Journal of Materials and
Environmental Sciences
ISSN : 2028-2508
CODEN : JMESCN

J. Mater. Environ. Sci., 2018, Volume 9, Issue 5, Page 1503-1511

https://doi.org/10.26872/jmes.2018.9.5.165

http://www.jmaterenvironsci.com

Health Prognostics of electrolytic capacitor using various environmental testing methods

Cherry Bhargava[1,2*], **Vijay Kumar Banga**[3], **Yaduvir Singh**[4]

1. Research Scholar, Department of ECE, IKG PTU, Kapurthala, 144603, India.
2. Assistant professor, Department of ECE, Lovely Professional University, Phagwara, 144411, India.
3. Principal, Amritsar College of engineering and technology, Amritsar, 143001, India.
4. Dean and professor, Department of EE, Harcourt Butler Technological University, Kanpur, 208301, India.

Received 22Jun 2017,
Revised 16Aug 2017,
Accepted 25 Aug 2017

Keywords
- ✓ Condition monitoring,
- ✓ Electrolytic Capacitor,
- ✓ Failure Prediction,
- ✓ Reliability,
- ✓ Accelerated life testing.

C. Bhargava
cherry.bhargava@lpu.co.in;
Phone: +91-81469-92303

Abstract

An electrolytic capacitor is widely used in various electronic design and manufacturing industries. Cheaper price and higher capacitance, makes it famous amongst other components. The reliability becomes a challenge as more and more components integrate on a single chip. The electrolytic capacitor derates on a faster pace, as environmental stress and electrical parameters enhances. An Electrolytic capacitor of 1000µf capacity is explored using environmental testing. Various techniques based on physics of failure are explored. This paper focuses on a new technique has been proposed, which explores the impact of ripple current, humidity and frequency along with thermal stress and voltage. Comparison shows that proposed technique has the least error i.e. 5.7% as compared to 23% for technique-A, 38.3% for technique-B and 54.5% for technique-C.

1. Introduction

Modern era is completely dependent on design and manufacturing industry. From ship to satellite, all devices are totally dependent on electronics. As more and more components integrate, reliability becomes a challenge. To judge the capability of a component, lifespan over the critical applications are examined. Electrolytic capacitor is heart of all electronic gadgets and devices. The lifetime of an electronic gadget depends upon the lifetime of an electrolytic capacitor (elcap) inside, in most of the electronic products [1]. During the designing phase, main consideration are space and cost. Before launching the device in real world, variety of experiments are conducted on the components. By assessing the results of these tests, a datasheet is prepared which contains all rated parameters along with maximum life span of the component. Actual application of device may alter the maximum lifespan of component or device, depends on criticality of application.

An aluminum electrolytic capacitor is a passive component which is lifeline of many devices and gadgets. Its charge storage capacity depends on the capacitance of that particular aluminium electrolytic capacitance. As the environmental parameters vary, the characteristics of elcap vary on a faster pace. Loss of electrolyte will increase the value of equivalent series resistance (ESR) [2]. Literature survey has been carried out to explore the capacitor lifetime at different operating conditions. It has been investigated that excessive temperature and voltage degrades the response as well as lifetime of capacitor. This paper reports the effect of ripple current, humidity and ESR along with above mentioned parameters and effective lifetime of capacitor has been analyzed. The thermal analysis of electrolytic capacitor is observed.

2. Thermal failure of electrolytic capacitor

Electrolytic capacitors are widely used in power electronic circuits. High ripple current and high temperature of the environment in which the capacitor operates cause heating of the capacitor due to power dissipation in it [3]. Temperature is an important factor which affects the life span of electrolytic capacitors and this aspect should be considered. Electrolytic capacitors can fail due to many reasons such as high temperature during soldering, internal power dissipation due to ripple, etc. high ambient temperature, reverse voltage, voltage transients, etc. The thermally induced failure mechanism in wet electrolytic capacitors is triggered by electrolyte evaporation at high temperature [4]. High temperatures cause hot spots within the capacitor and lead to its failure. In power electronic circuits, electrolytic capacitors are exposed to high temperatures and high ripple currents. When charging and discharging currents flow through a capacitor, losses are caused by ohmic resistance which causes an increase in temperature.

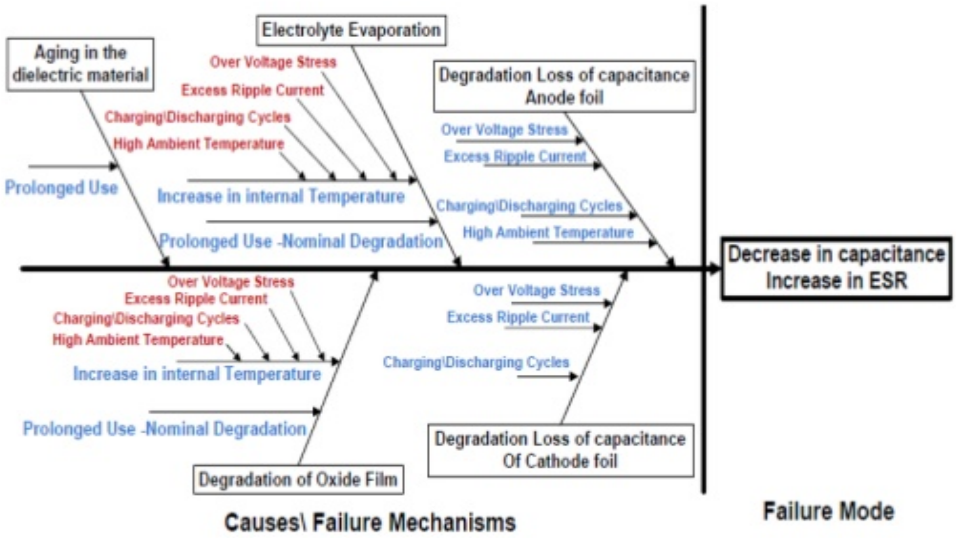

Figure1: Fishbone diagram for failure analysis of el-cap

Figure 1 Shows cause and effect of capacitor failure in terms of afishbone diagram. Several methods have been proposed to evaluate the degradation level of an aluminum electrolytic capacitor. Deterioration or evaporation of electrolyte can reduce the weight of the capacitor [5]. The derating and degradation of a capacitor are characterized by a decrease in capacitance and increased in equivalent series resistance (ESR). If the capacitance decreases below a particular value, the capacitor will no longer store the energy or filtering function. The integration of environmental, electrical and mechanical stress is the root cause of capacitor failure [6].

2.1 Failure criteria for electrolytic capacitors

The aluminum electrolytic capacitors are said to be failed if they fulfil all the following conditions. The value of capacitance, ESR and weight loss was measured after each and every thermal cycle.

1. Capacitance was decreased by 20% of its initial value.
2. The weight has been decreased by at least 50% of its initial value.
3. ESR value has been increased by 100% of its initial value.

As soon as heating will be accelerated, the electrolyte will start evaporating and it will consequently decrease the value of capacitance and increase the value of ESR. Weight loss is the key parameter to analyze evaporation of electrolyte [7].

3. Experimental setup

3.1 Materials and Methods used

For the accelerated life testing, twenty electrolytic capacitors were selected from two different manufacturers, divided in two set in set A and set B. Initially all the twenty capacitors were analyzed using LCR meter and initial readings were noted for capacitance, ESR and weight of each capacitor [8].

Table1: Capacitors Specifications of different manufacturers

Set-A/B	Capacity	Rated Voltage	Rated Current	Rated Humidity (%Rh)	Rated Temperature (^{O}C)	Lifetime (hours)	Weight (gms)
Set-A	1000 µf	16V	470mA	85	85	2500	7.5
Set-B	1000 µf	16V	577mA	80	105	2000	9

3.2. Experimental setup

After taking the initial reading, drilled a hole of 9mm in each capacitor and placed the capacitors on a hot plate, covered with sand so that uniform heating would be there.

Figure2: Capacitor with a drilled hole

All the electrolytic capacitors were fixed with a voltage source of 9V DC. Thermal stress was dispensed. The thermal profile has been shown in figure 3. The humidity of the closed chamber was set as $75R_H$. The accelerated temperature was set as 150^oC and the ambient temperature was chosen as 70^oC.

Figure 3: Experimental setup

At the start of the experiment, capacitors were placed at ambient temperature at the hot plate. Gradually, temperature was increased up to 150^oC (Ta=15 minutes). The total time for accelerated life testing is 240 hours. If we chose fast thermal cycling, it would have deleterious consequences on capacitor health, so slow heating was selected.

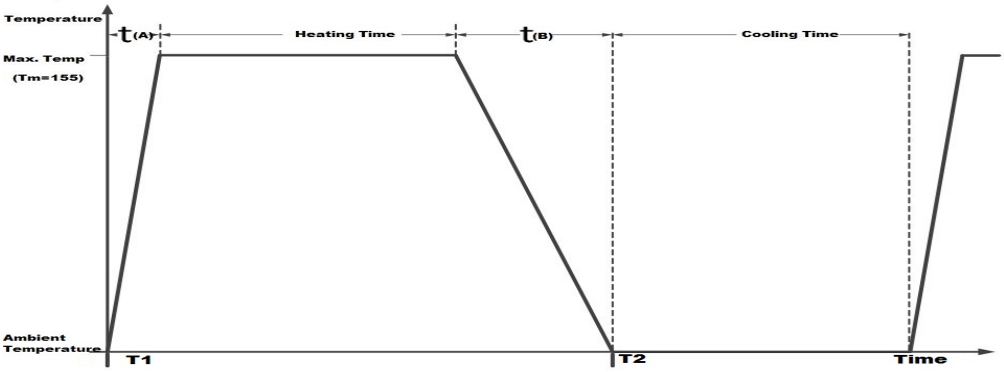

Figure 4: Accelerated testing time versus temperature

At the end, T1 and T2 times, the values of capacitance, ESR and weight loss were again measured. Failure time was calculated as the failure conditions [9].

3.3 Experimental results and analysis

The flowchart depicts the whole process of experimental setup and procedure. As soon as the temperature accelerates, the degradation of the capacitor also enhances [10].

If at final time T1 and T2, it was decided that all the three conditions were fulfilled, that capacitor was said to be failed [11].

After analysingeach and every capacitor, the average fail time was calculated for set A and set B eligible capacitors, who fulfilled the failure criteria, as per equation (1), (2) and (3)

$$FT(C) = \sum \text{(Heating time)}, \quad \text{if } C_{new} < 20\% \text{ of } C_{initial} \text{(for all eligible capacitors)} \qquad (1)$$

$$FT\ (ESR) = \sum \text{(Heating time)}, \quad \text{if } ESR_{new} > 100\% \text{ of } ESR_{initial} \text{ (for all eligible capacitors)} \qquad (2)$$

$$FT\ (W) = \sum \text{(Heating time)}, \quad \text{if } W_{new} < 50\% \text{ of } W_{initial} \text{ (for all eligible capacitors} \qquad (3)$$

FT(C) refers to cumulative failure time sum of all the capacitors, which could not satisfy equation (1), for both sets A and B, whereas FT (ESR) indicates the sum of the heating time of all capacitors which could not satisfy equation (2). Similarly, FT (W) refers to the capacitor total heating time which results in a reduction of weight by 50% as equation (3), then average failure time was calculated for both set.

It has been summarized in table2. With increase in temperature, performance characteristics vary on accelerated pace [12]. The weight loss is due to evaporation of electrolyte [13]. As the volume of electrolyte reduces, the value of ESR increases and capacitance decreases [14].

As the temperature rises, the evaporation of electrolyte accelerates which consequently, decreases the capacitance and increases the ESR. So, weight loss is the key factor for judging the failure of the capacitor. So, reliability of electrolytic capacitor is effectively explored using accelerated life testing technique [15].

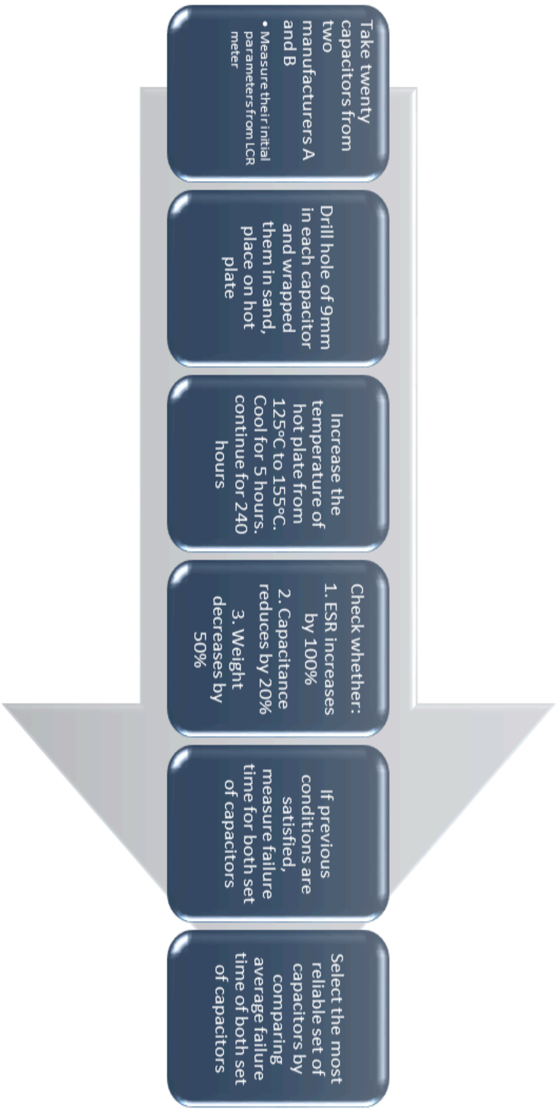

Figure 5: Flow chart of experimental test

Table 2: Average failure time of tested capacitors (Set A and Set B)

Set (A/B)	**∑ (C) (hours) capacitive failure time**	**∑(ESR) (hours) ESR failure time**	**∑(W) (hours) weight loss failure time**
A	301.6	295.5	277.1
B	292.7	255.6	235.9

4. Condition Monitoring of electrolytic capacitor using various theoretical methods

To estimate failure time of a capacitor, we used the experimental method. The industry uses different standards to find the failure time, based on various rules. Some methods are based on MILHDBK-217, FIDES, RIAC 17 plus. There are other theoretical methods which are based on failure of physics and theory of overstress [16-18]. In this paper, three various methods were used for calculating the failure time and then a comparison was done with the practical results.

4.1 Lifetime calculation using Method-A

As proposed by Whitman et. al [19], derating of capacitor life and its performance degradation accelerates with increased temperature. As the temperature increases, it initiates the change in chemical reactions, because an electrolytic capacitor is an electrochemical device [20]. It has been assumed that with every ten degrees rise in temperature, degrades the capacitor life by a factor of 2. So, increase in temperature, furthermore reduces the capacitance.

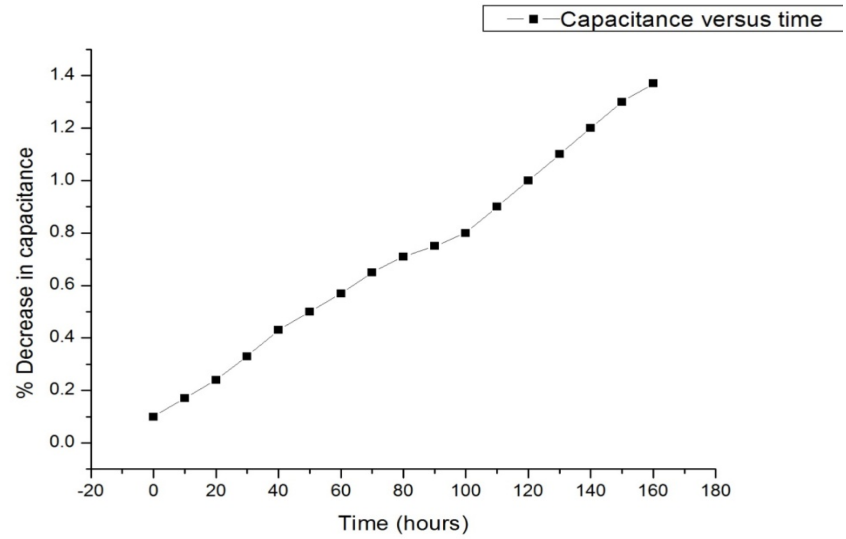

Figure6: Decrease in capacitance with time

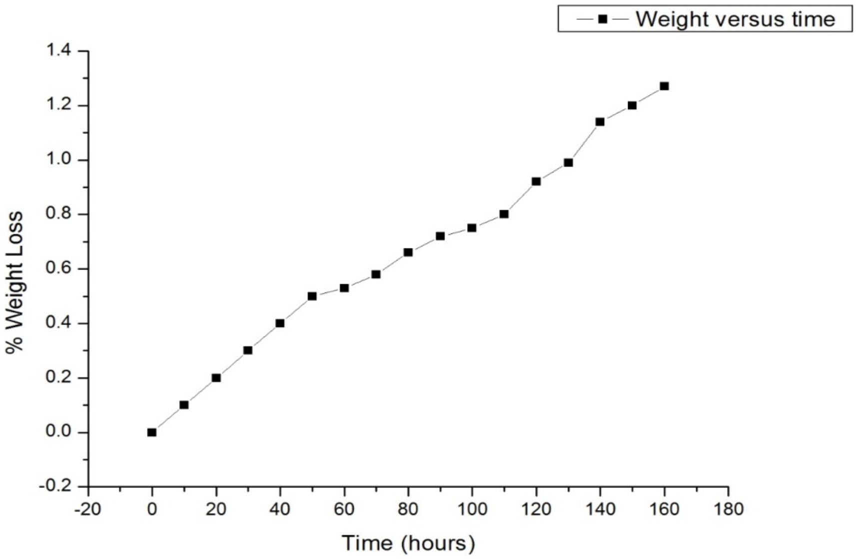

Figure7: Decrease in capacitor weight with time

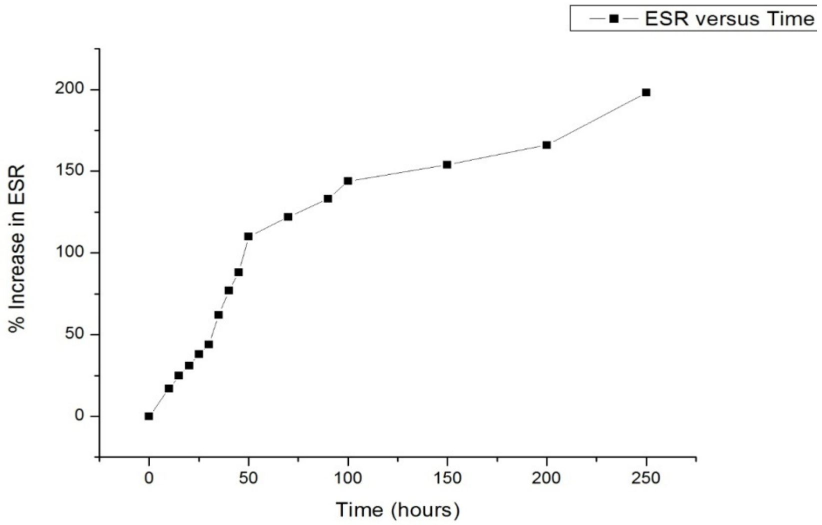

Figure 8: Incremental growth in ESR with time

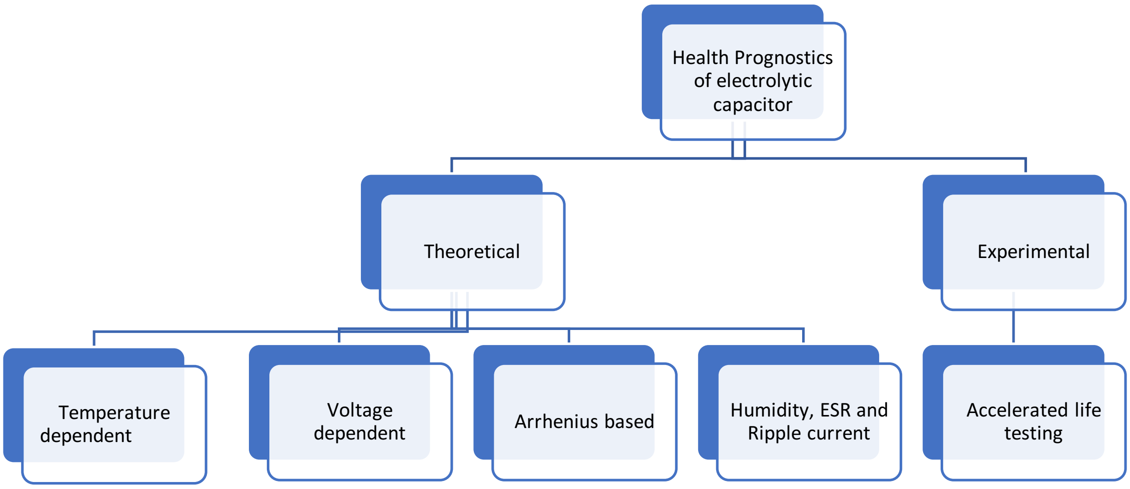

Figure9: Flow chart of capacitors' condition monitoring

The expected life using this method can be calculated as equation 4:

$$\mathrm{LT\ (expected)} = \mathrm{LT(datasheet)} \times \mathrm{K_T} \tag{4}$$

$$\mathrm{LT\ (expected)} = \mathrm{LT(datasheet)} \times 2^{\frac{(\mathrm{Tm\text{-}Ta})}{10}} \tag{5}$$

Where LT (expected)=expected lifetime of capacitor; LT(datasheet)=lifetime declared by manufacturer in datasheet; K_T=Temperature acceleration factor=$2^{[(Ta\text{-}Tm)/10]}$ and Tm (k)=Maximum Temperature and Ta (k) =Accelerated temperature

4.2 Lifetime calculation using Method-B

In method B, as suggested by A. Dehbi et. al [21], the degradation of capacitor life doesn't depend on only temperature acceleration factor, but also on the rated and operated voltage. The capacitor life will be more in case, it has been used within rated voltage limit [22]. The expected life using this methodology was calculated as equation (6), which is modified version of equation (4):

$$LT\ (expected) = LT(datasheet) \times K_T \times K_V \tag{6}$$

$$LT\ (expected) = LT(datasheet) \times 2^{\frac{(Tm-Ta)}{10}} \times \left(\frac{Va}{Vm}\right)^{-n} \tag{7}$$

Where K_V=Voltage acceleration factor= $(Vo/Vn)^{-N}$ and n=constant=1 for radial capacitors

4.3 Lifetime calculation using Method-C

This proposed method is based on the accelerated aging time, it is an effective prognostic technique which is used to predict residual life as well as its diagnosis the current health of the capacitor. Using Arrhenius law, the accelerated aging time has been calculated. Capacitors were set to operate in aggravated conditions of thermal stress, acceleration factor is calculated. For example, per the Arrhenius equation, a Sterile Barrier System that is subjected to 40 days of Accelerated Aging at +55° Celsius has similar aging characteristics as a 1-year-old Real time sample.

$$LT(expected) = \frac{1}{Hours\ of\ operationTime \times Total\ Number\ of\ devices} \times Af \tag{8}$$

Where Acceleration factor $\mathbf{A_F} = \mathbf{e}^{\frac{\mathbf{Ea}}{\mathbf{K}}\left[\frac{\mathbf{1}}{\mathbf{Tm}} - \frac{\mathbf{1}}{\mathbf{Ta}}\right]}$

4.4 Theoretical lifetime calculation

Using above suggested methods, the lifetime of the capacitor has been calculated and it has been summarized in table 3.

Table 3: Lifetime calculations using various theoretical methods

Set (A /B)	Calculated expected lifetime (hours)		
	Technique -A	Technique -B	Technique -C
A	112.8	144.8	208.2
B	91.2	191.1	205.6

5. Error analysis using theoretical and experimental methods

After analyzing the lifetime values using all three theoretical methods, a comparison has been explored with the practically achieved failure time. The percentage error has been calculated for all the three methods with respect to practically calculated value for capacitive, ESR and weight loss failure time.it has been analyzed that out of these three, the combined effect of temperature and voltage on lifetime has more impact on lifetime and it is more accurate to the practical results:

$$Error\ (\%) = \frac{(Experimental\ value - Theoretical\ value)}{Experimental\ value} \times 100 \tag{9}$$

$$Accuracy\ (\%) = 100 - Error(\%) \tag{10}$$

Using equation (9) and (10), the error analysis and accuracy of the prediction models can be accessed

Table 4: Error analysis of theoretical methods with experimental method

Set (A/B)	Set-A			Set-B		
	Technique - A	Technique - B	Technique - C	Technique - A	Technique - B	Technique - C
Error (C)%	62.5	51.9	30.9	68.8	34.7	29.7
Error (ESR)%	61.8	50.9	29.5	64.3	25.2	19.5
Error (W)%	59.2	47.7	24.8	61.3	18.9	12.8

6. Proposed method for lifetime calculation

All the theoretical techniques are assessed in terms of failure time for capacitance, ESR and weight loss [23]. The proposed method takes care humidity, ripple current as well as frequency, to calculate residual lifetime. The modified lifetime calculation for electrolytic capacitor is shown in equation (9), which has acceleration factor of all the five components. Humidity acceleration model is extended form of peck's law, as suggested by Nihal Sinnadurai et al. [24]. Electrolytic capacitors have higher heat dissipation due to ripple current. To guarantee the capacitor's life, the greatest ripple current of the capacitor is specified [13]. At the point when ripple current flows through the capacitor and the internal heat is produced inside the capacitor and the performance of capacitor starts degrading, when the internal heat exceeds beyond the limit, the capacitor gets fail. The frequency factor also affects the life of capacitor. The frequency exceeds as the internal ripple current starts rising, which subsequently evaporates the electrolyte:

$$LT\ (expected) = LT(datasheet) \times K_T \times K_V \times K_H \times K_I \times K_F \tag{11}$$

$$LT\ (expected) = LT(datasheet) \times\ 2^{\frac{(Tm-Ta)}{10}} \times \left(\frac{Va}{Vm}\right)^{-n} \times Ki^{A\frac{\Delta T}{10K}} \times \frac{\sqrt{ESR(fo)}}{\sqrt{ESR(fa)}} \times \exp\{0.00044 \times ((RHa)^n - (RHm)^n)\} \tag{12}$$

Where, K_H, K_I and K_F are acceleration factors of humidity, ripple current and frequency respectively.

6.1 Calculation of lifetime for Set A and Set B

For both sets, the effect of humidity has been analyzed along with temperature and voltage effect. The rated humidity value for Set-A is 85RH, whereas for Set-B, the rated humidity value is 80RH. Lifetime has been calculated as per equation (9). It has been summarized in table 5.

Table5: Calculated lifetime for both sets

Proposed Method		
Lifetime (hours)	Set-A	Set-B
	288.1	247.8

Furthermore, it has been explored that lifetime calculation using proposed method is very much close to the values that have been calculated by experimental methods.

7. Results and discussion

All the theoretical methods have been analyzed for calculation of electrolytic capacitors lifetime. Then these values were compared with experimental obtained results. This has been tabularized in table 6.
This proposed method was then used for set-A and set-B capacitors' lifetime calculation. The performance of this method was measured in terms of accuracy with respect to experimental results.

The table 6 shows that proposed method has the highest accuracy level for both sets. For set-A capacitors, accuracy is 96.4% in comparison to 38.8%, 49.7% and 71.6% for method-A, method-B and method-C respectively. Similarly, for set-B capacitors, proposed method has been proved the most accurate method with 92.21% accuracy, in comparison with 35.2%, 73.7% and 79.7% for method-A, method-B and method-C respectively.

Table 6: Accuracy analysis of lifetime calculation methods

Set→	Set-A				Set-B			
Theoretical Methods→	A	B	C	**Proposed Method**	A	B	C	**Proposed Method**
Accuracy (C)%	37.5	47.9	69.1	**95.6**	31.2	65.3	70.3	**84.7**
Accuracy (ESR)%	38.2	49.1	70.5	**97.5**	35.7	74.8	80.5	**96.9**
Accuracy (W)%	40.8	52.3	75.2	**96.1**	38.7	81.1	87.2	**95.1**
Average Accuracy (%)	**38.8**	**49.7**	**71.6**	**96.4**	**35.2**	**73.7**	**79.3**	**92.2**

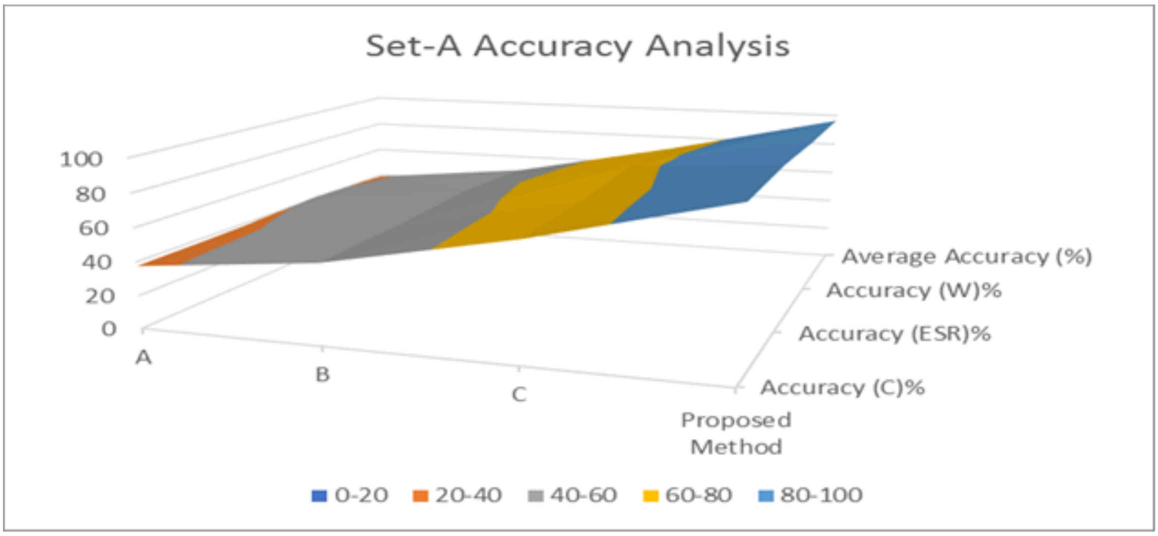

Figure10: Accuracy representation of all methods for set-A capacitors

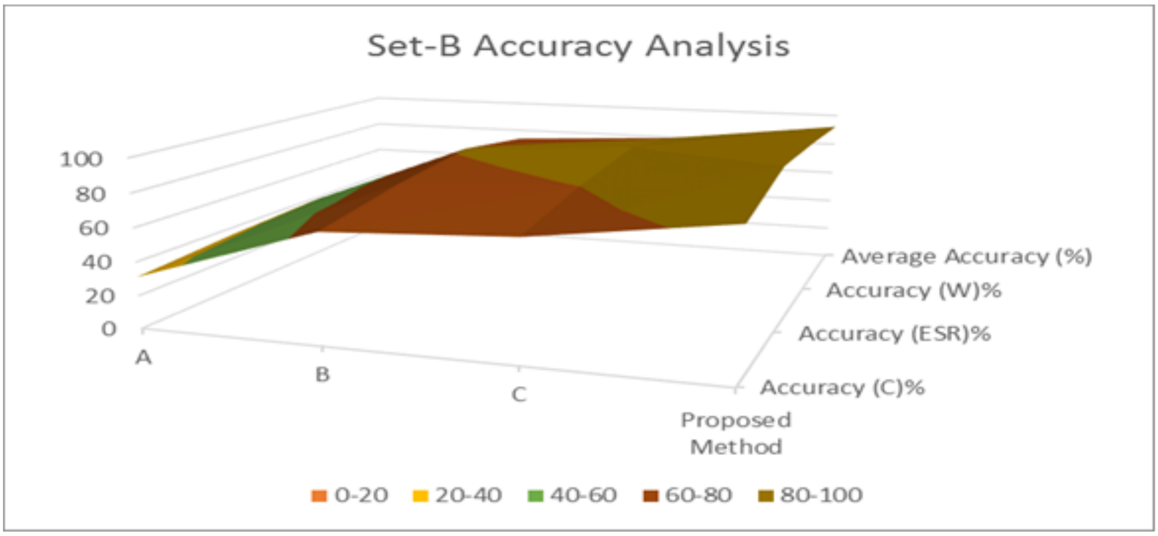

Figure 11: Accuracy representation of all methods for set-B capacitors

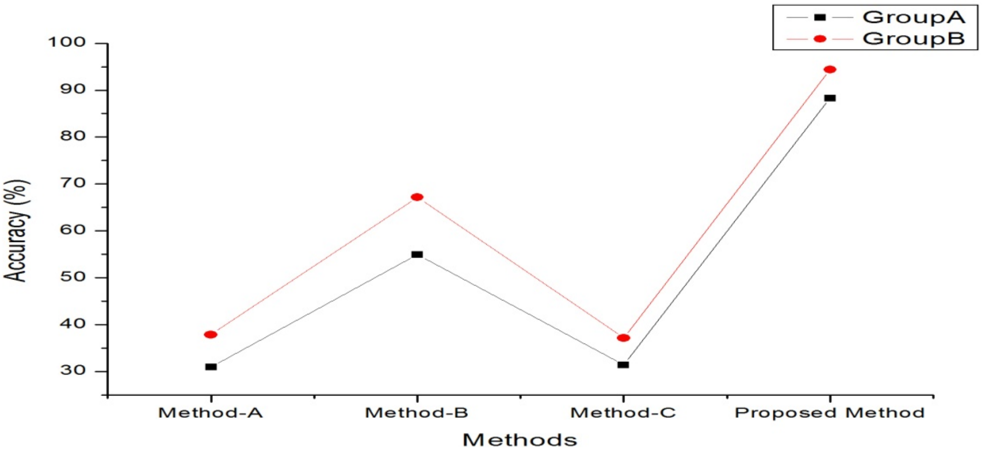

Figure 12: Accuracy analysis of all methods

The performnace variation of both techniques i.e. proposed as well as other methods are graphically shown as in figure 12. It further explores that the proposed method is validated and the most accurate method for health prognostics of electrolytic capacitors.

Conclusion

Condition monitoring becomes a challenge for widely used electrolytic capacitor. Lifetime has been explored for 1000µf electrolytic capacitor using various methods and comparison is made to assess the accurate model. At the end, proposed model provides an accuracy of 94.3% in comparison with technique-A, technique-B and technique-C, which have average accuracy of 36.75%, 61.7% and 75.45% respectively.

References

1. A. Bengt, *RIFA Electrolytic Capacitors*, Sweden (1995) 360.
2. B. Dimitri, *DEStech Publications* (2006) 605.
3. IEC-60068-1, IEC Standards (1988).
4. C. Bhargava, VK. Banga and Y. Singh, (2014), *IEEE conf. RAECS*, Chandigarh, (2014) 1-7.
5. R. Kotz, M. Hahn and R.Gallay, *J. power sources*, 154 (2006) 550–555.
6. VA. Sankaran, FL. Rees and CS.Avant, *IEEE Industry Applications Conference*, LA,(1997) 1058 - 1065.
7. R. Jano and D.Pitica, *ACTA Technical Napocensis,* 53 (2012) 36-41.
8. VNA. Naikan, and A. Rathore, *SRESA Nat. Conf. Relia.Saf. Engg.,* Mumbai, (2014) 79-82.
9. N. Ahmad, A. Islam and A. Salam, *Int. J. Qual. Reliab.Manag.,* 23 (2006) 1019X46.
10. JL. Stevens, JS. Shaffer and JT. Vandenham, *IEEE Trans. Ind. Appl.,*38(2002) 1441-1446.
11. S. Gulbrandsen, J. Arnold, G. Caswell, K. Cartmill, *Int. Sympo. Microelectr.,* San Diego, (2014) 000662-000667.
12. S.G. Parler, *IEEE Pwr. Electr. Soc. News Letter,* 16 (2004).
13. X. Huang, P.M. Denprasert, L. Zhou, A.N. Vest, S. Kohan, G.E. Loeb, *J. Biomed. Microdev.,* 19 (2017) 46-53
14. C. Kalaiselvan and LB Rao, *J. Measurement,* 88 (2016) 58-65.
15. P. Kurzweil, A. Hildebrand and M. Weib, *J. Chemelectrcochem.,* 2 (2015) 150-159.
16. B. Saha, K. Goebel, and J. Christophersen, *Trans. Inst. Measurment Control,* 31 (2009) 293-308.
17. H. Ma and L. Wang, *IEEE 31st Annu. Conf. of Ind. Electron.Soc. (IECON),* NC (2005) 1-8.
18. M. Held and K. Fritz, *Microelectron. Reliab.,*49(2009) 967-971.
19. CS. Whitman, *Microelectron. Reliab.,* 52(2012) 2-8.
20. M. Rusdi, Y. Moroi, H. Nakahara, and O. Shibata, *Langmuir,*36 (2005) 7308-7310.
21. A. Dehbi and W. Wondrak,*Microelectron. Reliab.,* 42 (2004) 835-840.
22. J. Renwick, CS. Kulkarni and JR. Celaya, *Ann. Conf. Prog. Health Manag. Soc.,* California, (2015) 1-7.
23. SM. Zaharia, S. Martinescu and CO. Morariu, *Eksploat Niezawodn*, 14 (2012) 99-106.
24. FN. Sinnadurai, *Microelectron. Reliab.,* 13(2014)23-27.

(2018) ; http://www.jmaterenvironsci.com