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Performance Evaluation of a Terminal Gas Turbine Generator of a Simulated and Modeled Gas Plant

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ABSTRACT: Gas turbine power plants have gained a wide spread acceptance in the power generation and mechanical drive. Their compactness, high power to weight ratio, ease of installation, early commissioning, fast starting and quick shut down time have made them popular prime mover. Hence, the objective of this paper was to investigate the performance evaluation of a terminal gas turbine generator of a gas plant simulated and modeled by MATLAB 2014 to analyze and evaluate the overall efficiency, thermal efficiency, thermal power, heat rate, specific fuel consumption, and work ratio. The results obtained shown that the overall efficiency, average thermal efficiency, average heat rate, average thermal power, average specific consumption, and average work ratio of gas turbine generator were gotten as 22.23%, 23.09%, 16250kW, 5892kW, 0.3390kg/kW-h, and 0.4564. Furthermore, the results revealed that overall efficiency, thermal efficiency, thermal power decrease as a result of increase in compressor inlet temperature.

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With the growth in industrialisation and population, there has been an increasing demand for electrical energy in Nigeria (Madu, 2018a; Igbagbon *et al.,* 2024a; Igbagbon *et al.,* 2024b; Orhorhoro; and Oghoghorie, 2024). The significance of electricity as a source of energy in the socio-economic development of Nigeria cannot be over-emphasized. Over the years concerted efforts have been made to improve on the electricity generation and distribution in the country (Sule and Anyanwu, 1994; Madu, 2018b; Madu, 2018c; Madu, 2018d; Madu, 2018e; Ukwamba *et al.,* 2018; Orhorhoro *et al.,* 2022; Oghoghorie *et al.,* 2024). Power generation in Nigeria is mainly from hydro-electric power stations, steam, and gas thermal stations (Orhorhoro *et al.,* 2017). According to Tsujikawa, and Sawada (1985), growth in thermal plants in Nigeria started with the installation of steam thermal plants at Oji River (1956), four units' gas thermal plants in Ijora (1966/78), twenty units' gas thermal plants in Delta (1966/90), four steam thermal plants at Sapele (1978/80), another eighteen units' gas thermal plants were installed at Afam (1982) and six steam thermal plants at Egbin (1985/87). A total of six power stations in all, consist of a total of fifty-five units capable of producing a total capacity of 5988 MW of

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electricity (1956/1994). Ondryas *et al.* (2007) in their report in 1994 revealed that only fifteen out of the fifty-five units were available for power generation as at 1994.

Gas turbines are common power generators which are used mainly in power generation systems and propulsion systems (Rahman *et al.,* 2010; Madu, 2018f; Madu, 2018g; Srinivas, 2018). Large percentage of existing gas turbines are internal combustion machines while the rest are fired externally (Orhorhoro, and Orhorhoro, 2016; Madu, 2018h; Kaviri *et al.,* 2012). The sizes of gas turbines can vary from 500kW to 250MW according to their applications (Chaker, and Meher-Homji, 2011). A typical gas turbine mainly consists of three components namely compressor, combustion chamber and turbine. Atmospheric air is compressed by the compressor then heated inside the combustion chamber and finally expanded inside the turbine (Mohanty and Paloso, 1995; Ameri and Hejazi, 2004; Mahmoudi *et al.,* 2009; Egware, 2013; Madu, 2018i). As a result of that the turbine produces work to the surrounding. Some fraction of that work is used by the compressor while the balance work can be considered as the network (Ameri *et al.,* 2005; Madu, 2018j). Several factors such as operation mode, poor maintenance procedures, age of plant, and discrepancies in operating data, high ambient temperature and relative humidity bring about drop in the efficiency of a gas turbine plants (Al-Tobi, 2009; Rahman et al., 2010). Power output and efficiency of a gas turbine plant depends largely on the condition of the compressor inlet air temperature (Madu, 2018k). The performance output during hot conditions is less compared to the performance at high air temperature, and humid environment (Abam *et al.,* 2011; Farzaneh-Gord and Deymi-Dashtebayaz, 2011). Thus, cooling the inlet air temperature of the gas turbine, and increasing the air density will enhance the mass flow rate of air and gives better power output.

Furthermore, high ambient temperature increases the turbine's heat rate which can results in gas turbine plants producing 25-35% less power in summer than winter at an average increase of 6% in fuel consumption (Alok Kumar and Sanjay, 2012; Madu, 2018l). Gas turbines convert fuel energy into mechanical power, and this is achieved by connecting it to electric generators (electric power). The underlying thermodynamic cycle, known as the Brayton Cycle, involves the compression of a gaseous medium (typically air), the addition of fuel energy through combustion or heat exchange, and expansion of the hot, compressed gas through a turbine to convert the thermal energy into shaft power. Hence, the objective of this paper was to investigate the performance evaluation of a terminal gas turbine generator of a gas plant simulated and modeled by MATLAB 2014 to analyze and evaluate overall efficiency, thermal efficiency, thermal power, heat rate, specific fuel consumption, and work ratio

MATERIALS AND METHODS

Modeling and Simulation of the Gas Turbine using MATLAB: MATLAB 2022 was used to simulated the gas turbine. It is a multi-paradigm numerical computing environment. A proprietary programming language developed by MathWorks. MATLAB applies matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran, and Python. Although, MATLAB is intended primarily for numerical computing, an optional toolbox uses the MuPAD symbolic engine, allowing access to symbolic computing abilities. An additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamics and embedded systems. MATLAB supports object-oriented programming, including classes, inheritance, virtual dispatch, packages, pass-by-value semantics, and pass-by-reference semantics. However, the syntax and calling conventions are significantly different from other languages. MATLAB has value classes and reference classes, depending on whether the class has handle as a super-class (for reference classes) or not (for value classes).

Description of the 3X 4.2MW Taurus 60 Terminal Gas Turbine Generators: The Taurus 60 gas turbine engines are of a two shaft, axial flow design consisting of: (i) Accessory drive assembly, (ii) Air inlet assembly, (iii) Engine compressor assembly, (iv) Combustor assembly, (v) Turbine assembly, (vi) Exhaust collector, and (vii) Output drive shaft

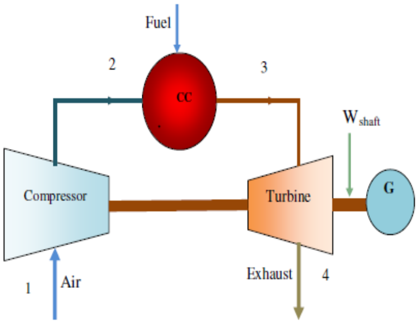

Fig. 1: Schematic diagram for a simple gas turbine

The major components of the engine are maintained in accurate alignment by mating flanges with pilot surfaces and are located together to form a rigid assembly. The accessory drive assembly, bolted to the air inlet assembly, is driven by the engine compressors rotor shaft. The accessories drive assembly support and drive the lube oil pump and other accessories and are initially driven by the shaft system. Reference locations of components on the engine and the entire package are forward, aft, right, and left. These directions are established by viewing the package or engine from the exhaust (aft) end.

The accessory drive assembly consists of housing, first stage helical reduction gears, second stage spur gears, accessory drive spur gears, bearings, main shaft, accessory shaft, starter adapter housing, starter clutch and starter pinion gears. The accessory drive assembly is mounted on the forward end of the air inlet assembly and receives power from the compressor shaft pinion gear. The starter adapter housing supports the starter motors. The motor imparts their drive through the gear to the starter clutch. Torque is transmitted to the second stage gear train and through the intermediate train to the first stage pinion and compressor rotor. Also, the engine accessory pumps are mounted on drive pads on the accessory drive housing and are driven by the accessory shafts and drive gear. The air inlet assembly, including the air inlet duct, is located aft of the accessary drive assembly. It is attached to the accessary drive housing and the compressor case. Air drawn through the air inlet filters and ducting follows an axial flow path to the air inlet duct. The air inlet duct provides a radial flow path for air drawn through the air inlet assembly into the engine compressor assembly. The air inlet duct contains bosses for water wash plumbing, temperature sensor, and a drain. An annular opening in the air inlet filter assembly redirects the radial flow path to an easier flow path. The opening is covered with a heavy mesh screen to prevent the entry of solid foreign material into the gas producer air inlet. This screen is not to be considered an air filtration device. Included in the air inlet assembly is support for the forward bearing housing assembly containing the sleeve bearing and labyrinth seals.

The power turbine assembly consists of the two-stage power turbine rotor, power turbine bearing housing, turbine exhaust diffuser, and exhaust collector. The power turbine bearing housing forward end, which supports the power turbine forward rotor bearing, is attached to the turbine exhaust diffuser.

The turbine exhaust diffuser is bolted to the combustor housing aft flange. The annular exhaust collector is bolted to the exhaust diffuser aft flange and it is insulated with stainless steel blanket. Also, the variable vane system is provided to maintain maximum engine compressor performance during starting and acceleration, and during normal operation. The system is automatically controlled and hydraulically operated to change the angle of the inlet guide vanes and first- and second- stage vanes to aerodynamically match the low-pressure stages of the compressor with the high-pressure stages. There are two distinct vane positions, which are open and close. This change of vane position varies the effective angle that air flows pass the rotor blades. The angle determines the compression characteristic for a particular stage of compression. The engine air system is used to pressurize the oil seals to cool the turbine rotor disc, and to aid in preventing surge conditions at critical speeds. The engine produces compressed air commencing when the engine compressor rotor is rotated by the starter.

Data Collection: Daily operating data of 3X 4.2MW Taurus 60 gas turbine generators was collected for a period of two years (2019-2020). The daily average operating variables were calculated and mean values computed monthly for a period of twenty-four months which is two years are presented in the results and discussion section. The Operating Data for Year 2019 is presented in Table 1. The Operating Data for Year 2020 is presented in Table 2, while the Table 3 shows the operating parameters of the gas turbine generator. The Table 4 shows the gas turbine engines specification.

Table 1: Operating Data for Year 2019

Para.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
T_{01} (^{O}C)	52.13	52.21	51.22	53.26	52.35	52.26	53.20	54.22	54.36	53.24	53.32	53.56
T_{02} (^{O}C)	73.31	72.21	73.21	74.22	74.28	75.50	74.66	74.20	72.25	75.50	75.01	74.25
T_{w1}(^{O}C)	28.20	28.30	27.22	27.21	27.22	28.03	27.20	28.21	27.25	27.21	28.20	29.20
T_{w2} (^{O}C)	34.22	35.20	35.22	34.71	34.25	35.22	34.21	34.25	34.80	35.70	33.23	35.21
T_1 (^{O}C)	23.22	23.41	24.21	25.32	27.31	29.22	30.23	32.50	33.40	33.40	30.60	33.30
T_2 (^{O}C)	359.21	360.50	359.75	355.20	358.80	356.20	366.21	355.30	357.30	358.90	357.25	350.75
T_3 (^{O}C)	1086.7	1066.2	1096.4	1046.2	1046.7	1036.7	1031.7	1054.7	1066.5	1056.7	1067.6	1074.3
T_4 (^{O}C)	548.10	536.20	554.30	536.60	537.30	524.60	528.10	555.30	566.10	556.20	528.25	540.30
P_1 (Bar)	102.10	101.30	101.20	102.10	101.10	101.10	102.10	101.10	101.10	102.10	101.60	102.16
P_2(Bar)	964.75	955.65	953.60	955.16	958.60	956.55	956.15	965.30	957.15	967.00	955.65	965.12

Table 2: Operating Data for Year 2020

Para.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
T_{01} (^{O}C)	53.10	52.31	52.20	53.26	52.45	53.20	53.30	54.35	55.30	53.54	53.40	54.50
T_{02} (^{O}C)	74.41	72.31	72.21	73.32	74.37	75.51	75.66	72.31	74.22	75.24	74.36	74.21
T_{w1}(^{O}C)	28.20	28.30	27.32	28.31	27.42	27.95	27.20	28.21	27.35	26.15	28.10	28.31
T_{w2} (^{O}C)	35.22	34.20	35.22	35.51	34.25	35.22	34.31	34.05	34.80	34.50	35.21	34.20
T_1 (^{O}C)	23.05	24.41	24.31	25.19	27.28	29.09	30.33	30.50	34.30	34.30	31.60	32.30
T_2 (^{O}C)	359.30	360.30	359.75	355.30	357.80	357.05	367.10	355.20	357.03	358.91	357.25	350.79
T_3 (^{O}C)	1085.7	1065.3	1098.2	1045.0	1046.0	1036.0	1032.7	1055.5	1067.5	1057.7	1066.6	1074.3
T_4 (^{O}C)	547.05	538.30	554.30	535.60	536.32	525.60	526.10	555.30	567.10	557.20	526.25	541.15
P_1 (Bar)	101.05	102.00	101.01	101.03	101.01	101.02	101.03	102.00	101.02	102.03	102.60	102.07
P_2(Bar)	964.65	957.55	953.60	956.16	958.60	955.85	957.08	965.20	956.07	967.91	956.57	965.22

*Para-Parameter description, *Ave.-Average

Table 3: Operating parameters of the gas turbine generator

S/N	Operating Parameters	Value	Unit
1	Temperature of intake air to compressor (T_1)	299.53	k
2	Mass flow rate of air through compressor ($\dot{m}_a$)	356.81	kg/s
3	Gp Speed	100.10	%
4	Pressure of intake air to compressor (P_1)	101.52	kpa
5	Exit temperature of air compressor (T_2)	645.48	k
6	Exit pressure of air from the compressor (P_2)	961.81	kpa
7	Assumed pressure drop in combustion chamber	1.8	%
8	Fuel gas (natural gas) mass flow rate ($\dot{m}_f$)	6.9	kg/s
9	Temperature of fuel gas (t_f)	326.15	k
10	Pressure of fuel gas (p_f)	2276	kpa
11	Turbine temperature (T_3)	1299.03	k
12	Exhaust temperature (T_4)	820.03	k
13	Mass flow rate of exhaust ($\dot{m}_{exh}$)	373.85	kg/s
14	Lower heating value (LHV)	55328.8	kj/kg
15	Isentropic efficiency of compressor	88.93	%
16	Isentropic efficiency of turbine	91.98	%
17	Combustion efficiency	99	%
18	Turbine pressure (P_3)	964.84	kpa
19	Specific heat capacity of air (C_{pa})	1.004	kj/kgk
20	Specific heat capacity of gas (C_{pg})	1.146	kj/kgk
21	Specific heat capacity of water (C_{pw})	4.2	kj/kgk
22	Pressure ratio	9.47	

Table 4: Gas turbine engines specification.

Description	Data
Compressor	
Type	Axial
Number of stages	12
Flow	11.5:1
Speed	21.1kg/sec
Combustion Chamber	
Type	Annular
Ignition	Torch
Number of fuel Nozzle	12
Gas Producer Turbine	
Type	Axial
Number of stages	2
Speed	15,000rpm
Power Turbine	
Type	Axial
Number of stages	2
Speed	14,300rpm
Bearings	
Journal	Tilt-Pad
Thrust	Tilt-Pad

RESULTS AND DISCUSSION

In this research work, MATLAB 2014 was used for the modeling and simulation of 3X 4.2MW Taurus 60 Gas Turbine Generator. Operating data collected for a period of two years of the turbine generators was used to evaluate the performance of the gas turbines generators. The performance of the plant was determined by simulation using MATLAB 2014 run in window 8 computers. This was used to obtain the compressor work, turbine work, other results achieved such as net-power, thermal efficiency, specific fuel consumption, and heat rate. The results obtained are shown in Table 5.

Table 5: Simulation Results of Gas Turbine Generator

S/N	Parameter	3X 4.2MW Taurus 60 Gas Turbine Generator
1	Average Overall Efficiency	22.54%
2	Average Thermal Efficiency	23.44%
3	Average Heat Rate	16400kW
4	Average Thermal Power	5967.86kW
5	Average Specific Fuel Consumption	0.340 kg/Kw-h
6	Average Work Ratio	0.455

The overall efficiency, average thermal efficiency, average heat rate, average thermal power, average specific consumption, and average work ratio of the gas turbine generator were gotten as 22.54%, 23.44%, 16400kW, 5967.86kW, 0.340kg/Kw-h, and 0.455 as shown in Table 5. Fig. 2 shows the effect of compressor inlet temperature on the overall efficiency of gas turbine generator, it was observed that as the compressor inlet temperature increases, the power overall efficiency decreases. These findings agreed with the study of Ukwamba *et al.* (2018). According to their research work, an increase in temperature results in reduced power output and efficiency of the gas turbine without absorption chiller. This is due to the fact that at higher temperature, the air entering the compressor is less dense. As a result, a higher compressor work and lower turbine output are obtained.

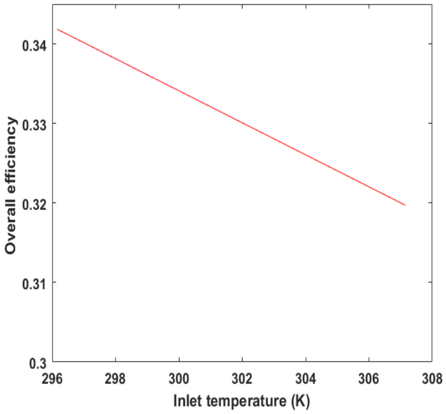

Fig. 2: Effect of compressor inlet temperature on the overall efficiency of the gas turbine generator

Fig. 3 shows the plot of compressor inlet temperature and thermal efficiency of gas turbine generator. The results obtained show that the thermal efficiency of both gas turbine generator decreases with an increasing compressor inlet temperature.

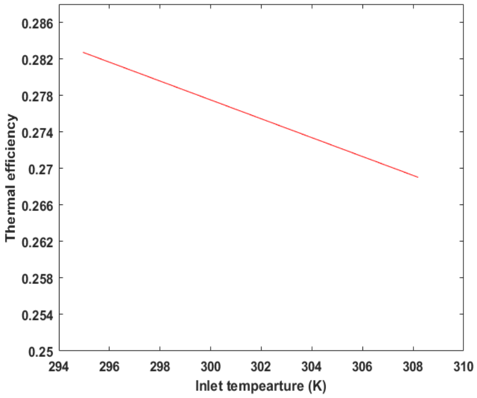

Fig. 3: Effect of compressor inlet temperature on the thermal efficiency the gas turbine generator

The decreased in thermal efficiency was as a result of decrease in net power output of the gas turbine cycle and this led to increase in compressor power, thus decreased in mass flow rate of gases. According to Kakaras *et al.,* (2004); Saravanamuttoo *et al.,* (2009); Hosseini *et al,* (2007); Ibrahim *et al.,* (2011), Orhorhoro and Orhorhoro (2016); Orhorhoro *et al.* (2017), there was an improvement in net power output and thermal efficiency when vapour absorption chiller was incorporated. The power output and thermal efficiency increases as a result of reduction in ambient air temperature which lower the compressor power. A lower ambient temperature leads to higher air density and lower compressor power. This in turn gives a higher net power out and higher thermal efficiency.Fig. 4 shows the plot of compressor inlet temperature and heat rate of the gas turbine generator. From the performance evaluation, it can be seen that as the compressor inlet temperature increases the heat rate increases. The increased in heat rate (HR) further confirm why there was dropped in both thermal and overall efficiency.

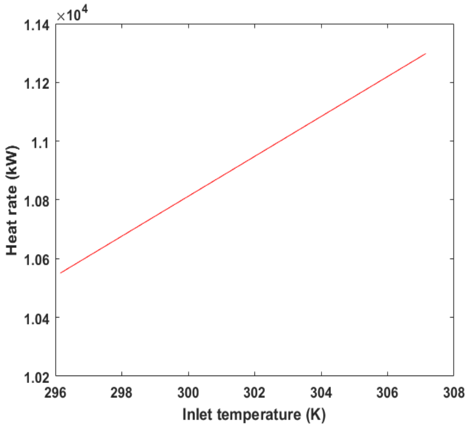

Fig. 4: Effect of compressor inlet temperature on the heat rate of gas turbine generator

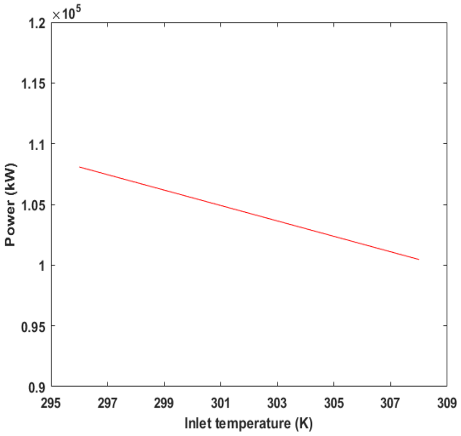

Fig. 5: Effect of compressor inlet temperature on thermal power of gas turbine generator

Fig. 5 shows the graph of compressor inlet temperature and heat rate of the gas turbine generator. It was observed that as the compressor inlet temperature increases, the thermal power output decrease. The highest thermal power was obtained at the lowest compressor inlet temperature while the lowest thermal power achieved at the highest compressor inlet temperature in both gas turbine generators used in this research work. Fig. 6 shows the graph of compressor inlet temperature and heat rate of gas turbine generator. It was observed that the compressor inlet temperature has a significant effect on specific fuel consumption of both gas turbine generators. An increased in compressor inlet temperature brings about a corresponding increase in the specific fuel consumption. The corresponding increase was as a result of increase in compressor power due to a higher intake of ambient air temperature. This increase in specific fuel consumption as a result of increase in compressor inlet temperature further confirmed the resulted decrease overall efficiency, thermal efficiency, and thermal power.

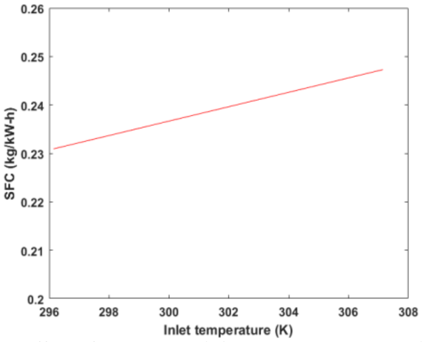

Fig. 6: Effect of compressor inlet temperature on specific fuel consumption of gas turbine generator

From Fig. 7 it can be seen that as the compressor inlet temperature increases the work ratio decrease. This decrease in work ratio reduces the effectiveness of the gas turbine generator. This is because a high work ratio is less vulnerable to irreversibility than low a work ratio.

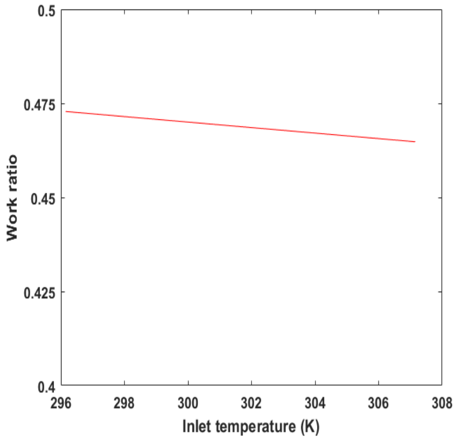

Fig. 7: Effect of compressor inlet temperature on work ratio of gas turbine generator

Conclusion: Gas turbines are generally used for electricity generation in Nigeria due to it availability and low prices of natural gas compared to distillate fuels in the country. For these reasons, their use is based on load units. The outcome of this study shows that the overall efficiency, thermal efficiency, thermal power all decrease as a result of increase in compressor inlet temperature. However, the specific fuel consumption, heat rate increases with increase in compressor inlet temperature. The work ratio decreases with increase in compressor inlet temperature, and this confirmed that gas turbine generators are vulnerable to high irreversibility at high compressor inlet temperature.

Declaration of Conflict of Interest: The authors declare no conflict of interest.

Data Availability: Data are available upon request from the authors.

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