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Performance Evaluation and Economic Analysis of Afam VI Unit Power Plant

Dr. K.O. Ikebudu PhD[a], Engr.O.N. K Swift[a,],Engr T.V Umeaduma[c*]

a Lecturer, Department of Mechanical Engineering Chukwuemeka Odumegwu Ojukwu University Uli, Nigeria

b Lecturer,Department of Mechanical Engineering Chukwuemeka Odumegwu Ojukwu University Uli, Nigeria

c Masters Student, Department of Mechanical Engineering Chukwuemeka Odumegwu Ojukwu University, Uli Nigeria

Abstract

This research presents the performance evaluation of Afam VI CCPP (using performance indicators such as cycle efficiency, outage cost of the plant due to system downtime, percentage availability /reduction of the plant) for the period of fifteen months. The power station consists of three gas turbine units (3X150MW) and one steam turbine unit (200 MW) with the total capacity of 650 MW. However, the cycle efficiency of the plant for the period of review is 42% as against efficiency of CCPP which falls between 47% - 52%. Also, 77.68% of the installed capacity was available in the period of review. The percentage of shortfall of energy generated in the period ranged from 16.85% - 24.96% as against the acceptable value of 5 – 10%.The average availability of the plant for the period was about 77.68% as against the industry best practice of 95%.For the fifteen months under review, there was energy generation loss of about 22.32% of expected energy generation of 7,098,000MWh with consequent plant performance of 77.68% which amounts to ₦86,719,713,724 ($240,888,093) .The study further revealed that the 22.32% of generation loss resulted in revenue loss of about ₦24,934,835,506 ($69,263,431).Implementation of condition monitoring/condition based maintenance will brought down the percentage short fall of energy of the plant to 8.2% which fall within the acceptable value of 5-10%. The improved average availability of the plant for the period under review was found to be 91.8% which was close to the industrial best practice of 95%. For period under review (15 months), the energy generation loss dropped to 8.2% of expected energy generation of 7,098,000Mwh with consequent improved plant performance of 91.8% which amounts to ₦121,572,000,000 ($337,700,000). However,8.2% of acceptable generation lossresulted to acceptable revenue loss of about ₦10,737,547,824($29,826,521.73). For boosting the plant availability, condition monitoring of the equipment along with condition based maintenance wasemployed. This was achieved by installation of sensors that monitors dislocation movements and grain boundaries of the systems blades,shafts, bearings etc.in other to detect possible critical event thatcauses forced outage even before they occur. The lost operation days was gained and availability of the plant was boosted because more of condition based maintenance was carried out instead of break down maintenance which normally causes forced outage.

Keywords-Performance evaluation, Economic analysis, combined cycle, improved availability, generated capacity

1.Introduction

One only has to experience power outage to be reminded of how much we take electricity for granted.Substantial expansion in quantity, quality and access to infrastructure services, especially electricity, is fundamental to rapid and sustained economic growth, and poverty reduction [1,2]. The acute electricity supply hinders the country's development and not only restricts socio-economic activities to basic human needs; it adversely affects quality of life. [3]

The objective of the electric energy system is to provide the needed energy services [4]. Energy services are the desired and useful products, processes or indeed services that result from the use of electricity, such as for lighting, provision of air-

conditioned indoor climate, refrigerated storage, and appropriate temperatures for cooking. [5]

We are clearly dependent on electricity for most of our everyday activities. This dependence also demonstrates why electricity is regarded as one of the most significant scientific invention of the 20th Century. [6] Although the United State and other neighbors enjoy the full benefits of electricity, the world's developing nations do not. The majority of Nigerians have no access to electricity and the supply to those provided is not regular. Only about 40% of the nation's over 130 million has access to grid electricity and at the rural level, where about 70% of the population live, the availability of electricity drops to 15% [7]

Before the advent of modern means of generating electrical energy, energy was being generated by a rather crude means such as burning of woods, striking of stones etc. Modern technology has initiated the production of electrical energy from Conventional Power plant such as Steam-Power Plants, Gas-Turbine Power Plants, Hydro-electric power Plants, Nuclear-Power Plants, etc. Non-conventional Power Plant such as Thermo-Electric Generators, Thermionic Generators, Fuel-Cells Power Plants, Photo-Voltaic Solar Cells, Biogas etc and the popular Diesel and Petrol Engines are used when blackouts occur.

A Power Plant is an Industrial Complex where power, especially electricity is generated from another source such as burning coal, flowing water etc. Various Power Plants are situated around the country such as the Afam Power Plant, Egbin thermal Power plant,kainji hydro-power plant etc. A hydro-power plant generates power at low cost, it is easy to manage, pollution free and makes no crippling demands on the transportation system; the major drawback is that, it operates at the mercy of nature. Poor rainfall has on a number of occasions shown the dangers of over dependence on hydropower. The major hurdle in the development of nuclear power in this country is lack of technical facility and foreign exchange required to purchase the main component of nuclear power plant. It is easy to operate a Gas Turbine plant in terms of source of fuel for areas with fairly good deposits of natural reserve (Natural Gas).

Global warming and fossil fuel depletion issues have escalated the need and importance of integrating several energy production units to utilize a common primary energy input in thermal power plants like gas turbine plant. Fossil fuels are used as the primary energy input to generate electricity while the exhaust flue gases can be utilized to drive other thermal cycles like steam Rankine cycle, heating units etc. Integrated multi energy generation is an emerging area with growing interest.

Afam VI gas power plant is considered in this study. The objectives of this study therefore includes: (1) to evaluate the cycle efficiency of Afam VI power plant over a period of fifteen months (Jan 2018 – March2019); (2) to evaluate the outage cost due to system downtime of the station over the period of fifteen months (Jan 218 – March 2019); (3) to determine the percentage availability/reduction of the plant over a period of fifteen months (Jan 2018 –March 2019).

2.0 Materials and methods

2.1 Afam VI Power plant

Afam power plant has six units. This study is on Afam VI combined cycle power plant. This plant was awarded in November 2005 to SPDC. It is located at Afam town, Rives state. The joint venture is being operated by shell petroleum development company (SPDC) with Nigerian National Petroleum Company (55%), shell (30%), Agip (5%) and total (10%) and being supervised by NERC. This plant of 650MW installed capacity uses a combined cycle of an open gas turbine system and a steam turbine system (three gas turbines and a single steam turbine). The 3 gas turbine started operation in January, 2009 while the combined – cycle started operation in December, 2010. Its main task is to deliver electricity to the National Gird via the Afam VI switchyard and import power from the national grid into the CCPP for the start-up process via the same yard. The combined cycle is an advanced design that requires only two-third of the gas

needed by many Nigeria's existing power plants to generate each unit of electricity. Afam VI uses three gas turbine of 150MW each and a steam turbine which is driven by the heat (in forms of steam) from the gas turbines to generate additional 200MW of (very low emission) electricity to give a total of 650MW.[8]

2.2 Methodology

2.2.1 Data Presentation

Data used for this study were collected from the power station's log book and Afam VI Power Station report such as:

- **(i)** average daily power generated (MW)
- **(ii)** pressure and temperature.
- **(iii)** Installed capacity (MW)
- **(iv)** Running days
- **(v)** Failure probability chart for gas turbines

Relevant plant and working fluid parameters (air and combustion gases specific capacities and universal constants) were obtained from appropriate thermodynamic table.

2.2.2 Assumptions

- Feed pump work neglected
- Pressure Losses neglected
- Change in kinetic energy is negligible
- Cycles for both steam and gas turbine are analyzed using the steady state energy equation Q **+ W =dh**
- The mass flow rate of fuel is negligible since air-fuel ratios of gas turbines are always high (80:1). This sets $\mathbf{m_a/m_f}$ to zero in the mixture entering the steam generators as shown in the relation $\mathbf{m_a + m_f = m_a (m_f/m_a + 1)}$.

2.3 Thermodynamic principle of operation of the plant

It operates on open Brayton cycle and the Schematic diagram of the Plant under study is shown in Figure 1 and shows the main work and energy flows and the state points which used in this analysis. The plant consists of an axial compressor, a combustion chamber, and gas turbine, HRSG, Steam turbine, condenser and pump. The T – s diagram is represented in figure 2&3

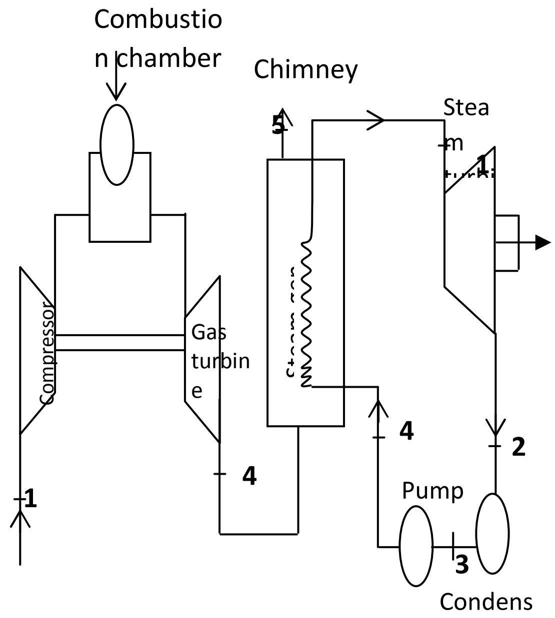

Fig 1: Gas and steam combine cycle

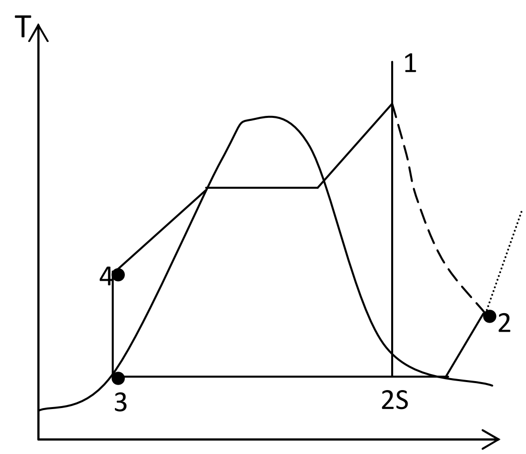

Fig 2: T-S diagram for Steam turbine

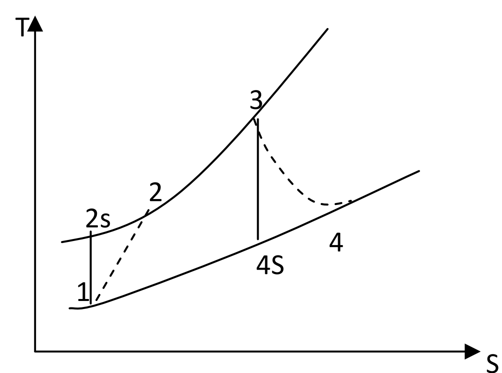

Fig 3: T-S diagram for gas turbine

2.4 Combines cycle efficiency

If $\dot{m}a$ = mass flow rate of air

$\dot{m}s$ = mass flow rate of steam

For energy balance on the steam generation, that is, heat lost = heat gained, we have (from fig 1)

$\dot{m}a4h_4 - \dot{m}_{a5}h_5 = \dot{m}_{s1}h_1 - \dot{m}_{s4}h_4$ **1**

Neglecting pressure losses $\dot{m}_{a4} = \dot{m}_{a5} = \dot{m}_a$ and $\dot{m}_{s4} = \dot{m}_{s5} = \dot{m}_s$

Therefore, equation (1) becomes

$\dot{m}a\ h_4 - \dot{m}_a h_5 = \dot{m}_s h_1 - \dot{m}_s h_4$................**2**

If dh =cpdT then, equation (2) becomes

$\dot{m}aCp(T_4 - T_5) = \dot{m}s\ (h_1 - h_4)$......................**3**

From (3) $\frac{\dot{m}a}{\dot{m}s} = \frac{h1-h4}{cp(T4-T5)}$..............................4

$\dot{m}_a$x (network output)$_{GT}$ + $\dot{m}_a$ (work output)$_{ST}$ = total power output $\frac{(mw)}{1000}$ **5**

From (4) $\dot{m}_a = \dot{m}_s \left[\frac{h1-h4}{cp(T4-T5)}\right]$........................6

Putting (6) into (5), we have

$\dot{m}_s \left[\frac{h1-h4}{cp(T4-T5)}\right] \left[cp_g(T_3 - T_4) - cp_g(T_2 - T_1)\right]$ +

$\dot{m}_s[\pi ST(h_1 - h_{2s})]$ = Total power output $\left[\frac{mw}{1000}\right]$ ..**7**

If equation (7) is transposed, $\dot{m}_s$is made the subject of formula. With $\dot{m}_s$ in equation (6) $\dot{m}_a$ is known

Combined cycle Efficiency = $\frac{total\ power\ (mw\ x\ 1000)}{\dot{m}_a\ x\ cp_g(T_3 - T_2)}$..**8**

2.5Availability/Reductionandoutagecostoftheplant

Power plant outage cost is determined by the following equation. [9]

$P_T = \sum_{i=1}^{n} P_{Ai}$ **9**

where PT is the total power outage cost due to system downtime for n number of months and PA is the monthly power outage cost for m number of units. But

$P_A = P_R\ X\ P_F\ X\ C_U$ **10**

$PR = \sum_{j=1}^{n} Pr$...**11**

$Pr = P_{IC} - P_{GC}$...**12**

$PF = \sum G_C / \sum I_C$ **14**

where PR is the monthly power generation reduction for m number of units.P_{GC} the annual generated energy capacity in MW h for individual unit, PF the monthly power factor for m number of units, GC the generated power capacity in MW for individual unit, IC the installed power capacity in MW for individual unit, P_{IC} the monthly energy capacity in MWh for individual unit.CU the unit cost of energy and its value is given as 0.6US dollar/kWh (N 20.3/KWh) as at 2018.

Table 1: Monthly Power Outage lost (P_A), Installed amount (IA) and Generated amount (GA). Unit cost of energy CU = ₦20.30/Kwh

Mnth	Installed cap (Mwh).	Generated cap(Mwh)	Capacity factor	Power generation reduction (Mwh).		Outage cost ₦ (OC)	Installed Amount ₦ (IA)	₦(GA)=(IA-OC) Generated Amt.
Jan 18	483,600	358,368	0.74	125,232		1,881,235,104	7,264,639,200	5,383,404,096
Feb18	434,800	351,888	0.81	84,912		1,396,208,016	7,149,416,400	5,753,208,384
Mar18	483,600	376,944	0.78	106,656		1,688,791,104	7,657,322,400	5,968,531,296
Apr 18	468,000	278,880	0.80	92,578		1,503,466,720	7,600,320,000	6,096,853,280

May18	483,600	389,136	0.80	94,464		1,534,095,360	7,853,664,000	6,319,568,640
Jun18	468,000	362,880	0.78	105,165		1,665,182,610	7,410,312,000	5,745,129,390
Jul18	468,000	357,672	0.76	110,328		1,702,140,384	7,220,304,000	5,518,163,616
Aug18	483,600	351,888	0.73	131,712		1,951,840,128	7,166,468,400	5,214,628,272
Sep18	468,000	376,944	0.81	91,056		1,497,233,808	7,695,324,000	6,198,090,192
Oct18	483,600	375,532	0.78	108,168		1,712,732,112	7,657,322,400	5,944,590,288
Nov18	468,000	389,136	0.83	78,864		1,328,779,536	7,885,332,000	6,556,552,464
Dec18	483,600	362,880	0.75	120,720		1,837,962,000	7,362,810,000	5,524,848,000
Jan19	483,000	358,368	0.74	125,232		1,881,235,104	7,255,626,000	5,374,390,896
Feb19	452,400	351,888	0.78	100,512		1,591,507,008	7,163,301,600	5,571,794,592
Ma19	483,600	370,848	0.77	112,752		1,762,426,512	7,559,151,600	5,796,725,088
TOTAL						**24,934,835,506**	**111,654,549,230**	**86,719,713,724**

Table 2: Improved Monthly Power Outage lost (P_A), Installed amount (IA) and Improved Generated amount (GA). Unit cost of energy CU = ₦20.30/Kwh

Month	Installed cap(Mwh)	Improved Generated cap(Mwh)	Improved capacity factor	Improved generation reduction (Mwh)	Improved outage cost ₦ (OC)	Installed Amount ₦(IA)	Improved generated amount₦(IA-OC)
Jan 18	483,600	444,912	0.92	38,688	722,537,088	9,031,713,600	8,309,176,512
Feb 18	434,800	398,640	0.92	36,160	673,001,138	8,092,392,000	7,419,390,862
Mar 18	483,600	447,888	0.93	35,712	671,418,565	9,092,126,400	8,420,707,835
Apr 18	468,000	433,440	0.93	34,560	649,759,902	8,798,832,000	8,149,072,098
May 18	483,600	446,832	0.92	36,768	689,642,505	9,070,689,600	8,381,047,095
Jun 18	468,000	427,392	0.91	40,608	752,814,844	8,676,057,600	7,923,242,756
Jul 18	468,000	420,000	0.90	48,000	874,461,538	8,526,600,000	7,651,538,462
Aug 18	483,600	457,920	0.95	25,680	493,621,852	9,295,776,000	8,802,154,148
Sep 18	468,000	439,452	0.94	28,548	544,173,412	8,920,875,600	8,376,702,188
Oct 18	483,600	442,656	0.92	40,944	760,792,757	8,985,916,800	8,225,124,043
Nov 18	468,000	435,696	0.93	32,304	610,506,173	8,844,628,800	8,234,122,627

Dec 18	483,600	430,752	0.89	52,848	955,576,816	8,744,265,600	7,788,688,784
Jan 19	483,000	430,752	0.89	52,248	945,901,427	8,744,265,600	7,798,364,173
Feb 19	452,400	419,760	0.93	32,640	614,786,954	8,521,128,000	7,906,341,046
Mar 19	483,600	441,600	0.91	42,000	778,552,854	8,964,480,000	8,185,927,146
TOTAL					**10,737,547,824**	**132,309,000,000**	**121,572,000,000**

Table 3: Percentage Power Generation/Availability

MONTH	Installed capacity (Mwh)	Generation reduction (Mwh)	Availability (Mwh)	Percentage reduction (%)	Percentage availability (%)
Jan 18	483,600	125,232	358,368	25.90	74.10
Feb18	434,800	84,912	351,888	19.35	80.93
Mar18	483,600	106,656	376,944	22.05	77.95
Apr 18	468,000	92,568	375,432	19.78	80.22
May18	483,600	94,464	389,136	19.53	80.47
Jun18	468,000	105,165	362,880	22.47	77.53
Jul18	468,000	110,328	357,672	23.57	76.43
Aug18	483,600	131,712	351,888	27.24	72.76
Sep18	468,000	91,056	376,944	19.45	80.54
Oct18	483,600	108,168	375,532	22.34	77.65
Nov18	468,000	78,864	389,136	16.85	83.15
Dec18	483,600	120,720	362,880	24.96	75.04
Jan19	483,600	125,232	358,368	25.90	74.10
Feb19	452,400	100,512	351,888	22.22	77.78
Mar19	483,600	112,752	370,848	23.32	76.68
TOTAL	**7,098,000Mwh**	**1,588,341Mwh**	**5,509,659Mwh**	**Avr=22.32%**	**Avr=77.68 %**

Table 4: Improved percentage power Generation/Availability

Month	**Installed capacity (Mwh)**	**Improved Generation reduction (Mwh)**	**Improved availability (Mwh)**	**Improved percentage reduction (%)**	**Improved percentage availability (%)**
Jan 18	483,600	38,688	444,912	8.695652	91.30435
Feb 18	434,800	36,160	398,640	9.070841	90.92916

Mar 18	483,600	35,712	447,888	7.973422	92.02658
Apr 18	468,000	34,560	433,440	7.973422	92.02658
May 18	483,600	36,768	446,832	8.228596	91.7714
Jun 18	468,000	40,608	427,392	9.501348	90.49865
Jul 18	468,000	48,000	420,000	11.42857	88.57143
Aug 18	483,600	25,680	457,920	5.607966	94.39203
Sep 18	468,000	28,548	439,452	6.496273	93.50373
Oct 18	483,600	40,944	442,656	9.24962	90.75038
Nov 18	468,000	32,304	435,696	7.414344	92.58566
Dec 18	483,600	52,848	430,752	12.26878	87.73122
Jan 19	483,000	52,248	430,752	12.12949	87.87051
Feb 19	452,400	32,640	419,760	7.775872	92.224413
Mar 19	483,600	42,000	441,600	9.51087	90.48913
TOTAL	**7,098,000Mwh**	**580,453Mwh**	**6,517,547Mwh**	**Avr=8.2 %**	**Avr=91.8 %**

3.0 Results and discussion

The expected full load installed capacity of the plant under study is 650 MW, but the generated capacity for the period under review (15 months) ranges from around 532MW and 555MW.However, the improved generated capacity when condition based monitoring is applied will be around 641MW and 646 MW. The total outage cost for the period under review is shown in table 1 as₦ 24,934,835,506which is 22.32% of the installed amount. The generated amount which is ₦86, 719,713,724 is about 77.68% of the installed amount (₦111,901,000,000). However, the improved total outage cost for the period under review is shown in table 2 as ₦10,737,547,824 which is 8.2% of the improved installed amount(₦132,309,000,000). The improved generated amount which is ₦121,572,000,000 is about 91.8% of the improved installed amount.(₦132,309,000,000).

The total cost resulting from full working capacity is gotten in table 1 as ₦111,901,836,506 while the improved full working capacity was found to be ₦132,309,000,000.From table 3, the percentage of shortfall of energy is22.32% while the improved percentages shortfall 8.2% from table 4. From table 3,there was a generation reduction of 1,588,341Mwh and availability of 5,509,659 Mwh out of the total installed 7,098,000Mwh while in table 4, there was improved generation reduction of 580,453Mwh and availability of 6,517,547Mwh out of the total 7,098,000Mwh.From table 3, percentage generation reduction is 22.32% against availability of 77.68% while the improved percentage generation reduction is 8.2% against 91.8% from table 4.

From the availability/reduction graph of fig 4 &5, the availability goes up and down across the month under review with November 2018 having the highest availability of 83.15% while the lowest availability was obtained August 2018 with 72.76%. From May, June, July 2018, there was a uniform drop in the availability of the plant which may have resulted due to shutting down of the plant around June 2018 because of maintenance of shell gas facilities.

From the percentage reduction graph, there was a rise in percentage reduction in August 2018 with 27.24% while the minimum percentage reduction was obtained in November 2018 with 16.85%. From the power outage graph, the outage cost is highest in August 2018 whereas the least occurred in November 2018.

From the results of efficiencies calculated, the Brayton cycle has the least (16%), followed by the Rankine cycle (31%).The highest occurred in the combined cycle (42%)

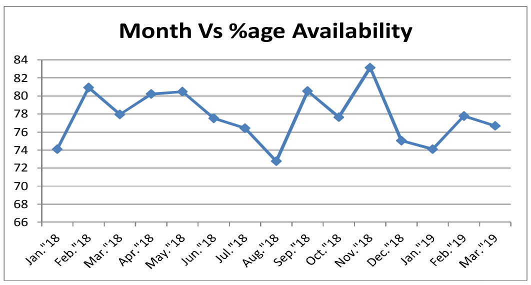

Fig 4: Variation of generation percentage availability with month

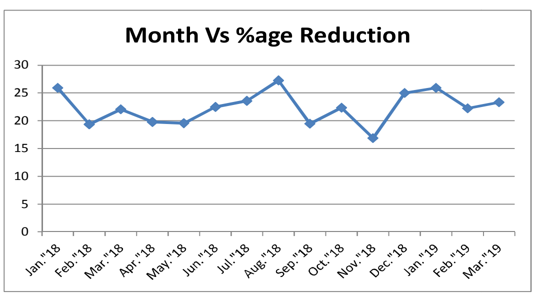

Fig 5: Variation of percentage power reduction with month

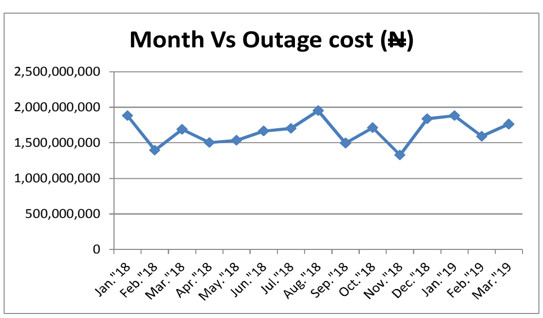

Fig 6: Variation of outage cost with month

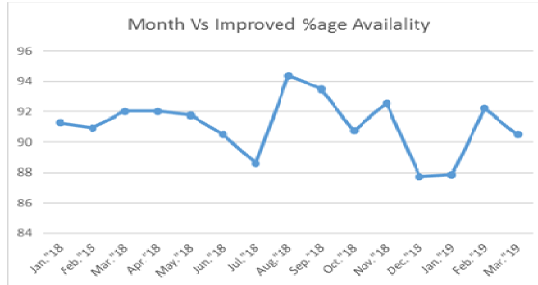

Fig 7: Variation of improved percentage generation availability with month.

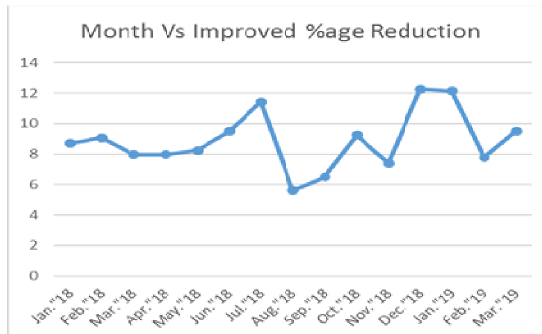

Fig 8: Variation of improved percentage reduction with month.

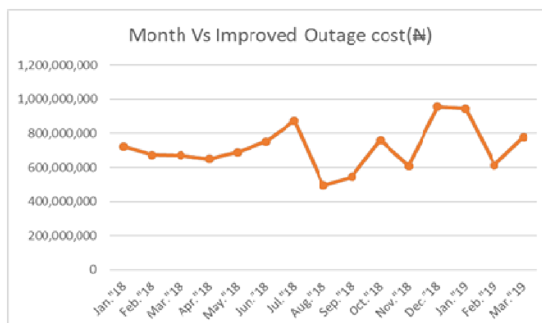

Fig 9: Variation of improved outage cost with month

4.0 Conclusion

Efficiency of Afam VI Unit CCPP

From the results discussed, the efficiency of Afam VI unit combined cycle power plant is approximately 42%. This result compared with the general efficiency of a combined cycle power plant which is between 47% - 52%, shows the though the said plants is not operating at its peak, but its performance is satisfactory.

Outage Cost

From the result of outage cost calculated, the installed amount is ₦ 111,901,000,000 (100%).The generated amount is ₦86, 719,713,724 (77. 68%).The outage cost due to system downtime is ₦ 24,934,835,506 (22. 32%).Since what was generated during the periodunder review is far above average, and the outage cost due to system downtime is far below average, it shows that the plant, though not at its best, has a better performance.

However, the improved installed amount is ₦132,309,000,000 (100%).However, if condition monitoring is implemented along with condition based maintenance, failures will be detected ahead before forced outage. Therefore, the improved generated amount will be₦121,572,000,000 (91. 8%).The improved outage cost due to system downtime is ₦10,737,547,824 (8.2%)

Availability/Reduction

From the result, the reduction for each month for the period under review is always far below average whereas the corresponding availability is far above average. Both the availability and reduction graph shows a slight constant decrease and increase during May, June, July 2018 which may have resulted due to shutting down of the plant for the shell gas facility maintenance during the month of June 2018.

However, the availability of the plant for the period of review is 77.68% against the industrial best practice of 95%. The percentage of shortfall of energy generated in the period ranged from 16.85% - 24.96% as against the acceptable value of 5% – 10%. The plants though not at its best still have a better performance.

However, the improved plant availability will be 91.8% which is close to the industrial best practice of 95%. The percentage shortfall of energy will be 8.2% which fall within the acceptable value of 5% - 10%.

Recommendations

The Combined Cycle Power Plant

More combined-cycle power plants should be sited since in conventional power plant, there is a considerable wastage of energy and harming of environment due to heat rejected which is not usefully used. One way of making the power production more efficient is to use a cycle combining two power units with heat rejected from the gas turbine supplying heat to the steam turbine. The best mix for combine –cycle power plant as at now, from technological point of view is that of gas and steam turbine cycles in combination. The gas turbine is the higher temperature unit and the gas leaving the expansion process is at sufficient high temperature to be used as a source of heat for the production of steam at suitable pressure and temperature.

Implementation of condition based maintenance through application of condition monitoring sensors and scanners.

Application of these components to the system will help to detect future possible failures through interpretation of the provided data of the machine during operation. Forced outage rate can be decreased by continuously monitoring GT operation and reacting quickly to GT trip/runbacks. With this, breakdown maintenance will totally decrease and availability of the plant will definitely increase.

Grid Instability

From findings, though the plant within the period of review was not 100% in production, sometimes, the National Grid is unable to transmit the total Megawatts produced per time. Therefore; the federal government should improve the grid receiving facilities in order to prevent instability in the Grids ability to transmit power generated in the plant.

Unresolved Commercial Agreements Issues

If the power upgrade programs of the Federal Government of Nigeria must be realized, the government should ensure that all commercial issues with generating plants are properly resolved. This will ensure that workers are paid promptly, equipment are properly maintained at the right time etc. Under this condition, a steady state operation can be realized.

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