IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 17, Issue 3 Ser. I (May - June 2020), PP 52-57
www.iosrjournals.org

Use of combined solar photovoltaic modules and polymer electrolyte membrane fuel cell for operating gas turbine

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Abstract: *In this present work gas turbine is operated by power obtained from solar photovoltaic modules and PEM(polymer electrolyte membrane) fuel cell for obtaining 1 MW power. Air at ambient temperature of Kolkata city, India enters the compressor. The air is compressed in compressor and sent to combustion chamber. In combustion chamber air is heated to 1000K from power obtained by solar photovoltaic modules with current of 100 A after passing through 50 ohm resistance throughout the day and year. During day time solar photovoltaic modules generates current and the required current goes to combustion chamber through charge controller and inverter for heating. The excess current during day time after meeting the combustion chamber's requirement goes PEM electrolyzer where water present there is dissociated into hydrogen and oxygen. The hydrogen generated occupies large volume, so in order to store in small tank the generated hydrogen is compressed by gas compressor which obtains its power from separate photovoltaic module system. During night time power is obtained from PEM fuel cell which utilizes hydrogen stored in storage tank. The present study is made for the month of May(summer) and December(winter) as May and December months have maximum and minimum temperature and solar radiation respectively and if it works well in these two months the system will work well throughout the year. The study reveals that 15144 solar photovoltaic modules in parallel each having 2 modules in series of Central Electronics Limited Make PM 150 with a 3077.965 kW electrolyzer and 445 PEM fuel cell stacks, each of 382.372 W, can support the energy requirement of combustion chamber of gas turbine and for gas compressor 6335 solar photovoltaic modules in parallel each having 2 modules in series of Central Electronics Limited Make PM 150 is needed for compressing hydrogen.*
Key Words*: Combustion chamber; Central Electronics Limited Make PM 150;Electrolyzer; PEM(polymer electrolyte membrane).*

Date of Submission: 14-05-2020 Date of Acceptance: 29-05-2020

I. Introduction

Gas turbine is a device to obtain power by heating gas coming from compressor at combustion chamber to elevated temperature by any means. Usually fuels are used for heating purposes.

In ref.[1] authors made a multi-criteria life cycle assessment of a prototype of molten carbonate fuel cells plant ; the results were subjected to a systematic sensitivity analysis and compared to those for three natural gas turbine plants. In [2] authors carried out thermodynamic calculations for evaluating the performance of small-scale gasifier–SOFC–GT(solid oxide fuel cell-gas turbine) systems of the order of 100 kW. The authors described the conceptual design of a hybrid MCFC(molten carbonate fuel cell) system to generate power and simultaneously capture CO_2 from small (<10MW) gas turbine exhaust streams in [3]. In [4] authors developed a small packaged natural gas fuelled sub-MW unit gas turbine for demonstrations purpose and completed the preliminary design of a 40 MW combined gas turbine and fuel cell cycle power plants including the key equipment layout and the site plan. In [5] authors addressed the design and off-design analysis of a hybrid system based on the coupling of a recuperated micro gas turbine (MGT) with a high temperature solid oxide fuel cell (SOFC) reactor. In [6] authors developed a detailed dynamic model of a solid oxide fuel cell/gas turbine (SOFC/GT) system where simulation representing the 220kW SOFC/GT hybrid system was developed by Siemens Westinghouse and comparison of results of the dynamic model and also experimental data gathered during the operation and testing of the 220kW SOFC/GT at the National Fuel Cell Research Center were done. Next addressing the possibility to burn hydrogen in a large size, heavy-duty gas turbine designed to run on natural gas as a possible short-term measure for reducing greenhouse emissions of the power industry was made in [7]. In [8] author offered a concept for innovative hybridization of gas turbine combined cycle plant and solar power system.

In the present paper gas turbine operated by combined solar photovoltaic modules and PEM electrolyzer-fuel cell is used for supplying power to combustion chamber of gas turbine for obtaining 1 MW power.

II. System layout

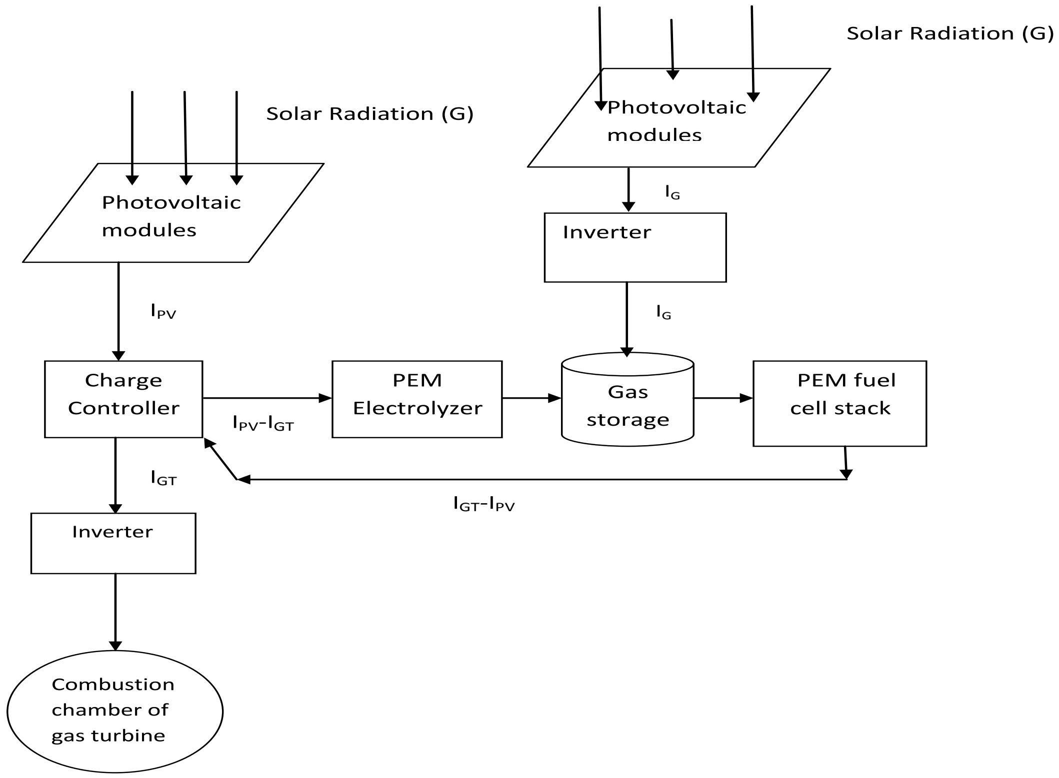

Fig.1: Schematic view of combined solar photovoltaic modules and PEM electrolyzer-fuel cell for supplying power to combustion chamber of gas turbine

Fig. 1 shows a layout of combined solar photovoltaic modules and PEM electrolyzer-fuel cell for supplying power to combustion chamber of gas turbine. During the daytime, solar radiation falls on solar photovoltaic modules and generates direct current (I_{PV}). It is sent through a charge controller. In the charge controller, the required current is sent to the combustion chamber of gas turbine (I_{GT}) after passing through an inverter. The remaining excess current(I_{PV}-I_{GT}) is sent to the electrolyzer. In electrolyzer, the water present is dissociated into hydrogen and oxygen. Hydrogen having low mass density needs a large tank for storage. Hence to reduce the storage tank size hydrogen is compressed which obtains its power(I_G) again from separate system of solar photovoltaic modules.

During night time when solar radiation is not available, the PEM fuel cell stack uses stored hydrogen from the storage tank and generates a current (I_{GT}-I_{PV}) and is sent to the combustion chamber through a charge controller.

Fig. 2 shows a layout of simple gas turbine plant. Air at ambient temperature (Kolkata city, India) enters to compressor at 1 and is compressed. This compressed air is sent to combustion chamber at 2 where it is heated to 1000 K by current coming from photovoltaic modules during day time and fuel cell during night time after passing through a definite resistance. The heated air is then passed through turbine and power of 1 MW is obtained. The mass flow rate of compressed air is adjusted in such a way that constant power of 1 MW power is obtained throughout the day and year.

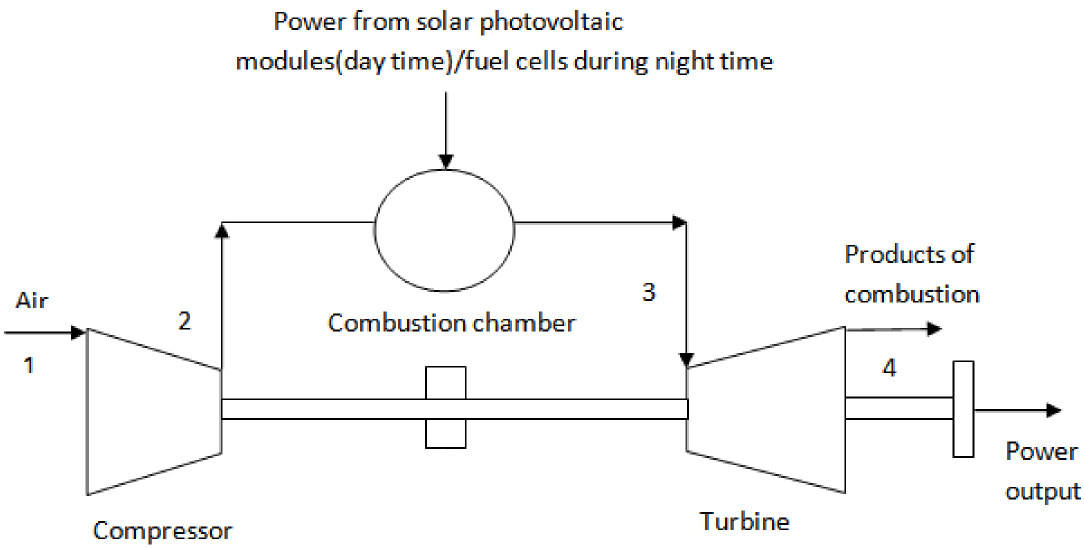

Fig. 2: A layout of simple gas turbine plant

The layout in fig. 1 and 2 are similar to that of layout present in ref. [9], except during night time power to combustion chamber of gas turbine is obtained from fuel cell instead of rechargeable battery.

III. Modeling

Modeling of gas turbine

The detailed modelling of gas turbine are available in ref. [9]. The current required for combustion chamber and resistance is 100 A and 50 ohm. The power obtained from turbine and power consumed by compressor adjusts in such a way that constant power of 1 MW is obtained throughout the day and year.

Modeling of solar photovoltaic modules

In present study Central Electronics Limited Make PM150 solar photovoltaic modules [10] is used. The detailed current calculations for photovoltaic cell are obtained from [11].

The number of solar photovoltaic modules needed in series and parallel are obtained from ref. [9] considering all assumptions same as in ref.[9]. The system voltage is considered to be 48V.

Modeling of PEM fuel cell

All the input parameters and calculations for finding net voltage are obtained from [12].

The peak hourly current required from fuel cell stack ($i_{fuelcell,GT}$) is given by:

$$i_{fuelcell,GT} = \frac{combustion\_chamber\_current}{\eta_{chargecontroller}} \tag{1}$$

Where, combustion chamber current is the current requirement at any hour during non sunshine hours i.e. from 1:00 hour to 5:00 hours and 19:00hours to 24:00 hours which is same at every hour, $\eta_{chargecontroller}$-charge controller efficiency(0.85)[12].

Number of PEM fuel cell stacks in parallel($N_{fc,parallel}$) is given by [12]:

$$N_{fc,parallel} = \frac{i_{fuelcell,GT}}{i_{cell}} \tag{2}$$

Where i_{cell}-current generated by single fuel cell.

The number of fuel cell connected in series($N_{fc,\ series}$) and is given by[12]:

$$N_{fc,series} = \frac{V_{system,fc}}{V_{fc}} \tag{3}$$

Where $V_{system,fc}$-system voltage of fuel cell(48V considered), V_{fc}-net voltage of PEM fuel cell.

The hourly hydrogen consumption of a fuel cell stack during non sunshine hours is given from [12]:

$$m_{fc,GT} = \frac{i_{fuelcell,GT} \times N_{fc,series} \times 3600 \times 2}{2 \times F \times \eta_{fuel}} \tag{4}$$

Where, F is Faraday constant (96500 C/mole), η_{fuel} -fuel utilization factor in fuel cell (considered 0.9).

Modeling of PEM electrolyzer

Excess current (I_{PV}-I_{GT}) after meeting the requirement of the combustion chamber load is sent to the PEM electrolyzer for dissociating water present in electrolyzer into oxygen and hydrogen. The number of cells in stack in series is taken as 30 and effective cell area is considered to be 86.4 cm^2 [12].

Amount of hydrogen produced(in gram mol)in electrolyzer with 30 cells in series in hourly basis is given by [12]:

$$M_{elec,GT} = \frac{(I_{PV} - I_{GT}) \times 30 \times \eta_{elec} \times 3600}{2 \times F} \quad (5)$$

Where, η_{elec}-electrolyzer electrical efficiency, I_{GT}- hourly current requirement from PV modules(6:00 hours to 18:00 hours).

Modeling of gas compressor

Hydrogen gas produced in the electrolyzer needs to be compressed to store it in less volume which is obtained from a separate system of a solar photovoltaic system. The required input parameter for power calculation in the gas compressor is obtained from [12]:

Current required for running the gas compressor at i_{th} hour in a day is given by:

$$i_{compressor,i} = \frac{W_{c,i}}{V_{system,compressor} \times PF \times \eta_{inverter}} \quad (6)$$

Where $V_{system,compressor}$- system voltage of compressor(48 V considered), $W_{c,i}$- power required to run the gas compressor in hourly basis(6:00-18:00 hours, sunshine hours),PF-power factor(0.85),$\eta_{inverter}$-inverter efficiency(0.85).

The design current($i_{spv,c}$) required from solar photovoltaic modules is similar to given by [12]:

$$i_{spv,c} = \frac{i_{compressor,total} \times DF}{sunshinehours \times \eta_{chargecontroller}} \quad (7)$$

Where,DF-derating factor of photovoltaic modules[12], $\eta_{chargecontroller}$-charge controller efficiency (0.85)[12],sunshine hours considered 7 for Kolkata city [12],$i_{compressor,total}$-total current required by gas compressor during sunshine hours(6:00 hours to 18:00 hours).

The number of photovoltaic modules in series($N_{s,compressor}$) is found to be 2 after considering system voltage to be 48V[12].

The number of photovoltaic modules in parallel ($N_{p,compressor}$) is given by [12]:

$$N_{p,compressor} = \frac{i_{spv,c}}{i_{mp}} \quad (8)$$

IV. Results and Discussion

The variation of mass flow rate of air(kg/s) to compressor with reasons in gas turbine for month of December and May are obtained from [9]. Also variation of turbine work output (kW), compressor work input(kW) for the month of December and May with reasons are available in [9].

Based on the assumptions made in [9] the number of solar photovoltaic modules needed in parallel and series for supplying current of 100 A (with 50 ohm resistance) to combustion chamber is found to be 15144 and 2 respectively of type Central Electronics Limited Make PM 150.

After meeting the current requirements for combustion chamber, extra current(IPV-IGT) is used for dissociating water into hydrogen and oxygen in electrolyzer. For that 30 PEM electrolyzer fuel cells in series are needed. The hydrogen generation by electrolyzer is proportional to (IPV-IGT) as can be seen in equation 5 and so increases from 6:00hours to 12:hours and again decreases from 12:00 hours to 18:00 hours due to the fact that solar radiation increases from 6:00hours to 12:hours and again decreases from 12:00 hours to 18:00 hours and as a result Ipv(current generated by photovoltaic modules) increases and decreases in the same fashion. It is seen that hydrogen production is more in May than December as shown in figs. 4 and 3 due to greater solar radiation in the month of May than December.For proper functioning of electrolyzer the power requirement is obtained as 3077.965 kW which is the maximum power required in a year during the month of May at 12:00 hours(maximum solar radiation) at 48 V system voltage and hydrogen generation is maximum in May at 12:00 hours so if it works well in May, electrolyzer will work well throughout the year.

During night time hourly current required by PEM fuel cell (ifuelcell,GT)for combustion chamber is obtained from equation 1 which is same at every hour of night as constant 1MW gas turbine power is needed throughout the day. From equation 2 and 3 the number of fuel cell needed in parallel and series is obtained as

445 and 47 respectively. Using equation 4 the hourly hydrogen consumption during non sunshine hours(19:00 hours to 5:00 hours) is constant i.e. 6894.341 gm mol of hydrogen which can be seen in figs. 3 and 4.

It is seen that cumulative hydrogen generation and consumption in December and May is found to be 122157.084 gm mol, 75837.751 gm mol and 208389.27 gm mol, 75837.751 gm mol respectively.

According to equation 6, current required by gas compressor for compressing generated hydrogen increases from 6:00hours to 12:hours and again decreases from 12:00 hours to 18:00 hours due to the fact that hydrogen generation increases from 6:00hours to 12:hours and again decreases from 12:00 hours to 18:00 hours. Hence power needed by gas compressor changes in that fashion. Power needed by compressor is considered at 12:00 hours in May(i.e.306.748 kW) because May has maximum solar radiation and maximum hydrogen production(25624.101 gm mol) at 12:00 hours . Hence if it works well in maximum radiation the compressor will work well throughout the year. The number of photovoltaic modules in parallel for gas compressor is obtained from equation 8 (found to be 6335 in parallel) and 2 in series of Central Electronics Limited Make PM 150 and is calculated for December since December has minimum solar radiation and if it works well in minimum radiation it will work well throughout the year.

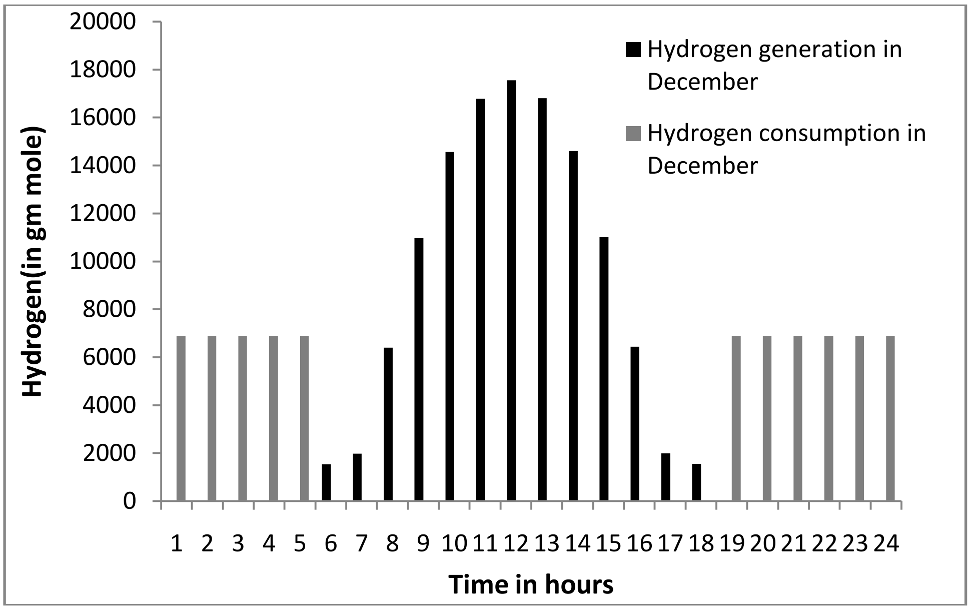

Fig. 3: Hydrogen generation and consumption for the month of December

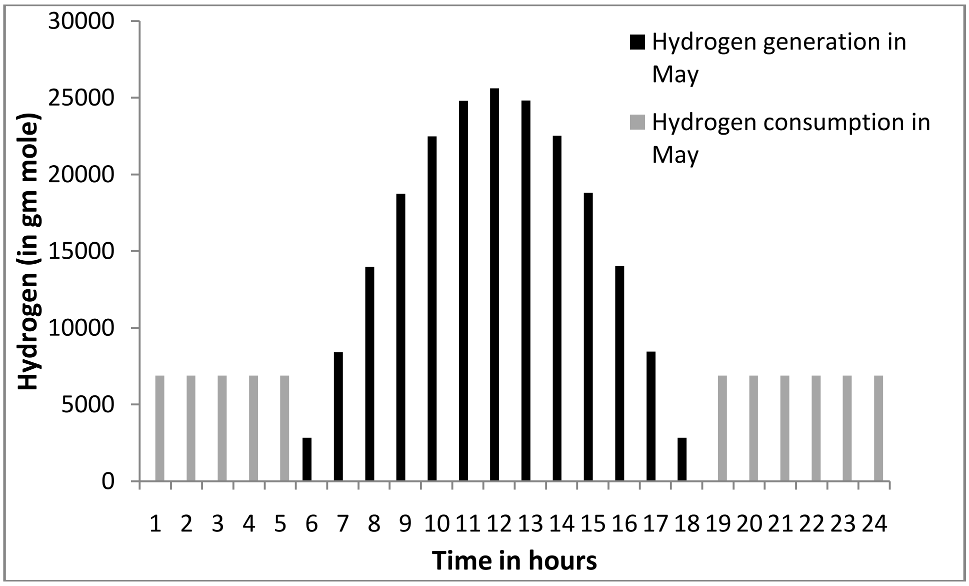

Fig.4: Hydrogen generation and consumption for the month of May

Table 1: Ratings of power system components.

Components of power system	Rating
No. of photovoltaic modules in parallel(N_p)	15144
No. of photovoltaic modules is series(N_s)	2
Electrolyzer input at 48V	3077.965 kW
No. of fuel cell in a stack($N_{fcseries}$)	47
No. of fuel cells stacks($N_{fcparallel}$)	445
Maximum output of each fuel cell stack	7.966A, 382.372 W
Gas compressor rating at 48V	306.748 kW
No. of photovoltaic modules in parallel for gas compressor($N_{p,compressor}$)	6335
No. of photovoltaic modules in series for gas compressor($N_{s,compressor}$)	2

V. Conclusion

It can be stated that for powering combustion chamber of gas turbine and to obtain 1 MW power, 15144 solar PV modules in parallel, 2 solar PV modules in series of Central Electronics Limited Make PM 150 with a 3077.965 kW electrolyzer and 445 PEM fuel cell stacks, each of 382.372 W can support the current requirement of combustion chamber throughout the year. 6335 solar photovoltaic modules in parallel each having 2 modules in a series of Central Electronics Limited Make PM 150 is needed to run the gas compressor for storing hydrogen in the cylinder during sunshine hours. In this work month, May and December are chosen as May has maximum solar radiation, maximum ambient temperature and December has minimum solar radiation, minimum ambient temperature for Kolkata city, India. Hence if the system works well in these two months the combined system will work well throughout the year. If the output power requirement from gas turbine increases the number of solar photovoltaic modules needed for combustion chamber and gas compressor will increase. Also number of elctrolyzer cells and fuel cells will increase.

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