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Mathematical Modelling and Residual Life Prediction of an Aluminium Electrolytic Capacitor

Bhargava, C.[1]*#, Banga, V. K.[2] and Singh, Y.[3]

[1]*Department of Electronics and Communication Engineering, IKG Punjab Technical University, Kapurthala 144603, Punjab, India*

[2]*Office of Principal, Amritsar college of Engineering and Technology, Amritsar 143001, Punjab, India*

[3]*Department of Electrical Engineering, Harcourt Butler Technological University, Kanpur 208301, Uttar Pradesh, India*

ABSTRACT

An electrolytic capacitor is a widely used, passive component in electronics and the manufacturing industry. But it is known for its low reliability when used in critical applications and environments. The prediction of the residual life of a capacitor is a challenging issue. It is beneficial for users as they will be ready to replace a component when it is faulty. This will save them replacement and repairing costs. This paper focusses on the mathematical modelling and behaviour analysis of electrolytic capacitors related to various electrical parameters and environmental stresses. A novel method is proposed to access the impact of humidity on the health of a capacitor. A capacitor's end of life is explored using the design of experiments approach. After calculating the lifetime of a capacitor, an expert system is modelled that can predict the sudden crash of the capacitor before it actually fails, using various statistical and analytical techniques. A comparison was done using the experimental calculated lifetime and proposed analytical method outcome. The proposed corrective model of lifetime calculation proves 92.76% accuracy. This shortfall is due to the fact that some electrical and environmental variables change at a pace that is too fast for the prediction system to respond.

Keywords: Accelerated testing, electrolytic capacitor, failure analysis, military handbook, reliability, Taguchi approach

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E-mail addresses:
cherry.bhargava@gmail.com (Bhargava, C.)
vijaykumar.banga@gmail.com (Banga, V. K.)
dryaduvirsingh@gmail.com (Singh, Y.)
*Corresponding Author

#Author's Current Affiliation:
Department of Electronics and Communication Engineering, Lovely Professional University, Phagwara 144411, Punjab, India

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INTRODUCTION

As thousands of electronic components are integrated on a single chip, the reliability of the chip may be compromised, and this poses a problem for manufacturers as well as users. Manufacturers of electronic components prepare a datasheet listing the lifetime of each

component that is produced. However, electronic products often have to perform in extreme environmental conditions or within varying electrical parameters that can cause their sudden failure. If a component fails before a certain period, the entire system can break down. This can lead to unnecessary costs incurred for replacement and repair of the failed system.

To ensure that electronic products are reliable and useful throughout their lifetime, different environmental stress tests as well as electrical parameter variation tests need to be carried out. The main cause of failure/degradation of electrolytic capacitors has been found to be the loss of electrolytes (Bengt, 1995). Kececioglu (2002) suggested that thermal stress causes a change in electrochemical reactions, resulting in evaporation of electrolytes.

Reduction in the weight of an electrolytic capacitor is the main indicator of electrolytic loss. Dehbi, Wondrak, Ousten and Danto (2002) suggested that not only temperature, but voltage and ripple current also play an important role in determining residual life. Saha, Goebel and Christophersen (2009) compared various algorithms for capacitor life calculation. This paper emphasises the calculation of an electrolytic capacitor's life based on various physics of failure laws. Based on the design of experiments (DOE) approach, the four-factor four-level design was selected. This design gives 16 combinations of input variables. Capacitor life was calculated using various laws. Then on the same set of combinational variables, the accelerated life testing method was used. Capacitor life was calculated using the Arrhenius law. The experimental and theoretical results were compared and analysed for error.

Mathematical Modelling of an Electrolytic Capacitor

Reliability has been a critical issue in the manufacture of electrolytic capacitors from design to development to marketing to real-time use. The key factor for success in the electronics industry is reliability of products. Sankaran, Rees and Avant (1997) suggested failure prediction techniques for capacitors. Different prediction models have also been considered based on components' parameters, stress factors and historical failure data etc. Bhargava, Banga and Singh (2014) reviewed the various reliability techniques for failure prediction of electronic components.

Empirical (Standard) Model

The empirical methods or standard prediction models are based on historical data of component failure and experience of the user. The standard set in the military handbook MILHDBK-217F and the telecommunication handbook, TELECORDIA, among others, is widely used for reliability estimation. The assumption for such models is that system failure is integrally associated with the component's failure. As suggested by Elbert and March-Force (1989), various environmental factors are considered for reliability calculation.

MILHDBK-217F is very well known as a reliability prediction model in military applications. The failure rate using this military handbook can be calculated as:

$$\lambda = \sum_{i=1}^{n} (\lambda ref, i * \pi S * \pi T * \pi E * \pi Q * \pi A) \quad [1]$$

where,

λref = Failure rate under reference conditions

πS = Stress factor

πT = Temperature factor

πE = Environmental factor

πQ = Quality factor

πA = Adjustment factor

However, because the military handbook's data were outdated, a revised version was launched, but this too met with some dissatisfaction. A telecommunication company then launched TELECORDIA SR-332 to address the infant mortality rate as well as the steady state useful operating life failure rate. On their part, Held and Fritz (2009) discussed various empirical standards for performance calculation of capacitors. The difference between both methods is summarised in Table 1.

Table 1
Comparison between MILHDBK and TELECORDIA

MILHDBK-217F	**TELECORDIA SR-332**
Acts as a reliability prediction model in telecommunication industry	Acts as a reliability prediction model in telecommunication industry
Military handbook uses failure in time (FIT) per million hours	Uses failure in time (FIT) per billion hours
It has 14 environment classifications (three ground, eight air, one space, two sea)	It has six environment classifications (four ground, one air, one space)
A specific SMT device model	No specific SMT device model
Handles lower number of gate count IC	Handles higher number of gate count IC
Provides only steady state useful life failure rate	Provides a measure of infant mortality rate and steady state useful operating life failure rate

Analytical Models for Life Prediction

Empirical models, which are based on historical or user data, are not up-dated. In contrast to empirical methods, there are several other parameters on which life of a system depends. These models analyse the acceleration factor, a constant multiplier for different stress levels. Then the effect of this stress level acceleration factor is studied on the life of the product, as claimed by the product's datasheet. Stevens and Dapo (2002) reviewed the service life of an aluminium electrolytic capacitor and its lifetime calculation.

Effect of Temperature on Lifetime

As proposed by Whitman (2012), de-rating of a capacitor's life and its performance degradation accelerates with increased temperature. As the temperature increases, the capacitor initiates a change in chemical reactions because an electrolytic capacitor is an electrochemical device. Kötz, Hahn and Gallay (2006) considered temperature a critical factor for evaluating the performance of capacitors. It has been assumed that every 10 degrees of rise of temperature degrades the capacitor's life by a factor of 2. So, increase in temperature furthermore reduces capacitance. The expected life using this method can be calculated as Equation [2]. Ma and Wang (2005) suggested various fault diagnosis techniques for electrolytic capacitors.

$$Lifetime\ (Expected) = Lifetime(D)\ \times A_T \quad [2]$$

$$Lifetime\ (E) = Lifetime(D) \times\ 2^{\frac{(Tm-Ta)}{10}} \quad [3]$$

where,
Lifetime (D) = lifetime declared by manufacturer in datasheet i.e. 2,000 hr
A_T = Temperature acceleration factor=$2^{[(Ta-Tm)/10]}$
Tm (k) = Maximum temperature i.e. 155°C=155+273=428K
Ta (k) = Accelerated temperature i.e. 105°C=105+273=378K

Effect of Voltage on Lifetime

As suggested by Naikan and Rathore (2016), the degradation of capacitor life does not depend on only temperature acceleration, but also on the rated and operated voltage. The capacitor life is longer if it is used within the rated voltage limit. Kulkarni, Biswas, Celaya and Goebel (2011) analysed the effect of electrical parameters on capacitor performance. The expected life using this methodology was calculated as Equation [5], which is a modified version of Equation [2]:

$$Lifetime\ (Expected) = Lifetime(D)\ \times A_T\ \times A_V \quad [4]$$

$$Lifetime\ (E) = Lifetime(D) \times\ 2^{\frac{(Tm-Ta)}{10}}\ \times \left(\frac{Va}{Vm}\right)^{-n} \quad [5]$$

where,
Va = Applied voltage=9V
Vm = Rated voltage=16V
A_V = Voltage acceleration factor= $(Vo/Vn)^{-N}$
N = constant=1 for radial capacitors

Effect of Ripple Current on Lifetime

Joule's law states that when ripple current is applied to an electrolytic capacitor, the capacitor generates heat. Due to heat generation, electrolytes evaporate. As electrolytes evaporate, indicated by weight loss, capacitance tends to decrease. Heat rise causes a reduction in life as

compare to Arrhenius law. Let the acceleration factor for ripple current be A_I. The expected lifetime also has influence on the ripple current acceleration factor. Parler Jr and Dubilier (2004b) suggested various multipliers for measuring the performance of a capacitor.

$$Lifetime\ (Expected) = Lifetime(D)\ \times A_T\ \times A_V \times A_I \quad [6]$$

$$Lifetime\ (E) = Lifetime(D) \times\ 2^{\frac{(Tm-Ta)}{10}} \times \left(\frac{Va}{Vm}\right)^{-n} \times Ki^{A\frac{\Delta T}{10K}} \quad [7]$$

where, $A_I = K_I^{[1-(Ia/Io)2]*[\Delta To/10K]}$
K_I = Ripple current multiplier=2
Ia = Applied and ripple current
Io = Maximum ripple current
ΔTo = Increase in core temperature

Corrective Analytical Model for Behaviour Analysis

As the literature suggests, while calculating the lifetime of an electrolytic capacitor, temperature, voltage and ripple current needed to be considered as they play an important impact on the lifetime of a capacitor. However, there are also several other electrical and environmental parameters that have an impact on degradation and life estimation of an electrolytic capacitor (Parler Jr & Dubilier, 2004a).

Impact of Humidity on Lifetime

Humidity plays an important role in capacitor reliability. It causes electrolytic corrosion due to moisture present in the capacitor. Moisture causes a decrease in the value of capacitance and subsequently affects the life of the capacitor. As suggested by Sinnadurai (1974), the humidity acceleration factor can be calculated using Equation [8], which is modified from Peck's law. It has been found that if a capacitor has been used more than the rated humidity, the capacitor's life is degraded at an exponential rate. After taking temperature, voltage and humidity into consideration, the equation formed is Equation [9] below.

$$Lifetime\ (Expected) = Lifetime(D)\ \times A_T\ \times A_V \times A_I \times A_H \quad [8]$$

$$Lifetime\ (E) = Lifetime(D) \times\ 2^{\frac{(Tm-Ta)}{10}} \times \left(\frac{Va}{Vm}\right)^{-n} \times Ki^{A\frac{\Delta T}{10K}} \times \exp\{C\ \times ((RHa)^n - (RHm)^n)\} \quad [9]$$

where,
C = Humidity constant = 0.00044
RHs = Rated relative humidity
RHa = Applied relative humidity = 30
A_H = Humidity acceleration factor = [exp $(C*((RH_S)^n-(RH_O)^n)]$
n = Humidity activation exponent = 2

Clearly, the life of a capacitor depends not only temperature, voltage and current, but also on humidity, as shown above in Equation [9].

Experimental Approach for Lifetime Calculation

Kalaiselvan and Rao (2016) explored the practical use of capacitors and found several factors that increase/reduce the value of their performance. To observe capacitor performance under various conditions for a couple of hours can be a tedious job. Accelerated life testing is the method by which a capacitor is placed under stressed conditions and then measured for output. For example, using the Arrhenius equation, a Sterile Barrier System that is subjected to 40 days of Accelerated Aging at +55° has similar ageing characteristics as a one-year-old Real Time sample. So, accelerated ageing test data are accepted by most regulation bodies.

METHOD AND MATERIALS

In experimental setup, we placed a capacitor, covered with sand on a hot plate. Environmental and electrical stresses were introduced and lifetime was observed using the Arrhenius equation (Huang et al., 2017). A hole of 0.9 mm was drilled on the capacitor to accelerate the heating process. Ahmad, Islam and Salam (2006) used the Weibull distribution to analyse accelerated life testing response.



Figure 1. Experimental setup for accelerated life testing

Failure in time (FIT) (per 10^9 h) was calculated using the Arrhenius equation of acceleration as given below:

$$FIT(\lambda) = \frac{F}{D \times T \times A_F} \quad [10]$$

where,
F = Number of failures
D = Number of devices tested
T = Test hours
A_F = Acceleration factor = $\exp^{Ea/k(1/T use^{-1/T test)}}$
E_a = Activation energy (ev)
K = Boltzmann constant
T_{use} = use temperature, T_{test} = test temperature as per datasheet

After calculating the failure rate, the MTBF corresponding to FIT was calculated as:

$$MTBF\ (hours) = \frac{1}{\lambda} \times 10^9 \quad [11]$$

The calculated life using accelerated life testing method is summarised in Table 2.

DOE Approach: Taguchi Method

Design of experiments (DOE) is the systematic approach to finding the relationship between process variables and response of system. The Taguchi approach is a systematic means of designing, conducting and analysing experiments that are of great significance in quality planning. The experiments are conducted based on the Taguchi approach and tool life values obtained. The use of the Taguchi approach leads to a significant economic advantage, resulting in reduction of material and machining time required for expedition due to the reduced set of experiments. The steps in designing, conducting and analysing experiments are as follows:

1. Selection of factors for the study: Temperature, ripple current, voltage and humidity.
2. Selection of the number of levels for the factors; four factors at four levels.

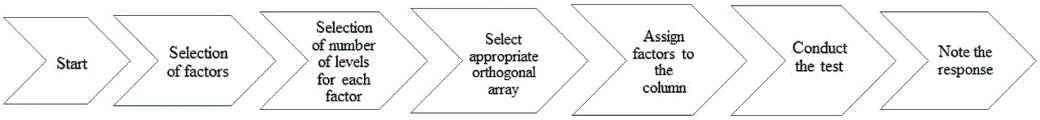


Figure 2. Flow chart of Taguchi approach

Table 2
Process variables and their levels

Process Variables	Units	Notation	Limits			
			1 (Low)	2 (Medium)	3 (High)	4 (Extremely High)
Temperature	°C	t	87	94	101	108
Ripple current	mA	r	26	28	30	32
Humidity	Rh	r	80	82	84	86
Voltage	V	v	5.8	6	6.2	6.4

3. Selection of appropriate orthogonal array. The L_{16} orthogonal array was selected for performing experiments using the Taguchi approach.

Table 3
L16 orthogonal taguchi approach

Run	Factors			
	Temperature	Ripple current	Humidity	Voltage
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	2	1	2	3
6	2	2	1	4
7	2	3	4	1
8	2	4	3	2
9	3	1	3	4
10	3	2	4	3
11	3	3	1	2
12	3	4	2	1
13	4	1	4	2
14	4	2	3	1
15	4	3	2	4
16	4	4	1	3

4. Assignment of factors to columns. To calculate the life of the capacitor, the values were assigned to all the factors, divided among four levels. Then, the acceleration factors were calculated for all the factors. Afterwards, the total lifetime of the electrolytic capacitor was calculated using Equation (10). The values of factors, as seen in Table 2 were inserted in Table 3. After inserting the values of the factors, acceleration factors corresponding to those factor values were calculated using Equations (3-11). Then, the lifetime of the capacitor was analysed.
5. Conduct of the test. Life calculation experiments were conducted as per the design matrix of Table 3. The different combinations of process variables and factors were conducted. The extremely high temperature corresponded to the accelerated stress factors and using the Arrhenius equation, the output life could be calculated. Then the analytical and experimental life has been compared.

Statistical Model of Lifetime Prediction

The regression technique was used to estimate the relationship of a response variable to a set of predictor variables to develop a mathematical model to predict the tool life of the capacitor. The relationship between the independent process parameter variables and capacitor life can be represented by the following mathematical model:

$$CL(Lifetime) = C(T^l \times R^m \times V^n \times H^o) \quad [12]$$

where, CL is the measure of response (capacitor life); T, R,V and H the values of the process parameters i.e. temperature, ripple current, voltage, frequency and humidity respectively; C is a model constant; and l, m, n, and o are model parameters.
The above Equation (14) can be represented in linear form as under:

$$\ln CL = \ln C + l \ln T + m \ln R + n \ln V + o \ln H \quad [13]$$

Equation (15) can be further modified as given below:

$$Y = \beta 0 + \beta 1\ X1 + \beta 2\ X2 + \beta 3\ X3 + \beta 4\ X4 \quad [14]$$

where, Y is the capacitor life on logarithmic scale; X1, X2, X3, X4 and X5 are logarithmic transformations of temperature, ripple current, voltage, frequency and humidity (i.e. X1=ln T; X2=ln R; X3=ln V; X4=ln H; β0=ln C; β1=l; β2=m; β3=n; β4=o). The values of β0, β1, β2, β3, β4 and β5 represent the regression coefficients to be determined. In this study, a multiple regression model using the linear regression technique was developed to predict tool life based on experimental values. The coefficients for the regression model were determined using Minitab statistical software.

RESULTS AND DISCUSSION

Using the design of experiment (DOE) approach, the L16 design matrix was generated. Life was calculated using the analytical method, statistical method and experimental method. Then, the different techniques were compared and the most accurate one was chosen.

Analytical Life Calculation

Using analytical life calculation models, the values of factors assigned in the design matrix and then the values of acceleration factors were calculated and substituted in Equation [8] to find the lifetime of the capacitor.

Table 4
Lifetime calculation using the analytical method

Run	Factors (Actual form)				Lifetime (hours) Using Analytical Method
	Temperature (^{O}C)	Ripple Current (mA)	Humidity (%Rh)	Voltage (Volts)	
1	87	26	80	5.8	8220.05
2	87	28	82	6.0	7648.26
3	87	30	84	6.2	7110.02
4	87	32	86	6.4	6639.03
5	94	26	82	6.2	4079.17
6	94	28	80	6.4	5087.09
7	94	30	86	5.8	4027.87
8	94	32	84	6.0	5077.32
9	101	26	84	6.4	2102.44
10	101	28	86	6.2	2070.36
11	101	30	80	6.0	3716.00
12	101	32	82	5.8	3684.14
13	108	26	86	6.0	1185.15
14	108	28	84	5.8	1569.27
15	108	30	82	6.4	1827.66
16	108	32	80	6.2	2438.30

Statistical Life Calculation

Using Minitab 18.1 software, regression analysis was done. The t-test was used to test the accuracy of the model. Accuracy was measured by the fact that the variance value should be minimal and the R^2 value should be higher.

Regression equation=-10465 + 2097.8 Temperature + 1840 Current 2653 Humidity + 5639 Voltage [15]

Table 5
Analysis of regression model

S	R-sq	R-sq (adj)	R-sq (pred)
208.913	99.39%	99.16%	98.76%

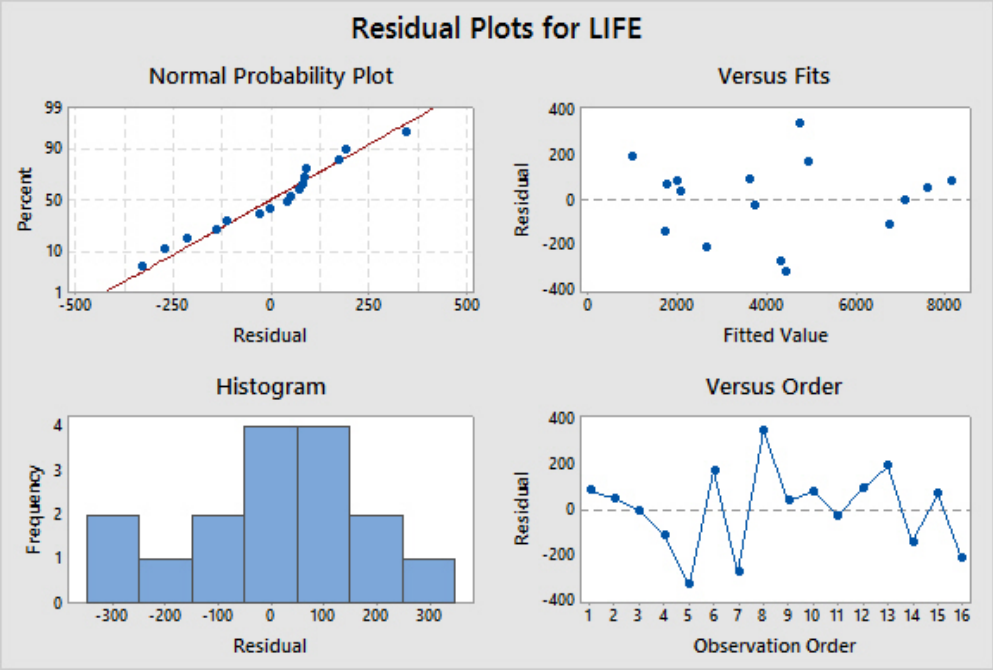


Figure 3. Regression outputs using Minitab software

Using Equation [15], life was calculated using the regression equation shown in Table 6.

Table 6
Lifetime calculation using regression method

Run	Factors (Actual Form)				Lifetime (hours) Using Regression	Error (%)= ([Analytical-Regression]/ Analytical)*100
	Temperature (^{O}C)	Ripple Current (mA)	Humidity (%Rh)	Voltage (Volts)		
1	87	26	80	5.8	8138.07	1.00
2	87	28	82	6.0	7598.97	0.64
3	87	30	84	6.2	7114.96	-0.07
4	87	32	86	6.4	6752.90	-1.72
5	94	26	82	6.2	4409.64	-8.10
6	94	28	80	6.4	4915.83	3.37
7	94	30	86	5.8	4303.34	-6.84
8	94	32	84	6.0	4731.87	6.80
9	101	26	84	6.4	2064.21	1.82
10	101	28	86	6.2	1990.80	3.84
11	101	30	80	6.0	3746.03	-0.81
12	101	32	82	5.8	3594.96	2.42
13	108	26	86	6.0	993.76	16.15
14	108	28	84	5.8	1710.95	-9.03
15	108	30	82	6.4	1758.78	3.77
16	108	32	80	6.2	2652.99	-8.80
					Average Error (%)	**0.28**

Experimental Life Calculation

Gulbrandsen, Arnold, Caswell and Cartmill (2014) analysed the lifetime of electrolytic capacitors using practical methods. In their experimental setup, different levels of stress were introduced to the component i.e. temperature, voltage, current and humidity. Twenty capacitors were put on a hotplate and covered with sand. The initial measured capacitance, ESR and weight of the individual capacitors showed changes in characteristics during heating. Those were measured again. If capacitance decreased by 20% or ESR increased by 100% and weight decreased, then the capacitor was said to be failed. Lifetime was calculated using the Arrhenius law as per Equation [10-11].

The extract lifetime, using the experimental method, is summarised in Table 7. The analytically calculated life is compared with the experimental value and the percentage error was calculated. Jano and Pitica (2012), and Ashburn and Skamser (2008) used accelerated life testing for exploring de-rating factors in the electrolytic capacitor.

Table 7
Error analysis of analytically calculated lifetime

Run	Lifetime (Experimentally) (hours) "A"	Lifetime Analytically (hours) "B"	Lifetime Statistically (hours) "C"	Error (%)= [(A-B)/A] *100	Error (%)= [(A-C)/A] *100
1	8,875.76	8,220.05	8,138.07	7.39	8.31
2	8,289.17	7,648.26	7,598.97	7.73	8.33
3	7,654.65	7,110.02	7,114.96	7.12	7.05
4	7,042.39	6,639.03	6,752.90	5.73	4.11
5	5,514.56	4,079.17	4,409.64	26.03	20.04
6	5,929.18	5,087.09	4,915.83	14.20	17.09
7	3,915.28	4,027.87	4,303.34	-2.88	-9.91
8	5,965.11	5,077.32	4,731.87	14.88	20.67
9	2,156.27	2,102.44	2,064.21	2.50	4.27
10	2,015.98	2,070.36	1,990.80	-2.70	1.25
11	3,946.79	3,716.00	3,746.03	5.85	5.09
12	3,741.43	3,684.14	3,594.96	1.53	3.91
13	1,315.29	1,185.15	993.76	9.89	24.45
14	1,662.12	1,569.27	1,710.95	5.59	-2.94
15	2,177.59	1,827.66	1,758.78	16.07	19.23
16	2,365.62	2,438.30	2,652.99	-3.07	-12.15

Comparison Between Experimental and Analytical Models

The lifetime of an electrolytic capacitor was calculated using the accelerated life testing method as well as the proposed model of analytical testing. The average error between analytical life and experimental calculated life, in percentage, was 7.24%. So, the proposed analytical method gives an accuracy of measure of 92.76%. The graphical analysis of lifetime calculation using both models, for various conditions as suggested by the Taguchi method is shown in Figure 3.

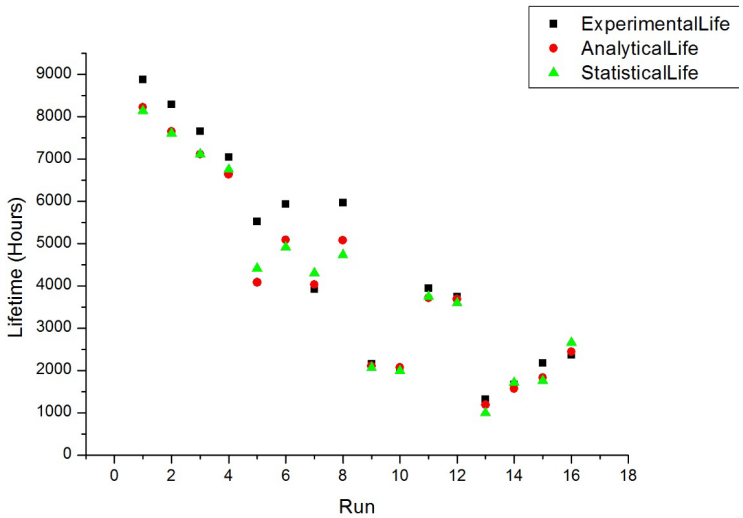


Figure 4. Graphical analysis of lifetime calculation

It has been seen that after considering the humidity factor and its effect on the performance of an electrolytic capacitor, the calculated lifetime (hours) was close to the value of lifetime (hours) that was received using the accelerated life testing method. Sometimes, it is not feasible to carry out experiments over long periods. In such cases, the analytical method can be used for failure prediction of an electrolytic capacitor.

CONCLUSION

The mathematical modelling of electrolytic capacitors was explored in this paper. The analysis of the performance of a capacitor with respect to various environmental conditions and electrical parameters were investigated. A new model was proposed for calculating residual life of an electrolytic capacitor; it considered the effect of humidity on performance and condition of the capacitor. Using the Taguchi method, experiments were designed and performed. Using the Minitab 18.1 software, the statistical method provided a regression analysis that had an average error rate of 0.28%. The corrected model of the analytical method stipulated that mean life was 4535.45 hr in comparison with the experimentally calculated mean life, which was. 4155.13 hr. After comparing the life time of the capacitor using the experimental and analytical methods, an error analysis was conducted and the error was calculated. The proposed corrective model had an error rate of 7.24% and accuracy of 92.76%, which validated the mathematical model.

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