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*Int. J. of Mechanical Computational and Manufacturing Research, Vol. 1. No. 1, (2012), 6-11, ISSN: 2301-4148*

# Optimal Preventive Maintenance Models for Steam Turbines: A Case Study of Egbin Thermal Station, Lagos, Nigeria

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**Abstract:** In this work, optimal preventive maintenance models have been developed using Weibull Distribution to predict maintenance models for Egbin steam turbines. The results obtained were practically correct in that there is an inverse relationship between the input and the output when the graphs of the models were plotted using MATLAB. It was clearly shown that the total cost of replacement was decreasing as the cycle length was increasing. For a cycle of $50{,}000 \leq t_p \leq 500{,}000$, the optimal total cost of replacement is approximately 800.54 USD (₦124,884.24) with current exchange rate of $1= ₦156. At the beginning of the cycle, 50,000 cycles, the total cost per unit turbine required to perform a preventive maintenance was 800.63 USD which was quite high. It implies that it is more expensive to perform a preventive maintenance at the inception of a preventive maintenance cycle. The cost decreases as the cycle increases. It is worthy of note that there exist an inverse relationship between the total cost of replacement and the cycle length. It reveals that for an increasing cycle length above 500,000 cycles, the total cost of replacement per unit turbine becomes constant; the optimal total cost per unit turbine of performing preventive maintenance. Also, the downtime continues to decrease until it gets to a very minimal level before it becomes steady. There also exist an inverse relationship between the total downtime (seconds) and the cycle length, and the expected cost of performing group maintenance and the number of days in a year. Hence, it requires a high cost at the beginning of the year to perform group maintenance than towards the end of the year. The expected cost of performing group maintenance continues to decrease through the year until the expected cost gets to about 1 USD at the 366$^{th}$ day.

**Keywords**: Preventive maintenance models, Egbin thermal station, cycle length, cost, downtime.

## 1 INTRODUCTION

A preventive maintenance system consists of routine action taken in a planned manner to prevent breakdowns and to ensure smooth operational accuracy in a power plant system. During preventive maintenance urgent cases are attended while the less urgent but important one should be planned against earliest possible time. The term optimum arises from the fact that the high frequency of preventive maintenance and replacement increases the total cost of maintenance and reduces the cost due to the downtime of the system whereas low frequency of preventive maintenance, replacement and inspection decreases the cost of total maintenance but increases the cost due to the downtime of the system. The primary function of the preventive maintenance and inspections is to control the condition of the equipment and ensure its availability.

Steam turbines are utilized in numerous industries to drive boiler fans, boiler feed and water pumps, process and chill compressors, blast furnace blowers, paper mill line shafts, sugar mill grinders, and generators in a variety of industries and applications. The steam turbine under consideration is a power plant steam turbine. A case study is the steam turbine at Egbin thermal station. Steam turbine plays a vital role in steam power plant system. Its continuous operation is required in power plant system which causes the turbine component to suffer fatigue and efficiency loss thus causing turbine failure and unavailability.

This paper is motivated by the dire need for optimum power production in the country in order to meet domestic and industrial power requirement. Nigeria currently generates about 4000MW which is not enough to meet the energy need of the country. Egbin thermal station contributes about 35% to the total, if we cannot generate more than 4000MW for now, at least it should not drop. This paper justly proposes a set of optimal maintenance model for a 220MW impulse reheat steam turbines at Egbin thermal station.

Numerous researchers have demonstrated great efforts towards the study of the maintenance modelling of steam turbines. Salisbury [1], Stodola [2] and Husain [3] showed that in steam turbines, erosions, roughness, steam path damage, etc., are factors that reduce power capacity in a steam turbine. Any power loss occurring locally in intermediate stages results in a more available energy at the downstream stages. Cotton [4] calculated the loss factor using the graphical method. Alejandro et al [5] introduced a new thermodynamic expression for the loss factor in order to improve applications to evaluate malfunctions in the first and intermediate stages of steam turbines. His new thermodynamic expressions are based on second law analysis; and concept like the internal parameter θ, and the dissipation temperature $T_d$ [6]. He analyzed a steam turbine in a conventional power plant of

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158MW by comparing a classical graphical method [4, 7] and proposed expression of the loss factor (LF). Kazunari and Katoshi [8] studied and presented a qualitative method for risk based maintenance and inspection for steam turbines. Paulina and Szezepaniak [9] presented a study on neural modelling of steam turbines. The neural modelling was also applied to complicated objects with many parameters such as turbo sets. The precision of the model is adequate for the analysis of the operating conditions of the turbo set, defining optimal conditions for the turbo set and predicting the heat and electrical energy requirement in different seasons of the year. The developed failure and fault liability modelling of a condensing steam turbine was focused on availability and cost prediction.

It should be noted that in the above review of the past works on modelling of steam turbine, no single work was done on maintenance modelling through reliability studies applying Weibull Distribution. In order to effectively carry out this study, Egbin thermal station was used as a case study.

Consequently, this paper develops some set of optimal maintenance model through reliability study using Weibull Distribution so as to improve efficiency, maximize power output and ensure turbines availability.

## 2 MATERIALS AND METHODS

### 2.1 Preventive Maintenance and Replacement Models for Steam Turbine: Cost Minimization

*Assumptions*

The following assumptions were made:

(i) The total cost associated with failure replacement is greater than that associated with a preventive maintenance action whatever it is a repair or replacement. That is, the cost to repair the turbine after its failure is greater than the cost maintaining the turbine before its failure.

(ii) The systems failure rate function is monotonically increasing with time.

(iii) Minimal repairs do not change the failure rate of the system.

(iv)The failure rate of the turbine follows a Weibull Distribution.

### 2.2 The Constant Interval Replacement Policy (CIRP) Goal

The objective above can be accomplished by developing a total expected cost function per unit time as follows:

$$c(t_p) = \frac{\text{Total expected cost in interval } (0,t_p)}{\text{Expected length of the interval}} \quad (1)$$

The total expected cost in the interval $(0, t_p)$ is the sum of the expected cost of failure replacement and the cost of the preventive replacement. During the interval $(0,t_p)$, one preventive replacement is performed at a cost of $c_p$ and $M(t_p)$ failure replacement at a cost of $c_f$ each, where $M(t_p)$ is the expected number of replacement (or renewals) during the interval $(0, t_p)$. The expected length of the interval is $t_p$. Eq. (1) becomes:

$$c(t_p) = \frac{c_p + c_f M(t_p)}{t_p} \quad (2)$$

Since the failure rate follows a Weibull Distribution of the form,

$$f(t) = \frac{\gamma}{\theta} t^{\gamma-1} e^{\frac{-t^\gamma}{\theta}} \qquad t > 0,\ \theta > 0$$

Hence, utilizing the asymptotic form of the renewal function, the expected number of failure $M(t_p)$ is expressed as:

$$M(t_p) = \frac{t_p}{\mu} + \frac{\sigma^2 + \mu^2}{2\mu^2} \quad (3)$$

Where

$\mu$ is the mean of the failure-time distribution

$\sigma$ is the standard deviation of the failure-time distribution.

Hence, the $\mu$ and $\sigma^2$ (variance) of the Weibull Distribution are

$$\mu = \theta^{\frac{1}{\gamma}} \Gamma(1 + \frac{1}{\gamma})$$

$$\sigma^2 = \theta^{\frac{2}{\gamma}} [\Gamma\left(1 + \frac{2}{\gamma}\right) - (\Gamma(1 + \frac{1}{\gamma}))^2]$$

and the gamma function is

$$(n) = \int_0^\infty x^{n-1} e^{-x} dx = 0.57721$$

The value of the shape and life characteristics of the distribution ranges from

$2 < \gamma < 3$ and $250 < \theta < 300$

Assuming $\gamma = 2$ and $\theta = 300$, then

$$\mu = \theta^{\frac{1}{\gamma}} \Gamma\left(1 + \frac{1}{\gamma}\right) = 300^{1/2} \Gamma\left(1 + \frac{1}{2}\right) = 14.99$$

$$\mu^2 = 224.7$$

$$\sigma^2 = \theta^{\frac{2}{\gamma}} [\Gamma\left(1 + \frac{2}{\gamma}\right) - (\Gamma(1 + \frac{1}{\gamma}))^2]$$

$$\sigma^2 = 300^{\frac{2}{2}} \left[\Gamma\left(1 + \frac{2}{2}\right) - \left(\Gamma\left(1 + \frac{1}{2}\right)\right)^2\right] = 121.435$$

$$\sigma^2 = 121.435$$

$$\Gamma = 0.57721$$

Therefore,

$$c(t_p) = \frac{c_p + c_f(\frac{t_p}{\mu} + \frac{\sigma^2 - \mu^2}{2\mu^2})}{t_p}$$

$$c(t_p) = \left(c_p + \frac{\sigma^2 - \mu^2}{2\mu^2}\right) + \frac{c_f}{\mu} \quad (4)$$

Assuming $c_p$ and $c_f$ are 5000 and 12000 dollars respectively, We have

$$c(t_p) = \frac{1}{t_p}(5000 + 0.229) + \frac{12000}{14.99}$$

$$c(t_p) = \frac{5000.229}{t_p} + 800.533 \quad (5)$$

Hence, the total expected cost of replacement is given by Eq. (5).

### 2.3 Preventive Maintenance and Replacement Model for Steam Turbine: Downtime Minimization Constant

*2.3.1 Interval Replacement Policy Goal*

Minimization of the total downtime per unit time, that is,

*Int. J. of Mechanical Computational and Manufacturing Research, Vol. 1. No. 1, (2012), 6-11, ISSN: 2301-4148*

minimize the unavailability of the turbine.

*Assumptions*
The following assumptions were made:
[i] Replacements are performed at predetermined age regardless of the age of the turbine being replaced.
[ii] Replacements are performed upon failure of the turbine.
Following Jardine and Albert [10] Eq. (1) becomes

$$D(t_p) = \frac{Total\ downtime}{Cycle\ length} \quad (6)$$

$$D(t_p) = \frac{Downtime\ due\ to\ failure + Downtime\ due\ to\ preventive\ replacement}{cycle\ lenght}$$

$$D(t_p) = \frac{M(t_p)T_f + T_p}{T_p + t_p} \quad (7)$$

Where the cycle length is the sum of the time to perform preventive maintenance and the length of the preventive cycle

$T_f$ = time to perform a failure replacement
$T_p$ = time to perform a preventive replacement
$M(t_p)$= expected number of failure in the interval $(0, t_p)$

If the failure rate follows a Weibull Distribution of the form

$$f(t) = \frac{\gamma}{\theta} t^{\gamma-1} e^{\frac{-t^\gamma}{\theta}}; \quad t > 0, \theta > 0$$

Then, the asymptotic form of the renewal equation is given as:

$$M(t_p) = \frac{t_p}{\mu} + \frac{\sigma^2 - \mu^2}{2\mu^2} \quad (8)$$

Where $\mu$ and $\sigma^2$ are the mean and variance of the Weibull Distribution and are given as

$$\mu = \theta^{\frac{1}{\gamma}} \Gamma(1 + \tfrac{1}{\gamma})$$

$$\sigma^2 = \theta^{\frac{2}{\gamma}} [\Gamma\left(1 + \tfrac{2}{\gamma}\right) - (\Gamma(1 + \tfrac{1}{\gamma}))^2]$$

And the gamma function is given as

$$\Gamma(n) = \int_0^\infty x^{n-1} e^{-x} dx$$

Eq. (7) becomes:

$$D(t_p) = \frac{T_f\left(\frac{t_p}{\mu} + \frac{\sigma^2 - \mu^2}{2\mu^2}\right) + T_p}{T_p + t_p} \quad (9)$$

According to the 2008 Annual Report, a total downtime of 16,296.7hrs was recorded.
Therefore, downtime per turbine assuming the turbines have the same failure and repair rate is given as

$$Total\ downtime\ \ per\ turbine "D(t_p)" = \frac{16296.7}{6} = 2716.1 hrs$$

Hence, equation (4) becomes:

$$D(t_p) = \frac{2716.1}{25000 + t_p} \quad (10)$$

Assuming $T_p = 25000\ cycles$ and $50000 < t_p < 500000$ cycles.

The optimum downtime is the lowest downtime computed and the corresponding $t_p$ is the optimal preventive replacement interval for the steam turbine.

### 2.4 Group Maintenance Model

*Assumptions*
The following assumptions were made:

(i) The steam turbines are identical.
(ii) They perform the same or similar function.
(iii) The steam turbines are independent in their operation and are subject to failure.
(iv) The steam turbines have identical failure distribution.

Considering a group of N independent turbines that are subject to failure, the repair cost is composed of a fixed cost $c_0$ for each repair and a variable cost $c_1$ per turbine. The repair cost per turbine decreases as the number of turbines requiring repairs increases while the production loss $c_2$ due to turbine breakdown increases.

Let N (t) represent the number of turbines operating at time t $(0 \leq N(t) < N)$.

Let $F$ (t) be the turbines identical failure distribution.

Hence, the distribution of N (t) is

$$P(t)\ n] = \binom{N}{n} [1 - F(t)]^n [F(t)]^{N-n} \quad (11)$$

Where P [N t) =n] = probability that the number of turbines operating at time t equals n. The distribution of N (t) is binomial with a mean of

$$E[N(t)] = N[1 - F(t)] \quad (12)$$

If the failed turbines are repairable at a fixed cost $c_0$, and variable cost $c_1$ per turbine. If a failed turbine is not repaired upon failure, then a production loss of $c_2$ is incurred. Since the production will increase as the scheduled time for repair increases and the repair cost per turbine decreases, then there exist an optimum scheduled time (maintenance time) that minimizes the expected total cost per unit time.

Following Park and Yoo [11]; considering a random maintenance scheduling that states that repairs are undertaken whenever the number of operating turbines reaches a certain level, n. The time to reach this level is a random variable, T with a cumulative density function (cdf) of G (t). T represents the nth order statistics of N random variables. The expected repair cost per cycle $R_c$ is expressed as:

$$R_c = c_0 + c_1 R_c = c_0 + c_1 N \int_0^\infty F(t) dG(t) \quad (13)$$

The expected production loss per cycle $P_c$ is

$$P_c = c_2 \int_0^\infty [N - E[N(t)]][1 - G(t)] dt$$

$$P_c = c_2 \int_0^\infty [N - E[N(t)]] \bar{G}(t) dt$$

$$P_c = c_2 N \int_0^\infty F(t) \bar{G}(t) dt \quad (14)$$

Where $\bar{G}(t) = 1 - G(t)$.

The total expected cost per unit time is

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$$c[G(t)] = \frac{R_c + F_c}{\int_0^\infty t\,dG(t)} \qquad (15)$$

Barlow, et al., (1965) shows that the optimum scheduling policy that minimizes equation (5) is deterministic. In other words,

$$G(t) = \begin{cases} 0 & if\ t \le t_0 \\ 1 & if\ t > t_0 \end{cases}$$

Where, $t_0$ is the scheduled time for group maintenance Thus equation (15) can be rewritten as

$$c(t_0) = \frac{1}{t_0}[c_0 + c_1 N F(t_0) + c_2 N \int_0^{t_0} F(t)\,dt] \qquad (16)$$

From equation (16), c (0)=∞ and c(∞)=$c_2 N$. This implies that the cost per unit time for the Optimum schedule is less than $c_2 N$.

The optimum schedule policy summarized as follows. Assume that $F(t)$ is continuous, the derivative of f (t) exist, and the failure rate per turbine is $\lambda$.

Suppose - $\frac{f(t)^* c}{f(t)} < \frac{c_1}{c^1}$ for t≫ 0. Then,

(1) If $\frac{c_2}{\lambda} < \frac{c_0}{N + c_1}$, then there exists a unique and finite optimum scheduling time $t_0$* that satisfies the following equations:

$$c_1 t_0 f(t_0)^* + c_2 t_0 f(t_0)^* - c_1 F(t_0)^* - c_2 \int_0^{t_0} F(t)\,dt = {c_0}/{N} \qquad (17)$$

The minimum cost per unit time is obtained by

$$c(t_0)^* = c_1 N f(t_0)^* + c_2 N f(t_0)^* \qquad (18)$$

(2) Otherwise, $t_0^* = \infty$

The condition in (1) is realistic. For instance, if the failure time distribution is assumed to be exponential with a rate of λ, then the condition - $\frac{f(t)^*}{f(t)} < \frac{c_2}{c_1}$ becomes $\left(\frac{c_2}{\lambda}\right) > c_1$, which translates to the average production loss per turbine. In addition, the condition $\frac{c_2}{\lambda} < \frac{c_0}{N + c_1}$ implies that the average production loss per turbine when group repair of *N* turbine is performed. Therefore it is reasonable to schedule the repair before the failure of all turbines according to Okumoto and Elsayed [13].

When *N* identical turbines each exhibit a constant failure rate λ, the condition for the existence of an optimum policy is given by $\frac{c_2}{\lambda} < \frac{c_0}{N + c_1}$. By substituting the p.d.f of the exponential distribution into equation (17), we obtained:

$$(X^* + 1)e^{-X} = A \qquad (19)$$

Where, $X^* = \lambda t_0^*$ (20)

$$A = \frac{{c_2}/{\lambda} - ({c_0}/{N + c_1})}{{c_2}/{\lambda} - c_1} \qquad (21)$$

Where equation (19) is the expected number of turbines to be repaired under the optimum policy,

The expected cost for the optimum policy is:

$$c(t_0)^* = c_2 N + N\lambda(c_1 - {c_2}/{\lambda})e^{-\lambda t_0^*} \qquad (22)$$

Egbin thermal station has 6 turbine units i.e $N = 6$

Then equation (22) becomes:

$$c(t_0)^* = 6[c_2 + \lambda(c_1 - {c_2}/{\lambda})e^{-\lambda t_0^*}] \qquad (23)$$

*Table 1: Details of the Treated and Untreated Defect Report*

| Month | Total Recieved | Total Treated |
|---|---|---|
| January | 18 | 14 |
| February | 14 | 14 |
| March | 22 | 22 |
| April | 27 | 27 |
| May | 19 | 19 |
| June | 73 | 72 |
| July | 31 | 28 |
| August | 27 | 26 |
| September | 31 | 27 |
| October | 26 | 24 |
| November | 13 | 12 |
| December | 9 | 8 |
| Total | 310 | 293 |

*Source: Egbin Electric Power Business Unit Annual Report [12]*

The defects per turbine is

$$Defects\ per\ turbine = \frac{310}{6} = 51.67 defects$$

In 2008, there were 366 days meaning it was a leap year, therefore there are (366× 24)$hrs$ of operating (running) time.

Running time = 8784hrs

$$failure\ rate\ per\ turbine(\lambda) = \frac{51.67}{8784} = 0.00588 def/hr$$

Assuming the production loss ($c_2$) and the variable cost ($c_1$) are 400 dollars and 200 dollars respectively.

Hence, equation (23) becomes

$$[c(t_0)* = 6[c_2 + 0.0059(c_1 - {c_2}/{0.0059})e^{-0.0059 t_0^*}]$$

$$[c(t_0)* = 6[c_2 + (0.0059 c_1 - c_2)e^{-0.0059 t_0^*}]$$

$$c(t_0)^* = 7.08 e^{-0.0059 t_0^*} \qquad (24)$$

In conclusion, equations (19) and (24) are the expected number of turbines to be repaired and the expected cost under the optimum policy.

## 3 RESULTS AND DISCUSSION

Figure 1 shows that the total cost of replacement is decreasing as the cycle length is increasing. For a cycle of between 50,000<$t_p$<500,000, the optimal total cost of replacement is approximately $800.54 which is equivalent to ₦124,884.24 with current exchange rate of $1USD = ₦156. At the beginning of the cycle, at 50,000 cycles, the total cost per unit turbine required to perform a preventive maintenance was 800.63 USD which is quite high, it is more expensive to perform a preventive maintenance at the start of a preventive maintenance cycle.

The cost decreases as the cycles increases. It is worthy of note that there exist an inverse relationship between the

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total cost of replacement and the cycle length.
According to Egbin Electric Power Business Unit Annual Report [12] as shown in table below, there were 310 total defects (failure) from the six turbines throughout the year.

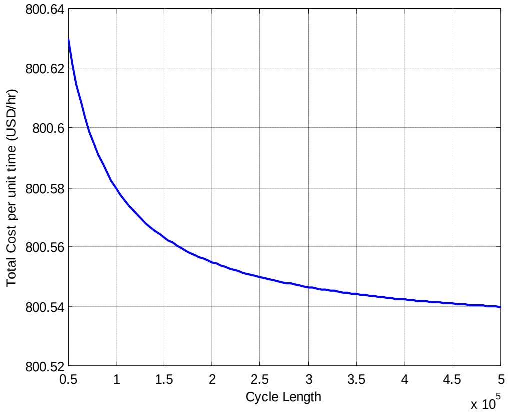


*Figure 1: Variation of Total Cost per unit Time against Cycle Length*

The first one-third of the graph shows a sharp decline in the total cost with respect to the cycle length while the last one-third shows an almost steady relationship between the total cost and the cycle length. It means that for an increasing cycle length above 500,000 cycles, the total cost of replacement per unit turbine will soon become constant that is, it will not change with cycle length. This is the optimal total cost per unit turbine of performing preventive maintenance.

Figure 2 shows the result for the downtime minimization model where the downtime in seconds was increasing as the cycle length was increasing. The optimum downtime recorded when a preventive or failure replacement wass carried out between a cycle of $50,000<t_p<500,000$, was approximately 18 seconds. At the beginning of the preventive maintenance cycle, an approximate total downtime of 130 seconds was recorded, which means that the downtime is greater at the start of the cycle. Also the graph shows that the downtime continues to decrease until it gets to a very minimal level before it becomes steady. Summarily, there also exist an inverse relationship between the total downtime (seconds) and the cycle length.

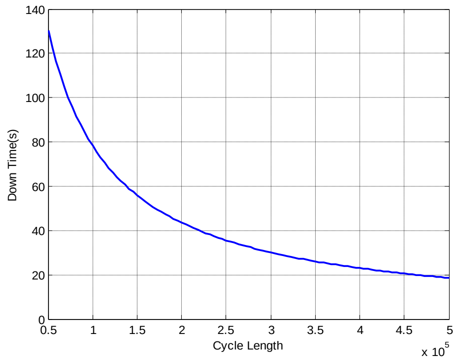


*Figure 2: Variation of Downtime against Cycle Length*

Figure 3 shows a similar result as the earlier models. It shows the expected total cost of performing group replacement decreasing as the number of days in year 2008 is increasing. For a scheduled time to perform group maintenance ranging from 0 to 366 days, the optimum expected total cost of performing group replacement is approximately 1USD which is equivalent to 156NAIRA based on the assumed values for the production loss, variable and fixed cost. There exist an inverse relationship between the expected cost of performing group maintenance and the number of days in a year. Hence, it requires a high cost at the beginning of the year to perform group maintenance than towards the end of the year. The expected cost of performing group maintenance continues to decrease through the year until the expected cost get to about 1 USD at the 366th day.

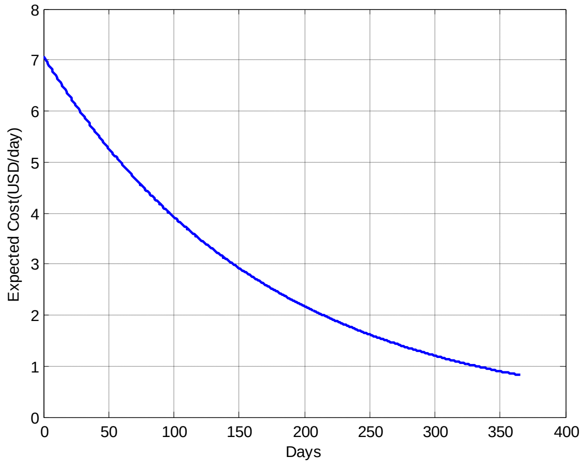


*Figure 3: Variation of Expected cost against number of days*

## 4 CONCLUSION

In this paper, optimal maintenance models for steam turbine have been developed. The maintenance models were used in the modelling of the steam turbines maintenance at Egbin using Weibull Distribution. The effects of cycle length on the total cost per unit time and downtime have been examined. From the present

theoretical investigation, the following conclusions were drawn:

1. The total cost of replacement is decreasing as the cycle length is increasing.
2. The downtime minimization model where the downtime in seconds was increasing as the cycle length was increasing.
3. The expected total cost of performing group replacement decreasing as the number of days is increasing.

The results obtained were similar in nature in that there was an inverse relationship between the input and the

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output when the graphs of the models were plotted using MATLAB when compared with experimental and practical results.

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