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Impact of Reliability Variations on Gas Turbine Power Plant Output and Overall Station Performance

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Abstract:

Using information from five GE MS5001 units, this work examines the reliability of gas turbine power plants between 2011 and 2022. It uses obtained data, derived equations and calculation outcomes to analyse and comprehend how variations in gas turbine reliability, impact overall station reliability and performance. The study findings highlights the importance of reliability in improving station performance by demonstrating that units with higher reliability ratings have higher contribution to total station generated power output. With high reliability levels, percentage output contributions, and total outputs of 23.24%, 94.5%, 2,617,899MW and 23.16%, 94%, 2,608,761MW, respectively, Units D and E stood out as the top contributors; Units A and C, on the other hand, showed lower reliability levels, percentage output contributions, and total outputs of 15.85%, 64.5%, 1,783,663MW and 16.63%, 67.8%, 1,873,504MW, respectively, indicating the need for improvements. The work further showed that in order to maximize unit performance and guarantee sustainable power generation, proactive maintenance, operational enhancements, and system resilience are critical. This improves output, efficiency, operational effectiveness, and consistent energy supply.Furthermore, the work enhances our understanding of energy systems engineering. Recommendations for enhancing reliability and optimizing output of gas turbine power generation have been provided to stakeholders.

Keywords **-**Reliability variation, Gas turbine power plant, Impact, Power output, Reliability analysis, Percentage contribution, Overall station performance

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I. INTRODUCTION

In the global energy landscape, gas turbine power plants are essential because they offer a reliable source of electricity for a variety of industrial, commercial, and residential sectors.In addition to being essential for satisfying the rising demand for electricity, these plants' productivity and efficiency also guarantee the stability and robustness of the entire energy system. According to [1], energy effectiveness is becoming a more significant topic, even though reliability is still the most important requirement for power generation in the oil and gas industry.gas turbines are effective and versatile instruments that can handle the various energy demand profiles in this industry. The ability of these systems to function consistently and productively over time without failure or breakdown is an essential component of gas turbine power plant performance; environmental considerations, operational stability, maintenance effectiveness, equipment integrity, and other factors are all included in the concept of reliability in gas turbine power plants. Power quality is characterised by the reliability of the power supply [2, 60], that is why station operations managers must ensure that sufficient resources are directed towards restoring generating unit's functionality as quickly as possible, in order to increase its reliability, because generating units will occasionally experience operational failures. In an assessment of Nigeria's hydroelectric power plants reliability, [3] demonstrated that the forced outages experienced by the generating units at Kainji hydropower station are indicative of the individual units' inconsistent performance, it noted that unreliable station efficiency is indicated by the high overall station mean loss of load (MLOL) of 9.87 MW.

Growing awareness of reliability stems from the fact that organisations must run its equipment in an efficient, cost-effective, and continuous manner in order to meet production targets [4]. The reliability of system segments, including generation, transmission, and distribution, should be balanced, but not equal, as different levels may be justified due to the importance of the load or localised failures [5]. As the minimum number of turbine units required for operation increases, a power plant's reliability decreases. In certain instances, reliability concerns might require the gas turbine to run at a lower capacity in order to stop additional damage or malfunctions, this was affirmed in a study by [6], where low performance of the gas turbine units resulted in a decrease in the output power generated by the station, where low reliability values indicated multiple failures and downtime. [7] Also, pointed out that ensuring plant reliability and rates is becoming more and more important.In order to fully understand how the various units affect generating station performance, it is crucial to recognise the need for significant power generation, output assessment, and power plant reliability, this is because the reliability of individual gas turbine units significantly affects the reliability of power stations.

The relationship between power output, reliability, and overall station performance for gas turbine power generation is examined in this study. It seeks to offer insights into how reliability variations affect operations, directing the formulation of strategies to enhance both individual gas turbine units and overall station reliability. Through in-depth analysis and empirical investigation. Data was gathered from the Ob Gas Plant, an oil and gas production facility, situated in Nigeria's Niger Delta. Using operating data from the units, over a 12-year period (2011 to 2022), the study examines how the reliability variations of various gas turbine units affects the overall reliability of the station. The gas turbines under evaluation are five GE MS5001 gas turbine plants with a nameplate capacity of 26.3MW. These units generate the electrical energy required by the facility. As part of its social corporate responsibility, it also supplies electricity to the nearby communities. Numerous researchers have examined the relationship between reliability and how it affects the output produced by power plants. A few examples of these studies are; combined cycle gas turbine power output prediction and data mining with optimized data matching algorithm [8], failure and reliability evaluation of turbines used in Nigerian thermal plant [9], and reliability analysis of gas turbine power plant based on failure data [10]. Nevertheless, no such research has been conducted on the power plant that is the subject of this case study.

II. METHODOLOGY

In order to develop planning, operation, and maintenance strategies, statistical information is essential to reliability studies. A gas turbine power station must employ appropriate method of data collection to obtain proper outage information [11]. The reliabilities of five GE MS5001 (A, B, C, D and E) over a twelve years period were obtained from the operations and maintenance data base of the facility and presented in a table, calculations were made of average reliabilities of the units for ease of computation. Equations were derived to calculate the units power output, overall station power output and the percentage contribution of the various units to the overall station reliability. Analysis were carried out on the collected data and outcomes of calculations made from derived equations, to ascertain the impact of reliability variations on gas turbine power plant output and overall station reliability.

A. Reliability (R)

According to [13], in the context of a gas turbine power plant, or any other system, reliability is the system's capacity to carry out required function under given conditions for a predetermined period of time without experiencing a breakdown. Any organization's operation and maintenance activities, in particular, depend heavily on improving asset

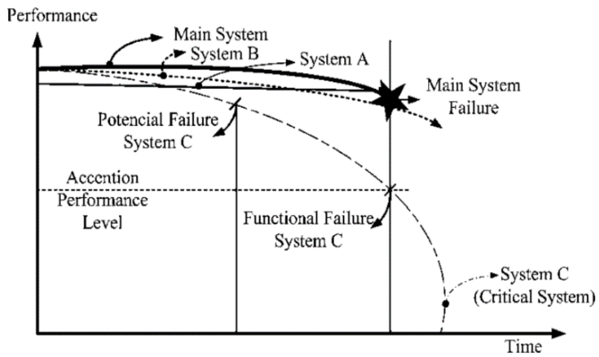

Fig. 1 Reduced system performance as a result of a component's functional failure [12, 199].

reliability [14, 152]. Reliability is symbolised by,

$$R(t) = 1 - F(t) \quad (1)$$

Where R(t) is the reliability at time t and F(t) is the probability of failure at time t. According to this definition, an equipment's physical performance over time is reflected in its reliability, which is regarded as a measure of its performance and efficiency. Thus, given that a gas turbine operates for a certain period of time (usually between 720 and 8700 hours), its maximum reliability is therefore extremely important. Furthermore, some gas turbine manufacturers define reliability asthe likelihood that the unit won't be forced out of service when it is needed, it comprises the hours of forced outage (FOH), that occur during reserve shutdown, while the system is in operation, and during the attempt to resume normal operations by period hours (PH); the units are in % [15]. It is determined by,

$$\text{Reliability} = \frac{PH - FOH}{PH} \times 100 \quad (2)$$

Forced outages are associated with random (or unexpected) failures. The interventions used in corrective maintenance addresses this kind of failure. The primary distinction between the manufacturers' methods of determining reliability is that they do not include a probability distribution; instead, they include FOH and PH. A power plant's reliability factor is primarily determined by its FOH, which is computed by dividing it by the actual operating time [16]. On the other hand, as noted by [17], in the oil and gas, and energy production chain, gas turbines are a key piece of machinery, and as such, their reliability is a concern because of the complexity of its systems. Given that a critical component failure can result in a forced outage, it is imperative to comprehend how component unreliability impacts system reliability. A failing bearing lubrication system can jeopardise a gas turbine's stability and reliability, emphasising the significance of reliability of components.

Reliability is characterized by the system's durability, maintainability, uninterrupted operation, and maintainability, all of which are interconnected to guarantee the energy system operates safely and steadily [18]. The behaviour of three parts of a system (A, B, and C) is depicted in Fig. 1, when component C's performance falls below what is necessary for it to carry out its function (functional failure), the system will fail regardless of whether the other components are operating in compliance with the operational standards, this anology is indicative of the fact that average reliability is a good measure of a power plant's overall reliability. In today's increasingly complex systems, reliability analysis is essential for evaluating power systems in order to lower costs, minimise failures, and improve security [19].Engineers and analysts can evaluate a power plant's average performance and its capacity to run smoothly for a given duration by measuring the reliability of each gas turbine units. To represent the average reliability, let's examine the case study power station with five gas turbine units (A, B, C, D, and E) and yearly reliabilities R_{2011}……R_{2022}. The sum of these reliabilities (R_{sum}) is used to calculate the system's average reliability (R_{ave}). The mathematical expression for the sum of the unit reliabilities and average reliability is,

$$R_{sum} = R_{2011} + R_{2012} + R_{2013} + R_{2014} + R_{2015} + R_{2016} + R_{2017} + R_{2018} + R_{2019} + R_{2020} + R_{2021} + R_{2022} \quad (3)$$

$$R_{sum} = \sum_{i=2011}^{2022} R_i \quad (4)$$

$$R_{ave} = \frac{R_{sum}}{12} \quad (5)$$

$$R_{ave} = \frac{1}{12}\sum_{i=1}^{12} R_i \quad (6)$$

By adding turbine units' reliabilities in the station and dividing the result by the total number of units, this formula determines the average reliability. The average reliability of the station, R_{save}, is determined using the expression,

$$R_{save} = \frac{R_A + R_B + R_C + R_D + R_E}{5} \quad (7)$$

$$R_{save} = \frac{1}{5}\sum_{i=A}^{E} R_i \quad (8)$$

B. Electricity Generated (E_g)

Gas turbines, also known as gas-fired power plants, are employed to generate electricity in gas turbine stations. These power plants use high-temperature, high-pressure gases produced by the combustion of natural gas to drive turbine generators and produce electricity [20, 12-42]. Natural gas is considered a cleaner burning fuel compared to coal and oil, emitting fewer pollutants such as sulphur dioxide and particulate matter into the atmosphere. In terms of reliability, a gas turbine power plant's annual electrical energy production is estimated by,

$$E_g = \text{Nameplate capacity} \times \text{Reliability} \times \text{Total yearly hours} \quad (9)$$

$$E_g = 26.3 \times \text{Reliability} \times 8760 \quad (10)$$

The individual unit generating output (E_{sum}) for the evaluation period is expressed as follows,

$$E_{sum} = E_{g2011} + E_{g2012} + E_{g2013}\, E_{g2014} + E_{g2015} + E_{g2016} + E_{g2017} + E_{g2018} + E_{g2019} + E_{g2020} + E_{g2021} + E_{g2022} \quad (11)$$

$$E_{sum} = \sum_{i=2011}^{2022} E_g \quad (12)$$

Similarly, the station overall output ($E_{Overall}$) is calculated thus,

$$E_{Overall} = E_{gA} + E_{gB} + E_{gC} + E_{gD} + E_{gE} \quad (13)$$

$$E_{Overall} = \sum_{i=A}^{E} E_{gsum} \quad (14)$$

C. Percentage Contribution to Total Station Power Output (%C)

One way to evaluate the relative importance of different units in a power generation system is to look at their percentage contribution to the total station power output. It shows the percentage of the total power output that is attributable to every individual unit. The percentage contribution to total station power output by the unit output can be determined using the expression,

$$\%C = \frac{\text{Unit power output}}{\text{Overall power output}} \times 100 \quad (15)$$

The percentage that each unit contributes to the overall power output gives information about the importance of each unit in the station. It also makes it easier to compare various units and provides information for strategic planning of projects, which is meant to improve the overall reliability and efficiency of the station.

III. RESULTS AND DICUSSIONS

Table 1 presents the reliabilities of the various units over the twelve-year evaluation period, whichwas derived from the organization's operations and maintenance data base, it also includes the average reliabilities of the units, which were calculated using Equation 6. Table 2 contains the yearly unit's power output, calculated from Equation 10, the table also displays the sum of annual power output of different units, determined by Equation 12 as well as the overall station power out calculated from Equation 14. Percentage contributions to total station power output were calculated using Equation 15 and presented in Table 3, Table 3 is also referred to as the

TABLE I.
UNITS YEARLY RELIABILITIES

Reliability Rates (%)													**Reliability Averages (%).**
Units	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	$R_{ave} = \frac{1}{12}\sum_{i=2011}^{2022} R_i$
A	64.0	61.2	65.9	61.3	65.5	63.2	70.0	64.4	65.7	62.4	72.4	58.2	64.5
B	83.4	82.1	87.5	86.4	78.8	88.85	88.6	85.4	84.4	88.6	89.6	88.5	86.0
C	65.7	70.9	68.3	66.9	67.2	65.8	68.4	67.5	69.1	70.3	67.9	66.0	67.8
D	92.0	96.8	96.0	95.1	93.7	97.7	94.3	93.6	95.5	95.4	94.2	92.0	94.5
E	93.7	96.3	93.1	94.7	95.8	95.3	94.7	93.1	92.5	96.5	93.1	93.1	94.0
Station average reliability = $R_{save} = \frac{1}{5}\sum_{i=A}^{E} R_i$													80.4

TABLE II.
CALCULATED YEARLY OUTPUT from TABLE 1 UNIT'S RELIABILITIES.

Year	**YearlyUnit Power Output (MWH)=** E_g = 26.3 × Reliability × 8760					**Station Overall Power Output=** $E_{Overall} = \sum_{i=A}^{E} \boldsymbol{E_{gsum}}$
	A	B	C	D	E	
2011	147,448	192,144	155,512	211,957	215,874	
2012	140,997	189,148	163,345	223,016	221,864	
2013	151,826	201,590	157,355	221,172	214,491	
2014	141,228	199,055	154,130	219,099	218,177	
2015	150,904	181,546	154,821	215,874	220,712	
2016	145,605	204,700	151,595	225,089	219,560	
2017	161,271	204,124	157,585	217,256	219,177	
2018	148,370	196,751	151,511	215,643	214,491	
2019	151,365	194,447	159,198	220,021	213,109	
2020	143,762	204,124	161,963	219,790	222,324	
2021	166,801	206,428	154,433	217,025	214,491	
2022	134,086	203,893	152,056	211,957	214,491	
Total yearly output (MWH) = $E_{sum} = \sum_{i=2011}^{2022} E_g$	1,783,663	2,377,950	1,873,504	2,617,899	2,608,761	11,261,777

TABLE III.
UNITS RELIABILITIES and CALCULATED YEARLY OUTPUT

Units	**Average Reliability Rates (%)**	**Unit Power Output (MWH)**	**Parentage Contribution (%)** $\%C = \frac{\text{Unit power output}}{\text{Overall power output}} \times 100$
A	64.5	1,783,663	15.85
B	86.0	2,377,950	21.12
C	67.8	1,873,504	16.63
D	94,5	2,617,899	23.24
E	94.0	2,608,761	23.16
	80.4	11,261,777	100

summary table as it contains units power output and average reliability rates.

As can be seen from Table 3, Unit D happens to be one of the units with the highest impact, contributing about 23.24% of the total power output. Unit 2540E also made a significant contribution, contributing about 23.16%. The two units also have the highest reliability of 94.5 and 94.5%, respectively; similarly, in Table 2, the two units was seen to have the highest generated power output of 2,617,899MW and 2,608,761MW respectively. Unit B demonstrated a moderate to high reliability of 86% and had a moderate impact, accounting for approximately 21.12% and generated output of 2,377,950MW. Unit C contributed 16.63%, while Unit A had the least amount of influence (15.85%), their respective reliability ratings were 64.5% and 67.8% and generated power output of 1,783,663MW and 1,873,504MW respectively.

With respective shares of roughly 23.24% and 23.16% of the total power output, Units D and E were found to be the primary contributors; the units in question demonstrated a robust correlation between output impact and reliability, as evidenced by their highest reliability ratings of 94.5% and 94%. Unit 2540B demonstrated a moderate to high reliability level of 86%, with an output contribution of roughly 21.12%, this unit's performance was balanced between output impact and reliability. With respective contributions of roughly 16.63% and 15.85%, Units C and A contributed less to the overall power output; at 64.5% and 67.8%, these units showed the lowest levels of reliability, out of the group, suggesting that their operational reliability may need to be improved.

The results show a distinct pattern in which units with higher power output contributions also tended to have higher reliability ratings. On the other hand, units that contributed less showed lower levels of reliability, highlighting the critical role that reliability plays in influencing the overall performance a gas turbine power station. The study emphasizes the importance of enhancing gas turbine unit reliability to boost power output and overall station reliability. It emphasizes the need for improved operational parameters, system resilience, and maintenance procedures in power plant operations to maximize output and ensure a steady energy supply. Investment in unit reliability significantly impacts gas turbine power plant performance.

Unreliable equipment can lead to higher maintenance costs, lower output, and revenue losses, affecting the plant's economic feasibility, on the contrary, reliable units improve safety and environmental performance by reducing operational hazards and environmental risks from unplanned failures. A reliable maintenance strategy is crucial for gas turbine power generation units to reduce costs and increase reliability, these includes predictive maintenance, condition monitoring, and routine inspections. Precision maintenance intervals can be calculated based on working hours and start-up frequency, a comprehensive strategy combiningtechnical advancements, maintenance strategy, and reliability analysis can achieve best results. Other methods of improving unit's reliability and overall stations performance include reducing system complexity, boosting reliability of components, leveraging standby and parallel redundancies, testing, and validation. Strict quality control procedures can identify flaws during manufacturing or production, while a clear maintenance plan involving inspections, repairs, and preventive maintenance can help identify and fix problems before they become failures.

IV. CONCLUSIONS

The study emphasises the significance of reliability in power generation facilities by showing how improving the reliability of gas turbine units can enhance power output and station reliability. Operators can maximise unit performance and create a more reliable and efficient energy supply by focusing on operational conditions, system resilience, and maintenance procedures. The results showed that Units A and C displayed lower output percentage contribution, reliability levels, and total output of 15.85%, 64.5%, 1,783,663MW and

16.63%, 67.8%, 1,873,504MW, respectivelytowards the overall station performance, indicating the need for improvements through careful maintenance practices, efficient monitoring systems, and investment in cutting-edge technologies to enhance reliability. Units D and E emerged as top contributors with high percentage output contribution, reliability levels, and total output of 23.24%, 94.5%, 2,617,899MW and 23.16%, 94%, 2,608,761MW, respectively. Reliability is crucial for optimizing production, minimising downtime, and advancing a sustainable energy infrastructure, it helps stakeholders identify the main electricity producing units, assess how resources are distributed, improve operational plans, and make guided decisions. Reliability has a major influence on the output, efficiency, long-term sustainability, safety, and environmental performance of gas turbine power plants. Proactive maintenance practices, risk management plans, and continuous improvement initiatives can boost the performance and reliability of gas turbine units, increasing power plant output and operational efficiency.

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