TELKOMNIKA Telecommunication, Computing, Electronics and Control
Vol. 18, No. 6, December 2020, pp. 3184~3190
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v18i6.16676

Modelling of solar micro gas turbine for parabolic dish based controller application

Syariffah Othman[1], Mohd Ruddin Ab. Ghani[2], Zanariah Jano[3], Tole Sutikno[4]
[1,2]Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia
[3]Centre for Languages and Human Development, Universiti Teknikal Malaysia Melaka, Malaysia
[4]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Indonesia

Article Info

Article history:

Received May 13, 2020
Revised Jul 1, 2020
Accepted Jul 9, 2020

Keywords:

Micro gas turbine
Dish system

ABSTRACT

Dish-Stirling unit and photovoltaic panels are the premier technologies available to generate off-grid solar energy. The major issue for both systems is in terms of producing output power. Air-Brayton cycle was utilized as an engine by converting the thermal energy to electricity. Micro gas turbine (MGT) has been recognized as one of the viable alternatives compared to Stirling engines, where it represents a state-of-art parabolic dish engine specifically in turbine gas technology. Hence, the micro gas turbine is a technology that is capable of controlling low carbon while providing electricity in off-grid regions. MGT uses any gas as its input like natural gas, biogas and others. Micro gas turbine has advantages for its high expansion ratio and less moving components. Compared to competing for diesel generators, the electricity costs from hybrid solar units were reduced between 10% and 43%, whereas specific CO_2 emissions reduced by 20-35%. MGT provides advantages over photovoltaic systems such as the inherent ability to hybridize the systems with hydrocarbon fuels to produce electricity around the clock, and the ability to operate more effectively in very hot climates with photovoltaic performance degradation over the lifetime of the system. Hybrid solar micro gas-turbines are cost-effective, eco-friendly and pollution free as they can work by burning any gas like natural gas, landfill gas and others. This paper presented the controls contained in the MGT-dish system consisted of temperature control, fuel flow control, speed and acceleration control. A conceptual design of the 25kW MGT-dish system was also covered.

Corresponding Author:

Mohd Ruddin Ab. Ghani,
Faculty of Electrical Engineering,
Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Durian Tunggal Melaka, Malaysia.
Email: dpdruddin@utem.edu.my

1. INTRODUCTION

Solar energy offers a sustainable and environmentally-friendly manner to reduce dependence on fuel especially for an area with the high solar energy resources. Off-grid solar power consists of two main technologies namely dish-Stirling units and photovoltaic panel [1, 2]. However, some features of these two technologies have few disadvantages. The impact of fluctuations in solar supplies is a major issue for both systems in producing output power. Although unused outputs are stored in batteries that have been integrated with photovoltaic panels, indirectly, the cost of producing electricity is increasing. Regarding dish-stirling, the low-cost thermal energy storage can be integrated with the unit. However, only the small storage capacity can be installed due to structural constraints by solar dishes. Hence, causing low availability of this system every year. Micro gas turbine (MGT)-dish will show some advantages over both systems [3]. The hybrid system, where solar energy comes with fuel reserves (such as local biodiesel), allows MGT solar to supply controlled power on demand to households, without the need for investment in expensive batteries [4-6]. Other than that, the thermal energy contained in the MGT exhaust also provides the opportunity to provide additional services, like heating, cooling, and water purification through the use of poly-generation technology [2, 7].

Micro turbine is a new generation of distributed technology. The structural is compact, small, containing high-speed combustion and high-speed turbines with an output between 25 kW and 500 kW [8, 9]. Micro turbine often produces electricity and heat on a relatively small-scale for stationary generation applications. The micro turbine provides mechanical input power in the form of high-speed rotation to the generator, and the generator turns it into electrical energy. Distributed generation using micro turbines is a typical solution for stand-alone, and the application on the site is far from the power grids [10, 11]. Other applications for this system are cogeneration generation (heat and power generation are combined), peak shaking, standing with power generation, increased reliability, energy cost reduction, power boost capacity and pollutant emission reductions.

Micro turbine offers a lot of advantages over other technologies, such as long lifetime (±45,000 hours), small size, lightweight, fast response, few moving parts, lower emission, higher efficiency, higher flexibility, lower electricity costs, and opportunity to utilize waste fuel with less noise than reciprocating engines [4, 12]. The micro turbine is expected to take a significant share in the distributed generation market because of its relatively small size, low capital costs, low operation and maintenance costs. In addition, the micro turbine offers clean and efficient solutions for a mechanical-driven direct market, such as air conditioning and air compression [13]. In this study, a conceptual design of a hybrid MGT-dish with 25 kW output was developed to achieve a better performance and prevent the disadvantages of the dish-Stirling. For this hybrid unit, a basic receiver was utilized by utilizing an impinging cavity receiver concept. Besides, a cavity shape was chosen from a semi-spherical bottom and a cylindrical absorber wall, because of its durability under high-pressure and temperature and simple structure [4, 14, 15].

2. SYSTEM DESCRIPTION AND METHODOLOGY

The hybrid gas turbine consists of compressor, recuperator, combustor, solar receiver and turbine, as shown in Figure 1. In most designs, combustor, and turbine of a high-temperature are placed in the center of the system in order to make the structure more compact and the receiver, the least heat loss. The system is surrounded by recuperator and cold air channel of a low-temperature [16-19]. The compressor compressed the air and was heated up by the recuperator. Then, the air was heated to higher temperature by solar receivers. Then, the air would enter the combustion chamber directly when it came out from the solar receiver. At the combustion chamber, the air was heated to fulfill the inlet turbine temperature requirement, which was set to 950°C just to maintain the uncooled blades [4, 20]. Then, the waste gas expanded to a single stage axial turbine coupled with the same shaft as the compressor and generator. Furthermore, to achieve high efficiency for a gas turbine, the receiver is placed before the combustor where the air can be heated to a higher temperature by the combustion chamber [21]. The MGT is designed at nominal conditions (an ambient temperature of 15°C and a solar direct normal irradiance of 800 W/m^2) for generating 25 kW [3, 16, 22]. The Matlab/Simulink tool was used to model the system and simulate the electric power generation under solar radiation. The simulation model for the proposed proportional derivative (PD) hybrid power generation system is illustrated in Figure 2.

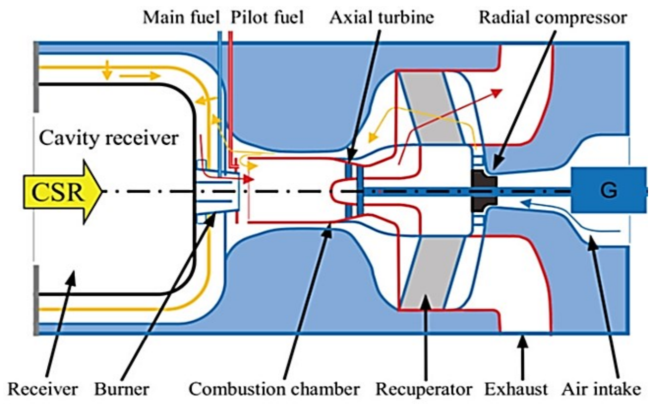

Figure 1. Schematic of the hybrid gas turbine [4]

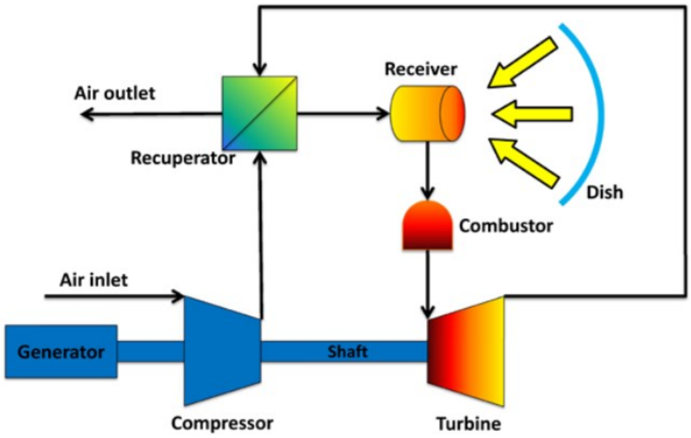

Figure 2. MGT-dish system (single-shaft design) [4]

2.1. PD system characteristic and model

In this MGT-dish design, the air was compressed in the compressor and recuperator warmed up the air in the second step. Then, the air from the recuperator enters the receiver through the combustor wall cooling ducts [23]. In the case of ‘sun on’, basically, the inlet parameters of the receiver are the outlet air parameters of the recuperator [24]. Hence, the reflectance of the dish was set to 96% (silver), and 45° of rim angle was set to fulfill the requirements of the gas turbine [4, 25]. Normally, most of the concentrated solar irradiation was absorbed through the aperture and blackbody where cavity receiver considered it as a receiver design. In this case, the estimate of the receiver optical efficiency including the intercept efficiency was 95%. In additon, the receiver thermal efficiency was estimated to 80% [4, 26]. Therefore, based on the reflectance of the dish, the heat power absorbed by the working fluid, and the efficiency of the receiver, the dish with a diameter of 11 metres was selected. One of the key parameters that could affect the optical efficiency and the final flux distribution on the focal plane beyond the reflectance was slope error. In this paper, a 2 metres radius dish slope error was estimated to measure data from DISTAL II and EuroDish [4, 27].

In the micro turbine system, the control system consisted of speed and acceleration control, temperature control, and fuel flow control. Speed control was to control the micro turbine speed at different load conditions. However, acceleration control was to control the speed rate limits during the initial micro turbine. Control limits of the output power upper limit acted by temperature control. Besides, the fuel flow controlled the amount of fuel that was put into the combustion when the load changed. The least value gate (LVG) would control all the output from control function block. Figure 3 shows micro turbine’s block diagram. It indicated the lowest output of three inputs and which input produced the least fuel to the turbine compressor. Each subsystem of the micro turbine is discussed in the following subsections [1, 2, 28-31].

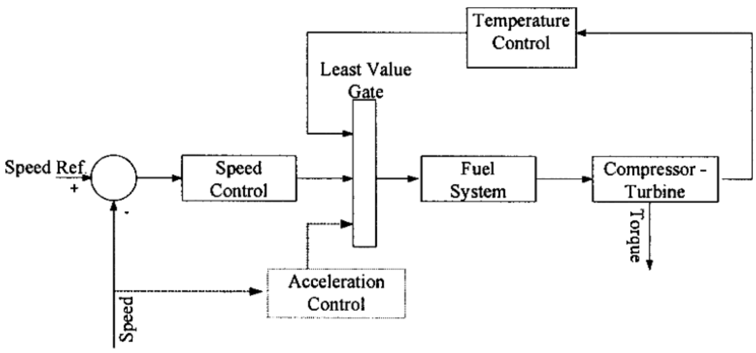

Figure 3. Block diagram of micro turbine [28]

2.2. Speed and acceleration control

In the MGT system, the speed control would operate on speed errors formed between the speed of the rotor and a reference (one per-unit) speed. This is how the micro turbine controlled the load for different conditions. Figure 4 shows the speed control that is often modeled by a PID controller or used a lead-lag transfer function. Acceleration control was used for start-up time of the MGT to limit the increasing rate of rotor speed before reaching the operating speed. The system operating speed was close to rated speed, causing the elimination of the acceleration control in the modeling. Yet, the present study utilized the acceleration control.

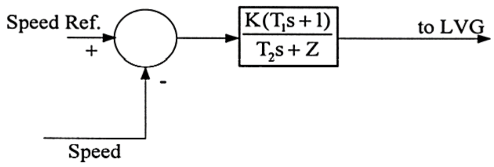

Figure 4. Speed control of a micro turbine [28]

2.3. Temperature control

The input signals to the temperature control system were fuel demand signal and turbine speed, which output was a temperature control signal to the LVG. A temperature control block diagram is shown in Figure 5. The thermocouple output was normally lower than the reference temperature. However, when thermocouple temperature was higher than reference value, the result was a negative error, which was the input of the LVG and temperature control started decreasing to reach the former temperature [28].

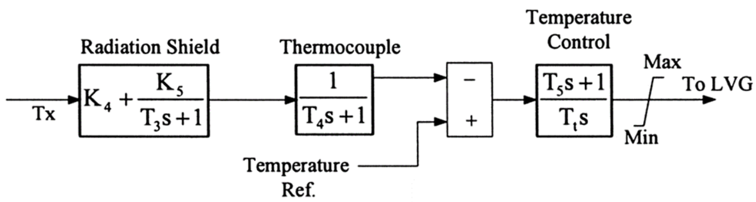

Figure 5. Temperature control of a micro turbine [28]

2.4. Fuel system

The fuel system control was a series block off the fuel valve and actuator. Figure 6 shows a fuel control system for the MGT. The output of LVG, V_{ce}, was scaled by the gain K3 and offset by K6 that was representing fuel flow at no load condition [28].

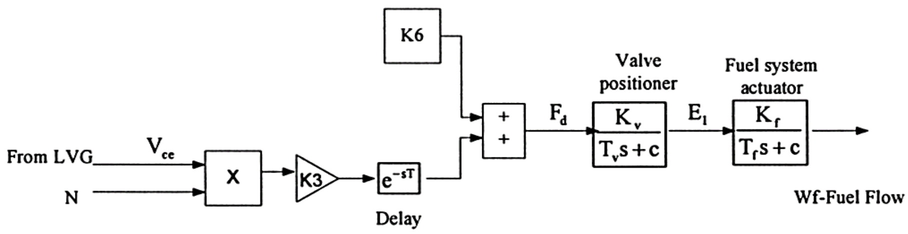

Figure 6. Fuel system of a micro turbine [28]

2.5. Compressor turbine system

The compressor turbine package was an important part of an MGT and they were considered as a package because they were mounted on the same shaft. The input signals to the gas turbine were the fuel flow W_f signal that was achieved from the fuel control system and the rotor speed deviation [28]. The compressor turbine system is represented in Figure 7. Basically, the torque and the characteristics of turbine exhaust temperature were both linear with respect to fuel flow and turbine speed. The following equation is as follows:

$$\text{Torque} = K_{HHV} (W_{f2} - 0.23) + 0.5(1\text{-}N) \text{ (Nm)}$$

$$\text{Exhaust Temp, } T_x = T_R - 700(1 - W_{f1}) + 550(1\text{-}N) \text{ (°F)}$$

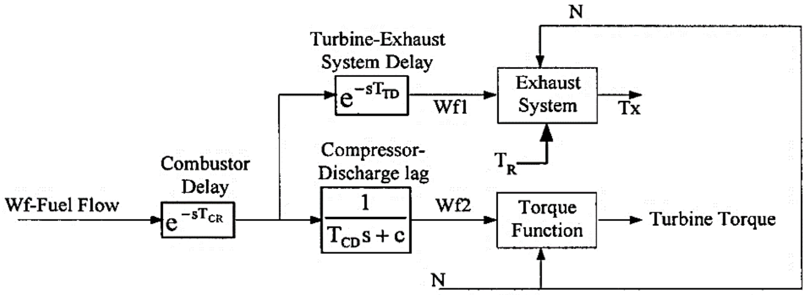

Figure 7. Compressor-turbine of a micro turbine [28]

3. SIMULATION ANALYSIS

MATLAB/Simulink was used in building a microturbine simulation model. For all simulations, speed reference was kept constant at 1 p.u. Initially, a simulation of the MGT system was operating without any load [32]. Figure 8 showed that when t = 10 seconds, the MGT system used 200kW and it increased to 400 kW at t = 15 seconds. This showed that the output power reacted to the load. Figure 9 shows the fuel used by the microturbine for the load conditions. The fuel demand was equal to 23% (0.23 p.u.) until the load was applied to the system at *t* = 10 seconds, increasing the amount of fuel required to keep the combustion process alive. Note that the fuel demand signal was 0.62 p.u. at 200 kW load and increased to 1 p.u. at 400 kW (full load).

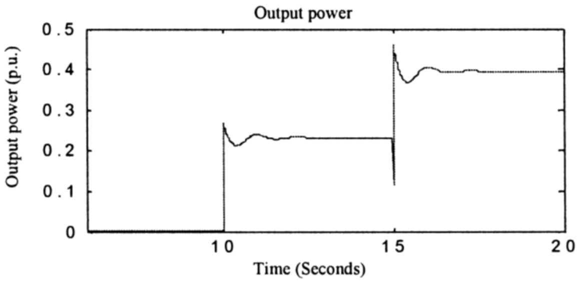

Figure 8. Output power of MGT

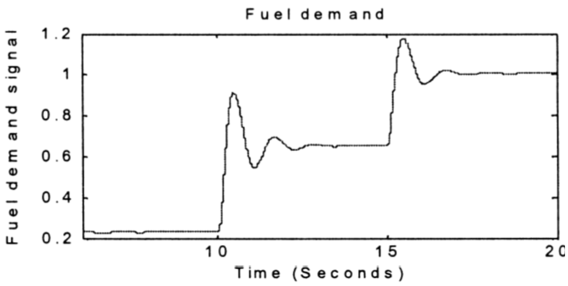

Figure 9. Fuel demand

4. CONCLUSION

In conclusion, the development of an MGT system (single-shaft design) is deemed suitable for hybrid MGT-dish to achieve a better performance. This model is good for the study of hybrid power generation systems. Detailed mathematical modeling of the control systems of the turbine is given and simulations of the developed MGT system model are carried out. The results show that the developed model has the ability to meet the load requirements and maintain the rated value of voltage.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the funding support provided by the Universiti Teknikal Malaysia and Ministry of Education Malaysia under the research grant No. PJP/2016/FKE/HI5/S01482.

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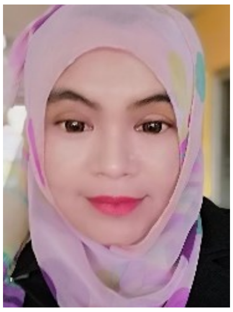
BIOGRAPHIES OF AUTHORS

Syariffah Othman received her B. Eng in electrical engineering from the Universiti Teknologi Malaysia (UTM) and M. Sc degrees from the Universiti Kebangsaan Malaysia (UKM). She joined the Polytechnic Department, Ministry of Education, Malaysia as a lecturer in 2001. She is currently pursuing her PhD at the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia. Her current research interests include the renewable energy and concentrating solar energy.

Mohd Ruddin Ab. Ghani is a professor and the Rector of the Universiti Teknikal Malaysia Melaka (UTeM). Before coming to UTeM, he was professor and the dean of the Faculty of Electrical Engineering at Universiti Teknologi Malaysia (UTM). Prof. Mohd. Ruddin Ab. Ghani obtained his Ph.D. in Systems Engineering and Control from the University of Manchester Institute of Science and Technology in 1989. His current research interests include: dynamic economic load dispatch and unit commitment, distribution automation, renewable energy and technology, optimization of large-scale power systems, system identification, expert system applications and advanced control techniques to power systems. He has published over 200 papers and articles in the related fields. Besides actively involved in research and publications, he is also a committee member of various distinguished boards such as: committee member of Malaysian International Electro-technical Commission (IEC), Intensification of Research in Priority Areas (IRPA) and IEEE Malaysia chapter. He is also member of Advisory Council Member of Malaysian Armed Forces Academy, and a member of Energy Technology Committee under Economic Planning Unit, Prime Minister Department, Malaysia.



Zanariah Jano obtained her PhD in Multimedia Interactive System in 2015 from Universiti Sains Malaysia (USM) and Master's degree in Communication Studies (IT) from University of Brighton, United Kingdom in 2005 and Bachelor Degree in Teaching English as a Second Language from University of Winnipeg, Canada. She started her career as a language teacher in Universiti Kebangsaan Malaysia. She is currently serving as a senior lecturer at Universiti Teknikal Malaysia and holding a post as the Head of Human Development Department and used to hold several administrative posts as the Head of Department (2015-16) and Deputy Dean of Research. She is an active researcher and supervisor. She is also a consultant for many projects involving Problem Based Learning with other institutions and Leadership Academy of Higher Education Malaysia (AKEPT), English proficiency training with Kementerian Pendidikan Malaysia, Business English with UKM Holdings and others. Her research areas include Problem Based Learning, Multimedia and Culture, Web Communication, Cross cultural in web design.

Tole Sutikno, Associate Professor in Electrical and Computer Engineering, Universitad Ahmad Dahlan (UAD), Yogyakarta, Indonesia. He received his B.Eng., M.Eng. and Ph.D. degree in Electrical Engineering from Universitas Diponegoro (Semarang, Indonesia), Universitas Gadjah Mada (Yogyakarta, Indonesia) and Universiti Teknologi Malaysia (Johor, Malaysia), in 1999, 2004 and 2016, respectively. He has been a Associate Professor in UAD, Yogyakarta-Indonesia since 2008. His research interests include the field of power electronics, industrial applications, industrial elecctronics, industrial informatics, motor drives, FPGA applications, intelligent control and digital library.