

Determination of Unit Fuel Cost Effect on Optimal Designed Parameters of Delta IV Ughelli Gas Turbine Power Plant Unit

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Abstract: The effect of variation on optimal decision variables with respect to unit cost of fuel (sensitivity analysis) for optimal performance of 100MW Delta IV ughelli gas turbine power plant unit was determined using optimal operating parameters and exergoeconomics. The optimization tool is an evolutionary algorithm known as Genetic Algorithm (GA). The computer application used in this work is written in matlab programming language. Eight optimal operating parameters of the plant were used: compressor inlet temperature (T_1), compressor pressure ratio (r_p), compressor isentropic efficiency (η_{ic}), turbine isentropic efficiency (η_{it}), turbine exhaust temperature (T_4). Air mass flow rate, fuel mass flow rate and fuel supply Temperature (T_f). These decision variables were optimally adjusted by the Genetic Algorithm (GA) to minimize the objective function. The objective function representing the total operating cost of the plant defined in terms of \$ per hour is the sum of operating cost (i.e fuel consumption cost rate), rate of capital cost (i.e optimal investment and maintenance expenses) and rate of exergy destruction cost. The optimal values of the decision variables were obtained by minimizing the objective function. The determined values of the optimal operating variables were $r_p = 9.76$, $\eta_{ic} = 86.4\%$, $\eta_{it} = 89.12\%$, $T_3 = 1,481.8K$, $\eta_e = 29\%$, $\eta_E = 31\%$, Total Cost Rate = 13292\$/hr, $W_t = 277.11MW$, $W_c = 169.63MW$, air mass flow rate = 530kg/s and fuel mass flow rate = 7.00kg/s. The variation of optimal decision variables with unit cost of fuel showed that by increasing the unit fuel cost, the pressure ratio (r_p), compressor isentropic efficiency (η_{ic}), exergy efficiency (η_e), Energy efficiency (η_E), total cost rate, turbine output power (W_t) and compressor input power (W_c) increase. The increase in η_{ic} , η_e , η_E and W_t guarantees less exergy destruction in compressor and turbine as well as less net cycle fuel consumption and operating cost.

Keywords: Sensitivity Analysis, Unit Fuel Cost, Optimal Parameters, Genetic Algorithm

1. Introduction

The remarkable variation in electricity generation and its demand has posed a great concern to power plant operators with the task of economic operation. In order to have a closer study it is important to verify the optimum results against the variation of a key parameter. This analysis is a tool that helps in evaluating how sensitive the output is, by the changes in one input while keeping the other inputs constant. In this study, the unit cost of fuel is the input variable while the optimal decision variables such as compressor compression ratio, compressor isentropic efficiency, total cost rate, exergetic efficiency etc. are the output variables. This study is important especially in a country such as Nigeria, where

the cost of fuel varies very often.

This research uses exergy analysis, a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of thermal systems [1]. Genetic Algorithm was used to minimize the exergy destruction by optimally adjusting the operating parameters. Genetic Algorithm as an optimization tool works based on Charles Darwins theory of evolution (survival of the fittest). Genetic algorithm was originally designed as simulator but has proven to be a robust optimization technique [2-3].

Genetic algorithm uses two operators to generate new solutions from existing ones: crossover and mutation. The crossover operator is the most important operator of GA. In

crossover, two chromosomes called parents are combined to form new chromosomes, called off-springs. The parents are selected among the existing chromosomes in the population with preference to fitness. This enables the off-springs to inherit good genes making them better than their parents. By iteratively applying the crossover operator, genes of good chromosomes are expected to appear more frequently in the population, eventually leading to convergence to an overall good solution. The mutation operator introduces random changes into the characteristics of the chromosomes. The aim of mutation is to introduce new genetic material into existing individual; that is, to add diversity to the genetic characteristics of the population. The population which is created randomly at the onset is called initial population. The size of this population may vary from several tens of chromosomes (strings) to several thousands. The criterion applied in determining an upper bound for the size of population, that is further increase does not result in improvement of near-optimal solution. The upper bound for each problem is determined after some test runs. For most applications, the best population size lies within the limits of 100 – 1000 strings [2-3]. On the basis of the optimality (measure of goodness) value, an objective function value or fitness value is assigned to each string. This fitness usually set as the amount of optimality of each string in the population divided by the average population optimality. Effort is always made to ensure that the fitness value is a positive number [2]. It is possible that a certain string does not reflect an allowable condition. For such a case, the fitness of the string is penalized with a very low value, indicating in such a way to the GA that it is not a good string. Similarly, other constraints may be implemented in the GA. The “operators”, which are kinds of population transformation devices, are applied to the population. As a result of these operators, a new population is created, that will hopefully consist most optimal strings. The old population is replaced by new one. A predefined stopping criterion, usually maximum number of generation s to be performed by the GA is checked. If the criterion is not satisfied, a new generation is started, otherwise, the GA terminates.

The objective this study is to evaluate the operating cost for optimal performance of 100MW Gas Turbine Power Plant using GA to minimize the exergy destruction cost rate by optimally adjusting the operating parameters.

2. Materials and Method

The data used for this analysis are real time values recorded in the station's operational log book for the period of January 2005 – December 2014 [4] for 100MW Delta IV gas turbine at various state points. These recorded values of the parameters were taken in the station every one hour interval for twenty four hours (i.e. daily). Then, the daily, monthly and yearly average values of the parameters were calculated using the EXCEL statistical tool. This exercise is carried out for ten consecutive years. The analysis was carried out with GA tool box in Matlab (Version 2011b).

Figure 1 shows the schematic diagram of the power plant demonstrating all its relevant components

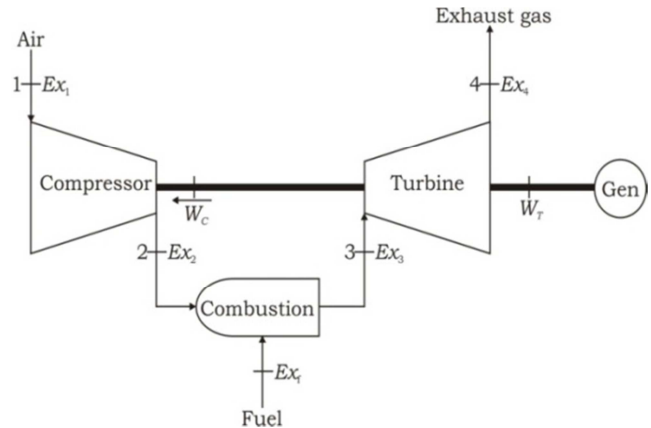


Figure 1. Schematic diagram of the plant.

In analysis of the plant, the optimum operating parameters of the plant [5] as shown in table 1 below and exergoeconomic principles were used.

Table 1. Optimum Operating Parameters of Delta iv power plant.

Property	Value
Ambient Temperature, T_1	300K
Compressor outlet temperature, T_2	590K
Temperature of the fuel T_f	298.15K
Turbine inlet temperature, T_3	1481.8K
Turbine outlet temperature, T_4	1000K
Compressor inlet pressure, P_1	1.013bar
Compressor outlet pressure, P_2	9.89bar
Compressor pressure ratio, r_p i.e. $\frac{P_2}{P_1}$	9.76
Compressor isentropic efficiency, η_{ic}	86%
Turbine isentropic efficiency, η_{it}	89%
Mass flow rate of fuel, \dot{m}_f	7.00 kg/s
Inlet mass flow rate of air, \dot{m}_a	530 kg/s
Power output, \dot{W}_{net}	107.48MW
Plant exergetic efficiency, η_e	29%
Plant energy efficiency, η_E	31%
Total cost rate, C_T	13292\$/hr

2.1. Exergoeconomic Principles

The capital investment cost rates for the components were determined based on the modeling expression recommended by [6]. Using the capital recovery factor ($CRF(i, n)$) and present worth factor ($PWF(i, n)$), the annual levelized cost may be written as:

$$\dot{C} = PEC - (SV)PWF(i, n)CRF(i, n) \quad (1)$$

Where $SV = 0.1PEC$, $CRF(i, n) = i/[1 - (1 + i)^{-n}]$, $PWF(i, n) = (1 + i)^{-n}$,

And PEC is the purchased-equipment cost. Equations for calculating the purchased-equipment costs for the components of the gas turbine power plant [10] are:

For the Compressor, we have

$$PEC_{ac} = \left(\frac{71.1m_a}{0.9 - \eta_{ic}} \right) \left(\frac{P_2}{P_1} \right) \ln \left(\frac{P_2}{P_1} \right) \quad (2)$$

For the Combustion Chamber, we have

$$PEC_{cc} = \left[\frac{46.08m_a}{0.995 - \frac{P_3}{P_2}} \right] [1 + \exp(0.018T_3 - 26.4)] \quad (3)$$

For the Turbine, we have

$$PEC_{gt} = \left(\frac{479.34m_g}{0.92 - \eta_{it}} \right) \ln \left(\frac{P_3}{P_4} \right) [1 + \exp(0.036T_3 - 54.4)] \quad (4)$$

Dividing the levelized cost by 8000 annual operating hours (about one month in a year the power plant will be off for maintenance) [7], we obtain the capital cost rate for the k^{th} component of the plant:

$$\dot{Z}_k = \left(\frac{\phi_k \dot{C}_k}{8000} \right) \quad (5)$$

The maintenance cost is taken into consideration through the factor $\phi_k = 1.06$ for each plant component whose expected life is assumed to be 15 years and the interest rates is 14% [8]. The number of hours of plant operating per year and the maintenance factor utilized in this study are the typical numbers employed in standard exergoeconomic analysis [9]

The formulations of cost balance for each component and the required auxiliary equations are:

For the compressor, we have

$$\dot{C}_2 = \dot{C}_1 + \dot{C}_{wc} + \dot{Z}_c \quad (6)$$

where the subscripts w_c denotes the power input to the compressor.

For the Combustion Chamber, we have

$$\dot{C}_3 = \dot{C}_2 + \dot{C}_f + \dot{Z}_{cc} \quad (7)$$

For the Turbine, we have

$$\dot{C}_4 + \dot{C}_{wc} + \dot{C}_{wt} = \dot{C}_3 + \dot{Z}_t \quad (8)$$

$$\frac{\dot{C}_3}{\dot{E}_3} = \frac{\dot{C}_{wt}}{W_t} \quad (9)$$

Where W_t denotes the net power generated by the turbine. Auxiliary equation [8] is written assuming the same unit cost of incoming fuel and outgoing exergy streams. A zero unit cost is assumed for air entering the compressor (i.e. $\dot{C}_1 = 0$). Additional auxiliary equation is formulated assuming the same unit cost of exergy for the net power output of the system and power input to the compressor:

$$\frac{\dot{C}_{wt}}{W_t} = \frac{\dot{C}_{wc}}{W_c} \quad (10)$$

The information of the cost streams help in exergoeconomic evaluation of the system. In exergoeconomic evaluation of thermal systems, certain quantities, known as exergoeconomic variables, play an important role. These are the average unit cost of fuel ($c_{f,k}$), average unit cost of product ($c_{p,k}$), the cost rate of exergy

destruction ($\dot{C}_{D,k}$), and the exergoeconomic factor (f_k).

Mathematically, these are expressed [10] as:

$$c_{f,k} = \frac{\dot{C}_{f,k}}{\dot{E}_{f,k}} \quad (11)$$

$$c_{p,k} = \frac{\dot{C}_{p,k}}{\dot{E}_{p,k}} \quad (12)$$

$$\dot{C}_{D,k} = c_{f,k} \dot{E}_{D,k} \quad (13)$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \quad (14)$$

Exergy costing balances (exergoeconomic balances) were carried out for each component. The exergy cost balance consists of operating cost rate (fuel cost rate), capital cost rate and product cost rate.

The cost balance equation is given as;

$$\dot{Z}_K + \sum \dot{C}_{F,K} = \sum \dot{C}_{P,K} \quad (15)$$

2.2. Economic Constraints

For a component receiving a heat transfer and generating power, cost balance equation may be written as [11]:

$$\sum_e \dot{C}_{e,K} + \dot{C}_{W,K} = \dot{C}_{Q,K} + \sum_i \dot{C}_{i,K} + \dot{Z}_K \quad (16)$$

where \dot{C} denotes a cost rate associated with an exergy stream and the variable \dot{Z} represents non-exergetic costs.

2.3. The Objective Function

The objective function expresses total cost rate of the plant in terms of naira per unit time.

$$\text{i.e. } OF = \dot{C}_{Ptotal} = \dot{C}_f m_f LHV + \sum \dot{Z}_K + \sum \dot{C}_{D,K} \quad (17)$$

The thermal system requires two conflicting objectives; one being increase in exergetic and energy efficiencies and the other is decrease in product cost to be satisfied simultaneously. The maximization of exergetic efficiency means minimization of exergy destruction cost. Thus, the objective function becomes a minimization problem. The objective function for this problem is defined as to minimize a total cost function \dot{C}_{Ptotal} which is modelled as:

$$\dot{C}_{Ptotal} = \dot{C}_{Ftotal} + \sum \dot{Z}_K \quad (18)$$

In this optimization, compressor pressure ratio (r_p), compressor isentropic efficiency (η_{ic}), turbine isentropic efficiency (η_{it}), combustion product temperature (T_3), air mass flow rate (m_a), fuel mass flow rate (m_f), temperature of the fuel (T_f) are taken as decision variables.

The stopping conditions used for solving the optimization problem are the maximum number of generations and cumulative function tolerance, which are shown in Table 2.

Table 2. Stop criteria for the optimization algorithm.

Stop criterion	Value
Number of generation	300
Function tolerance	1×10^{-7}

2.4. Genetic Algorithm Optimization

The optimization is done using Non-Dominated Sorting Genetic Algorithm (NSGA) proposed by [12]. The algorithm eliminates higher computational complexity, lack of elitism and the requirement for specifying sharing parameter. The developed GA code selects the decision variables in such a way to decrease the objective function. The flowchart of the algorithm is shown in Figure 2. The optimization code was written in MATLAB programming language. The optimal values of the decision variables (constraints) were obtained by minimizing the objective function.

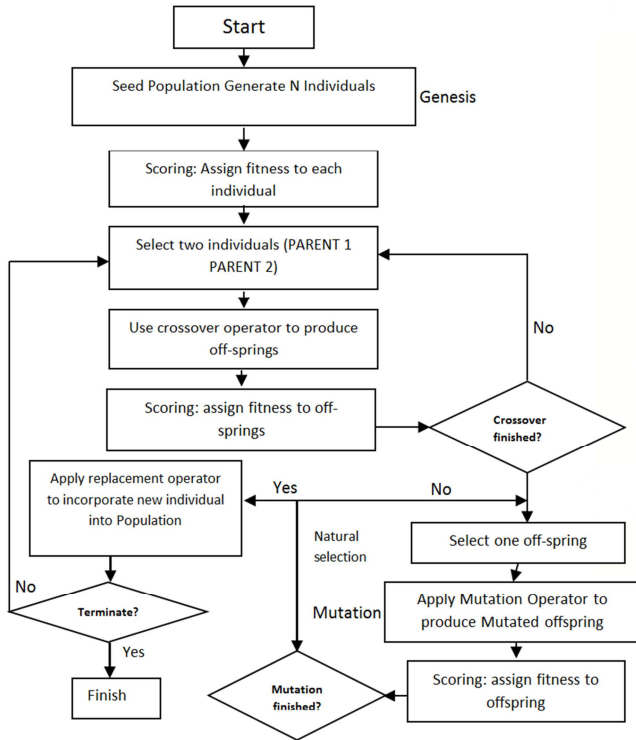


Figure 2. Flowchart for GA optimization Source [5].

3. Results and Discussion

In Nigeria, the unit cost of fuel varies very often. Thus, the effect of variation of optimal decision variables with unit cost of fuel is a good tool for making estimations and predictions. Hence, this offers a good insight into the study [14]

These results are shown in figures (3-8). The variations of the optimal decision variables with unit cost of fuel show that, by increasing the fuel cost, the pressure ratio, r_p (figure 3) increases. Compressor isentropic efficiency η_{ic} (figure 4) also increases with increase in unit fuel cost. Higher compressor isentropic efficiency η_c implies less exergy destruction in the compressor. It is also observed that the total cost rate, C_t (figure 7) variation with respect to unit fuel cost is low as a result of re-optimization of the operating parameters. The turbine output power, W_t (figure 5) increases appreciably as unit fuel cost increases. This implies that when the unit fuel cost increases the mass flow rate of the fuel increases and this results to increase in power output.

The compressor input power, W_c (figure 8) also increases as unit fuel cost increases. Comparing figure 5 and figure 8, it is observed that on the average the rate of power output (W_t) is higher than the rate of power input (W_c). This implies that the net power output ($W_t - W_c$) increases as we keep on re-optimizing the operating parameters. Similarly, the Exergy efficiency, η_E (figure 6) increases as unit fuel cost increases. In summary, higher η_{ic} , η_E , η_E and W_t guarantees less exergy destruction in compressor and turbine as well as less net cycle fuel consumption and operating cost.

Furthermore, by increasing the fuel cost, the value of objective function (total cost rate, \hat{C}_T) increases. In this case, genetic algorithm works by selecting the decision variable in a way that the mass flow rate of the combustion chamber decreases.

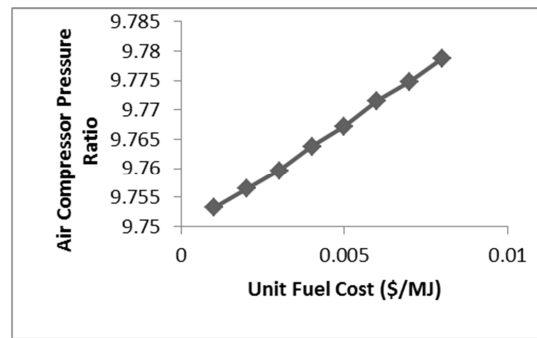


Figure 3. The effect of unit cost on the optimal value of air compressor pressure ratio.

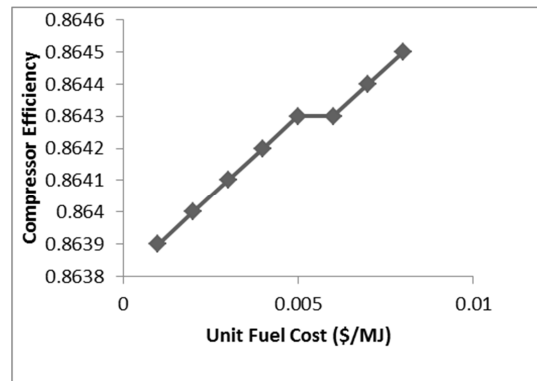


Figure 4. The effect of unit fuel cost on the optimal value of compressor isentropic efficiency.

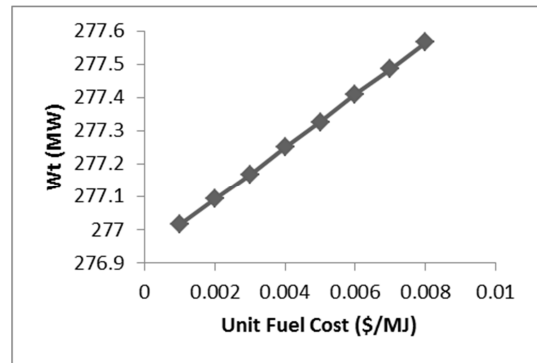


Figure 5. The effect of unit fuel cost on the optimal value of power output (W_t).

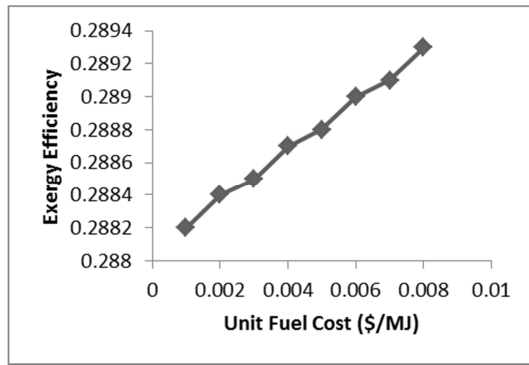


Figure 6. The effect of unit fuel cost on the optimal value of exergy efficiency.

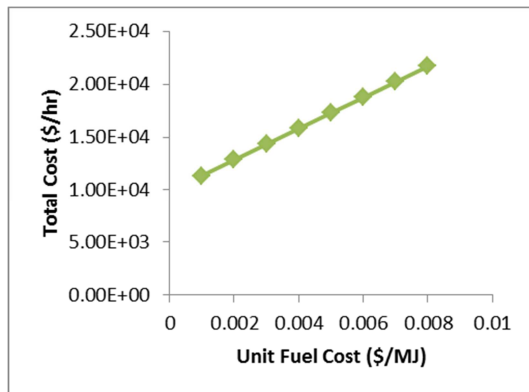


Figure 7. The effect of unit cost on the optimal value of total cost.

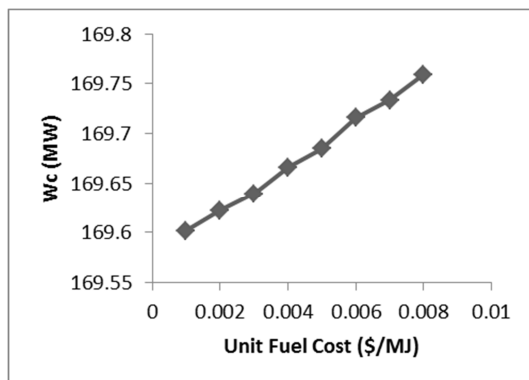


Figure 8. The effect of unit fuel cost on the optimal value of energy efficiency.

4. Conclusions

In this study, the sensitivity analysis is performed based on main parameter which is the unit fuel cost and the resultant trend on optimal parameters presented as shown in figures 3-9.

The variation of optimum decision variable with unit cost of fuel showed that by increasing the unit fuel cost, pressure ratio (γ_p), compressor isentropic efficiency (η_{ic}), exergy efficiency (η_e), energy efficiency (η_E), turbine output power (\dot{W}_t) and compressor input power (\dot{W}_c) increase. The increase in η_{ic} , η_e , η_E and \dot{W}_t guarantee less exergy destruction in compressor and turbine as well as less net cycle fuel consumption and operating cost.

Furthermore, by increasing the unit fuel cost the value of objective function (total cost rate, C_T) increases. In this case, genetic algorithm works by selecting the decision variable in a way that the mass flow rate of the combustion chamber decreases.

The sensitivity analysis revealed that the minimum unit cost of fuel for optimum performance was achieved when $\gamma_p = 9.75$, $\eta_c = 0.86$, $\dot{C}_T = 13292 \$/\text{hr}$, $\dot{W}_c = 169.6 \text{ MW}$, $\dot{W}_t = 277 \text{ MW}$, $\eta_e = 28.82\%$, $\eta_E = 30.69\%$.

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