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Modeling of Gas Turbine Operated by Solar Photovoltaic Modules

Dr. Kamaljyoti Talukdar

Assistant Professor, Department of Mechanical Engineering,
Bineswar Brahma Engineering College, Kokrajhar, Assam
E-mail: kamaljyoti.talukdar@gmail.com

Abstract—*In this present work gas turbine is operated by power obtained from solar photovoltaic modules. Air at ambient temperature of Kolkata city, India enters the compressor. The air is compressed and sent to combustion chamber. In combustion chamber air coming from compressor is heated 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 to rechargeable battery after passing through charge controller. During night time (solar deficient) the current requirement for combustion chamber heating comes from rechargeable battery which gets stored during day time after passing through charge controller. 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. It is found that 2 modules in series and 15144 modules in parallel with system voltage of 48V of Central Electronics Limited Make PM 150 and 209700 Ah capacity rechargeable battery is sufficient to operate the system. The cumulative battery charging and discharging for the month of December and May is 275101 Ah, 39193 Ah and 469106 Ah, 39193 Ah respectively. The air is heated to 1000K in combustion chamber and this heated gas is passed through turbine. In turbine power is obtained and some amount of power is sent to compressor for its operation. The system is adjusted in such a way that turbine power minus compressor work is approximately 1 MW throughout the day and year.*

1. INTRODUCTION

Gas turbine is a promising technology where power, heat or both power and heat can be obtained by burning different types of fuel in combustion chamber. Gas turbine can be operated by solar energy. In ref. [1] authors used gas turbine waste heat to supplement the TES (thermal energy storage) system providing operating flexibility while enhancing the efficiency of gas utilization thereby producing solar-derived electricity and gas-derived electricity at lower costs than either system operating alone. In ref. [2] author used combined closed-cycle gas turbine (CCGT) power conversion system and a point-focusing distributed solar receiver system, consisting of parabolic dish reflectors with focal-mounted heat source exchangers and a centralized prime-mover, representing a power plant concept well suited to the needs of a small urban/industrial community. In ref.[3] authors developed a novel hybrid solar/gas system intended to provide cooling/heating and electricity generation for buildings. In ref. [4] author described and compared several power generation cycles which have been developed to take advantage of the gas turbine's thermodynamic characteristics giving emphasis on systems involving heat recovery from the gas turbine's exhaust and these included the combined, Kalina, gas/gas recuperation, steam injection, evaporation and chemical recuperation cycles.

The present paper is based on gas turbine where heating in combustion chamber is done by solar photovoltaic modules after passing through resistance.

2. SYSTEM CONFIGURATION

Figure 1 shows a layout of solar photovoltaic system. During day time when solar radiation falls on photovoltaic modules current I_{PV} is generated. The current required in combustion chamber for gas turbine (I_{GT}) goes to combustion chamber after passing through charge controller and inverter. The excess current (I_{PV}-I_{GT}) after meeting combustion chamber's current (I_{GT}) goes to rechargeable battery for storage. During night time required current (I_{GT}-I_{PV}) for gas turbine's combustion chamber comes from rechargeable battery which gets stored during day time.

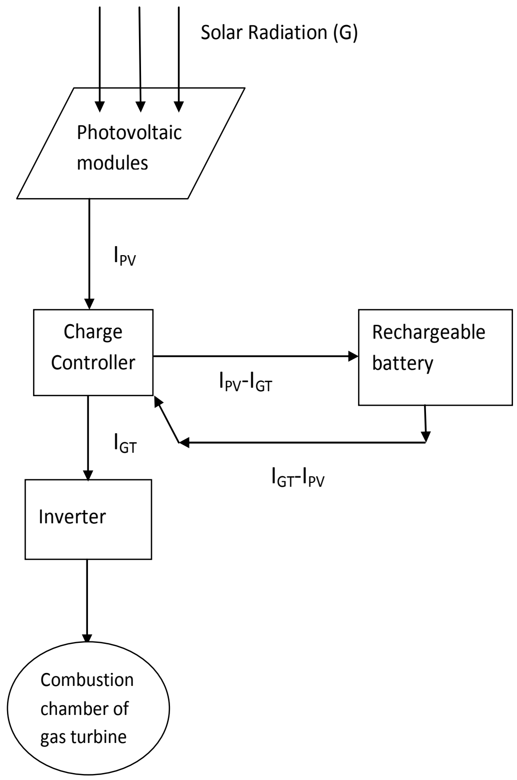

Figure 1: Schematic view of photovoltaic system

Figure 2 shows a brief layout of gas turbine. Air at ambient temperature enters into compressor and is sent to combustion chamber. During day time in combustion chamber air coming from compressor is heated by power obtained from solar photovoltaic modules after passing through resistance. During night time power is obtained from rechargeable battery which stores excess power during day time. The heated air is passed through turbine where some amount of power obtained in turbine is passed to compressor for running and remaining power is used by turbine for producing power approximately 1 MW.

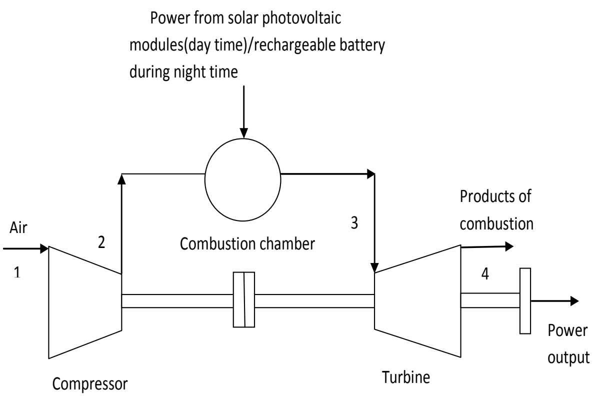

Figure 2: Schematic view of gas turbine operated by solar photovoltaic modules

3. MODELING

3.1 Gas turbine modeling

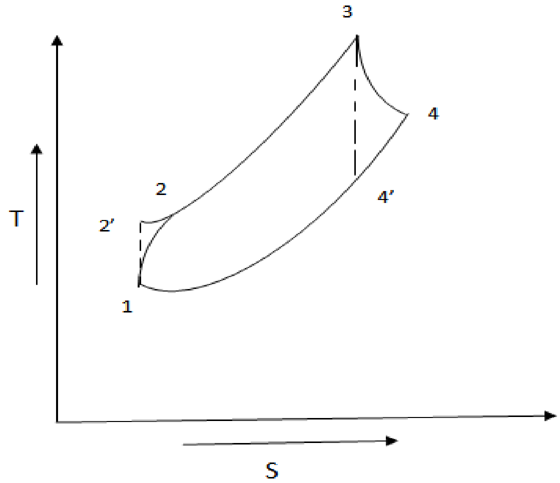

Figure 3: T-S diagram of figure no.2

Figure 2 shows temperature-entropy (T-S) diagram of GT plant. Process 1-2' shows isentropic compression of air in compressor. T_1 is the air inlet to compressor at ambient temperature of Kolkata city, India [5]. $T_{2'}$ is the temperature given by equation no.1 [6]:

$$T_{2'} = T_1 \times \left[\frac{P_2}{P_1}\right]^{\frac{\gamma_i - 1}{\gamma_i}} \qquad (1)$$

$\frac{P_2}{P_1}$ =pressure ratio (considered 6 in present study), γ_i=1.4 k J/ kg. K [6].

Process 1-2 shows actual compression of air given by equation no. 2 [6]:

$$T_2 = T_1 + \frac{T_{2'} - T_1}{\eta_C} \qquad (2)$$

η_C= 0.85 [7].

Process 2-3 is the heating process taking place by photovoltaic modules in combustion chamber. Temperature of heated air (T_3) coming out from combustion chamber is considered constant (1000 K).

Process 3-4' is the isentropic expansion of heated air from combustion chamber in GT and temperature ($T_{4'}$) is given by equation no. 3 [6]:

$$T_{4'} = T_3 \times \left[\frac{P_4}{P_3}\right]^{\frac{\gamma_i - 1}{\gamma_i}} \qquad (3)$$

$\frac{P_4}{P_3}$ = pressure ratio (considered $\frac{1}{6}$ in present study), γ_i=1.4 k J/kg. K [6].

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Process 3-4 shows actual expansion of combustion gas in GT given by equation no. 4 [6]:

$$T_4 = T_3 - \eta_T \left(T_3 - T_{4'}\right) \qquad (4)$$

η_T=0.9 [8].

Mass flow rate of air is given by equation no. 5 after making some modification from [6]:

$$\dot{m}_a = \frac{1000}{\left[C_{pa}\times(T_3-T_4)+\frac{C_{pa}\times(T_3-T_2)}{I^2\times R}\times C_{pa}(T_3-T_4)\right]-\left[\frac{C_{pa}}{\eta_m}\times(T_2-T_1)\right]} \qquad (5)$$

Where 1000-net power in k W, C_{pa}-1.005 k J/kg.K [6], η_m=0.95 [7], I-current to combustion chamber from solar photovoltaic modules (100 A), R-resistance in combustion chamber (50 ohm).

Compressor work is given by equation no. 6.

$$W_C = \frac{\dot{m}_a \times C_{pa} \times \left(T_2 - T_1\right)}{\eta_m} \qquad (6)$$

Turbine work is given by equation no. 7:

$$W_T = \dot{m}_a \times C_{pa} \times \left(T_3 - T_4\right) \qquad (7)$$

Net power in gas turbine is given by equation no. 8:

$$W_{net} = W_T - W_C = 1000 \text{ k W (approximate)} \qquad (8)$$

3.2 Solar photovoltaic and rechargeable battery modeling

In present study Central Electronics Limited Make PM150 solar photovoltaic modules [9] is used. The detailed current calculations for photovoltaic cell are obtained from [10].

The number of solar photovoltaic modules in series (N_S) is given by:

$$N_S = \frac{V_{system}}{V_{module}} \qquad (9)$$

Where V_{system} is the system voltage of the photovoltaic

array (considered 48 V in present study) and V_{module} is the maximum voltage obtained from single module[9].

The total electrical power ($i_{GT,total}$)(Ah) required for combustion chamber is given by:

$$i_{GT,total} = \frac{I^2 \times R \times 24}{V_{system} \times PF \times \eta_{inverter}} \qquad (10)$$

Where $I^2 \times R \times 24$ is power supplied for 24 hours with I-100 A and R-50 ohm, PF-power factor(0.85), $\eta_{inverter}$-inverter efficiency(0.85)

The design current required from photovoltaic array (i_{spv}) is given by [11]:

$$i_{spv} = \frac{i_{GT,total} \times 1.25}{peaksunshine\ hours \times \eta_{chargecontroller}} \qquad (11)$$

Where 1.25-derating factor of photovoltaic modules [12], peak sunshine hours-7 hours[13], $\eta_{chargecontroller}$-efficiency of charge controller(0.85)[12].

Number of modules in parallel (N_p) is given by:

$$N_p = \frac{i_{spv}}{i_{mp}} \qquad (12)$$

Where i_{mp}-maximum current obtained from a module [9].

Net current obtained from solar photovoltaic array (I_{PV}) is :

$$I_{PV} = i_{pv} \times N_p \qquad (13)$$

Where, i_{pv}-current obtained from single photovoltaic module .

The battery charging done (E_{bg}) is given by:

$$E_{bg} = (I_{PV} - i_{spv,i}) \times 0.9 \times 0.85 \qquad (14)$$

Where $i_{spv,i}$-current required from photovoltaic modules for each hour, 0.9-battery charging efficiency, 0.85-charge controller efficiency.

The battery discharging done (E_{bd}) is given by:

$$E_{bd} = \frac{\left(i_{spv,i} - I_{PV}\right)}{0.85} \qquad (15)$$

Where 0.85-charge controller efficiency.

The battery capacity considering 3028 Ah load for each hour, 3 days autonomy, 80% depth of discharge [12] and expected battery capacity(1.3)[12] is obtained as 209700 Ah[12].

4. RESULTS AND DISCUSSIONS

Figure 4 shows variation of air flow rate(kg/s) for the months of December and May.

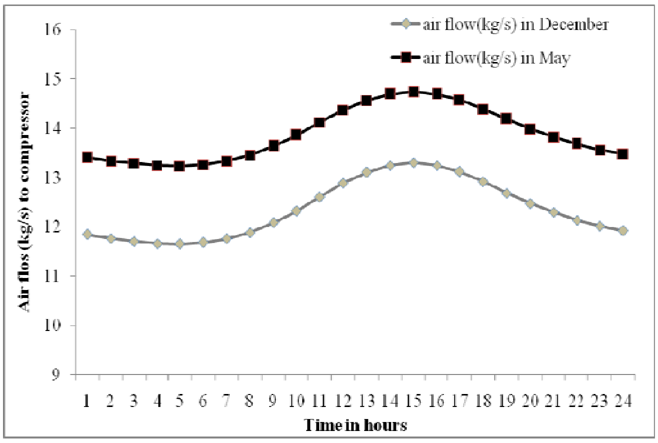

Figure 4: Variation of air flow rate(kg/s)to compressor

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In figure 4 it is seen that air flow decreases from 1:00 hour to 5:00 hours which is due to the fact that temperature T_1 decreases from 1:00 hour to 5:00 hours and as a result T_2, T_4 decreases. As can be seen in equation no.5, (T_3-T_4) and (T_3-T_2) increases having T_3(1000K constant) and (T_2-T_1) remains almost constant. Hence increase in value in denominator of equation no. 5 results in decrease in mass flow rate.

Next it is seen that mass flow rate of air increases from 6:00 hours to 15:00 hours since T_1 increases from 6:00 hours to 15:00 hours, as a result T_2, T_4 increases. As can be seen in equation no.5, (T_3-T_4) and (T_3-T_2) decreases having T_3(1000K constant) and (T_2-T_1) remains almost constant. Hence decrease in value in denominator of equation no. 5 results in increase in mass flow rate of air.

Again air flow rate decreases from 16:00 hours to 24:00 hours due to the same reason mentioned for 1:00 hour to 5:00 hours.

It is seen that mass flow rate of air in May is more than December due to the fact that May have higher temperature T_1 than December and accordingly it changes as in equation no. 5.

Figure 5 shows variation of turbine work output (k W), compressor work input(k W) for the month of December and May.

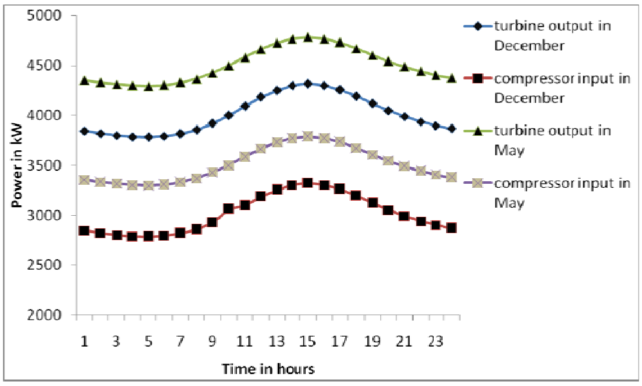

Figure 5: Variation of turbine power and compressor power

It is seen that compressor work input power decreases from 1:00 hour to 5:00 hours due to decrease in mass flow rate of air to compressor in equation 6. However (T_2-T_1)remains almost constant. It is seen that compressor work input increases from 6:00 hours to 15:00 hours due to increase in mass flow rate of air. Again compressor work input decreases from 16:00 hours to 24:00 hours due to decrease in mass flow rate of air.

It is seen that compressor work input is more in May than December due to greater mass flow rate of air in May than December.

It is seen that turbine work output decreases from 1:00 hour to 5:00hours due to the fact that mass flow rate of air decreases from 1:00 hour to 5:00 hours and T_4 also decreases due to decrease in T_1.Thus (T_3-T_4) increases. But increase in (T_3-T_4) is less dominant than decrease in mass flow rate of air as can be seen in equation no. 7.

It is seen that turbine work output increases from 6:00 hours to 15:00hours due to the fact that mass flow rate of air increases from 6:00 hours to 15:00 hours and T_4 also increases due to increase in T_1.Thus (T_3-T_4) decreases. But decrease in (T_3-T_4) is less dominant than increase in mass flow rate of air as can be seen in equation no. 7.Again turbine work output decreases from 16:00 hours to 24:00 hours due to the same reason mentioned for 1:00 hour to 5:00 hours.

Turbine work output is found to be more in May than December due to greater mass flow rate of air in May than December.

Based on equation no. 9, it is found that number of modules in series is obtained 2 and according to equation no. 12 number of modules in parallel is found to be 15144 of Central Electronics Limited Make PM 150.

Figure 6 and 7 shows variation of battery charging and discharging for the month of December and May respectively.

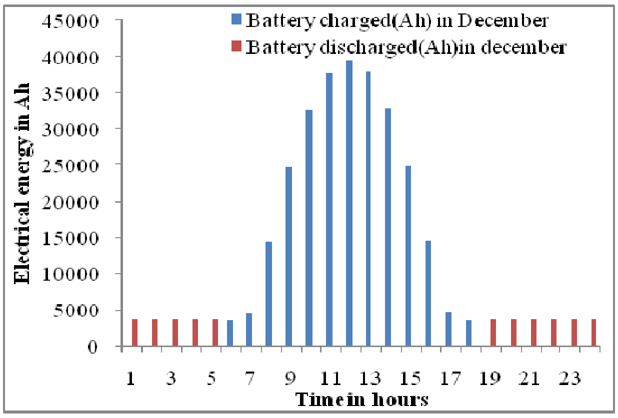

Figure 6: Variation of battery charging and discharging for the month of December

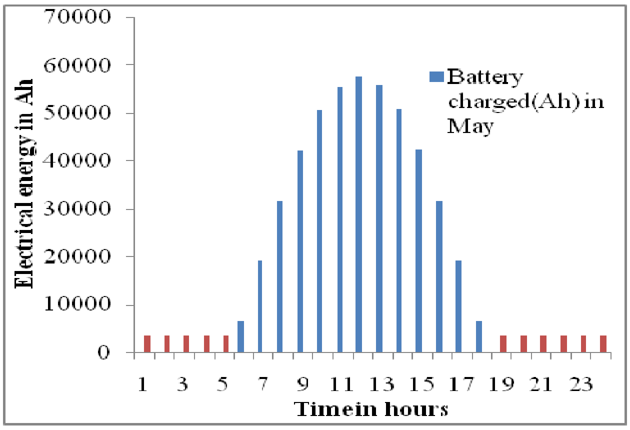

Figure 7: Variation of battery charging and discharging for the month of May

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In figure 6 and 7 it is seen that battery charging increases from 6:00 hours to 12:00 hours and again decreases till 18:00 hours due to the fact that solar radiation increases from 6:00 hours to 12:00 hours, hence I_{PV} increases in equation no. 14 and $i_{spv,i}$ remains constant. From 13:00 hours to 18:00 hours I_{PV} decreases due to decrease in solar radiation. The discharging of battery from 19:00 hours to 5:00 hours remains constant due to use of same amount of current (100 A) and resistance(50 ohm) in combustion chamber of gas turbine.

It is seen that battery charging is more in May (figure 7) than December (figure 6) due to greater amount of solar radiation in May than December hence I_{PV} is more in May than December.

The cumulative battery charging and discharging for the month of December and May is 275101 Ah, 39193 Ah and 469106 Ah, 39193 Ah respectively.

Conclusions

It is found that for powering combustion chamber of gas turbine 2 modules in series and 15144 modules in parallel of Central Electronics Limited Make PM 150 and 209700 Ah capacity rechargeable battery are sufficient to obtain a net power of 1 MW approximately from gas turbine. For greater amount of power greater amount of solar photovoltaic modules are necessary. Two months May and December are chosen because May and December have maximum solar radiation, maximum ambient temperature; minimum solar radiation, minimum solar radiation respectively and if it works well in this two months the system will work well throughout the year.

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7. Nomenclature

C_{pa}	specific heat of ambient air (k J/kg. K)
GT	gas turbine
$\dot{m}_a$	mass flow rate of air (kg/s)
P	pressure (bar)
T	temperature (K)
W_C	compressor work (k W)
W_T	turbine work (k W)
γ_i	ratio of specific heat of air
η_c	isentropic efficiency of compressor
η_T	isentropic efficiency of turbine
η_m	mechanical transmission efficiency of power from turbine to compressor