

Figure 11) reduction of the receiver inlet temperature when recuperation control strategy is applied

Because of the same reason which was discussed about rotational speed in figure 10, the rotational speed will also remain constant when the recuperation control is applied with the above mentioned strategy. However, the recuperation control has the flexibility to combine with the power regulation setting different control objectives. Figure 11 shows how the receiver inlet temperature decreases when the recuperation control is applied. With the reduced temperature at the inlet of the receiver and lower mass flow, the generated power by the MGT is controlled and maintained on a constant level depending as is shown by figure 13. The generated power level after starting of the recuperation control depends on the point at which this strategy has been applied. Figure 12 shows how the efficiency of the system decreases as a results of recuperation by-pass. This effect is more significant when the recuperator is by-passed in lower DNI values.

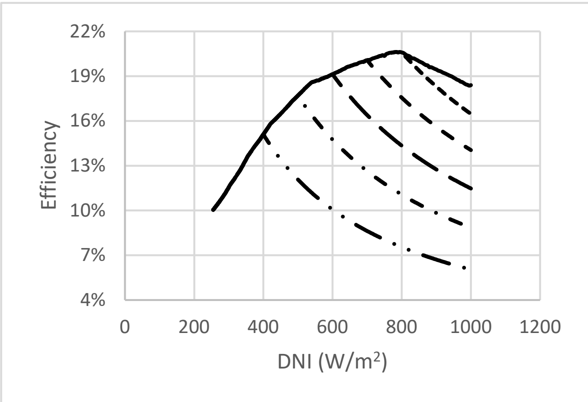

Figure 12) effect of recuperation control strategy on the efficiency of the system

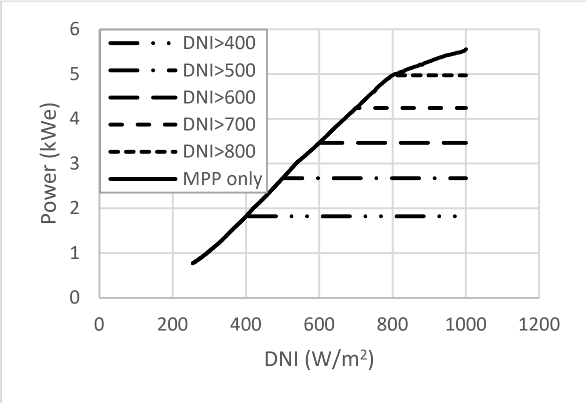

Figure 13) generated power vs DNI. Recuperation control strategy allows for keeping a constant power output by fixing the TIT and speed through the control loops

The concept of recuperation control has the potential to be applied for further advancements in the operation and control of the solar-only micro gas turbine systems as explained in the following two paragraphs.

The flexibility that the recuperation control brings to the control system can also be beneficial when the dish-MGT system is required to deal with particular circumstances such as start up or re-starting after a passing cloud. Depending on the DNI value at which the dish-MGT is starting, overheating of the receiver may occur. As the DNI increases, the minimum speed which the MGT becomes self-sustained increases, but the maximum speed of the high speed alternator in motoring mode is limited and this may cause low mass flow rate and overheated receiver.

Two proposed simpler concepts related to the recuperation control can also be effective to improve the flexibility of the solar MGT systems. The first is to only use the V2 valve as a bleed-off valve which partially diverts the turbine exit flow to the recuperator exhaust and the second idea relies on the application of just the V1 valve. The latter is less effective because the thermal input to the system is not expected to be highly affected in this method. These ideas however, require transient simulation of the micro gas turbine system as they impose a thermal imbalance on the hot and cold side of the recuperator and depends on the thermal inertia of this component as well as the rest of the system. Such ideas and also the issue related to the start-up of the solar-only dish-MGT systems are to be studied in a future work by the authors.

COMPARISON OF METHODS

Performance of the dish-MGT system is compared for the operation strategies which are studied here. The simulation has been done when the system is installed in Casaccia in Italy and Seville in Spain. The dish-MGT system of OMSoP project is to be installed in Casaccia. The overall performance of the system is determined by the annual generated electricity as given by equation 1 and the solar to electric efficiency. Results for annual generated electricity are presented in figure 14.

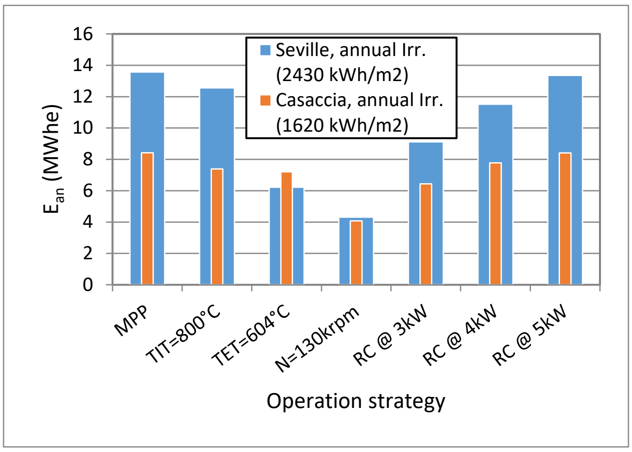

Figure14) annual generated electricity for different operation strategies (RC: Recuperation Control)

Three recuperation control strategies (abbreviated in the graphs as RC) are also examined in the simulations. Operation of the system for these three cases is actually a combination of MPP strategy and recuperation control. For the low DNIs when the output power is below a particular value, the system operates in MPP strategy and no by-pass is required. For higher DNI values, recuperation control is activated. The results shown here are for the case that the control system keeps the generated power and TIT constant which is similar to the performance of the system shown in figures 11 to 13. The only difference is that the recuperation control is activated at a particular power rather than a DNI value. The results are shown for three cases when the recuperation control begins at output power equal to 3kWe, 4kWe and 5kWe. The latter is the expected power at the design point and therefore it means that for this particular case, the recuperation control is applied when the DNI exceeds the nominal value of 800W/m^2. All solar data are taken from HelioClim1 and HelioClim3 data bases for year 2005 which is available online [22]. DNI data are provided on an hourly basis for each day.

For each of the constant TIT, TET and speed operation strategies, the corresponding constant value of the design point is considered for a proper comparison. The results show that in general, the generated electricity in Seville is higher than Casaccia because it receives higher annual solar irradiance. However, it can be seen that for constant TET operation, the annual generated electricity of the system in Casaccia is higher than Seville. It shows that the total duration time for the range of DNI that the MGT can be safely operated with constant TET is larger in Casaccia than Seville. Nevertheless, the MPP operation strategy shows maximum generated electricity in both geographical positions and will be the first choice for a solar-only dish-MGT system when its generated power is fed to a large grid. However, when the system is required to be load-oriented, recuperation control can be considered for the power generation. The system performance when recuperation control is applied above the design point shows almost no difference with MPP strategy either for Casaccia or Seville. However, using the recuperation control just above the design point also restricts the flexibility of the system to a narrow band of DNI above 800W/m^2. It is interesting that because the duration of low DNI values is relatively higher for Casaccia than Seville, the degradation of system performance is less significant for Casaccia than Seville when recuperation control starts from lower output power (hence lower DNIs). It is therefore advisable to apply recuperation control strategy when the dish-MGT system is in regions with lower duration of excessive DNI values. In other words, the potential for dish-MGT system to be used in a load oriented application is higher in such regions whilst in high DNI areas it is better to use the purely solar powered dish-MGT units with an MPP operation strategy in a power network to achieve highest allowable efficiency.

The overall solar efficiency of the dish-MGT system, defined as the ratio of the annual generated electricity by a particular system over the annual solar heat received at the dish area.

$$\eta_{solar} = \frac{E_{an}}{DNI_{an} A_{Dish}} \qquad (7)$$

Where DNI_{an} (in kJ/m^2) is the annual solar radiation per unite area.

The concept of solar efficiency helps to envisage the points mentioned before regarding the comparison of the annual generated electricity for different operation strategies. It can be seen that the solar efficiencies when the dish-MGT system is operated in constant TET or speed are higher for Casaccia than Seville because the distribution of solar irradiance in Casaccia is much more in favor of these two operation strategies compared to Seville. For the same reason, the solar efficiency is also higher in Casaccia when recuperation is applied from relatively higher DNI values.

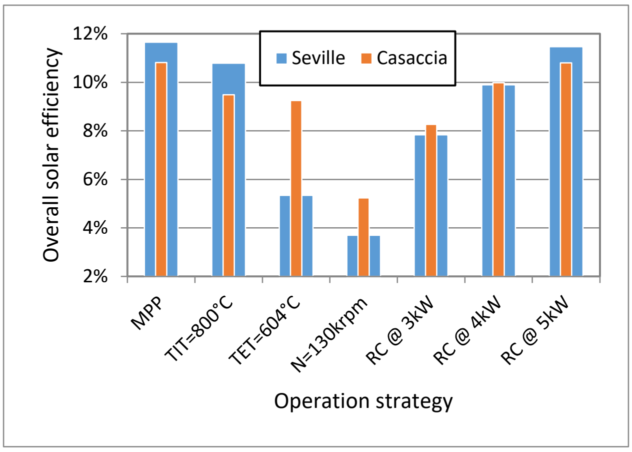

Figure 15) overall solar efficiency for different operation strategies

CONCLUSION

Two concepts for the control of solar powered micro gas turbines were proposed and analyzed for two different applications. The first is 'power regulation control' which can be applied using sophisticated power electronics to operate the MGT in MPP strategy leading to maximum power generation when the system has no restrictions on the load side. The second is the 'recuperation control', which was introduced as a control strategy to match the electric load when dish-MGT is used in a load-driven application. It was shown that the latter is very useful in terms of the improved flexibility and control. It was also shown that an efficiency penalty is inevitable when the recuperation control is applied compared to the MPP operation. However, the significance of this penalty highly depends on the settings of the recuperation control starting point and DNI spectrum received at the location of the installation. From cycle analysis point of view, the reduction of efficiency results from the loss of thermal energy to the exhaust. If the thermal energy on the higher temperature exhaust products are utilized, this reduces the significance of the efficiency loss of the MGT

Recuperation control strategy would also require relatively higher capital cost as two additional proportional valves would be required to perform the control. However, compared to the total initial cost of a dish-MGT unit, the added investment is not significant. Therefore, selection of the appropriate control and operation strategy should be determined based upon the application which is considered for the dish-MGT unit.

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