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Performance Measures of Power Generation Systems

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Abstract
The performance of heat base power generation systems such as spark ignition engines, compression ignition engines, combustion turbine power plant, steam Ranking power plant (steam turbine) and combined cycle power plant have been analysed using the traditional assessment measures such as thermodynamic performance (energy and exergy efficiency) and technical characteristics (reliability, availability, maintainability measures etc). These measures when used, assesses the system independently of the other. Being that an improvement of one measure cause an increase or deterioration of the other, the need to harness these performance measures for holistic assessment becomes imperative. In this study, the exergy efficiency and availability measure is used in the assessment of First Independent Power Limited (FIPL) gas turbine power plant. A new measure called the Bassy-1 index is developed and used in the assessment of the power plant. A four year assessment period of 2013, 2014, 2018 and 2019 is considered across different base loads of 80, 120 and 140 MW. The performance of the power plant showed a deteriorating trend across the years for exergy efficiency and availability measures. The exergy efficiency of the plant showed improvement as base load increases. Bassy-1 index exhibited the combined characteristic of exergy efficiency and availability measures which suggest a better assessment criteria than the independent assessment approach of the power plant using exergy efficiency and availability measures independently. The proposed Bassy-1index is considered a better assessment approach and is recommended for use in the evaluation of heat base power generation systems.
Keywords: *gas turbine, exergy analysis, availability, performance measures, combined assessment index*

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I. INTRODUCTION

Adequate and sustainable electric power generation to meet domestic and industrial needs have become one of the catalyst that drives growth and development [1]. This is evident in developed nations like US, UK, Russia, China etc., where guaranteed grid power supply is assured, as well as in underdeveloped nations like Chad, Angola, Burkina Faso etc., where grid power is not readily available to a larger population, hence hindering growth and developmental drives.

Conventional electric power generation usually takes place at power stations or industrial facilities which may be classified under large scale or low scale facility depending on the amount of power generated. While they may be different energy sources for electric power generation such as: hydro, natural gas, nuclear fuel, fuel oil, coal etc, the classification of electric power generation systems in terms of grid base and off grid system becomes imperative. Grid based electric power are national electric power networks in which homes, organizations and industrial setup connect to for electric power supply. The conventional power generation systems used here are hydroelectric power station, nuclear power station, spark ignition engines, compression ignition engines, combustion turbine power plant, steam Ranking power plant (steam turbine) and combined cycle power plant [2]. Other power sources (unconventional power sources) such as solar photovoltaic and wind power can also be used.

Off grid power systems are standalone power systems in which an individual or organization uses to generate and provides for itself electric power. Its sources of power may be either from wind, solar, fuel oil or coal etc [1].

One common factor between the grid based power system and the off grid power system is that both systems experience system fluctuations or perturbations. While there may be little or no disturbances in the standalone system, the same is not the case for grid based power system owing to many factors such as abrupt changes in power demand, electrical disturbances such as lightning strike or grid faults, faulty equipment, inadequate power supply infrastructure, and fluctuations in power generation, especially in renewable energy systems which are affected by weather conditions etc., [1,3]. While there are remedial actions such as load management, power conditioning, power factor correction and regular maintenance actions that can be taken to ameliorate the effect of the disturbances. It is important to note that these actions are expensive to implement and require highly technical and competent personnel for its execution in grid base network management [1,4].

Power generation systems, whether grid base or off grid base are evaluated using same indexes. These indexes are termed performance measures and they vary in context and unit depending on the evaluation criteria. Several performance measures exist and have been used in the evaluation of power systems. Examples of these measures are energy and exergy efficiency, reliability, availability and maintainability etc [3,5]. Several authors have proposed and analysed exergy efficiency of power generation systems in broader perspective with the introduction of modified exegetic measures such as exergo-economic and exergo-environmental analysis [3,10]. However, it is important to note that the energy and exergy analysis of power generation systems falls under the thermodynamic performance.

However, for reliability, availability and maintainability measures, there are classified as technical characteristics of power generation system [12]. They are measures that can be used independently or collectively under reliability engineering discipline, in the evaluation of power generation systems.

The concept of reliability as a technical characteristic, measures the probability of failure-free operation within a given time interval. It is a measure of success for a failure-free operation. Reliability deals with the reduction of failure frequency over a given time interval [6]. Generation system reliability may be dichotomized into adequacy and security [7,8]. System adequacy has to do with the existence of sufficient generators within the system in order to satisfy the customer load demand or system operational constraints. Its deals with static conditions of the system and does not include system disturbances (or perturbations) [1,5]. On the contrary, system security relates to the ability of the system to respond to perturbations that occur within the system. Therefore, system security deals with the response of a system to whatever disturbances it may be subjected to [5,9].

The availability measure is interested in how often a system is alive and well. It is an expression that shows the duration of up-time for operations.

Maintainability measure as earlier mentioned is a characteristic of design and installation expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when maintenance is performed in accordance with prescribed procedures and resources [11]. It is the ease with which maintenance of a functional unit can be performed in accordance with prescribed requirements. Power generation systems may be analysed base on its thermodynamic performance (i.e., energy and exergy efficiency) or its technical characteristic which are: reliability, availability, maintenance requirements, environmental impacts and sustainability [12]. Both availability and maintenance of a system have significant effects on its reliability. A system is considered sustainable when environmental impacts of such a system are negligible.

A little consideration shows that these measures are traditional measures and an improvement of one may lead to an upgrade or deterioration of the other. It is also understood that some technical characteristics may have some kind of relationship with the thermodynamic performance (energy or exergy efficiency) of some heat driven generation systems. Hence, an understanding of this relationship is imperative to the development of new approaches or solution methods for the analysis of the performance of power generation systems. On this note, this study seeks to combine exergy efficiency being one of the thermodynamic performance measure with availability being one of the technical characteristic of power generating systems in the formulation of a new performance index called the *Bassy-I* index in the evaluation of heat base power generation systems.

II. MATERIALS AND METHODS

2.1 Materials

A 180MW GT13E2 simple cycle gas turbine power plant of First Independent Power Limited (FIPL) Afam, situated in Oyigbo Local Government Area, Rivers State was selected for assessments. The plant obtains its natural gas supply from Shell Nigeria, and exports an average of 3500MWH per day into the national grid. The power plant consists of a rotary type air compressor, a combustion chamber and a turbine, coupled along a single shaft.

2.2 Methodology

2.2.1 Data collection

The following data were collected for the analysis.

a) Plant operational data from the operational log sheet. The data include the mass flow rate at different sections (inlet to compressor, inlet to combustion chamber, inlet to turbine, exhaust and fuel line). The temperatures and pressures at each section were also obtained at instance of time for some days across the study periods (2013-2019).
b) Frequency and duration information on planned and forced outages of the selected plant was obtained on monthly bases, from 2013 to 2019.

2.2.2 Structure of the analysis

a) Thermodynamic performance of the power plant was carried out based on the energy and exergy analysis method. This brought the First and Second law of thermodynamics to bear. A comparative analysis of the thermodynamic performance of this plant at base load of 80, 120 and 140 MW over a period of four years (i.e., 2013, 2014, 2018 and 2019) was performed.
b) The power plant availability for the periods (2013, 2014, 2018 and 2019) were determined.
c) A model that combines exergy efficiency and availability was developed and proposed.

2.2.3 System specification

The technical data of GT13E2 gas turbine is presented Table 1. The components of the system include an air-compressor (AC), a combustion chamber (CC), and a gas turbine (GT). Air enters the compressor at 25°C and has a mass flow rate of 566.0 kg/s. The ISO input temperature and pressure are 25°C and 1.0135 bar, respectively. The compressor has isentropic efficiency of 83% and amplifies the pressure up to 18.2 bar. The turbine isentropic efficiency is 88%, with turbine inlet temperature of 1046°C.

Table 1: Technical Data of GT13E2, FIPL Afam

GT13E2 performance Parameters	Specification	GT13E2 performance Parameters	Specification
Frequency	50 Hz	Number of Compressor stages	16
Fuel	Natural gas	Number of turbine Stages	5
Net Thermal Efficiency (LHV)	39.0%	Number of Combustor Cans	48 (AEV burners)
Gross Electrical Output	180 MW	GT Generator cooling medium/fluid	Air
Turbine speed	3000 rpm	Exhaust Energy (MM kJ/hr)	1219
Gross Heat rate	8980 Btu/kWh	Exhaust gas temperature	515 ºC or 959 ºF
Compressor pressure ratio	18.2:1	Exhaust gas flow	537 kg/s

2.2.4 Thermodynamic model for the gas turbine power plant

Exergy is defined as the maximum theoretical work that can be extracted from a "combined system" consisting of a "system" under study and its "environment". As the system passes from an initial state to a state of equilibrium with the environment [13,14]. According to [15], the total exergy (Ex) of a system is divided into four main components: physical exergy (Ex_{ph}), chemical exergy (Ex_{ch}), kinetic exergy (Ex_{kn}) and potential exergy (Ex_{pt}).

The system under consideration here is the gas turbine power plant as shown in Figure 1, and its cycle diagram represented in Figure 2. The following are the basic assumptions for the plant:

Basic Assumptions:

1. The working fluid/medium for the system is air.
2. Fuel used is natural gas (LHV =47141kJ/kg).
3. The flow is of steady state.
4. The working fluid obeys the ideal gas law.

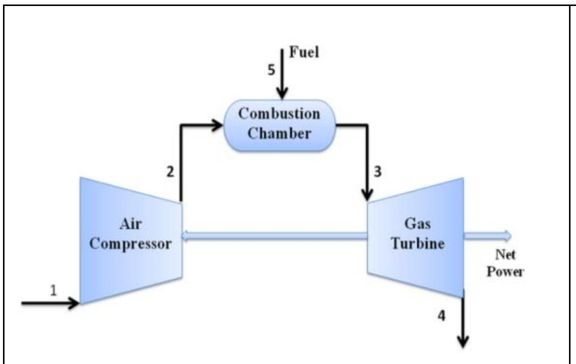

Fig. 1. Flow diagram of simple gas turbine [13]

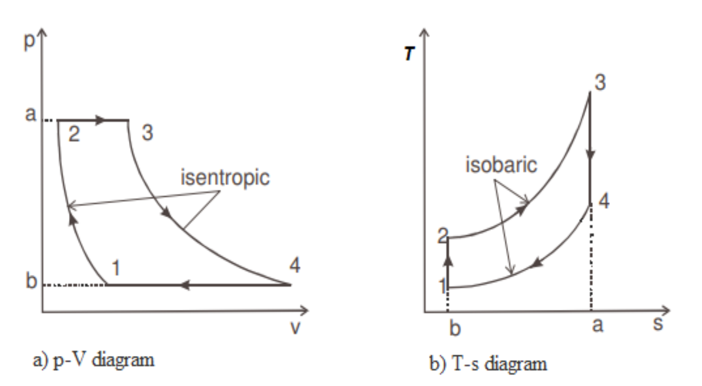

Fig. 2. Gas power cycle diagram [13]

The exergy equation of the steady state model of the gas turbine power plant represented in Figure 1 may be expressed as [15]:

$$Ex = Ex_{ph} + Ex_{ch} + Ex_{kn} + Ex_{pt} \quad (1)$$

Since the system is at rest relative to the environment, exergy potential and kinetic value are assumed to be zero ($Ex_{kn} = Ex_{pt} = 0$). Thus under this condition, the total exergy of the plant is defined as given by [14]:

$$Ex = Ex_{ph} + Ex_{ch} \tag{2a}$$

for a mass specific exergy of the plant, we have

$$ex = ex_{ph} + ex_{ch} \tag{2b}$$

Physical Exergy:

For an ideal gas scenario, the physical exergy can be expressed as a function of enthalpy (h) and entropy (s). The relationship between the enthalpy (h) and entropy (s) is shown in equation (3a).

$$Ex_{ph} = \mathrm{m}\left[C_p(T_1 - T_0) - T_0(s_1 - s_0)\right] \tag{3a}$$

Specific physical exergy (ex_{ph}) can be written as:

$$ex_{ph} = \left[(T_1 - T_0) - T_0(s_1 - s_0)\right] \tag{3b}$$

where, T represent the absolute temperature, subscript o represent ambient condition, subscript 1 represent state 1 of the system. While h and s denote the specific enthalpy and entropy respectively.

The change in the system entropy may be expressed as:

$$(s_1 - s_0) = C_p \mathrm{In}\left(\frac{T_1}{T_0}\right) - \mathrm{R In}\left(\frac{P_1}{P_0}\right) \tag{4}$$

where, C_p = specific heat at constant pressure and R = gas constant

Putting equation (4) into (3a) we have:

$$Ex_{ph} = \mathrm{m}\left[C_p(T_1 - T_o) - T_o\left[C_p \mathrm{In}\left(\frac{T_1}{T_0}\right) - R\mathrm{In}\left(\frac{P_1}{P_0}\right)\right]\right] \tag{5}$$

The heat capacity (C_p) is obtained by polynomial form as a function of temperature as given by equation (6) [16]:

$$C_p = a + bT + cT^2 + dT^3 \tag{6}$$

It should be noted that no chemical reaction or combustion takes place in the turbine and compressor. Hence, the chemical exergy value of both components will be considered to be zero.

Chemical Exergy:

For many fuels, the chemical exergy can be estimated on the basic of the lower heating value (*LHV)*. The relation between the LHV and the chemical exergy for gaseous fuel with formular C_nH_m based on the atomic composition is given by [14] as:

$$\varphi = \frac{e_f^{-ch}}{LHV} \cong 1.033 + 0.0169\frac{m}{n} - \frac{0.0698}{n} \tag{7}$$

where, φ is the ratio of fuel exergy and the lower heating value of the fuel and e_f^{-ch} is the fuel exergy. For the majority of gaseous fuel, the value of φ is normally close to 1. For fuel like methane, φ_{CH4} = 1.06 and for hydrogen fuel, φ_{H2} = 0.985 [17,18].

The rate of chemical exergy flow can be expressed as:

$$Ex_{ch} = \dot{\mathrm{m}}\, e_f^{-ch} \tag{8}$$

Exergy destruction overall (E_D) and overall exergy efficiency (η_{Π})

Exergy destruction of each component of gas turbine engine is given as [13,14]:

$$E_D = Ex_{in} + Ex_{out} \quad (9)$$

The exergetic efficiency (η_{Π}) of each component of the gas turbine power plant is defined by [15]:

$$\eta_{\Pi} = \frac{Ex_{out}}{Ex_{in}} \quad (10)$$

Exergy-in (Ex_{in}), exergy-out (Ex_{out}), exergy destruction (E_D) and exergy efficiency (η_{Π}) on component bases are presented in Table 2.

Table 2: Exergy existing equilibrium of each component [13]

Components	Ex_{in} (MW)	Ex_{out} (MW)	E_D (MW)	η_{Π} (%)
Compressor	$W_c + Ex_1$	Ex_2	$W_c + Ex_1 - Ex_2$	$\frac{Ex_2}{W_c + Ex_1}$
Combustion C.	$Ex_2 + Ex_5$	Ex_3	$Ex_2 + Ex_5 - Ex_3$	$\frac{Ex_3}{Ex_2 + Ex_3}$
Gas Turbine	Ex_3	$Ex_4 + W_{gt}$	$Ex_3 - (Ex_4 + W_{gt})$	$\frac{Ex_4 + W_{gt}}{Ex_3}$

Overall plant exergetic efficiency ($\eta_{II,\text{Power plant}}$)

The exergy efficiency of the entire power plant is, according to [19, 20] obtained by:

$$\eta_{\Pi,Power\ plant} = \frac{W_{net}}{Ex_5} \quad (11)$$

where, W_{net} is the turbine Net-work and Ex_5 is the fuel (natural gas) entering the combustion chamber.

Average performance data of four year period (2013, 2014, 2018 and 2019) from the operational log sheet is presented in Tables 3, 4 and 5 at 80, 120 and 140 MW base loads, respectively. This information was used in computing the exergy efficiency of the plant.

Table 3: Power plant thermodynamics performance parameters at 80 MW base load

Date	T_1	T_3	T_4	P_1	M_f	η_c	η_t	γ_a
	(K)	(K)	(K)	(Bar)	(kg/s)	%	%	
2013	298	1420.551	475.3101	1.008	5.9	0.83	0.88	1.4
2014	300	1449.495	485.4604	1.009	6.1	0.83	0.88	1.4
2018	301	1521.697	545.1804	1.008	6.6	0.83	0.88	1.4
2019	298	1463.954	475.4289	1.006	6.2	0.83	0.88	1.4

Source: FIPL Log Book, 2013-2019

Table 4: Power plant thermodynamics performance parameters at 120 MW base load

Date	T_1	T_3	T_4	P_1	M_f	η_c	η_t	γ_a
	(K)	(K)	(K)	(Bar)	(kg/s)	%	%	
2013	299	1472.053	493.8423	1.011	7.8	0.83	0.88	1.4
2014	299	1472.053	492.9484	1.007	7.8	0.83	0.88	1.4
2018	300	1472.053	494.4478	1.007	7.8	0.83	0.88	1.4
2019	301	1448.863	453.5563	1.007	7.6	0.83	0.88	1.4

Source: FIPL Log Book, 2013-2019

Table 5: Power plant thermodynamics performance parameters at 140 MW base load

Date	T_1	T_3	T_4	P_1	M_f	η_c	η_t	γ_a
	(K)	(K)	(K)	(Bar)	(kg/s)	%	%	
2013	299	1538.116	515.3822	1.01	8.5	0.83	0.88	1.4
2014	298	1549.494	540.7719	1.007	8.6	0.83	0.88	1.4
2018	300	1526.734	513.2827	1.01	8.4	0.83	0.88	1.4
2019	298	1606.295	539.3035	1.007	9.1	0.83	0.88	1.4

Source: FIPL Log Book, 2013-2019

where, T_1 is the compressor inlet temperature, P_1 is the compressor inlet pressure, T_3 is the flue gas temperature, T_4 is the turbine outlet temperature M_f is the mass of fuel, η_c is the compressor efficiency, η_t is the turbine efficiency, and γ_a is the specific heat ratio of air.

2.2.5 Availability Model

Availability (ψ) is a measure of the percentage of time that an equipment is capable of producing its end product at some specified acceptable level. Availability is concerned with the duration of up-time for operations and is a measure of *how often* the system is alive and well [21]. Usually, it is expressed as (up-time)/(up-time + downtime) with many different variants. Up-time signifies capability to perform the task while down-time means not being able to perform the task. Mathematically, availability may be expresses as:

$$\psi = \frac{\mu}{(\mu+\lambda)} \qquad (12)$$

Alternatively,

$$\psi = \frac{MTBF}{MTBF+MTTR} \qquad (12b)$$

where,

MTBF - mean time between failures and, MTTR - mean time to repair.

Hence,

$$MTTR = \frac{\sum_{i=1}^{n} \lambda_i M_i}{\sum_{i=1}^{n} \lambda_i} \qquad (13)$$

where,

M_i The time needed to repair when component *i* fails (the maintenance time for preventive maintenance activity *i)*

n - Number of repaired components in the system

λ_i Failure rate of the i^{th} repairable component in the system (λ_i = 1/$MTBF_i$)

The availability data of the power plant for a-four-year period (2013, 2014, 2018 and 2019) is presented in Table 6. Operational data of year 2015 and 2016 are not available because the plant was not in operation at that time.

Table 6: Four-year outage frequency data of FIPL Plant

	FIPL AFAM									
Year	**Outages due to grid disturbances**		**Outages due to gas constraint**		**Outages due to system failure**		**Total outages**		**Period hours**	**Service hours**
	Freq.	Dur. (hrs)	Freq.	Dur. (hrs)	Freq.	Dur. (hrs)	Freq.	Dur. (hrs)	(hrs)	(hrs)
2012	15	209.95	1	0.77	5	77.62	21	288.34	1752	1463.66
2013	53	332.78	16	1208.63	11	423.37	80	1964.78	8760	6795.22
2014	32	1088.8	11	2755.53	20	403.56	63	4247.90	8760	6720.10
2015	-	-	-	-	-	-	-	-	-	-
2016	-	-	-	-	-	-	-	-	-	-
2017	1	3.97	1	446.3	1	29.97	3	480.22	744	263.78
2018	55	645.2	21	858.17	24	1421.45	100	2924.82	8760	5835.18
2019	10	204.3	8	280.15	10	339.72	28	824.17	2160	1335.83

Source: FIPL Log Book, 2013-2019

2.2.6 Exergy Efficiency Modification

Original equipment manufacturer (OEM) usually specify the design efficiency of each power plant type. For gas turbine, the exergy efficiency ranges between 0.25 to 0.4, depending on the made and technology. Never the less, during operations, the operating efficiency of power plant may be lower, equal or a little higher than the designed efficiency. These changes in operating efficiency value may be attributed to certain operation conditions in which the power plant is subjected to. Hence, in this analysis, a modified exergetic efficiency concept is adopted. It is an expression of the ratio of the operating exergy efficiency to the design exergy efficiency. With this concept, a common base of measurement is attained in comparing exergy performance index.

Mathematically, the modified plant exergetic efficiency (E) is expressed as:

$$E = E_o / E_d = \left(\frac{Plant\ thermal\ efficiency}{Design\ efficiency} \times 100\right) \quad (14)$$

Where,

E_o - Operating exergetic efficiency in percentage

E_d - Plant designed exergetic efficiency in percentage

Where,

$E_o = \eta_{II,\text{Power plant}}$ (the exergy efficiency of the entire power plant)

2.2.7 Model Formulation for *Bassy-1 Index* (Exergy efficiency and availability relation)

Exergy efficiency and availability are gas turbine performance parameters that deteriorate with time. Hence, they are viewed as time derivative functions.

Let's consider the performance of a system as a function of two independent factors such that the overall performance of the system is the product of the two factors.

If the first factor be denoted as *A* and the second be *B*. Thus, overall system performance (***Bassy-I Index***) is equal to

$$\textbf{\textit{Bassy-I Index}} = A \times B \quad (15)$$

If factor A = exergetic performance (E)

And, factor B = Actual revenue/ expected revenue

Therefore, ***Bassy-I Index*** = the product of performance A and $B = A \times B$

$$= E \times (OH \times R_t)/(AH \times R_t) \quad (16)$$

$$= E \times (OH/AH) \quad (17)$$

$$= E \times \psi \quad (18)$$

where

E - Plant Exergetic efficiency performance

ψ - Plant system availability

E_d - Plant designed exergy efficiency in percentage

R_t - Revenue per hour

OH - Operating hour

AH - Available hour

ER - Expected revenue

AR - Actual Revenue

The unit for ***Bassy-I Index*** is dimensionless since E and ψ are dimensionless.

Note that: Actual revenue (AR) = OH x R_t
Expected revenue (ER) = AH x R_t

III. RESULTS AND DISCUSSION

Performance results of FIPL gas turbine power plant are presented here with respect to the traditional performance indexes and the proposed (***Bassy-1***) index. The availability state of FIPL power plant was computed from the failure frequency data obtained from the plant operational data sheet. Figure 3 presents the failure rate information of the power plant. According to [5, 22], higher failure rate indicates low availability values. The grid unit recorded higher failure rate compared to the gas supply unit and the sub-system unit. The high values of failure rate for grid unit cause significant rise in the failure rate of the power generation system.

Figure 4 present the availability state of the plant. Total available hours of operation in the years under review were 8760, 8760, 8760 and 2160 hours for years 2014, 2018 and 2019, respectively. The sub-system and generation system availability show a downward trend, corroborating [23]. Grid system availability decreased in the year 2014 and peaked in the year 2018, it slightly fell in the year 2019.

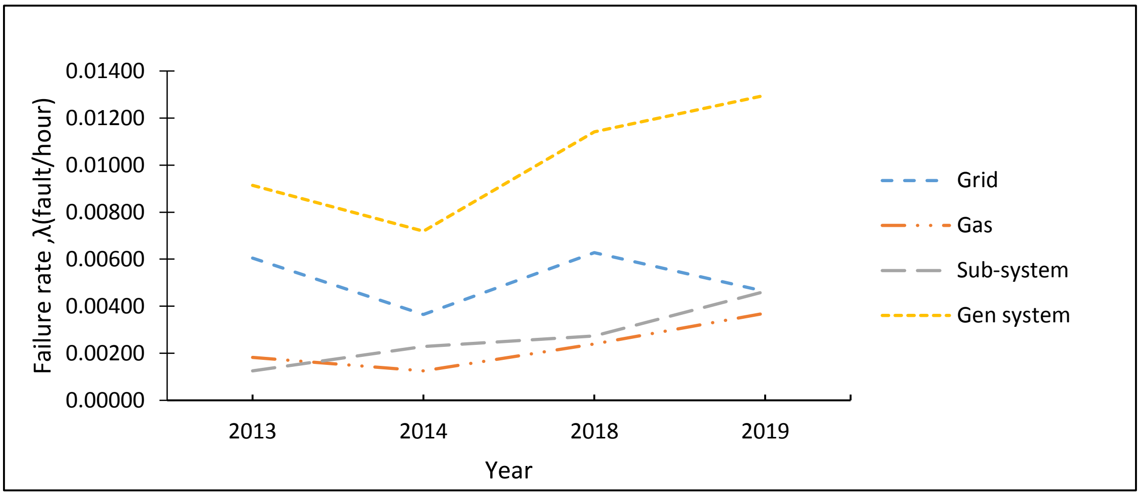

Fig 3: Failure rate of FIPL Afam for the years understudy

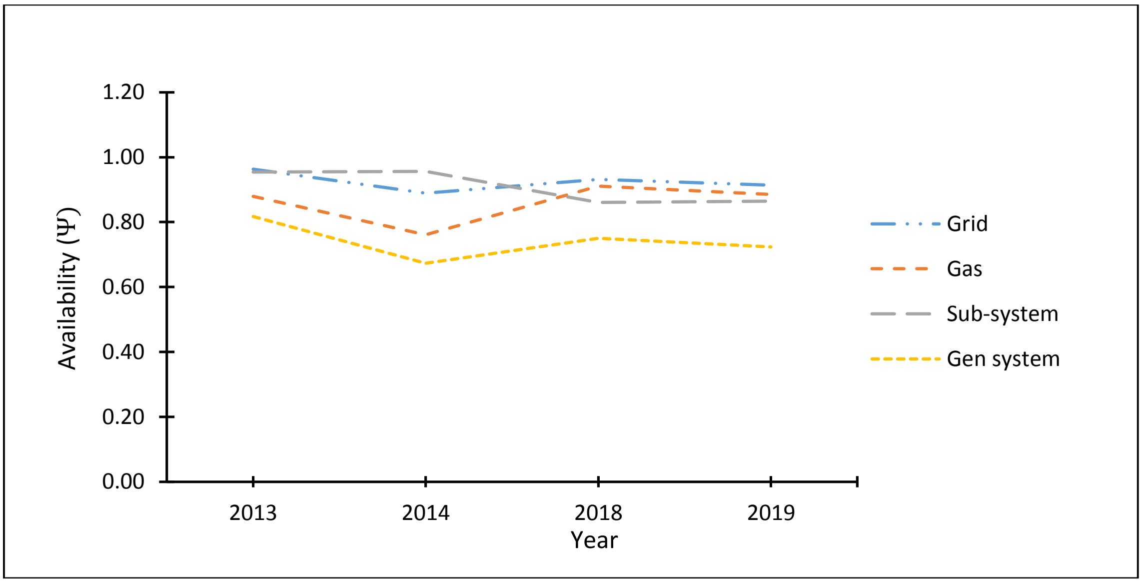

Fig 4: Availability of FIPL Afam for the years understudy

The operating exergy efficiency of the plant was compared at base load of 80, 120 and 140 MW, as shown in Fig. 5. The result showed that the thermal efficiency increases as base load increases. This means that gas turbine operations at higher base load are more exergy efficient than at reduced or minimal base load [24,25,26]. The trend of the graph was studied over the years and it showed that there was a decreasing trend on the thermal efficiency across the base loads despite the up and down fluctuations in between the years.

Average operating exergy efficiency (E_o) and average exergy efficiency *(E)* of the plant at base load of 80 MW, 120 MW and 140 MW for the period under review (2013, 2014, 2018 and 2019) are presented in Figure 6 and 7 respectively.

The results of ***Bassy-I Index*** is presented in Figure 8. A similar downward trend as seen in Figure 6 and 7 of the plant performance across the years is replicated here. Higher base loads accounted for higher performance and lower base load accounted for lower performance [27].

Figures 9,10 and 11 show the gas turbine power plant performances in terms of operating exergetic efficiency (E_o), Plant Exergetic Efficiency (*E*), Availability (ψ), and *Bassy-I Index* for the years under study.

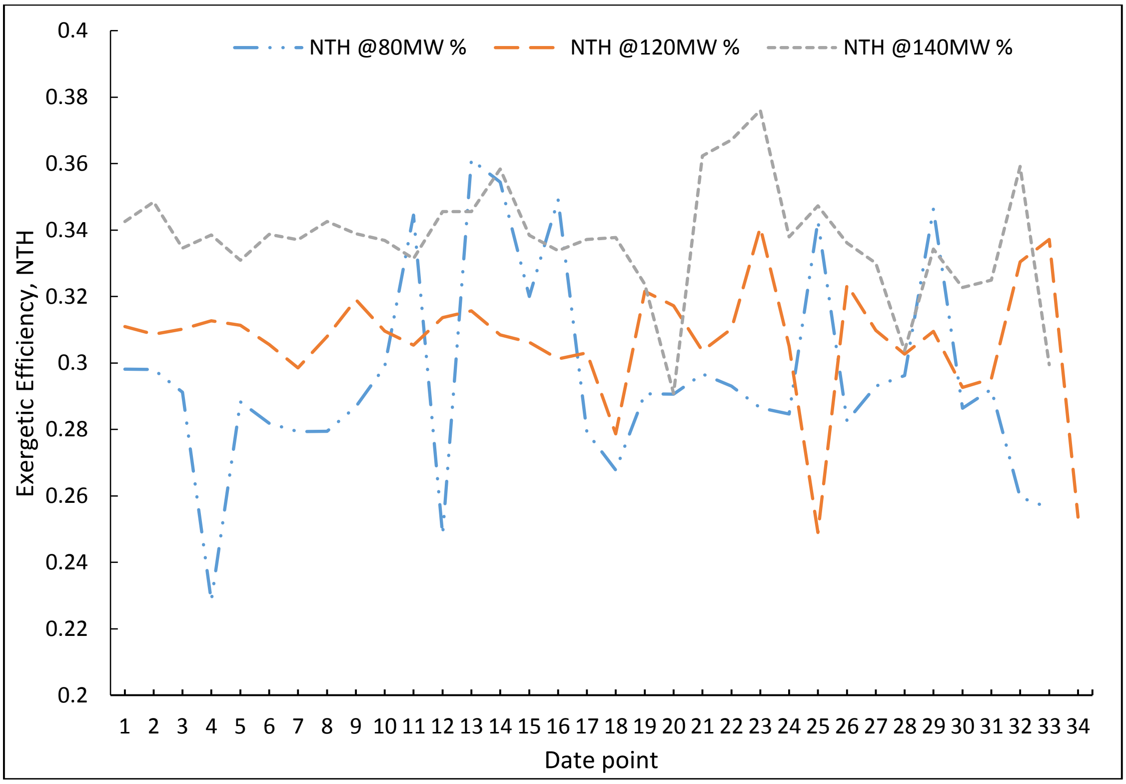

Fig. 5: Thermal efficiency (E_o) variation at base loads of 80, 120 and 140 MW

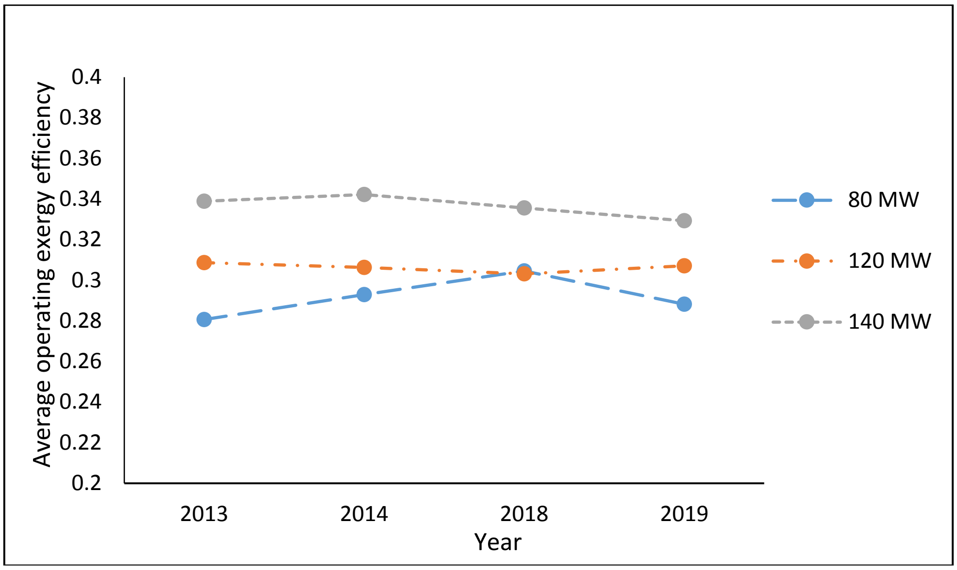

Fig. 6: Average operating exergy efficiency, Eo

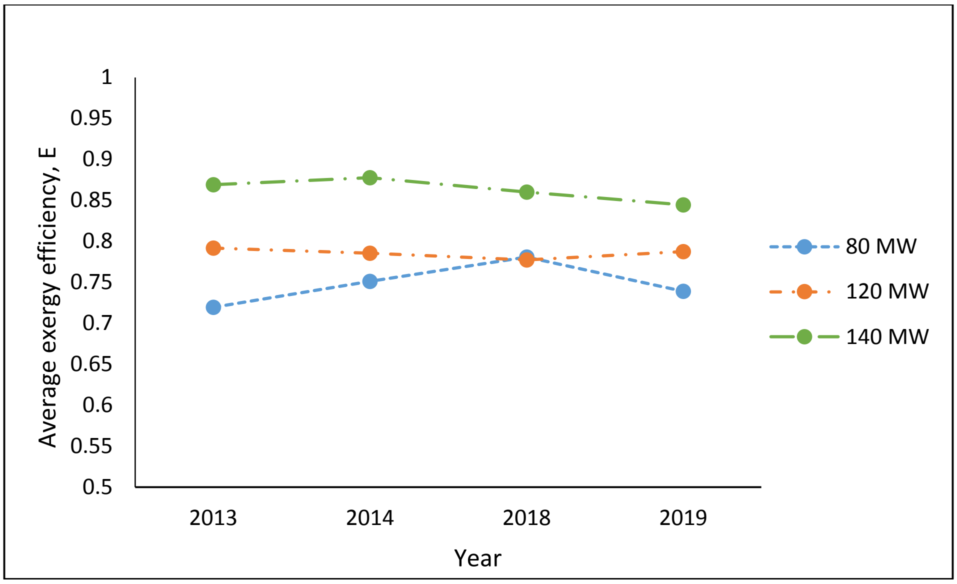

Fig. 7: Average Exergy efficiency, E at base load of 80, 120 and 140 MW

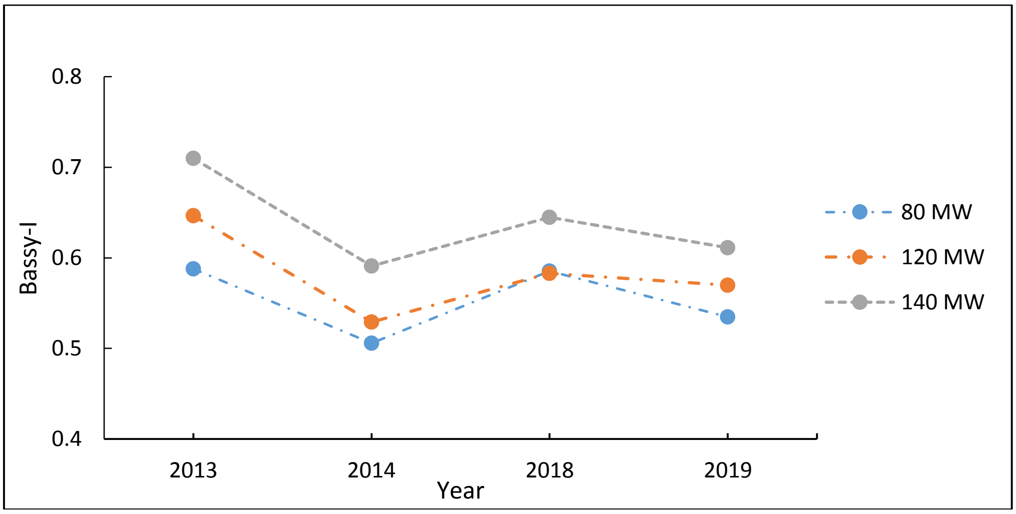

Fig. 8: *Bassy-I Index* performance measure at 80, 120 and 140 MW base loads

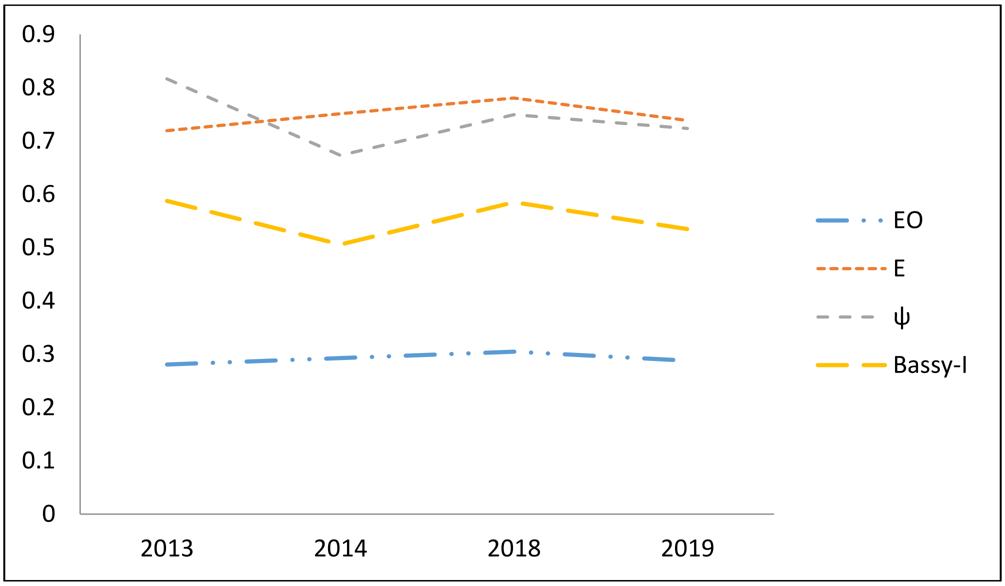

Fig. 9: Performance measures comparison at 80 MW base load

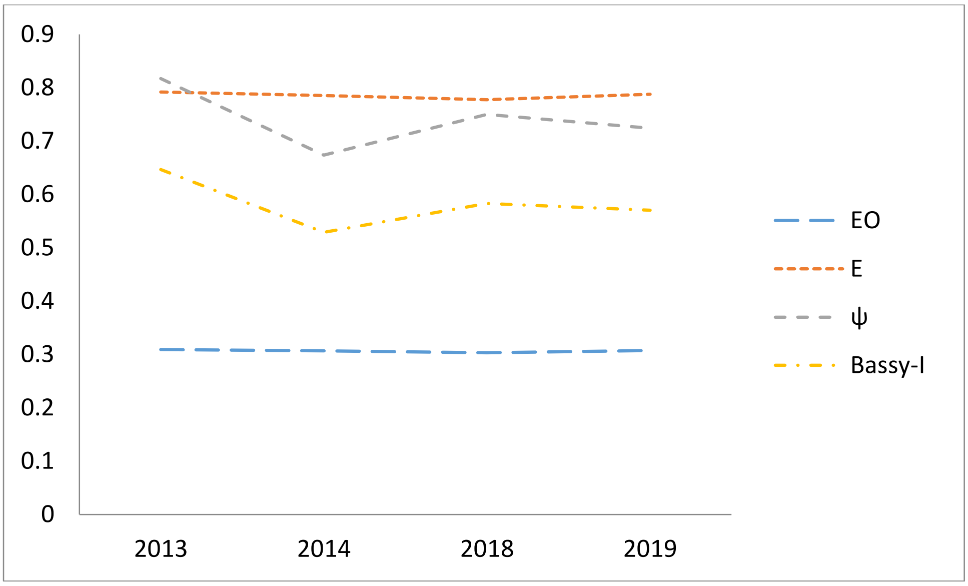

Fig. 10: Performance measures comparison at 120 MW base load

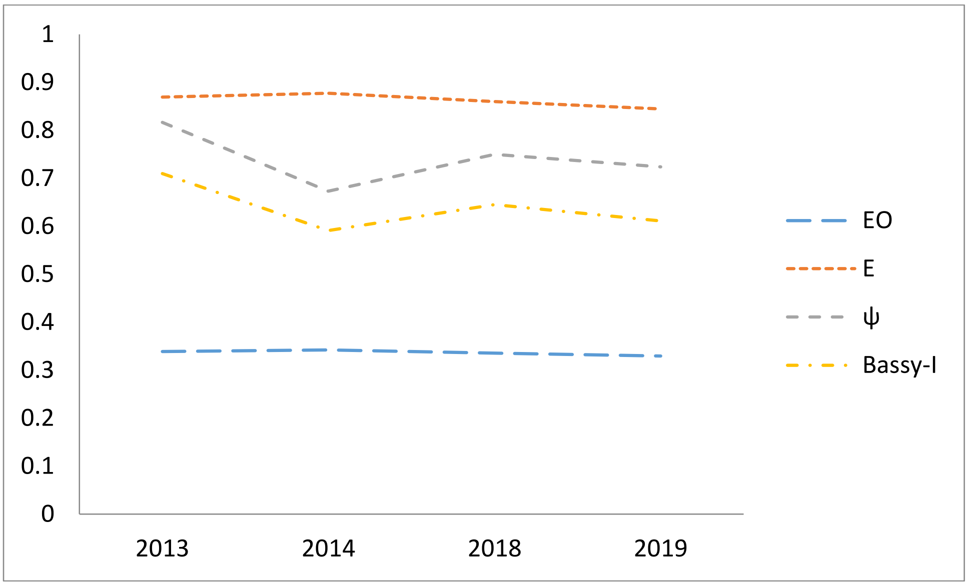

Fig. 11: Performance measures comparison at 140 MW base load

IV. CONCLUSION

This study assesses the performance of FIPL gas turbine power plant. Traditional assessment indexes such as exergetic efficiency and availability measures were used. A new assessment index called ***Bassy-1 index*** was developed and used in the assessment of the power plant. The performance of the plant with respect to the exergy efficiency, availability and the ***Bassy-1 index*** was compared. Results showed that ***Bassy-1 index*** provided a better reflection of the performance state of the plant than the independent assessment approach of exergy efficiency and availability. Hence, ***Bassy-1 index*** is recommended for used in heat driven power generation systems for holistic assessment of power generation systems.

COMPETING INTEREST

Authors have declared that no competing interest exist.

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